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Influence of cracking clays on satellite observed and model simulated soil moisture

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Abstract

Vertisols are clay soils that are common in the monsoonal and dry warm regions of the world. A defining feature of these soils is the development of shrinking cracks during dry periods, the effects of which are not described in land surface models nor considered in the surface soil moisture estimation from passive microwave satellite observations. To investigate the influence of this process we compared the soil moisture (θ in $\text{m}^3 \text{m}^{-3}$) from AMSR-E observations and the Community Land Model (CLM) simulations over vertisols across mainland Australia. Both products agree reasonably well during wet seasons. However, during dry periods, AMSR-E θ falls below values for surrounding non-clays, while CLM simulations are higher. The impacts of soil property used in the AMSR-E algorithm, vegetation density and rainfall patterns were investigated, but do not explain the observed θ patterns. Analysis of the retrieval model suggests that the most likely reason for the low AMSR-E θ is the increase in soil porosity and surface roughness through cracking. CLM does not consider the behavior of cracking clay, including the further loss of moisture from soil and extremely high infiltration rates that would occur when cracks develop. Analyses show that the corresponding water fluxes can be different when cracks occur and therefore modeled evaporation, surface temperature, surface runoff and groundwater recharge should be interpreted with caution. Introducing temporally dynamic roughness and soil porosity into retrieval algorithms and adding a “cracking clay” module into models, respectively, may improve the representation of vertisol hydrology.

1 Introduction

Soil moisture is a key variable in the water and energy cycles, and its accurate representation and measurement is required for estimation and prediction of infiltration, evaporation, runoff and estimates of latent, sensible and ground heat fluxes. Soil moisture over large scales can be derived from satellite observations or model simulations

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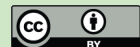
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(Owe et al., 2008; Gao et al., 2006). Comparing remotely sensed soil moisture with other independent soil moisture products, e.g. ground observations, models or other remote sensing techniques (McCabe et al., 2005a; Scipal et al., 2008; Draper et al., 2009), allows for better evaluation of soil moisture estimates derived from different techniques and provide enhanced understanding of the processes causing soil moisture variability (Wagner et al., 2003). Several such studies have been conducted and generally show reasonably good correspondence between remotely sensed and modeled soil moisture (Choi et al., 2008; Rüdiger et al., 2009; Santanello Jr. et al., 2007; Vischel et al., 2008).

However, these comparison studies pay little attention to large vertisol regions. Vertisols cover more than 3 million km² globally, with major areas including Eastern Australia (particularly Queensland with 0.5 million km² and New South Wales), the Deccan Plateau of India, Eastern Africa, South America and parts of eastern China. They have swelling (during wetting) and shrinking (during drying) characteristics, with cracks opening up under dry conditions. The pore volume changes with variations in soil moisture, which increases the difficulty in accurately estimating soil moisture (Cornelis et al., 2006). Due to the desirable agricultural and hydraulic characteristics of clay soils, they are disproportionally important for cropping and irrigation in particular, which makes accurate representation of the behavior of the soil moisture response important in characterizing water and energy balance studies.

We aim to investigate whether the soil moisture dynamics in vertisols affects the soil moisture retrievals from passive microwave remote sensing at the satellite footprint scale. Soil moisture content (θ in m³ m⁻³) retrievals derived from the Advanced Microwave Scanning Radiometer – Earth Observation System (AMSR-E) are used here. In the absence of direct coincident in situ soil moisture measurements over large vertisol regions, we compare satellite passive microwave soil moisture with land surface model simulations from the Community Land Model (CLM) over mainland Australia. More details about AMSR-E and CLM will be described in Sect. 2.

The monthly averages of AMSR-E and CLM θ for January and October 2004 over

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mainland Australia are shown in Fig. 1. January 2004 is the monsoon season for north Australia and dry season for the south, while October 2004 is the wet season over south Australia (particular southeast and southwest) and dry season over the north, which can be clearly reflected in the surface soil moisture patterns. Figure 1a and b shows that both AMSR-E and CLM θ over vertisol regions in north Australia are higher than the non-clays in the vicinity in January 2004. In October 2004, CLM θ over vertisols is still higher than surrounding non-clay soils (Fig. 1d). Conversely, the AMSR-E θ retrievals are apparently lower over vertisols (Fig. 1c). Under similar meteorological conditions, the soil moisture content of clay soils would not be expected to be lower than non-clay soils, since the smaller clay particles are able to retain more water molecules.

