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Simulation of soil moisture and evapotranspiration in a soil profile during the 1999 MAP-Riviera Campaign

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Abstract

Detailed plot-scale observations of basic hydrometeorological variables represent valuable data for assessing the quality of the soil moisture module and evapotranspiration scheme in hydrological models. This study presents the validation of soil moisture and evapotranspiration (ET) simulation during the special observing period (R-SOP) of the Riviera Project (July–November 1999), a sub-project of the Mesoscale Alpine Programme (MAP). The location investigated was a sandy soil plot at the edge of a corn field. The hydrological model PREVAH was driven using three meteorological data sets: hourly data from an experimental tower in the Riviera Valley (southern Switzerland), hourly data interpolated for the Riviera site during the R-SOP period from permanent automatic stations (MeteoSwiss network) and interpolated daily data (1980–2000). The quality of the interpolated meteorological data was evaluated with respect to data collected at an experimental tower. The interpolated data proved fairly representative for the location under investigation. The hydrological simulations were compared with recorded observations of soil moisture and latent heat flux (LE). The simulation of soil moisture was accurate in case of all three meteorological data sets. The results of ET simulations with three simple parameterisations showed high correlation to LE derived using the Bowen ratio and measured through eddy correlation. The quantitative agreement between observed and simulated LE was poorer because of the presence of a fully developed wind valley system during periods of good weather. This wind system claims part of the available energy and therefore reduces the amount of energy available for LE. The 21-year simulation at daily time step shows that the R-SOP period in 1999 was warm and wet compared to the last 21 years.

Keywords: MAP-Riviera Project, soil moisture, evapotranspiration, hydrological modelling, model evaluation

Introduction

Both soil moisture and evapotranspiration are elements of the water cycle. Their correct representation within hydrological models is essential for an accurate simulation of the exchange processes between soil, vegetation and atmosphere from the plot-scale up to the macroscale. The range of available land surface schemes (LSSs) or SVATS (Soil – Vegetation – Atmosphere Transfer Schemes) to simulate such interaction is very broad (Betts *et al.*, 1996; Henderson-Sellers *et al.*, 1993; Schlosser *et al.*, 2000). The development and reliability assessment of simple and complex LSSs is generally characterised by comparisons with observations at the microscale. The validated LSSs are then scaled up and integrated within hydrological models (Walko *et al.*, 2000), climate models at regional scale, numerical weather prediction models and general circulation models. Sellers *et al.* (1997b) provide a comparative review of LSSs used in numerical models of the atmosphere, which are increasingly capable of representing the complex feedbacks of land-surface / atmosphere interactions. Spatially distributed hydrological models used to predict runoff in an entire catchment often use more simplified surface layer schemes (Manabe, 1969; Bergström, 1982; Simmons and Mayer, 2000; Jothityankoon *et al.*, 2001) to obtain the fluxes of sensible and latent heat from energy balance equations (e.g. Gurtz *et al.*, 1999; Carlaw, 2000).

The basis for the development, validation and intercomparison of LSSs with different degrees of complexity is the availability of detailed time series observations from highly instrumented test sites (Schlosser *et al.*, 1997; Aubinet *et al.*, 2000; Mihailovic *et al.*, 2000; Gurtz *et al.*, 2003) and the launch of large international programmes and projects like FIFE (Sellers *et al.,* 1988), GEWEX (*Global Energy and Water Cycle Experiment*, Coughlan and Avissar, 1996), BOREAS (*Boreal Ecosystems Atmosphere Study*; Sellers *et al.*, 1997a), BALTEX (*Baltic Sea Experiment*; Raschke *et al.*, 1998) and MAP (*Mesoscale Alpine Programme*; Bougeault *et al.*, 2001).

MAP is an international research initiative devoted to the study of atmospheric and hydrological processes over mountainous regions. The MAP research activities related to surface hydrology aim in particular to improve the understanding of orographically-influenced precipitation events and related flooding episodes and to improve the numerical prediction of moist processes in regions with complex topography, including interactions with land-surface processes (Binder, 1996). These issues were investigated, both through modelling (Benoit *et al.,* 2002; Jasper *et al.,* 2002) and field experiments (Rotach *et al.*, 2004; Matzinger *et al.* 2003; Bacchi and Ranzi, 2003).

This study is based on the hydrometeorological observations conducted in the summer and autumn of 1999 in the framework of the MAP-Riviera field experiment. Recorded measurements included soil moisture, soil temperature, soil heat flux, precipitation, and leaf interception — all of which were measured as time series with high temporal resolution (Zappa *et al.*, 2001). These data, which were collected concurrently with the micrometeorological observations at towers along the Riviera valley, comprise a unique data set for testing and validating both the complex LSSs and the more simple evapotranspiration schemes available within distributed hydrological models.

The qualitative assessment of the soil moisture module and of the three simple evapotranspiration schemes available in the hydrological model PREVAH (Gurtz *et al.*, 1999; Zappa, 2003) is a first application of this valuable data set and represents the focus of this paper. Simulated evapotranspiration was compared with observed fluxes of latent heat. The simulation of soil moisture was compared against the observed values. The temporal resolution for simulations and data analyses is one hour for the period from August to October 1999. The standard application of the hydrological model relies on observations by the MeteoSwiss service. This study also evaluated how reliable the interpolation of the meteorological data is by comparing the observed meteorology in the main research area for the hydrological observations (Fig. 1) with the interpolated meteorology for this same location. Lastly, the conditions for the period from July to November 1999 at this site are discussed with respect to the same period from 1980 to 2000.

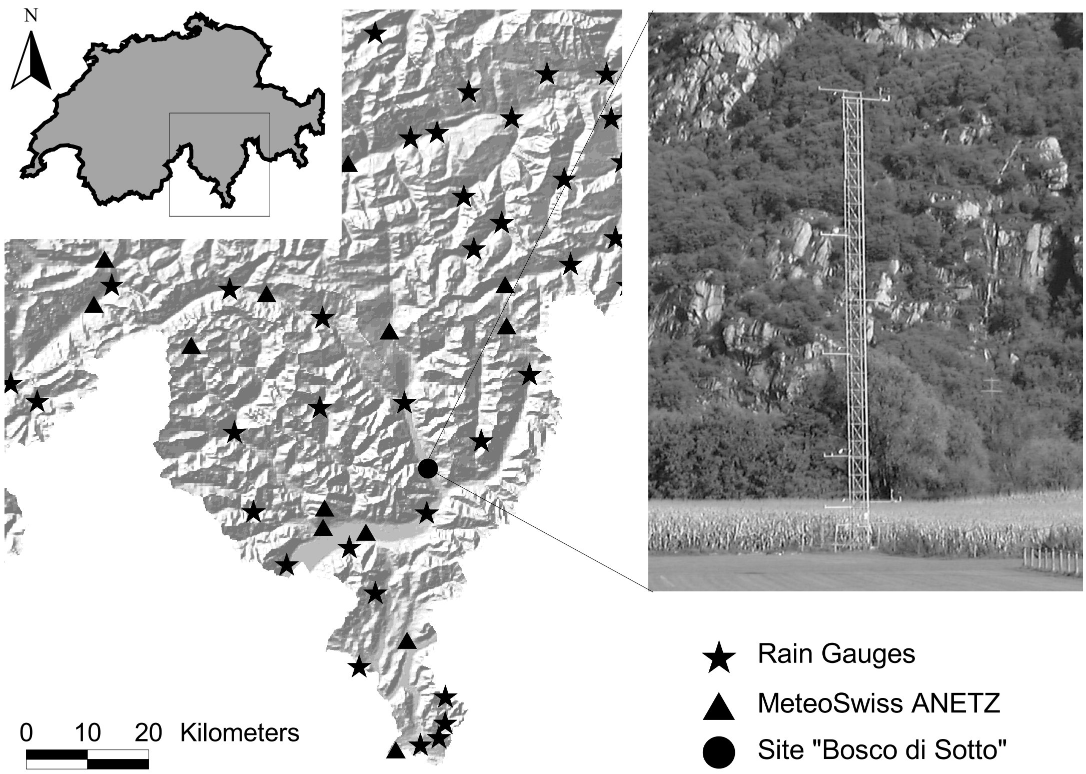

Fig. 1. *Location of the investigated MAP-Riviera site "Bosco di Sotto", Ticino-Switzerland, as well as of the surrounding meteorological stations and rain gauges of MeteoSwiss.*

The MAP-Riviera field experiment

The Ticino-Toce catchment (CH-I) was one of the MAP test sites (Ranzi, 2003). During the MAP Special Observing Period (SOP, 15 September to 15 November 1999; Bougeault *et al.*, 2001), boundary layer processes in highly complex topography were investigated in the Riviera valley in southern Switzerland (Rotach *et al.,* 2004; Matzinger *et al.,* 2003). This valley is midway between the 'Lago Maggiore' and the Swiss Central Alps (Fig. 1). The main focus of the Riviera-Project was on the turbulence structure and turbulent exchange processes at the valley surfaces with respect to the free troposphere. Due to the anticipated spatial inhomogeneity, many turbulence probes (sonic anemometers, fast-response hygrometers and scintillometers) were deployed on a cross-section through the valley. Also, a light research aircraft with high temporal sampling resolution equipment flew various patterns within the valley to yield information on the turbulence structure. Additional instrumentation such as a radio sounding system, a passive-microwave temperature profiler and a tethered balloon were operated during selected periods (De Wekker *et al.*, 2004). The Riviera Special Observing Period (R-SOP) started on 24 July 1999 and lasted until the 10 November 1999. The principal field survey area was located in the Riviera valley at the site 'Bosco di Sotto' (Fig. 1).

