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Seasonal Changes of Energy Fluxes in an Estuarine Wetland of Shanghai, China

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Abstract: The energy budget and regulating factors were investigated over an estuarine wetland during one year of continuous measurement in 2006. The results show that the seasonal changes of the energy fluxes and Bowen ratio (β) were greatly affected by incoming shortwave radiation and canopy growth. During the non-growing season and early-growing season, sensible heat (H) dominated the energy flux, and β could reach a maximum of 2.5, while during most of the growing season, latent heat dominated the energy flux and β fluctuated from 0.4 to 1.0. The energy budget ratio in growing season was about 0.76, and the value would be higher if heat exchange during tidal flooding was included. During tidal flooding days, β was slightly higher than that at exposure days in most cases. Vegetation cover seems exert little effect on energy partitioning except in March when the standing dead grass intercepted the incoming radiation that might reach the soil surface and reduce the turbulence between soil and atmosphere, thus suppressing the evaporation from the soil though the soil mositure was high at that time.

Keywords: Bowen ratio; estuarine wetland; energy partitioning; vegetation coverage; tidal flooding

1 Introduction

Energy exchange between the land surface and the atmosphere is among the most important processes in wetland systems because it affects temperature, water transport, plant growth, and many other ecosystem processes (Dennison and Berry, 1989). Understanding the magnitude and changes of various energy fluxes as well as the regulatory mechanisms, for example, is critical for predicting ecosystem functions and their responses to climate change.

Generally, evapotranspiration consumed largest part of available energy during growing season in vegetated wetlands (Kurbatova *et al.*, 2002; Admiral *et al.*, 2006; Admiral and Lafleur, 2007). Furthurmore, the standing water could also be an important consumer of incoming radiation in some vegetated wetlands and open water area (Burba *et al.*, 1999a; 1999b; 1999c; Heilman *et al.*, 2000; Silis *et al.*, 1989). Although meaningful explanation on the regulations of ecosystem energy fluxes have been made in peatland (Kurbatova *et al.*, 2002; Admiral *et al.*, 2006; Admiral and Lafleur, 2007), prairie wetland (Burba *et al.*, 1999a; 1999b; 1999c), and coastal wetland (Lafleur and Rouse, 1988; Silis *et al.*, 1989), very little is known about the energy fluxes in estuarine wetland, where tidal activities and upstream hydrology can play significant roles in regulating the magnitude and dynamics of the energy budget through horizontal transportation of mass and energy (Odum, 2000; Teal and Howes, 2000).

Vegetation coverage was always considered an important factor in regulating energy partitioning (Burba *et al.*, 1999a), but there still existed controversy on this effect. Lafleur and Rouse (1988) found that Bowen ratio (β) increased with the vegetation cover in a marsh since it could act as a shelter for radiation and thus reduced evaporation. While, rough canopy generally exhibits strong evapotransporation and low β compared to smooth canopy (Chapin *et al.*, 2002), since rough canopy could create more mechanical turbulence to heat transport.

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In the site of this study, the marked differences in vegetation coverage between north and south fetches provided an opportunity to investigate how vegetation coverage would affect the energy partitioning.

The previous studies on wetland energy fluxes were often restricted to a limited time span ranging from a few days to several months (Rouse *et al.*, 1987; den Hartog *et al.*, 1994; Lafleur *et al.*, 1997; Heilman *et al.*, 2000; Shimoyama *et al.*, 2003; Noormets *et al.*, 2004), which was probably due to the difficulty in establishing and maintaining proper field equipment on wetalnds. In August of 2004, we established one eddy covariance (EC) tower in the low elevation of Dongtan (a newly formed estuarine wetland), Shanghai to perform micrometeorological surveys (Guo *et al.*, 2009). The objectives of this study are to: 1) examine seasonal variations in the energy flux and partitioning pattern; 2) explore the regulation of environmental factors on energy flux; and 3) quantify the effect of tidal flooding and vegetation coverage on energy partitioning in the estuarine wetland in Shanghai.

