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Historical Aurora Borealis Observations in Anatolia during medieval period: Implications for the past solar activity

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Abstract: In this paper, it is reviewed the relationships between the aurora observations, past solar activity and climatic change in Anatolia during medieval period. For this purpose, it is presented two historical aurora catalogs for Anatolia and Middle East regions at various dates in order to understand the past solar activity and possible physical mechanism using historical texts, chronicles and other auroral records. The available catalogs in literature are covered records observed in the Europe, Japan, China, Russia and Middle East. There is no study dealing only with the historical aurora observations recorded in Anatolia. The data of the catalog strongly support that there is a considerable relationship between the aurora activity and past strong solar activity. An unusually high auroral activity during the years around 1100 in Anatolia and Middle East is quite consistent with the past solar variability, geomagnetic field intensity and planetary climatic changes drastically impacting on the economy and human events.

Keywords: Historical aurora records; Solar activity; Climatic changes; Anatolia.

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1. Introduction

A number of researchers presented the low and middle-latitude aurora catalogs (Table 1) from Europe (Mairan, 1733; Frobesius 1739; Fritz, 1873; Schove, 1948; Link, 1962; Dall'Olmo, 1979; Stothers, 1979; Krivsky and Pejml, 1988; Vaquero et al., 2010; Scafetta and Willson, 2013), Arabic countries (Basurah, 2006), Japan (Matsushita, 1956; Nakazawa et al., 2004; Shiokawa et al., 2005), and China (Schove and Ho, 1959; Keimatsu,1976; Hayakawa et al., 2015). Aurorae are the most majestic luminous phenomenon observed in the sky. The historical aurora catalogs have been used to recognize the past solar activities (Siscoe, 1980; Silverman, 1992; Schröder, 1992; Schröder 1994; Basurah, 2006; Vazquez et al., 2006; Hayakawa et al., 2015), Earth's climate change (Pang and Yau, 2002; Schröder, 2004; Gallet et al., 2005; Bard and Frank, 2006; Scafetta, 2012) and perception of human civilizations (Schröder, 2004; Gallet et al., 2006; Silverman, 2006). The state of the geomagnetic field and the form of magnetosphere extremely control the location of auroral zone (Korte and Stulze, 2016). The visibility of the aurorae at low latitudes is very scarce and closely connected with the strong geomagnetic storms related to the high-speed solar wind or interplanetary transients (Eather, 1980; Basurah, 2006; Vazquez et al., 2006).

Mairan (1733) presented that the first scientific monography covers a list of 229 historical aurorae during the period of 502-1731. In I852, Wolf noticed that the aurorae match with periods of high sunspot number, according to the historical aurora catalog including more than 6300 records (Wolf, 1857). Fritz (1873), who listed 77 European Aurora records during 1707-1708, published the historical auroral catalog and separated auroral sightings into five categories based on the latitude and longitude (Schröder, 1994). Link (1962) published a useful aurora catalog seen in European countries based

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on eight previous catalogs compiled by Frobesius (1739), Mairan (1754), Schoning (1760), Boué (1856), Wolf (1857), Lovering (1868), Fritz (1873) and Seydl (1954).

Dall'Olmo (1979) listed 59 auroral observations displayed throughout medieval period reported from European sources. Stothers (1979) compiled an extensive ancient aurora catalog in Europe observed by the Mediterranean basin peoples and proved the ancient auroral cycle simulates the modern cycle.

Vaquero et al. (2010) declared a set of auroral observation of Francisco Salva Campillo who recorded in Barcelona during 1780-1825. This catalog represents a sudden drop in the number of annual auroral observations at about 1793 owing to the secular minimum in solar activity (Vaquero et al., 2010). Scafetta and Willson (2013) studied the historical Hungarian auroral records covering 438 years. They found that the maxima of the auroral observations conform to the maxima in the sunspot records and there is a positive correlation amidst the auroral records, the solar and climate activities. Korte and Stolze (2016) showed that the intensity and tilt of the geomagnetic field and high solar activity are closely related to the Aurora occurrence.

The available catalogs described above present a number of records covering Europe, Japan, China, Russia and Middle East. There is no study dealing only with the historical aurora observations recorded in Anatolia. Anatolia have not been studied until now with respect to meteorological and aurora observations. The goal of this study is to compile a historical Anatolian aurora catalog (hAAc) during medieval period by scanning the available sources and catalogs in literature. The catalog could be used to analyze the past solar activity and planetary climatic changes impacting on the economy and human events. This research may also contribute to the understanding of public perception of the historical auroras.

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2. Historical Anatolian Aurora Catalog (hAAC) through medieval period

It is propounded a historical aurora catalog observed only in Anatolia during medieval period collected from Link (1962), Botley (1964), Baldwin (1969), Newton (1972), Stothers (1979), Eather (1980), Melissinos, (1980), Silverman (1998), Dall'Olmo (1979), Andreasyan (2000), Little (2007), Silverman (2006), Neuhäuser and Neuhäuser (2015) resources. In this catalogue, 23 different historical aurora records observed in Anatolia are presented during medieval period in Table 2. The location map of the historical Anatolian observations is given in Figure 1. A number of Anatolian aurora observations are summarized in Table 3. Another collected ancient aurora catalog consisting 45 auroral observations is shown in Table 4 for the Middle East region during the same period using Islamic historical texts, Arabic chronicles and other auroral records given in Table 1. These two catalogues are plotted in Figure 2 and evaluated altogether. The historical Anatolian and Middle East aurora records overlap through medieval period especially between 1097 and 1129 years (Figure 3). Also, Chinese and European aurora observations are in harmony with each other in this period (Siscoe, 1980).

According to the paper by Neuhäuser and Neuhäuser (2015), five criteria are implemented to perform the aurora catalogs as night-time (darkness, sunset, sunrise), non-southern directions (northern, NE, NW, E-W, W-E), color (red, reddish, fiery, bloody, green, black), dynamics (fire, fiery), and repetition. The strength of the aurora can be determined by considering its color, brightness, dynamics, duration, geomagnetic latitude. The observation is classified as potential (N=0), possible (N=1), very possible (N=2), probable (N=3), very probable (N=4), or certain (N=5) according to the criteria number (N) satisfied (Neuhäuser and Neuhäuser, 2015).

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In Anatolia, the first auroral observation was done in Constantinople at 333 (Stothers, 1979). Stothers (1979) described these observations as a sky fire (N=1) according to the works of Aurelius Victor (320-390), who was a historian and politician of the Roman Empire. On the other hand, Eather (1980) described an Aurora observation over Constantinople at about 360 BC during the siege on Byzantium by Philip of Macedonia.

Little (2007) described an aurora observation record in Constantinople at 396: “A fiery cloud was observed from the East while the city darkened. At first, it was small, but later gradually grew and moved towards the city. At last, it terribly enlarged and poised over the entire city. A terrifying flame appeared to hang down. All people stacked to the church, and the place could not receive huge mass” (N=3).

