A modelling platform for climate change impact on local and regional crop water requirements

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Abstract

The impact of climate change on agriculture is projected to be more severe over the coming years due to changing intensity, magnitude and distribution of precipitation, soil water content, atmospheric water vapor, higher temperatures, and thus larger evapotranspiration. This will have significant consequences for irrigation requirements, especially in semi-arid area of Southern Europe recognized as hotspot of climate change. Since the total water use to satisfy agricultural demand is currently about 25% of total water withdrawal in Europe and up to 80% in some Mediterranean countries, improvements in water use management are needed to cope with worsening climate conditions. Although several crops and hydrological models have been developed, only a few couple crop growth, soil water flow, and irrigation mechanics to assess agricultural water management both at local and regional scale. In this work, the Simulation of Evapotranspiration of Applied Water (SIMETAW#) model is implemented in R with two new versions able to estimate crop water consumption, irrigation demand and scheduling at local (SIMETAW_R) and regional scale (SIMETAW_GIS platform) using extensive climate and environmental geospatial datasets. SIMETAW_R was validated in ten experimental sites, and SIMETAW_GIS performance in Mediterranean countries was assessed by estimating the impact of climate change on maize, wheat, and wine grape water needs in the past (1976-2005)and future climate conditions (2036-2065), under RCP4.5 and RCP8.5 scenarios. Results showed that in Mediterranean countries, maize, wheat, and grape production will require on average about 13%, 16%, and 10% more water, respectively, under future climate, representing a considerable challenge for water resources management, especially with demand increases in other sectors. The tool showed great potential in estimating climate change impact on crop water consumption and irrigation requirements, both at local and regional scale, and offers new analytical skills for water resources management planners for improved decision-making.

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A Modeling Tool to Assess the Impact of Climate Change on Crop Water Requirement at Local and Regional Scale

Highlights:

- New SIMETAW# versions (-R and -GIS) are introduced, described, and tested.
- Great potential in estimating climate change impact on crop water requirements.
- Maize, wheat, and grape irrigation demand is expected to rise under climate change.
- Increases in water-related issues in the Mediterranean basin are highlighted.
- Both tools could be used to address decision making at local and regional scale.

A Modeling Tool to Assess the Impact of Climate Change on Crop Water Requirement at Local and Regional Scale

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The impact of climate change on agriculture is projected to be more severe over the coming years due to changing intensity, magnitude and distribution of precipitation, soil water content, atmospheric water vapor, higher temperatures, and thus larger evapotranspiration. This will have significant consequences for irrigation requirements, especially in semi-arid area of Southern Europe recognized as hotspot of climate change. Since the total water use to satisfy agricultural demand is currently about 25% of total water withdrawal in Europe and up to 80% in some Mediterranean countries, improvements in water use management are needed to cope with worsening climate conditions. Although several crops and hydrological models have been developed, only a few couple crop growth, soil water flow, and irrigation mechanics to assess agricultural water management both at local and regional scale. In this work, the Simulation of Evapotranspiration of Applied Water (SIMETAW#) model is implemented in R with two new versions able to estimate crop water consumption, irrigation demand and scheduling at local (SIMETAW_R) and regional scale (SIMETAW_GIS platform) using extensive climate and environmental geospatial datasets. SIMETAW_R was validated in ten experimental sites, and SIMETAW_GIS performance in Mediterranean countries was assessed by estimating the impact of climate change on maize, wheat, and wine grape water needs in the past (1976-2005)and future climate conditions (2036-2065), under RCP4.5 and RCP8.5 scenarios. Results showed that in Mediterranean countries, maize, wheat, and grape production will require on average about 13%, 16%, and 10% more water, respectively, under future climate, representing a considerable challenge for water resources management, especially with demand increases in other sectors. The tool showed great potential in estimating climate change impact on crop water consumption and irrigation requirements, both at local and regional scale, and offers new analytical skills for water resources management planners for improved decision-making.

Keywords:

SIMETAW model, spatial modeling, water scarcity, RCPs, crop irrigation requirement, evapotranspiration.

1. Introduction

Climate change is one of the most important challenges in the 21st century. The Intergovernmental Panel on Climate Change (IPCC) stated that climate-related hazards will worsen in the coming decades with significant variations in the Earth`s climate (IPCC, 2013; IPCC 2018a). Rising greenhouse gas (GHG) concentration in the atmosphere is causing strong changes in the hydrological cycle (IPCC, 2014; Kleidon and Renner, 2018) that are expected to intensify by the end of the century when high flood frequency and perennial drought may characterize large areas (IPCC, 2018b; EEA 2019).

Climate models foresee non-uniform variation in global hydrological cycles. An increase of annual precipitation in Northern Europe and a strong reduction in the number of rainy days with a consequent higher risk of drought periods is predicted in central Europe and Mediterranean areas (IPCC, 2013). Water scarcity is expected to increase worldwide, and this trend will be exacerbated not only by climate change but also by demographic growth, socio-economic development, increasing demand for raw materials and energy, extension of residential centres, as well as improvement of quality of life and technology (Brooks, 2012). Increasing competition for water resources, threatening a sustainable balance between water demand and supply, is expected to worsen water scarcity globally, with the Mediterranean expected to be a water scarcity 'hotspot' (Giorgi 2006; OECD, 2017; Cramer 2018).

Agriculture is one of the most water demanding sectors in Mediterranean countries. The agricultural sector is responsible for about 70% of water withdrawal globally (World Bank, 2017), while is about 25% at European level, where the percentage in Central and Western parts (27%) is slightly higher than in Eastern areas (21%) (FAO, 2016). This is much higher in southern Europe and Mediterranean area, where some countries stand out with extremely high values, i.e., Syria (88%), Morocco (87%), Egypt (86%), and Libya (83%) (Climate-ADAPT, 2016; Ferragina and Canitano, 2014). In some Southern and Eastern Mediterranean countries, Ferragina and Canitano (2014) reported that the Water Exploitation Index (WEI, where WEI > 40% indicates a water stress conditions) is far higher than 40% (99% in Jordan, 94% in Egypt, 86% in Syria, and 80% in Israel), highlighting a severe impact on renewable water resource exploitation, and suggesting a significant water management challenge under changing water and socio-economic conditions. The overexploitation of both surface and ground water resources requires further efforts to improve irrigation efficiency to compensate increases in crop water demand due to climate change, and to identify strategies to sustain food security (Fader et al., 2016; Masia et al., 2018).

Despite the high percentages of agricultural water use, it is crucial to emphasize the water-food nexus to explain the critical role of water to guarantee food security to supply the growing population, to alleviate poverty, and to stimulate the rural socio-economic development (Ferragina and Canitano, 2014; World Bank, 2017). Given the large irrigated areas in the Mediterranean regions and projected influence of climate change, the development of models in the agricultural sector becomes essential to simulate current and expected future water requirements under different emissions scenarios, climatic conditions and crop management regimes. This can help farmers, decision and policy makers to develop optimal strategies balancing economic growth and environmental sustainability (i.e. water demand vs available resources).

Although the number of crop models (e.g. WOFOST, van Diepen et al., 1989; EPIC, Williams, 1990; CROPSYST; Stockle et al., 2003; CERES-Maize, Bao et al., 2017) and hydrological models (SWAT, Santhi et al., 2001; DREAM, Monfreda et al., 2005; Wasim-ETH, Schulla and Jasper, 2007), is rising, more effort is needed to improve the simulation on the effect of irrigation management and practices, together with soil water balance and crop water consumption, with outcomes on irrigation demand, crop growth and yield, both at local and regional scale. Even though model coupling is still at an early stage (Siad et al., 2019), there is an advantage of this approach for quantifying interactions among different elements in complex systems. More specifically, there is a growing need of coupled models that are able to estimate and forecast atmosphere-soil-water-crop-irrigation applications interactions at different time and spatial scale in order to improve water system management.

In this work, the Simulation of Evapotranspiration of Applied Water model (SIMETAW# model; Mancosu et al., 2016), which is able to estimate the daily reference crop and actual evapotranspiration (ET_o, ET_c, ET_a), the evapotranspiration of applied water (ET_{aw}), irrigation scheduling, and the rainfed and irrigated crop growth and yield for a specific experimental site, was implemented in the R platform (SIMETAW_R) to estimate crop consumption and irrigation requirements at local scale. The new tool was integrated into a GIS spatial platform under R, thus named SIMETAW_GIS, which couples and processes different geospatial climate and environmental data and reiterates simulations over regional scales. The aim of this paper is to introduce and demonstrate both new SIMETAW# versions (-R and -GIS), and highlight their added value for water resources planning and management under expected climate change conditions.

2. Materials and Methods

2.1 SIMETAW_R and SIMETAW_GIS model description

Two new versions of SIMETAW#, (Mancosu et al., 2016) are introduced, described, and tested in this work. The new versions are able to perform at local (i.e. site specific) "SIMETAW_R" and wider spatial scale "SIMETAW_GIS" (Figure 1). Full details of the original SIMETAW# model is found in Mancosu et al. (2016).

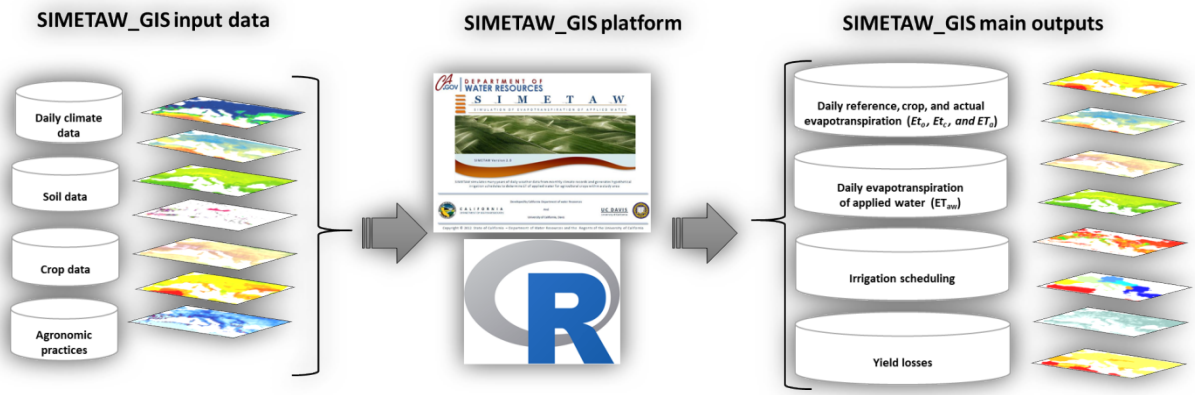

Fig. 1. Scheme of SIMETAW_GIS platform.

The SIMETAW_R modelling scheme, designed for site-specific applications, was validated at 10 experimental sites, and then implemented for spatially distributed applications using GIS libraries available in R within the spatial platform named SIMETAW_GIS (Figure 1). The spatial platform couples and automates interactions with large geodatasets of climate variables, environmental conditions, and agronomic practices, to process the soil water balance for multiple years and pixels across regional and continental scales. SIMETAW_GIS was

tested by running regional simulation of water consumption and net water application in the Mediterranean domain (www.cordex.org) under past (1976-2005) and future (2036-2065) climate conditions, under RCP 4.5 and RCP 8.5 scenarios. Both versions were tested for grape, maize, and wheat.

SIMETAW#/R/GIS are daily crop-soil-water balance programs developed to compute the reference evapotranspiration (ET_o), the crop evapotranspiration (ET_c), the actual evapotranspiration (ET_a), and the evapotranspiration of applied water (ET_{aw}). Note that ET_o is the evapotranspiration from a virtual reference surface having known aerodynamic and canopy resistances and is based on an equation using data from a well-designed and managed weather station surrounded by an extensive grass surface. While the surface is virtual, the equation was developed by comparing it with energy-limited evapotranspiration from a well-watered 12 cm tall, cool-season grass. The crop evapotranspiration (ET_c) is the energy limited evapotranspiration from a large field of a well-watered, healthy crop that is experiencing little or no stress. The ET_a is actual evapotranspiration, which is what would be measured over a crop whether stressed or not. The energy limited ET_c is calculated as: $ET_c=ET_o \times K_c$ where K_c is the crop coefficient. The actual ET_a is calculated as: $ET_a=ET_c \times K_s$ where K_s is the stress coefficient. Note that K_s=0.00 when there is no ET and K_s=1.00 when there is no ET reducing stress and $ET_a=ET_c$. In addition, the actual ET_a is calculated as: $ET_a=ET_o \times K_c \times K_s=ET_o \times K_a$ where K_a is the actual coefficient.

The ET of applied water (ET_{aw}) is an estimate of how much water from the irrigation of a crop contributes to the crop evapotranspiration during a season. It does not include water from other sources like preseason stored soil water, in-season effective rainfall, seepage from levees or water from water tables. Once the ET_{aw} is estimated, the required water diversion for irrigation can be assessed by dividing the ET_{aw} by the irrigation system Distribution Uniformity (DU) assuming that the low quarter[1] is refilled at each irrigation.

The ET_{aw} is calculated as:

$$ET_{aw} = \sum_{i=1}^{n} NA_i = CET_c - CE_{spg} - CE_r - \Delta SW \qquad (1)$$

where $\sum_{i=1}^{n} NA_i$ is the sum of the net applications (i.e., depths applied to the low quarter of the field), CET_c is the cumulative ET_c, CE_{spg} is the cumulative seepage or water table contribution, and CE_r is the cumulative effective rainfall during the season.

