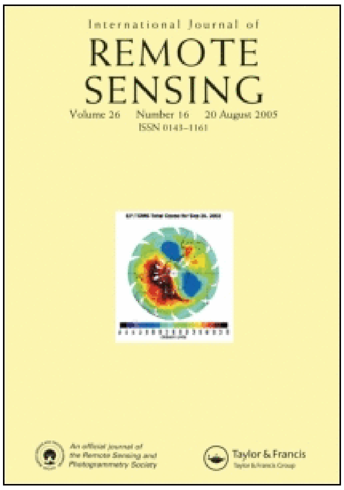

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713722504

Quantification of land-atmosphere exchanges of water, energy and carbon dioxide in space and time over the heterogeneous Barrax site

Z. Su [a]; W. Timmermans [a]; A. Gieske [a]; L. Jia [b]; J. A. Elbers [b]; A. Olioso [c]; J. Timmermans [a]; R. Van Der Velde [a]; X. Jin [d]; H. Van Der Kwast [e]; F. Nerry [f]; D. Sabol [g]; J. A. Sobrino [h]; J. Moreno [h]; R. Bianchi [i]
[a] International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, the Netherlands [b] Alterra, Wageningen University and Research Centre, Wageningen, the Netherlands [c] INRA, Avignon, France [d] China University of Geosciences, Beijing, China [e] University of Utrecht, Utrecht, the Netherlands [f] TRIO/ULP, Strasbourg, France [g] University of Washington, Seattle, WA [h] University of Valencia, Valencia, Spain [i] Mission Experts Division, EO Science and Applications Department, ESA/ESRIN, Frascati, Rome, Italy

Online Publication Date: 01 January 2008

To cite this Article Su, Z., Timmermans, W., Gieske, A., Jia, L., Elbers, J. A., Olioso, A., Timmermans, J., Van Der Velde, R., Jin, X., Van Der Kwast, H., Nerry, F., Sabol, D., Sobrino, J. A., Moreno, J. and Bianchi, R.(2008)'Quantification of land-atmosphere exchanges of water, energy and carbon dioxide in space and time over the heterogeneous Barrax site',International Journal of Remote Sensing,29:17,5215 — 5235

To link to this Article: DOI: 10.1080/01431160802326099

URL: http://dx.doi.org/10.1080/01431160802326099

International Journal of Remote Sensing
Vol. 29, Nos. 17–18, September 2008, 5215–5235

Taylor & Francis
Taylor & Francis Group

Quantification of land–atmosphere exchanges of water, energy and carbon dioxide in space and time over the heterogeneous Barrax site

Z. SU*†, W. TIMMERMANS†, A. GIESKE†, L. JIA‡, J. A. ELBERS‡, A. OLIOSO§, J. TIMMERMANS†, R. VAN DER VELDE†, X. JIN¶, H. VAN DER KWAST**, F. NERRY††, D. SABOL‡‡, J. A. SOBRINO§§, J. MORENO§§ and R. BIANCHI¶¶

†International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, the Netherlands
‡Alterra, Wageningen University and Research Centre, Wageningen, the Netherlands
§INRA, Avignon, France
¶China University of Geosciences, Beijing, China
**University of Utrecht, Utrecht, the Netherlands
††TRIO/ULP, Strasbourg, France
‡‡University of Washington, Seattle, WA, USA
§§University of Valencia, Valencia, Spain
¶¶Mission Experts Division, EO Science and Applications Department, ESA/ESRIN, Frascati, Rome, Italy

(*Received 21 December 2006; in final form 5 July 2008*)

To advance our understanding of land–atmosphere exchanges of water, energy and carbon dioxide (CO_2) in space and time over heterogeneous land surfaces, two intensive field campaigns were carried out at the Barrax agricultural test site in Spain during 12–21 July 2004 (SPARC 2004) and 8–14 July 2005 (SEN2FLEX 2005) involving multiple field, satellite and airborne instruments for characterizing the state of the atmosphere, the vegetation and the soil from the visible to the microwave range of the spectrum. Part of the experimental area is a core site of area 25 km^2, within which numerous crops are grown, on both irrigated and dry land, alongside fields of bare soil. The campaigns were carried out in the framework of the Earth Observation Envelope Programme of the European Space Agency (ESA) with the aim of supporting geophysical algorithm development, calibration/validation and the simulation of future spaceborne Earth Observation missions. Both campaigns were also contributions to the EU 6FP EAGLE Project. The emphasis of this contribution is on the *in situ* measurements of land–atmosphere exchanges of water, energy and CO_2 as well as the thermal dynamic states of the atmosphere, the soil and the vegetation. Preliminary analysis and interpretation of the measurements are presented. These two data sets are open to the scientific community for collaborative investigations.

1. Introduction

As turbulent fluxes (water vapour, heat and CO_2) occur from scales of an air molecule to terrain characterized by synoptic circulation and are influenced by both internal biophysical characteristics of the soil and vegetation and external forcings (e.g. solar radiation and wind), the measurements of these fluxes are most

*Corresponding author. Email: b_su@itc.nl

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2008 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160802326099

challenging over heterogeneous terrains. In addition to the organized patterns and circulations of turbulent fluxes due to land uses and dominated by radiative forcing, the terrain heterogeneity also causes secondary effects either in terms of surface geometrical conditions (roughness) or thermal dynamic conditions (dryness or wetness), which may cause local circulation of turbulent fluxes. The latter are much more difficult to observe and characterize. A large number of ground-based instruments are therefore necessary for a complete observation and understanding of the turbulent fluxes in space and time. For this purpose several mobile instrument towers, including four eddy correlation devices and two scintillometers, were deployed in the field to monitor the individual components of the energy, water and CO_2 flux exchanged over different surfaces at the Barrax site in Spain. When these measurements are combined with airborne and satellite data, such as the new Airborne Hyperspectral System (AHS), operated by Spain's Instituto Nacional de Técnica Aeroespacial (INTA), CHRIS data, ENVISAT Medium Resolution Imaging Spectrometer (MERIS) and Advanced Along Track Scanning Radiometer (AATSR) data, data from the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) instrument onboard the Meteosat Second Generation (MSG)-1 satellite, as well as Landsat data, the Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data, detailed quantification of the characteristics of turbulent fluxes over different surfaces at different scales becomes feasible and the scaling from one scale to another becomes important. The availability of such detailed data sets provides unprecedented opportunity for studying of the scaling behavior of the land–atmosphere exchanges of water and energy and CO_2. These measurements were carried out in two intensive field campaigns at the Barrax agricultural test site in Spain during 12–21 July 2004 (SPARC 2004) and 8–14 July 2005 (SEN2FLEX) within the framework of the Earth Observation Envelope Programme of the European Space Agency (ESA), which carries out a number of ground-based and airborne campaigns to support geophysical algorithm development, calibration/validation and the simulation of future spaceborne Earth Observation missions.

1.1 *The study area*

The study area is the well-known Barrax test site, situated at a plateau 700 m above sea level within the La Mancha region, in the south of Spain. The test site is located in the west of the Albacete province, 20 km away from the capital town Albacete. The area is characterized by a flat morphology and large, uniform land use units and consists of approximately 65% dry land and 35% irrigated land with different agricultural crops and fruits. The climatic conditions are Mediterranean with precipitations in spring and autumn but little in summer. With an annual rainfall average of about 400 mm, La Mancha is one of the driest regions of Europe. The regional groundwater table is about 20–30 m below the land surface. The test area has the coordinates (UTM Zone 30, DATUM WGS84): Corner 1: 575505.9523E 4323210.7146N, Corner 2: 585226.6519E 4325555.7469N, Corner 3: 575039.5028E 4325144.3194N, Corner 4: 584760.2034E 4327489.3472N.

1.2 *The SPARC 2004 Campaign*

The SPECTRA Barrax Campaign (SPARC 2004) was conducted with the aim of advancing our understanding of land–atmosphere exchanges of water and energy in space and time over heterogeneous land surfaces. It was carried out at the Barrax agricultural test site involving multiple field, satellite and airborne instruments for characterizing the state of the atmosphere, the vegetation and the soil from the visible to the microwave range of the spectrum. Part of the experimental area is a core site of area 25 km^2, within which numerous crops are grown, on both irrigated and dry land, alongside fields of bare soil. This campaign formed part of the preparatory study for a proposed ESA Earth Explorer mission called SPECTRA (Surface Processes and Ecosystem Changes Through Response Analysis) of the ESA, and was named SPARC in combination with the EU 6FP EAGLE Project. More details about SPARC 2004 can be found in the experimental handbook (University of Valencia 2004; www.uv.es/leo/sparc2004/).

