The Kind and Distribution of Mid-Latitude Periglacial Features and Alpine Permafrost in Eurasia

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Abstract

The distribution of different periglacial landforms in various mid-latitude mountains of Eurasia is described. Alpine discontinuous and continuous permafrost is present in all these mountains, but in the humid mountains, this zone is very small due to the lower elevation of the glacier snowline (or ELA). In the more continental regions of Asia, this zone is much broader due to high elevation of the ELA. In these areas cryoplanation terraces, patterned ground, and rock glaciers occur in relative low elevations and are also widespread within the forest ecotone. On the other hand, solifluction features occur in higher regions due to arid conditions and especially the lack of soil humidity during the freeze-thaw cycles. In the Verkhoyansk Mountains further north in latitude, even in the mountain foreland and in the boreal forest of the Lean-Aldan Basin, periglacial features are widespread on continuous permafrost.

Keywords: Central Asia; European Alps; mid-latitude; periglacial features; permafrost.

Introduction

This paper presents a comprehensive review study concerning the kind and distribution of periglacial phenomena of mid-latitude mountains of Eurasia. New results are from continental Asia, in particular the mountain areas of Western Mongolia, the Russian Altai, and the Verkhoyansk Mountains (Fig. 1). The distribution of different periglacial landforms in these mountains is compared to the European and Japanese Alps. A first overview concerning mid-latitude periglacial landforms is given by Höllermann (1985); an overview for the high Asian mountains is given by Matsuoka (2003).

Periglacial Landforms in Mountain Areas

Concerning periglacial phenomena in mountain environments, especially small-scale periglacial or cryogenic landforms, are studied in the literature (e.g., Washburn 1979). Active solifluction (or gelifluction) generally occurs above the timberline as the forests stabilise and protect the ground. In general, the periglacial zone can divide into two sub-belts: First, the lower periglacial sub-belt, which includes mainly bound or turf-banked solifluction (steps, benches, terraces, lobes), and second, the upper sub-belt. The latter is characterized by unbound (or free) solifluction, blockfields, debris, stone pavements, and patterned ground (Troll 1973, Höllermann 1985). This periglacial zonation is obvious in most mid-latitude mountains above the timberline and provides information on the geoecology of high mountain environments, as the distribution of these landforms depends on several different factors (e.g., topography, geology and substrate, climate, vegetation, and soil water; see Fig. 2). Periglacial phenomena are generally controlled by cold climatic conditions, where the mean annual air temperature (MAAT) as well as the duration and depth of snow cover are low. The modern altitudinal belts of the vegetation, the soils, and the geomorphological processes are controlled by these general climatic conditions, but also by the different radiation on the northern and southern slopes (Höllermann 1985). However, new results from the European Alps show that active soil movements only occur in the upper sub-belt (Veit 2002).

Besides the different small-sized landforms of solifluction rock glaciers are typical landforms of high mountain environments. Two types are distinguished: (1) ice-cemented rock glaciers built up by unconsolidated rock or talus, and (2) morainic deposits. They are generated by the creep of mountain permafrost saturated or supersaturated with ice. Ice-cored rock glaciers consist of glacier ice mantled with a debris cover and originate from dead ice (Ishikawa et al. 2001). Rock glaciers affect unconsolidated but frozen rock fragments, creating characteristic landforms with a tongue or lobate shape and a surficial pattern of furrows and ridges that indicate the internal flow process (Barsch 1996, Fort 2002, Haeberli 2000). In addition, protalus ramparts, and talus slope or talus cone rock glaciers are described in the literature (e.g., Barsch 1996).

It is generally accepted that the distribution of rock glaciers is a good marker of discontinuous mountain permafrost (e.g., Barsch 1996). However, Fort (2002) mentioned that the identification of rock glaciers in the Himalayas is similar to other features such as rockslides and/or debris covered glaciers and, therefore, it is sometimes difficult to distinguish these landforms. Rock glaciers are described in detail especially in the European Alps and in mountain regions of North America (see reference in Barsch 1996). The knowledge of the distribution of rock glaciers in the different mountain systems on Earth is still very incomplete (Barsch 1996). Nevertheless, mountains with a continental climate, and thus the greatest differences between timberline and snowline (up to 1500 m) are more favourable for rock glaciers than those with a difference of less than 500 m (Höllermann 1985, Barsch 1996).

