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.

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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?

[3] Although the coupling issue was investigated in previous studies [*Ruiz-Barradas and Nigam*, 2005; *Dirmeyer et al.*, 2006; *Zhang et al.*, 2008], only the relationship between soil moisture, evaporation, and precipitation was assessed. Different ways of characterizing the land-atmospheric feedback were proposed and included, for instance, the calculation of feedback (recycling) numbers based on atmospheric budget analysis [*Trenberth*, 1999] and the diagnosis of a coupling coefficient from ensemble model experiments [*Koster et al.*, 2004]. However. these methods, in general, heavily relied on model or reanalysis results. The more fundamental coupling issue regarding the efficiencies of exchanging energy and water vapor between the land surface and the atmosphere still remains poorly understood. Therefore, the main objective of this study is to develop a framework based on analysis of surface exchange coefficients to address this issue by employing long-term observations at diverse locations. As a first step, this paper investigates two specific questions: 1) what is the coupling strength between land surface and the atmosphere over different land-cover types? and 2) how well is this coupling represented by the Noah land surface model (LSM), which is widely used for examining land-atmospheric interactions in regional and global models?

2. Methods and Observational Evidences

[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

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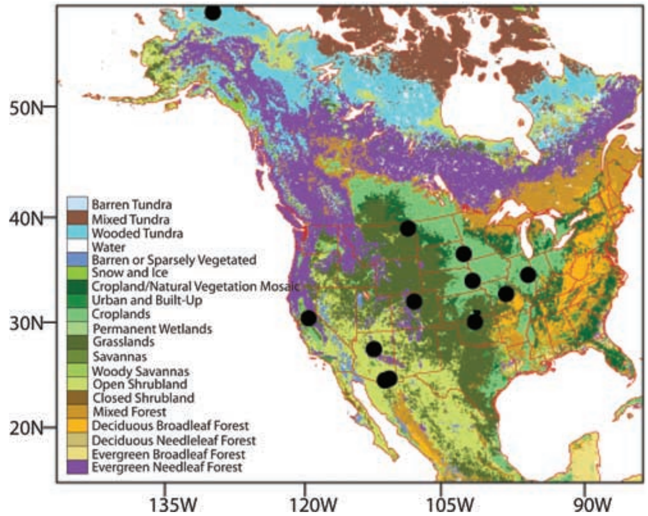

Figure 1. Locations of 12 AmeriFlux sites (in dark circles) selected for this study. Also shown is the distribution of vegetation based on the IGBP/MODIS land cover classification.

formation of clouds and precipitation. Surface heat fluxes are, as a common practice in LSMs, related to mean properties of the flow through the use of bulk transfer relations [*Garratt*, 1992] such as

$$SH = \rho C_p C_h |U_a| (\theta_s - \theta_a) \quad (1)$$

$$LE = \rho C_e |U_a| (q_s - q_a) \quad (2)$$

where ρ is the air density and C_p the air heat capacity. The atmospheric quantities $|U_a|$ (wind speed), θ_a (air potential temperature), and q_a (air specific humidity) are evaluated at the lowest model level or at a specific measurement height above the ground, while θ_s and q_s are surface values. C_h and C_e are the surface exchange coefficient for heat and moisture, respectively, which are directly related to the coupling strength. *LeMone et al.* [2008] pointed out that modifying these surface exchange coefficients allows modeled *SH* and *LE* to match observations, while changing soil moisture and vegetation phenology input only has minor impact on LSM performance. Therefore, our approach is to explore the land-atmospheric coupling strength through examining the variations of C_h and C_e 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 $C_e \equiv C_h$ and hereafter focus on C_h.

[6] Instruments at AmeriFlux sites directly provide *SH* and $|U_a|$; θ_a and θ_s 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].

[7] 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 summertime 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 summertime 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

[8] 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

Site Location	Latitude, Longitude	Elevation (m)	Land-Cover Type	Canopy Height (m)	Years of Data Used
Ivotuk (AK)	68.49, −155.75	568	open shrub	0.1	2004, 2005, 2006
Brookings (SD)	44.35, −96.83	510	temperate grass	0.2 to 0.4	2005, 2006, 2007
Audubon Research Ranch (AZ)	31.59, −110.51	1469	desert grassland	0.1 to 0.2	2004, 2005, 2006, 2007
Fort Peck (MT)	48.31, −105.10	634	grass	0.2 to 0.4	2004, 2005, 2006, 2007
Kendal Grassland (AZ)	31.74, −109.94	1531	warm C4 grass	0.5	2005, 2006, 2007
Vaira Ranch (CA)	38.41, −120.95	129	grazed C3 grass	0.55 ± 0.12	2004, 2005, 2006, 2007
ARM SGP Main (OK)	36.61, −97.49	311	winter wheat	0 to 0.5	2003, 2004, 2005, 2006
Mead (NE)	41.16, −96.47	362	maize-soybean rotation	2.9	2002, 2003, 2004, 2005
Bondville (IL)	40.01, −88.29	219	maize-soybean rotation	3.0 (maize), 0.9 (soybean)	2003, 2004, 2005, 2006
Flagstaff (AZ)	35.09, −111.76	2215	ponderosa pine forest	18	2006, 2007
Niwot Ridge (CO)	40.03, −105.55	3050	subalpine coniferous forest	11.5	2002, 2003, 2006, 2007
Ozark (MO)	38.74, −92.20	219.4	oak hickory forest	24.2	2005, 2006, 2007

