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RELATIONSHIPS BETWEEN MERIDIONAL PROFILES OF SATELLITE-DERIVED VEGETATION INDEX (NDVI) AND CLIMATE OVER SIBERIA

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ABSTRACT

This study investigates the regional relationship between the satellite-derived vegetation index (Normalized Difference Vegetation Index, NDVI) and climatological parameters (temperature and precipitation) over Siberia on a 5-year (1986–1990) annual mean basis. The NDVI in Siberia shows a large value around the 60°N zone, and it gradually decreases toward the southern arid region and the low temperature polar region. This meridional profile (south–north regionality) of the NDVI was analysed in two meridional transects, along 75°E (arid–forest transect) and 110°E (forest–tundra transect). A modified warmth index ($WI_{(0)}$) was utilized as a temperature index.

In the 75°E transect, high positive (0.79) and negative (-0.58) correlations were found in the NDVI–precipitation and the NDVI–$WI_{(0)}$ meridional profiles, respectively. This fact implies that precipitation plays a role in providing water and dominates the vegetation distribution, while high temperature induces dryness and water shortages, i.e. the critical factor for the vegetation meridional profile is available water in the arid–forest transect. In the 110°E transect, a high positive (0.92) correlation was found, which suggests that the dominant factor for the NDVI profile is temperature in the forest–tundra transect, i.e. the critical factor for the vegetation meridional profile here may be temperature. Furthermore, these meridional profiles were scrutinized in terms of the station altitude and it was suggested that the NDVI tends to change depending on the $WI_{(0)}$ and precipitation at regional variations, which are basically the result of the altitude difference between the stations.

The comprehensive relationship between the NDVI, $WI_{(0)}$ and precipitation regionalities is discussed in terms of six vegetation types. The result shows that high NDVI (>0.2) is observed when the $WI_{(0)}$ is over 40°C and precipitation is more than $2.5 \times WI_{(0)} + 50$. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: taiga; tundra; GVI; plant geography; ecosystem; temperature; precipitation

1. INTRODUCTION

The different types of vegetation cover, spreading over the land area of the earth, are strongly characterized by the climate of each region, as is noted in much of the literature (e.g. Walter, 1973; Woodward, 1987). Thick and vigorous forests flourish in temperate and humid climatic zones, while either desert or grassland instead prevails in arid or low temperature regions. Since the 1980s, global vegetation data have been provided by satellite measurement from space. Currently, there are massive amounts of information relating to global vegetation available for climatological and plant geographical studies on the vegetation over extensive regions.

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1.1. Normalized Difference Vegetation Index (NDVI)

The difference of spectral reflectance of chlorophyll pigment between the visible and the near-infrared parts of the spectrum provides the means for monitoring the density and vigour of green vegetation (e.g. Tarpley *et al.*, 1984). The NOAA satellite has a five-channel radiometer (Advanced Very High Resolution Radiometer, AVHRR), with channel 1 in visible (0.58–0.68 μm) and channel 2 in near-infrared (0.73–1.10 μm) spectral bands. The NDVI, which is the most well-known vegetation index, is computed by the equation $\mathrm{NDVI} = (Ch2 - Ch1)/(Ch2 + Ch1)$, where $Ch1$ and $Ch2$ are values from AVHRR channels 1 and 2, respectively (e.g. Tarpley *et al.*, 1984). The NDVI theoretically ranges from -1.0 to 1.0. For the actual Earth's surface, the NDVI ranges from -0.1 to 0.7. This remotely sensed value of the NDVI allows us to analyse the 'greenness' of vegetation from a regional to a global scale.

For example, Malingreau (1986) described the relationship between the NDVI time series and the phenological characteristics of vegetation in some areas of Asia. Moulin *et al.* (1997) visualized the phenological evolution (dormancy, growth and senescence) of global vegetation by analysing the seasonal variation of the NDVI. Furthermore, classifications of global vegetation cover have been carried out according to the NDVI-derived phenological characteristics of vegetation (e.g. Norwine and Greegor, 1983; DeFries and Townshend, 1994). Efforts have also been made to relate the NDVI to some vegetation properties, such as the Leaf Area Index (LAI) (e.g. Cihlar *et al.*, 1991; Wulder *et al.*, 1998) and the Net Primary Production (NPP) (e.g. Box *et al.*, 1989; Hunt, 1994) of ground surface vegetation.

A conventional vegetation map, which is usually inserted in an atlas, provides us with information on vegetation type regionality, but it is only discrete information. On the other hand, this remotely sensed NDVI allows us to treat quantitatively the greenness over regional to global scale regions. The NDVI data, which provide us with spatially continuous and long-term information on vegetation, should hold valid information for investigation into the relationship between vegetation and climate.

1.2. Background and purpose of the study

The objective of this work, i.e. the study of the relationships between the NDVI and the climate, has been discussed previously. However, the main target of most studies has been the vegetation in low latitude regions, such as tropical forest or arid regions (e.g. Nicholson *et al.*, 1990; Gutman, 1991; Di *et al.*, 1994; Anyamba and Eastman, 1996; Shinoda, 1995). To our knowledge, no study has focused on the NDVI–climate relationship in high latitude regions, such as Siberia.

As for the global scale relationship between the NDVI and the climate regionalities, some previous studies did discuss it and provided noticeable knowledge on it. For example, Schultz and Halpert (1995) investigated the global scale relationship between the NDVI and the climatological elements, such as land surface temperature and precipitation. They demonstrated that the annual cycle of the NDVI has a positive correlation to the temperature annual cycle over the Northern Hemisphere. It is also noteworthy to refer to Potter and Brooks (1998), who statistically investigated the relationship between a kind of NDVI and annual climatological indices of temperature, precipitation and radiation at a global level. They demonstrated a regression algorithm of climatological indices for the NDVI. However, these previous studies on a global scale do not hold sufficient information relating to Siberia. Potter and Brooks (1998) pointed out that the accuracy of the regression in the high northern latitudes has a serious limitation.

This study focuses on the climate and NDVI regionalities over Siberia on a continental scale from a plant geographical view point. Siberia is one of the key regions where a remarkable long-term rise in temperature has been found, especially in winter, relating to global warming (IPCC, 1996). Furthermore, the thick taiga vegetation over the extensive area should have a great potential to provide water vapour to the atmosphere through its transpiration activity (e.g. Suzuki *et al.*, 1998). As a part of the GEWEX Asian Monsoon Experiment (GAME), an international project under the Global Energy and Water Cycle Experiment (GEWEX). GAME-Siberia is being implemented in the Lena River basin, focusing on energy and water cycle processes (GAME-International Science Panel, 1998). Thus, it can be expected that the results of this study will provide meaningful information with regard to hydrometeorological science over Siberia.

