

## Recent interdecadal changes in the interannual variability of precipitation and atmospheric circulation over northern Eurasia

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## LETTER

## Recent interdecadal changes in the interannual variability of precipitation and atmospheric circulation over northern Eurasia

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2 June 2016Tetsuya Hiyama<sup>1</sup>, Hatsuki Fujinami<sup>1</sup>, Hironari Kanamori<sup>1</sup>, Takaya Ishige<sup>2</sup> and Kazuhiro Oshima<sup>3</sup><sup>1</sup> Institute for Space–Earth Environmental Research (ISEE), Nagoya University, Japan<sup>2</sup> Graduate School of Environmental Studies, Nagoya University, Japan<sup>3</sup> Institute of Arctic Climate and Environment Research (IACE), Japan Agency for Marine–Earth Science and Technology, JapanE-mail: [hiyama@nagoya-u.jp](mailto:hiyama@nagoya-u.jp)**Keywords:** interannual variability, trend, summer precipitation, moisture flux convergence, Siberian river basins, Mongolia, Arctic

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**Abstract**

This study investigated the interannual variability and trends in precipitation and atmospheric circulation patterns over northern Eurasia using long-term Precipitation REConstruction over Land and atmospheric Japanese 55-year Reanalysis data (JRA-55) from 1958 to 2012. Special emphasis was placed on the recent increase in summer (June, July and August) precipitation around the Lena river basin in eastern Siberia. We found interdecadal modulation in the relationships between interannual variability in summer precipitation and atmospheric circulation patterns among the three major Siberian river basins (Lena, Yenisei, and Ob). The interannual variations in summer precipitation over the Ob and Lena river basins were negatively correlated from the mid-1970s to the mid-1990s. However, after the mid-1990s, this negative correlation became insignificant. In contrast, a significant positive correlation was apparent between the Yenisei and Lena river basins. We also found that there has been a significant increasing (positive) trend in geopotential height in the low-level troposphere since the mid-1980s over Mongolia and European Russia, resulting in an increasing trend of westerly moisture flux into the Yenisei and Lena river basins. Summer precipitation in both basins was continuously high from 2005 to 2008 under a trough that broadly extended from the Yenisei and Lena river basins, which has been a typical pattern of interannual variation since the mid-1990s. This trough increased the meridional pressure gradient between Mongolia and eastern Siberia in combination with the trend pattern. This further enhanced the eastward moisture flux towards the Lena river basin and its convergence over the basin, resulting in high summer precipitation from 2005 to 2008.

**1. Introduction**

The Arctic water cycle has experienced an unprecedented change that may be having planetary-scale effects (Shiklomanov and Lammers 2009). Screen and Simmonds (2010) found that recent Arctic warming is strongest at the surface, which is consistent with the observed reductions in sea ice cover. The authors also indicated that increases in atmospheric water vapour content, partly in response to the reduced sea ice cover and increases in evaporation, may have enhanced warming in the lower part of the atmosphere during the summer and early autumn. Thus, Arctic warming is accompanied by increases in atmospheric water vapour content, which accelerates the water cycle in the Arctic region.

In the middle of the Lena river basin in eastern Siberia, the thawing depth (active layer depth) in late summer drastically deepened, and soil moisture increased from 2005 to 2008 (Ohta *et al* 2008, Iijima *et al* 2016). Velicogna *et al* (2012), Vey *et al* (2013) and Suzuki *et al* (2016) detected an increase in terrestrial water storage in the Lena river basin during the period from 2002 to 2008 using monthly solutions from the Gravity Recovery And Climate Experiment satellite mission. These were partly due to high rainfall in late summer and high snowfall in winter (Hiyama *et al* 2013a, Iijima *et al* 2016). Subsequently, permafrost-forest degradation and waterlogging have been detected in this region (Ohta *et al* 2008, 2014, Iijima *et al* 2010, 2016, Fedorov *et al* 2014). Although permafrost-forest degradation has not yet drastically affected

permafrost groundwater in eastern Siberia (Hiyama *et al* 2013b), interdecadal changes in annual low river flows (or base flows) during the open water season have revealed changes in the active layer depth, resulting from permafrost thawing at the scale of the upstream river basin (Brutsaert and Hiyama 2012). From another hydrological point of view, Shiklomanov and Lammers (2009) suggested that 2007 was not only unique in terms of the minimum sea ice extent in the Arctic Ocean but was also a record-breaking year for Eurasian river discharge to the Arctic Ocean. From a meteorological point of view, Zhang *et al* (2013) showed that enhancement of poleward atmospheric moisture transport and the associated increase in precipitation over northern Eurasia decisively contribute to increased river discharges in the region.

Previously, Serreze *et al* (2003) examined the large-scale hydroclimatology of the terrestrial Arctic drainage system. They described a geographical view of the seasonal and interannual water budgets of the four major river basins of the Lena, Yenisei, Ob, and Mackenzie rivers. Recently, Oshima *et al* (2015) investigated climatological features over the three major Siberian river basins (Lena, Yenisei, and Ob) using a decomposition analysis of the moisture flux, and revealed that moisture transport associated with cyclone activity dominated in the Lena basin, whereas that associated with seasonal mean winds dominated in the Ob basin. They also found that both transport processes affected the Yenisei. In this context, Fukutomi *et al* (2003) focused on the features of the interannual signatures of summer precipitation, moisture convergence, and runoff in the three river basins and the linkage of these to the large-scale water vapour transport and atmospheric circulation fields over northern Eurasia in the period from 1979 to 1995. They found an east–west dipole structure of circulation and precipitation anomalies over the Lena and Ob. This ‘saw-tooth-like’ interchange of dry and wet regimes associated with the dipole pattern occurred between eastern and western Siberia on a timescale of around 6–8 years. Additionally this east–west dipole pattern is well related to the east–west shift of storm tracks across Siberia (Fukutomi *et al* 2004, 2007). More recently, Fujinami *et al* (2016) investigated the spatio-temporal patterns of summer precipitation over eastern Siberia using empirical orthogonal function (EOF) analysis for the period from 1979 to 2007. They showed an increasing trend of summer precipitation for the period (29 years) in eastern Siberia, and also revealed the leading modes of interannual variation in the region. The increasing trend in the summer precipitation was related to the decreasing trend of low-level geopotential height around the region. They also showed that the spatial pattern of atmospheric circulation responsible for the wet years of the first leading mode was similar to that of the trend over eastern Siberia, indicative of the frequent appearance of a quasi-stationary trough over eastern Siberia in recent

