Energy and Net Ecosystem CO_2 Exchange between Agro-ecosystems and the Atmosphere over a Complex Terrain in Korea

Zhao, Peng (1); Lüers, Johannes (1); Kim, Jea-Chul (3); Seo, Bumsuk (2); Lindner, Steve (2); Lee, Bora (2); Lee, Chong Bum (3); Thieme, Christoph (1); Serafimovich, Andrei (1); Tenhunen, John (2); Foken, Thomas (1)

(1) Department of Micrometeorology, University of Bayreuth, Germany, peng.zhao@uni-bayreuth.de, johannes.lueers@uni-bayreuth.de, thomas.foken@uni-bayreuth.de
(2) Department of Plant Ecology, University of Bayreuth, Germany, bumsuk.seo@uni-bayreuth.de, steve.lindner@yahoo.de, puplebr@gmail.com, john.tenhunen@uni-bayreuth.de
(3) Department of Environmental Science College of Natural Science, Kangwon National University, South Korea, kjc25@kangwon.ac.kr, cbl@kangwon.ac.kr

Abstract: Our research project is focused on the energy and net ecosystem exchange of agro-ecosystems over a complex mountainous landscape in South Korea. Eddy-covariance technique was used at a flooded and a dry crop field during the growing season in 2010. The footprint model shows that the target farmlands generally contributed most of the relevant area to the turbulent flux measurements. The turbulent energy exchange was controlled by the cover of leaves on the surface. Net ecosystem CO_2 exchange (NEE) was controlled predominantly by solar radiation with respect to diurnal patterns and predominantly by the growing stage of the crop with respect to the seasonal pattern. A late-season depression of NEE was observed at the potato field caused by the postponed harvest, which turned the field into a small source of carbon dioxide. An innovative gap filling method on the basis of Michaelis-Menten function was raised for rapidly developed crop sites without long term measurements, and showed a better regression than the traditional method. A comparison between eddy-covariance and chamber measurements showed poor agreement, which needs further study. WRF model was evaluated using quality controlled eddy-covariance measured fluxes. The simulated data had a better agreement with the observed data for both sensible and latent heat flux at the rice field than at the potato field. The underestimation of sensible heat flux and overestimation of latent heat flux at the potato field is similar to the WRF performance at a mountainous forest site in Germany.

Keywords: *eddy-covariance; net ecosystem exchange; gap filling; complex terrain; WRF model; chamber measurement*

1. Introduction

Complex terrain in mountainous areas attracts much research interest as it makes up 20% of the Earth's terrestrial surface (Becker & Bugmann 1997), and it plays an important role in the ecosystem services and climate changes. The changing monsoon climate and the local land use management leads to more complications in ecosystem carbon budget at complex mountainous area in Korean Peninsula (Kwon et al. 2009).

As a useful and effective tool, eddy-covariance technique has been widely used to measure energy and net ecosystem exchange (NEE) between the earth surface and atmosphere (Baldocchi et al. 2001). Eddy-covariance method is well known for the ability of running continuously and directly quantifying the energy and matter exchange without disturbing the ecosystem, while it is required to fulfill many assumptions (Foken 2008). Homogeneous surface is one of the most limiting circumstances, which eliminates the influence of advection (Aubinet et al. 2003). However, natural ecosystems are often located on complex terrains with a variety of characteristics such as climate gradient, different soil properties, patches of land use type, and so on. The influence of complex topography on flux measurement was evaluated by several research groups (e.g. Aubinet et al. 2003). For forest sites during nighttime, the influence of advection is mainly determined by local slope, land cover and horizontal source heterogeneities (Aubinet et al. 2005). For low level canopy ecosystem such as meadow, advection can be neglected and eddy-covariance measurements can be applied in the shallow equilibrium layer where the wind field exhibits characteristics akin to level terrain (Hammerle et al. 2007) .

