Evaluation of the Community Microwave Emission Model Coupled with the Community Land Model over East Asia

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Abstract The Community Microwave Emission Model (CMEM) developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) can provide a link between surface states and satellite observations and simulate the passive microwave brightness temperature of the surface at low frequencies (from 1 GHz to 20 GHz). This study evaluated the performance of the CMEM coupled with the Community Land Model (CLM) (CMEM-CLM) using C-band (6.9 GHz) microwave brightness temperatures from the Advanced Microwave Scanning Radiometer on Earth Observing System (AMSR-E) over East Asia. Preliminary results support the argument that the simulated brightness temperatures of CMEM-CLM from July 2005 to June 2010 are comparable to AMSR-E observational data. CMEM-CLM performed better for vertical polarization, for which the root mean square error was approximately 15 K, compared to over 30 K for horizontal polarization. An evaluation performed over seven sub-regions in China indicated that CMEM-CLM was able to capture the temporal evolution of C-band brightness temperatures well, and the best correlation with AMSR-E appeared over western Northwest China (over 0.9 for vertical polarization). However, larger biases were found over southern North China and the middle and lower reaches of the Yangtze River.

Keywords: Community Microwave Emission Model, Community Land Model, microwave brightness temperature, AMSR-E


1 Introduction

Land data assimilation, which can combine complementary information from measurements and land surface models, is an effective method to obtain superior estimates of land surface variables, e.g., soil water content and soil temperature (Robock et al., 2000). Low-frequency (~20 GHz) microwave brightness temperatures, which are sensitive to near surface soil moisture content (Njoku et al., 2003), can be assimilated into a land surface model to improve the estimation of soil moisture and, thus, the surface energy budget. Crow and Wood (2003) assessed the potential of assimilating surface brightness temperature data into a TOPMODEL-based (topography-based variable contributing area model) land surface model using an ensemble Kalman filter (EnKF) method. Yang et al. (2007) developed a land data assimilation system to assimilate Advanced Microwave Scanning Radiometer-EOS (AMSR-E) microwave brightness temperature data. Jia et al. (2009) presented an assimilation framework which was able to improve soil moisture profiles considerably by assimilating gridded AMSR-E brightness temperature data, even though satellite observations were only available for the surface soil layer. These studies have shown that to assimilate microwave brightness temperatures directly into land surface models, a suitable radiative transfer model (RTM) for the description of radiative transfer processes (Tian et al., 2010) is necessary. The RTM acts as the observation operator and provides a link between the forecast model states and the observational microwave brightness temperature (e.g., AMSR-E). Therefore, the performance of an RTM can largely determine the capability of a land data assimilation system (LDAS) to simulate surface states.

Several RTMs (Dobson et al., 1985; Weng et al., 2001; Drusch et al., 2001; Chen et al., 2003; Shi et al., 2005; Wigneron et al., 2007) have been proposed to simulate microwave brightness temperatures over various surface conditions. The Community Microwave Emission Model (CMEM) was developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) as the forward operator for low frequency passive microwave brightness temperatures (from 1 GHz to 20 GHz) of the surface (Holmes et al., 2008; Drusch et al., 2009). It combines many choices regarding the physical parameterizations for soil, vegetation, and atmospheric dielectric layers. de Rosnay et al. (2009) found that CMEM was able to reproduce the temporal and spatial variability related to measured brightness temperatures over West Africa for 2006.

In this study, CMEM simulations coupled with the Community Land Model version 3.0 (CLM3, Oleson et al., 2004) (hereafter CMEM-CLM), which was used as a forecast operator in previous studies (Jia et al., 2009; Tian et al., 2010), is presented. C-band microwave brightness temperatures from AMSR-E from July 2005 to June 2010 were selected to evaluate the performance of CMEM-CLM over East Asia, and the error distribution of CMEM-CLM over East Asia is shown.

