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宁南半干旱地区农田和草地生态系统能量通量的季节变化

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摘要：根据 2002～2003 年宁南山区不同下垫面小气候考察资料，用能量平衡法计算了不同下垫面不同季节的感热、潜热通量。分析结果表明：(1)宁南半干旱地区夏季农田和草地的净辐射峰值可达到 700 W/m² 以上，土壤热通量的值比净辐射小 1 个量级。同类下垫面净辐射通量日积分值夏季＞春季＞秋季＞冬季。(2)宁南半干旱山区感热输送强度以典型草地的最大，其次是禁牧草地，稀树草地的最小。春季各类下垫面地表热量平衡以感热输送为主。在春、夏、秋季的晴天，感热通量日积分值为正，冬季为负。(3)农田在夏、秋季、冬季水汽输送大于各类草地的，其次是稀树草地的，典型草地向上的水汽输送量是最小的。夏季白天农田 β 在 0.2～0.7，稀树草地 β 为 0.2～1.0，能量输送以潜热为主。禁牧草地 β 为 0.2～9.2，典型草地为 1.5～13.1，能量输送以感热为主。(4)宁南半干旱地区宜退耕，发展典型草原，在水分充足的山地背阴坡少量发展稀树草地。

关键词：感热；潜热；土壤热通量；退耕还草；能量平衡法；草地；农田

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Seasonal differences of energy fluxes among crop and grass ecosystems in semiarid region of southern Ningxia

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Abstract: Human activities have dramatically influenced terrestrial ecosystems through altering the surface energy balance in the atmosphere-land interactions. Understanding the surface energy balance in various vegetation surfaces and ecosystems is essential for evaluating the impacts of management activities on the succession of natural and anthropogenic ecosystems. In the semiarid region in Southern Ningxia of China, expanding agricultural and overgrazing grasslands has resulted in degradation of natural grass ecosystems. Recently, a management policy-crop-to-grassland conversion has been practiced in this area to prevent deterioration of ecological processes. To understand the effects of this management activity on ecological processes, we examined microclimate and energy fluxes in four types of ecosystems, including typical grassland (TG), which are grasslands with regular grazing, grazing-forbidden grassland (GFG), which are grasslands without grazing, semiarid savanna (SS), which are grasslands with sparse trees, and cropland (CL). The objectives of this study were to (1) examine microclimate differences in the four crop and grassland ecosystems; (2) quantify each component of surface energy balance (i. e., net radiation, soil heat flux, sensible heat flux, and latent heat flux) in different ecosystem types and seasons; and (3) evaluate the benefits of crop-to-grassland conversion in semiarid agricultural area.

This study was conducted in Haiyuan County, Ningxia Hui Autonomous Region, China, located between 1 528～2 600 m

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elevation within 36°2′4″ ～36°27′54″ N, 105°32′42″ ～105°37′36″E. All microclimatic measurements were collected manually or automatically once an hour during Spring (April 17～26, 2001), Summer (July 13～22, 2001), Fall (October 15～24, 2001), and Winter (January 15～24, 2002). We measured net radiation (B) at 1.5 height and soil heat flux (Qs) at 5cm depth. We also measured air temperature, relative humidity, and wind speed at 0.5, 1.0, 1.5, and 2.0m in height above the ground. Using those measurements and Energy Balance method ($B=H+LE-Qs$), we calculated sensible heat flux (H) and latent heat flux (LE). Bowen Ratio ($\beta=H/LE$) was also computed to evaluate the features of heat and water vapor transportation in the four types of ecosystems.

Our results indicated that the magnitudes and diurnal patterns of net radiation, soil heat flux, sensible heat flux, and latent heat flux were significantly different among typical grassland, grazing-forbidden grassland, semiarid savanna, and cropland in four typical seasons:

Net radiation had regular diurnal patterns in all seasons. Positive net radiation occurred during the daytime (7:00～18:00) with maximum up to 700 W/m^2(12:00～14:00), while negative net radiation displayed at night with minimum less than 100 W/m^2. The highest daily accumulated net radiation occurred in the summer, and the lowest occurred in the winter. In the spring, daily accumulated net radiation was larger than that in the fall. Comparing daily accumulated net radiation among the four types of ecosystems, we found that semiarid savanna had relatively larger daily accumulated net radiation in the spring and fall seasons and smaller daily accumulated net radiation in the summer than the other three types cropland experienced the highest daily accumulated net radiation during the summer. Daily accumulated net radiation in typical grassland and semiarid savanna was negative during winter.

Soil heat flux was ten times less than net radiation. It indicated that up to 90% of net radiation was allocated to sensible and latent heat flux (i.e., H and LE) rather than soil heat flux. However, the seasonal patterns of soil heat flux determined daily and annual increase and decrease in soil temperature. For example, in the spring, soil heat flux (90 W/m^2) was used to heat soil surface in the daytime and resulted in an increase in soil temperature; soil heat flux (30 W/m^2) escaped from soil surface during the nighttime and resulted in decrease in soil temperature. Soil heat flux showed a general seasonal pattern, which showed the largest in the spring, the second largest in the summer, and the smallest in the winter. In the four ecosystem types, typical grassland and grazing-for bidden grassland had similar diurnal patterns of soil heat flux. Semiarid savanna had smaller values than typical grassland during the nighttime because this type of ecosystem was dominant in the shaded slopes. It suggested that semiarid savanna experienced less soil temperature fluctuation in a day or in seasons than the other three types of ecosystem. Comparing the fluctuation of soil heat flux, we found that the maximum of soil heat flux in the summer and fall (30～50 W/m^2) was significantly lower than that in the spring (90 W/m^2). During the winter, heat was transported from the soil surface, resulting in a decrease in soil temperature.

