Operational Evapotranspiration Estimates from SEVIRI support Sustainable Water Management

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ABSTRACT

This study aimed at exploring the accuracy of the Evapotranspiration (ET) operational estimates from the Meteosat Second Generation (MSG) Spinning Enhanced Visible Infra-Red Imager (SEVIRI) at a range of selected ecosystems in Europe. For this purpose were utilised *in-situ* eddy covariance measurements acquired from 7 selected experimental sites belonging to the CarboEurope ground observational network, acquired over 2 full years of observations (2010-2011). Appraisal of ET accuracy from this product was also investigated with respect to land cover, season and each site(s) degree of heterogeneity, the latter being expressed by the fractional vegetation cover (FVC) operational product of SEVIRI.

Results indicated a close agreement between the operational products ET estimates and the tower based *in-situ* ET measurements for all days of comparison, showing a satisfactory correlation (r of 0.709) with accuracies often comparable to previous analogous studies. From all land cover types, the grassland and cropland sites exhibited the closest agreement (r from 0.705 to 0.759). Among seasons, strongest correlations were observed during the summer and autumn (r of 0.714 & 0.685 respectively), whereas with FVC a highest correlation of 0.735 was observed for the class FVC 0.75-1 when compared against the observed values for the complete monitoring period. Our findings support the potential value of the SEVIRI ET product for regional to mesoscale studies and corroborate its credibility for usage in many practical applications. The latter is of particular importance for water limiting environments, such as those found in the Mediterranean basin, as accurate information on ET rates can provide tremendous support in sustainable water resource management as well as policy and decision making in those areas.

KEYWORDS: *evapotranspiration, ET, SEVIRI, water management, Earth Observation, CarboEurope*

1. INTRODUCTION

The combined impacts of climate change, population increase and migration to urban areas are likely to cause significant water resource crises in the coming decades (Jones, 2014). The temporal and spatial scales of these crises mean that mitigation of, and adaptation to them, require reliable data on which management decisions can be made (Wagner *et al.*, 2015). However, these data are lacking for a number of important hydrological processes, especially in regions such as Africa (Legesse *et al.*, 2003) South America (Smolders *et al.*, 2004) and Asia (Remesan and Holman, 2015; Srinivasan *et al.*, 2015). One such process which is of key importance in many practical applications is evapotranspiration (Srivastava *et al.*, 2013c; Ireland *et al.*, 2015). This critical process is the way in which water is transferred as vapour from the terrestrial and marine environments into the atmosphere and is principally influenced by meteorological factors and soil moisture availability (Srivastava *et al.*, 2013a; Sepulcre-Canto *et al.*, 2014). As such, it is central to the hydrological cycle as well as to hugely significant biogeochemical cycles (in particular carbon), and is the main pathway of the energy system by which solar energy is transferred through latent heat (LE). As a result, its importance as a control on regional climate characteristics (Jung *et al.*, 2010; Srivastava *et al.*, 2015c), agriculture and regional water resources cannot be understated (Buytaert *et al.*, 2006; Srivastava *et al.*, 2013b; Srivastava *et al.*, 2015b).

There is a long history of ground surface-based instrumental retrieval of ET using a number of techniques, including evaporation pans, atmometers and lysimeters (for a review see (Petropoulos *et al.*, 2013). Such techniques are limited by the fact that they are often used in single sites and are also unable to provide spatiotemporal estimates of ET at regional or continental scales. In recent years there a number of ground monitoring networks have been developed (e.g. Fluxnet) in order to integrate data collected at single sites around the world (Wang and Dickinson, 2012). However, the development of regional estimates of ET remain limited by the cost of instrumentation implementation and the fact that such measurements are time-consuming and labour intensive.

The advent of Earth Observation (EO) technology has led to the development of a number of modelling techniques which have been proposed to obtain spatiotemporal estimates of ET (Sun *et al.*, 2011; Gellens-Meulenberghs *et al.*, 2012; Marshall *et al.*, 2013; Cruz-Blanco *et al.*, 2014; Ghilain *et al.*, 2014). Some studies of ET have also been performed on European ecosystems using mesoscale model derived weather variables (Verstraeten *et al.*, 2005; Srivastava *et al.*, 2014; Srivastava *et al.*, 2015d) as well as satellites such as MODIS (Srivastava *et al.*, 2015a), SEVIRI (Petropoulos *et al.*, 2015a), and AVHRR (Taconet *et al.*, 1986). In contrast to conventional ground surface-based methods, these methods can provide maps of ET at varying spatial and temporal resolutions and at relatively low or often no cost. Yet, before such EO-derived maps are used, it is essential to undertake validation studies for a number of reasons (Jia *et al.*, 2010; Petropoulos *et al.*, 2013), including: (i) to determine the suitability and credibility of an EO algorithm or operational product before it is used for practical applications; (ii) to allow for the identification, quantification and understanding of the sources of errors in algorithm formulation and (iii) to direct efforts to re-evaluate and improve ET retrieval parameters and algorithm structure. These reasons allow environmental managers, regulatory agencies and disaster management agencies to use the product with greater confidence and also, crucially, allow for climate change projections to be evaluated (Mueller *et al.*, 2011; Kalivas *et al.*, 2013).

EO technology is currently at a level of maturity which allows the development and distribution of related products at operational scales. Such operational products have proven to be generally of high demand from research groups and communities interested in modelling the carbon cycle, understanding the relationships between fire regime and climate, atmospheric emissions and pollution, amongst others. One such ET product currently available is provided from the geostationary orbit Spinning Enhanced Visible Infra-Red Imager (SEVIRI) of the Meteostat Second Generation (MSG) satellite. In this product, ET is estimated operationally every 30' from the SEVIRI radiometer, whereas a daily ET flux operational product is also generated with a lag time of one day at a spatial resolution of 3.1 km at the sub-satellite point. These two products are provided for the full disk divided in four sub regions (Europe, North Africa, South Africa and South America) through the LSA-SAF web site (see http://landsaf.meteo.pt/). Yet, to our knowledge, very few validation studies have been concerned with establishing the accuracy of the SEVIRI ET instantaneous operational product, particularly at a continental scale. Such studies have so far been focused primarily on performing either direct comparisons against corresponding *in-situ* measurements acquired concurrently (Hu *et al.*, 2015; Petropoulos *et al.*, 2015b), or others based on performing inter-comparison studies against other operational products or model outputs (Fensholt *et al.*, 2011; Ghilain *et al.*, 2011). Indeed, thus far only a few other validations of SEVIRI ET product have been published and these have focused on evaluating the product accuracy on a continental scale (Sepulcre-Canto *et al.*, 2014). As such, there is an urgent need for more validation studies on this product.

In this context, the aim of this study has been to evaluate the accuracy of the SEVIRI ET operational product at a range of European ecosystems for 2 complete years of analysis. This is achieved through examining the agreement between these estimates and rates of ET measured at a range of CarboEurope flux tower sites with respect to (i) different land-use and land cover types commonly found in Europe; (ii) seasonality and (iii) experimental site(s) heterogeneity as expressed by the Fractional Vegetation Cover (FVC).

2. EXPERIMENTAL SET UP

2.1 Datasets

2.1.1 MSG-2 SEVIRI ET Estimates

A series of operational products from SEVIRI are provided by EUMETSAT at no cost, distributed by the Satellite Application Facility (SAF) on Land Surface Analysis (LSA) (http://landsaf.meteo.pt/). For the purposes of the study, the SEVIRI instantaneous ET product (MET) was acquired for the Euro region of the Meteosat disk. The method developed by LSA-SAF allows estimation of both the instantaneous and daily total ET by the MSG SEVIRI radiometer. It follows a physically-based approach and can be described as a simplified SVAT model modified to accept EO data combined with data from other sources as forcing. The SVAT model employed is essentially a simplified version of the SVAT model TESSEL (Tiled ECMWF Surface Scheme for Exchange Processes over Land; (Viterbo and Beljaars, 1995), which computes land surface processes taking both EO and atmospheric parameters as inputs. The algorithm is then adapted to accept real-time data from meteorological satellites as forcing (Gellens-Meulenberghs *et al.*, 2007). The main forcing to the model comes from the remote sensing inputs including the daily albedo (Geiger *et al.*, 2008a) and half-hourly short-wave (Geiger *et al.*, 2008b) and long-wave fluxes (Ineichen *et al.*, 2009). To provide ET with a limited amount of missing values, a gap filling procedure is also adopted in the operational algorithm. The daily ET operational product is derived by temporal integration of instantaneous ET operational product values. The integration limits correspond to the first (theoretically at 00:30 UTC) and last (theoretically at 24:00 UTC) existing slots for a given day, and the integration step is 30'. A detailed description of the SEVIRI operational ET estimation algorithm is available in Ghilain *et al.*, (2011). The retrieval accuracy of ET is generally claimed to be 25% if ET is greater than 0.4 mm h^{-1} and 0.1 mm h^{-1} in any other case (Ghilain *et al.*, 2011). The MET product contains instantaneous values of ET (in mm h^{-1}) plus an associated quality flag (MSG-2 ET Product ATBD, 2008).