The understanding of ecosystem-atmosphere exchange is limited by the missing data and the choice of gap-filling algorithms that cause the uncertainties of eddy-covariance method (Kutsch et al. 2010). In general, 20–60% of flux observations are reported as missing or rejected due to system failure, bad weather condition and quality control (Moffat et al. 2007). A suitable gap filling method is needed for the completeness of data that is important for the daily and annual sum. Many gap filling techniques have been developed, e.g. non-linear regression (NLR), dual unscented Kalman filter (UKF), artificial neural networks (ANN), look-up table (LUT), marginal distribution sampling (MDS), semi-parametric model (SPM), mean diurnal variation (MDV), multiple imputation method (MIM), and biosphere energy-transfer hydrology model (BETHY) (Moffat et al. 2007). Most of these methods work well for forest and meadow sites based on long-time measurements and slowly developed biomass during growing season, while few studies quantify the uncertainty of eddy-covariance measurement at crop sites where it could cause problems if there is no long-time dataset or if the crops develop rapidly and the growing season is very short.

The Weather Research and Forecasting model (WRF) is a next generation meso-scale forecast model for assimilation at the regional level. It is useful for up and down scaling of weather and climate ranging from a kilometer to thousands of kilometers and useful for deriving meteorological parameters required for air quality models (Skamarock et al. 2005). Complex terrain features and land-surface characteristics are the most important elements in WRF modeling. It has been found that the land-use distribution influences the wind behaviour significantly by affecting the local ground heat budget and thus the surface temperature distribution (Lee et al., 2005). Eddy-covariance based observation could help evaluate the performance of WRF model.

The objective of this study is to use eddy-covariance technique to quantify the energy and carbon dioxide exchange in typical agro-ecosystems at a complex mountainous area in South Korea. We used a footprint model to check the influence by patches of land use types. Good quality data were picked out for comparison with chamber measurements and with Weather Research and Forecasting (WRF) model. An innovative gap-filling algorithm was developed to complete the full time series at crop sites. Then we discussed the influence of monsoon and land use management on daily and seasonal variation of energy and carbon dioxide exchange.

2. Materials and Methods

2.1 Study Sites

The measurement was conducted from May 12th to November 8th, 2010, at Haean-myun Catchment, Yanggu-gun, Kangwon-do, South Korea. Two types of typical farmlands were chosen to apply eddy-covariance technique, including a dry farmland planted with potatoes (Korea-Potato, KR-P), and an irrigated farmland planted with rice paddies (Korea-Rice, KR-R).

KR-P (38°17’ N, 128°07’ E, 455 meter a.s.l.) and KR-R (38°17’ N, 128°08’ E, 457 meter a.s.l) are located at the bottom of Haean catchment with a terrain slope of ca. 3°. Haean is an intensively used landscape with longitude 128° 5' to 128° 11' E, latitude 38° 13' to 38° 20' N, altitude from ca. 500 m (valley) to 1100 m (mountain ridge). The average annual air temperature in 2010 is ca.10.5°C at valley sites and ca. 7.5°C at the mountain ridge. Average precipitation is estimated at 1200 mm with 50% falling during the summer monsoon. Rice paddies and potato fields are two major types of farmlands in Haean, which cover ca. 25% and 15% of the farmland area, respectively. More details about KR-P and KR-R can be found in (Zhao et al. 2011).

2.2 Field Measurements

Eddy-covariance method was used to measure CO_2 flux, sensible and latent heat fluxes at a height of 2.5 m above ground at KR-P and 2.8 m at KR-R. The measurement complex was equipped with a sonic anemometer (METEK USA-1) and an open-path gas analyzer (LI-7500). The sampling frequency was 20 Hz. The instruments were moved between the two sites and biomass was sampled every half a month. The leaf area index (LAI) and weights of different plant parts were measured too. Basic meteorological parameters and the net radiation were recorded by an automatic weather station (WS-GP1) and a net radiometer (NR-LITE).

