On the coupling strength between the land surface and the atmosphere:
From viewpoint of surface exchange coefficients

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[1] This study addresses the land-atmospheric coupling strength by using long-term AmeriFlux data from a wide range of land covers and climate regimes to reconstitute the surface exchange coefficient, $C_h$, which governs the total surface heat fluxes. For spring and summer, results show stronger coupling for tall canopy with $C_h$ values ten times larger than for shorter vegetation. Observed $C_h$ are then compared to values from the Noah land model. Results indicate that Noah underestimated (overestimated) $C_h$ for forest (grass and crops), implying an insufficient (too efficient) coupling for tall canopy (short canopy). This discrepancy is attributed to the treatment of the roughness length for heat. With modest adjustments, the Noah model can reproduce the observed $C_h$. This study highlights the crucial role of treating the surface exchange processes in coupled land/weather/climate models and the need to use long-term flux data for different vegetation types and climate regimes to assess and mitigate their deficiencies.


1. Introduction

[2] Land-atmospheric interactions (e.g., feedback between soil moisture and precipitation) may hold the key for improving the predictability of weather and climate [e.g., Betts et al., 1996; Pielke et al., 1999; Chen et al., 2001; Trier et al., 2004; los et al., 2006]. In particular, analysis of simulations using coupled land-surface/climate models by Koster et al. [2004] revealed several “hot spots” in terms of strong coupling between soil moisture and summer rainfall. Such studies, however, depend on the reliability of land-surface models (LSMs) in predicting the strength of surface-atmosphere coupling, as expressed by the surface exchange coefficients. For example, Ruiz-Barradas and Nigam [2005] argued that excessively land-atmospheric coupling in models (manifested in too large latent heat flux) might lead to an incorrect relationship between soil moisture and precipitation, and the results of Zhang et al. [2008] did not support the hot spot hypothesis of Koster et al. [2004] for the central Great Plains. These results underline the critical importance of representing land-atmospheric interactions in atmospheric models and naturally raise a question: what is the right coupling between the land surface and the atmosphere?

[4] The AmeriFlux network, established in 1996, provides continuous observations of surface fluxes of water vapor and energy and currently comprises measurement sites from North America, Central America, and South America. Our goal is to explore the land-atmospheric coupling in spring and summer during vegetation growing season, when the land surface plays a more prominent role in transporting heat and water vapor to the atmosphere due to higher incoming solar radiation and photosynthetically active vegetation. After a careful inspection of data quality and length (at least two years of data) for variables required (surface energy budgets and near-surface weather variables) in our study, we selected 12 AmeriFlux sites spanning different land-cover types (snow, cropland, grassland, shrub, forest) and climate regimes (wet, semi-arid and arid regions). Figure 1 shows the geographical locations of these sites and the general information about these sites is given in Table 1. More information about the AmeriFlux network can be found at http://public.ornl.gov/ameriflux/.

[5] One primary function of LSMS is to provide sensible heat flux ($SH$) and latent heat flux (or surface evaporation, $LE$) as lower boundary layer conditions to the coupled atmospheric models. These fluxes are responsible for driving the diurnal evolution of the boundary layer, modifying its stability, and subsequently affecting the
are calculated from observed air temperature and \( C_0 \) and \( C_1 \) for different land-cover types and climate regimes because they control the total amount of energy going back to the atmosphere. In this investigation, we make the common assumption that \( C_v \equiv C_h \) and hereafter focus on \( C_h \).

Instruments at AmeriFlux sites directly provide \( SH \) and \( LE \). \( \theta_a \) and \( \theta_e \) are calculated from observed air temperature and outgoing longwave radiation flux. Note that some AmeriFlux sites provide \( SH \) at several levels above the ground, but we elect to use the data measured at/above the canopy top, because they are more representative of the energy transported to the atmosphere. \( C_h \) can be reconstituted by using equation (1) and AmeriFlux 30-minute data, and then averaged from 1000 to 1500 local time to obtain midday values, similar to the analysis of Trier et al. [2004].

Figure 2 shows the reconstituted midday values of \( C_h \) for the 12 AmeriFlux sites through spring (March–April–May) and summer (June–July–August) for the years documented in Table 1. For the Ivotuk, Alaska, site, the land cover changes from the predominant snow in spring to low shrubs in summer, leading to a large increase in summer-time \( C_h \) due to the rougher surface. That aside, the values of summer \( C_h \) are comparable to or slightly larger than that for spring, and spring \( C_h \) varies more than summer-time values. More importantly, the variability of \( C_h \) across land cover types becomes immediately clear and can be roughly divided into three categories in order of increasing \( C_h \): very smooth surface (snow), short vegetation (grass, crop, shrub), and tall vegetation (forests). Tall vegetation has rougher surfaces, larger \( C_h \), and hence stronger coupling. For instance, \( C_h \) for forests can be 10 times larger than that for short vegetation (crops, grassland, and shrubs).