2 Materials and Methods

2.1 Site description

The study area (31˚25'–31˚38'N, 121˚50'–122˚05'E) is an estuarine wetland located in Dongtan of Chongming Island, northeast of Shanghai, China (Fig. 1). The wetland gradually expanded towards the sea at a rate of 64 m/yr between 1987 and 2004, primarily due to the large sediment carried down by the Changjiang (Yangtze) River (Zhao *et al.*, 2008).

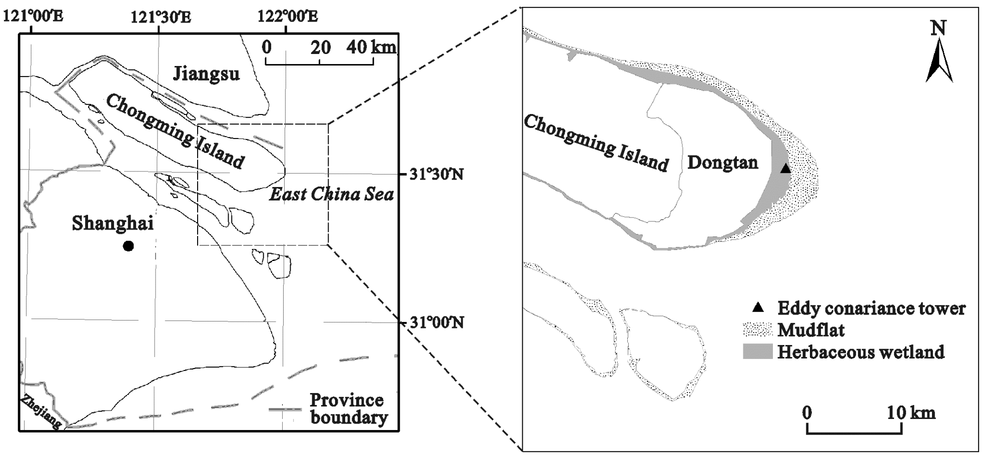


Fig. 1 Location of study area and eddy covariance tower

The climate is subtropical monsoon climate, with distinct seasonal variations of temperature and an abundance of precipitation. The mean annual temperature and annual precipitation in 2006 was 16.3°C and 2 324 mm, respectively. From December to next February, the north-west wind prevails; from April to July and from September to October, the south-east wind dominates; while in March, August and November, wind blows both from north-west and south-east. The tides in this area are semi-diurnal with a mean tidal range of 2.0 m to 3.1 m above the Wusong Tidal Height Datum (Sun *et al.*, 2001), which changes on a bi-weekly cycle.

The dominant plant species include *Phragmites australis*, *Scirpus mariqueter* and *Spartina alterniflora*. The growing periods for *P. australis* and *S. mariqueter* are ~220 days from April to October and ~190 days from April to September, respectively, while *S. alterniflora* has a longer growing period (~270 days from March to November) (Liao *et al.*, 2007). The canopy height is less than 3 m. Within a radius of 300 m, the south fetch was near full vegetation cover, while only about 50% of the north fetch was covered by vegetation.

2.2 Field measurement

Sensible heat (H) and latent heat (LE) fluxes were quantified by using an EC system. The system consistes of a three-dimensional sonic anemometer (CSAT-3, Campbell Scientific Inc. (CSI), Logan, UT, USA), which measures wind speed and sonic temperature, and an open-path infrared gas analyzer (IRGA, Li-7500, Li-Cor Inc., Lincoln (Li-Cor), NE, USA) that measures densities of CO_2 and water vapor. Both CSAT-3 and Li-7500 were mounted at the top of a 5-m triangular tower, and were operated at a frequency of 10 Hz. The data were stored in a built-in datalogger (CR5000, CSI).

Continuous measurements of micrometeorological parameters were included to support flux measurement, including air temperature and relative humidity at heights of 1.8 m, 2.5 m and 4.8 m (HMP45C, Vaisala, Finland), net radiation (CNR1, Kipp and Zonen, Delft, Holland), incoming shortwave solar radiation (Li-210x, Li-Cor), and precipitation (TE525, Texas Electronics, Texas, USA), all of whose sensors were mounted at the heights of 4.0 m to 4.5 m. Soil temperature (CS107, CSI), soil moisture (CS616, CSI), and soil heat flux (HFT-3, CSI) were also measured at a depth of 5 cm. Because of the sizable variation in soil moisture and large heat storage above the soil heat flux plates, adjustments were made on April 7 to the depths of 1 cm, 5 cm and 10 cm. The soil moisture sensor was set up in a depth of 0–10 cm. All of the above variables were sampled every 20 s and averaged (or totaled) in 30-min intervals and stored in the CR5000 datalogger. Additionally, we installed a water level gauge (Sonde, model 600LS, YSI, USA) in late November 2005 to record tidal water depth when floods occurred. However, because of the high proportion of sediment in the tidal water, the instrument did not provide accurate data of water depth on occasions.

2.3 Data processing

The quality assurances and quality controls (QA/QC) of the EC data were processed following Mauder *et al.* (2008) with the EdiRe software package (Institute of Atmospheric and Environmental Sciences, School of GeoSciences, the University of Edinburgh, England). Prior to calculating the fluxes of sensible and latent heat, the wind velocity was rotated so that 30-min mean vertical and crosswind components equated to zero. The influence of water vapor on the sonic temperature measurement (Kaimal and Gaynor, 1991), and the effect of air density fluctuation on CO_2 and heat fluxes (Webb *et al.*, 1980) were corrected in sequence.

The corrected dataset was further filtered with spikes, weather condition (rain event), and instrument malfunctions. Stationary test was applied with a threshold of 30% (Foken and Wichura, 1996). Overall, approximately 71% and 57% of the 30-min data of H and LE were retained, respectively.

2.4 Calculation method

The energy balance ratio (EBR) was frequently used as an independent method to assess the reliability of the EC measurement (Wilson *et al.*, 2002). Because of the relatively short vegetation in this area, the heat stored in the canopy and air is negligible. EBR is expressed as:

$$BER = (H+LE)/(R_n-G-G_s) \qquad (1)$$

where R_n is net radiation, G is soil heat flux, and G_s is the heat exchange with tidal water during flooding. However, due to the difficulty in estimation, G_s was not included in EBR calculation in this study. Daytime Bowen ratio (β) (H/LE) was calculated to depict which energy component (H or LE) dominated. Data between 11:00 and 16:00 were used in this study.

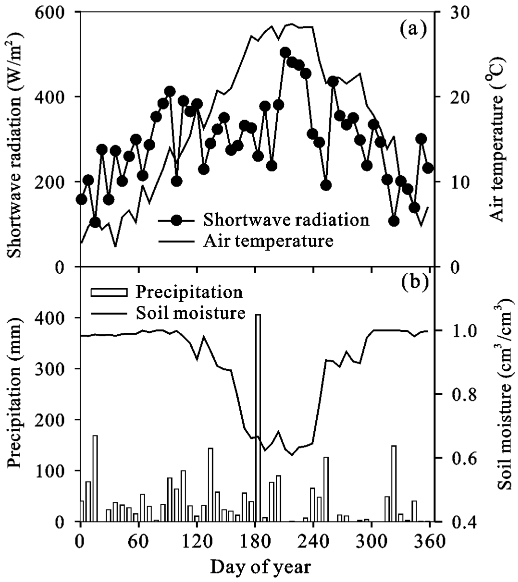
3 Results

3.1 Meteorological variables

Distinct seasonal changes of air temperature and incoming shortwave radiation (R_s) were observed. The lowest mean daily temperature was recorded in February, while the highest was recorded in August (Fig. 2a). The seasonal change of the incoming shortwave radiation was relatively small (Fig. 2a). The soil moisture was consistently high during the non-growing season and early- and late-growing season, and reached the minimum in July and August (Fig. 2b). Precipitation was recorded year-round, with about 78% of the total precipitation (2 324 mm) falling between January and July (Fig. 2b).