In addition, the SEVIRI FVC product was also acquired to facilitate the analysis of site heterogeneity on ET retrieval accuracy. This product is generated daily at the full spatial resolution of the MSG/SEVIRI instrument (3 km). It is computed using three short-wave channels as inputs (VIS 0.6µm, NIR 0.8µm, SWIR 1.6µm) and a parametric Bi-directional Reflectance Distribution Function (BRDF) model. In the product, FVC is delivered daily and is expressed as percentage corrected from uncertainty derived of the view/sun angles and also the anisotropy effects of surface reflectance in the SEVIRI image. The FVC product includes routine quality check and error estimates. For each day and geographical region, the FVC product, its error estimate and the processing flag were acquired in Hierarchical Data Format (HDF5) and HDF5 file attributes. In our study, the SEVIRI FVC product was downloaded for the Euro region of the Meteosat disk for both 2010 and 2011. All SEVIRI data was obtained free of charge through the LSA-SAF web site (see http://landsaf.meteo.pt/).

2.1.2 Study Sites: In-situ ET Measurements

In-situ ET measurements for a total of 7 flux experimental sites of the CarboEurope network (Baldocchi, 2003) were utilised in this study. CarboEurope is part of FLUXNET, the largest global "network of regional networks" to coordinate regional and global analysis of micrometeorological fluxes and ancillary parameters. The flux tower sites of the individual networks utilise the same eddy covariance method to measure the exchanges of carbon dioxide (CO_2), water vapour, and energy between terrestrial ecosystems and the atmosphere to a good level of standardisation. This enables uniform measurement comparisons between sites and datasets. ET is measured as a core parameter at half-hourly intervals using the eddy covariance system. In our study, *in-situ* data for the complete years 2010 and 2011 were acquired from 7 CarboEurope sites of varying environmental and ecosystem conditions. These sites included 5 situated within a Mediterranean environment (Spain and Italy) and 2 others located in temperate climate zones (France and UK), representative of open shrubland, grassland, evergreen needle-leaf forest and cropland land cover types. In this study sites were only selected where continuous long term datasets are available for use. Further, during the selection of sites weather conditions are also a deciding factor when using the Visible/Infrared satellite measurements. Sometime data are available but due to cloudy conditions either there is high noise in the datasets or not available at all over the installed Fluxnet sites. Other important factors during the selection of sites are homogeneity in the land cover type. To avoid any mixed pixel effects on the overall performance, satellite pixels are chosen over the Fluxnet tower having the large homogenous land cover. In addition, the sites proposed are a complementary selection compared to other validation studies of the same product.Site names and their main characteristics are listed in **Table 1**. All *in-situ* data were obtained from the CarboEurope website (http://gaia.agraria.unitus.it/) and where possible, verified by the site manager.

2.2 Methods

The acquired ET product images were re-projected from Normalized Geostationary Projection (NGP) to a regular latitude/longitude grid and tailored from the full disk image to the study region (34º-45ºN, 11ºW-5ºE). Each image was subsequently clipped into the separate European countries in which our experimental sites were located. Periods for which more than 10 % of each of the half-hour SEVIRI estimated ET (granules) was missing from a "site-day" were omitted from the comparisons. The data were further refined by excluding granules with negative values from the dataset. These values corresponded to flags or no-data values which were inappropriate for use in assessing the agreement between both datasets. In addition, a scaling factor was applied to each MET 30' product to derive the actual ET value (MSG-2 ET Product ATBD, 2008). Subsequently, the pre-processed *in-situ* ET values that corresponded to the date/time of the satellite overpass were extracted (Excel MacroVBA), and assigned to point shapefiles of the test sites, where there was one shapefile per country (tabular join in ArcMap 10.1). These shapefiles were overlain on the pre-processed SEVIRI images in the BEAM VISAT + SMOS toolbox. Using the BEAM correlation tool, the *in-situ* ET was matched against the SEVIRI ET of the pixel containing the site point. These pixels were then extracted to Microsoft Excel for further analysis and comparisons against the *in-situ* data.

2.3 Statistical Analysis

Agreement between the ET SEVIRI predictions and the corresponding *in-situ* data was evaluated based on direct point by point comparisons. Several statistical performance assessment metrics were used to evaluate the agreement between the compared datasets. These included the Root Mean Square Difference (RMSD), the Pearson's Correlation Coefficient (r) (including the Slope and Intercept of the regression equation), the Mean Bias Error (MBE) or Bias (*in-situ* minus estimated), and the Mean Standard Deviation (MSD) or Scatter. A robust regression was computed using iterative re-weighted least squares (Street *et al.*, 1988), which is influenced less by outliers than the ordinary least-squares fit (Entekhabi *et al.*, 2010). These statistical metrics have been prominently used in analogous validation experiments of relevant operational products validation studies (e.g. LSA-SAF Validation Report Evapotranspiration Products, 2010).

Additional analyses were performed exploring the agreement between the satellite-derived and *in-situ* ET as a function of land cover type, seasonality and surface heterogeneity (expressed as FVC percentage derived from the SEVIRI FVC product). For the analysis by land cover type, agreement was evaluated for 7 sites inclusive of 4 different land cover types: ES_Agu and ES_Lju – open shrubland, IT_Ren – Evergreen Needle-Leaf Forest, IT_Mbo and UK_Ebu – grasslands, IT_Cas and FR_Mau – croplands. Similarly, agreement was also evaluated for the 4 seasons, spring (Mar-May), summer (Jun-Aug), autumn (Sep-Nov) and winter (Dec-Feb), and analysed separately for FVC ranges with different percentage coverage thresholds: 0-24, 25-49, 50-74 and 75-100. Direct point-by-point comparisons were performed at every *in-situ* station to evaluate the statistical agreement for each threshold. Analysis was performed for each scenario independently for both 2010 and 2011, and also for both years combined into a single dataset.

3. RESULTS

This study has been concerned with the verification of the operational retrieval of satellite-derived ET estimates from the MSG SEVIRI sensor. **Table 2** illustrates the key results from the comparison between the satellite-derived ET estimates and the corresponding *in-situ* observed for all days of analysis per experimental site. In **Figure 1**, examples of spatial maps of ET derived from the SEVIRI operational product on the 6th of August 2011 for Spain at two different times of day are shown (7a.m. UTC/11a.m. UTC). A qualitative comparison of the spatial distribution of

ET in comparison to the FVC indicates a good agreement in the spatial patterns between both the SEVIRI FVC and MET products, highlighting a key link between ET spatial distribution and other biophysical parameters. It can be observed from **Figure 1** that the areas of maximum ET estimation (which range between 0.093 and 0.523 mm h^{-1} dependent on time of day) can be seen in northern Spain, which clearly correspond to the areas of maximum FVC (up to 100%) for the same date (FVC is provided as a daily product). The larger area to the south and south east exhibited low to very low (near zero) ET, which again correlate with areas of low FVC. There is also a clear trend in the dynamic rates of ET at different times throughout the day, underlining the capability of the operational product to capture the temporal variability of ET. ET rates are at their lowest point during the early morning, increasing to their maximum at midday and then decreasing yet again in the early afternoon, showing a positive correlation with amount of incoming solar radiation at the surface.

Despite the variability in accuracy found in different land covers, seasons and using different FVC thresholds (sections 3.1, 3.2, 3.3), in absolute terms, a good agreement was found between the two datasets, with a correlation between the point predicted ET resulting in an r of 0.709. The SEVIRI MET estimates exhibited a minor overestimation of the observed with a mean positive bias of 0.001 mm h^{-1}. The mean scatter of 0.065 mm h^{-1}, although a significant increase on the bias results, indicated a reliable estimation of the in-situ data by the operational product. Evidently, the mean RMSD of 0.065 mm h^{-1} in the estimation of ET when all days were considered was within the accepted accuracy range for the operational retrieval of ET (retrieval within ~25% of in-situ if ET is greater than 0.4 mm h^{-1} (LSA-SAF, 2010; (Ghilain *et al.*, 2011)). These findings are also well-aligned to previous analogous validation studies of the SEVIRI MET product (e.g. (Ghilain *et al.*, 2011)(Petropoulos *et al.*, 2015b).

3.1 Land use and land cover comparisons

Table 2 summarises the comparisons of predicted and observed rates of ET on the seven experimental sites of varying land use and land cover in 2010 and 2011. In general, when data for both years combined are plotted for the individual sites, it is clear that the grassland and cropland sites (IT_Mbo/IT_Cas/Fr_Mau/UK_Ebu) exhibited the closest agreement of all land cover types (r from 0.705 to 0.759). However, notably, this is not reflected in the error metrics (**Table 2**) where both the shrubland sites (ES_Agu/ES_Lju) returned the lowest RMSD and MAE of all sites, between 0.035-0.044 mm h^{-1} and between 0.021-0.025 mm h^{-1} respectively. In comparison, the agreement over the grassland and cropland sites resulted in much higher error ranges (UK_Ebu being the only exception). The error results are also mirrored in the bias and scatter results, where the three sites of lowest RMSD (ES_Agu/ES_Lju/UK_Ebu) exhibited a decrease in scatter and bias of ~50% in comparison to all other sites. Evidently, the RMSD is derived predominantly from the scatter and not the bias for all sites. Interestingly, the poorest performing site when both years were combined was the IT_Ren Evergreen Needleleaf Forest site (RMSD of 0.093 mm h^{-1}), suggesting that the taller and/or denser vegetation cover may have detrimental implications for the operational products retrieval accuracy.

