# Modelling Key Parameters Characterising Land Surface in 1D Space using the SimSphere SVAT model: Findings from its use at European Ecosystems

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**ABSTRACT**

The present study investigates the ability of SimSphere, a Soil Vegetation Atmosphere Transfer (SVAT) model, to predict key parameters in characterising land Surface interactions. In particular, the model's performance in predicting Net Radiation ($R_{net}$), Latent Heat (LE), and Sensible Heat (H) was examined. For this purpose, concurrent *in-situ* measurements of the corresponding parameters for a total of 70 days of the year 2011 from 7 CarboEurope network sites were acquired, incorporating a variety of environmental biomes and climatic conditions in the model evaluation. In overall, SimSphere was largely able to accurately predict the variables against which it was evaluated for most of the experimental sites. Statistical analysis showed highest agreement of H fluxes to the measured *in-situ* values for all ecosystems, with an average RMSD of 55.36 $Wm^{-2}$. Predicted LE fluxes and $R_{net}$ also agreed well with the corresponding *in-situ* data with RSMDs of 62.75 $Wm^{-2}$ and 64.65 $Wm^{-2}$ respectively. Our findings contribute towards a better understanding of the model structure, functioning and its correspondence to the real world system. Also further establish its capability as a useful teaching and research tool in modelling Earth's land surface interactions. This is important given its increasing use, including its synergies with Earth Observation data.

**KEYWORDS:** *SimSphere, Validation, SVAT, CarboEurope, Earth Observation*

# 1 INTRODUCTION

Accurate monitoring of water and vegetation stress is now of prominent global concern and it is regarded as a high priority issue (Petropoulos et al., 2016). Much emphasis is placed on the accurate monitoring of the effects of climate change on water and vegetation, particularly for communities located in the Mediterranean region having water scarce ecosystems (Amri et al., 2014). Thus, studies on the partitioning of incoming energy into heat and water fluxes is crucial in understanding the mechanism of climate change. The terrestrial boundary layer and its vegetation play a critical role in regulating the partitioning of incoming energy (into Latent (LE), Sensible (H) and Ground (G) heat fluxes), having an effect in photosynthesis and the energy and water vapour cycles (Prentice et al., 2014).

Research on improving our understanding of the representation of land atmosphere interactions has led to the development and exploration of a wide variety of different modelling schemes. A number of Land Surface Models (LSMs) for assessing the contribution of different variables associated with land surface interaction at various degrees of complexities have been developed since the 1970's. Since then, LSMs have evolved from simple bucket models without vegetation consideration (e.g. Manabe, 1969) into contemporary versions with credibly detailed representations of the exchanges of energy, water and $CO_2$ in the soil-vegetation-atmosphere continuum. Among various forms of LSMs, Soil Vegetation Atmosphere Transfer (SVAT) models are increasingly gaining recognition in land surface processes and Earth's system component studies (Ireland et al., 2015). SVATs are mathematical representations of vertical 'views' of the physical mechanisms controlling energy and mass transfers in the soil -vegetation-atmosphere continuum. Those models are able to provide deterministic estimates of the time course of soil and vegetation state variables at time-steps compatible with the dynamics of atmospheric processes. Fine temporal resolution (often <1 hour) of SVAT models allows simulations to be in satisfactory agreement with the timescale of the physical process being simulated.

Developed by Carlson and Boland (1978), SimSphere is a SVAT model that simulates and enhances our understanding of boundary layer processes and is being extensively used as a research, educational and training tool within several universities worldwide. SimSphere these days has gained a lot of popularity as an extensive tool being synergistically used with Earth Observation (EO) data due to its ability to provide spatio-temporal estimates of evapotranspiration (ET) rates and surface soil moisture. Most of these investigations have been based around the implementation of a data assimilation technique termed the "triangle" (Petropoulos & Carlson, 2011). Variants of this technique are currently investigated by different Space Agencies for developing related operational products (Chauhan et al., 2003; Piles et al., 2011; Piles et al., 2016). A series of SA experiments have already been conducted on SimSphere (Petropoulos et al., 2009b; Petropoulos et al., 2013a-c; 2014). Those studies provided for the first time independent evidence to enhance our understanding of the model's behaviour, coherence and correspondence to that it has been built to simulate (Petropoulos et al., 2009a; Petropoulos et al., 2013a-c; 2014). However, SimSphere validation has previously only been performed over a very small range of land use/cover types (e.g. Todhunter and Terjung, 1987; Ross and Oke, 1988; Petropoulos et al., 2015). Given its current global expansion, such a comprehensive validation of it is both timely and of fundamental importance to further establishes the model's structure, coherence and representativeness in terms of its ability to realistically represent Earth's land surface interactions.

In light of the above, this study's objective has been to investigate the ability and applicability of SimSphere to simulate a series of significant variables characterising land surface interactions and specifically: Net Radiation ($R_{net}$), Latent Heat (LE) and Sensible Heat (H). For this, purpose, *in-situ* measurements a total of 70 days selected from 7 model European ecosystems sites representative of different conditions the CarboEurope monitoring network in Europe have been used to validate the model's output.

## 2 MODEL FORMULATION

SimSphere simulates the land-atmosphere exchanges taking place in a vertical column that extends from the root zone below the soil surface up to a level well above the surface canopy, the top of the surface mixing layer. SimSphere was considerably modified to its current state by Gillies et al. (1997) and later by Petropoulos et al. (2013d) and Anagnostopoulos et al., (in press). It is currently maintained and freely distributed by Aberystwyth University, United Kingdom (http://www.aber.ac.uk/simsphere). A detailed description of its architecture can be found in Gillies (1993) and an overview on its use can be found in Petropoulos et al., (2009 b).

Briefly, SimSphere is a 1-dimensional two-source SVAT model with a plant component (input parameters shown in **Table 1**). The model structure is an integrated form of 3 major components namely the *physical, vertical* and *horizontal* layers. The *physical* component determines the microclimate in the model and primarily takes account of the available radiant energy radiant energy reaching the surface in clear sky condition or the plant canopy. The component is calculated as a function of sun and Earth geometry, atmospheric transmission factors for scattering and absorption, the atmospheric and surface emissivity's and surface (including soil and plant) albedos. The *vertical structure* components (Fig. 1, right), effectively corresponds to the components of the Planetary Boundary Layer (PBL) that are divided into three layers - a surface mixing layer, a surface of constant flux layer and a surface vegetation or bare soil layer. Vegetation and soil fluxes mix at the top of the vegetation canopy. Their relative weights depend on the fractional vegetation cover (FVC), specified as an input to the model. The soil hydraulic parameters are prescribed from the Clapp and Hornberger (1978) classification. The soil surface turbulent fluxes are determined following the Monin and Obukhov (1954) similarity theory which takes into account atmospheric stability. The Atmospheric Boundary Layer (ABL) conditions are provided by a one dimensional ABL model.

SimSphere simulates the processes and the interaction between soil, plant and atmosphere layers over a 24-hour cycle. The cycle runs at a chosen time step, starting generally from the early morning (at 06: 00 am local time) to monitor the continuously evolving interaction between the input layers. A number of input parameters are required to parameterise the model, categorised into 7 defined groups (**Table 1**) and the model provides predictions as a function of time for a total of more than 30 variables (**Table 1**).

**Figure 1***: (Left) The three facets of SimSphere Architecture , (Right) different layers represented within SimSphere's vertical domain*

## 3 MATERIALS AND METHODS

**Figure 2** provides details of the methodology followed to parameterise and validate SimSphere targeted outputs, whereas the major steps involved in this process are outlined below.

### 3.1 *In-situ* Datasets Collection

This study evaluates the ability of SimSphere Soil Vegetation Atmosphere Transfer (SVAT) model in providing diurnal estimates of key variables characterising water and energy balance at 7 CarboEurope sites, part of a larger observational network, FLUXNET (Baldocchi et al., 2001),. The sites used in our study were selected as representative of different ecosystem types (see **Table 2**). *In–situ* data for selected sites were acquired from the European Fluxes database Cluster (http://gaia.agraria.unitus.it/) for the year 2011. In particular Level 2 data were obtained across all selected sites for consistency. This product includes the originally acquired *in-situ* measurements from which only the removal of erroneous data caused by obvious instrumentation error were undertaken. In addition, atmospheric profile (i.e. radiosonde) data as atmospheric temperature profile, dew point temperature, wind direction, wind speed and atmospheric pressure were obtained for each site/day from the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html).

