1-km-resolution land surface analysis over Japan: Impact of satellite-derived solar radiation

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Abstract:

Recent advances in remote-sensing technology have enabled estimation of surface solar radiation, which is an important input for land surface models (LSMs). This study investigates the impacts of satellite-derived solar radiation on an LSM by performing sensitivity experiments with and without a satellite-derived solar radiation product known as “EXAM”. Using the LSM “SiBUC-SIMRIW”, land surface analyses over Japan at a 1-km resolution were performed, comparable to observations from flux towers. We demonstrate that using the EXAM solar radiation improves not only the net solar radiation analyses, but also the analyses of net long-wave radiation, sensible heat flux, and latent heat flux at four ground observation sites. This suggests that using the satellite-derived EXAM solar radiation improves the three main budgets, i.e., radiation, heat and water budgets, of the land surface simulation. The findings demonstrate consistent improvements, therefore, SiBUC-SIMRIW-based land surface analyses can be expected to be improved using EXAM. The sensitivity experiments over Japan demonstrate that the change in solar radiation inputs largely affects the simulated sensible and latent heat fluxes. A relatively large change in surface runoff is evident in heavy snowfall regions in winter, which could be caused by a change in the snow melting period.

KEYWORDS land surface model; solar radiation; Japan; EXtreme speed and Approximation Module (EXAM); 1 km simulation

INTRODUCTION

Recent advances in remote-sensing technology have made observations of the atmospheric and surface conditions of the earth at high spatial and temporal resolutions possible with earth observing satellites. Several studies have estimated solar radiation on the surface using such satellite-derived observations (e.g., Dorvlo et al., 2002; Zhang et al., 2004; Takenaka et al., 2011). Solar radiation is an important input for land surface models (LSMs). LSMS simulate energy, water and radiation budgets on the surface using the following seven meteorological forcing data: precipitation, short-wave radiation (i.e., solar radiation), long-wave radiation, atmospheric pressure, specific humidity, atmospheric temperature and wind speed. Improvements in satellite-derived solar radiation data are expected through the use of observation data from new satellites such as Himawari-8/9. Our present focus is the extent to which satellite-derived solar radiation data may possibly improve simulations using LSMS.

To investigate the impacts of satellite-derived solar radiation on LSMs, we perform several sensitivity experiments by changing the solar radiation data source. Although the satellite-derived solar radiation data have been validated using ground-based observations (Zhang et al., 2004; Takenaka et al., 2011), their impacts on LSMs have not been published thus far, to the best of the authors’ knowledge. Therefore, this study seeks to investigate whether or not the radiation budget on the land surface can be improved using satellite-derived solar radiation. In this study, we perform land surface analyses over Japan at a 1-km resolution, comparable to data observed at flux towers. Previous studies performed several land surface analyses over Japan (Yoshimura et al., 2007, 2008; Kotsuki et al., 2013), but none investigated the impacts of solar radiation on LSMs. This study also aims to produce a high-resolution and high-accuracy land surface analysis dataset during the experiments.

EXPERIMENTAL SETTING

Land surface analysis

For the land surface analyses, we used the Simple Biosphere Model including Urban Canopy (SiBUC; Tanaka, 2004) coupled with a rice growth model based on Horie (1987), known as SIMRIW (Simulation Model for Rice-weather relations), termed the coupled “SiBUC-SIMRIW” model (Kotsuki et al., 2013). Soil physical parameters and land surface data were obtained from the National Land Numerical Information download service maintained by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT, 2014). The leaf area index (LAI) was estimated using the empirical equations of Sellers et al. (1996) and Normalized Difference Vegetation Index (NDVI) data from the SPOT VEGETATION (Maisonorange, 2004).

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Meteorological forcing data

To investigate the impacts of satellite-derived solar radiation on the LSM SIBUC-SIMRIW, we performed three experiments by changing the meteorological forcing (Table I). Experiment 1 follows Yoshimura et al. (2008) and used analyzed data from the Japan Meteorological Agency (JMA) operational Meso-Scale Model (MSM). The initial conditions from the MSM’s grid point value dataset (GPV/MSM, 5-km resolution) were used in Experiment 1. Daily short-wave radiation and long-wave radiation were estimated from GPV/MSM using the empirical equations by Kondo and Miura (1985). Experiment 2 used the Japanese 55-year reanalysis (JRA55; Kobayashi et al., 2015, 1.25-degree resolution). All seven meteorological forcing data were obtained from JRA55 (“anal_surf125” and “fcst_phy2m125” in Table I). Finally, Experiment 3 also used JRA55, but solar radiation was replaced by data from the EXtreme speed and Approximation Module multiple drive system (EXAM SYSTEM; Takenaka et al., 2011). The EXAM SYSTEM estimates solar radiation using a neural network with an improved learning algorithm to approximate the radiative transfer code. Using data from the Multi-functional Transport SATellite (MTSAT), solar radiation over Japan was estimated by the EXAM SYSTEM at a spatial resolution of 1 km. The solar radiation estimated by the EXAM SYSTEM is simply referred to as “EXAM” hereafter. The Japan Meteorological Agency (JMA) 1-km-resolution Radar/ Raingauge-Analyzed Precipitation was used for all experiments as precipitation data.

