Satellite-based estimates of vegetation density over Australia during 1988–2008

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Abstract Vegetation density plays an important role in the water and energy balance. Satellite based passive microwave instruments have shown an ability to monitor the total above-ground vegetation biomass at global scales. A recently developed approach to retrieving vegetation optical depth (VOD, an index of vegetation density) from microwave emissions can be used for all bands in the microwave domain, allowing data collected by different satellites (e.g. Special Sensor Microwave/Imager (SSM/I from middle 1987), Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI from 1998) and Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E from middle 2002)) to yield a long-time series. However, differences in measurement specifications prevent merging the data directly. Here we develop a merged product by adjusting SSM/I and TMI products against the reference sensor (AMSR-E) using the cumulative distribution frequency matching approach. Results of Mann-Kendall trend analysis on the merged VOD product during 1988–2008 show that northwest Australia experienced considerable increases in vegetation density, whereas southeast Australia experienced considerable declines. Gridded rainfall and temperature products were used to assess climate induced changes during the study period over Australia. By performing multiple linear regression analysis over varying periods of precipitation, temperature and annual maximum monthly VOD, we identify the proportion of VOD change that is explained by precipitation and temperature, and distinguish the contribution of natural climate from human activities on the long-term change. Expanding analysis to the global scale along these lines should increase our understanding of the natural and anthropogenic impacts on terrestrial hydrology and vegetation dynamics.

Key words vegetation density; passive microwave; long term

INTRODUCTION

The Normalized Difference Vegetation Index (NDVI), derived from the Advanced Very High Resolution Radiometer (AVHRR) series of satellites (first launched in 1981), is a commonly used satellite-based long-term vegetation greenness product (Tucker *et al.*, 2005). It can provide a relatively high spatial resolution product (up to 1 km), but is affected by the atmosphere and clouds, and is limited to monitoring the canopy level. Satellite-based passive microwave instruments have shown an ability to monitor the total above-ground vegetation biomass at global scales, albeit at relatively coarse spatial resolution (>10 km) (Shi *et al.*, 2008). The advantages of microwave-based approaches are the near all-weather retrieval capacity and deeper penetration capacity into the canopy. Therefore NDVI and passive microwave vegetation products are expected to be complementary and provide more reliable vegetation information when combined.

However, there is no consistent and continuous satellite-based passive microwave program covering the period comparable with AVHRR. A recently developed approach to retrieve vegetation information from microwave emissions can be used for all bands in the microwave domain (Owe *et al.*, 2008), allowing data collected by different satellites to yield a long-term time series of vegetation optical depth (VOD, a measure of vegetation density). However, differences in measurement specifications of different satellites prevent merging the data directly.

The objective of this paper is three-fold. First, to develop a method to merge the currently available passive microwave vegetation products into one long-term data set over Australia. Second, to detect the long term change in vegetation density using the merged product, and finally to distinguish the climate or human-induced causes of long-term changes.

DATA

Vegetation Optical Depth – VOD

The VOD products used in this analysis are VU Univeristy Amsterdam – NASA (VUA-NASA) passive microwave products derived from different instruments (Owe *et al*., 2008). Characteristics of these datasets are listed in Table 1. All vegetation products were re-sampled to 0.25° and daily interval.

Monthly average VOD from AMSR-E, TMI and SSM/I for March and September 2003 are shown in Fig. 1. All products show similar spatial and temporal patterns. High values are always observed over forests along the eastern coast. Over northern Australia, values are higher in March; over the south, values are higher in September, which are in line with rainfall seasons.

Table 1 Comparisons of major characteristics of passive microwave instruments used in this study.