The hydrology sub-project was also integrated into the framework of the EU-MAP Project RAPHAEL (Runoff and Atmospheric Processes for flood hAzard forEcasting and controL; Bacchi and Ranzi, 2003). The aim of this hydrological sub-project was to collect large amounts of data to investigate the established parameterisation in hydrological models. The measured soil moisture values were transmitted during the MAP-SOP to the MAP centre in Innsbruck and to the MAP-Hydrology database for use in the coupled meteorological and hydrological forecasts. These data were used for the validation and improvement of high-resolution numerical weather prediction (Kouwen, 1996; Carlaw, 2000; Benoit *et al.*, 2002) and hydrological and coupled models in mountainous terrain (Binder, 1996; Benoit *et al.*, 2000).

The soil profile investigated was located at the edge of a cornfield (Fig. 2b). It consisted of a 40 cm deep humus layer (partly mixed with clean sand) followed by a 60 to 80 cm deep clean sand layer. Soil samples were collected at eight levels. The porosity and the field capacity were determined via laboratory tests. The lowest observed soil moisture was 0.09 $cm^3\ cm^{-3}$. The wilting point was assumed to be 0.06 $cm^3\ cm^{-3}$. The root zone of the corn reached 60 cm depth. Table 1 gives an overview of the soil characteristics up to 65 cm depth.

Fig. 2. *Instrumentation at the site 'Bosco di Sotto'. Left: asymmetric ultrasonic anemometer combined with a fast-response krypton hygrometer. Right: soil moisture detection by TDR-probes.*

Table 1. Physical parameters of the modelled 650 mm deep soil profile.

Parameters	*Unit*	*Symbol*	*Value*
Porosity	$cm^3\ cm^{-3}$	η	0.530
Field Capacity	Vol%	*FC*	0.305
Wilting Point	Vol%	*WP*	0.060
Plant available field capacity	Vol%	*AFC*	0.245
Maximum storage capacity	mm	*SFC*	159.0

DATA SETS

HYDROMETEOROLOGICAL FIELD OBSERVATIONS

The soil moisture was measured hourly with a Tektronix-TDR-System. With the Time Domain Reflectometry technique (TDR), it is possible to measure the changes in the relative dielectric properties of the soil in relation to the changes in the soil moisture to determine the soil's volumetric water content (Topp *et al.*, 1980). Six TDR probes (Fig. 2b) and three temperature probes (thermocouples) were buried in the soil at different depths (5 to 120 cm depth) to obtain a representative profile of the vertical changes of soil temperature and water content. The TDR signals were analysed as proposed by Roth *et al.* (1990).

A meteorological tower at the same location was equipped to observe data at different levels (Fig. 1). From 12 August 1999 to 10 November 1999, the following variables were collected using a time resolution of 30 minutes and then aggregated to hourly data (data set TOWER):

- the vertical profile of air temperature, relative humidity and wind speed (1.5 m, 3 m, 6 m, 12 m, 19 m, and 28 m heights);
- net radiation, global radiation, outgoing short-wave radiation and incoming and outgoing long-wave radiation at 1.5 m height;
- soil heat flux at 5 cm depth;
- precipitation at 3 m height (Tognini gauge).

The data from the 1.5 m and 6 m heights of the meteorological tower were used for the computation of the Bowen ratio (β) (Bowen, 1926) and assessment of the latent heat flux (Zappa *et al.*, 2001). The quality and physical consistency of the energy fluxes derived from the Bowen ratio were analysed as proposed by Ohmura (1982) and similarly to Konzelmann *et al.* (1997) and Müller (1989). Konzelmann *et al.* (1997) determined that the relative uncertainty of the Bowen ratio method for the computation of the hourly turbulent fluxes ranges between 10% and 20%. This method assumes that the energy balance at the investigated site is closed (Ohmura, 1982).

Furthermore, the tower was instrumented with asymmetric ultrasonic anemometers (sonics) type R2A (Gill Instruments) at three levels (4 m, 16 m and 28 m), combined with KH2O fast-response krypton hygrometers at the upper and lower level (Fig. 2a). Andretta *et al.* (2000, 2001) and Matzinger *et al.* (2003) show the first results of the analysis of the eddy correlation (EC) observations at various sites within the Riviera Valley. It should be kept in mind that the measurement of the turbulent fluxes through EC is fully representative only for the point where the observation is taken and can fluctuate considerably within a few metres' distance. Additionally, the separation between specific humidity observations and the temperature fluctuations (Fig. 2, left) causes a systematic underestimation of the turbulent fluxes by up to 5% (Andretta *et al.*, 2001). For this study, an hourly time series of latent heat fluxes by EC was prepared for the period from 1–22 September 1999. Further information on MAP-Riviera is available online (http://www.iac.ethz.ch/en/research/map_riviera/).

INTERPOLATED ANETZ DATA

MeteoSwiss operates a network of more than 70 automatic stations (ANETZ), which are distributed throughout Switzerland. Data from stations surrounding the Riviera valley (up to 50 km from the target site) were used to create two representative data sets for the 'Bosco di Sotto' location (Fig. 1):

- interpolated data at hourly time steps for the period from July to November 1999 (Data set $ANETZ_H$);
- interpolated data at daily time steps for the period from 1980 to 2000 (Data set $ANETZ_D$).

The procedure used for interpolation is described in Schulla (1997) and Klok *et al.* (2001) and is based on the combination of altitude dependent regression and inverse distance weighting.

Hydrological modelling

The hydrological model PREVAH (Precipitation-Runoff-Evapotranspiration HRU model, Gurtz *et al*., 1999, 2003; Zappa *et al.*, 2003) was used. It is structured using the concept of hydrological response units (HRU). This gives the model a high degree of flexibility, allowing for both spatially distributed and plot-scale simulations (Zappa, 2003). For distributed simulations, a set of HRUs is defined using the characteristics controlling the spatial differentiation of the hydrological processes. For plot-scale simulations, as in this study, a single HRU is used to describe the local characteristics of the site to be modelled (Table 1).

Three semi-empirical equations are implemented for the calculation of evapotranspiration:

- the Penman-Monteith equation (Penman, 1948; Monteith, 1975 and 1981);
- the Wendling equation (1975), as reported in Schulla (1997); and,
- the Turc equation (1961) as reported in DVWK (1996).

Six meteorological variables are required to operate PREVAH using Monteith. These are precipitation, air temperature, wind speed, global radiation, sunshine duration, and either water vapour pressure or relative humidity. For model runs using Wendling and Turc, only precipitation, air temperature and global radiation are needed. The potential evapotranspiration is limited by the plant-available field capacity of the soil. A linear function is used to account for this limitation and allow for calculating the actual evapotranspiration. This paper will analyse only the simulated actual evapotranspiration and will refer to it as evapotranspiration (ET). Also, if both latent heat flux (LE) and ET are plotted on the same y-axis then the axis will be labelled as ET only.

Figure 3a presents the conceptual structure of the soil model, including the module of runoff generation in the upper zone (*SUZ*) (Bergström, 1976, 1982). The link between the loss of water by evapotranspiration and runoff is given by the plant-available water storage in the aeration zone of the soil (*SSM*). The parameterisation of the maximum plant available water storage (*SFC*, in mm) depends on the soil depth (*Z*), the effective root-depth, and the plant-available field capacity of the soil (*AFC*, in $cm^3\ cm^{-3}$). The inflow into the soil model (P_b) is supplied by the precipitation reaching the soil and by snowmelt. The parameter *BETA* controls the redistribution of P_b between *SSM* and *SUZ*. The inflow into the runoff generation module (*DSUZ*) is regulated by *SFC* by:

$$DSUZ = P_b \left(\frac{SSM}{SFC} \right)^{BETA} \quad (1)$$

The soil moisture recharge (*SMR*) is the difference between P_b and *DSUZ* which increases with increasing *BETA* (Uhlenbrook, 1999). The generation of surface runoff and interflow is governed by the threshold parameter *SGR* and by the storage coefficients K_0 and K_1. Table 2 gives further details on the free parameters and variables.