The upper limit of the periglacial belt results from steep high mountain topography or from the extent of perennial snow and ice in the higher altitudes (glacial belt).

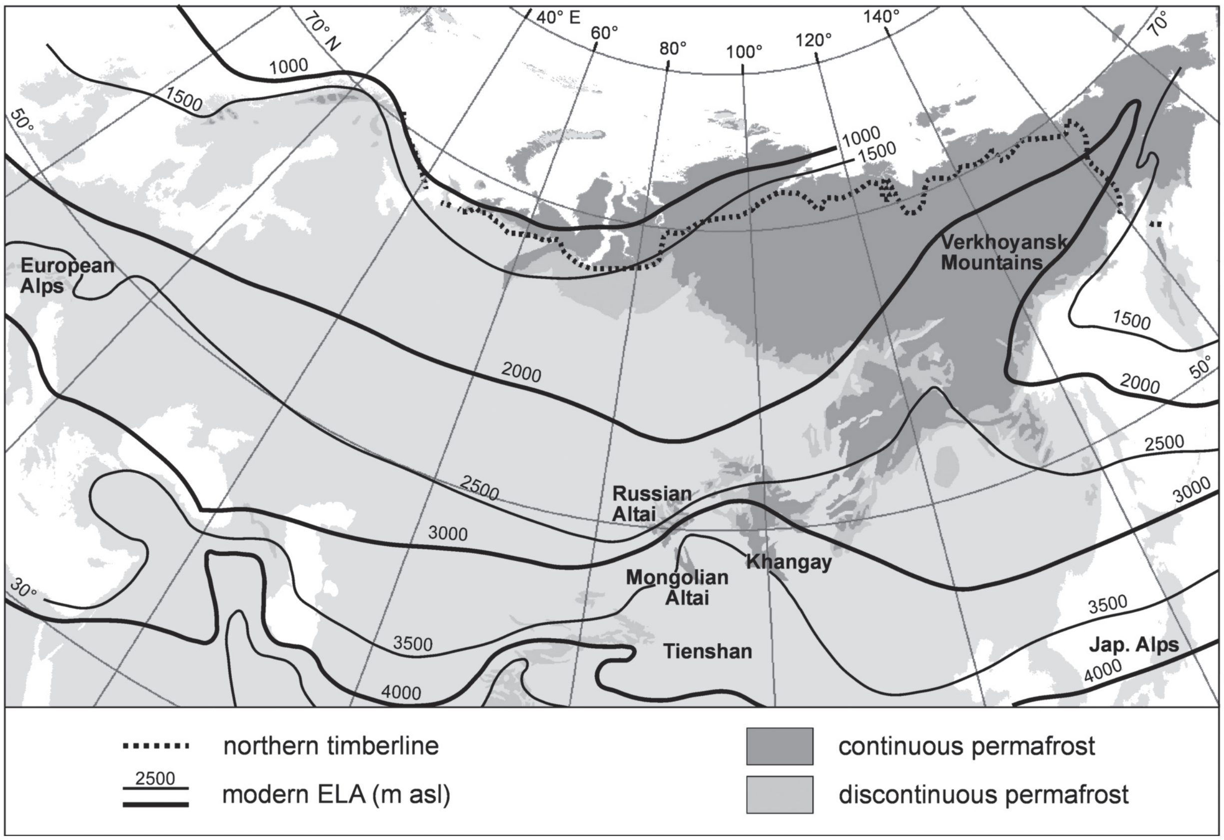

Figure 1. Map of study areas including the distribution of permafrost (modified according to Brown et al. 2001) and the modern ELA (m a.s.l., modified according to Wilhelm 1995).

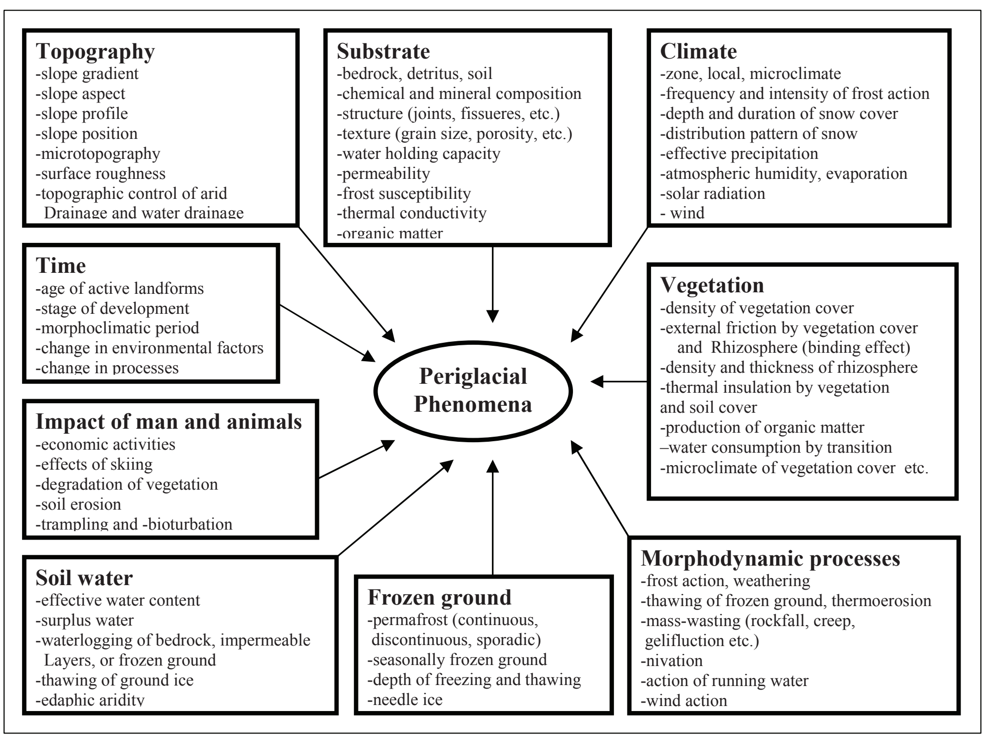

Figure 2. Main factors for the development and distribution of periglacial phenomena. Modified according to Höllermann (1985).

Results

In the following, the distribution of periglacial phenomena, such as lower limit of solifluction and rock glaciers, are described for the different mountain areas. The details for the lower limit of different periglacial and glacial features are given in Fig. 5 and Table 1.

European Alps

In the European Alps there are several studies regarding the periglacial phenomena. Veit (2002) summarized the current state of research for the European Alps. The periglacial phenomena can be divided in the humid European Alps into two sub belts: the lower limit of bound or turf-banked solifluction (occurs roughly above the timberline, Fig. 3) and the zone of unbound solifluction, dominated by blockfields, patterned ground, and bare bedrock. Active rock glaciers and other indicators of discontinuous permafrost are assumed to be generally in the upper periglacial sub-belt of the European Alps and of similar mountains. Active solifluction (or gelifluction) generally occurs above the timberline (see above). However, studies concerning the processes show that active movements occurs only in the upper part of the periglacial sub-belt (unbound solifluction); the turf-banked solifluction are fossil landforms (Jaesche 1999, Veit 2002).

Figure 3. Solifluction lobe (bound or turf-banked solifluction) in the Grossglockner region, European Alps, Elevation: 2200 m a.s.l.

Figure 4. Rock glacier in the Khangay Mountains, Mongolia. Granite bedrock on the eastern slope of the Otgon Tenger. Elevation: about 3000 m a.s.l.

In this paper the results from own field work from two mountain areas with the central part of the European Alps are described (Lehmkuhl 1989). These are the southernmost glaciated areas in the western part of the Alps (Pelvoux Mountains, France, 45°N/6°30′E) and the easternmost glaciated part of the Alps (Hohe Tauern, Austria, 47°N/13°E). Both regions are situated in the central part of the Alps, having more continental climatic conditions much more suitable for rock glaciers than the more humid margin ranges of the Alps (Barsch 1986, Höllermann 1985). The mean monthly air temperature in 2000 m a.s.l. varies between -4°C in January and +12°C in July (MAAT around 0°C). Annual precipitation ranges between 900 mm in valleys and >2000 mm in the mountains.

Rock glaciers occur in 2400 to 2500 m a.s.l., turf-banked solifluction in 2350 and 2200 m a.s.l. and unbound solifluction in 2750 and 2500 m a.s.l. (see Table 1 and Fig. 5).