According to the Link (1962), an aurora appeared in Asia Minor on 22 August 502, Thursday. This aurora was also observed both in Edessa (Botley, 1964) and Palestine after an earthquake (Russell, 1985) based on to the Chronicle of Joshua the Stylite. Joshua the Stylite described it: “On the 22rd of August this year, on the night preceding Friday, a great fire appeared to us blazing in the northern quarter the all night. It was believed that the whole earth was going to be devastated that night by a fire storm. However, the mercy of our Lord preserved us without damage” (N=3). This appearance of the aurora borealis was also reported in Chronicon Edessenum without apocalyptic detail (Trombley and Watt, 2000).

According to the Historia Ecclesiastica of Ptolomaeus Lucensis there was an aurora sighting at a night of 633 in Constantinople (Dall’Olmo, 1979): “A bloody sign appearing just at that time was sighted. A bloodstained spear and a sharp light were observed on the sky for nearly all night” (N=4). Theophanes (758/760-817), a Byzantine

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monk, theologian, and chronicler, reported an observation in 667 winter: “There was a sign which appeared in the sky in the same winter” (N=1). Theophanes reported another observation in 675-676: “This year a sign was seen in the sky on a Sabbath day” (N=1; Turtledove, 1982).

Theophanes recorded three aurora events for 734, 743 June and 744 in Constantinople. The first aurora observation was reported in 734: “A fiery sign shining like a burning brand appeared in the sky in Constantinople” (N=2). The second aurora observation was recorded by Theophanes in June of 743: “In the northern sky of Constantinople, a sign was observed in the month of June” (N=1; Turtledove, 1982). The last aurora record was observed in Constantinople for 744: “In the northern sky, a sign seemed this year, and dust fell in several places” (N=1; Turtledove, 1982; Neuhäuser and Neuhäuser, 2015).

The low-latitude aurorae of 772-773 are interesting, as being very close to the extreme solar event of 774-775 (Miyake et al., 2012; Usoskin et al., 2013; Mekhldi et al., 2015). Harrak (1999) listed two aurorae records observed near Amida in the early 770s based on the Chronicle of Zuqnin. In the Chronicle of Zuqnin, the first observation was recorded in 772, Amida (Turkey): “Another sign was seen in the northern side, and its view gave evidence about the menace of God against us. It appeared at reaping time, while wrapping the whole northern side of the sky from west to east end. It was look like a green sceptre, a red one, a yellow one, and a black one. It was ascending from the ground and changing into 70 shapes, while one sceptre was emerging and another disappearing” (N=3). The second observation was recorded in the Chronicle of Zuqnin in 773, Amida (Turkey): “In the month of June, on a Friday, another sign that was seen a year ago in the northern region was appeared again this year. It was on Fridays that it

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used to appear during these three consecutive years, stretching itself out from the eastern side to the western side. The sign would change into many shapes in such a way that as soon as a green ray vanished, a red one would appear, and as soon as the yellow one vanished, a green would appear, and as soon as this one vanished, a black one would appear" (N=3; Harrak, 1999; Neuhäuser and Neuhäuser, 2015). These two observations listed by Harrak (1999) and Neuhäuser and Neuhäuser (2015) based on the Chronicle of Zuqnin were also cited by Dall'Olmo (1979) according to the Chronique de Denys de Tell-Mahré (Chabot, 1895) with different dating. Mekhaldi et al. (2015) indicated that these two extreme events (772/773) were five times greater than any other recorded solar storms with instruments. In Constantinople, another aurora observation was recorded in 988: "A luminous star and fiery pillars seen in the northern region of the sky for some nights. They frightened the people who saw them." (N=3; Dall'Olmo, 1979).

Matthew of Edessa, who wrote a chronicle, described the events that occurred between the years 952 and 1136, and reported four aurora observations around the year 1100 (Andreasyan, 2000). Matthew of Edessa reported the first aurora observation in the Armenian year 546 (25.02.1097–24.02.1098): "In this year, an odd and horrible signs were observed in the the northern side of the sky. No one had ever seen such an amazing omen so far. In the month of November, the sky kindled and reddened though the air was clear and quiet. The bloody sky was covered with stacks as if clustered on top of one another becoming colorful. The stacks were set to slip through in an easterly direction, dispersed after having gathered, and enveloped the large amount of the sky. Then, the dark redness such an amazing degree reached up to the middle of the sky vault. The savants and sages interpreted this phenomenon that, it was a sign of

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bloodshed. Actually, terrible events and disasters we included as a short story in our book were soon to be fulfilled." (N=3).

Krey (1921) described an aurora observation during the siege of Antioch on the account of eyewitnesses and participants in the first crusade: "A great earthquake occurred on the third day before the Kalends of January (30 December 1097), and a very fabulous sign was noticed in the sky. Northern part of the sky was so red that it appeared as if sun rose to inform the day in the first sight of the night" (N=3). This observation was also described by Baldwin (1969): "There was an earthquake on December 30th, and a frightening display of the aurora borealis next evening, and in this way God chastised his army, so that we were intent upon the light which was rising in the darkness, yet the minds of some were so blind and abandoned that they were recalled neither from luxury nor robbery. At this time the Bishop prescribed a fast of three days and urged prayers and alms, together with a procession, upon the people; moreover, he commanded the priests to devote themselves to masses and prayers, the clerics to psalms". On the other hand, another aurora was observed on 3 June 1098 at Antioch based on the Link (1962) catalog as a fiery red sky (N=2; Silverman, 2006).

The Matthew of Edessa recorded second aurora observation in the Armenian year 547 (25.02.1098–24.02.1099). "In the same year, a new sign appeared in the northern part of the sky. At the fourth hour of the night, the sky appeared more inflamed than before, and a dark red color. This phenomenon lasted from the evening until the fourth hour of the night. Such a terrible omen had never been seen so far. This omen raised upwards gradually and covered the northern portion of the sky with the lines reaching the hills. All stars took a fiery color. This phenomenon was an omen of rage and catastrophe" (N=4; Andreasyan, 2000). Botley (1964) reported an auroral

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observation in Antioch as a blaze of light girdled Pole (N=1). Link (1962) dated this observation on September 27, 1098.

In the Armenian year 548 (25.02.1099–24.02.1100) Matthew reported another aurora observation: “A fiery sign of dark red color appeared in the sky in this year. This omen heading from the northern to the eastern part of the sky appeared until the seventh hour of the night and then became black. It was said that this phenomenon was a sign of bloodshed of Christians. These predictions were truly realized. No favorable omen did not appear since the day when the Franks began their expedition. All omens, however, marked to realize the destruction, death, slaughter, famine and other diverse disasters” (N=3; Andreasyan, 2000).

Matthew recorded the last aurora observation in the Armenian year 549 (25.02.1100–24.02.1101): “The northern part of the sky flushed red for the fourth time in this year. The fiery red omen appeared more horrific than the previous one and subsequently changed into black. This fourth appearance coincided with a lunar eclipse. This phenomenon was a sign of the celestial wrath of God over the Christians as previously said by the prophet Jeremiah with these words: “His wrath will blaze up from the northern part of the sky. Indeed, several misfortunes occurred as we never could have expected” (N=3; Andreasyan, 2000).