The focus of this paper is to seek answers to the following questions: what causes the low values of AMSR-E soil moisture over vertisols during dry periods and how to address this issue; does CLM reasonably represent the soil moisture over vertisols during dry periods; if not, what are the potential impacts on other hydrological components and how to improve estimates of the hydrological cycle and energy fluxes.

2 Data and methods

2.1 AMSR-E soil moisture

The AMSR-E sensor onboard NASA’s Aqua satellite has provided passive microwave measurements at 6.9 GHz (C-band) and five higher frequencies (including 36.5 GHz Ka-band) since May 2002, with daily ascending (13:30 LT) and descending (01:30 LT) overpasses.

There are several algorithms to retrieve soil moisture using AMSR-E observed brightness temperatures. Draper et al. (2009) illustrated that the soil moisture retrievals by an algorithm developed by Vrije Universiteit Amsterdam, in collaboration with NASA (hereafter VUA-NASA algorithm), has good correspondence to in situ data over the

South-Eastern Australia compared with other retrievals. In addition, no apparent radio frequency interference on AMSR-E C-band brightness temperature was observed over Australia (Njoku et al., 2005). Therefore, the AMSR-E soil moisture product from the VUA-NASA algorithm is applied in this study.

5 The VUA-NASA algorithm uses the Land Parameter Retrieval Model (LPRM) horizontal (H) and vertical (V) polarization C-band and V polarization Ka-band brightness temperatures (T_b) (Owe et al., 2008). Soil surface temperature is estimated from Ka-band T_b (Holmes et al., 2009). The vegetation optical depth (τ , dimensionless) and soil-water mixture dielectric constant are derived simultaneously. The soil moisture is solved from the dielectric constant using the Wang-Schmugge model (Wang and Schmugge, 1980). Several assumptions are made in the LPRM for retrieving surface soil moisture (De Jeu, 2003): a constant single scattering albedo, canopy surface temperature equal to soil surface temperature, vegetation parameters being the same for both H and V polarizations, and minimal effect of surface roughness.

10 The LPRM and CLM model use the common soil property dataset (<http://ldas.gsfc.nasa.gov/GLDAS/SOILS/GLDASsoils.shtml>). The dataset is based on the Food and Agriculture Organization (FAO) Soil Map of the World linked to a global database of over 1300 soil samples and was spatially re-sampled to 0.25° resolution before applied in LPRM and CLM.

15 Here we use the θ retrievals acquired by descending passes, as the minimal temperature gradients at midnight are more favorable for the retrievals (De Jeu, 2003). The soil moisture retrievals from C-band, representing roughly the top 1.5-cm, were re-sampled into 0.25° (about 25 km) resolution for mainland Australia.

2.2 Land surface model soil moisture

25 The CLM is a publicly available distributed land surface model that combines components from the Common Land Model and the National Center for Atmospheric Research Land Surface Model (NCAR-LSM) (Oleson et al., 2004; Dai et al., 2003).

In CLM, the vertical profiles of sand and clay are taken into account by using a 10-

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layered soil component (Bonan et al., 2002). In this study, we only use the top layer soil moisture (about 1.8 cm), giving a depth comparable with the AMSR-E soil moisture. Soil moisture dynamics of the top layer are governed by infiltration, surface and sub-surface runoff, gradient diffusion, gravity and evapotranspiration, with soil hydraulic properties defined as functions of sand and clay percentage (p_{sand} and p_{clay}). Equations describing the soil properties are given below. Additional details about CLM can be obtained from Oleson et al. (2004).

$$\theta_{\text{sat}} = 0.489 - 0.00126(p_{\text{sand}}) \quad (1)$$

$$\Psi_{\text{sat}} = -10.0 \times 10^{1.88 - 0.0131(p_{\text{sand}})} \quad (2)$$

$$B = 2.91 + 0.159(p_{\text{clay}}) \quad (3)$$

$$\Psi = \Psi_{\text{sat}}(\theta/\theta_{\text{sat}})^{-B} \quad (4)$$

θ_{sat} , Ψ_{sat} , θ and Ψ are, respectively, the saturated soil moisture ($\text{m}^3 \text{m}^{-3}$), saturated soil matric potential (mm), soil moisture ($\text{m}^3 \text{m}^{-3}$) and soil matric potential (mm) (Oleson et al., 2004). More discussions about these equations are presented in Sect. 5.