When sites were analysed per year, similar trends were clearly evident (**Table 2**). In 2010, the bias is low for all land use and land cover types (< 0.030 mm h^{-1}) and this is also the case in 2011 where the maximum bias is 0.024 mm h^{-1}. The lowest errors are seen in sites with short or low vegetation cover and areas which contain bare ground i.e. the shrublands of ES_Agu and ES_Lju, and the grassland of UK_Ebu where the RMSD are all below 0.04 mm h^{-1}. These sites also show the lowest bias (all within 0.007 mm h^{-1} in 2010, with variation by site) and the lowest scatter which is also less than 0.04 mm h^{-1}. The highest correlations between predicted and observed ET rates are seen in the grasslands sites of UK_Ebu and IT_Mbo ($r > 0.700$). These results are generally mirrored in the results for 2011, with some differences. For example, although bias and errors are still low, they are greater than in 2011 than in 2010 for the ES_Agu, ES_Lju and UK_Ebu sites. The correlation in 2011 for IT_Mbo is lower than that recorded for 2010 at 0.706, but the correlation for UK_Ebu continues to be high. In overall, when results are stratified by year, trends in product accuracy dependent on land cover are clearly evident. Furthermore, error for all sites is predominantly the result of scatter rather than the bias.

3.2 Seasonality

The temporal trends between in-situ and predicted ET from SEVIRI for different seasons during 2010 and 2011 are shown in **Figure 2a-b** for few selected sites. In general, comparisons between the in-situ and SEVIRI ET time series exhibit a high temporal variability with seasons and depicting a strong seasonal cycle. Generally, ET values are highly responsive with the seasonality indicated by marked fluctuations over the entire period with rapid and sharp responses, even to small changes in weather. The pattern shows that months from June-August (summer) are drier with ET values peaking during these months. Further, ET started to decrease during the autumn (September to November) with its lowest values during December to February (winter). Rising temperatures in Europe from spring to summer are reflected in a gradual rise in ET during this period. From the results summarised in those figures it is evident that in summer, typically, very high ET values were found, while during the winters a decline in ET values are recorded. Increasing temperatures and high evaporation through the summer period lead to a progressive drying of the soil and therefore decreasing ET values. Some dips in the ET values during the summer can be attributed to some short-duration storms. Generally winter is the relatively wettest period during the analysis, because of occurrence of some precipitation events, further solar radiation and temperature are also low during the winters leading to decreases in ET rates during winter months.

Table 3 summarises the comparisons between winter, spring, summer and autumn ET rates for all sites together in 2010 and 2011. **Figure 3** shows the agreement between predicted and observed ET rates for the different seasons separately for 2011 and 2012. In common with the results for land cover and land use type, the bias is very low (all within 0.020 mm h^{-1}), as are the scatter and RMSD (all less than 0.100 mm h^{-1}). RMSD seems to be at its highest in spring and summer. The main pattern that can be seen in these results is that the correlation between predicted and observed rates of evaporation seems to be strongest during the summer and autumn. This is the case when both years are taken together, and when the two years are taken apart (e.g. the correlation coefficient is 0.714 and 0.687 in summer and autumn respectively when both years are taken together, 0.731 and 0.706, respectively in 2010 and 0.707 and 0.685, respectively in 2011). The weakest correlations are seen in winter, in 2010 and 2011 and when both years are taken together. The correlation patterns which are observed are strengthening of the correlation as the year progresses from winter through spring, summer and on to autumn, possibly reflecting the increasing areal extent of homogenous vegetation cover from winter to spring and summer, and a slight loss as that vegetation cover begins to be lost during the autumn. Interestingly, the error statistics, in contrast to the correlation results, exhibit the adverse trend, with highest RMSD and MAD prevalent during the spring and summer months for both years separately and also for the 2 years combined. Similarly to the land cover results, error was predominantly the result of high scatter and not the bias prediction.

3.3 Fractional Vegetation Cover

Table 4 shows the comparison of ET rate statistics for all sites in 2010 and 2011 with four different thresholds of FVC (0-0.24/0.25-0.49/0.50-0.74/0.75-1) ranging from 0 to 1, and **Table 5** summarises these data for both years combined an for all experimental sites. Also **Figure 4** shows the agreement between the predicted ET and in-situ for different FVC ranges. By investigating the agreement between the two datasets within varying FVC thresholds, is possible to analyse the influence of site or land cover homogeneity on the accuracy of the ET operational product retrieval. When data for all sites and years were combined, bias was once again low for all FVC thresholds (all thresholds within 0.020 mm h^{-1}). Scatter and RMSD results (**Table 5**) were low for 3 out of the 4 bands when both years of data were combined, <0.67 mm h^{-1} and <0.69 mm h^{-1} for scatter and RMSD respectively, with the 0.50-0.74 FVC threshold being the only exception, resulting in high scatter and RMSD above 0.1 mm h^{-1}. Although both the 0.25-0.49 and 0.75-1 thresholds exhibited lower error in comparison to the 0.50-0.74 threshold, they were still markedly higher compared to the RMSD for the lowest FVC threshold (0-0.24) (0.042 mm h^{-1}). Overall, the error statistics results) suggested a positive trend between RMSD and FVC percentage i.e. as FVC increases the RMSD also increases in correlation.

The correlation between predicted and observed rates shows a generally strengthening trend moving from the low FVC thresholds to the highest (**Figure 4**). For example, in 2011 the correlation coefficient increased from 0.430 in the 0-0.24 band to 0.674 in the 0.25-0.49 band to 0.690 in the 0.50-0.74 band and to 0.771 in the 0.75-1 band. This pattern was mirrored when both years were taken together. The only outlier to this pattern was a weaker correlation in the 0.25-0.49 band in 2010 than was observed in the 0-0.25 band. This increase in correlation could again be related to the increasing homogeneity of the land cover as FVC increases, thus decreasing the spatial variability in land cover and ET rates.

More variability is apparent, however, when the sites are treated separately (**Table 4**). At sites where there is more than one FVC threshold (ES_Agu/IT_Ren/IT_Mbo/UK_Ebu) the pattern is less clear. At ES_Agu, the correlation strengthens as FVC increases in 2010, but decreases in 2011. At IT_Ren, a steady increase in the correlation coefficient is seen in 2010, but a decrease is seen between the 0.5-0.74 and the 0.75-1 FVC thresholds in 2011. At UK_Ebu, the correlation strengthens in 2011, but weakens between the 0.5-0.74 and the 0.75-1 FVC thresholds in 2011. At IT_Mbo an increase in the correlation coefficient is seen in both years. Mirroring the results seen for the land use and land cover analysis, the strongest correlations (generally greater than 0.75) are seen in the Grassland/Cereal Crops of IT_Mbo, UK_Ebu and FR_Mau, where the homogeneity of vegetation species, extent and crown elevation is greater and thus where the rates of ET are more uniform.

4. DISCUSSION

This study represents a systematic and robust evaluation of the SEVIRI ET operational product at selected ecosystems in Europe for the period of 2010-2011. The effect of varying land cover, landscape homogeneity (percentage of FVC) and seasonality on the accuracy of the ET retrieval algorithm is analysed, allowing a more robust and comprehensive evaluation of the performance of the operational product. Overall, findings of the study were similar to previous validations of the SEVIRI ET product (e.g.Ghilain *et al.*, 2011; Gellens-Meulenberghs *et al.*, 2012; Petropoulos *et al.*, 2015b. The agreement between the ET predicted from SEVIRI and the CarboEurope *in-situ* measurement returned a high correlation coefficient (r – 0.709), highlighting a strong linear relationship between the two datasets and suggesting that the satellite product showed good ability to estimate actual ET measurements. The low error metrics represented by an RMSD and MAE of 0.065 mm h^{-1} and 0.037 mm h^{-1} respectively, indicated that the results of the study met the quality criterion adopted to assess the quality of the results as suggested by the EUMETSAT operational product development team. These criterion were the following: error within 25% of the *in-situ* if ET is greater than 0.4 mm h^{-1} and error within 0.1 mm h^{-1} of the *in-situ* if ET is less 0.4 mm h^{-1} (Ghilain *et al.*, 2011). These results underline the potential applicability of the SEVIRI MET product for operational implementation over Europe.