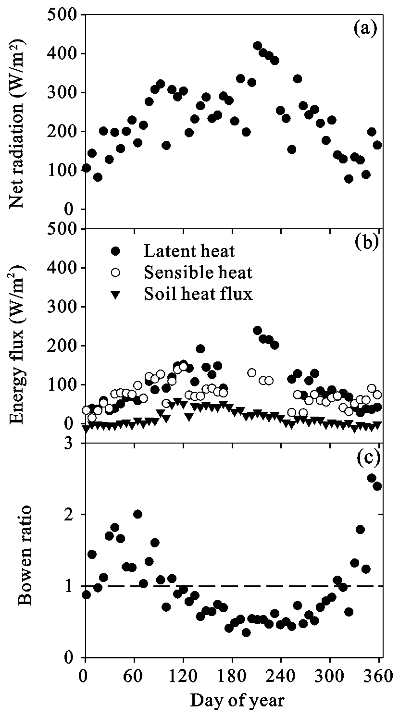
3.2 Seasonal energy flux and partitioning

Net radiation (R_n) exhibits a clear seasonal dynamic (Fig. 3a), fluctuating in concert with R_s (Fig. 2a). Both LE and H show seasonal dynamics, but dominate in different seasons (Fig. 3b). Bowen ratio (β) therefore shows a marked difference between growing and non-growing seasons (Fig. 3c). From April to November, β is below unity, reaching as low as 0.4, and then rises to a maximum of 2.5 in December. Between June and September, though R_n shows great variation, β is comparable steady. From January to April, both LE and H increase with R_n rising; while from October to December, both LE and H decline with R_n reducing, and LE shows a slightly higher dependency on R_n than H. The soil heat flux (G) shows little variation through seasons with low magnitudes (Fig. 3b).



The statistics were calculated at a 7-day frequency

Fig. 2 Seasonal changes of meteorological variables



For each 7-day period, we used the days when at least 80% of data were avaible

Fig. 3 Seasonal changes of radiation (a), energy flux (b) and Bowen ratio (c)

Diurnal variation of energy fluxes (both LE and H) changes with R_n, both in growing and non-growing seasons (Fig. 4). In non-growing season, R_n reaches as high as 482 W/m^2, and LE and H peak at 73 W/m^2 and 138 W/m^2, respectively. In growing season, R_n increases to 720 W/m^2, and LE shows a dramatic increase up to 354 W/m^2, but H only reaches maximum at 177 W/m^2. Both LE and H peak one or two hours after R_n reaches maximum, while G shows a four to five hours lapse. The energy balance ratio during growing season is 0.76.

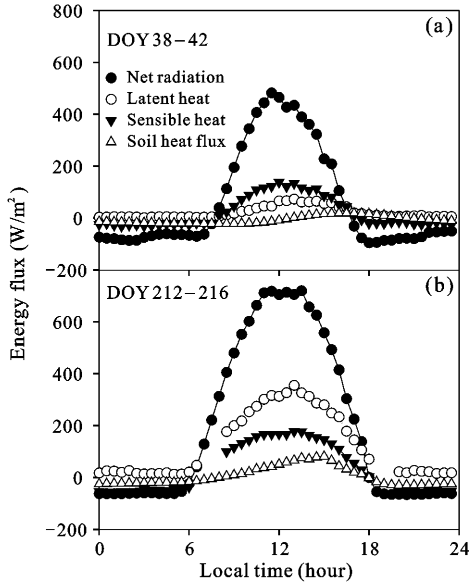
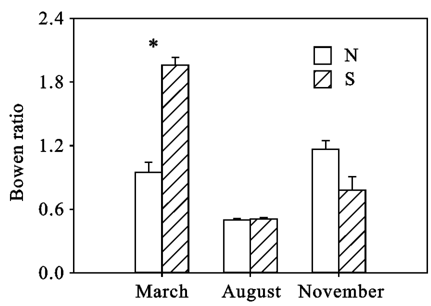


Fig. 4 Five days ensemble averages of diurnal energy fluxes in non-growing (a) and growing season (b)

3.3 Effect of vegetation cover and tidal activity on energy partitioning

Vegetation coverage exerts little effect on energy partitioning in August (north vs south: 0.50 vs 0.51) and November (1.17 vs 0.78), while shows strong effect in March (0.95 vs 1.97) (Fig. 5). However, the significant difference in March is more likely due to the physical effect of standing dead grass, since only *S. alterniflora* emerged as seedlings at that time.

