ASSIMILATION OF THERMAL AND MICROWAVE DATA TO IMPROVE FAO-56 METHOD FOR EVAPOTRANSPIRATION ESTIMATES IN SEMI-ARID REGIONS

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Abstract: FAO-56 is one of the widely used formulations to estimate the actual crop evapotranspiration (ET_a) due to its operational nature and since it represents a reasonable compromise between simplicity and accuracy. In this vein, the objective of this paper was to examine the possibility of improving ET_a estimates through remote sensing data assimilation. For this purpose, SMAP-based surface soil moisture (SM) was assimilated into the soil evaporation (E_s) component through the soil evaporation coefficient, and Landsat land surface temperature (LST) was assimilated into the actual crop transpiration (T_a) component through the crop stress coefficient. By using SMAP-based SM and Landsat-LST, results also improved in comparison with standard FAO and reached a RMSE of 0.73 mm/day against eddy-covariance ET_a measurements.

Keywords: evapotranspiration; data assimilation; soil moisture; land surface temperature

Introduction

Evapotranspiration (ET) is an essential component of the water and energy exchanges between surface and the atmosphere. Since ET is a crucial flux of the water cycle and helps understanding the hydrological processes, it's estimation accurately is a must. ET has an important role for water resource management, drought monitoring and climate simulation (Tasumi, 2019). Arid and semi-arid regions suffer from many problems related to water resources and water use, where optimizing the use of irrigation water could help to deal with these issues. To do so, a quantification of crop water requirements which is equivalent to precise ET estimates is needed (Allen et al., 2011).

Several instruments have been used to measure ET at local scale, such as eddy correlation system (Allen et al., 2011), weighing lysimeter (Daamen et al., 1993), sap flow (Rafi et al., 2019) and Scintillometer that can provide ET at 10 km transect (Ezzahar and Chehbouni, 2009). Remote sensing data has the privilege to assess the ET indirectly at a global scale by using related remotely sensed indicators. Among these indicators, Leaf Area Index (LAI), Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST) (Li et al., 2009) and soil moisture (Elfarkh et al., 2021).

FAO dual crop coefficient (FAO-2Kc) is one of widely used model to assess ET (Allen et al., 1998). FAO model is extensively used for modeling water consumption and growth of plants, due to its operationality and simplicity as well as requires few input variables (Alberto et al., 2014). Many researchers have used FAO-56 to retrieve ET over contrasted area and different crop types, including, wheat (e.g., Amazirh et al., 2021; Olivera-Guerra et al., 2018; Rafi et al., 2019), olive (e.g., Er-Raki et al., 2010; Rallo et al., 2014), grapes and vineyards (Ferreira et al., 2012), as well as citrus (Rallo et al., 2017).

The FAO-2Kc approach is based on partitioning the ET into soil evaporation and plant transpiration by separating the crop coefficients (K_c) into a basal crop K_{cb} and a soil evaporation K_e coefficients. The ET under well-watered conditions (ET_a) is obtained by multiplying both coefficients by reference evapotranspiration (ET_0), then the real ET is obtained by readjusting ET_a through integrating the crop stress coefficient when more factors limit moisture transport to the atmosphere. Several studies agreed about the fact that ET was under/overestimates by FAO double coefficient over bare and quasi bare soil conditions especially at the beginning or/and at the end of the crop growth season (e.g., Amazirh et al., 2021; Olivera-Guerra et al., 2018). This is because FAO-56 uses the water balance model at the surface to estimate soil evaporation where, its component such as irrigation is not available all time which could lead to uncertainties. To overcome this issue soil moisture data has been successfully used to estimate the ET under bare soil conditions (Amazirh et al., 2018; Baghdadi and Zribi, 2006). Transpiration also could lead to uncertainties in FAO-ET modeling, where FAO used water balance in root zone, where the difficulty in modeling root zone soil moisture from meteorological data alone could provide some uncertainties on transpiration estimates. Several researchers attempt to improve the ET estimates using remotely sensed data, including Land surface temperature (LST) and soil moisture (Amazirh et al., 2021). Other research used data assimilation techniques to estimate ET where in Er-Raki et al. (2008) the assimilation of the LST into the single crop FAO-56 model provides better results than the standard FAO-56.

In this regard, data assimilation technic was used to improve the FAO-2Kc ET, SM and LST data are jointly assimilated, to improve soil evaporation using SM and to correct the wheat crop transpiration by using LST. Sequential assimilation scheme was applied in order to update the E and T_r estimates. The LST derived from Landsat 7/8 and disaggregated SMOS-SM were used at field scale. The assimilation approach was applied over a wheat field named F16 (2015-2016) near to Marrakech city in center Morocco.