Dall'Olmo (1979) reported an aurora observation based on the Chronicle of Michael the Syrian translated into French by Chabot (1968): “In the year 1108, a light like the sunlight was seen in the middle of the night, and remained about three hours in Djihan region near Adana” (N=2). Dall'Olmo (1979) was also cited 12 auroral records observed probably in the Middle East from 745 to 1141 (Table 4) according to the Chronicle of Michael the Syrian (Chabot, 1968).

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On December 16, 1117, an aurora was recorded in Asia Minor (Link, 1962). In the same date, two observations were also reported in the Middle East (Newton, 1972) and in Palestine (Botley, 1964). These two observations could be same event. Link (1962) described other observations in Asia Minor in the year 1119. This event might be the same record observed in Armenia (Botley, 1964) given in Table 4.

Priest Grigor, who continued the Matthew's Chronicle and recorded events for the years 1136/37-1162/63, added one aurora observation in about the year 1143. In the Armenian year 592 (14.02.1143-13.02.1144) Priest Grigor described the aurora observation: "On Holy Thursday (1 April 1143), an omen forming of a luminous column appeared in the northern portion of the sky. This omen was visible for eight days. Three sovereigns died after the appearance of this phenomenon" (N=3; Andreasyan, 2000).

3. Results and Discussions

The main purpose of this study is to present an aurora catalog for the Anatolia during the medieval period. 23 different historical aurora records are presented during the medieval period in Anatolia (Table 2). Another aurora catalog containing 45 records collected from different sources is also given (Le Strange, 1890; Link, 1962; Botley, 1964; Newton, 1972; Dall'Olmo, 1979; Silverman, 1998; Basurah, 2006) for the Middle East region (Table 4). The aurora observations were described as "sign", "a fiery shining sign", "a very fabulous sign", "red sky", "a fiery red sky", "sky fire", "a great fire", "a fiery cloud", "a frightful and strange omen", "a fire-like omen", "a bloody spear light", "blaze of light", "a sunlight light". The form of aurorae was defined as "luminous column". The aurorae were generally seen in the northern and eastern part of the sky. The color of the aurora observations were red, green, yellow and black depending on the height and

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relative concentrations of the nitrogen and oxygen compounds in the atmosphere (Eather, 1980). The number N sort out only the probability that an event could be an aurora or not. The possibility of the aurora could be decided by regarding its duration geomagnetic latitude, color, brightness and dynamics. Aurorae observations with N≥3 tend to be true.

The aurora records strongly correlated to high solar activity (Siscoe, 1980) provide some information about the Sun-Earth interaction as previously proved by Scafetta (2012). They are the longest direct observational records available for studying solar and space weather dynamics. Stronger solar dynamics were realized in aurorae with color green-yellow-red as seen in 772 and 773 in Amida. Miyake et al. (2012) and Usoskin et al. (2013) confirmed the 770s high solar events presenting ^{14}C measurements from the annual rings of the cedar trees in Japan and inappropriate carbon cycle model in German oak, respectively. The auroral records have also proven itself to be a valuable data source for the investigation of the secular variation of solar activity. Paleomagnetic researchs demonstrate that the recent dipole strength was nearly 50% weaker than it was 2500 years ago (Raspopov et al., 2003). Siscoe and Siebert (2002) indicated that the dipole strength was 1.5 times as large as that of the present value. The long-term variation of the geomagnetic latitude and dipole moment might be the reason of observing aurorae in Anatolia. The average dipole moment for 750 and 1250 are 8.85 10^{22} Am^2 and 8.90 10^{22} Am^2 slightly higher than the present value of 7.78 10^{22} Am^2 (Korte and Constable, 2005; Gallet et al., 2005). According to the Kawai et al. (1965) the axis of geomagnetic dipole could have inclined towards Asia at around the 11^{th}-12^{th} centuries. In addition, the possibility of auroral occurrence at low latitudes could demonstrate changes in the location of the North magnetic pole

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(Silverman, 1998). This study could also be significant constraints for exploration of solar activity on Earth's atmosphere and climate during the historical periods previously proved by Bard and Frank (2006). According to the Bard and Frank (2006) solar fluctuations caused climatic changes called Medieval Warm Period (900–1400). The Maunder Minimum (1645-1715) which delineates the coldest part of the Little Ice Age (Eddy, 1976) is depicted by a solar activity reduction, as well as a sunspots scarcity. A new low sunspot number and lower aurora activity, which occurring in the period between 2014 and 2025 (Li et al., 2018), might have led to a temporary change in natural environment influencing the general public's attitudes and socio-economic factors. Also, resource scarcity and disparities could also lead to social tensions in the communities for the next ten years.

The position of the magnetic poles is the most important factor defining whether the aurora was observed at a geographic region. Palaeomagnetic data provides similar longitude values (85° N, 115° E) for the north geomagnetic pole (Merrill and McElhinny, 1983). The positions of the north magnetic pole have changed from 10° to 358° in longitude and between 79° and 88° in latitude over the past 2500 years (Ohno and Hamano, 1992). During the interval of 1127–1129, the north geomagnetic pole was located at a geographic latitude of 80° N, and geographic longitudes including East Asia (Merrill and McElhinny, 1983; Constable et al., 2000). According to the Fukushima (1994), the north magnetic pole was located at 81°N in the eastern hemisphere near East Asia (100°E to 130°E) in the medieval period. The north geomagnetic pole of dipole axis computed from the average spherical harmonic models were 84.8° N and 103.8° E in 1100 (Constable et al., 2000).

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The geomagnetic latitude of Amida (Turkey) in the late 8th century to be about 50.1° (Neuhäuser and Neuhäuser, 2015) based on the Holocene geomagnetic field (Nilsson et al., 2014) and 45° (Hayakawa et al., 2017) based on the location of the North Geomagnetic Pole over the past 2000 years (Merrill and McElhinny, 1983). According to the Silverman (2006), the geomagnetic latitude of Edessa and Antioch was 41° and 40°, respectively. Strong geomagnetic storms, indicating strong solar activity around 770 and 1100 should have been exist in Amida (45°), Edessa (41°) and Antioch (40°).

The Medieval Climate Anomaly characterizing by warmer and drier climate conditions generally related to relatively prolonged solar activity during the 12th and 13th centuries (Jirikowic and Damon, 1994). Damon and Jirikowic (1992) estimated that the rise of global temperature maxima stays below 0.8°C and anomalously high temperatures pursue during the 12th and 13th centuries. Sharma (2002) revisited the issue and proposed that very large solar variations have modulated climate over the past 200 millennia. Gallet et al. (2006) demonstrated that fluctuations in the geomagnetic field might trigger significant climate change impacting on some major societal events in the Middle East at longer time. An inverse relationship amidst the aurora records, severe winter and famine is estimated during the years of 1100 in Anatolia. The high aurora activity could be reason of temperature rise during the medieval period in Anatolia.