In Siberia, a boreal forest called taiga is seen over a broad zone around the latitudinal line of 60°N. On the other hand, its southern and northern regions are mostly characterized by non-forest vegetation, i.e. steppe to the south (i.e. Kazakh Steppe and the steppe in Mongolia) and tundra to the north (regions near the Arctic Ocean). This meridional (south–north) transition of vegetation should be dominated by the climate regionality. This study aims to quantify the relationship between the meridional profile of the NDVI and the climate elements of temperature and precipitation in Siberia. To survey the meridional profile of the NDVI and the two climatological parameters, two meridional transects are constructed for arid–forest and forest–tundra climatic zones. Analyses are carried out on a 5-year (1986–1990) annual mean basis. The seasonal cycle and interannual variation of the analyses are not the concern of this study. Instead, this study aims to explain the plant geographical relationship between vegetation and climate meridional profiles in Siberia.

2. DATA AND ANALYSES

2.1. Analysis of the two transects

The study analyses the annual mean values of the NDVI, temperature and precipitation meridional profiles from 1986 to 1990 in two meridional transects, which are indicated in Figure 1. One transect is located along the meridional line of 75°E from 40° to 60°N (to be referred to as '75°E transect'), which covers the area from the Kazakh Steppe and desert to the forest regions. The other transect covers the meridional line of 110°E from 60° to 75°N (to be referred to as '110°E transect'), which covers the area from the forest (taiga) to the tundra regions. The west–east longitudinal range of these transects increases with the latitude from the south to the north, as can be seen in Figure 1. This is because the west–east geographical distance of the transects was set to be constant. The NDVI in these transects gradually decreases from the forest zone from 60°N to either a low latitude area (75°E transect) or a high latitude area (110°E transect).

2.2. Gallo's Global Vegetation Index

The original 1.1×1.1 km resolution data of AVHRR were processed and the weekly Global Vegetation Index (GVI) product, which has $0.144° \times 0.144°$ spatial resolution (i.e. 16×16 km resolution at the equator), was constructed (e.g. Tarpley, 1991). Gallo's monthly GVI (Gallo, 1992), included in a

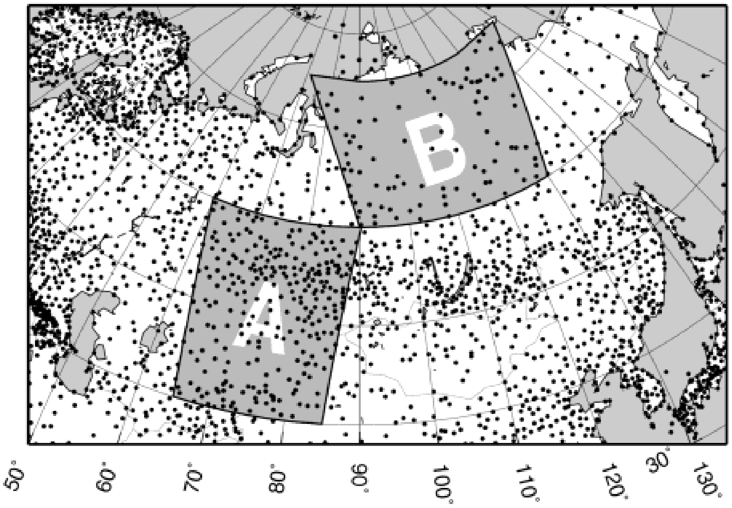

Figure 1. Coverage of the (A) 75°E transect and (B) the 110°E transect. The distribution of GDS stations is denoted by dots

CD-ROM entitled 'Experimental Calibrated Global Vegetation Index from NOAA AVHRR, 1985–1991' (NOAA/NESDIS Office of Research and Application, 1992), is a slightly modified version of the GVI that has $0.167° \times 0.167°$ ($10' \times 10'$) resolution. In Gallo's GVI, the NDVI pixels that were contaminated with either cloud or low solar elevation ($<15°$) were screened; subsequently, unreliable values, especially those in the winter season in the high latitude region, were excluded from the data set. The monthly NDVI value was represented by the maximum NDVI from the biweekly GVIs for each pixel. This process should be more efficient in removing the cloud contamination from the monthly GVI than averaging two biweekly GVIs.

As summarized by Goward *et al.* (1993), the GVI data product generally has some problems that originate in the latitudinal difference in the geometry of the Sun, the Earth's surface and the satellite, and in the process of making the GVI from the high resolution data set. Although Gallo's monthly GVI may still contain some unfavourable biases or errors in the data product, the process should reduce those biases enough for the present analysis.

In the two transects, the NDVIs at all GVI pixels in a $1° \times 1°$ box (i.e. 6×6 pixels) that had a global daily summary (GDS) (see the following subsection) synoptic station close to its centre were averaged using Gallo's monthly GVI. Based on this area mean value, 5-year mean NDVIs for each GDS station were calculated. The NDVI values in November, December and January are not used for this statistic because the NDVI in those months frequently contains meaningless values as a result of low solar illumination (e.g. Justice *et al*., 1985).

2.3. Temperature and precipitation

Surface air temperature and precipitation data are obtained from the CD-ROM 'Global Daily Summary' (GDS) that is provided by the National Climate Data Center (1994). The GDS has daily maximum and minimum temperatures, daily precipitation and 3-h weather at 10 277 surface World Meteorological Organization (WMO) stations in the world. Figure 1 indicates the stations distributed over the Eurasian continent northern area. There are 238 and 83 GDS stations in the 75° and 110°E transects, respectively, that are available for analysis.

As for the surface air temperature analysis, this study utilized a cumulative monthly temperature that has a slightly modified concept of Kira's warmth index. Kira (1948) discussed the climatic zone and vegetation in Japan using the warmth index (WI), which is defined as an annual cumulative temperature of the monthly mean temperature exceeding a threshold of 5°C. The WI is a kind of effective temperature for vegetation and has been applied in studies that investigate the relationship between geographical distribution of vegetation and temperature (e.g. Grishin, 1995). The present study changed the threshold temperature to 0°C and accumulated the monthly mean temperatures exceeding this value through the year for each GDS station. This modified WI will be referred to as $WI_{(0)}$ in this paper.

Figure 2 indicates the 5-year averaged monthly mean temperature and the NDVI at all GDS stations in both transects. The region to the south of 50°N in the 75°E transect is mainly characterized by arid climate. The values for stations in this region are plotted using an open-square symbol. The NDVI value shows a small value (under 0.1) when the monthly temperature is below freezing point but it demonstrates a dramatic increase over 0°C at many stations. Actually, in the figure, there are many plotted points that show a small NDVI value even if there is a positive temperature condition. These plotted points are stations to the south of 50°N, i.e. in the arid region. This relation allows us to consider that air temperature over 0°C is effective for the Siberian vegetation activity.

Moreover, if the threshold temperature is set at 5°C, as was originally defined for WI (Kira, 1948), the WI would be calculated as 0°C, especially at high latitude stations near the Arctic Sea. This yields a meaningless meridional temperature profile for that region. Considering these conditions, this study adopted the accumulated monthly mean temperature over 0°C through the year, and averaged it over the 5 years. The monthly mean temperature was calculated from the daily temperature of $(Td_{max} + Td_{min})/2$, where Td_{max} and Td_{min} are the daily maximum and minimum temperatures, respectively (daily mean temperature is not available in the GDS). The meridional profiles of the 5-year mean NDVI, the annual precipitation and the $WI_{(0)}$ are compared along the two transects from a climatological view point.