**Figure 2:** Overall methodology of SimSphere validation followed in this study

Initially, for each site, cloudy days were identified and were subsequently excluded from further analysis. Identification of cloudy days was carried out using diurnal incoming global solar radiation (Rg) observations. As cloud-free days were flagged as those having smoothly symmetrical Rg curves and as cloudy those having an asymmetrical one (Carlson et al., 1991). Subsequently, energy balance closure (EBC) for those clouds free days only was evaluated. EBC is believed to be the most relevant energy measurement tool as its magnitude depends on more accurate entities such as Latent Heat (LE) and Sensible Heat (H) and not on other scaler fluxes such as $CO_2$ (Wilson et al., 2002; Foken et al., 2006). EBC was evaluated principally by calculating the linear regression coefficients (slope and intercept) as well as the coefficient of determination ($R^2$) from the ordinary least squares (OLS) relationship between the half-hourly estimates of the dependent flux variables (LE+H) and the independently derived available energy ($R_{net}$-G-S). In addition, the Energy Balance Ratio (EBR) was also computed by cumulatively summing $R_{net}$-G-S and LE+H from the 30-min mean average surface energy flux components, and then rationing each of the cumulative sums as follows (Liu et al., 2006):

$$EBR = \frac{\sum (LE + H)}{\sum (Rnet - G - S)} \qquad (1)$$

where LE is the Latent Heat, H is the Sensible Heat, $R_{net}$ is the net radiation, G is the heat flux into the soil, and S is the rate of change of heat storage (air and biomass). This index ranges generally from zero to one, with values closer to one highlighting a satisfactory diurnal energy closure, indicating a good quality of *in-situ* measurements.

All days with low EBC (i.e. EBR<0.750, slope < 0.85, $R^2$< 0.930) were excluded from further analysis. Further constraints were applied to calibrate the selected data quality with the *in-situ* data quality which was performed over several steps. Secondly, atmospherically stable conditions, such as low wind speeds and small available energy, were selected for the evaluation simulation days (Maayar et al., 2001). Such conditions were identified during evaluation of the *in-situ* dataset, where direct measurements of wind speed and energy flux amplitude and diurnal trend were used as indicators of atmospherically stable conditions. In total a set of 70 non-consecutive days from the 7 CarboEurope sites were identified as being suitable to include in the model verification.

## 3.2 SimSphere Parameterisation & Implementation

SimSphere parameterisation was carried out at the measurement scale of the flux tower observations, i.e. the area of the possible measurement fetch around which the tower is built and the footprint of the turbulent flux measurements, representing an area of ~1km$^2$ for the test sites as they are relatively homogeneous. On this basis, SimSphere was parameterised to the daily conditions existent at the flux tower for each of the selected days.

For each day the model was parameterised to the daily existing conditions at the flux tower up to a height of 54,000ft. Initial conditions for air temperature, dew point temperature, atmospheric pressure, wind speed and direction were used within the 'Wind Sounding' and 'Water Vapour Sounding' components of the model. These details were data were acquired from the publically available University of Wyoming database, and were collected at 6:00am GMT to correspond to the model's initialisation. Ancillary information on vegetation and soil parameters (e.g. Leaf area index - LAI, FVC, vegetation height, soil type etc.) was also used directly within the model's initialisation. Such information was acquired in most cases directly from communication with the principal investigators of each respective site, though in some cases it had to be acquired from standard literature sources (e.g. Mascart et al., 1991; Carlson et al., 1991). The soil type parameters were obtained using the soil texture data provided at each CarboEurope test site. Similarly, this was also the case for the topographical information that was required in model initialisation. Upon model initialisation, the model was executed for each site/day and the 30' average value of each of the evaluated parameters per site for the period 0530-2330 hours was subsequently exported in SPSS for comparisons against the corresponding *in-situ* data.

## 3.4 Validation

To analyse the correlation of the model simulated values to the observed, a series of statistical approaches based on the results of many previous similar studies (e.g. Giertz et al., 2006; Marshall et al., 2013). Those included were root mean square difference [RMSD], the linear regression fit model coefficient determination [$R^2$], the Bias or Mean Bias Error [MBE], the Scatter or mean standard deviation [MSD], the mean absolute error [MAE] and the NASH index, tabulated in **Table 3**. MSD was employed to express the model precision and ultimately for the correction of non- systematic error. All statistical matrices were computed from the comparative analysis of the two datasets for each day of comparison at 30' intervals. The same set of statistical metrics was performed on the dataset for each of the CarboEurope sites for each of the selected days.

# 4 RESULTS

## 4.1 Net Radiation ($R_{net}$) flux

The results of the analysis between SimSphere predicted and *in-situ* Net radiation measurement are summarised in **Table 4**. Furthermore, **Figure 3a** illustrates the agreement between the *in-situ* and the predicted $R_{net}$ for all days of comparisons from all experimental sites. For most of the compared days diurnal variation of the simulated $R_{net}$ in general was found in close correspondence with the observed $R_{net}$ both in shape and magnitude (although results are not shown here for brevity).

In overall, $R_{net}$ simulated by SimSphere was found to be reasonably accurate with an average RMSD of 64.65 Wm$^{-2}$ and a correlation coefficient of 0.96. A minor underestimation of the *in-situ* data was evident for all sites and days combined (MBE = -2.07 $Wm^{-2}$), though overall $R_{net}$ showed a significant range of agreement, with RMSD ranging from 24.38 to 98.26 $Wm^{-2}$ between the validation days. Interestingly, a noticeable trend between extended observation time period and simulation accuracy was observed within a number of test sites. Also, notably, there were increased periods within a number of test sites where simulation accuracy was found increasing depending on the period in which the simulation days were located. Such trends were observed for the IT_Ro3 cropland site, where error ranges decreased for the period between late April (21/04/2011) and late August (28/08/2011), before increasing in early September (09/09/2011). However, the periods of increased accuracy varied on a per site basis and were only prevalent within the olive plantation (ES_Lju), grassland (IT_Mbo), cropland (IT_Ro3) and deciduous broadleaf forest (IT_Col) sites. Daily $R^2$ values exhibited less variance with generally more comparable ranges (0.909 – 0.998) between all the study days, suggesting a satisfactory agreement between both datasets, also illustrated by the distribution of the points around the 1:1 line in **Figure 3a**. This was also reflected within the NASH index values reported (0.897 – 0.999).

When averaged per site, RMSD showed significantly less variance, exhibiting a range from 55.86$Wm^2$ (IT_Lav) to 68.49 $Wm^{-2}$ (FR_Pue). This trend was also reflected by lower variance in correlation coefficients ($R^2$ = 0.936 – 0.970) and NASH index values (0.943 – 0.981) for the per site averages. The evergreen needle-leaf forest site, IT_Lav, consistently demonstrated the highest model performance in simulating $R_{net}$ with an RMSD value of 55.86 $Wm^{-2}$, that being 8.79 $Wm^{-2}$ lower than the overall average. MBE between sites showed significant variability, ranging from a moderate underestimation of the *in-situ* measurements over the evergreen broadleaf forest site (-15.99 $Wm^{-2}$), to a moderate overestimation within the shrubland site (15.02 $Wm^{-2}$). All in all, SimSphere was able to reproduce $R_{net}$ reasonably well in terms of both amplitude and trend. Indeed, this is reflected in the low MSD values of all sites (55.01 - 68.03 $Wm^{-2}$), particularly so at sites such as IT_Lav (55.01 $Wm^{-2}$) and ES_Agu (60.92 $Wm^{-2}$).

**Figure 3:** Comparisons of predicted and observed a) $R_{net}$ fluxes ($Wm^{-2}$), b) LE fluxes ($Wm^{-2}$), c) H fluxes ($Wm^{-2}$), and d) Tair at 50m (°C)

## 4.2 Latent Heat (LE) flux

SimSphere simulated LE flux and the CarboEurope LE measurement for all combined days exhibited an overall average RMSD error of 62.75 $Wm^{-2}$ and a correlation coefficient value of 0.542 respectively (**Table 5**). Although RMSD for the LE output showed a better agreement in comparison to the $R_{net}$ output (section 4.1), $R^2$ was significantly lower (a decrease of 0.408). As can be seen from **Figure 3b**, the distribution of points shows an increased dispersion from the 1:1 line in comparison to the $R_{net}$ output. There was also an apparent overestimation of the *in-situ* measurements by the model for the LE flux (MBE = 15.78 $Wm^{-2}$). $R^2$ values varied significantly between all simulation days from 0.020 – 0.961, suggesting notable discrepancies between the predictions and observations. Additionally, daily RMSD values also varied significantly, reflecting the trends observed in the $R^2$ statistics. RMSD varied from 22.08 $Wm^{-2}$ to 86.45 $Wm^{-2}$ between all days of simulation. When analysed on a site by site basis, average RMSD exhibited comparable ranges to those reported for the individual simulation days, with RMSD varying from 37.25 $Wm^{-2}$ (ES_Agu - Shrubland) to 75.36 $Wm^{-2}$ (IT_Col, deciduous broadleaf forest). On a per site basis, ES_Agu shrubland site consistently demonstrated above average correlation to the *in-situ* measurements with the lowest RMSD and MAE values of all sites, 37.25 $Wm^{-2}$ and 25.58 $Wm^{-2}$ respectively. Lowest agreement between the LE fluxes predicted from SimSphere and those from the *in-situ* measurements was in the IT_Col deciduous broadleaf forest site (RMSD = 75.36 $Wm^{-2}$, MAE = 55.86 $Wm^{-2}$) and IT_Mbo grasslands site (RMSD = 74.66 $Wm^{-2}$, MAE = 52.87 $Wm^{-2}$) respectively. On the whole, SimSphere was consistent in terms of its ability to reproduce *in-situ* LE fluxes, with low MSD values across most sites. Yet, the IT_Mbo (grassland) and IT_Ro3 (cropland) sites exhibited the largest MSD of 74.58 $Wm^{-2}$ and 68.48 $Wm^{-2}$ respectively, an increase of 15.64 $Wm^{-2}$ and 9.54 $Wm^{-2}$ on the overall average suggesting a weaker systematic replication of LE fluxes over those sites (**Table 5**). There was a systematic overestimation of LE for the majority of sites. Exceptions were only the IT_Mbo and IT_Ro3 sites, exhibiting a small average underestimation (MBE) of -3.45 $Wm^{-2}$ and -0.87 $Wm^{-2}$ respectively. Interestingly, both broad-leaf forest sites, IT_Col (deciduous broad-leaf forest) and FR_Pue (evergreen broad-leaf forest), showed the highest overestimation of LE fluxes with moderately high MBE values of 33.67 $Wm^{2}$ and 37.56 $Wm^{-2}$ respectively.

