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Comments on the use of the Vegetation Health Index over Mongolia

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The Vegetation Health index (VHI) is based on a combination of products extracted from vegetation signals, namely the Normalized Difference Vegetation Index (NDVI) and from the brightness temperatures, both derived from the NOAA Advanced Very High Resolution Radiometer (AVHRR) sensor. VH users rely on a strong inverse correlation between NDVI and land surface temperature, since increasing land temperatures are assumed to act negatively on vegetation vigour and consequently to cause stress. This Letter explores this hypothesis with data from Mongolia incorporating information from six different ecosystems. It was found that the northern ecosystems are characterized by positive correlations, implying that rising temperature favourably influences vegetation activity. It is concluded that the VHI should be used with caution, especially in high latitude regions.

1. Evolution of the Vegetation Health index

Spaceborne data have been widely used for estimating herbaceous biomass accumulation in grasslands and steppes. The first satellite application for assessing biomass was in northern Senegal in 1981–1983 (Tucker *et al.* 1983, 1985). Subsequently, other investigators expanded this work throughout the Sahelian zone and elsewhere, and reported similar results. Among the various available sensors, the Advanced Very High Resolution Radiometer (AVHRR), onboard National Oceanic and Atmospheric Administration (NOAA) satellites, has been the most suitable and has been used for this purpose. This instrument provides two major land products—the Normalized Difference Vegetation Index (NDVI) and the Land Surface Temperature (LST). The NDVI is the most frequently used vegetation index, and is based on the ratio between the maximum absorption of radiation in the red (R) spectral band and the maximum reflection of radiation in the near-infrared (NIR) spectral band (Tucker 1979). Since the Earth's surface temperature influences vegetation growth (Running *et al.* 1995, White *et al.* 1997, Tucker *et al.* 2001, Badeck *et al.* 2004), LST values have been used as criteria, in addition to the NDVI, for evaluating the status and development of vegetation.

Using these AVHRR-derived products, various researchers have developed algorithms for time-series analysis, or for relating a specific period of interest to a

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long-term statistic, e.g. the NDVI Anomaly Index (Liu and Negron-Juarez 2001) and the Standardized Vegetation Index (Anyamba *et al.* 2001, Peters *et al.* 2002). Following this approach, Kogan (1995) has suggested the Vegetation Condition Index (VCI):

$$\mathrm{VCI}=\frac{(\mathrm{NDVI}-\mathrm{NDVI}_{\min})}{(\mathrm{NDVI}_{\max}-\mathrm{NDVI}_{\min})} \tag{1}$$

This equation relates the NDVI of the composite period of interest (which can be a week, dekad, month, or a year) to the long-term minimum NDVI ($\mathrm{NDVI}_{\min}$), normalized by the range of NDVI values calculated from the long-term record of the same composite period. The VCI values range from 0 to 1, the low values representing stressed vegetation conditions, middle values representing fair conditions, and high values representing optimal or above-normal conditions.

On the presumption that the LST provides additional information about vegetation condition, Kogan (1995) adapted the VCI normalization approach to LST and developed the Temperature Condition Index (TCI):

$$\mathrm{TCI}=\frac{(\mathrm{BT}_{\max}-\mathrm{BT})}{(\mathrm{BT}_{\max}-\mathrm{BT}_{\min})} \tag{2}$$

where BT represents the brightness temperature derived from the AVHRR band 4. Note that, in order to apply the TCI for determining temperature-related vegetation stress, it was formulated in reverse ratio to the VCI, based on the hypothesis that the higher the temperature, the worse the conditions for vegetation. Consequently, low TCI values (close to 0) indicate harsh weather conditions (due to high temperatures), relative to the composite period, middle values reflect fair conditions, and high values (close to 1) reflect mostly favourable conditions.

Several authors have used the combined responses of reflected (e.g. NDVI, VCI) and thermal (e.g. LST, brightness temperature) products of the NOAA-AVHRR to provide a more ecological and physical interpretation of remotely sensed data for examining vegetation conditions (e.g. Gutman 1990, McVicar and Jupp 1998, Karnieli & Dall'olmo 03). This innovative approach assumes a strongly negative correlation between NDVI and LST, due to an increase in evaporation along with a decrease in soil moisture, caused by higher temperatures, resulting in a decline in the vegetation cover (Nemani and Running 1989, Lambin and Ehrlich 1996). For example, McVicar and Bierwith (2001) use the ratio of LST and NDVI (LST/NDVI) to provide a rapid means of assessing drought conditions.