Sensible heat flux showed typical diurnal patterns that had been reported in other semiarid and arid area. Sensible heat flux was positive during the daytime but negative during the nighttime. This feature of sensible heat flux significantly differed from the patterns observed in moist climatic zones, which might have lower positive value or remain negative all day long. Apparently, moisture conditions controlled the magnitudes and diurnal patterns of sensible heat flux. Because there was significant variation among the four types of ecosystems, a variety of patterns of sensible heat flux appeared. In the spring, sensible heat flux was the most important part of surface energy budget and differed in different ecosystem types. For example, sensible heat flux was 70%～95 % of net radiation in typical grassland and 40%～60% in grazing-forbidden grassland and semiarid savanna. In the summer, sensible heat flux was still the major distribution of net radiation. In typical grassland, 60%～80% of net radiation was contributed to sensible heat flux, and less than 50% of net radiation was contributed to sensible heat flux in other types of ecosystems. In the fall, the maximum of sensible heat flux occurred at 381 w/m^2 in typical grassland, and cropland had the lowest peak value of sensible heat flux (128 W/m^2) in the four types of ecosystems. In the winter, there was a strong diurnal pattern in typical grassland, but it was not observable in other ecosystem types.

Latent heat flux indicated that the features of water vapor transport were significantly different in the four ecosystem types. Compared with the other three types of grasslands, cropland had the greatest upward water vapor transport in the summer, fall, and winter. The lowest upward water vapor transport occurred in typical grassland. In the daytime of spring, because semiarid savanna received the most net radiation of the ecosystem types and also had relatively sufficient water

supplement for evapotranspiration, upward water transport was the greatest in the four ecosystem types with the maximum 283 w/m^2 in a day and daily accumulated value 3.5 w/m^2. In grazing-forbidden grassland, the most upward water transport during a day occurred between 9:00~12:00 with the maximum 159 w/m^2 at 11:00 in the morning. Meanwhile, typical grassland had the lowest upward water transport in the three measured ecosystem types. These three types of ecosystem had negative latent heat flux, indicating slight water condensation during the spring nighttime. During the summer, cropland had the largest upward water vapor transport with the maximum 495 W/m^2. Grazing-forbidden grassland and semiarid savanna displayed similar variations in latent heat flux. Typical grassland had the lowest upward water vapor transport in the four ecosystem types. During the nighttime, typical grassland did not have water condensation, while water condensation appeared in the other three types. In the fall daytime, cropland maintained the highest value of latent heat flux, but the value was significantly lower than that in the summer and close to the value that occurred in the spring. Water condensation appeared around 19:00 in cropland. Daily accumulated latent heat flux in cropland was the largest in the four types of ecosystem and followed by those in semiarid savanna, grazing-forbidden grassland, and typical grassland, respectively. In the winter, the maximum latent heat flux occurred in semiarid savanna with 133 W/m^2. Cropland and grazing-forbidden grassland had slight upward water transport, and typical grassland had almost no upward water transport.

From the Bowen Ratio (β), we found that during the daytime in summer, β ranged from 0.2~0.7, 0.2~1.0, 0.2~9.2, and 1.5~13.1 in cropland, semiarid savanna, grazing-forbidden, and typical grassland, respectively. These values were much lower than the values in extremely arid area such as dessert and Gobi area. Compared to cropland, semiarid savanna had a similar range of β values, whereas typical grassland had a larger β value. It suggests that semiarid savanna did not differ from cropland very much from water consumption point of view, but typical grassland consumed much less water than cropland during the summer. On the other hand, grazing-forbidden grassland covered a larger range of β values than cropland. It indicates that highly spatial variability and ecological complexity should be considered in this type of ecosystem.

We concluded the practice of crop-to-grassland conversion was important to restore ecological processes and protect natural resources in semiarid southern Ningxia. This study suggests that crop-to-grassland conversion will help to save water resources in this semiarid region. Although typical grassland consumes less water than grazing-forbidden grassland and semiarid savanna during the summer, grazing-forbidden grassland has potential ecological significance in the long term, and semiarid savanna should be restricted in north-facing slopes with abundant ground water.

