Hyperspatial mapping of land surface water, energy and CO₂ fluxes from Unmanned Aerial Systems - DTU Orbit (16/08/2019)

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The sustainable management of water resources and agricultural production is a key issue for socio-economic development. A first step to improve monitoring of water consumption, ecosystem production and water use efficiency of agricultural or natural ecosystems is to provide valuable and near-real time information to stakeholders. As an interdisciplinary approach, land surface modelling is an essential tool to quantify the coupled water, energy and CO₂ fluxes, calculation of the land surface and the atmosphere, e.g. net radiation (Rn), soil moisture, evapotranspiration (ET) and gross primary productivity (GPP). Unmanned aerial systems (UAS) can provide remotely sensed imagery of ecosystems at very high spatial resolution (meter level) with low cost and flexible revisit times regardless of cloudy conditions, which can be incorporated into land surface models. However, there remain challenges for operational monitoring of land surface fluxes from UAS, especially in northern latitudes: the limited payload capacity (< 2kg) of most commercial UAS, low signal-to-noise ratios of miniaturized sensors, the frequent cloudy weather, the lack of ad-hoc operational methodologies to estimate fluxes, implications of flying under overcast conditions, or temporal gaps in fluxes between the image acquisitions. This thesis aims to design an operational UAS monitoring system to estimate land surface fluxes by integrating land surface models and UAS imagery. Specifically, the thesis addresses the following questions: (Objective 1) Can high quality reflectance and thermal imagery be obtained from UAS for quantitative remote sensing research? What kind of accuracy can be achieved for UAS imagery obtained in low and variable irradiance? (Objective 2) Can the high spatial resolution of land surface water, energy and CO₂ fluxes be mapped from UAS imagery? What controls the spatial variability of land surface fluxes? (Objective 3) Can UAS based instantaneous estimates of fluxes be temporally upscaled to the continuous daily values? Is there any important environmental factor to influence the temporal dynamics of land surface fluxes at the considered ecosystem? To achieve these objectives, UAS optical and thermal imagery and eddy covariance observations were integrated with ‘top-down’ operational land surface models, which quantify ET and GPP with joint environmental constraints. Case studies were mainly conducted in a Danish willow bioenergy forest eddy covariance site (DK-RCW), while the long-term eddy covariance observations from a deciduous beech forest eddy covariance site (DK-Sor) were used for model development. The thesis includes three main parts to address each of the three objectives stated above. Sensor calibration and image processing: With thorough laboratory sensor calibration for low illumination and application of the improved image processing procedures, the potential of UAS multispectral mapping in low and variable irradiance conditions of northern latitudes was exploited. Particularly, a four-way Tucker tensor decomposition method was used to remove the cloud shadow in UAS imagery. Outdoor experiments indicate that the multispectral imagery can provide reliable reflectance with root mean square deviations (RMSDs) around 3%. This shows the potential of UAS mapping for quantitative Remote sensing research. Spatial variability of land surface fluxes: A simple but operational ‘top-down’ ET and GPP snapshot model, which jointly estimates evapotranspiration and carbon assimilation with the same environmental constraints, was developed (Wang et al., II). To provide soil moisture constraints for ET simulation, the root-zone soil moisture from UAS optical and thermal imagery was estimated by the modified temperature-vegetation triangle approach at DK-RCW showing the benefits of incorporating tree height from the Structure-from-Motion (SfM) (Wang et al., III). Furthermore, high spatial resolution of Rn, ET and GPP at the time of flights was estimated with the ‘top-down’ snapshot model (Wang et al., IV). Compared to the source-weighted footprint, the case study at DK-RCW shows that this joint model with UAS optical and thermal imagery can well estimate ET, GPP, and water use efficiency with RMSDs equal to 41.2 W·m⁻², 3.12 μmol·C·m⁻²·s⁻¹, and 0.35 g·C·kg⁻¹, respectively. Our spatial scale analyses stressed the importance to consider the heterogeneity within the eddy covariance footprint, as the model performance degraded with coarser spatial resolution. By using the semivariogram and an experiment aggregating model inputs into different spatial resolutions, it was found that imagery resolution consistent with the tree crown size (1.5 m in our case) was sufficient to capture the spatial heterogeneity of the fluxes. Our results highlight the importance of considering the heterogeneity of land surface for flux modeling and the source contribution within the eddy covariance footprint for model benchmarking at appropriate spatial resolutions. Temporal variability of land surface fluxes: In the temporal upscaling from the instantaneous to the diurnal, it was found that it is important to consider the change of eddy covariance footprints during the course of the day for model benchmarking with eddy covariance observations (Wang et al., IV). To temporally interpolate the flux estimates between days without UAS data acquisitions, a dynamic Soil-Vegetation, Energy, water and CO₂ traNsfer model (SVEN) was developed (Wang et al., V). Based on instantaneous estimates (Wang et al., IV), this model can accurately provide continuous estimates of land surface fluxes. This provides a methodology to temporally upscale the remote sensing based instantaneous estimates into daily or longer time scales. Furthermore, with 11-year long-term eddy covariance observations, Wang et al. (II) analysed the independent and joint effects from diffuse radiation on the temporal variability of GPP and ET. In this Danish ecosystem, diffuse radiation plays a crucial role to enhance ecosystem light use efficiency and water use efficiency. This UAS based monitoring system can be valuable for applications in agricultural and water resources management, and it would also be beneficial for scientific communities, e.g. remote sensing, ecohydrology and micrometeorology, to identify processes at high spatial resolution. Additionally, this system requires limited ground observations and can be applied for routine monitoring applications in data-scarce regions.

General information

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