Journal of Arid Environments 109 (2014) 31–38

Contents lists available at ScienceDirect

Journal of Arid Environments

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

Application of a satellite-based aridity index in dust source regions of northeast Asia

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ARTICLE INFO

Article history:
Received 21 November 2013
Received in revised form
20 April 2014
Accepted 19 May 2014
Available online 11 June 2014

Keywords:
Arid regions
Asian dust
Land-surface temperature
Northeast Asia
Remote sensing

ABSTRACT

A modified temperature-vegetation dryness index based on land-surface temperature was used to represent land-surface aridity in northeast Asia. Past results indicated that saltation activity and dust emission did not often occur in northeast Asia when soil water content was greater than 4% and normalized soil water content was greater than 0.2. The threshold value of the modified temperature-vegetation dryness index for dust emissions was assumed to be 0.8 when the normalized soil water content was 0.2. However, a detailed grid of meteorological data is needed to predict the modified temperature-vegetation dryness index; therefore, large-scale use is presently difficult. A new satellite-based aridity index using day/night land-surface temperature differences has been introduced and tested to represent the modified temperature-vegetation dryness index. The satellite-based aridity index was 0.03 when the modified temperature-vegetation dryness index was 0.8, which is the threshold for dust emissions. The relationship between coverage of satellite-based aridity index values greater than 0.03 in the target area (35°N–45°N and 100°E–115°E) and Asian dust events over Japan was analyzed for 2000–2011. Results indicated that coverage of satellite-based aridity-index values greater than 0.03 significantly affects Asian dust events over Japan ($R^2 = 0.4117$, $p < 0.05$).

1. Introduction

In January and February 2013, cross-border $PM_{2.5}$ pollution became very serious in Japan (http://www.nies.go.jp/whatsnew/2013/20130221/20130221.html). Soil dust, industrial emissions, coal burning, vehicle exhaust emissions, and waste incineration were thought to be major sources of particulate pollution emissions in large cities in China (Qin and Xie, 2011; Sun et al., 2004). It has been reported that $PM_{2.5}$ has detrimental effects on human health. For example, $PM_{2.5}$ leads to health problems and is closely correlated with increased respiratory morbidity and mortality (Dockery and Pope, 1994; Sun et al., 2004). The Ministry of Environment of Japan has determined that the air quality standard for $PM_{2.5}$ requires that air have less than a daily average of 35 $\mu g\ m^{-3}$, but $PM_{2.5}$ concentrations above this standard have been frequently observed, especially in western Japan.

Another problem in Japan is Asian dust events that occur in springtime (March through May). Most particles of Asian dust flowing into Japan are smaller than 4 μm and include $PM_{2.5}$. Asian dust consists of soil or mineral particles originating mainly from severe dust storms in arid and semi-arid regions of northeast Asia, particularly the Taklimakan Desert, the Gobi Desert, the Hexi Corridor, and the Loess Plateau regions of China and Mongolia. Asian dust particles consist mostly of rock-forming minerals like quartz and feldspar; however, ammonium, sulfate, and nitrate ions, which do not originate in the soil, have also been detected. This means that suspended soil dust can absorb air pollutants originating from human activity. Adhesion to mold, bacteria, and viruses is also possible (Ichinose, 2011).

The springtime Asian dust event is a well-known seasonal meteorological event in Japan (Iwasaka et al., 2009). The main problems caused by Asian dust in Japan are visibility degradation for automobile drivers, pollution of laundry, and prevention of solar radiation in greenhouses. In recent years, detrimental effects on human health have been confirmed. For example, it has been statistically proven that Asian dust leads to the intensification of health problems (e.g., worsening of symptoms of asthmatic patients in springtime in western Japan) (Otani et al., 2011; Watanabe et al., 2010). As a result, an early warning and monitoring system based on dust modeling, remote sensing, and weather forecasts is

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http://dx.doi.org/10.1016/j.jaridenv.2014.05.007

badly needed in Japan to prevent damage due to Asian dust (Ministry of the Environment, 2005).

Increased desertification in Asian dust source areas has contributed to an increased number of dust events in northeast Asia (Igarashi et al., 2011; Ministry of the Environment, 2005). Therefore, clarifying the effect of land-surface conditions (e.g., vegetation cover ratio, soil water content (SWC), and soil-particle size distribution) on these dust outbreaks is an important part of increasing the accuracy of dust emission models. Analyses by Kimura et al. (2009) and Kimura and Shinoda (2010) based on SYNOP weather reports and actual observations suggested that the threshold vegetation cover ratio for preventing dust outbreaks was 20% (values greater than 0.2 of the Normalized Differential Vegetation Index (NDVI)) in the Loess Plateau of China and the grasslands of Mongolia. Referring to past results, Kimura (2012a,b) was able to locate the target dust-source area in northeast Asia (35°N–45°N and 100°E–115°E) and reported a decreasing trend in Asian dust events over Japan (ADEs) since 2000, corresponding to an increase in vegetation in the target area. The Grain for Green Program, a national project of the Chinese government, was initiated in 2002 (Yamanaka, 2008), and natural vegetation has gradually increased as a result of this project's efforts to reduce farmland and promote greening in certain river basins on the Loess Plateau (Kimura et al., 2006). The afforested area increased drastically, especially from 2002 to 2004, according to the China Science Portal (http://www.spc.jst.go.jp/statistics/statictisc_index.html). However, it cannot be concluded at this stage that this decreasing trend in ADEs is an outcome of the Grain for Green Program in China because the study period (2000–2011) was short.