Key words: heat flux; latent flux; soil heat flux; crop-to-grassland conversion; energy balance method; grassland; cropland

人类活动通过改变近地面的能量平衡来影响陆地生态系统[1],摸清各种植被表面和生态系统的能量平衡对评价人类活动对自然和人工生态系统的演替的影响至关重要[2~4]。宁夏南部山区过去由于过度开垦农田和过度放牧,导致了自然草地的退化[5]。近年来随着退耕还林(草)战略的实施,宁南草地的进一步退化得到遏制。为弄清这项措施的效果,在典型草地、禁牧草地和农田等4种类型的生态系统开展了小气候观测和能量通量观测,旨在通过小气候考察,摸清宁南不同下垫面类型的能量平衡的结构,能量、水汽收支和输送特点,分析不同下垫面的小气候效应,评价半干旱地区退耕还草的气候效益。

1 观测场地和资料

1.1 观测场地概况

观测地段选择在海原县移民迁出区的月亮山南坡(典型草地),鸭儿湾(禁牧草地),南华山北坡(稀树草地)和固原市黑城镇的团庄(典型农田),位于东经105°32′42″~105°37′36″,北纬36°12′4″~36°27′54″。观测点间南北相距15km,东西相距5km。观测区海拔1 528~2 600m,地貌特征为丘陵山地,下垫面均匀,坡面平坦。土壤类型以黑垆土和山地灰褐土为主。年降水量300~400mm、年平均温度6~8℃。观测点位于典型植被类型的中央,观测地段距草地边缘>1km。草地生态类型为典型的杂类草草甸草原向干草原过度地带,长茅草和短花针茅为草原建群种或优势种,铁杆蒿和冷蒿为草原的重要建群成分和优势成分。观测地段各类生态系统的基本特征见表1。

1.2 小气候观测及资料处理

月亮山、鸭儿湾、团庄的小候观测观测为人工观测,采用梯度观测法,在典型季节春(2001年4月17~26日)、夏(2001年7月13~22日)、秋(2001年10月15~24日)、冬(2002年1月15~24日)分别进行为期10d的常规观测和晴天条件下的每小时1次的加密观测。分别在0.5、1.0、1.5m和2.0m高处设4层风、温、湿梯度观测。辐射观测仪器安装在1.5m高的铁架上,采用锦州三二二所生产的TBB-1型净辐射仪,观测误差≤5%。土壤温度设在0、5、10、15、20cm 5个深度。每个样地在地表下5cm处

分别埋设2个锦州三二二所生产的HF-1型土壤热流板观测土壤热通量，灵敏度为0.03～0.05mv.m²/W。温度表观测精度≤0.1℃。风速观测精度≤0.1m/s。

2002年7月以后，南华山稀树草地小气候观测采用中国华云公司组装的HY-1型农林小气候观测自动气象站，每小时记录1次数据。自动气象站的观测项目、观测时间、仪器架设高度与人工观测的相同。

为了准确分析宁南不同下垫面的湍流特征量，对资料进行了筛选。具体步骤如下：

(1)首先剔除可靠性差的资料，对原始数据剔除奇异点，采用内差补齐[2]。

(2)对因仪器故障短缺的个别资料用内差法计算得到[2]。

(3)通量计算过程中，相关参数如水的汽化潜热、湿球温度等随每个样地气压、温度、高度的变化而变化，因此，对这些气象要素进行了气压、温度、高程订正。

表1 不同生态类型的基本特征

Table 1 Basic characteristic in different ecological system

指标 Index	典型草地 Typical grassland (TG)	禁牧草地 Grazing-forbidden grassland (GFG)	稀树草地 Semiarid savanna (SS)	农田 Cropland (CL)
盖度(%)Cover	60	85	95	100
高度(cm)Height	5～15	10～25	30～50	0～65
丰富度(种/m²) Richness	12	18	21	5
地上部生物产量(kg/(hm²·a)) Grass or crop yield on the ground	4 500	5 250	7 500	—

2 方法

2.1 感热通量和潜热通量的计算

根据能量平衡原理，地表面热平衡方程[6]为：

$$B = H + LE - Q_s = -\rho C_p K_t \cdot \frac{\partial T}{\partial Z} - \rho L_v K_q \frac{\partial q}{\partial Z} - Q_s \tag{1}$$

式中，B为净辐射(W/m²)，H为感热通量(W/m²)，LE为潜热通量(W/m²)，K_t和K_q分别为热量交换系数和水汽交换系数(m²/s)，一般情况下，$K_t=K_q$[6,7]；q为比湿(g/g)，$q=0.622\frac{e}{P}$；L_v为水的汽化潜热(MJ/kg)，ρ为空气密度(kg/m³)；C_p为空气定压比热，本文取$C_p=1\ 005$ J/(kg·k)。Q_s为地表热通量(W/m²)。由于测点海拔较高，需要对P、L_v、ρ进行订正，根据联合国粮农组织给出的经验公式[7]有：

$$L_v = 2.501 - 2.361 \times 10^{-3} \times T_a \tag{2}$$

$$\rho = \frac{3.486\,P}{T_v},P = 101.3\left(\frac{293 - 0.006\,5\,z}{293}\right)^{5.26} \tag{3}$$

式中，T_a为空气温度；P为海拔为z(m)高度处的大气压(kPa)；T_v为虚温(K)，$T_v = T(1-0.378\frac{e_d}{P})^{-1}$，$T$为绝对温度(K)，$e_d$为实际水汽压(kPa)。

如果以差分代替微分，解出K，则有：

$$K = \frac{(B + Q_s)\cdot \Delta Z}{\rho C_p \Delta T + \rho L_v \Delta q} \tag{4}$$