In this study, the CLM model was run at a 3-h temporal interval and the outputs were re-sampled into 0.25° spatial resolution. To match the time of AMSR-E descending overpass time, the CLM soil moisture values at 01:00 a.m. LT were used for comparison. The CLM soil moisture was converted to volumetric soil moisture for direct comparison with AMSR-E θ retrievals.

3 Methods

To investigate possible reasons for the discrepancy in AMSR-E θ between vertisols and non-clay soils during dry periods, we first examine the impacts of soil property on AMSR-E θ retrievals by running the retrieval algorithm using a uniform soil property (i.e., same soil porosity and fractions of sand/clay).

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The accuracy of AMSR-E θ retrievals are also influenced by vegetation density: higher accuracy of θ retrievals can be expected with lower vegetation density. The Normalized Difference Vegetation Index (NDVI) product, captured by the Advanced Very High Resolution Radiometer (AVHRR) instruments on-board the National Oceanic and Atmospheric Administration (NOAA) platforms and provided by Global Inventory Monitoring and Modeling Studies (GIMMS <http://glcf.umiacs.umd.edu/data/gimms/>) (Tucker et al., 2005), was used in this study to examine vegetation density, together with the monthly AMSR-E optical depth (τ) which is simultaneously retrieved with AMSR-E θ . Both of these variables are indicators of vegetation density, although they have different physical interpretations. In general, NDVI represents the greenness of vegetation, and vegetation optical depth is largely a function of vegetation water content and total biomass (De Jeu, 2003).

In addition, the patterns in θ would be expected to be related to rainfall (McCabe et al., 2005b). Thus gridded rainfall data for mainland Australia were also included in the analysis for comparison. Gridded rainfall data across Australia were interpolated from point observations by the Queensland Department of Natural Resources and Mines (<http://www.longpaddock.qld.gov.au/silo/>). The original 0.05° resolution gridded data was re-sampled into 0.25° resolution to allow direct comparison.

4 Results

Monthly averages of AMSR-E surface soil moisture retrievals for January and October 2004, using uniform soil porosity and fractions of sand/clay in the retrieval algorithm are shown in Fig. 2. In comparison with Fig. 1, although values of θ retrievals over vertisols get closer to surrounding non-clay soils in January 2004, the contrast between vertisols and non-clay soils becomes even more obvious in October 2004. As a result it seems that soil property information is not the cause for the different θ patterns seen over vertisols and non-clay soils.

The monthly NDVI and AMSR-E τ for January and October 2004 are shown in Fig. 3.

Both of these are indicators of vegetation density, and we can observe that the vegetation density is low over vertisols during January and October 2004, indicating that their impacts on the accuracy of θ retrievals are minimal.

The monthly total rainfall for January and October 2004 are shown in Fig. 4. It can be seen that vertisol regions in north Australia did not receive more rainfall in January 2004 or less rainfall in October 2004 than surrounding non-clay soils. Again we can conclude that rainfall does not explain the distinct AMSR-E θ behaviors over vertisols observed in Fig. 1.

5 Discussion

Since the low AMSR-E θ values over vertisols in the dry season can not be attributed to the above three factors, the most likely reason lies in the unique physical characteristics of vertisols shrinking and cracking under dry conditions. Figure 5 qualitatively illustrates how soil cracking increases soil porosity and further leads to an underestimation of soil moisture. We suppose that under the condition of no cracks, soil porosity of the entire soil column is $0.5 \text{ m}^3 \text{ m}^{-3}$ and soil moisture is $0.1 \text{ m}^3 \text{ m}^{-3}$. When cracks are open, the soil porosity of top soil layer increases to $0.6 \text{ m}^3 \text{ m}^{-3}$ and the soil moisture is assumed to be $0.1 \text{ m}^3 \text{ m}^{-3}$. The increases in soil porosity increase the proportion of air and decrease the fraction of soil (including soil water and solid soil material) within a certain volume. The dielectric constant of air is much smaller than solid soil and water, thus increasing soil porosity will reduce the mixture dielectric constant for the same soil moisture (Fig. 5b). Figure 5c shows that if the increases in soil porosity (i.e., from 0.5 to 0.6) are not considered, the retrieved soil moisture will be lower than the actual soil moisture. One might expect that the difference between retrieved and actual soil moisture will be greater when the cracks at the surface are wider. In addition, the quantitative difference between retrieved and actual soil moisture depends on fractions of clay and sand (i.e., wilting point) and the effective temperature of the surface layer.