When results were stratified by land cover type, a clear inter-site variability in retrieval accuracy was evident. The open shrubland site of ES_Agu, Spain returned the lowest error of all sites (RMSD of 0.035 mm h^{-1}) with ES_Lju also performing well (RMSD of 0.044 mm h^{-1}). The SEVIRI MET product was able to reliably estimate ET rates over the open shrubland land cover types, particularly in the Mediterranean region. This could be due to a more consistent land cover extent and type throughout the year, compared to the varying nature of cropland, for example. Furthermore, the performance degradation at ES_Agu between 2010 and 2011 might be due to a change of input data characteristics of the operational product, particularly from the ECMWF forecasts of superficial soil moisture (change of parameterization, with a new operational cycle end of 2010), in the implementation of the ET algorithm. The highest error (RMSD of 0.1 mm h^{-1}) bias (0.028 mm h^{-1}) and scatter (0.096 mm h^{-1}) were seen for the cropland site of IT_Cas in Italy, with the other cropland site of FR_Mau in France exhibiting similar high error statistics. This may be due to sub-annual, temporal changes in land use and/or land cover depending on the growing season and different agricultural practices that reduce the type and height of vegetation. The high error, scatter and bias at IT_Mbo, and high error at IT_Ren, Italy are more difficult to explain given that they are grassland and evergreen forests sites, respectively, and would not be subject to as many changes, especially in terms of agricultural practices. A possible reason for this would be the more frequent occurrence of seasonal snow cover at these sites, leading to a greater annual variability in land surface characteristics than suggested by vegetation type alone. In fact, the IT_MBo and IT_Ren are both situated in a mountainous environment where there is a lot of uncertainty potentially introduced to the ET retrievals due to fragmentation of landscape between forests and alpine pastures, and as discussed, due to snow cover. This can lead to uncertainty in the remote sensing signal and in the accuracy of the numerical weather forecasts used as input in such regions, resulting to a significant impact on the remotely sensed ET retrievals.

Previous examinations of the performance of the SEVIRI MET algorithm over different land cover types in Europe have also returned comparable results and observations to those reported in this study. Ghilain *et al.*, (2012) performed a validation of the SEVIRI MET product through direct comparisons with *in-situ* data over four land cover types in Europe. Both the grassland and evergreen forest sites returned high errors comparable to this study. Similarly, Ghilain *et al.*, (2011) evaluated the performance of the operational products algorithm over six European sites. The algorithm again performed poorly over grassland sites (RMSD ranging between 0.07 to 1 mm h^{-1}). More recently, Petropoulos *et al.*, (2015b),evaluated the SEVIRI ET estimates against *in-situ* data for 9 sites form the CarboEurope network. A clear correlation was also evident between the performance of the algorithm dependent on land cover type between the result presented herein and those of Petropoulos *et al.*, (2015b), with open shrubland (0.049 mm h^{-1}) sites outperforming the grassland (RMSD of 0.072 mm h^{-1}) and evergreen forest sites (RMSD of 0.152 mm h^{-1}). Notably, all authors reported an overestimation of the *in-situ* data by the MET product in a significant majority of the comparisons, which is something also found in this study.

Although the results presented herein underline the significant potential of the SEVIRI ET operational product for the accurate estimation of ET, a number of possible sources of error for the satellite-based daily ET estimates and limitations on the flux tower measurements exist. In this study, the satellite data are assumed to represent the average of a grid cell corresponding to the station fetch used for validation. This assumption can be problematic, as a large spatial discrepancy exists between the coarser satellite-based ET retrievals (3 km spatial resolution), and the flux tower measurements (a fetch in the order of meters). In sites of diverse land cover conditions (fragmented, different vegetation types, areas of bare soil), different ET values are prevalent at different spatial scales. Thus if a remotely sensed footprint includes heterogeneous and/or rough terrain, eddy formation can be highly variable and may not be consistent with that of the flux tower fetch (Marshall *et al.*, 2013). Furthermore, since the majority of flux towers are located in close proximity to vegetated areas, they tend to give higher ET measurements than the spatially averaged satellite values, particularly so in more fragmented landscapes (Sun *et al.*, 2012).This discrepancy was evident when analysing the correlation between the satellite estimates and the *in-situ* data in the study herein, where a positive correlation was exhibited between the percentage of FVC and R. These results suggest that the higher the FVC (i.e. the more homogenous the site), the more representative the ET point measurements were of the SEVIRI MET pixel. A possible solution to overcome the issue of spatial discrepancy and representativeness between the datasets would be to evaluate the satellite-based estimates using several flux towers within a satellite grid cell/footprint, each tower representing the various land cover types and taking a weighted average to compare to the coarser remotely sensed estimate (Marshall *et al.*, 2013). Limitations are also evident concerning the "ground truth" data used to validate the operational product. Measured surface-atmosphere fluxes of energy (H and LE) and CO_2 by the eddy covariance method represents the ''true'' flux plus or minus potential random and systematic measurement errors (Wilson *et al.*, 2002; Petropoulos *et al.*, 2013). Generally, the verification or validation of fluxes by the eddy covariance utilises the energy balance closure (EBC) approach. A lack of EBC with the eddy correlation technique, as used in FLUXNET, has been shown to lead to uncertainty on fluxes measurement up to ~20%, which could potentially be translated to a lack of accuracy when compared against satellite retrievals (Falge *et al.*, 2002; Wilson *et al.*, 2002) . EBC may also ignore any biases in the half-hourly data, where for example, there is trend for the eddy covariance system to overestimate positive fluxes during the daytime and underestimate negative fluxes at night (Mahrt, 1998).

5. CONCLUSIONS

The aim of this study was to perform an extensive and systematic evaluation of the operationally distributed SEVIRI evapotranspiration (ET) product at 7 selected European sites belonging to the CarboEurope ground monitoring network, representative of a variety of land cover characteristics. To our knowledge, our study is one of the few published so far that provides such a comprehensive evaluation of this operational product, looking at evaluating the product accuracy from different perspectives.

Overall, the point by point comparisons between the satellite and *in-situ* ET for the combined dataset of all days of analysis resulted in a close agreement (r of 0.709) and a low error exhibited by the model (RMSD of 0.065 mm h^{-1}). Those findings were comparable to similar validation studies. A clear inter-site variability in retrieval accuracy was evident when results were stratified by land cover type. With regards to the seasonal differences in SEVIRI MET retrieval performance, RMSD was at its highest in spring and summer, whereas the correlations between predicted and observed rates of evaporation were strongest during the summer and autumn. Results suggest that the higher the FVC (i.e. the more homogenous the site), the more representative the ET point measurements were of the SEVIRI MET pixel, overcoming issues related to spatial discrepancy between the datasets.

An update of the algorithm (version 2) is foreseen to release the ET products in 2016, with an expected improvement of the quality and the stability over dry areas thanks to the assimilation of more SEVIRI products, like land surface temperature and vegetation related characteristics . Studies such as this are important steps in the validation of operational satellite products and are vital for the future development of SEVIRI's operational capacity on a global scale. The identification of strengths and weaknesses of the current operational products by means of such studies is a driver of new capabilities developments.

Acknowledgments

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List of Figures

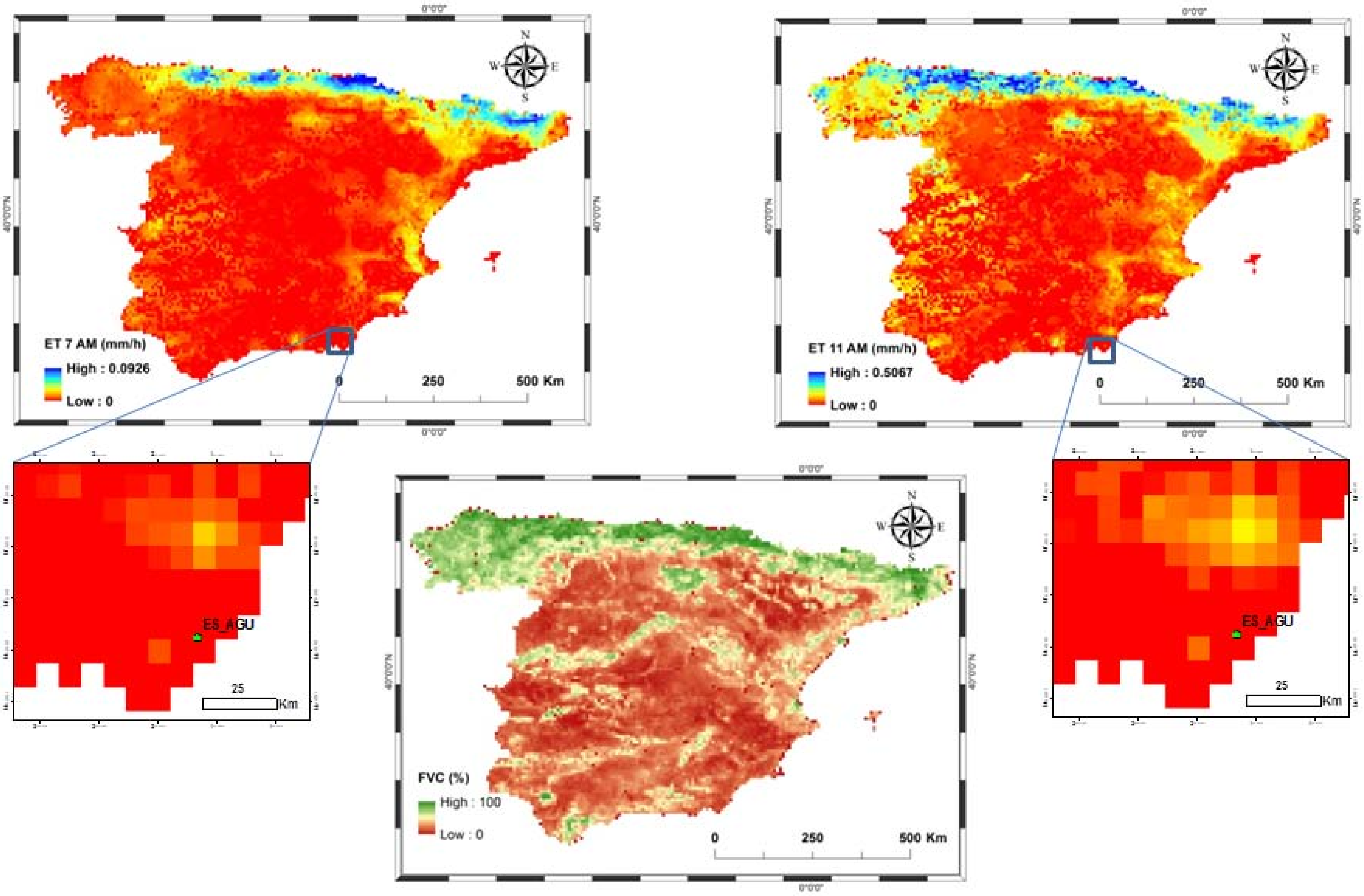

Figure 1: Maps of the SEVIRI ET product on August 6th, 2011 for Spain with the site ES_AGU in the zoomed area. The map in the middle is the map of the Fractional Vegetation Cover as seen from the SEVIRI sensor.

