Response to Dr. Klaus Arpe's comments (P. 1-6)

The paper tries to find connections between the river discharges of 2 main rivers in Siberia and the atmospheric circulation. It is well written and I enjoyed reading it and found is inspiring. I would recomment accepting it for printing it even if it far from reflecting a breakthrough in science.

Thank you very much for your review comments on the original manuscript. We have revised the manuscript according to your comments. Our point-by-point replies are as follows.

I would add a plot in the introduction of topograpy and catchment areas to set the scene, like the attached file Fig_K1_oro. The Fig.1 provided in the manuscript, showing nearly the same, has too much information and the essentials are not easily to be seen.

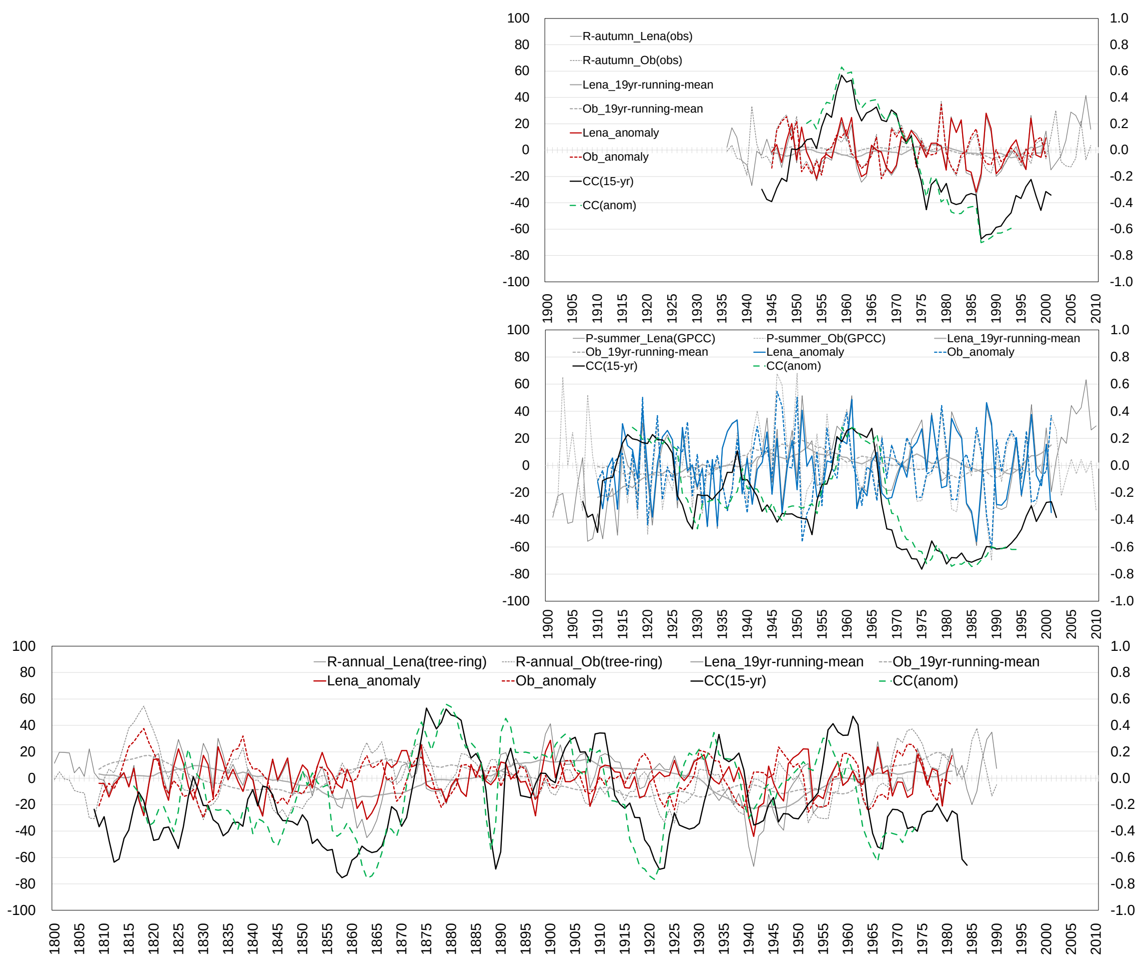
As advised, we deleted vector and remade Figure 1 simply.

I further suggest to add some Teleconnection maps (correlation maps) between the discharge or the precipitation over the catchment areas and the precipitation at each grid point as attached File figK2.jpg and FigK3.jpg for the Lena and figK4.jpg and figK5.jpg for the Ob. as suggested in the manuscript, I averaged the precipitation from June to September for such a comparison with the August to November river discharge. It shows nicely the catchment areas (figK2 and FigK4), though the higher correlations between river discharge and precipitation extend a little further, for the Lena to the SE and for the Ob beyond the Ural mountains but no connections between the 2 rivers. I am using the anomaly correlation, i.e. taking away a long term mean from each time series because in meteorology we are mostly interested in the deviations from the climatological mean. For convenience I use the mean of the whole time series provided. The values are given in the plots in % for clarity with less digits to be printed. I wonder if the definition of correlation has changed during the last 40 years, since I wrote most of my programs. Modern papers show always very high values of > 0.9 while here the best values are> 0.7 and in most of my publications I am happy to reach correlations of up to 0.4.

As you confirmed by the horizontal maps, the variation in P over the Lena river basin is basically related to the R of the Lena and the Ob river is the same when using data during the whole period. That is the same as the positive correlation between the P and R as shown in previous studies (Fukutomi et al. 2003, Serreze et al. 2003, Oshima et al. 2015). However, the first point here is a difference in the relationship (correlation) between the Lena and Ob in each of the epochs. That means that the Rs/Ps of Lena and Ob sometimes show negative correlation and occasionally positive correlation or no correlation in the other period (Figure 2). Fukutomi et al. (2003) revealed the strong negative correlation of P/R between the Lena and Ob Rivers during 1980s to mid-1990s. The associated precipitation anomaly maps were shown in Figure 6 of Fukutomi et al. (2003), and we described about those in the third paragraph of the Introduction. The second point of our finding in this study is that such negative correlation is frequently seen during the past two centuries based on the tree-ring-reconstructed Rs (Figure 2c) and then we discussed about the associated atmospheric circulation over the region. About those points, we modified some descriptions in the Abstract and the first paragraph of the Summary.

I tried also to reproduce the anti-correlation between the Ob and Lena in the 1970/1980s, but could not find anything in the precipitation like that although Fig.2b of the manuscript shows quite a few events like that. Plotting time series of precipitation over the Ob and Lena catchment areas with a running 19 year mean shows for the Ob a steady decline of precipitation since the early 1950s while the Lena keeps its mean nearly for the whole period. This might be the reason for the negative correlation between both rivers shown in Figure 2a and b since 1970, when the area mean precipitation drops below its long term mean.

The time period of the anti-correlation (negative correlation) is not in the 1970/1980s, but from 1980s to mid-1990s. When we remove the 19-year running mean from the time-series of Figure 2a-c, the correlations (black lines in Figure 2) do not change so much, as confirmed by the following figures. We added this result in the second paragraph of Sub-subsection 3.1.1. Additionally, we made minor revisions in Figure 2.



The main outcome in the paper is that the Ob discharge variability, and that of the Lena are not related to each other. The question is of course why do we expect such a relation. If both rivers would have a common forcing that could be expected. A strong large scale forcing all over the world is ENSO, which even reaches the Baltic Sea but does not seem to reach the 2 rivers. My attached plots FigK3 and FigK5 show clearly that when there is a major event of precipitation in one of the catchment areas, it is likely that the whole catchment area is affected but restricted to one catchment area, with no connection to the other catchment area perhaps enhaced by the mountain range between them. With this statement one has to be careful as one has to take the method of precipitation analysis into account. The method looks for each grid point into 4 directions to find the nearest observational station and makes then a weighted (by the distance) average. In FigK7_stat_dens one can see that the station density, provided by GPCC, in Siberia is very low, especially between both catchment areas, so all grid points within one catchment area will get higher weights to observations within that catchment area. This figure explains as well why in FigK3 and K5 the restriction to the catchment area is stretching for the Ob past the Ural and for Lena towards the SE as these are areas with a higher station density.