将K代入(1)式有：

$$H = \frac{B + Q_s}{1 + \frac{L_v}{C_p}} \cdot \frac{\Delta q}{\Delta T} \quad LE = \frac{B + Q_s}{1 + \frac{C_p}{L_v}\cdot\frac{\Delta T}{\Delta q}} \tag{5}$$

式中，$\Delta Z = Z_2 - Z_1, \Delta T = T_2 - T_1, \Delta q = q_2 - q_1$。

2.2 其它相关计算

当土壤热通量板出现故障时，在土壤水分没有明显变化时，土壤热通量采用下式计算[8]

$$Q_s = \lambda_s \frac{\partial T}{\partial Z} \tag{6}$$

式中，λ_s为土壤导热率(w/m·℃)。

在南华山(稀树草地)无土壤热通量观测点，采取FAO提供的近似公式[7]计算： 白天 $Q_s=-0.1B$，夜间 $Q_s=-0.5B$。

3 结果与分析

3.1 不同季节晴天条件下净辐射和土壤热通量变化

不同季节的净辐射和土壤热通量有较规则的日变化。净辐射在白天(7:00～18:00)为正，在夜间为负值(图1)。净辐射峰值在夏季最大，可以达到700W/m²左右；春季次之，冬季最小，只有300 W/m²左右。土壤热通量比净辐射小一个量级，最大值在

100 W/m² 左右。这表明净辐射的 90％都用于感热和潜热消耗。春夏季节土壤热通量值明显大于秋冬季节(图 1)。

春季(图 1a)禁牧草地和典型草地的净辐射日循环规律基本相同，其净辐射峰值(509 W/m²)略小于稀树草地(589 W/m²)，这是因为稀树草地处于阴坡，春季无高大灌木、乔木树叶遮挡阳光，其地温低于典型草地，长波辐射量小，加上反射辐射量也小，造成净辐射量高于其它草地的事实。春季典型草地、禁牧草地、稀树草地净辐射日积分值分别为 8.9、7.3、10.0 MJ/(m²·d)。

春季不同下垫面土壤热通量变化规律也很一致。白天净辐射的部分热量用于加热土壤，通量峰值达 90 W/m² 左右。夜间土壤释放热量，其量值＜30 W/m²。

夏季不同下垫面的净辐射有明显的区别(图 1b)。典型草地和禁牧草地的净辐射日变化规律相似(注：13:00～14:00 禁牧草地有云影响)。典型草地的净辐射峰值达 700 W/m² 以上，大于荒漠戈壁的 400 W/m² 左右[9]。农田的则在 12:00 以后迅速增大，其净辐射量峰值与典型草地的相当。稀树草地因有树叶遮挡，净辐射明显小于其它下垫面的。典型草地、禁牧草地、稀树草地、农田的净辐射日积分值分别为 11.8、11.8、7.9 MJ/(m²·d)和 12.5 MJ/(m²·d)。典型草地和禁牧草地的土壤热通量日循环形态和量值基本相同。稀树草地夜间的土壤热通量小于典型草地，这与阴坡草地地温低有关。

秋季(图 1c)各类下垫面因植被覆盖度加大，其净辐射和土壤热通量变化表现相当一致，净辐射峰值以典型草地最大，为 526 W/m²。稀树草地的最小，为 341 W/m²。秋季典型草地、禁牧草地、稀树草地、农田的净辐射日积分值分别为 4.8、4.3、5.8 MJ/(m²·d)和 5.5 MJ/(m²·d)。土壤热通量则以稀树草地的最大，这与阴坡地表降温幅度大有关。

冬季(图 1d)净辐射峰值以禁牧草地的最高，为 305 W/m²；稀树草地的最低，为 195 W/m²。夜间净辐射以地表长波辐射为主，典型草地和稀树草地的净辐射稳定维持在－90～－50 W/m²，农田和禁牧草地的则没有明显的变化规律。典型草地、禁牧草地、稀树草地、农田的净辐射日积分值分别为－0.9、2.2、－1.3 MJ/(m²·d)和 1.5 MJ/(m²·d)。除(13:00～17:00)外的其它大部分时间里，土壤都在向上输送热量。