decades. However because their investigation was limited to the period from 1979 to 2007, it is necessary to extend the analysis period to more comprehensively examine the interannual variability, using longer-term data that includes the period before 1979 and after 2007.

Accordingly, it is meaningful to further discuss the atmospheric circulation pattern associated with precipitation variability in the summer over northern Eurasia, including Mongolia and Europe, from the period before the 1970s to after the 2000s. Because summer precipitation in the Lena river basin was high from 2005 to 2008, the aim of this study is to investigate the interannual variability and trend in precipitation and atmospheric circulation pattern over northern Eurasia, with emphasis on the recent 4 year wet period (2005–2008), with regard to summer precipitation around the Lena river basin in eastern Siberia.

## 2. Data and methods

Archived (station observation-based) precipitation and atmospheric reanalysis data were used in this study. The precipitation data, which included gridded precipitation data interpolated from more than 17 000 observation stations over land, were from the National Oceanic and Atmospheric Administration (NOAA)’s Precipitation REConstruction over Land (PREC/L; Chen *et al* 2002). The observed precipitation data were collected by the global historical climatology network version 2 together with the climate anomaly monitoring system. Their horizontal resolution is  $1^\circ \times 1^\circ$ . Monthly precipitation from 1958 to 2012 (55 years) was used for this study.

We also used 6-hourly atmospheric data from the Japanese 55-year Reanalysis (JRA-55) project (Ebita *et al* 2011, Kobayashi *et al* 2015). The data were calculated from 6-hourly original (00, 06, 12, and 18 UTC), monthly, seasonal (3 months), and annual data. The available period (duration) was from 1958 to 2012 (55 years), and the horizontal resolution was  $1.25^\circ \times 1.25^\circ$ . A geopotential height of 850 hPa (m) and water vapour fluxes in the  $qu$  (zonal component) and  $qv$  (meridional component) ( $\text{kg m}^{-1} \text{s}^{-1}$ ) were mainly used in this study. The atmospheric moisture fluxes were vertically integrated from the bottom to top of the atmosphere in the reanalysis model field, after which the convergence was calculated.

The concept of atmospheric water budget analysis (i.e., Peixoto and Oort 1983, 1992) was applied using the following equations

$$\begin{aligned} \frac{\partial PW}{\partial t} &= -\nabla \cdot \frac{1}{g} \int_{P_b}^{P_t} qv dp + E - P \\ &= -\nabla \cdot \langle qv \rangle + E - P, \end{aligned} \quad (1)$$

$$P - E = -\nabla \cdot \langle q\mathbf{v} \rangle - \frac{\partial PW}{\partial t}, \quad (2)$$

where  $P$  is precipitation,  $E$  is evapotranspiration, and  $PW$  denotes precipitable water, which is an integral of  $q$  in the atmospheric column. The  $g$ ,  $q$ , and  $\mathbf{v}$  terms represent acceleration due to gravity, specific humidity, and the horizontal wind vector, respectively. The range of the integral in the first term on the right-hand side of equation (1) and  $PW$  are from the bottom ( $P_b$ ) to the top of the atmosphere ( $P_t$ ).

When an average is calculated over a long period of time (i.e., 1 year), the second term on the right-hand side of equation (2) is negligible, and the equation can be rewritten as follows:

$$\bar{P} - \bar{E} \approx -\nabla \cdot \langle \bar{q}\bar{\mathbf{v}} \rangle. \quad (3)$$

Thus, net precipitation ( $P - E$ ) is the same as atmospheric moisture flux convergence (MFC), and can be estimated assuming there is no temporal change in  $PW$ . That is, ( $P - E$ ) can only be calculated from the reanalysis data of  $q$  and  $\mathbf{v}$ . However, care is needed in using equation (3) for the evaluation of ( $P - E$ ) if the target period is less than 1 year. In cases where it can be assumed that the trend and interannual variability in  $PW$  are negligible, it can also be assumed that those of MFC are equal to ( $P - E$ ).

In this study, annual total values of precipitation and MFC were cumulative from December of the previous year to November of the current year. Seasonal values were calculated every 3 months; winter was from December of the previous year to February of the current year (DJF); spring was March–May (MAM), summer was June–August (JJA), and autumn was from September to November (SON). The primary target areas of the analyses were the three major river basins of Siberia (figure 1), Lena (110–137 °E, 57–64 °N), Yenisei (92–105 °E, 51–65 °N), and Ob (60–86 °E, 52–62 °N), and the target season was the JJA season.