1.3 *The SEN2FLEX 2005 campaign*

The SENtinel-2 and FLuorescence EXperiment (SEN2FLEX) is a campaign that combines different activities in support of initiatives related both to fluorescence experiments (AIRFLEX) for observation of solar-induced fluorescence signals over multiple surface targets and to the GMES (Global Monitoring for Environment and Security) Sentinel-2 initiative for prototyping of spectral bands, spectral widths and spatial/temporal resolutions to meet mission requirements. Both initiatives require simultaneous airborne hyperspectral and ground measurements for interpretation of fluorescence signal levels (AIRFLEX), and simulation of an optical observing system capable of assessing geo- and biophysical variables and classifying target surfaces by spectral, spatial and temporal signatures (Sentinel-2). The SEN2FLEX campaign also includes activities in support of the EC Water Framework Directive (WFD) EO projects for the improvement of protection and management of Europe's water resources. More details about the SEN2FLEX can be found in the experimental handbook (University of Valencia 2005; www.uv.es/leo/sen2flex/).

This contribution focuses on the *in situ* measurements with the general aim of providing a thorough description of the details of the *in situ* data related to radiation, CO_2 and H_2O fluxes and surface thermal dynamic properties, while issues relating to data processing and analysis of satellite data are dealt with by contributions in Sobrino (2007).

2. *In situ* observation of land–atmosphere exchanges during SPARC 2004

The *in situ* data relevant to land–atmosphere exchanges (fluxes and state variables) included the following measurements:

(1) Radiation balance and sensible heat fluxes from scintillometer systems
(2) Turbulence, CO_2, H_2O fluxes and CO_2 concentration from eddy correlation systems
(3) Soil heat flux, soil temperatures, air temperature and humidity and leaf temperatures
(4) Radiometric surface temperature measurements
(5) Photosynthesis, conductance and transpiration measurements at leaf level.

The locations of the measurements are indicated in figure 1, with instruments, period of measurements and surface characteristics given in tables 1–3. In the following sections, the measurements taken in the vineyard are described in detail according to relevant scales. Other relevant issues are described in Gieske *et al.* (2005b), Su *et al.* (2005) and Timmermans *et al.* (2005, 2008a,b).

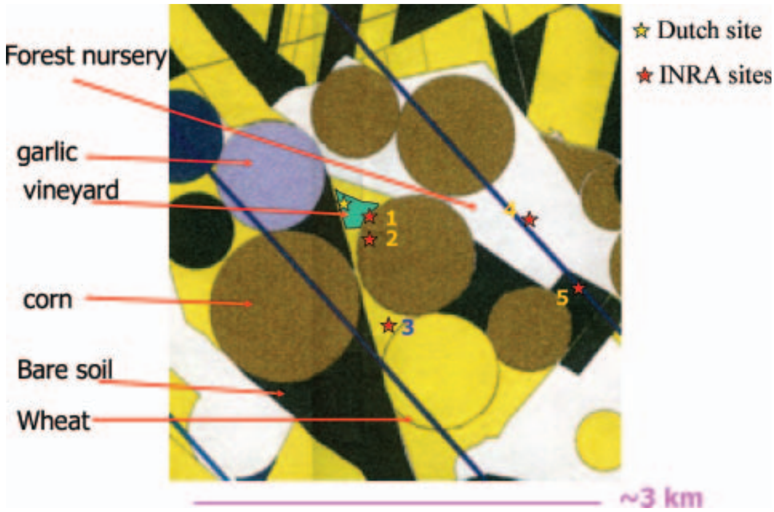

Figure 1. Locations of flux measurements in SPARC 2004. The base station of the scintillometer and the eddy correlation station were located in the vineyard during the complete campaign period. Other stations were installed for a limited period at different locations.

2.1 *Radiation balance and sensible heat fluxes from the scintillometer systems*

The radiation balance was measured at the scintillometer receiver at the base station in the vineyard for DOY 196–202 (14–20 July 2004). Measurements made at 1-min intervals included shortwave incoming and outgoing radiation, longwave incoming and outgoing radiation (all at a height of 4.80 m), soil heat flux (0.5 cm below the surface, at three locations in the middle of the vine row and below the vine), soil temperature at four depths (10.5, 16.5, 21.0 and 28.0 cm below the surface), relative humidity and air temperature at two levels (2.50 and 4.78 m), wind speed at two levels (2.60 and 4.88 m), wind direction at 4.88 m, and the large-aperture scintillometer (H-LAS) at 5.06 m. Figure 2 shows the radiation components, which were similar for all days of the observation period. Figure 3 shows the energy

Table 1. Location of turbulent fluxes and energy balance measurements in SPARC 2004.

Field (field code)	Code	Device height (m)	Period (DOY)	GPS position
Vineyard (V)	Dutch	3.4	195–203	39°03′37″ N, 02°06′09″ W
Corn–vineyard (C2)	1	4.4	197–202	30 S 0577843 UTM 4323710
Corn (C2)	2	2.94	197–202	30 S 0577804 UTM 4323457
Stubble (CW1)	3	–	196–202	30 S 0577968 UTM 4323029
Forest nursery (F)	4	1.65	199–201	30 S 0578826 UTM 4323757 altitude 701 m
Bare soil (BS1)	5	1.10	201–202	30 S 0579263 UTM 4323247

Code refers to the location shown in figure 1.

Table 2. Locations of scintillometers and energy balance measurements in SPARC 2004.

Field (field code)	Device height (m)	Period (DOY)	GPS position
Vineyard (V, base R)	5.06	196–202	39°03′38″ N, 02°06′10″ W
Stubble (CW1, base T)	4.64		39°03′14″ N, 02°05′60″ W
Corn (C2, R)	2.965	198–199	39°03′25″ N, 02°06′04″ W
Corn (C2, T)	2.965		39°03′38″ N, 02°05′54″ W
Forest nursery (F, R)	2.265	199–200	39°03′30″ N, 02°05′20″ W
Forest nursery (F, T)	2.265		39°03′44″ N, 02°05′16″ W
Sunflower (SF1, R)	2.265	200–201	39°04′35″ N, 02°07′06″ W
Sunflower (SF1, T)	2.265		39°04′54″ N, 02°07′13″ W
Bare soil (BS1, R)	2.215	201–202	39°03′21″ N, 02°05′06″ W
Bare soil (BS1, T)	2.215		39°03′10″ N, 02°05′00″ W

The code refers to the land use map; T, transmitter; R, Receiver.

balance terms as estimated at the H-LAS receiver site. The sensible heat fluxes (H) measured with the mobile H-LAS are shown in figure 4 together with that measured at the base station. The forest nursery field shows the highest value of H and also the highest variability in H.

2.2 *Turbulent sensible heat flux, water vapour flux and CO_2 flux in the vineyard from the eddy correlation systems*

The turbulent sensible heat flux (H), water vapour flux (H_2O), CO_2 flux and CO_2 concentrations were measured for DOY 195–203 (13–21 July 2004) with an eddy correlation system (Gill 3D sonic + closed path Licor gas analyser: CO_2 and H_2O + nitrogen reference gas + pneumatic mast + data loggers). The measurement frequency was 20 Hz and the signal was averaged to 10, 30 and 60 min for further analysis (figure 5(*a*)). The most striking feature when comparing the results of the three averages is that temporal averaging smoothes significantly the peak fluxes (e.g. the latent heat flux was reduced from 500 W/m^2 to approximately 400 W/m^2), which poses a serious challenge when fluxes from different measurement and estimation

Table 3. Surface and vegetation characteristics in SPARC 2004.

Field (field code)	Other characteristics
Vineyard (V)	Row distance 3.35 m Plant distance 1.5 m Plant height 1.5 m LAI = 0.52 Vine coverage 33%
Corn (C2)	Plant height 2.0 m (16 July 2004), 2.2 m (19 July 2004) LAI = 1.22 Corn coverage ~69%
Stubble (CW1)	–
Forest nursery (F)	Dry plants 20–40 cm height Plastic nets 35 cm height around young trees, spaced 3 m apart in the row and 4 m between rows Dry plants ~50%
Bare soil (BS1)	–
Sunflower (SF1)	–

LAI, Leaf Area Index.