	SSM/I	TMI	AMSR-E
Platform	DMSP F8, F11, F13	TRMM	AQUA
Time series used	Jan. 1988–Dec. 2007	Jan. 1998–Dec. 2008	Jul. 2002–Dec. 2008
Channel used (GHz)	19.3	10.7	6.9
Spatial resolution (km*km)	69*43	59*36	76*44
Spatial coverage	Global	38°N to 38°S	Global
Approximate equatorial crossing time	F8: ascending, 0630; F11/13: descending, 0630	Completing an orbit every 91 mins, 15.7 orbits per day	Descending, 0130

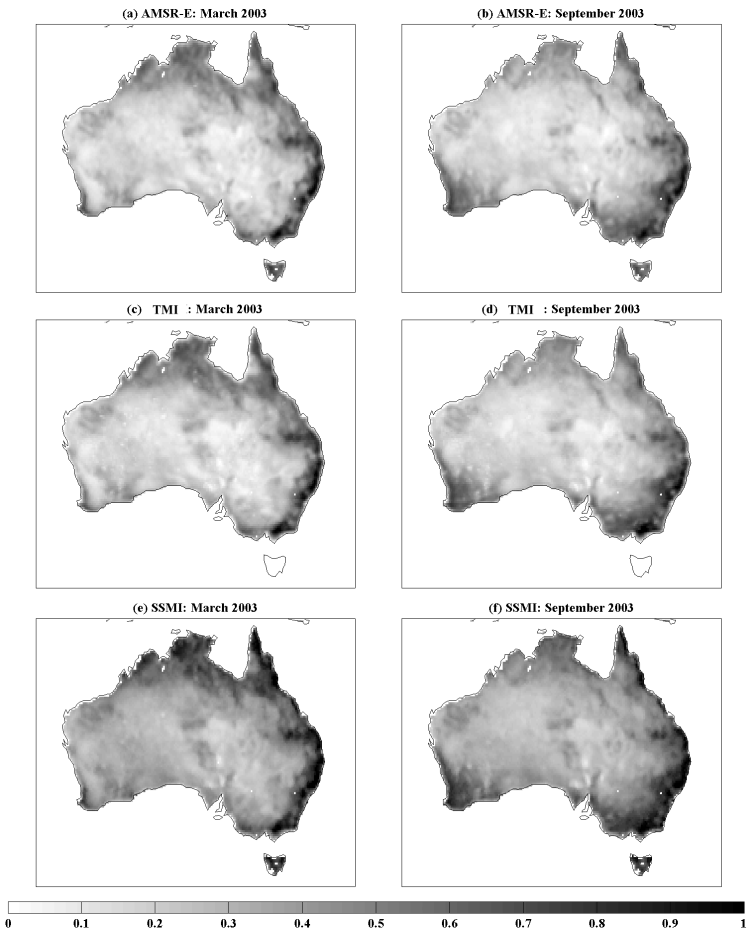

Fig. 1 Monthly average vegetation density (via optical depth) for March and September 2003 derived from (top) AMSR-E, (middle) TMI and (bottom) SSM/I.

Precipitation and temperature

To distinguish the effects of climate and human factors on long-term change in vegetation density, the gridded daily rainfall and maximum and minimum temperature data for Australia for the same period were also included in the analysis. Gridded climate data across Australia were interpolated from point observations by the Bureau of Meteorology (BoM) National Climate Centre (NCC) for the Australian Water Availability Project (Jones *et al*., 2009). The average of daily maximum and minimum temperature was used in this analysis (referred to as mean temperature). The original 0.05° resolution gridded rainfall and mean temperature were re-sampled into 0.25° resolution to allow direct comparison.

METHODS AND RESULTS

Rescaling and merging

Although VOD values retrieved from different instruments have different absolute values (see Fig. 1), they show similar temporal patterns. Compared with SSM/I and TMI, AMSR-E has a comparatively low measuring frequency (6.9 GHz), high spatial resolution, and high temporal interval, which is expected to generate more reliable retrievals. The Pearson correlation coefficients (*R*) between AMSR-E and TMI and SSM/I, respectively, were calculated for their overlapping period (1 July 2002–31 December 2007) (see Fig. 2). The number of coincident values used to calculate *R* is more than 500 (i.e. $N > 500$), and the critical value of being significant at the level of 5% for N equal to 500 is around 0.09. Therefore, TMI and SSM/I are significantly correlated with the AMSR-E product over most of Australia, which creates the possibility to rescale SSM/I and TMI and merge them with AMSR-E to yield a long-term data set.