## 4.3 Sensible Heat (H) flux

Concerning the H fluxes, results showed high performance of the model in simulating values for H fluxes with an average RMSD of RMSD of 55.36 $Wm^{-2}$ and an $R^2$ value of 0.83 ( **Figure 3c , Table 6**). A significant improvement in the accuracy of the simulation of the model output in comparison to both the $R_{net}$ and LE was evident. H flux results exhibited a decrease in overall RMSD of 9.29 $Wm^{-2}$ and 7.39 $Wm^{-2}$ respectively. Similar trends were also evident in both the MBE (-0.08 $Wm^{-2}$) and MSD (53.56 $Wm^{-2}$) results for this output, where model performance was better in comparison to both the $R_{net}$ and LE outputs. Although with regards to $R^2$, the H flux output exhibited a minor decrease in correlation (0.83) compared to the $R_{net}$ output When examining the $R^2$ values for the individual simulation days, there was a significant variation in both correlation coefficients ($R^2$ = 0.607 – 0.982) and RMSD (RMSD = 20.03 - 91.07 $Wm^{-2}$). RMSD ranged from 35.50 $Wm^{-2}$ (ES_Agu) to 71.93 $Wm^{-2}$ (IT_Ro3) on a site by site basis. Similarly to LE flux, the ES_Agu site reported the highest simulation accuracy (RMSD = 35.50 $Wm^{-2}$, $R^2$ = 0.944, MBE = -7.01 $Wm^{-2}$, MSD = 34.80 $Wm^{-2}$). On the contrary, the cropland site IT_Ro3 consistently reported a less satisfactory agreement between model prediction and *in-situ* data for H flux. Generally, SimSphere was often unable to represent the peak of H flux across all sites diurnally; this is shown by a scatter of peak values as reported in **Figure 3c.** However, the model did neither consistently overestimate nor underestimate H flux, but produced a range of bias values, with an average error of -0.08 $Wm^{-2}$. Both the FR_Pue and ES_Lju sites showed a predominant underestimation of H flux at -16.29 $Wm^{-2}$ and -17.17 $Wm^{-2}$ respectively. Yet, for the IT_Mbo site, a moderate overestimation of 16.41 $Wm^{-2}$ was reported, suggesting land cover type may be related to simulation accuracy.

# 5. DISCUSSION

This study presents an evaluation of the SimSphere SVAT model's ability in simulating key variables characterising Earth's land/surface interaction across a range of European ecosystems. The model was parameterised for seven sites where a total of 70 days (10 days per site) from the year 2011 were selected to validate the model's ability to predict Net Radiation ($R_{net}$), Latent Heat (LE) and Sensible Heat (H). The agreement between the two datasets was evaluated based on a series of computed statistical metrics using, as reference, in-situ data acquired from selected sites belonging to the CarboEurope monitoring network.

In overall, results showed highest agreement of H fluxes to the measured *in-situ* values for all ecosystems, with an average RMSD of 55.36 $Wm^{-2}$. Predicted LE fluxes and $R_{net}$ also agreed well with the corresponding *in-situ* data with RSMDs of 62.75 $Wm^{-2}$ and 64.65 $Wm^{-2}$ respectively. Very high values of the Nash-Sutcliffe efficiency index were also reported for all of the model outputs evaluated ranging from 0.720 to 0.998, suggesting a very good model representation of the observations.

Those findings are largely in accordance to previous analogous verification studies reported on the model. For example, Ross and Oke (1988) performed a validation of a previous version of SimSphere over an urban environment of Vancouver, Canada and reported an acceptable agreement for H fluxes (average RMSE = 56 $Wm^{-2}$); however significant average error ranges for LE fluxes (RMSE = 107 $Wm^{-2}$) were also reported in their study. Also, Ross & Oke (1988) noted that noted that peak values of air temperature diurnal variability should be observed between 1030 – 1430 LST, this is in close correlation to this present study, further appraising SimSphere's representation of $T_{air}$ at 50m. Todhunter and Terjung (1987) further described in detail how earlier versions of SimSphere dissipated too much of Rnet as LE flux and too little to be lost to H; the latter correlates well to the Ross and Oke's findings (1988) but also the findings reported within; where average bias values indicate general net overestimations of LE flux in the order of 15.78 $Wm^{-2}$, compared to the slight average underestimation of H flux at -0.08 $Wm^{-2}$. Yet when compared with $R_{net}$, the simulated values of LE and H fluxes demonstrated improved model performance confirmed by the low average RMSD and high overall $R^2$**.** Petropoulos et al. (2015) in a verification of the model outputs at ecosystems located in the USA and Australia a good agreement between the model predictions and the *in-situ* measurements (particularly so for the LE, H, with RMSDs of 39.47 $Wm^{-2}$ and 55.06 $Wm^{-2}$ respectively).

Among all selected experiment sites, the shrubland located at ES_Agu consistently showed remarkably low average RMSD in all model outputs assessed, particularly so for LE and H fluxes. This is likely to be related to the site's characteristics, located within a water limited environment, where transpiration effects are much lower in amplitude and thus more predictable, especially given the site's relative homogeneity (Maayar et al., 2001). Akkermans et al. (2012) stated that underestimations of LE can largely be attributed to overestimations of H. Such effects were seen most prominently in our validation site ES_LJU, where a general underestimation of LE (MBE = -17.17 $Wm^{-2}$) partly contributed to the significant overestimation of H flux (MBE = 21.09 $Wm^{-2}$). Also, for example Marshall et al. (2013) have suggested that ecosystems which exhibit increased stand complexity and heterogeneity, such as forested environments (particularly those with understory vegetation), can have a profound effect on the overall exchange of mass and energy.

In the overall evaluation of the results concerning the model agreement to the *in-situ*, instrumentation uncertainty in the measured variables themselves should also be partially taken into account when attempting to explain the disagreement between the simulated and observed variables (Bellocchi et al., 2010; Oncley et al., 2007; Verbeeck et al., 2009). Generally, $R_{net}$ measurement accuracy error is in the order of 10 %, although, an additional 10% instrumentation uncertainty should be added due to limited view angle/measuring volume (especially in the case of rugged terrains) (Baldocchi et al., 2001). Typical uncertainty in the LE and H estimation using the eddy covariance generally varies between 10% to 20% but can be much higher during periods of low flux magnitude and/or limited turbulent mixing such as at night (Petropoulos et al. 2013d). For example, Hollinger and Richardson (2005) showed that uncertainty in flux measurements is inversely proportional to magnitude, the smaller the flux the greater the relative uncertainty. Also, it should be noted that for some days included in our comparisons, a characteristic of the acquired *in-situ* data for those days was the presence of many spikes (indicative of very high or very low values). Possible reasons for those spikes could be instrumental errors, horizontal advection of $H_2O$ and $CO_2$, footprint changes as well as a non-stationarity of turbulent regime within the atmospheric surface layer (Papale et al., 2006). For those days, comparisons resulted in a somewhat lower accuracy of model predictions as such conditions cannot be replicated by the model which assumes homogeneity of vegetation canopy and ignores horizontal advection.

On the whole, despite the occasionally inferior performance of SimSphere in simulating the examined model outputs for some days/sites, model predictions were found significant in terms of the representation of the physical and dynamic processes involved in the interactions of the complex nature of the soil-land–atmosphere system. Moreover, it is important to recognise that uncertainty is inevitable in any model, which as a model will never be as complex as the reality it portrays. In this way, SimSphere fulfils its objective as a tool as it identifies the expected trends and patterns of change, if not always the magnitudes.

## 6. CONCLUDING REMARKS

In this study, key findings from a large scale validation of the SimSphere land biosphere model in numerous European environments were reported. In total, the model's ability to predict Net Radiation ($R_{net}$), Latent Heat (LE) and Sensible Heat (H) at 7 ecosystems and for 70 cloud free days in 2011 was examined. A systematic statistical analysis was employed to assess the agreement between model predictions and corresponding *in-situ* measurements. To our knowledge, this is the first study reporting results on the validation of SimSphere's ability in accurately simulating key variables characterising land surface processes, particularly so in European ecosystems.

