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Climatic and soil characteristics and crop parameters of optimized agro-climatic regions for maize

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Abstract

Popova, Z., Ivanova, M., Dimitrov, E., & Varlev, I. (2020). Climatic and soil characteristics and crop parameters of optimized agro-climatic regions for maize. *Bulg. J. Agric. Sci., 26 (6)*, 1232–1246

The objectives of the study are to discuss and provide appropriate climatic and soil characteristics and crop parameters for decision making on maize irrigation relative to five agro-climatic regions in the form of: a) quantiles of inter-annual and inter-regional variability of precipitation and ET^0; b) Bulgarian maps with average precipitation and average reference evapotranspiration ET^0; c) Bulgarian soil classes in terms of texture, field capacity, wilting point and total available soil water (mm m^{-1}); d) validated crop ET modelling parameters, as limiting dates of local maize development stages, appropriate crop coefficients *Kc* and soil water depletion fractions for no stress *p*. Finally, the conventional maize irrigation depths are compared with that simulated through the validated soil water balance (SWB) WinISAREG model application to identified agro-climatic regions.

Considered ET^0 and precipitation are the main climate variables that influence crop water requirements for irrigation. However, irrigation requirements are also influenced by soil characteristics, mainly FC, WP and TAW, and crop parameters, as rooting zone depth, validated *Kc* - coefficients and *p* – fractions relative to the crop development stages and respective limiting dates. All these parameters are also required input for SWB and irrigation scheduling WinISAREG, PILOTE and others model application. Map of Bulgarian soils and results of previous studies support identification of soil classes of small, average and large water holding capacity for each agro-climatic regions.

Keywords: maize irrigation requirements, SWB WinISAREG model, precipitation, reference evapotranspiration PM–ET^0, soil classes, agro-climatic regions identification, spatial distribution maps

Introduction

Climatic and soil characteristics and crop ET parameters are indispensable in the development of national irrigation requirement and scheduling system (Popova (Ed.) 2012; Pereira & Paredes, 2018). In our former studies the simulation soil water balance *SWB* and irrigation scheduling ISAREG model (Teixeira & Pereira, 1992; Pereira et al., 2003) used to be validated to maize crop grown at several experimental fields, representing the "soil-climate-irrigation management" conditions of Bulgarian plains (Popova, 2008; Ivanova and Popova, 2011; Popova & Pereira, 2011; Ivanova, 2013). The validated crop parameters, as the dates limiting crop growth periods and related to them crop coefficients *Kc,* that is a ratio between crop and reference evapotranspiration, and depletion fractions *p*, that is the soil water fraction that may be extracted by the crop without causing water stress, used to be implemented latter on to assess the vulnerability of Bulgarian agriculture to drought and to optimise irrigation scheduling options for maize crop in terms of "soil-irrigation technology-climate" under historical, present and scenario built weather conditions (Popova, 2008; Popova & Pereira, 2011; Alexadris et al. (Ed.G.Gregorich), 2012; Popova et al., 2015).

In our last studies the validated *SWB* WinISAREG model used to be applied also to simulate net irrigation requirements for maize in the scale of Agro-Climatic regions (AC), identified on the basis of average reference evapotranspiration for July and August PM-ET$^0_{\text{July-Aug}}$ computed for the period 1951-2004 (BJAS, 2018).

The objectives of present study are to discuss and provide the required climate and soil characteristics and crop parameters for these AC regions in terms of: a) Quantiles of "inter-annual" and "inter-regional" variability of precipitation and ET^0; b) Bulgarian maps with average precipitation and average reference evapotranspiration ET^0; c) Bulgarian soil classes in terms of texture, Field Capacity, Wilting Point and Total Available soil Water TAW (mm m^{-1}); d) Validated crop ET modelling parameters, as appropriate crop coefficients *Kc* and soil water depletion fractions for no stress *p* relative to the duration of local crop growth stages and limiting dates; e) Comparing simulated net irrigation requirements using WinIsareg model with the conventional depths (Zahariev et al., 1986).

Material, Methods and Results

Climatic characteristics for identified AC regions

Climate of the identified Agro-Climatic regions (*AC*) was characterised on the basis of a long-term (1951-2004) data relative to representative meteorological stations at: Sofia field (AC I), Silistra (AC II), Lom and Varna (AC III), Pleven, Plovdiv and Stara Zagora (AC IV) and Sandanski (AC V) (Fig. 1).

The climate is featured as *a moderately continental* in Sofia field (AC I) and northern locations of Silistra, Lom and Pleven (AC II, AC III and AC IV) and *a transitional continental* over the Thracian plain, South Bulgaria, as represented by the stations in Stara Zagora and Plovdiv (AC IV). The climate is *a northern Black Sea* in Varna (AC III), while it is a transitional Mediterranean in Sandanski (AC V).

Monthly precipitation and reference evapotranspiration (ET^0) relative to the period 1951 to 2004 at selected locations are presented in Fig. 2.

Precipitation represents wet, average and dry years, i.e., when the probability for being exceeded is respectively 10, 50 and 90%. The precipitation during the maize cropping season ("May-Sept") shows a great inter-annual variability and a non-negligible seasonality, with less precipitation during the months of July, August and September, when maize flowering and yield formation occur (Fig. 2a, 2c, 2e, 2g and 2i). Due to the Balkan mountain that crosses the country from East to West, there is also an evident spatial variability with larger precipitation in the stations of large elevation (like Sofia, 550 m a.s.l., AC I, Fig. 2a) and in the northern locations representing AC regions II (Silistra, Fig. 2c), III (Lom, Fig. 2e) and IV (Pleven, Fig. 2g).

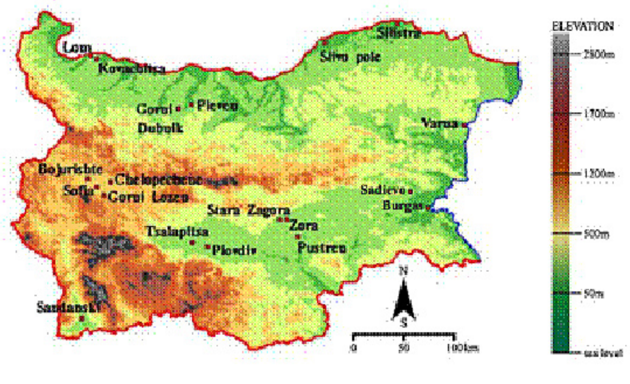

Fig. 1. Experimental fields of *ISSAPP* and meteorological stations of *NIMH* in Bulgaria

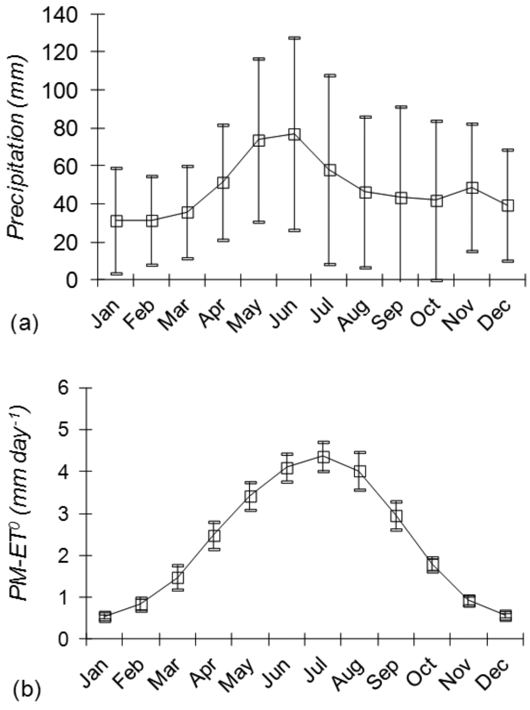

Fig. 2. Average monthly precipitation (mm) and reference evapotranspiration *PM-ET^0* (mm day^{-1}) (□) for the period 1951-2004; bars represents 80% confidence interval for the averages during the whole period 1951-2004; *I AC Region* (*a*, *b*) Sofia; *II AC Region* (*c*, *d*) Silistra; *III AC Region* (*e*, *f*) Varna and Lom; *IV AC Region* (*g*, *h*) Pleven and Plovdiv; *V AC Region* (*i*, *j*) Sandanski

