Derivation of a global soil moisture and vegetation database from passive microwave signals

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ABSTRACT

A series of validation studies for a recently developed soil moisture retrieval algorithm is presented. The approach is largely theoretical, and uses a non-linear iterative optimisation procedure to solve for soil moisture and vegetation optical depth with a radiative transfer model from satellite microwave observations. The new theoretical approach is not dependent on field observations of soil moisture or canopy biophysical measurements and can be used at any wavelength in the microwave region. Details of the model and its development are discussed. Satellite retrievals were derived from 6.6 GHz Nimbus/SMMR brightness temperatures, and were validated with soil moisture data sets from the U.S., Mongolia, and Turkmenistan. Time series of the satellite-derived surface moisture compared well with the available ground observations and precipitation data. The vegetation optical depth showed similar seasonal patterns as the NDVI.

Keywords: remote sensing, microwave, SMMR, soil moisture, vegetation optical depth

1. INTRODUCTION

Soil moisture information at larger scales has been identified as a parameter of significant potential for improving the accuracy of large-scale land surface atmosphere interaction models[1,2,3]. Soil moisture is an important link between the exchange of water and energy at the soil-atmosphere interface[4]. For example, it has been shown that numerical forecasting of precipitation extremes over the United States are strongly affected by soil moisture fields[5].

Numerous studies have successfully demonstrated that passive microwave remote sensing has great potential for monitoring soil moisture at larger scales[6,7,8,9]. The techniques developed in these studies provide spatially averaged hydrological data, which is ideal for environmental modeling and monitoring. Such spatially averaged area sets are logistically and economically difficult to obtain through in situ measurement techniques.

Traditional methodologies have attempted to relate remotely sensed estimates of soil moisture to observed ground data, and then solve for the optical depth as a residual. These approaches are not ideal because of poor ground-based data sets, and inability to quantify spatially representative estimates of surface soil moisture and vegetation biophysical properties at satellite scale.

Recently, a new methodology has been presented that retrieves soil moisture and vegetation optical depth without observations of soil moisture or biophysical parameters[10]. This unique technique is based on a radiative transfer model and only uses the horizontal and vertical polarization brightness temperatures of one frequency and a surface temperature algorithm based on the vertical polarized 37 signal.

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The current analysis provides additional validation studies in a variety of global locations for this new approach. It is tested with 6.6 GHz Scanning Multichannel Microwave Radiometer (SMMR) data over footprint-sized areas in the U.S. (two in Illinois and one in Iowa), Turkmenistan, and Mongolia. Results are compared with soil moisture field observations, precipitation data, and satellite-derived vegetation index data.

2. THEORY AND BACKGROUND

Passive microwave remote sensing is based on the measurement of thermal radiation from the land surface in the centimeter wave band, and is largely determined by the physical temperature and the emissivity of the radiating body. The emitted radiation in the microwave region is extremely low as compared to longwave infrared radiation. An approximation for the Planck equation, at low frequencies (f < 117 GHz), is the Rayleigh-Jeans approximation, and can be shown to lead to

$$T_{b(l)} \approx e_{(l)} T \tag{1}$$

where l refers to either horizontal or vertical polarization, T_b is the observed microwave brightness temperature, T is the physical (thermometric) temperature of the emitting layer, and e is the smooth-surface emissivity. If the assumption is made that the dielectric in the soil has a smooth boundary and that the temperature and surface moisture distributions are uniform, the reflectivity, R (where R = 1- e), may be calculated from the Fresnel equations

$$R_H = \left| \frac{\cos u - \sqrt{k - \sin^2 u}}{\cos u + \sqrt{k - \sin^2 u}} \right|^2 \tag{2}$$

and

$$R_V = \left| \frac{k \cos u - \sqrt{k - \sin^2 u}}{k \cos u + \sqrt{k - \sin^2 u}} \right|^2 \tag{3}$$

where k is the absolute value of the complex dielectric constant of the soil ($|\varepsilon|$), u is the incidence angle of the sensor and H and V refer to the polarization of the emitted radiation. The soil dielectric constant is determined largely by a variety of factors, e.g. soil physical properties, surface roughness, soil temperature, vegetation, and also sensor characteristics. In general, the soil dielectric constant is a function of individual dielectric constants of the soil components (i.e. air, water, rock, etc).

