11.2 ASSESSING THE ROLE OF HILLSLOPE-SCALE HETEROGENEITY IN SOIL MOISTURE REMOTE SENSING AND DATA ASSIMILATION USING MICROWAVE RADIOMETRY

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ABSTRACT Land surface remote sensing and soil moisture data assimilation studies rely extensively on radiative transfer models to simulate observations of microwave radiobrightness temperature, given the spatial distribution of surface moisture and vegetation. The purpose of this modeling study is to assess the sensitivity of commonly-used radiative transfer schemes to hillslope-scale variation in topography. The effects of topography on modeled radiobrightness temperatures are twofold: (1) topography controls the local incidence angle the observing sensor makes with the local land surface, and (2) the spatial distribution of moisture, surface and canopy temperature, and vegetation depends on topography. Hillslope-scale incidence angles can be explicitly computed at every element in a computational domain knowing the local terrain slope and aspect, and the relative sky position of the sensor. A spatially-distributed, physically-based watershed ecohydrology model is used to account for topography-dependent variation in moisture, surface and canopy temperature, and vegetation biomass. These hillslope-scale heterogeneities affect both the spatial distribution of radiobrightness temperatures at hillslope scales, as well as the aggregate radiobrightness temperature at a spatial scale consistent with observations. Specifically, the spatial organization of channels and hillslopes within a watershed leads to a distribution of local incidence angles that is not well described by an average value of the satellite look angle. Furthermore, because of significant North-South contrasts in land surface states, for particular geomorphic contexts and polarizations the aggregate predicted radiobrightness temperature can exhibit sensitivity to the relative orientation of the sensor and the land surface. Implications for development of soil moisture retrieval algorithms, soil moisture data assimilation, and spatial disaggregation of radiobrightness temperature observations are discussed.

1. INTRODUCTION

Soil moisture, and its spatial distribution, imposes an important land surface constraint in global- and synoptic-scale meteorological modeling. For instance, *Chen et al.* [2001] found that the dynamics of soil moisture significantly effect 12 hr lead time precipitation forecasts. It is commonplace to initialize meteorologic models using moisture fields retrieved from space-borne passive microwave sensors. Passive soil moisture remote sensing in the microwave region of the electromagnetic spectrum (i.e., 1 to 6 GHz) and assimilation of these observations into land surface models depends heavily on the use of radiative transfer models (RTMs) [*Njoku and Entekhabi*, 1996; *Crow et al.*, 2001, *Kerr et al.*, 2001; *Entekhabi et al.*, 2004].

Previous soil moisture remote sensing and data assimilation studies have largely ignored the impact of topography on predicted radiobrightness temperatures, because commonly used land surface models resolve energy and mass balance at resolutions of 1 km or greater. At these resolutions, subgrid-scale topographic influence on moisture redistribution must either be treated in a parametric fashion or entirely neglected. Predicted radiobrightness temperatures computed from surface states at resolutions of 1 km or coarser also neglect the impact of topography on local incidence angle, substituting the sensor look angle for incidence angle. At finer spatial resolutions (i.e., hillslope scales) the role of topography in moisture redistribution has been well studied [*Western et al.*, 1999]. Moreover, because of the well-known sensitivity of radiobrightness temperature to incidence angle [e.g., *Njoku and Kong*, 1977; *Mo et al.*, 1982; *Njoku and Entekhabi*, 1996], effects of topography on incidence angle cannot be neglected when simulating emission of microwave radiation at hillslope scales.

In this work, we explore the role that topography plays in the distribution of radiobrightness temperatures at hillslope scales. Topography exerts control on the distribution of hillslope-scale radiobrightness temperatures in two distinct ways: (1) it constrains the surface states that determine emission of microwave radiation from the surface through its control on the organization of moisture and soil temperatures, which subsequently influence the distribution of biomass over longer timescales, and (2) through local slope and aspect, topography determines the incident angle a remote sensor makes with the land surface, for given satellite sky position. In this modeling study we simulate the distribution of soil moisture, soil and canopy temperature, and vegetation biomass using a physically-based model that resolves energy, mass, and carbon balance. Local incidence angle is computed explicitly using local slope and aspect, using an assumed satellite sky position. We investigate the influence of topography on microwave radiation emission both at the hillslope scale and at the watershed scale by aggregating hillslope-scale radiobrightness temperatures. Impacts of topography-controlled heterogeneity in soil moisture, soil and canopy temperatures, and biomass on emission of microwave radiation is assessed independently of the topography-controlled distribution of local incidence

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angles. Results presented have important implications in areas of soil moisture remote sensing and data assimilation. In particular, by accounting for subgrid-scale heterogeneity in incidence angle it may be plausible to more effectively bound subgrid-scale variations in moisture, temperature, and vegetation state while not explicitly modeling surface states at hillslope scales. In data assimilation algorithms such as the ensemble Kalman Filter (EnKF) [*Evensen*, 1994; 2003] the cross-covariance structure between modeled moisture and temperature states, which exhibit topography-dependent spatial structures, and the predicted observations are the means by which noisy coarse-scale observations inform hillslope-scale model states.