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2 Models and methods

2.1 CMEM

CMEM was developed by the ECMWF for numerical weather prediction applications and is used to simulate passive microwave brightness temperatures of the surface at low frequencies (from 1 GHz to 20 GHz) (Holmes et al., 2008; Drusch et al., 2009). CMEM consists of the physics and parameterizations used in the Land Surface Microwave Emission Model (LSMEM; Drusch et al., 2001) and the L-band Microwave Emission of the Biosphere (L-MEB; Wigneron et al., 2007). For polarization (p), the brightness temperatures over snow-free areas at the top of the atmosphere (TOA) \( T_{\text{toa},p} \), which result from the contributions of three dielectric layers (soil, vegetation, and atmosphere), can be expressed as follows:

\[
T_{\text{toa},p} = T_{\text{atm},p} + e^{-\tau_{\text{atm},p}} \cdot T_{\text{veg},p} + e^{-\tau_{\text{veg},p}} \cdot T_{\text{soil},p} + e^{-\tau_{\text{soil},p}} \cdot T_{\text{soil},p},
\]

where \( T_{\text{toa},p} \) is the top-of-vegetation brightness temperature when the vegetation is represented as a single-scattering layer above a rough surface; \( \tau_{\text{atm},p} \) is the atmospheric optical depth; \( T_{\text{atm},p} \) and \( T_{\text{soil},p} \) are the upward and downward atmospheric emissions, respectively; and \( T_{\text{veg},p} \) and \( T_{\text{soil},p} \) are the soil and vegetation layer contributions, respectively. Here, \( r_{\text{p}} \) is the soil reflectivity of a rough surface (one minus the emissivity \( \varepsilon_{\text{soil}} \)), and \( \tau_{\text{veg},p} \) is the vegetation optical depth along the viewing path. Additionally, snow is represented through the Helsinki University of Technology (HUT) snow emission model (Pulliainen et al., 1999) as a single additional homogeneous snow layer with low attenuation and an additional dielectric boundary.

CMEM includes a modular choice regarding the physical parameterizations for the soil, vegetation, and atmosphere dielectric layers. For soil, as described in Drusch et al. (2009), three parameterizations are considered for the soil dielectric constant, four for the effective temperature, two for the smooth emissivity model, and five for soil roughness. The vegetation optical depth can be represented through a choice among four different parameterizations, while the atmospheric opacity can be represented by three parameterizations. Consequently, there are a total of 1440 different configurations provided by CMEM. More detailed descriptions of CMEM can be found in Holmes et al. (2008) and Drusch et al. (2009). However, we could not test all of these possible configurations. Because the most important contributors affect the sensitivity of the TOA brightness temperature (Jones et al., 2004), the vegetation optical depth and the soil dielectric constant are strongly related to vegetation water content and soil moisture, respectively. It was noted by de Rosnay et al. (2009) that the best CMEM configuration in the African Monsoon Multidisciplinary Analysis (AMMA) Land Surface Models Intercomparison Project for Microwave Emission Models (ALMIP-MEM) experiment was the one that used the Kirdyashev opacity model (Kirdyashev et al., 1979) and the Wang and Schmugge (1980) dielectric model. In this study, the same configuration is used to investigate the performance of CMEM-CLM over East Asia. The detailed parameterizations used in this study are presented in Table 1.

2.2 The CMEM-CLM experiments

CLM3 (Oleson et al., 2004) is a land surface model designed for use in coupled climate models. In CLM3, a nested sub-grid hierarchy in which grid cells are composed of multiple land units, snow/soil columns, and plant functional types (PFTs) is used to represent surface spatial heterogeneity. Each grid cell can include a different number of columns, and each column can include multiple PFTs. CLM3 has one vegetation layer, ten unevenly spaced vertical soil layers, and up to five snow layers (depending on the total snow depth). It computes soil temperature and soil water content in the ten soil layers to a depth of 3.43 m in each column.

To perform the CMEM-CLM experiments, we first used the 20-year observation-based atmospheric forcing data (1985–2004) of Qian et al. (2006) to run CLM3 to spin up deep soil layers and obtain an equilibrium state. Then, atmospheric forcing dataset with a high temporal-spatial resolution (hourly, 0.1°×0.1°) from Shi (2008) was used to force CLM3 in the study domain (15–55°N, 75–135°E) during the period from July 2005 through June 2010. The outputs of CLM3, including soil moisture, soil temperature, ground temperature, snow depth, and snow density, were provided to CMEM. Additionally, other auxiliary datasets required by CMEM, e.g., the percentages of sand and clay and the fraction of vegetation, were provided from the surface datasets of CLM3 (Oleson et al., 2004).