Tianshan and Russian Altai

There are only a few studies regarding periglacial features in the Russian Altai. Schröder et al. (1996) and Fickert (1998) summarized in a north-south transect the distribution of periglacial phenomena. Their results concerning Tienshan (Sailijskij-Alatau, 42°N/77°E) and the results from own observations from the central part Russian Altai (Katun Ridge, 50°N/86°E) are given in Figure 5 and Table 1. The latter region is characterized by continental conditions with mainly summer precipitation and low winter temperatures resulting in the distribution of rock glaciers down to elevations of about 1600 m a.s.l. These low elevation rock glaciers occur in the forest belt indicating the high amplitude of temperatures with winter temperatures below -20°C and relative high summer precipitation. The precipitation values above 1000 mm/a are similar to those of the central European Alps. Further references see Marchenko et al. (2007).

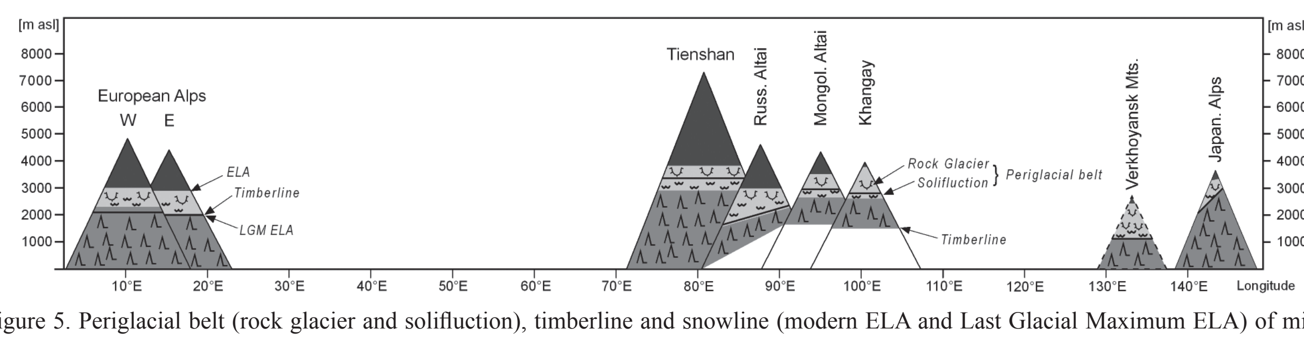

Figure 5. Periglacial belt (rock glacier and solifluction), timberline and snowline (modern ELA and Last Glacial Maximum ELA) of mid-latitude mountains from the European Alps to the Japanese Alps.

Table 1. Elevations (m a.s.l.) of snowline (ELA), timberline and selected lower limits of rock glaciers and solifluction (for the Alps: unbound solifluction in parentheses) from selected mid-latitude mountains between 40 and 50°N.

	Western European Alps	Eastern European Alps	Tienshan	Russian Altai	Mongolian Altai	Khangay	Verkhoyansk
Modern snowline (ELA)	3000	2900	3700-3900	2900-3000	3500	>3800	2500
Timberline	2300	2050	2900 (N)	2200-2400	2600–2700 (N)	2600 (N)	1100
Late Pleistocene ELA	ca. 2100	ca. 2000	2700?	1800-2200	2900–3000	2700-2900	1200
Pleistocene ELA-depression	ca. 1200	ca. 1100	1000?	800–1200	600	1000-1200	1300
Diff. Timberline-ELA	700	750	800	700	800–900	>1200	1400
Rock glaciers	2400	2500	2900	1600	2600	3200	--
Solifluction	2350 (2750)	2200 (2500)	2600	2200	2700	2900	800

Mongolian Altai and Khangay

Due to the low winter temperatures and the small amount of snow, frost weathering occurs in the mountains of Mongolia down to the basins below 900 m a.s.l. Other periglacial phenomena, such as solifluction, palsas, and earth hummocks are related to soil moisture, and therefore occur in higher elevations or exceptional geoecological sites with a higher water supply; for example, on north-facing slopes below larch forest spots. However, the distribution of rock glaciers in the continental climate conditions of western Mongolia is determinate on low temperatures, and mainly on the occurrence of granite and metamorphic rocks (Fig. 4). The detailed observations concerning the distribution of periglacial landforms and processes are based on several joint field expeditions and studies of the processes (Lehmkuhl 1999). Detailed investigations from the Mongolian Altai and Khangay are presented, for example, by Klimek & Starkel (1980), Pekala & Repelewska-Pekalowa (1993), Lombroinchen (1998), Lehmkuhl & Klinge (2000), Klinge (2001), Lehmkuhl et al. (2003) and Sharkhuu (2003). Further references can be found therein.

Hourly measurements of the soil temperatures of different depths at distinct geoecological sites in elevations between 1775 and 2760 m a.s.l. were carried out in two measuring cycles (Lehmkuhl & Klinge 2000). The main difference in the intensity of periglacial processes in the basins and mountains areas, respectively, can be seen in the freeze-thaw cycles in springtime. In this time the precipitation in the mountains is still snowfall, and moisture can infiltrate into the soils. Due to higher temperatures the precipitation (mainly rain) in the basins evaporates and rapid drying out of the soils occurs. Therefore, the main controlling factor for the cryogenic and especially solifluction processes in the mountains is the amount of precipitation during springtime. The freeze-thaw cycles during the relatively dry autumn season are a subordinated factor for the periglacial activity. At sites with low radiation, as caused for example, through shading effects in relief, the freeze-thaw cycles displace towards the summer with more precipitation. Therefore, periglacial processes on low-radiation sites are laced to the strength of the summer precipitation. On the other hand, the frequent freeze-thaw cycles at sites with high radiation drop towards the dry winter season, and therefore, the periglacial activity is low at such sites. Accumulation of snow (e.g., in nivation hollows) and/or the occurrence of frozen ground could guarantee sufficient soil humidity apart from the distribution of precipitation during the highest freeze-thaw cycles in the spring and autumn seasons and determines cryogenic processes and periglacial forms (e.g., earth hummocks, patterned grounds). This local influence can be reinforced by effects of radiation. In the larch forests at northern slopes, a cooler local climate with reduced transpiration in the summer allows the preservation of frozen ground and/or permafrost.

The details presented for this paper (Table 1) are based on two mountains ranges: (1) the Turgen-Kharkhiraa Mountains (49°30′N/91°E) as the northernmost part of the Mongolian Altai and (2) the Angarkhoy Mountains (47°N/101°E) as the central part of the Khangay. Mean monthly air temperature varies between -20°C in January and +20°C in July. The MAAT is, for example, about -4°C in the basin of the Uvs Nuur. Annual precipitation ranges between 200 mm in the basins and up to >400 mm in the mountain ranges. Solifluction and rock glaciers occur in elevations above 2600 m. Initial observations from other parts of the Mongolian Altai and the western Russian Altai show that such landforms can be found in almost every mountain system which comprise granite or other metamorphic rocks.

Verkhoyansk Mountains

The Verkhoyansk Mountains are much further north in latitude, and the climate is extremely continental. Mean monthly air temperature varies between -40°C in January and +20°C in July. Annual precipitation ranges between 220 mm in the lowlands around Yakutsk and up to 700 mm on the western flank of the Verkhoyansk Mountains. The observations presented in this paper focused on the central part of the Verkhoyansk Mountain range (64–65°N, 126–130°E) and based on fieldwork and remote sensing analysis (Stauch 2006, Stauch et al. 2007). Permafrost features such as pingos and thermokarst depressions and lakes (alases) are widespread on continuous permafrost even in the mountain foreland and in the boreal forest of the Lean-Aldan Basin. However, solifluction, nivation, and cryoplanation terraces can be found in elevations above 800 m a.s.l. only. No rock glaciers can be found in this study area.

Japanese Alps

Studies concerning mountain permafrost in Japan are summarised in Ishikawa et al. (2003). Mountain permafrost seems to be restricted mainly to north-facing slopes above 3000 m a.s.l. and in some rock glaciers. Matsuoka (2003) presents some more details concerning other periglacial features.

The details presented for this paper (Table 1) based also on own observations and discussions during an excursion led by Y. Ono in 2001 in the central Japanese Alps. MAAT in 2600 m a.s.l. is about 0°C, mean temperature in January and July were estimated to be -11.3 and +12.6°C, respectively. Annual precipitation is rather high (no data published) and northwestly wind across the Japan Sea provides a large amount of snow on the northern and eastern ranges in winter, the Pacific part of the mountains is much drier (Ishikawa et al. 2003).

