

## SATELLITE BASED ARIDITY MAPPING

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**KEY WORDS:** MODIS, Land surface temperature, Solar flux, Thermal admittance

### ABSTRACT:

For the instantaneous dryness mapping, the satellite derived aridity index is proposed. The proposed index is derived from the day/night surface temperature and the maximum solar flux, also it is proved that the index corresponds to the thermal admittance from the theoretical analysis of the surface energy balance. From the MODIS LST and reflectance product during 10 years, daily/monthly global aridity map are made and compared with the NDVI and solar zenith.

### 1 INTRODUCTION

The aridity index is widely used for the climate based land classification from the stand point of the dryness (Arora, 2002). Since all of the definitions of the aridity index use the climate values such as annual precipitation, annual mean temperature and so on, the short term change of the dryness cannot be estimated. To estimate the instantaneous change of the dryness, satellite based aridity estimation scheme is established. So far in the remote sensing field, the day/night temperature difference is used for this purpose (V. Caselles and Mella, 1983), however the day/night temperature difference is affected by various environmental parameters. In this study the surface temperature variation in one day is characterized by shortwave radiation, latent/sensible heat transfer and ground heat transfer and satellite based aridity index is defined by using day/night surface temperature difference and maximum shortwave radiation absorption which is derived from the solar zenith and surface reflectance. Also the 10 years global aridity map is made from MODIS dataset.

### 2 SATELLITE BASED ARIDITY INDEX

#### 2.1 Theoretical Background

To clarify the effect of the environmental parameters relevant to the temporal characteristic of the land surface temperature, the surface energy balance model under the assumption that the land surface temperature, solar flux and air temperature sinusoidally change is considered (Kondo, 1994).

$$A_T = \frac{R \cos(\phi) + B\xi \cos(\alpha - \phi)}{\mu + \Gamma} \quad (1)$$

Eq. (1) shows the relationship between the amplitude of the land surface temperature  $A_T$ , the surface absorbed solar flux  $R$  and the air temperature  $B$ . Also Eq. (1) shows the relationship between the 3 kinds of amplitude and the phase difference between solar flux and land surface temperature  $\phi$ , the phase difference between solar flux and air temperature  $\alpha$ , the sum of sensible heat

flux and outgoing longwave flux divided by the average difference between the land surface temperature and air temperature  $\xi$ , the sum of sensible heat flux, latent heat flux and outgoing longwave flux divided by the average difference between the land surface temperature and air temperature  $\mu$  and the ground heat flux divided by the amplitude of the land surface temperature  $\Gamma$ .

The surface aridity primarily affects on the ground heat flux, in other word, we can find the aridity effect on  $\Gamma$  in Eq. (2). To express the effect, what contain in the term  $\Gamma$  is clarified. Under the above assumptions, the parameter  $\Gamma$  is expressed by the thermal admittance  $Y$  as Eq. (2)

$$\Gamma = Y \sqrt{\omega} \cos(\psi) \quad (2)$$

where  $\omega$  and  $\psi$  are the angular velocity of the land surface temperature change ( $\omega = 7.27 \times 10^{-5} [\text{sec}^{-1}]$ ) and the phase difference between the land surface temperature and the ground heat flux ( $\simeq \pi/4$ : 3 hours) respectively (Kondo, 1994). Also the thermal admittance can be expressed as the product of the following three parameters as Eq. (3).

$$Y = \sqrt{c\rho\lambda} \quad (3)$$

where  $c$ ,  $\rho$ ,  $\lambda$  show the specific heat, density and thermal conductivity of the surface respectively. And the product of specific heat and density is called heat capacity. For the moist surface case, because of the high heat capacity of the water, the thermal admittance becomes larger (Kasubuchi, 1975). From these facts, The day/night land surface temperature difference becomes larger in the case of the drier surface.