The soil moisture is not explicitly calculated by PREVAH. Figure 3b shows how the model conceptualises the description of the soil moisture into three parts: the water content below the wilting point (*WP*), the content of *SSM* (limited by *AFC*) and *SUZ*. The water content below *WP* has to be added to the modelled *SSM* and *SUZ* to have a representative actual value of the soil moisture with respect to the observed water content of the soil. The maximum water content of a soil profile is theoretically given by the

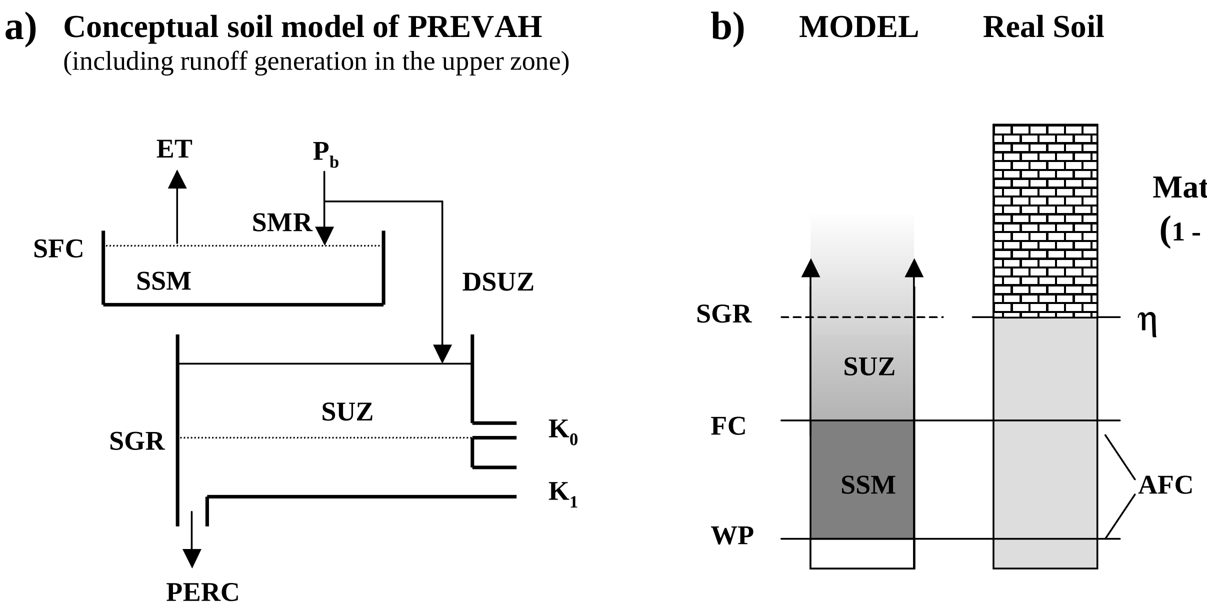

Fig. 3. *(a) Conceptualisation of the soil model in PREVAH. (b) Schematic conceptualisation of the real soil and of its parameterisation in the hydrological model. Acronyms are defined in the text and reported in Tables 1 and 2.*

Table 2. Definition of internal variables of the hydrological model (plain records) and declaration of the calibrated model parameters (italic records).

Parameter	*Symbol*	*Unit*	*Value*
Inflow in the soil model	P_b	mm h^{-1}	-
Evapotranspiration	ET	mm h^{-1}	-
Water storage in the aeration zone of the soil	SSM	mm	-
Model Parameter	BETA	-	6.5
Soil moisture recharge	SMR	mm	-
Inflow in the runoff generation module	DSUZ	mm	-
Water storage in the upper zone	SUZ	mm	-
Threshold parameter for surface runoff	SGR	mm	30
Storage coefficient for surface runoff	K_0	h	3
Storage coefficient for interflow	K_1	h	75
Deep Percolation	PERC	mm h^{-1}	0.08

porosity (η) and the soil depth (*Z*) (Table 1). The maximum value for *SUZ* is not assigned (Fig. 3b). However the model structure implicitly allows values of *SUZ* above *SGR* only for a limited number of time steps, as governed by the storage coefficients K_0 and K_1 and by the rate of deep percolation *PERC* (Table 2).

Three statistical coefficients are used to evaluate the simulated (S) with respect to the observed variables (O): the empirical coefficient of correlation (R_{os});

$$R_{os} = \frac{\sum_{i=1}^{N}\left(S_i - \bar{S}\right)\left(O_i - \bar{O}\right)}{\sqrt{\sum_{i=1}^{N}\left(S_i - \bar{S}\right)^2 \sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2}} \quad (2)$$

the coefficient of efficiency E_2 (Legates and McCabe, 1999; Nash and Sutcliffe, 1970);

$$E_2 = 1 - \frac{\sum_{i=1}^{N}\left| O_i - S_i \right|^2}{\sum_{i=1}^{N}\left| O_i - \bar{O} \right|^2} \quad (3)$$

and the root mean square error (RMSE);

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(S_i - O_i\right)^2}{N}} \quad (4)$$

with $\bar{O}$ and $\bar{S}$ being the mean of the observations (O_i) and of the simulated values (S_i) respectively and N being the number of observations. R_{os} approaches unity as the simulated values have similar dynamics with respect to the observations. E_2 quantifies the relative improvement of the model compared with the mean of the observations, and any positive value corresponds to an improvement. E_2 approaches unity as S_i tends towards O_i. RMSE allows quantifying the magnitude of the deviation between the simulated and observed values.

Results

INTERCOMPARISON OF THE THREE METEOROLOGICAL TIME SERIES

Figure 4 and Table 3 show the results of the comparisons between the meteorological data of the TOWER data set and the two interpolated data sets $ANETZ_H$ (triangles in Fig. 4) and $ANETZ_D$ (squares in Fig. 4).

Air temperature: The average interpolated temperature during the period from August to November is approximately 1 K higher than the observed values at 3 metres height in Claro (Table 3). R_{OS} between air temperature of the TOWER and interpolated air temperature of the other two meteorological time series is high throughout the period. Both interpolated air temperature data sets are aligned slightly above the 1:1 line with respect to the TOWER data (Fig. 4a). This confirms the presence of a bias between measured and interpolated data. The agreement between the temporal patterns of locally observed and interpolated air temperature is high (R_{OS} = 0.98).

Global radiation: The average interpolated global radiation overestimates the observed average during the whole R-SOP period. The range of the differences is 3 to 11 W·m^{-2} (Table 3). The scatter plot between observations and the interpolated radiation data shows a good alignment along the 1:1 line (Fig. 4b). The correlation R_{OS} is high and confirms the presence of a good agreement between the locally observed and interpolated temporal pattern of global radiation.

Precipitation: As expected, the largest differences between the observed and the interpolated time series concern precipitation. The correlation between the two ANETZ time