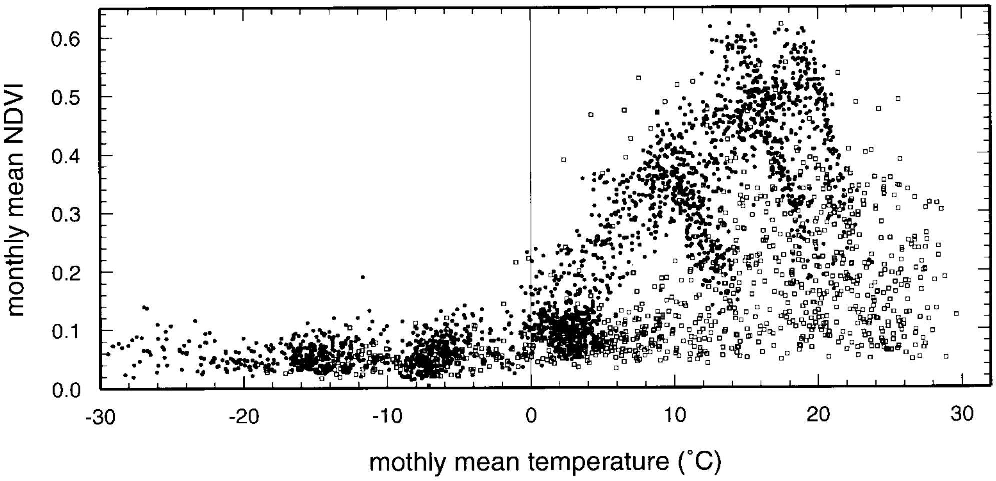

Figure 2. Monthly mean temperature and NDVI at all the GDS stations in the 75° and 110°E transects. The values at the station to the south of 50°N in the 75°E transect are plotted by squares. The other values are plotted by dots. The values in January, November and December are not plotted

2.4. Vegetation classification data

The vegetation classification data were used in the following and 'Discussion' sections. The data set 'Olson World Ecosystems', in the CD-ROM 'Global Ecosystem Database Version 1.0' (Olson, 1992), provides a global distribution of 59 vegetation cover types for a $10' \times 10'$ grid. In the present analysis, those 59 types were recategorized into six major types (A–F; see Table I). Then, the recategorized type that had the largest number of pixels in the $1° \times 1°$ box (6×6 pixels), which includes a GDS station close to the centre of the box, was adopted as the GDS station's type of vegetation.

3. GENERAL FEATURES OF TEMPERATURE, PRECIPITATION AND VEGETATION

Before describing the two transects, the general aspects of climate and vegetation over northern Asia are examined. The 5-year mean annual temperature distribution in the region bounded by 40°E, 160°E, 35°N and 75°N is shown in Plate 1. A south–north temperature gradient is found that is an essential climatological change from low to high latitude. The highest temperature (around 20°C) is found in the southwest part of the region, while the lowest (around −15°C) is found in northeast Siberia.

Plate 1 indicates the 5-year mean annual precipitation distribution. Over the coastal region in the east of the map, considerably large amounts of precipitation (over 1000 mm/year) are found as a result of

Table I. Recategorization of the original 59 vegetation types into six major types

Type A (tundra and polar desert)	Tundra; wooded tundra margin or mountain scrub/meadow; polar desert
Type B (taiga)	Main boreal conifer forest; cold cropland and pasture; cold steppe/meadow; northern or maritime taiga
Type C (snowy forest and mire)	Snowy non-boreal conifer forest; conifer/deciduous forest; snowy deciduous forest; mires include peaty bogs and fens; snowy forest/field; southern dry taiga
Type D (cool field)	Cool farmland and settlements; cool grass/shrub; snowy field/woods complex
Type E (warm grassland and steppe)	Mild/warm/hot grass/shrub; semi-desert/desert scrub/succulent/sparse grass; cool/cold shrub semi-desert/steppe
Type F (desert)	Desert; warm/hot cropland irrigated extensively; sand desert

Descriptions for the original classification by Olson were simplified.

monsoonal activity over that region. The southwest regions have a very small amount of precipitation because of the arid climate in which desert and steppe prevail. Precipitation over Siberia is 200–400 mm/year.

The outline of the vegetation covers over Siberia can be seen in Plate 2, which exhibits the distribution of six vegetation types based on Olson World Ecosystems. Roughly speaking, the vegetation covers in this region are divided zonally from south to north and the west–east contrast is rather small. The prevailing vegetation in the south part of the region (south of approximately 55°N line) is primarily non-forest vegetation covers, such as warm grassland and steppe (Type E) and cool field (Type D). Around the Aral Sea etc., desert (Type F) land cover spreads over broad areas. Snowy forest (non-boreal forest) and mires (Type C) can be seen in the north of the non-forest zone. Taiga (Type B) is the dominant vegetation cover in the zone from 60° to 70°N. This taiga zone is relatively wide in the eastern region compared with the western region of Siberia. The main vegetation cover in the arctic region, north of the taiga zone, is tundra and polar desert (Type A). This vegetation type is also spattered along the Verkhoyansk Mountain Range.

The 5-year mean distribution of the NDVI from Gallo's GVI is plotted in Plate 3. A zonal region with very high NDVI if found along approximately 60°N latitudinal line in Siberia, which roughly corresponds to the forest region. From this zone, the NDVI gradually decreases both southward and northward, the value being very small to the south and north of Siberia. This meridional gradient of NDVI should be the result of the vegetation change from forest to arid or mountainous regions (in the south) and to tundra (in the north).

From the maps of the NDVI (Plate 3), temperature and precipitation (Plate 1), it is exhibited that the 75°E transect covers from the low-NDVI/high-temperature/low-precipitation to the high-NDVI/mid-temperature/high-precipitation region from its southern to its northern parts. The coverage of the 110°E transect corresponds to the region from high-NDVI/mid-temperature/low-precipitation to low-NDVI/low-temperature/low-precipitation from its southern to its northern parts. From the vegetation map (Plate 2), it is shown that these transects represent vegetational transitions from arid to forest type (75°E transect) and the taiga forest to tundra type (110°E transect). Although the mountainous taiga area around the boundary of Russia and Mongolia may be another major landscape of Siberia, this study did not use it in the analysis because of its complicated topography.

4. MERIDIONAL PROFILES OF THE NDVI, TEMPERATURE AND PRECIPITATION

4.1. The correlation among meridional profiles

Meridional profiles of the 5-year mean NDVI, the $WI_{(0)}$ and the annual precipitation in the 75° and 110°E transects are indicated in Figures 3 and 4. The solid lines in each panel are meridionally smoothed profiles by a low-pass filter, which applies a moving average method with normal curve weights (Holloway, 1958). The response of the low-pass filter is 50% at 1.0/degree of the cutoff frequency. A dot plotted in the figure corresponds to the value at each GDS station.