2.3 Observed Flux Determination

We used the software package TK2 (Mauder & Foken 2004) to calculate and correct turbulent fluxes of sensible heat and latent heat from raw high frequency data. The correction strategy includes spike check (Vickers & Mahrt 1997), planar fit (Wilczak et al. 2001), spectral corrections (Moore 1986), conversion from sonic temperature fluctuations to real temperature fluctuations (Schotanus et al. 1983), density correction for water vapour (Webb et al. 1980), iterative determination, and quality control(Foken & Wichura 1996; Foken et al. 2004). Fluxes with quality flags of 7 to 9 were marked as bad quality and rejected.

Footprint analyses were performed using a Lagrangian stochastic forward model to estimate two-dimensional contributions of source areas (Rannik et al. 2000; Göckede et al. 2004). As the model takes much time on computations, source weight functions for half-hourly measurement were picked from pre-calculated tables following a procedure used in Göckede et al. (2004; 2006; 2008).

2.4 Gap Filling

As different regressions were used for filling the gaps during daytime and nighttime, daytime data must be segregated from nighttime data. It depended not only on the astronomical sunrise and sunset time at the measurement sites, but also on whether the global radiation is larger than 10 W m^{-2} (Ruppert et al. 2006).

For nighttime regression, the Lloyd-Taylor function (Lloyd & Taylor 1994) were used to simulate nighttime ecosystem respiratory flux rates $F_{R,eco}$:

$$F_{R,eco} = F_{R,10}\, e^{E_0\left(\frac{1}{283.15-T_0}-\frac{1}{T-T_0}\right)} \tag{1}$$

where $F_{R,10}$ is the respiration rate at 283.15 K, E_0 is the temperature sensitivity of respiratory fluxes, and T_0 is constant with a value of 227.13 K.

For daytime regression, we used the traditional Michaelis-Menten function (MMF, (Michaelis & Menten 1913), on the basis of which we raised an innovative function called normalized Michaelis-Menten function (NMMF).

MMF is:

$$F_{C,day} = \frac{aR_g F_{C,sat}}{aR_g + F_{C,sat}} + F_{R,day} \tag{2}$$

where $F_{C;day}$ is the daytime NEE, a and $F_{R,day}$ are the initial slope and the offset of the function, respectively, R_g is the solar radiation, and $F_{C;sat}$ is the saturated NEE when Rg is ∞.

NMMF is:

$$F'_{C,day} = \frac{a' R_g F'_{C,sat}}{a' R_g + F'_{C,sat}} + F'_{R,day} \tag{3}$$

The prime signal means the variable is normalized, i.e. the half-hourly valued over daily mean value.

2.5 WRF Model

In this study, an advanced NOAA (National Oceanic and Atmospheric Administration) land surface model (LSM) has been coupled to the WRF, which provides surface sensible and latent heat fluxes, and surface skin temperature in the lower boundary layers. Furthermore, in order to better represent the physical processes involved in the exchange of heat, momentum, and water vapour in the meso-scale model, the UCM is coupled to the WRF model.

We built over a mother domain (D1) with 27 km spatial resolution, centered at 38°N, 126°E. The innermost domain (D5) is centered over the Haean basin and consists of 54 columns and 57 rows of 0.3 × 0.3 km^2 grid cells. The five domains interact with each other through a one-way nesting strategy. The vertical structure of the model includes 30 layers. Topography and land use datasets were interpolated from the SRTM (Shuttle Radar Topography Mission) and KME (Korea Ministry of Environment) with the appropriate spatial resolution for each domain (30' and 3' for D1, D2, D3, D4 and D5 respectively). The KMA medium-category land use classification was considered to represent dominant vegetation types. The WRF simulations were driven by the National Centers for Environmental Prediction (NCEP) Global Tropospheric Analyses with 1° X 1° spatial resolution and temporal resolution of 6 h. The initial meteorological condition was determined using the regional data assimilation and prediction system (RDAPS), which was provided by KMA with 30 km spatial and temporal resolution of 3 h. In this study, the Yonsei University (YSU) planet boundary layer scheme was adopted. The YSU scheme is a modification of the MRF (medium-range forecast) scheme to include explicit entrainment fluxes of heat, moisture and momentum, counter-gradient transport of momentum, and different specifications of the PBLH. RRTM radiation scheme, WSM 6-class microphysics and Noah land surface model were used for the simulation period of September 24-27, 2010. Since the grid size is very fine, no cumulus scheme was used.