2. METHODOLOGY

In a set of synthetic experiments, we use a spatially distributed ecohydrology model to simulate the primary spatially-varying inputs to a radiative transfer model: (1) soil moisture, (2) soil temperature, (3) canopy temperature, and (4) leaf area index (LAI). The model used is the Triangulated Irregular Network-based Realtime Integrated Basin Simulator (tRIBS) with dynamic vegetation (VEGGIE). A very brief description of the tRIBS+VEGGIE model is given here, and the interested reader is referred to more detailed discussion of the model framework in *Ivanov et al.* [2004a,b; 2007a-c].

The tRIBS component of the coupled model stresses the role of topography in lateral soil moisture redistribution and accounts for the effects of sloped, heterogeneous, and anisotropic soil [*Ivanov et al*., 2004a,b]. The dynamic vegetation model (VEGGIE) operates on specified plant functional types (PFTs) at a location captures near-surface characteristics affecting soil water state prior to rainfall events and the redistribution of infiltrated moisture after rainfall cessation. VEGGIE models plant carbon assimilation by representing coupled: (1) biophysical energy processes (e.g., partitioning of input solar radiation in the canopy and soils), (2) biophysical hydrologic processes (e.g., partitioning of rainfall into interception, throughfall, plant water uptake, etc.), and (3) biochemical processes and vegetation phenology. For each PFT, tRIBS+VEGGIE simulates biophysical processes of plants that effect land-atmosphere carbon exchanges: (1) photosynthesis, (2) autotrophic respiration, (3) stress induced foliage loss, and (4) tissue turnover. These processes determine the net land-atmosphere CO_2 exchange, with plant carbon storage distributed across three pools: foliage, sapwood, and fine roots. The photosynthetic model couples carbon assimilation with surface energy and water balance through a stomatal resistance model. Surface energy balance is determined by longwave and shortwave radiation budget, and soil moisture throughout the rooting profile. The model requires precipitation and meteorological forcings as input, and topographic and soil boundary conditions [*Ivanov et al.* 2004a,b; 2007a-c].

Local incidence angle is computed explicitly using the spherical law of cosines at any computational pixel as a function of slope, aspect, and a satellite sky position described by azimuth angle and zenith angle [*Iqbal*, 1983]. Here, slope is defined as the topographic gradient in the direction of steepest descent, and aspect is the cardinal direction of steepest descent. For a low Earth orbit satellite, the zenith angle can be well approximated by the sensor look angle, which is assumed to be 40° in agreement with conceived and existing microwave radiometers [e.g., *Entekhabi et al.,* 2004]. We consider two cases for the satellite azimuth angle: (1) azimuth angle equal to 150°, approximating the azimuth angle encountered during the ascending limb of a sun-synchronous orbit, and (2) azimuth varying from 0° to 360° to investigate the sensitivity of aggregated radiobrightness temperatures to relative satellite sky position.

The areas considered correspond to two synthetic landscapes subjected to substantially different erosion mechanisms and were generated using a landscape evolution model [*Tucker and Bras*, 1998; *Tucker et al*., 2001a,b]. Each landscape consists of 2400 uniformly spaced hexagonal computational pixels within a 2 km square area. One landscape is characterized by long hillslopes and shallow slopes associated with diffusive erosion, while the other is characterized by short hillslopes and steep slopes associated with fluvial erosion. For each domain, instantaneous values of the land surface state required by the RTM were obtained from tRIBS+VEGGIE simulations: (1) soil moisture in the top 25 mm, (2) soil surface temperature, (3) canopy temperature, and (4) leaf area index. The land surface state is taken for a hypothetical midday on August 14 with no rain or clouds. The effective dielectric constant was determined from the empirical relationship of *Topp* [1986] that is a function of soil moisture only. Soil textural heterogeneity was not considered. Radiobrighness temperatures are computed each computational pixel within each synthetic landscape. The following informative cases were considered:

1. Spatial distribution of horizontally and vertically polarized radiobrightness temperatures using **spatially distributed** tRIBS+VEGGIE model output, satellite azimuth fixed at 150°.
2. Spatial distribution of horizontally and vertically polarized radiobrightness temperatures using **spatially averaged** tRIBS+VEGGIE model output, satellite azimuth fixed at 150°.
3. Spatially averaged horizontally and vertically polarized radiobrightness temperature using **spatially distributed** tRIBS+VEGGIE model output, satellite azimuth varying form 0° to 360°.
4. Spatially averaged horizontally and vertically polarized radiobrightness temperature using **spatially averaged** tRIBS+VEGGIE model output, satellite azimuth varying form 0° to 360°.