In the 75°E transect (Figure 3), the NDVI gradually increases with latitude, corresponding to the vegetation change from the arid region (such as steppe and desert) in the southern part to the forest zone in the northern part. This meridional vegetation change can be observed on the vegetation map indicated in Plate 2. The NDVI at 40–50°N is around 0.15, while at 55–60°N it is about 0.3. A high NDVI peak is found in the northern side of the Tien Shan Mountain Range (around 43°N) that may be related to irrigation and sufficient water resources.

Note that the meridional profile of the annual precipitation is quite similar to that of the NDVI, i.e. the precipitation gradually increases with latitude. By contrast, the profile of $WI_{(0)}$ is in the opposite phase of the NDVIs profile that decreases with the latitude. Scatter diagrams for the NDVI–$WI_{(0)}$ and the NDVI–precipitation relationships in the 75°E transect are indicated in Figure 5. The correlation coefficients (r) of the NDVI–$WI_{(0)}$ and the NDVI–precipitation are -0.58 and 0.79, respectively

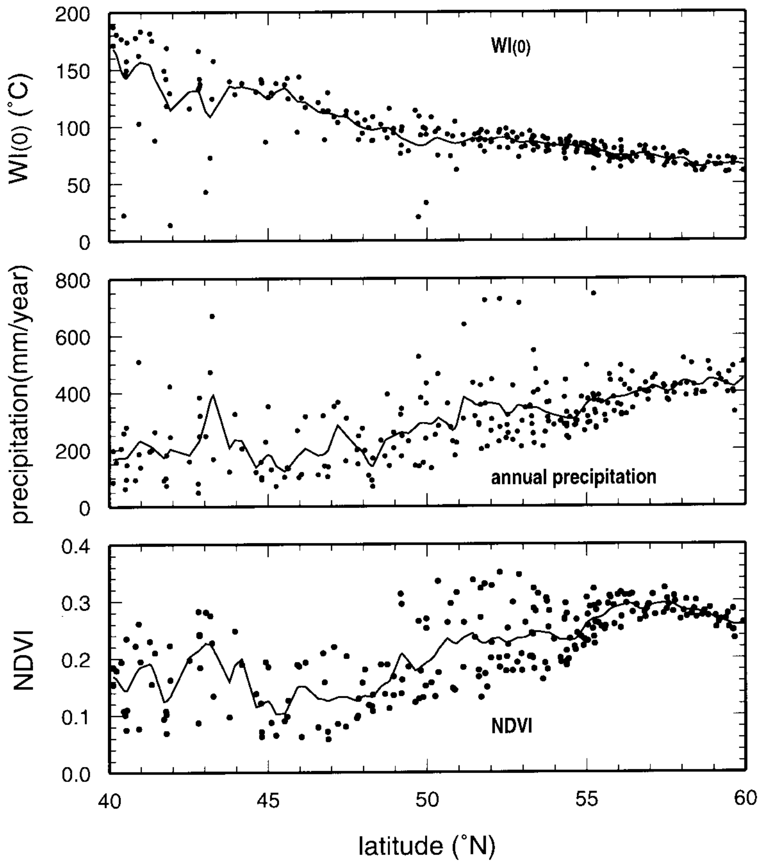

Figure 3. Meridional profiles of the $WI_{(0)}$ (top), the annual precipitation (middle) and the NDVI (bottom) in the 75°E transect. Solid lines indicate the smoothed profile

($r = 0.17$ at the 99% significance level in the 75°E transect), suggesting that precipitation is a predominant climatological factor and that the $WI_{(0)}$ is a secondary factor for vegetation in the 75°E transect. It can be considered that the 75°E transect is the moisture-dominant transect for the vegetation and that precipitation amount is positively reflected in the NDVI, while higher temperatures tend to bring dryer climates causing smaller NDVI.

Their relationships in the 110°E transect are in contrast to those in the 75°E one. The mean NDVI gradually decreases with the latitude, as indicated in Figure 4 (NDVI ~ 0.23 around 60°N, 0.11 around 75°N). This meridional gradient corresponds to the vegetation change from taiga to tundra, as can be seen in Plate 2. The $WI_{(0)}$ profile exhibits a very similar variation to the NDVIs profile, while the precipitation profile does not have an obvious trend in its profile.

As indicated in Figure 5, the correlation between the $WI_{(0)}$ and the NDVI profiles is very strong ($r = 0.92$), whereas the correlation between the NDVI and the precipitation profile is not so large ($r = 0.41$) in the 110°E transect ($r = 0.28$ at the 99% significance level in the 110°E transect). This means that temperature is a dominant factor for the NDVI gradient over the 110°E transect and that the higher temperature is reflected in a higher NDVI. It also suggests that the crucial factor for taiga in this transect is temperature.

4.2. The altitude of the station and the NDVI

This section focuses on the influence of the station's altitude on the NDVI meridional profile by analysing the high frequency component (i.e. the deviation of plot points from the smoothing lines in

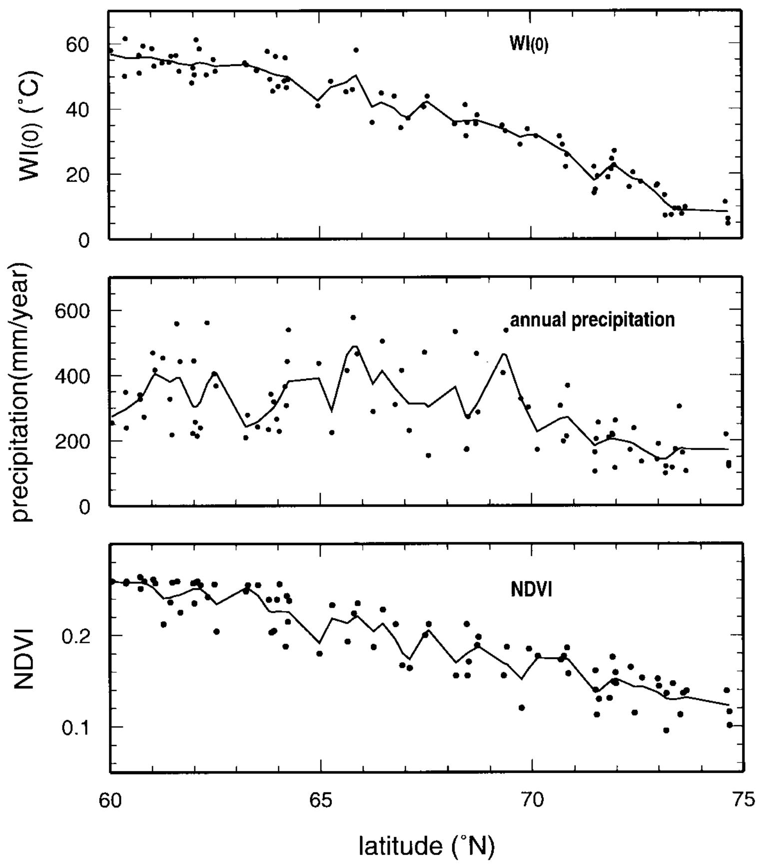

Figure 4. Meridional profiles of the $WI_{(0)}$ (top), the annual precipitation (middle) and the NDVI (bottom) in the 110°E transect. Solid lines indicate the smoothed profile

Figures 3 and 4) of the NDVI, the $WI_{(0)}$ and the precipitation profiles in conjunction with the station's altitude. For example, similar scattering can be seen in both the NDVI and the $WI_{(0)}$ in the 110°E transects (Figure 4), i.e. when the NDVI scatters toward positive from the smoothing line, the $WI_{(0)}$ also tends to scatter likewise. This feature of the scattering seems to be related to the station's altitude.

