Impacts of Climate Change and Land Use Changes on Land Surface Radiation and Energy Budgets

Abstract—**Land surface radiation and energy budgets are critical to address a variety of scientific and application issues related to climate trends, weather predictions, hydrologic and biogeophysical modeling, and the monitoring of ecosystem health and agricultural crops. This is an introductory paper to the special issue of land surface radiation and energy budgets from an international conference on this subject. The temporal trends of these components are first discussed in the context of climate change and human induced land use changes. After a brief introduction to the conference, results from each paper of this special issue are summarized.**

Index Terms—**Radiation budget, energy budget, land use, climate change, remote sensing.**

I. INTRODUCTION

CLIMATE change is one of the most pressing issues of our time. Although its causes are still under debate with respect to natural variability and human activities, climate change does touch our society on a variety of scales, from local to global and from individual to societal. Greenhouse gases and land uses are known as primary human impacts on climate change. Land use changes have contributed to significant alterations in land surface properties and dramatic changes in land surface radiation and energy budgets. Land cover influences surface climate, both through biophysical interactions that affect the surface energy balance and through biogeochemical interactions that affect carbon cycling [1].

Land surface radiation budgets describe the radiation balance (net radiation) between the incoming radiation and outgoing radiation in both shortwave and longwave spectra. The land energy budget is comprised primarily of the surface radiation budget (net radiation), heat conduction (i.e., soil heat flux) and turbulent heat flux components (i.e., sensible and latent heating). All these components are highly variable in a changing environment, and some of them are elaborated upon below.

(a) Incoming solar radiation. Evidence from ground measurements, satellite observations and indirect sources indicates that incident solar radiation undergoes significant decadal variations, with widespread decrease in surface solar radiation between the 1950s and the 1980s ("global dimming") and a partial recovery more recently at many locations ("brightening") [2]. Variability in solar radiation reaching Earth's surface has a number of causes. Variations are found under both cloudy and cloud-free atmospheres, indicating an anthropogenic contribution through changes in aerosol emissions governed by economic development and air pollution regulations [3]. Variations in incident solar radiation may have great consequences on the Earth system. Brightening may have significantly contributed to the rapid surface warming over Europe [4], [5]. Mercado *et al.* [6] suggested that global dimming and brightening contributed to an increase and decrease in the land carbon sink, respectively. Unfortunately, most state-of-the-art Global Circulation Models (GCM) have not been able to reproduce the decadal variations in the incident solar radiation and their impacts [2].

(b) Albedo. Outgoing solar radiation at the surface is controlled by surface shortwave albedo. Human activities through urbanization, deforestation, irrigation, and land degradation have greatly changed surface albedo. Urbanization leads to higher albedos although the combination of material and geometry sometimes results in a decrease in albedo toward the urban center in Ouagadougou, Burkina Faso, located in the West African Sahel [7]. Surface albedo change can be compared with greenhouse-gas emissions through the concept of radiative forcing. Radiative forcing calculations could be used to translate albedo changes into equivalent carbon emissions [8]. Deliberate land-use change (afforestation or reforestation) has been accepted as a mechanism to remove CO_2 from the atmosphere and sequester carbon in trees and soils. Davin [9] showed that surface albedo increases owing to deforestation (large-scale replacement of forests by grassland) has a cooling effect of -1.36 K globally. This effect is greater at high latitudes and impacts both land and ocean [9]–[11]. At high latitudes, terrestrial changes in summer albedo contribute substantially to recent warming trends. While the lengthening of the snow-free season increased atmospheric heating locally by about 3 Wm^{-2}, shrub and tree expansion resulting from climate warming is expected to amplify the land surface albedo feedback by two to seven times [12].

Variability in albedo and the temperature response can be further illustrated by ice-albedo feedback [13]: if global temperatures cool, ice sheets grow. As ice sheets grow, the albedo increases, reflecting more solar energy out to space, lowering global temperatures. Conversely, a warming Earth leads to smaller ice sheets, which decreases albedo and causes the Earth to absorb more solar energy, further increasing the warming. The recent warming of the Arctic may be related to changes in surface albedo that transpire from the absorption of more solar energy in areas of reduced sea ice [14].