3. Results and Discussions

3.1 Influence of Complex Terrain, Climate and Field Management

The footprint model showed that both the target potato field and rice field contributed about 95% of the related area in unstable and neutral stratification conditions. In stable conditions KR-P was influenced by the adjacent cabbage field and KR-R was slightly influenced by the adjacent field road and the grass verge (Fig. 1).

Fig. 2 shows that the sensible heat flux had two peaks, one at the beginning and the other at the end of potato growing period, while only one peak was observed at the rice field before harvest. These peaks were apparently due to a small LAI (not shown here) when there was much bare soil surface exposed to the air. The latent heat fluxes increased with the development of crops, indicating that it was controlled by plant transpiration.

During the crop initial stages and development stages, the net ecosystem CO_2 exchange (NEE) at both sites was generally negative during daytime (sink) and positive during nighttime (source) as a result of photosynthesis and respiration, respectively (Fig. 3). The diurnal pattern of NEE was mainly controlled by solar radiation, and the day-to-day pattern was controlled by the growing stages of the crops. CO_2 fluxes reached the peak simultaneously with the maximum of LAI during mid-day. A depression in NEE during Changma was reported by Kwon et al. (2009), but it was not observed in this study possibly because of the exclusion of data with bad quality during rain events.

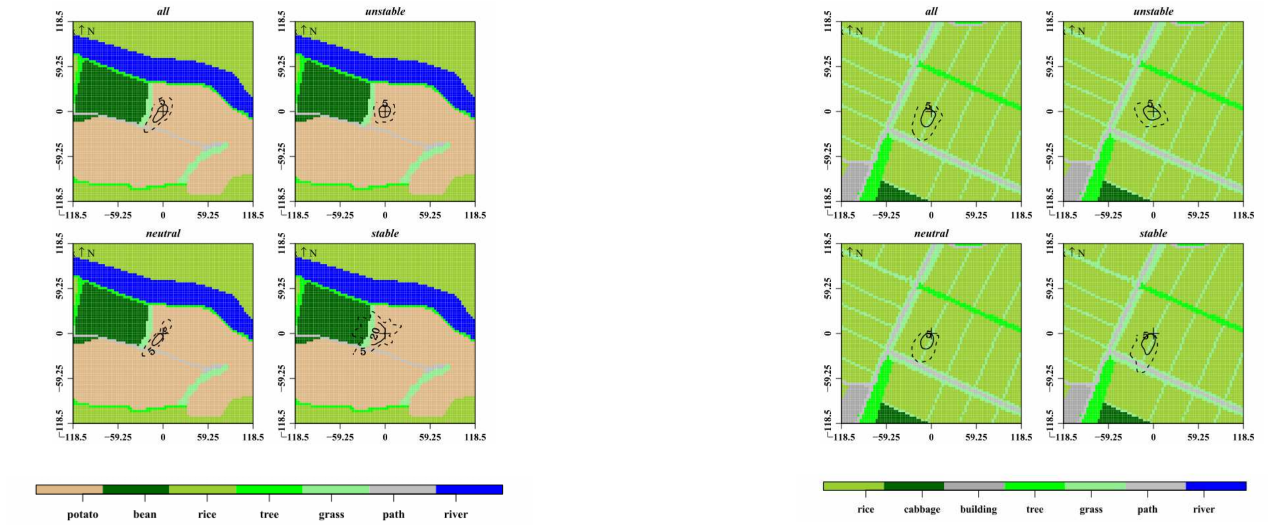

Figure 1. Footprint (left: from 2010-07-06 to 2010-07-22 at KR-P; right: from 2010-07-22 to 2010-08-11 at KR-R)

