

Applications of the Temperature-Based Solar Radiation Estimation Models in Turkey

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Keywords : solar radiation, temperature, daily total global solar radiation, model comparison, meteorological models, model validation, model calibration.

ABSTRACT

In the cloudless and open weather, the solar radiation can be expressed by physical equations. In cloudy and complicated sky conditions, the expression of solar radiation becomes difficult, and empirical models are used. These models reflect the mathematical relationships established by various meteorological data. In many developing countries, meteorological stations measure the main meteorological parameters, but solar radiation measurements cannot be available in the data sets. Solar radiation measurements may not be widely available in many locations due to installation costs, maintenance, repair and calibration requirements. In Turkey, solar radiation measurements are taken at main meteorological stations. These stations may sometimes have interrupted and missing data. In cases where measurements are not available or interrupted, estimation models can obtain solar radiation values by other meteorological parameters. The application of estimation of solar radiation in Turkey has not been widely found in the literature. In this study, temperature based solar radiation estimation models have been applied for Turkey in a wide geographical area. In this context, Allen, Hargreaves, Bristow-Campbell and Chen models were calibrated for Turkey. Empirical coefficients were derived and model errors were analyzed.

INTRODUCTION

Solar radiation is an important parameter for daily life and engineering applications.

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important for architectural applications, energy sector, and engineering designs. In developing countries, measurement records of solar radiation may not be available due to the equipment's cost, maintenance, and calibration requirements. Even if solar radiation measurements were taken, interruptions in data sets were seen in some cases. In these cases, it is appropriate to use solar radiation estimation models. There are several empirical models in the literature to predict the global solar radiation (Chen et al., 2004; Menges et al., 2006).

Average daily solar energy density is about 3.6 kWh/m² in Turkey, the most common application of the solar energy is the solar water heating systems (Menges et al., 2006).

In this study, verification of the models that predict the daily total global solar radiation based on maximum and minimum air temperature parameters were applied for Turkey. The meteorological data used in this study were taken from Turkish National Weather Service. The models in the literature were calibrated and the empirical coefficients of the meteorological stations were derived. Errors were analyzed between the measured values and the values obtained from the models.

Calibration laboratory of the National Weather Service was established in 2008. It has been thought that; the measurement's reliability is higher in the data which have been recorded after this date. Meteorological parameters were taken between 2009 and the first half of 2016.

SOME OF THE MAIN MATHEMATICAL FORMULAS ABOUT THE SOLAR RADIATION

The rotation plane of the earth around the sun is called the ecliptic plane. The rotation axis of the earth itself is called polar axis. The earth's rotation around itself causes the diurnal changes in solar radiation. The position of the earth's axis causes seasonal changes in solar radiation. The angle between a line joining the centers of the sun and the earth to the equatorial plane is called the solar declination angle; δ (Iqbal, 1983).

Solar declination angle's mathematical expression is given in Equation 1. J is the calendar day of the year; $J = 1$ on January 1 and $J = 365$ (or 366 during leap years) on December 31 (Hargreaves, et al., 1985).

$$\sin \delta = 0.39785 * \sin[278.97 + 0.9856J + 1.9165 * \sin(356.6 + 0.9856J)] \quad (1)$$

Sunrise hour angle is given in Equation 2. ω_s is sunrise angle; ϕ is the latitude of the site (Iqbal, 1983).

$$\omega_s = \cos^{-1}[-\tan \phi * \tan \delta] \quad (2)$$

Eccentricity correction factor of the earth's orbit is called eccentricity factor; E_0 . The simple expression of the eccentricity factor is given in Equation 3 (Iqbal, 1983).

$$E_0 = 1 + 0.033 * \cos[(\frac{2\pi * J}{365})] \quad (3)$$

Daily extraterrestrial radiation is given in Equation 4 (Iqbal, 1983). I_{sc} is the solar constant and it is equal to 4.921 MJ/day.m² (Menges et al., 2006). The mathematical expressions given in this section are often used in the modeling of solar radiation.

$$H_0 = \frac{24}{\pi} * I_{sc} * E_0 * \sin \phi * \sin \delta * [(\frac{\pi}{180}) * \omega_s - \tan \omega_s] \quad (4)$$

MODEL DESCRIPTION

Hargreaves Model

Hargreaves has proposed a simple model for estimating total global solar radiation. The mathematical expression of the model is given in equation 5. “a” and “b” are the empirical coefficients (Hargreaves et al., 1985). T_{max} was taken as the daily maximum air temperature and T_{min} was daily minimum air temperature. H is the daily total global solar radiation.

$$\frac{H}{H_0} = a * (T_{max} - T_{min})^{0.5} + b \quad (5)$$

Allen Model

Allen reported a self-calibrating model to estimate mean monthly global solar radiation. Allen model is seen in Equation 6 (Allen, 1997).

$$\frac{H}{H_0} = a * (T_{max} - T_{min})^{0.5} \quad (6)$$

“a” is an empirical coefficient. This coefficient varies from region to region for estimation of solar radiation and is derived with using meteorological station data (Meza et al., 2000).

Bristow-Campbell Model

Bristow and Campbell suggested a relationship between solar radiation as a function of the difference

between the maximum and minimum air temperatures (Equation 7). “a”, “b” and “c” are the empirical coefficients (Bristow et al., 1984).

$$\frac{H}{H_0} = a * [1 - \exp(-b\Delta T^c)] \quad (7)$$

Chen Model

Chen et al. presented the model in equation 8 (Chen et al., 2004).

$$\frac{H}{H_0} = a * \ln(T_{max} - T_{min}) + b \quad (8)$$

CLIMATIC DATA

In this study, meteorological data were used to calibrate the models. In this calibration process, the empirical coefficients of the models were derived with the help of the data. Daily measurements were obtained from the meteorological stations given in Table 1.