The meteorological forcing data were bilinearly interpolated onto the experimental 1-km-resolution grid using the surrounding four grid points of the original forcing data (e.g., from 1.25-degree resolution of JRA55 to 1 km; see Supplement Text S1 for details). Using SIBUC-SIMRIW, we performed the three experiments in 2007 after three-year spin-up simulations.

RESULTS AND DISCUSSION

Comparison at observation sites

This study investigated the impacts of satellite-derived solar radiation on land surface analysis by comparing the results from Experiments 1, 2, and 3. The simulated surface fluxes were compared at four observation sites (Supplement Figure S1): Fuji Hokuroku Site (Site A, 138°45’53”E/35°26’37”N), Seto Mixed Forest Site (Site B, 137°04’00”E/35°15’00”N), Takayama Evergreen Coniferous Forest Site (Site C, 137°25’23”E/36°08’46”N) and Takayama Deciduous Broadleaf Forest Site (Site D, 137°22’15”E/36°08’23”N). The observed fluxes at the four sites were obtained from the AsiaFlux research network (AsiaFlux, 2014). We first compared short-wave and long-wave radiations between the flux-tower observations and input forcing data used for the three simulations. Table I shows the correlation coefficients (R) and the root mean square errors (RMSE) for daily fluxes. The results were consistent at all four sites. Namely, the EXAM solar radiation showed the best agreement with the flux-tower observations at the four sites. Also, the estimated short-wave and long-wave radiations using the empirical equation (Kondo and Miura, 1985) for Experiment 1 were worse than those from JRA55 (Experiments 2 and 3). Table II suggests that short-wave and long-wave radiation used in Experiment 3 had the best agreement with the flux-tower observation.

Table III shows the R and RMSE between the observed and simulated daily fluxes. We compared the following surface fluxes: net short-wave radiation (SWn), net long-wave radiation (LWn), sensible heat flux (SHF), and latent heat flux (LHF). The simulated SWn, LWn, SHF, and LHF under Experiment 3 with the satellite-derived EXAM solar radiation consistently showed the best agreements with the observed fluxes among the four sites, with the only exception being R of LHF at Site A. While Experiment 3 showed the worst R of LHF at Site A, the statistical inference suggests no significant difference among the three experiments (see Supplement Text S2 for details). At Site A, Experiment 3 showed the lowest RMSE for LHF. The time series of simulated and observed daily LHF (Supplement Figure S2) showed that simulated LHF under Experiment 3 corresponded well to the observation compared to that under Experiment 1. The satellite-derived solar radiation improved not only the radiation budget but also the heat and water budgets. Because the improvements were consistent, the SIBUC-SIMRIW-based land surface analysis using EXAM (Experiment 3) could be expected to be more accurate than that using JRA55 (Experiment 2). The SIBUC-SIMRIW-based analysis using JRA55 (Experiment 2) was more accurate than that under Experiment 1 using estimated radiations from the empirical equations of Kondo and Miura (1985). The empirical equations were used in previous land surface analysis over Japan (Yoshimura et al., 2008). Our results suggest that using JRA55 for land surface analyses over Japan may be better than using the empirical equations as in Experiment 1.

| Exp. Name | Exp. Resolution | Meteorological forcing |
|-----------|-----------------|------------------------|
| Experiment 1 | 1 km | Radar/Raingauge-Analyzed Precipitation |
| Experiment 2 | 1 km | Kondo and Miura (1985) |
| Experiment 3 | 1 km | EXAM | MSM_Lsurf |
The time series of the simulated and observed weekly short-wave and long-wave fluxes at the four sites are shown in Figure 1. Figure 2 shows the time series of weekly downward and upward long-wave radiations of the observations and Experiment 3 at the four sites. The downward long-wave radiation is one of the sets of forcing data for the simulations. Next, we focus on the differences between the observations and Experiment 3.