SWC is also an important factor in preventing dust emissions (Shao, 2000). Ishizuka et al. (2005) demonstrated the effect of surface soil moisture on wind erosion in the Taklimakan Desert in China. Kimura et al. (2009) found that dust events were rare on the Loess Plateau in China when the surface volumetric SWC exceeded a threshold value. These studies suggest the importance of monitoring the spatial and temporal distributions of surface SWC and using these data in dust-modeling systems. However, little consideration has been given to monitoring spatial and temporal distributions of surface aridity in dust source regions of northeast Asia using satellite data.

In this study, a modified temperature-vegetation dryness index (MTVDI) and a new satellite-based aridity index (SbAI) based on land-surface temperature were used to represent land-surface aridity and to determine the threshold surface aridity for dust emissions in northeast Asia using spatial and temporal distributions of SbAI.

2. Method and data

2.1. Indices used

2.1.1. MTVDI

Kimura (2007) defined MTVDI as:

$$\mathrm{MTVDI} = \frac{T_s - T_{\mathrm{smin}}}{T_{\mathrm{smax}} - T_{\mathrm{smin}}}, \tag{1}$$

where T_s is the observed daytime surface temperature (°C or K), T_{smin} is the minimum surface temperature for the reference crop, and T_{smax} is the maximum surface temperature for the reference crop (Allen et al., 1998) simulated using energy-balance equations and meteorological data (°C or K). The effects of physiological activities on T_s can be separated from meteorological effects by normalization. For a dry surface, MTVDI is close to unity. Kimura (2007) found that MTVDI corresponds well to seasonal variations in moisture availability (m_a, calculated as the ratio of actual to reference evapotranspiration by Allen et al., 1998) in an area of varied land use. According to Allen (2000), m_a is constant during a given day, and therefore the MTVDI value corresponding to m_a is also presumed to be constant during a given day (Kimura, 2007).

In some cases, T_s as given by Eq. (1) might be higher than T_{smax} for the hypothetical reference crop of Allen et al. (1998) because the parameters used for estimating T_{smax} are not site-specific. When $T_s > T_{\mathrm{smax}}$ during the calculations, MTVDI is set to one.

2.1.2. New satellite-based aridity index

The aridity index is widely used for climate-based land classification from a dryness standpoint (Arora, 2002; UNEP, 1997). Because all the variables in the aridity index involve climate values such as annual precipitation and annual mean temperature, short-term changes in dryness cannot be estimated. The day/night land-surface temperature difference can be used to estimate instantaneous changes in dryness from satellite observations (Caselles et al., 1983). However, this difference is affected by various environmental parameters. In this study, a surface energy-balance model has been assumed to clarify the effect of environmental parameters relevant to the temporal characteristics of land-surface temperature under the assumption that land-surface temperature, solar flux, and air temperature change sinusoidally (Kondo, 1994):

$$A_T = \frac{R\cos\phi + B\xi\cos(\alpha - \phi)}{\mu + \Gamma}, \tag{2}$$

where A_T is the amplitude of land-surface temperature; R is the amplitude of surface-absorbed solar radiation; B is the amplitude of air temperature; ϕ is the phase difference between solar radiation and land-surface temperature; α is the phase difference between solar radiation and air temperature; ξ is the sum of sensible heat flux and outgoing long-wave radiation divided by the average difference between land-surface temperature and air temperature; μ is the sum of sensible heat flux, latent heat flux, and outgoing long-wave radiation divided by the average difference between land-surface temperature and air temperature; and Γ is the ground heat flux divided by the land-surface temperature.

Land-surface aridity affects ground heat flux, as shown by the aridity effect on Γ in Eq. (2). Under the above assumptions, Γ can be expressed as a function of thermal admittance Y as:

$$\Gamma = Y\sqrt{\omega}\cos\psi, \tag{3}$$

where ω is the angular velocity of land-surface temperature change and ψ is the phase difference between land-surface temperature and ground heat flux (Kondo, 1994). Furthermore, thermal admittance can be expressed as:

$$Y = \sqrt{c\rho\lambda}, \tag{4}$$

where c is specific heat, ρ is density, and λ is the thermal conductivity of the land surface. The product of specific heat and density is known as heat capacity. Thermal admittance increases for a moist surface because of the high heat capacity of water (Kasubuchi, 1975). Therefore, the day/night land-surface temperature difference increases when the surface is drier.

The day/night land-surface temperature difference reflects dryness information and the effects of other parameters, especially solar radiation. For satellite observations, fine-grid meteorological data synchronized with the observations cannot be obtained, and therefore the pixel-wise latent and sensible heat fluxes cannot be estimated. To reduce the solar-radiation effect and define satellite-derived parameters, the parameter R/A_T is introduced: