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HOLOCENE CLIMATE CHANGES AND CULTURAL RESPONSES IN CENTRAL ASIAN ARID ZONE

The synthesized regionally-averaged temperature-index curve from the entire Altai Mountains within the Central Asian Arid Zone (CAAZ) shows that the Holocene temperature has sensitively responded to the annual solar irradiance. The synthesized regionally-averaged aridity-index curve exhibits a persistent and slight drying trend during the Holocene in high-elevation regions and the effect of permafrost thawing in high-elevation regions was blamed for the drying trend. The persistent wetting trend in low-elevation regions, together with the induced Holocene precipitation increasing trend, seems to be parallel with the increasing trend of the winter precipitation anomaly in Norway, and both (precipitation index in Altai and winter precipitation anomaly in Norway) were probably causally associated with the AMO-like event trend in the North Atlantic Ocean.

Being compensatory or supplementary or contradictory with the aforementioned moisture declining trend in high-elevation regions and with the aforementioned moisture rising trend in low-elevation regions, more recent reports show that the averaged light absorbance (a humification proxy) curve from the southern Altai Mountains within the Central Asian Arid Zone (CAAZ) is a bow-shaped one. That is, the highest light absorbance occurred in the middle Holocene (~8200-~4200 cal. yr BP) when regionally-averaged moisture was the lowest under relatively high-temperature conditions. And, this bow-shaped curve is well corroborated by other proxy data from nearby sites. In addition, superimposed on the bow-shaped curve are several major troughs (i.e., wetter intervals). The troughs definitely occurred in following intervals: ~8600-~8400, ~7800-~7400, ~6500-~5300, ~3800-~3200 and ~1900-~1200 cal. yr BP.

The $\delta^{13}C$-signified moisture reconstruction in the Yushenkule Peat within the southern Altai Mountains or Chinese Altai revealed four wet stages (~200 BC-~400 AD, ~600-~800 AD, ~1000-~1250 AD, ~1600-2013 AD) and three dry stages (~400-~600 AD, ~800-~1000 AD, ~1250-~1600 AD) during the past ~2200 years. The moisture variations over the past 2200 years seem to have been generally controlled by the mean annual precipitation (MAP) and somewhat modulated by the summer (JJA) temperature reconstructed from the northern Altai Mountains. In general, the climate (temperature, precipitation, and moisture) of the past ~2000 years was modulated by solar activities.

Key words: Central Asian Arid Zone, Holocene, Climate Change, Altai Mountains.

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Голоценді ауа-райының өзгеруі және Орталық Азия аридтік аймағының мәдени өзгеруі

Орта Азиялық аридтік аймақтың (CAAZ) ішіндегі бүкіл Алтай тауларынан аймақтық синтезделген температура индексі қисығы, голоцен температурасы жыл сайынғы күн сәулесіне өте сезімтал әсер еткенін көрсетеді. Синтезделген аймақтық орташа кеуімділік индексі жоғары деңгейлі аймақтарда голоцен кезеңінде тұрақты және аздап құрғау үрдісін көрсетеді, ал биік таулы аймақтарда мәңгі мұзды еру әсері кептіру үрдісі үшін айыпталды. Төменгі биіктіктегі ылғалдың тұрақты тенденциясы, галогендік жауын-шашынның көтерілу тенденциясы, Норвегиядағы қысқы жауын-шашын аномалиясының өсу тенденциясымен параллель көрінеді және екеуі де (Алтайдағы жауын-шашын индексі және Норвегиядағы қысқы жауын-шашын аномалиясы) Солтүстік Атлант мұхитындағы АМО-ға ұқсас оқиға трендімен байланысты болуы мүмкін.

Соңғы өте жоғары есептер жоғары биіктіктегі аймақтардағы ылғалдың төмендеу тенденциясымен және төмен ылғалданған аймақтарда ылғалдың көтерілу тенденциясымен өтемдік немесе қосымша немесе қайшылықты бола отырып, соңғы есептер оңтүстік Алтай тауларынан түсетін жарық сіңірудің (ылғалдандыру проксиі) қисығы екендігін көрсетеді. Орталық Азияның құрғақ зонасы (CAAZ) – садақ тәрізді аймақ. Яғни, ең жоғары жарық сіңіру орташа холоценде (~ 8200 – ~ 4200 кал.э.д. BP) болды, салыстырмалы жоғары температура жағдайында аймақтық орташа ылғалдылық ең төмен болған кезде. Бұл садақ тәрізді қисық сызық жақын жердегі басқа прокси деректермен жақсы расталады. Сонымен қатар, садақ тәрізді қисық сызық бірнеше негізгі өзектер болып табылады (яғни, ылғалды аралықтармен). Табандар келесі аралықтарда пайда болды: ~ 8600- ~ 8400, ~ 7800- ~ 7400, ~ 6500- ~ 5300, ~ 3800- ~ 3200 және ~ 1900 ~ ~ 1200 кал. (yr BP).

Оңтүстік Алтай тауларындағы немесе Қытайлық Алтайдағы δ13C белгісімен ылғалдың қалпына келуі төрт ылғалды кезеңді анықтады (б.э.д. 200 – ~ 400 ж., ~ 600 – ~ 800 AD, ~ 1000 – ~ 1250 AD, ~ 1600-2013 BC)) және соңғы ~ 2200 жыл ішінде үш құрғақ кезең (~ 400 – ~ 600 AD, ~ 800 – ~ 1000 AD, ~ 1250 – ~ 1600 AD). Соңғы 2200 жылдағы ылғалдың өзгеруі орташа жылдық жауын-шашынмен (MAP) бақыланған және жазғы (JJA) солтүстік Алтай тауларынан қалпына келтірілген температурамен реттелген сияқты. Жалпы, соңғы ~ 2000 жылдағы климат (температура, жауын-шашын және ылғалдылық) күн белсенділігімен модуляцияланды.

Түйін сөздер: Орта Азияның құрғақ зонасы, голоцен, климаттың өзгеруі, Алтай таулары.

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Изменения климата в голоцене и культурные реакции в аридной зоне Центральной Азии

Синтезированная регионально-усредненная кривая температурного индекса для всего Горного Алтая в пределах Центрально-Азиатской аридной зоны (CAAZ) показывает, что температура голоцена чутко реагировала на годовое солнечное излучение. Синтезированная кривая индекса засушливости, усредненная по регионам, демонстрирует устойчивую и незначительную тенденцию к высыханию в течение голоцена в высокогорных регионах, а эффект таяния вечной мерзлоты в высокогорных районах был объяснен тенденцией к высыханию. Устойчивая тенденция к увлажнению в низинных регионах, вместе с индуцированной тенденцией к увеличению количества осадков в голоцене, похоже, наблюдается параллельно с тенденцией увеличения аномалии зимних осадков в Норвегии, при этом оба (индекс осадков на Алтае и аномалия зимних осадков в Норвегии) были, вероятно, причинно связаны с тенденцией событий, подобных АМО, в северной части Атлантического океана.

Будучи компенсирующими, дополнительными или противоречащими вышеупомянутой тенденции к снижению влажности в высокогорных районах и вышеупомянутой тенденции повышения влажности в низинных регионах, более поздние отчеты показывают, что усредненная кривая поглощения света (гумификационный прокси) для южных районов Алтая в пределах Центральноазиатской аридной зоны (ЦААЗ) – дугообразная. То есть наибольшее поглощение света имело место в среднем голоцене (~ 8200- ~ 4200 кал. Лет назад), когда регионально усредненная влажность была самой низкой в условиях относительно высоких температур. И эта дугообразная кривая хорошо подтверждается другими прокси-данными с подобных сайтов. Кроме того, на дугообразную кривую накладывается несколько основных впадин (т.е. более влажные интервалы). Впадины определенно происходили в следующих интервалах: ~ 8600- ~ 8400, ~ 7800- ~ 7400, ~ 6500- ~ 5300, ~ 3800- ~ 3200 и ~ 1900- ~ 1200 кал. (yr BP).

Реконструкция влажности в торфе Юшенкуле на юге Алтая или в Китайском Алтае, означающая δ13C, выявила четыре влажные стадии (~ 200 г. до н.э.- ~ 400 г. н.э., ~ 600- ~ 800 г. н.э., ~ 1000- ~ 1250 г. н.э., ~ 1600-2013 гг.) и три стадии засухи (~ 400- ~ 600 нашей эры, ~ 800- ~ 1000 нашей эры, ~ 1250- ~ 1600 нашей эры) за последние ~ 2200 лет. Изменения влажности за последние 2200 лет, по-видимому, в основном контролировались среднегодовым количеством осадков (MAP) и в некоторой степени модулировались летней температурой (JJA), восстановленной по данным северных гор Алтая. В целом климат (температура, осадки и влажность) за последние ~ 2000 лет был изменен солнечной активностью.

Ключевые слова: аридная зона Центральной Азии, голоцен, изменение климата, горный Алтай.

Eurasian Perspectives of Modern Climate

The Central Asian Arid Zone (CAAZ: 50-110°E and 35-50°N) is loosely defined as the area stretching from western Kazakhstan to eastern Mongolia and is a result of the combined effects of the Siberian High in the eastern part and the Azores High in the western part. Specifically, westward extension of the Siberian High during cold seasons and eastward extension of the Azores High during warm seasons resulted in a nearly permanent high pressure ridge in the CAAZ where deserts and steppes developed (Feng et al., 2011). The cold-season climate in the CAAZ is presently controlled by the interactions between the Siberian High and the Westerlies and the latter (i.e., Westerlies) is in turn modulated by the North Atlantic Oscillation (NAO) (Fig. 1A). Specifically, negatively-phased NAO induces the westward and southward expansion of the Siberian High, consequently lowering the winter temperature and precipitation in the downwind areas including the CAAZ (Aizen et al., 2001; Bridgman and Oliver, 2006; Meeker and Mayewski, 2002). The warm season climate in the CAAZ is presently controlled by the interactions between the Asian Low occupying the interiors of Asia and the Azores High reaching the CAAZ (Fig. 1B).

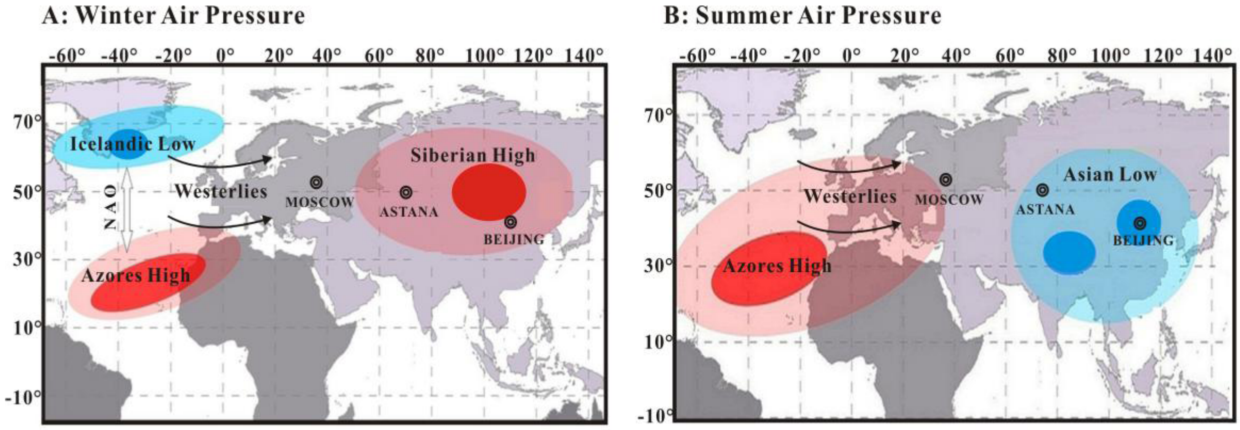

Figure 1 – Climatic systems influencing the Central Asian Arid Zone (CAAZ). A: Winter air pressure systems: the strength of Siberia High is modulated by North Atlantic Oscillations (NAO) that are in turn controlled by the pressure contrast between Icelandic Low and Azores High. B: Summer air pressure systems: the Asian Low not only allures the Pacific High to the Asian interior but also induces the Azores High to penetrate into the CAAZ. Note 1: the dark-red circles within the light-red circles are the cores of high pressure cells. Note 2: the dark-blue circles within the light-blue circles are the cores of low pressure cells.

Holocene (i.e., past ~11,700 years) climate changes are of particular significance because the future climate changes will most likely occur under similar boundary conditions (Ruddiman, 2014). However, the temporal and spatial patterns and the driving mechanisms of the Holocene moisture variations in the CAAZ with the Altai Mountains in the center have been heatedly debated. For example, Herzschuh (2006) argued that the westerlies-dominated CAAZ has experienced a similar Holocene moisture trend with that of monsoon-dominated China, i.e., a warm-wet early-middle Holocene and a cool-dry late Holocene in the CAAZ. However, Chen et al. (2008) contested that CAAZ has witnessed a Holocene moisture-change trend opposite to that of monsoon-dominated China, i.e., a warm-dry early-middle Holocene and a cool-wet late Holocene in CAAZ. Furthermore, Feng et al. (2017) and Xu et al. (2019) reported a severe mid-Holocene drier interval (~7000-~4000 cal. yr BP) in the Altai Mountains.

Central Asian Perspectives of Holocene Moisture

Assuming that the synthesized annual temperature anomaly of Northern Hemisphere (Marcott et al., 2013) is more or less universally acceptable for the entire Northern Hemisphere, the chronological relationships between the temperature anomaly and the regionally-averaged moisture index (i.e., RA-Moisture Index or Normalized Moisture Index) retrieved from the Central Asian Arid Zone (CAAZ) are far from being straightforward. Specifically, the regionally-averaged moisture index curve in northern Xinjiang (Fig. 2A) and the reconstructed woody coverage (as a moisture proxy) in Kazakhstan Hills (Fig. 2B) show that the moisture in the arid core of CAAZ (including northern Xinjiang and eastern Kazakhstan) has been increasing during the past ~8000 years (Ran et al., 2015; Tarasov et al., 1997). The increasing trend was proposed to have been associated with the increasing trend of cold-season temperature in northern Europe that might have led to an increasing trend of positively-phased North Atlantic Oscillations (NAO) (Ran et al., 2015).