Related to the previous second comment, the main outcome of this study is not the no relationship between the Lena and Ob, but the Rs of the Lena and Ob frequently show negative correlation. While, when analyzing during the whole period, the R of the Lena (Ob) related to the P over the Lena (Ob) river basin, but the Ps over the Lena and Ob sometimes indicate a negative correlation as in the cases of 1980s and mid-1990s. Please see Figure 6 of Fukutomi et al. (2003). About the main outcome of our study, we modified some descriptions in the Abstract and the first paragraph of the Summary.

As you mentioned, in terms of the observation station density over Siberia, it is a concern and discussed in previous studies (e.g., Serreze and Barry, 2005: The Arctic Climate System.

Cambridge University Press, Section 6.1, 148-152). Oshima et al. (2015) investigated the correspondence among components of the water balance by using several datasets based on the independent data sources. We compared discharges from the observation station nearest the river mouth, P-E estimated from meteorological data (specific humidity and wind) of several reanalyses on the basis of the atmospheric water balance method, and P based on satellite and station observations for the three Siberian rivers (Lena, Yenisei, Ob). The results indicated good correspondences in balance and variation. The long-term averages of R and P-E were comparable in magnitude and the P was strongly correlated with R and P-E for the individual rivers. Of course, we should be a careful to discuss quantitatively about the P, but the above results indicated that the P dataset from the GPCC and other precipitation products (e.g., PREC/L, APHRODITE) are useful to examine the interannual variation in this region. We added some explanation about the P dataset in the second paragraph of Section 2 “Data and analysis methods”.

Coming back to why do we expect a relation between both rivers? I think it is our inability to imagine the wast extends of the areas in Siberia. Already Napoleon and Hitler fell victim of this inability even for Eurpean Russia.

It is not so difficult to understand that. We demonstrated that, over the summertime Siberia, the east-west seesaw pattern of large-scale atmospheric circulation frequently emerges as natural internal variability. This east-west seesaw pattern affects opposite influence on the Ps over the Lena and Ob. When the cyclonic anomaly emerges over eastern Siberia, that atmospheric circulation anomaly induces a convergence of moisture flux and then increases the P and R of the Lena River. Simultaneously, the anticyclonic anomaly emerges over western Siberia and induces a divergence of moisture flux, then decreases P and R of the Ob River, and vice versa. This results in out-of-phase of the Ps/Rs between the two rivers. We modified the explanation in the third paragraph of the Introduction.

Here some comments in detail:

page 3 line7: Salehard in the datset by Duemenil et al it is called Salekhard, also looking at google map only Salekhard is known

As described in the manuscript, we used the ArcticRIMS data where the station is named as “Salehard” and we employed that name instead of “Salekhard”. Because it is easy to find the used data on the ArcticRIMS website (http://rims.unh.edu/data/station/list.cgi?col=1).

page 4 line 6: you could mention that in Arpe K., Leroy S. A. G., Wetterhall F., Khan V., Hagemann S. and H. Lahijani: Prediction of the Caspian Sea Level using ECMWF seasonal forecasts and reanalysis. Theor Appl Climatol DOI 10.1007/s00704-013-0937-6, 2013 the Volga river discharge has been successfully estimated from the water budget calculations using ERA interim data and there they use a minimum of 3 month delay between precipitation events and river discharge events, longer in winter.

Thank you for introducing other example of seasonal time lag between R and P. This kind of seasonal time lag may be seen in seasonally frozen rivers. We referred this paper in the last paragraph of Section 2 “Data and analysis methods”.

page 7 line 11: do you really mean dumping not damping?

I made a typo. That is “damping”. We added some explanations in the second paragraph of Section 4. Thank you very much for your careful review.

Response to Dr. Stefan Hagemann's comments (P. 7-13)

Major remarks

The authors analyse the different long-term behaviour of precipitation and river runoff over the Lena and Ob catchments. Their analysis uses observations, GCM simulations and reconstructed discharges based on tree rings. They could link the anti-correlated behaviour during some periods to an east-west seesaw pattern that seems to be a feature of the general large-scale circulation and the atmospheric internal variability. The study is interesting and provides robust results due its combination of various observation and model data sources.

Thank you very much for the review comments on the original manuscript. We have revised the manuscript according to your comments. Our point-by-point replies are as follows.

I only miss some more embedding of the results into the present day climate research. What is the reason for the seesaw pattern? Is there a larger scale process that creates this pattern? Is the seesaw pattern, e.g., related to the circumglobal wave train found by Ding and Wang (2005) in the northern hemispheric during boreal summer? They pointed out that this pattern can favour co-varying patterns of rainfall anomalies over South and East Asia.

Ding, Q., and B. Wang (2005), Circumglobal teleconnection in northern hemisphere summer, J. Climate, 18, 3482-3505.

As mentioned in the manuscript, the reason for the east-west seesaw pattern is a summertime atmospheric internal variability over Siberia. The AGCM control simulation demonstrated the seesaw pattern over Siberia in summer. Thus, without external forcing like changes in SST, sea ice, greenhouse gases and solar activity, the seesaw pattern often emerges by chance.

In addition, we discussed about other reasons for the large-scale atmospheric circulation associated with P variability over Siberia. In the last part of Section 4, we described that the remote influence of Atlantic multidecadal variation, quasi-stationary Rossby waves over Eurasia and Arctic dipole anomaly affect the Siberian P based on the previous studies. As you pointed out, the circumglobal wave train may be another candidate. However, those specific effects are not clear in our analysis and future work is needed. We described about these in the last paragraphs of Section 4.

As the seesaw pattern and the anti-correlation is a real climate feature, do you it can be used as an index to evaluate the performance of GCMs or ESMs? If yes, you may suggest how in the conclusions section?

Yes. In this study, we evaluated the seesaw pattern and negative correlation in the AGCM and CMIP3 simulations on the basis of three ways. As for the negative correlation, we calculated the two statistics of median and skewness for the 15-year running correlations (Sub-subsection 3.1.2). As for the seesaw pattern, we performed an EOF analysis to identify the dominant pattern of large-scale circulation, and then calculated the pattern correlation of EOF2 between the JRA-55 and each of the simulations (Subsection 3.2). As for the relationship between the negative correlation and the seesaw pattern, we defined two indices of $\Delta Z500_{WE}$ and ΔP_{LO} and calculated the correlation between them (Subsection 3.2). Our explanations were insufficient and we described about these in the corresponding sections.

In section 3, skewnesses are shown in Fig. 3b and Table 2, but it is motivated neither why they are shown nor what the skewness results mean in the context of the present study. If there is not a clear benefit for the study, they may be removed.

As you know, the skewness is a measure of asymmetry of probability or frequency distribution. Here, we examined the frequency distribution of correlations of P between the Lena and Ob. So, when the correlation is distributed in the negative side, the skewness has positive value. We added this explanation in the second paragraph of Sub-subsection 3.1.1.

I suggest accepting the paper for publication after some revisions have been conducted.

I don't wish do stay anonymous, Stefan Hagemann

Thank you, Stefan.

Minor remarks

In the following suggestions for editorial corrections are marked in *Italic*.

Thank you for the careful review.

p.1 – line 9

… Ocean, *whereat* the …

We corrected as suggested.

p.1 – line 16

… (AGCM) and *fully coupled atmosphere-ocean GCMs* conducted …

We corrected as suggested.

p.2 – line 11

Regarding the interannual …

We corrected it.

p.2 – line 12

… due to *the* large …

We corrected it.

p.3 – line 5

… 3 (CMIP3*; Meehl et al. 2007*).

Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., Stouffer, R. J., and Taylor, K. E.: The WCRP CMIP3 multi-model dataset: A new era in climate change research, Bull. Amer. Meteor. Soc. 88, 1383-1394, 2007.

We added this reference.

p.3 – line 10

It is written:

“Because of limitations on the time period …”

This statement is probably not, what you really mean. In my opinion, the period 1936-2009 of the discharge observation is already quite long. It is probably more that you would like to have even more data to reduce the noise to find significant patterns of variability. Then, you should write this more clearly.

