(Reviewer 1 responses)

Dear Reviewer,

First of all, we would like to thank you for the time spent on our manuscript and to express regret that it left you such a negative impression.

At the very beginning of your review, you wrote that "the overall quality is neither sufficient for Clim Past nor for any other peer-reviewed journal". This is a very strict verdict, and, such opinion should be supported by well justified arguments. However, in our opinion, you did not provide valid points supporting your verdict. Specifically, you wrote that:
1) "The English style and grammar both require thorough improvement".
2) "figure captions that lack the necessary level of information".
3) "manuscript's structure is sometimes challenged by weak and confusing chains of arguments".
4) "I am not fully convinced that the TRW dataset (sample size and age structure), the standardization applied (age-dependent splines) and the chronology option used (residuals) are indeed ideal (?) for the development of robust precipitation reconstructions".
5) "I recommend removing all of the spectral analyses and its vague and misleading interpretation, because the time-series are too short to reveal any meaningful patterns and behavior".
6) "I believe that stable isotopes could help improving the climate signal substantially".
7) after revision and improvements, our manuscript "should be submitting to a more specialized journal"

Please, find below our answers to your comments and the summary at the end of this letter

1) English/grammar problems
This comment is in the first place; therefore, it is probably your biggest concern. However, the grammar in our manuscript has been corrected by the American Journal Experts (AJE). We are sure that they are native speakers (at least, this is stated on their website). It would be very helpful if you highlighted the specific problems (incorrect phrases or sentences) in the text or, possibly, some unsuccessful terms that make the manuscript incomprehensible. If there are too many such sentences and terms, then you could select them for example on several pages. Since you did not do this, it is very difficult to understand exactly what the problem is. Thus, we believe that without mentioning single specific example, this point cannot be considered. Also, we would like to highlight that this is not our first article in English and, at least some of us, are fluent in "international English" and these authors previously published papers in respected journals (sometimes even without professional check of grammar). To conclude, we believe that there could be some problematic parts or errors in English in our manuscript. Such problems, however, could occur also in manuscripts authored by native speakers. Thus, we believe that your concern that we are not native speaker is unfair and kind of offensive. Helpful review normally highlights such specific points or point out kindly to some general problem(s). Just to be clear, we would be happy to ask another native speaker to improve our English, but we do not agree, also on the base of our experience, that the level of English so low that it is not understandable at its current stage. We think you would be interested in reading these articles: https://www.sciencemag.org/careers/2019/10/reviewers-don-t-be-rude-nonnative-english-speakers and maybe also this: https: / /link.springer.com/article/10.1007/s00264-020-04504-1. You may know them well, but if not, it will be very useful for other reviews.

2) Problems with illustrations
It would be helpful if you wrote, the captions for which illustrations do not contain enough information and what information they should contain. Again, thus comment is of very low relevance and cannot not directly aid us to improve the manuscript, which is a pity.

3) Manuscript structure and argument chain
We are very sorry, but we cannot understand at what moment you were lost in the chain of our arguments and what are the drawbacks of the structure of the manuscript. It is possible that some parts of the manuscript need to be interchanged and some additional explanations should be made. Changes in structure are commonly suggested by reviewers as they can see manuscripts from different perspective and we always try to improve manuscript according the specific recommendations of the reviewers (as well as we provide such recommendations in our reviews). However, again, you did not provide specific details and suggestions how to improve the manuscript.

4) Not ideal dataset and methods
We should say that the concepts of “ideal” and “not ideal” are subjective, and we (since we are scientists) should use what can be calculated or measured. There are important tables in our article - Table 1 (descriptive statistics of the signal-free chronologies) and Table 2 (calibration and verification statistics of the reconstruction equations). The statistics in these tables, although not the best among other similar works, are at a fairly high level and sufficient for the purpose of our study according the clearly described standards. The same goes for the explained variance, and you have not given at least some evidences to the contrary.

5) Spectral analysis: too short series and vague and misleading interpretation
Unfortunately, we cannot agree that our reconstructions are too short for spectral analysis. We can agree that the reconstruction of the NSA is relatively short (155 years), but the SSA series has a length of 412 years and this can be considered a good result. When spectral analysis is performed, what is important is how long the cycles will be statistically significant. First, we are talking about relatively short cycles (< 100 years). Secondly, cycles of about 60 years are statistically significant for SSA reconstruction and marginally significant for the other two points and we are talking about this. Shorter cycles are again significant for SSA and marginally significant for CSA and NSA. Thus, as you do not provide any support of your suggestion (e.g. published and generally accepted criticism of our approach) and, on the contrary, we are following the well-accepted methodology, we prefer to keep this analysis in our manuscript. We would be happy to improv the interpretation of this analysis, as you think it is misleading, but again, as you did not provide specific details what is misleading, we are not able to grant your non-specific comment.

6) Isotope analysis
Without going deep into the details, if we have good statistics for TRW dataset there is no need to look for some other proxy, especially very expensive isotope analysis.

7) A more specialized journal
We are sorry, but this is very personal opinion, and this is choice of editors which already considered it and concluded that topic is interesting for this journal as they send it for review.

Now we will return to the very beginning of our answer and your general opinion that "the overall quality is neither sufficient for Clim Past nor for any other peer-reviewed journal". We could agree with your conclusion (or at least humbly accept it) if in your review you convincingly proved that we incorrectly collected the data and/or used the wrong methods for its statistical analyses (or simply used the reliable methods incorrectly) and/or having incorrectly collected materials and incorrect methods, we obtained the wrong results and make the wrong conclusions based on them. But, unfortunately, your further comments are not clear because they are far too general. Therefore, we cannot use your review to improve our manuscript and also cannot consider it as an objective evaluation of the pros and cons of our manuscript. Thus, we respectfully recommend you to provide next time review containing necessary details and avoid comments which: 1) cannot aid authors in manuscript improvement (i.e. very general or irrelevant), 2) are subjective, or 3) even rude and racist (see the articles provided at the end of our answer to the first point). Only specific comments can actually help author(s) to improve the manuscript and thus make reviewers work useful (and in our experience somehow satisfying, unless one is satisfied by meaningless comments). We believe that only such unbiased author-reviewer relationship, and thus whole peer-review system, can lead to the progress of science and this should be our joint goal. We strongly believed that your review was not personal. Similarly, we hope that you will understand and accept our answers and opinion.

(Reviewer 2 responses)

Dear Reviewer,

We would like to express our gratitude for the careful analysis of the manuscript and valuable comments and suggestions for improving the article. Please, find below our answers to your comments.

1. Please give a brief explanation to Skew/Kurtosis in Table 1

At the very beginning of each of the three chronologies (where EPS < 0.85, Fig. 3) there are few (2-4) outliers that appeared due to averaging of a small number of tree-ring index values (low sample depth). Since the normal distribution is very sensitive to outliers, even one such outlier significantly influences the value of skew/kurtosis. For example, for SSA chronology these outliers are only two values: 1.556 and 1.429. With these values, the skew and kurtosis are 0.402 and 0.537, respectively. If we filter out these two values based on the Z-score, then the skew and kurtosis will be 0.234 and -0.087, respectively, i.e. the distribution of tree-ring index values will become much closer to normal. The same is true for other chronologies.

In addition, we can take into account that parts of chronologies where EPS < 0.85 were not used for precipitation reconstruction.

We placed in Table 1 two values of skew/kurtosis for each chronology - before and after filtering outliers and gave explanations in the Supplement, Figures S2 and S3.

Note that the skew/kurtosis values before filtering outliers have changed, since the STATISTICA, where we performed additional calculations, uses different formulas than ARSTAN.

2. Table 1 shows that the MS of the tree-ring width chronologies at all three locations appear not high relative to nearby areas. Can you give some explanations on the MS values.