The regionally-averaged moisture curves in the Altai Mountains (Fig. 2C) and in the adjacent Baikal Basin (Fig. 2D) seem to be more or less parallel with the Holocene warm-season temperature curve in northern Europe that is in turn more or less parallel with the annual temperature anomaly curve of Northern Hemisphere (Wang and Feng, 2013). However, a later synthesis (Zhang and Feng, 2018) and several later works (Zhang et al., 2020a, 2020b) show that the Holocene moisture evolution problems in the Altai Mountains, probably as well as in the Baikal Basin, were not yet sufficiently resolved (see next section for details).

The regionally-averaged moisture curves in northern Mongolian Plateau (Fig. 2E) and in southern Mongolian Plateau (Fig. 2F) seem to be inversely correlated with the annual temperature anomaly curve of Northern Hemisphere. That is, the Holocene regionally-averaged moisture in the generally hyper-arid Mongolian Plateau has been nearly completely controlled by the temperature. In other words, the higher the temperature, the lower the moisture was (Wang and Feng, 2013).

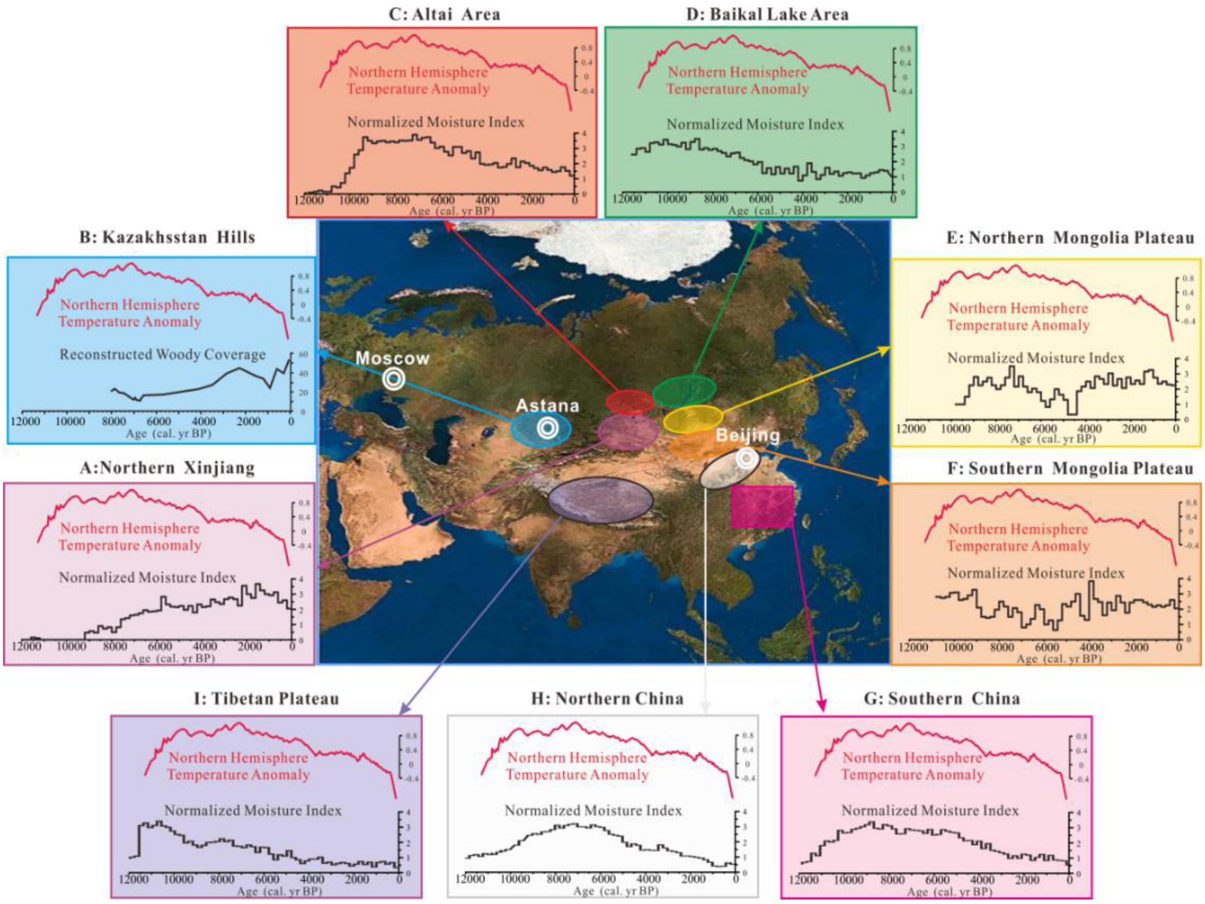

Figure 2 – Moisture variations in CAAZ and the surrounding areas and their comparisons with the temperature anomaly of Northern Hemisphere (Marcott et al., 2013). A: Regionally-averaged moisture index (RA-Moisture Index or Normalized Moisture Index) in northern Xinjiang (Ran et al., 2015). B: Reconstructed woody coverage (as a moisture proxy) in Kazakhstan Hills (Tarasov et al., 1997). C: RA-Moisture Index in the Altai Mountains (Wang and Feng, 2013). D: RA-Moisture Index in Baikal basin (Wang and Feng, 2013). E: RA-Moisture Index in northern Mongolian Plateau (Wang and Feng, 2013). F: RA-Moisture Index in southern Mongolian Plateau (Wang and Feng, 2013). G: RA-Moisture Index in northern China (Ran and Feng, 2013). H: RA-Moisture Index in southern China (Ran and Feng, 2013). I: RA-Moisture Index in the Tibetan Plateau (Ran and Feng, 2013)

The regionally-averaged moisture curves in northern China (Fig. 2G) and in southern China (Fig. 2H) appear to well reflect the East Asian Monsoon intensity that was determined by the sea-surface temperature (SST) in the West Tropical Pacific Ocean, the latter (i.e., SST) being in turn determined by the summer insolation in Northern Hemisphere (Ran and Feng, 2013; Sun and Feng, 2013).

The regionally-averaged moisture curve in the Tibetan Plateau (Fig. 2I) shows that the moisture has been persistently declining since ~11,000 cal. yr BP and that the period between ~11,500 and ~7500 cal. yr BP was the Holocene Moisture Optimum. The parallel trends between the moisture level in the Tibetan Plateau and the Indian summer monsoon strength retrieved from the Arabian Sea suggest that the Tibetan Plateau might have been under influence of the Indian summer monsoon throughout the Holocene (Ran and Feng, 2013).