Surface roughness increases the emissivity of natural surfaces, and is caused by increased scattering due to the increase in surface area of the emitting surfaces[11]. Roughness also reduces the sensitivity of emissivity to soil moisture variations, and thus reduces the range in measurable emissivity from dry to wet soil conditions[12]. However, there is some speculation that the effect of surface roughness is minimal in most locations at satellite scales, except in areas of mountainous terrain or extreme relief. Van de Griend and Owe[9] found that a surface roughness of 0 gave the lowest rms errors in satellite-derived soil moisture over a southern African test site.

Vegetation canopies will also affect the microwave emission because they absorb and reflect the soil emission and also emit their own radiation. A simple physical based model that accounts for the effects of vegetation is the model of Mo et al.[13] and is given as a radiative transfer equation

$$T_{b(l)} = T_s e_{(l)} \Gamma_{(l)} + (1 - \omega_{(l)}) T_c (1 - \Gamma_{(l)}) + (1 - e_{(l)})(1 - \omega_{(l)}) T_c (1 - \Gamma_{(l)}) \Gamma_{(l)} \tag{4}$$

where T_s and T_c are the thermometric temperatures of the soil and the canopy respectively, ω is the single scattering albedo, and Γ the transmissivity.

The transmissivity is the ratio of the radiant energy transmitted through a medium to that incident upon it, and may be expressed as a function of the optical depth, τ, such that

$$\Gamma_{(l)} = \exp \frac{-\tau_{(l)}}{\cos(u)} \tag{5}$$

The optical depth is related to the canopy density, and for frequencies less that 10 GHz has been shown to be a linear function of vegetation water content. Typical values of τ for agricultural crops have generally been given as less than one[7,13].

3. DATA DESCRIPTION

3.1 Satellite data

Nimbus-SMMR: The microwave data used to retrieve soil moisture and vegetation optical depth is from the Scanning Multichannel Microwave Radiometer (SMMR) on board the Nimbus-7 satellite. The data set used for this study consists of dual-polarization 6.6 GHz (λ=4.5 cm) and 37 GHz (λ=0.8 cm) vertical polarization brightness temperatures. SMMR began transmitting data in October 1978, and was eventually deactivated in August 1987. The polar orbiting satellite had a 24 hour on-off cycle permitting both day (12:00 hr) and night (24:00 hr) data set with a spatial resolution of approximately 150 km for the 6.6 GHz and 25 km for the 37 GHz signals. The spacecraft circled the Earth 14 times in one day, resulting in a temporal resolution of about 2 to 3 times per week at mid-latitudes. The incidence angle (u) was 50.3°[14].

NOAA-AVHRR: Normalized Difference Vegetation Index (NDVI) data derived from the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA-AVHRR) reflectances were used for comparison to the vegetation optical depth. The data set begins in 1981 and continues through the present. The data set has an 8 km spatial resolution and a 15-day temporal resolution over North America, while the remainder of the globe is reported at a one-degree spatial and monthly temporal resolution.

3.2 Land surface data

Precipitation: Precipitation data for the U.S. originates from the National Climate Data Center (NCDC). Both daily (18,770 stations) and hourly (6,801 stations) precipitation totals are compiled by cooperative stations throughout all fifty states and U.S. territories. Daily precipitation data for the period 1978 to 1987 was used for this study.

Soil Properties: Soil physical property data such as porosity and wilting point were extracted from the Land Data Assimilation System (LDAS) at 1/8 degree resolution for the U.S.[15,16], and from the International Satellite Land Surface Climatology Project (ISLSCP) one-degree global soil property maps for the remainder of the world[17,18,19].

Soil Moisture: Soil moisture data for the 5 test sites were obtained from the Global Soil Moisture Data Bank[20]. Two locations from Eurasia (Turkmenistan and Mongolia) and three from the U.S. (one in Iowa and two in Illinois) were used (**Figure 1**). Observations were made mostly in grassland and agricultural areas.

4. MICROWAVE MODEL

The technique presented here solves for the soil moisture and vegetation optical depth simultaneously, using the simple radiative transfer equation (4) and the horizontal and vertical brightness temperature at 6.6 GHz. For each of the test sites, the 6.6 GHz and 37 GHz observations covering the field stations were extracted from the SMMR data set and the 37 GHz signals (i.e. these signals had a resolution of approximately 25 km) were converted to the 6.6 GHz footprint (~150 km) with a nearest neighbor interpolation technique.