From the above discussion, the day/night land surface temperature difference contains not only the dryness information also the other parameter effect especially the solar flux. And for the satellite observation, the fine grid meteorological data which synchronized with the satellite observation cannot be obtained so that the pixel-wise latent and sensible heat flux cannot be estimated. To reduce the solar flux effect and for the satellite derived parameter

definition, the parameter  $R/A_T$  as Ed. (4) is considered.

$$\frac{R}{A_T} = \frac{\mu + \Gamma}{\cos(\phi)} - \frac{B\xi \cos(\alpha - \phi)}{A_T \cos(\phi)} \quad (4)$$

The first term of the right hand side of Ed. (4) corresponds to the outgoing energy from the surface and the second term corresponds to the longwave radiation and the sensible heat flux, so that the right hand side corresponds to the ground heat flux and the latent heat flux which highly related to the surface dryness.

To estimated the solar flux dependency of the day/night land surface temperature and the proposed parameter  $R/A_T$  to solar flux, the land surface temperature is computed from the bulk energy balance model (Kondo, 1994). Under the condition which the air temperature amplitude  $B$  is 4 [K], the relative transpiration is 0.2, the sensible heat exchange rate is 0.01 [m/Dec], the thermal admittance is 1250 and the surface albedo is 0.2, the relationship between the average air temperature and the day/night land surface temperature difference and the proposed index  $R/A_T$  related to the three kinds of solar flux are computed. These results are shown in Figure 1 and 2.

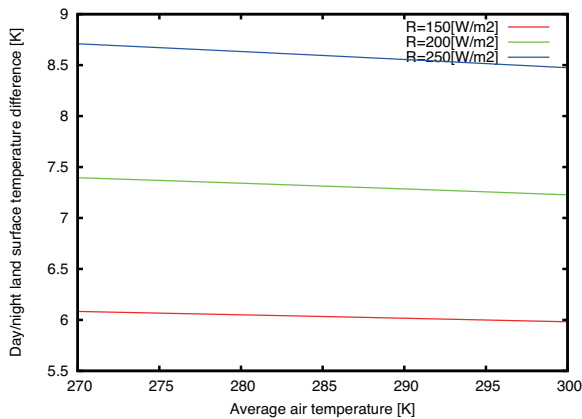


Figure 1: The relationship between the average air temperature and the day/night land surface temperature difference under the various solar flux.

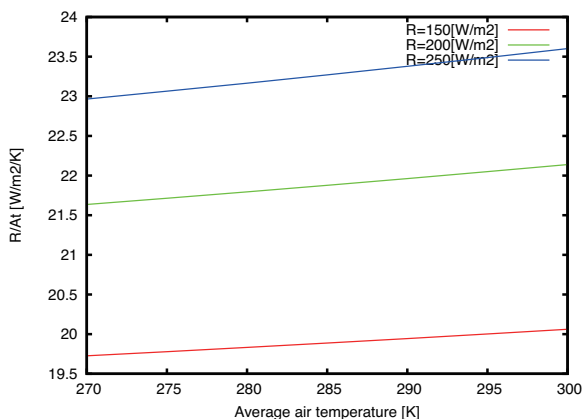


Figure 2: The relationship between the average air temperature and the proposed index under the various solar flux.

When the solar flux changes from 150 [ $\text{W}/\text{m}^2$ ] to 250 [ $\text{W}/\text{m}^2$ ], the day/night land surface temperature difference increases about 45%, but the  $R/A_T$  increases about 15%. This means that the  $R/A_T$  shows the less sensitivity with the solar flux (solar zenith) compared with the day/night land surface temperature difference.

## 2.2 Proposed Algorithm

The index  $R/A_T$  becomes numerically unstable in the case of the small day/night land surface temperature difference and such case is difficult to predict. On the other hand, the absorbed solar flux  $R$  is easy to predict the value, for example  $R$  becomes small in the case of low solar elevation and high albedo. So that the parameter  $A_T/R$  can be used as the satellite derived aridity index. For the dry surface,  $A_T/R$  becomes large.