SIMETAW estimates the amount of water required by irrigated crops, schedules the number of irrigation events, and the net amount of water to be applied per each event (net application; NA). The "SIMETAW#" model was improved by integrating into SIMETAW_R and GIS program the computation of the reference evapotranspiration (ET_o). Daily ET_o is estimated with three alternative methods: (i) the original equation from Hargreaves and Samani-HS (1985); (ii) the modified HS equation (Samani, 2000) (ET_o_HS), and standardized

[1] The low quarter water application is the mean irrigation applied to the quarter which receives the least amount of water, while the high quarter water application is the mean depth of water applied to the quarter which receives the largest quantity of water. The second and the third quarters water application are the mean depths of water applied to the intermediate quarters (Mancosu et al, 2016).

reference evapotranspiration equation for short canopies (ET_o_PM) (Allen et al., 1998; Allen et al., 2005; Allen et al., 2006). Following Snyder (2012), the model adjusts the canopy resistance (r_c, eq. 2) allowing the assessment of the effect of CO_2 concentration changes in the atmosphere.

$$r_c = \frac{1000}{1.44(14.18 - 0.0112CO_2)} \quad \text{(m s}^{-1}\text{)} \qquad (2)$$

One of the most relevant characteristics of the model is that it computes the seasonal crop coefficient (K_c) trend using inflection points identified as a percentage of the growing season and daily K_c values at the beginning of the season, midseason, and at the end of late season to define the seasonal crop coefficient changes. This allows users to easily define the daily crop coefficients they need by changing the starting and ending of the growing season dates.

SIMETAW allows for adjustment of the midseason K_c (Kc_{mid}) as a function of the local climate as:

$$K_{Cmid} = K_{ctab} + 0.261 \cdot (ET_0 - 7.3) \cdot (K_{Ctab} - 1) \qquad (3)$$

where K_{Ctab} is the tabular K_c from research that is expected in a climate with $ET_o \approx 7.3$ mm day^{-1} (Guerra et al., 2014). Crops with a $K_{Cmid}>1.00$ in areas with ET_o of 7.3 mm day^{-1} will have a higher K_{Cmid} in a climate with $ET_o>7.3$. In a climate with $ET_o<7.3$ mm day^{-1}, a lower K_{Cmid} is expected.

The allowable depletion (AD), i.e. the amount of available water which corresponds to the yield threshold depletion, is a default value in the model equal to 50% of the plant available water. The model also estimates the soil water depletion (SWD=FC-SWC), where FC is the soil field capacity and SWC is the measured or estimated soil water content. The current day's *SWD* is calculated adding the SWD of the previous day (SWD_{i-1}), the crop evapotranspiration of the current day (ET_{ci}), the capillary rise from a water table or seepage (C_i), percolation below the root layer (D_i), the depth of irrigation (I_i), and the runoff (R_{offi}) (eq. 4). When precipitation (P_{cpi}) is higher than SWD, then the effective rainfall is $R_e=SWD$, otherwise $R_e=P_{cpi}$ (Mancosu et al., 2016). In the first case, the *SWC* returns to field capacity and (*FC*) is achieved, while in the second case the *SWC*< *FC*.

$$SWD_i = SWD_{i-1} + ET_{ci} + P_{cpi} + C_i - D_i - R_{offi} + I_i \quad \text{(mm)} \qquad (4)$$

The calculation of daily soil water depletion is necessary to define the irrigation events that occur before the SWD exceeds the management of allowable depletion (MAD, mm), thus the computation of MAD is essential to define irrigation scheduling.

MAD is the amount of water that can be depleted between water irrigation applications without incurring water deficit. It is considered as the water amount necessary to refill the soil to field capacity (Net Application, NA, mm). The model computes the evapotranspiration of the applied water (ET_{aw}, mm), i.e. the sum of the net irrigation application ($\sum$NA).

At the end of the initial growth period, only 10% of soil is covered by the crop, in this growth stage the crop evaporation is considered equal to the soil evaporation process, thus NA is computed as:

$$NA_c = \overline{ET}_0 \cdot K_e \cdot d_e \quad \text{(mm)} \qquad (5)$$

where *Ke* is the coefficient of evaporation of bare soil, $\overline{ET_o}$ (mm) represents the mean daily reference evapotranspiration during initial growth period (i.e. from planting to 10% ground shading), which is stage A to B of the growing season, and d_e the number of water applications during this time step. It is assumed that the ET from a crop having less than 10% ground shading is equal to bare soil evaporation. The K_e is computed as:

$$K_e = \frac{2.54}{\sqrt{CET_0}} \quad (6)$$

where 2.54 represents a typical soil hydraulic factor and CET_o is the cumulative ET_o.

At the beginning of the mid-season NA_c is computed as:

$$NA_c = (1 - R_{off}) \cdot RT \cdot AR \cdot D_u \quad \text{(mm)} \quad (7)$$

where *RT* is the runtime that depends on the irrigation method, *AR* is the application rate (mm h^{-1}), and D_u is the distribution uniformity expressed as a fraction (Mancosu et al., 2016). The program helps to plan for the number and frequency of irrigation events during the midseason in the case of full (100% water allocation percentage, WAP = 100%) or deficit irrigation (WAP < 100%). For fully irrigated crops, the number of water applications (N_{ic}) is computed as the ratio between the ET_{awe} and the management allowable depletion (MAD_c) in well-watered conditions:

$$N_{ic} = \frac{ET_{awe}}{MAD_c} \quad \text{(mm)} \quad (8)$$

The number of water applications for deficit irrigation (N_{ia}) is computed assuming that the plant irrigation requirement (*PIR*) is less than 100%:

$$N_{ia} = \frac{\sum NA_a}{MAD_c} \quad \text{(mm)} \quad (9)$$

where the sum of the irrigation depths applied to the low quarter of a crop cultivated in deficit irrigation conditions ($\sum NA_a$) is:

$$\sum NA_a = (WA - \sum R_o) \cdot D_u \quad \text{(mm)} \quad (10)$$

where *WA* is the water allocation, i.e. the mean amount of water available for irrigation, R_o is the runoff coefficient and D_u the distribution uniformity. For a crop with water deficit, the actual MAD (MAD_a) is:

$$MAD_a = \frac{\sum NA_a}{N_{ia}} \quad \text{(mm)} \quad (11)$$

The evapotranspiration of the applied water of a well-watered crop (ET_{awe}) is then computed as:

$$ET_{awe} = CET_c - \left(YTD_c - \frac{YTD_{os}}{2}\right) \quad \text{(mm)} \quad (12)$$

where CET_c is the cumulate value of ET_c during the entire growing season, YTD_c is the yield threshold depletion during the mid-season, and YTD_{os} represents the yield threshold depletion during the off-season.

SIMETAW# and SIMETAW_R estimate the yield losses at a specific site considering that the irrigation in the field is not uniform (see Mancosu et al., 2016) while in SIMETAW_GIS the yield losses at regional scale is computed following Steduto et al. (2009):

$$1 - \frac{Y_a}{Y_m} = K_y \cdot \left(1 - \frac{ET_a}{ET_c}\right) \quad (13)$$

where Y_a is the actual crop yield, Y_m the maximum expected crop yield, and K_y the yield response factor. This equation explains the link between water use and crop yield and shows how yield losses correspond to a reduction in evapotranspiration. Further details of the original SIMETAW# model, are found in Mancosu et al. (2016).

2.2 SIMETAW_R validation and SIMETAW_GIS application.

2.2.1 SIMETAW_R validation

SIMETAW_R was validated at ten European sites (Table 1) selected through the international FLUXNET network (http://fluxnet.fluxdata.org/). Model performance was assessed by comparing actual evapotranspiration simulated by the model and the latent heat flux (LE) measured through the Eddy covariance technique in each site. LE was converted from W m^{-2} to MJ m^{-2} d^{-1} using the conversion factor of 0.0864 and from MJ m^{-2} d^{-1} to mm d^{-1} using the conversion factor of 0.408. Maize, wheat, and grape crop water consumption were estimated for each stage of the growing season and under different soil and climatic characteristics. Eddy covariance fluxes and climate data for each site were provided by meteorological, radiometric, and micrometeorological stations set up at each experimental site. In addition, a questionnaire was circulated to collect information about crop and soil characteristics and irrigation practices. Additional supplementary information was obtained through a literature review.

Pearson`s coefficient (r), Root Mean Square Error (RMSE), Mean Bias error (MBE), Mean Absolute Error (MBA), and Index of Agreement (AI) were used to evaluate the SIMETAW_R performance. In addition, model performance was explained by taking into account the percentage of gap filled observed data. Missing measured data were gap-filled following Falge et al. (2001). Days with less than 30% missing half-hourly observations were acceptable for the model evaluation.

The flux energy budget closure (EBC) was used to assess half-hour measured data reliability, by plotting the ratio $H+LE$ Vs R_n-G, where R_n is the net radiation (W m^{-2}), G is the soil heat flux (W m^{-2}), H is the sensible heat flux (W m^{-2}), and LE is the latent heat flux (W m^{-2}). Measured data are considered reliable when the sum of H+LE is equal to R_n-G. According to the literature (Baldocchi et al., 1988; Twine et al., 2000; Wilson et al., 2002) an energy balance closure deviation of 20-30% is acceptable. The residual of the energy balance was also computed as LE`=RN-G-H to assess the quality of the half-hour measured data.

In addition, SIMETAW_R performance in assessing ET_o was evaluated for both Hargreaves Samani (ETo_HS) and the standardized FAO-56 Penman-Monteith (ETo_PM) equations, calculated using gridded datasets and observed daily climate data obtained for each site. The E-OBS (European high-resolution gridded data set) gridded observation climate data (Haylock et al., 2008) and the COSMO-CLM RCM (Consortium for Small scale Modeling in Climate Model) (Rockel et al, 2008) forced by Era-Interim reanalysis were used as climate gridded datasets for the comparison.

Tab.1. Crop characteristics and experimental sites selected through the FLUXNET network.

Code	*SITE*	*Country*	*Lat*	*Lon*	*Elevation (m.a.s.l.)*	*Crop*	*Sowing-Harvest date*

IT-Neg	Negrisia	Italy	45.75	12.45	11	Wine Grape	01.04.2007/15.10.2007
IT-Neg	Negrisia	Italy	45.75	12.45	11	Wine Grape	01.04.2008/27.10.2008
IT-VdA	Valle dell'Adige	Italy	46.20	11.11	207	Wine Grape	15.04.2009/05.09.2009
IT-BCi	Borgo Cioffi	Italy	40.52	14.96	13	Maize	17.05.2005/24.08.2005
IT-BCi	Borgo Cioffi	Italy	40.52	14.96	13	Maize	27.04.2006/22.08.2006
IT-BCi	Borgo Cioffi	Italy	40.52	14.96	13	Maize	09.05.2007/24.08.2007
IT-BCi	Borgo Cioffi	Italy	40.52	14.96	13	Maize	12.06.2009/08.09.2009
DE-Kli	Klingenberg	Germany	50.89	13.52	468	Wheat	25.09.2005/06.09.2006
DE-Kli	Klingenberg	Germany	50.89	13.52	469	Maize	23.04.2007/2.10.2007
DE-Geb	Gebesee	Germany	51.10	10.91	157	Wheat	09.11.2006/07.08.2007
FR-Lam	Lamasquere	France	43.50	1.24	182	Wheat	18.10.2006/15.07.2007
FR-Lam	Lamasquere	France	43.50	1.24	182	maize	01.05.2006/31.08.2006
FR-Gri	Grignon	France	48.84	1.95	117	wheat	28.10.2005/15.07.2006
FR-Gri	Grignon	France	48.84	1.95	117	maize	09.5.2005/28.09.2005
CH-Oe2	Oensingen	Switzerland	47.29	7.73	450	wheat	19.10.2006/16.07.2007
BE-Lon	Lonzee	Belgium	50.55	4.75	165	wheat	14.10.2004/03.8.2005
BE-Lon	Lonzee	Belgium	50.55	4.75	165	wheat	13.10.2006/05.08.2007
NL-Dij	Dijagraaf	The Netherlands	51.99	5.65	9	maize	08.05.2007/27.09.2007

2.2.2 Climate data

The simulations covered the Mediterranean domain. Daily climate variables, over this domain, derived from the Global Circulation Model CMCC-MED (Coupled Model of Atmosphere-Ocean-Sea-Ice with a focus on Mediterranean region) developed by the Euro-Mediterranean Center on Climate Change (Scoccimarro et al., 2011; Gualdi et al., 2013) and downscaled to a spatial resolution of 14 km with the Regional Climate Model COSMO-CLM RCM, were used to estimate daily ET_c, ET_a, and ET_{aw} at Mediterranean scale for the baseline (1976-2005) and the future (2036-2065) climate periods.

The climate Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios, with projected radiative forcing for the future (Taylor et al., 2012) were used for climate change projections. The COSMO-CLM RCM forced by Era-Interim reanalysis (EI) produced by ECMWF (The European Centre for Medium-Range Weather Forecasts) (Dee et al., 2011) and the E-OBS data were used for assessing ET_o in the past period. EI data downscaled with COSMO-CLM RCM and E-OBS have a resolution of 14 and 21 km, respectively. E-OBS data are the result of the gridded interpolation of several meteorological stations over Europe. This dataset is known as the largest resolution of daily historical climate gridded dataset for Europe (Hofstra et al., 2009).

2.2.3 Soil and crop input data

Soil data were included in the soil water budget to compute ET_c, ET_a and ET_{aw}. The soil water holding capacity from the ISRIC-WISE (Global Data Set of Derived Soil Properties, 5 minutes Grid) (Batjes, 2000) database, and the maximum soil depth from the HWSD v1.2 (30 arc-second raster Harmonized World Soil Database) (Wieder et al., 2014) were used.
The sowing and harvest date for maize and wheat, both under irrigated and rainfed conditions, were obtained from the AgMiP (Agricultural Model Inter-comparison and Improvement Project) database (Elliott et al., 2015).