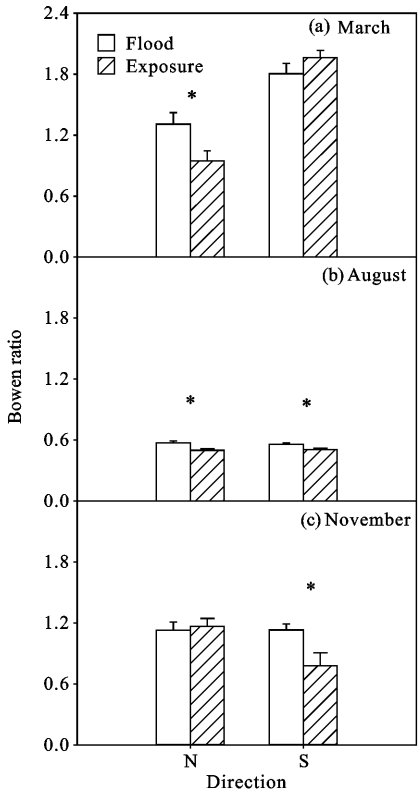
For cases with siginificant differences, more energy was partitioned as sensible heat during flooding days



N: north fetch; S: south fetch

* means statistically significant at $p<0.05$ (t-test)

Fig. 5 Daytime average Bowen ratio from north and south fetches in three months than during exposure days, and more obvious in March and November (Fig. 6). In March, β reaches 1.31 during flooding days, while declines to 0.95 during expousre days in the north fetch. When it comes to August, β varies in the range of 0.50–0.57. In November, β exhibits significant difference only in south fetch (flooding vs exposure: 1.13 vs 0.78). In comparison, for south fetch in March and north fetch in November, latent heat assumes more energy during exposure days than during flooding days though without significant differences.



N: north fetch; S: south fetch

* means statistically significant at p<0.05 (t-test)

Fig. 6 Daytime average Bowen ratio from north and south fetches during flooding and exposure days in three months

4 Discussion

Our study site was virtually flat (the average slope is around 0.02%–0.04%) (Zhao *et al.*, 2008), homogeneous, and covered with short vegetation, yet we still found a low value of energy budget ratio, which was little lower than the mean value reported in Fluxnet (0.79) (Wilson *et al.*, 2002). The imbalances of energy budget have been observed in almost every EC system, and possible explanation, like sampling mismatch and calculation error, were summarized in Wilson *et al.* (2002). Besides these causes, the heat exchange between tidal water and ecosystem during flooding would also account for this imbalance in our study area. Burba *et al.* (1999c) reported the heat stored in 0.5 m deep water body could reach 200 W/m^2 in the daytime, which consumed 20%–30% of R_n, and became a significant energy source in the night. If this part of heat exchange can be quantified, the energy budget ratio would be greatly improved.

Distinct seasonal variations of energy fluxes were mainly driven by incoming radiation, which also drove the diurnal pattern. While, canopy growth also contributed to the seasonal dynamic of energy partitioning, especially when plant emerged and became senescent. The relatively consistent values of β between June and September indicated that the vegetation could maintain the energy partitioning at certain pattern, even the percent of vegetation coverage varying from 50% to 100%. We hypothesized that the north fetch behaved more like rough canopy compared to the south fetch, and produced more mechanical turbulences that aid heat transport (Chapin *et al.*, 2002), which would partly compensate for the difference caused by low vegetation coverage. Furthermore, evaporation in bare ground under high temperature may also compensate for the possible differences caused by vegetation coverage. However, without tidal activity maintaining the hydrological condition of the wetland through refilling the soil water, the soil water would soon evaporate into air, and the energy flux pattern therefore would be greatly changed.

Large *LE* was expected, but the energy partitioning pattern in this study was much different from the previous researches in wetlands, especially for the relatively high β during the growing season. We observed the minimum β of 0.41 that was higher than that (0.10–0.20) reported in a northern boreal fen (Lafleur *et al.*, 1997) and that (0.36) reported in a lakeshore (Souch *et al.*, 1996). We attributed the high β to the combined results of high leaf area index and high temperature. In the south fetch, the dense canopy acted as a shelter that shaded the incoming radiation that could arrive at the soil surface (Linacre *et al.*, 1970), thus reducing the evaporation rate and making more available energy dissipated as *H*. While at north fetch, though soil was frequently replenished by tidal water, the quick dry-out surface soil could act as "mulch" that inhibited the evaporation from below the wet soil (Kurbatova *et al.*, 2002), likely helping to keep the magnitude of *H* at high levels.