Table 1. Meteorological stations that measured solar radiation and geographical coordinates of the stations

Stations	Latitude	Longitude	Height (m)
Adana	37.0041	35.3443	23
Afyon	38.738	30.5604	1034
Aksaray	38.3705	33.9987	970
Ankara	39.9725	32.8639	887
Antalya Elmalı	36.7372	29.9121	1095
Artvin	41.1752	41.8187	613
Balıkesir Burhaniye	39.4983	26.9755	20
Bartın Amasra	41.7526	32.3827	73
Bolu	40.7329	31.6022	743
Bursa	40.2308	29.0133	100
Erzincan Tercan	39.7769	40.3906	1429
Eskişehir Sivrihisar	39.4453	31.5354	1070
Hakkari	37.5745	43.7388	1727
Isparta	37.7848	30.5679	997
İstanbul Samandıra	40.9866	29.2135	123
İzmir Menemen	38.6237	27.0433	10
Karaman	37.1932	33.2202	1018
Kastamonu	41.371	33.7756	800
Kayseri Develi	38.3744	35.4797	1204
Kırklareli	41.7382	27.2178	232
Konya Beyşehir	37.6777	31.7463	1141
Mersin Tarsus	36.8942	34.9597	12
Rize	41.04	40.5013	3
Sinop	42.0299	35.1545	32
Sivas Divriği	39.3618	38.1142	1121
Şanlıurfa Ceylanpınar	36.8406	40.0307	360
Tokat	40.3312	36.5577	611
Yozgat Boğazlıyan	39.1897	35.2532	1070

METHODS OF COMPARISON AND MODEL EVALUATION

Performances of the models were evaluated with mean percentage error, mean bias error and root mean square error. Mathematical expressions of MPE , MBE , and $RMSE$ are given in equation 10, 11 and 12. $H_{i,m}$ is the i th measured value, $H_{i,c}$ is the i th calculated value and N is the total number of observations (Menges et al., 2006). $RMSE$ gives the information about short-term performance with a term-by-term

comparison of the deviations between the observed and calculated values. *MBE* presents the systematic error and provides information on the long-term performance. Positive values of *MBE* show an over-estimate; negative values provide an under-estimate. *MPE* is calculated from the actual differences between calculated and measured values and gives the percentage errors of the correlation (Almorox, 1983). When *MBE* converges to zero, it is the ideal performance for the model, while a low value of *RMSE* and low *MPE* are desirable (Iqbal, 1983).

$$MPE = \sum_{i=1}^n \frac{\left[\frac{H_{i,m} - H_{i,c}}{H_{i,m}} \right] * 100}{N} \quad (10)$$

$$MBE = \frac{\sum_{i=1}^n H_{i,c} - H_{i,m}}{N} \quad (11)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (H_{i,c} - H_{i,m})^2}{N}} \quad (12)$$

The Nash-Sutcliffe equation is an error evaluation method that corresponds to a perfect match between observed and calculated results. A model is more efficient when *NSE* is closer to 1. *NSE* equation is given in equation 13. $\bar{H}_m$ is the mean measured global radiation (Menges et al., 2006).

$$NSE = 1 - \frac{\sum_{i=1}^n (H_{i,m} - H_{i,c})^2}{\sum_{i=1}^n (H_{i,m} - \bar{H}_m)^2} \quad (13)$$

RESULTS AND DISCUSSIONS

Solar radiation data can provide useful information about engineering designs and solar energy applications. If the solar radiation data is not available, it can be obtained by empirical models. In this study Allen, Hargreaves, Bristow-Campbell, and Chen models were applied for Turkey. The empirical coefficients of the models were derived for the meteorological stations, error analysis was applied. Validation of the models was performed with *MPE*, *MBE*, *RMSE* and *NSE* methods.

Derivation of Empirical Coefficients for Meteorological Stations in Turkey

All models were analyzed separately and empirical coefficients were derived using MATLAB. Empirical coefficients is given in Table 2. Using these coefficients, the relevant models can be used directly in the regions.

Error Analyzes of the Models for Turkey

NSE, *MBE*, *RMSE* and *MPE* values are given in Table 3. In addition, monthly percentage errors were calculated and show monthly performances. *NSE* values are given in Figure 1. As the results error analyses, it can be seen whether the models are applicable for Turkey's regions or not.

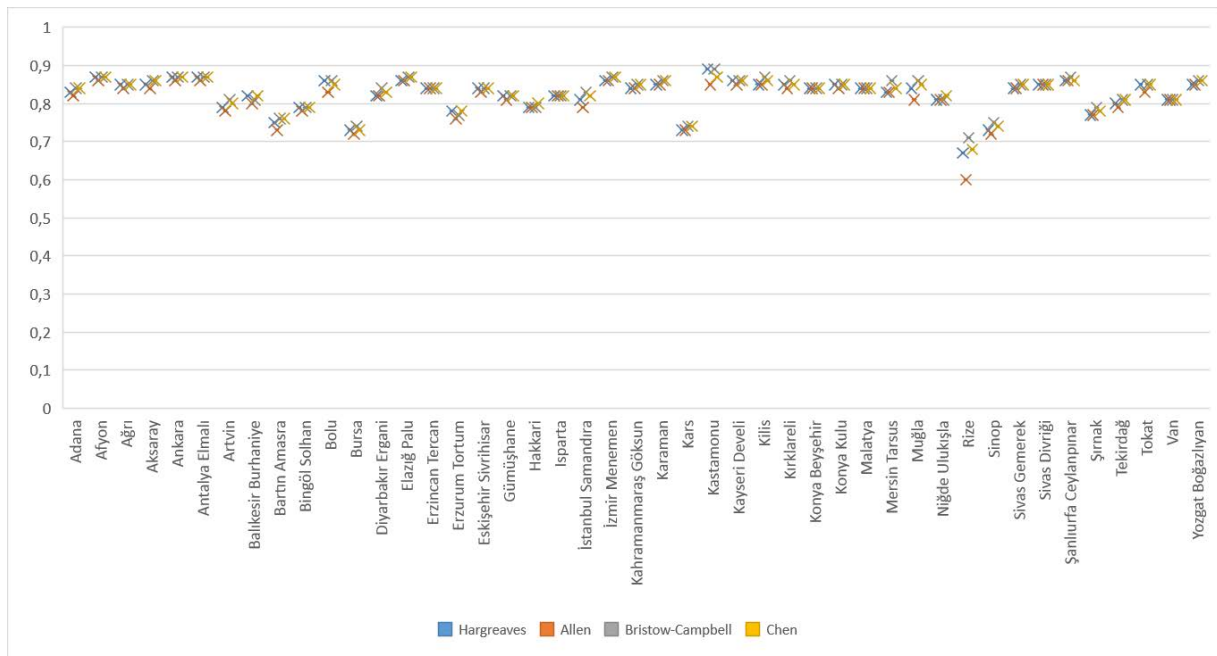


Fig. 1. NSE values of the models

In Figure 1, *NSE* results are seen acceptable and generally in the range of 0,7 to 0,9. In most cases, values are greater than 0.80. However, for Black Region cities, such as Rize and Sinop, the values are

lower. Black Sea region has complicated cloudy and rainy weather conditions. It may be difficult to express solar radiation in complex weather conditions. *NSE* values are higher for terrestrial climatic regions.