A NetCDF file containing the mean grape bud break and harvest Julian Day (JD) was created. Mean values for the growing season stages were obtained from the literature and through the PEP725 database (Templ et al., 2018) (see Appendix 1). Three assumptions were made: i) the mean values are uniform within any country, ii) no differences in *Vitis vinifera* varieties between countries, and iii) the dates are averages of those found in the literature review (see Appendix 1). The countries included in the new gridded layer were selected considering a grape production area greater than 10,000 hectares according to FAOSTAT (http://www.fao.org/faostat/en/#data/QC) data, and the availability of bud break and harvest data from literature and from PEP725 database (Appendix 1).

The maximum rooting depths suggested by the FAO irrigation and drainage paper 56 (Allen et al., 1998) are used for crop at maturity and scaled down for the other stages. Specifically, the maximum rooting depths of 1650 mm (maize), 1650 mm (winter wheat), and 1500 mm (wine grape) were used.

The SPAM database (Spatial Production Allocation Model) from You et al. (2014), was used to define the crop spatial distribution. The spatial crop allocation was expressed in hectares both for irrigated and rainfed crops with a resolution of 5 minutes. Grape distribution was obtained from the MIRCA 2000 (Global data set of monthly irrigated and rainfed crop areas around the year 2000) database (Portmann et al., 2010).

2.2.3 Crop management data

The crops under investigation were not pre-irrigated. The reduction of planted land was not taken into account, and the water application percentage, i.e. the percentage of full water application for the specific crop allocated for the crop growing season (WAP), was set equal to 100% for irrigated crops. The allowable depletion (AD) was set equal to 50% thus the yield threshold depletion (YTD), when irrigation was applied, was equal to half of the plant available water (PAW). The sprinkler irrigation method with a distribution uniformity (DU) of 75%, and an application rate (AR) of 3.2 mm h^{-1} was applied to run simulations for maize and irrigated wheat at Mediterranean scale. The drip method was chosen to simulate grape water consumption and the related net water applications. In this case, DU and AR were set equal to 85% and 0.7 mm h^{-1}, respectively. The runoff was set equal to zero. The use of neither pesticides nor fertilisers is considered. The growing season is assumed not to change in future.

3. Results

Model performances are shown both at local and regional scale. Local simulations of ET_a are compared with observed LE (converted to ET_a) (section 3.1.1), while at regional scale, observed ET_a calculations are compared using gridded input data simulated by SIMETAW_GIS (session 3.1.2). Model validation is accomplished by estimating ETa in the Mediterranean domain (section 3.2).

3.1 SIMETAW and GIS model validation

3.1.1. Evaluation of SIMETAW_R model performance in estimating actual evapotranspiration at local scale

The SIMETAW_R performance are showed in Table 2. In general, the model performance was good at all experimental sites. The promising ability of the model to estimate crop water consumption is confirmed by the mean r=0.80, which was statistically significant at each site ($P \leq 0.001$). Furthermore, the mean RMSE= 0.99 mm, mean MBE of 0.36 mm, mean MBA of 0.77 mm, and mean AI of 81% demonstrate high modelling performance for estimating ET_a (Table 2).

In general, the model tends to slightly overestimate ET_a. The lowest and highest model overestimation of ET_a were observed for wine grape, in IT-VdA (MBE = 0.06 mm) and IT-Neg (MBE = 1.30 mm), respectively. The ET_a overestimation tendency was also reported in Mancosu et al. (2016), where fruit tree evapotranspiration was assessed. The model underestimates the actual crop water consumption in CH-Oe2, FR-Lam 2006-2007, and NL-Dij sites during the rainfed season. However, best model performances are reported for the CH-Oe2 site, where no LE data were gap filled. Even if only years with less than 30% of missing half-hourly LE measured data, the amount of available meteorological and LE data affected model performance. RMSE was, higher than 1.20 during each season in IT-Bci site, mainly

due to both a short period with a high percentage of LE gap-filled data and energy balance closure (Table 2). In general, the highest RMSE values have also a lower energy balance closure (Table 2). Some differences between measured and modelled data were attributed to rainy conditions during *LE* measurements that can reduce sensor accuracy when in measuring *LE* fluxes (Burba, 2013) even after quality check controls are performed.

In this work, the energy balance closure from available half-hour data (% of missing data is shown in Table 2) was acceptable with the mean slope of 0.75 and with the mean R^2=81% showing a good reliability of the Eddy covariance measured data. In addition, the measured data accuracy is shown by the mean r=0.84 between LE and LE`. The statistics in Table 2 indicate that the SIMETAW_R model fits the observed data reasonably well, and could be used for predictive analysis for agricultural water management purposes.

Tab. 2. SIMETAW_R performance shown through the comparison of observed and modelled ET_a in ten experimental sites. Measured data quality are shown through statistical indices, the energy balance closure (EBC) and the correlation between LE measured and LE residual (LE vs LE`).

			Observed ETa vs Modelled ETa					EBC			LE vs LE`
Code	**YEAR**	**Crop**	**r**	**RMSE**	**IA**	**MBE**	**MBA**	**R^2**	**Y = aX + b**	**Gaps**	**r**
				mm	%		mm	%		%	
FR-Gri	2005	Corn	0.81	0.75	89	0.04	0.63	91	Y = 0.7583X	19	0.89
FR-Gri	2005-2006	Wheat	0.85	0.61	91	0.12	0.45	87	Y = 0.6748X	16	0.87
DE-Geb	2006-2007	Wheat	0.75	1.14	78	0.69	0.78	77	Y = 0.7335X	15	0.85
DE-Kli	2007	Corn	0.84	1.39	67	1.23	1.24	56	Y = 0.4694X	32	0.61
DE-Kli	2005-2006	Wheat	0.88	0.82	88	0.57	0.65	67	Y = 0.8379X	33	0.62
CH-Oe2	2006-2007	Wheat	0.92	0.75	94	-0.44	0.58	68	Y = 0.8037X	34	0.82
NL-Dij	2007	Corn	0.71	0.68	82	-0.14	0.54	73	Y = 0.7905X	15	0.87
FR-Lam	2006-2007	Wheat	0.82	0.72	90	-0.23	0.55	83	Y = 0.7254X	41	0.83
FR-Lam	2006	Corn	0.61	1.22	76	0.43	0.92	90	Y = 0.7838X	42	0.91
BE-Lon	2006-2007	Wheat	0.78	0.91	82	0.57	0.72	82	Y = 0.8487X	20	0.84
BE-Lon	2004-2005	Wheat	0.89	0.89	90	0.14	0.65	82	Y = 0.8454X	23	0.85
IT-Bci	2005	Corn	0.64	1.21	73	0.62	0.92	92	Y = 0.7794X	26	0.92
IT-Bci	2006	Corn	0.62	1.29	69	0.73	0.97	86	Y = 0.7894X	39	0.82
IT-Bci	2007	Corn	0.63	1.48	68	0.93	1.12	94	Y = 0.778X	37	0.95
IT-Bci	2009	Corn	0.63	1.32	75	0.51	1.03	91	Y =0.7405X	50	0.94
IT-VdA	2009	Wine Grape	0.82	0.68	90	0.06	0.5	77	Y =0.6866X	23	0.93
IT-Neg	2007	Wine Grape	0.83	1.91	77	1.3	1.6	na*	na*	na*	na*
IT-Neg	2008	Wine Grape	0.58	2.45	67	1.31	1.88	na*	na*	na*	na*

* Soil heat flux (G) input data not available.

3.1.2 SIMETAW_GIS model performance in estimating reference evapotranspiration at regional scale

The model computes ET_o using Hargreaves Samani equation (Hargreaves and Samani, 1985) and the standardized FAO-56 Penman-Monteith equation (Allen et al. 2005), by using the Era Interim (EI) and EOBS climate datasets to represent historical trends. The Penman Monteith (PM) method generally performs better than Hargreaves Samani (HS) equation for computing ET_o (Table 3). Unlike EI, the EOBS provides fewer climate variables sufficient to parameterize the HS method alone. Both HS and PM method can be implemented with EI. Correlation values

higher than 0.80 were computed by comparing gridded PM estimated ET_o using EI data with observations in almost all sites located in Northern Europe. The best correlations for HS and PM were obtained for crops with longer growing seasons as these data sets tend to have more pronounced seasonal ET_o variation, which reduces ratio between data noise and variation. In CH-Oe2, FR-Gri 2005-2006, DE_Geb 2006-2007, and BE-Lon 2004-2005 sites, a correlation higher than 0.80 was observed considering outcomes with the HS and PM equations, using both climate datasets. At these sites, the model accuracy was confirmed by an index of agreement higher than 85%. As observed by other authors (Allen et al., 1998; Temesgen et al., 1999; Droogers and Allen, 2002; Martinez-Cob and Tejero, 2004; Alexandris et al., 2008; de Sousa Lima et al., 2013), an overestimation of ET_o with HS was noticed at sites characterized by high humidity (Klingenberg, Grignon, Oensingen) characterized by more rainy days. Based on this finding, the ETo_PM was used for regional ET_a simulations (Section 3.2).

Tab. 3. Assessment of modelled ET_o computed using Hargreaves (with E-OBS and EI gridded data) and Penman Monteith (EI gridded data) equation against site observations (FLUXNET sites). Values are expressed as a mean of the values estimated in each site and for each available growing season.

HS_EOBS vs HS_site	HS_EI vs HS_site	PM_EI vs PM_site
	RMSE (mm)	
1.74	1.85	1.01
	MBE (mm)	
0.86	0.89	-0.03
	MAE (mm)	
1.49	1.59	0.79
	IA (%)	
59	59	81

3.2 SIMETAW_GIS application at Mediterranean scale

SIMETAW_GIS model was applied to estimate ET_c, ET_a, yield, and irrigation requirements for maize, grape, and wheat in the Mediterranean domain for the baseline period (1976-2006) and future period (2036-2065) under RCP 4.5 and 8.5 climate scenarios.

3.2.1 Climate projections for precipitation

The most severe impact of climate change on precipitation in Mediterranean countries is expected under RCP 8.5 (Table 4). Historically, largest precipitations are estimated for the Balkan countries, with a peak of 1441 mm in Montenegro. The lowest precipitations are evaluated in Libya, Egypt, and Israel showing a general low precipitation regime (Table 4). Under climate change conditions, precipitation reduction higher than 15% were estimated in Algeria, Greece, Morocco, and Tunisia under both RCPs and in Libya under RCP 8.5. The lowest precipitation decrease is expected to occur in France and Israel under RCP 8.5 and in Cyprus under RCP 4.5 (pcp reduction < - 1%). No changes are projected in Egypt under RCP 4.5. In the other Mediterranean countries, precipitation reduction ranged from 1% to 14%. In some countries (i.e., Croatia, Egypt, France, and Slovenia with RCP 8.5; Israel and Syria with RCP 4.5) the projected cumulated precipitation values are higher than in the baseline period (Table 4).

Tab. 4. Precipitation values in the baseline period (pcp bas, mm) and climate anomalies (%) in the Mediterranean Countries for RCP 4.5 and 8.5 scenarios.

	Algeria	Albania	Bosnia and Herzegovina	Cyprus	Croatia	Egypt	France	Greece	Israel	Italy
pcp bas	185	1095	1026	165	895	38	882	521	134	834
pcp45-bas	-15.75	-9.56	-7.45	-0.62	-4.66	0	-2.97	-18.35	5.65	-7.52
pcp85-bas	-26.08	-6.39	-5.65	-12.37	1.08	5.29	0.12	-16.21	-0.96	-7.54

	Lebanon	Libya	Morocco	Montenegro	Slovenia	Spain	Syria	Tunisia	Turkey
pcp bas	397	76	352	1441	1084	711	146	163	479
pcp45-bas	-3.08	-13.21	-19.01	-9.53	-2.61	-10.48	4.3	-15.9	-6.35
pcp85-bas	-14.33	-22.79	-27.49	-4.81	5.5	-6	-6.43	-28.7	-8.52

3.3.2 Impact of climate change on crop water consumption and irrigation requirement

Regional baseline values for maize, grape, and wheat ET_c, ET_a, and ET_{aw} are shown in Figure 2 for the Mediterranean domain and discussed for each crop in the next sections. The estimated actual evapotranspiration (Figures 2b, 2e, 2h) is lower than the crop water consumption (Figures 2a, 2d, and 2g), highlighting a water stress coefficient $K_s<1$ within the study areas, with consequent yield losses (Figure 3). This is most likely related to the pedo-climatic (climate, maximum soil depth, soil water holding capacity, and maximum rooting depth) conditions and management practices, i.e., assumptions about (1) the percentage of full water allocation applied, (2) planted area, (3) irrigation system, and (4) allowable depletion.