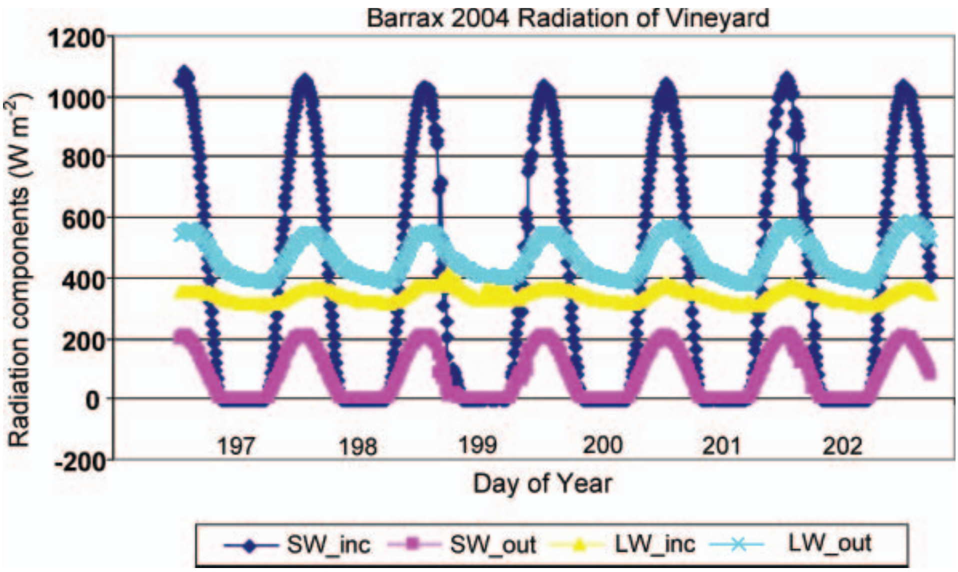

Figure 2. Radiation components in the vineyard in SPARC 2004. SW_inc, incoming shortwave radiation; SW_out, reflected shortwave radiation; LW_int, incoming longwave radiation; LW_out, outgoing longwave radiation.

methods are compared to each other (University of Valencia 2004). The diurnal change in the evaporative fraction was clearly observed (figure 5(*b*)). In estimation of daily evaporation, the evaporative fraction is often assumed as constant during the day in some algorithms but clearly needs a correction to convert it to a daily average value as suggested by Chehbouni *et al.* (2007). While the sensible heat flux, H, remained approximately constant over the whole observation period, the latent heat flux, LE, decreased gradually with the changing of the local meteorological conditions (i.e. changes in wind direction, see figure 6). The influence of the drying

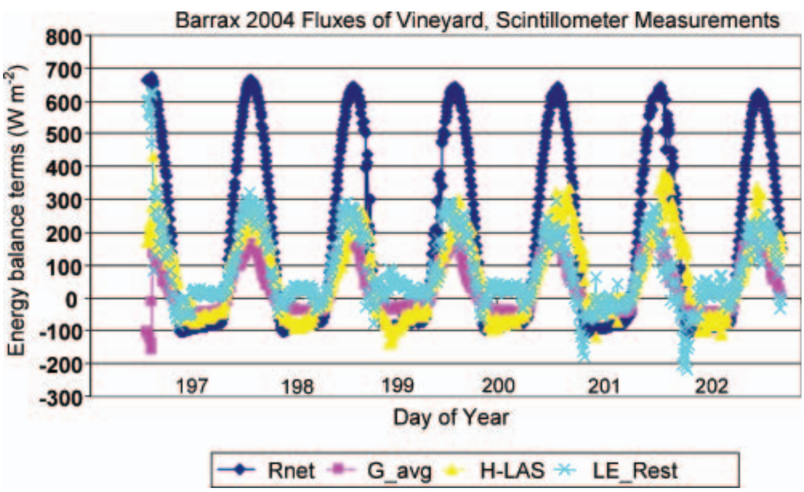

Figure 3. Energy balance components in the vineyard in SPARC 2004. Rnet, net radiation; G_avg, average soil heat flux; H_LAS, sensible heat flux; LE_Rest, latent heat flux estimated as residual of the energy balance.

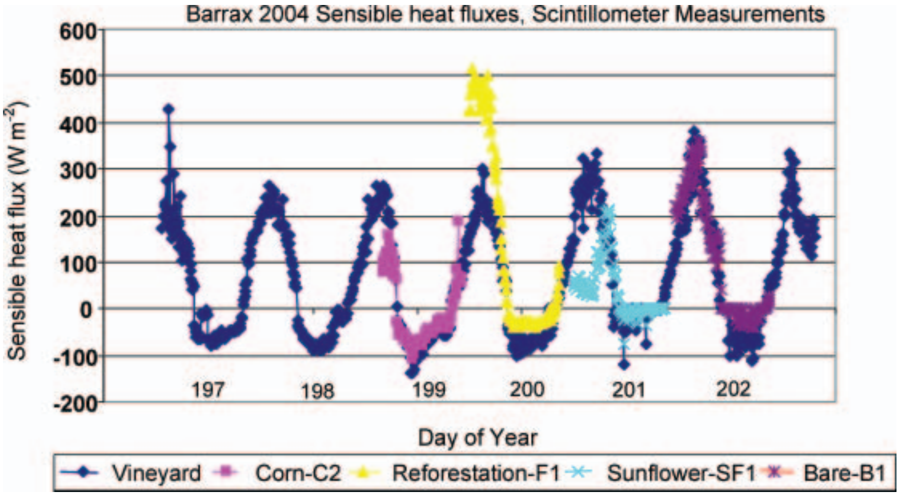

Figure 4. Sensible heat flux in SPARC 2004 (measurements made with scintillometers over different fields. See tables 1 and 2 for field code).

processes in the vineyard was probably not the cause because the vineyard was drip irrigated and the humidity of the surface air increased from the beginning to the end of the measurement period (see later discussions on humidity profile).

Figure 6 shows the observed H for DOY 198–202. On DOY 202, the wind direction changed from predominantly east and southeast (coming from the corn field) to west and northwest (from the vineyard). While H values in the previous day were from negative to slightly above zero, H values for the last day were at or above 200 W/m^2.

2.3 *Soil heat flux, soil temperature, air temperature and humidity and leaf temperature at the eddy correlation location*

The soil heat fluxes at the eddy correlation location were measured with four soil heat flux plates buried at a depth of 1 cm below the surface, with two placed in the middle of the row and two under the vine (shaded). Figure 7 shows the dynamics and variability of the measured fluxes. The soil temperatures were measured with thermal couples at two levels (figure 8), air temperature and humidity measured at three levels (figure 9) and leaf temperatures (thermal couples) (figure 10). All these measurements were recorded at 10-min intervals during DOY 195–203 (13–21 July 2004).

From figure 7, it can be observed that the variability in soil heat flux is very large (e.g. from 50 to 200 W/m^2) even within a short distance, primarily because of the variations in radiation and soil moisture states. The same physical factors also influence the soil temperature, as shown in figure 8, in addition to the variations caused by the depth of the sensor's positions.

The humidity information shown by the wetbulb and drybulb temperatures (figure 9) indicated that from the height of 0.65 m (approximately the vertical centre of the crown layer, which may also be considered as the averaged source of the transpiration) to just above the top of the canopy at 1.65 m and to about twice the canopy height at 3 m, the humidity reduces gradually, indicating the primarily vertical water vapour diffusion from the crown layer into the dry air above the field.