### 3. Results

#### 3.1. Interannual variability in precipitation and MFC in the Lena river basin

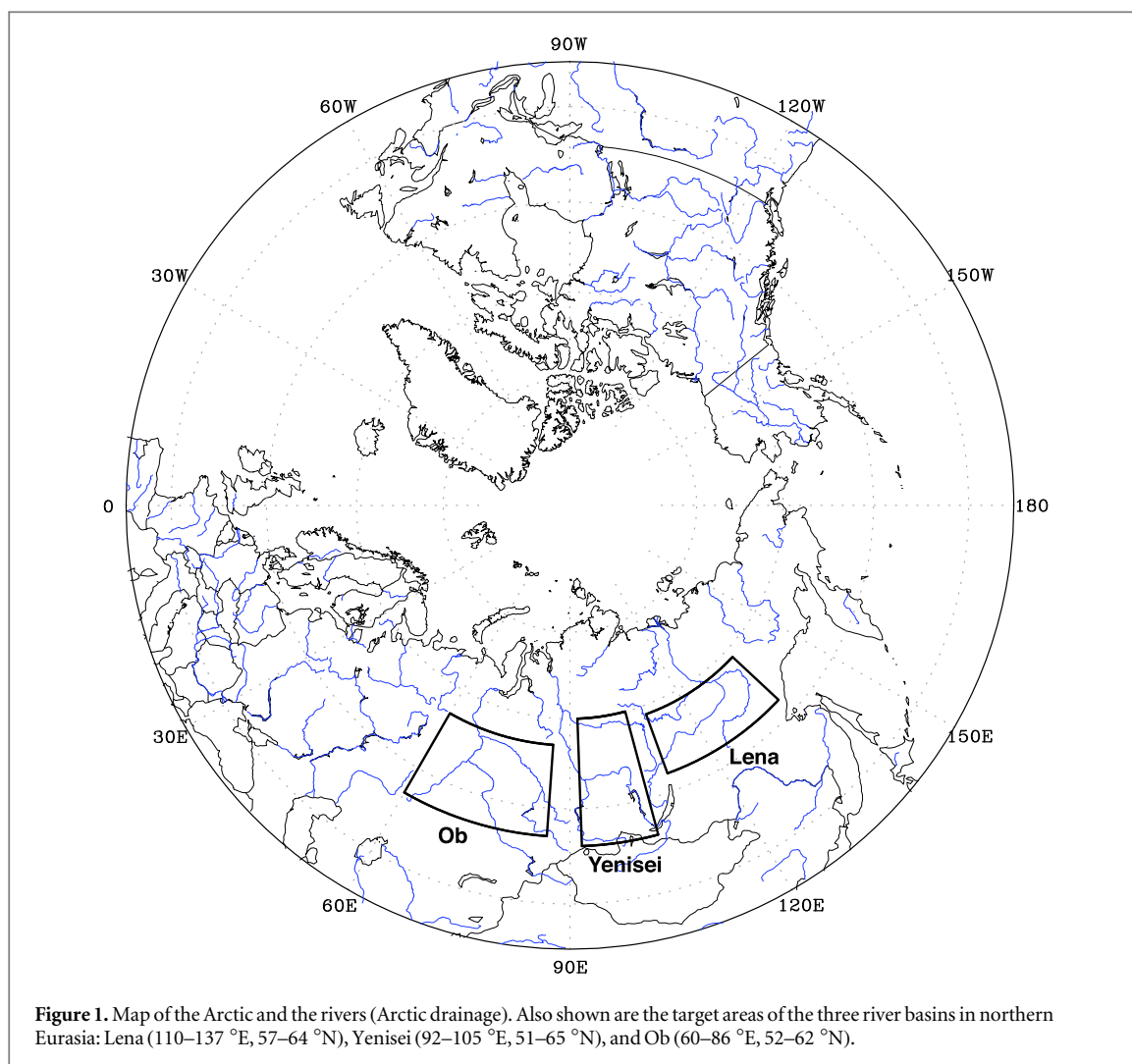
First, the long-term interannual variability of summer precipitation and summer MFC in the Lena river basin was investigated to confirm the current rapid change in water cycles in the mid part of the Lena river basin. Figure 2(a) shows the interannual changes in annual precipitation from 1959 to 2011, plotted alongside changes in the summer, autumn, winter, and spring precipitation in the Lena river basin. High amplitudes in the interannual variation were found for both annual precipitation (figure 2(a)) and annual MFC (figure 2(b)). Annual precipitation varied from 255 to 430 mm. The summer and autumn precipitation accounted for 47% and 26% of the total, respectively. Therefore, the variability in summer precipitation was the main contributor to the variation in annual precipitation and MFC. Additionally, the interannual

change in summer precipitation was coincident with that of annual precipitation. The correlation coefficient,  $r$ , between the interannual changes in summer and annual precipitation was 0.86. This was also apparent in the MFC (figure 2(b)), with  $r = 0.84$ . Thus, it is important to analyse the summer atmospheric circulation pattern in the Lena river basin in conjunction with interannual variability.

The most interesting feature in figure 2(a) is the remarkable increasing trend in annual precipitation since the mid-1980s, which corresponds well with the trend in summer and autumn precipitation. The increasing trend in the annual precipitation from 1984 to 2011 was statistically significant at the 99% level following a Mann–Kendall test. The increasing trends in summer and autumn precipitation during the same period were also statistically significant at the 99% level. These trends were partly derived from the extraordinarily high precipitation during the late summer of 2005–2008 (Hiyama *et al* 2013a). The period from 2005 to 2008 consisted of four successive wet years in the Lena river basin. It should be noted that the increasing trend of precipitation since 1984 has not been a steady and persistent throughout the analysis period, but rather, has been an increasing ‘phase’ of interdecadal variation that has persisted for approximately 30 years since 1984. Hereafter, this study focuses on the recent 4 year wet period (2005–2008) in the Lena river basin, and considers the reason why the wet years appeared in this period. In order to fully determine this, it was recognised that intensive analysis was needed to clarify the interdecadal modulation of interannual variation in precipitation and atmospheric circulation in the increasing phase.