1. Material and method

1.1. Data and study sites

The study was investigated over a 4 hectares wheat field that have been monitored during the 2015-2016 wheat agricultural season named 'F16'. This field is in the eastern part of the Tensift basin, Central Morocco, 40 km east of the Marrakech city (Figure 1). The climate is of semi-arid continental type, with low and irregular rainfall (~250 mm/year), temperatures rather low in winter (4.9 °C as average of the minima) and very high in summer (37.7 °C as average of the maxima) (Er-Raki 2007), and a very high evaporative demand (~1600 mm/year). This region has been the subject of several research studies since 2002 addressing various problems regarding the use of water, understanding the integrated hydrological functioning of the Tensift semi-arid basin, as well as improving our knowledge of fundamental hydrological processes (Amazirh et al., 2017). Flood gravitation irrigation system was adopted for watering this field, where the irrigation volume was measured by the installed flowmeters. The irrigation frequency was 1 to 3 weeks, where the field was irrigated 8 times with a volume of 64 mm each during the wheat agricultural season. The filed is known for high clay contents (47%) and 18% of sand fraction. The sowing date was the 13th December 2015 (Amazirh et al., 2017).

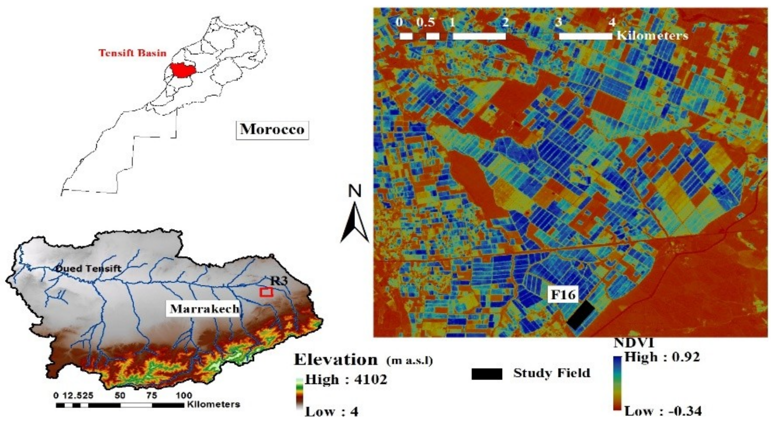

figure 1. Study area.

An eddy covariance station (EC) was installed in the field, to monitor energy fluxes, including, vertical sensible heat (H_{obs}) and latent heat (LE_{obs}) fluxes which is equivalent to ET_{obs}. Other instruments were also installed on the EC tower to provide additional measurements such as the surface net radiation (net radiometer CNR4) and the three components of wind speed (3D sonic anemometer). Soil heat flux (G) was also measured at 5 cm depth by using two heat flux plates (HPF01). In order to assess the reliability of the energy fluxes, a comparison of the surface available energy (R_n-G) to the sum of turbulent fluxes (H_{obs}+ LE_{obs}) called the energy balance closure is needed. The energy budget closure was achieved in Amazirh et al. (2017) for the same site with a strong coefficient of determination (R^2=0.91).

Remotely sensed data were also used to provide soil moisture and Land surface temperature. LST data were provided by the Landsat-7 (L7) and Landsat-8 (L8) while soil moisture data were acquired from disaggregated SMAP data (Ojha et al., 2019) (Table 1).

Table 1. Technical characteristics of satellite products.

Sensors /Mission	Acquisition Time	Bands	Spatial resolution (m)	Temporal resolution (Day)
Soil Moisture Active Passive (SMAP)	06:00 AM/PM	Brightness temperature	36 km	2-3
Landsat 7 and Landsat 8 (L7/L8)	~11:30 AM	- VNIR$^+$ (L7: B3 & B4; L8: B4 & B5) - TIR (B6 for L7 and B10 et B11 for L8)	60 m and 100 for TIR 15 m for VNIR	8

Thermal infrared (TIR) data were converted to LST data after applying atmospheric correction and correction of surface emissivity. The followed steps are described in Tardy et al. (2016) and the same processing chain was used and validated by in situ LST measurements in Amazirh et al. (2018, 2019). The 36 km SMAP soil moisture was disaggregated to 100 m resolution by Ojha et al. (2019) using DISPATCH (DISaggregation based on Physical and Theoretical scale Change) method. The followed disaggregation steps were described in Ojha et al. (2019). The disaggregated SMAP-SM products were evaluated over 22 irrigated fields in the same used area where the *in situ* SM measurements have been collected and calibrated as in Amazirh et al. (2018) during the same 2015–2016 season.