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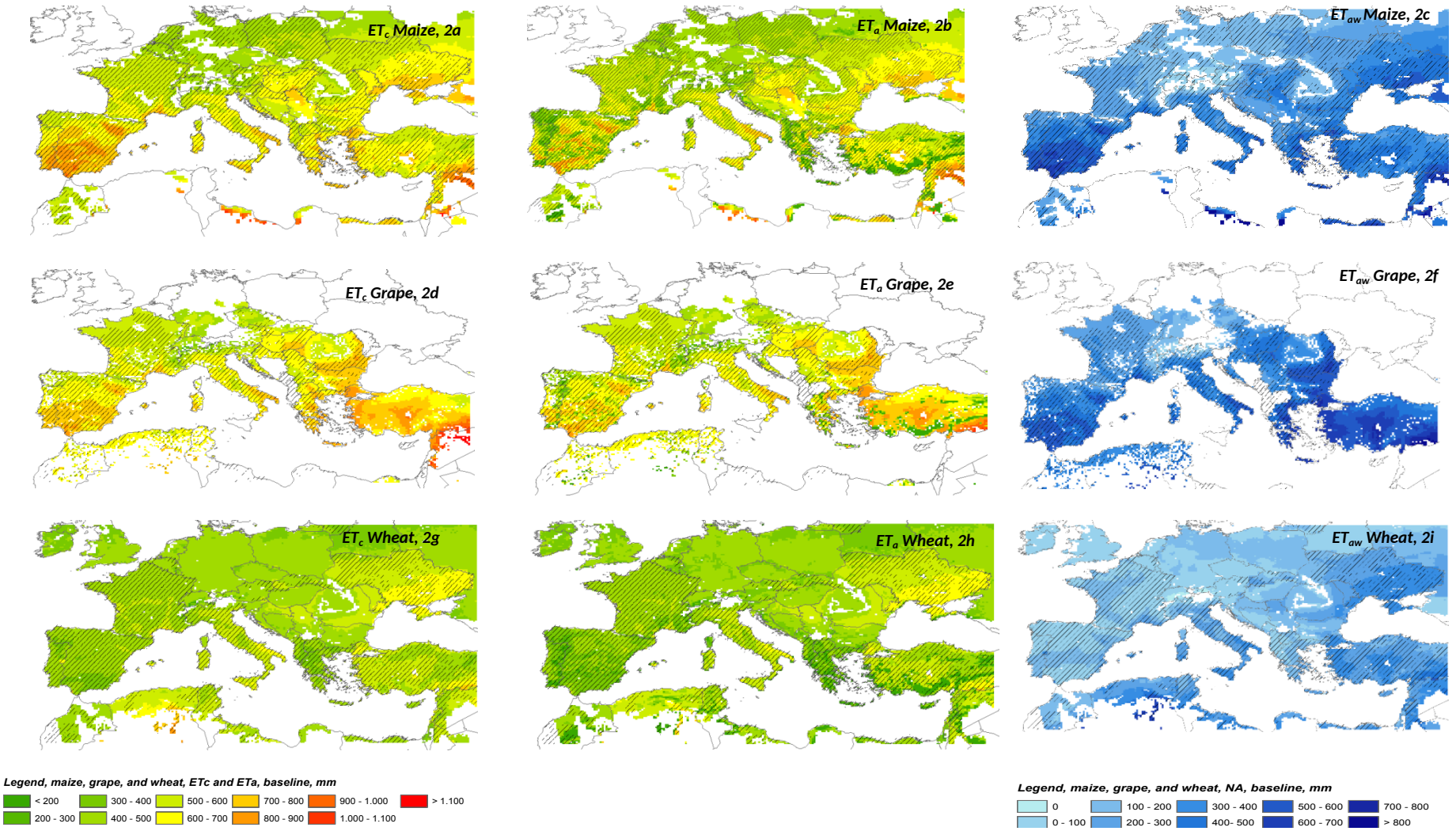


479 *Fig. 2. Regional mean of ET$_c$ (2a, 2d, 2g), ET$_a$ (2b, 2e, and 2h) and ET$_{aw}$ (2c, 2f, and 2i) for maize, grape and wheat during1976-2005 considering potential*
480 *crop distribution widespread in the entire domain. The effective crop irrigated areas are distinguished using solid diagonals lines.*

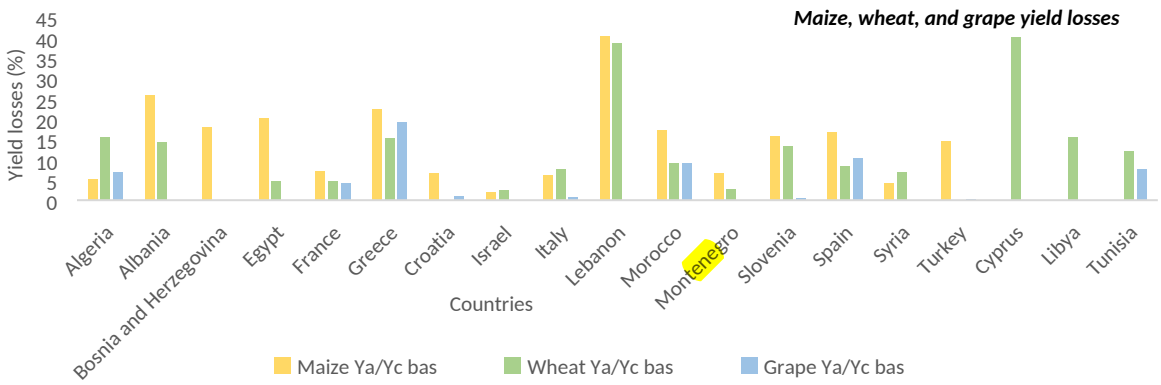


Fig. 3. Regional mean yield responses to water deficit (Y_a/Y_c) for maize, grape and wheat during 1976-2005.

3.3.2.1 *Maize*

The Mediterranean region baseline crop evapotranspiration estimated for maize under optimal water supply on a country average varied in a range from 533 mm (Morocco) to 893 mm (Algeria) (Figure 2a). Under climate change, an overall increase of ETc was foreseen. High rates of change (increase of 5-6%) were observed in most Balkan countries. The most severe impact of climate change was found in Italy where future maize water consumption increase, under both RCPs, by about 7-8% (Figure 4e). In general, the largest changes were estimated under RCP8.5, except for Spain and Syria. Slight differences between the two climate scenarios were estimated. The trend of ET_a is the same as ET_c but, due to stress conditions, the values estimated for ET_a in 2036-2065 were slightly lower than ET_c (1-2%) (Figures 4a, 4b, 4e).

The evapotranspiration of applied water (ET_{aw}) within the baseline period ranged from 210 mm (Slovenia) to 769 mm (Algeria) (Figure 2c). In most countries, the changes in ET_{aw} follow the precipitation variability under the two scenarios (Table 4). A future increase in irrigation demand was observed in all Mediterranean countries, with peaks of 25-28% found in France, Italy, Slovenia, and Montenegro. The lowest increase of crop water demand (1-6%) was estimated under RCP4.5 in Algeria, Israel, Egypt, Lebanon, Syria, and Turkey. Irrigation demand was expected to increase from about 14-17% in Morocco, Spain, Croatia and Albania (Figures 4c, 4d, 4e).

Despite maize being irrigated both during baseline and future periods, water applications were not completely adequate to fully satisfy crop water needs, causing a limited water stress, which led to yield losses (Figure 3 and 4e). The highest difference of yield losses between future and past values were estimated in France, Italy, Slovenia, Bosnia and Herzegovina, and Montenegro. The lowest changes were estimated in Turkey (RCP 4.5) and Syria (both RCPs). Maize production was found to be higher (i.e. lower losses) under climate change in Algeria, Israel (RCP 8.5), and Morocco (RCP 4.5) (Figure 4e).

In general, a trend of maize yield reduction is in line with Giannakopoulos et al. (2005), Gallo (2015), and Tubiello et al., (2000). The impact of climate change on future ET_c, ET_a and ET_{aw} for maize in the Mediterranean countries, under both RCPs, is expected to be on average about 4%, 3%, and 13% higher than the baseline, respectively. The trend for increasing maize water requirement from Northern to Southern Italy under both RCP 4.5 and 8.5 scenarios is in line with Gallo (2015). An increase between 7% and 9% of maize irrigation requirement under the 5°C climate trajectory was estimated by Fader et al. (2016) in Mediterranean countries. Furthermore, an increase of maize ET_{aw} of 35% was found by Kapur et al. (2007) under [illegible] climate change conditions. Lower change (increase of 5%) was estimated by Mancosu (2013) for maize cultivated in Sardinia (Italy). Increasing irrigation needs of spring-summer crops were also projected by Lovelli et al. (2010).

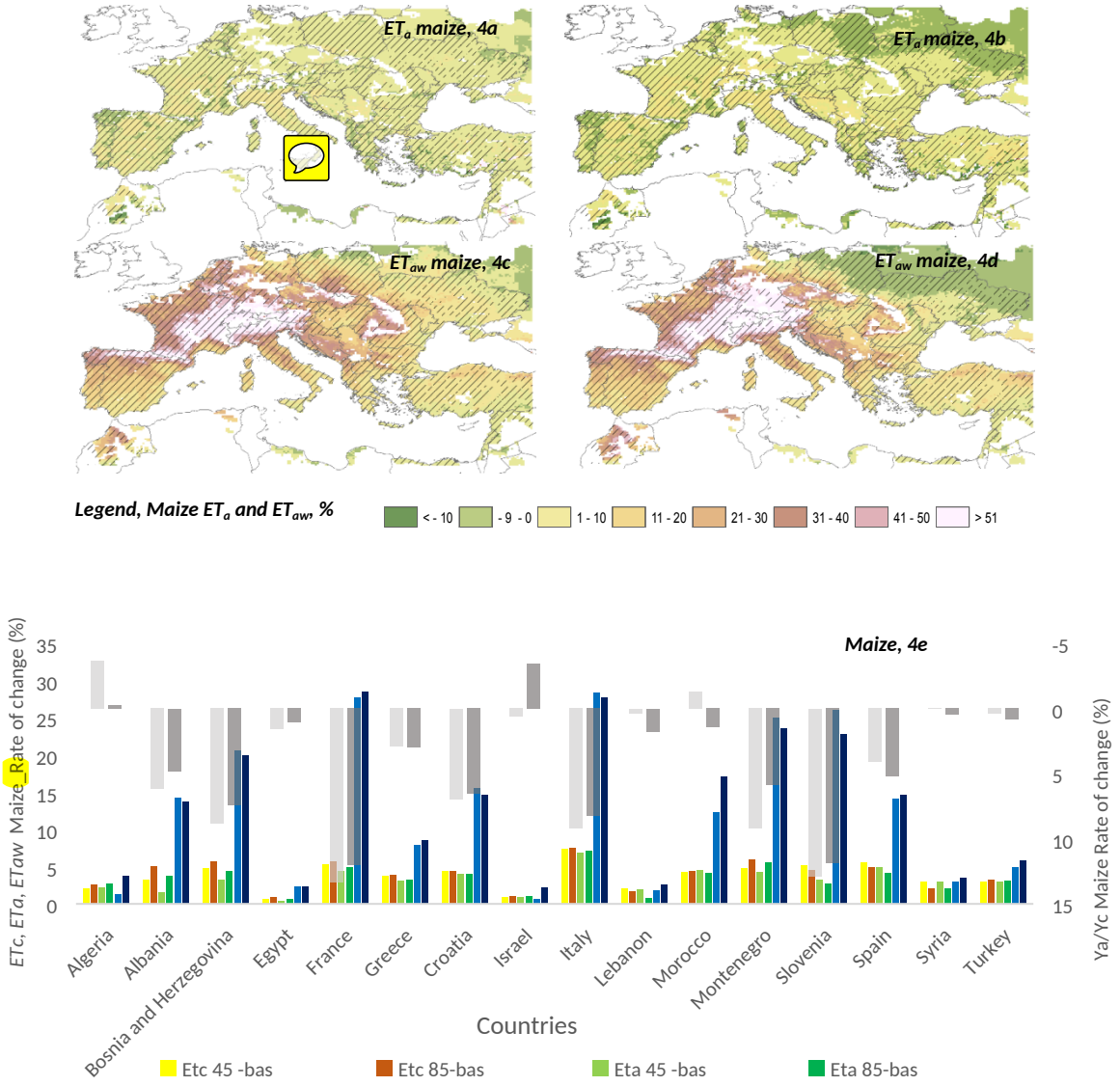


Fig. 4. Rate of change of ET_a (4a. ET_a 45-bas, 4b. ET_a 85-bas) and ET_{aw} (4c. ET_{aw} 45-bas, 4d. ET_{aw} 85-bas) values weighted for the irrigated maize distribution between future climate condition (2036-2065) under both RCP 4.5 and 8.5 scenarios, and the baseline (1976-2005) for the entire domain with a focus on the Mediterranean countries (Fig. 4e). Rate of changes of maize ET_c (ET_c 45-bas, ET_c 85-bas) and yield losses (Y_a/Y_c 45-bas, Y_a/Y_c 85-bas) between future and baseline period in the Mediterranean countries are shown in figure 4e.

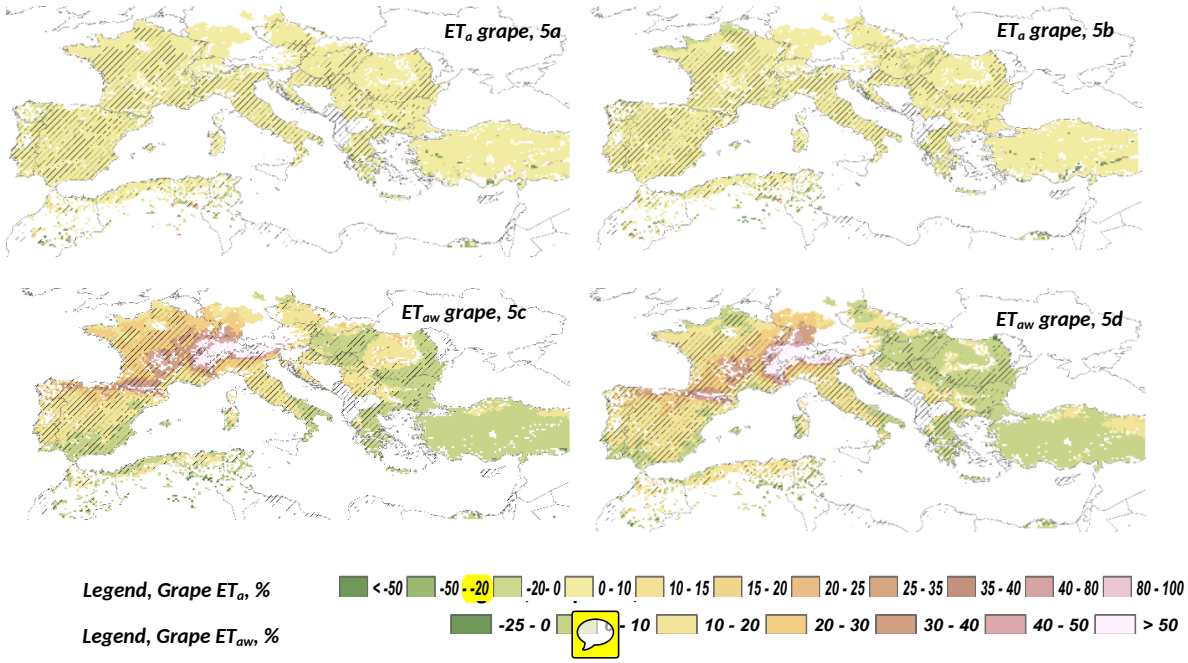
3.3.2.2 Grape

The greatest average crop water consumption in the baseline was estimated in Turkey (888 mm), with the lowest in Slovenia (570 mm). Values between 700 and 800 mm were found in Spain and Greece, and between 600 mm and 700 mm in all other Mediterranean countries (Figure 2d). Under climate change conditions, a mean increase (3%) of crop evapotranspiration was expected in the Mediterranean countries with peaks (~ 6%) in France and Italy under the RCP 4.5 scenario. The crop water consumption estimated under RCP 8.5 was slightly lower (-0.70% on average) than under RCP 4.5 in France, Croatia, Italy, Slovenia, Spain, and Turkey. During the baseline, the trend of ET_a was the same as that estimated for ET_c (Figure 2e).

Although actual grape water consumption tending to rise in all countries, they were still lower than full crop water requirements (optimal water irrigation supply), except for Turkey where no relevant difference was found. A reverse trend was shown in Tunisia where the ET_a values were ~ 4% lower than in the baseline (Figure 5e). The highest yield reduction occurs in Greece (19%), Morocco and Spain (10%) while the lowest in Italy and Croatia (1%) (Figure 3). No changes between future and past yield losses happen in Turkey under both RCPs and Slovenia under RCP 8.5. Under RCP 4.5, the yield losses in Morocco and Slovenia are slightly lower than during the baseline (~2-3%). The peak of future yield reduction is projected for Tunisia under both RCPs with losses up to 51% (RCP 4.5). Using different meteorological gridded input data, Moriondo et al. (2011) projected a decrease in future yield in Tuscany (Italy). Ferrise et al. (2016) attribute the negative impact of increasing temperature and precipitation reduction on grape yield in the Mediterranean basin to shorter phenological growth periods.

As for ET_c and ET_a, the highest irrigation demand (ET_{aw}) in the baseline occurs in Turkey (706 mm) and the lowest in Slovenia (289 mm). A peak of about 600 mm was found in Greece, followed by Tunisia and Spain, where values between 400 mm and 500 mm are reported. Lower values (400-500 mm) occur in Italy, Algeria, France, Croatia, and Morocco (Figure 2f). In general, the grape irrigation demand (ET_{aw}) followed precipitation patterns (Table 4). The largest increase of irrigation requirement, under both RCPs, is expected in France (~ 19%) and Italy (~ 15%) followed by Slovenia, Croatia, and Spain (~ 11%). Changes no higher than ~ 6% are predicted for Tunisia, Greece, and Turkey (Figure 5c, 5d, 5e).

A focus on the Mediterranean Countries shows a mean ET_{aw} value about 10 % higher in the future under both RCPs. Although grape is usually cultivated under rainfed conditions in Sardinia region, the ET_{aw} is expected to increase by about 6% with climate change (Mancosu, 2013).



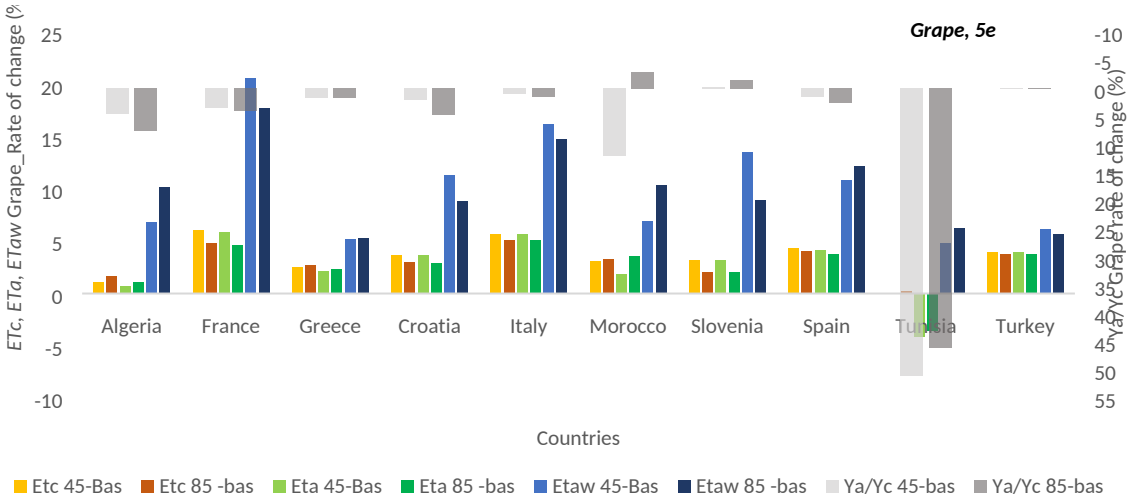


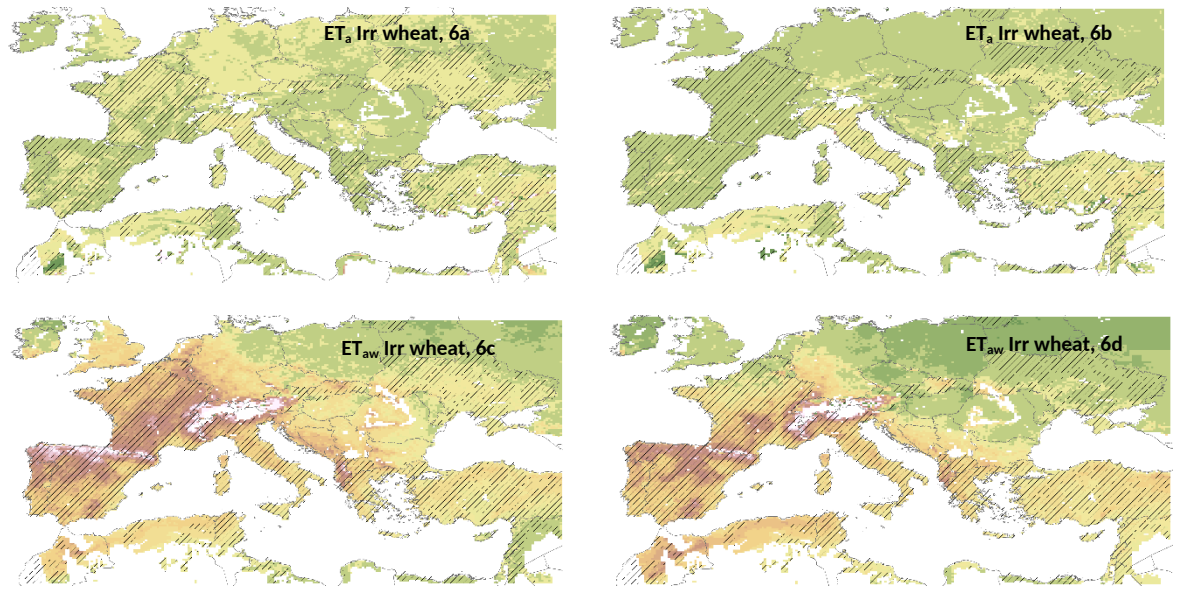
Fig. 5. Rate of change of ET_a (5a. ET_a 45-bas, 5b. ET_a 85-bas) and ET_{aw} (5c. ET_{aw} 45-bas, 5d. ET_{aw} 85-bas) values weighted for the irrigated grape distribution between future climate condition (2036-2065) under both RCP 4.5 and 8.5 scenarios, and the baseline (1976-2005) for the entire domain with a focus on the Mediterranean countries (Fig. 5e). Rate of changes of maize ET_c (ET_c 45-bas, ET_c 85-bas) and yield losses (Y_a/Y_c 45-bas, Y_a/Y_c 85-bas) between future and baseline period in the Mediterranean countries are shown in figure 5e.

3.3.2.3 *Irrigated wheat*

Although wheat is generally cultivated under rainfed conditions, there are some irrigated areas concentrated in the Mediterranean basin. The trend of wheat evapotranspiration for the baseline period estimated in this work is in line with Saadi et al. (2014), even if two different approaches were adopted. Yield losses over Mediterranean countries are estimated as the difference between ET_c and ET_a values. Losses up to 40% are shown for Cyprus and Lebanon during the baseline period (Figure 3). Under climate change, the highest difference between future and past climate are estimated for Albania, France, Montenegro and Spain (Y_a/Y_c > 20%), while lower losses are predicted in Egypt (both RCPs) and Israel (RCP 4.5). These trends are in line with Saadi et al. (2014) and in contrast with Moriondo et al. (2011) who project an increase of not irrigated winter wheat yield in the same area. In this analysis, ET_c values ranged from 409 to 631 mm (Figure 2g), where the lowest and the highest values are 100 mm higher and 233 mm lower, respectively, than the values estimated by Saadi et al. (2014). The highest mean difference of wheat water consumption is estimated for Morocco (increase of ~ 4%) under both RCPs. Negative ET_c rate of change values are expected in Albania, Libya, and Tunisia under both RCPs and in Egypt, France, Slovenia, and Spain under RCP 8.5. In these countries, the ET_c values predicted under future climate conditions are lower than the ones estimated in the baseline (Figures 6a, 6b, 6e). In the baseline, ET_a values range from 525 mm (Italy) to 277 mm (Cyprus) (Figure 2h). In several countries (Figures 6a, 6b, 6e), under climate change conditions, the values of ET_a increased relative to the baseline. Indeed, negative changes between future and baseline ET_a values countries with peak of -5% and -4% are expected in Albania, under RCP 4.5, and in Spain, under RCP 8.5.

Figure 2i shows crop irrigation requirement values lower than 100 mm in Albania, France, Montenegro, and Spain. The highest applied water demand in the baseline is reported for Syria and Turkey (304 mm). Irrigation demand under climate change is expected to slightly decrease in Egypt under both RCPs while in Israel, Lebanon, and Syria only under RCP 4.5. A noticeable increase (~ 40 - 46%) of wheat irrigation demand under climate change is projected for France, Spain, Montenegro, and Albania under RCP 4.5. As a result of slightly higher

precipitation under RCP 8.5 compared to RCP 4.5 (Table 4), in the same countries lower ET_{aw} values were found under RCP 8.5 (Figures 6c and 6d). The highest difference between the two climate scenarios arises in France (27%) with the lowest in Italy (0.16%). Considering a doubling of atmospheric CO_2 concentration, wheat ET_a values are expected to decrease by about 28 % (CGM2 data) 8 % (RCM data) in the period 2070-2079 in Turkey according to Yano et al. (2007). While increasing ET_c values are projected in this work, decreasing ET_c, in no-stress conditions, are reported in Saadi et al. (2014) and Supit et al. (2010). They attribute the change in ET_c to a shorter growing season. The negative impact of climate change, i.e. the increase of wheat net water application is in agreement with other studies (Tubiello et al., 2000; Yano et al., 2007; Özdogan, 2011; Saadi et al., 2014; Valizadeh et al., 2014). In contrast, in Southern Italy in 2071, Lovelli et al., (2010) state that no significant ET_{aw} increase in autumn-winter crops is anticipated, while increasing ET_{aw} is expected for spring-summer crops.