Following the above-mentioned hypothesis, Kogan (1995) proposed another index, the Vegetation Health Index (VHI), which is an additive combination of VCI and TCI:

$$\mathrm{VHI}=\alpha\mathrm{VCI}+(1-\alpha)\mathrm{TCI} \tag{3}$$

where α is the relative contribution of VCI and TCI in the VHI. In most published analyses, α has been assigned a value of 0.5, assuming an even contribution from both elements in the combined index, due to the lack of more accurate information (Kogan 2000). The VHI has been applied for different applications, such as drought detection, drought severity and duration, early drought warning (Seiler *et al.* 1998), crop yield and production during the growing season (Unganai and Kogan 1998), vegetation density and biomass estimation (Gitelson *et al.* 1998), assessment of irrigated areas (Boken *et al.* 2004), and estimation of excessive wetness (in contrast to drought) (Unganai and Kogan 1998). These applications have been demonstrated in various scales—global (Kogan 1997, 2000), regional (Liu and Kogan 1996), and national (Seiler *et al.* 1998)—in many parts of the world.

Recently, Kogan *et al.* (2004) dealt with applying the VHI for drought detection and derivation of pastoral biomass in Mongolia. The VCI, TCI and VHI were computed from the long-term NOAA Global Vegetation Index (GVI) dataset for the period 1985–2000, in 16 km × 16 km resolution (Kidwell 1997). Due to a lack of more accurate information on the influence of VCI and TCI on the VHI in Mongolia, the α coefficient of the VHI equation was fixed at 0.5. Spatial results of the VH, for the three relevant years, from the Gobi desert in the south (41° N), to north of the Lake Baykal in Siberia (56° N), are presented (Kogan *et al.* 2004).

The prime objective of the current Letter is to investigate the VHI-based hypothesis that increasing temperatures act negatively on vegetation vigour and consequently cause stress. The territory of Mongolia (about 1.5 million km^2) can serve as a good example for such research, as this country is located in the cold desert belt of central-east Asia. Mongolia is characterized by mostly natural vegetation, without anthropogenic influences, such as urban heat islands, industry, agricultural crops, etc. The north–south transect across the country is relatively short (ca 1000 km), but covers six different ecosystems, namely Taiga, High Mountains, Forest Steppe, Steppe, Desert Steppe, and Desert, from the north southwards (figure 1). Mean annual temperature increases gradually from −7°C in the north to 7°C in the south, while mean annual precipitation ranges from less than 75 mm in the south to more than 350 mm in the north.

2. Dataset and methodology

The Pathfinder AVHRR Land (PAL) NDVI and brightness temperatures, in bands 4 and 5, were used in this study. Data are composed of monthly maximum values, with an 8 km spatial resolution, in geographical (lat/long) projection, spanning a period from 1981 to 1999. The PAL dataset was generated from the NOAA satellites

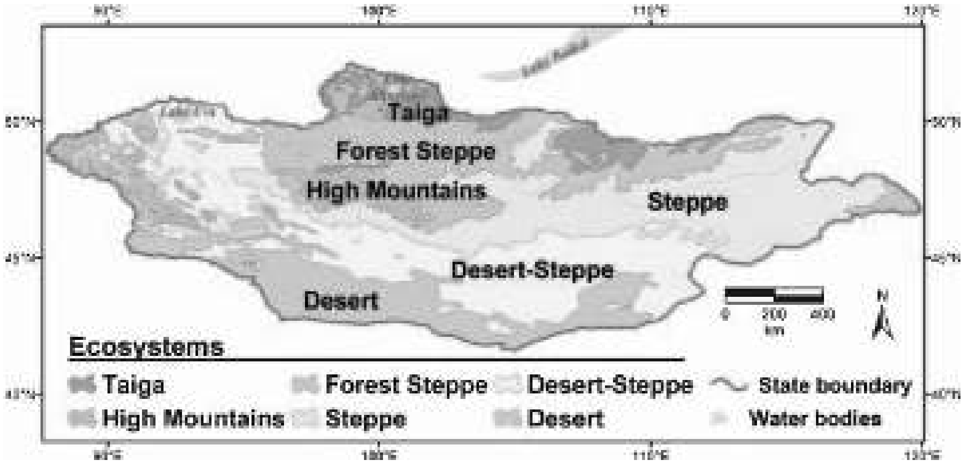

Figure 1. Ecosystem map of Mongolia.

7, 9, 11 and 14 (Agbu and James 1994) and was obtained from the Goddard Space Flight Center (GSFC) Distributed Active Archive Center (DAAC).

