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# A global study of NDVI difference among moderate-resolution satellite sensors

Xingwang Fan [a,b], Yuanbo Liu [a,*]

[a] Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[b] Key Laboratory of Watershed Geographic Sciences, Chinese Academy of Sciences, Nanjing 210008, China

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ABSTRACT

Moderate-resolution sensors, including AVHRR (Advanced Very High Resolution Radiometer), MODIS (MODerate-resolution Imaging Spectroradiometer) and VIIRS (Visible-Infrared Imager-Radiometer Suite), have provided over forty years of global scientific data. In the form of NDVI (Normalized Difference Vegetation Index), these data greatly benefit environmental studies. However, their usefulness is compromised by sensor differences. This study investigates the global NDVI difference and its spatio-temporal patterns among typical moderate-resolution sensors, as supported by state-of-the-art remote sensing derived products. Our study demonstrates that the atmosphere plays a secondary role to LULC (Land Use/Land Cover) in inter-sensor NDVI differences. With reference to AVHRR/3, AVHRR/1 and 2 exhibit negative NDVI biases for vegetated land cover types. In summer (July), the area of negative bias shifts northward, and the magnitude increases in the Northern Hemisphere. For most LULC types, the bias generally shifts in the negative direction from winter (January) to summer. A linear regression of the NDVI difference versus NDVI shows a close correlation between the slope value and vegetation phenology. Overall, NDVI differences are controlled by LULC type and vegetation phenology. Our study can be used to generate a long-term, consistent NDVI data set from composite MODIS and AVHRR NDVI data. LULC-dependent and temporally variable correction equations are recommended to reduce inter-sensor NDVI differences.



## 1. Introduction

Satellite sensors have accumulated over forty years of scientific data that meet the critical demands of the scientific community (Gutman and Ignatov, 1998; Ricotta et al., 1999; Lunetta et al., 2006; Wu et al., 2013). These data are affected by the atmosphere and generally need to be corrected for atmospheric effects (Rahman and Dedieu, 1994; Vermote et al., 1997; Tachiiri, 2005). Transforming satellite data into spectral indexes provides an alternative means of reducing atmospheric effects (Gutman, 1991; Huete et al., 2002; Ji et al., 2014). One of the most commonly used spectral indexes is the Normalized Difference Vegetation Index (NDVI), which is defined as the difference between the Near-Infrared (NIR) and Visible (VIS, generally red) bands divided by their sum (Tucker, 1979). There has been substantial evidence that NDVI formulation can reduce atmospheric, Bidirectional Reflectance Distribution Function (BRDF) and other effects (Epiphanio and Huete, 1995; Teillet et al., 1997; van Leeuwen et al., 2006).

Moderate-resolution satellite sensors provide frequent observations of the world under varying atmospheric conditions and at different observational geometries. The NDVI formulation may mitigate the abovementioned effects. In addition, compositing and noise reduction techniques are conducive to deriving temporally consistent NDVI data (Holben, 1986; Michishita et al., 2014; Maeda et al., 2016). These mathematical manipulations are generally efficient and effective for individual sensors (Yang et al., 2012; Zhang et al., 2015). However, sensor replacement and upgrading often lead to multi-sensor data discrepancies that may propagate to downstream products (Brewin et al., 2014; Pisek et al., 2015). As a result, the inter-sensor ('cross-sensor' in Volpi et al., 2015 or 'multi-sensor' in Geiß et al., 2015) band/NDVI difference has been extensively investigated among a wide variety of sensors (Trishchenko et al., 2002; Trishchenko, 2009; Gonsamo and Chen, 2013; Fan et al., 2016). These sensors include obsolete, in-orbit and planned instruments, which constitute a chronologically continuous observation system. Typical sensors include the National

* Corresponding author.
*E-mail address:* yb218@yahoo.com (Y. Liu).

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Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) (Cracknell, 1997), TERRA/AUQA MODerate-resolution Imaging Spectroradiometer (MODIS) (Justice et al., 1998) and Suomi National Polar-orbiting Partnership (NPP) Visible-Infrared Imager-Radiometer Suite (NIIRS) (Cao et al., 2013). These sensors have spatial resolutions of 250–4400 m and are collectively known as moderate-resolution sensors (Trishchenko et al., 2002). Specifically, the AVHRR covers three generations of spectrally similar sensors, namely, AVHRR/1 for NOAA-8/10, AVHRR/2 for NOAA-7/9/11/12/14, and AVHRR/3 for NOAA-15 and thereafter (Trishchenko et al., 2002). These inter-sensor differences, if uncorrected, may introduce both systematic and unsystematic errors into long-term NDVI time series data (Miura et al., 2013; Tian et al., 2015).

Linear regression provides a simple method for correcting NDVI differences that is widely used at the local and regional scales (Steven et al., 2003; Thenkabail, 2004; Martínez-Beltrán et al., 2009). Miura et al. (2006) concluded that inter-sensor NDVI exhibited a nonlinear relationship. Consequently, numerous studies have used quadratic regressions to correct NDVI differences (Trishchenko et al., 2002; van Leeuwen et al., 2006; Gonsamo and Chen, 2013). However, Miura et al. (2006) proposed that the quadratic method may suffer from bias error, and the land cover dependence needed to be explicitly accounted for to reduce the error. Generally, land cover varies in space (e.g., the vegetation distribution varies with latitude and altitude) and with time (e.g., vegetation phenology). The spatio-temporal characteristics may largely complicate the patterns of inter-sensor NDVI differences, which cannot be corrected with site-independent and time-invariant methods. As a result, it is difficult to reliably use multi-sensor long-term NDVI time series data, even if the component sensor NDVI data have been accurately processed. Therefore, the dependence of the NDVI difference on land cover needs to be investigated both spatially and temporally.