The 74-year record (1936-2009) of observed R is not long enough for this study. As in Figure 2a, we could find the negative correlation period of the Lena and Ob Rs during 1980s to mid-1990s and the positive correlation period during 1960s to 1970s, one by one. But we couldn’t judge whether there is a certain tendency of the correlation based on the 74-year record. On the other hand, we could reveal the tendency of frequent negative correlation based on the 191-year record of reconstructed R. The 111-year record of observed P also show the similar tendency of negative correlation. The time scale of negative correlation seems one or two decades. To detect such a tendency of the correlation on decadal timescale, the usage of long-term record is desirable. In addition, to detect a robust tendency of the correlation, we made subset of 150-year records and increased sample size of data. We added the explanation in the first paragraph of Section 2.

p.3 – line 24/25

…control simulation *is* the … …resolution *is* about … …and the vertical *discretization comprises* 20 layers ...

We corrected them.

p.4 – line 4

… R *comprises annual values*, we …

We corrected as suggested.

p.4 – line 5

… P *has* large …

This is not corresponding. The sentence was changed.

p.4 – line 7

Using a similar method *as* Tachibana ...

We corrected as suggested.

p.4 – line 9

…2009 *are* ..

We corrected it.

p.5 – line 31

… (EOF1) *is* the ..

We corrected it.

p.7 – line 9 It is written:

"The results in simulations give us several more implications for …"

Strange sentence/English. Please rewrite

We revised this sentence.

p.7 – line 11

What do mean with "dumping"? Please rewrite more clearly.

We made a mistake and "damping" is correct. We added some explanation in the second paragraph of Section 4.

p.7 – line 24/25

… warming *(Solomon et al. 2007; IPCC 2013)*.

Solomon, S., D. Qin, M. Manning, M. Marquis, K. Averyt, M. M. B. Tignor, H. L. Miller Jr., and Z. Chen, Eds. (2007), Climate change 2007: The physical science basis, Cambridge University Press, 996 pp.

IPCC (2013), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia,

V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.

We corrected these references.

Figure 1

I cannot really see the thick gray lines. Please improve figure. Actually, the figure looks quite busy. I suggest making two panels out of it.

As the first reviewer of Dr. Arpe pointed out, we deleted vector and remade it simple.

Figure 2

I suggest adding lines to show the 95% level of significance.

We added the lines of the 95% significant level.

Figure 4

Green dashed inset boxes are hard to see. Please improve figure.

We changed the color of inset boxes.

Response to Dr. Xiangdong Zhang's comments (P. 14-18)

This manuscript presents a statistical analysis on the relationship of river discharges and precipitations between the Lena and Ob river basins using the reconstructed data sets, AGCM simulation, and CMIP3 fully coupled climate model outputs. The results show a time varying correlations in all three data sets, consistent with previous results using shorter observational data set. The variability of sea-saw pattern between the west and east Eurasian continent is responsible for the decadal variation of the correlation coefficients. The research result is important for understanding Eurasian Arctic water cycle and its decadal variability and long-term changes. The manuscript could be publishable after a revision as described below:

Thank you very much for your review comments on the original manuscript. We have revised the manuscript according to your comments. Our point-by-point replies are as follows.

1. The authors attribute the sea-saw pattern is internal variability, but state it is important for long-term changes. Variability and long-term change are two different concepts, with latter generally describing externally forced trend. I would suggest the authors to separate them in the manuscript.

As you pointed out, the long-term change is also important for P and R variabilities. While Fukutomi et al. (2003) and MacDonald et al. (2007) discussed about the long-term variations on decadal timescale, it seems that the long-term changes do not affect the time series of 15-year running correlation in Figure 2. In fact, as replied to Dr. Klaus Arpe's comment, when we remove the 19-year running mean from the raw time-series of P and R in Figure 2a-c, the correlations do not change so much. We added this result in the last part of Section 3.1.1.

2. Throughout the manuscript, the authors simply mention negative or positive

correlations of R and P. This causes confusion of correlation between R and P or correlation of R or P between Lena and Ob. I suggest the authors to provide complete description on this.

I agree with you. That point was confusing and we revised the expression clearly throughout the manuscript.

3. The authors analyzed the AGCM and CMIP3 climate model outputs to examine the correlation relationship of R and P between the Lena and Ob rivers. To help readers to better understand the modeling results, I suggest the authors to provide full description which AGCM was used and how surface boundary conditioned were defined, as well as how long time the model simulation was carried out. I also suggest the authors to provide information which CMIP3 models were used in 20C3M and PICTL.

While the description of the AGCM control simulation was shown in the third paragraph of Section 2, we added further explanation about the 20C3M and PICTL simulations in the fourth paragraph of Section 2.

4. When comparing the AGCM and CMIP3 climate model results, the authors state that air-sea interaction acts as a damping factor of sea-saw pattern. It is hard for me to understand this. From my understanding, when the modeled P is closer to the reconstructed R, there should be better correlations between P and R. I suggest the authors to clarify this.

We examined the relationship between R and P based on the observation and reconstruction. On the other hand, in the AGCM and CMIP3 simulations, we examined the relationship between the P and atmospheric circulation and did not analyze simulated R. While the AGCM control simulation is forced by the fixed boundary conditions, the CMIP3 simulations are based on ocean-atmosphere coupled model and have the effect of air-sea interaction. If possible, it is better to simulate the P and large-scale circulation over Siberia with the same kind of AGCM and coupled GCM. But, unfortunately, we don't have a coupled model and cannot do that. Our discussion in this study is only based on the CCSR/NIES AGCM and CMIP3 simulations. We added further discussion in the second paragraph of Section 4.

5. In line 6 (P. 2), the authors mention "these variables". It is not clear which variables are. In fact, P has been already included in P-E.

We specified the variables (i.e., R and P-E).

6. In line 13 (P. 2), "terrestrial processes" should be specified.

The discharge control via dams, permafrost condition associated with runoff process, distributions of lake, wetland and vegetation associated with evapotranspiration are included in the terrestrial processes. We added these in the text.

7. In line 11 (P. 3), it would be better to discuss why analyzing the 5 subsets of the data.

As in Figure 2, the negative correlations were frequently seen during the past two centuries (Figure 2c) and the time scale of the negative correlation seems one or two decades. To detect a robust tendency of the correlation, we made subset of 150-year records and increased sample size of data. We added that explanation in the first paragraph of Section 2.

8. In line 16 (P. 3), it needs to be clarified what time period was used to do correlation analysis between GPCC P and R.

The time period of the correlation is from 1901 to 2010. We described it.

9. In line 25 (P. 3), the AGCM resolution of about 300 km seems very low to describe water cycle in the river basins. I suggest authors to provide evidence that such a low resolution still can correctly capture P in the river basins.

As you pointed out, the resolution of our simulation is lower than in the recent AGCM/GCM's studies. In the previous studies, however, Numaguti 1999 and Kurita et al. 2005 examined precipitation recycling and source of precipitating water over Eurasia using an AGCM with T42 spatial resolution same as in our simulation. They indicated that the spatial pattern and seasonal cycle of simulated P and P-E over Eurasia are generally consistent with the observed features in the seasonal timescale. In this study, observed features of the negative correlation of P between eastern and western Siberia, the east-west seesaw and the relationship between the negative correlation and seesaw pattern were reproduced in the AGCM simulation. Therefore, this resolution of about 300km is enough for the purpose of this study. We added this explanation in the third paragraph of Section 2.

Numaguti, A. (1999), Origin and recycling processes of precipitating water over the Eurasian continent: Experiments using an atmospheric general circulation model, J. Geophys. Res., 104(D2), 1957–1972, doi:10.1029/1998JD200026.

Kurita, N., A. Sugimoto, Y. Fujii, T. Fukazawa, V. N. Makarov, O. Watanabe, K. Ichiyanagi, A. Numaguti, and N. Yoshida (2005), Isotopic composition and origin of snow over Siberia, J. Geophys. Res., 110, D13102, doi:10.1029/2004JD005053.

10. In line 30 (P. 4), what specific discrepancy occurs between P and R?

There are some error and uncertainty for both the observed P and reconstructed R and they result in the discrepancy between the P an R. The observation stations of P are sparse in Siberia and there is difficulty in the P measurement such as wind-induced undercatch, wetting, and evaporation losses. These make an error and uncertainty for the P. The long-term R during the past two centuries is reconstructed based on the tree-ring width. While the tree-ring width has an indirect relation with the R, the both are mainly related through the P. There are also other influences such as SAT, solar radiation, nitrogen and so on. In addition, the tree-ring width is affected by meteorological conditions during the growing season in summer and there must be less contribution from the P during winter. As a result, the reconstructed Rs could explain 43% of the observed variability for the Lena and 51% for the Ob (MacDonald et al. 2007). We added some explanation in the second paragraph of Sub-subsection 3.1.1.