MPE values are slightly worse for Allen model, Bristow-Campbell and Chen models perform slightly better in whole *MPE* analyzes. Especially for cities in the Black Sea region, percentage errors have increased. In Bristow-Campbell model, monthly *MPE* values appear to be more homogeneous and the differences between the months are less than the other models. In Allen and Hargreaves models, high percentage errors are seen in winter months. Cities in the East and the Black Sea region, there are high percentages of errors in the winter months. These errors may be caused due to measurement defects or regional climatic conditions. Allen and Hargreaves's models give worse results in terms of monthly percentage errors. During heavy rainy seasons and cloudy weather, models may not be able to predict solar radiation successfully. In Figure 2, 3 and 4, the monthly *MPE* values of Yozgat are given for Hargreaves, Allen and Chen models. It is seen, *MPE* errors are increasing in cloudy seasons.

There are not much differences between the models for *MBE* values. Bristow-Campbell model gave high *MBE* values for several stations. *RMSE* values are lower for Bristow-Campbell model. *MBE* analyses provide information about short-term performances of the models. It can be said that the Bristow-Campbell model is better than other models in short-term performance for Turkey.

It is possible to say that Bristow-Campbell and Chen models give better results than Allen and Hargreaves models for the geography of Turkey.

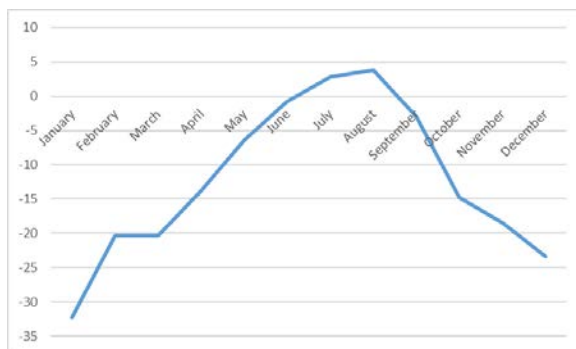


Fig. 2. Hargreaves model's monthly MPE for Yozgat

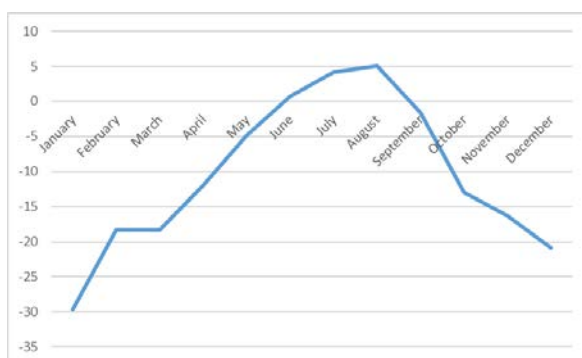


Fig. 3. Allen model's monthly MPE for Yozgat

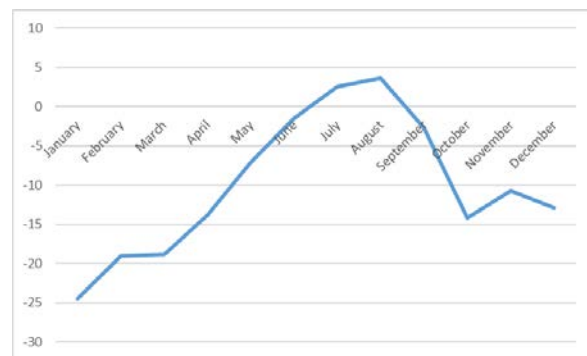


Fig. 4. Chen model's monthly MPE results for Yozgat

CONCLUSIONS

Empirical models are useful tools for estimating global solar radiation if radiation parameters are not available. The main purpose of the study is to apply models to the geography of Turkey to predict solar radiation. In this study, temperature-based solar radiation estimation models are calibrated for Turkey and error analyzes were applied.

In applications in the Black Sea region with complex weather conditions, it is possible to mention that the solar radiation estimation models are relatively low in terms of suitability and the percentage errors are higher. This situation has been observed in provinces such as Rize and Sinop, which have a coast on the Black Sea. For Artvin, where is located inner hinterland of the Black Sea and climate transition zone with terrestrial climate, the model errors are lower and the conformity of the models are higher than Rize and Sinop. It is thought that the models give better results in regions where terrestrial climate is dominant and climatic conditions are more stable. It is possible to say that the models give better results for the inner hinterland of the Black Sea region.

It is thought that errors in solar radiation estimation models may also be caused by measurement errors. Calibration of models is considered less accurate when measurements are not traceable and accurate.

In this study, Allen, Hargreaves, Bristow-Campbell and Chen models were made ready-to-use for Turkey. Temperature-based solar radiation estimation models were calibrated and regional empirical coefficients were presented. Bristow-Campbell and Chen models seem to give better results for Turkey. However, it is thought that it would be more correct to examine the results of regional errors in order to decide which model to use in the region.