Haldon et al. (2014) subdivided Medieval into four climatic phases as dry (270-540), very wet (540-750), moderately dry (750-950) and moderately wet (950-1400) depending on archaeological, environmental, climate, high resolution pollen and stable isotope data from sites in central and northwestern Turkey. However, this subdivision should be revised as dry (0-560), very wet (560-725), moderately dry (725-990) and

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moderately wet (990-1400) as given in Table 5 by using Anatolian and Middle Eastern aurora observations besides meteorological data. Affective cold winter, wet climate conditions, drought and famine could be occurred for Asia Minor and Middle East region during 990-1400. It seems that the relatively high auroral activity during the years around 1100 both in Anatolia and Middle East indicates that solar activity must have been intense rather than moderate causing the climate warmer (Fig. 2). In this period, Islamic world was converted into an enlightened center for science, education, medicine, and philosophy as previously stated by Hamilton (1982). An important increase in agricultural production and population seems to have occurred in Anatolia after the year of 1100 where the aurora observations are intense (Fig. 2). Vaquero and Trigo (2012) stated the period from 1095 to 1204 as an average solar cycle length. Bekli et al. (2017) demonstrated that the naked-eye sun spot observations from 974 to 1278 and aurora records from 965 to 1273 show multiple unusual peaks related to the high solar activitiy at latitudes below 45° by using Chinese and Korean historical sources.

In the medieval period, the people were thought that the aurora was a sign of anger of God, menace, threat, apocalyptic, doomsday, misfortunes, war, slaughter and blodshed. Little (2007) described an aurora observation record in Constantinople at 396: “All people stacked to the church, and the place could not receive huge mass. But after that great tribulation, when God had accredited His word, the cloud began to diminish and at last disappeared. The people, freed from fear for a while, again heard that they must migrate, because the whole city would be destroyed on the next Sabbath. The whole people left the city with the Emperor; no one remained in his house. The city was

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saved. What shall we say? adds Augustine. Was this the anger of God or rather His mercy"?

In the Chronicle of Zuqnin, an aurora observation recorded in 772, Amida (Turkey) was described: "Another sign was seen in the northern side, and its view gave evidence about the menace of God against us. For the intelligent person the sign indicated menace. Many people said many things about it; some said it announced bloodshed, and others said other things. But who knows the deeds of the Lord"?

Matthew of Edessa described the aurora phenomenon as a sign of rage, catastrophe, and celestial wrath of God over the Christians and bloodshed of Christians. Matthew of Edessa reported: "These predictions were truly realized. No favorable omen did not appear since the day when the Franks began their expedition. All omens noticed to realize the destruction, death, slaughter, famine and other diverse disasters" (Andreasyan, 2000).

4. Conclusions

This study establishing the strong solar activity during medieval period reports the aurora observations recorded both in Anatolia and Middle East region integrating meteorological data. The following conclusions can be summarized as follows:

1. Historical Anatolian aurora catalog (hAAc) containing 23 different aurora records provide important information on variations in geomagnetic and auroral activity during medieval period.
2. In Anatolia and Middle East, there was a relatively high auroral activity during the years around 1100 is quite consistent with the naked-eye sunspot observations.

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3. *The historical Anatolian Aurora catalog exceptionally promote that there is a remarkable correlation between the past solar activity and aurora activity.*
4. The intensity of dipole moment and position of the geomagnetic pole might be the most important factors observing aurorae in Anatolia and Middle East regions during medieval period.
5. In the Medieval period, Four climatic phases portrayed by Haldon et al. (2014) is revised as dry (0-560), very wet (560-725), moderately dry (725-990) and moderately wet (990-1400) depending on aurora observations besides meteorological data.
6. Further investigations are required to establish a relationship between the solar variability and climatic changes, such as the Medieval Climate Anomaly or Little Ice Age.
7. People in medieval Anatolia were believed that the aurora was a sign of celestial wrath of God, menace, threat, apocalyptic, doomsday, misfortunes, war, slaughter, rage, catastrophe and bloodshed.

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6. References

Andreasyan, H.D.: Urfalı Mateos vekayinamesi (952-1136) ve Papaz Grigor'un zeyli (1136-1162), Türk Tarih Kurumu, Ankara (in Turkish). 2000.

Baldwin, M.W.: A History of the Crusades: The First Hundred Years, University of Pennsylvania Press, 1969.

https://doi.org/10.5194/angeo-2019-97
Preprint. Discussion started: 6 August 2019

379 Bard, E. and Frank, M.: Climate change and solar variability: What's new under
380 the sun, Earth and Planetary Science Letters, 248(1), 1-14. 2006
381 Basurah, H. M.: Records of aurora in the Islamic chronicles during 9th–16th
382 centuries. Journal of Atmospheric and Solar-Terrestrial Physics, 68(8), 937-941, 2006.
383 Bekli, M.R., Zougab, N., Belabbas, A., Chadou, I.: Non-parametric Data Analysis
384 of Low-latitude Auroras and Naked-eye Sunspots in the Medieval Epoch, Solar Physics
385 292:52, 2017.
386 Botley, C.M.: Aurora in S.W. Asia 1097-1300. J. British Astr. Assoc. 74, 293-296,
387 1964.
388 Chabot, J.B.: Chronique de Michel le Syrien, (French translation accompanied by
389 the original Syrian text), vols. 1-4, photo-printed edition, Culture and Civilisation,
390 Brussels. 1968.
391 Constable, C. G., Johnson, C. L., and Lund, S. P.: Global geomagnetic field
392 models for the past 3000 years: transient or permanent flux lobes? Phil. Trans. R. Soc.
393 Lond., A 358, 991-1008, 2000.
394 Dall'Olmo, U.: An additional list of auroras from European sources from 450 to
395 1466 A.D., Journal of Geophysical Research, 84, 1525-1535, 1979.
396 Damon, P.E. and Jirikowic, J.L.: Solar Forcing of Global Climate Change?: In
397 Taylor, R.E., Long, A., and Kra, R. (eds.), *Four Decades of Radiocarbon*, Springer-
398 Verlag, New York, 117 pp., 1992.
399 Eather, R.H.: Majestic light: The Aurora in Science, History and the Arts, AGU,
400 Washington D.C., 1980.
401 Eddy, J.A.: The Maunder Minimum, *Science* 192, 1189–1202, 1976.
402 Fritz. H.: Verzeichnis beobachteter Polarlichter, C. Gerold's Sohns, Vienna, 1873.

https://doi.org/10.5194/angeo-2019-97
Preprint. Discussion started: 6 August 2019

Frobesius, J.N.: Luminis Atque Aurorae Borealfs Spectaculorum Recensio Chronologica, Helmstadt, Germany, 1739.

Gallet, Y., Genevey, A., and Fluteau, F.: Does Earth's magnetic field secular variation control centennial climate change? Earth and Planetary Science Letters, 236(1), 339-347, 2005.

Gallet, Y., Genevey, A., Le Goff, M., Fluteau, F., and Eshraghi, S.A.: Possible impact of the Earth's magnetic field on the history of ancient civilizations. Earth and Planetary Science Letters, 246(1), 17-26, 2006.

Haldon, J., Roberts, N., Izdebski, A., Fleitmann, D., McCormick, M., Cassis, M., Doonan, O., Eastwood, W., Elton, H., Ladstätter, S., Manning, S., Newhard, J., Nicoll, K., Telelis, I., and Xoplaki, E.: The Climate and Environment of Byzantine Anatolia: Integrating Science, History, and Archaeology, Journal of Interdisciplinary History, XLV (2), 113–161, 2014.

Hamilton, A.R.G.: Studies on the civilization of Islam. United States. Princeton University Press, 1982.