For the satellite derived variable use, the amplitude of the land surface temperature during a day  $A_T$  is replaced with the day/night land surface temperature difference  $\Delta T_S$ , and the amplitude of the absorbed solar flux is replace with the absorbed solar flux at the culmination  $R_{max}$ . Thus the satellite derived aridity index  $\eta$  is expressed as Eq. (5).

$$\eta = \frac{\Delta T_S}{R_{max}} \quad (5)$$

Among the Terra/MODIS product, the daily global Day/Night land surface temperature product MOD11C1, and the daily global surface reflectance product MOD09CMG are used in this study. The spatial resolution of these two products is the same, 0.05 [deg.], and the processing software is Collection 5. The absorbed solar flux  $R_{max}$  is computed as Eq. (6) under the assumption that the atmospheric effect is neglected.

$$R_{max} = (1 - r)S_0 \cos(\theta_c) \quad (6)$$

where  $r$ ,  $S_0$  and  $\theta_c$  means the broadband albedo of the surface, the solar constant ( $1367[\text{W}/\text{m}^2]$ ) and the solar zenith at the culmination respectively. Since the MOD09CMG product contains the spectral reflectance  $r_i$  of chs. 1–7, the broadband albedo is estimated from the experimental formula as Eq. (7) (Liang, 2004).

$$r = 0.160r_1 + 0.291r_2 + 0.243r_3 + 0.116r_4 + 0.112r_5 + 0.081r_7 \quad (7)$$

where the subscripts means the MODIS spectral channels.

From MOD09CMG, the spectral reflectance is used for the broadband albedo computation and the line/pixel position and the date are used for the culmination solar zenith computation. From MOD11C1, the day/night land surface temperature is used for the temperature difference computation. these process are shown in Figure 3. Also the daytime and nighttime LST and visible reflectance on Dec. 21 2001 are shown in Figure 4, 5 and 6. Also the day/night land surface temperature difference is shown in Figure 7.