There have not been many works discussing the trends of land surface albedo. Analysis of MODIS albedo products from 2003 to 2008 by Zhang *et al.* [15] revealed an increased albedo of about 0.01 over the Southern Hemisphere and a decreased albedo of the same magnitude over the Northern Hemisphere. The authors also tried to correlate the trends of lower albedo with higher vegetation index over the vegetated surfaces.

(c) Downward longwave radiation. Consistent with global warming, downwelling longwave radiation increases substantially. Using radiative transfer, Prata [16] calculated that from 1964 to 1990, downward longwave radiation increased globally under clear-sky conditions. The global trend is approximately $+1.7\ \mathrm{Wm}^{-2}$ per decade. Wang and Liang [17] calculated an

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average increase of 2.2 Wm^{-2} from 1973 to 2008 under all-sky conditions (based on 3200 global daily observation stations). Wild *et al.* [18] estimated an increase at 2.1 $\mathrm{Wm}^{-2}\mathrm{decade}^{-1}$ over the period 1986–2000, and of 2.6 $\mathrm{Wm}^{-2}\mathrm{decade}^{-1}$ over the period 1992–2000 using Baseline Surface Radiation Network (BSRN) data. The rising trend results from increases in air temperature, atmospheric water vapor and CO_2 concentration. From 1973 to 2008, it increased worldwide, while for high latitudes in the Northern Hemisphere it increased at a higher rate.

(d) Surface temperature. With increased air temperature, surface temperature that contributes to upwelling longwave radiation has also increased. Long-term records of land surface temperature are not widely available, but there are a few studies on estimating the annual increasing trend from satellite observations. Using MODIS data from 2000 to 2006, Qin *et al.* [19] estimated an increase of 0.1–0.2 K per year over the Tibetan Plateau at altitudes of 3000 m to 4800 m. Similar work has been reported earlier using AVHRR data which produced estimates of increased surface air temperature somewhat larger than those obtained using in situ measurements [20].

(e) Net radiation. Changes in individual radiation budget components result in changes of net radiation that have great implications for the water cycle and other environmental changes. Wild *et al.* [18] estimated that surface net radiation over land has increased by about 2 Wm^{-2} decade^{-1} from 1986 to 2000, after several decades with no evidence of an increase. They attributed this increase to a combination of solar radiation "brightening" with more transparent atmospheres, and an increased flux of downward longwave radiation, due to enhanced levels of greenhouse gases. Urbanization increased the all-wave net radiation [7].

(f) Evapotranspiration (ET). One expected consequence of global warming is the increase in ET. However, many observations show that the rate of evaporation from open pans of water has steadily decreased all over the world in the past 50 years [21]–[23]. This contrast between expectation and observation is called the "evaporation paradox". The pan ET differs from actual ET [24]. Actual ET showed strong regional and temporal trend differences [25]. For southeastern China, the eastern U.S. and the U.K., ET decreased over the past 30 years, while in the western U.S. and northwestern China ET has increased, as shown by Gordon *et al.* [26]. Other water budget-based studies demonstrated long-term changes in ET in northeastern and central China [27], [28], decreases over the eastern U.S., and increases over the western U.S. [29]–[31]. Using a modified Penman–Monteith method with station measurements, Wang *et al.* [32] recently calculated that the global ET over land increased by 0.6 Wm^{-2} per decade equal to 1.2 Wm^{-2} (about 2.2% in relative value since global averaged land ET is $\sim$55 Wm^{-2}) or 15 mm yr^{-1} in water flux from 1982 to 2002. This variability is related to changes in cloudiness and aerosols in moist regions, but more dependent on fluctuations of precipitation in more arid regions. Land cover changes, such as shrub and forest expansion at high latitudes, can significantly alter ET. Increased ET due to conversion to deciduous forest can lead to atmospheric heating of the same magnitude as radiative forcing caused by land surface albedo changes [33]. A recent study using satellite-based surface temperature fields found that large changes in wetland extent for the Niger Inland Delta affects regional heat transport dynamics which in turn can have a significant impact on regional cloud cover development and precipitation patterns [34].