#### 3.2. Changing relationships in summer precipitation and summer MFC among three Siberian basins

Our comparisons of summer precipitation and summer MFC using longer time series data (1958–2012) revealed that the negative correlation between the Lena and Ob (from the mid-1970s to mid-1990s) was unclear from the mid-1990s (figure 3(a)). More interestingly, figure 3(a) shows a significant positive correlation between the Lena and Yenisei with regard to summer precipitation from approximately 1995 to 2005. Similar tendencies were also found in summer MFC (figure 3(b)), except for a shift of a few years in both correlations. This evidence of a significant positive correlation in summer precipitation between the Lena and Yenisei from about 1995 to 2005 is probably indicative of the enhancement of cyclonic circulation from the Eurasian side of the Arctic Ocean to the region across the Yenisei and Lena. If so, it is meaningful to refer to the relationship between interannual variations in the Arctic sea ice extent in September and summer surface pressure fields (Ogi and Wallace 2007). Thus, the spatial patterns of



moisture flux vectors in the summer and the atmospheric circulation over the Arctic circumpolar region are described in the following text.

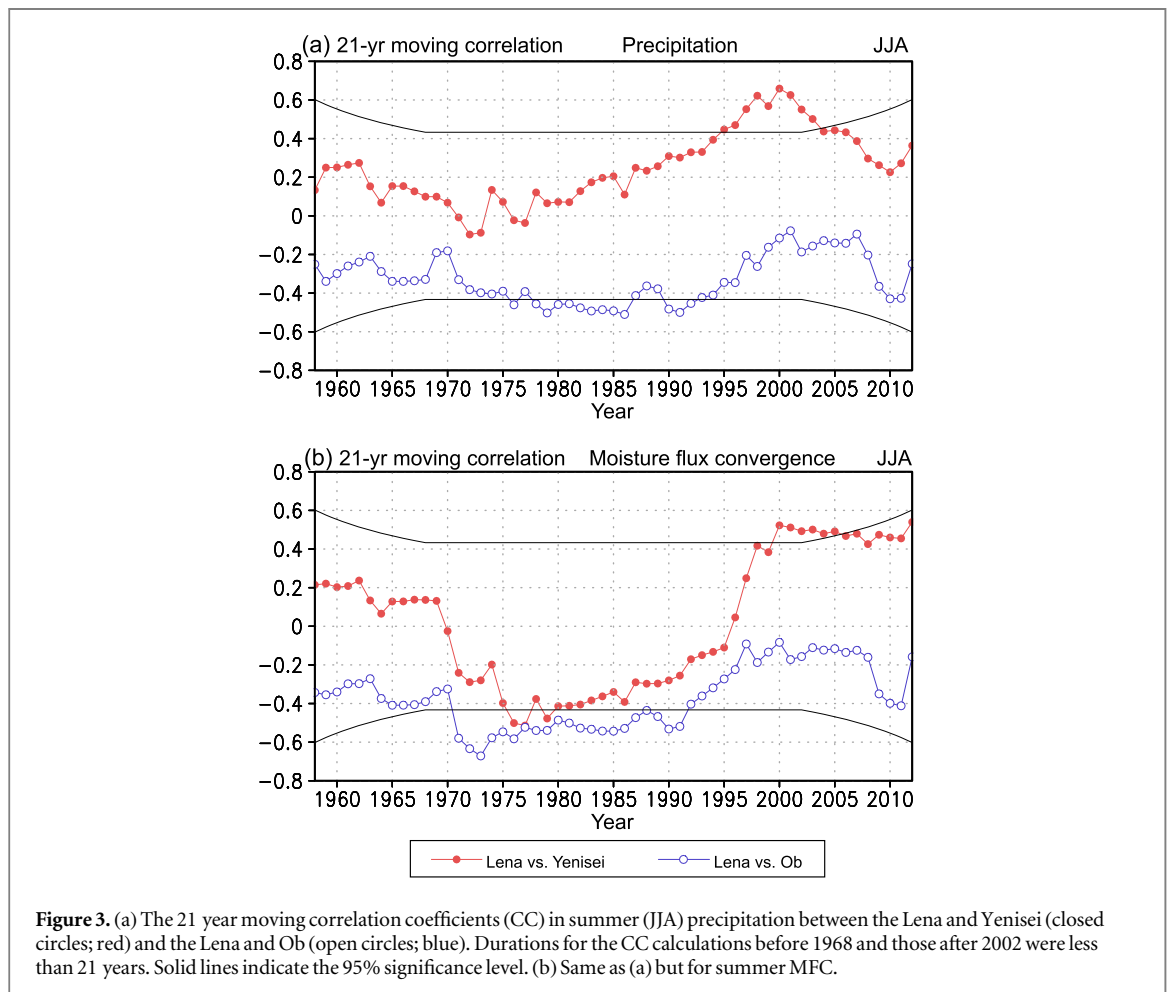
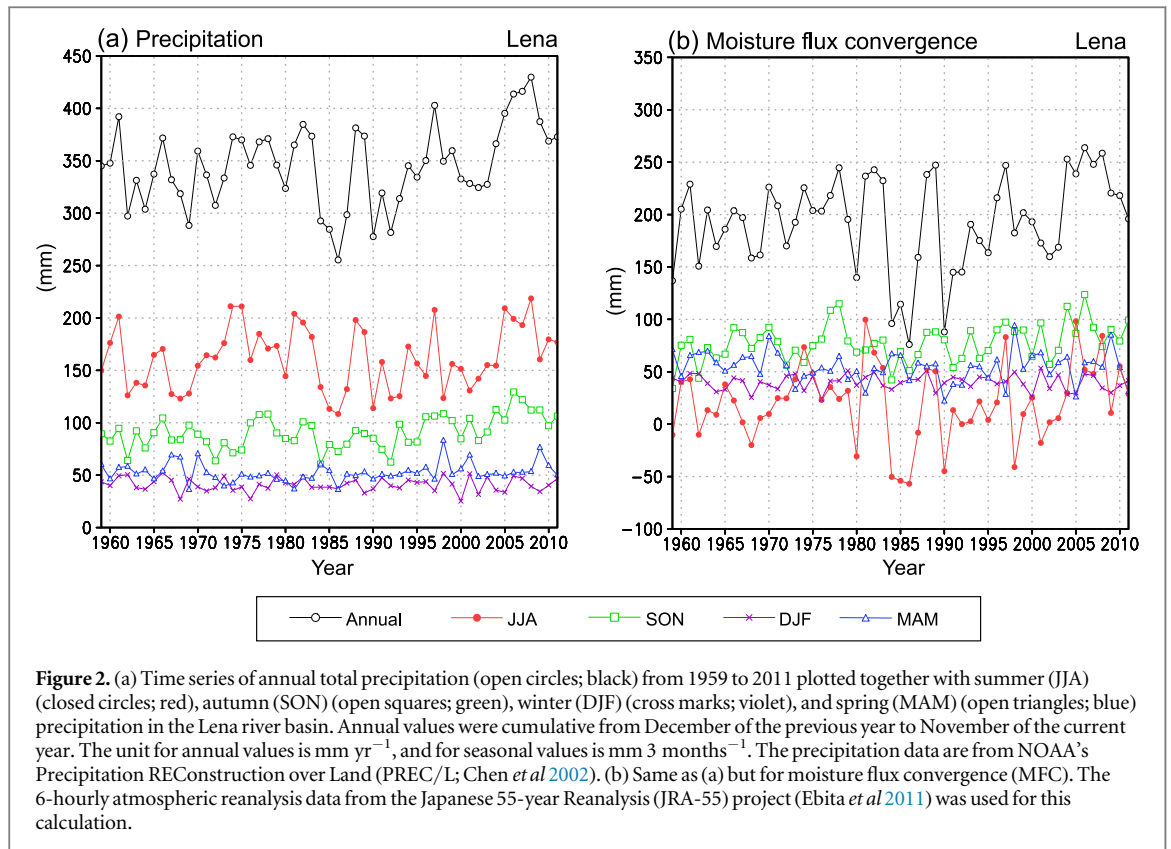
Based on the results from figures 3, 4 shows the regression patterns of atmospheric circulation and moisture fields in the summer over the Arctic circumpolar region for the two periods of 1979–1995 and 1995–2011. As Fukutomi *et al* (2003) reported, an east (Lena) to west (Ob) dipole pattern was clearly shown from 1979 to 1995 (figure 4(a)). Interestingly, in recent years (1995–2011), a monopole pattern was observed over Yenisei and Lena (figure 4(b)). This interdecadal modulation of regression patterns is consistent with the results shown in figure 3. Most of the correlations in figure 4(b) are statistically insignificant. This may be partly due to the sparsity of station data, as well as the large contribution of interannual variability to the high level of noise in the used data products.