Schneeberger et al. (2004) demonstrated an air-to-soil transition model, including

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dielectric mixing effects due to the changes in soil porosity and surface roughness, which can considerably improve the estimation of surface soil moisture. In that model, the surface roughness is defined as the height between the peak and bottom of cracks, and the soil porosity is positively related with the surface roughness. The field experiment conducted by Escorihuela et al. (2007) found an inverse relationship between surface roughness and soil moisture and suggested that it might be modeled using soil texture and density. De Jeu et al. (2009) also demonstrated that introducing a temporally dynamic roughness parameter would improve the accuracy of remote sensing soil moisture retrievals. However, the roughness parameter defined in any manner is likely to vary temporally and spatially. Thus sufficient in situ measurements (e.g. soil moisture, porosity and surface roughness) over large scale vertisols are highly demanded to improve the accurate estimation of soil moisture.

When it comes to CLM θ in the dry season, the lowest θ stays at the permanent wilting point when Ψ_{\max} is equal to $-1.5 \cdot 10^5$ mm (pF=4.2). From Eqs. (1–3), it can be seen that minimum soil moisture are dependent on fractions of clay and sand. Clay soils have greater Ψ_{sat} , higher θ_{sat} and higher value of B. From Eq. (4), we can calculate that under the same Ψ , the θ of clay soils are higher than non-clay soils. For soils without cracking characteristics, it might be valid that the lowest θ is reached at the permanent wilting point. However, the field experiment conducted by Chan and Hodgson (1981) in southeast Australia revealed that once cracks in vertisols are formed, further loss of moisture from soil also occurs as direct evaporation, drying the soil to below the permanent wilting point. Selim and Kirkham (1970) performed a laboratory experiment and found that cracks could increase the total evaporation by 2.5 cm over 12 days, 30% higher than soils without cracks. Without considering open cracks, soil moisture will be overestimated and evaporation will be underestimated, which might lead to an overestimation of sensible heat and surface temperature over vertisols.

Figure 6 shows the spatial correlation between summer (December to February) temperature bias produced by a regional climate model (Evans and McCabe, 2010) and the spatial distribution of vertisols that regularly dry out and crack at this time of

year over south-east Australia. The errors accumulated in the regional climate model over vertisols are most likely due to poor representation of the cracking clay soils. In addition, the difference between model assumed albedo and real albedo might be a possible reason for the overestimated surface air temperature.

5 The impacts of soil cracking on the hydrological cycle are not limited to surface soil moisture and evaporation. Austin and Prendergast (1997) conducted a border (also referred to as flood, surface or bay) irrigation experiment over cracked soils in south-east Australia and found that the infiltration through soil cracks represented almost half of the total irrigation. In the Ord River Irrigation Area in north-western Australia, 10 Smith (2008) observed the persistent groundwater rise during the past 10 years, and attributed this to large infiltration losses through cracking clays in the early wet season. Over the rain-fed crops in central Queensland, the infiltration rate when cracks are open is greater than 25 mm per hour, while the infiltration rate is only 1–2 mm per hour when no cracks are present. Outside Australia, Allen et al. (2005) monitored the rainfall, 15 runoff, soil moisture, and groundwater levels over a hydrological year in north-central Texas and found that recharge through the cracks allowed rapid and relatively deep wetting of otherwise impermeable clays. This finding is also supported by Amidu and Dunbar (2007).

20 Since cracking of clays has clear impacts on the partitioning of precipitation/irrigation water into groundwater recharge, soil moisture, surface runoff and evaporation, model outputs from CLM and AMSR-E retrievals should be interpreted with caution over these soil conditions.

6 Conclusions

25 AMSR-E retrievals and CLM simulations provide two different approaches to approximating the actual soil moisture. Responses of estimated soil moisture to meteorological conditions correspond well during wet periods. However, neither approach adequately accounts for the behavior of cracking clays under very dry conditions, which potentially

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could have significant impacts on the water and energy cycles.