Moisture Variation in Altai Mountains during Past ~10,000 Years

Now we zoom into the Altai Mountains within the center of the CAAZ. The mountain range might have been an important climatic conjunction between the westerlies airflows and the Asian monsoonal airflows during the Holocene (Blyakharchuk et al., 2007; Chen et al., 2008; Feng et al., 2017; Rudaya et al., 2009). And, the mountain range is also reported to have been a topographic barrier or bridge of the communication between the oriental cultures and the occidental cultures and the Holocene climate change might have affected the effectiveness of the barrier or bridge (Blyakharchuk and Chernova, 2013).

Differences between high-elevation and low-elevation regions

Based on pollen data from the 30 pollen sequences published so far, the spatial and temporal variations in temperature and also in aridity during the Holocene in the Altai Mountains and also in the surrounding areas were synthesized by Zhang and Feng (2018). The synthesized regionally-averaged temperature-index curve (Fig. 3b) from the entire Altai Mountains shows that the climate was consistently warming from ~12,000 and ~9000 cal. yr BP and has experienced a gradual cooling since ~9000 cal. yr BP. It means that the Holocene temperature has sensitively responded to the annual solar irradiance, being more or less parallel with the annual temperature anomaly curve of Northern Hemisphere (Fig. 3a).

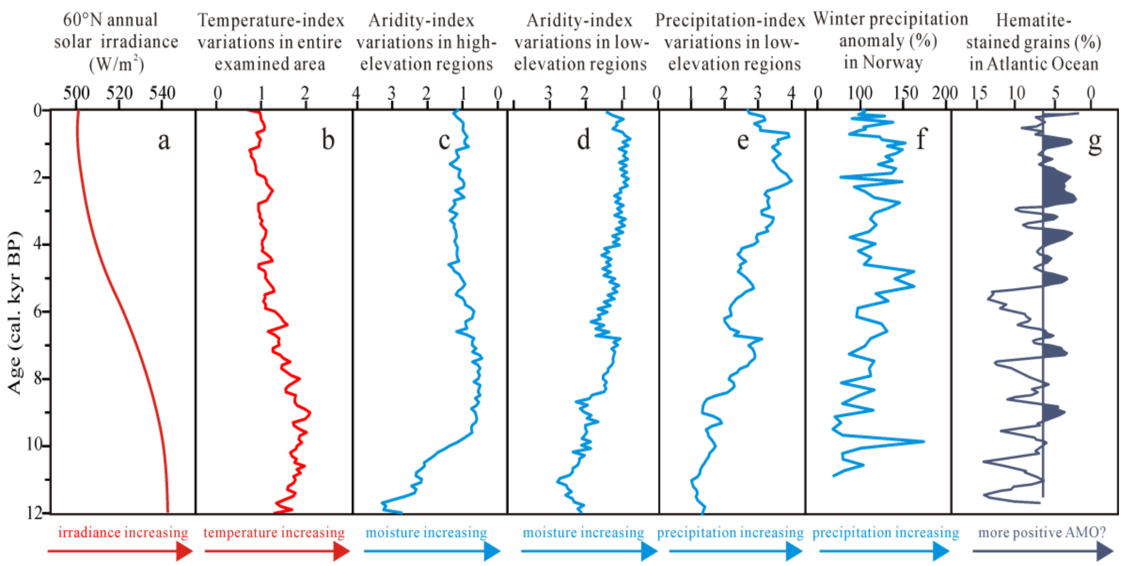

Figure 3 – Holocene climate changes in the Altai Mountains. a: 60°N annual solar irradiance; b: Temperature-index variations in the Altai Mountains (Zhang and Feng, 2018); c: Aridity-index variations in high-elevation regions of the Altai Mountains (Zhang and Feng, 2018); d: Aridity-index variations in low-elevation regions of the Altai Mountains (Zhang and Feng, 2018); e: Induced precipitation-index variations in low-elevation regions of the Altai Mountains (Zhang et al., 2018); f: Winter precipitation anomaly in Norway (Bakke et al., 2008); g: Percentage of Hematite-stained grains in the North Atlantic Ocean (Bond et al., 1997)

The synthesized regionally-averaged aridity-index curve exhibits a persistent and slight drying trend during the Holocene in high-elevation regions (Fig. 3c). The drying trend is similar to the one reported by Wang and Feng (2013) and the effect of permafrost thawing in high-elevation regions was blamed for the drying trend (Zhang and Feng, 2018). In contrast, the synthesized regionally-averaged aridity-index curve (Fig. 3d) exhibits a persistent wetting trend during the Holocene in low-elevation regions (Zhang and Feng, 2018). The deduced Holocene precipitation-index variations (Fig. 3e) suggest that the Holocene wetting trend in low-elevation regions was resulted from a combined effect of temperature decreasing and precipitation increasing (Zhang et al., 2018). The induced Holocene precipitation increasing trend, together with the persistent wetting trend, seems to be parallel with the increasing trend of the winter precipitation anomaly in Norway (Bakke et al., 2008), and both (precipitation index in Altai and winter precipitation anomaly in Norway) were probably causally associated with the Holocene AMO-like events in the North Atlantic Ocean (Feng et al., 2009) that are expressed as the percentages of hematite stained grains (Bond et al., 1997).

Differences among difference time periods

The Holocene that began at ~11,700 cal. yr BP was divided into three stages by the international stratigraphic chronology committee: warming Greenlandian stage (~11,700-~8200 cal. yr BP), warm Northgrippian stage (~8200-~4200 cal. yr BP) and cooling Meghalayan stage (~4200-0 cal. yr BP) (Walker et al., 2012; Ran and Chen, 2019). The three-stage division was reported to be reasonably corroborated by the averaged light absorbance residuals of the four studied peat cores (Narenxia, Tuolehaite, Ganhaizi, Kelashazi; Zhang et al., 2020b). Specifically, the averaged residuals of the four studied peat cores (Fig. 4a) are generally higher in the middle Holocene (~8200-~4000 cal. yr BP) than in the early Holocene (before ~8200 cal. yr BP) and also than in the late Holocene (after ~4000 cal. yr BP). The light absorbance residual-indicated three-stage division in the southern Altai Mountains is reasonably corroborated by several Holocene moisture sequences from nearby sites that were relatively well dated and in which the used proxies for moisture were well justified.