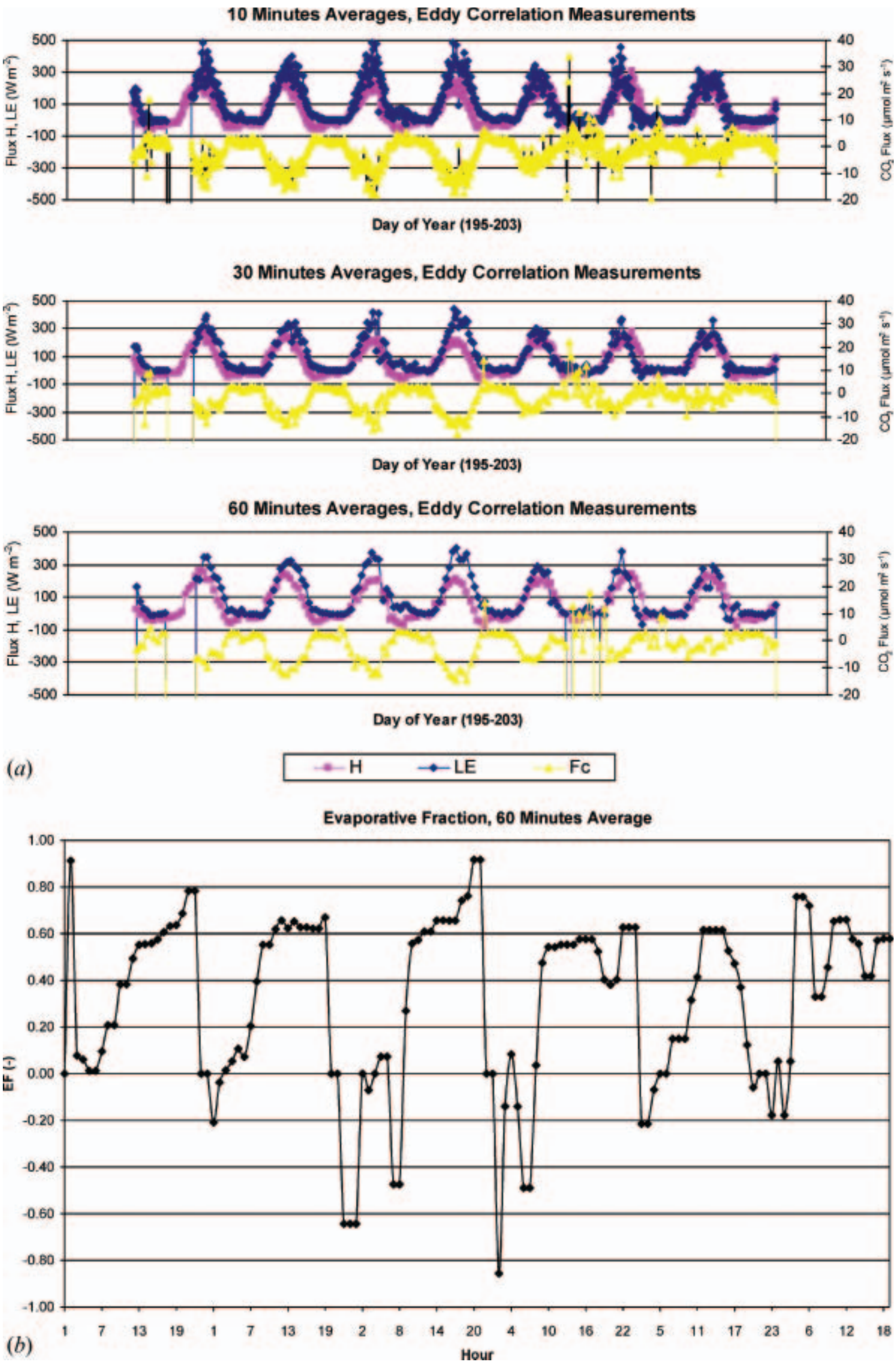

Figure 5. (*a*) Time-averaged sensible heat flux (H), H_2O (LE) and CO_2 (Fc) fluxes and (*b*) time-averaged evaporative fraction (EF) measured with the eddy correlation station in SPARC 2004.

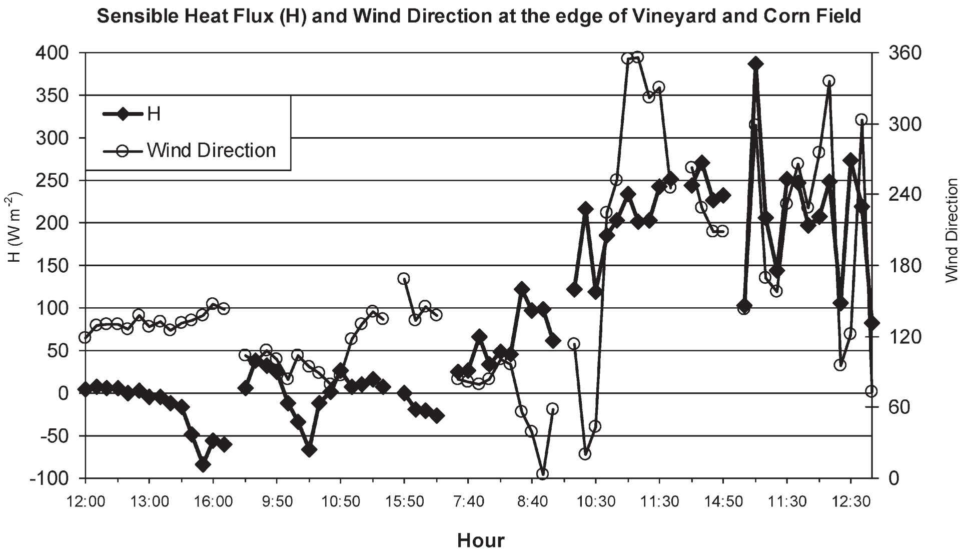

Figure 6. Time-averaged sensible heat flux measured with a 3D sonic anemometer at the corn–vineyard edge in SPARC 2004 (code 1 in figure 1 and table 1; north is set at 0°).

The measured leaf temperatures indicated that the differences in leaf temperatures in the sunlit leaves and shaded leaves reached 8°C, while it has been often suggested in the literature that leaf temperatures could be treated as equal. Similarly, the difference between the air temperature and the leaf temperatures could vary from 1°C in the earlier morning when the air temperature is the lowest up to 11°C in the afternoon (6°C for sunlit leaves).

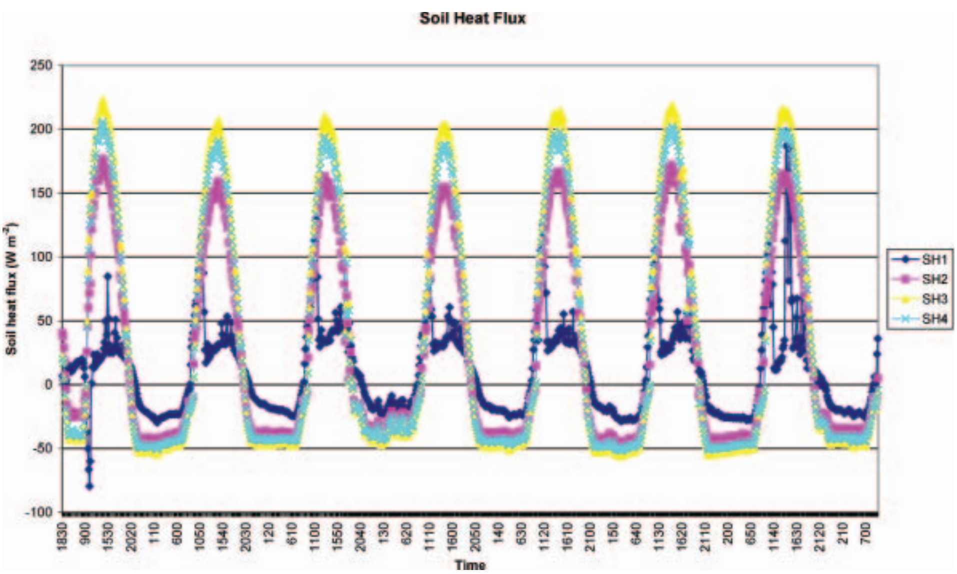

Figure 7. Soil heat fluxes in SPARC 2004. Soil heat flux plates SH1 and SH4 were in the shade; SH2 and SH3 were in the sunlit areas.

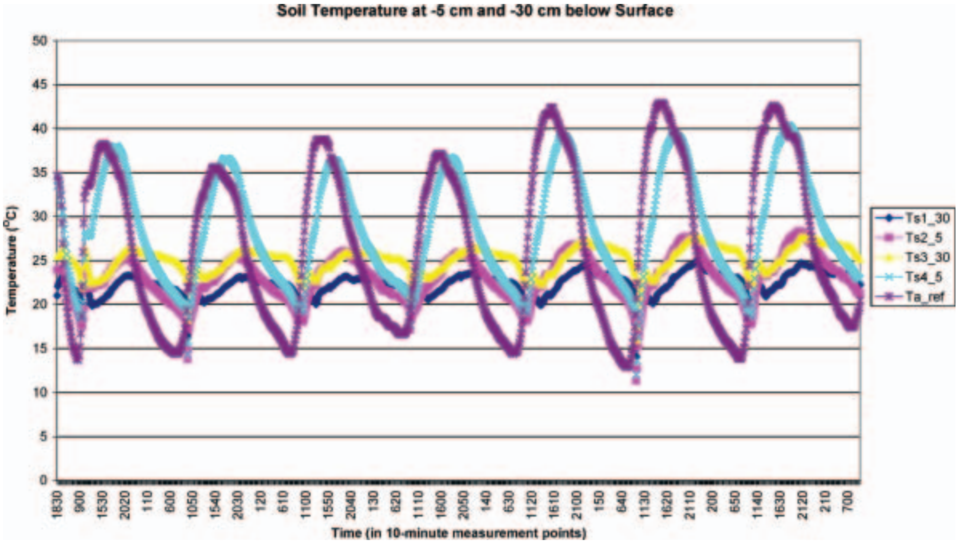

Figure 8. Soil temperatures measured with thermal couples at two levels in SPARC 2004. Ts1_30, Ts2_5, Ts3_30 and Ts4_5 are 30, 5, 30 and 5 cm below the surface, respectively; Ts1_30 and Ts2_5 are under the vine, while Ts3_30 and Ts4_5 are in the middle of the row; Ta_ref is the reference air temperature measured at the eddy correlation station as shown in figure 5.