From the aspect of AMSR-E retrievals, the assumption of constant soil porosity and surface roughness in the retrieval algorithm results in the underestimation of soil moisture. How to cope with temporal changes in soil porosity and surface roughness remains a challenge to retrieving soil moisture from passive microwave satellite observations. This study illustrates that the effect of soil cracking is one reason why it is unlikely that we can derive estimates of soil moisture content of the top few cm of soil with good absolute accuracy. Even if we could, the relationship of absolute water content between top layer and greater depth can be weak, not just because of soil water movement (e.g. infiltration into open cracks), but also due to vertical changes in structure and bulk density (van Dam, 2000). This need not be a major obstacle for successful uses of satellite passive microwave soil moisture for many purposes however.

From the land surface scheme perspective, if the influence of soil cracking are not considered, the partitioning of precipitation into soil moisture, evaporation, infiltration and surface runoff is likely incorrect, suggesting that more caution be used in interpreting these model outputs. Despite uncertainties related to cracking clay, useful information can still be obtained from comparisons between AMSR-E and CLM soil moisture. The differences between CLM and AMSR-E soil moisture might indicate the periods of crack formation, expanding and resealing. Developing a dynamic module of “cracking clays” and incorporating this into land surface and hydrological models may improve the estimates of hydrological cycle and energy fluxes.

The influence of cracking vertisols on AMSR-E retrieved soil moisture that was illustrated in this paper may still be an issue to address in the new missions – Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active/Passive (SMAP), as both of them aim at providing volumetric soil moisture with the accuracy of $0.04 \text{ m}^3 \text{ m}^{-3}$ or better (Kerr et al., 2000; SMAP Mission, 2007).

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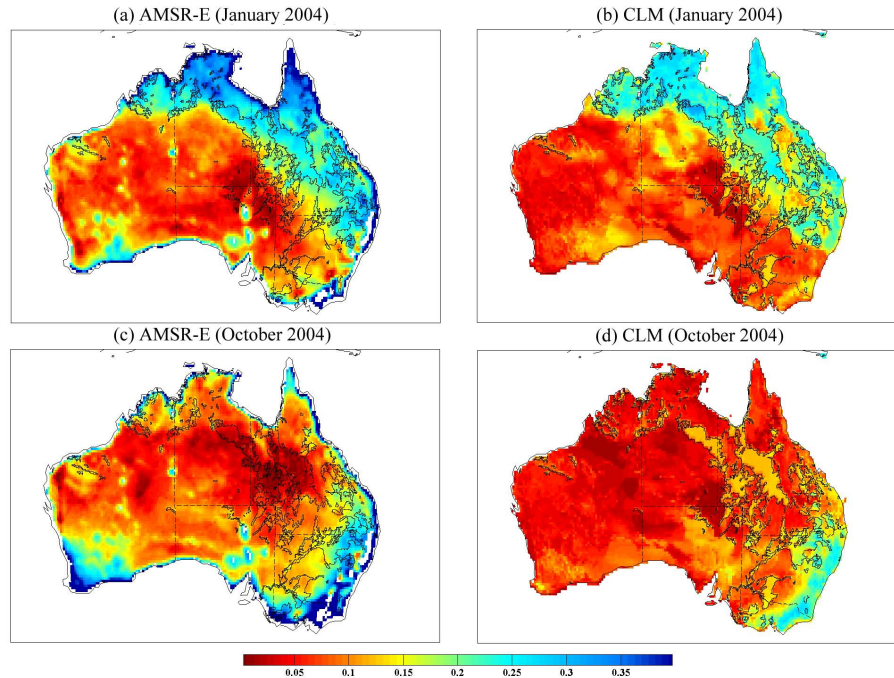


Fig. 1. Monthly averages of AMSR-E observed and CLM simulated θ for January and October 2004, which are, respectively wet and dry season for northern Australia. The regions surrounded by the black lines represent Vertisols (i.e., cracking clay soils) (Unit: $\text{m}^3 \text{m}^{-3}$).