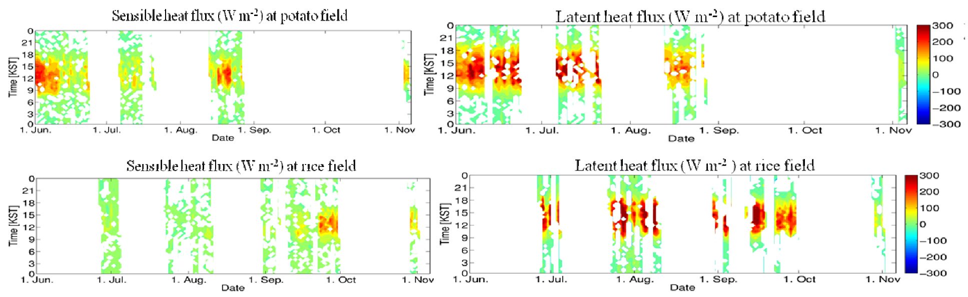

Figure 2. Turbulent energy fluxes at KR-P and KR-R

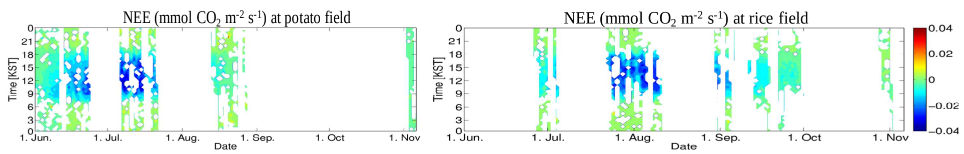

Figure 3. NEE at KR-P and KR-R

During the mid- and late season stages of the crops, the farmland became a smaller sink for CO_2 as the LAI decreased. Normally farmers harvest potatoes when the fields are dry in August or beginning of September, but in 2010 the intensive rainfalls made the fields wet, and farmers could not harvest potatoes until the fields were dry at the end of September or beginning of October. As there were less and less green leaves or photosynthesis during the late season stage, the potato field became a slight source of CO_2.

3.2 Gap Filling

The comparison between MMF and NMMF regressions shows that NMMF worked better than MMF at KR-P (Fig. 4). MMF simulation used the whole daytime dataset as input data, and produced smoothed output data, because this regression procedure only considered the influence of air temperature (*T*) and R_g but ignored the development of green leaves. As the green leaves of potato plants developed very rapidly during the development stage (June 1 to July 7), NEE is apparently overestimated at first week, and underestimated at the middle of this period. During the mid-season stage (July 6 to August 28), NEE is underestimated at the beginning and overestimated at the end, because the green leaves were decreasing during this stage. A poor linear relationship between the simulated and observed data was found (Fig. 5). Integrated with LAI, NMMF simulation shows a more reasonable day-to-day variation of NEE, and performs a much better agreement with the observed data.