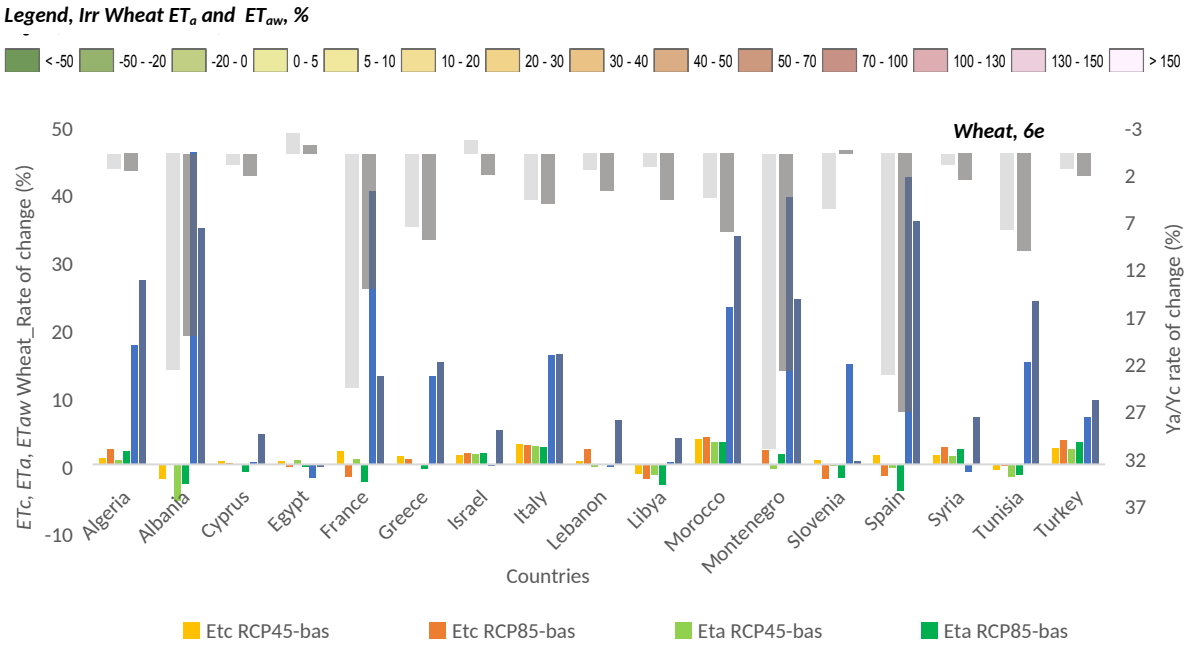


Fig. 6. Rate of change of ET_a (6a. RCP45-bas, 6b. RCP85-bas) and ET_{aw} (6c. RCP45-bas, 6d. RCP85-bas) values weighted for the irrigated wheat distribution between future climate condition (2036-2065) under both RCP 4.5 and 8.5 scenarios, and the baseline (1976-2005) with a focus on the Mediterranean countries (Fig. 6e). Rate of changes of wheat yield losses between future and baseline period are shown in figure 6e.

4 Discussion

The findings show an overall reduction of projected precipitation in Southern Mediterranean countries which, in line with Keuler et al. (2016), is in general greater under RCP 8.5. The simulated reference, crop, and actual evapotranspiration, as well as irrigation requirement are projected to increase under future climate conditions, and often differences between future and past climate conditions are greater under the RCP 4.5 scenario. On average, the maize and grape crop water consumption in the Mediterranean countries is expected to increase on average ~ 3-4% under both RCPs, with the most consistent increases in Italy (~ 7% under both RCPs) and in France (~ 6% under RCP 4.5). Lower values are projected for wheat which is expected to consume on average ~ 0.5% more under climate change conditions with peak of ~ 4% in Morocco.

Generally, under both RCPs, the rate of change of maize, wheat, and grape water consumption under deficit water and non-optimal pedo-climatic conditions (ET_a) are on average lower than in well watered conditions. In Mediterranean countries, maize, wheat, and grape production will require on average about 13%, 16%, and 10% more applied water under climate change conditions, respectively. The amount of water applied to satisfy grape needs in the future decades is higher in relevant wine producing countries such as France (~19%), Italy (15%), and Spain (11%) than in other Mediterranean countries. Rates of change are particularly high in the southern part of these countries (Figure 5c and 5d), where conflicts on water use and less favorable conditions could lead to impact on crop productivity. Yet, a high quality wine production may be enhanced. The lowest impact of climate change on grape irrigation demand is expected in Turkey, Tunisia, and Greece (increase of ~ 6%). A future increase of applied water between ~ 20% – 29% is expected for maize production in Bosnia and Herzegovina, France, Italy, Slovenia and Montenegro due to reduced precipitation during 2036-2065 (Table 4). In France, Albania, Spain, and Morocco the wheat irrigation is estimated to increase under climate change by more than ~ 40% under RCP 4.5. In general, Egypt, Israel, and Lebanon show the least change for maize water needs (ET_{aw} increase < ~ 3% under both RCPs), whereas the lowest wheat water applications are needed in Cyprus, Egypt, Israel, Libya, and Syria (-2%<ET_{aw}<0% under RCP 4.5).

Although irrigation application is practiced, the ET_a estimated was in general lower than ET_c due to the pedoclimatic conditions and management practices assumed in this work. Assuming no changes in input data, actual evapotranspiration values may increase changing the frequency and number of irrigation events (AD < 50%). This management strategy can reduce water stress (but increase water demand) therefore increasing ET_a, which in turn reduces yield losses. It is worth noting that, in this case, much water may be applied for the crop growth, and an environmental-economic analysis could help in achieving the best balance between the impact on water resources and yield losses. In addition, the price of water should be taken into account, since it impacts farm business.

This work is in line with several studies investigating crop water consumption and irrigation requirements using models at different scales and at different resolutions, and considering different scenarios. Keeping a focus on Mediterranean irrigated agriculture, this study agrees with an expected increase in crop water needs due to increasing drought risk which

is expected to characterize Southern Countries in the near future (Rodriguez-Diaz et al., 2007; Saadi et al., 2014; Tanasijevic et al., 2014; Fader et al., 2015; Fader at al., 2016).

Irrigation practices are exacerbated in Mediterranean regions due to the projected warmer and drier summer months when the amount of agricultural water is constrained due to other sectors' water needs. Tourism is a critical economic sector, but also demands considerable drinking water and water for leisure facilities leading to increased conflicts among sectors for water use. Uncontrolled water abstraction may exacerbate the water security issues by creating imbalances between water supply and demand (Collins, 2009). Such inter-sectoral water-related issues could hamper efforts throughout the region in achieving SDG6 goals. This work further highlights the potential severity of increases in water-related issues in the Mediterranean, related to both expected supply decline and demand increase. Unfortunately, in this region water security challenges are not the only issue to be confronted regarding agricultural production.

This work suggests widespread crop yield declines resulting from water shortages, especially for food-supply crops such as maize and wheat. As aforementioned, despite the crops being irrigated, the study shows that water applications are inadequate to fully satisfy crop water needs, resulting in a stress coefficient K_s<1 and consequent crop yield reductions. In Mediterranean countries, the beneficial effect of future increasing atmospheric CO_2 concentration on yield losses is more evident on grape and wheat, with yield losses limited to about 8%, while for maize yield losses can reach about 13%. Grape yield losses are possibly related to increasing temperature effects on the length of the growing season (Ferrise et al., 2016). Although C3 plants, i.e., wheat and grape, may benefit from increasing levels of atmospheric CO_2 due to their physiology (Patterson et al., 1984; Cure and Acok, 1986), this positive effect may be threatened by other factors such as the changes in precipitation frequency and intensity, which can lead to negative effects on crop production (IPCC, 2007), particularly in areas where water resources are scarce.

In the near future, non-irrigated crop production in southern Europe is expected to decrease by about 50%, and this may lead to climate change induced crop abandonment (EEA, 2019). Decreases in crop yield and the abandonment of productive land could threaten local, regional, and European food security, which led to the global challenge to achieve the Sustainable Development Goals 2 (SDG 2) in the Mediterranean basin (SDSN, 2019). Furthermore, unsustainable agriculture may lead to an increase in food imports, with a consequent increase in food prices and food supply vulnerability. It can cause lower and/or less stable income for farmers with an unavoidable impact on the agricultural sector. Taken together, the potential for agricultural water demand leading to increased water competition and threats to water supply, and the expected decreases in crop yields partly due to water and climate impacts, strongly suggest that increasing the resilience of agricultural sector to extreme events in Mediterranean countries is a critical priority from local to European governments in terms of managing water consumption (SDG6) while also maintaining crop production (SDG2).

The first step to cope with these issues is to increase knowledge about the water consumption and irrigation requirements of Mediterranean crops to better manage water resources, as well as better understanding of yield declines, particularly in regions already largely affected by water scarcity and a multitude of water-demanding sectors. This study further contributes to such knowledge. Although the adaptation of the agricultural sector to

715 climate change is progressing, the process needs to be accelerated. Policies targeted to facilitate
716 and speed up this transition at different time and spatial scales should be addressed by decision
717 makers faster and better (EEA, 2019).
718 Some limitations in this study will be addressed in future work, such as: (i) changes in
719 crop breeding, new cultural practices and technologies, and shifts in sowing, bud break, and
720 harvest date, which may have an impact on crop adaptation to climate change conditions, (ii)
721 changes in the percentage of cultivated areas due to climate or anthropogenic factors, (iii)
722 evaluation of more crops under several water management scenarios, (iv) availability of higher
723 resolution input gridded data to include more details in the outcomes at Mediterranean scale,
724 and (v) use of climate models ensemble to reduce result uncertainties, and, model biases.
725
726
727 **5 Conclusions**
728 In this work, the Simulation of Evapotranspiration of Applied Water (SIMETAW#) model was
729 implemented in two new versions able to simulate crop water consumption and irrigation
730 demand at both local (SIMETAW_R) and regional scale (SIMETAW_GIS) according to the
731 stakeholder`s needs. SIMETAW# model was converted and implemented in R programming
732 language.
733 SIMETAW_R was validated in ten experimental sites, and the SIMETAW_GIS performance
734 in Mediterranean countries was assessed by estimating the impact of climate change on maize,
735 wheat, and grape water consumption and irrigation requirements for the baseline (1976-2005)
736 and the future climate conditions (2036-2065), under RCP 4.5 and 8.5 scenarios.
737 SIMETAW_R performed well at the local level. Estimated increases in crop water
738 needs under future climate conditions in Mediterranean Countries are predicted. Irrigation
739 demand increases were often greater under RCP 4.5 than 8.5 scenario. Crop yields are also
740 expected to decline in many southern Mediterranean countries. The increased water demand
741 and decreasing crop yields pose dual challenges for local to European agricultural policy
742 regarding efforts towards achieving goals in SDG2 and SDG6. The SIMETAW_R model
743 outcomes at local scale as well as the SIMETAW_GIS platform gridded outcomes at regional
744 scale contribute to increase awareness on climate change issues regarding crop water
745 consumption and irrigation requirements and agricultural production in Mediterranean regions.
746 To tackle climate change impact on the agricultural sector, adaptation strategies should be
747 developed, supported, and implemented. In view of the rapid demographic growth and the
748 consequent food security issue, it is necessary to cope with climate change through strategies
749 targeted to achieve agricultural sustainable production. In this context, this study adds useful
750 information to better inform such policy decisions surrounding agricultural practices and crop
751 water management both at local and regional scale.
752

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Appendix 1

ID	*ZONE_NAME*	*Grape - Bud break literature*
5	Algeria	Same as Morocco
15	Austria	Templ et al., 2018
26	Bosnia and Herzegovina	Templ et al., 2018
35	Bulgaria	Same as Romania
66	Egypt	Same as Morocco
74	Czechia	Same as Slovakia
83	France	Jones and Davis 2000; Andreini et al., 2009; Valdez-Gomez et al.; 2009; Nendel, 2010
93	Germany	Templ et al., 2018; Nendel, 2010; Schwab et al., 2000
97	Greece	Anderson et al., 2014
106	Croatia	Templ et al., 2018
107	Hungary	Same as Slovakia
116	Italy	Cortesi et al., 1997; Novello and Palma 2008; Tomasi et al. 2011; Mancosu, 2013
140	Slovakia	Templ et al., 2018; Nendel 2010
153	Macedonia	Same as Greece
156	Morocco	Ezzhaouani et al., 2007
189	Portugal	Same as Spain
196	Romania	Same as Greece and Slovakia
201	Saudi	Same as Morocco
208	Slovenia	Same as Croatia
213	Spain	Camps and Ramos 2012; Lopez - Urrea et al. 2012; Picon - Toro et al., 2012
214	Serbia	Same as Bosnia
220	Syrian	Same as Greece
221	Switzerland	Same as Austria
231	Tunisia	Same as Morocco
232	Turkey	Same as Greece

ID	*ZONE_NAME*	*Grape - Harvest literature*
5	Algeria	Same as Morocco
15	Austria	Templ et al., 2018
26	Bosnia and Herzegovina	Templ et al., 2018
35	Bulgaria	Same as Romania
66	Egypt	Same as Morocco
74	Czechia	Same as Slovakia
83	France	Jones and Davis, 2000; Valdez-Gomez et al., 2009
87	Georgia	Same as Greece
93	Germany	Templ et al., 2018; Schwab et al., 2000; Christoph et al., 2003
97	Greece	Anderson et al., 2014
106	Croatia	Same as Italy
107	Hungary	Same as Austria
116	Italy	Tomasi et al., 2011; Mancosu, 2013
140	Slovakia	Same as Austria
153	Macedonia	Same as Greece

156	Morocco	Ezzhaouani et al., 2007
189	Portugal	Same as Spain
196	Romania	Same as Greece and Slovakia
201	Saudi	Same as Morocco
208	Slovenia	Same as Italy
213	Spain	Camps and Ramos 2012; Lopez - Urrea et al. 2012; Picon - Toro et al., 2012
214	Serbia	Same as Bosnia
220	Syrian	Same as Greece
221	Switzerland	Templ et al., 2018; Meier et al., 2007
231	Tunisia	Same as Morocco
232	Turkey	Same as Greece

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Figures:

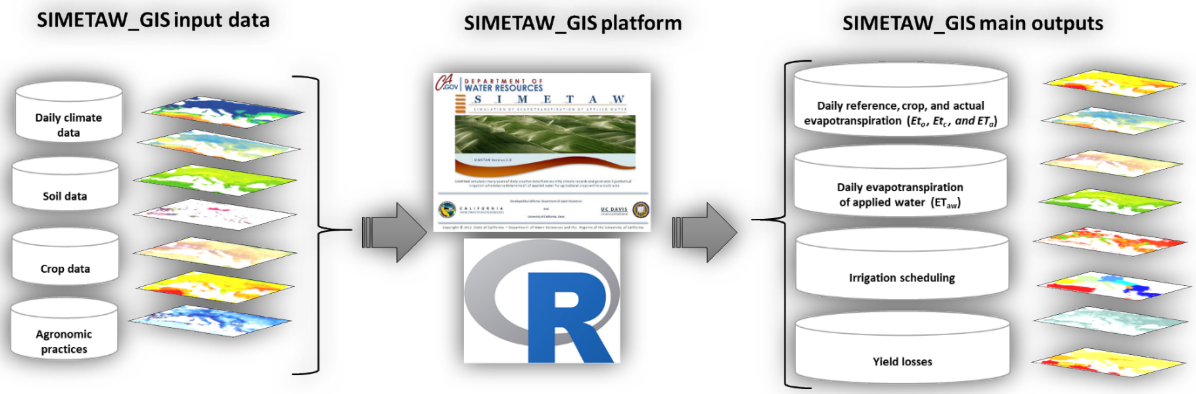

Fig. 1. Scheme of SIMETAW_GIS platform.

