Remote Sensing of Environment 113 (2009) 392–397

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Effects of atmospheric variation on AVHRR NDVI data

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ARTICLE INFO

Article history:
Received 19 May 2007
Received in revised form 3 October 2008
Accepted 11 October 2008

Keywords:
AVHRR
NDVI
Global change
Error
Uncertainty
PAL
GIMMS
GVI
LTDR
AERONET
Accuracy
Precision

ABSTRACT

The AVHRR (Advanced Very High Resolution Radiometer) series of instruments has frequently been used for vegetation studies. The 25+ year record has enabled important time-series studies. Many applications use NDVI (Normalized Difference Vegetation Index), or derivatives of it, as their operational variable. However, most AVHRR datasets have incomplete atmospheric correction, because of which there is considerable, but largely unknown, uncertainty in the significance of differences in NDVI and other short wave observations from AVHRR instruments.

The purpose of this study was to gain better understanding of the impact of incomplete or lack of atmospheric correction in widely-used, publicly available processed AVHRR-NDVI long-term datasets. This was accomplished by comparison with atmospherically corrected AVHRR data at AERONET (AErosol RObotic NETwork) sunphotometer sites in 1999. The datasets included in this study are: TOA (Top Of Atmosphere) that is with no atmospheric correction; PAL (Pathfinder AVHRR Land); and an early version of the new LTDR (Long Term Data Record) NDVI. The other publicly available datasets like GIMMS (Global Inventory Modeling and Mapping studies) and GVI (Global Vegetation Index) have atmospheric error budget similar to that of TOA, because no atmospheric correction is used in either processing stream. Of the three datasets, LTDR was found to have least errors (accuracy = 0.0064 to −0.024, precision = 0.02 to 0.037 for clear and average atmospheric conditions) followed by PAL (accuracy = −0.145 to −0.035, precision = 0.0606 to 0.0418), and TOA (accuracy = −0.0791 to −0.112, precision = 0.0613 to 0.0684). It was also observed that temporal maximum value compositing technique does not cause significant improvement of precision in regions experiencing persistently high AOT (Aerosol Optical Thickness).

1. Introduction

The AVHRR (Advanced Very High Resolution Radiometer) is a meteorological sensor system onboard the NOAA (National Oceanic and Atmospheric Administration) series of sun-synchronous, polar-orbiting satellites (Kidwell, 1998). The AVHRR sensor collects data in the visible, near infrared and thermal infrared wave lengths. After its capability for measuring Earth surface properties was demonstrated (Townshend & Tucker, 1981; Tucker et al., 1984), these data have been used extensively for Earth system science research. The most useful features of the AVHRR dataset are: its temporal extent of more than 26 years which continues to be extended; appropriate resolution for global and regional scale monitoring (finest resolution of local area coverage 1 km^2, and global area coverage 4.4 km^2); and the extension of the record by next generation sensors, such as MODIS (Moderate Resolution Imaging Spectroradiometer), The Sea-viewing Wide Field-of-view Sensor (SeaWiFS), SPOT-vegetation and, in the future, with VIIRS (Visible Infrared Imager/radiometer Suite) (Tucker et al., 2005; van Leeuwen et al., 2006). These qualities have made the AVHRR data indispensable for global change and Earth system science research.

Most Earth surface vegetation studies make use of the visible and near-infrared channels of the AVHRR in the form of vegetation indices, chiefly the Normalized Difference Vegetation Index (NDVI). Various other data products derived from AVHRR also use NDVI as primary input, e.g. global land cover maps (DeFries et al., 1995; DeFries et al., 1999), NPP (Net Primary Production) (Prince & Goward, 1995), burned area product (Barbosa et al., 1999), fPAR (Fraction of Absorbed Photosynthetically Active Radiation), LAI (Leaf Area Index) (Myneni et al., 1997), land surface temperature (Jin, 2004; Otterman & Tucker, 1982), and air temperature (Prihodko & Goward, 1997).