Solifluction and rock glaciers occur in elevations above 2600 m a.s.l.; there are no modern glaciers in this part of the Japanese Alps.

Conclusion

As stated above, the distribution of various periglacial landforms depends on several different factors (e.g., climate, topography, geology and substrate, vegetation, and soil water; see Fig. 2). Periglacial phenomena are generally controlled by cold climatic conditions, where the mean annual air temperature is below 0°C and the duration and depth of snow cover are low.

The distribution of the periglacial belt in Eurasia at 40 to 50°N is given in the schematic profile in Fig. 6. All altitudinal lines are drawn relatively to the timberline as base level. Alpine discontinuous and continuous permafrost is present in all these mountains, but in the humid this zone is very small due to the lower elevation of the snowline (or recent equilibrium line of glaciers = ELA). In the more continental regions of Asia, like the Altai Mountains, this zone is much broader due to high elevation of the ELA. In addition, cryoplanation terraces, patterned ground, and rock glaciers occur in relative low elevations and are also widespread within the forest ecotone (Table 1).

The Verkhoyansk Mountains are further north in latitude and much drier. In this region, even the mountain foreland and in the boreal forest, permafrost activity and pingos are widespread. However, periglacial features, especially solifluction, occur only in mountain ranges above 800 m a.s.l. There are no active rock glaciers, as the humidity is not sufficient. These results fit recent observations in 2007 in the Gobi Altai, a mountain range within the driest part

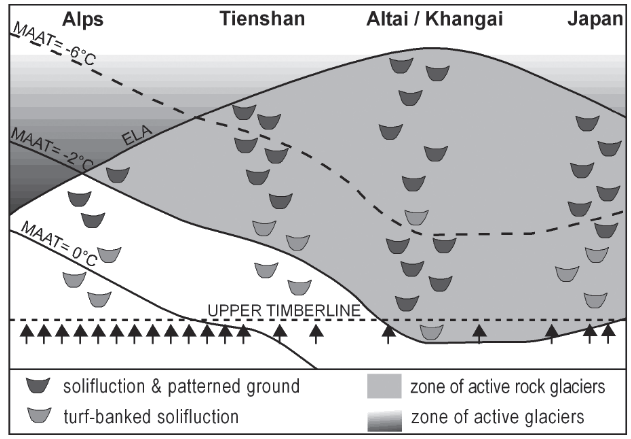

Figure 6. Schematic profile of the periglacial belt in Eurasia at 40 –50°N. All altitudinal lines are drawn relatively to the timberline as base level. Modified according to Höllermann (1985).

of Mongolia, where a few rock glaciers occur only in the highest and more humid parts of the Ikh Bogd Mountain above 3500 m a.s.l. (44°57′N, 100°18′E).

The Japanese Alps are more humid, and especially the thick winter snow cover reduced periglacial activity and permafrost distribution, including rock glaciers, toward a small zone in the highest mountain areas.

These results show that periglacial phenomena occur in the continental part of Asia even in the forest zone. Especially solifluction, but also rock glaciers, are determined through existence of soil humidity during the freeze-thaw cycles. Therefore the distribution of these features in the continental areas of Asia is smaller than in the humid European and Japanese Alps and, for example, restricted to northern slopes or higher elevations. Observations and soil temperature measurements in the Altai Mountains show that active rock glaciers and discontinuous permafrost occur in lower elevations than solifluction features. Thus, solifluction landforms in continental Asia depend more on moisture supply than rock glaciers. However, towards the arid regions of Central Asia, the lower limit of solifluction landforms, glaciers, and the lower timberline are rising in general; whereas the distribution of rock glaciers is even lower than in the humid parts of Europe and Pacific parts of Asia including Japan.

The modern ELA has the lowest position in the humid European Alps. The most significant difference between the timberline and the modern ELA occurs in the Khangay and Verkhoyansk Mountains. (Fig. 5, Table 1). The smallest amount of Pleistocene ELA-depression is in the arid regions of the Altai. However, the distribution of glaciers is related to temperature and moisture supply. The generalised contour lines of the modern ELA in Figure 1 show the influence of the humid mountains of the Altai and the dry part of eastern Siberia on the elevation of the snowline. As the northern timberline is related to summer temperatures and the humidity is even sufficient in the continual parts of Asia, this line shows a west–east latitudinal trend.

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