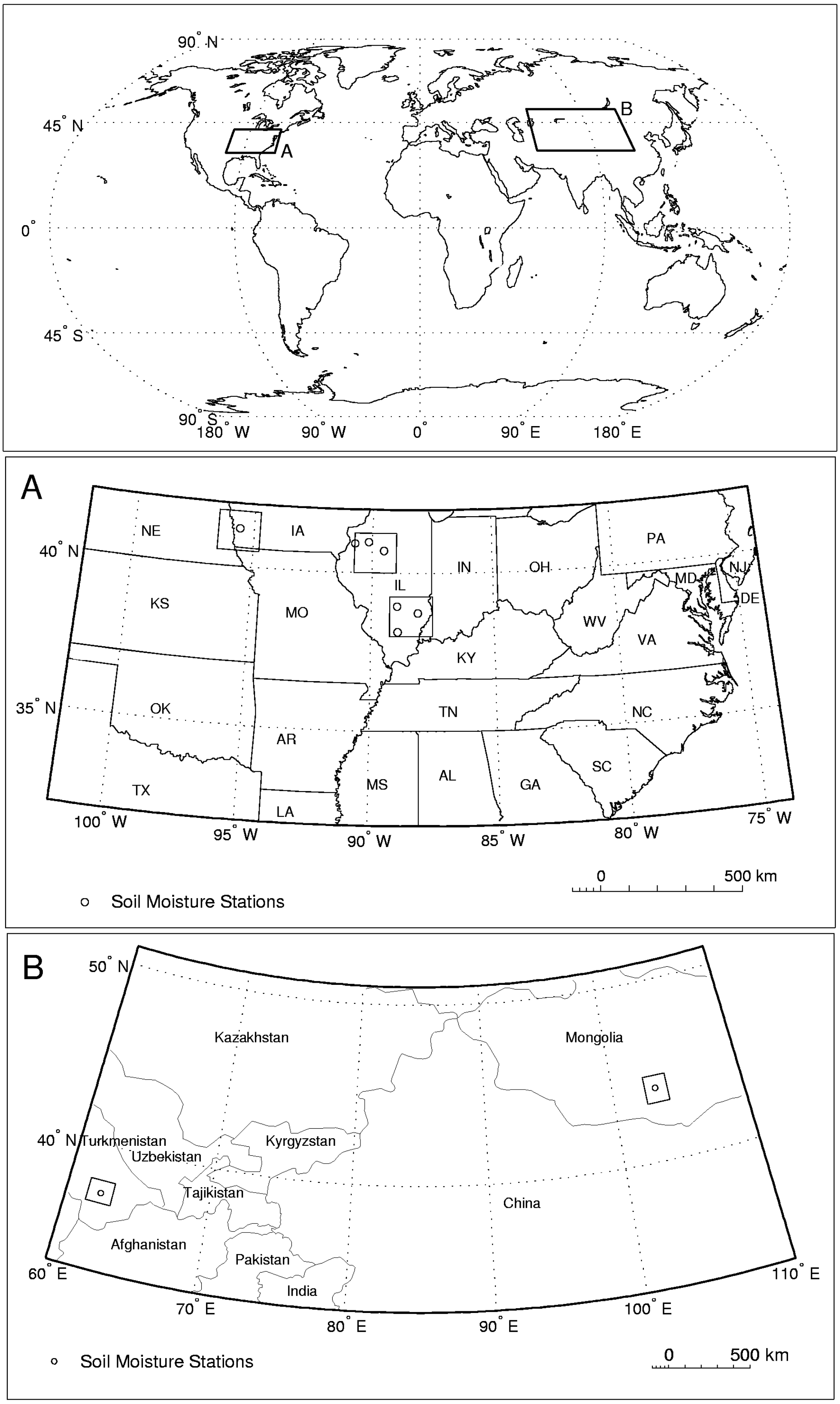

Fig. 1: Location maps of the field stations. Figure (A) shows the U.S. sites, and (B) the Eurasian sites.