Influence of atmospheric internal variability on the long-term Siberian water cycle during the past two centuries

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Abstract. River discharges from Siberia are a large source of freshwater into the Arctic Ocean, whereat~~although~~ the cause of the long-term variation in Siberian discharges is still unclear. The observed river discharges of the Lena in the east and the Ob in the west indicated different relationships in each of the epochs during the past seven decades. The correlations between the two river discharges were negative during the 1980s to mid-1990s, positive during the mid-1950s to 1960s, and became weak after the mid-1990s. More ~~L~~long-term records of tree-ring-reconstructed discharges ~~during the past two centuries~~ have also shown differences in the correlations in each epoch. ~~However, i~~It is noteworthy that the correlations obtained from the reconstructions tend to be negative during the past two centuries. Such tendency~~negative correlations~~ has~~ve~~ also been obtained from precipitations~~ over the Lena and Ob~~ in observations, and in simulations with an atmospheric general circulation model (AGCM) and fully ~~multi-~~coupled atmosphere-ocean ~~model~~GCMs conducted for the Fourth Assessment Report of the IPCC. The AGCM control simulation further demonstrated that an east–west seesaw pattern of summertime ~~atmospheric~~ large-scale atmospheric circulation frequently emerges over Siberia as an atmospheric internal variability. This result in an opposite anomaly of precipitation over the Lena and Ob and~~, resulting in~~ the negative correlation~~ between the Lena and Ob~~. Consequently, the summertime atmospheric internal variability of east–west seesaw pattern over Siberia is a key factor influencing the long-term variation in precipitation and river discharge, i.e., the water cycle in this region.

1 Introduction

The river discharge (*R*) from the pan-Arctic terrestrial area supplies freshwater, nutrients, and organic matter to the Arctic Ocean. The three great Siberian rivers, the Lena, Yenisei and Ob (Figure 1) account for about 60% of the total *R* into the Arctic Ocean and have an important role in the freshwater budget and climate system in the Arctic (e.g., Aagaard and Carmack, 1989, 1994). Numerous studies have investigated the interannual variation and linear trend of the Siberian *R* (e.g., Berezovskaya, et al., 2004; Ye et al., 2004; McClelland et al., 2004, 2006; Rawlins et al., 2006; MacDonald et al., 2007; Shiklomanov and Lammers, 2009), however they have mainly analyzed the *R* dataset from a hydrological perspective. Several other studies have been conducted to determine the linkages among atmospheric circulation, moisture transport, precipitation (*P*), precipitation minus evapotranspiration (*P-E*), and the *R* for Siberian rivers using atmospheric reanalysis combined with the *R* dataset (Fukutomi et al., 2003; Serreze et al., 2003; Zhang et al., 2012; Oshima et al., 2015). To understand such linkages, it is necessary to improve our knowledge of the atmospheric and terrestrial ~~and atmospheric~~ water cycles in the region.

Theoretically, *P-E* over a basin, which is the net input of water from the atmosphere to the land surface, corresponds to *R* at the river mouth as a long-term average. Indeed, they quantitatively agree well for the individual Siberian rivers (e.g., Zhang et al., 2012; Oshima et al., 2015). The~~se variables~~ *R* and *P-E* are strongly affected by the *P* and associated atmospheric moisture transport over the individual regions ~~(Figure 1)~~. Processes of the atmospheric moisture transport associated with the *P-E* show regional difference among the Siberian rivers (Oshima et al., 2015). The *P-E* over the Lena ~~(Ob)~~ is mainly supplied by a transient ~~(stationary)~~ moisture flux associated with cyclone activity and that over the Ob is mainly supplied by a stationary moisture flux associated with ~~(~~seasonal mean wind~~)~~. Both processes affect the area over the Yenisei.

Regarding ~~to~~ the interannual variations, the moisture transport, *P-E*, *P*, and *R* also relate to each other, while those relationships have some seasonal time lag due to the large area of the basin, snow accumulation in winter, negative or near zero *P-E* in summer and terrestrial processes (e.g., discharge control via dams, permafrost condition associated with runoff process, distributions of lake, wetland and vegetation associated with evapotranspiration) as discussed in Oshima et al. (2015). More details about this are given in the last part of next section. Fukutomi et al. (2003) elucidated that the interannual variation in summer *P* over the Lena was negatively correlated with that over the Ob during the 1980s to mid-1990s. The summer ~~(~~*P-E*~~)~~s of the two rivers and corresponding autumn *R*s , respectively, ~~of the two rivers~~ were also negatively correlated in the same period. Furthermore, Fukutomi et al. (2003) indicated that the negative correlations were affected by an east–west seesaw pattern of ~~atmospheric~~ large-scale atmospheric circulation and associated moisture transport over Siberia. When the ~~*P* is large (small) over the Lena (Ob),~~ cyclonic ~~(anticyclonic)~~ anomaly~~ies~~ of atmospheric circulation emerges over the Lena ~~(Ob)~~ river ~~basin~~, the simultaneous anticyclonic anomaly emerges over the Ob river. The~~se~~ cyclonic anomaly~~ies~~ induces~~result in~~ a convergence ~~and divergence~~ of moisture flux over the Lena basin~~s~~, then ~~and the coincident~~ increases~~changes in~~ *P* and ~~then produce the negative correlation of~~ *R* of the Lena river~~between the two rivers~~. In contrast, the anticyclonic anomaly over the Ob induces a divergence of moisture flux, then decreases *P* and *R* of the Ob river, and vice versa. Thus, the east–west seesaw pattern produced the negative correlation of *R*s/*P*s between the Lena and Ob during the 1980s to mid-1990s. While the influence of cyclone activity on the interannual variations in *P-E* and *R* was discussed in their studies (Fukutomi et al., 2004, 2007, 2012), the cause of the negative correlations has not been fully explained, and it is not certain whether the negative correlation occurs in other periods.

The negative correlation noted above was apparent during the 1980s to mid-1990s. More recently, several drastic changes in the terrestrial water cycle have occurred around Yakutsk in eastern Siberia. Increases in *P* and soil moisture, and deepening of the active layer (Ohta et al., 2008, 2014; Iijima et al., 2010; Iwasaki et al., 2010) have been observed, particularly during 2005–2008, and the wet conditions have induced flooding (Fujiwara, 2011; Sakai et al., 2015) and forest degradation (Iwasaki et al., 2010; Iijima et al., 2014; Ohta et al., 2014). Moreover, effects of permafrost degradation on changing thermokarst lakes and landscapes have been reported in the last two decades (Fedorov et al., 2014). While these are local changes, the observed results suggest that some changes on a large spatial scale also occurred in this region in recent decades. Indeed, Iijima et al. (2016) showed that the increase in *P* and the wet conditions in eastern Siberia during the mid-2000s were affected by cyclone activity accompanied by changes in large-scale atmospheric circulation over Siberia. This suggests that the relationship between the Lena and Ob, which was negative correlation during the 1980s to mid-1990s, recently changed. However, the long-term variation and its effects on the water cycle in this region are still unclear.

To examine the long-term variation in *R* of the Lena and Ob Rivers, in addition to the observed *R* during the past seven decades, we analyzed reconstructed *R* based on tree rings during the past two centuries. We investigated whether the negative correlation of *R* between the Lena and Ob occurred before 1980s. We further examined an influencing factor on the long-term variation in *R* and *P*, and the associated atmospheric circulation using atmospheric reanalyses and simulations with an atmospheric general circulation model (AGCM) and atmosphere-ocean coupled models archived in the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3, Meehl et al., 2007).

2 Data and analysis methods

Monthly *R* observed near the river mouths of the Lena and Ob (i.e., Kusur and Salehard, Figure 1) from the Arctic-Rapid Integrated Monitoring System for the period of 1936–2009 (http://rims.unh.edu/), and ~~the reconstructed~~ annual *R* reconstructed based on tree rings for the period of 1800–1990 (MacDonald et al., 2007, http://onlinelibrary.wiley.com/doi/10.1029/2006JG000333) were used. While the negative correlation was seen during the 1980s to mid-1990s, the time scale of the negarive correlation seems one or two decades. To detect a robust tendency of the correlation, we made subsets of the dataset and increased sample size of data. ~~Because of limitations on the time period, i~~In addition to the entire period, we analyzed subsets of 150-year periods for the reconstructed *R*. There is a 191-year record of reconstructed *R*, and we produced 5 subsets of 150-year records, with the start years delayed successively by one decade.

Monthly *P* from the Global Precipitation Climatology Center (GPCC, Schneider et al., 2013) was compared to the *R*. While we here used the GPCC product, it has been confirmed that the *P* from the other products (e.g., PREC/L: Chen et al. 2002, APHRODITE: Takashima et al. 2009; Yatagai et al. 2012) also have strong positive correlation with *R* for the Lena and Ob Rivers (Oshima et al. 2015). For simplicity, we defined the area of 50–70°N and 110–135°E as the Lena region, and the area of 50–70°N and 60–85°E as the Ob region. The area averaged *P* over these regions corresponded well with the averages over the individual river basins. The correlations during 1901-2010 were 0.89 for the Lena and 0.86 for the Ob. In analyses of atmospheric circulation, geopotential height at 500 hPa (*Z500*) from two atmospheric reanalyses, the Japanese 55-year Reanalysis (JRA-55, Kobayashi et al., 2015; Harada et al., 2016) and the National Oceanic and Atmospheric Administration-Cooperative Institute for Research in Environmental Sciences (NOAA/CIRES) Twentieth Century Reanalysis (20CR, Compo et al., 2011), was used. The time period of the *P* and *Z500* datasets was from 1901 to 2010, except for the JRA-55, which started from 1958.

There are long-term records of tree-ring-reconstructed *R*s over the past two centuries, whereas the meteorological data are limited to the 20th century. To examine the long-term variation and intrinsic atmospheric circulation associated with the *P*, a 300-year control simulation was performed with an AGCM developed by the Center for Climate System Research, University of Tokyo, and the National Institute for Environmental Studies (Numaguti et al., 1995, 1997). The setting of the control simulation ~~wa~~is the same as in Ogata et al. (2013). The horizontal resolution ~~wa~~is about 300 km and the vertical discretization comprises~~level was~~ 20 layers (T42L20). It started from a state of rest with constant temperature, and was forced by the climatological seasonal cycle of sea surface temperature (SST), sea ice, and fixed greenhouse gases (GHG) as boundary conditions. We excluded the first 5 years of data from the 300-year simulation as the spin-up time. ~~As in the reconstructed *R*, f~~For the AGCM control simulation, we made 15 subsets of 150-year records, with the start years delayed successively by one decade. As in Numaguti (1999) and Kurita et al. (2005) based on the same AGCM with the same horizontal resolution, the spatial pattern and seasonal cycle of simulated *P* and atmospheric circulation over Siberia are generally consistent with the observed features in the seasonal timescale.

In addition, control simulations under pre-industrial conditions (PICTL) and “the 20th century climate in coupled models” (20C3M) simulations in the CMIP3 multi-models conducted for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4, Meehl et al., 2007, IPCC 2007) were compared to the AGCM control simulation. The 20C3M and PICTL simulations were forced by the GHG increasing as observed through the 20th century and the constant pre-industrial levels of GHG, respectively. ~~23 CMIP3 models with all of the multi-ensemble members were used.~~ While the time periods of the CMIP3 simulations were different among the models, the 20C3M simulations were from 1850–1900 to 2000–2001. The PICTL simulations had time records from 81 to 1001 years. We analyzed the PICTL simulations that were longer than 150 years and made subsets of 150-year records with the start years delayed successively by five decades in each of the PICTL simulations. All of the 23 ~~CMIP3~~ models with ~~all of~~ the multi-ensemble members in the CMIP3 simulations under the PICTL and 20C3M scenarios were used.

Although the reconstructed *R* ~~was~~ comprises an annual value, we analyzed seasonal mean values for the observed *R*, *P*, and *Z500*, because of ~~there is~~ the~~a~~ seasonal time lag between *P* and *R*, and the large seasonality of atmospheric circulation and *P* ~~have large seasonality~~. As in Tachibana et al. (2008) for the Amur River and Arpe et al. (2014) for the Volga River, it is expected that t~~T~~he summer *P*-*E* may correspond to autumn *R* ~~as in Tachibana et al. (2008)~~, and the summer *P*-*E* and *P* are governed by atmospheric circulation in summer. Using a ~~In the~~ similar method of Tachibana et al. (2008), we compared all possible combinations of *P-E* and *R* pairs and found that summer period from June to September and autumn period from August to October are best match for the Lena and Ob Rivers. The correlations during 1936–2009 are 0.79 for the Lena and 0.64 for the Ob, both significant above the 99% significance level (Table 1). In addition, due to the large amount and large variability of water vapor in summer, it is expected that the interannual variations in summer *P* and corresponding autumn *R* dominate the annual values. While those were still indicated in the previous studies (Fukutomi et al., 2003; Zhang et al., 2012), we confirmed the contribution of seasonal values of *P* and *R* to annual values. The correlation between the summer *P-E* (autumn *R*) and its annual value is 0.91 (0.79) for the Lena, and that for the Ob is 0.64 (0.91). Therefore, we employed the summer *P* and *Z*500 averaged fromduring June to September and autumn *R* averaged fromduring August to October in the analysis.

3 Results

3.1 Long-term variation

3.1.1 Observed and reconstructed river discharges

Figure 2a shows the time-series of observed autumn *R* at the river mouths of the Lena (red solid line) and Ob (red dashed line) during the past seven decades (1936–2009), with 15-year running correlations between them (black line). Although the correlations were strong and negative during the 1980s to mid-1990s as in Fukutomi et al. (2003), those were positive during the 1950s to 1960s and became weak after the 1990s. As mentioned above, these autumn *Rs* correspond to the summer *Ps*. The time-series of the summer *P* over the Lena and Ob regions (Figure 2b) indicate a negative correlation around the 1910s, during the 1940s to mid-1950s, and after the 1980s. The correlations of *P* were near zero in the 1920s, and were weak and positive during the 19640s to 1950s. While there were some differences between the observed *R* and *P*, the *P* displayed a strong negative correlation in the 1980s and positive correlation in the 1960s, with no correlation in the 2000s. These results from the observations indicate that the relationship of between the *R* and /*P* betweenof the Lena and Ob wasere different in each of the epochs.

Figure 2c shows a long-term time-series of tree-ring-reconstructed annual *R* of the Lena and Ob during the past two centuries (1800–1990). Similar to the observation, the correlations of reconstructed *R* were negative during the 1980s to mid-1990s and positive during the 1950s to 1960s, while there was some discrepancy between the observed *P* and reconstructed *R* in the early 20th century. The discrepancy may be due to errors and uncertainty both in the observation and reconstruction and observation. The observation stations of *P* are sparse in Siberia and there is difficulty in the *P* measurement. While the reconstructed *R* is based on the tree-ring width, the tree-ring width has an indirect relationship with the *R* and the both are mainly related through the *P*. There are also other influences such as air temperature, solar radiation, nitrogen and so on. In addition, the tree-ring width is affected by meteorological conditions during the growing season in summer and there must be less contribution from the conditions during winter. As a result, the reconstructed *R*s can explain 43% of the observed variability for the Lena and 51% for the Ob (MacDonald et al. 2007). In the 19th century, the correlations of reconstructed *R* were strong and negative in some epochs (1810s, 1850s, and 1890s) and moderate or weak and positive in some other epochs (1880s and 1900s). These results also indicate that the relationship between the Lena and Ob differed in each epoch. However, it is noteworthy that negative correlations were frequently seen in the time~~-~~series of reconstructed *R* (black line in Figure 2c). As shown by the red bar histogram in Figure 3a, many of the correlations for reconstructed *R* were negative. The correlations of observed *R* and *P* also tended to have negative values, although these results may not be as robust due to relatively short records (observed *R*: 74 years, *P*: 111 years). It is considered that the long-term change on decadal timescale or long-term trend may affect the correlations in Figure 2. While Fukutomi et al. (2003) and MacDonald et al. (2007) discussed about the long-term variations on decadal timescale, it seems that the long-term changes do not affect the time series of the correlations. Indeed, when we remove the 19-year running mean from the raw time-series of *P* and *R* in Figure 2a-c, the correlations do not change so much (not shown) and there is the tendency of frequent negative correltion. To quantitatively show a tendency of the correlation, we calculated median and skwness as a metric of the frequent distribution of the correlations. The skewness is a measure of asymmetry of frequency distributions. When the frequent distribution is distributed in the negative (positive) side, the skewness has positive (negative) value. As a result, the medians of the~~se~~ 15-year running correlations in the observeion and reconstruction were negative and their skewnesses were positive, although the skewness of observed *P* was nearly zero (~~Table 2,~~ Figure 3b and Table 2). Therefore, the interannual variation in *R*s/*P*s of the Lena and Ob Rivers has tended to be out~~-~~of~~-~~phase during the past two centuries. This may suggest that the east–west seesaw pattern frequently emerges over Siberia.