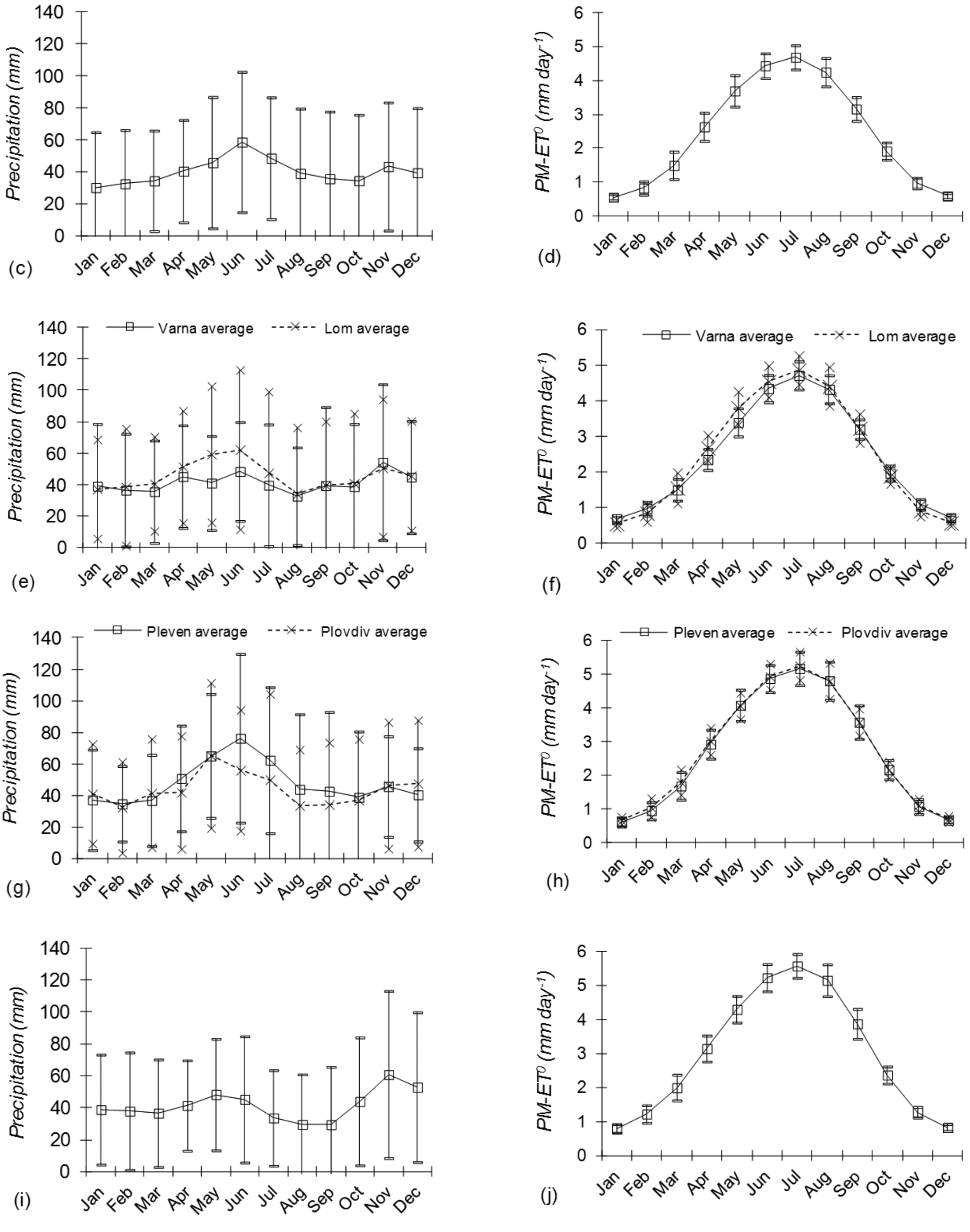

Fig. 2. Continued

ET^0 was computed with the PM–ET^0 equation (Allen et al., 1998) using only temperature data as described by Popova (2008), Ivanova & Popova (2011) and Popova et al. (2015). ET^0 refers to low, average and high climatic demand conditions, when ET^0 values are exceeded with a probability 90, 50 and 10% respectively. ET^0 shows much less inter-annual variability than precipitation, as indicated by the bars representing the 80% confidence interval, and is predominantly higher in southern regions, reaching in July 5.6 mm day^{-1} at AC region V (Sandanski, Fig. 2j) and 5.3 to 5.2 mm day^{-1} at AC region IV (Plovdiv/Pleven and Stara Zagora, Fig. 2h).

High Peak Season ET^0 is 4.9-4.7 mm day^{-1} in the northern regions AC III (Lom, Varna) and AC II (Silistra) (Figs. 2f and 2d) and reaches a minima of 4.4-4.0 mm day^{-1} in AC region I (Sofia field) (Fig. 2b). ET^0 follows a regular seasonal distribution, with maxima in July and August when precipitation is smaller (Fig. 2).

Probability curves of occurrence for seasonal precipitation and reference evapotranspiration ET^0, relative to the whole "May-Sept" season and the high demand "July-Aug" period are compared for the representative locations in Figs. 3 and 4.

The "May-Sept" seasonal precipitation is the highest and practically identical at AC regions I (Sofia) and IV (Pleven), varying between 120 and 550-700 mm and could be quite different within the AC regions IV (Plovdiv vs. Pleven) and III (Varna vs. Lom) (Fig. 3a). As it may be observed compar-

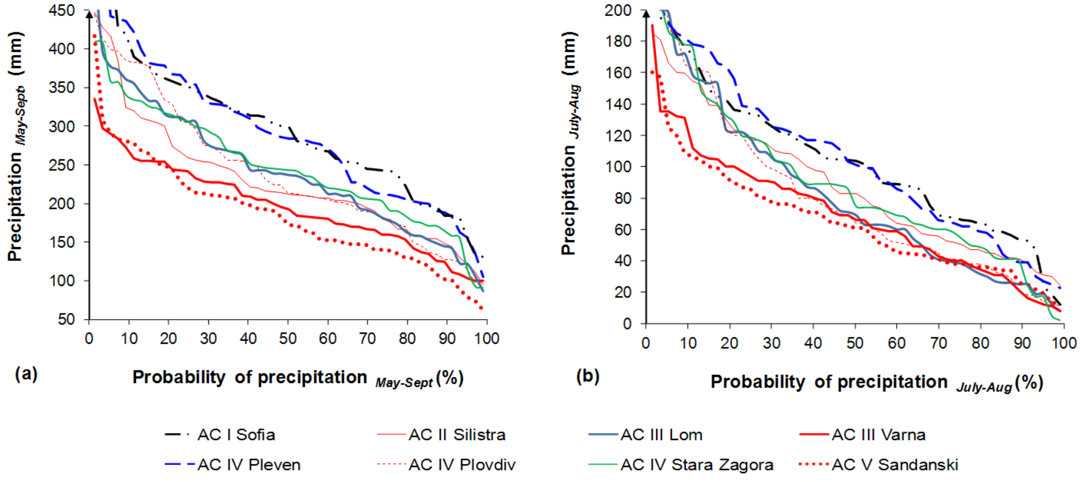

Fig. 3. Comparison of precipitation (mm) probability of exceedance curves for eight climate stations, representing the identified AC regions and relative to: *a*) Cropping Season "May-Sept"; *b*) High Demand Season "July-Aug", 1951-2004

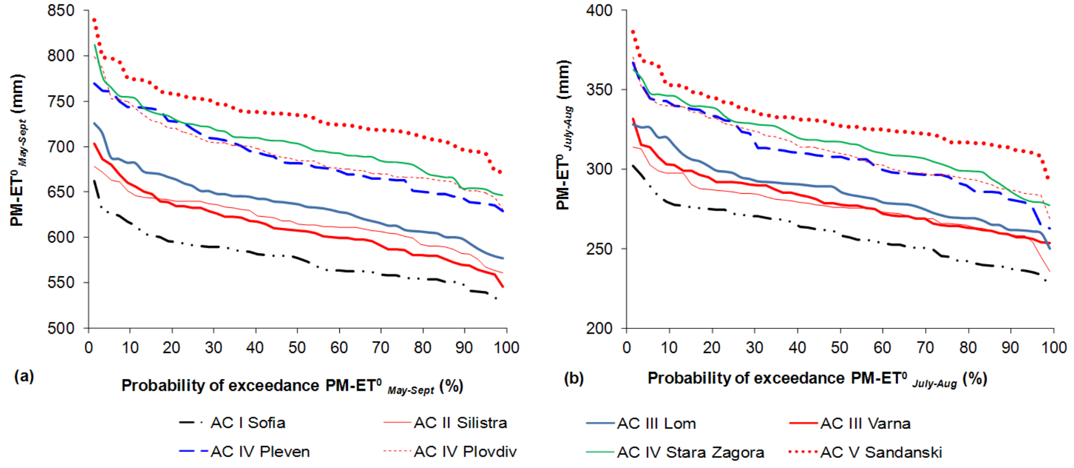

Fig. 4. Comparison of reference evapotranspiration *PM-ET⁰* (mm) probability of exceedance curves for eight climate stations, representing the identified AC regions and relative to: *a*) Cropping Season "May-Sept"; *b*) High Demand Season "July-Aug", 1951-2004

ing the probability curves in the figure, the curves for Sofia and Pleven are above all others. Comparing the eight curves, it may be also concluded that seasonal precipitation "May-Sept" for maize should increase in the following order: Sandanski (AC V), Varna (AC III), Silistra (AC II), Lom (AC III), Plovdiv and Stara Zagora (AC IV), Pleven (AC IV) and Sofia (AC I).