In overall, SimSphere was able to predict largely accurately the evaluated parameters for most of the experimental sites. The evaluation and analysis of a model performance allowed for an increased understanding of the model's representation. This study results provide further independent evidence that SimSphere has a high capability of simulating variables associated with the Earth's energy and water balance. As noted by Verbeeck et al. (2009), discrepancies found in any validation study should be regarded as a positive step when evaluating model performance. Such studies can also advance our understanding on the amount of complexity required for adequate representation of land surface processes and interactions between different components of our Earth system. Further efforts should be directed towards validating SimSphere at other ecosystems globally as this will allow assessing its applicability as a universally applied SVAT model. Moreover, as use of the model is currently being explored synergistically with EO data, including its possible expansion to a 2D model, it would be of utmost interest to evaluate the overriding effects of SimSphere predictions to the overall prediction error derived from such synergistic methods.

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# List of Figures



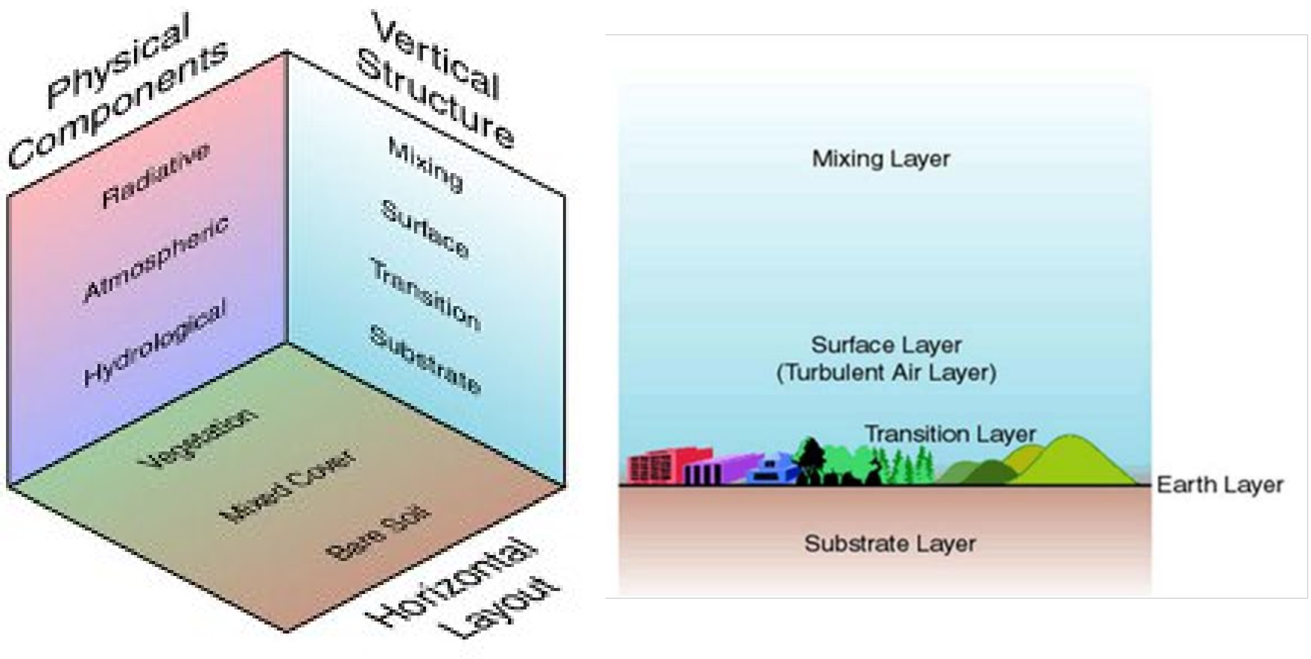


**Figure 1**: *(Left) The three facets of SimSphere Architecture , (Right) different layers represented within SimSphere's vertical domain*