Accurate estimates of radiation and energy budget components are essential to address a variety of scientific and application issues related to climate trends, weather predictions, hydrologic and biogeophysical modeling, monitoring ecosystem health and agricultural crops, and water and solar energy resources. Extensive field studies have been conducted and measurement networks designed to quantify land surface radiation and energy budgets from ground-based instrumentation [35]. These have been used to develop techniques and validate estimates from remote sensing-based methods and output from land surface models. However, the estimation of land surface radiation and energy budgets and their variations involves large uncertainties [35]. More studies are needed to quantify these uncertainties and analyze the causes of variations and trends in parameters used to calculate radiation and energy budgets. Consequences of changes in land surface radiation and energy budgets and their feedback to the climate also remain unclear. However, remote sensing-based methods in linking changes in land surface fluxes and resulting impacts on the environment due to climate anomalies (e.g., drought) are reaching a level of maturity where routine monitoring and assessments at regional and continental scales is becoming feasible [36].

To address some of these concerns, the International Conference on Land Surface Radiation and Energy Budgets: Observations, Modeling and Analysis was held at Beijing Normal University (BNU), China, March 18–20, 2009. More than 300 participants from 15 countries attended the meeting. The conference was highlighted by four keynote speeches, four special sessions (land surface albedo, radiation and energy budgets of the Tibetan Plateau, evapotranspiration and drought monitoring, and LandFlux), and one town hall meeting on albedo validation. Besides poster sessions, 65 authors gave oral presentations. This three-day conference provided an international forum to examine achievements in quantifying the earth's energy balance of land surfaces and to discuss future research directions to address current deficiencies in modeling, measurement and remote sensing of radiation and surface energy budgets.

This special issue collects a subset of papers presented in the conference, which is briefly overviewed below.

Liang *et al.* [35] provide a comprehensive review of recent advances in estimating insolation, albedo, clear-sky longwave downward and upwelling radiation, all-wave net radiation and evapotranspiration from ground measurements and remote sensing algorithms and products, as well as numerical model simulations. They report dramatic differences of these land surface radiation and energy budget components as simulated by different numerical models. They also identify the challenges using ground measurements to validate remote sensing products and further calibrate and validate model simulations.

Liu *et al.* [37] propose a new multi-angular and multi-spectral bidirectional reflectance distribution function (BRDF) model (ASK Model). By adding component spectra into kernels as prior known driven variables, the new model expresses the BRDF as a linear combination of kernels expressed as functions of observation geometry and wavelength, and wavelength independent kernel coefficients. It therefore allows integrating observations of different view and sun geometry, but also of different wavelengths, resulting in a more reliable inversion in case of restricted angular sampling. The traditional narrowband to broadband conversion is based on empirical weights at several spectral bands, whereas the new algorithm derives broadband albedo as a weighted linear combination of kernel integrations in the angular and spectral domain. Results show that the ASK model can be used to retrieve broadband albedo from multi-source satellite observations.

Li *et al.* [38] develop a procedure to correct Landsat data using coupled physically based atmospheric (MODTRAN4) and BRDF (MODIS shape functions) models. The resulting Landsat reflectance values at two sites with differing land cover in Australia show good agreement with ground-based spectroradiometer measurements. Results for two overlapping images from adjacent paths indicate that most of the BRDF effect is removed without empirical adjustment. The normalization of reflectance data is especially important when using multi-seasonal Landsat data. The within-scene anisotropy effects due to sensor view angle variation are small compared to effects introduced by sun angle variation throughout the year.

Fensholt *et al.* [39] investigate a methodology based on the sensitivity of shortwave infrared (SWIR) reflectance to variations in leaf water content from geostationary MSG (Meteosat Second Generation) SEVIRI (Spinning Enhanced Visible and Infrared Imager) data as compared to polar orbiting environmental satellite (POES) based MODIS (Moderate Resolution Imaging Spectroradiometer) data. The shortwave infrared water stress index (SIWSI) is evaluated against *in situ* measured canopy water content indicators at a semi-arid grassland savanna site in Senegal 2008. Daily SIWSI from both MODIS and SEVIRI data yield an inverse relation to NDVI (Normalized Difference Vegetation Index) throughout the growing season, but only SIWSI observations from SEVIRI are found to be sensitive to short term variations of *in situ* measured plant water content indicators for leaf area $\sim$1–2. They conclude that the improved temporal resolution with a fixed viewing angle from the SEVIRI sensor is a complementary data source to POES-based SIWSI monitoring in semi-arid environments.