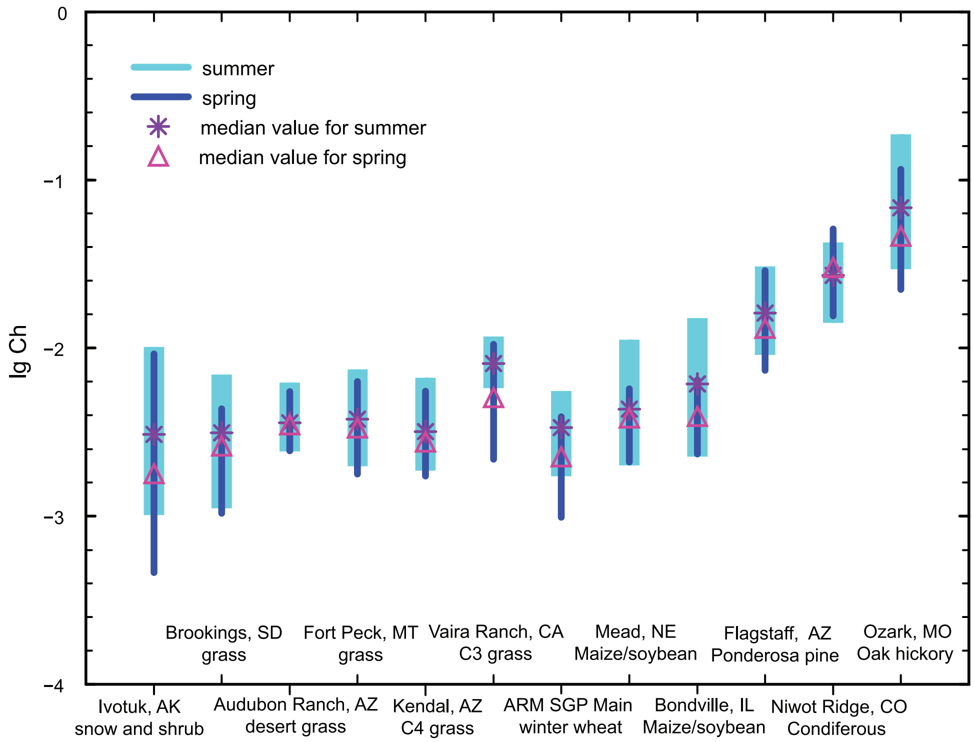

Figure 2. C_h (plotted at $\log_{10}$ scale) derived from AmeriFlux observations for different land-cover types. These are midday (1000–1500 LST) values and averaged for spring (March–April–May) and summer (June–July–August). The median values of spring (summer) average C_h are represented by triangles (stars). The blue (cyan) bars comprise 75% of all midday values C_h for spring (summer) for each site.

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]:

$$z_{ot} = z_{om} \exp\left(-kC_{zil}\sqrt{R_e}\right) \tag{3}$$

where $k = 0.4$ is the von Kármán constant, and R_e 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.

[9] 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] in 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.

[10] There is a rich literature investigating the complex relationship of z_{ot}/z_{om}, also known as parameter $kB^{-1} = \ln(z_{om}/z_{ot})$ 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): $z_{ot} = 0.395\ \nu/u_*$; b) for bluff-rough surfaces and short vegetation: $z_{ot} = 7.4\ z_{om} \exp(-2.46\ R_e^{1/4})$; 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:

$$C_{zil} = 10^{(-0.4h)} \tag{4}$$

[11] C_h, calculated with the above methods, is shown in Figures 4a and 4b (only the median values are plotted for