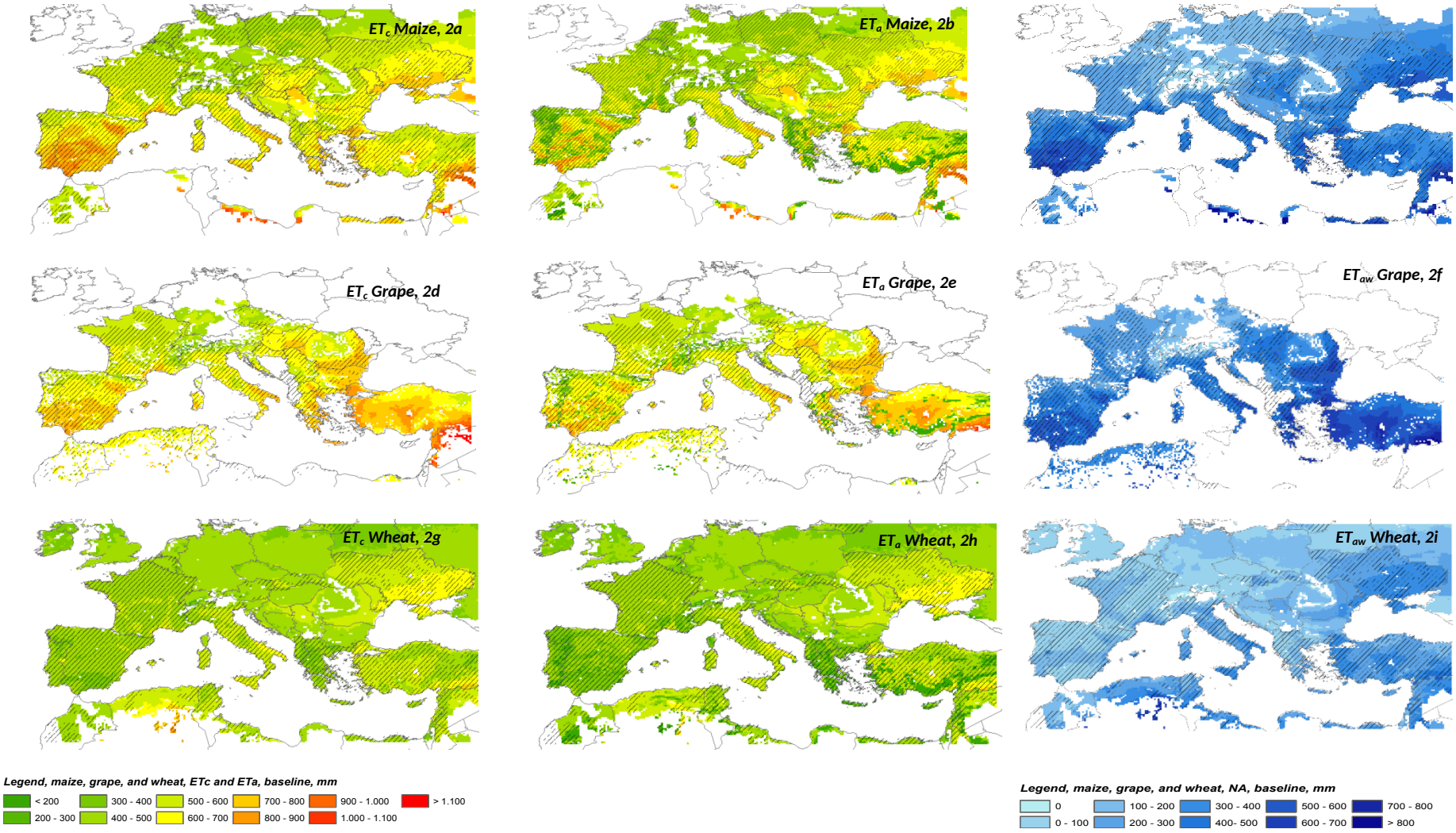

Fig. 2. Regional mean of ET_c (2a, 2d, 2g), ET_a (2b, 2e, and 2h) and ET_{aw} (2c, 2f, and 2i) for maize, grape and wheat during1976-2005 considering potential crop distribution widespread in the entire domain. The effective crop irrigated areas are distinguished using solid diagonals lines.

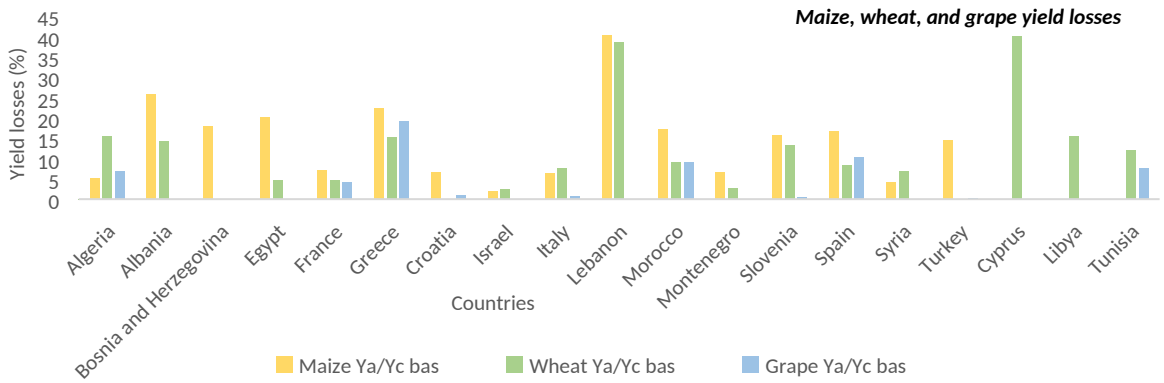

Fig. 3. Regional mean yield responses to water deficit (Y_a/Y_c) for maize, grape and wheat during 1976-2005.

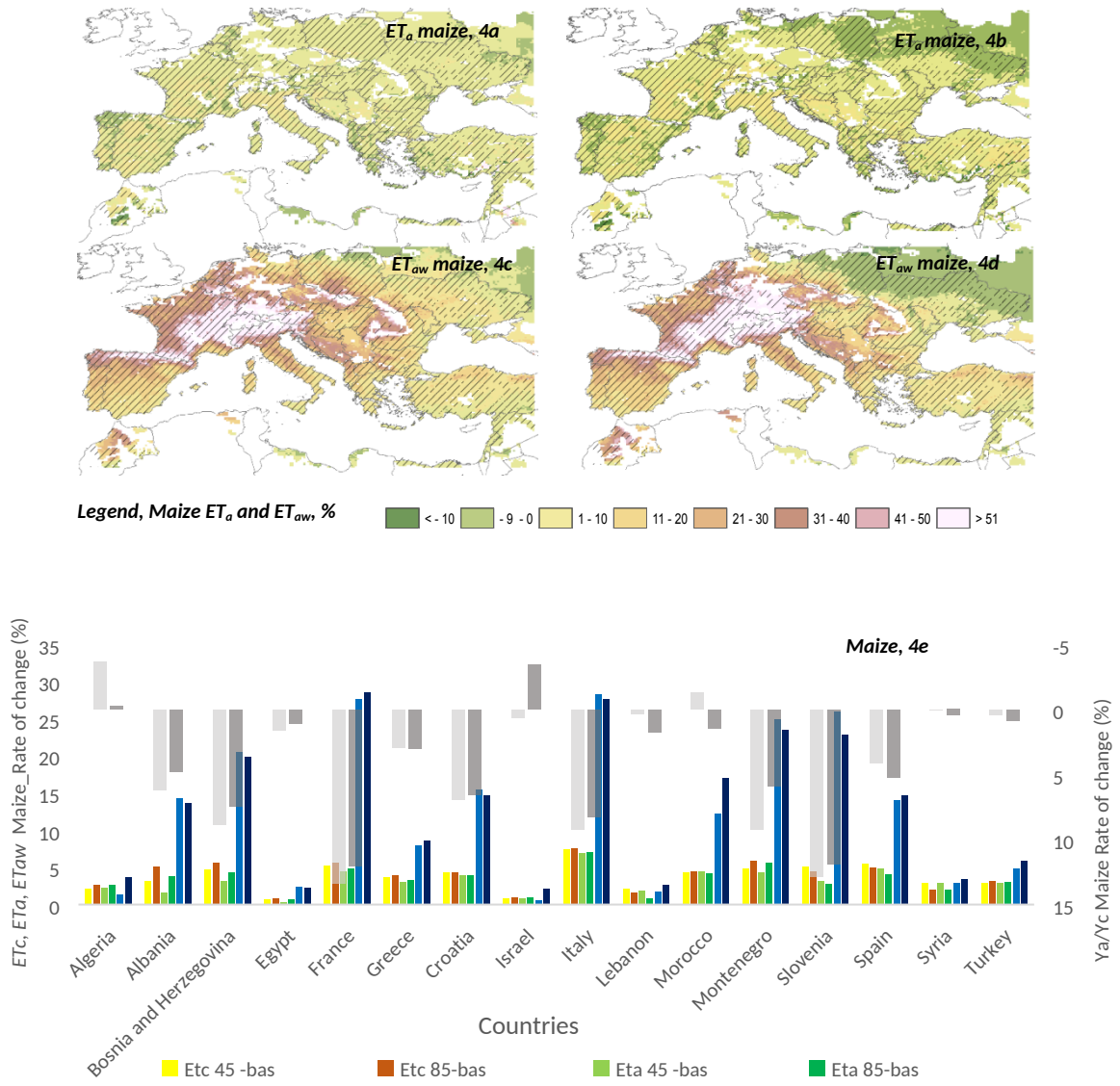

Fig. 4. Rate of change of ET_a (4a. ET_a 45-bas, 4b. ET_a 85-bas) and ET_{aw} (4c. ET_{aw} 45-bas, 4d. ET_{aw} 85-bas) values weighted for the irrigated maize distribution between future climate condition (2036-2065) under both RCP 4.5 and 8.5 scenarios, and the baseline (1976-2005) for the entire domain with a focus on the Mediterranean countries (Fig. 4e). Rate of changes of maize ET_c (ET_c 45-bas, ET_c 85-bas) and yield losses (Y_a/Y_c 45-bas, Y_a/Y_c 85-bas) between future and baseline period in the Mediterranean countries are shown in figure 4e.