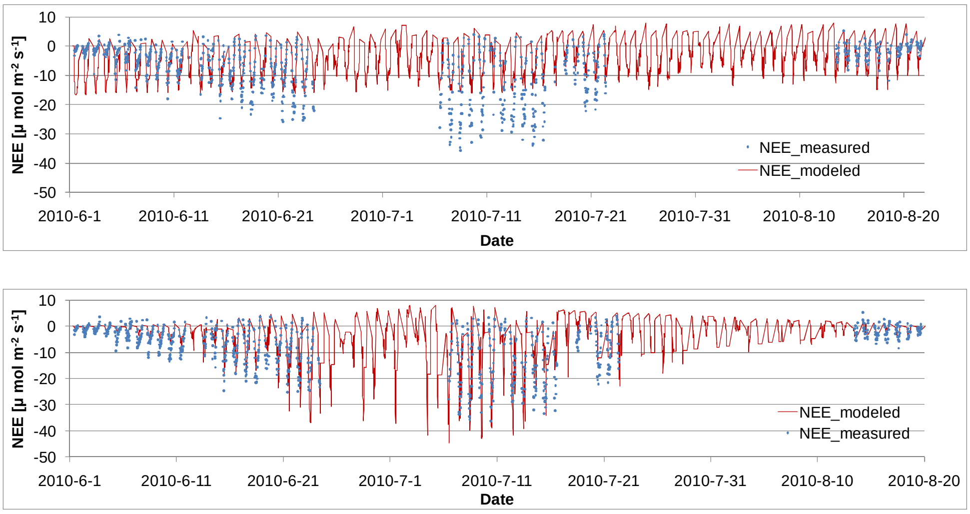

Figure 4. Daytime NEE measured and modeled by gap filling methods at KR-P. Above: traditional MMF; below: NMMF

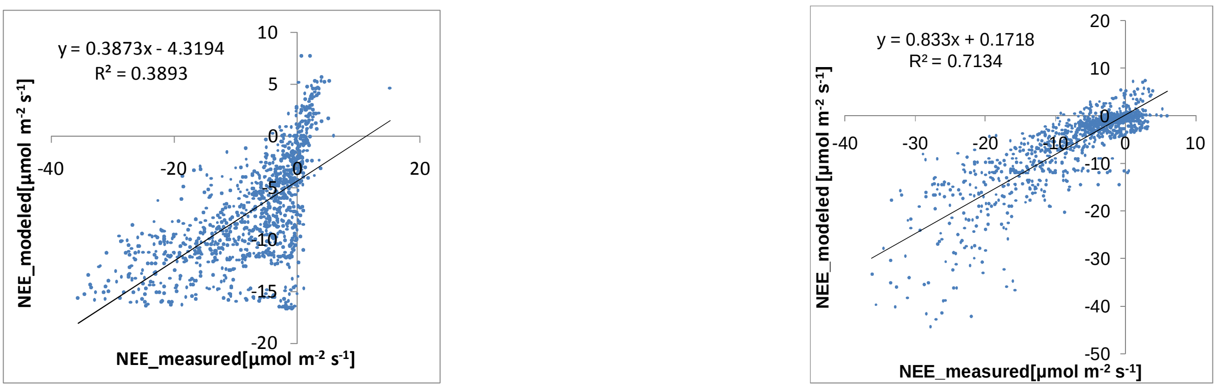

Figure 5. Scatterplots of the measured and modeled NEE data presented in Figure 4.Left: MMF; Right: NMMF

3.3 Comparison of Eddy-Covariance and Chamber Measurements

Eddy-covariance measured NEE was compared with the chamber measured NEE at both KR-P and KR-R. The preliminary results show a bad agreement between them (Fig. 6). Generally, NEE had a larger value measured by eddy-covariance than by chamber measurement. Only on July 27 did they have a good agreement. The reason is not clear at the moment and it needs further investigation.

Figure 6. NEE measured by eddy-covariance and chamber technique. Left: KR-P; right: KR-R

3.4 Comparison of Observations and WRF Modeling Results

The WRF modelled results show different performances between KR-P and KR-R. At KR-P, the sensible heat flux (SHF) is generally underestimated with a mean bias error (MBE) of –34.7 W m^{-2}, while the latent heat flux (LHF) is overestimated with a MBE of 88.6 W m^{-2} (Fig. 7). This is similar to the previous research at a mountainous forest site in Germany (Fig. 9). The index of agreement (IA) is 0.77 for SHF and 0.34 for LHF. At KR-R, the IA is 0.87 for SHF and 0.83 for LHF, which are closer to 1 than KR-P (Fig. 8). The summary of SHF and LHF, as well as the Bowen ration, looks also better simulated at KR-R than at KR-P. This indicates that WRF works better for the rice field than for the potato field.