3.1.2 Simulated precipitation

To determine the intrinsic atmospheric circulation associated with the variation in summer *P*, we ~~examined~~ analyzed the AGCM control simulation. As with the reconstructed *R*, the correlations of ~~between the~~ simulated summer *P* ~~over~~between the Lena and Ob regions were largely negative ~~(Table 2 and Figure 3)~~. The histogram of the correlations of simulated *P* was distributed in the negative side (blue line in Figure 3a), the median was negative and the skewness was positive (blue cross markes in Figure 3b and Table 2). Compared to the reconstructed *R*, the distribution of simulated *P* was more negative than positive (Figure 3a) and the median and skewness from the simulated summer *P* (Table 2) tended to be more negative and positive, respectively (Figure 3b). The~~se~~ results indicate that atmospheric internal variability in summer leads to the negative correlation of ~~out-of-phase~~ summer *P*. The AGCM control simulation has no external forcing, and boundary conditions such as SST, sea ice, solar activity, and GHG are fixed. Consequently, the variation in simulated *P* and *Z500* in the control simulation can be interpreted as internal variability in the model.

The 20C3M and PICTL simulations in the CMIP3 coupled models provided more evidence for intrinsic atmospheric variability, including air–sea interactions. The medians and skewness of the correlations of~~between the~~ summer *P* between~~over~~ the Lena and Ob regions in the CMIP3 simulations were~~are~~ plotted in Figure 3b (black and gray cross marks); the plotted marks were largely distributed in the upper-left side and the~~y~~ median and skewness also tended to be negative and positive, respectively, ~~but~~while they were well scattered. This suggests that some models failed to reproduce the summer *P* variability and atmospheric circulation over Siberia. However, note that many simulation results were plotted around the tree-ring-reconstructed *R* and most results from the CMIP3 simulations were distributed toward the center compared to those from the AGCM control simulation (Figure 3b). These results imply some effects of air–sea interactions on the *P* variability over the Lena and Ob. This is discussed in the final section.

As a result, similar to the observation and reconctuction, the AGCM and CMIP3 simulations demonstrated that the *P* over the Lena and Ob tends to be out-of-phase. While there were weak and positive correlations of summer *P* in several periods (Figures 2 and 3a), we focused on the negative correlation and further examined summertime atmospheric circulation pattern associated with the *P* over Siberia.

3.2 Atmospheric circulation associated with the negative correlation of precipitations

To identify~~ the~~ summertime dominant atmospheric circulation patterns associated with summer *P* variability, we performed an empirical orthogonal function (EOF) analysis on summer *Z500* over the three great Siberian river basins (blue inset box in Figure 4). The spatial pattern of the first EOF mode (EOF1) ~~wa~~is the cyclonic circulation anomaly centered in the vicinity of the coast in central Siberia (not shown). This pattern only enhances the eastward moisture transport over Siberia, and the effect on moisture convergence/divergence over the Lena and Ob regions is small. The EOF2 indicated an east–west seesaw pattern similar to Fukutomi et al.~~,~~ (2003). While Figure 4 is the spatial pattern of EOF2 based on the JRA-55, the result of 20CR showed a similar pattern~~ to that of EOF2~~, for which the pattern correlation was 0.89. This~~e~~ seesaw pattern of EOF2 directly affects moisture convergence and divergence over the two river basins and results in changes in the *P* over the regions.

To confirm the effects of the east–west seesaw pattern on the *P*, we compared the difference in *Z500* over the western and eastern Siberia regions (west–east difference in *Z500*: $\Delta Z500_{WE}$) and the difference in *P* over the Lena and Ob regions (Lena–Ob difference in *P*: ΔP_{LO}). We defined the Lena and Ob regions for *P* (green inset boxes in Figure 4), which cover almost all of the basins, while the regions for the *Z500* were shifted 10° westward (purple inset boxes), which covered almost all of the negative and positive centers of action of EOF2. As described in the Introduction, when *Z500* anomalies are negative over the east and positive over the west as shown in Figure 4, *P* anomalies must be positive over the Lena region and negative over the Ob region. As expected, ΔP_{LO} was positively correlated with $\Delta Z500_{WE}$. The correlation coefficients were 0.72 for the JRA-55 and 0.60 for the 20CR, both significant above the 99% significance level (Figure 5).

Similar results (i.e., the east–west seesaw pattern of EOF2 and the positive correlation between the ΔP_{LO} and $\Delta Z500_{WE}$) were obtained in the AGCM control simulation and in the 20C3M and PICTL simulations from the CMIP3 coupled models, while some CMIP3 simulations failed to reproduce these features. The pattern correlation of~~between~~ the EOF2 patterns between~~of~~ the JRA-55 and AGCM was 0.83. The pattern correlations with JRA-55 for the 20C3M and PICTL simulations ranged from -0.62 to 0.94, but those in 81% of the 20C3M and 76% of the PICTL simulations ~~the correlations~~ were greater than 0.7. Several CMIP3 models simulated the ~~east–west~~ seesaw pattern in the EOF3. These results from the AGCM and CMIP3 simulations indicated that the seesaw pattern emerges as a dominant mode of the summertime atmospheric circulation over Siberia. The correlation between the ΔP_{LO} and $\Delta Z500_{WE}$ in the AGCM was 0.55 for the entire period of the 295-year record and 0.53–0.63 for the 15 subsets of 150-year records. The correlations between the ΔP_{LO} and $\Delta Z500_{WE}$ in 94% of the 20C3M and 90% of the PICTL simulations were greater than 0.7. The above results in the simulations also indicated that the east-west seesaw pattern is related with the negative correlation of *P*.

Therefore, the results of the simulations with~~of~~ the AGCM and CMIP3 models were basically consistent with the reconstructed *R* and observations, and they support the linkage between the summertime east–west seesaw pattern over Siberia and the out-of-phase *P* over the Lena and Ob regions.

4 Summary and discussion

We examined the long-term variations in the *R*s and corresponding *P*s for the Lena in eastern Siberia and the Ob in western Siberia based on observations, tree-~~-~~ring reconstructions, and simulations with the AGCM and CMIP3 models. The observations during the past seven decades indicated that correlations of ~~between the~~ observed *R*s between~~of~~ the Lena and Ob were negative during the 1980s to mid-1990s as in Fukutomi et al.~~,~~ (2003), but positive during the mid-1950s to 60s and became weak in recent decades (Figure 2a). This suggests that the relationship between the Lena and Ob *R*s was different in each of the epochs. However, the reconstructed *R*s during the past two centuries indicated that the Lena and Ob tended to be negatively correlated, i.e., out-~~-~~of-~~-~~phase ~~during the past two centuries~~ (Figures 2c and 3). The observed *P*s over eastern and western Siberia also frequently had negative correlations in the 20th century (Figure 2b), which were affected by the east–west seesaw pattern of summertime atmospheric circulation over Siberia (Figure 4). Compared to the reconstructed *R* and observed *P*, the simulated *P*~~s~~ in the AGCM control simulation indicated more frequent negative correlations in association with the seesaw pattern (Figure 3). Because of the fixed boundary conditions, the control simulation demonstrated that the negative correlation and the seesaw pattern emerge as summertime atmospheric internal variability over Siberia. Although the results from the 20C3M and PICTL simulations vary among the models, they basically support the above features. As a consequence, the east–west seesaw pattern of large-scale~~atmospheric~~ circulation frequently emerges as summertime atmospheric internal variability over Siberia and ~~affects~~ induces the convergence/divergence of moisture flux and ~~the~~ associated opposite anomaly, i.e.

negative correlation, of the summer *P*s over eastern and western Siberia, resulting in the out-of-phase autumn *R*s of the Lena and Ob Rivers. Therefore, the summertime atmospheric internal variability of the seesaw pattern over Siberia is a key factor influencing the water cycles in this region.