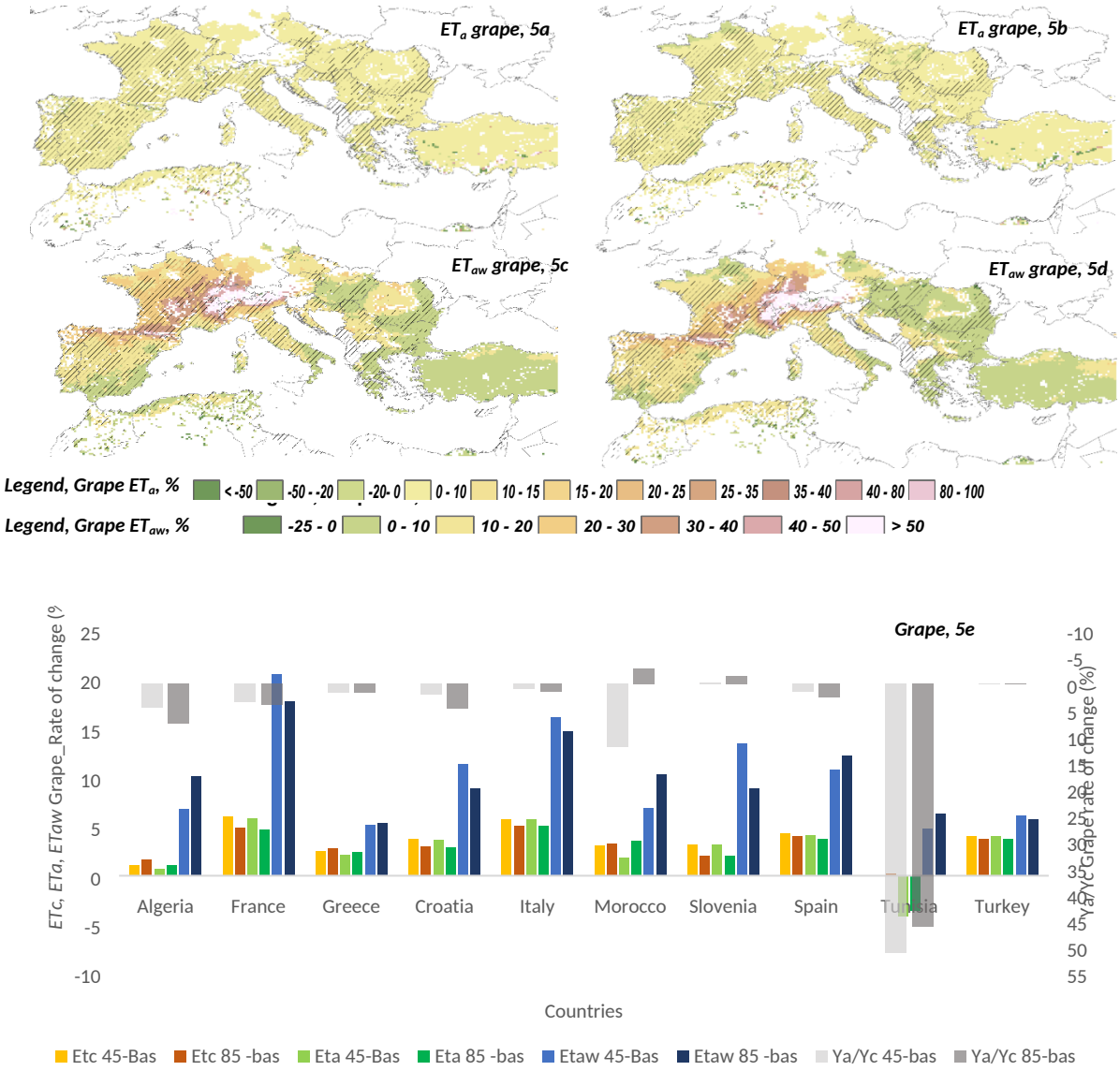

Fig. 5. Rate of change of ET_a (5a. ET_a 45-bas, 5b. ET_a 85-bas) and ET_{aw} (5c. ET_{aw} 45-bas, 5d. ET_{aw} 85-bas) values weighted for the irrigated grape distribution between future climate condition (2036-2065) under both RCP 4.5 and 8.5 scenarios, and the baseline (1976-2005) for the entire domain with a focus on the Mediterranean countries (Fig. 5e). Rate of changes of maize ET_c (ET_c 45-bas, ET_c 85-bas) and yield losses (Y_a/Y_c 45-bas, Y_a/Y_c 85-bas) between future and baseline period in the Mediterranean countries are shown in figure 5e.

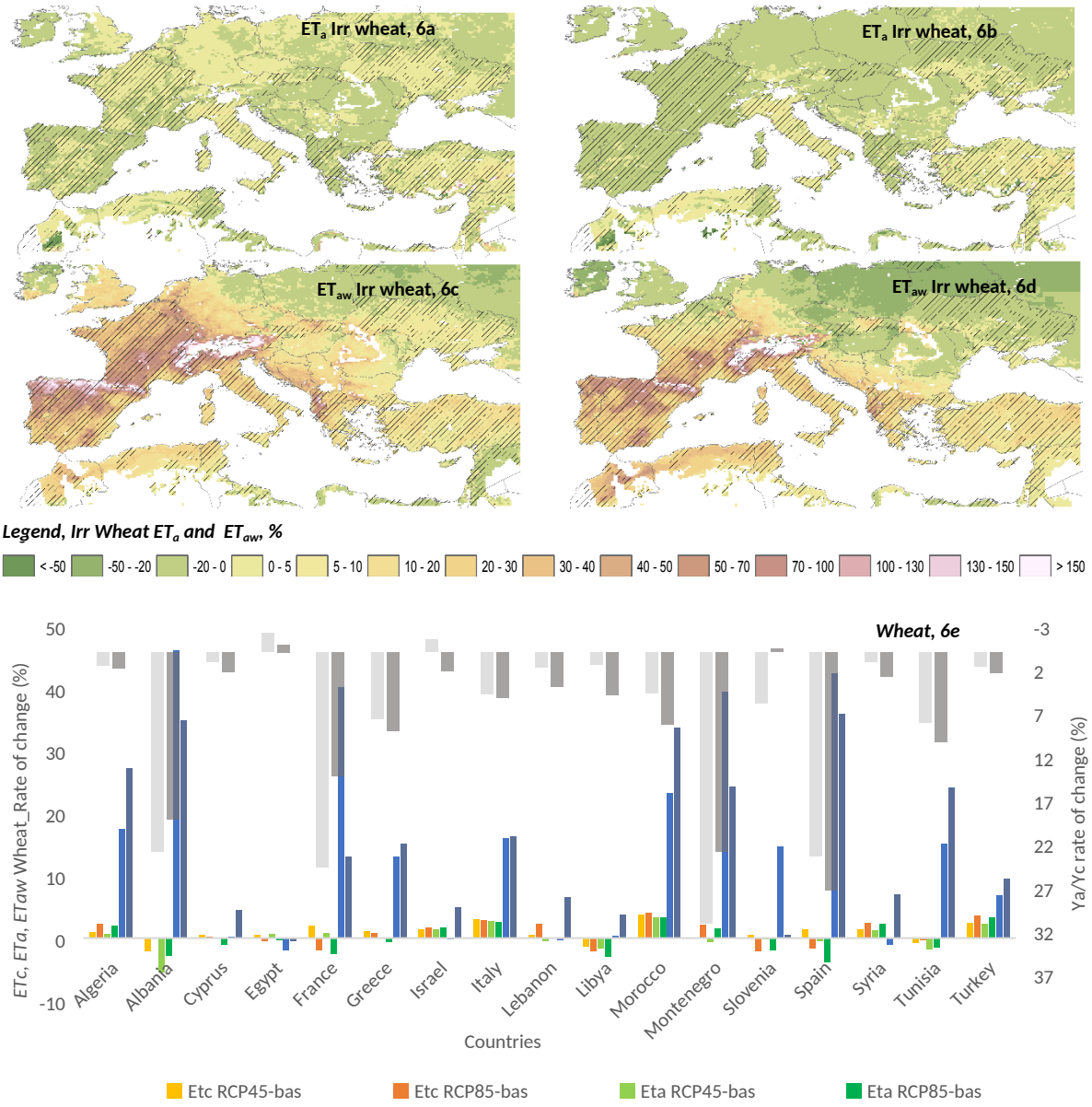

Fig. 6. Rate of change of ET$_a$ (6a. RCP45-bas, 6b. RCP85-bas) and ET$_{aw}$ (6c. RCP45-bas, 6d. RCP85-bas) values weighted for the irrigated wheat distribution between future climate condition (2036-2065) under both RCP 4.5 and 8.5 scenarios, and the baseline (1976-2005) with a focus on the Mediterranean countries (Fig. 6e). Rate of changes of wheat yield losses between future and baseline period are shown in figure 6e.

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Tables:

Tab.1. Crop characteristics and experimental sites selected through the FLUXNET network.

Code	*SITE*	*Country*	*Lat*	*Lon*	*Elevation (m.a.s.l.)*	*Crop*	*Sowing-Harvest date*
IT-Neg	Negrisia	Italy	45.75	12.45	11	Wine Grape	01.04.2007/15.10.2007
IT-Neg	Negrisia	Italy	45.75	12.45	11	Wine Grape	01.04.2008/27.10.2008
IT-VdA	Valle dell'Adige	Italy	46.20	11.11	207	Wine Grape	15.04.2009/05.09.2009
IT-BCi	Borgo Cioffi	Italy	40.52	14.96	13	Maize	17.05.2005/24.08.2005
IT-BCi	Borgo Cioffi	Italy	40.52	14.96	13	Maize	27.04.2006/22.08.2006
IT-BCi	Borgo Cioffi	Italy	40.52	14.96	13	Maize	09.05.2007/24.08.2007
IT-BCi	Borgo Cioffi	Italy	40.52	14.96	13	Maize	12.06.2009/08.09.2009
DE-Kli	Klingenberg	Germany	50.89	13.52	468	Wheat	25.09.2005/06.09.2006
DE-Kli	Klingenberg	Germany	50.89	13.52	469	Maize	23.04.2007/2.10.2007
DE-Geb	Gebesee	Germany	51.10	10.91	157	Wheat	09.11.2006/07.08.2007
FR-Lam	Lamasquere	France	43.50	1.24	182	Wheat	18.10.2006/15.07.2007
FR-Lam	Lamasquere	France	43.50	1.24	182	maize	01.05.2006/31.08.2006
FR-Gri	Grignon	France	48.84	1.95	117	wheat	28.10.2005/15.07.2006
FR-Gri	Grignon	France	48.84	1.95	117	maize	09.5.2005/28.09.2005
CH-Oe2	Oensingen	Switzerland	47.29	7.73	450	wheat	19.10.2006/16.07.2007
BE-Lon	Lonzee	Belgium	50.55	4.75	165	wheat	14.10.2004/03.8.2005
BE-Lon	Lonzee	Belgium	50.55	4.75	165	wheat	13.10.2006/05.08.2007
NL-Dij	Dijagraaf	The Netherlands	51.99	5.65	9	maize	08.05.2007/27.09.2007

Tab. 2. SIMETAW_R performance shown through the comparison of observed and modelled ET_a in ten experimental sites. Measured data quality are shown through statistical indices, the energy balance closure (EBC) and the correlation between LE measured and LE residual (LE vs LE`).

			Observed ETa vs Modelled ETa					EBC			LE vs LE`
Code	**YEAR**	**Crop**	**r**	**RMSE**	**IA**	**MBE**	**MBA**	**R^2**	**Y = aX + b**	**Gaps**	**r**
				mm	%		mm	%		%	
FR-Gri	2005	Corn	0.81	0.75	89	0.04	0.63	91	Y = 0.7583X	19	0.89
FR-Gri	2005-2006	Wheat	0.85	0.61	91	0.12	0.45	87	Y = 0.6748X	16	0.87
DE-Geb	2006-2007	Wheat	0.75	1.14	78	0.69	0.78	77	Y = 0.7335X	15	0.85
DE-Kli	2007	Corn	0.84	1.39	67	1.23	1.24	56	Y = 0.4694X	32	0.61
DE-Kli	2005-2006	Wheat	0.88	0.82	88	0.57	0.65	67	Y = 0.8379X	33	0.62
CH-Oe2	2006-2007	Wheat	0.92	0.75	94	-0.44	0.58	68	Y = 0.8037X	34	0.82
NL-Dij	2007	Corn	0.71	0.68	82	-0.14	0.54	73	Y = 0.7905X	15	0.87
FR-Lam	2006-2007	Wheat	0.82	0.72	90	-0.23	0.55	83	Y = 0.7254X	41	0.83
FR-Lam	2006	Corn	0.61	1.22	76	0.43	0.92	90	Y = 0.7838X	42	0.91
BE-Lon	2006-2007	Wheat	0.78	0.91	82	0.57	0.72	82	Y = 0.8487X	20	0.84
BE-Lon	2004-2005	Wheat	0.89	0.89	90	0.14	0.65	82	Y = 0.8454X	23	0.85
IT-Bci	2005	Corn	0.64	1.21	73	0.62	0.92	92	Y = 0.7794X	26	0.92
IT-Bci	2006	Corn	0.62	1.29	69	0.73	0.97	86	Y = 0.7894X	39	0.82
IT-Bci	2007	Corn	0.63	1.48	68	0.93	1.12	94	Y = 0.778X	37	0.95
IT-Bci	2009	Corn	0.63	1.32	75	0.51	1.03	91	Y =0.7405X	50	0.94
IT-VdA	2009	Wine Grape	0.82	0.68	90	0.06	0.5	77	Y =0.6866X	23	0.93
IT-Neg	2007	Wine Grape	0.83	1.91	77	1.3	1.6	na*	na*	na*	na*
IT-Neg	2008	Wine Grape	0.58	2.45	67	1.31	1.88	na*	na*	na*	na*

Tab. 3. Assessment of modelled ET_o computed using Hargreaves (with E-OBS and EI gridded data) and Penman Monteith (EI gridded data) equation against site observations (FLUXNET sites). Values are expressed as a mean of the values estimated in each site and for each available growing season.

HS_EOBS vs HS_site	**HS_EI vs HS_site**	**PM_EI vs PM_site**
	RMSE (mm)	
1.74	1.85	1.01
	MBE (mm)	
0.86	0.89	-0.03
	MAE (mm)	
1.49	1.59	0.79
	IA (%)	
59	59	81

Tab. 4. Precipitation values in the baseline period (pcp bas, mm) and climate anomalies (%) in the Mediterranean Countries for RCP 4.5 and 8.5 scenarios

	Algeria	**Albania**	**Bosnia and Herzegovina**	**Cyprus**	**Croatia**	**Egypt**	**France**	**Greece**	**Israel**	**Italy**
pcp bas	185	1095	1026	165	895	38	882	521	134	834
pcp45-bas	-15.75	-9.56	-7.45	-0.62	-4.66	0	-2.97	-18.35	5.65	-7.52
pcp85-bas	-26.08	-6.39	-5.65	-12.37	1.08	5.29	0.12	-16.21	-0.96	-7.54
	Lebanon	**Libya**	**Morocco**	**Montenegro**	**Slovenia**	**Spain**	**Syria**	**Tunisia**	**Turkey**	
pcp bas	397	76	352	1441	1084	711	146	163	479	
pcp45-bas	-3.08	-13.21	-19.01	-9.53	-2.61	-10.48	4.3	-15.9	-6.35	
pcp85-bas	-14.33	-22.79	-27.49	-4.81	5.5	-6	-6.43	-28.7	-8.52	