Table 2. Empirical coefficients of the solar radiation estimation models for Turkey

Station	Allen	Hargreaves		Bristow-Campbell			Chen	
	a	a	b	a	b	c	a	b
Adana	0,160088	0,17	-0,01299	0,64	0,0221	1,99	0,273	-0,0981
Afyon	0,15399	0,194	-0,1336	0,748	0,05577	1,294	0,284	-0,1554
Aksaray	0,15782	0,193	-0,1042	0,682	0,01921	1,93	0,31	-0,1976
Ankara	0,152358	0,206	-0,1734	0,734	0,041	1,44	0,307	-0,2138
Antalya Elmalı	0,15584	0,192	-0,1354	0,72	0,03186	1,56	0,322	-0,2588
Artvin	0,149808	0,191	-0,11	0,621	0,03727	1,76	0,274	-0,1268
Balıkesir Burhaniye	0,1733	0,122	0,1802	0,652	0,07067	1,71	0,195	0,1208
Bartın Amasra	0,2193	0,131	0,2301	0,654	0,0806	1,98	0,177	0,2375
Bolu	0,13374	0,183	-0,1504	0,719	0,04155	1,36	0,272	-0,177
Bursa	0,130338	0,161	-0,08403	0,582	0,03974	1,6	0,23	-0,0883
Erzincan Tercan	0,151361	0,169	-0,07848	0,697	0,04037	1,46	0,296	-0,2162
Eskişehir Sivrihisar	0,159584	0,198	-0,1296	0,7	0,03675	1,59	0,296	-0,1705
Hakkari	0,171652	0,18	-0,03	0,645	0,04171	1,76	0,279	-0,0902
Isparta	0,1627	0,149	0,03861	0,705	0,06045	1,39	0,242	-0,0354
İstanbul Samandıra	0,158637	0,173	-0,01173	0,634	0,05472	1,7	0,226	0,02382
İzmir Menemen	0,167827	0,145	0,07914	0,644	0,04115	1,79	0,232	0,01215
Karaman	0,1698	0,188	-0,05874	0,733	0,02839	1,74	0,308	-0,159
Kastamonu	0,129266	0,193	-0,2189	0,859	0,03731	1,22	0,3	-0,2753
Kayseri Develi	0,166948	0,211	-0,1576	0,719	0,0278	1,71	0,339	-0,2584
Kırklareli	0,147688	0,192	-0,1308	0,673	0,04288	1,51	0,265	-0,1179
Konya Beyşehir	0,159227	0,164	-0,01752	0,696	0,04527	1,52	0,271	-0,1123
Mersin Tarsus	0,152358	0,206	-0,1734	0,734	0,041	1,44	0,307	-0,2138
Rize	0,138916	0,253	-0,2683	0,587	0,01039	2,52	0,317	-0,2029
Sinop	0,235906	0,157	0,1841	0,658	0,3177	1,13	0,165	0,2801
Sivas Divriği	0,14929	0,174	-0,09924	0,705	0,04423	1,4	0,283	-0,1864
Şanlıurfa Ceylanpınar	0,14626	0,143	0,0142	0,654	0,02155	1,8	0,258	-0,1235
Tokat	0,142029	0,191	-0,1636	0,73	0,04048	1,41	0,301	-0,2335
Yozgat Boğazlıyan	0,142079	0,143	0,00664	0,681	0,0389	1,49	0,253	-0,1155

Table 3. Error analyzes of the temperature-based solar radiation estimation models for Turkey

Monthly MPE					Whole Model				
Adana									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreave	Allen	Bristow Camp.	Chen
January	-45,68	-41,74	-19,27	-32,82	MBE	0,17	-0,41	0,48	0,14
February	-25,41	-21,46	-17,15	-22,04	RMSE	3,02	3,08	2,91	2,83
March	-20,18	-16,15	-17,79	-18,85	MPE	-15,67	-11,88	-11,65	-12,87
April	-19,27	-15,10	-17,65	-18,18	NSE	0,83	0,82	0,84	0,84
May	-10,98	-7,12	-13,53	-10,95					
June	3,12	6,43	-0,26	2,81					
July	8,55	11,58	5,82	8,27					
August	6,26	9,53	2,33	5,82					
September	-1,09	2,55	-5,46	-1,53					
October	-9,83	-5,98	-9,63	-9,14					
November	-18,33	-14,29	-15,79	-17,15					
December	-43,57	-39,44	-25,34	-30,89					
Afyonkarahisar									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreaves	Allen	Bristow Camp.	Chen
January	-0,29	-11,29	4,72	3,35	MBE	-0,05	-0,21	0,12	-0,06
February	2,77	-2,92	5,03	3,23	RMSE	2,99	3,10	2,97	3,06
March	-14,24	-19,61	-12,28	-13,75	MPE	-5,72	-8,44	-5,07	-4,48
April	-9,61	-10,89	-9,94	-10,80	NSE	0,87	0,86	0,87	0,87
May	-11,44	-11,92	-13,16	-11,87					
June	-3,50	-2,69	-5,33	-4,19					
July	1,09	4,27	-0,41	1,67					
August	0,48	3,57	-1,09	0,98					
September	-1,54	0,69	-2,25	-0,95					
October	-10,56	-15,07	-10,01	-3,78					
November	-13,82	-20,01	-11,18	-10,26					
December	-6,18	-15,98	-1,67	-5,36					
Aksaray									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreaves	Allen	Bristow Camp.	Chen
January	-40,69	-46,44	-24,55	-30,96	MBE	0,09	-0,47	0,46	0,06
February	-21,64	-22,33	-17,69	-19,87	RMSE	3,33	3,45	3,25	3,27
March	-22,67	-21,99	-20,19	-21,31	MPE	-13,46	-12,47	-11,15	-10,73
April	-10,30	-8,05	-10,15	-9,57	NSE	0,85	0,84	0,86	0,86
May	-10,46	-6,75	-14,35	-10,92					
June	-2,01	1,55	-6,97	-2,74					
July	5,22	9,03	1,29	4,83					