Figure 6 shows the relationship among the high-pass filtered meridional profiles (i.e. deviation) of $WI_{(0)}$, precipitation, the NDVI and the station altitude in two transects. Table II shows the correlation coefficient among those parameters. The frequency response of the high-pass filter, which applied a moving average method weighted by a normal curve, was set at 50%, 0.5/degree of the cutoff frequency.

In the 75°E transect, a positive correlation ($r = 0.66$) was found between the precipitation and the NDVI deviation, as indicated in Figure 6(b) and Table II. This fact means that the NDVI tends to deviate to a higher/lower value according to higher/lower precipitation variation and, at the same time, illustrates that the NDVI in this transect sensitively changes as a result of the station-to-station local precipitation variation. The correlation coefficient between precipitation and altitude is not as large but is positive, and that may suggest that the large amount of precipitation is induced by the forced convection at high altitude stations. The correlation between the NDVI and the $WI_{(0)}$ deviations is weak but negative ($r = -0.28$). At the same time, a strong negative correlation ($r = -0.93$) is found between altitude and $WI_{(0)}$ deviations. This may demonstrate that the higher/lower temperature resulting from the lower/higher altitude of each station is a factor that causes dryer/wetter climate, and that the vegetation is sensitively influenced by this variation. This fact should support the idea that the vegetation in the 75°E transect is very sensitive to the available water, which is controlled by precipitation and temperature.

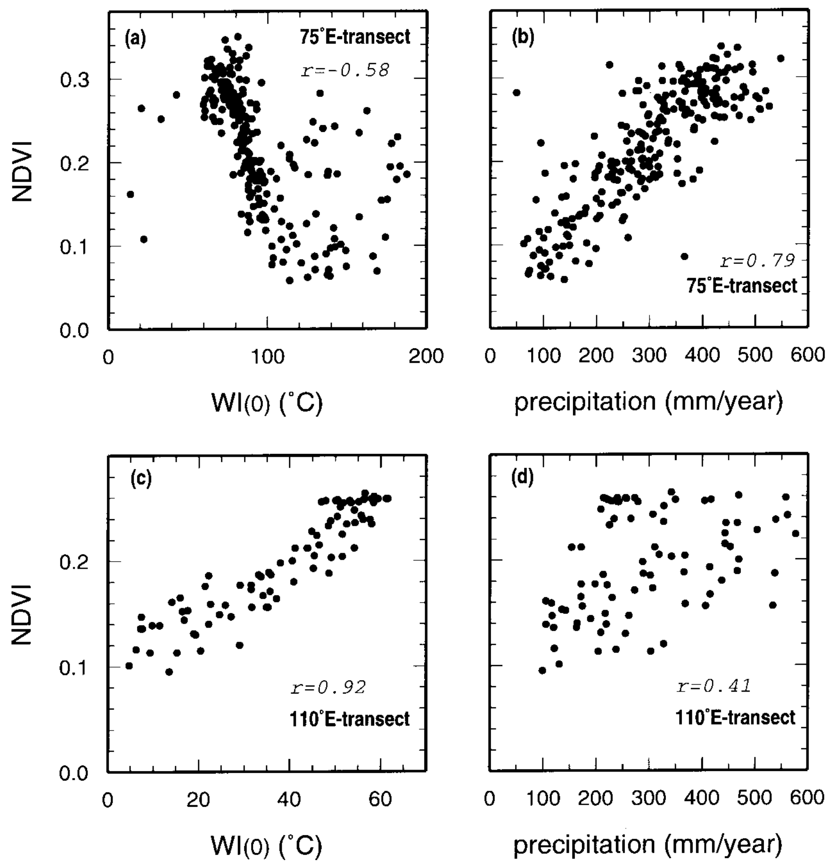

Figure 5. Scatter diagrams for (a, c) the NDVI and the $WI_{(0)}$ and (b, d) the NDVI and the annual precipitation in the 75° and 110°E transects, respectively

Figure 6 also indicates the correlation diagrams for the 110°E transect. There is a positive correlation ($r = 0.43$) between the $WI_{(0)}$ and the NDVI (Figure 6(c)). Although this correlation coefficient is not high, it implies that the NDVI at a station with higher $WI_{(0)}$ tends to be higher. It should be noted that the correlation coefficient between the $WI_{(0)}$ and the altitude is -0.46. From this figure, it can be supposed that one of the causes of the scattering of the NDVI in Figure 6 is the local temperature difference, which originates in a few hundred meters difference among the station's altitude. The NDVI in the 110°E transect possibly changes sensitively as a result of the altitude. This fact may be further supported by the idea that temperature is the crucial climatological factor for the vegetation in the 110°E transect.

5. DISCUSSION

Through the analysis of meridional profiles of the NDVI, the $WI_{(0)}$ and the precipitation along two transects, it was quantitatively revealed that the NDVI profile has an intimate relationship with $WI_{(0)}$ and precipitation. This section discusses the climatological conditions (both factors of $WI_{(0)}$ and precipitation) required for a high NDVI (>0.2) in two transects. Because the mean NDVI ranges from 0.0 to 0.4, 0.2 is approximately the middle value of this range.

Plate 4 exhibits the scatter diagram that shows the relation among the NDVI, $WI_{(0)}$, precipitation and the six major types of vegetation categories in the two transects. This diagram was constructed by plotting each station's NDVI (colour scale) and vegetation type (symbol) on the orthogonal coordinates of $WI_{(0)}$