Regarding the peak demand period "July-Aug", inter-regional precipitation differences are about half of those related to the whole cropping season. Except for Silistra (AC II), they increase in a similar order as that relative to "May-Sept" (Fig. 3b). However, "inter-regional" differences become much smaller in the dry years ($P > 90\%$) and augment over the average and wet years. It could be concluded that seasonal and high demand season precipitation are the lowest at AC V (Sandanski) and AC III (Varna) and the highest at AC regions I (Sofia) and IV (Pleven) (Figs. 3a and 3b).

The inter-seasonal variability of reference evapotranspiration totals PM-ET^0 "May-Sept", compared with precipitation, is much lower (Fig. 4).

Seasonal evapotranspiration demands PM-ET^0 "May-Sept" are the largest in the driest AC Region V (Sandanski) ranging 740 to 840 mm and about 30-110 mm less than that in AC Region IV (Stara Zagora, Plovdiv and Pleven). ET^0 "May-Sept" are 70-90 mm lower than that in AC Regions III and II (Lom, Silistra and Varna) and the least in AC Region I (Sofia) (Fig. 4a).

During the high demand season "July-Aug" the differences between locations in terms of ET^0 are half than those relative to ET^0 "May-Sept" (Fig. 4b).

In order to characterise the distribution of seasonal precipitation and monthly PM-ET^0 over the agricultural country territory, references on respective maps based on more than 40 agro-meteorological stations of good spatial coverage in elevation and climate zones were studied as well (Alexandrov, 2011; Moteva et al., 2015).

Spatial distribution of seasonal precipitation in Bulgaria is characterised as a nonuniform over the country territorry (Alexandrov, 2011; Fig. 5a).

During the warm half of the year (April to September) most of the Eastern communities and those along the Black-sea coast are exposed to a greate risk of drought (Fig. 5a). The same holds thrue for the communities of Petrich and Sandanski (AC region V) in Blagoevgrad region. It is important to drow attention to the whole South-East Bulgatia (except for the community of Malko Tarnovo) that is potentially vulnarable to atmosheric drought during the period from April to September (AC regions IV and V, Fig. 5a).

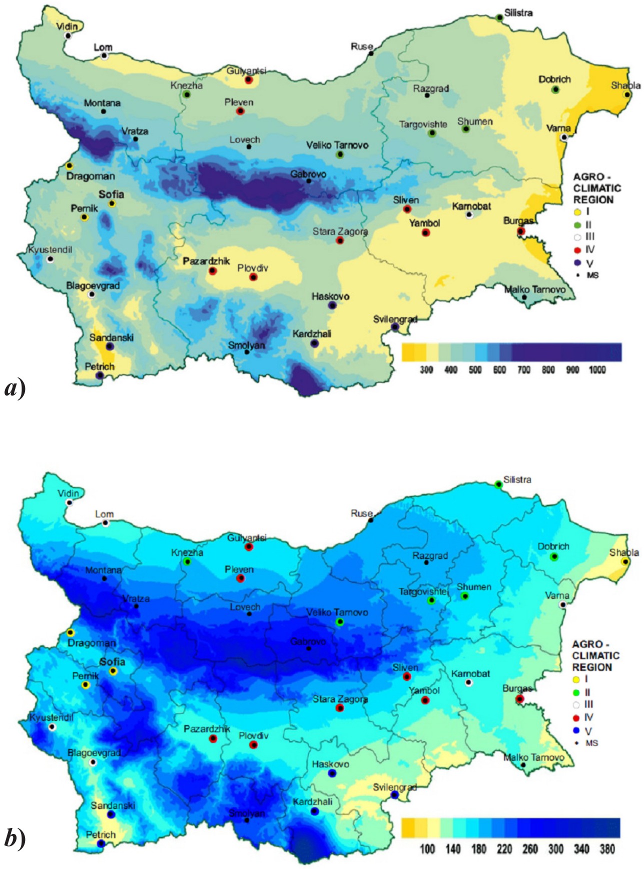

Fig. 5. Spatial distribution of:
***a*) Seasonal Precipitation "April-September" (mm);**
***b*) Summer Precipitation (mm) (Alexandrov, 2011)**

It is observed also that the territories around Yambol (AC region IV) and along the river valley of lower Struma (AC region V), around Sofia (AC region I) and Plovdiv (AC region IV), South Bulgaria, are potentially vulnerable to drougth in spring. Gulyantsi community near by Pleven, North Bulgaria (AC region IV) is at risk of seasonal drougth too (Fig. 5a). The communities around Haskovo and Svilengrad (AC region V), Yambol and Burgas (AC region IV) and Karnobat (AC region III), South Bulgaria, and Dobrich (Balchik and Kavarna, AC region II) and Shabla (AC region I) and the extreme South-West part of the country are the most vulnerable to drought due to the scarce precipitation in summer (Fig. 5b). During summer the Danube plain gets more precipitation than the Thracian Lowland while in autumn the former is potentially vulnerable to the smaller precipitation (Alexandrov, 2011).

Monthly (average for the period 1981-2010) distribution of ET^0 (mm) indicates that the stations of Sandanski, Petrich, Haskovo and Kardjali (AC V) and Yambol, Sliven, South Bulgaria and Pleven, North Bulgaria (AC IV), have the greatest evapotranspiration demand in all months (Fig. 6, Moteva et al., 2015).

The stations of Sofia and Dragoman, South Bulgaria and Shabla, North-East Bulgaria (AC I), have the lowest ET^0 demands (Figs. 6a, 6b, 6c). According to Moteva et al. (2015) the ET^0 monthly climatic values vary over the country in the following ranges: in April – 62.9-92.3 mm; in May – 86.9-130.3 mm; in June – 107.7-162.0 mm (Fig. 6a); in July –127.4-184.2 mm (Fig. 6b); in August – 109.8-157.8 (Fig. 6c); and in September – 70.8-103.5 mm.

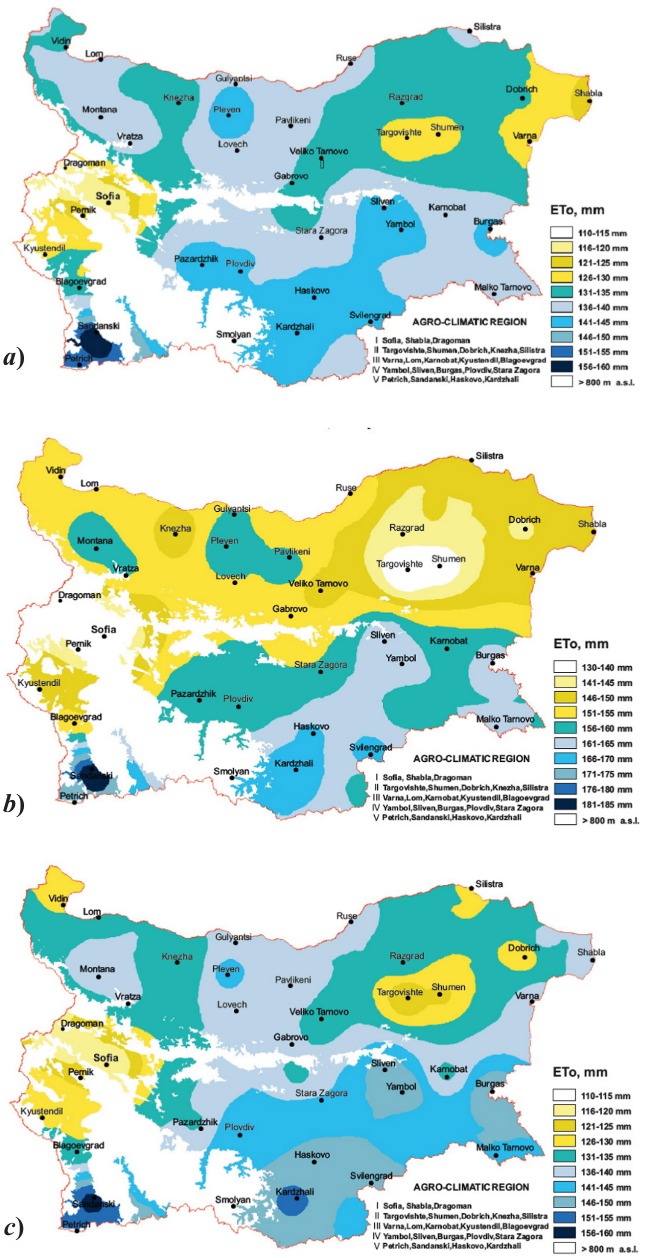

Fig. 6. Spatial distribution of the average reference evapotranspiration *PM-ET⁰* (mm) in 1981-2010: *a*) June; *b*) July; *c*) August (Moteva et al., 2015)