NDVI values were extracted directly from the PAL archive. LST values were computed from the brightness temperatures in the thermal bands, by a split-window algorithm (Price 1984) of the form:

$$\mathrm{LST} = \mathrm{BT}_4 + A(\mathrm{BT}_4 - \mathrm{BT}_5) + B(\varepsilon) \tag{4}$$

where BT_4 and BT_5 are brightness temperatures in bands 4 and 5, respectively, A ($=2.63$) is a coefficient related to atmospheric transmittance, being dependent on the atmosphere type, and $B(\varepsilon)=1.27$ is the emissivity effect, which depends on both the channel surface emissivities (ε_4 and ε_5) and atmosphere type. Price (1984) assumed that the emissivity of most of the land surface and vegetation cover is equal to 0.96, so this value was used in the current research.

3. Analysis, results, and discussion

Scatterplots of the NDVI vs the LST values are presented in figure 2. Linear regression analysis of the entire dataset reveals a significant ($F<0.001$) inverse relationship between NDVI and LST. This trend is well documented on regional and continental scales (e.g. Nemani *et al.* 1993). However, the regression results of the six separated distinct clusters, representing the six different ecosystems, reveal a different situation. Individual regression analysis results of these clusters reveal negative relationships between NDVI and LST for the southern ecosystems (Desert, Desert Steppe, and Steppe); a flat relationship for the Forest Steppe ecosystem; and positive relationships for the northern ecosystems (High Mountains and Taiga). Note that the regressions of the Taiga, Steppe and Desert Steppe were found to be statistically significant ($F<0.05$). Gradual transition from the most negative (Desert), to the most positive (Taiga), relationships can be observed. A time series

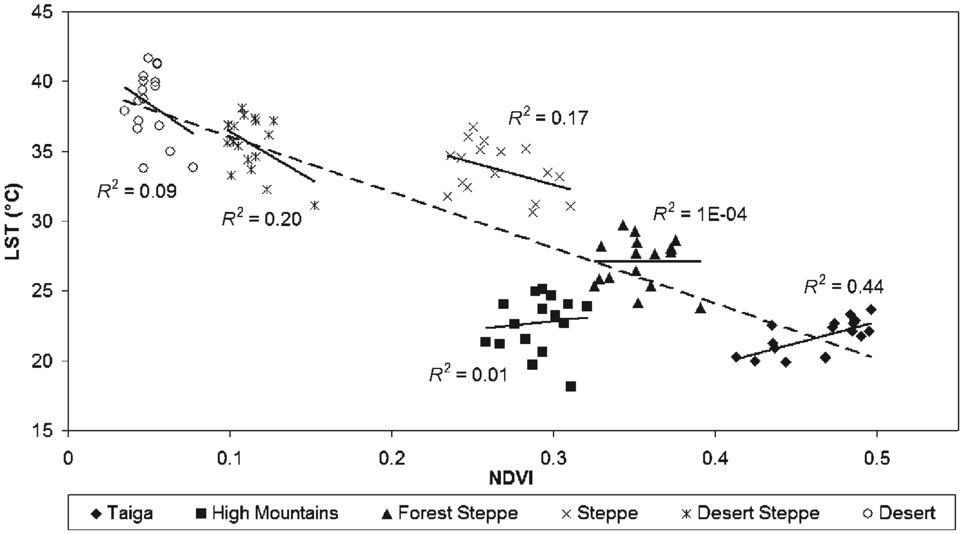

Figure 2. Scatterplot of LST against the NDVI. Note an overall significant negative relation between the two variables. When examining each ecosystem separately, the northern ecosystems are characterized by a positive trend.

of NDVI and LST values for the Desert Steppe ecosystem, as representative of out-of-phase relationships, is presented in figure 3(*a*). A mirror reflection of the two trends can be seen. By contrast, the two variables progress almost in-phase along the study period in the Taiga ecosystem (figure 3(*b*)).

These results are consistent with previous observations showing a substantial change in the correlation slopes between NDVI and LST (e.g. Lambin and Ehrlich 1996, Tateishi and Ebata 2004). Low latitude regions of the Northern Hemisphere are characterized by negative correlations, as water is the main limiting factor for vegetation growth. On the other hand, mid and high latitude regions, where energy is the major limiting factor for vegetation development, are characterized by a positive correlation, implying that rising temperatures favourably influence