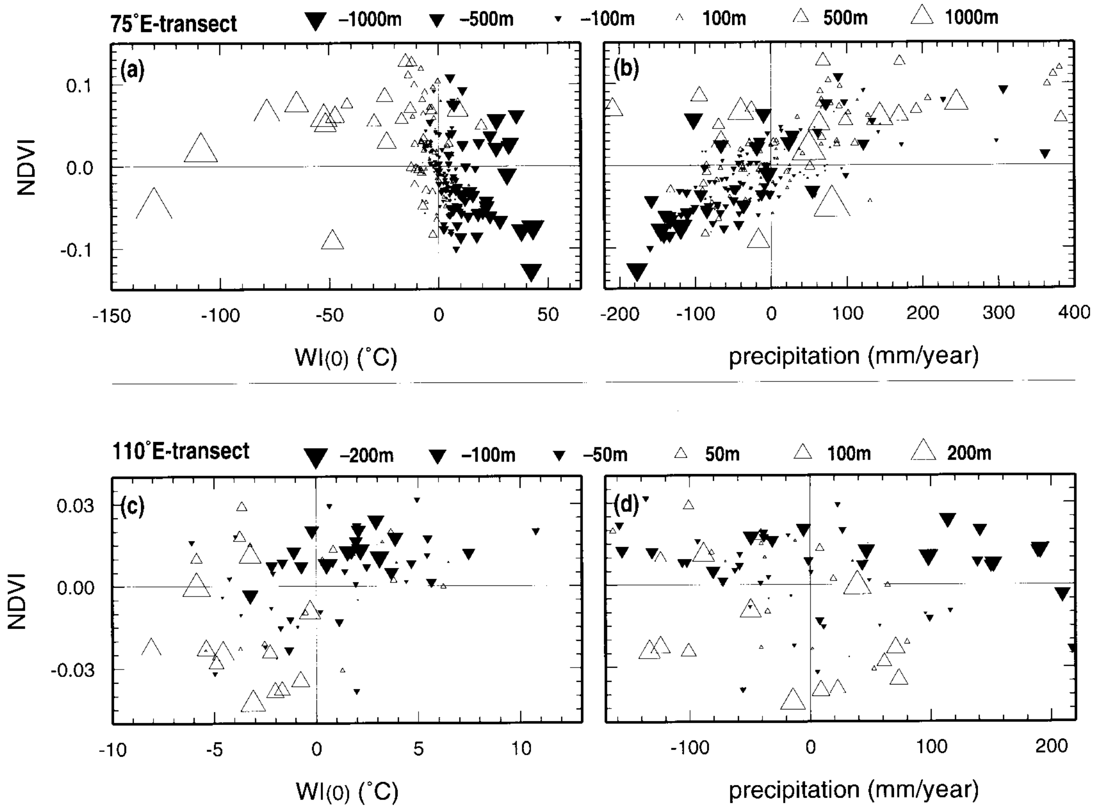

Figure 6. The scatter diagram of the meridionally high-pass filtered $WI_{(0)}$, the precipitation and the NDVI in conjunction with the altitude of stations in 75° and 110°E transects. The altitude, which is also meridionally high-pass filtered, is represented by the size (diameter) of the triangle (negative value is denoted by inverted black triangle)

Table II. Correlation coefficients among high-pass filtered profiles of $WI_{(0)}$, precipitation, NDVI and station altitude in 75° and 110°E transects

	NDVI	$WI_{(0)}$	Precipitation
75°E-transect			
$WI_{(0)}$	*−0.28*	–	–
Precipitation	*0.66*	*−0.32*	–
Altitude	*0.26*	*−0.93*	*0.23*
110°E-transect			
$WI_{(0)}$	*0.43*	–	–
Precipitation	−0.18	−0.09	–
Altitude	*−0.47*	*−0.46*	−0.27

The values that exceed the significant level at 99% (0.17 in 75°E transects and 0.28 in 110°E transect) are italicized.

and precipitation. Contours (0.02 interval) are drawn as supplemental information for the NDVI value because it would be difficult to read the precise NDVI value from the colour of each symbol.

High NDVIs (> 0.2) can be seen around 80°C of $WI_{(0)}$ and 400 mm/year of precipitation, and correspond to the vegetation categories of taiga (Type B) and snowy forest and mire (Type C). The high NDVI is seen when the $WI_{(0)}$ and the annual precipitation (P) are roughly satisfied with the following criteria:

$$\mathrm{WI}_{(0)} > 40$$

and

$$P > 2.5 \times \mathrm{WI}_{(0)} + 50.$$

The first criteria roughly corresponds to the boundary between tundra and other vegetation types. That is, the vegetation change in low $\mathrm{WI}_{(0)}$ climatological condition tends to depend only on the temperature factor. On the other hand, the vegetation profile in arid conditions, represented by the second criteria, is dependent on both temperature and precipitation factors. For example, although the precipitation is the same at 200 mm/year, the NDVI indicates a large value (about 0.22; taiga) at 50°C of $\mathrm{WI}_{(0)}$ and a low value (about 0.10; warm grassland and steppe) at 130°C of $\mathrm{WI}_{(0)}$. This illustrates that a high $\mathrm{WI}_{(0)}$ induces a dry climate because of the higher potential for evaporation, which causes unsuitable conditions for a thick vegetation. This characteristic was also mentioned in the analysis on the NDVI, the $\mathrm{WI}_{(0)}$ and the precipitation profiles in the 75°E transect in the former section.

Plate 4 also tells us that taiga is the high NDVI forest established in the climatological condition with the lowest temperature ($\mathrm{WI}_{(0)}$ is around 55°C) and the smallest precipitation (around 250 mm/year) compared with other high NDVI forest types. Despite the small precipitation amount, the climate may be maintained at adequate humidity for a high NDVI forest because of little evaporation owing to low temperature.

For many years, the relationship among the biome, precipitation and temperature has been a major theme of plant geographical studies. For example, Whittaker (1975) presented a diagram that showed the relationship among annual mean temperature, annual precipitation and vegetation type in the world. The diagram indicated that the biome type and its distribution are primarily controlled by temperature and precipitation, and that taiga occurs when the annual mean temperature is around 0°C and the annual precipitation is around 1000 mm/year. The annual precipitation that is appropriate for taiga in Whittaker (1975) is considerably larger than in the present study (200–600 mm/year). However, Whittaker analysed global vegetation while this study focused only on Siberia. This difference of view point resulted in the difference in the required precipitation for taiga.

6. CONCLUSIONS

Using satellite-sensed vegetation data, the meridional profiles of the NDVI regionality were investigated in relation to the climatological regionality of Siberia. The study established two meridional transects along 75°E (arid–forest) and 110°E (forest–tundra) transects. As to the temperature factor, a modified warmth index ($\mathrm{WI}_{(0)}$) was calculated, which was defined as a cumulative temperature of monthly mean air temperature exceeding a threshold of 0°C through the year.

The NDVI meridional profile in two transects was analysed in relation to the temperature and precipitation profiles. In the 75°E transect, high positive (0.79) and negative (-0.58) correlations were found in the NDVI–precipitation and the NDVI–$\mathrm{WI}_{(0)}$ meridional profiles, respectively. This suggested that the crucial factor for the NDVI profile in the arid–forest transect is available water for the vegetation, i.e. precipitation plays a role in providing water to the vegetation, while high temperature induces dryness and a shortage of water for the vegetation. In the 110°E transect, a high positive (0.92) correlation was found, which implies that temperature is the dominant factor for the NDVI profile in the forest–tundra transect, i.e. temperature may be the critical factor for taiga.

High frequency components (i.e. deviation from the smoothed line) of the NDVI meridional variation in the two transects were analysed in conjunction with the station's altitude. Consequently, it was suggested that the NDVI tends to change sensitively in response to the variation of the $\mathrm{WI}_{(0)}$ and precipitation deviations, which seem to originate in altitude difference among stations.