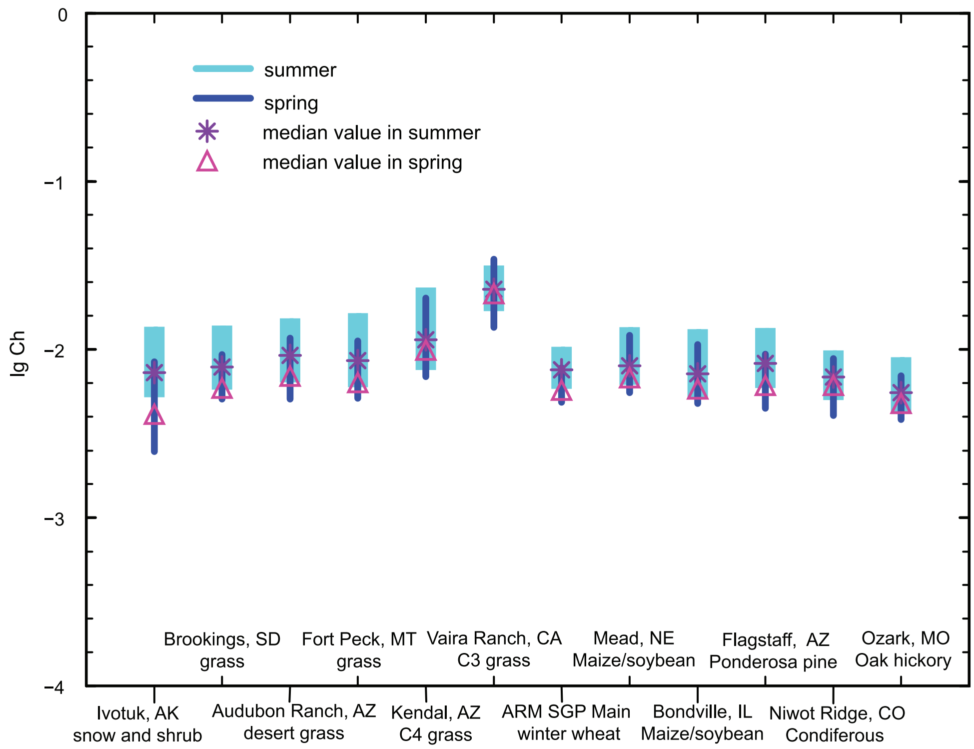

Figure 3. Same as in Figure 2 but for C_h calculated by the Noah LSM.

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)

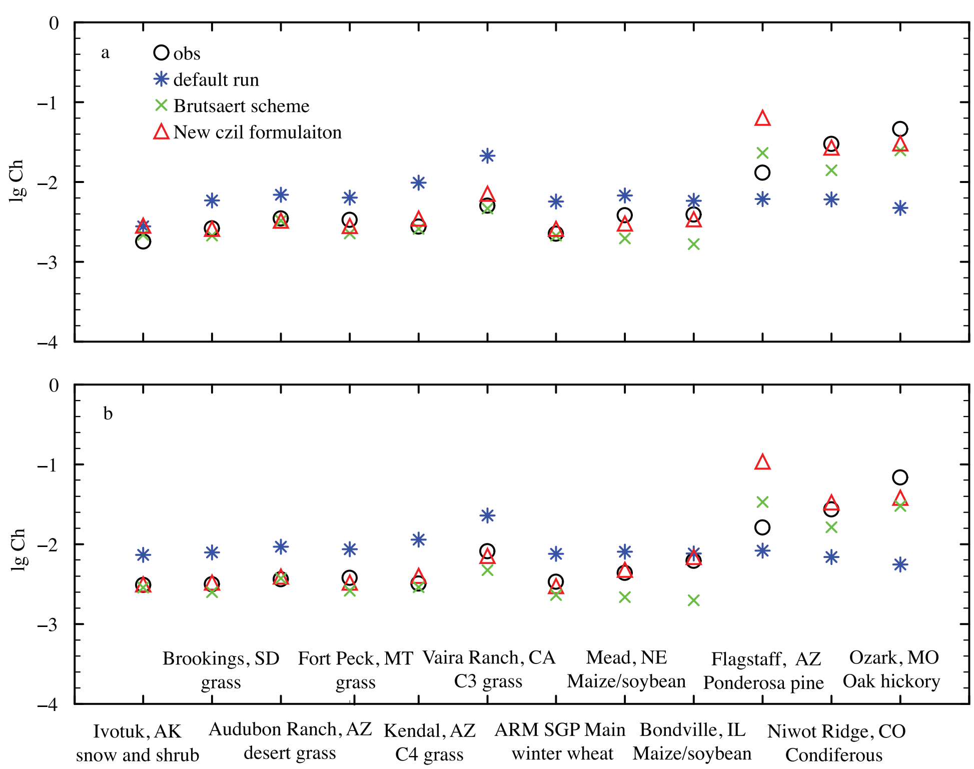

Figure 4. The median values of C_h (a) for spring season and (b) for summer season. Observations are represented by circles; for C_h calculated by Noah, using the default C_{zil} = 0.1 are represented by stars; using the C_{zil}-h relationship of equation (4) are represented by triangles; x symbols represent 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 overestimate C_h for short vegetation such as grass, shrubs, and crops. This seems to confirm the finding of *Ruiz-Barradas and Nigam* [2005] in that LSMs may be too efficiently coupled to the atmospheric models and lead to an overly strong soil moisture-precipitation feedback for 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_{zil} 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_{zil} 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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