The comparison of energy partitioning between flooding and exposure days was worth noting. We assumed the high water vapor density or low vapor pressure deficit during flooding days depressed the evaporation or transpiration. The stress under water flooding may also suppress transpiration activity (Wang *et al.*, 2006). Considering the high heat capacity of water, tidal water would probably warm the air in cold days, like in March and November, and thereby increase *H*, but may also cool the air in August. Thus, different mechanisms may exist for tidal effect on energy partitioning, which requires further work.

5 Conclusions

The energy budget and regulating factors were investigated over an estuarine wetland during one year of continuous measurement in 2006. Like observed in other vegetated wetlands, latent heat was the largest consumer of incoming energy during most of growing season. In comparison, more energy was disspiated as sensible heat during non-growing season. The distinct seasonal variation in energy partitioning was greatly affected by canopy growth and incoming radiation. Incoming radiation also drove the diurnal pattern of energy fluxes.

Tidal flooding could make more energy dissipated as sensible heat (*H*) in most cases. Relatively higher values of Bowen ratio (β) than those reported in other wetland ecosystems were observed. We reasoned that the dense canopy in our system or dried-out surface soil greatly reduced the incoming radiation that might reach the soil surface or underlying soil, which also partly explained the weak effect of vegetation coverage on energy partitioning.

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References

Admiral S W, Lafleur P M, 2007. Partitioning of latent heat flux at a northern peatland. *Aquatic Botany*, 86(2): 107–116. DOI: 10.1016/j.aquabot.2006.09.006

Admiral S W, Lafleur P M, Roulet N T, 2006. Controls on latent heat flux and energy partitioning at a peat bog in eastern Canada. *Agricultural and Forest Meteorology*, 140(1–4): 308–321. DOI: 10.1016/j.agrformet.2006.03.017

Burba G G, Verma S B, Kim J, 1999a. A comparative study of surface energy fluxes of three communities (*Phragmites australis*, *Scirpus acutus*, and open water) in a prairie wetland ecosystem. *Wetlands*, 19(2): 451–457.

Burba G G, Verma S B, Kim J, 1999b. Energy fluxes of an open water area in a mid-latitude prairie wetland. *Boundary-Layer Meteorology*, 91(3): 495–504.

Burba G G, Verma S B, Kim J, 1999c. Surface energy fluxes of *Phragmites australis* in a prairie wetland. *Agricultural and Forest Meteorology*, 94(1): 31–51.

Chapin, F S, Maston P A, Mooney H A, 2002. *Principles of Terrestrial Ecosystem Ecology*. New York: Springer-verlag.

den Hartog G, Neumann H H, King K M *et al*., 1994. Energy budget measurements using eddy correlation and Bowen ratio techniques at the Kinosheo Lake tower site during the northern wetlands study. *Journal of Geophysical Research*, 99(D1): 1539–1549.

Dennison M S, Berry J F, 1989. *Wetlands: Guide to Science*, *Law*, *and Technology*. Park Ridge: Noyes Publications, 439.

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

Guo Haiqiang, Noormets A, Zhao Bin *et al*., 2009. Tidal effects on net ecosystem exchange of carbon in an estuarine wetland. *Agricultural and Forest Meteorology*, 149(3): 1820–1828. DOI: 10.1016/j.agrformet.2009.06.010

Heilman J L, Heinsch F A, Cobos D R *et al*., 2000. Energy balance of a high marsh on the Texas Gulf Coast: Effect of water availability. *Journal of Geophysical Research*, 105(D17): 22371–22377.

Kaimal J C, Gaynor J E, 1991. Another look at sonic thermometry. *Boundary-Layer Meteorology*, 56(4): 401–410.