The soil dielectric (ε) was modeled with a well-known dielectric-mixing model[21], that uses porosity, wilting point, soil temperature, frequency of the microwave signal, and soil moisture as input parameters. It is assumed that $T_s = T_c$ and the mean surface temperature was derived off-line from 37 GHz vertical polarized brightness temperature with a recently developed algorithm[22]. However, the surface temperature may be provided from other sources as well. The single scattering albedo was derived from values found in the literature and was set to 0.06. Sky background radiation is not included at this time, but will be added later.

The model now has two remaining parameters; the vegetation parameter or optical depth and the soil moisture parameter. Solving for these two variables, requires a more unique approach, however, and is described below.

According to a series of theoretical simulations it has been shown that the vegetation optical depth is a function of the Microwave Polarization Difference Index (MPDI) and the dielectric constant of the soil[10]. The MPDI is frequently used to remove the temperature dependence of T_b, resulting as a parameter that is quantitatively, and more highly related to the dielectric properties of all the emitting surfaces. At the 37 GHz frequency, the MPDI is mainly a function of the overlying vegetation, and consequently is a good indicator of the canopy density[23]. At a frequency of 6.6 GHz, the MPDI will not only contain information on the canopy, namely the optical depth, but will also contain significantly more information on the soil emission and consequently the soil dielectric properties. The MPDI is defined as

$$MPDI = \frac{T_{b[V]} - T_{b[H]}}{T_{b[V]} + T_{b[H]}} \tag{6}$$

By using the newly developed vegetation optical depth algorithm, the only remaining term in the radiative transfer equation (4) is the soil emissivity (*e*). As H polarization has the greatest sensitivity to soil moisture we solve for *e* using T_b. The emissivity of the soil is calculated from the Fresnel equations (Equation 2 and 3), where the only unknown is the dielectric constant of the soil. We now have both the vegetation optical depth and the soil emissivity defined in terms of soil dielectric constant. Next, the model uses a non-linear iterative procedure to solve the radiative transfer equation (4) in a forward approach, by optimizing on the dielectric constant. Once convergence of the calculated and observed brightness temperatures is achieved, the model uses information on soil physical properties, such as porosity, and wilting point together with a dielectric mixing model to solve for the surface soil moisture. In **Figure 2** the soil moisture retrieval technique is presented in a simplified diagram.

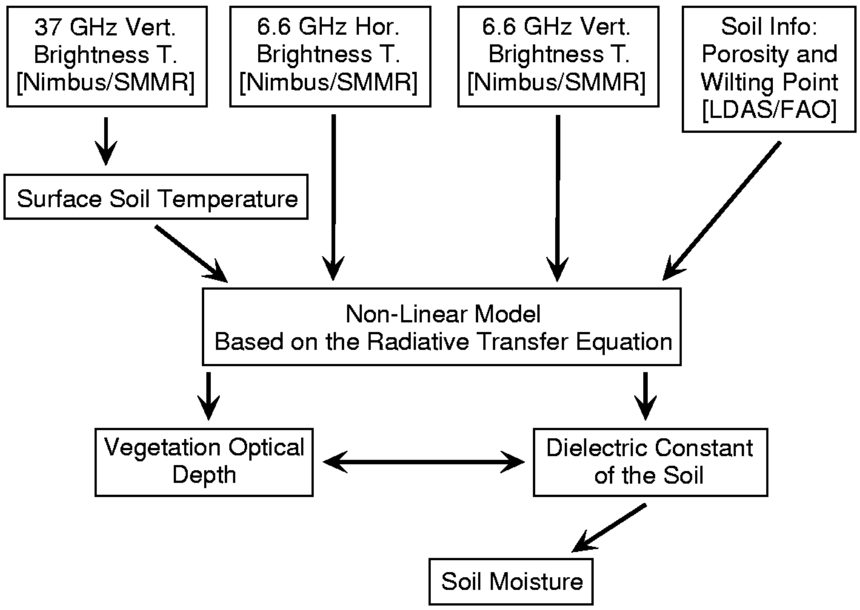

Fig 2: A simplified diagram of the soil moisture retieval methodology

5. VALIDATION RESULTS

The methodology outlined above for retrieving of both surface soil moisture and vegetation optical depth has been applied to the historical data of SMMR brightness temperatures for the previously described locations; Turkmenistan, Mongolia, Iowa and Illinois. These sets were selected because of the availability of long term soil moisture data that can be used for validation purposes. While not necessarily the most optimum data set for microwave validation, these sets are only one of the few data sets in the world, that cover such a large area for such a lengthy period.