The statistical and graphical analysis of average ET^0 in terms of the identified unified agro-climatic regions shows that:

- The climate in *AC region V* is a Transitional-Mediterranean having the highest reference evapotranspiration during July and August $ET^0_{July\text{-}Aug} = 5.6\text{-}5.2$ mm/d in this country (Fig. 2j). It spreads over the blue and black zones in extreme southern Bulgaria covering a range of $166 < ET^0_{July} < 185$ mm month^{-1} (Fig. 6b) and $146 < ET^0_{Aug} < 160$ mm month^{-1} (Fig. 6c).
- It is followed by the *AC region IV* that covers the gray and green zones of average reference evapotranspiration within the range $156 < ET^0_{July} < 165$ mm month^{-1} (Fig. 6b) and the blue zone of $141 < ET^0_{Aug} < 150$ mm month^{-1} (Fig. 6c) corresponding to a daily rate of $ET^0_{July\text{-}Aug} = 5.4\text{-}5.2$mm/d in Plovdiv, Pleven and Stara Zagora (Fig. 2h).
- *AC region III* unifies the communities of Varna, Lom, Vidin, Kyustendil, Blagoevgrad and Karnobat that experience a highest risk of atmospheric drought during the warm half of the year (Fig. 5a). *AC III* is characterized as a region of lower reference evapotranspiration in July and August (4.9 - 4.7 mm/d, Fig. 2f) relative to the dark yellow zones of $146 < ET^0_{July} < 156$ mm month^{-1} (Fig. 6b) and the green to grey zones of $130 < ET^0_{Aug} < 140$ mm month^{-1} (Fig. 6c).
- *AC Region II* spreads over the white to yellow areas around Targovishte, Shumen, Dobrich, Silistra, Pavlikeni and Kneza communities in the Danube Plain (Fig. 6b) where maximums of average $ET^0_{July\text{-}Aug} = 4.7\text{-}4.2$ mm/d have been observed (Fig. 2d). Monthly ET^0 totals range within the limits $130 < ET^0_{July} < 146$ mm month^{-1} (Fig. 6b) and $125 < ET^0_{Aug} < 135$ mm month^{-1} respectively of the yellow and green zones in Fig. 6c.
- *AC Region I* consists of Sofia field, Dragoman, Elin Pelin and Shabla communities. It should be characterized as a region of the lowest average monthly maximums of $ET^0_{July\text{-}Aug} = 4.4\text{-}4.0$ mm/d in this country (Fig. 2b). *AC I* covers the white and light-yellow zones of $130 < ET^0_{July} < 146$ mm month^{-1} in July (Fig. 6b) and $110 < ET^0_{Aug} < 125$ mm month^{-1} in August (Fig. 6c).
- In final analyses the highest ET^0 maximums and the scarce summer precipitation are inherent to *AC regions V* (Sandansky, Svilengrad, Haskovo and Kardjali, Figs. 2i 2j 5b 6a 6b 6c). The minimum average ET^0 values from April to June are calculated for the Black Sea Region (Varna, *AC*

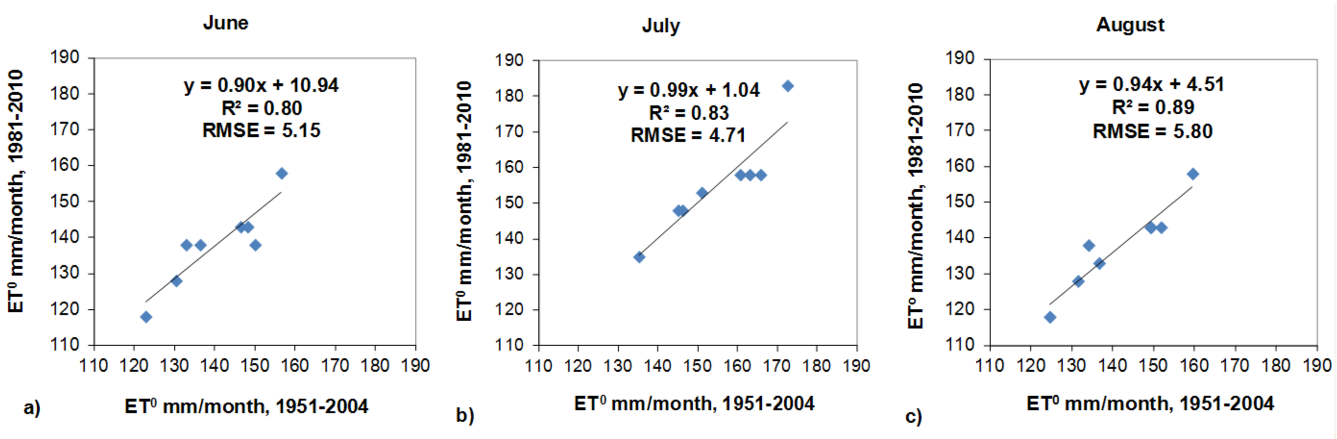

Fig. 7. “One-to-one” relationships between the average monthly ET⁰ values relative to the periods 1951- 2004 (Popova et al., 2014) (X – axis) and 1981-2010 (Moteva et al., 2015) (Y – axis) for: *a*) June, *b*) July, *c*) August

Region III, Fig. 2f) and from July to September – for the Danube Plain (Targovishte, Shumen and Dobrich, AC region II, Figs. 6b and 6c).

• Up to the period “April-September”, the lowest minimal, maximal and average ET⁰ values are peculiar to AC regions I, II and III, while the highest ones – to AC regions IV and V (Figs. 4a and 6).

Fig. 7 shows ”one-to-one” relationships derived between the average monthly values of reference evapotranspiration *PM-ET⁰-FAO56* (mm/month), computed with climate data observed in the agro-meteorological stations at Sofia, Plovdiv, Stara Zagora, Sandanski and Lom, Pleven Silistra and Varna during two different periods: from 1951 to 2004 (Popova et al., 2015) (X – axis) and from 1981 to 2010 (Moteva et al., 2015) (Y – axis).

Statistical analyses show that the best coincidence between the ET⁰ results ($R^2 = 0.89$) is found for the month of August. The coefficient of determination relative to June and July is slightly lower ($R^2 = 0.80$ and $R^2 = 0.83$), showing acceptably precise relationship at a standard error of estimation below 5.80 mm/month and a slope coefficient ranging from 0.90 for June to 0.99 for July.

Soil characteristics for identified agro-climatic regions

Soil characteristics for identified AC regions are based on former studies on physical, hydraulic, hydrological, mineralogical and other soil properties (Doneva, 1976; Eneva, 1993; Varlev et al., 1994; Koinov et al., 1998; Stoyanov, 2008; Mikova, 2002; Boneva, 2012), carried out in the experimental fields of “N. Poushkarov” Institute of Soil Science at Bojurishte, Chelopechene and Gorni Lozen (AC Region I), Slivo Pole (AC II), Sadievo and Kovachitsa (AC III), Tsalapitsa, Zora, Pustren and Gorni Dabnik (AC IV) and others (Fig. 1).

Detailed data on soil genesis and texture, field capacity FC (cm^{-3} cm^{-3}), wilting point WP (cm^{-3} cm^{-3}), mineral content in % of clay fraction in the soil have been defined for a number of soil profiles (peddons) and used to build a dataset on *TAW* (mm m^{-1}) (Eneva, 1997; Varlev & Popova, 1999; Varlev, 2008; Stoyanov, 2008; Popova et al., 2006; Popova, 2008; Popova et al., 2015). Three soil classes in terms of *TAW* have been defined for the purpose of multiplication of WinISAREG model results in the scale of the country (Boneva, 2012).