2.4 *Radiometric surface temperature measurements*

In addition to the leaf temperatures measured with thermal couples, component radiometric temperatures were measured with a Rytek portable radiometer. The

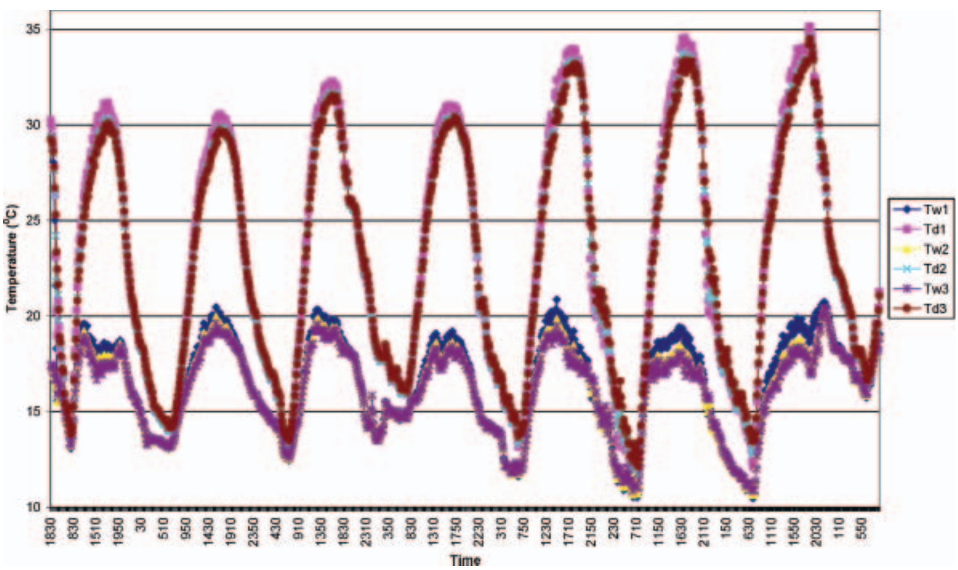

Figure 9. Air temperature and humidity measured at three levels. Tw is the wetbulb and Td the drybulb temperature; Tw1 and Td1 were set at a height of 0.65 m, Tw2 and Td2 at 1.65 m, and Tw3 and Td3 at 3.0 m.

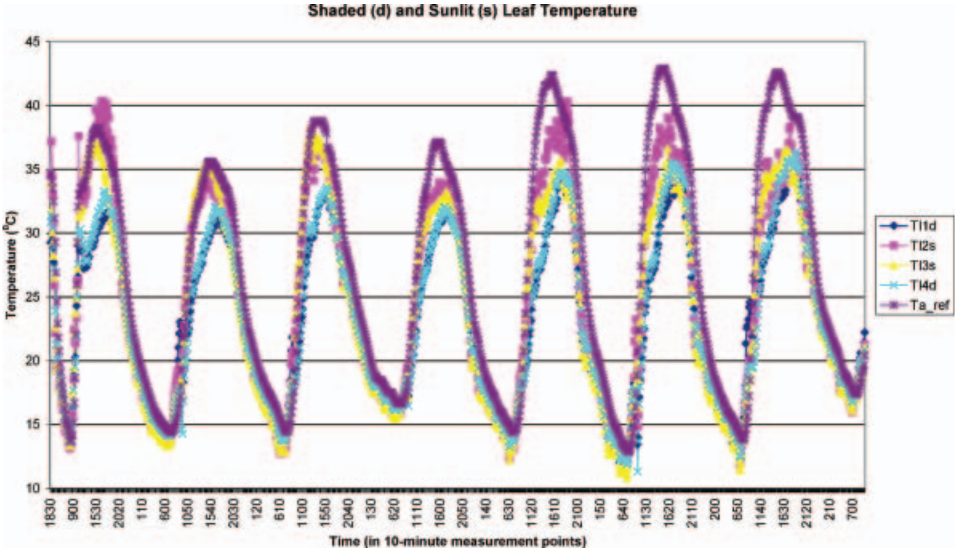

Figure 10. Leaf temperatures measured with thermal couples attached to the back of leaves in SPARC 2004. Tl1d and Tl4d were for shaded leaves, Tl2s and Tl3s were for sunlit leaves, Ta_ref is also shown as a reference.

differences among the shaded leaves, shaded soil, sunlit leaves and sunlit soil (in general order of increasing radiometric temperature) can be clearly distinguished (a range of 30°C on DOY 200). This indicates that in any modelling or validation studies, care must be taken in the interpretation of the variability in temperature measurements when only limited small-scale measurements are available. It is all too easy to reach false conclusions if the thermal dynamic state of the surface is not well quantified. Figure 11 shows explicitly the differences between sunlit and shaded radiometric temperatures measured with a fixed setup and recorded at an interval of

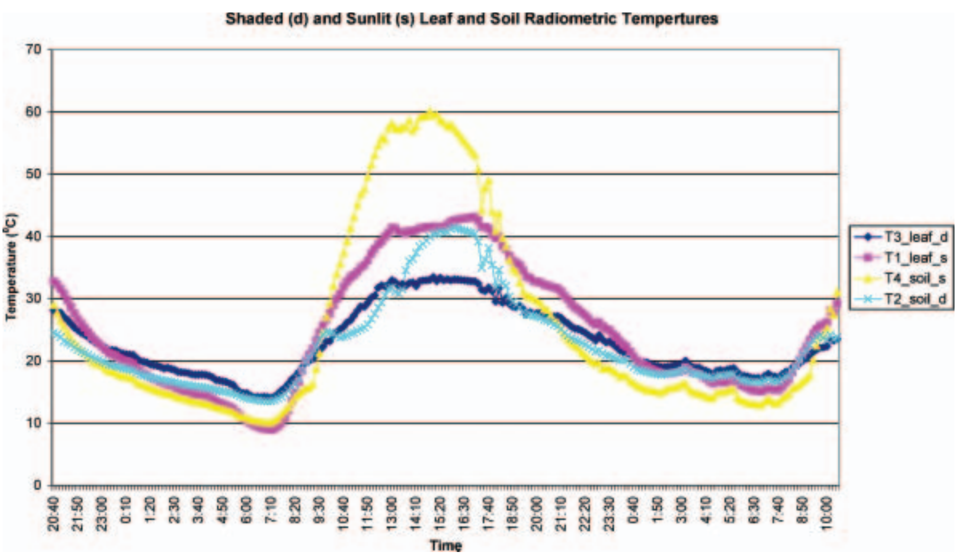

Figure 11. Component radiometric temperature for leaves and soil in SPARC 2004.

10 min. The maximum difference between sunlit and shaded leaf temperatures reached 10°C in the later afternoon (an intriguing finding), while the difference between sunlit and shaded soil temperatures reached 26°C at noon. Figure 11 also shows a clear phase shift of approximately 1 h in the surface radiometric temperature of the soil, while such is not observed in leaves. The most plausible cause of such a phase shift is that the shaded soil (as opposed to sunlit soil) is mainly heated up by multiply reflected solar radiation, thermal radiation and sensible heat flux exchanged with the in-canopy air, and the combination of these effects is slower than direct solar heating of the sunlit soil. Another factor of importance is the solar radiation transmitted through the canopy layer reaching the shaded soil.

Measurement further indicates that while the shaded leave temperatures agree with each other within 2°C when measured with a radiometer and a thermal couple, the sunlit leave temperatures can reach a difference of 10°C in the afternoon due to differential heatings when the solar position changes.

Figure 12 shows a thermal image taken with an FLIR thermal camera with an observed radiometric temperature range of 35°C from 21.67°C to 56.67°C. Clearly, the component temperatures observed in previous figures can also be separated easily (observation with high resolution and not in the hotspot position). The lowest temperature observed is on the wet soil under the vine due to drip irrigation.