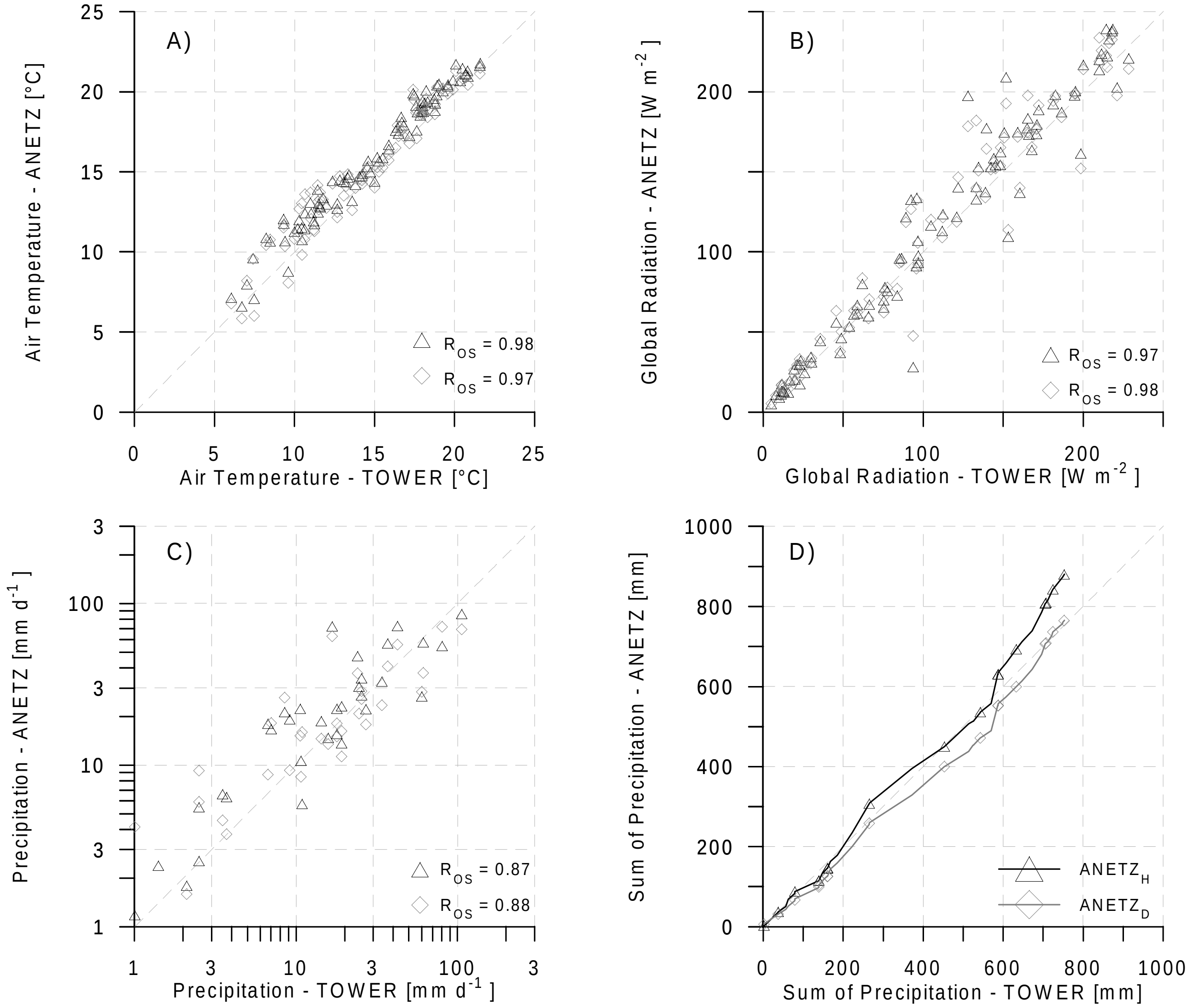

Fig. 4. *Correlation between the TOWER data set and the two interpolated time series ($ANETZ_H$ and $ANETZ_D$) during the whole MAP-Riviera campaign. (a) average daily air temperature. (b) average daily global radiation. (c) daily precipitation rates. (d) cumulative precipitation rates.*

Table 3. Intercomparison of the three available meteorological time series with respect to the average air temperature (T), the average global radiation (RGL) and the precipitation sums (P).

Dataset	*Variable*	*Unit*	*August*	*September*	*October*	*November*	*Total*
$ANETZ_H$	T	°C	20.1	17.9	12.3	11.5	15.8
$ANETZ_D$	T	°C	19.8	17.6	12.2	11.1	15.5
TOWER	T	°C	19.2	17.0	11.2	10.2	14.8
$ANETZ_H$	RGL	W m^{-2}	173	131	87	51	117
$ANETZ_D$	RGL	W m^{-2}	168	134	88	52	117
TOWER	RGL	W m^{-2}	162	123	85	48	110
$ANETZ_H$	P	mm	115	420	273	71	880
$ANETZ_D$	P	mm	104	368	236	57	764
TOWER	P	mm	140	404	164	45	752

series and the TOWER data set is above 0.85 (Fig. 4c). The absolute values are underestimated in the period of calibration and overestimated during the period of validation (Table 3). The cumulative precipitation of $ANETZ_D$ is very close to the observations (Fig. 4d). The cumulative precipitation of $ANETZ_H$ is 17% higher than the observations. There are differences between the temporal patterns of locally observed and interpolated precipitation.

Although $ANETZ_H$ and $ANETZ_D$ showed good correlation with the TOWER data set, there is some evidence that indicates that their relevance for this location is only qualitative.

SIMULATION OF SOIL MOISTURE

The free parameters (italic parameters in Table 2) were calibrated on the period 12 to 31 August 1999 using the data set TOWER and Monteith for the computation of ET. The hydrological model was operated using the meteorological data collected at the 3 m level on the tower. The remainder of the R-SOP was used to validate the quality of the conceptual soil model of PREVAH (Fig. 3). Then the model was run with the same set of free parameters using the meteorological time series $ANETZ_H$. The quality of the model simulation was assessed by comparing both the observed soil moisture and latent heat fluxes with the values obtained from the simulation. Table 4 shows a month by month overview of the statistical performance of the soil moisture simulation at the site 'Bosco di Sotto' for both runs.

The quality of the simulation using the TOWER data is very high in both periods of calibration and validation. R_{OS} and E_2 are above 0.8 and the average RMSE is low. The month by month performance of the model indicates that the quality of the TOWER simulation is constantly high during the whole R-SOP period. The calibrated free parameters allow a good description of the dynamic of soil moisture recharge and depletion.

The results of the simulation based on the $ANETZ_H$ data set are also good. With exception of the month of August, the statistical analysis of the $ANETZ_H$ run with respect to the observed soil moisture gives similar results to the TOWER run. The model performance in August with the $ANETZ_H$ data set is clearly affected by the event on 26 August. The RMSE in August is more than double that calculated for the $ANETZ_H$ run (10.4 mm) with respect to the TOWER run (4.4 mm). Both R_{OS} (0.73 *v.* 0.96) and E_2 (0.38 *v.* 0.89) confirm this behaviour. On 26 August, a very active convective cell caused heavy precipitation in the area surrounding the investigated area (Fig. 5b). This rainfall event was characterised by very high rain intensities (up to 35 mm h^{-1}) and caused a rapid increase in soil moisture (Fig. 5c). Since this heavy event was very localised, it was not possible to reconstruct it accurately using the data from the standard MeteoSwiss network (Fig. 5a). The result of this lack of information on rain rates and intensities caused an underestimation of the soil moisture recharge in the $ANETZ_H$ simulation. This situation lasted until the next small precipitation event on 4 September (Fig. 5). This was characterised by advective precipitation and was therefore easier to reconstruct by interpolation (Figs. 5a and 5b). The following dry period is characterised by an underestimation of the depletion of soil moisture for the TOWER data set.

The observed soil moisture after the third week of September can be modelled accurately using both meteorological time series. However, there is another important variation between the two runs during the dry phase after the rainfall on 4 October. The soil moisture simulated using $ANETZ_H$ (RMSE 6.3 mm in October) dries more than both the observed and the simulated values from the TOWER (RMSE 4.4 in October). After the harvesting of the cornfield on 27 October, the model is capable of following the moisture content changes accurately as the cornfield is covered with bare soil and stubble only.

By using the same configuration of free model parameters (Table 2), PREVAH was driven for the 21-year period from 1980 to 2000 using the interpolated $ANETZ_D$ data set. Figure 6 shows the part of this simulation that includes the

Table 4. Statistical analysis between observed and simulated soil moisture (hourly data) in case of the model runs with the TOWER and the $ANETZ_H$ time series. The statistical indexes R_{OS}, E_2 and RMSE are defined in the text.

Dataset	*Variable*	*Unit*	*August*	*September*	*October*	*November*	*Period*
TOWER	R_{os}	-	0.96	0.98	0.98	0.98	0.98
$ANETZ_H$	R_{os}	-	0.73	0.97	0.97	0.93	0.95
TOWER	E_2	-	0.89	0.96	0.89	0.81	0.95
$ANETZ_H$	E_2	-	0.38	0.95	0.87	0.80	0.88
TOWER	RMSE	mm	4.41	5.63	4.41	4.10	4.81
$ANETZ_H$	RMSE	mm	10.40	6.26	6.27	4.20	7.20