In Illinois two 150 km test sites were selected for illustration (See **Figure 1**), with each site containing 3 observation stations, The soil moisture field data is reported as average volumetric moisture content in the top 10 cm profile. The Iowa location contained two research catchments with three soil moisture measuring stations in each. Measurements for this location gave the average moisture for the top 7.5 cm soil layer. An one year time series of SMMR-derived surface moisture along with the observed soil moisture from these three U.S. test sites are given in **Figure 3**. Daily precipitation is also included in the time series to assist in understanding the observed changes in soil moisture.

The Mongolia and Turkmenistan locations could be characterized by only one soil moisture stations each. Both the Mongolian and the Turkmenistan sites (See **Figure 1**) are characterized as semi-arid areas. The Mongolian site is located in the southern part of the Gobi desert and the Turkmenistan site in the southern part of the Kara Kum Desert. The Mongolian soil moisture measurements were derived from the top 5 cm profile, while the Turkmenistan station reports soil moisture values of the first 10 cm. Compared to the U.S. test site, the satellite data is able to clearly differentiate between the dry and wet locations. All time series of satellite-derived soil moisture illustrate discernable seasonal patterns, although correspondence with the ground observations is not always perfect.

It is important that one does not forget several important differences when comparing the satellite-derived surface moistures with the ground observations. First, the SMMR-derived surface moisture is an average value integrated over the entire footprint, whereas the ground data are point measurements. The ground data are also on average soil moisture within the top 5 to 10 cm profile, while SMMR retrievals reflect only the moisture content of the microwave soil moisture sampling depth, which is at most only about 1 cm. Additionally, ground and satellite observations rarely occur on the same day. Lastly, while the SMMR observations are displayed with connecting lines (see Figure 3), it is done so only to assist in following the general trends of the time series. It is important to realize that significant changes in surface moisture frequently occur during the periods between observations, but may go totally undetected by both the satellite and the ground observations.

Time series of the retrieved optical depths for the same test sites were given in **Figure 4**. Fifteen day NDVI composite data are averaged for the U.S. SMMR footprints (monthly for the Eurasian), and are included for comparison. A distinct annual course is observed in the optical depth time series, and coincides well with the NDVI at all sites. The optical depth, however, is seen to be much more variable in time than the NDVI. This is due to the inherent characteristics of the NDVI compositing procedure, where only one value is selected during the composite window to represent the entire composite period. The inability to quantify the vegetation biomass at shorter (i.e. daily) time scales is often a drawback of the NDVI. This may be rather significant in arid and semi-arid regions, where greening and senescing of the vegetation canopy (especially grasses) can occur over very short time periods in response to localized and individual precipitation events. The microwave optical depth may actually be a better indicator of green biomass and vegetation dynamics at shorter time scales.

However, it is also important to understand that the NDVI and the microwave optical depth respond to entirely different vegetation properties. The NDVI responds to differences in the reflectivities of visible (red) and near infrared wave bands, and is influenced by several canopy properties, including not only leaf water content, but color as well. The microwave optical depth, on the other hand, responds primarily to the vegetation water content, as a function of the vegetation dielectric properties.