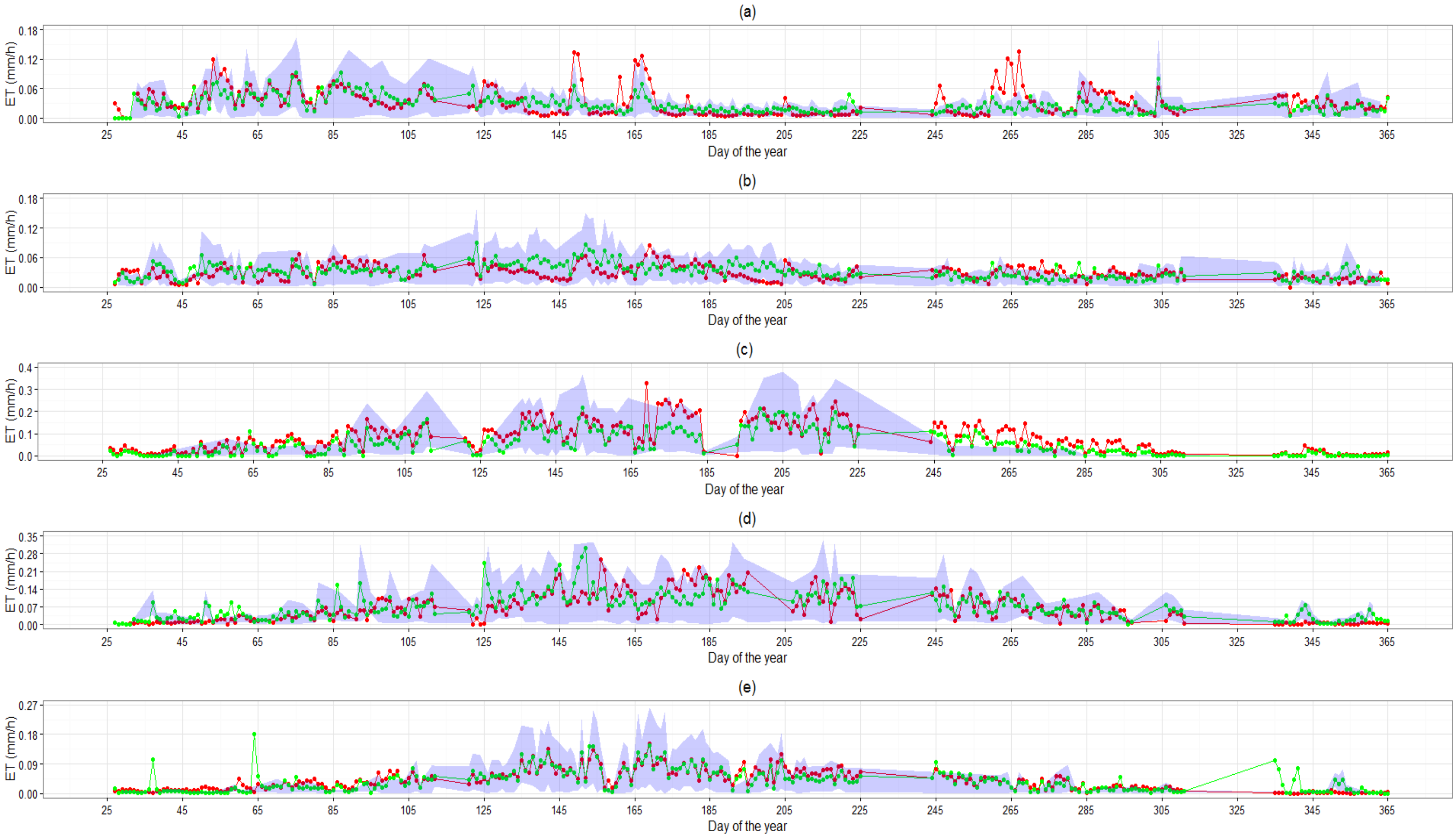

Figure 2a: Examples of the agreement between in-situ and predicted ET from SEVIRI for the different seasons for year 2010 for different sites. In particular, results are shown for: (a) ES_AGU; (b) ES_LJU; (c) IT_CAS; (d) UK_EBU and (e) IT_MBO. Green represents the in-situ ET daily mean, Red is the SEVIRI-predicted ET, Blue is daily standard deviation of the in-situ ET.

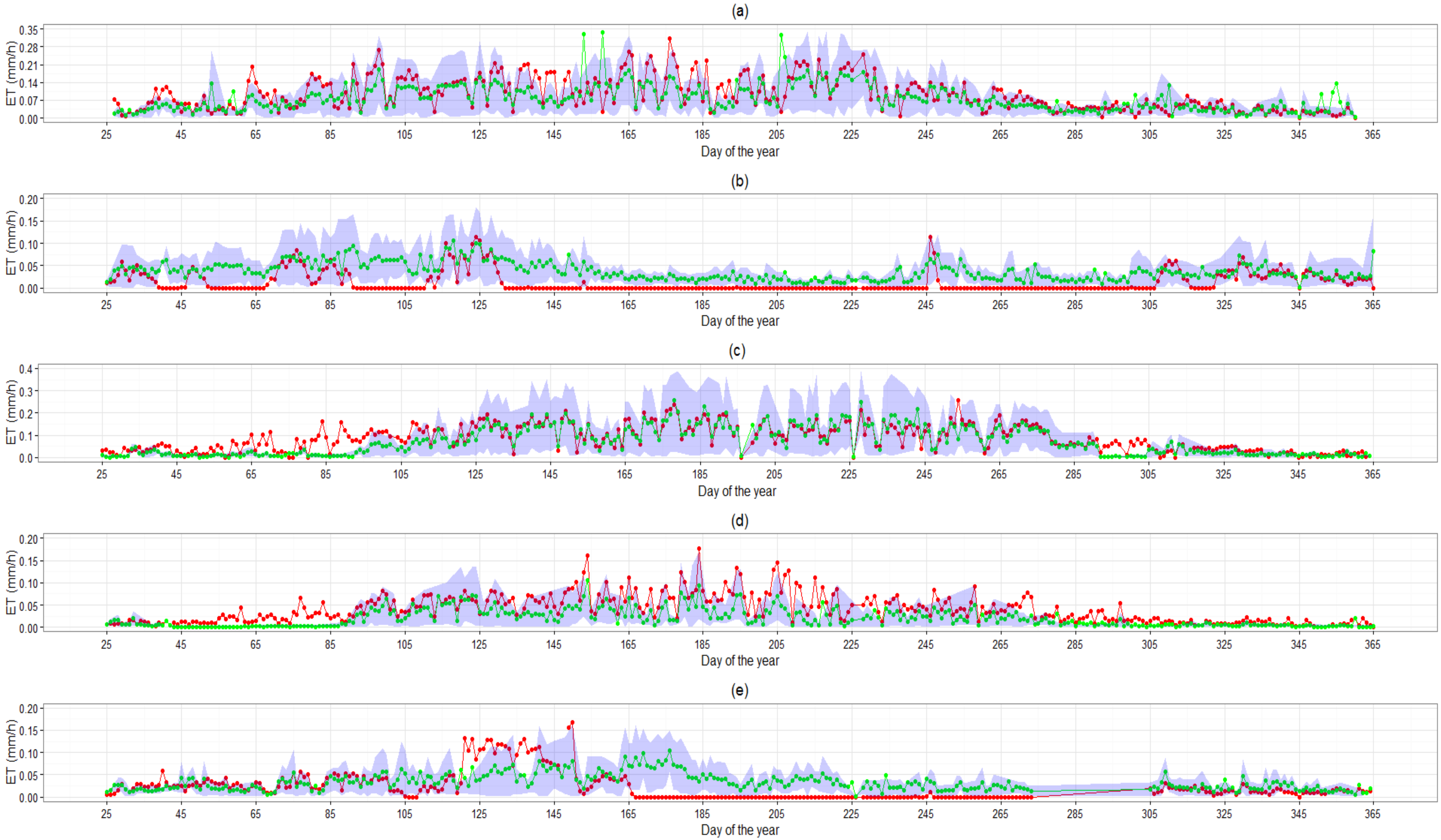

Figure 2b: Examples of the agreement between in-situ and predicted ET from SEVIRI for the different seasons for year 2011 for different sites. In particular, results are shown for: In particular, (a): FR_MAU; (b): ES_AGU; (c):IT_MBO; (d): UK_EBU and (e): ES_LJU. Green represents the in-situ ET daily mean, Red is the SEVIRI-predicted ET, Blue is daily standard deviation of the in-situ ET.