The results ~~in~~from the AGCM and CMIP3 simulations and previous studies give us further~~several more~~ implication~~s~~ for the *P* variability and associated atmospheric circulation ~~the east–west seesaw~~ pattern over Siberia. Compared to the AGCM control simulation, the CMIP3 simulations mostly plotted around the reconstructed *R* (Figure 3b), suggesting that the air–sea interaction acts as a da~~u~~mping of the seesaw pattern and a breaking of the negative correlation of *P*. An external forcing such as a SST or sea ice anomaly may affect large-scale circulation and *P* over Siberia. Moreover, while the negative correlation dominated in ~~of~~ the *P* variations between eastern and western Siberia, ~~was related to atmospheric internal variation,~~ the positive and weak correlation periods were also seen in some periods as shown by the time-series in Figure 2. This imply that, in addition to the east–west seesaw patter of atmospheric internal variability, there are other effects on the summertime *P* variability over Siberia~~may have been affected by an external forcing such as an SST or sea ice anomaly~~. Indeed, Sun et al. (2015) reported the remote influence of Atlantic multidecadal variation, which is an oscillation of North Atlantic SST between basin-wide uniform warm and cold conditions, on the variation in summertime *P* over Siberia on decadal or multidecadal timescales. Iwao and Takahashi (2006, 2008) indicated that the effects of quasi-stationary Rossby waves originated from blocking anticyclones in the North Atlantic–European sector on the precipitation seesaw pattern between northeast Asia and eastern Siberia. Ding and Wang (2005) showed a circumglobal teleconnection with zonal wavenumber-5 structure in the Northern hemisphere mid-latitude, resulting in *P* anomalies in various areas of the world including Siberia. Iijima et al. (2016) indicated the impact of enhanced storm activity on the~~an~~ increase in *P* and permafrost degradation in eastern Siberia during the mid-2000s and they discussed the relationship with the Arctic dipole anomaly associated with the sea ice reduction. As in Iijima et al. (2016), Fujinami et al. (2016) and Hiyama et al. (2016) also showed the similar result for the *P* over eastern Siberia. While they studied somewhat different time~~-~~scales and different regions, the ~~variation in~~ *P* variability over the Lena and Ob must be affected by a combination of these processes including internal variability. However, this study did not examine those specific effects and future work is needed. In addition, it seems that the differences between the 20C3M and PICTL simulations are not large (Figure 3b), and there should be no significant influence of changes in GHG on the ~~long-term variation in~~ *P* variability in Siberia, while *P* in future projections will increase under global warming (IPCC, ~~AR4 WG1~~ 2007, ~~AR5 WG1~~ 2013).

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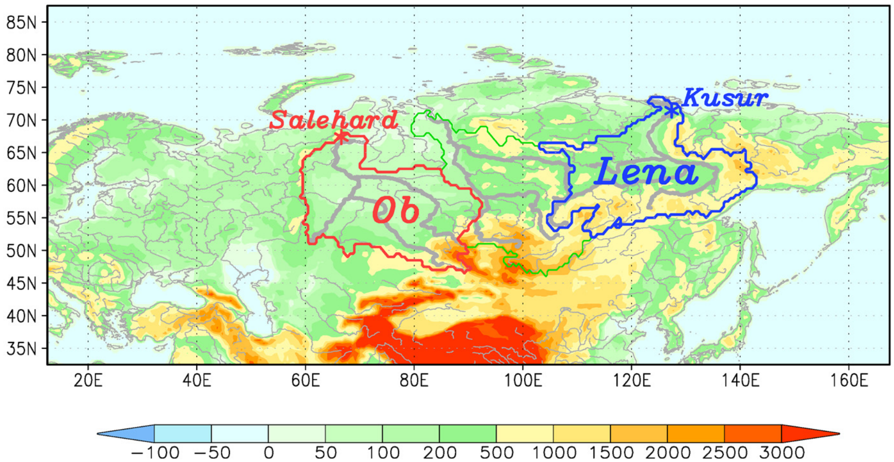
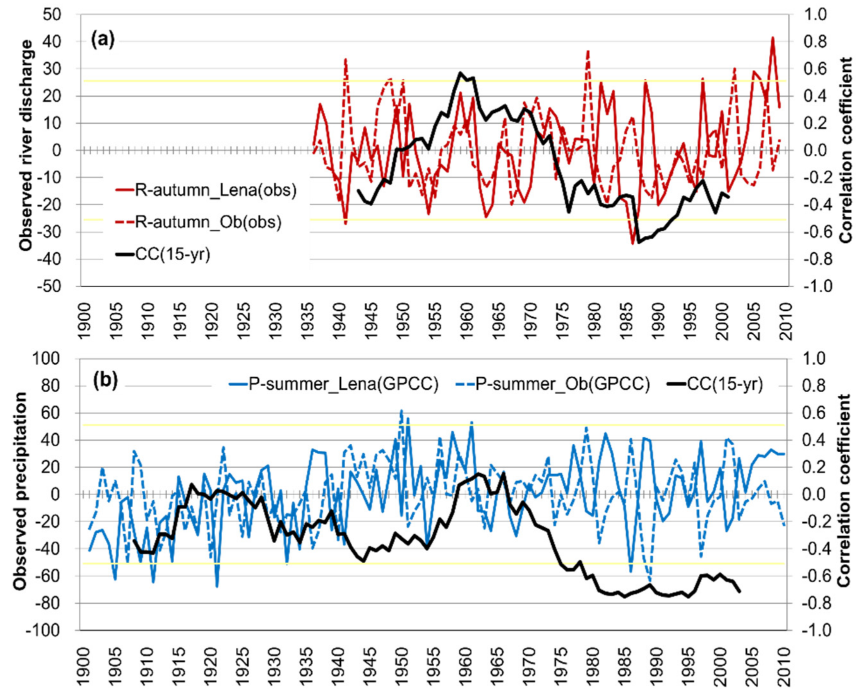
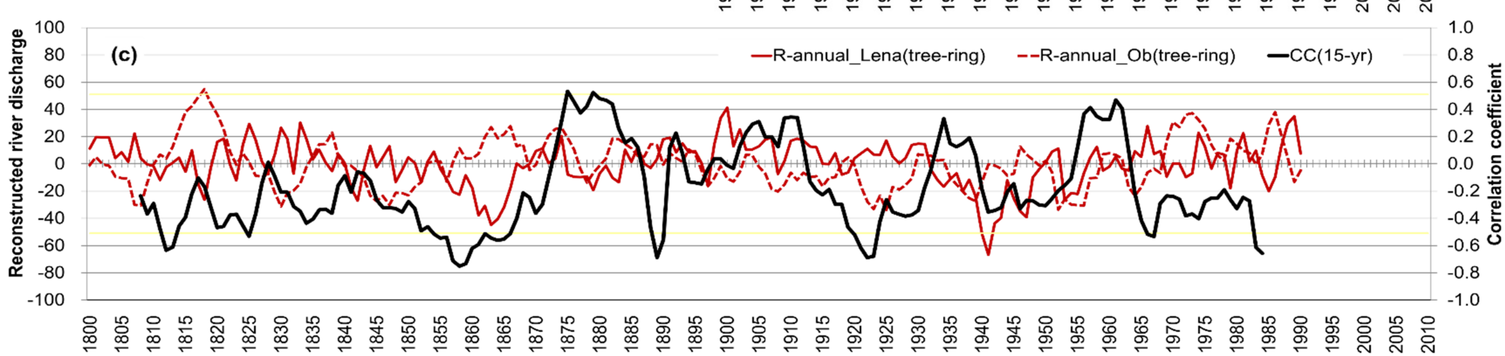


Figure 1: Map of study area of Siberia. The colored solid contours show the boundaries of each river basin (Lena: blue and Ob: red). The asterisks denote the locations of Kusur and Salehard, which are the observation stations nearest the river mouths. ~~The vectors show climatological vertically integrated moisture flux (kg/m/s) in summer (June to September) averaged from 1981 to 2010 based on the JRA-55.~~ The color shades and thick gray lines denote elevation and major flow paths, respectively.