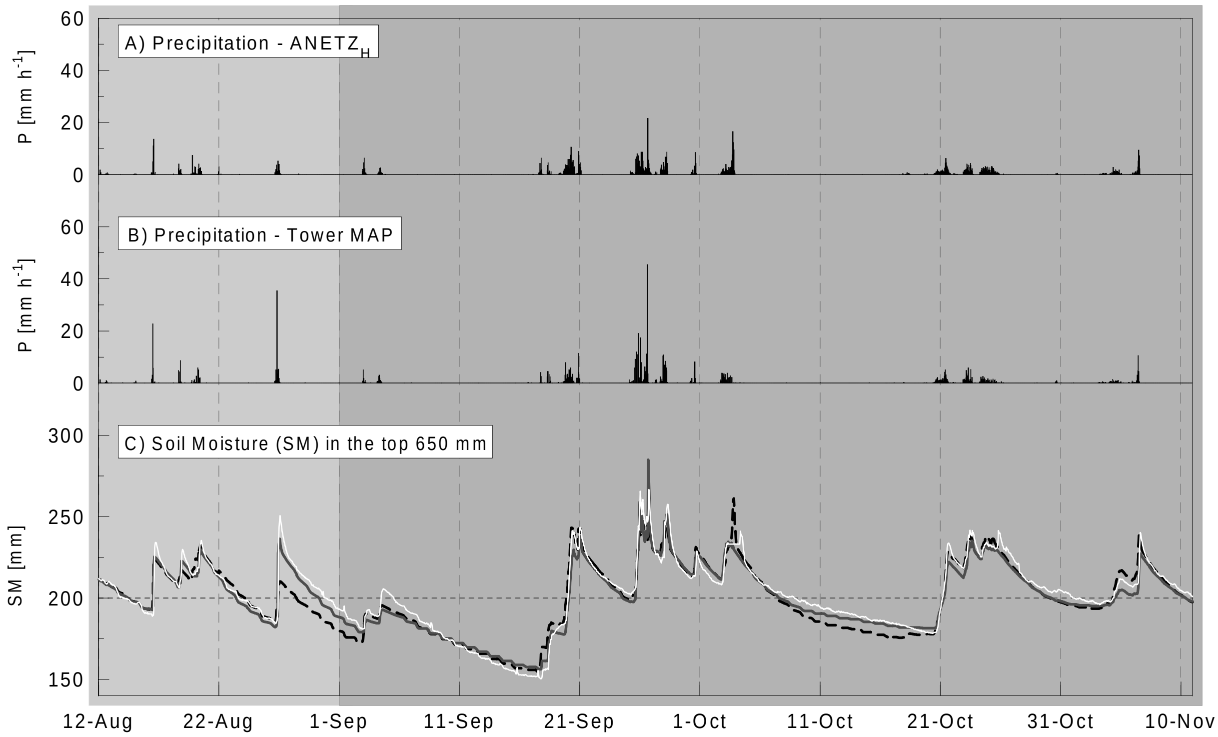

Fig. 5. *Soil moisture simulation. The light grey background indicates the calibration period, the dark grey background the period of validation. a) Hourly precipitation rates of the ANETZ*$_H$ *data set. b) Hourly precipitation rates of the TOWER data set. c) Observed hourly soil moisture (white line), simulation with TOWER (grey line), simulation with ANETZ*$_H$ *(dashed black line).*

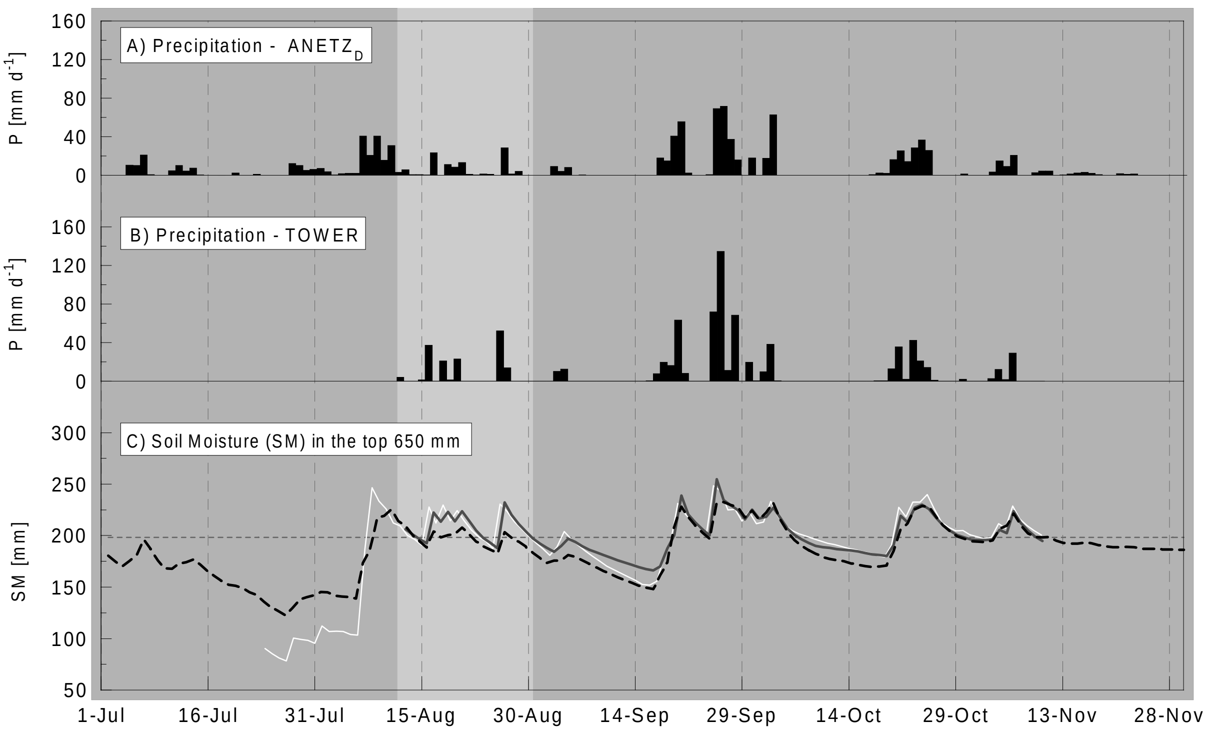

Fig. 6 *Similar to Figure 5, but daily values. (a) Daily precipitation rates of the ANETZ*$_D$ *data set. (b) Daily precipitation rates of the TOWER data set. c) Observed soil moisture at the end of each day (white line), simulation with TOWER (grey line), simulation with ANETZ*$_D$ *(dashed black line).*

R-SOP period compared to the TOWER simulation and the observed soil moisture (Fig. 6c). Since daily time steps are used here, the plotted values refer to the observed and simulated values at the end of each day (Monteith was used in this case for the computation of ET). The correlation between the simulations and the TOWER data is high (R_{OS} of 0.97 and E_2 of 0.93), while the use of the $ANETZ_D$ data set allows the simulation of the soil moisture but with slightly less satisfying results (R_{OS} of 0.93 and E_2 of 0.70). The low E_2 is caused by a systematic underestimation of soil moisture between 15 August and 20 September 20. This behaviour is due to the underestimation of precipitation during this sub-period, as is shown by comparing Fig. 6a with Fig. 6b.

SIMULATION OF THE EVAPOTRANSPIRATION

The latent heat flux data computed using the Bowen ratio (LE) from the observed vertical profile of air temperature and relative humidity were used to quantify the quality of the evapotranspiration as simulated by the hydrological model for the 'Bosco di Sotto' site. Figure 7 shows a comparison between LE-β and the corresponding values simulated by PREVAH driven using the TOWER data set (Monteith was used for this specific analysis). The qualitative comparison between LE and the simulation is very good, having R_{OS} = 0.92 and E_2 = 0.83. The fluctuation in magnitude of hourly evapotranspiration from day-to-day is caused by the alternation of dry and wet weathering periods. This behaviour is accurately reproduced.

PREVAH computes the hourly evapotranspiration between sunrise and sunset from the daily evapotranspiration values as a function of precipitation and radiation. This is the main reason for the underestimation of hourly evapotranspiration during the day and for the absence of condensation during the night (negative latent heat flux). The model is only valid for the qualitative estimation of hourly evapotranspiration. The model, however, does not diagnose the accumulation of dew on the canopy. This phenomenon was observed regularly after cloudless nights.

Figure 8 and Table 5 show the comparison between the daily LE-β and the daily ET computed using different model runs. The second last (E_2 to LE) and third last records (R_{OS} to LE) in Table 5 show the statistical analysis of both Figs. 8a and 8b. Figure 8a shows a scatter-plot between LE and ET-TOWER for the three schemes used to compute ET. The simulated daily ET is well aligned along the 1:1 line when PREVAH is configured to use Turc and Wendling for estimating ET. However, low LE values tend to be overestimated while high values tend to be slightly underestimated. If PREVAH is configured to use Monteith, a significant underestimation of the LE values can be observed, which is even larger in the case of high LE values. Some large positive outliers erroneously compensate this systematic underestimation in days with low LE and relatively high wind speed. This indicates that in days with low energy availability and high wind speed, the ET computed by Monteith is not well correlated with LE-β, while Wendling and Turc, which do take wind speed into consideration, maintain their correlation with LE, which is also not directly dependent on wind speed.