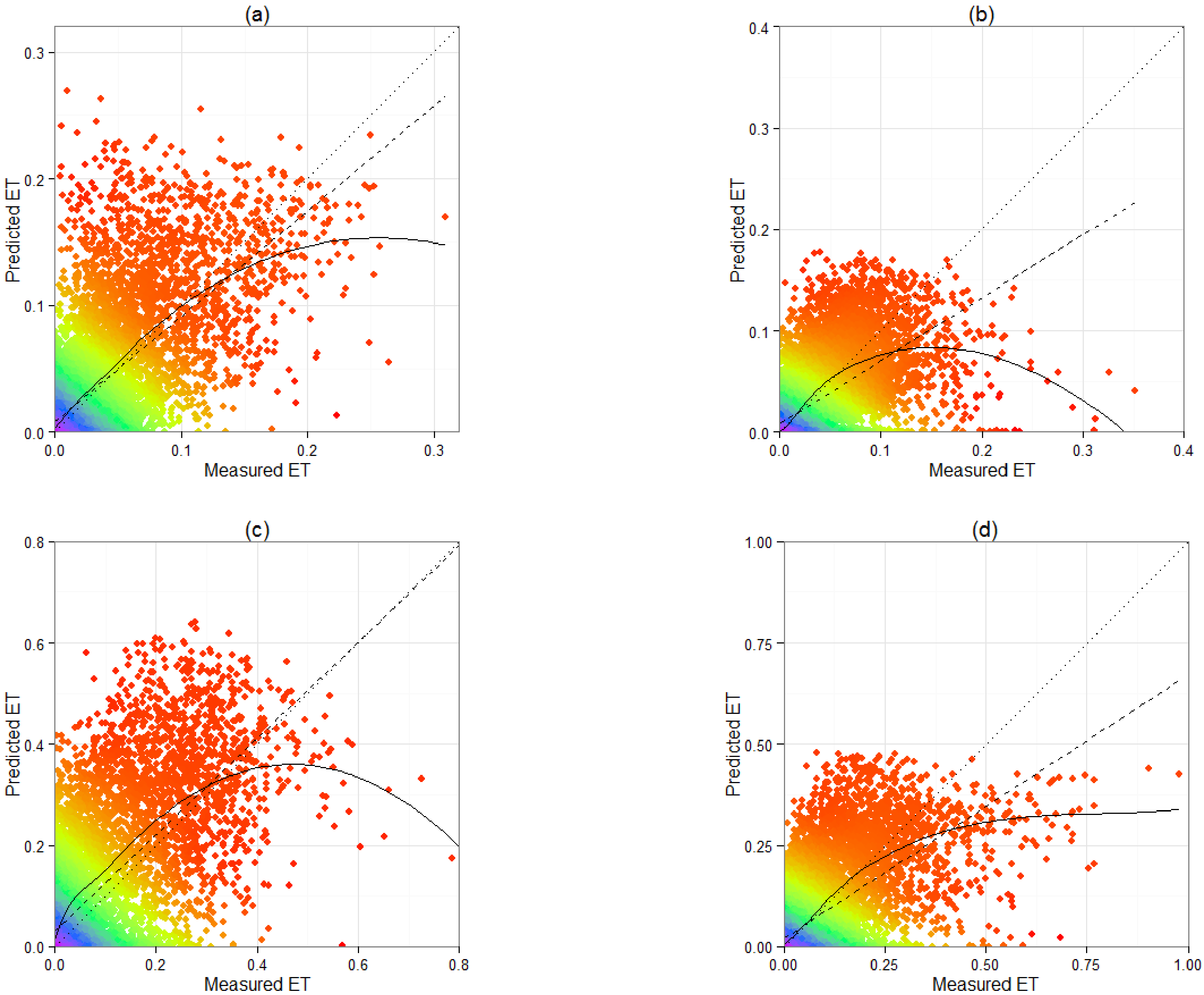

Figure 3a: Agreement between in-situ and predicted ET from SEVIRI for the different seasons for all sites together shown here for year 2010. In particular, (a): autumn, (b)winter, (c): spring and (d): summer; dashed = linear regression, continuous line = locally polynomial (package loess), dotted = y=x line. Units of ET are in mm h^{-1}

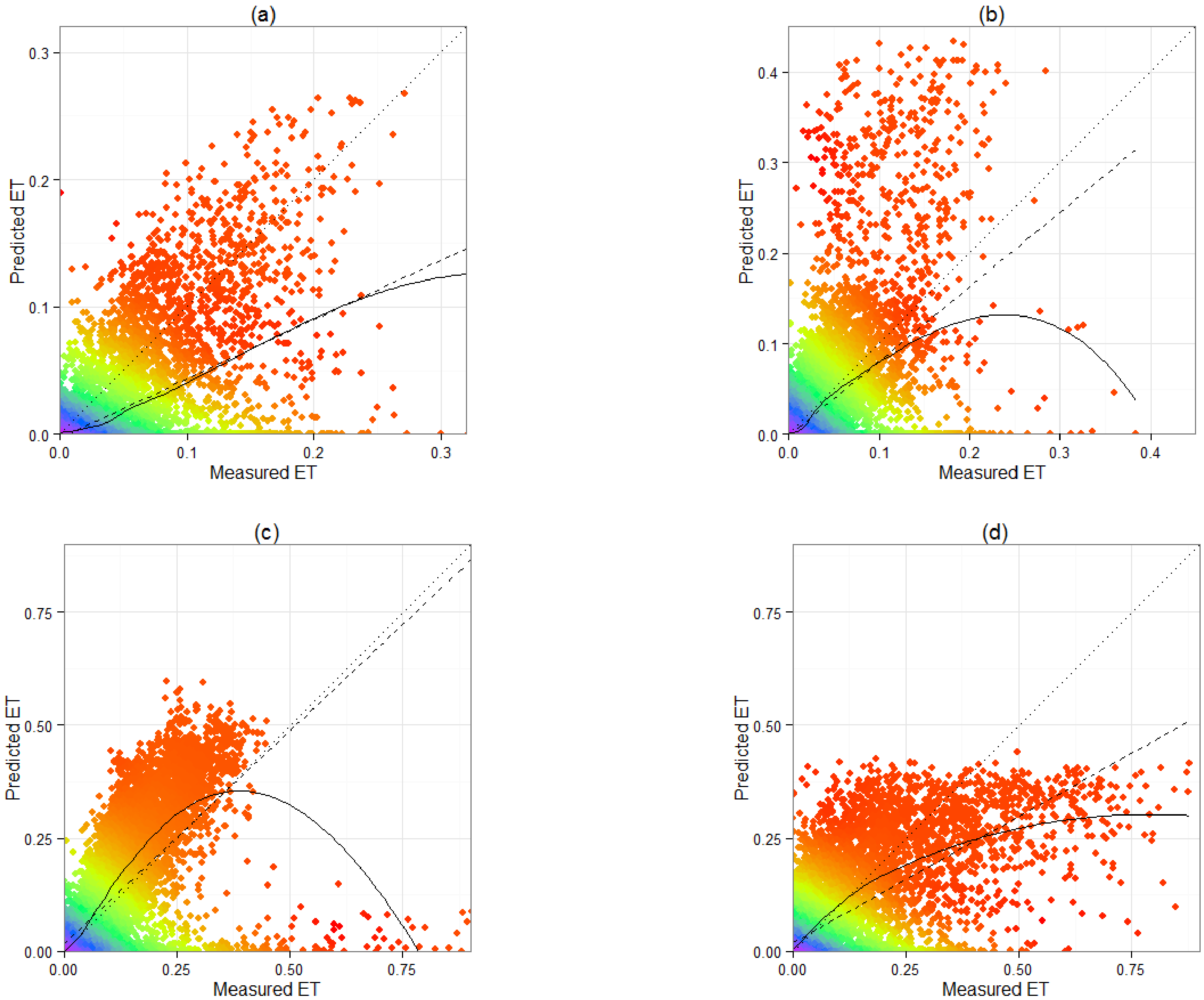

Figure 3b: Agreement between in-situ and predicted ET from SEVIRI for the different seasons for all sites together shown here for year 2011. In particular, (a): autumn, (b)winter, (c): spring and (d): summer; dashed = linear regression, continuous line = locally polynomial (package loess), dotted = y=x line. Units of ET are in mm h^{-1}