2.5 *Leaf level photosynthesis, conductance and transpiration measurements*

Leaf level photosynthesis, conductance and transpiration measurements were taken during 17–19 July 2004 using a handheld CIRAS instrument from PP systems. Attempts were made to cover the complete 3 days from dawn to dusk with a measurement interval of 1 h; however, reliable data from the first day were only available from 1000 h due to battery failures. Measurements were made from two

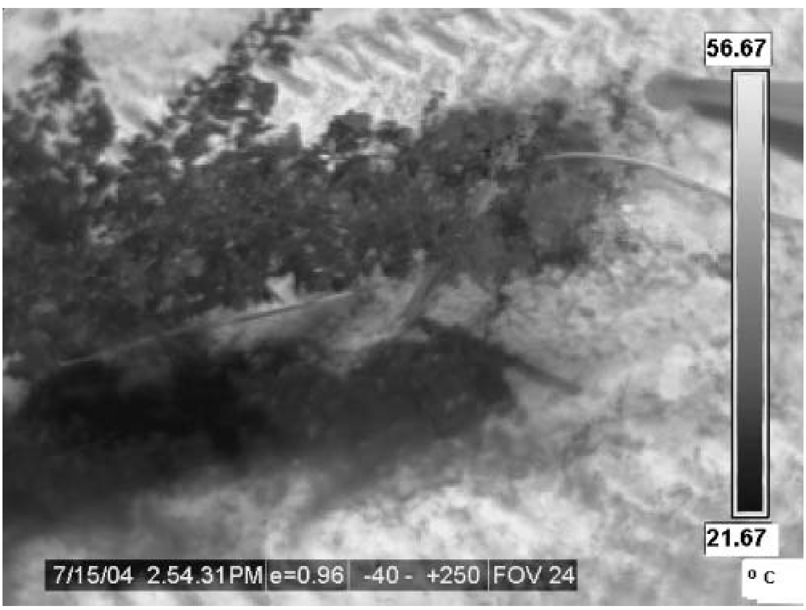

Figure 12. Radiometric temperature of the vineyard measured with an FLIR thermal camera in SPARC 2004. The spatial dimension of the image is approximately 8 m × 6 m.

vine plants by selecting healthy young and old leaves at different height positions of the canopy and including both sunlit and shaded leaves resulting in a total of 725 usable measurements. The leaf internal CO_2 concentration ranged from 200 to 500 ppm, which was very different from those values often assumed in photosynthesis models, especially those for dynamic vegetation simulation. Although the transpiration, leaf temperature and assimilation show a positive correlation, detailed analysis is necessary to quantify the details and is presented in the following sections.

The relationship between assimilation and photosynthetic active radiation (PAR) is positive. Although the coefficient of determination is 0.76, indicating a high correlation, the scatter is fairly large, especially at large PAR values (e.g. above 1000 mmol $m^{-2} s^{-1}$, the scatter covers almost the whole range of the observed assimilation). This reveals the limitations in photosynthesis models based on only PAR and empirical relationships.

In figure 13 the relationship between assimilation and leaf conductance is examined. Although in state-of-the-art photosynthesis models the relationship between photosynthesis and leaf conductance is explicitly formulated and interactively solved, our measurements have shown that such a relationship is most likely to be valid only for sunlit leaves as there is almost no assimilation in the shaded leaves even though the leaf conductance is non-zero.

The relationship between assimilation and leaf transpiration is shown in figure 14, which is broadly similar to that shown in figure 13. If sunlit and shaded leaves are not separated in the analysis, the resulting coefficient of determination is very low, indicating the general failure of the regression type of model in estimation of assimilation on the basis of transpiration and vice versa. It is also interesting to note that in the shaded leaves there is transpiration taking place while the assimilation is zero. A possible explanation of this phenomenon is that the leaves need to remain at some biologically tolerable temperature range (the measured maximum was 37.2°C on 19 July 2004 with CIRAS and 40.38°C on 14 July 2004 and 40.34°C on 18 July 2004 with thermal couples as shown in figure 10; the minimum leaf temperature measured was 12.1°C at 0728 h on 19 July 2004 with CIRAS and 10.71°C at 0710 h on 19 July 2004 with thermal couples). Under such conditions, although the assimilation is zero because the leaves are in the shade, the stomata are open and transpiring to keep the leaves cool.

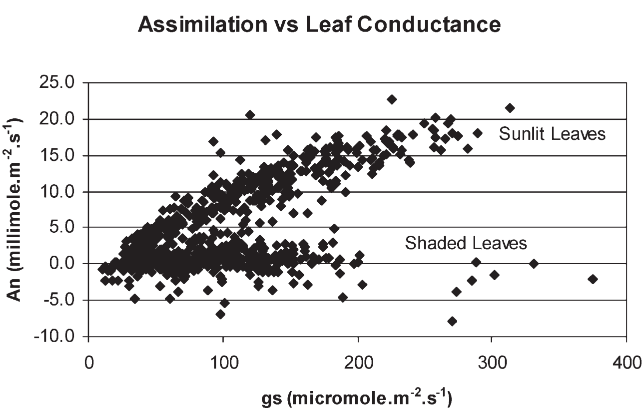

Figure 13. Relationship between assimilation and leaf conductance in SPARC 2004.

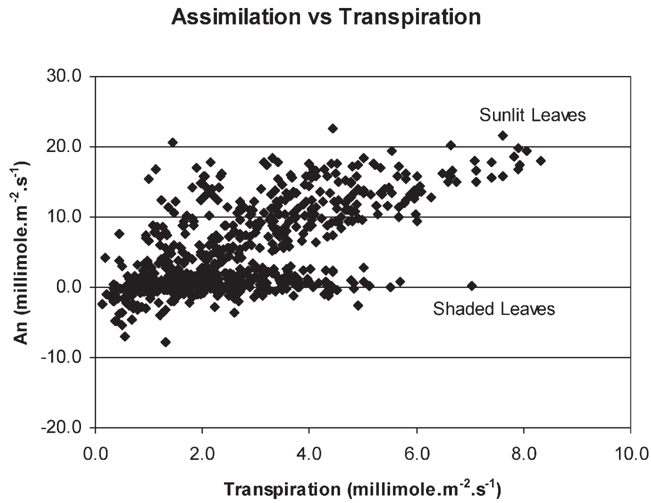

Figure 14. Relationship between assimilation and transpiration in SPARC 2004.

2.6 *Observation uncertainty and energy closure*

In this section, the fluxes measured with different instruments are compared so that a first-order analysis of the uncertainties could be given. By comparing H measured by the eddy correlation system (H_ED) to that by the scintillometer (H_LAS), it can be observed that H_LAS is higher than H_ED for both 10 and 60 min averages (figure 15). The uncertainties may be caused by the different heights of the instruments and certainly by the different fetches covered by each instrument. In addition, the LAS covered part of the stubble field with higher sensible H, where its transmitter was located. H_LAS is approximately 13% higher than H_ED.

The energy closure was examined for both 10-min and 60-min averaged fluxes (figure 16), and in both cases the energy closure is not reached, with the sum of the turbulent fluxes (H_ED + LE_ED) measured by the eddy correlation system being 10% higher than the available energy (Rn (net radiation) – G0 (soil heat flux)). Assuming that all the measurements are of comparable reliability, this is then a striking finding in its own right, because if this is indeed true, the extra energy measured by the eddy correlation system must be advected to the field being measured from neighbouring dry fields by local circulation.