Clerici *et al.* [40] present a series of improvements on the earlier developed method for generating reliable surface products and associated uncertainties from MODIS land surface albedo products. Two-stream approximate radiative transfer models are computationally efficient, but may not be very accurate. Their study can estimate the parameters of the two-stream RT model so that its calculated albedo will match satellite albedo products. It bridges satellite albedo products and the approximate RT models usually used in land surface models for climate study.

Zhang *et al.* [15] analyze MODIS land surface albedo products from 2000 to 2008 by calculating mean values and variability for global, Northern Hemisphere (NH), Southern Hemisphere (SH), and 15 International Geosphere-Biosphere Program (IGBP) ecosystem surface types. They compare MODIS albedo products with other satellite products and numerical model simulations, and found large differences among them. They also explore the long-term trends of land surface albedo products and relate the temporal variations of MODIS albedo products to changes in green vegetation.

Liu and Cheng [41] describe an algorithm for estimating photosynthetic light use efficiency (LUE) of green vegetation from hyperspectral remote sensing data. LUE characterizes the ability of green vegetation canopy to convert photosynthetically active radiation into biomass. They establish leaf-level LUE models for winter wheat based on field measurements of relative solar-induced chlorophyll fluorescence at 688 nm and 760 nm.

Huang *et al.* [42] present a three-part article series on modelling of vegetation directional brightness temperature, including the hot spot and its relation to canopy properties of different crop types. The first part presents simulations based on two models (*Cupid* and *TRGM*) over simple canopies with triangular leaves and row-planted wheat and corn, including row structure, leaf area index and angle distribution, component temperature distribution, and microclimate. Results reveal three types of directional emission shapes in the solar principal plane: the bowl, dome, and bell shapes.

Cheng *et al.* [43] apply three analytical radiative transfer (RT) models and a numerical RT model to simulate the thermal-infrared (8–13 μm) emissivity spectra of snow surfaces. The single-scattering albedo and asymmetry factor calculated by Mie theory, in conjunction with that modified by two existing packing correction methods, are used as inputs to these RT models. The simulated snow emissivity spectra are compared with *in situ* measurements. The utility of the different models for simulating snow emissivity spectra are evaluated and recommendations on which modeling approach works best for specific emissivity products are discussed.

Xiong *et al.* [44] presents a method to map regional ET at 1 km resolution from MODIS and other meteorological data. Their strategy is to use the Surface Energy Balance System model to partition available energy, to use LAI as a scalar for estimating canopy conductance from stomatal conductance, and to revise the Penman–Monteith model by adding vapor pressure deficit and temperature constraints on canopy surface resistance. With a new gap-filling technique, they apply this method to estimate the actual ET over North China.

Zhao *et al.* [45] evaluated flux variance (FV) and surface renewal (SR) methods for estimating the turbulent fluxes, sensible (H) and latent (LE) heat in comparison to eddy covariance (EC) measurements for a wheat field in a semi-arid area, a rice paddy in a humid region in China. The results indicated that the FV and SR methods had good agreement with H from the EC technique, while more significant differences were associated with LE, especially over the rice paddy field (wet surface) in a humid climate. At both study sites, the FV and SR estimates of LE were greater than the EC measurements, particularly for the rice paddy field.

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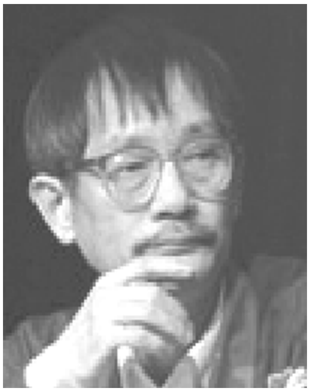

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