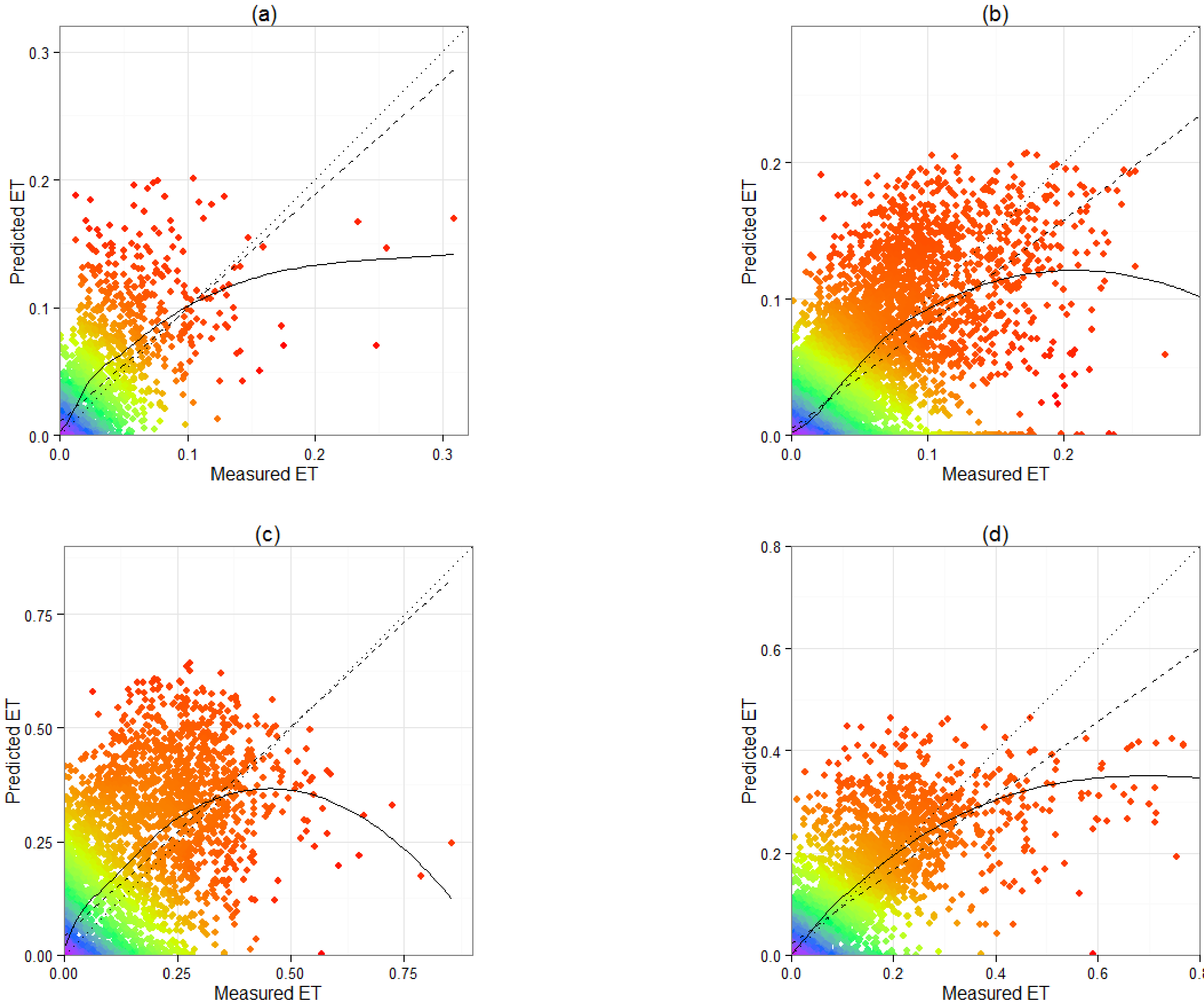

Figure 4a: Agreement between in-situ and predicted ET from SEVIRI for the different Fractional Vegetation Cover (FVC) ranges for all sites together for year 2010. In particular, (a): 0-24% FVC; (b):25-49% FVC; (c): 50-74% FVC and (d): 75-100% FVC; dashed = linear regression, continuous line = locally polynomial (package loess), dotted = y=x line. Units of ET are in mm h^{-1}

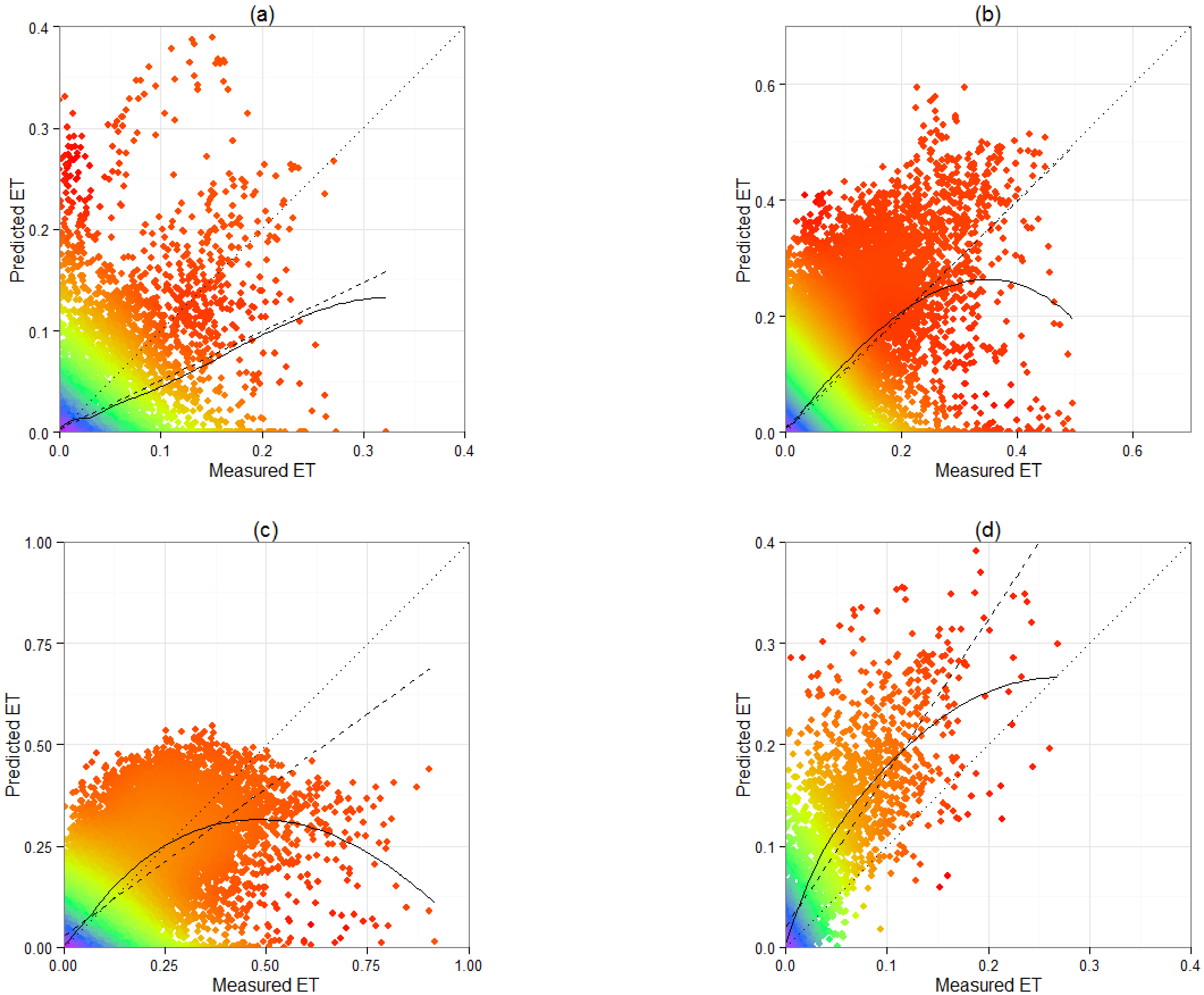

Figure 4b: Agreement between in-situ and predicted ET from SEVIRI for the different Fractional Vegetation Cover (FVC) ranges for all sites together for year 2011. In particular, (a): 0-24% FVC; (b):25-49% FVC; (c): 50-74% FVC and (d): 75-100% FVC; dashed = linear regression, continuous line = locally polynomial (package loess), dotted = y=x line. Units of ET are in mm h^{-1}

Table 1: Description of the selected sites for MSG SEVIRI product validation over Europe

Site Name	Aguamarga	Llano de los Juanes	Renon/Ritten (Bolzano)	Monte Bondone	Castellaro	Mauzac	Easter Bush- Scotland
Site Abbreviation	**ES_Agu**	**ES_LJu**	**IT_Ren**	**IT_Mbo**	**IT_Cas**	**FR_Mau**	**UK_EBu**
Lat/Long	*36.9406/-2.0329*	*36.9283/-2.7505*	*46.5878/11.4347*	*46.0296/11.0029*	*45.07/8.7175*	*43.3853/1.2922*	*55.866/-3.2058*
Country	*SPAIN*	*SPAIN*	*ITALY*	*ITALY*	*ITALY*	*FRANCE*	*United Kingdom*
Vegetation Type	*Open Shrublands*	*Open Shrublands*	*Evergreen Needleleaf Forests*	*Grasslands*	*Croplands*	*Grasslands*	*Grasslands*
Plant Functional Type	*Shrub*	*Shrub*	*Evergreen Needleleaf Trees*	*Annual Grass Vegetation*	*Cereal crop*	*Cereal crop*	*Grass*
Climate	*Arid Steppe, cold*	*Warm, temperate, with dry, hot summer*	*Snow, fully humid, cool summer*	*Snow, fully humid, warm summer*	*Warm, temperate, humid with hot summer*	*Warm, temperate, humid with warm summer*	*Warm, temperate, fully humid with warm summer*
LAI F/PAR Land Cover	*Shrubs*	*Shrubs*	*Evergreen Needleleaf Forest*	*Grasses/Cereal Crops*	*Grasses/Cere al Crops*	*Grasses/Cereal Crops*	*Grasses/Cereal Crops*
Elevation (m)	*195*	*1622*	*1794*	*1547*	*0*	*0*	*208*
Dominant Species/Genius	*Sumac (Rhus), Toyon (Heteromeles, Coffee berry (Rhamnus) species*	*Olea europaea, Macchia*	*Picea*	*Nardetum alpinum*	*Cereal Crop*	*Cereal Crop*	*C3 grasses*

Table 2: Results from land cover type comparison between SEVIRI-predicted and in-situ ET half-hourly estimates (mm.h[-1]) for the seven selected sites over Europe in 2010, 2011, both years and a statistical summary for all sites.