August	3,95	8,05	0,48	3,74					
September	-2,13	2,41	-3,38	-1,78					
October	-16,73	-14,61	-16,56	-15,78					
November	-15,15	-17,94	-3,05	-5,72					
December	-26,00	-30,54	-13,69	-16,36					
Ankara									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-18,69	-40,41	-8,30	-8,10	MBE	-0,09	-0,34	0,12	-0,11
February	-16,39	-27,08	-12,16	-13,71	RMSE	3,03	3,20	3,01	3,06
March	-13,58	-19,62	-11,38	-12,75	MPE	-8,44	-12,49	-7,14	-6,55
April	-8,18	-8,74	-8,69	-8,71	NSE	0,87	0,86	0,87	0,87
May	-11,81	-10,75	-13,88	-12,90					
June	-8,59	-6,17	-10,90	-9,18					
July	0,85	5,09	-1,61	1,02					
August	2,32	6,61	0,04	2,59					
September	2,60	5,65	1,02	2,77					
October	-6,44	-9,95	-5,97	-4,05					
November	-11,00	-16,04	-8,81	-8,64					
December	-8,70	-23,18	-1,95	-3,52					
Antalya									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-8,86	-20,70	-0,40	-1,99	MBE	-0,14	-0,12	0,20	-0,15
February	-1,05	-7,55	1,29	2,02	RMSE	2,93	2,99	2,92	2,90
March	-3,63	-7,27	-4,25	-3,03	MPE	-5,24	-8,12	-5,01	-3,78
April	0,17	-1,14	-1,97	-0,13	NSE	0,87	0,86	0,87	0,87
May	-10,98	-11,64	-14,07	-11,58					
June	-5,87	-5,14	-9,00	-6,26					
July	-2,56	-0,83	-4,63	-2,37					
August	-1,76	0,01	-3,71	-1,53					
September	-0,92	0,55	-2,21	-0,56					
October	-12,50	-14,77	-12,53	-11,44					
November	-9,83	-13,98	-8,42	-8,00					
December	-4,04	-12,17	0,24	0,31					
Artvin									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-15,99	-22,47	-7,07	-9,72	MBE	0,09	-0,23	0,47	0,08
February	-21,02	-23,56	-18,42	-17,44	RMSE	3,44	3,53	3,30	3,34
March	-24,61	-25,74	-19,97	-19,82	MPE	-15,20	-16,02	-13,70	-12,88
April	-39,21	-35,24	-37,34	-36,46	NSE	0,79	0,78	0,81	0,80
May	-18,33	-16,13	-19,60	-17,75					
June	-6,76	-6,05	-8,42	-6,67					
July	-2,02	-1,56	-3,14	-1,69					
August	4,05	5,44	-1,00	2,89					
September	-3,80	-2,24	-5,93	-3,56					
October	-16,49	-17,38	-15,64	-13,78					
November	-18,99	-24,00	-12,55	-15,10					
December	-19,37	-24,34	-15,05	-15,51					
Balıkesir									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-51,05	-39,33	-56,42	-48,71	MBE	0,21	-0,06	1,08	0,19
February	-37,22	-27,83	-38,82	-34,47	RMSE	3,65	3,77	3,70	3,59
March	-32,12	-25,22	-36,51	-30,45	MPE	-18,14	-13,26	-22,14	-17,01
April	-17,99	-15,95	-21,77	-17,20	NSE	0,82	0,80	0,81	0,82
May	-15,72	-13,30	-20,41	-15,28					
June	-0,48	-0,34	-6,07	-0,75					
July	7,20	7,47	1,24	6,83					
August	6,50	7,40	-0,04	6,15					
September	-0,75	0,23	-6,67	-0,90					
October	-17,67	-11,18	-18,68	-15,68					
November	-25,42	-17,23	-27,49	-23,37					
December	-45,84	-34,46	-46,19	-42,42					
Bartın									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-46,18	-35,37	-37,25	-42,60	MBE	0,25	0,04	1,01	0,23
February	-18,15	-14,48	-17,15	-16,68	RMSE	4,24	4,39	4,14	4,15
March	-41,98	-34,63	-30,60	-38,33	MPE	-18,07	-13,65	-17,47	-16,64
April	-22,39	-21,51	-22,45	-21,23	NSE	0,75	0,73	0,76	0,76
May	-18,40	-14,17	-20,51	-17,67					
June	1,49	3,13	-4,89	1,30					
July	4,92	5,56	-1,81	4,61					
August	0,87	1,98	-5,93	0,60					
September	-5,03	-4,29	-12,76	-5,42					
October	-19,54	-14,10	-17,91	-17,79					
November	-33,95	-23,31	-24,07	-30,35					
December	-18,18	-9,68	-11,32	-14,98					
Bolu									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-31,89	-48,00	-24,14	-21,95	MBE	0,03	-0,51	0,14	0,01
February	-25,83	-38,30	-19,21	-15,84	RMSE	3,14	3,40	3,12	3,20