As shown in Figure 1, simulated LWn was lower than the observations in summer (from the 120th to 240th day of year (DOY) in 2007) at Site B, and throughout the year at Sites C and D. At Site B, downward long-wave radiation agrees well with the observations in summer. The lower LWn in summer was caused by larger upward long-wave radiation, which may be caused by higher surface temperature at Site B. The larger upward long-wave radiation at Site D (from 210th to 240th DOY in 2007) may also be caused by the higher surface temperature. At Sites C and D, downward long-wave radiation was lower than the observations, especially in winter. The lower downward long-wave radiation causes lower LWh at Sites C and D. The observed SHF at Site B generally occurred during the leaf emergence season. They reported that the observed SHF decreased markedly with an increase in LHF from spring to summer.
summer (from the 120th to 240th DOY in 2007). The underestimation of SHF and overestimation of LHF in this study may result from the overestimated LAI from winter to spring. The Bowen ratio (SHF/LHF) over forests is generally underestimated when the LAI is overestimated in a simulation because relatively more energy is used for transpiration. The small Bowen ratio corresponds to small SHF and large LHF. Because we could not obtain observed LAI, it is impossible to validate the estimated LAI using the empirical equations of Sellers et al. (1996).

Table III shows that the correlation coefficients $R$ of SHF and LHF were relatively lower than those of SWn and LWn. The Bowen ratio is strongly affected by surface temperature because saturated vapor pressure ($E_{\text{sat}}$) depends on surface temperature. Improvements in surface temperature would lead to further improvements in the simulation accuracy of SHF and LHF.

**Comparison of spatial patterns over Japan**

This subsection describes the impacts of satellite-derived solar radiation on the spatial patterns of the land surface analysis over the entirety of Japan. Figure 3 shows the correlation coefficient of simulated daily land surface analyses between experiments with and without EXAM (Experiments 2 and 3) in 2007. In addition to the four fluxes in Figure 1, surface radiative temperature ($R_{\text{adT}}$, K), (f) snow water equivalent (SWE, kg/m$^2$), (g) surface runoff ($Q_s$, kg/s/m$^2$), and (h) sub-surface runoff ($Q_{sb}$, kg/s/m$^2$), respectively.
were also compared. Figure 4 is similar to Figure 3, except for winter (December, January, and February) and summer (June, July and August). Warm colors in Figure 3 represent relatively large changes due to changes in solar radiation from JRA55 to EXAM.

SHF and LHF changed largely in response to different solar radiation data. As mentioned in the previous subsection, the Bowen ratio is sensitive to surface temperature. On the other hand, RadT, LWn and SWE did not show much sensitivity to solar radiation in the correlation coefficients. The change in SHF and LHF in summer was larger than that in winter (Figure 4). Namely, the Bowen ratio in summer would be more sensitive to the solar radiation than that in winter over Japan. Figure 4 also shows the relatively large change in surface runoff (Qs) in the heavy snowfall region in winter. A small change in surface temperature may change the snow melting period and eventually may cause a larger change in surface runoff in the region.

The simulation indicated that the LAI used in this study may be overestimated from winter to spring. Further validations can be performed using the LAI products from MODIS (MODerate resolution Imaging Spectroradiometer), and this is the subject of future research. We have not investigated the impacts of spatial resolution on the land surface analysis. This is also an important subject for future research. This study also aimed to produce a high-resolution and accurate land surface datasets based on the experiments, datasets which we plan to make open for use in the near future.

SUMMARY

In this study, we investigated the impacts of satellite-derived solar radiation on the LSM SiBUC-SIMRIW by performing sensitivity experiments with and without the satellite-derived solar radiation product EXAM. We performed off-line land surface analyses over Japan at a higher spatial resolution of 1 km compared to previous studies (Yoshimura et al., 2007, 2008; Kotsuki et al., 2013). We first demonstrated that EXAM improved not only the net short-wave radiation analyses, but also the analyses for net long-wave radiation, sensible heat flux, and latent heat flux at the four observation sites. Because the improvements were consistent at all four sites, we concluded that the SiBUC-SIMRIW-based analysis using EXAM is more accurate than that using JRA55. We also demonstrated that the change in solar radiation largely affected the sensible and latent heat fluxes over Japan. By contrast, the change in solar radiation had smaller impacts on the correlation coefficients for net long-wave radiation and surface radiative temperature than sensible and latent heat fluxes. A relatively large change in surface runoff was found in the heavy snowfall region in winter. A small change in surface temperature may lead to a change in the snow melting period and eventually may cause a larger change in surface runoff in the region.