Harrak, A.: The Chronicle of Zuqnīn, Parts III and IV: AD 488-775: Translated from Syriac with Notes and Introduction, 36, 404p., PIMS, 1999.

Hayakawa, H., Tamazawa, H., Kawamura, A. D., and Isobe, H.: Records of sunspot and aurora during CE 960–1279 in the Chinese chronicle of the Sòng dynasty. Earth, Planets and Space, 67(1), 1-14, 2015.

Hayakawa, H., Mitsuma, Y., Fujiwara, Y., Kawamura, A. D., Kataoka, R., Ebihara, Y., Kosaka, S., Iwahashi, K., Tamazawa, H., and Isobe, H.: The earliest drawings of datable auroras and a two-tail comet from the Syriac Chronicle of Zūqnīn. Publications of the Astronomical Society of Japan, 69(2), 2017.

https://doi.org/10.5194/angeo-2019-97
Preprint. Discussion started: 6 August 2019

Jirikowic, J.L., Damon, P.E.: The medieval solar activity maximum, Climatic Change 26(2), 309–316, 1994.

Kawai, N., Hirooka, K. and Sasajima, S.: Counterclockwise rotation of the geomagnetic dipole axis revealed in the world-wide archaeo-secular variations, Proc. Japan Acad., 41, 398-403, 1965.

Keimatsu, M.: A chronology of aurorae and sunspots observed in China, Korea and Japan, Ann. Sci., 13, 1-32, 1976.

Korte, M., and Constable, C.G.: The geomagnetic dipole moment over the last 7000 years-new results from a global model. Earth and Planetary Science Letters, 236(1), 348-358, 2005.

Korte, M. and Stolze, S.: Variations in mid-latitude auroral activity during the Holocene, Archaeometry, 58 (1), 159-176, 2016.

Krey, A.C.: The First Crusade: The Accounts of Eyewitnesses and Participants, Princeton, 139-142, 1921.

Krivsky, L., and Pejml, K.: Solar activity aurorae and climate in Central Europe in the last 1000 years. Bulletin of the Astronomical Institute of the Czechoslovak Academy of Sciences No 75,1988.

Le Strange, G.: Palestine under the Moslems. Houghton, Mifflin and Company, Boston and New York, 1890.

Fi, F.Y., Kong, D.F., Xie, J.L., Xiang, N.B., Xu, J.C.: Solar cycle characteristics and their application in the prediction of cycle 25. Journal of Atmospheric and Solar-Terrestrial Physics, 181, 110-115, 2018.

Link, F.. Observations et catalogue des aurores boréales apparues en Occident de-626 à 1600. Geofys. Sb. X, 297–392, 1962.

https://doi.org/10.5194/angeo-2019-97
Preprint. Discussion started: 6 August 2019

Little, L.K.: Plague and the end of antiquity: the pandemic of 541-750. Cambridge University Press, UK, 2007.

Lovering, J.: On the periodicity of the aurora Borealis, Mem. Amer. Acad. Arts Sci., X., 1868.

Mairan, J.J.: Traite physique et historique de l'aurore borale. Paris, 1733.

Mairan, J.J.: de Ort, Traite Physique et Historique de l'Aurore Boreale, Imprimerie Royale, Paris, 1754.

Matsushita, S.: Ancient aurorae seen in Japan, J. Geophys. Res., 61, 297-302, 1956.

Mekhaldi, F., Muscheler, R., Adolphia, F., Aldaha, A., Beer, J, McConnel, J.R., Possnert, G., Sigl, M., Svensson, A., Synal, H.A., Welten, K.C. and Woodruff, T.E.: Multirodionuclide evidence for the solar origin of the cosmic-ray events of AD 774/5 and 993/4, Nature Communications 6:8611, 2015.

Merrill, R.T. and McElhinny, M.W.: The Earth's Magnetic Field: Its History, Origin and Planetary Perspective, Academic Press, London, 1983.

Miyake, F., Nagaya, K., Masuda, K., and Nakamura, T.: A signature of cosmic-ray increase in AD 774-775 from tree rings in Japan, Natura 486 (7402), 240, 2012.

Nakazawa, Y., Okada, T., & Shiokawa, K.: Understanding the "SEKKI" phenomena in Japanese historical literatures based on the modern science of low-latitude aurora. Earth, planets and space, 56(12), e41-e44, 2004.

Neuhäuser, R. and Neuhäuser, D.L.: Solar activity around AD 775 from aurorae and radiocarbon. Astronomische Nachrichten, 336, 225–248, 2015.

Newton, R.R.: Medieval Chronicles and the Rotation of the Earth, the Johns Hopkins University Press, Baltimore, 1972.

https://doi.org/10.5194/angeo-2019-97
Preprint. Discussion started: 6 August 2019

475 Nilsson, A., Holme, R., Korte, M., Suttie, N. and Hill, M.: Reconstructing Holocene
476 geomagnetic field variation: new methods, models and implications. - Geophysical
477 Journal International, 198(1), 229-248, 2014.
478 Pang, K.D., and Yau, K.K.: Ancient observations link changes in Sun's brightness
479 and Earth's climate. Eos, Transactions American Geophysical Union, 83(43), 481-490,
480 2002.
481 Russell, K.W.: The earthquake chronology of Palestine and northwest Arabia from
482 the 2nd through the mid-8th century AD. Bulletin of the American Schools of Oriental
483 Research, 37-59, 1985.
484 Scafetta, N.: A shared frequency set between the historical mid-latitude aurora
485 records and the global surface temperature. Journal of Atmospherical and Solar–
486 Terrestrial Physics 74, 145–163, 2012.
487 Scafetta, N., and Willson, R.C.: Planetary harmonics in the historical Hungarian
488 aurora record (1523–1960). Planetary and Space Science, 78, 38-44, 2013
489 Schoning, G.: Nordlyset Aelde. Skrift. Kiobenh. Selsk. 8, 1760.
490 Schove, D.J.: Sunspot epochs 188 A. D. to 1610 A. D, Popular Astronomy, 56,
491 247-251, 1948.
492 Schove D.J. and Ho P.Y.: Chinese aurorae: AD 1048-1070, J. British. Astr. Soc.
493 69, 295-304, 1959.
494 Schröder, W.: On the Existence of the 11-Year Cycle in Solar and Auroral Activity
495 before and during the So-Called Maunder Minimum. Journal of geomagnetism and
496 geoelectricity, 44(2), 119-128, 1992.
497 Schröder, W.: Aurorae during the so-called Spoerer minimum. Solar physics,
498 151(1), 199-201, 1994.

https://doi.org/10.5194/angeo-2019-97
Preprint. Discussion started: 6 August 2019