| Table 1 Physical parameterizations used in CMEM-CLM experiments. |
|-----------------|-----------------|-----------------|
| Module          | Variable        | Parameterization |
| Soil            | Soil dielectric constant | Wang and Schmugge (1980) |
|                 | Soil effective temperature | Choudhury et al. (1982) |
|                 | Smooth emissivity | Fresnel equation |
|                 | Soil roughness | Choudhury et al. (1979) |
| Vegetation      | Vegetation optical depth | Kirdyashev et al. (1979) |
| Atmosphere      | Atmospheric optical depth | Pellarin et al. (2003) |
| Snow            | Snow reflectivity | Pulliainen et al. (1999) |
2.3 AMSR-E satellite data

AMSR-E was developed by the National Space Development Agency of Japan (NASDA) and was launched in December 2002 on NASA’s Aqua satellite. The AMSR-E instrument operates in a polar sun-synchronous orbit with equator crossings at 1:30 am (descending) and 1:30 pm (ascending) local solar time (Njoku et al., 2003). It measures microwave brightness temperatures at six frequencies in the range 6.9–89 GHz, all of which are dual polarized, at a fixed incidence angle of 55°. Njoku et al. (2003) noted there were only C-band (6.9 GHz) and X-band (10.7 GHz) channels suitable for soil moisture monitoring. The AMSR-E brightness temperature at 6.9 GHz is sensitive to soil moisture from the top surface layer (~2 cm), vegetation water content, and surface effective temperature (de Rosnay et al., 2009). However, possible Radio-Frequency Interference (RFI) has been observed at 6.9 GHz over many areas, most of which are densely concentrated in the United States, Japan, and the Middle East and sparsely concentrated in Europe (Li et al., 2004; Njoku et al., 2005). In other areas, the accuracy of the measured brightness temperature is better than 1 K.

In this study, the 6.9 GHz (C-band) brightness temperatures of AMSR-E from July 2005 to June 2010 were selected to evaluate the CMEM-CLM simulation of microwave brightness temperatures over East Asia, where they are not affected by RFI. The AMSR-E data were provided by the National Snow and Ice Data Center (NSIDC) and were interpolated to a global cylindrical, equidistant latitude-longitude projection at a 0.25 degree resolution (Knowles et al., 2006). The temporal resolution was daily.

3 Results

In this section, the CMEM-CLM is implemented and evaluated with a regional simulation experiment over East Asia from July 2005 to June 2010.

3.1 General features of C-band brightness temperatures over East Asia

The five-year mean C-band (6.9 GHz) brightness temperatures simulated from CMEM-CLM experiments over East Asia are presented in Fig. 1 for both horizontal (H) and vertical (V) polarizations. Generally, high brightness temperature values are shown south of 30°N, corresponding to high surface temperatures. In contrast, low values are mainly found over the Tibetan Plateau and Mongolia only for horizontal polarization. Larger biases between CMEM-CLM and AMSR-E are found over India and North China, where the vegetation type is mainly crops. These discrepancies over India and North China may have been caused by soil moisture estimations of CLM3 with large biases (Tian et al., 2010) and poorer simulations of CMEM over crop fields. Moreover, the differences between CMEM-CLM and AMSR-E are larger for the H polarization than those for V polarization. The root mean square errors (RMSEs) of the CMEM-CLM-simulated brightness temperatures compared to those from AMSR-E are more than 30 K for H polarization for both the ascending and descending orbits, while those for V polarization are approximately 15 K. Additionally, the spatial correlation coefficients of CMEM-CLM with AMSR-E for H polarization are obviously lower than those for V polarization. However, the correlation coefficient of V polarization was just about 0.4, which is lower than the value over West Africa (0.6) that was reported by de Rosnay et al. (2009).

3.2 Evaluation for sub-regions in China

To obtain more accurate information regarding the error distribution of CMEM-CLM with respect to observational data, an investigation of the performance of CMEM-CLM over different areas was required. Thus, we evaluate the simulated brightness temperatures from CMEM-CLM over seven sub-regions in China. The locations of these sub-regions, which are the same as those used by Tian et al. (2010), are shown in Table 2.