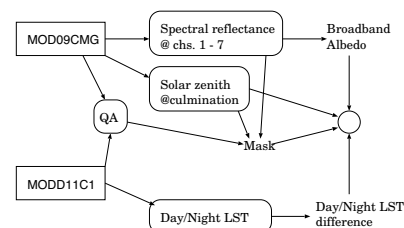


Figure 3: The data processing flow

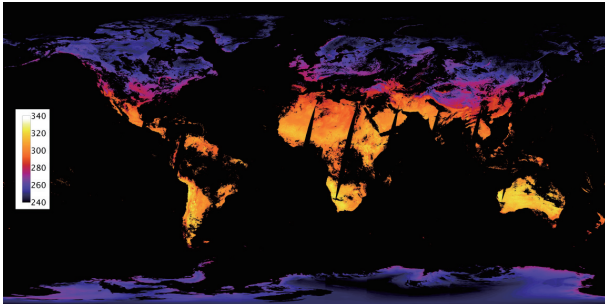


Figure 4: Daytime LST on Dec. 31, 2001

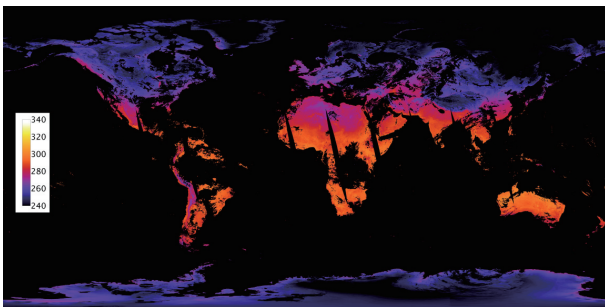


Figure 5: Nighttime LST on Dec. 31, 2001

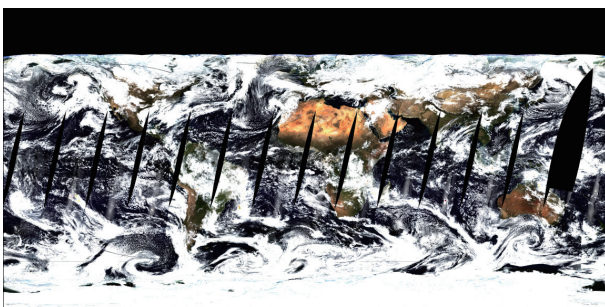


Figure 6: Visible reflectance on Dec. 31, 2001

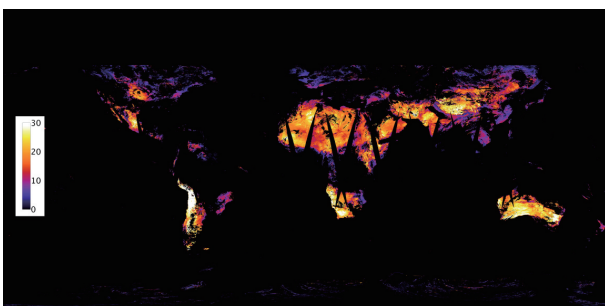


Figure 7: Day/night land surface temperature difference on Dec. 31, 2001

As the mask data, the following 3 kinds of pixels are eliminated from the processing, 1) not the good pixel in day or night land surface temperature and the reflectance, 2) the culmination solar zenith is larger than 80 [deg.] and 3) the surface reflectance is larger than 0.7. AS the mask data example, Figure 8 shows the mask data on Dec. 31, 2001. In the image the white area are used for the processing.

From the above scheme, the aridity index during Mar. 5, 2000 to

Dec. 31, 2009 are computed. As an example of the aridity index, the data on Dec. 31, 2000 is shown in Figure 9.

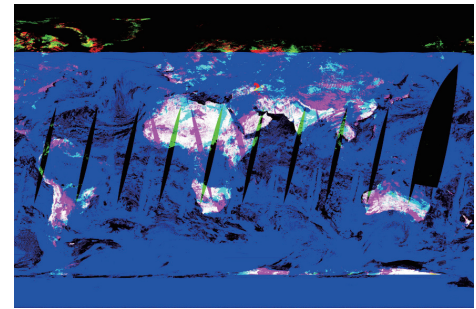


Figure 8: Mask data on Dec. 31, 2001

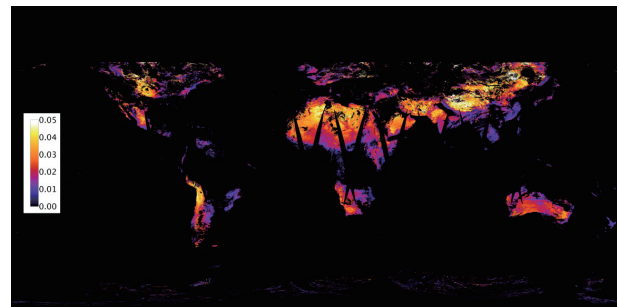


Figure 9: Aridity index on Dec. 31, 2001

### 3 RESULTS AND DISCUSSION

#### 3.1 Solar zenith and NDVI dependency

The two kinds of correlation analysis between the proposed aridity index and the solar zenith are made. The first analysis is the scene base analysis which compute the correlation coefficient with in the scene. The second analysis is the pixel base which compute the correlation coefficient at every pixel during the period. The scene based correlation coefficient between the solar zenith and the proposed index and the day/night land surface temperature difference are shown in Figure 10. The proposed aridity index shows the less correlation to the solar zenith compared with the day/night land surface temperature difference.

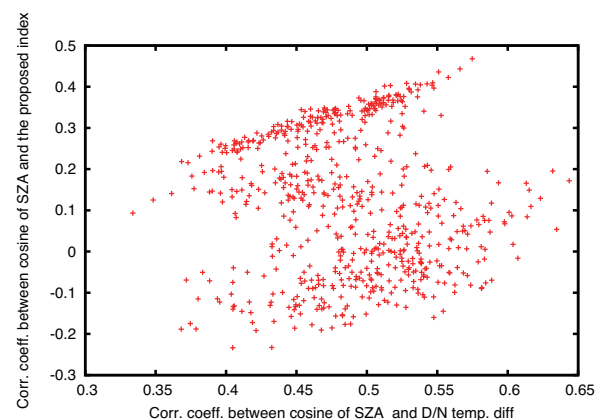


Figure 10: The scene base correlation coefficient

Also the pixel based correlation coefficient are shown in Figure 11 and 12. In this analysis, the proposed index shows the less correlation to the solar zenith.