Typical soils in the plains of South Bulgaria are the Leached Cinnamonic Forest soils of small, medium to large water holding capacity, as: *TAW* = 106 mm m^{-1} at Chelopechene EF (AC I); *TAW* = 136 mm m^{-1} at Zora EF (AC IV) and *TAW* = 171-178 mm m^{-1} at Gorni Lozen (AC I) and Sadievo (AC III) EFs (soil №8 in Fig. 8).

The Vertisols are soils of predominantly large *TAW* that varies within the limit $173 < TAW < 180$ mm m^{-1}, as it is observed in the fields at AC I (Bojurishte) and AC VI (Pustren) (Figs. 1 and 8; Popova, 2008). Except for Sofia field and Stara Zagora region, the Vertisols are also wide-spread around Burgas (AC IV), Haskovo (AC V) and Karnobat (South-East Bulgaria, AC III) (Stoyanov, 2008; Mikova, 2002).

Soils of small to average water holding capacity ($106 \leq TAW \leq 133$ mm m^{-1}), as coarse-textured Luvisols and Alluvial/Deluvial-meadow soils, are found on the river terraces located in Sofia field (Chelopechene EF) and Thracian Lowland (Tsalapitsa EF), as well as in the valleys along The Struma and The Mesta Rivers in Sothern Bulgaria (soil №12 in Fig. 8).

Fig. 8. Soil map of Bulgaria in *Atlas of the soils in Bulgaria* (Koinov et al., 1998)

The most wide-spread soils in North Bulgaria are the Chernozems (Koinov et al., 1998). Total Available Water of these soils ranges within the limits 157 mm m^{-1} (Slivo Pole) ≤ *TAW* ≤ 180 mm m^{-1} (Kovachitsa) (Stoyanov, 2008; Boneva, 2012). Chernozems are soils of MI (Montmorillonite – Illite) type that are constituted predominantly of Montmorillonite mineral, consisting 10 to 20% of the soil. That percent changes gradually from the Danube River to the south, i.e. from Calcareous (soil №1) to Leached (Slivo Pole EF) and Degraded (Gorni Dabnik EF) chernozems (soils №3 and №4, Fig. 8). A feature characteristic of the later is a larger content of Vermiculite, which in combination with the Montmorillonite, determines larger *TAW* values of chernozems located in the Middle Danube Plain and the "Ludogorska-Dobrichka" chernozems' subzone (Boneva, 2012).

Some Vertisol clay soils of large water holding capacity (*TAW* ≥ 180 mm m $^{-1}$) are widespread around Vidin, North-West Bulgaria. Small spots of soils called "Karasolutsi" of *TAW* > 180 mm m^{-1}, which in terms of water holding capacity are similar to the Vertisols, are specific for the "Ludogorska-Dobrichka" region in North-East Bulgaria (Fig. 8).

Soils of smaller water holding capacity ($106 \leq TAW \leq 116$ mm m^{-1}), as the coarse-textured Alluvial/Deluvial-meadow soils, are located on the river terraces in The Danube plain (soil №12 in Fig. 8; Koinov et al., 1998; Boneva, 2012)

Thus, soil water holding capacity in Bulgaria, herein the total available soil water *TAW* values, is used to define three main soil classes occurring in the identified AC regions represented by the locations referred above, namely "small" ($106 \leq TAW \leq 133$ *mm m^{-1}*), "medium" (about $136 \leq TAW \leq 157$ mm m^{-1}) and "large" ($168 \leq TAW \leq 180$ mm m^{-1}) (Fig. 8).

Crop parameters for the identified agro-climatic regions (duration of crop growth stages, limiting dates and maize varieties for Zahariev and WinISAREG applications)

Comparing crop parameters requires knowing if duration of crop growth stages and limiting dates are the same for Zahariev et al. (1986) and for WinISAREG *SWB* model (Pereira et al., 2003) applications. While "Planting" and "Full maturity/Harvesting" dates of maize are found to be the same for both approaches, names of some crop growth stages, as well as average night and day air temperature, are not completely identical (Fig. 9).

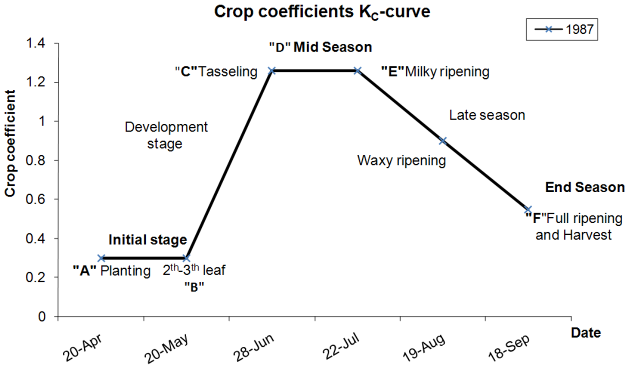

Fig. 9. Comparing duration of observed crop growth stages according to Bulgarian standards, including planting and harvesting date, with that required for WinISAREG model application. *Kc*-curve and crop development stages relative to maize hybrid H708, Tsalapitsa EF, 1987

Six Agro-climatic groups were defined in Zahariev et al. (1986) by using the temperature conditions characteristics in spring, pronounced by the date of a permanent increase of average night and day air temperature T_{av} over 5, 10 and 15°C, and the temperature sums during vegetation period. Average air temperature for Zahariev T_{av} is computed as an average of observed air temperatures at 7am, 1pm and 9pm, using following equation:

$$T_{av} = (T_{7am} + T_{1pm} + 2*T_{9pm})/4 \qquad (1)$$

Thus, the starting date of each vegetation period is considered to be the first day of a decade, during which the average air temperature T_{av} (eq.1) is constantly over 5°C. The regions, having stable increase of the average temperature T_{av} above 10 and 15°C, are separated in two more groups. The existing network of 97 Hydro-meteorological stations, having a complete 35-year (1946-1980) observation period at least, served as a basis for "Zahariev" irrigation regions identification.

The application of WinISAREG model requires observation of real maximum T_{max} and real minimum T_{min} air temperatures that are also used for the estimation of average night and day air temperature (Allen et al., 1998):

$$T_{average} = (T_{max} + T_{min})/2 \qquad (2)$$

Relative to other simulation models, like the mechanistic Water Fluxes and Yield (*W&Y*) WAVE model (Vanclooster et al., 1994), crop development is based on application of the *DVS* (development stage) approach. The *DVS* is proportional to the sum of effective air temperatures required by the crop to reach the beginning/the end of "vegetative" (1) and "reproductive" (2) phase (Feddes et al., 1978; Varlev & Popova, 1999; Doneva & Popova, 2016). In the modified CERES-NC-maize model (Jones & Kiniry, 1989; Gabrielle et al., 1995; Popova, 2008) a water flow sub-model has been implemented, while crop development stages are six and each one is related to a new organ appearance that is simulated by applying the calibrated so called "degree days" approach.

Regarding Zahariev et al. (1986) and Bulgarian standards, the duration of maize crop growth stages is based on observation of the occurrence dates relative to: Planting "A", Emergency, 2-3rd to 10-12th leaf appearance "B", Tasseling "C", Flowering, Milky ripening "E", Waxy ripening and Full ripening "F", (Fig. 9, Table 1).

The duration of crop growth stages in the *SWB* WinISAREG model (Pereira et al., 2003) is also based on regular field observations, but the limiting dates and stages are that defined by FAO (Fig. 9):

Initial stage starts at "A" (Planting) and ends at "B" when 10% of the ground is covered or when, according to Bulgarian standards, "2nd-3rd leaf" has appeared (Popova et al., 2006b; Popova & Pereira, 2011; Ivanova & Popova, 2012). Crop coefficient for this stage Kc_{ini} refers generally to soil evaporation, which is small except when numerous wetting events occur.

Crop Development Stage starts at "B" and ends at "C", i.e. its duration is from "10% ground cover" to "Full ground cover", when leaf area index is higher than 3 (LAI > 3) that also corresponds to the Bulgarian "Tasseling" stage for maize crop (Popova, 2008; Ivanova, 2013).