Figure 2: Time series of (a) observed autumn *R* during 1936–2009, (b) observed summer *P* during 1901–2010, and (c) tree-ring-reconstructed annual *R* during 1800–1990 of the Lena and Ob Rivers. Red (Blue) solid and dashed lines denote the *R*s (*P*s) of the Lena and Ob, respectively. Black thick lines denote 15-year running correlations between the Lena and Ob *R*s/*P*s. The significant levels at 90%, 95% and 98% for the 15-year correlation are 0.44, 0.51 <u>(yellow lines)</u> and 0.59. Note that the axes of the *R* and *P* are shown on the left side of the panel and the axes of the correlations are shown on the





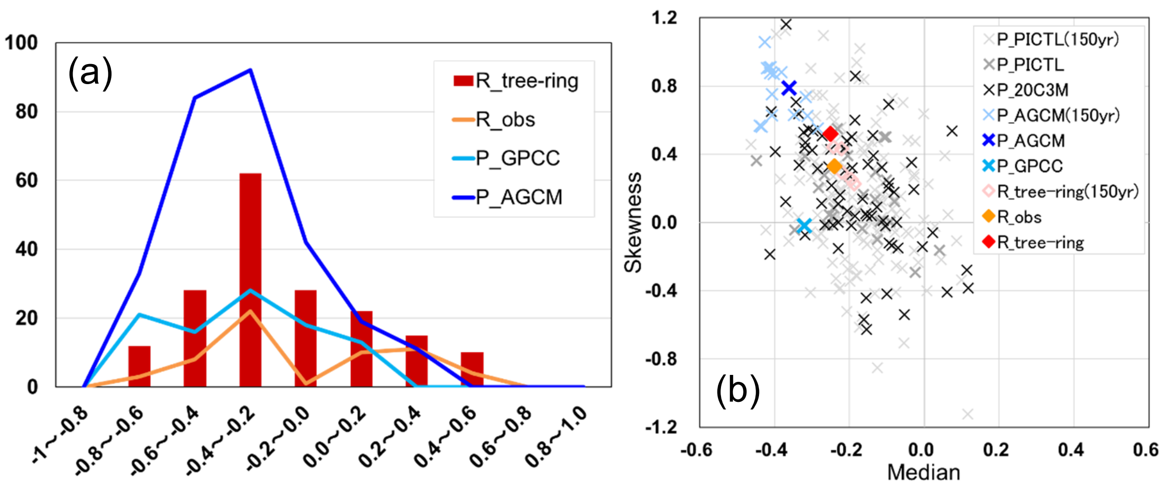


Figure 3: (a) Histogram of 15-year running correlations from the tree-ring-reconstructed annual *R* (red bars), observed autumn *R* (orange line), observed summer *P* (light blue line), and AGCM simulated summer *P* (blue line). (b) Scatter diagram between median and skewness of each of the 15-year correlations. Simulated *P* in the CMIP3 models' simulations (20C3M and PICTL), and subsets of 150-year record for the reconstructed *R* (5 samples), AGCM simulated *P* (15 samples), and PICTL simulated *P* (over 100 samples) are also plotted.

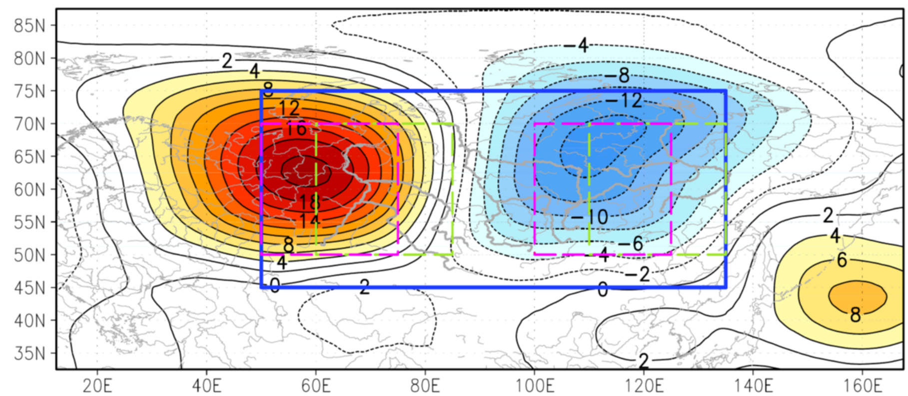


Figure 4: Spatial pattern of EOF2 (19.9% of explained variance) for the summertime *Z500* over Siberia region (blue line inset box: 45–75°N, 50–135°E, covering the three great Siberian rivers). Green (magenta~~purple~~) dashed inset boxes cover almost all areas of the Lena and Ob river basins (western and eastern centers of action of EOF2). The EOF analysis is based on JRA-55.

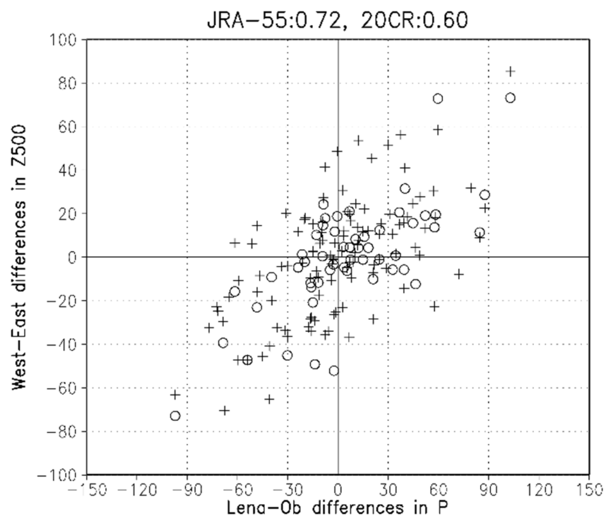


Figure 5: Scatter plot of the summer *P* differences between the Lena and Ob regions (ΔP_{LO}) and the summer *Z500* differences between the western and eastern Siberia regions ($\Delta Z500_{WE}$). The areas of ΔP_{LO} ($\Delta Z500_{WE}$) are defined as green (purple) dashed inset boxes in Figure 4. The $\Delta Z500_{WE}$ based on JRA-55 and 20CR are plotted as marked with circles and crosses. Correlation coefficients between ΔP_{LO} and $\Delta Z500_{WE}$ are shown in the upper side of the scatter plot.

Table 1: Correlation coefficients among the summer *P*, annual *P*, autumn *R*, and annual *R* for (a) the Lena and (b) Ob Rivers during 1936–2009. Summer (autumn) averaging period is from June to September (from August to October). The *P* and *R* are based on the Arctic-RIMS and GPCC. All values are above the 99% significance level. Bold values are specifically described in the text.

Lena	Summer *P*	Annual *P*	Autumn *R*	Annual *R*
Summer *P*	1.00	**0.91**	**0.79**	0.66
Annual *P*		1.00	0.72	0.73
Autumn *R*			1.00	**0.79**
Annual *R*				1.00
Ob	Summer *P*	Annual *P*	Autumn *R*	Annual *R*
Summer *P*	1.00	**0.64**	**0.63**	0.57
Annual *P*		1.00	0.64	0.57
Autumn *R*			1.00	**0.91**
Annual *R*				1.00

Table 2: Median and skewness of the 15-year running correlations for the tree-ring-reconstructed annual *R* (Figure 2c), observed autumn *R* (Figure 2a), observed summer *P* (Figure 2b), and simulated summer *P*. The observed *P* and simulated *P* are based on the GPCC and AGCM. A histogram and scatter diagram for these values are shown in Figure 3a and 3b. Values in brackets are the results from 5 (15) subsets of 150-year records for the reconstructed *R* (simulated *P*).

	Median	Skewness
***R*_tree-ring**	**-0.25** (-0.24 to -0.19)	**0.52** (0.23 to 0.44)
*R*_obs.	-0.24	0.33
*P*_GPCC	-0.32	-0.02
***P*_AGCM**	**-0.36** (-0.44 to -0.28)	**0.79** (0.55 to 1.06)