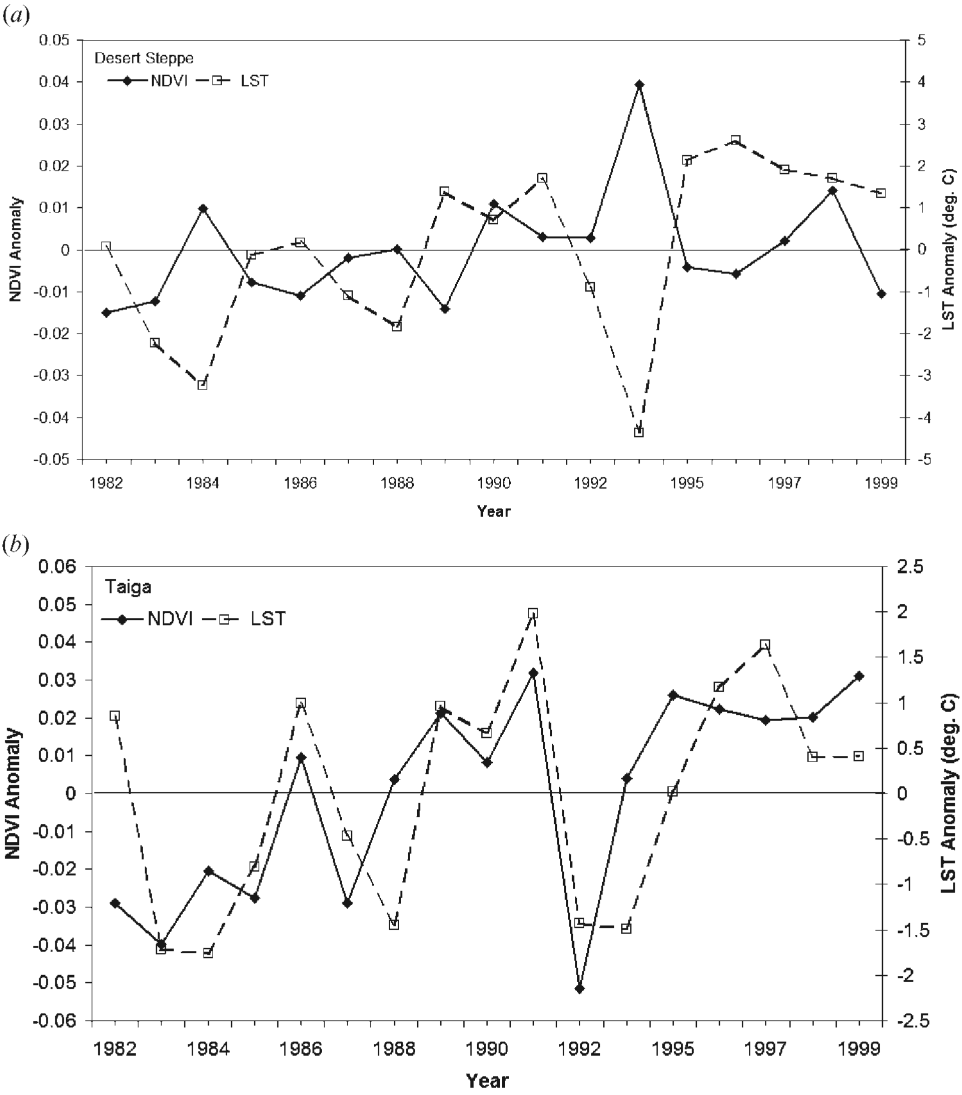

Figure 3. Time series of NDVI and LST values for the (*a*) Desert Steppe ecosystem, and (*b*) Taiga ecosystem. Note the out-of-phase and in-phase relationships in (*a*) and (*b*), respectively.

vegetation activity. Temperature is the main driver of many biological processes, namely chemical (enzyme-catalysed) reactions, which usually increase plant maturation (Badeck *et al.* 2004). Mongolia, located in the cold desert belt of central-east Asia, exhibits along a relatively short distance, both precipitation-dependent ecosystems in the south, and temperature-dependent ecosystems in the north. Therefore, the VHI cannot be applied to the entire territory.

Conclusions

This study attempted to investigate the VHI-based hypothesis that increasing temperatures act negatively on vegetation vigour and consequently cause stress. It is shown that analysis of spaceborne-derived vegetation indices, such as NDVI/LST and VHI, which are based on the NDVI and LST, requires a good understanding of the relationships between these variables in different ecosystems. Since the role of the α coefficient in the VHI is to determine the individual contributions of the NDVI and the LST to the vegetation condition, it is generally expected that α correlates to the slope of the regression of these two factors. As was demonstrated, however, not only does the magnitude of the slope vary across different ecosystems, its direction can be reversed. Consequently, in its present form, the VHI can be successfully applied only in the low latitudes, mainly in arid, semi-arid, and sub-humid climatic regions, where water is the main limiting factor for vegetation growth. Another physiology mechanism exists in the tropics around the Equator and in the humid regions of the high latitudes, where vegetation development is primarily limited by energy. In these regions, higher temperatures speed up plant development and, therefore, using the VHI to assess vegetation state and condition has to be undertaken with caution.

Further research should be conducted to refine the existing VHI formulation, in order to apply it to a wide range of ecosystems.

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