March	-20,39	-27,23	-15,10	-16,41	MPE	-12,90	-15,82	-10,47	-10,10
April	-14,59	-13,54	-13,42	-13,88	NSE	0,86	0,83	0,86	0,85
May	-10,14	-7,32	-11,31	-9,09					
June	-5,93	-2,62	-7,86	-7,54					
July	1,52	5,93	-0,63	0,38					
August	-1,88	3,46	-3,25	-1,50					
September	-1,88	1,06	-1,38	-0,47					
October	-7,67	-11,23	-4,27	-5,07					
November	-11,04	-14,61	-7,40	-8,57					
December	-17,96	-25,82	-13,07	-17,41					
Bursa									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-31,61	-37,33	-19,68	-24,25	MBE	0,11	-0,43	0,42	0,09
February	-42,54	-48,38	-30,26	-32,03	RMSE	4,18	4,28	4,10	4,16
March	-44,53	-44,94	-38,27	-41,06	MPE	-23,90	-23,22	-21,13	-20,32
April	-37,29	-33,77	-34,81	-35,76	NSE	0,73	0,72	0,74	0,73
May	-14,55	-10,48	-16,53	-15,19					
June	-10,45	-6,70	-13,80	-10,91					
July	-17,25	-11,81	-24,10	-18,65					
August	6,37	10,95	2,58	5,92					
September	-8,35	-6,44	-7,21	-3,46					
October	-31,43	-33,10	-26,04	-22,44					
November	-26,47	-27,24	-20,96	-22,09					
December	-18,73	-21,32	-14,43	-11,68					
Erzincan									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-18,80	-26,94	-14,52	-13,75	MBE	-0,20	0,15	0,13	-0,22
February	7,67	2,32	8,52	9,36	RMSE	3,35	3,38	3,29	3,30
March	-13,01	-18,65	-11,11	-10,51	MPE	-7,58	-11,68	-7,62	-6,02
April	-18,75	-23,80	-19,88	-17,89	NSE	0,84	0,84	0,84	0,84
May	-9,41	-12,71	-13,64	-10,28					
June	-3,14	-4,50	-6,43	-3,51					
July	-2,33	-3,01	-4,05	-2,11					
August	-2,07	-2,51	-3,62	-1,76					
September	-5,41	-6,48	-6,42	-4,87					
October	-11,40	-15,39	-12,64	-9,97					
November	-5,77	-12,09	-2,73	-2,34					
December	-5,71	-13,12	-1,52	-1,41					
Eskişehir									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-18,58	-33,08	-9,87	-7,63	MBE	-0,14	-0,14	0,29	-0,15
February	-8,89	-15,78	-6,59	-8,24	RMSE	3,38	3,45	3,32	3,40
March	-17,45	-22,00	-18,38	-16,76	MPE	-8,12	-11,78	-8,08	-6,35
April	-13,48	-14,24	-16,43	-14,22	NSE	0,84	0,83	0,84	0,84
May	-12,49	-13,57	-16,69	-13,78					
June	-7,07	-7,24	-10,69	-7,09					
July	-3,37	-1,83	-5,88	-3,06					
August	-0,66	0,33	-3,88	-0,74					
September	-0,44	0,58	-2,41	-0,07					
October	-6,09	-11,00	-5,97	-2,50					
November	-2,50	-9,38	0,28	0,09					
December	-12,97	-25,99	-3,43	-7,31					
Hakkari									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-18,94	-22,05	-9,65	-13,67	MBE	0,02	0,14	0,50	0,19
February	-0,55	-2,57	1,26	0,53	RMSE	3,54	3,55	3,52	3,49
March	-19,67	-21,72	-20,05	-19,33	MPE	-12,28	-13,78	-12,18	-11,82
April	-19,26	-20,70	-23,07	-20,41	NSE	0,79	0,79	0,79	0,80
May	-15,47	-16,59	-20,63	-17,06					
June	-2,56	-2,80	-5,82	-3,88					
July	-1,58	-1,77	-4,58	-2,89					
August	-4,52	-4,72	-7,74	-5,91					
September	-1,79	-2,03	-4,42	-2,91					
October	-19,59	-21,05	-20,51	-19,65					
November	-7,26	-9,45	-4,14	-5,68					
December	-29,01	-32,32	-19,74	-24,19					
Isparta									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-18,82	-17,67	-8,58	-14,40	MBE	-0,22	0,05	0,15	-0,25
February	-8,11	-7,56	-0,77	-4,55	RMSE	3,49	3,49	3,47	3,45
March	-11,56	-11,82	-8,61	-10,48	MPE	-8,37	-9,22	-6,99	-7,03
April	-7,79	-8,85	-8,37	-7,63	NSE	0,82	0,82	0,82	0,82
May	-12,48	-13,78	-15,17	-12,43					
June	-4,96	-6,83	-9,99	-5,73					
July	3,20	1,11	-0,95	2,96					
August	0,49	-1,76	-3,19	0,50					
September	-1,78	-3,91	-3,81	-1,33					
October	-7,08	-8,16	-5,74	-5,65					
November	-7,59	-8,36	-4,44	-5,51					

December	-22,55	-22,08	-14,23	-18,89					
İstanbul									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreaves	Allen	Bristow Camp.	Chen
January	-52,54	-44,10	-42,60	-46,93	MBE	0,28	-0,64	0,70	0,24
February	-44,29	-36,67	-26,06	-29,08	RMSE	3,78	3,93	3,57	3,68
March	-43,88	-35,85	-29,31	-34,81	MPE	-24,56	-17,36	-19,23	-20,01
April	-30,87	-23,17	-22,18	-25,68	NSE	0,81	0,79	0,83	0,82
May	-11,81	-5,07	-10,99	-9,27					
June	-1,29	4,99	-5,93	-2,27					
July	7,89	13,67	0,85	6,56					
August	1,39	7,51	-5,23	-0,06					
September	-10,04	-3,36	-10,48	-8,79					
October	-33,25	-25,93	-21,77	-24,12					
November	-33,11	-25,53	-22,37	-28,70					
December	-49,39	-41,00	-38,36	-45,01					
İzmir									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreaves	Allen	Bristow Camp.	Chen
January	-33,88	-26,32	-19,93	-26,59	MBE	0,08	-0,01	0,49	0,06
February	-26,94	-21,21	-18,52	-22,61	RMSE	3,06	3,08	2,97	2,98
March	-25,17	-21,09	-22,13	-22,99	MPE	-12,14	-9,91	-11,13	-10,50
April	-10,58	-9,54	-11,68	-10,07	NSE	0,86	0,86	0,87	0,87
May	-10,33	-9,86	-12,18	-10,08					
June	-1,57	-1,78	-4,67	-1,74					
July	6,25	5,94	2,39	5,86					
August	1,55	1,25	-2,10	1,23					
September	-3,75	-4,01	-6,73	-3,89					
October	-14,54	-12,64	-16,28	-13,94					
November	-12,24	-8,72	-11,67	-11,00					
December	-21,74	-15,51	-11,86	-17,43					
Karaman									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreaves	Allen	Bristow Camp.	Chen
January	-23,80	-27,37	-8,59	-15,00	MBE	-0,01	-0,24	0,30	-0,07
February	-11,50	-12,89	-5,32	-8,42	RMSE	3,48	3,51	3,35	3,39
March	-15,66	-16,03	-12,84	-14,61	MPE	-11,72	-11,98	-8,06	-8,40
April	-13,86	-13,41	-13,52	-13,40	NSE	0,85	0,85	0,86	0,86
May	-10,33	-9,32	-13,15	-10,74					
June	-3,33	-1,89	-8,21	-4,14					
July	1,81	3,63	-1,84	1,49					
August	2,45	4,34	-0,87	2,25					
September	-2,59	-0,64	-3,44	-2,21					
October	-15,29	-14,83	-14,21	-14,29					
November	-29,03	-33,02	-7,75	-10,71					
December	-24,81	-28,67	-7,16	-11,96					
Kastamonu									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreaves	Allen	Bristow Camp.	Chen
January	-2,20	-31,01	-1,57	7,70	MBE	-0,09	-0,47	0,07	-0,10
February	-15,27	-30,69	-14,71	-13,62	RMSE	2,84	3,24	2,83	3,00
March	-17,31	-27,26	-16,74	-17,14	MPE	-5,91	-13,29	-6,46	-1,88
April	-9,26	-12,21	-10,00	-7,01	NSE	0,89	0,85	0,89	0,87
May	-10,34	-9,59	-11,20	-11,55					
June	-8,68	-7,65	-9,93	-11,35					
July	2,53	7,48	0,91	1,91					
August	-0,45	5,77	-1,91	-0,16					
September	-4,71	-2,52	-5,48	-4,05					
October	1,97	-8,10	0,06	11,77					
November	-8,94	-16,70	-9,26	-8,55					
December	5,77	-20,50	5,86	16,11					
Kayseri									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreaves	Allen	Bristow Camp.	Chen
January	-27,98	-43,68	-19,36	-20,56	MBE	-0,20	-0,06	0,17	-0,22
February	-6,08	-15,12	-3,23	-4,03	RMSE	3,26	3,34	3,25	3,24
March	-15,29	-22,15	-15,04	-14,76	MPE	-8,02	-12,77	-7,56	-6,03
April	-9,51	-13,33	-11,55	-9,73	NSE	0,86	0,85	0,86	0,86
May	-11,67	-13,85	-16,04	-12,62					
June	-6,71	-6,74	-10,30	-7,16					
July	-0,91	1,09	-2,52	-0,54					
August	-1,01	1,07	-2,41	-0,57					
September	0,29	1,39	-2,04	0,30					
October	-9,03	-12,87	-11,77	-9,49					
November	-3,24	-14,05	2,24	4,24					
December	-1,69	-14,62	6,43	4,66					
Kırklareli									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreaves	Allen	Bristow Camp.	Chen
January	-35,29	-45,55	-25,82	-31,58	MBE	-0,01	-0,40	0,13	0,01
February	-12,09	-19,61	-6,69	-6,95	RMSE	3,20	3,35	3,16	3,26
March	-16,42	-20,67	-11,90	-14,58	MPE	-13,93	-16,16	-10,81	-10,89
April	-17,47	-16,84	-16,71	-17,63	NSE	0,85	0,84	0,86	0,85
May	-8,03	-4,46	-9,65	-8,75					