3. RESULTS AND CONCLUSIONS

Hillslope-scale radiobrightness temperatures vary from approximately 224 to 302 K in the horizontal polarization and from approximately 304 to 320 K in the vertical polarization for the diffusive erosion domain. North- and West-facing hillslopes are associated with the lowest values of horizontally polarized radiobrightness temperature. Vertically polarized radiobrightness temperatures are lowest on the South- and East-facing pixels in the diffusive erosion domain. For both polarizations, local differences between radiobrightness temperatures computed with spatially-distributed versus those computed with spatially-averaged surface states are most strongly influenced by the spatial pattern of soil surface temperature for the diffusive erosion domain. Local differences in brightness temperature range from approximately -5.8 to +2.4 K, with enhanced brightness temperatures on South- and Southeast-facing hillslopes and corresponding diminished brightness temperatures on North- and Northwest-facing hillslopes.

For the fluvial erosion domain, brightness temperatures vary from approximately 112 to 303 K in the horizontal polarization and from approximately 126 to 320 K in the vertical polarization. Similar to the diffusive erosion domain, horizontally polarized brightness temperatures are higher on South- and Southeast-facing hillslopes and lower on North- and Northwest-facing hillslopes in the fluvial erosion domain. However, interpretation of spatial patterns in vertically polarized brightness temperatures is difficult for the fluvial erosion domain. This difficulty arises because of the dependence of hillslope-scale incidence angle on topography and satellite sky position and viewing angle. Steep slopes within the fluvial erosion domain lead to large incidence angles at pixels with aspects oriented in directions similar to the viewing sensor. Vertically polarized radiobrightness temperature is non-monotonic in incidence angle, although non-monotonicity is encountered only at incidence angles greater than approximately 65°. Beyond incidence angles of approximately 65°, vertically polarized brightness temperatures decreases rapidly as incidence angle approaches 90°. For a given satellite sky position, pixels presenting incidence angles greater than or equal to 90° cannot be observed by the sensor. In both polarizations, local differences between brightness temperatures computed with spatially-distributed versus those computed with spatially-averaged surface states closely follow the spatial pattern of soil surface temperature. Local differences in brightness temperature range from approximately -26.0 to +5.5 K.

Watershed-scale (aggregated) brightness temperatures vary smoothly with azimuth angle to the satellite in the diffusive erosion domain for both polarizations. The aggregate brightness temperature captures well spatially averaged behavior in the underlying surface states in the diffusive erosion domain, irrespective of satellite azimuth. On the other hand, the relationship between aggregated brightness temperature and satellite azimuth angle is non-smooth in the fluvial erosion landscape. Moreover, the degree to which the aggregate brightness temperature captures the spatially-averaged behavior of the land surface depends on the satellite azimuth angle. This is due to the aforementioned unobservability of pixels with incidence angles greater than or equal to 90°.

Our work has important implications for soil moisture remote sensing and data assimilation when the spatial scale of interest is the hillslope. Operational algorithms to retrieve the spatial distribution of soil moisture from observations of surface microwave radiobrightness temperatures are often developed through so-called Observing System Synthetic Experiments (OSSEs) [e.g., *Crow et al.* 2001; 2005]. The OSSE framework is commonly used to develop soil moisture retrieval algorithms as follows: (1) energy- and mass-balance resolving land surface models are used to generate spatially-distributed output characterizing the near-surface moisture and temperature state of a region, (2) model outputs are used as input to RTMs to generate predicted radiobrightness temperature observations at the resolution of the model, which are then aggregated to the resolution of the satellite observation, and (3) approximate inverse models (retrieval algorithms) are developed to obtain the spatial distribution of moisture at the resolution of the satellite observation, from the predicted radiobrightness temperatures at these resolutions. Soil moisture data assimilation studies have used algorithms such as the EnKF to update the model soil moisture state, given the brightness temperature observation [e.g. *Margulis et al.*, 2002; *Reichle et al.*, 2002]. The EnKF and similar algorithms require RTMs as observation operators, which project the prior model state estimate to observation space where the difference between the actual and predicted observations (the innovation) is computed.

Substantial effort in the remote sensing and meteorological communities has gone to assessing the impacts of soil moisture heterogeneity and its uncertainty on numerical weather forecast skill [e.g., *Chen et al.*, 2001; *Koster et al.*, 2004]. Undoubtedly, the spatial scale of soil moisture variability input to atmospheric models will continue to be refined. Remote sensing of soil moisture is a critical tool to verify land surface conditions forecast by coupled land-atmosphere models and update land surface states. This work contributes to constraining radiobrightness temperature variation at resolutions finer than are presently considered in soil moisture data assimilation and remote sensing studies. Specifically, we demonstrate topographic dependence of incidence angle at hillslope scales given the satellite sky position. We also show the impacts of systematic heterogeneity in near-surface soil temperature and moisture and vegetation biomass (controlled by topography) on radiobrightness temperature at hillslope and catchment scales.

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