The first such a site is Tuolehaite Peat (48.44°N, 87.54°E, 1700 m a.s.l.) where the A/C (i.e., *Artemisia*/Chenopediaceae) ratio was justified to be indicative of the basin-wide moisture (Zhang et al., 2020a). As shown in Figure 4b, the A/C ratio-indicated moisture level was generally lower in the middle Holocene (~8500-~4000 cal. yr BP) than in the early Holocene (before ~8500 cal. yr BP) and than in the late Holocene (after ~4000 cal. yr BP). The second such a site is Ganhaizi Peat (48.41ºN, 87.56ºE, 1926 m a.s.l.) where the n-alkane-based P_{aq} (the proportion of aquatic components) was justified to be indicative of the peat-surface moisture (Ran et al., 2020). As shown in Figure 4c, the P_{aq}-indicated moisture level was generally lower in the middle Holocene (~9000-~4500 cal. yr BP) than in the early Holocene (before ~9000 cal. yr BP) and than in the late Holocene (after ~4500 cal. yr BP). The third such a site is Kanas Lake site (48.72°N, 87.02°E, 1365 m a.s.l.) where the A/C-indicated basin-wide moisture variations (Fig. 4d; Huang et al., 2018) are in a relatively good agreement with the three-stage variations in the averaged light absorbance residuals of the four studied peat cores (Fig. 4a). The fourth such a site is Big Black Peat (48.68°N, 87.18°E, 2100 m a.s.l.) where the A/C-indicated basin-wide moisture variations (Fig. 4e; Xu et al., 2019) are in a broad agreement with the three-stage variations in the averaged light absorbance residuals. Finally, the three-stage variations in the averaged light absorbance residuals in the southern Altai Mountains (Fig. 4a) are reasonably corroborated by the synthesized aridity index from four pollen sequences including Achit Lake, Bayan Nuur, Uggi Lake and Telmen Lake in the adjacent western Mongolia (Fig. 4f; Zhang and Feng, 2018). That is, the moisture level in western Mongolia was definitely lower in the middle Holocene (~8500-~4000 cal. yr BP) than in the early Holocene (before ~8500 cal. yr BP) and also than in the late Holocene (after ~4000 cal. yr BP).

In terms of the regional Holocene temperature in the Altai Mountains, the average n-alkane chain length (ACL) data from Ganhaizi Peat (48.41ºN, 87.56ºE, 1926 m a.s.l.) seem to tell a similar story as the temperature anomaly of the Northern Hemisphere (Marcott et al., 2013). The average n-alkane chain length (ACL) is the weighted mean n-alkane chain length of a given sample. The justification for the temperature proxy is that plants prefer to develop longer chain alkanes under warmer conditions in order to avoid loss of water during transpiration. Thus, higher ACL values are indicative of warmer conditions and vice verse (Ran et al., 2020). The ACL-recorded temperature in Ganhaizi Peat displays a straight warming trend before ~8500 cal. yr BP and a general cooling trend after ~8500 cal. yr BP (Fig. 4g; Ran et al., 2020), being more or less consistent with the temperature anomaly synthesized for the Northern Hemisphere (Fig. 4h; Marcott et al., 2013).

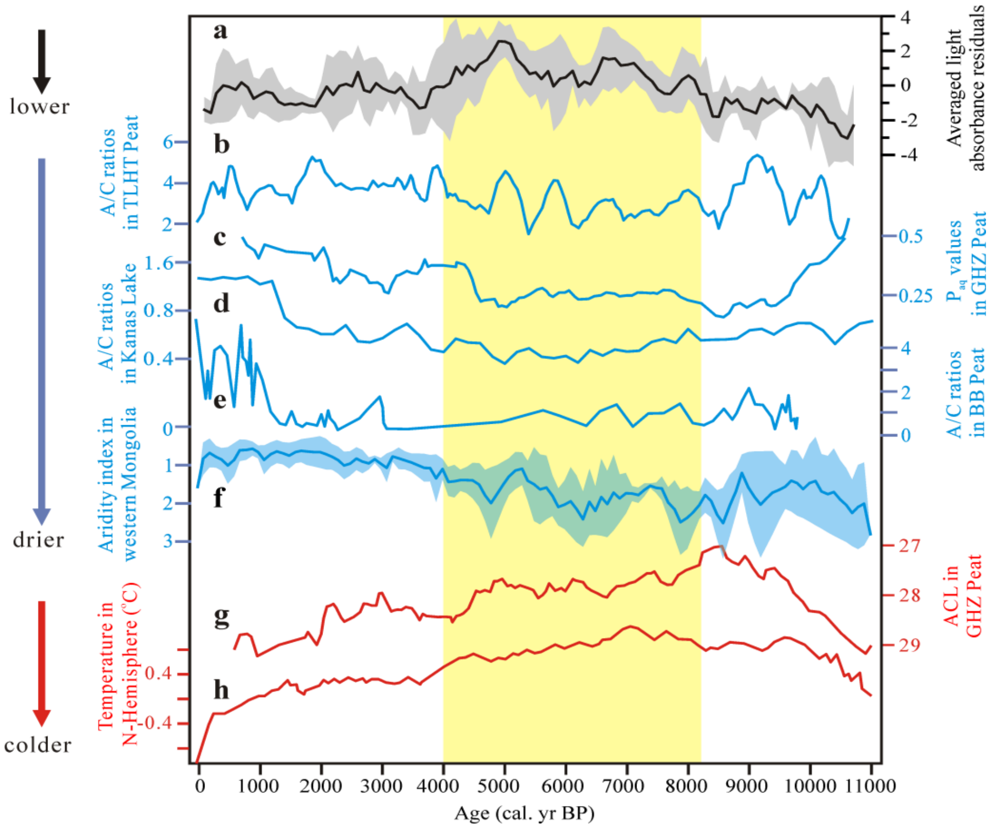

Figure 4 – Comparison of the Holocene climate records in the southern Altai Mountains and the surrounding areas. a, Averaged light absorbance residuals of four peat cores (Narenxia, Tuolehaite, Ganhaizi and Kalashazi; Zhang et al., 2020b); b, A/C-indicated moisture in Tuolehaite Peat (Zhang et al., 2020a); c, P_{aq}-indicated moisture in Ganhaizi Peat (Ran et al., 2020); d, A/C-indicated moisture in Kanas Lake (Huang et al., 2018); e, A/C-indicated moisture in Big Black Peat (Huang et al., 2018); f, Synthesized aridity index in western Mongolia (Zhang and Feng, 2018); g, ACL (average chain length)-indicated temperature in Ganhaizi Peat (Ran et al., 2020); h, Temperature anomaly in the Northern Hemisphere (Marcott et al., 2013)

Millennial-scale humification variations

As shown in Figure 4a, the averaged light absorbance curve is a bow-shaped one (Zhang et al., 2020b). That is, the highest averaged light absorbance occurred in the middle Holocene (~8200-~4200 cal. yr BP) when regionally-averaged moisture was the lowest (Fig. 4b-f) under relatively high-temperature conditions (Fig. 4g-h). And, superimposed on the bow-shaped curve are several major troughs (i.e., low light-absorbance intervals or low-humification intervals or wetter intervals). The troughs definitely occurred in following intervals: ~8600-~8400, ~7800-~7400, ~6500-~5300, ~3800-~3200 and ~1900-~1200 cal. yr BP, and two more troughs might have occurred at ~10,600-~10,400 and ~9700-~9400 cal. yr BP (Fig. 5a). It is quite noticeable that those humification troughs in the southern Altai Mountains are chronologically correspondent with those high-percentage intervals of the hematite-stained grains in the North Atlantic Ocean (Fig. 5b; Bond et al., 1997). It means that the decay degree of organic matter in the peats of the southern Altai Mountains was lower during lower sea surface temperature (SST) intervals as suggested by higher percentages of the hematite-stained grains in the North Atlantic Ocean. In other words, the millennial-scale chronological correspondence between the lower SST intervals in the North Atlantic Ocean and the lower humification intervals in the southern Altai Mountains implies that both the lower temperature and the lower temperature-suppressed evaporation (i.e., elevated moisture level) were most likely responsible for inerting the microbial activity in the uppermost peat layer in the southern Altai Mountains (Zhang et al., 2020b).