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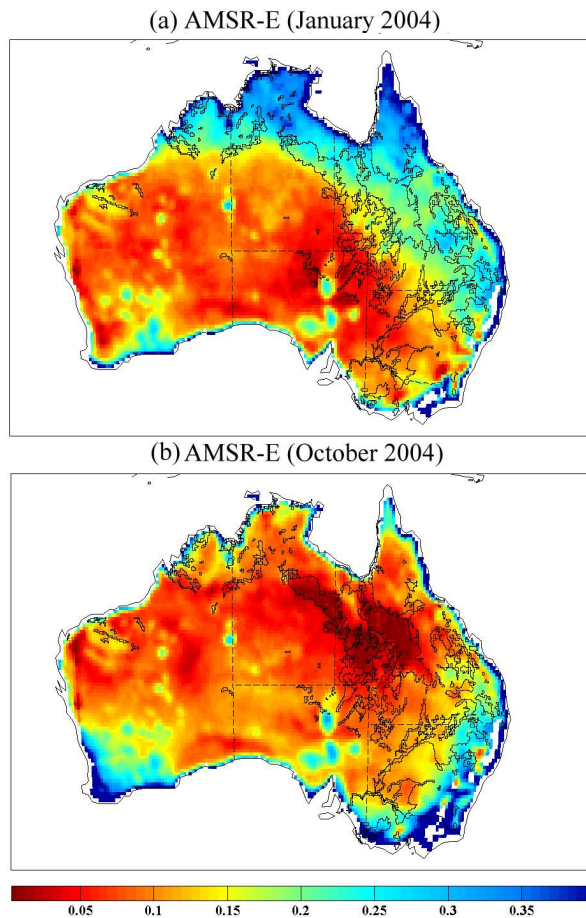


Fig. 2. Monthly averages of AMSR-E surface soil moisture retrievals for January and October 2004, using a uniform soil property (soil porosity and fractions of sand/clay) in the retrieval algorithm (Unit: $\text{m}^3 \text{m}^{-3}$).

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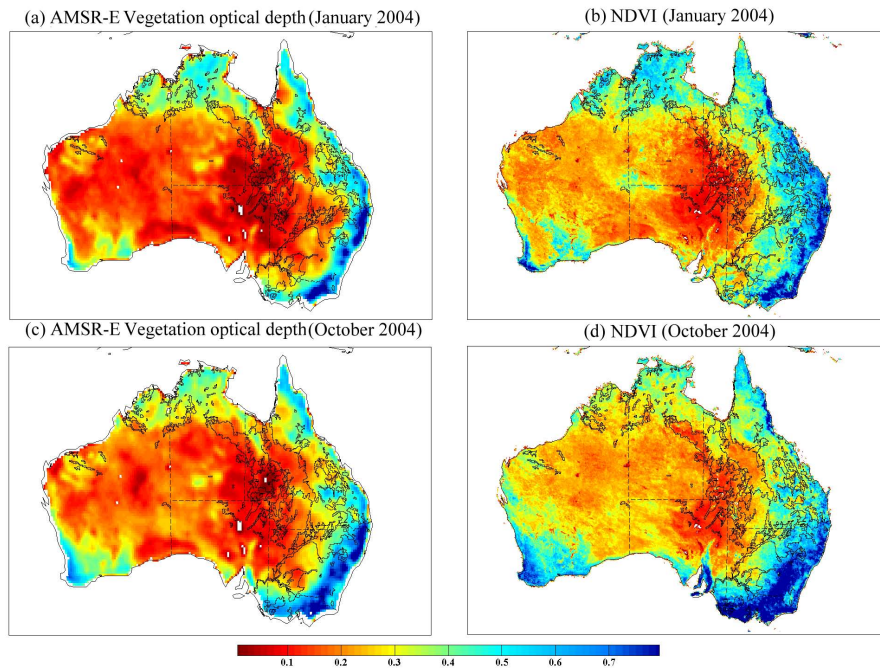


Fig. 3. Monthly averages of AMSR-E observed vegetation optical depth (τ) and NDVI for January and October 2004.

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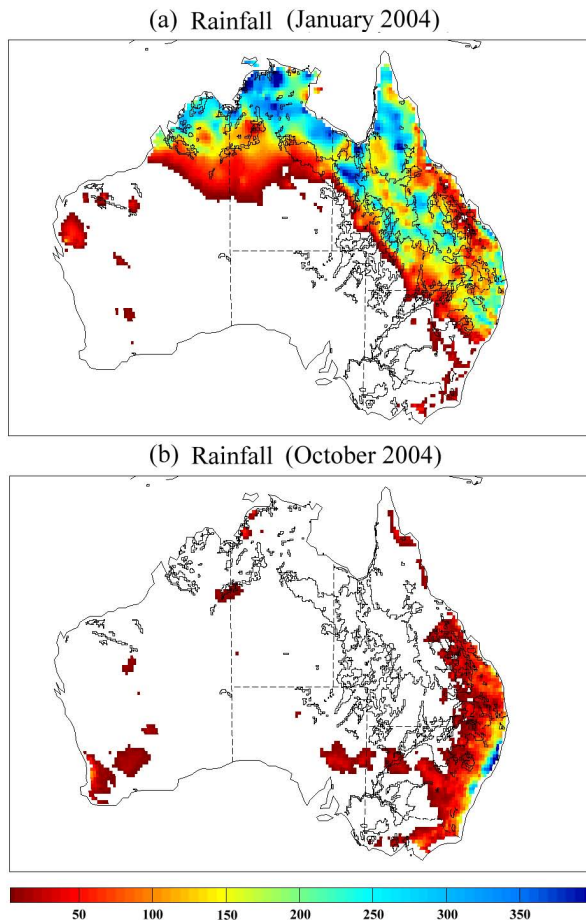