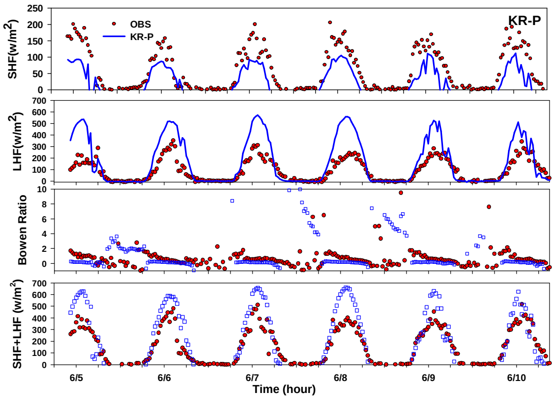

Figure 7. Observed and WRF modelled turbulent energy fluxes at KR-P

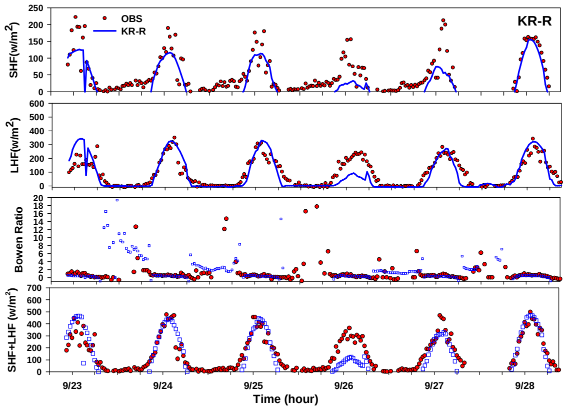

Figure 8. Observed and WRF modelled turbulent energy fluxes at KR-P

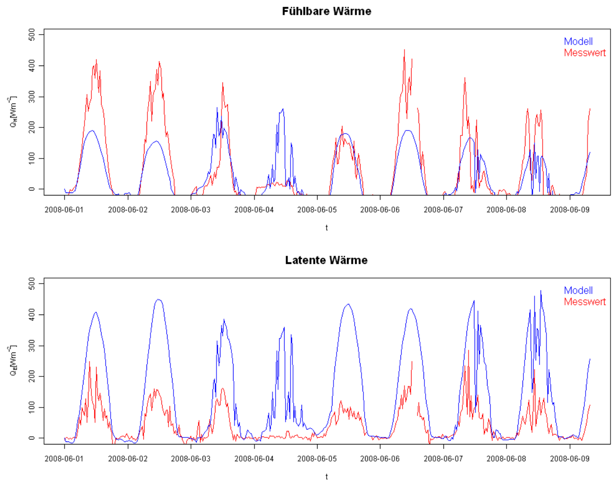

Figure 9. Observed and WRF modelled turbulent energy fluxes at a forest site in Germany

4. Summary

We studied the energy and net ecosystem exchange at two typical agro-ecosystems over a complex mountainous terrain in South Korea. The footprint model shows that the target farmlands generally contributed most of the related areas to the turbulent flux measurements. The sensible and latent heat flux depended on the coverage of leaves on the surface. NEE was controlled by solar radiation for the diurnal pattern and by the growing stages for the seasonal pattern. A late-season depression of NEE was observed at the potato field caused by the postponed harvest, which turned the filed into a slight source of CO_2.

An innovative gap filling method on the basis of Michaelis-Menten function was raised and showed a better regression than the traditional method. It could be useful for rapidly developed crop sites without long time measurements.

Eddy-covariance measurements were compared with chamber measurements. The agreement between them is not good. Further study is expected to explain it.

Quality controlled eddy-covariance measured fluxes were used to evaluate the performance of WRF model. The simulated data had a better agreement with the observed data for both sensible and latent heat flux at the rice field than at the potato field.

References

A Aubinet, M., Heinesch, B. & Yernaux, M., 2003. Horizontal and Vertical Co2 Advection In A Sloping Forest. *Boundary-Layer Meteorology*, 108, pp.397-417.

Aubinet, M. et al., 2005. Comparing CO2 Storage and Advection Conditions at Night at Different Carboeuroflux Sites. *Boundary-Layer Meteorology*, 116, pp.63-93.