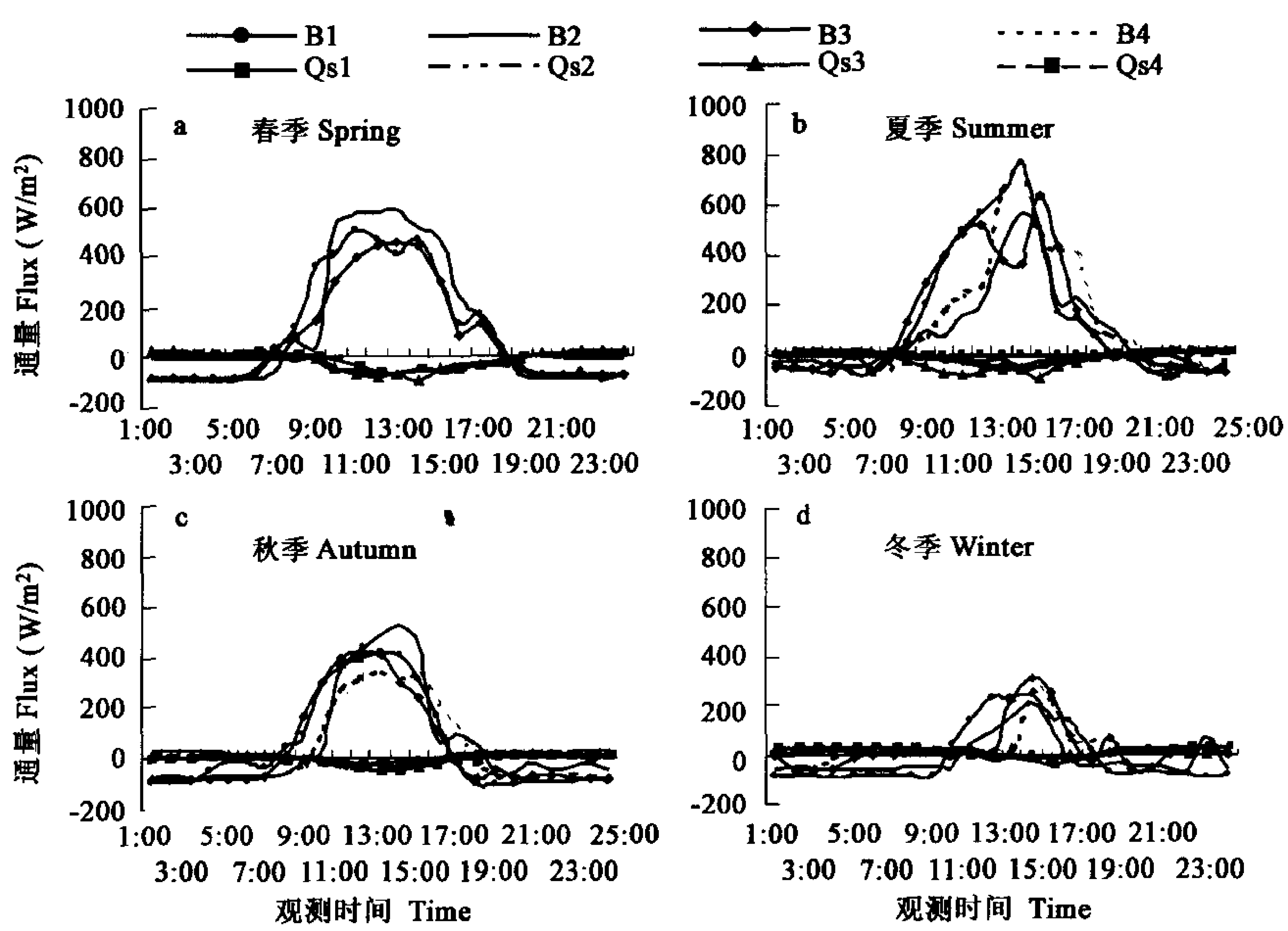

图 1　不同季节晴天条件下净辐射和土壤热通量变化

Fig. 1　Comparison of net radiation and soil heat fluxes on a clear day in different season

B1、B2、B3、B4、Qs1、Qs2、Qs3、Qs4　分别代表典型草地、稀树草地、禁牧草地、农田的净辐射和土壤热通量 Stands for net radiation and soil heat fluxes in typical grassland, semiarid savanna, grazing-forbidden grassland and cropland, respectively

3.2　不同季节晴天条件下感热通量的变化

在半干旱地区，感热输送有明显的日循环形态。春季(图 2a)地表热量平衡以感热输送为主，白天典型草地感热可占净辐射的 70％～95％，其次是禁牧草地的，稀树草地的所占比重最少，在 40％～60％。夏季白天典型草地以感热输送为主，占净辐射的 60％～80％，其它类型白天的大部分时间内感热输送＜50％(图 2b)。白天感热通量为正值，夜间为负值。这与几乎整天感热通量很小甚至为负值的湿润地区农田的特征[10,11]有很大不同，这种特征与其它干旱地区的类似[2,9]。

秋季(图 2c)白天感热输送从大到小依次为典型草地、禁牧草地、稀树草地、农田。典型草地输送峰值可达 381 W/m²，而农田的最小，为 128 W/m²。

冬季感热通量除典型草地有明显的日循环，其它类型下垫面感热变化规律不明显(图 2d)。

四季中，春夏季感热输送量最大，其通量峰值在 400 W/m^2 左右，秋季次之，在 381 W/m^2，冬天最小，为 208 W/m^2。典型草地春、夏、秋三季感热输送日积分值最大，稀树草地在春、夏季最小。春夏季 4 类下垫面感热输送日积分值为正值，气温有上升趋势；冬季 4 类下垫面感热输送日积分值为负值(见表 2)，气温总体有下降趋势。

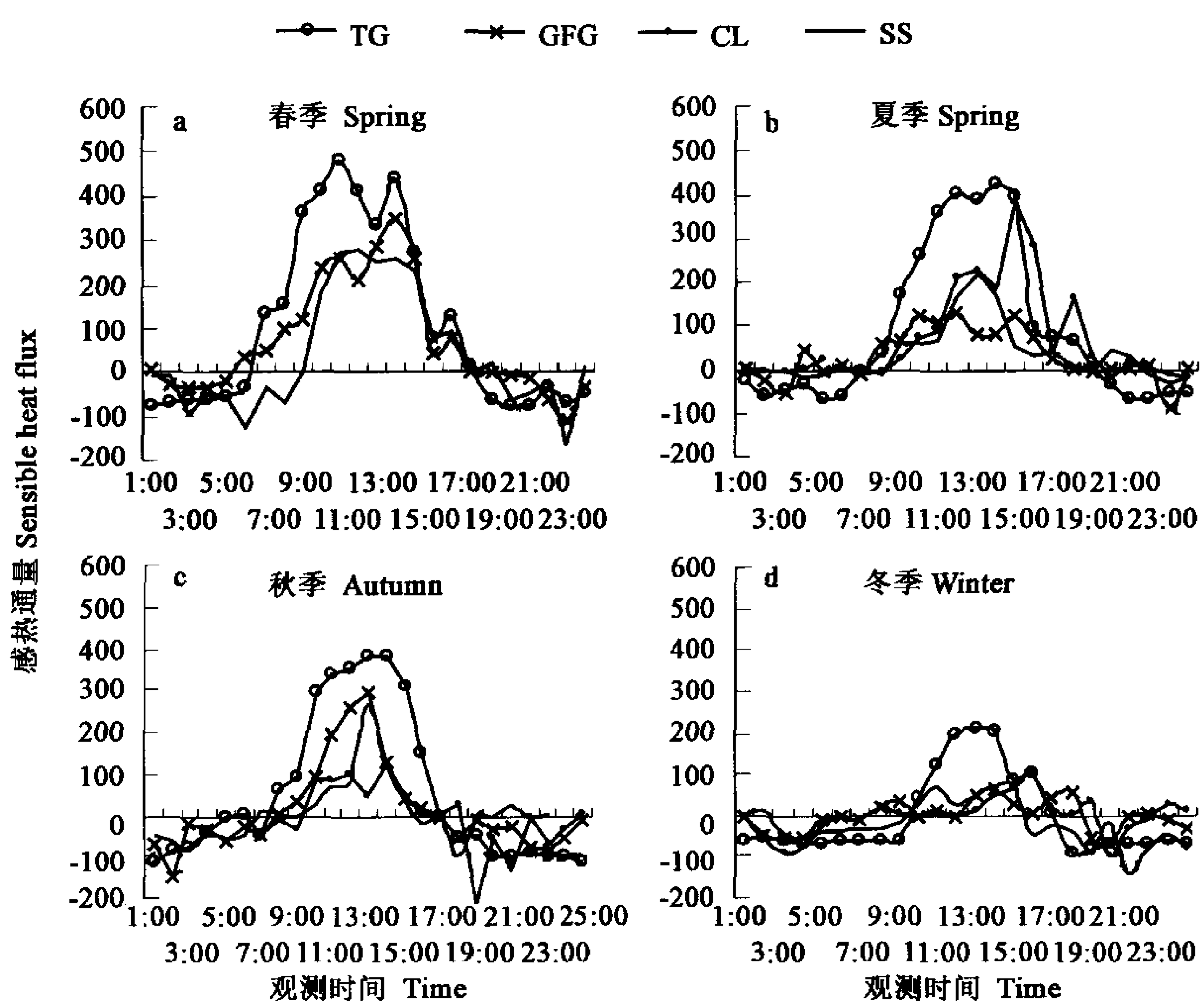

图 2 不同季节晴天条件下感热通量的变化

Fig. 2 Comparison of sensible heat flux on a clear day in different season

3.3 不同季节晴天条件下潜热通量的变化

春季白天，稀树草地获得的净辐射最多，用于潜热蒸发的水源充足，向上的潜热输送最大，其潜热输送峰值达 283 W/m^2(见图 3a)，并在整个白天稳定维持在高值，其潜热输送日积分值为 3.5 MJ/(m^2 · d)。白天 Bowen 比(β)在 0.6～1.2，说明稀树草地在春季有增加空气湿度的作用。禁牧草地在 9:00～12:00 也有少量向上的水汽输送，这时 β 在 1.6～5.8 之间。潜热输送峰值在 11:00，量值达 159 W/m^2。典型草地在白天只有微量水汽输送。3 类下垫面在夜间(18:00～7:00)都伴有少量的水汽凝结现象。典型草地和禁牧草地的潜热输送日积分值为负值，总体从空气中吸收水分。

夏季(图 3b)有明显的潜热通量日循环。白天农田向上输送的潜热通量最大，最大达 495 W/m^2。禁牧草地和稀树草地的潜热通量变化基本一致；典型草地的水汽输送峰值最小，为 176 W/m^2。在凌晨 5:00 和晚 21:00，农田、禁牧草地、稀树草地有水汽向下输送，并伴有水汽凝结。典型草地在夜间没有明显的水汽凝结现象。夏季白天农田 β 在 0.2～0.7，以农田的 β 值最小。这与刘树华[9]的计算结果基本一致。稀树草地 β 为 0.2～1.0，禁牧草地为 0.2～9.2，典型草地为 1.5～13.1。β 值远小于荒漠戈壁的 10～100[2,9]，大于农田和水分充分供应草地[10,12,13]的。夏季禁牧草地、稀树草地和农田的潜热输送日积分值比较接近，远大于典型草地的(见表 2)，这时的潜热通量值在四季中是最高的。

秋季(图 3c)白天农田的潜热输送峰值最高，量值已明显低于夏季，接近春季。其次是稀树草地的，典型草地的最低。夜间稀树草地在 1:00，5:00 有明显的水汽凝结发生。农田水汽凝结则发生在 19:00 左右。潜热输送日积分值农田最高，其次是禁牧草地的，稀树草地收支相当。典型草地略有水分散失(见表 2)。

冬季(图 3d)白天潜热输送强度更低，峰值稀树草地最大，为 133 W/m^2，其次为农田，禁牧草地也有小量水汽向上输送，典型草原几乎没有输送。稀树草地在 16:00 以后有水汽向下输送。稀树草地潜热输送日积分值为负，水汽来源是山体上层蒸发的水汽。农田有少量水汽损失，禁牧草地有微量水汽损失。典型草地则没有水分损失。

4 讨论与结论

能量平衡法计算各参量时，假设在某时刻比湿和温度梯度随高度变化为常数，没有平流热量和水汽输送。这就要求观测时没有大规模的平流输送。而且，能量平衡法在计算感热和潜热时，把热量平衡方程中热流板以上土层的热储存量和地表植被空

隙间的热量忽略不计，这就给计算值带来一定的误差。但因这种方法只需要观测两个高度的温、湿度，对下垫面的要求也不高，经费花费也比较少，比较适合复杂地形条件下的通量观测和分析。

表 2　不同下垫面四季 H 和 LE 的日积分值（MJ/(m²·d)）

Table 2　Daily integral values of H and LE in different underlying and season

下垫面类型 Underlying type	H 典型草地 Typical grassland	稀树草地 Grassland with parse trees	禁牧草地 Grassland forbidden to pasture	农田 Cropland	LE 典型草地 Typical grassland	稀树草地 Grassland with parse trees	禁牧草地 Grassland forbidden to pasture	农田 Cropland
春季 Spring	9.1	3.5	7.7	—	−0.7	3.5	−1.2	—
夏季 Summer	7.5	2.8	2.8	5.7	2.7	5.3	5.2	5.4
秋季 Autumn	4.7	0.6	1.1	−0.3	0.2	0.0	1.7	4.3
冬季 Winter	−0.4	−1.8	−0.1	−0.1	0.0	−0.6	0.5	1.3