499 Schröder, W.: A note on auroras during the so-called Maunder-Minimum. Acta
500 Geodaetica et Geophysica Hungarica, 39(4), 355-358, 2004.
501 Sharma, M.: Variations in solar magnetic activity during the last 200,000 years: is
502 there a Sun–climate connection? Earth Planet. Sci. Lett. 199, 459–472, 2002.
503 Shiokawa, K., Ogawa, T., and Kamide, Y.: Low-latitude auroras observed in
504 Japan: 1999–2004, Journal of Geophysical Research: Space Physics, 110(A5), 2005.
505 Silverman, S.M.: Secular variation of the aurora for the past 500 years, Reviews
506 of Geophysics, 30, 333-351, 1992.
507 Silverman, S.: Early auroral observations, Journal of Atmospherical and Solar–
508 Terrestrial Physics, 60(10), 997-1006, 1998.
509 Silverman, S.M.: Comparison of the aurora of September 1/2, 1859 with other
510 great auroras. Advances in Space Research, 38(2), 136-144, 2006.
511 Siscoe, G.L.: Evidence in the auroral record for secular solar variability,
512 Geophys., 78,647-658, 1980.
513 Stothers, R.B.: Solar cycle during classical antiquity, Astron. Astrophys., 77, 121-
514 127, 1979.
515 Seydl, A.: A list of 402 northern lights observed in Bohemia, Moravia and Slovakia
516 from 1013 to 1951, Geofys. Sb., 17, 159, 1954.
517 Trombley, F.R. and Watt, J.W.: The chronicle of pseudo-Joshua the Stylite, 32,
518 Liverpool University Press, UK, 2000.
519 Turtledove, H.:The Chronicle of Theophanes: Anni Mundi 6095-6305 (AD 602-
520 813). University of Pennsylvania Press, USA, 1982.

https://doi.org/10.5194/angeo-2019-97
Preprint. Discussion started: 6 August 2019

Usoskin, I.G., Kromer, B., Ludlow, F., Beer, J., Fiedrich, M., Kovaltsov, G.A., Solanki, S.K. and Wacker, L.: The AD 775 cosmic event revisited: the Sun is to blame, Astronomy & Astrophysics 552, L3, 2013.

Vaquero, J.M., Gallego, M.C. and Garcia, J.A.: A 250-year cycle in naked-eye observations of sunspots, Geophysical Research Letters, 29 (20), 1997, doi:10.1029/2002GL014782, 2002.

Vaquero, J.M., Gallego, M.C., Barriendos, M., Rama, E., and Sanchez-Lorenzo, A.: Francisco Salvá's auroral observations from Barcelona during 1780–1825. Advances in Space Research, 45(11), 1388-1392, 2010.

Vaquero, J.M., Trigo, R.M.: A Note on Solar Cycle Length during the Medieval Climate Anomaly, Solar Physics 279, 289-294, 2012.

Vazquez, M., Vaquero, J.M., Curto, J.J.: On the connection between solar activity and low-latitude aurorae in the period 1715–1860. Solar Physics, 238, 405–420, 2006.

Wolf, R.: Nordlichtcatalog, Vierteljahresschro Naturforsch. Ges. Zuerich, 2, 353, 1857.

https://doi.org/10.5194/angeo-2019-97
Preprint. Discussion started: 6 August 2019

TABLES CAPTIONS:

Table 1. Historical Aurora catalogs compiled by different authors.

Table 2. Historical Anatolian Aurora catalogs during medieval period compiled in this study.

Table 3. The number of historical aurora records observed in Anatolia.

Table 4. Ancient aurora observations recorded in Middle East region during medieval period.

Table 5. Summary of Ancient climate change based on the aurora observations and meterological data in Anatolia during medieval period.

FIGURE CAPTIONS:

Figure 1. The location map of the historical Anatolian records during medieval period.

Figure 2. Comparison of historical aurora observations with climate change and meteorological data in Anatolia and neigbouring regions. The upper panel shows the meteorological data climatic subdivisions, the middle panel shows the aurora observations in Anatolia and Middle East regions and the lower panel shows the land use and population in Anatolia. Meteorogical and land use data are taken from Haldon et al. (2014).

Figure 3. The number of aurorae records per century observed in the Anatolia and in Middle East.

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TABLES

Table 1.

Sources	Number of Observations	Region	Period
Link, 1962	385	Europe	626 B.C. to 1600 A.D.
Link, 1964	209	Europe	1600-1700 A.D.
Stothers, 1979	67	Greece and Italy	480 B.C. to 333 A.D.
Newton, 1972	65	Europe	450-1263 A.D.
Dall'Olmo, 1979	61	Europe	450-1461 A.D.
Keimatsu, 1976	260	China, Korea, and Japan	687 B.C. to 1600 A.D.
Matsushita, 1956	18	Japan	620-1909 A.D.
Basurah, 2006	18	Arabia, North Africa, Spain	800-1600 A.D.
This Study	23	Anatolia	1-1453 A.D.
This Study	45	Middle East	1-1453 A.D.

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573 **Table 2.**

#	Date	Location	Description	N	References
1	333	Constantinople	Sky fire.	1	Stothers, 1979
2	396	Constantinople	A fiery cloud was seen from the East.	3	Little, 2007
3	22 Ağustos 502, Thursday	Edessa	A great fire appeared to us blazing in the northern quarter the whole night.	3	Link, 1962 Botley, 1964
4	633	Constantinople	A bloody spear and a light of the sky were sighted for nearly the all night.	4	Dall'Olmo, 1979
5	668	Constantinople	There was a sign appeared in the sky in the same winter.	1	Turtledove, 1982
6	675	Constantinople	In this year, a sign was seen in the sky on a Sabbath day.	1	Turtledove, 1982
7	734	Constantinople	There was a sign in the sky which shone like a burning brand.	2	Turtledove, 1982
8	June 743	Constantinople	In June, a sign appeared on the northern sky.	1	Turtledove, 1982
9	744	Constantinople	This year, a sign appeared on the northern sky.	1	Turtledove, 1982
10	772	Amida	Another sign appeared in the northern side.	3	Harrak, 1999
11	June 773, Friday	Amida	The sign that was seen a year ago in the northern region was seen again in this year, in the month of June, on a Friday.	3	Neuhäuser and Neuhäuser, 2015 Harrak, 1999
12	988	Constantinople	Frightened fiery pillars seen in the northern region for some nights.	3	Dall'Olmo, 1979
13	21 November 1097, Monday	Edessa	A frightful and strange omen appeared in the northern portion of the sky.	3	Link, 1962 Silverman, 2006 Andreasyan, 2000 Botley, 1964
14	30 December 1097, Friday	Antioch	A very fabulous sign was watched in the sky.	3	Silverman, 1998 Baldwin, 1969 Botley 1964 Kery, 1921
15	3 June 1098, Saturday	Antioch	A fiery red sky was seen.	2	Link, 1962 Silverman, 2006 Botley 1964

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Table 2 continued.