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June	-8,98	-6,87	-9,48	-9,21					
July	0,53	4,73	-1,65	0,73					
August	0,62	5,56	-1,48	0,86					
September	-5,87	-2,35	-6,93	-6,11					
October	-19,77	-25,34	-14,77	-14,13					
November	-10,75	-16,91	-3,61	-11,00					
December	-30,26	-41,37	-17,79	-28,36					
Konya Beyşehir									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-23,30	-24,74	-15,48	-18,44	MBE	-0,03	-0,03	0,46	-0,06
February	-4,29	-5,01	-2,74	-2,32	RMSE	3,34	3,34	3,37	3,31
March	-8,50	-8,98	-8,43	-7,43	MPE	-10,22	-10,61	-10,38	-8,32
April	-8,78	-8,94	-11,44	-8,80	NSE	0,84	0,84	0,84	0,84
May	-12,62	-12,72	-16,53	-12,90					
June	-4,17	-4,08	-9,35	-4,76					
July	2,89	3,08	-1,30	2,64					
August	0,49	0,72	-3,41	0,37					
September	-3,75	-3,52	-5,33	-3,15					
October	-16,43	-16,78	-18,49	-16,18					
November	-24,68	-25,72	-17,09	-17,76					
December	-23,52	-24,78	-17,15	-18,20					
Mersin									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-57,24	-51,53	-17,46	-40,05	MBE	0,22	0,20	0,59	0,19
February	-28,68	-26,58	-14,93	-23,53	RMSE	3,11	3,12	2,85	2,99
March	-18,95	-18,24	-15,83	-17,73	MPE	-17,56	-16,25	-11,33	-14,06
April	-16,74	-16,45	-14,16	-15,55	NSE	0,83	0,83	0,86	0,84
May	-13,32	-12,74	-15,49	-12,99					
June	2,66	3,30	-1,75	2,52					
July	9,04	9,90	5,07	8,90					
August	5,63	5,99	-0,80	5,04					
September	-1,02	-1,16	-6,23	-1,53					
October	-14,89	-15,00	-11,38	-13,40					
November	-32,12	-31,26	-24,61	-29,57					
December	-32,08	-29,28	-13,95	-21,04					
Rize									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-54,64	-56,39	-46,50	-46,01	MBE	0,25	-0,73	0,43	0,21
February	-28,56	-30,16	-20,28	-20,95	RMSE	4,44	4,91	4,18	4,37
March	-42,55	-45,49	-28,20	-32,79	MPE	-30,60	-30,13	-24,21	-25,21
April	-17,33	-21,72	-3,12	-9,80	NSE	0,67	0,60	0,71	0,68
May	-7,65	-9,66	-0,36	-5,50					
June	-15,94	-16,82	-10,46	-14,32					
July	-21,00	-18,38	-20,07	-21,58					
August	-21,16	-16,01	-22,60	-22,75					
September	-29,13	-22,11	-29,15	-29,95					
October	-41,04	-41,94	-32,64	-38,78					
November	-31,81	-33,43	-23,09	-26,82					
December	-60,90	-53,17	-58,60	-58,49					
Sinop									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-42,73	-36,61	-38,41	-40,75	MBE	0,26	0,26	0,42	0,23
February	-40,93	-33,83	-33,13	-37,45	RMSE	4,55	4,69	4,45	4,52
March	-37,04	-29,80	-28,58	-34,62	MPE	-25,56	-22,19	-23,82	-24,72
April	-15,98	-14,09	-9,99	-12,66	NSE	0,73	0,72	0,75	0,74
May	-14,99	-11,81	-13,20	-14,44					
June	-0,76	-1,37	-3,64	-1,26					
July	2,20	1,64	-1,03	1,53					
August	-3,02	-4,33	-6,78	-3,69					
September	-19,03	-19,70	-22,45	-19,48					
October	-56,63	-49,02	-54,19	-55,81					
November	-29,64	-24,15	-26,11	-29,20					
December	-49,85	-43,33	-47,21	-49,78					
Sivas Divriği									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>
January	-9,03	-23,05	1,73	-0,55	MBE	-0,24	0,08	0,15	-0,25
February	-3,90	-13,88	1,02	-0,68	RMSE	3,20	3,24	3,23	3,19
March	-12,88	-20,67	-10,98	-11,97	MPE	-7,37	-12,82	-6,65	-5,20
April	-11,72	-15,88	-14,35	-12,58	NSE	0,85	0,85	0,85	0,85
May	-13,87	-16,76	-18,61	-15,36					
June	-5,17	-6,08	-9,00	-5,60					
July	0,51	0,67	-2,16	0,95					
August	-1,59	-1,33	-4,09	-1,02					
September	-3,59	-4,29	-6,44	-3,47					
October	-15,32	-21,07	-16,05	-14,54					
November	-14,45	-24,49	-9,01	-9,34					
December	2,99	-7,24	8,95	8,78					
Şanlıurfa									
	<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>		<i>Hargreaves</i>	<i>Allen</i>	<i>Bristow Camp.</i>	<i>Chen</i>