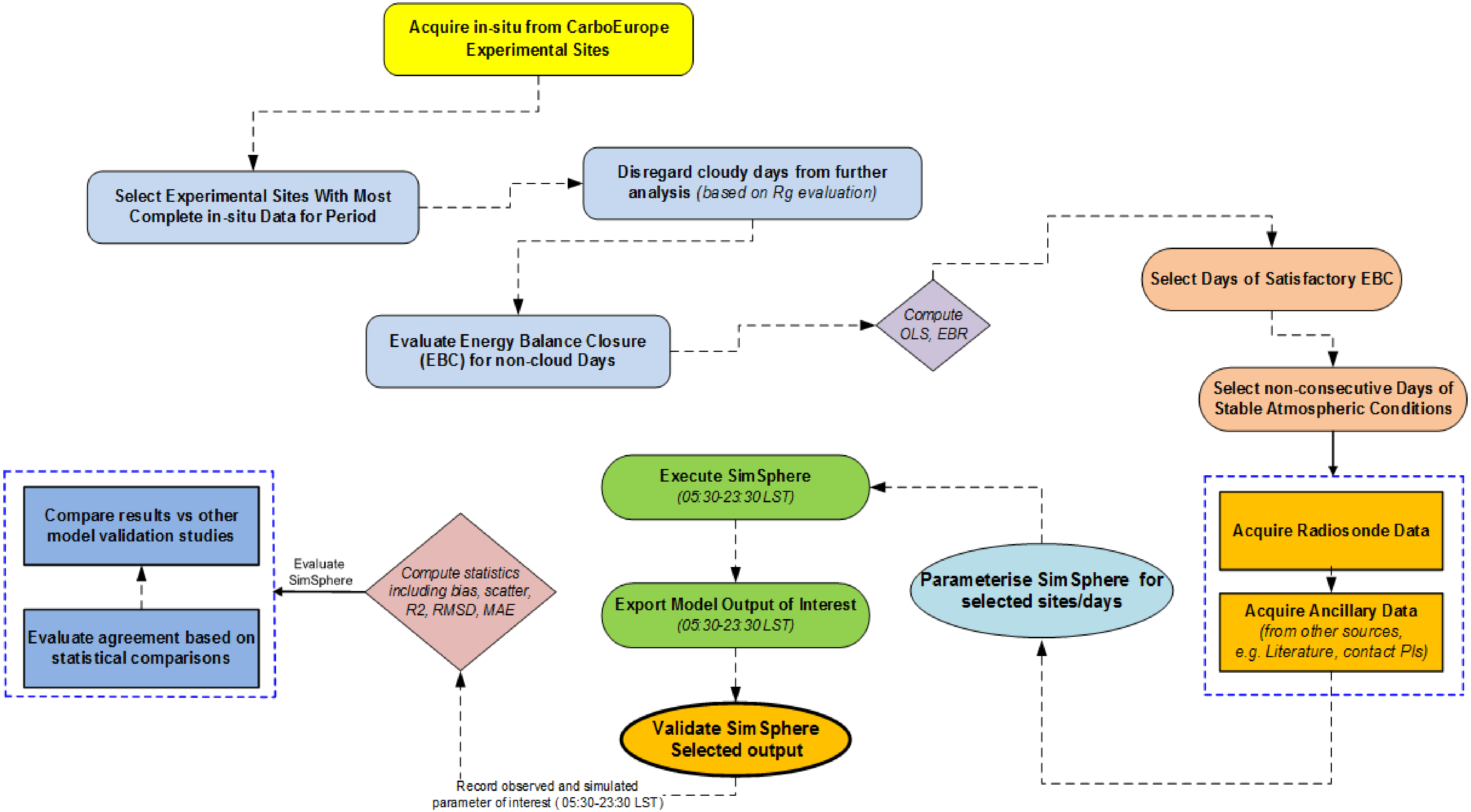


**Figure 2:** Overall methodology of SimSphere validation followed in this study

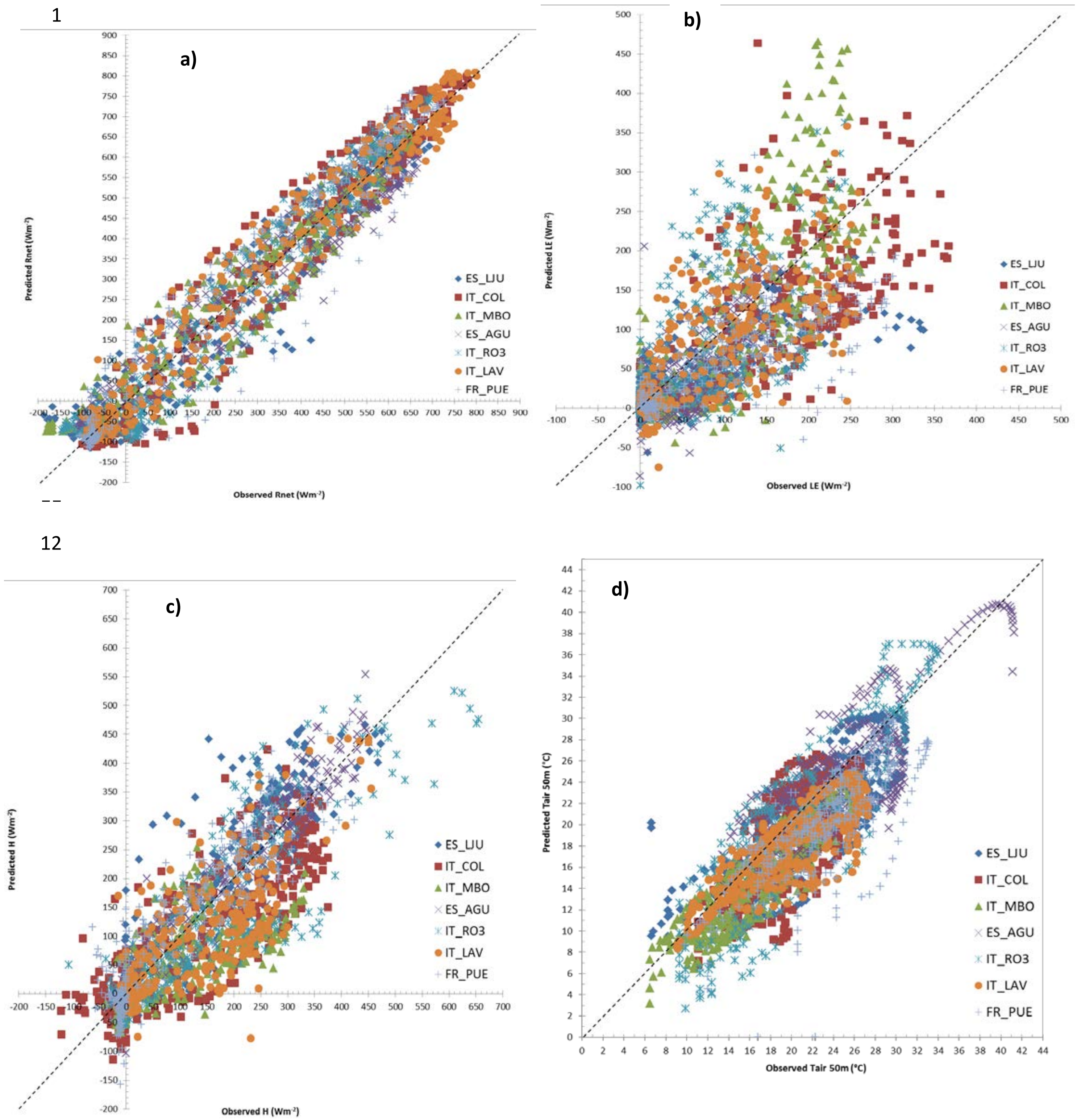


**Figure 3:** Comparisons of predicted and observed a) $R_{net}$ fluxes ($Wm^{-2}$), b) LE fluxes ($Wm^{-2}$), and c)H fluxes ($Wm^{-2}$)

**Table 1:** Summary of the main SimSphere inputs (top) and of its simulated outputs (bottom). The units are also provided in parentheses where applicable

| NAME OF THE MODEL INPUT | PROCESS IN WHICH PARAMETER IS INVOLVED | MIN VALUE | MAX VALUE |
|---|---|---|---|
| Slope *(degrees)* | TIME & LOCATION | 0 | 45 |
| Aspect *(degrees)* | TIME & LOCATION | 0 | 360 |
| Station Height *(meters)* | TIME & LOCATION | 0 | 4.92 |
| Fractional Vegetation Cover *(%)* | VEGETATION | 0 | 100 |
| LAI *( $m^2m^{-2}$)* | VEGETATION | 0 | 10 |
| Foliage emissivity *(unitless)* | VEGETATION | 0.951 | 0.990 |
| [Ca] (external [$CO_2$] in the leaf) *(ppmv)* | VEGETATION | 250 | 710 |
| [Ci] (internal [$CO_2$ ] in the leaf) *(ppmv)* | VEGETATION | 110 | 400 |
| [03] (ozone concentration in the air) *(ppmv)* | VEGETATION | 0.0 | 0.25 |
| Vegetation height *(meters)* | VEGETATION | 0.021 | 20.0 |
| Leaf width *(meters)* | VEGETATION | 0.012 | 1.0 |
| Minimum Stomatal Resistance *( $sm^{-1}$)* | PLANT | 10 | 500 |
| Cuticle Resistance *( $sm^{-1}$)* | PLANT | 200 | 2000 |
| Critical leaf water potential *( bar)* | PLANT | -30 | -5 |
| Critical solar parameter *($Wm^{-2}$)* | PLANT | 25 | 300 |
| Stem resistance *( $sm^{-1}$)* | PLANT | 0.011 | 0.150 |
| Surface Moisture Availability *(vol/vol)* | HYDROLOGICAL | 0 | 1 |
| Root Zone Moisture Availability *( vol/vol)* | HYDROLOGICAL | 0 | 1 |
| Substrate Max. Volum. Water Content *(vol/vol)* | HYDROLOGICAL | 0.01 | 1 |
| Substrate climatol. mean temperature *( $^oC$ )* | SURFACE | 20 | 30 |
| Thermal inertia *( $Wm^{-2}K^{-1}$)* | SURFACE | 3.5 | 30 |
| Ground emissivity *(unitless)* | SURFACE | 0.951 | 0.980 |
| Atmospheric Precipitable water *(cm)* | METEOROLOGICAL | 0.05 | 5 |
| Surface roughness *(meters)* | METEOROLOGICAL | 0.02 | 2.0 |
| Obstacle height *(meters)* | METEOROLOGICAL | 0.02 | 2.0 |
| Fractional Cloud Cover *(%)* | METEOROLOGICAL | 1 | 10 |
| RKS (satur. thermal conduct.*(Cosby et al., 1984)* | SOIL | 0 | 10 |
| Cosby B *(see Cosby et al., 1984)* | SOIL | 2.0 | 12.0 |
| THM (satur.vol. water cont.) *(Cosby et al., 1984)* | SOIL | 0.3 | 0.5 |
| PSI (satur. water potential) *(Cosby et al., 1984)* | SOIL | 1 | 7 |
| Wind direction (*degrees*) | WIND SOUNDING PROFILE | 0 | 360 |
| Wind speed *(knots)* | WIND SOUNDING PROFILE | --- | --- |
| Altitude *(1000's feet)* | WIND SOUNDING PROFILE | --- | --- |
| Pressure *(mBar)* | MOISTURE SOUNDING PROFILE | --- | --- |
| Temperature *(Celsius)* | MOISTURE SOUNDING PROFILE | --- | --- |
| Temperature-Dewpoint Temperature *(Celsius)* | MOISTURE SOUNDING PROFILE | --- | --- |

| SimSphere Simulated Outputs | | | | |
|---|---|---|---|---|
| **Output Name** | **Units** | | **Output Name** | **Units** |
| Air temperature at 1.3m | $^{o}C$ | | Radiometric Temperature | $^{o}C$ |
| Air temperature at 50m | $^{o}C$ | | Root Zone moisture Avail. | n/a |
| Air temperature at foliage | $^{o}C$ | | Sensibel heat flux | $Wm^{-2}$ |
| Bowen ratio | n/a | | Short-wave flux | $Wm^{-2}$ |
| [$CO_2$] on canopy | ppmv | | Specific humidity at 1.3m | $gKg^{-1}$ |
| [$CO_2$] flux | micromolesm$^{2}$s$^{-1}$ | | Specific humidity at 50m | $gKg^{-1}$ |
| Epidermal water potential | Bars | | Specific humidity at foliage | $gKg^{-1}$ |
| Global $O_3$ flux | $Ugm^{-2}s^{-1}$ | | Stomatal resistance | $sm^{-1}$ |
| Ground flux | $Wm^{-2}$ | | Surface moisture availability | n/a |
| Ground water potential | bars | | Vapor pressure deficit | Mbar |
| Latent Heat flux | $Wm^{-2}$ | | Water Use Efficiency | n/a |
| Leaf water potential | bars | | Wind at 10m | Kts |
| Net Radiation | $Wm^{-2}$ | | Wind at 50m | Kts |
| [$O_3$] canopy | ppmv | | Wind in foliage | Kts |
| [$O_3$] flux plant | $Ugm^{-2}s^{-1}$ | | | |

**Table 2:** *Some of the main characteristics of the selected CarboEurope sites used for SimSphere validation.*

| Site Name | Site Abbreviation | County | Geographic Location | PFT | Ecosystem Type | Dominant Species | Elevation | Climate |
|---|---|---|---|---|---|---|---|---|
| Llano de los Juanes | Es_Lju | SPAIN | 36.9266/-2.1521 | OLI | Olive Plantation | Oleaeuropea, Macchia | 1622m | Warm Temperate with dry, hot summer |
| Collelongo-SelvaPiana | It_Col | ITALY | 41.8493/13.5881 | DBF | Deciduous Broadleaf Forest | Fagussylvatica | 1645m | Warm temperate fully humid with warm summer |
| Monte Modone | It_Mbo | ITALY | 46.0296/11.0829 | GRA | Grassland | Alpine meadow | 1547m | Snow fully humid warm summer |
| Aguamarga | Es_Agu | SPAIN | 36.8347/-2.2511 | SHR | Annual Broadleaf Shrub | Sumac (Rhus), Toyon (Heteromeles) and Coffeeberry (Rhamnus) Species | 195m | Arid Steppe Cold |
| Lavarone | It_Lav | ITALY | 45.9553/11.2812 | ENL | Evergreen Needle leaf forest | Pinussylvestris | 1353m | Warm temperate fully humid with warm summer |
| Puechabon | Fr_Pue | FRANCE | 43.7414/3.5958 | EBF | Evergreen Broadleaf forest | Quercus ilex | 211m | Warm Temperate with dry, hot summer |
| Roccarepampani | It_Ro3 | ITALY | 42.3753/11.9154 | CRO | Cropland | Cereal Crop | 320m | Warm Temperate with dry, hot summer |