Table 1. Limiting dates of main crop development stages, observed for the maize hybrids grown at Sadievo Experimental Field (II and III AC regions) over the period 1964-1993

		Maize growth stages								
		“A“		“B“	“C“	“E“		“F“		
Crop growth stages :	**FAO**	**Planting**		**10% ground cover**	**Full ground cover**	**Start of Senescence/Maturity**		**Full ripening**	hybrid	
	Bulgarian standards	**Planting**	Emergency	**2nd-3rd leaf**	**Tasseling**	**Milky ripening**	Waxy ripening	**Full ripening/ harvest**		
№	years									
1	1964	26/04/1964	12/05/1964	18/05/1964	14/07/1964	**09/08/1964**	26/08/1964	07/09/1964	Viskonsin - 641 AA	
2	1965	20/04/1965	14/05/1965	21/05/1965	16/07/1965	12/08/1965	30/08/1965	06/09/1965	Viskonsin - 641 AA	
3	1966	27/04/1966	09/05/1966	14/05/1966	18/07/1966	06/08/1966	29/08/1966	14/09/1966	Kanzas - 1859	
4	1967	06/05/1967	19/05/1967	24/05/1967	12/07/1967	07/08/1967	20/08/1967	02/09/1967	Kanzas - 1859	
5	1968	22/04/1968	06/05/1968	12/05/1968	10/07/1968	10/08/1968	24/08/1968	04/09/1968	Kanzas - 1859	
6	**1969**	**26/04/1969**	**10/05/1969**	**16/05/1969**	**10/07/1969**	**07/08/1969**	**20/08/1969**	**07/09/1969**	**Kanzas - 1859**	**the AVG**
7	**1970**	**04/05/1970**	14/05/1970	**19/05/1970**	**26/07/1970**	**09/08/1970**	04/09/1970	**16/09/1970**	Kanzas - 1859	**the latest**
8	1971	06/05/1971	18/05/1971	27/05/1971	12/07/1971	07/08/1971	27/08/1971	07/09/1971	Kanzas - 1859	
9	1972	14/04/1972	27/04/1972	17/05/1972	06/07/1972	04/08/1972	26/08/1972	14/09/1972	Vir - 42	
10	1973	13/04/1973	03/05/1973	05/05/1973	04/07/1973	03/08/1973	14/08/1973	02/09/1973	SK - 4	
11	1974	25/04/1974	07/05/1974	09/05/1974	16/07/1974	10/08/1974	26/08/1974	08/09/1974	Bc - 6625	
12	**1975**	**12/04/1975**	29/04/1975	**12/05/1975**	**10/07/1975**	**05/08/1975**	**08/08/1975**	**04/09/1975**	Kneja - 601	**the AVG**
13	1976	07/04/1976	28/04/1976	06/05/1976	10/07/1976	05/08/1976	24/08/1976	16/09/1976	Bc - 6625	
14	1977	25/04/1977	04/05/1977	09/05/1977	20/06/1977	22/07/1977	10/08/1977	27/08/1977	KWS - 725	
15	1978	**28/04/1978**	08/05/1978	**12/05/1978**	10/07/1978	02/08/1978	22/08/1978	**08/09/1978**	Bc - 6625	
16	1979	**23/04/1979**	04/05/1979	08/05/1979	06/07/1979	04/08/1979	26/08/1979	14/09/1979	H - 708	
17	**1980**	**21/04/1980**	04/05/1980	**07/05/1980**	15/07/1980	**10/08/1980**	30/08/1980	**18/09/1980**	**H - 622**	**the AVG**
18	**1981**	**16/04/1981**	26/04/1981	**28/04/1981**	**02/07/1981**	**28/07/1981**	14/08/1981	**22/08/1981**	Kneja - 2Л - 611	**the earliest**
19	**1982**	**02/04/1982**	22/04/1982	**29/04/1982**	08/07/1982	**06/08/1982**	18/08/1982	**31/08/1982**	**Kneja - 2Л - 611**	
20	**1983**	**07/04/1983**	22/04/1983	**28/04/1983**	06/07/1983	**06/08/1983**	20/08/1983	**02/09/1983**	Kneja - 611	
21	1984	14/04/1984	05/05/1984	23/05/1984	17/07/1984	**22/08/1984**	15/09/1984	04/10/1984	H - 708	
22	1985	23/04/1985	11/05/1985	19/05/1985	24/07/1985	14/08/1985	26/08/1985	15/09/1985	H - 708	
23	1986	25/04/1986	12/05/1986	26/05/1986	12/07/1986	05/08/1986	28/08/1986	15/09/1986	H - 708	
24	1987	20/04/1987	09/05/1987	25/05/1987	15/07/1987	28/07/1987	04/08/1987	21/09/1987	Alfa	
25	1988	24/04/1988	08/05/1988	19/05/1988	07/07/1988	25/07/1988	04/08/1988	19/09/1988	Alfa	
26	1989	23/04/1989	10/05/1989	15/05/1989	16/07/1989	25/07/1989	03/08/1989	18/09/1989	Alfa	
27	1990	23/04/1990	30/04/1990	07/05/1990	10/07/1990	27/07/1990	26/08/1990	20/09/1990	Alfa	
28	1991	17/04/1991	02/05/1991	09/05/1991	31/07/1991	18/08/1991	28/08/1991	22/09/1991	H - 708	
29	**1992**	**20/04/1992**	25/04/1992	**08/05/1992**	**19/07/1992**	**25/08/1992**	10/09/1992	**25/09/1992**	H - 708	**the latest**
30	1993	21/04/1993	05/05/1993	13/05/1993	12/07/1993	06/08/1993	22/08/1993	11/09/1993	H - 708	
	Average 1964-1993	**21-Apr**	05-May	**13-May**	**12-Jul**	**06-Aug**	22-Aug	**11-Sep**		
	Duration (days)	**Initial Stage 22**			**Mid Season "D" 25**			**Full ripening 11-Sep**		
	STDEV (days)	**8**	**7**	**8**	**8**	**8**	**10**	**10**		
	Cv (%)	**7**	**6**	**6**	**4**	**4**	**4**	**4**		
	Average 1964-1978	**22-Apr**	07-May	**13-May**	**10-Jul**	**05-Aug**	23-Aug	**08-Sep**		
	Duration (days)	**Initial Stage 21**			**Mid Season "D" 26**			**Full ripening 08-Sep**		
	STDEV (days)	**8**	**6**	**6**	**8**	**5**	**7**	**6**		
	Cv (%)	**7**	**5**	**5**	**4**	**2**	**3**	**2**		

Stage "D" Mid Season (Yield formation) is from effective full ground cover "C", when Kc_{mid} is maximum and could be considered constant to "E" ("Start of senescence" or "Maturity") when "Milky ripening" stage occurs for maize crop in Bulgarian field observations (Varlev & Popova, 1999; Doneva & Popova, 2016).

Late season stage is from "E" ("Start of senescence" or "Maturity"), or from "Milky ripening", to "F" "Full senescence"/"Full ripening" and "Harvest".

The construction of *Kc*-curve requires Kc_{ini}, Kc_{mid} and Kc_{end} and the length of each crop development stage (Fig. 9) that is of great importance in crop water requirements estimations for evapotranspiration and irrigation.

When considering a long-term period of past and present weather conditions however, it is important to know how maize varieties have changed over the years. A description of maize hybrids grown at Sadievo *EF* from 1964 to 1993 is provided with the assistance of Mikova (2002) (Table 1).

Obviously, maize varieties have certainly changed over the years. The old varieties, as "Golden horse tooth" and others had been grown before 1960. The transition period from the old varieties to more productive maize hybrids took part around 1962 (Varlev, 2008).

Early KWS (100-200 according to FAO), semi-early SK4 and Vir42 (300-400 according to FAO) and semi-late Kanzas-1859 and Viscosin-641 AA (600 according to FAO) maize hybrids had been introduced in Bulgaria during the period 1964-1978 (Table 1).

Highly productive maize hybrids, as the American late H708 (700-800) and semi-late H622 (600-700), and the adapted to local conditions "drought – resistant" semi-late Bulgarian hybrids, as Kn-2L-611, Kn-611 and BC-66-25 (600-700 according to FAO), have been predominantly grown after 1978 up to 1994.

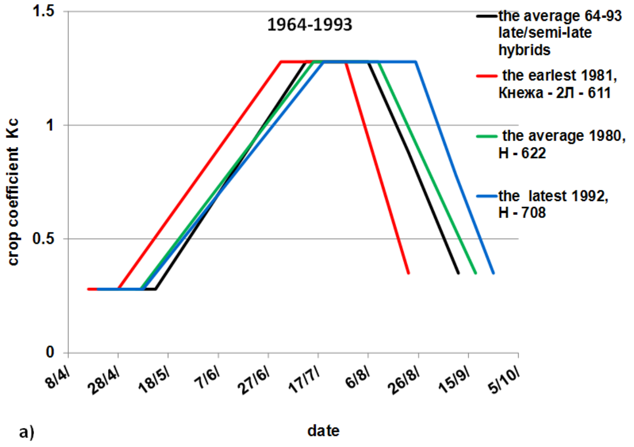

Fig. 10a. Comparing the limiting dates of FAO maize crop development stages, observed in years representing: the earliest (1981), the average (1980) and the latest (1992) crop development relative to semi-late (Kn-2L-611, Kn-601 and H-622) and late (H708) maize hybrids grown at Sadievo EF (III AC Region), 1964 -1993

The semi-early maize hybrids Px-20 и P-37-37 had been grown during the period 1975-1991, while Bulgarian Kn 530, Kn 509 maize hybrids have been introduced after 2000 (Varlev, 2008).