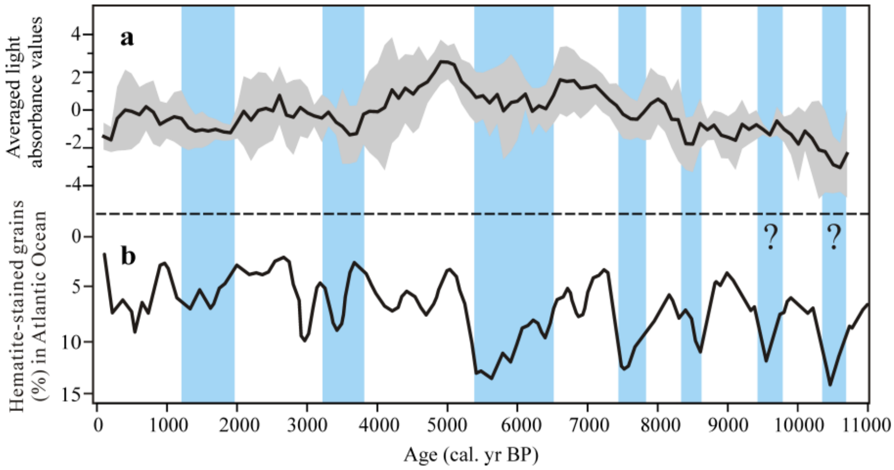

Figure 5 – Comparison of the hematite-stained grains (%) in the North Atlantic (b) (Bond et al., 1997) with the averaged light absorbance residuals (a) of four peat cores (Narenxia, Tuolehaite, Ganhaizi and Kalashazi; Zhang et al., 2020b) in the southern Altai Mountains. Vertical bands indicate the corresponding relationships between the lower-value stages of the light absorbance residuals in the southern Altai Mountains and the higher-value stages of the hematite-stained grains (%) in the North Atlantic Ocean

Controversies continue

As stated earlier, the temporal and spatial patterns and the driving mechanisms of the Holocene moisture variations in the CAAZ with the Altai Mountains in the center have been heatedly debated. For example, Herzschuh (2006) argued that the westerlies-dominated CAAZ has experienced a similar Holocene moisture trend with that of monsoon-dominated China, i.e., a drying trend in the CAAZ. However, Chen et al. (2008) contested that CAAZ has witnessed a Holocene moisture-change trend opposite to that of monsoon-dominated China, i.e., a wetting trend in CAAZ. Furthermore, Feng et al. (2017) and Xu et al. (2019) reported a severe mid-Holocene drier interval (~7000-~4000 cal. yr BP) in the Altai Mountains. The drying-trend proposal (Herzschuh, 2006) was supported by our pollen-data synthesis for high-elevation regions (Wang and Feng, 2013; Zhang and Feng, 2018), and the wetting-trend proposal (Chen et al., 2008) was supported by our pollen-data synthesis for low-elevation regions (Zhang and Feng, 2018; Yang et al., 2019a). Furthermore, the severe mid-Holocene (~7000-~4000 cal. yr BP) dry-interval proposal (Feng et al., 2017; Xu et al., 2019) was reasonably well corroborated by recent pollen- and humification-based works (Zhang et al., 2020a, 2020b) as shown in Figure 4. Were these aforementioned differences or discrepancies resulted from the differences in elevations or/and in latitudes or/and in longitudes? Or were they resulted from differences in archive types (e.g., lakes, peats, loess section)? Or were they resulted from the differences in local hydrological settings (e.g., glacier-meting related, permafrost-thawing related, winter snowfall related, summer rainfall related)? Or were they resulted from differences in temporal scales (general trends, millennial, centennial) or/and in spatial scales (e.g., lake-wide signature, low-relief basin-wide signature, high-relief basin-wide signature)? All in all, more intensive and more extensive in-depth investigations in the CAAZ (Central Asian Arid Zone) including the Altai Mountains are still in need.

Moisture Variation in Altai Mountains during Past ~2000 Years

General information

This part of our paper deals with a well-dated peat core (88-cm long) obtained from the Yushenkule Peat in the southern Altai Mountains or Chinese Altai (46°49′N, 90°52′E, 2636 m a.s.l.) by analyzing the carbon isotopic composition of peat *sphagnum*. The environmental meaning of peat *sphagnum* $\delta^{13}C$ values was well supported by the reconstructed peat surface moisture in the adjacent southern Siberia (Willis et al., 2015). The moisture history over the past 2200 years in the southern Altai Mountains or Chinese Altai was reconstructed on the basis of peat *sphagnum* $\delta^{13}C$ values (Fig. 6; Yang et al., 2019b), and the results were compared with the summer (JJA) temperature reconstruction (Büntgen et al., 2016) and the mean annual precipitation (MAP) reconstruction (Kalugin et al., 2013) in the northern Altai Mountains for delineating the regional hydroclimate history.

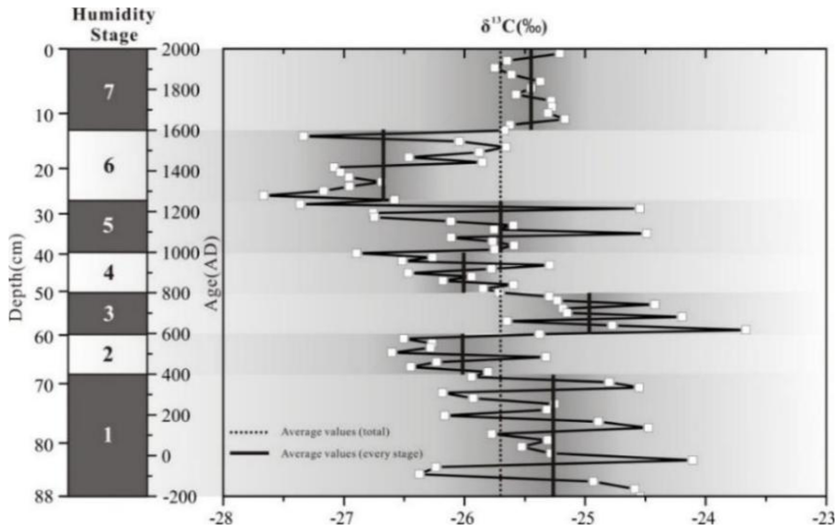

Figure 6 – Peat sphagnum $\delta^{13}C$ data were retrieved from a well-dated peat core (88-cm long) obtained from the Yushenkule Peat in the southern Altai Mountains or Chinese Altai (46°49′N, 90°52′E, 2636 m a.s.l.) (Yang et al., 2019b)

Peat *sphagnum* $\delta^{13}C$ data from Yushenkule Peat

The peat *sphagnum* $\delta^{13}C$ data (Yang et al., 2019b) show that the moisture variations of the past ~2200 years from Yushenkule Peat can be divided into seven stages (Fig. 6). Stage 1 (~200 BC-~400 AD) was a wet period with a moisture decreasing trend. Stage 2 (~400-~600 AD) experienced a moderately drying. Stage 3 lasting from ~600 to ~800 AD was the wettest period followed by the drying stage 4 (~800-~1100 AD). Stage 5 (~1100-~1250 AD) was a relatively wet period with drastic fluctuations. Stage 6 (~1250-~1600 AD) was typified by a remarkable drying, and the stage 7 lasting from ~1600 to 2013 AD was typified by a generally wet and relatively stable climate conditions.