Fig. 4. Monthly total rainfall for January and October 2004.

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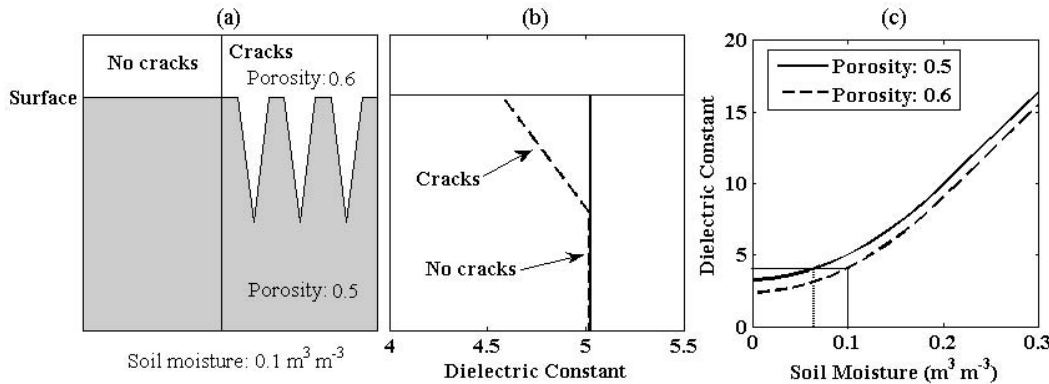


Fig. 5. Simplified illustration of how open cracks increase soil porosity and further lead to an underestimation of soil moisture. With cracks opening, the porosity at the surface will increase. Due to the low dielectric constant of air, the mixed dielectric constant at the surface will decrease. Without considering the increase in porosity, the estimated soil moisture will be lower than the actual one.

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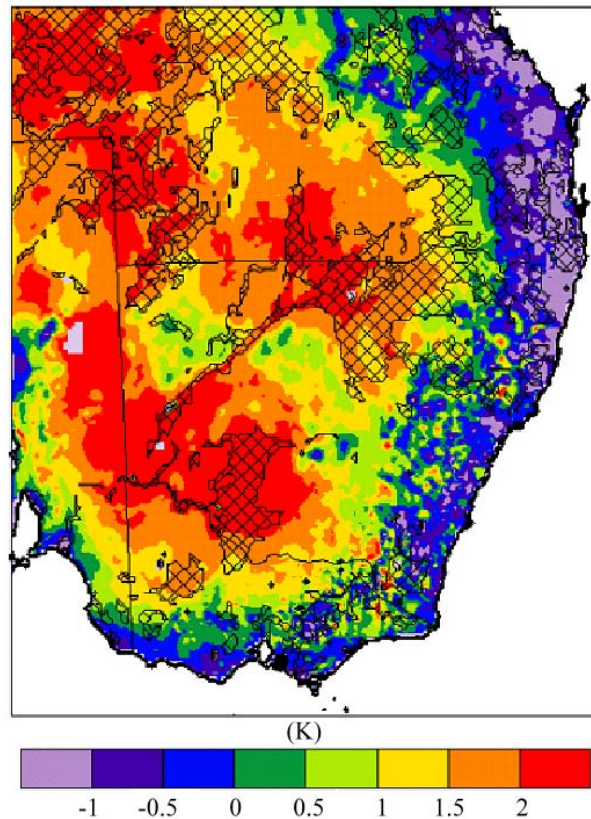


Fig. 6. Average summer surface air temperature bias over a 24-year period (1985–2008) produced by the simulations of the Advanced Weather Research & Forecasting in comparison with the gridded observations created by the Australian Water Availability Project. Shaded areas show the locations of clay soils.

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