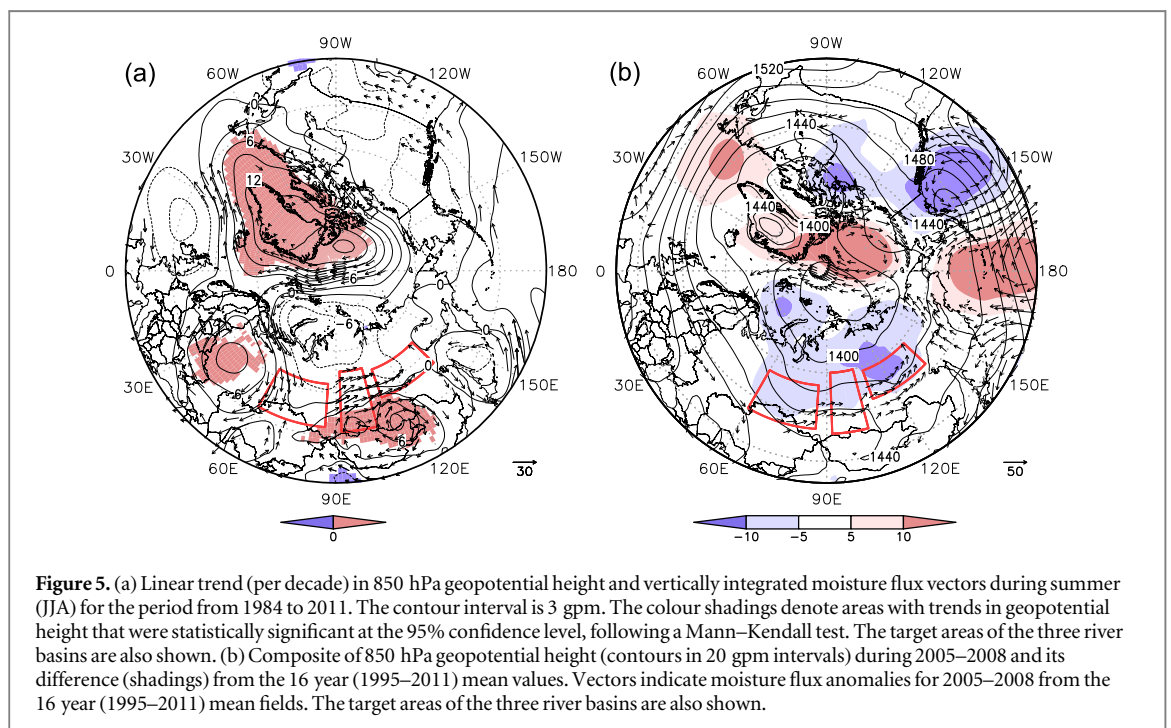
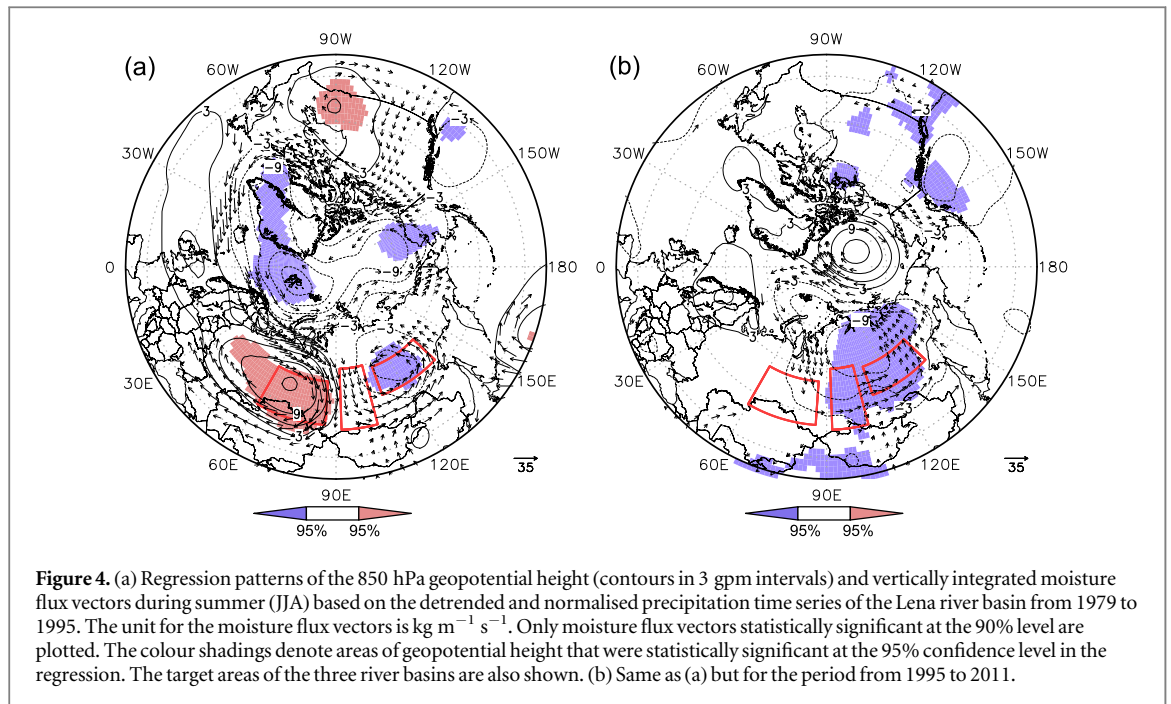
### 3.3. The atmospheric circulation pattern and moisture fields in the Arctic circumpolar region, with special emphasis on the wet summers in the Lena river basin