**Table 3**: *An overview of the statistical measures implemented in this study to evaluate SimSphere's outputs against the corresponding in-situ data*

| Name | Description | Mathematical Definition |
|---|---|---|
| Bias/MBE | Bias (accuracy) or Mean Bias Error | $bias = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)$ |
| $R^2$ | Linear Correlation Coefficient of Determination of $P_i$ to $O_i$ | $R^2 = \left[ \sum_{i=1}^{N}(P_i - \overline{P})(O_i - \overline{O}) \Big/ \left[ \sum_{i=1}^{N}(O_i - \overline{O})^2 \sum_{i=1}^{N} P_i - \overline{O})^2 \right]^{0.5} \right]^2$ |
| Scatter/MSE | Scatter (precision) or Mean Standard Deviation | $scatter = \frac{1}{(N-1)}\sum_{i=1}^{N}(P_i - O_i - \overline{(P_i - O_i)})^2$ |
| RMSD | Root Mean Square Difference | $RMSD = \sqrt{bias^2 + scatter^2}$ |
| MAE | Mean Absolute Error | $MAD = N^{-1}\sum_{i=1}^{N}\lvert P_i - O_i \rvert$ |
| NASH | Nash Sutcliffe Efficiency | $NASH = 1 - \left[\frac{\sum_{i=1}^{N}(Oi - Si)^2}{\sum_{i=1}^{N}(Oi - \bar{O})^2}\right]$ |

**Table 4**: *An overview of $R_{net}$ simulation accuracy*

| Site | PFT | Day | Bias | Scatter | RMSD | MAE | NASH |
|---|---|---|---|---|---|---|---|
| ES_LJU | OLI | 14/04/2011 | -24.55 | 42.31 | 48.91 | 32.45 | 0.921 |
| | | 09/05/2011 | -19.34 | 60.31 | 63.33 | 47.55 | 0.976 |
| | | 24/06/2011 | 12.18 | 67.54 | 68.63 | 57.97 | 0.916 |
| | | 27/06/2011 | 6.06 | 66.98 | 67.25 | 47.26 | 0.978 |
| | | 19/07/2011 | 26.05 | 57.38 | 63.01 | 44.21 | 0.934 |
| | | 28/07/2011 | 34.52 | 56.12 | 65.89 | 47.60 | 0.971 |
| | | 04/08/2011 | 15.06 | 51.08 | 53.25 | 33.81 | 0.930 |
| | | 22/08/2011 | 8.26 | 57.55 | 58.14 | 47.33 | 0.899 |
| | | 25/08/2011 | 10.23 | 59.03 | 59.91 | 49.44 | 0.978 |
| | | 28/09/2011 | -19.69 | 92.19 | 94.27 | 78.84 | 0.998 |
| | | **Average** | **4.88** | **64.78** | **64.96** | **48.65** | **0.950** |
| IT_COL | DBF | 26/06/2011 | -29.91 | 67.82 | 74.12 | 52.94 | 0.969 |
| | | 08/07/2011 | -23.15 | 46.34 | 51.80 | 41.84 | 0.978 |
| | | 13/07/2011 | -12.95 | 56.81 | 58.27 | 50.16 | 0.934 |
| | | 18/07/2011 | -23.69 | 54.99 | 59.87 | 48.72 | 0.978 |
| | | 11/08/2011 | -10.67 | 63.23 | 64.12 | 50.03 | 0.974 |
| | | 23/08/2011 | 14.50 | 64.17 | 65.79 | 54.93 | 0.940 |
| | | 11/09/2011 | 40.85 | 53.96 | 67.67 | 47.63 | 0.899 |
| | | 15/09/2011 | 38.95 | 59.52 | 71.13 | 52.79 | 0.969 |
| | | 16/09/2011 | 18.84 | 70.23 | 72.71 | 50.39 | 0.999 |
| | | 17/09/2011 | 44.54 | 54.46 | 70.36 | 47.23 | 0.920 |
| | | **Average** | **4.61** | **68.03** | **68.19** | **51.16** | **0.956** |
| IT_MBO | GRA | 10/04/2011 | -45.49 | 54.34 | 70.87 | 47.71 | 0.979 |
| | | 10/05/2011 | -22.05 | 41.00 | 46.56 | 37.14 | 0.936 |
| | | 25/06/2011 | -11.70 | 21.39 | 24.38 | 18.92 | 0.901 |
| | | 03/07/2011 | -12.38 | 66.20 | 67.35 | 56.63 | 0.978 |
| | | 24/08/2011 | 40.61 | 55.84 | 69.04 | 46.81 | 0.925 |
| | | 25/08/2011 | 41.22 | 61.04 | 73.66 | 50.97 | 0.978 |
| | | 13/09/2011 | -23.86 | 80.95 | 84.39 | 78.38 | 0.963 |
| | | 21/09/2011 | -21.12 | 75.19 | 78.10 | 69.16 | 0.910 |
| | | 26/09/2011 | -3.44 | 67.29 | 67.38 | 59.95 | 0.912 |
| | | 30/09/2011 | -5.05 | 49.55 | 49.81 | 43.63 | 0.978 |
| | | **Average** | **-6.33** | **65.07** | **65.38** | **50.93** | **0.946** |
| ES_AGU | SHR | 07/04/2011 | -49.42 | 23.11 | 54.55 | 49.42 | 0.978 |
| | | 27/04/2011 | -62.87 | 26.14 | 68.09 | 62.87 | 0.963 |
| | | 08/05/2011 | -41.11 | 19.67 | 45.58 | 41.11 | 0.974 |
| | | 14/05/2011 | -14.87 | 34.17 | 37.26 | 33.38 | 0.954 |
| | | 23/05/2011 | -24.01 | 24.79 | 34.51 | 31.38 | 0.960 |
| | | 13/07/2011 | 27.95 | 26.78 | 38.71 | 32.17 | 0.980 |
| | | 29/07/2011 | 52.86 | 64.52 | 83.40 | 68.43 | 0.979 |
| | | 14/08/2011 | 55.68 | 50.21 | 74.97 | 67.51 | 0.968 |
| | | 26/08/2011 | 59.11 | 52.30 | 78.92 | 70.46 | 0.989 |
| | | 07/09/2011 | 41.81 | 48.79 | 64.25 | 59.21 | 0.972 |
| | | **Average** | 15.02 | 60.92 | 62.75 | 53.40 | 0.972 |
| IT_RO3 | CRO | 09/04/2011 | -8.20 | 85.76 | 86.16 | 76.40 | 0.912 |
| | | 11/04/2011 | -52.87 | 46.21 | 70.22 | 55.97 | 0.913 |
| | | 18/04/2011 | 13.74 | 80.88 | 82.03 | 72.17 | 0.990 |
| | | 21/04/2011 | 24.95 | 56.34 | 61.62 | 55.09 | 0.982 |
| | | 20/06/2011 | -12.51 | 53.15 | 54.60 | 48.95 | 0.937 |
| | | 26/06/2011 | -22.36 | 48.39 | 53.30 | 42.70 | 0.972 |
| | | 24/08/2011 | 13.94 | 54.53 | 56.28 | 41.84 | 0.961 |
| | | 28/08/2011 | -8.98 | 59.95 | 60.62 | 51.20 | 0.899 |
| | | 09/09/2011 | -19.92 | 67.62 | 70.49 | 62.77 | 0.897 |
| | | 11/09/2011 | 2.40 | 68.15 | 68.19 | 55.23 | 0.971 |
| | | **Average** | **-6.98** | **66.53** | **66.90** | **56.23** | **0.943** |
| IT_LAV | ENL | 27/06/2011 | -24.60 | 57.52 | 62.56 | 46.13 | 0.971 |
| | | 03/07/2011 | -60.69 | 39.12 | 72.21 | 63.35 | 0.986 |
| | | 09/07/2011 | -35.90 | 57.43 | 67.73 | 58.59 | 0.971 |
| | | 11/08/2011 | -16.51 | 31.22 | 35.32 | 30.06 | 0.998 |
| | | 12/08/2011 | -0.79 | 31.24 | 31.25 | 24.10 | 0.996 |
| | | 20/08/2011 | 3.59 | 31.32 | 31.53 | 21.85 | 0.975 |
| | | 21/08/2011 | 23.69 | 29.01 | 37.46 | 32.13 | 0.989 |
| | | 24/08/2011 | 47.45 | 25.99 | 54.10 | 47.45 | 0.990 |
| | | 09/09/2011 | 33.71 | 46.83 | 57.70 | 49.08 | 0.979 |
| | | 30/09/2011 | 58.84 | 78.66 | 98.26 | 78.02 | 0.954 |
| | | **Average** | **-9.70** | **55.01** | **55.86** | **44.02** | **0.981** |
| FR_PUE | EBF | 06/04/2011 | -48.91 | 48.89 | 69.15 | 52.63 | 0.978 |
| | | 09/04/2011 | -39.03 | 51.27 | 64.43 | 50.03 | 0.913 |
| | | 16/04/2011 | -57.09 | 45.67 | 73.11 | 57.57 | 0.932 |
| | | 17/05/2011 | -27.98 | 49.22 | 56.62 | 46.95 | 0.946 |
| | | 28/05/2011 | -38.36 | 48.14 | 61.55 | 50.92 | 0.961 |
| | | 19/06/2011 | -58.10 | 49.41 | 76.27 | 64.97 | 0.947 |
| | | 08/07/2011 | -27.62 | 38.41 | 47.31 | 37.66 | 0.975 |
| | | 26/09/2011 | 49.90 | 44.96 | 67.17 | 49.90 | 0.963 |
| | | 14/09/2011 | 60.09 | 48.58 | 77.27 | 60.09 | 0.978 |
| | | 20/09/2011 | 47.71 | 62.85 | 78.91 | 51.51 | 0.938 |
| | | **Average** | **-15.99** | **66.60** | **68.49** | **52.47** | **0.953** |
| **ALL SITES** | | **AVERAGE** | **-2.07** | **63.85** | **64.65** | **50.98** | **0.96** |