Climate Change of Past ~2000 Years

The $\delta^{13}C$-signified moisture reconstruction in the Yushenkule Peat within the southern Altai Mountains or Chinese Altai revealed four wet stages (~200 BC-~400 AD, ~600-~800 AD, ~1000-~1250 AD, ~1600-2013 AD) and three dry stages (~400-~600 AD, ~800-~1000 AD, ~1250-~1600 AD) (i.e., last curve in Fig. 7). The moisture variations over the past 2200 years in the southern Altai Mountains seem to have been generally controlled by the mean annual precipitation (MAP) (i.e., middle curve in Fig. 7) and somewhat modulated by the summer (JJA) temperature (i.e., first curve in Fig. 7) in the northern Altai Mountains. It should be particularly noted that both the MAP and the summer temperature in the northern Altai Mountains were quantitatively reconstructed on the basis of statistical relationships between the instrument records and the used proxy data (i.e., tree rings for temperature and sediment chemical compositions for precipitation). It should also be particularly noted that a generally wet condition during the last ~200 years (~1800-~2013 AD) in the Yushenkule Peat can be explained neither by the decreased precipitation nor by the increased summer temperature. The oddness was speculated to be associated with the observed sudden change in plant composition (Yang et al., 2019b).

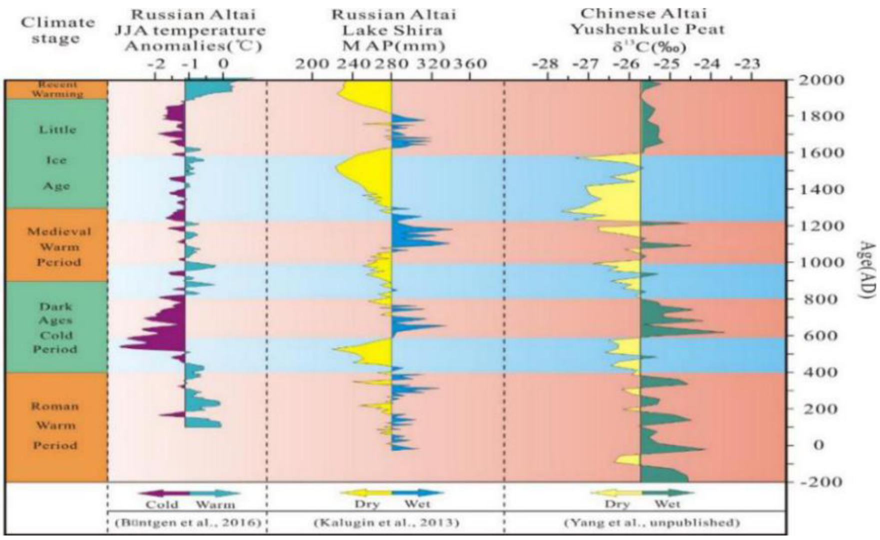

Figure 7 – Comparison of three sets of data. The first curve is the tree ring-based summer (JJA) temperature reconstruction in the northern Altai Mountains (Büntgen et al., 2016). The second curve is the lacustrine sediment-based mean annual precipitation (MAP) reconstruction in the northern Altai Mountains (Kalugin et al., 2013). The third curve is the $\delta^{13}C$-signified moisture reconstruction in the Yushenkule Peat (Yang et al., 2019b)

Late Holocene Cultural Evolution and Climate Change

The existing data show that large scale human activities occurred at least during the late part of Neolithic Time across the Eurasian steppes. For example, after the emergence of nomadic cultures, the Minusinsk Basin and the surrounding areas (Fig. 8) have been the center of east-west nomadic culture convergence (Allentoft et al., 2015; Blyakharchuk and Chernova, 2013; Blyakharchuk, et al., 2014).

Afanasievo Culture

About 5000 years ago, the Yamnaya Culture occupied a large area of the eastern European steppes between Hungary and Ural. A branch of the Yannaya Culture spread eastward to the Minusinsk Basin within the western Asian steppes to form the Afanasievo Culture (Fig. 8a) that was most likely the direct ancestor of the much late Avatar Culture (Allentoft et al., 2015). This long-distance cultural spreading from the eastern Europe, across the Altai Mountains, to the Minusinsk Basin appeared to have occurred under relatively dry conditions in the Altai Mountains (Blyakharchuk and Chernova, 2013). That is, grassland expansions in south Siberia under dry conditions might have effectively encouraged nomadic cultures to spread.

Okunevo Culture

The Okunevo Culture, belonging to the early Bronze Age, existed from ~5000 to ~4000 years ago in southern Siberia and also in the Altai Mountains. The culture developed primarily on the basis of the Afanasievo Culture (Fig. 8b). Compared with the preceding time (i.e., Afanasievo Culture time), the climate during the Okunevo Culture time in central and south Siberia became even drier under which the forested area further shrank and the grassland-covered area further expanded (Blyakharchuk et al., 2014). Again, grassland expansions in south Siberia under dry conditions might have effectively encouraged nomadic cultures to spread.

Andronovo Culture

The Andronovo Culture, belonging to the mid Bronze Age, existed between ~4100 and ~3800 years ago in south Siberia. It was believed that the nomadic tribes of Arians in the southwest migrated to Khakassia area in south Siberia at ~4000 years ago, forming the Andronovo Culture. However, Allentoft et al. (2015) recently showed that the Corded Ware Culture spread eastward to the Caspian Sea and also to the northern shore of the Black Sea to form the Sintashta Culture, which further spread eastward and then formed the Andronovo Culture in south Siberia. That is, The Andronovo Culture was the result of the migration of the ancient Indo-European peoples from west (Fig. 8c). This cultural expansion and transformation at ~4000 years ago occurred under dramatically fluctuated climatic conditions in many part of Eurasian continental interiors (Staubwasser and Weiss, 2006). Again, grassland expansions in south Siberia under dry conditions at ~4000 years ago might have effectively encouraged nomadic cultures to spread.