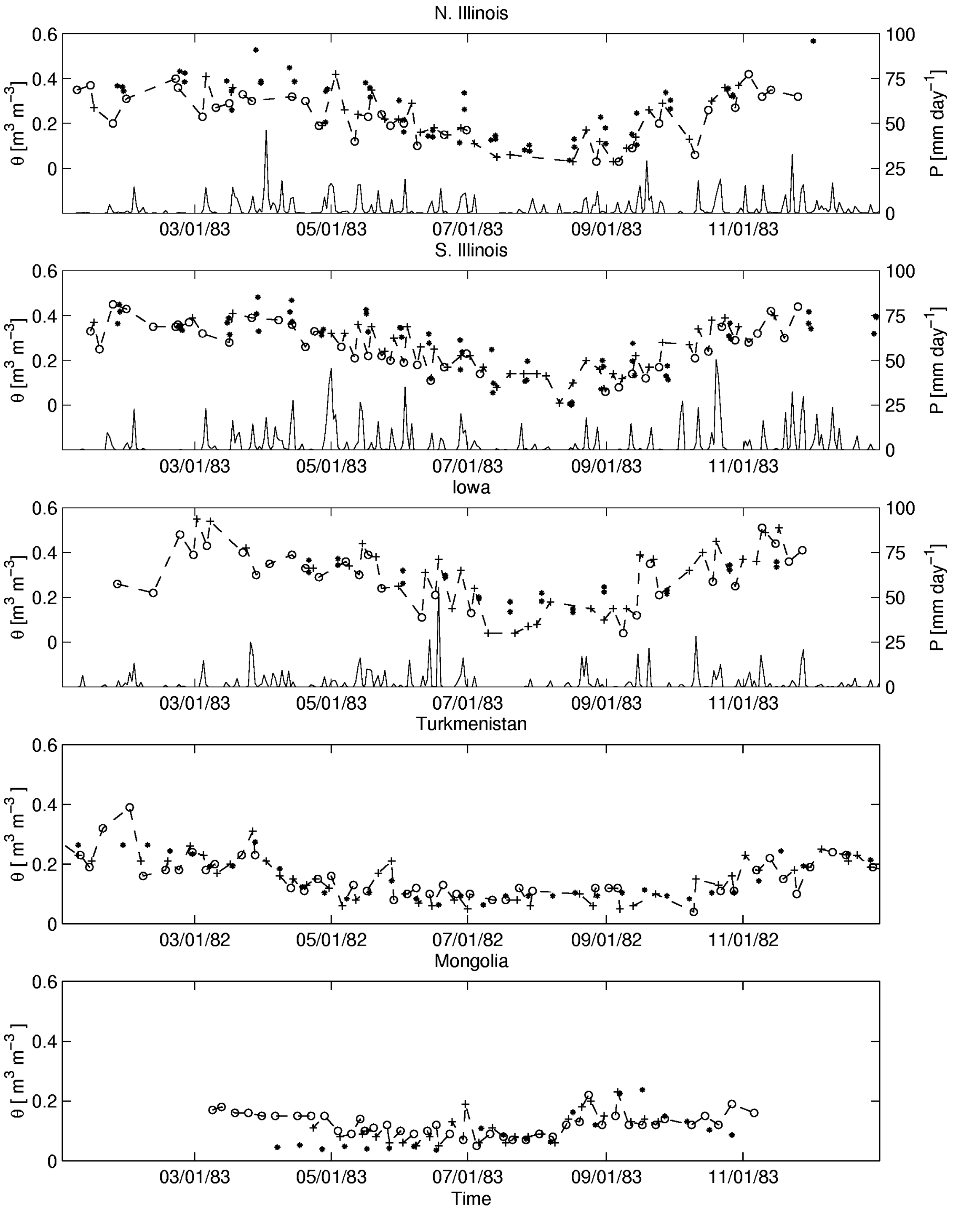

Fig. 3: Time series of satellite derived day-time (o) and night-time (+) soil moisture and ground observations (∗) for the test sites. For comparison the precipitation is included for the American sites.