Figure 2 shows the five-year mean of the C-band brightness temperature, area averaged for each sub-region. Compared with AMSR-E, CMEM-CLM was able to capture the temporal evolution of C-band brightness temperatures for V polarization, but the simulation for H polarization was worse. The same conclusion can be inferred from Fig. 3, which shows that CMEM-CLM presents larger biases and a lower correlation with AMSR-E for H polarization. CMEM-CLM performed the worst compared to AMSR-E over southern North China (China III) and the middle and lower reaches of the Yangtze River (China IV), where the MBEs are more than 40 K and 20 K for H and V polarizations, respectively. The correlation coefficients for these areas are also the lowest among the seven sub-regions. For V polarization, CMEM-CLM shows very good agreement with AMSR-E over the China II (northern North China), V (eastern Northwest China), and VI (western Northwest China) sub-regions. The correlation coefficients are all greater than 0.8 and even over 0.9 for China VI. The smallest biases between CMEM-CLM and AMSR-E were observed for China II. Moreover, CMEM-CLM shows a similar performance, the biases and correlation coefficient are all close, between the ascending and descending orbits for all seven sub-regions investigated in this study. However, a problem with CMEM-CLM remains because it shows almost no differences between V and H polarization from August to October. Additional sensitivity experiments will be required to investigate this question in the future.

4 Summary and conclusions

In this study, a simulation using CMEM coupled with CLM (CMEM-CLM) was performed over East Asia, and it was evaluated using observational data from AMSR-E C-band (6.9 GHz) microwave brightness temperatures. CLM3 was first spun-up for 20 years and was then run, forced by atmospheric forcing data from Shi (2008) to provide surface variables to CMEM, such as soil water content, soil temperature, surface temperature. The auxil-
Figure 1  Comparison of C-band (6.9 GHz) microwave brightness temperatures between CMEM-CLM (left column) and AMSR-E (right column) for horizontal (H) and vertical (V) polarization; A is the ascending orbit; D is the descending orbit. Units: K.

The results from July 2005 to June 2010 indicate that CMEM-CLM shows better agreement with AMSR-E for vertical polarization, for which the RMSE was approximately 15 K, whereas it was greater than 30 K for horizontal polarization. Although CMEM-CLM shows similar areas with high and low brightness temperature values as AMSR-E, the spatial correlation coefficient was low (no greater than 0.5). Large discrepancies could be found over North China and India, which are areas mainly covered by crops.

To quantify a more accurate error distribution for
Table 2  Locations of the seven sub-regions in China.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Region Name</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>China I</td>
<td>Northeast China</td>
<td>40–50°N, 120–135°E</td>
</tr>
<tr>
<td>China II</td>
<td>northern North China</td>
<td>40–45°N, 110–120°E</td>
</tr>
<tr>
<td>China III</td>
<td>southern North China</td>
<td>34–40°N, 110–120°E</td>
</tr>
<tr>
<td>China IV</td>
<td>middle and lower reaches of the Yangtze River</td>
<td>30–34°N, 110–122°E</td>
</tr>
<tr>
<td>China V</td>
<td>eastern Northwest China</td>
<td>34–42°N, 95–110°E</td>
</tr>
<tr>
<td>China VI</td>
<td>western Northwest China</td>
<td>40–50°N, 80–95°E</td>
</tr>
<tr>
<td>China VII</td>
<td>Southwest China</td>
<td>20–34°N, 100–110°E</td>
</tr>
</tbody>
</table>

Figure 2  The 2005–10 mean of C-band (6.9 GHz) brightness temperatures for CMEM-CLM and AMSR-E in the China I–VII regions defined in Table 2. $T_b$ is brightness temperature.

CMEM-CLM to improve its application to a land data assimilation system as an observation operator, the evaluation was also presented over seven sub-regions in China. It was found that CMEM-CLM exhibits very good performance and captures the temporal evolution of C-band brightness temperatures over northern North China and Northwest China, where the correlation coefficients are greater than 0.8 and even more than 0.9 over western Northwest China.

However, it should be noted that only one configuration is used in this study, though it was the best configuration found in the ALMIP-MEM experiments, as indicated by de Rosnay et al. (2009). Additional sensitivity experiments related to soil dielectric constant and vege-
tation optical depth parameterizations are needed in the future. Additionally, an improvement of the brightness temperature simulations of CMEM over some regions in China, e.g., southern North China and the middle and lower reaches of the Yangtze River, by introducing a better RTM or a multi-model method is required.

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References