3. Evaluation and Discussion of the Noah Model Results

Because the Noah LSM [Chen and Dudhia, 2001; Ek et al., 2003] has been widely used in mesoscale and global models for investigating the feedback between soil moisture and precipitation [Chen et al., 2001; Koster et al., 2004; Trier et al., 2004, 2008; Dirmeyer et al., 2006; Zhang et al., 2008], we will next evaluate its \( C_h \) calculation.

Table 1. General Information About the 12 AmeriFlux Sites Used in This Study

<table>
<thead>
<tr>
<th>Site Location</th>
<th>Latitude, Longitude</th>
<th>Elevation (m)</th>
<th>Land-Cover Type</th>
<th>Canopy Height (m)</th>
<th>Years of Data Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ivotuk (AK)</td>
<td>68.49, −155.75</td>
<td>568</td>
<td>open shrub</td>
<td>0.1</td>
<td>2004, 2005, 2006</td>
</tr>
<tr>
<td>Brookings (SD)</td>
<td>44.35, −96.83</td>
<td>510</td>
<td>temperate grass</td>
<td>0.2 to 0.4</td>
<td>2005, 2006, 2007</td>
</tr>
<tr>
<td>Audubon Research Ranch (AZ)</td>
<td>31.59, −110.51</td>
<td>1469</td>
<td>desert grassland</td>
<td>0.1 to 0.2</td>
<td>2004, 2005, 2006, 2007</td>
</tr>
<tr>
<td>Fort Peck (MT)</td>
<td>48.31, −105.10</td>
<td>634</td>
<td>grass</td>
<td>0.2 to 0.4</td>
<td>2004, 2005, 2006, 2007</td>
</tr>
<tr>
<td>Kendall Grassland (AZ)</td>
<td>31.74, −109.94</td>
<td>1531</td>
<td>warm C4 grass</td>
<td>0.5</td>
<td>2005, 2006, 2007</td>
</tr>
<tr>
<td>Vaira Ranch (CA)</td>
<td>38.41, −120.95</td>
<td>129</td>
<td>grazed C3 grass</td>
<td>0.55 ± 0.12</td>
<td>2004, 2005, 2006, 2007</td>
</tr>
<tr>
<td>ARM SGP Main (OK)</td>
<td>36.61, −97.49</td>
<td>311</td>
<td>winter wheat</td>
<td>0 to 0.5</td>
<td>2003, 2004, 2005, 2006</td>
</tr>
<tr>
<td>Mead (NE)</td>
<td>41.16, −96.47</td>
<td>362</td>
<td>maize-soybean rotation</td>
<td>2.9</td>
<td>2002, 2003, 2004, 2005</td>
</tr>
<tr>
<td>Bondville (IL)</td>
<td>40.01, −88.29</td>
<td>219</td>
<td>maize-soybean rotation</td>
<td>3.0 (maize), 0.9 (soybean)</td>
<td>2003, 2004, 2005, 2006</td>
</tr>
<tr>
<td>Flagstaff (AZ)</td>
<td>35.09, −111.76</td>
<td>2215</td>
<td>ponderosa pine forest</td>
<td>18</td>
<td>2006, 2007</td>
</tr>
<tr>
<td>Ozark (MO)</td>
<td>38.74, −92.20</td>
<td>219.4</td>
<td>oak hickory forest</td>
<td>24.2</td>
<td>2005, 2006, 2007</td>
</tr>
</tbody>
</table>
The Noah model uses an extension of the similarity-theory-based stability functions of Paulson [1970] to calculate $C_h$ [Chen et al., 1997], which uses different roughness lengths for momentum ($z_{om}$) and for heat ($z_{ot}$). It is well documented that $z_{ot}$ is different from $z_{om}$ because heat and momentum transfer are determined by different resistances and mechanisms in the roughness layer [e.g., Brutsaert, 1982; Sun and Mahrt, 1995]. In Noah, $z_{ot}$ is related to $z_{om}$ as a function of atmospheric flow proposed by Zilitinkevich [1995]:

$$z_{ot} = z_{om} \exp \left(-\frac{kC_{zil} \sqrt{Re}}{C_0}\right)$$

where $k = 0.4$ is the von Kármán constant, and $Re$ is the roughness Reynolds number. $C_{zil}$ is an unknown empirical coefficient and currently specified as 0.1 in Noah based on calibration with field data measured over grassland [Chen et al., 1997]. For a given AmeriFlux site, we assuming $z_{om}$ is 7% of the canopy height [Molder and Lindroth, 1999], and 30-minute fluxes, air temperature, humidity, pressure, and wind speed measured at the site are used to obtain $C_h$.

Figure 3 shows midday $C_h$ calculated by Noah and averaged for spring and summer. Comparing to observation-derived values in Figure 2, the modeled $C_h$ has much smaller variability across land-cover types. It illustrates two deficiencies in Noah: overestimating $C_h$ for short vegetation and substantially underestimating it for tall vegetation. This finding seems to agree with Ruiz-Barradas and Nigam [2005] that LSMs may have an overly strong coupling and hence provide too much water vapor for the U.S. Great Plains, where the short vegetation (grass and crops) is predominant. On the other hand, land surface models may significantly underestimate the coupling for forested regions.