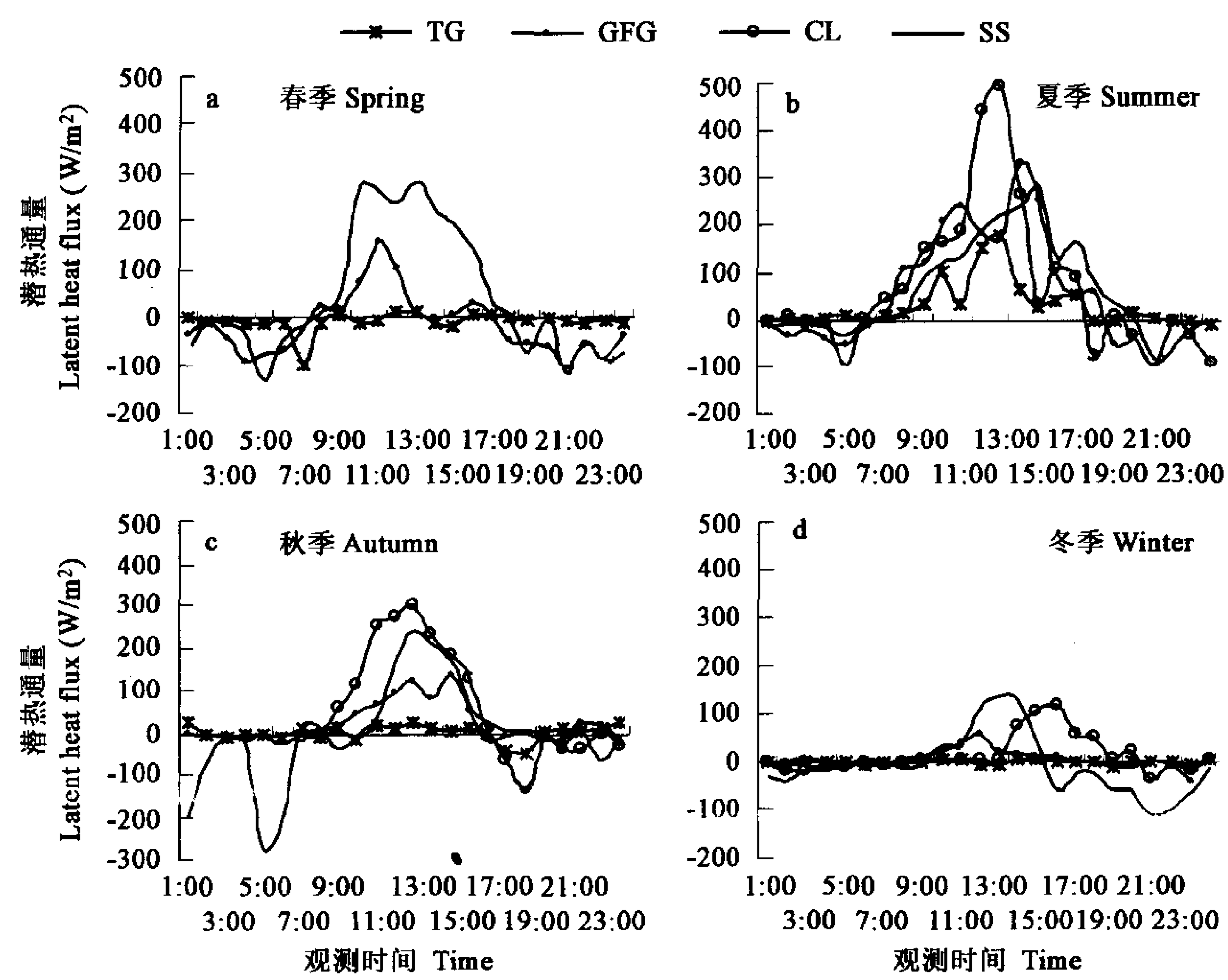

图 3　不同季节晴天条件下潜热通量的变化

Fig. 3　Comparison of latent heat flux on a clear day in different season

在能量平衡法中，引起感热和潜热通量相对误差的量有 β、Q_s 和 B 的观测精度，而 β 又依赖于 ΔT（干球温差）、ΔT_w（湿球温差）的观测精度，一般而言，β 的绝对值越小，观测精度越高。本文计算的 β 值绝大部分在 10 以内，夏季则在 2 以内。观测地段开阔，下垫面均匀，观测期间风速很少超过 1.0m/s，可以认为平流输送物质能量很少。Q_s 和 B 的观测精度可以保证，因此，计算结果的精度可以保证。从观测结果来看，能量平衡各分量不仅能反映周日循环规律，而且能反映季节变化和不同下垫面的能量、物质输送特点和差异。计算得到的潜热通量反映的地面水分凝结现象，与观测人员现场观测的现象很吻合。因此，能量平衡法观测复杂地形条件下的能量平衡是有效可行的。

宁南半干旱地区，因降水量少于 400mm。在生长季（春夏秋季）的白天，农田的潜热通量明显大于典型草地和禁牧草地的，其潜热通量的日积分值在全年都保持最大，并且为正值，这就是说农田的水分消耗量明显大于草地；而且农田在冬、春季（9 月～翌年 3 月）地表裸露，土壤易风蚀沙化，地表水分蒸发量也明显大于草地。从水分和水土保持的角度来看，农田不宜在这里发展。这里宜发展典型草原，通过封山禁牧，提高地表植被覆盖度。2002 年观测地段禁牧草地长势很好，天然降水完全能满足茂密草地的生长。稀树草地因植被生长茂盛，其蒸散量仅次于农田。而且稀树草地中灌木和乔木的水分消耗量远大于草地[14]，这对山地水分涵养不利，这类草地仅适合山地背阴坡水源充足的地段少量发展。

通过观测地段禁牧草地和典型草地植被覆盖度和地上部分草的生物产量的实际情况也可以看出，在没有干扰（放牧、耕种

农田)的情况下,禁牧草地的生物量、丰富度、盖度明显大于典型草地。因此,如果长期坚持封山禁牧、退耕还草,宁南山区的地表覆盖度会进一步增大,地表粗糙度随之增大,这有助于减小贴地层风速,减少贴地层向上的水汽输送量,这有利于土壤水分涵养,有利于草地生态环境的改善。

根据计算结果和以上分析,得出以下几点结论:

(1)宁南半干旱地区夏季净辐射峰值最大,冬季最小;夏季农田和草地的净辐射峰值可达到 700 W/m^2 以上,冬季只有 300 W/m^2 左右。土壤热通量的值比净辐射小 1 个量级,同类下垫面净辐射通量日积分值夏季>春季>秋季>冬季。

(2)四季中,春季感热通量峰值最大,冬季最小。4 类下垫面中,感热输送强度以典型草地的最大,其次是禁牧草地,稀树草地的最小。春夏季白天典型草地以感热输送为主,占净辐射的 60%~80%,稀树草地和农田白天的大部分时间内感热输送不到净辐射的一半。在春、夏、秋季的晴天,感热通量日积分值为正,冬季为负。

(3)四季中,潜热通量峰值夏季>秋季>春季>冬季。农田在夏、秋季、冬季水汽输送大于各类草地的,典型草地向上的水汽输送量是最小的,其次是禁牧草地的。夏季白天农田 β 在 0.2~0.7,稀树草地 β 为 0.2~1.0,能量输送以潜热为主;禁牧草地 β 为 0.2~9.2,典型草地 β 为 1.5~13.1,能量输送以感热为主。

(4)宁南半干旱地区宜退耕还草,发展典型草原,在水分充足的山地背阴坡可以少量发展稀树草地。

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