For long-term monitoring of land surface biophysical variables, it is essential for the data to be well calibrated and have consistent dynamic range through out the time series. However, AVHRR lacks on-board calibration, sun-sensor geometry changes systematically during the course of satellite's life due to satellite orbital drift (temporal precession of the equatorial crossing-time) and accurate atmospheric correction is difficult (El Saleous et al., 2000). This paper investigates the extent of uncertainty due to incomplete atmospheric correction in extant AVHRR NDVI datasets.

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doi:10.1016/j.rse.2008.10.007

Atmospheric scattering and absorption affect the visible and near infrared radiance reaching the sensor substantially. The variation in water vapor, ozone and aerosol optical thickness (AOT) in the atmosphere adds uncertainties to the calculations of surface properties. Unlike MODIS, AVHRR does not have additional spectral channels that allow derivation of information about atmospheric composition to be used for correction. Temporal compositing techniques, like maximum NDVI, are generally used to minimize the effect of atmospheric spectral attenuation (Cihlar et al., 1994; Holben, 1986), but this technique is of limited use in daily or short compositing periods (El Saleous et al., 2000).

The approximate precision of NDVI of terrestrial vegetation is often assumed to be between 0.03 and 0.08 NDVI units. For example Jia et al. (2003) reported changes in the vegetation of arctic Alaska over 21 years using AVHRR data. The increase was 0.056±0.0032 to 0.082±0.028 NDVI units. Slayback et al. (2003) reported an increase of 0.027 to 0.081 NDVI units for a period of 18 years (1982–99) for global latitude bands from 35° to 75° N. Piao et al. (2003) reported an increase of similar magnitude (0.0325 NDVI units) in 18 years in China. There are many other studies using AVHRR NDVI (Piao et al., 2006; Young & Harris, 2005), where changes much smaller than 0.03 units are treated as significant. At this time the accuracy of the AVHRR data implied in these studies has not been validated, and it is impossible to calculate per-pixel accuracy on a routine basis. Thus it is possible that some studies have assumed greater accuracy than is justified.

Most vegetation studies using AVHRR do not use at-sensor measures (TOA, Top Of Atmosphere) for individual overpasses, but use processed datasets, such as PAL (Pathfinder AVHRR Land) (James & Kalluri, 1994), GVI (Global Vegetation Index) (Gutman et al., 1995; Kogan & Zhu, 2001) and GIMMS (Global Inventory Modeling and Mapping studies) (Tucker et al., 2005). Most of these datasets use some kind of spatiotemporal aggregation, such as temporal maximum value compositing, and spatiotemporal smoothing. Some of these datasets have been partially corrected for atmospheric perturbation and may omit extreme view zenith angles. These corrections are generally acknowledged to decrease uncertainty in the satellite measurements of surface properties.

Past studies of uncertainty in AVHRR reflectance and NDVI datasets have used various methodologies such as comparison with improved data from the same (Goward et al., 1993) or other sensors, validation using in situ data, analysis of variation of the measurements for assumed stable targets (Cihlar et al., 1998) and use of spatial statistical methods such as semivariograms (Eklundh, 1995). AVHRR data are often evaluated by comparison with better processed datasets or data from other sensors, for example Fensholt et al. (2006) evaluated GIMMS and PAL AVHRR NDVI datasets by comparing them to data from SPOT, and Gallo et al. (2005) compare AVHRR NDVI data to MODIS and investigate the feasibility of providing continuity of NDVI products through future sensor systems.

Validation using in situ measurements is a direct method which gives the most useful information about uncertainty. For example, evaluation of AVHRR-NDVI and MODIS-NDVI datasets using two years of in situ measurements of vegetation indices in Senegal (Fensholt et al., 2005) provided a detailed insight into the performance of AVHRR-NDVI and how it compares with NDVI products derived from MODIS for semi-arid environments.