Kurbatova J, Arneth A, Vygodskaya N N *et al*., 2002. Comparative ecosystem-atmosphere exchange of energy and mass in a European Russian and a central Siberian bog I: Interseasonal and interannual variability of energy and latent heat fluxes during the snowfree period. *Tellus*, 54(5): 497–513.

Lafleur P M, McCaughey J H, Joiner D W *et al*., 1997. Seasonal trends in energy, water, and carbon dioxide fluxes at a northern boreal wetland. *Journal of Geophysical Research*, 102(D24): 29009–29020.

Lafleur P M, Rouse W R, 1988. The influence of surface cover and climate on energy partitioning and evaporation in a subarctic wetland. *Boundary-Layer Meteorology*, 44(4): 327–347.

Liao Chengzhang, Luo Yiqi, Jiang Lifeng *et al*., 2007. Invasion of *Spartina alterniflora* enhanced ecosystem carbon and nitrogen stocks in the Yangtze estuary, China. *Ecosystems*, 10(8): 1351–1361. DOI: 10.1007/s10021-007-9103-2

Linacre E T, Hicks B B, Sainty G R *et al*., 1970. The evaporation from a swamp. *Agricultural Meteorology*, 7(5): 375–386.

Mauder M, Foken T, Clement R *et al*., 2008. Quality control of Carbon Europe flux data-Part 2: Inter-comparison of eddy-covariance software. *Biogeosciences*, 5(2): 451–462.

Noormets A, Chen J Q, Bridgham S *et al*., 2004. The effects of infrared loading and water table on soil energy fluxes in northern peatlands. *Ecosystems*, 7(5): 573–582. DOI: 10.1007/s100-21-004-0013-2

Odum, E P, 2000. Tidal marshes as outwelling/pulsing systems. In: Weinstein M P, Kreeger D A (eds.). *Concepts and Controversies in Tidal Marsh Ecology*. Dordrecht: Kluwer Academic Publishers.

Rouse W R, Hardill S G, Lafleur P M, 1987. The energy balance in the coastal environment of James Bay and Hudson Bay during the growing season. *International Journal of Climatology*, 7(2): 165–179.

Shimoyama K, Hiyama T, Fukushima Y *et al*., 2003. Seasonal and interannual variation in water vapor and heat fluxes in a West Siberian continental bog. *Journal of Geophysical Research*, 108(D20): 46–48. DOI: 10.1029/2003JD003485

Silis A, Rouse W R, Hardill S, 1989. Energy balance of the intertidal zone of western Hudson Bay I: Ice-free period. *Atmosphere-Ocean*, 27(2): 327–345.

Souch C, Wolfe C P, Grimmond C S B, 1996. Wetland evaporation and energy partitioning: Indiana Dunes National Lakeshore. *Journal of Hydrology*, 184(3–4): 189–208.

Sun Shucun, Cai Yongli, Liu Hong, 2001. Biomass allocation of *Scirpus mariqueter* along an elevational gradient in a salt marsh of the Yangtse River estuary. *Acta Botanica Sinica*, 43(2): 178–185. (in Chinese)

Teal J M, Howes B L, 2000. Salt marsh values: Retrospection from the end of the century. In: Weinstein M P, Kreeger D A (eds.). *Concepts and Controversies in Tidal Marsh Ecology*. Dordrecht: Kluwer Academic Publishers.

Wang Qing, Wang Chenghuan, Zhao Bin *et al*., 2006. Effects of growing conditions on the growth of and interactions between salt marsh plants: Implications for invasibility of habitats. *Biological Invasions*, 8(7): 1547–1560. DOI: 10.1007/s10530-00-5-5846-x

Webb E K, Pearman G I, Leuning R, 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. *Quarterly Journal of the Royal Meteorological Society*, 106(447): 85–100.

Wilson K, Goldstein A, Falge E *et al*., 2002. Energy balance closure at FLUXNET sites. *Agricultural and Forest Meteorology*, 113(1–4): 223–243.

Zhao Bin, Guo Haiqiang, Yan Yaner *et al*., 2008. A simple waterline approach for tidelands using multi-temporal satellite images: A case study in the Yangtze Delta. *Estuarine, Coastal and Shelf Science*, 77(1): 134–142. DOI: 10.1016/j.ecss.2007.09.0-22