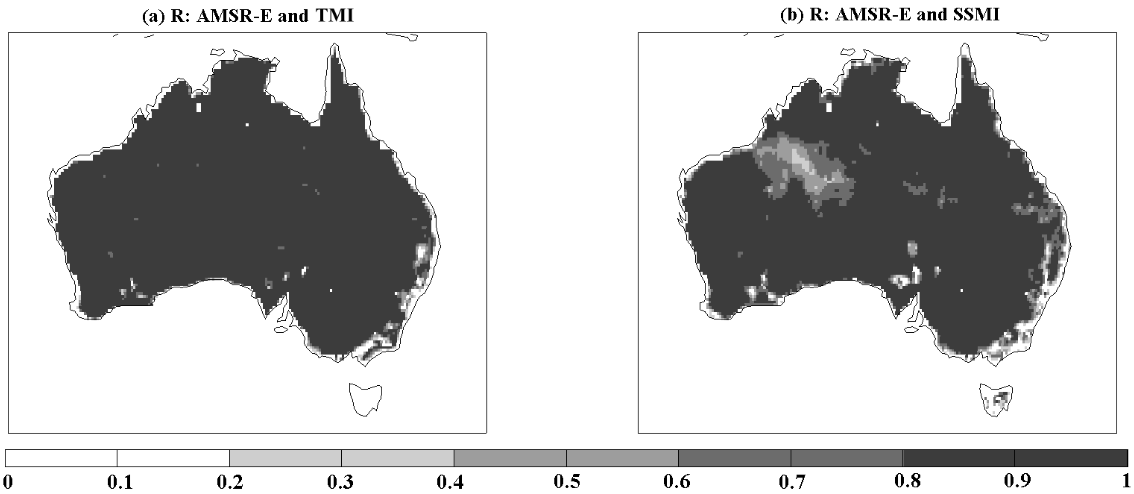

Fig. 2 Correlation coefficient (*R*) between (a) daily AMSR-E and TMI, (b) daily AMSR-E and SSM/I products from July 2002 until December 2007.

The cumulative distribution function (CDF) matching technique was chosen as the rescaling method. A similar approach was successfully used in previous studies (e.g. Reichle & Koster, 2004; Liu *et al*., 2009). The piece-wise linear CDF matching analysis was conducted pixel-by-pixel according to the following steps: (1) Build CDF curves for AMSR-E, TMI and SSM/I over their overlapping period (1 July 2002–31 December 2007). (2) Use the 0, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95 and 100 percentiles of each CDF curve to define 12 segments. (3) For each segment, perform a linear regression to obtain a linear equation (i.e. slope and intercept) between TMI or SSM/I and AMSR-E. That is, for TMI or SSM/I values falling into every segment, there is one linear equation to rescale them against AMSR-E values. (4) Apply the 12 segments' linear equations to TMI (1 January 1998–31 December 2008) and SSM/I (1 January 1988–31 December 2007). The TMI and SSM/I values outside of the range of CDF curves were rescaled using the linear equation of the closest value. Figure 3 displays one example how the original products were rescaled and merged into one time series.