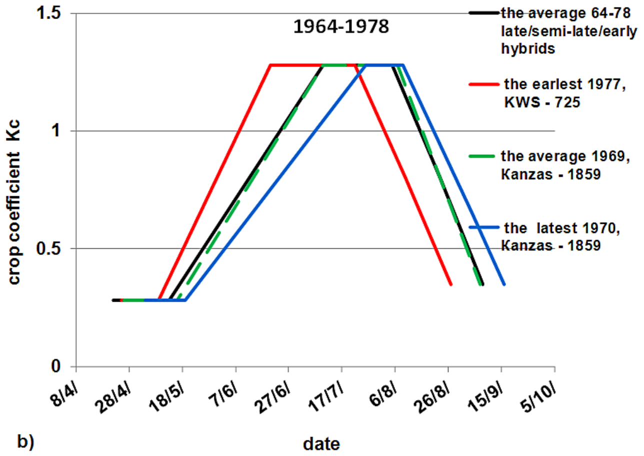

Fig. 10b. Comparing the limiting dates of crop development stages, observed during seasons representing: an "early" (1977), an "average" (1969) and a "late" (1970) crop development relative to "early" (KWS) and "semi-late" (Kanzas-1859 and BC-6625) maize hybrids grown at Sadievo EF (AC III), 1964 -1978

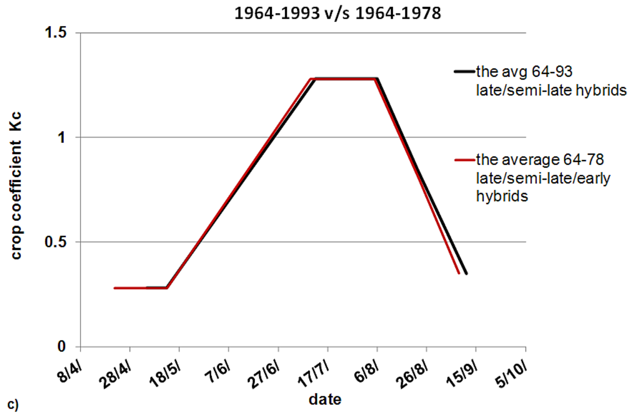

Fig. 10c. Comparing the limiting dates of crop development stages relative to statistically average *Kc*-curves relative to two periods: 1964-1993 ("semi-late" Kn-2L-611, Kn-601, H-622 and "late" H708 maize hybrids) and 1964-1978 ("semi-late" Kanzas-1859 and BC-6625 and "early" KWS maize hybrids), Sadievo *EF* (AC III Region)

Most of the maize hybrids grown at Sadievo Experimental Field *EF* during the whole 1964-1993 period however were Semi-Late (600 according to FAO) or Late (700 according to FAO) (Table 1, Fig. 10a).

Considering the earlier half period (1964-1978), semi-late (600 according to FAO) and semi-early (200-400 according to FAO) maize hybrids had been preferably grown there (Table 1, Fig. 10b).

Regardless variability of grown hybrids at Sadievo *EF* over the periods referred above (Figs. 10a and 10b), statistical average of the dates, limiting main crop development stages (parameters of *Kc*-curve) during the whole (1964-1993) and the first half (1964-1978) periods are identical (Fig. 10c).

Since the duration of crop development stages depends mostly on planting date and MTO conditions during the vegetation period, there is no zoning of corn varieties in Bulgaria. The principle is to choose a lower maize hybrid group according to FAO at sites of shorter vegetation period (those of higher altitude and smaller sum of active temperatures).

Crop parameters for identified agro-climatic regions (computed Kc-coefficients and p-fractions for ISAREG model, root zone depth used for Zahariev and WinISAREG applications)

The maize crop, considered in this study, was parameterized using detailed data from field experiments, as described by Popova et al. (2006), Popova (2008), Popova & Pereira (2011), Ivanova & Popova (2011). Main characteristics relative to the limiting dates of crop growth stages, calibrated crop coefficients *Kc* and soil water depletion fractions for no stress *p* are summarized in Tables 2-5.

Three-year field experiments with observation of soil water, crop development and *LAI* dynamics under fully irrigated and rainfed maize provided data for crop parameters calibration and validation at Chelopechene (1997-2000) and Bojurishte (2003-2005) *EFs*. These fields represent the soil classes of “small” and “large” TAW in AC I (Popova, 2008; Ivanova, 2013). Detailed soil characteristics, including soil water retention and water conductivity curves (*WRC* and *WCC*), field capacity (*FC*), wilting point (*WP*) for genetic soil layers and total available soil water *TAW*, relative to a local Chromic Luvisol soil (Chelopechene) and a Vertisol soil (Bojurishte) were taken from references (Koleva, 1973; Doneva, 1976; Popova, 2008). Dates, limiting maize crop development stages were those observed under the semi-early maize hybrids *Kn-530* and *Kn-509* grown at both fields, while initial crop coefficients *Kc* and soil water depletion fractions for no stress *p* were those recommended by Allen et al. (1998) and than calibrated by minimising differences between simulated and observed soil water for both irrigation and rainfed treatments in 2004, as summarised in Table 2.

The calibrated *Kc*-curve and *p*-curve were validated using the independent field data for 2003.

Crop parameters, namely the dates limiting maize development stages in Table 3, are relative to the semi late *H-622* hybrid, grown at Sadievo *EF*, AC III, during the average 1980, as evidenced in Fig. 10a and Table 1.

The considered regions of Silistra, Varna, Lom and Karnobat are normally exposed to a greatest risk of seasonal drought, as identified by “the yellow zone” in *Fig. 5a* (Alexandrov, 2011). Related parameterization and dates for 1980 at Sadievo (Fig. 10a) were extended to the other *EFs* located near by Lom, Varna (AC III) and Silistra (AC II) (Table 3). Soil characteristics required in present model calibration were taken from references (Stoyanov, 2008; Mikova, 2002). Soil water depletion fractions for no stress *p* relative to the soil class of “small *TAW”* were extended from Tsalapitsa *EF* (Popova and Pereira, 2011), while *p*-fractions for the chernozem soils of “average *TAW”* (Slivo Pole *EF*, Silistra, AC II) and “large *TAW* ”(Kovachitsa *EF*, Lom; Sadievo *EF*, Karnobat and Varna, AC III), were those recommended by Dorenboss & Pruitt (1977) and Allen et al. (1998).

Detailed information on soil water dynamics, irrigation management and crop growth stages for maize crop,

Table 2. Dates of maize development stages in 2004, model calibrated crop coefficients *Kc* and soil water depletion fractions for no stress *p* relative to Chromic Luvisol soil (*TAW* = 106 mm m^{-1}, Chelopechene EF) and Vertisol soil (Total Available Water *TAW* = 180 mm m^{-1}, Bojurishte EF), AC I – Sofia field, South Bulgaria, RZ = 1.15 m

Crop growth stages	Dates 2004	*Kc*	*p* - fractions	
Experimental field	AC I Bojurishte		Chelopechene	Bojurishte
Soil			Chromic Luvisols *TAW* 106 mm m^{-1}	Vertisol *TAW* 180 mm m^{-1}
Maize hybrids	Semi-early		Kneja 530	Kneja 509
Initial stage	05/05 to 06/06	0.4	0.80	0.46-0.75
Mid season	01/08 to 01/09	1.28	0.66	0.60
End season	20/10 (harvest)	0.6	0.80	0.78

Table 3. Dates of maize development stages in 1980 (semi-late H-622 hybrid, extended from Sadievo EF), model calibrated crop coefficients *Kc* and soil water depletion fractions for no stress *p* relative to three soils: Alluvial (*TAW* = 116 mm m^{-1}, Tsalapitsa EF), Leached Chernozem (*TAW* = 157 mm m^{-1}, Slivo pole EF) and Calcic Chernozem (*TAW* = 178 mm m^{-1}, Kovachica EF) , AC II – Silistra and AC III – Varna and Lom, North Bulgaria, RZ = 1.15 m