16	27 September 1098, Monday (10:00)	Edessa	A second omen appeared in the northern portion of the sky at the fourth hour of the night the sky flared up more than it had before and turned a deep red color.	4	Andreasyan, 2000 Link, 1962
17	27 September 1098, Monday	Antioch	Blaze of light girdled Pole.	1	Link, 1962 Botley, 1964
18	1099	Edessa	A fire-like omen of a very deep red color appeared in the sky.	3	Andreasyan, 2000 Link, 1962 Silverman, 2006
19	18 November 1100, Sunday	Edessa	The northern portion of the sky reddened, appearing more frightful and wondrous than the previous phenomenon.	3	Andreasyan, 2000 Silverman, 2006 Link, 1962
20	1108	Adana	A light like the sunlight was seen in the middle of the night, and remained about three hours in Djihan.	2	Chabot, 1968 Dall'Olmo, 1979
21	16 December 1117, Monday	Asia Minor			Link, 1962 Newton, 1972
22	1119	Asia Minor			Link, 1962
23	1 April 1143, Thursday	Edessa	A sign appeared in the sky from the north in the form of a luminous column	3	Andreasyan, 2000

584 **Table 3.**

#	City	Latitude [Degree, N]	Longitude [Degree, E]	Numbers of observation
1	Constantinople	41.03	28.99	9
2	Edessa	37.17	38.79	6
3	Amida	37.93	40.21	2
4	Antioch	36.2	36.16	3
5	Adana	36.99	35.34	1
6	Asia Minor	39.93	32.85	2
			Total	**23**

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593 **Table 4.**

#	Date	Place	Decriptions	References
1	65	Jerusalem		Botley, 1964
2	66	Jerusalem		Botley, 1964
3	400	Byzantium		Link, 1962
4	402	Byzantium		Link, 1962
5	473	Byzantium		Link, 1962
6	474	Byzantium		Link, 1962
7	502 Agust 22	Palestine	A great fire appeared to us blazing in the northern quarter the whole night	Botley, 1964
8	743 June	Syria	A mighty sign appeared in the heavens like columns of fire blazing in June	Chabot, 1968
9	743 September	Middle East	Another sign appeared in September like a flame of fire and spread from the East to the West	Cook, 2001
10	745 January	Middle East	In the middle of the sky, a large column of fire appeared during the night	Chabot, 1968
11	793 May 11-17	Iraq	There occurred a violent wind and overshadowing of the heavens and a redness in the sky, on the night of Sunday	Basworth, 1989
12	817 October 29	Iraq	A reddish glow appeared in the sky and stayed until late at night like a two red columns	Basurah, 2006
13	840 September 24	Middle East	A fiery cloud appeared in the northern part of the sky, moving from east to West.	Dall'Olmo, 1979
14	931 November 9	Baghdad	An intense red glow appeared in the city of Al-Salam (Baghdad)	Basurah, 2006
15	939 October 17	Syria	An intense red glow appeared in the atmosphere coming from North and West	Basurah, 2006
16	1050 Agust 5	Middle East	Through which light shone out broad and glittering, and then became extinguished	Le Strange, 1890
17	1097	Palestine		Botley, 1964
18	1100	Palestine		Botley, 1964
19	1102	Palestine		Botley, 1964
20	1106	Syria		Botley, 1964
21	1110	Syria		Botley, 1964
22	1117 December 16	Palestine		Newton, 1972 Botley, 1964
23	1119	Armenia		Botley, 1964
24	1121 May, Monday	Syria	There appeared a full arc, which had not been observed for many enerations	Botley, 1964
25	1129 January	Middle East	A fire appeared in the northern region. A sort of pillar was stretched toward the south.	Dall'Olmo, 1979
26	1129 March	Middle East	A fire appeared in the northern region. A sort of pillar was stretched toward the south.	Dall'Olmo, 1979

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Table 4. continued

27	1129 April	Middle East	A fire appeared in the northern region. A sort of pillar was stretched toward the south.	Dall'Olmo, 1979
28	1130 November	Middle East	A burning fire was seen in the northern region	Dall'Olmo, 1979
29	1135 July 21	Middle East	A light like a torch moved from east to West. The light of the moon and of the stars was obscured. A frightful noise followed	Dall'Olmo, 1979
30	1138 October	Syria	A red sign was seen in the northern part of the sky	Botley, 1964
31	1140 June 22	Syria	Red lances were seen in the northern region.	Botley, 1964
32	1141 August	Middle East	Rays of fire were observed in the northern region.	Dall'Olmo, 1979
33	1141 September	Syria	A brightness as bright as the sun broke out in the northeast. It shone as if the sky were on fire.	Botley, 1964
34	1149	Syria		Botley, 1964
35	1150	Palestine		Botley, 1964
36 37	1176 September 6 - October 5	Syria	An intense red light appeared in the sky from the East	Basurah, 2006
	1179 May 7	Syria	The sky became cloudy and pillars of fire appeared at the horizon	Basurah, 2006
38	1182	Byzantium		Link, 1962
39	1187 July	Tiberias, Israel		Botley, 1964
40	1223 October 26	Syria	We saw from Bani Helal Mountain (toward the North direction) a hugelight over Gassune; we thought that Damascus was on fire.	Basurah, 2006
41	1264 July 20–30	Syria	A bright glowing columns appeared toward North-West	Basurah, 2006
42	1370 November 27	Jerusalem	A great reddish glow appeared in the sky of Jerusalem	Basurah, 2006
43	1370 November 27	Damascus	A great reddish glow appeared in the sky of Damascus	Basurah, 2006
44	1370 November 27	Homs	A great reddish glow appeared in the sky of Homs	Basurah, 2006
45	1370 November 27	Aleppo	A great reddish glow appeared in the sky of Aleppo	Basurah, 2006

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Table 5.

Medieval Period		Climate
Haldon et al. (2014)	**This Study**	
270-540	0-560	Dry
540-750	560-725	Very wet
750-950	725-990	Moderately dry
950-1400	990-1400	Moderately wet