Next, based on the remarkable increasing trend in precipitation and MFC after the mid-1980s (figure 2),

the long-term trends (1984–2011) in the atmospheric circulation patterns and moisture fields were analysed (figure 5(a)). Positive trends in the 850 hPa geopotential height were not only detected over Greenland but also over Mongolia and European Russia. Although the enhancement of cyclonic circulation around the Lena river basin was statistically insignificant, there was clear enhancement of the atmospheric moisture flux over the southern parts of the Yenisei and Lena river basins. To reveal the differences in summer precipitation in the Arctic circumpolar region, with special emphasis on the 4 wet years (2005–2008) in the Lena river basin, we produced a composite map (figure 5(b)) showing the 850 hPa geopotential height during 2005–2008, and its difference from the 16 year period of 1995–2011. This figure shows a trough extending from the regions of the Kara and Barents seas to the region across the Yenisei and the Lena, with a remarkable cyclonic anomaly centred on the Lena river basin during the 4 years (2005–2008) with highest summer precipitation. An enhancement of atmospheric moisture flux vectors was also clearly observed over the southern parts of the Yenisei and Lena.

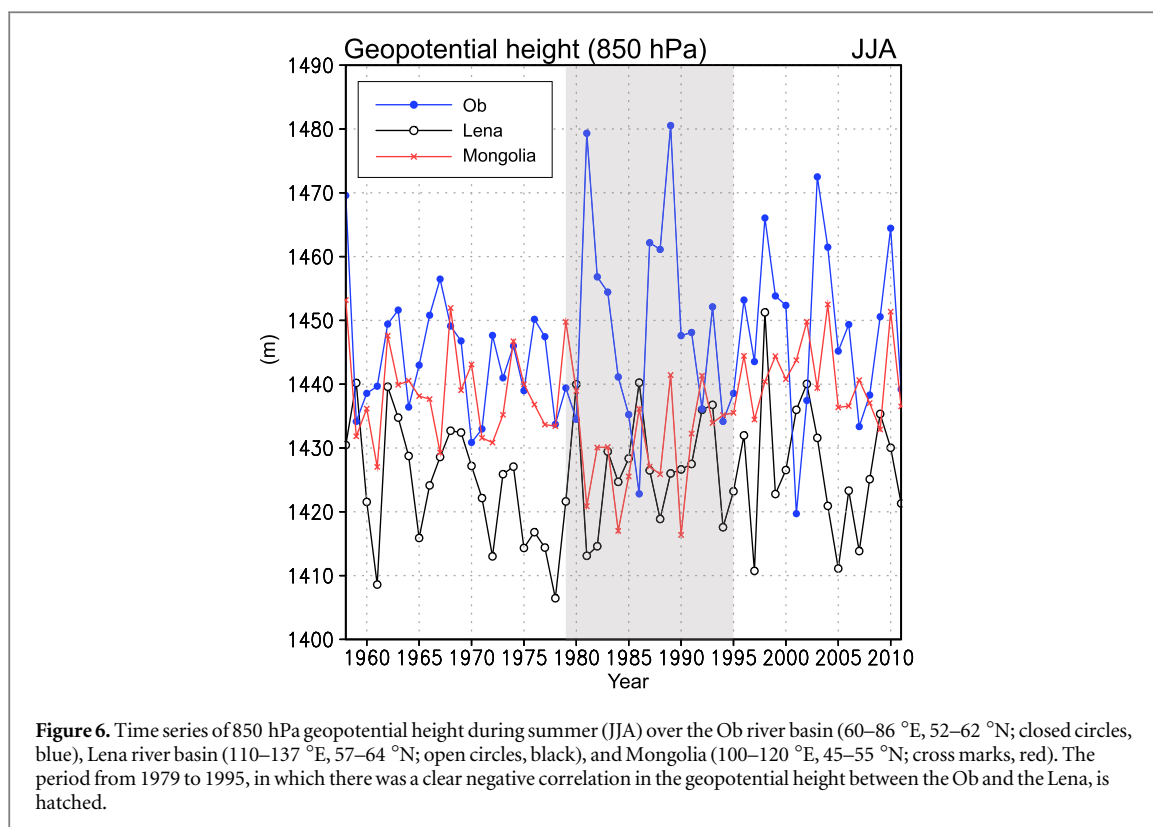
The interannual variability in the 850 hPa geopotential height in summer over the Ob (60–86 °E,





52–62°N), the Lena (110–137°E, 57–64°N) and Mongolia (100–120°E, 45–55°N) is shown in figure 6. Because the choice of the boundaries did not have a large effect on the results, they were determined based on figure 1 for the Ob and Lena river basins and on figure 5(a) for Mongolia, where a significant positive trend in the geopotential height was observed. As shown in figure 6, there was a clear negative correlation in the geopotential height between the Ob and the Lena from the late-1970s to mid-1990s (also see figure 4(a)). In the Mongolia region, an

abrupt decrease in the 850 hPa geopotential height was observed in the early 1980s. Interestingly, it started to increase after the mid-1980s (also see figure 5(a)). This means that the westerly MFC was enhanced in recent decades, because the meridional pressure gradient between eastern Siberia and Mongolia increased. It is also possible that interdecadal modulation of atmospheric pressure fields between the Lena and the Ob and between the Lena and Mongolia enhanced the MFC in the Lena river basin (figure 5).



#### 4. Discussion

The interannual variability and long-term trends in atmospheric circulation patterns over northern Eurasia are discussed here in more detail. As indicated in the previous section, this study found a remarkable trough extending from the Kara and Barents seas to the region across the Yenisei and the Lena during the 4 wet years (2005–2008) in the Lena river basin. This trough corresponded to a remarkable cyclonic anomaly centred on the Lena river basin. In contrast, positive long-term trends (1984–2011) in the 850 hPa geopotential height were observed over the regions of Mongolia and European Russia.

Recently, Fujinami *et al* (2016) found that the enhanced south-westerly MFC in summer over eastern Siberia was related to changes in stationary Rossby waves along the polar jet across the northern Eurasian continent. They suggested that atmospheric teleconnection was a major factor in the increasing trend and interannual variation in summer precipitation over eastern Siberia, i.e., the Lena basin. Although Fujinami *et al* (2016) discussed how the wet years in the Lena were related to the east–west dipole between the Ob and Lena basins, the present study revealed an interannual relationship between the three major river basins have been changing since around the mid-1990s. The 2005–2008 wet event in the Lena presented a quite different spatial structure compared with the former wet years, which was induced by the east–west dipole pattern observed remarkably in the 1980s (EOF2 in Fujinami *et al* 2016).

The trends and changes in the leading modes of the atmospheric teleconnection pattern in summer over northern Eurasia might be responsible for the recent interdecadal changes in interannual variability of the atmospheric pressure fields. Schubert *et al* (2014) showed that the main feature of summer precipitation and temperature trend over northern Eurasia in the last three decades (after the 1980s) are forced by the leading patterns of sea surface temperature (SST) variability (e.g. the global trend and the dominant patterns of SST variability in the Pacific and Atlantic oceans). The precipitation trend in their study around northern Eurasia is consistent with our results (figure 2(a)). External forcing by SST can induce a positive geopotential height trend (or anomaly) over the mid-latitude westerly zone of Eurasia, including around Mongolia, which is consistent with our result for the increasing trend in geopotential height (figures 5(a) and 6). Thus, external forcing could be a factor inducing a positive geopotential trend around Mongolia after the 1980s (figure 6).