There is a rich literature investigating the complex relationship of $z_{ot}/z_{om}$, also known as parameter $kB\frac{1}{C_0}$ in the agricultural and boundary layer community [e.g., Duynkerke, 1992; Stewart et al., 1994; Troufleau et al., 1997; Verhoef et al., 1997]. Recent numerical simulations demonstrated the important role of $z_{ot}$ in land surface modeling, boundary layer development, and summer convective initiation [LeMone et al., 2008; Trier et al., 2004]. Hence, we also tested the Brutsaert [1982] approach to calculating $z_{ot}$: a) for smooth surfaces (e.g., snow, ice): $z_{ot} = 0.395 \frac{n}{u^*}$; b) for bluff-rough surfaces and short vegetation: $z_{ot} = 7.4 z_{om} \exp (-2.46 R_{1/4})$; and c) for tall trees: $z_{ot} = \beta z_{om} (1/7 < \beta < 1/3)$. The other approach tested here is to still employ equation (3) but calibrate the constant $C_{zil}$ for each given site following the method of Chen et al. [1997]. For most sites, the calibrated summer $C_{zil}$ values are close to the spring values. Also note that $C_{zil}$ is close to zero for the Ozark forest site with the tallest canopy among the 12 sites, and it is argued that $z_{ot}$ can be larger than $z_{om}$ (thus a zero or negative $C_{zil}$) for tall forest [Molder and Lindroth, 1999]. Using the least-squares regression method, these calibrated $C_{zil}$ can be related to the canopy height $h$ (in meters) as:

$$C_{zil} = 10^{(-0.4h)}$$

Figure 2. $C_h$ (plotted at $\log_{10}$ scale) derived from AmeriFlux observations for different land-cover types. These are midday (1000–1500 LST) values and averaged for spring (March–April–May) and summer (June–July–August). The median values of spring (summer) average $C_h$ are represented by triangles (stars). The blue (cyan) bars comprise 75% of all midday values $C_h$ for spring (summer) for each site.
clarity). When compared to the results using the default $C_{zil} = 0.1$ in Zilitinkevich’s formulation, using Brutsaert’s different $z_{ot}$ formulations for different canopy types significantly improves $C_h$ calculations for short and tall vegetation, only it underestimates $C_h$ for crops. Using the $C_{zil}-h$ relationship in equation (4) produces results similar to Brutsaert’s scheme. This exercise demonstrates that a modest adjustment in constant $C_{zil}$ values in equation (3)

Figure 3. Same as in Figure 2 but for $C_h$ calculated by the Noah LSM.

Figure 4. The median values of $C_h$ (a) for spring season and (b) for summer season. Observations are represented by circles; for $C_h$ calculated by Noah, using the default $C_{zil} = 0.1$ are represented by stars; using the $C_{zil}-h$ relationship of equation (4) are represented by triangles; x symbols represent using Brutsaert scheme.
or in the treatment of $z_{ot}$ can substantially alter or improve the land-atmospheric coupling strength for different land cover types. However, systematic research is still needed to understand the underlying physics and to improve the representation of $C_h$ for different land-cover types and climate regimes.

4. Conclusions

[12] This study has sought to develop a framework, using multiple-year observed surface flux and weather variables and the Noah LSM as an example, to assess the land-atmospheric coupling strength for different land-cover types and climate regimes. Multiple-year AmeriFlux data are used to reconstitute the surface exchange coefficients $C_h$ for spring and summer seasons. $C_h$ is a critical parameter controlling the total energy transported from the land surface to the atmosphere and directly reflects the land-atmospheric coupling strength. Observations show higher $C_h$ and stronger coupling for tall vegetation than that for short vegetation, but the Noah model tends to underestimate $C_h$ for short vegetation such as grass, shrubs, and crops. This seems to confirm the finding of Ruiz-Barradas and Nigam [2005] that LSMs may be too efficiently coupled to the moisture-transport models and lead to an overly strong soil moisture-potential feedback in the U.S. Great Plains, where the short vegetation (grass and crops) is predominant. Equally important and less known is that the model may substantially underestimate the coupling strength for forested regions. Therefore, it highlights the importance of correctly determining the coupling strength, which is in turn related to defining the roughness length for heat/moisture $z_{ot}$ in LSMs and demonstrates that assigning different $C_{m1}$ values for different land-cover types in Zilitinkevich's formulation will allow Noah to reasonably reproduce the observed $C_h$. Note that this study was conducted with an offline model and the issue of defining $C_{m1}$ constant may be specific to Noah, so these results should not be pushed very far. Nevertheless, it highly complements previous model-based investigations and provides a potentially valuable framework for analyzing, through evaluating modeled $C_h$ against long-term observations, the correctness of representing land-atmospheric coupling strength in other LSMs used for weather and climate models.

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