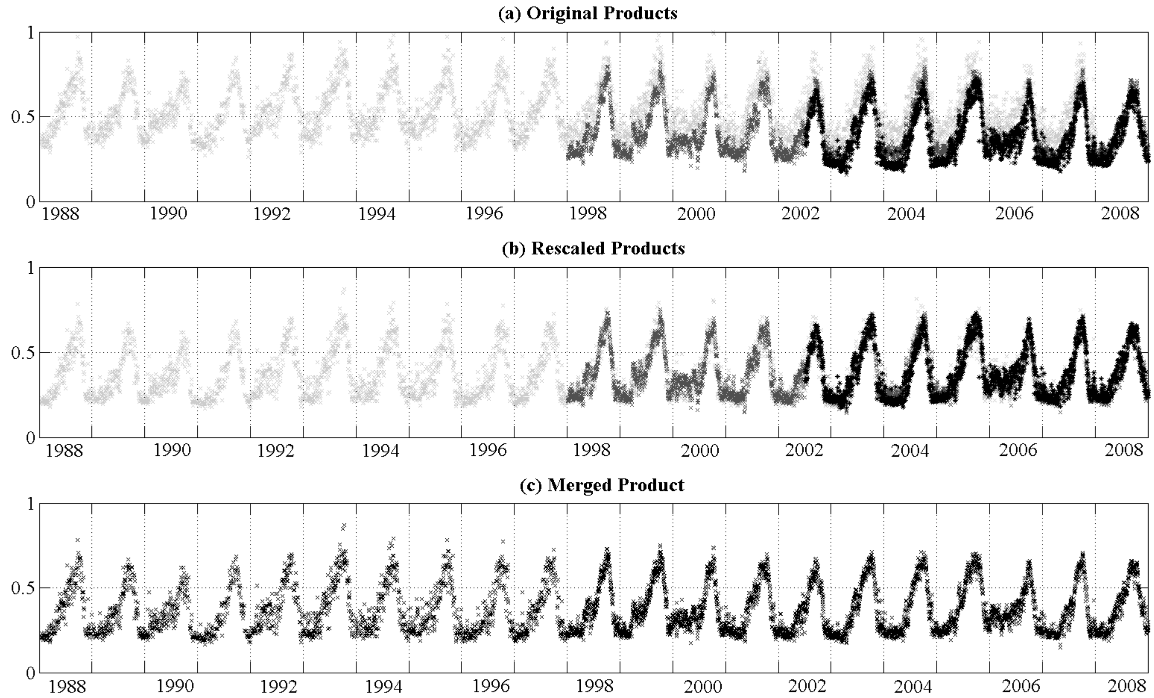

Fig. 3 Example illustrating how: (a) the original time series (SSM/I: light grey; TMI: dark grey; AMSR-E: black) were adjusted into (b) rescaled products using CDF matching technique. (c) The merged product was derived by taking the average of all rescaled products. The grid cell is centred at 32.375°S, 147.375°E.

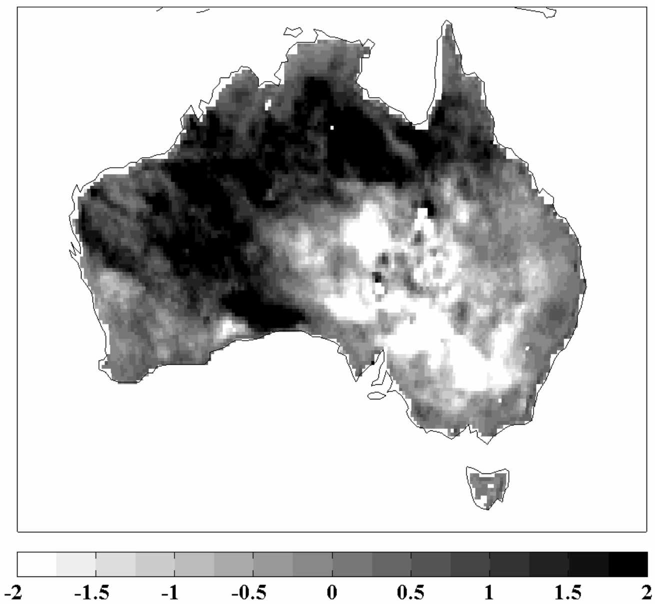

Fig. 4 Spatial distribution of changes (% / year) in vegetation density over the period from 1988 to 2008. The percentage is the annual change relative to the average over 1988 to 2008.