The Northern Hemisphere annular mode (NAM) in summer, which is the dominant mode of summer atmospheric circulation in the northern hemisphere (Ogi *et al* 2004), can also affect atmospheric circulation in northern Eurasia. The spatial structure of the summer NAM has centres of action over the Arctic Ocean and northern Eurasia in the lower troposphere. Interestingly, Ogi and Yamazaki (2010) found that the index of summer NAM has displayed a negative trend since 1996, when the interannual relationship among the three Siberian river basins began to change



(figure 3). The spatial structure in geopotential height in the lower troposphere related to the negative trend (figure 3(c) in their study) is similar to the regression pattern based on the precipitation variability over the Lena river basin from 1995 to 2010 (figure 4(b) in the present study). However, because the NAM is an internal mode of atmospheric circulation, the mechanism that leads to the change in its trend around 1996 is unclear.

In contrast, the negative correlation between the Lena and Ob river basins (figure 4(a)), which is remarkable from the 1970s to the 1990s, was the first leading mode of the atmospheric teleconnection pattern over mid- and high-latitude Eurasia during this period (Fukutomi *et al* 2003). Recent studies have also shown an identical teleconnection pattern as a leading mode of interannual variation that can induce temperature and precipitation variability over northern Eurasia during summer (Schubert *et al* 2014, Fujinami *et al* 2016). The pattern can be interpreted as stationary Rossby waves along the polar jet. The stationary Rossby waves are likely driven by internal dynamics, because the correlation with SST variation is weak for the waves (Schubert *et al* 2014). Thus, the cause of the change in the atmospheric leading modes for precipitation variability over the Lena river basin remains unclear.

Other than Siberia, these atmospheric modes and trends likely affect the recent Arctic sea ice melt and hydroclimate around Mongolia. The circulation pattern over the Arctic that leads to the sea ice melt is nearly identical to that shown in figure 4(b) (also see Ogi and Wallace 2007, Ogi and Yamazaki 2010, Screen *et al* 2011, Knudsen *et al* 2015). Erdenebat and Sato (2016) recently explored the reasons for the recent (since the late 1990s) increase in heat wave frequency around Mongolia. They focused on the roles of atmospheric forcing and the possible influence of soil moisture deficit in Mongolia, and found that an atmospheric ridge appeared when heat wave events were observed in the region. The ridge around Mongolia was associated with summertime stationary Rossby waves (Iwao and Takahashi 2006, Schubert *et al* 2014, Fujinami *et al* 2016), superimposed on the increasing trend in geopotential height around Mongolia (figure 5(a)). Through the changes in the atmospheric circulation pattern over northern Eurasia, the recent enhancement of the cyclonic anomaly over the Lena basin is closely related to the recent increase in heat wave frequency around Mongolia. Additionally, Krishnamurti *et al* (2015) reported that the Asian summer monsoon could have a link to the rapid Arctic sea ice melt through a teleconnection. These issues, including potential land–atmosphere–ocean interactions and the effects on the long-term trend and interannual variability, should be further investigated in the future. The use of Atmosphere–Ocean General Circulation Models is appropriate for exploring the

cause of interdecadal changes in atmospheric circulation patterns.

In summary, we conclude that the recent (2005–2008) enhancement of the cyclonic anomaly over the region across the Yenisei and the Lena was induced as a composite effect of the long-term trend and interannual variability. Consequently, the atmospheric moisture flux from the west to the Lena river basin significantly increased, creating a positive anomaly in summer precipitation and MFC during 2005–2008. Very recently, Iijima *et al* (2016) also indicated that wet ground surface conditions in eastern Siberia during this period were likely caused by the enhancement of cyclones over the Arctic Ocean, and the eastward propagation of storm activity during late summer and early winter. This eastward propagation of storm activity could be the same as the cyclonic anomaly over the region across the Yenisei and the Lena, which was identified in our study.

## 5. Concluding remarks

This study investigated the interannual variability and trends in precipitation and atmospheric circulation pattern over northern Eurasia, with an emphasis on the recent increase in summer precipitation around the Lena river basin in eastern Siberia, using long-term (55 years) data sets of precipitation and atmospheric reanalysis. Based on the analyses, interdecadal modulation of interannual variability in summer precipitation and the atmospheric circulation pattern were found in the region. The detailed results are as follows.

- (1) A significant positive correlation in summer precipitation appeared from around the mid-1990s to the mid-2000s between the Lena and Yenisei river basins. In contrast, the negative correlation between the Lena and Ob river basins became insignificant from the mid-1990s.
- (2) Although an insignificant long-term trend in the 850 hPa geopotential height was observed from 1984 to 2011 in the Lena and Yenisei river basins, a clear enhancement of the atmospheric moisture flux over the southern parts of both basins was detected. This was because a significant increasing (positive) trend in the low-level troposphere was observed over Mongolia.
- (3) In the 4 years (2005–2008) with the highest summer precipitation in the Lena river basin during the period from 1958 to 2012, a trough with a remarkable cyclonic anomaly was detected over the regions from the Kara and Barents seas to the Yenisei and Lena basins. The deviation of the height field and the atmospheric moisture flux from the west to the Lena river basin were significantly increased, forming a positive anomaly in summer precipitation.

It should be noted that the recent interdecadal changes in the interannual variability of the atmospheric circulation pattern over northern Eurasia has not only resulted in permafrost–forest degradation in eastern Siberia (Ohta *et al* 2008, 2014, Iijima *et al* 2010, 2016, Fedorov *et al* 2014) as a result of the increase in summer precipitation, but also increased heat wave frequency around Mongolia (Erdenebat and Sato 2016). Because the atmospheric circulation pattern over northern Eurasia might be connected with atmospheric pressure fields over the Arctic Ocean and the Asian summer monsoon over southern Eurasia, further investigation is required to explore possible land–atmosphere–ocean interactions.

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