1.2. Methodology

Evapotranspiration was estimated using the dual crop coefficient FAO-56 that allows for partitioning ET into bare soil evaporation and wheat crop transpiration beyond standard conditions using two coefficients: the soil water evaporation coefficient (K_e) to describe evaporation from the soil surface and the basal crop coefficient (K_{cb}) to describe plant transpiration with an adjustment to obtain the real crop evapotranspiration ET_a, by introducing the water stress coefficient K_s, according to Equation (1):

$$\frac{ET_a}{ET_0} = (K_{cb}K_s + K_e) \qquad (1)$$

with ET_0 being the ET rate over a well-watered crop land covered by a short green, grass-like crop (reference ET), depending only on atmospheric conditions; K_{cb} and K_e being the basal crop coefficient and the bare soil coefficient, respectively. Soil evaporative coefficient (K_e) is calculated as a function of the amount of water in the soil, soil properties and the exposed and wetted soil fraction to solar radiation where most evaporation occurs (f_{ew}). tK_s is the water stress calculated based on a daily computation of the water balance for the root-zone layer Z_r (m). All equations were described in Allen et al. (1998). As stated before, the assimilation approach seeks to improve the evaporation component by assimilating SM in K_e ($K_{e,New}$) and transpiration component by assimilating LST into Ks ($K_{s,New}$). Sequential Kalman filter was used for this issue as proposed by Schuurmans et al. (2003) and used by Er-Raki et al. (2008). This method has been chosen due to its simplicity and to keep FAO-2Kc method operational. SM was assimilated directly into the K_e, while a normalized LST (LST_{proxy}) was assimilated into K_s ($K_{s,LST}$). The LST was normalized by its maximal and minimal values as in Idso et al. (1981). Figure 2 illustrates the flowchart of retrieved approaches.

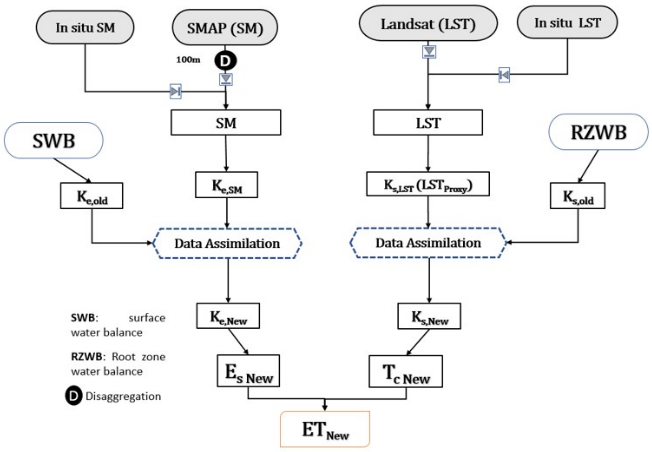

figure 2. Schematic diagram of the assimilation approach. $E_{s\ New}$, $T_{c\ New}$, $K_{e,New}$, $K_{s,New}$ are the updated evaporation, transpiration, evaporation and stress coefficient after assimilation, respectively. $K_{e,old}$ and $K_{s,old}$ are K_e and K_s before assimilation, respectively.

2. Results and discussions

To evaluate the spatial extensibility of the assimilation scheme, the daily ET_a over the selected F16 field during 2015–2016 was simulated at a spatial resolution of 100 m. SM data was derived from SMAP data product, which were disaggregated to 100 m (Ojha et al., 2019), and LST data were derived from Landsat-7 and Landsat-8 data. Figures 3 and 4 present the scatter and time series plots of the obtained results using the assimilation technique, respectively.