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SUPPLEMENTS

Text S1. Interpolation process for meteorological forcing data
Text S2. Statistical inference for the correlation coefficients
Figure S1. Location of the four observational sites
Figure S2. Time series of simulated and observed daily latent heat flux (LHF; W/m²) at Sites A, B and D
Figure S3. Schematic showing (a) the bilinear interpolation and (b) interpolation processes applied to atmospheric temperature and atmospheric pressure
Table S1. P-values [%] of the statistical inference for the correlation coefficients (R) and root mean square errors (RMSE) shown in Tables II and III

REFERENCES

AsiaFlux. http://www.asiaflux.net/. Last access September 26, 2014.
Dorvlo A, Jervase J, Al-Lawati A. 2002. Solar radiation estimation using artificial neural networks. *Applied Energy* 71: 307–319. DOI: 10.1016/S0306-2619(02)00016-8.
Horie T. 1987. A model for evaluating climate productivity and water balance of irrigated rice and its application to Southeast Asia. *The Southeast Asian Studies* 25: 62–74.
Kobayashi S, Ota Y, Harada Y, Ebita A, Moriya M, Onoda H, Onogi K, Kamahori H, Kobayashi C, Endo H, Miyaoa K, Takahashi K. 2015. The JRA-55 reanalysis: general specifications and basic characteristics. *Journal of the Meteorological Society of Japan* 93: 5–48. DOI: 10.2151/jmsj.2015-001.
Kondo J, Miura A. 1985. Heat budget of the western Pacific for May 1979. *Journal of the Meteorological Society of Japan* 63: 633–646.
Kotsuki S, Tanaka K, Kojiri T. 2013. Estimation of climate change impact on Japanese water resources: Part 1 The development of a Japanese water resource model. *Journal of Japan Society of Hydrology and Water Resources* 26: 133–142. DOI: 10.3178/jjshwr.26.133 (in Japanese with English abstract).
Maisongrande P, Duchemin B, Dedieu G. 2004. VEGETATION/SPOT: an operational mission for the Earth monitoring; presentation of new standard products. *International Journal of Remote Sensing* 25: 9–14. DOI: 10.1080/0143116031000115265.
Matsumoto K, Ohta T, Nakai T, Kувada T, Daikoku K, lida S, Yabuki H, Kononov AV, Molen MK, Kodama Y, Maximov TC, Dolman AJ, Hattori S. 2008. Energy consumption and evapotranspiration at several boreal and temperate forests in the Far East. *Agricultural and Forest Meteorology* 148: 1978–1989. DOI: 10.1016/j.agrformet.2008.09.008.
MLIT (Ministry of Land, Infrastructure, Transport and Tourism in Japan), National Land Numerical Information download service in Japan. http://nlftp.mlit.go.jp/ksj-e/index.html. Last access September 26, 2014.
Sellers PJ, Tucker CJ, Collatz GJ, Los SO, Justice CO, Dazlich DA, Randall DA. 1996. A revised land surface parameterization (SiB2) for atmospheric GCMs. Part II: the generation of global fields of terrestrial biophysical parameters from satellite data. *Journal of Climate* 9: 706–737. DOI: 10.1175/1520-0442(1996)009<0706:ARLSPF>2.0.CO;2.
Takenaka H, Nakajima T, Higurashi A, Higuchi A, Takamura T, Pinker P, Nakajima T. 2011. Estimation of solar radiation using a neural network based on radiative transfer. *Journal of Geophysical Research* 116: D08215. DOI: 10.1029/2009JD013337.
Tanaka K. 2004. Development of the new land surface scheme SiBUC commonly applicable to basin water management and numerical weather prediction model. Doctoral Dissertation, Graduate School of Engineering, Kyoto University, Kyoto; 289.
Yoshimura K, Okazawa K, Kim H, Seto S, Koiva Y, Oki T, Kanae S. 2007. Development and verification of a predicting system of river discharge over Japan using JMA-MSM-GPV. *Proceedings of Hydraulic Engineering* 51: 403–408. DOI: 10.2208/prohe.51.403 (in Japanese with English abstract).
Yoshimura K, Sakimura T, Oki T, Kanae S, Seto S. 2008. Toward flood risk prediction: a statistical approach using a 29-year river discharge simulation over Japan. *Hydrological Research Letters* 2: 22–26. DOI: 10.3178/HRL.2.22.
Zhang Y, Rossow W, Lacis A, Oinas V, Mishchenko M. 2004. Calculation of radiative fluxes from the surface to top of atmosphere based on ISCCP and other global data sets: refinements of the radiative transfer model and the input data. *Journal of Geophysical Research* 109: D19105. DOI: 10.1029/2003JD004457.