3. *In situ* observation of land–atmosphere exchanges during SEN2FLEX 2005

Measurements of surface layer heat and moisture fluxes, directional thermal radiation and other relevant meteorological variables were carried out at Barrax during the SEN2FLEX campaign of 10–17 July 2005. Data used for quantification of heat, water vapour and CO_2 transfer between the surface and the atmosphere were collected by the ITC Team over vineyard, bare soil and reforestation areas. The measurements were grouped into the following categories in terms of the main instrumental and measurement characteristics:

(1) Goniometric measurements
(2) Canopy temperature gradient measurements in the vineyard
(3) Meteorological measurements
(4) Scintillometer measurements of sensible heat fluxes

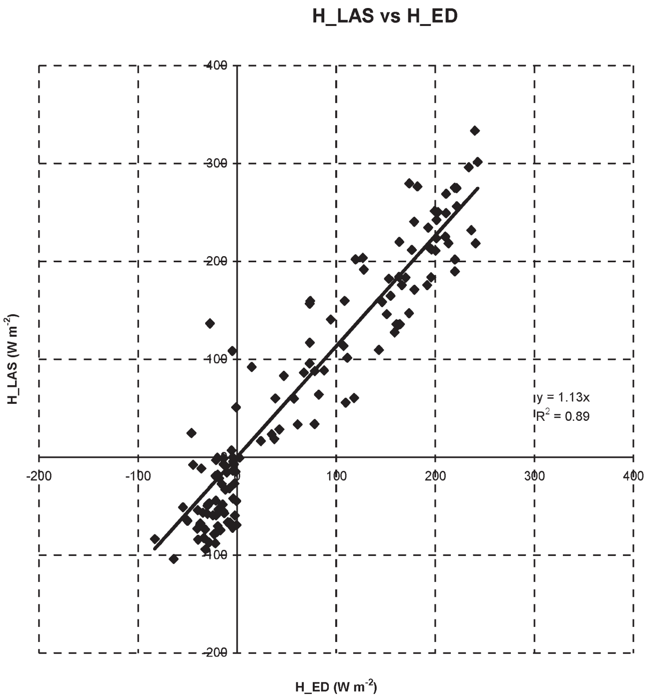

Figure 15. Scatter plots of sensible heat fluxes measured by the eddy correlation system and the scintillometer system with 60-min average in SPARC 2004.

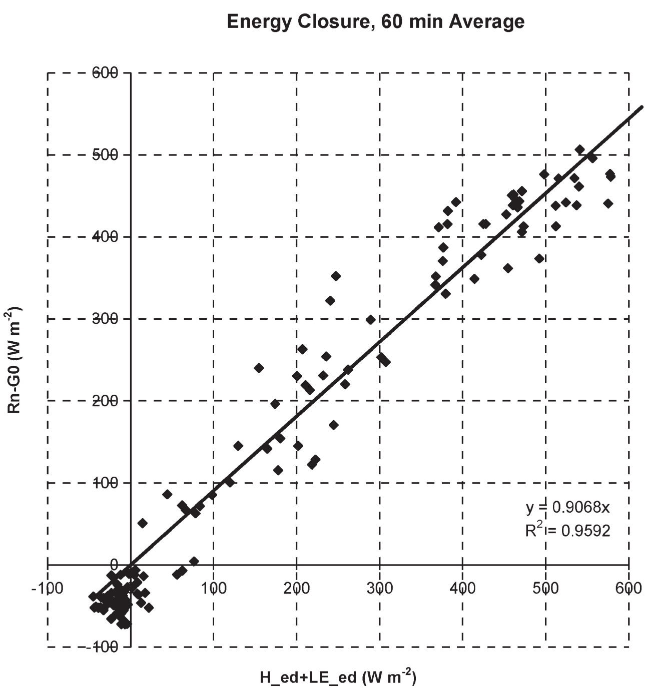

Figure 16. Energy closure with 60-min average in SPARC 2004.

(5) Eddy correlation measurements of sensible heat flux, latent heat flux and CO_2 fluxes at two levels
(6) Temperature profile measurements.

A summary of the ITC measurements is given in table 4 and the locations of the measurements are given in table 5.

3.1 *Goniometric measurements*

A goniometer was deployed in the vineyard area during the fieldwork in July 2005 (Barrax, Spain). The sensors mounted included a digital camera, a thermal imager and a thermal sensor. Other measurements were made with a Semal camera, a thermal camera and an ASD spectroradiometer in collaboration with the groups of CTCD, LSIIT and the University of Valencia. A digital camera, Canon Powershot 110, was used for orientation purposes and operated in movie mode. The Irisys 1011 Thermal imager was used for capturing thermal imagery. The Irisys 1011 has 16×16 pixels for detection and can acquire thermal imagery at speeds of eight images per second. The sensitivity of the camera is 0.3 K at 300 K and it has an operating range of 260 K to 570 K. The imager was attached to the goniometer and operated in automatic retrieval mode. Other relevant issues are described in Timmermans *et al.* (2008a,b) and Gieske *et al.* (2005b).

3.2 *Canopy temperature gradient measurements in the vineyard*

Measurements of sunlit/shaded leaf/soil component temperatures are crucial for understanding the anisotropy of the thermodynamically heterogeneous canopy and are needed for validation of the radiative transfer model of a three dimensional (3D) canopy. The actual surface temperature of the individual leaves and the surface temperature of the ground were measured using NTCs (IC temperature probes), with these NTCs connected to individual leaves by means of plastic paperclips (Timmermans *et al.* 2007).

3.3 *Meteorological measurements*

For the investigation of the 3D coupling between the land and atmosphere, the net fluxes of radiation, heat, water vapour and CO_2 must be known. These fluxes are measured with scintillometer and eddy correlation installations. A flux tower measuring both standard meteorological variables, such as solar radiation, humidity, wind speed and air temperatures, and sensible heat fluxes with a scintillometer receiver was installed in the vineyard (the transmitter was located in a bare soil field, see table 5 for detailed locations). A portable scintillometer was used in the reforestation area. A second main system, an eddy correlation mast with two CSAT3/LICOR-7500 systems, was installed in the vineyard.

Soil-temperature probes and soil heat flux plates were placed in the soil at different distances from the crops (sunlit position, shaded position and intermediate position). The flux plates were placed at depths of 0.5 cm at all positions. The four soil thermistor probes were put in pairs, two at a depth of 0.5 and two at a depth of 15 cm below the surface. All data was collected at 1-min intervals, with the exception of the scintillometer data which were sampled at a frequency of 1 s and then averaged per minute.

Table 4. Summary of measurements and instrumentation used by the ITC Team in SEN2FLEX 2005.

Measurements	Instrumentation		Level	Height (cm)	Location	Comment
Turbulence, H_2O, CO_2 fluxes and CO_2 concentrations	Eddy correlation system					
	3 dimensional wind speed	CSAT3	2	410 805	Vineyard	20 Hz
	CO_2, H_2O	Open-path LICOR-7500	2	410 805		
	Relative humidity, Air temperature	HMP45C	2	413 808		
Sensible heat flux	Scintillometer data logger	Kipp & Zn CR23x	1	499	Vineyard	On top of the meteo-tower, 1 Hz
Sensible heat flux	Scintillometer data logger	Kipp & Zn CR23x	1	220	Reforestation	Portable, on tripods, 1 Hz
Meteo-tower	Four-component Radiation	CNR1	1	454	Vineyard	
	Relative humidity, Air temperature	Campbell 207	2	264 462		
	Wind speed	Vector A100L	2	276 474		
	Wind direction	Vector W200P	1	474		0.5 cm depth
	Soil heat flux	Huksflux HFP01	1			
	Soil temperature	Campbell 107	4			1-min interval
Canopy temperature	Temperature	NTC	4		Vineyard	16 sensors
Directional	Goniometer	CAS			Vineyard	
	TIR camera	Irisys 1011			Grass	
	TIR sensor	Everest				

Note: the abbreviations used are names of the instruments and/or manufactures, except the following. CO_2 – carbon dioxide flux, H_2O – water vapour flux, TIR – thermal infrared.

Table 5. Positions of instruments in SEN2FLEX 2005.

Instrument	xUTM (m)	yUTM (m)	Location
Goniometer (grass)	577853	4323826	Las Tiesas
Goniometer (vineyard)	577836	4323786	Vineyard
Meteo-tower, scintillometer 1, receiver	577753	4324071	Vineyard
Scintillometer 1, transmitter	577996	4323356	Ploughed bare soil
Scintillometer 2, receiver	578947	4323847	Reforestation
Scintillometer 2, transmitter	579067	4324383	Reforestation

3.4 *Scintillometer measurements of sensible heat fluxes*

Because the scintillometer integrates over its optical path, the structure parameter is in fact a path-averaged value. Path averaging is the most important advantage of the scintillation method compared to traditional (point) measurement techniques, and as such has a direct link with area-averaged turbulent flux estimates from satellite or airborne remote sensing measurements. The scintillometer method was used at two locations. The first location was in the vineyard area, where receiver and transmitter were located in the same spots as in the SPARC 2004 field campaign. The reforestation area was chosen as the second location because the SPARC 2004 field campaign had shown that the unexpectedly high sensible heat transport from this type of surface (low shrub with yellow senescent grasses) needed further study. A mobile scintillometer on tripods (2.20 m above surface level) was used to make measurements in the reforestation area.