Treating land cover dependency is complicated, especially when considering the atmosphere. Many studies have addressed NDVI differences in response to sensor differences due to atmospheric variations (van Leeuwen et al., 2006; Nagol et al., 2009). More studies have focused on NDVI differences resulting from sensor differences associated with land cover (Trishchenko et al., 2002; Miura et al., 2006, 2008, 2013; Trishchenko, 2009). These studies generally used twin satellite images (Rochdi and Fernandes, 2008; Li et al., 2013), hyperspectral data (Yoshioka et al., 2003; Kim et al., 2010) and simulated data (van Leeuwen et al., 2006; Gonsamo and Chen, 2013) to explore inter-sensor NDVI relationships. The satellite images, which are multispectral or hyperspectral, are confined to a specific area. Thus, the results cannot be readily transferred to other locations with different atmospheric states and surface conditions. Simulations based on canopy and radiative transfer (RT) models may disclose NDVI differences among varying sensors, over different land cover types and under different atmospheric states. However, the spatial distribution and time-varying characteristics of NDVI differences cannot be straightforwardly displayed. Therefore, a global inspection of NDVI differences among moderate-resolution sensors is needed to understand how different these NDVIs are in space and time.

To investigate inter-sensor NDVI differences among moderate-resolution sensors, state-of-the-art remote sensing derived products were used to model monthly global NDVI. These products were supported by Spectral Response Functions (SRFs) in the VIS and NIR bands of AVHRRs, MODIS and VIIRS. The multi-sensor NDVIs were compared to study spatio-temporal patterns of NDVI differences and the potential relationship with land cover. Our study furthers the understanding of global NDVI differences among multiple moderate-resolution satellite sensors, contributes to the explanation of land cover dependence of NDVI differences, and provides recommendations for generating long-term, consistent NDVI data sets. This paper is organized as follows: Section 2 describes the data collection and processing; Section 3 states the methodologies; Section 4 presents the main results, followed by detailed discussions in Section 5; and Section 6 summarizes the major findings throughout this study.

## 2. Data description and processing

The objective of this section is to discuss the data collection and processing methods. Data used in this study are sensor SRFs, remote sensing derived products and spectral measurements. The major data processing schemes include spectral, spatial and temporal matching, which were used to obtain spectrally, spatially and temporally consistent data.

### 2.1. Spectral response functions

The moderate-resolution satellite sensors in this study include AVHRR/1 onboard NOAA-6/8/10, AVHRR/2 onboard NOAA-7/9/11/12/14, AVHRR/3 onboard NOAA-15∼19/MetOp-A, MODIS and VIIRS. Fig. 1 shows the SRFs in the VIS and NIR bands. The SRFs of AVHRR/1∼2 were acquired from the NOAA Polar Orbiter Data User's Guide (http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/podug/html/c1/sec1-4.htm), and those of AVHRR/3 were obtained from the NOAA KLM User's Guide (http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/klm/html/d/app-d.htm). For the two narrow-band sensors, MODIS SRFs were collected from the Ocean-Color Documents (http://oceancolor.gsfc.nasa.gov/ DOCS/RSR_tables.html), and VIIRS SRFs were obtained from the NOAA National Calibration Center (https://cs.star.nesdis.noaa.gov/NCC/SpectralResponseVIIRS). MODIS sensors were onboard the TERRA and AQUA satellites, and only TERRA MODIS was selected due to data similarities. For VIIRS, the NG October 2011 band-averaged version of the SRF was used, as recommended in Moeller et al. (2011).

Fig. 1 shows the sensor SRFs, including 1a for AVHRR/1∼2, 1b for AVHRR/3 and 1c for MODIS and VIIRS. With respect to AVHRR/1∼2, the VIS and NIR bands overlap in the VIS-NIR transition region. The AVHRRs onboard NOAA-9/11 behave differently than other AVHRR sensors in the VIS band. The spectral responses are lower in the longer portion of the VIS spectral domain. Unlike AVHRR/1∼2, no overlaps are found for AVHRR/3. Specifically, the VIS bands are narrower, and the NIR bands are flatter. Notable differences are observed in the NIR band where NOAA-18 AVHRR shows the maximum response and NOAA-19 AVHRR shows the minimum response in the longer portion of the NIR spectral domain. In contrast to the AVHRRs, MODIS and VIIRS exhibit much narrower spectral widths in both the VIS and NIR bands. These bands are less affected by atmospheric absorption.

The main preprocessing of SRF data was spectral resampling. Because the data were collected from different sources, the spectral resolutions were 2.0 nm, 1.0 nm and 0.1 nm for the AVHRR, MODIS and VIIRS spectral bands, respectively. These resolutions were resampled to 2.5 nm, as required by the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) RT code (Vermote et al., 1997). The resamplings were performed using a linear interpolation method, yielding SRF data in the range of 470–1100 nm. The lower and upper limits were based on two qualifications. First, the SRF value should be less than 0.1% beyond the range of all sensors. Second, the range should be covered by the center wavelengths of the MODIS reflective solar bands (see Section 2.2).