January	-14,72	-13,22	-2,64	-7,16	MBE	-0,0003	-0,07	0,36	-0,03
February	-11,46	-10,35	-8,49	-8,64	RMSE	2,97	2,97	2,83	2,89
March	-12,78	-11,86	-11,54	-11,44	MPE	-10,57	-9,86	-8,78	-8,27
April	-8,85	-8,31	-12,13	-9,09	NSE	0,86	0,86	0,87	0,86
May	-6,51	-6,11	-11,52	-7,17					
June	1,67	1,91	-1,42	1,43					
July	-25,86	-25,69	-26,37	-25,41					
August	-2,69	-2,55	-3,02	-2,30					
September	-4,49	-4,26	-6,74	-4,51					
October	-5,33	-4,87	-6,42	-4,87					
November	-10,69	-9,91	-6,70	-7,45					
December	-25,49	-23,56	-6,02	-10,92					
Tokat									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreaves	Allen	Bristow Camp.	Chen
January	-22,50	-39,33	-14,31	-14,31	MBE	-0,11	-0,32	0,31	-0,13
February	-18,92	-27,16	-18,40	-18,40	RMSE	3,26	3,45	3,27	3,27
March	-23,63	-29,39	-22,55	-22,55	MPE	-12,10	-16,96	-12,80	-9,61
April	-17,74	-18,81	-16,75	-16,75	NSE	0,85	0,83	0,85	0,85
May	-11,06	-10,96	-10,93	-10,93					
June	-4,26	-3,21	-4,99	-4,99					
July	-3,79	-2,38	-3,58	-3,58					
August	-0,39	1,40	-0,32	-0,32					
September	-3,06	-1,15	-2,82	-2,82					
October	-6,96	-12,14	-4,14	-4,14					
November	-10,46	-24,70	-0,39	-0,39					
December	-25,25	-41,07	-16,60	-16,60					
Yozgat									
	Hargreaves	Allen	Bristow Camp.	Chen		Hargreaves	Allen	Bristow Camp.	Chen
January	-32,31	-29,71	-18,15	-24,50	MBE	0,06	-0,18	0,31	0,03
February	-20,40	-18,28	-16,48	-19,05	RMSE	3,22	3,23	3,15	3,16
March	-20,36	-18,32	-17,60	-18,83	MPE	-12,98	-11,12	-10,23	-10,43
April	-13,78	-12,02	-14,81	-13,79	NSE	0,85	0,85	0,86	0,86
May	-6,42	-4,82	-9,77	-7,12					
June	-0,73	0,76	-4,46	-1,50					
July	2,84	4,19	-0,32	2,55					
August	3,78	5,11	1,11	3,62					
September	-3,04	-1,63	-4,01	-2,66					
October	-14,83	-13,00	-14,47	-14,16					
November	-18,47	-16,34	-7,67	-10,75					
December	-23,37	-20,93	-9,79	-12,88					

REFERENCES

- Allen, R.G., "Self-calibrating method for estimating solar radiation from air temperature," *J. Hydrol. Eng.*, Vol.2, No.2, pp.56-67 (1997).
- Almorox, J., "Estimating global solar radiation from common meteorological data in Aranjuez, Spain," *Turkish journal of physics*, Vol.35, No.1, pp.53-64 (2011).
- Bristow, K.L., and Campbell, G.S., "On the relationship between incoming solar radiation and daily maximum and minimum temperature," *Agric. For. Meteorol.*, Vol.31, No.2, pp.159-166 (1984).
- Campbell, G.S., Norman, J.M., *An introduction to environmental biophysics*, Springer Science & Business Media (1998).
- Chen, R., Ersi, K., Yang, J., Lu, S., and Zhao, W., "Validation of five global radiation models with measured daily data in China," *Energy Convers. Manag.*, Vol.45, No.11, pp.1759-1769 (2004).
- Hargreaves, G.L., Hargreaves, G. H., and Riley, J.P., "Irrigation water requirements for Senegal River basin," *J. Irrig. Drain. Eng.*, Vol.111, No.3, pp.265-275 (1985).
- Iqbal M., *An Introduction to Solar Radiation*, Academic Press, Toronto (1983).
- Menges, H.O., Ertekin, C., and Sonmete, M.H., "Evaluation of global solar radiation models for Konya, Turkey," *Energy Convers. Manag.*, Vol.47, No.18, pp.3149-3173 (2006).
- Meza, F., and Varas, E., "Estimation of mean monthly solar global radiation as a function of temperature," *Agric. For. Meteorol.*, Vol.100, No.2, pp.231-241 (2000).