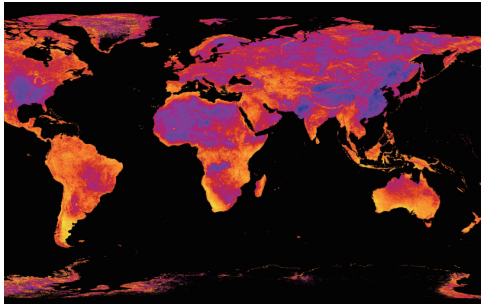


Figure 11: The pixel base correlation coefficient between the proposed index and the solar zenith

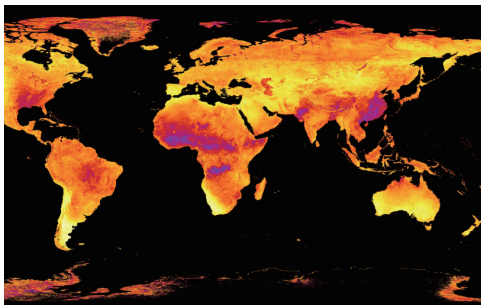


Figure 12: The pixel base correlation coefficient between the day/night land surface temperature difference and the solar zenith

And the pixel base correlation analysis between the proposed index and NDVI are made. NDVI is computed from the chs. 1 and 2 reflectance from MOD09CMG. The results are shown in Figure 13 and 14. Also the proposed index shows the less dependency to NDVI.

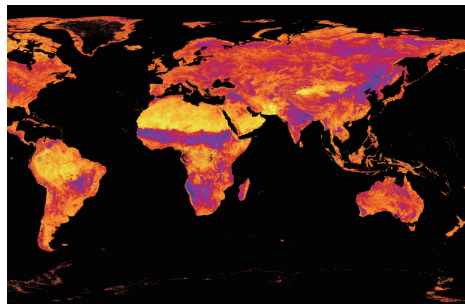


Figure 13: The pixel base correlation coefficient between the proposed index and NDVI

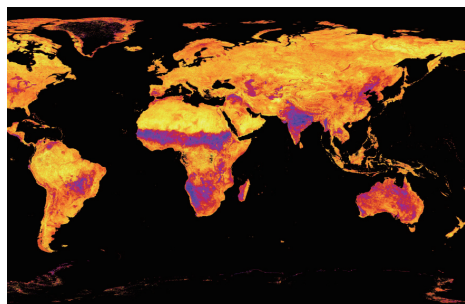


Figure 14: The pixel base correlation coefficient between the day/night land surface temperature difference and NDVI

The results of the dependency analysis show that the proposed aridity index has less dependency to the solar zenith and NDVI. This means that the proposed aridity index is easy to understand the dryness without any concern about the location, season and vegetation amount.

### 3.2 Temporal characteristics

As an example of the temporal analysis, 2001 monthly mean aridity index are shown in Figure 15, significant aridity change are shown in Australia and central Africa.

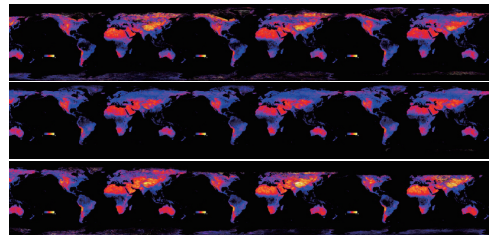


Figure 15: Monthly mean aridity index (2001)

## 4 CONCLUSIONS

These results lead the following conclusions. From the day/night land surface temperature difference and the surface albedo, the aridity index are proposed. From the theoretical analysis, it is clarified that the index corresponds to the surface dryness. And from the MODIS data processing, it is clarified that the index has less sensitivity to the solar zenith and NDVI, it make the instantaneous surface dryness analysis more easy.

## ACKNOWLEDGMENTS

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