**Table 5***: An overview of LE simulation accuracy*

| Site | PFT | Day | Statistical Test | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Bias** | **Scatter** | **RMSD** | **MAE** | **NASH** |
| ES_LJU | OLI | 14/04/2011 | 13.10 | 43.69 | 45.62 | 34.00 | 0.987 |
| | | 09/05/2011 | -8.48 | 37.57 | 38.51 | 26.45 | 0.993 |
| | | 24/06/2011 | 42.62 | 62.22 | 75.42 | 63.34 | 0.977 |
| | | 27/06/2011 | 46.98 | 59.15 | 75.53 | 60.96 | 0.968 |
| | | 19/07/2011 | 17.78 | 25.03 | 30.70 | 23.02 | 0.954 |
| | | 28/07/2011 | 26.35 | 23.88 | 35.57 | 30.00 | 0.961 |
| | | 04/08/2011 | -13.97 | 24.09 | 27.85 | 21.57 | 0.966 |
| | | 22/08/2011 | -3.40 | 38.77 | 38.92 | 28.53 | 0.987 |
| | | 25/08/2011 | 22.97 | 33.43 | 40.56 | 29.31 | 0.902 |
| | | 28/09/2011 | 22.00 | 28.76 | 36.21 | 26.91 | 0.903 |
| | | **Average** | **21.09** | **51.49** | **55.64** | **37.22** | **0.983** |
| IT_COL | DBF | 26/06/2011 | 26.53 | 30.72 | 40.59 | 30.21 | 0.915 |
| | | 08/07/2011 | 2.34 | 71.20 | 71.24 | 51.70 | 0.936 |
| | | 13/07/2011 | 33.33 | 53.23 | 62.81 | 47.75 | 0.976 |
| | | 18/07/2011 | 35.85 | 70.07 | 78.71 | 62.73 | 0.935 |
| | | 11/08/2011 | 32.46 | 68.31 | 75.63 | 65.57 | 0.894 |
| | | 23/08/2011 | -25.34 | 81.15 | 85.01 | 50.98 | 0.900 |
| | | 11/09/2011 | 56.10 | 42.26 | 70.23 | 56.10 | 0.986 |
| | | 15/09/2011 | 60.69 | 49.42 | 78.27 | 61.47 | 0.984 |
| | | 16/09/2011 | 50.25 | 47.72 | 69.30 | 53.45 | 0.987 |
| | | 17/09/2011 | 6.74 | 26.51 | 27.35 | 21.59 | 0.993 |
| | | **Average** | **33.67** | **67.43** | **75.36** | **55.86** | **0.951** |
| IT_MBO | GRA | 10/04/2011 | 16.85 | 25.39 | 30.47 | 21.85 | 0.989 |
| | | 10/05/2011 | -35.35 | 42.72 | 55.45 | 40.52 | 0.913 |
| | | 25/06/2011 | 6.87 | 59.93 | 60.33 | 49.33 | 0.976 |
| | | 03/07/2011 | -26.51 | 73.75 | 78.37 | 56.20 | 0.911 |
| | | 24/08/2011 | -19.29 | 51.79 | 55.27 | 37.79 | 0.978 |
| | | 25/08/2011 | 26.85 | 68.15 | 73.25 | 61.21 | 0.936 |
| | | 13/09/2011 | -8.09 | 44.20 | 44.93 | 36.71 | 0.998 |
| | | 21/09/2011 | 14.93 | 53.34 | 55.39 | 34.19 | 0.936 |
| | | 26/09/2011 | 14.52 | 52.12 | 54.10 | 39.33 | 0.978 |
| | | 30/09/2011 | 26.21 | 37.65 | 45.88 | 33.52 | 0.980 |
| | | **Average** | **-3.45** | **74.58** | **74.66** | **52.87** | **0.959** |
| ES_AGU | SHR | 07/04/2011 | -20.76 | 30.09 | 36.55 | 25.02 | 0.990 |
| | | 27/04/2011 | -21.86 | 29.03 | 36.34 | 28.04 | 0.994 |
| | | 08/05/2011 | -9.68 | 21.12 | 23.23 | 16.54 | 0.996 |
| | | 14/05/2011 | 9.05 | 20.14 | 22.08 | 17.51 | 0.990 |
| | | 23/05/2011 | 10.84 | 25.10 | 27.35 | 19.64 | 0.986 |
| | | 13/07/2011 | 27.01 | 28.63 | 39.36 | 31.06 | 0.884 |
| | | 29/07/2011 | 34.47 | 25.94 | 43.14 | 34.81 | 0.754 |
| | | 14/08/2011 | 25.42 | 24.42 | 35.25 | 28.31 | 0.947 |
| | | 26/08/2011 | 28.00 | 52.61 | 59.60 | 40.41 | 0.975 |
| | | 07/09/2011 | 36.65 | 37.96 | 52.76 | 39.47 | 0.953 |
| | | **Average** | **13.99** | **34.53** | **37.25** | **25.58** | **0.947** |
| IT_RO3 | CRO | 09/04/2011 | -34.88 | 54.19 | 64.45 | 39.69 | 0.996 |
| | | 11/04/2011 | -39.35 | 43.02 | 58.30 | 41.49 | 0.997 |
| | | 18/04/2011 | -17.47 | 21.90 | 28.02 | 20.97 | 0.998 |
| | | 21/04/2011 | 1.65 | 27.69 | 27.74 | 20.70 | 0.998 |
| | | 20/06/2011 | 51.85 | 54.15 | 74.97 | 55.86 | 0.954 |
| | | 26/06/2011 | 38.33 | 31.82 | 49.81 | 39.17 | 0.960 |
| | | 24/08/2011 | 12.15 | 28.29 | 30.79 | 22.73 | 0.984 |
| | | 28/08/2011 | 18.05 | 26.51 | 32.07 | 23.96 | 0.973 |
| | | 09/09/2011 | 46.93 | 45.17 | 65.14 | 47.73 | 0.972 |
| | | 11/09/2011 | 49.09 | 54.13 | 73.07 | 51.67 | 0.986 |
| | | **Average** | **-0.87** | **68.48** | **68.48** | **47.51** | **0.982** |
| IT_LAV | ENL | 27/06/2011 | -9.09 | 38.54 | 39.59 | 29.72 | 0.938 |
| | | 03/07/2011 | 23.40 | 41.88 | 47.97 | 38.47 | 0.973 |
| | | 09/07/2011 | -16.39 | 55.28 | 57.66 | 41.60 | 0.912 |
| | | 11/08/2011 | 32.47 | 44.84 | 55.36 | 41.66 | 0.899 |
| | | 12/08/2011 | 29.70 | 67.43 | 73.68 | 59.10 | 0.937 |
| | | 20/08/2011 | 31.48 | 80.52 | 86.45 | 63.16 | 0.936 |
| | | 21/08/2011 | -12.13 | 45.44 | 47.04 | 33.46 | 0.938 |
| | | 24/08/2011 | -21.87 | 57.06 | 61.11 | 46.97 | 0.989 |
| | | 09/09/2011 | 27.18 | 69.22 | 74.37 | 59.71 | 0.935 |
| | | 30/09/2011 | 9.78 | 40.27 | 55.69 | 48.69 | 0.913 |
| | | **Average** | **8.47** | **58.32** | **58.93** | **41.39** | **0.937** |
| FR_PUE | EBF | 06/04/2011 | 52.85 | 57.24 | 77.91 | 56.05 | 0.980 |
| | | 09/04/2011 | -17.44 | 39.39 | 43.08 | 25.79 | 0.996 |
| | | 16/04/2011 | 43.76 | 41.67 | 60.43 | 45.93 | 0.977 |
| | | 17/05/2011 | 45.00 | 59.73 | 74.78 | 56.06 | 0.990 |
| | | 28/05/2011 | 46.25 | 61.55 | 76.99 | 55.46 | 0.985 |
| | | 19/06/2011 | 28.64 | 43.41 | 52.01 | 39.13 | 0.993 |
| | | 08/07/2011 | 22.05 | 38.52 | 44.38 | 33.47 | 0.983 |
| | | 26/09/2011 | 49.04 | 44.60 | 66.28 | 50.75 | 0.985 |
| | | 14/09/2011 | 62.28 | 39.97 | 74.00 | 62.28 | 0.954 |
| | | 20/09/2011 | 11.54 | 19.56 | 22.71 | 18.02 | 0.987 |
| | | **Average** | **37.56** | **57.77** | **68.91** | **47.46** | **0.988** |
| **ALL SITES** | | **AVERAGE** | **15.78** | **58.94** | **62.75** | **43.98** | **0.964** |