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Figures

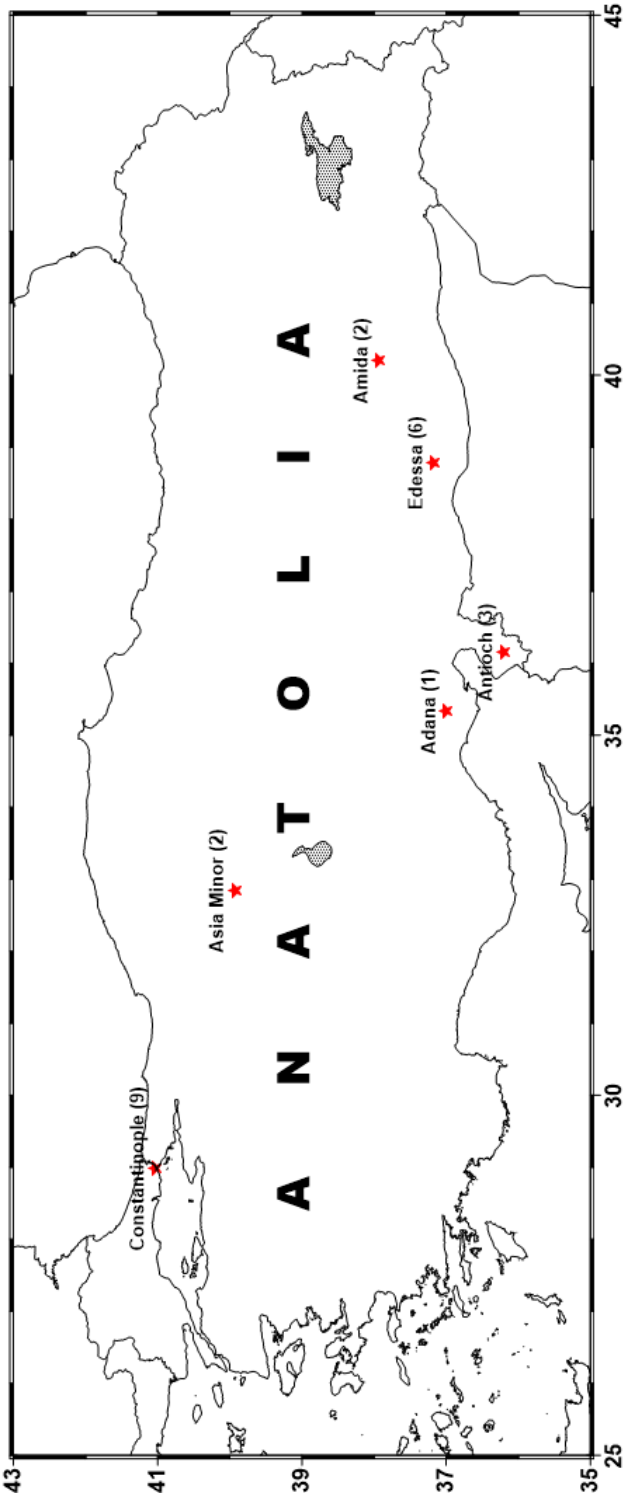

Figure 1.

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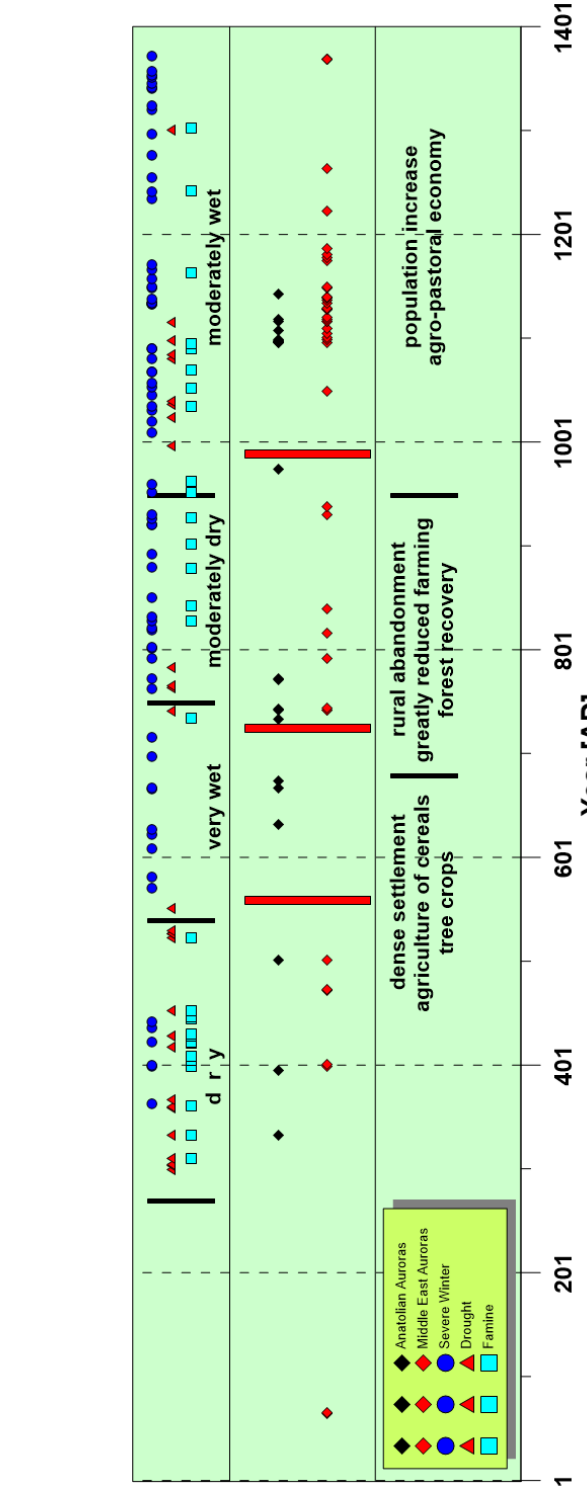

Figure 2.

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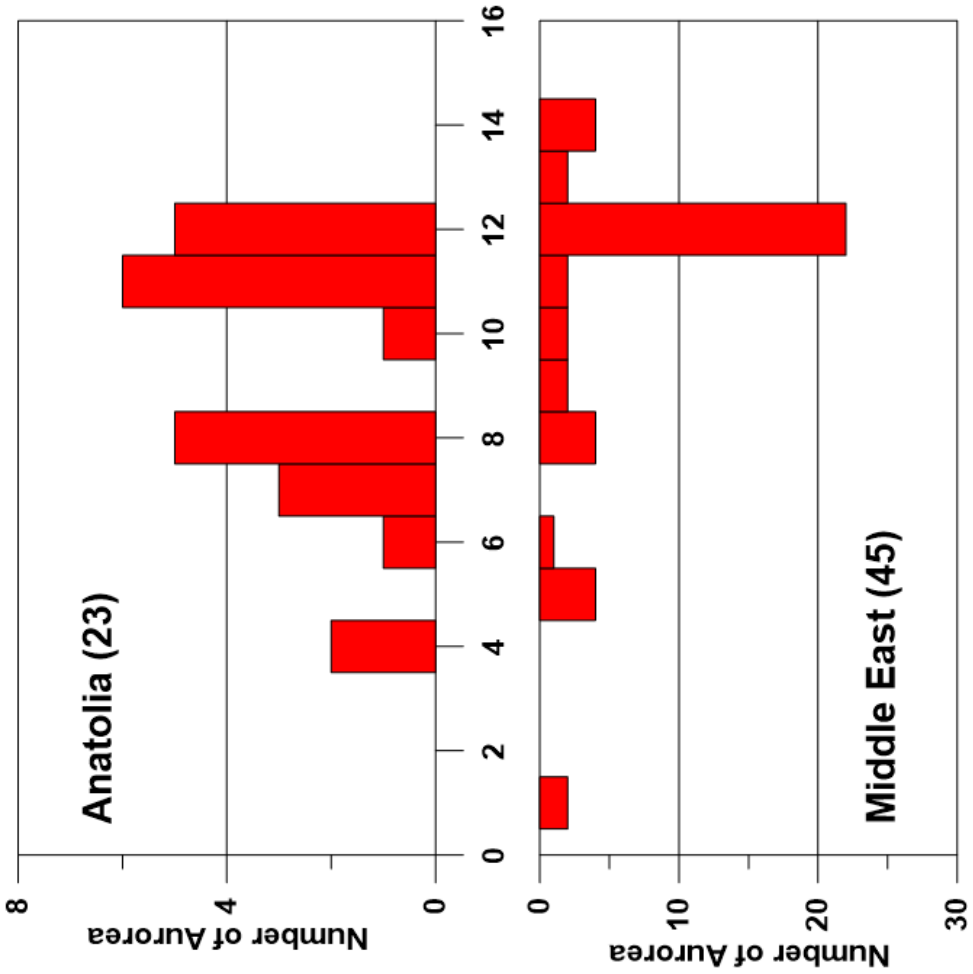

Figure 3.