3.5 *Eddy correlation measurements of sensible heat flux, latent heat flux and CO_2 flux*

A 3D eddy correlation system was set up in the vineyard field to observe the turbulent exchange of sensible, latent heat and CO_2 fluxes above the canopy by measuring the covariance of the vertical wind velocity with, respectively, the air temperature, water vapour density and CO_2 density. The system consisted of two CSAT3 sonic anemometers, and two open-path LICOR-7500 IR analysers operating at a frequency of 20 Hz. The systems were installed at heights of 410 cm and 805 cm. At about the same heights two HMP45C relative humidity/air temperature sensors were also mounted.

A rose diagram of wind speeds for the period 10–17 July 2005 (Barrax, Spain) was used to examine the relative orientation of the upper and lower CSAT3/LICOR systems. There was an angle of 104° between the directions of the two CSAT3 systems. Conditions were optimal for the system at 410 cm except for the last day, when strong winds blew from the southeast. The effect of the relative orientation of the CSAT3 systems is still under study.

The system was operating at a frequency of 20 Hz throughout the fieldwork period and all relevant raw data were stored, while preliminary 10-min flux averages were also produced for the two different heights. The heights of measurements were at 410 and 805 cm above the ground corresponding to eddy fluxes to an upwind surface fetch over a range between 10 to over 100 times the height of the sensors.

3.6 *Temperature profile measurements*

To examine whether remote sensing-based flux estimates can be improved by incorporating lower Atmospheric Boundary Layer (ABL) spatial and temporal variability, ground measurements of surface temperature and air temperature profiles over two different land cover areas were carried out during a two consecutive days in the SEN2FLEX campaign. The first profile experiment was carried out in the reforestation area near the scintillometer receiver, using thermometers mounted at a temporary mast. In the second profile experiment the thermometers were installed at the meteo-scintillometer mast.

Landcover unit 1, Forest nursery (Lat/Long: 39°03′30″ N, 02°05′19.1″ W UTM: X/Y: 578852/4323645). Air temperatures at seven different levels were measured at 1-min interval, from 13 July (1330 h local time) to 17 July (1200 h local time) 2005. In addition, radiometric temperature was measured using an Everest Interscience series 3000.5ZL infrared temperature sensor at 1-min intervals from a height of 136 cm at an angle of 45°.

Landcover unit 2, Vineyard (Lat/Long: 39°03′38″ N, 02°06′01″ W UTM: X/Y: 577843/4323882). Air temperatures at eight different levels were measured at 1-min intervals, from 12 July (2100 h local time) to 17 July (1200 h local time) 2005.

3.7 *Observation uncertainty*

Most of the data from SEN2FLEX, for example heat fluxes, gradient of air temperature and humidity and component temperature, have undergone only preliminary processing. A significant amount of processing is still required to make all necessary corrections and quality checks before firm conclusions with regard to observation uncertainty and energy closure gap can be drawn.

A plot of the scintillometer measured H versus Rn – G from the meteostation data indicated that the scintillometer picked up much more of the signal of the dry farmland around the vineyard, where evapotranspiration was very small, except during the last day when the LAS result showed H>Rn – G, resulting from strong winds that may have caused strongly advective conditions.

A plot of H+LE from the EC system versus Rn – G indicates that:

(a) the last day shows the highest deviations, perhaps due to the strong southeasterly wind, leading to aerodynamic problems with CSAT3;
(b) systematic deviations occurred during the night-time; and
(c) correspondence during the middle of the day was good; however, the eddy correlation measurements showed strong turbulence as was to be expected.

In general, on days 192–194 and 196 the turbulent fluxes were higher than the available energy confirming the findings on energy imbalance found in SPARC 2004.

4. Conclusions

This paper has presented a complete account of the *in situ* measurements of the land–atmosphere exchanges of energy, water and CO_2 from leaf level to field scale, including both fluxes and thermal dynamics of the surface and near-surface atmosphere of the heterogeneous land surface in Barrax, Spain. The preliminary analyses of the observation data and relevant findings are presented in each section accompanying the observations. The three most important findings on the basis of the SPARC 2004 data are: (1) the temporal averaging significantly smoothed the peak fluxes (e.g. the latent heat flux was reduced from 500 W/m^2 to approximately

400 W/m^2 when the averaging time changed from 10 to 60 min), which poses a serious challenge when fluxes from different measurements and estimation methods are compared to each other; (2) models of photosynthesis and leaf conductance must be used with caution and must take into account the temperature difference in sunlit and shaded leaves (up to 10°C observed difference); there was almost no assimilation in the shaded leaves even though the leaf conductance was not zero; and (3) the energy imbalance, that is the sum of the turbulent fluxes (H_ED + LE_ED) measured by the eddy correlation system was 10% higher than the available energy (Rn – G0). This indicates that the extra energy measured by the eddy correlation system must be advected from neighbouring dry fields by local circulation.

Some preliminary results from SEN2FELX 2005 data are shown but firm conclusions can only be made after further data processing and analysis. These data sets are open to the scientific community for collaborative investigations and are accessible at the ESA's Principle Investigators portal http://earth.esa.int/ or by contacting the authors directly.

Acknowledgements

The SPARC 2004 and SEN2FLEX 2005 campaigns were carried out in the framework of the Earth Observation Envelope Programme of the ESA and financed in part by the EU 6FP EAGLE Project and the NOW SRON EO-04/071 EcoRTM Project. We thank two anonymous reviewers for their very helpful and constructive comments.

References

CHEHBOUNI, A., HOEDJES, J.C.B., WATTS, C., RODRIGUEZ, J.-C. and GARATUZA, J., 2008, Remote sensing based estimates of daytime area-averaged surface fluxes over agricultural patchwork. *Agricultural and Forest Meteorology*.

GIESKE, A.S.M., HENDRIKSE, J.H.M., RETSIOS, V., VAN LEEUWEN, B., MAATHUIS, B.H.P., ROMAGUERA, M., SOBRINO, J.A., TIMMERMANS, W.J. and SU, Z., 2005a, Processing of MSG-1 SEVIRI data in the thermal infrared-algorithm development with the use of the SPARC2004 data set. In *Proceedings of the ESA WPP-250*, SPARC final workshop, 4–5 July 2005 (Enschede: ESA).

GIESKE, A.S.M., TIMMERMANS, J., TIMMERMANS, W.J., VAN DER VELDE, R. and SU, Z., 2005b, *Goniometer and Surface Energy Budget Measurements*, SEN2FLEX data report. Available online at: www.uv.es/leo/sen2flex/.

SOBRINO, J.A. (Ed.), 2007, *Recent Advances in Quantitative Remote Sensing II* (Valencia: Servicio de Publicaciones, Universitat de Valencia).

SU, Z., LIA, J., GIESKE, A.S.M., TIMMERMANS, W.J., JIN, X., ELBERS, J.A., VAN DER KWAST, H., OLIOSO, A., SOBRINO, J.A., NERRY, F., SABOL, D. and MORENO, J., 2005, In-situ measurements of land–atmosphere exchanges of water, energy and carbon dioxide in space and time over the heterogeneous Barrax site during SPARC2004. In *Proceedings of the ESA WPP-250*, SPARC final workshop, 4–5 July 2005 (Enschede: ESA).

TIMMERMANS, J., VAN DER TOL, C., VERHOEF, W. and SU, Z., 2008a, Contact and directional radiative temperature measurements of sunlit and shaded land surface components during the SEN2FLEX 2005 campaign, *International Journal of Remote Sensing*, **29**, pp. 5183–5192.

TIMMERMANS, W.J., BERTOLDI, G., ALBERTSON, J.D., OLIOSO, A., SU, Z. and GIESKE, A.S.M., 2008c, Accounting for atmospheric boundary layer variability on flux estimation from RS observations, *International Journal of Remote Sensing*, **29**, pp. 5275–5290.

TIMMERMANS, W.J., VAN DER KWAST, J., GIESKE, A.S.M., SU, Z., OLIOSO, A., JIA, L. and ELBERS, J.A., 2005, Intercomparison of energy flux models using ASTER imagery at the SPARC 2004 site (Barrax, Spain). In *Proceedings of the ESA WPP-250*, SPARC final workshop, 4–5 July 2005 (Enschede: ESA).

UNIVERSITY OF VALENCIA, 2004, *SPARC2004 Experimenters Handbook.* Available online at: www.uv.es/leo/sparc2004/.

UNIVERSITY OF VALENCIA, 2005, *SEN2FELX Experimenters Handbook.* Available online at: www.uv.es/leo/sen2flex/.