Trend analysis

Spatial patterns of Mann-Kendall trends in annual averages of vegetation optical depth are shown in Fig. 4. As can be seen, northwest Australia experienced increases in vegetation density, whereas southeast Australia experienced declining trends. These apparent changes may be caused by climate or human activities, or a combination of the two.

Climate or human activities

In this section we develop a method to identify and remove climate-related VOD trends over northwest and southeast Australia. Spatial patterns of Mann-Kendall trends in annual average rainfall and temperature over the same period (1988–2008) are displayed in Fig. 5. Visually, trends in VOD seem similar to those in rainfall, and to a lesser extent, temperature. To distinguish the contribution of natural climate influences on the declines observed in vegetation optical depth, we (1) selected the maximum monthly VOD value of each year to obtain a time series, referred to as VOD_{max}, (2) performed multiple linear regressions between varying periods of precipitation, temperature and VOD_{max} for each grid cell, and (3) identified the optimal "modelled VOD_{max}" (see equation (1)) that has highest correlation coefficient with VOD_{max} (Evans & Geerken, 2004).

$$Modelled\ VOD_{max} = a \times P_i + b \times T_j + c \qquad (1)$$

where P_i represents rainfall totals for accumulation periods of between one and eight months, and for lead times of zero to seven months prior to the timing of VOD_{max}, T_j represents temperature averages for accumulation periods of between one to eight months, and for lead times of zero to seven months prior to the timing of VOD_{max}. When the optimal modelled VOD_{max} is achieved, accumulation periods and leading times for precipitation and temperature are not necessarily the same, thus different subscripts are used for P and T. The optimal modelled VOD_{max} can be interpreted as the contribution of natural climate influences on the VOD_{max}. Mann-Kendall trends in the residuals (i.e. VOD_{max} minus "optimal modelled VOD_{max}") over Australia are displayed in Fig. 6. As demonstrated, the main cause for the long-term trends in VOD_{max} over Australia from 1988 to 2008, is climate.