In recent years extensive remote sensing validation networks have been established in a wide variety of land cover types and latitudinal zones. Some prominent examples are EOS (Earth Observation System) Land Validation Core Sites (Morisette et al., 2002), LTER (Long Term Ecological Research) network (Franklin et al., 1990), FLUXNET (Baldocchi et al., 2001), and AERONET (AErosol RObotic NETwork) (Holben et al., 2001). The study presented in this paper made extensive use of data from AERONET.

AERONET is a world-wide aerosol monitoring network consisting of automatic sun and sky scanning spectral radiometers which measure every 15 min. The data from these instruments are processed to derive atmospheric aerosol optical properties, precipitable water, and aerosol size distribution (Holben et al., 2001). In 1999, there were about 100 operational sites and by 2006, the network had grown to more than 300. This network provides an opportunity to validate atmospheric correction algorithms for application to data obtained from satellites.

The purpose of this study was to explore the uncertainty due to incomplete or lack of atmospheric correction in TOA, PAL, and an early version of the new LTDR (Long Term Data Record) (http://ltdr.nascom.nasa.gov/ltdr/ltdr.html) (Pedelty et al., 2007). The other publicly available datasets like GIMMS and GVI have atmospheric error budget similar to that of TOA because no atmospheric correction is used in either processing streams, and they rely solely on temporal compositing to reduce the effects of changes in atmospheric properties. Uncertainty was assessed by comparing the processed AVHRR datasets to atmospherically corrected AVHRR data at AERONET sites and analyzing simulated AVHRR NDVI data.

2. Data and methods

2.1. Approach

The extent of uncertainty due to inadequate atmospheric correction in the widely used AVHRR NDVI datasets was investigated by comparison with data to which comprehensive atmospheric correction has been applied. Atmospheric compositions derived from AERONET sunphotometer data were used for space and time-specific atmospheric correction. These corrected data are referred to as reference data.

This study evaluated TOA (no atmospheric correction) (Pedelty et al., 2007), PAL, and LTDR datasets. The PAL processing stream includes correction for Rayleigh scattering and ozone, while the early version of LTDR that was tested here is corrected for Rayleigh scattering, ozone, and atmospheric water vapor (Pedelty et al., 2007). Ancillary data for the Rayleigh scattering and water vapor corrections used in the processing stream of these datasets were obtained from the NCEP (NOAA Center for Environmental Prediction) (Kistler et al., 2001), while ozone measurements were obtained from the TOMS (Total Ozone Mapping Spectrometer) (McPeters & Labow, 1996). PAL data was resampled from 8 km to 5 km resolution using nearest neighbor method to make it comparable to LTDR and TOA data available at 5 km resolution. The year 1999 was used for this investigation because uncomposited individual satellite overpass data were available for all the three datasets used (TOA, PAL, and LTDR) and there were adequate number of operational AERONET sites.

Although 1999 provided a useful overview of the error patterns in AVHRR NDVI data record, it represented only one year and most of these data points were in North America and in semi arid and desert areas elsewhere owing to the smaller network of AERONET stations at that time. Moreover, aggressive cloud mask derived from AERONET led to very few data points being available to investigate the impacts of temporal compositing. To overcome these shortcomings, further analysis was performed on simulated AVHRR data for representative sites in tropical forest (Belterra, Brazil), savanna (Skukuza, South Africa), and semi arid (Sevilleta, Arizona, USA) landcover. This was done by using atmospheric conditions and cloud cover frequency from AERONET, NDVI phenology derived from MODIS, and sun-target-sensor geometry from full length (1981–2000) of AVHRR data record was used.

The statistical metrics defined by the NPOESS (National Polar-orbiting Operational Environmental Satellite System) project for evaluation of the Earth Data Record (EDR) (Vermote & Kotchenova, in press) were used in this study to give a better insight into the effects of atmospheric variation on AVHRR NDVI data. The three metrics utilized were accuracy, precision, and uncertainty (APU). The accuracy