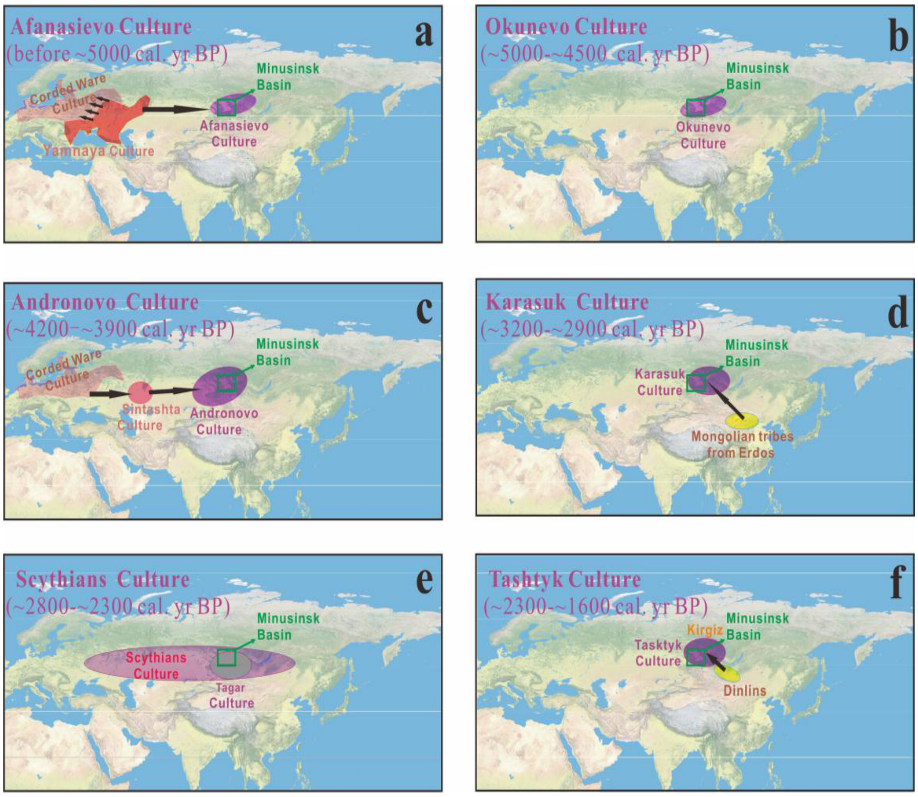

Figure 8 – Archaeological Cultures in the Eurasian steppes. a: Afanasievo; b: Okunevo; c: Andronovo; d: Karasuk; e: Scythians; f: Tashtyk.

Karasuk Culture

The Karasuk Culture appeared in the late Bronze Age at ~3200-~2900 years ago and occupied the vast grassland areas between the Mongolian Plateau and the Ural Mountains. The pollen-based evidence shows that there was a continental scale drought event at ~3200 years ago, resulting in the shrinkage of forest area and also the expansion of grassland area in south Siberia (Blyakharchuk and Chernova, 2013). Attracted by this drought-resulted grassland expansions, the nomadic tribes in the Ordos Plateau migrated to the Minusinsk Basin most likely searching for relatively good grassland conditions (Fig. 8d; Blyakharchuk et al., 2014). It means that the grassland expansion in the Minusinsk Basin might have attracted the "ecological refugees" from the Ordos Plateau.

Scythian (Tagar) Culture

The Scythian refers to the nomadic culture that occupied the northern portion of the Caucasus Mountains and south Siberia at ~2700-~2300 years ago. The Scythian Culture was mainly represented by the Tagar Culture that appeared at ~3200-~2900 years ago in south Siberia and also in the Altai mountains (Fig. 8e). van Geel et al. (2004) proposed that the climate transformation (cooling and wetting) at ~2700 year ago might have led to the transition of civilization types in the Eurasian steppe from the Bronze Age to the Iron Age. Under the colder and wetter climate conditions after ~2700 years ago, the grassland-covered area in southern margins of the CAAZ expanded considerably and the livestock carrying capacity increased significantly, providing the material basis for the rise and expansion of the nomadic culture of the Scythian Culture in the Eurasian steppes.

Tashtyk Culture

The Tashtyk Culture, an Iron Age culture, existed from~2300 to ~1600 years ago in south Siberia. It was believed that the Tashke Culture was formed by the migration of the nomadic people from the Mongolian Plateau. According to the records of the later Han Dynasty, the original residents of the Minusinsk Basin were known as the "Jiankun people" (Kirgiz). At that time, the Dinglin tribes in the northwestern Mongolian Plateau belonged to the Mongolian ethnic group. The Tashtyk Culture should be a mixture of "Jiankun people" (Kirgiz) and Dinglin tribes (Fig. 8f). Available pollen data show that there was more precipitation in the Altai Mountains and the Sayan Ridge at ~2300-~1500 years ago (Blyakharchuk and Chernova, 2013). It seems that during this period of ~2300-~1500 years ago, the steppes to the east of the Altai Mountains and the Sayan Ridge were drier and the steppes to the west of the Altai Mountains and the Sayan Ridge were wetter. Under the drought stress in the east of the Altai Mountains and the Sayan Ridges, the nomadic people in the east migrated to the west.

Mongolian Empire

The Mongol Empire was founded by Genghis Khan, a Mongol political and military leader who united the Mongol tribes for the first time. Between AD 1206 when Temujin received his title as Genghis Khan and AD 1370 when the last emperor in China's Yuan Dynasty died in exile, the Mongol's Great Khans established the largest contiguous empire in the world history. Social and cultural factors might be somewhat responsible for the rising and falling of the Mongol Empire, and the factors may include strong personalities of Genghis Khan and disconnection of China's Yuan Dynasty from the Mongolian steppes. But, available highly-resolved tree-ring data and stalagmite data almost unequivocally demonstrated that the rising of the Mongol Empire was associated with warmer and wetter climate in the hinterland of the Mongolian Plateau that provided the material basis for the expansion of the nomadic culture (Pedersona et al., 2014) and the falling of the Mongol Empire was associated with cooler and drier climate in the northern China that sparked massive peasant uprisings in Mongol-governed China (Zhang PZ et al., 2008).

Ending notes

As for the relationships between cultural evolution and climate change, it is too early to confidently draw any conclusions simply because the extremely high-level inadequacies in data coverage (geography) and also in data qualities (chronology and proxy). The data available so far seem to suggest that the nomadic cultural spreading and transformation were mainly encouraged by drying-resulted grassland expansions along the northern margin of the CAAZ (Central Asian Arid Zone). The wetting-resulted grassland expansions along the southern margin of the CAAZ might have encouraged the dramatic expansion of the Scythian Culture. The moisture contrast between the eastern side and the western side of the Altai Mountains and the Sayan Ridges was most likely the driver for the nomadic people to migrate between the east and the west. Again, more intensive and more extensive in-depth investigations in the CAAZ including the Altai Mountains are still in need for elevating our understanding of the relationships between cultural evolution and climate change.

Acknowledgments

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