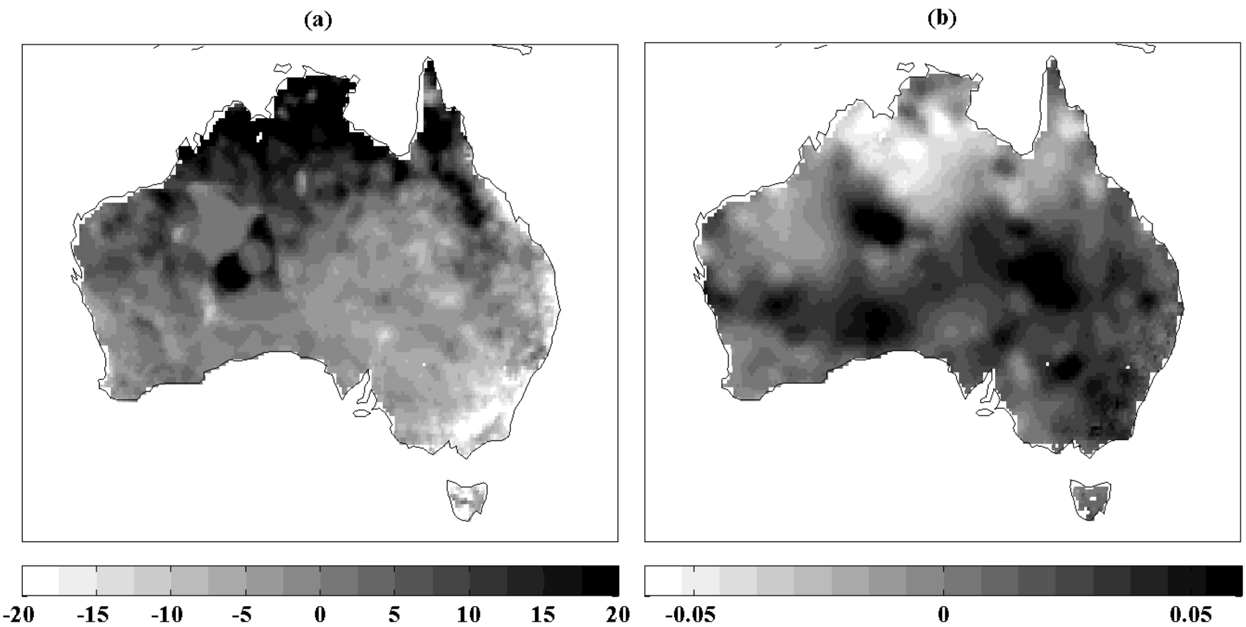

Fig. 5 Spatial distribution of changes in: (a) annual rainfall (mm/year), and (b) mean temperature (°C/year) over the period 1988–2008.

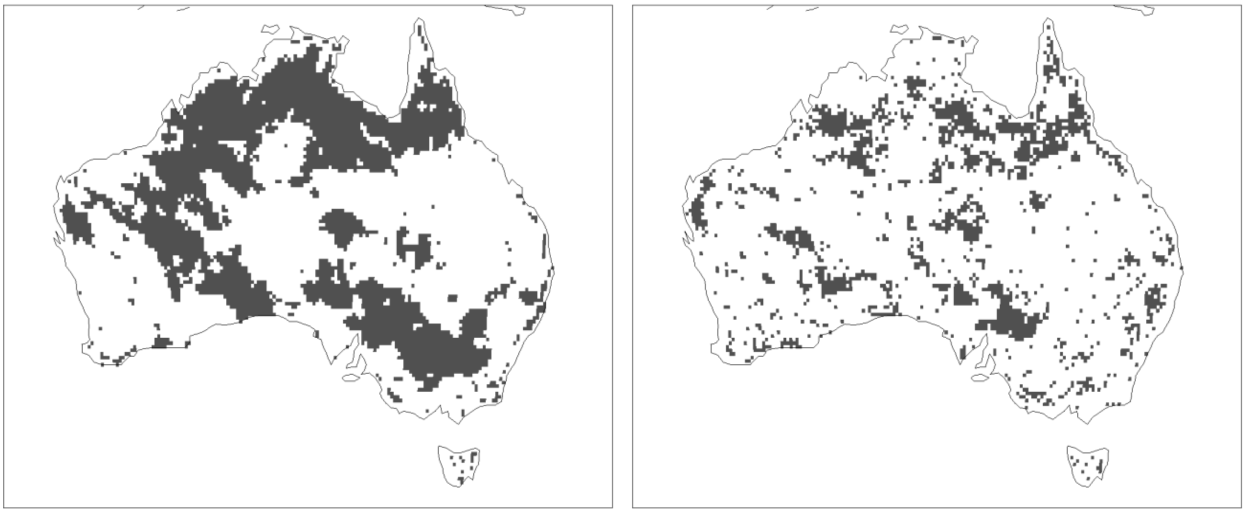

Fig. 6 Spatial patterns of changes (statistically significant at the level of 5%) in (left) VOD_{max} and (right) residuals after removing the effects of rainfall and temperature.

SUMMARY

We developed a method to merge three available passive microwave-based vegetation data sets (SSM/I, TMI and AMSR-E) into one long-term global product. Our method allows the long term product to be extended with more data being available. The potential to monitor the total above ground biomass, near all-weather retrieval capacity and high temporal interval of satellite-based passive microwave instruments, together with high spatial resolution and canopy greenness of NDVI, are expected to bring more reliable information to characterize vegetation dynamics.

Results of Mann-Kendall trend analysis on the merged product during 1988–2008 show that northwest Australia experienced considerable increases in vegetation density, whereas southeast Australia experienced considerable declines. Linear regression analysis over varying periods of precipitation, temperature and annual maximum monthly VOD revealed that the long-term change in Australia is probably mainly caused by climate factors. Further investigations along these lines should increase our understanding of the natural and anthropogenic impacts on terrestrial hydrology and vegetation dynamics.

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