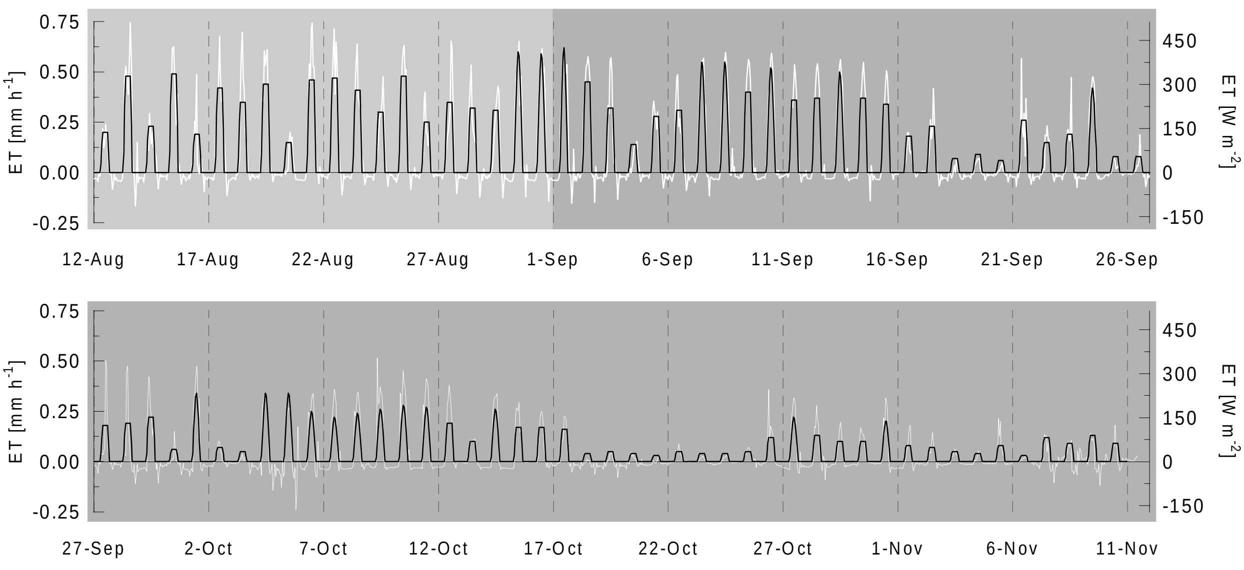

Fig. 7. *Simulation of evapotranspiration. The light grey background indicates the calibration period, the dark grey background the period of validation. The white line indicates LE computed by Bowen Ratio, the black line the simulation with TOWER.*

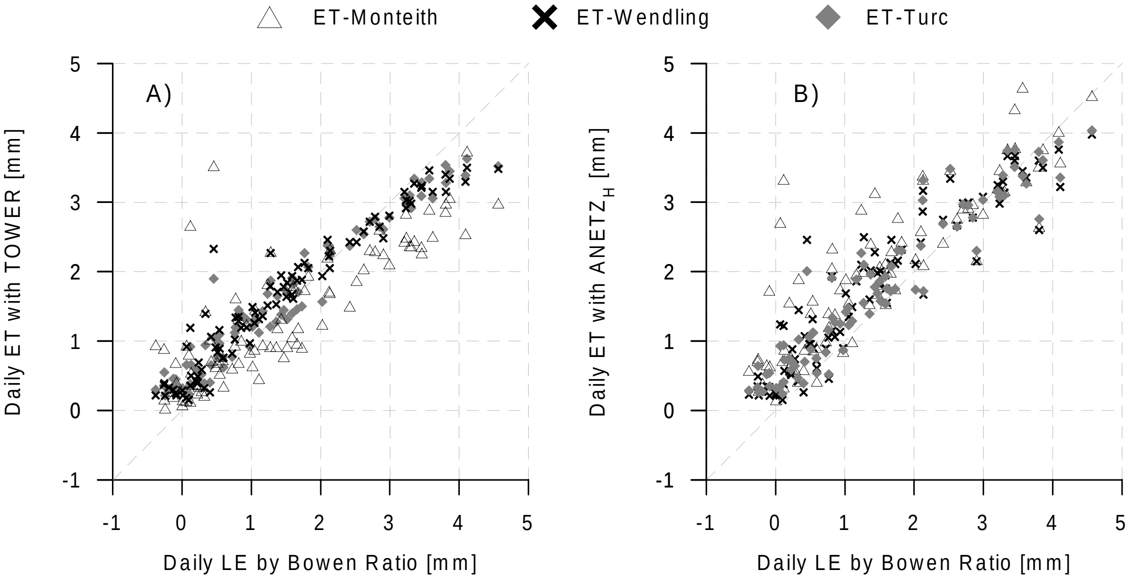

Fig. 8. *Comparison between the daily latent heat flux (LE) computed by Bowen Ratio and the simulated daily evapotranspiration (ET) between 12 August and 10 November 1999 with three evapotranspiration schemes. (A) Model run with the TOWER data set. (B) Model run with the* $ANETZ_H$ *data set.*

Table 5. Statistical analysis between observed and simulated evapotranspiration/latent heat flux (daily data) for the seven model runs. The cumulative evapotranspiration between 12 August and the indicated dates is given in mm. See the body of the paper for further details.

Method *Meteo*	*LE-β* *TOWER*	*Monteith* *TOWER*	*Wendling* *TOWER*	*Turc* *TOWER*	*Monteith* $ANETZ_H$	*Wendling* $ANETZ_H$	*Turc* $ANETZ_H$	*Monteith* $ANETZ_D$
15 Aug.	10.7	9.9	9.8	10.3	13.4	10.5	11.0	13.4
30 Aug.	50.6	41.7	47.2	49.8	57.2	51.1	53.8	57.2
15 Sept.	94.9	77.7	90.7	92.8	106.0	96.5	98.9	106.0
30 Sept.	106.6	91.0	106.8	110.3	130.0	115.3	119.0	128.4
15 Oct.	124.8	108.6	131.2	130.0	162.9	142.2	141.6	161.1
30 Oct.	130.1	119.0	141.4	139.7	176.2	152.0	151.2	171.4
10 Nov.	133.4	127.2	150.1	146.6	188.9	161.5	158.9	181.8
R_{os} *v.* LE-β	-	0.83	0.96	0.97	0.77	0.93	0.95	0.78
E_2 *v.* LE-β	-	0.67	0.88	0.90	0.35	0.81	0.85	-
R_{os} *v.* LE-EC	0.94	0.90	0.93	0.93	0.86	0.90	0.91	0.81

Figure 8b is similar to Fig. 8a; the data set $ANETZ_H$ is used instead of TOWER for the simulation of ET with PREVAH. Also in this case the use of Turc and Wendling leads to better correlation to LE than using Monteith (Table 5). Both the statistical analysis (smaller R_{OS} and E_2) and the visual comparisons indicates a larger scatter of the simulated ET-values with respect to the 1:1 line values in the case of the simulation using the $ANETZ_H$ data set. Both R_{OS} and E_2 decrease largely when using Monteith for evapotranspiration. This indicates problems in the spatial interpolation of the meteorological elements other than precipitation, global radiation and air temperature (i.e. wind speed and water vapour pressure).

The quantitative agreement between LE and the different simulated values is shown on Table 5. The cumulative LE and simulated ET of 7 model runs (values in mm) is calculated at regular time intervals between 15 August and 10 November 1999. Only one model run (Monteith-TOWER) underestimates the cumulative LE during the period considered. Larger ET values are computed using the $ANETZ_H$ and $ANETZ_D$ data sets than with TOWER. The overestimation of LE with the Monteith-approach and interpolated meteorology is very large (more than 30%), even when the three main climate elements are in good agreement with the TOWER data set. The main reason for the increase in ET between the TOWER and the $ANETZ_H$ experiments lies in the amount of precipitation available for soil moisture recharge and runoff generation .

The latent heat flux through eddy correlation observations and analysis (LE-EC) was measured for the period between 2 and 22 September (Fig. 2 left). Similarly to Fig. 8, Fig. 9 shows a comparison between simulated ET by PREVAH and the observed LE, in this case directly determined through eddy correlation and not though the Bowen ratio method as in Fig. 8. The last line in Table 5 indicates the correlation between LE-EC and LE-β and the different model runs. Even though the correlation between LE-EC and the other methods is generally high (i.e. no value below 0.8), both Figs. 9a and 9b show that LE and all ET-simulations are aligned well above the 1:1 line in the two scatter diagrams (Figs. 8a and 8b). Rotach *et al.* (2004) also discusses this systematic overestimation of LE-EC by the other methods. They show that the energy balance is by no means closed at 'Bosco die Sotto', in particular during clear sky days where the valley wind system is fully developed. The energy balance equation in its simplest form reads:

$$NR = H + LE + G \qquad (5)$$

where *NR* is the net radiation, *H* is the sensible heat flux, *LE* is the latent heat flux associated with both evaporation and transpiration, and *G* is the ground heat flux. All terms in Eqn. (5) are in $W \cdot m^{-2}$. The methods to determine LE, which are based on the energy balance closure (i.e. the Bowen ratio approach and the Penman-Monteith equation), assume that Eqn. (5) is closed and assign the whole available energy (*NR* – *G*) to *LE* and *H*.