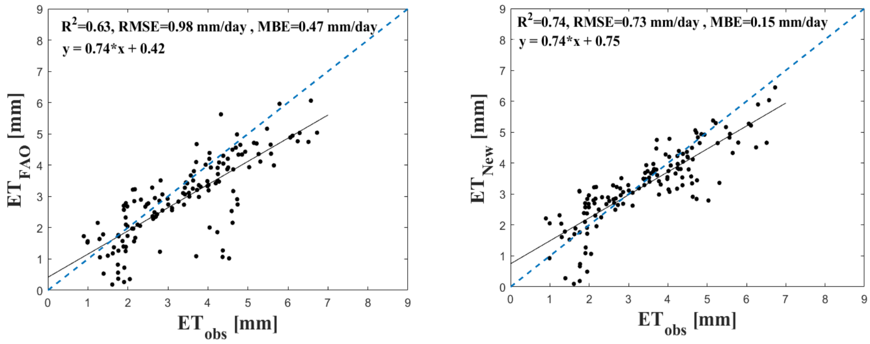

figure 3. Scatter plot comparison between FAO-56 and observed ET_a (ET_{obs}) without assimilation (ET_{FAO}), and with assimilation (ET_{New}).

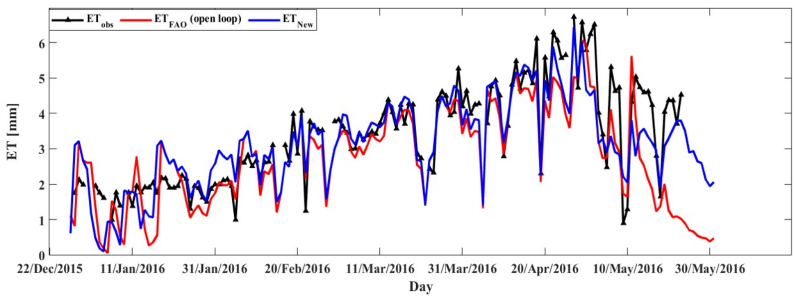

figure 4. Daily temporal comparison between FAO-56 after and before assimilation and observed ET (ET_{obs}).

From the obtained results in Figures 3 & 4, the assimilation of LST and SM conjointly tend to improve the ET_a estimates. Figures 3 compare the results of the assimilation procedure with the one from the open-loop ET_{FAO} (no assimilation). For the other case, when coupled assimilation of $SM_{DISPATCH}$ and LST through using the normalized LST proxy, the RMSE is equal to 0.73 mm/day with a bias that doesn't exceed 0.15 mm/day. Without assimilation (ET_{FAO}), FAO-2K_c severely underestimates ET_a during the senescence period, where the assimilation experiment has improved the accuracy in ET_a estimates. This is seen especially at the beginning and the end of the wheat growing season (Figure 4), where the SM improves the soil E_s when soil is under bare soil conditions. The assimilation of SM allows the updating of the surface depletion (D_e), thus controlling the water budget at the surface then updating the K_e coefficient of evaporation. By integrating the LST information, this allows the updating of the root zone depletion D_r, which controls the temporal course of the root zone water budget, which leads to correcting the K_s values. The idea of assimilating LST into the stress coefficient is to improve the transpiration component. The selected site was well irrigated, and the stress appears just in some periods during the investigated study. The real impact of LST on the water balance at the root zone could be seen clearly in the case of a field that undergoes several stress periods when irrigation is deliberately cut. In this study, just on some dates that the field is undergoing stress period and by assimilating LST into FAO model we succeeded to capture the stress periods.

Conclusion

This work aims to improve the actual crop evapotranspiration (ET_a) estimates using data assimilation technique. The idea was to improve the accuracy of the FAO-56 ET components through assimilating remote sensing data. Surface soil moisture (SM) data is assimilated in order to update soil evaporation and land surface temperature (LST) is assimilated to update the crop wheat transpiration. SMAP disaggregated SM and Landsat derived LST were used at field scale. The investigated technique was tested over F16 field located in central Morocco, during the 2015-2016 wheat growing season. The modelled ET_a tracks successfully the ET_a observation, by coupling SM and LST assimilation. However, some uncertainties were observed, and this could be due to the sensing depth of SM data. The assimilation technique has demonstrated the potential of inferring valuable information from remotely sensed land surface data (SM and LST) for evaluating distributed water balance models, given that forcing data (including irrigation) are accurately known.

The proposed study showed its capability to retrieve ET_a at field scale. Furthermore, a spatialization of ET_a over a large scale (basin, region, national scales) is needed. This could be done by using LST and SM products at high resolution (Amazirh et al., 2019; Ojha et al., 2019). Recently, Amazirh et al. (2021) proposed a new evaporation formulation by including the soil texture information into the reduction coefficient (K_r). The proposed formulation demonstrates its better performance than the classical FAO. Combining the assimilation of SM into E_s formulation developed in Amazirh et al. (2021) could provide more accurate results by improving the E_s component.

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