Baldocchi, D. et al., 2001. FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities. *Bulletin of the American Meteorological Society*, 82, pp.2415-2434.

Becker, A. & Bugmann, H., 1997. *Predicting global change impacts on mountainhydrology and ecology: integrated catchment hydrology/altitudinal gradient studies (the IGBP mountain workplan)*, IGBP Report 43, IGBP Secretariat. Stockholm, Sweden.

Foken, T., 2008. *Micrometeorology*, Springer.

Foken, T. & Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements. *Agricultural and Forest Meteorology*, 78(1-2), pp.83-105.

Foken, T. et al., 2004. Post-field data quality control. *Handbook of micrometeorology*, pp.181–208.

Göckede, M. et al., 2008. Quality control of CarboEurope flux data - Part 1: Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems. *Biogeosciences*, 5, pp.433-450.

Göckede, M. et al., 2006. Update of a Footprint-Based Approach for the Characterisation of Complex Measurement Sites. *Boundary-Layer Meteorology*, 118, pp.635-655.

Göckede, M., Rebmann, C. & Foken, Thomas, 2004. A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites. *Agricultural and Forest Meteorology*, 127(3-4), pp.175-188.

Hammerle, A. et al., 2007. Eddy covariance measurements of carbon dioxide, latent and sensible energy fluxes above a meadow on a mountain slope. *Boundary-Layer Meteorology*, 122, pp.397-416.

Kutsch, W.L. et al., 2010. The net biome production of full crop rotations in Europe. *Agriculture, Ecosystems & Environment*, 139(3), pp.336-345.

Kwon, H., Kim, J. & Hong, J., 2009. Influence of the Asian Monsoon on net ecosystem carbon exchange in two major plant functional types in Korea. *Biogeosciences Discuss.*, 6(6), pp.10279-10309.

Lloyd, J. & Taylor, J.A., 1994. On the temperature dependence of soil respiration. *Functional ecology*, 8(3), pp.315–323.

Mauder, M. & Foken, T., 2004. *Documentation and instruction manual of the eddy covariance soft-ware package TK2*, Universität Bayreuth, Abt. Mikrometeorologie, Print, ISSN 1614-8916, Arbeitsergebnisse 26.

Michaelis, L. & Menten, M., 1913. Die Kinetik der Invertinwirkung. *Biochem.*, Z. 49, pp.333-369.

Moffat, A.M. et al., 2007. Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. *Agricultural and Forest Meteorology*, 147(3-4), pp.209-232.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. *Boundary-Layer Meteorology*, 37, pp.17-35.

Rannik et al., 2000. Footprint analysis for measurements over a heterogeneous forest. *Boundary-Layer Meteorology*, 97(1), pp.137–166.

Ruppert, J. et al., 2006. Innovative gap-filling strategy for annual sums of CO2 net ecosystem exchange. *Agricultural and Forest Meteorology*, 138(1-4), pp.5-18.

Schotanus, P., Nieuwstadt, F.T.M. & de Bruin, H.A.R., 1983. Temperature measurement with a sonic anemometer and its application to heat and moisture fluxes. *Boundary-Layer Meteorology*, 26, pp.81-93.

Skamarock, W.C. et al., 2005. *A description of the Advanced Research WRF Version 2*, Citeseer.

Vickers, D. & Mahrt, L., 1997. Quality control and flux sampling problems for tower and aircraft data. *Journal of Atmospheric and Oceanic Technology*, 14(3), pp.512–526.

Webb, E.K., Pearman, G.I. & Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorological Society*, 106, pp.85-100.

Wilczak, J.M., Oncley, S.P. & Stage, S.A., 2001. Sonic Anemometer Tilt Correction Algorithms. *Boundary-Layer Meteorology*, 99, pp.127-150.

Zhao, P. et al., 2011. *Documentation of the Observation Period, May 12th to Nov. 8th, 2010, Haean, South Korea*, Universität Bayreuth, Abt. Mikrometeorologie, Print, ISSN 1614-8916, Arbeitsergebnisse 45.