Site Abbrev.		**ES_Agu**	**ES_LJu**	**IT_Ren**	**IT_Mbo**	**IT_Cas**	**FR_Mau**	**UK_EBu**	**Statistical Summary**
Statistical parameter	**Year of analysis**	**Shrubs**	**Shrubs**	**Evergreen Needleleaf Forest**	**Grasses/ Cereal Crops**	**Grasses/ Cereal Crops**	**Grasses/ Cereal Crops**	**Grasses/ Cereal Crops**	
Bias	2010	0.003	-0.004	-0.007	0.022	0.028		0.003	**0.001**
	2011	-0.024	-0.007	-0.016	0.013		0.012	0.020	
	both	-0.001	-0.006	-0.012	0.017			0.012	
Scatter	2010	0.035	0.032	0.091	0.078	0.096		0.039	**0.065**
	2011	0.038	0.050	0.092	0.087		0.085	0.037	
	both	0.035	0.043	0.092	0.084			0.039	
RMSD	2010	0.036	0.032	0.092	0.081	0.100		0.039	**0.065**
	2011	0.045	0.051	0.093	0.088		0.086	0.042	
	both	0.035	0.044	0.093	0.085			0.041	
MAE	2010	0.022	0.021	0.056	0.054	0.059		0.020	0.037
	2011	0.030	0.057	0.054	0.058		0.047	0.023	
	both	0.021	0.025	0.055	0.057			0.022	
Slope	2010	0.832	0.622	0.650	0.883	0.951		0.785	0.772
	2011	0.466	0.823	0.558	0.785		0.941	1.346	
	both	0.776	0.738	0.591	0.829			0.904	
Intercept	2010	0.008	0.008	0.021	0.031	0.031		0.011	0.012
	2011	-0.003	-0.002	0.019	0.030		0.017	0.013	
	both	0.006	0.003	0.021	0.030			0.015	
r	2010	0.684	0.620	0.644	0.794	0.705		0.801	**0.709**
	2011	0.546	0.536	0.696	0.706		0.730	0.792	
	both	0.655	0.552	0.669	0.744			0.759	

Table 3: Summary of the comparisons per season between satellite-derived and observed ET estimates ($mm.h^{-1}$) in the validation sites for 2010, 2011 and both years.

2010	SEASONS	Bias	Scatter	RMSD	MAE	Slope	Intercept	r
ALL SITES (EUROPE)	AUTUMN	0.006	0.052	0.052	0.030	0.796	0.014	0.706
	WINTER	-0.001	0.037	0.037	0.019	0.403	0.011	0.432
	SPRING	0.007	0.070	0.070	0.040	0.735	0.021	0.658
	SUMMER	0.017	0.091	0.092	0.054	0.903	0.024	0.731

2011	SEASONS	Bias	Scatter	RMSD	MAE	Slope	Intercept	r
ALL SITES (EUROPE)	AUTUMN	-0.005	0.057	0.057	0.032	0.642	0.011	0.685
	WINTER	-0.004	0.041	0.041	0.020	0.272	0.012	0.344
	SPRING	0.013	0.073	0.075	0.046	1.022	0.012	0.707
	SUMMER	-0.008	0.090	0.091	0.056	0.719	0.016	0.707

2010 & 2011	SEASONS	Bias	Scatter	RMSD	MAE	Slope	Intercept	r
ALL SITES (EUROPE)	AUTUMN	0.000	0.055	0.055	0.031	0.686	0.013	0.687
	WINTER	-0.003	0.039	0.040	0.020	0.317	0.012	0.376
	SPRING	0.010	0.072	0.073	0.043	0.877	0.017	0.679
	SUMMER	0.006	0.091	0.092	0.055	0.813	0.021	0.714

Table 4: Agreement between SEVIRI predicted and in-situ ET estimates ($mm.h^{-1}$) as a function of Fractional Vegetation Cover (FVC) for the selected sites in 2010 and 2011.

Val. Sites	FVC ranges	Year	Bias	Scatter	RMSD	MAE	Slope	Intercept	r
ES_AGU	FVC 0-0.24	2010	0.009	0.028	0.029	0.016	0.835	0.011	0.663
		2011	-0.013	0.036	0.038	0.023	0.394	0.000	0.545
	FVC 0.25-0.49	2010	0.007	0.035	0.036	0.022	0.824	0.013	0.771
		2011	-0.011	0.038	0.039	0.021	0.278	0.007	0.428
ES_LJU	FVC 0.25-0.49	2010	-0.003	0.029	0.030	0.019	0.759	0.004	0.665
		2011	-0.006	0.047	0.048	0.025	0.822	-0.002	0.535
IT_REN	FVC 0.25-0.49	2010	0.000	0.082	0.082	0.055	0.520	0.034	0.540
		2011	0.009	0.072	0.073	0.043	0.790	0.019	0.620
	FVC 0.5-0.74	2010	0.001	0.108	0.108	0.071	0.642	0.034	0.581
		2011	-0.037	0.108	0.114	0.072	0.512	0.020	0.707
	FVC 0.75-1	2010	-0.004	0.109	0.109	0.072	0.629	0.040	0.686
		2011	-0.008	0.084	0.084	0.056	0.912	-0.002	0.677
IT_MBO	FVC 0.25-0.49	2010	0.043	0.081	0.092	0.117	1.115	0.040	0.487
		2011	0.025	0.066	0.070	0.044	1.058	0.022	0.680
	FVC 0.5-0.74	2010	0.008	0.084	0.084	0.060	0.905	0.021	0.833
		2011	0.000	0.106	0.106	0.078	0.745	0.033	0.692
UK_EBU	FVC 0.25-0.49	2010	0.000	0.033	0.033	0.019	0.838	0.007	0.818
		2011	0.022	0.037	0.043	0.024	1.454	0.025	0.645
	FVC 0.5-0.74	2010	0.005	0.033	0.034	0.022	1.030	0.003	0.910
		2011	0.015	0.036	0.039	0.025	1.021	0.014	0.787
	FVC 0.75-1	2010	-0.001	0.036	0.036	0.023	0.859	0.008	0.890
		2011	0.038	0.052	0.064	0.042	1.470	0.021	0.795
IT_CAS (2010)	FVC 0.25-0.49	2010	0.024	0.074	0.077	0.045	0.884	0.028	0.632
	FVC 0.5-0.74	2010	0.035	0.117	0.122	0.079	0.919	0.043	0.683
FR_MAU (2011)	FVC 0.25-0.49	2011	0.010	0.079	0.079	0.043	0.914	0.016	0.727
	FVC 0.5-0.74	2011	0.024	0.101	0.104	0.063	1.029	0.021	0.755

Table 5: Summary of the agreement between SEVIRI predicted and in-situ ET estimates ($mm.h^{-1}$) as a function of Fractional Vegetation Cover (FVC) in 2010 and 2011.

Val. Sites	FVC ranges	Year	Bias	Scatter	RMSD	MAE	Slope	Intercept	R
ALL SITES (EUROPE)	FVC 0-0.24	2010	0.009	0.028	0.029	0.016	0.835	0.011	0.663
		2011	-0.008	0.044	0.044	0.026	0.445	0.004	0.430
		Both	-0.005	0.042	0.042	0.024	0.470	0.006	0.445
	FVC 0.25-0.49	2010	0.011	0.056	0.057	0.032	0.813	0.017	0.611
		2011	0.003	0.064	0.064	0.036	0.910	0.007	0.674
		Both	0.005	0.061	0.061	0.034	0.882	0.010	0.658
	FVC 0.5-0.74	2010	0.018	0.106	0.108	0.071	0.845	0.034	0.705
		2011	-0.005	0.103	0.103	0.066	0.694	0.029	0.690
		Both	0.006	0.105	0.105	0.068	0.757	0.032	0.692
	FVC 0.75-1	2010	-0.002	0.071	0.071	0.041	0.723	0.021	0.773
		2011	0.036	0.054	0.065	0.042	1.373	0.023	0.771
		Both	0.014	0.067	0.069	0.041	0.753	0.030	0.735