The comprehensive relationship among the NDVI, the $\mathrm{WI}_{(0)}$ and the precipitation was discussed in relation to six vegetation types and empirical formulae that schematically represent the temperature and precipitation required for high NDVI (>0.2) were proposed. The result showed that tundra and other high NDVI vegetation (taiga etc.) are divided by the line of $WI_{(0)}=40$. It also explained that both temperature and precipitation have a relationship to the high NDVI vegetation in the case of arid areas.

The result obtained in this study quantitatively illustrated that the meridional profile of the NDVI regionality in Siberia has an intimate relationship with temperature and/or precipitation. In addition, an essential and fundamental relationship between the vegetation and the climate over an extensive area of Siberia was demonstrated using satellite-sensed vegetation data NDVI and global meteorological data.

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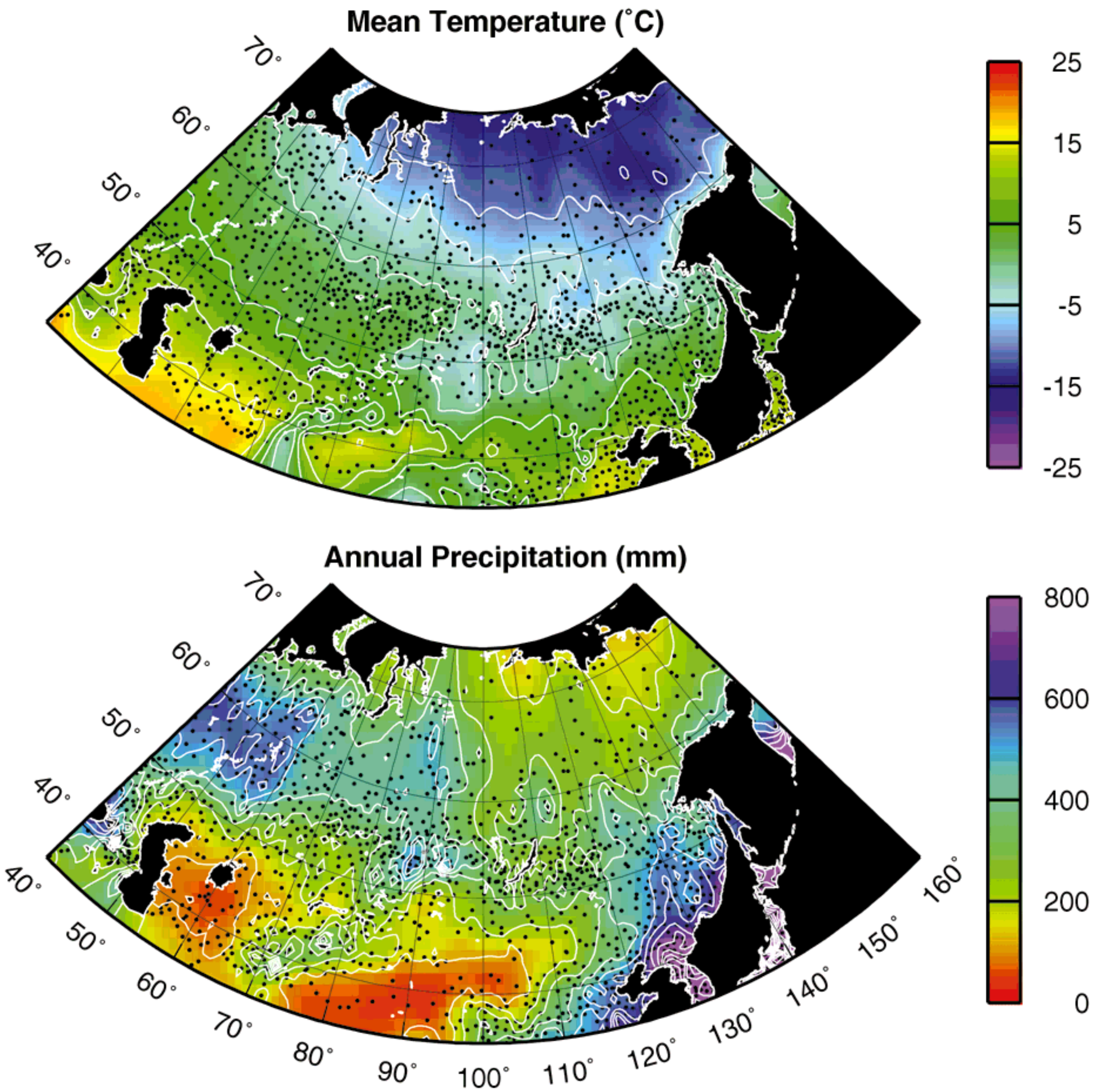

Plate 1. The distribution of the annual mean surface air temperature (upper) and annual precipitation (lower). The distribution of GDS stations is denoted by dots. Contours are drawn at every 5°C for temperature and every 100 mm/year for precipitation

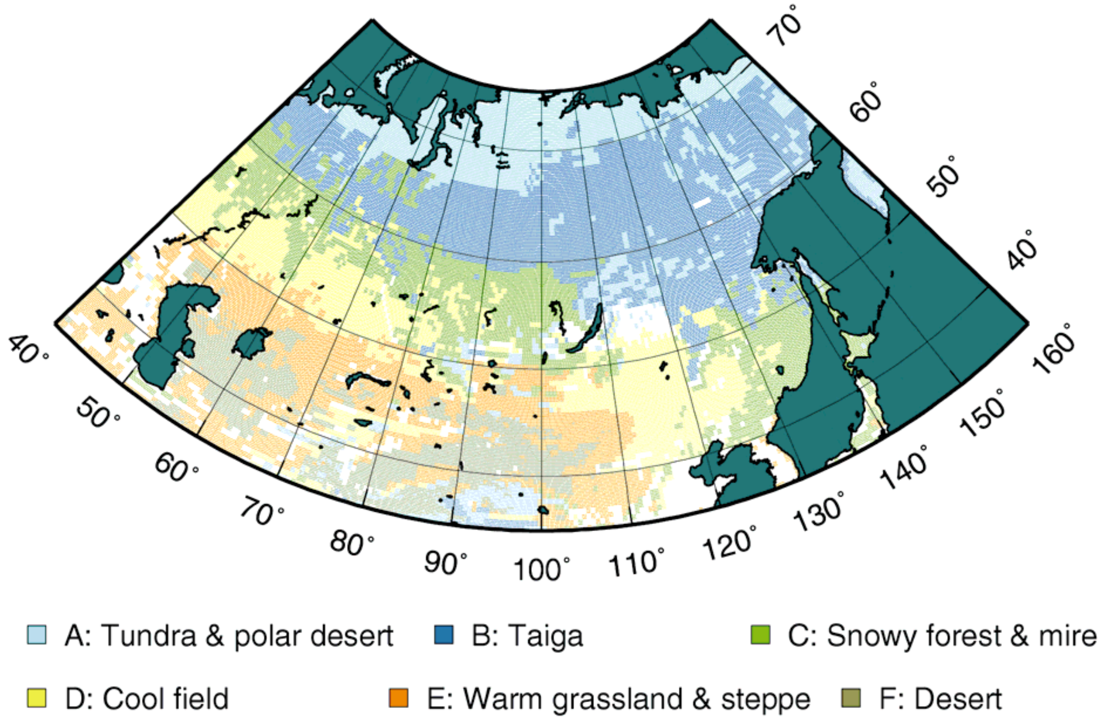

Plate 2. The distribution of the six recategorized vegetation types. The areas with no colour (white) are uncategorized areas through the recategorizing process. Details of each vegetation category can be found in Table I