Crop growth stages	Dates 1980	*Kc*	*p* - fractions		
Experimental field	AC III Sadievo (Karnobat)		Tsalapitsa	AC II Slivo pole (Silistra)	AC III Kovachica (Lom)
hybrid / soil	Semi-late hybrid H-622	Kn-2L-611	Alluvial soil *TAW* 116 mm m^{-1}	Leached Chernozem *TAW* 157 mm m^{-1}	Calcic Chernozem *TAW* 178 mm m^{-1}
Initial stage	21/04 to 07/05	0.28	0.80	0.45-0.75	0.46-0.75
Mid season	15/07 to 10/08	1.28	0.66	0.65	0.60
End season	18/09 (harvest)	0.35	0.80	0.80	0.78

Table 4.1. Dates of maize development stages in 1988, model calibrated crop coefficients *Kc* and soil water depletion fractions for no stress *p* relative to an Alluvial soil (*TAW* = 116 mm m^{-1}, Tsalapitsa *EF*), a Vertisol soil (*TAW* = 173 mm m^{-1}, extended from Pustren *EF*) and a Degraded Chernozem soil (*TAW* = 168 mm m^{-1}, Gorni Dubnik *EF*), AC IV – Plovdiv and Pleven community, South and North Bulgaria, RZ = 1.15

Crop growth stages	Dates 1988	*Kc*	*p* - fractions		
Experimental field	AC IV Tsalapitsa			Pustren	Gorni Dubnik
hybrid / soil	late hybrid H 708		Alluvial soil *TAW* 116 mm m^{-1}	Vertisol *TAW* 173 mm m^{-1}	Degraded Chernozem *TAW* 168 mm m^{-1}
Initial stage	30/04 to 19/05	0.3	0.8	0.45-0.75	
Mid season	10/07 to 26/07	1.26	0.66	0.60	
End season	30/09 (harvest)	0.23	0.8	0.78	

Table 4.2. Dates of maize development stages in 1976 and model calibrated crop coefficients *Kc* and soil water depletion fractions for no stress *p* for a Chromic Cambisol soil (*TAW* = 136 mm m^{-1}, Zora EF) and a Vertisol soil (*TAW* = 173 mm m^{-1}, Pustren EF), AC region IV – Stara Zagora community, RZ = 1.15 m

Crop growth stages	Dates 1976 late hybrid		*Kc*		*p* - fractions	
Experimental field	Zora	Pustren	Zora	Pustren	Zora	Pustren
hybrid / soil	Kn-2L-611	H 708			Chromic Cambisol *TAW* 136 mm m^{-1}	Vertisol *TAW* 173 mm m^{-1}
Initial stage	26/04 to 19/05		0.28	0.28	0.8	0.45-0.75
Mid season	07/07 to 09/08	15/07 to 09/08	1.28	1.28	0.65	0.60
End season	30/09 (harvest)		0.35	0.23	0.35	0.78

previously used to validate WinISAREG model at Plovdiv (Tsalapitsa EF, Popova and Pereira, 2011) and Stara Zagora (Pustren and Zora EFs, Popova et al., 2006; Popova, 2008), AC IV, South Bulgaria, originated from long-term (9 to 16-year) field irrigation experiments, as reported by Varlev et al. (1994), Eneva (1993, 1997), Varlev & Popova (1999) and Varlev (2008) (Tables 4.1 and 4.2).

Regarding Pleven region (also AC IV, Table 4.1), North Bulgaria, dates of crop development stages, model calibrated crop-coefficients *Kc* and depletion fractions for no stress *p* relative to an alluvial soil were these extended from Tsalapitsa *EF*, while in the case of Degraded Chernozem soil of large *TAW* at Gorni Dubnik *EF p*-fractions were those recommended by Doorenbos & Pruitt (1977). Dates of maize development stages, model calibrated *Kc*-coefficients and *p*-fractions, adapted to the soil classes of "small" (116 mm m^{-1}) and "large" (178 mm m^{-1}) *TAW* were used for WinISAREG model application to Sandanski (AC V), as given in Table 5.

Using the updated limiting dates of crop development stages observed at Sadievo *EF* (Table 3) and root zone depth RZ = 1 m, as accepted in Zahariev et al. (1986) produced improvements in model simulated net irrigation requirements *NIRs* relative to Lom, Varna and Silistra (AC III and AC II) and to the past 1951-1980 period by approaching them to the traditional "Zahariev-86" irrigation requirements (Popova et

Table 5. Dates of maize development stages, model calibrated crop coefficients *Kc* and soil water depletion fractions for no stress *p* relative to Alluvial/Delluvial/meadow soil (*TAW* = 116 mm m^{-1}, extended from Tsalapitsa EF) and Leached Cinnamonic Forest soil (*TAW* = 178 mm m^{-1}, extended from Sadievo EF), AC region V – Sandanski, RZ = 1.15 m

Crop growth stages	Dates 1988	*Kc*	*p* - fractions	
Experimental field	Tsalapitsa			Sadievo
Hybrid/soil	late hybrid H 708		Alluvial/Delluvial/meadow soil *TAW* 116 mm m^{-1}	Leached Cinnamonic Forest soil *TAW* 178 mm m^{-1}
Initial stage	30/04 to 19/05	0.3	0.8	0.45-0.75
Mid season	10/07 to 26/07	1.26	0.66	0.60
End season	30/09 (harvest)	0.23	0.8	0.78

al., 2018).

Conclusions

The study solves some drawbacks and provides innovation in improving modeling efficiency of irrigation requirements for maize crop in the scale of the country by identifying five agro-climatic AC regions on the grounds of average reference evapotranspiration PM-ET^0 $_{\text{July-Aug}}$.

In terms of climate characteristics for these AC regions relative to 1951-2004 period, it is found that:

1. "Inter-annual" variability of monthly precipitation (mm) is much larger than that of monthly reference evapotranspiration ET^0 (mm/day^{-1}). Regarding precipitation, deviation from the average value is over 100% while for ET^0 it is below 15-20%. In terms of the high irrigation demand season "July-August", precipitation totals vary over the years in a ratio 1:35 (Plovdiv), while the respective ET^0 values vary only in a ratio 1:1.36.

2. Comparing climate variables relative to the peak demand "July- August" period, the average precipitation totals are the highest, about 55 mm/month, at Sofia (AC I) and Pleven (AC IV) and the least, 30 mm/month, at Sandanski (AC V region). Considering Silistra (AC II), Varna and Lom (AC III) and Plovdiv (AC IV), average precipitation in July and August is about 40 mm/month. It is important to know that there are years with rainfall sum less than 15-20 mm for July and August, when drought brings influence to all summer crops in this country.

3. The least average monthly reference evapotranspiration values ET$^0_{\text{July}}$ and ET$^0_{\text{Aug}}$, ranging from 4.0 to 4.4 mm d^{-1}, are inherent to Sofia field (AC I) while the peak average evapotranspiration demands of 5.6 – 5.2 mm d^{-1} are relative to Sandanski (AC V region). In terms of AC IV (Plovdiv, Pleven and Stara Zagora), the average maximum ET^0 is 5.4 – 5.2 mm d^{-1}. In final analyses, regardless of a medium size country territory, the average reference evapotranspiration for July and August varies within a comparatively small range – from 4.0 to 5.6 mm d^{-1}.

4. "Inter-regional" variability of average reference evapotranspiration totals PM-ET^0 $_{\text{July-Aug}}$ shows a range from 270 to 340 mm (Fig. 4b), while respective average precipitation relative to the same months varies from 110 to 60 mm only (Fig. 3b). Respective precipitation totals are less than 10-20 mm in the dry years (having probability of occurrence P>90%), when significant drought consequences are expected over the country territory.

Considered ET^0 and precipitation are the main climate variables that influence crop water requirements for irrigation. In terms of soil and crop characteristics however, irrigation requirements and scheduling depend substantially also on water holding capacity of the soil, root zone depth, maize hybrids grown and, at last but not at least, on the appropriately calibrated and validated ET modeling crop parameters, as duration of crop development stages and respective crop coefficients *Kc* and soil water depletion fractions for no stress *p*. Using information on soil water observations and respective limiting dates for crop development stages is indispensable for reliable ISAREG model calibration, validation and application for irrigation management under climate uncertainties in the scale of identified AC regions.

Having average precipitation and average ET^0 values laid down in maps (Alexandrov, 2011; Moteva et al., 2015), together with the locations, representing each of the identified agro-climatic regions helps decision making for maize irrigation management in these regions (Popova et al., 2015, 2018).

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