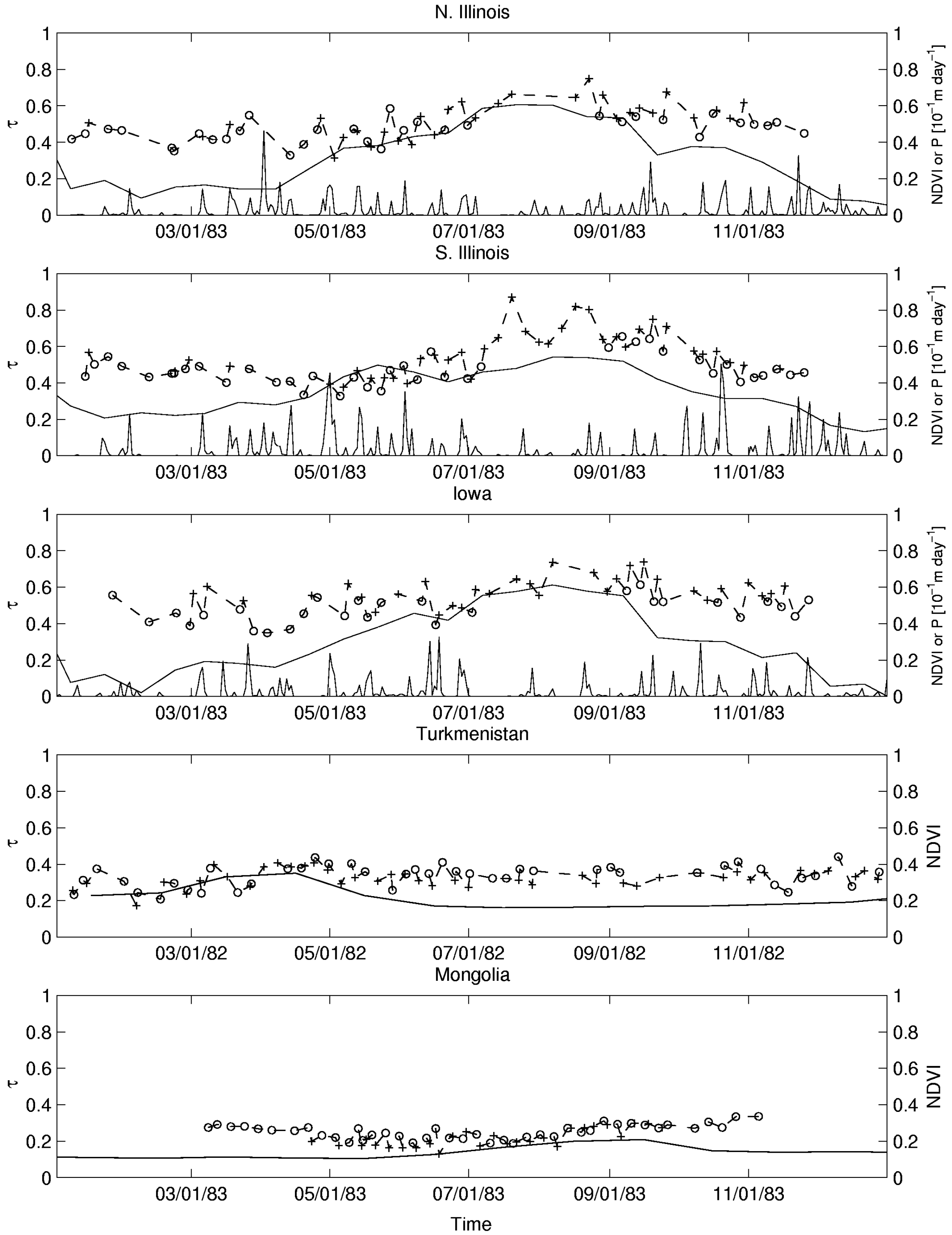

Fig. 4: Time series of satellite derived day-time (o) and night-time (+) vegetation optical depth and NDVI (-) for the test sites. For comparison the precipitation is included for the American sites.

6. DISCUSSION AND CONCLUSIONS

Soil moisture retrieval by microwave has been shown to be the most reliable remote sensing technique, since the up-welling microwave energy is a direct response to the absolute water content in the soil. The retrieval method presented here, is a direct radiative transfer approach, and requires no calibration based on geographic location, vegetation biophysical properties, or other ground-based data sets of soil moisture. It appears to be the first technique of its kind to successfully retrieve space-based estimates of absolute soil moisture at the global scale.

Microwave vegetation optical depth may be a highly useful tool for monitoring various biophysical aspects of vegetation. While this parameter has some distinct advantages over visible/near infrared instruments, such as all-weather capability, it is not meant to replace these. Because these various parameters are derived from different sensors, and hence, are a response to totally different biophysical properties, they should complement each other. When taken together, their interpretation should yield a more highly accurate picture of vegetation biophysical characteristics.

Soil moisture and vegetation optical depth are retrieved from dual polarized microwave brightness temperature observations,and were applied to 6.6 GHz SMMR data. Some assumptions regarding the different elements of the radiative transfer equation are made in order to reduce the number of variables. The model assumes a constant value for the scattering albedo, based on a series of previous studies.

A non-linear iterative approach is used to solve for the surface moisture and vegetation optical depth, both of which are derived from the soil dielectric constant. The model was applied to several sites with observations of surface moisture, located in the U.S., Mongolia and Turkmenistan. Time series of the satellite-derived surface moisture compared well with the available ground observations and precipitation data. The vegetation optical depth showed similar seasonal patterns as the NDVI.

ACKNOWLEDGEMENTS

This study was supported by NASA ?? Code ? through the NSIPP program.

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