**Table 6***: An overview of H simulation accuracy*

| Site | PFT | Day | Statistical Test Bias | Scatter | RMSD | MAE | NASH | Site | PFT | Day | Statistical Test Bias | Scatter | RMSD | MAE | NASH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ES_LJU | OLI | 14/04/2011 | -29.24 | 44.75 | 53.45 | 39.51 | 0.985 | IT_RO3 | CRO | 09/04/2011 | 10.92 | 39.80 | 41.27 | 26.92 | 0.934 |
| | | 09/05/2011 | -11.76 | 32.57 | 34.63 | 30.29 | 0.963 | | | 11/04/2011 | 31.67 | 30.24 | 43.79 | 34.75 | 0.919 |
| | | 24/06/2011 | -47.07 | 39.11 | 61.20 | 48.54 | 0.945 | | | 18/04/2011 | 42.10 | 42.34 | 59.71 | 44.00 | 0.958 |
| | | 27/06/2011 | -28.81 | 38.98 | 48.47 | 37.58 | 0.948 | | | 21/04/2011 | 33.35 | 52.28 | 62.01 | 42.53 | 0.961 |
| | | 19/07/2011 | -27.46 | 38.74 | 47.48 | 35.77 | 0.978 | | | 20/06/2011 | -9.57 | 73.29 | 73.91 | 52.42 | 0.958 |
| | | 28/07/2011 | -43.87 | 50.48 | 66.88 | 51.27 | 0.915 | | | 26/06/2011 | 17.25 | 89.42 | 91.07 | 70.44 | 0.983 |
| | | 04/08/2011 | 18.95 | 38.42 | 42.84 | 31.95 | 0.934 | | | 24/08/2011 | 16.30 | 43.62 | 46.56 | 36.97 | 0.917 |
| | | 22/08/2011 | -3.39 | 51.14 | 51.25 | 39.75 | 0.964 | | | 28/08/2011 | -17.29 | 48.32 | 51.32 | 30.11 | 0.913 |
| | | 25/08/2011 | 17.21 | 52.08 | 54.85 | 44.13 | 0.964 | | | 09/09/2011 | -15.89 | 39.23 | 42.32 | 28.03 | 0.978 |
| | | 28/09/2011 | 13.23 | 41.60 | 43.65 | 29.29 | 0.978 | | | 11/09/2011 | -22.61 | 61.45 | 65.48 | 44.20 | 0.928 |
| | | **Average** | **-17.17** | **60.22** | **62.62** | **43.97** | **0.957** | | | **Average** | **15.53** | **70.23** | **71.93** | **47.95** | **0.945** |
| IT_COL | DBF | 26/06/2011 | 1.74 | 46.77 | 46.80 | 33.26 | 0.899 | IT_LAV | ENL | 27/06/2011 | -22.70 | 68.75 | 72.40 | 51.93 | 0.968 |
| | | 08/07/2011 | 18.13 | 64.78 | 67.27 | 51.57 | 0.924 | | | 03/07/2011 | -35.97 | 64.90 | 74.20 | 54.32 | 0.974 |
| | | 13/07/2011 | 9.77 | 44.49 | 45.55 | 41.51 | 0.970 | | | 09/07/2011 | -25.35 | 48.49 | 54.72 | 40.30 | 0.913 |
| | | 18/07/2011 | 12.29 | 57.20 | 58.50 | 51.31 | 0.941 | | | 11/08/2011 | 5.65 | 41.04 | 41.42 | 32.01 | 0.978 |
| | | 11/08/2011 | -3.40 | 37.51 | 37.66 | 29.44 | 0.991 | | | 12/08/2011 | 0.32 | 32.85 | 32.85 | 25.04 | 0.963 |
| | | 23/08/2011 | 55.49 | 53.01 | 76.74 | 60.69 | 0.997 | | | 20/08/2011 | 7.77 | 56.67 | 57.20 | 38.05 | 0.918 |
| | | 11/09/2011 | 32.16 | 37.20 | 49.17 | 36.64 | 0.969 | | | 21/08/2011 | 9.11 | 51.09 | 51.90 | 38.97 | 0.978 |
| | | 15/09/2011 | 21.18 | 73.90 | 76.88 | 62.74 | 0.879 | | | 24/08/2011 | 18.93 | 56.46 | 59.55 | 46.52 | 0.899 |
| | | 16/09/2011 | 23.20 | 43.50 | 49.30 | 41.64 | 0.969 | | | 09/09/2011 | 3.34 | 71.63 | 71.71 | 55.63 | 0.910 |
| | | 17/09/2011 | -0.51 | 59.69 | 59.69 | 45.19 | 0.914 | | | 30/09/2011 | 41.43 | 41.04 | 58.31 | 43.60 | 0.989 |
| | | **Average** | **14.72** | **58.78** | **60.59** | **46.84** | **0.945** | | | **Average** | **-6.72** | **56.95** | **57.34** | **39.18** | **0.949** |
| IT_MBO | GRA | 10/04/2011 | -29.74 | 51.93 | 59.84 | 48.15 | 0.910 | FR_PUE | EBF | 06/04/2011 | -36.45 | 36.93 | 51.89 | 38.72 | 0.978 |
| | | 10/05/2011 | 0.29 | 20.03 | 20.03 | 16.50 | 0.971 | | | 09/04/2011 | -4.73 | 61.85 | 62.03 | 46.98 | 0.995 |
| | | 25/06/2011 | 4.97 | 32.86 | 33.23 | 25.14 | 0.896 | | | 16/04/2011 | -42.22 | 50.00 | 65.44 | 49.12 | 0.914 |
| | | 03/07/2011 | 15.82 | 67.80 | 69.62 | 42.00 | 0.941 | | | 17/05/2011 | -50.66 | 49.10 | 70.55 | 53.69 | 0.968 |
| | | 24/08/2011 | 36.06 | 22.46 | 42.48 | 37.55 | 0.879 | | | 28/05/2011 | -4.18 | 60.90 | 61.04 | 49.30 | 0.978 |
| | | 25/08/2011 | 32.11 | 22.49 | 39.20 | 32.69 | 0.986 | | | 19/06/2011 | -37.85 | 59.70 | 70.69 | 64.09 | 0.925 |
| | | 13/09/2011 | 15.15 | 26.73 | 30.73 | 22.44 | 0.976 | | | 08/07/2011 | -14.58 | 40.37 | 42.93 | 35.78 | 0.946 |
| | | 21/09/2011 | 31.57 | 24.50 | 39.96 | 32.22 | 0.936 | | | 26/09/2011 | 11.57 | 31.31 | 33.38 | 26.11 | 0.917 |
| | | 26/09/2011 | 16.48 | 13.24 | 21.14 | 17.15 | 0.914 | | | 14/09/2011 | 23.07 | 42.11 | 48.01 | 38.77 | 0.913 |
| | | 30/09/2011 | 41.43 | 41.04 | 58.31 | 43.60 | 0.989 | | | 20/09/2011 | -6.86 | 28.55 | 29.36 | 20.38 | 0.979 |
| | | **Average** | **16.41** | **40.97** | **44.13** | **31.74** | **0.940** | | | **Average** | **-16.29** | **52.98** | **55.43** | **42.29** | **0.951** |
| ES_AGU | SHR | 07/04/2011 | -1.09 | 30.30 | 30.32 | 25.05 | 0.991 | | | | | | | | |
| | | 27/04/2011 | -17.07 | 24.53 | 29.89 | 24.17 | 0.930 | | | | | | | | |
| | | 08/05/2011 | -8.29 | 29.72 | 30.85 | 22.23 | 0.978 | | | | | | | | |
| | | 14/05/2011 | -10.76 | 24.77 | 27.00 | 22.46 | 0.915 | | | | | | | | |
| | | 23/05/2011 | -30.75 | 33.29 | 45.32 | 33.51 | 0.997 | | | | | | | | |
| | | 13/07/2011 | -27.78 | 33.14 | 43.24 | 31.19 | 0.937 | | | | | | | | |
| | | 29/07/2011 | -4.41 | 37.58 | 37.84 | 28.45 | 0.914 | | | | | | | | |
| | | 14/08/2011 | 20.68 | 35.58 | 41.16 | 31.22 | 0.989 | | | | | | | | |
| | | 26/08/2011 | 8.19 | 47.52 | 48.22 | 34.04 | 0.937 | | | | | | | | |
| | | 07/09/2011 | 0.07 | 30.02 | 30.02 | 22.99 | 0.993 | | | | | | | | |
| | | **Average** | **-7.01** | **34.80** | **35.50** | **25.03** | **0.958** | | | | | | | | |
| **ALL SITES** | | **AVERAGE** | **-0.08** | **53.56** | **55.36** | **39.57** | **0.95** | | | | | | | | |