However, the measurement of all components in Eqn. (5) at the 'Bosco di Sotto' site showed that the gap between the observed (*NR* – *G*) and (*H* + *LE*) can reach several hundreds of $W \cdot m^{-2}$. Rotach *et al.* (2004) suggest that this missing closure of the near-surface energy balance at the test site during the so-called 'valley-wind days' (i.e. periods of fine weather) is most likely related to local advection processes. If it should turn out that indeed the missing energy balance closure is due to local advection and is a consequence of the valley wind system itself, this would give rise to a modification of these methods for the estimation of evapotranspiration in complex terrain and their application at particular sites under specified conditions.

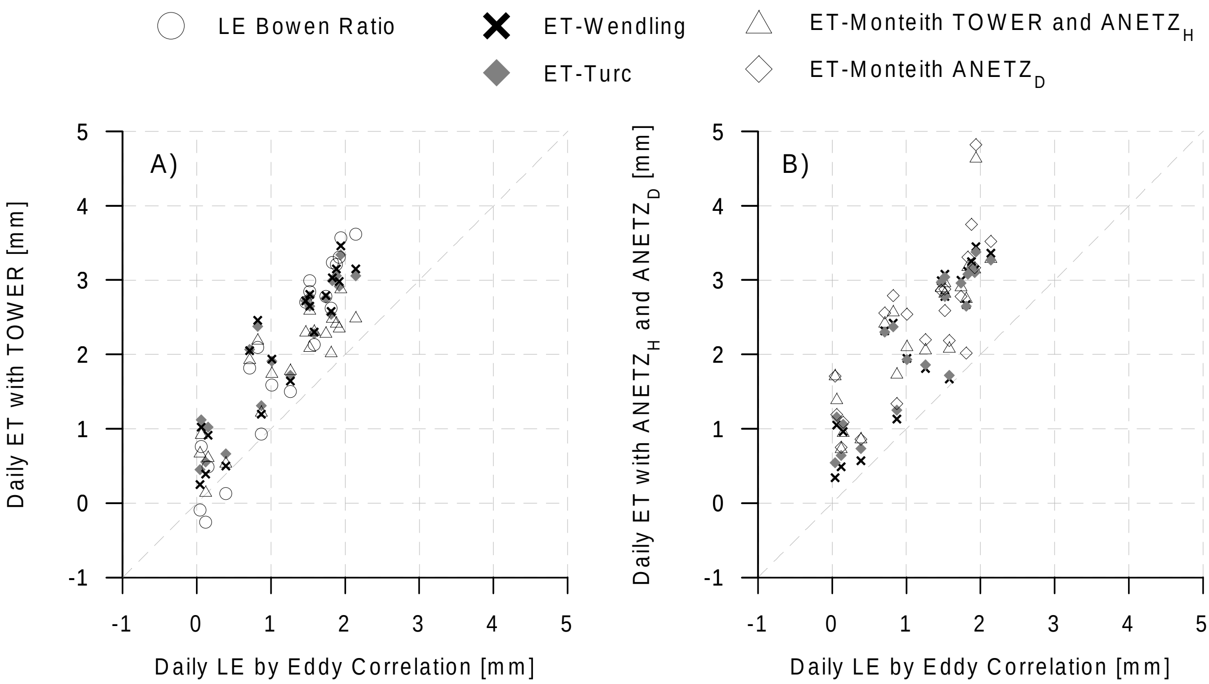

Fig. 9. *Comparison between the daily latent heat flux (LE) observed through eddy correlation and the simulated daily evapotranspiration (ET) between 2 and 22 September 1999 with three evapotranspiration schemes. (A) Model run with the TOWER data set. (B) Model run with the $ANETZ_H$ and $ANETZ_D$ time series.*

R-SOP between 1980 and 2000

Many scientists involved in the MAP-Project have spent some time thinking about what would have been the results of the R-SOP if it had not occurred in 1999, but rather in one of the previous years or in the year 2000 (e.g. Steinacker, 2000a,b). A hydrological completion to this discussion was possible in the case of MAP-Riviera through the 21-year $ANETZ_D$ data set, which is reasonably representative for the investigated area 'Bosco di Sotto' (see previous sections). Figures 10 and 11 show the results of this analysis.

Figure 10 shows the intercomparison of some average elements of the hydrological cycle for the period 1980–2000. As Fig. 10a shows, 1999 was a good choice for the R-SOP with respect to the precipitation amounts, but 2000 would have been even better. 1999 (1063 mm rainfall) is ranked 2nd after the year 2000 (1326 mm) for the amount of precipitation in the period July to November. In 1999, 70% of rainfall occurred before the end of September, while in 2000, 63% of the total precipitation occurred in October and November. This caused a major flood along the Lago Maggiore area. Other major floods in this area occurred in 1987 and 1993 (both in autumn). 1999 was the third warmest year in the 21-years time series under consideration (Fig. 10b). The simulated average plant-available field capacity (Fig. 10c) is highly correlated (R_{os} of 0.81) with the amounts of precipitation. Years with less rainfall are often characterised by large soil moisture deficits (e.g. the year 1991), with the exception of years 1992 and 1998. The sum of precipitation in 1991 up to 20 September is 140 mm, about three times less than in 1992 (383 mm) and 1998 (420 mm). At the end of November, these three years all have a cumulative precipitation of approximately 670 mm. The difference in the temporal occurrence of precipitation is responsible for the large differences in evapotranspiration (Fig. 10d) and average plant-available field capacity (Fig. 10c) between 1991 (dry summer and soils) and 1992/1998 (dry autumn and large evapotranspiration in summer).

Figure 11a shows the average simulated plant-available soil moisture (*SSM*, in percent of *AFC*) of 1999 in comparison with the period average, maximum, and minimum (Monteith is used). Since 1999 was the second wettest July-November period, it can be seen that the average field capacity in the R-SOP year is above the average *SSM* of the last 21 years during most of the R-SOP-period. Additionally the *AFC* in 1999 is coincident with the period

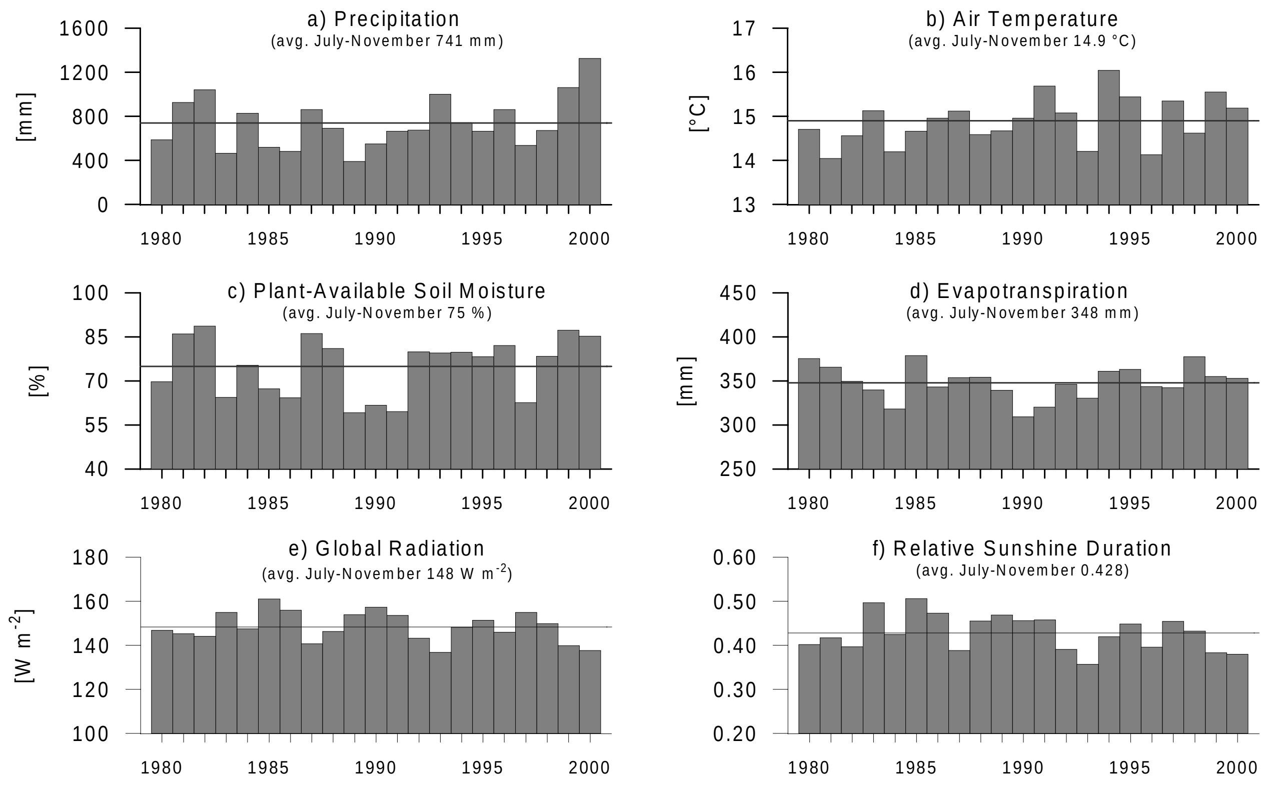

Fig. 10. *Analysis of the $ANETZ_D$ simulation in the period 1980-2000 (July to November only). (a) Total interpolated precipitation. (b) Average interpolated air temperature. (c) Average simulated plantavailable soil moisture in percent of the plant-available field capacity. (d) Average simulated actual evapotranspiration (e) Average global radiation. (f) Average relative sunshine duration.*