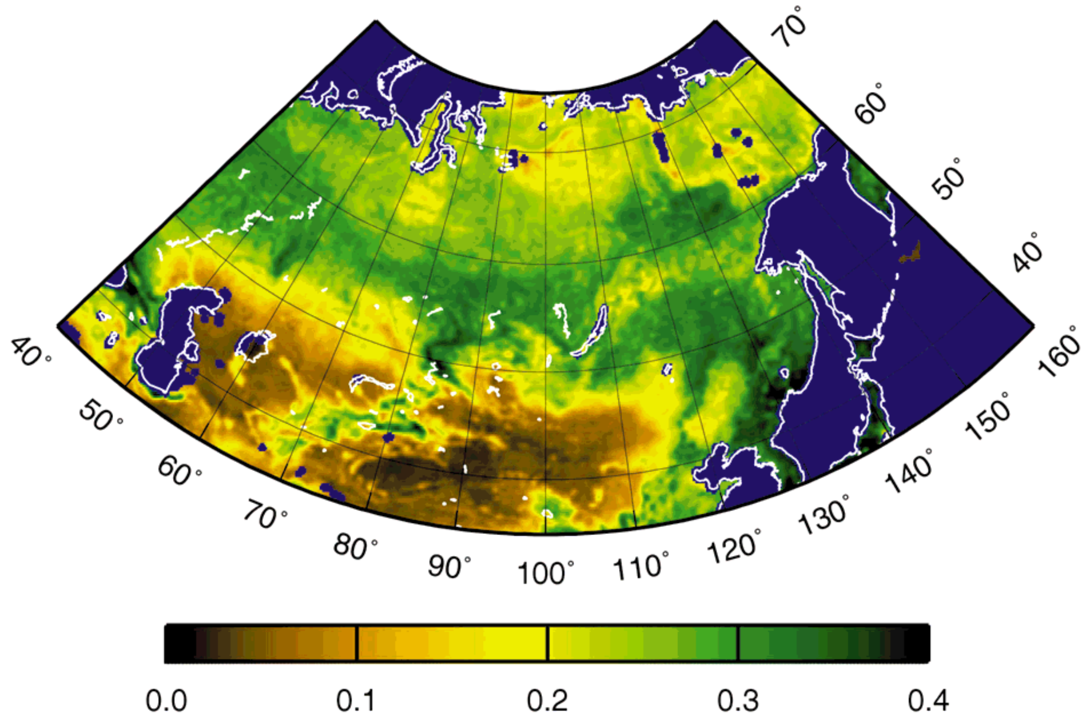

Plate 3. The distribution of the 5-year mean NDVI (January, November and December are excluded). The water surface and the missing data area are coloured in blue

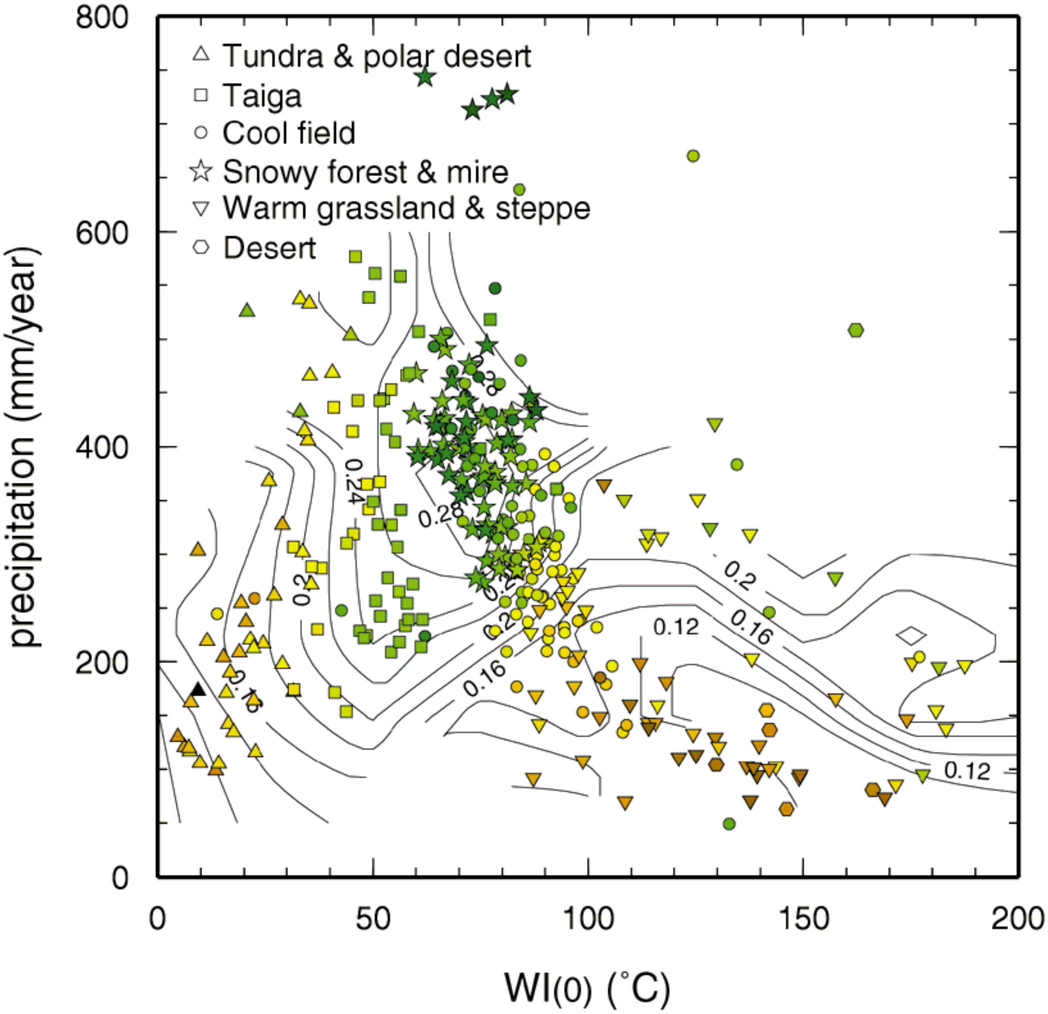

Plate 4. The relationship among the $WI_{(0)}$, the annual precipitation, the vegetation types and the NDVI. The NDVI value is represented by the colour that has the same colour scale with Plate 3. The contour lines are drawn based on the NDVI value (smoothed) with an interval of 0.02