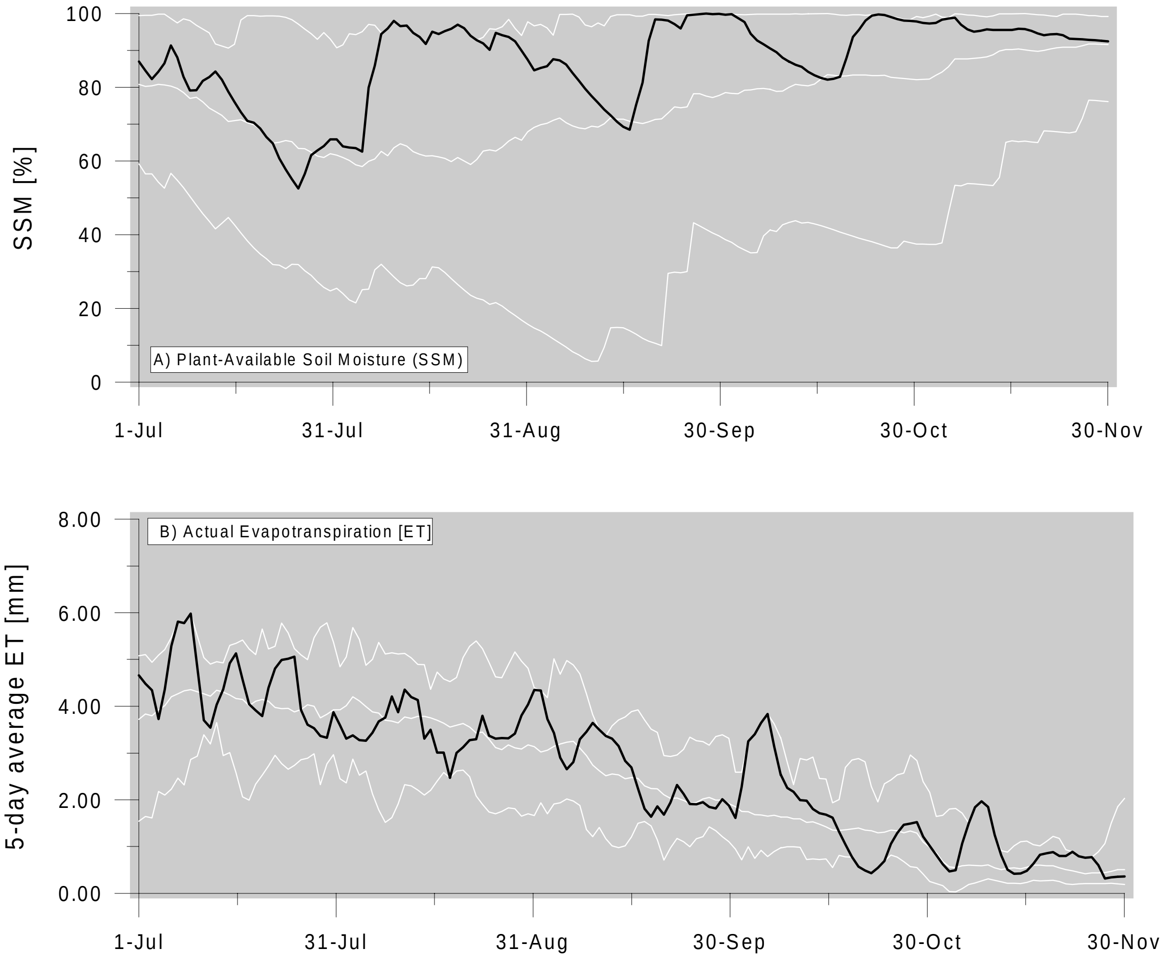

Fig. 11. *a) Maximal, average and minimal simulated plant available soil moisture (in percent of the plant-available field capacity) between July and November in the period 1980-2000 (white lines). The black line indicated the simulated plant-available soil moisture at the end of each day in the MAP-year 1999. b) similar to a) for the 5-day running average of the simulated actual evapotranspiration.*

maximum during several days, mainly after heavier rainfall events. Figure 11b shows a similar analysis as Fig. 11a, but for the 5-day running average of the simulated evapotranspiration. Although 1999 was the third warmest year in the period under consideration and the availability of water for evapotranspiration was high, it can be seen that the time series of evapotranspiration in 1999 is seldom coincident with the period maximum but fluctuates slightly around the period average and touches in some cases the line of the period minimum. 1999 is ranked only 7th with respect to total evapotranspiration in the period from July to November. The main reason for this is the low radiation amount in 1999. With an average of 140 $W \cdot m^{-2}$ 1999 is ranked only 19th for the energy input by global radiation (Fig. 10e), below the period maximum of 161 $W \cdot m^{-2}$ in 1985. 1985 is ranked 1st with respect to evapotranspiration (Fig. 10d).

Conclusions

This paper analyses the quality of the soil moisture module within the hydrological model PREVAH and evaluates the use of interpolated meteorological data sets with different temporal resolution for plot-scale simulations of soil moisture and evapotranspiration.

The methods adopted for the spatial interpolation of the meteorological data from permanent stations of the MeteoSwiss network proved to be accurate for air temperature and global radiation. An accurate interpolation of precipitation was only possible in the case of advective rainfall events. The temporal dynamics of rainfall intensities for thunderstorms and local convective precipitation events were not modelled accurately. In addition, a large over-estimation of the total rainfall is present in the case of the interpolated data set with hourly time steps. The underestimation of the rain intensities, particularly if using a daily time step, leads to systematic errors in the computation of the soil moisture. Such systematic errors disappear as soon as both the modelled soil zone and the real soil zone reach field capacity during a persisting advective precipitation event. The development of a more robust method for spatial rainfall interpolation should be considered for the hydrological model for both plot-scale and spatially distributed applications.

Both the statistical and the subjective visual analyses showed that PREVAH has a simple conceptual soil model that performs well. The good results during the calibration phase were confirmed by both the analysis of the validation period and the simulations with interpolated meteorology. The assessment of the quality of the soil model is only possible when detailed specific observations are available at the plot-scale. This underlines the importance of performing process-related investigations, both in instrumented research catchments (Schlosser *et al*., 1997; Gurtz *et al*., 2003) and within the framework of term-projects such as MAP.

The performance analysis of three simple parameterisations for evapotranspiration showed better correlation with observations when the local meteorology is used. The hydrological modellers' generally used approach of Penman-Monteith resulted in poorer correlations than the more conceptual parameterisations after Wendling and Turc. The reasons for such partial failure of the Penman-Monteith scheme can be found in the preprocessing and assimilation of the interpolated wind speed data. Wendling and Turc have the additional advantage that less climate data are needed. However, their usefulness for spatially distributed simulation is low, since there is little chance of parameterisation of these two schemes for different land use types. This limitation is not present for the Monteith approach, which is therefore preferred by modellers if all the required meteorological data are available. The available data set proved suitable for evaluation of the quality of the component of a rainfall-runoff model. Further work will include the use of the same data set to assess the quality of selected land surface schemes with different degrees of complexity.

This study also showed that the MAP-year 1999 was a good choice for the scientists interested in warm and wet weather; both precipitation and air temperature were clearly above average for the last 21 years. The plant-available soil moisture was seldom below the period average between 1980 and 2000. On the other hand, the large precipitation amounts were accompanied by frequent cloudiness which made the MAP-1999 period one of the years with lowest direct radiation.

In a project like MAP-Riviera, the hydrology sub-project was able to benefit from the availability of detailed micrometeorological observations of fellow scientists who were interested in the structure of the turbulence within an alpine valley. The confluence of interest and the exchange of know-how are additional components which allow an unique combination of research activities. The main result of this collaboration so far is the identification of a 'bias term' in the energy balance equation which reduces the available energy for evapotranspiration on clear-sky days when an internal wind system develops within valleys. If this assertion is confirmed, it is possible that both the hydrology and the atmospheric science communities will have to rethink the parameterisation of the turbulent fluxes in valleys. In the case of rainfall-runoff models, the reduction in evapotranspiration through energy consumption for the development of a valley wind system would mean higher average soil moisture and, therefore, a reduced need of moisture recharge during precipitation which would mean higher water availability for runoff generation.

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