In Fig. 1, we refer to 7 studies with the nearest precipitation reconstructions; 4 of them contain information on the mean sensitivity: Chen et al., 2016, MS = 0.216; Liu et al., 2004, MS = 0.45; Liu et al., 2009, MS = 0.23 and Liu et al., 2010, MS = 0.42. Thus, in the first and third studies, the mean sensitivity is lower than in our work, and in the second and fourth it is higher. The mean sensitivity value in our work was expected result, since we collected cores in a closed-canopy stands, where trees are relatively less sensitive to climate changes. Mean sensitivity higher than 0.3, as far as we know, can be expected when cores were collected from single trees growing close to extreme climatic conditions, for example, near a tree line on mountain peaks. For example, in Liu et al., 2010 we found that “The sampling sites are covered with stunted trees or vegetation and sparse Chinese pine trees (*Pinus tabulaeformis* Carr.), which grow on thin soil (10–20 cm deep) with poor nutrition. These sites are very open, with 50–200 m distance between individual trees.”

We added words “closed-canopy” to line 106: “All samples were collected from old-growth trees in natural closed-canopy Korean pine-broadleaved forests.”

3. You used residual chronologies for precipitation reconstruction, which is different from most other studies using standard chronologies. Can you add some explanations?

Indeed, most studies use standard chronologies, since it preserves much lower frequency signals (Cook and Kairiukstis, 1990). But, on the other hand, residual chronology has had all autocorrelation stripped from the series, making it more suitable chronology for regression analysis (Speer, 2010). In our case, the main reasons why we chose the residual chronology were that a) standard chronologies for all three points had significantly lower mean sensitivity (0.210, 0.192 and 0.196 for SSA, CSA and NSA respectively), b) standard chronologies much weaker correlated with precipitation. We added additional information in section 2.2 and Figure S4 to the Supplement to make this clear.

4. There are two figures named "Figure 7" in the paper. Please modify.
This mistake was corrected after a technical check of the manuscript before it was sent for review. Apparently, the old version of the manuscript came to you.

5. It appears that there are more words after line 265. Please complete it.
The same as for the previous comment.

6. I do not suggest to use the periodicity detected in the tree-ring reconstruction to infer the potential linkages with ENSO and PDO. There are other climate modes having similar periodicities also. In addition, it does not mean the climate is under control by a climate mode even their periodicity is very close.
We agree that there can be other climatic modes that may have similar periodicity and also influence precipitation. Therefore, in our study we are talking about the relationship between the periodicity in reconstructions and ENSO and PDO as an assumption, taking into account a large number of studies from this region where ENSO and PDO usually indicated as some of the most significant. We made minor corrections to the sentences where we talk about the effects of PDO and ENSO, to emphasize that this is suggestion.

7. It is helpful to compare your reconstructions with nearby reconstruction to highlight the common climate anomalies.
We agree that it would be very helpful to make such a comparison with reconstructions from nearby territories. Of course, we tried to find reconstructions with which our results could be compared. But as we wrote (Discussion): “Most of the studies available from China, South Korea or Japan ... were aimed at precipitation reconstructions during the summertime monsoon period and rarely covered the spring-to-early-summer period. Thus, comparing our spring-to-early-summer precipitation reconstruction with generally available summer-time monsoon period (June to August) is not suitable as these two periods featured entirely different weather patterns (Mezentseva and Fedulov, 2017). Hence, we decided to conduct only a qualitative analysis of the wet and dry period coincidences with other reconstructions.
We compared the data obtained with the identified wet / dry periods in terms of precipitation from the previous October to the current September, which were studied by Chen et al. (2016) for the southern part of northeast China (Changbai Mt., Qainshan Mt.) and the northern part of South Korea ... ”(Lines 319-333).
Thus, we made a comparison with one study, and did not find other studies with which we also could compare our results. And in order to show that our study area is far from other reconstructions, we showed them in Fig. 1.

(Reviewer 3 responses)

Dear Reviewer,

We would like to thank you for your careful analysis of our manuscript and your valuable suggestions that have helped improve it. Please, find below our answers to your comments.

1) The authors state that they sampled trees in an area where almost no anthropogenic activity occurred over the last 300 to 500 years, this is really interesting. Do the authors think that it could be possible to extend back in time the existing records? I would discuss somewhere in the discussion whether it would be possible to extend the chronology back in time using living, dead and/or subfossil materials.
I think that most of the reader never had the chance to go the Sikhote-Alin Mountain Range. Would it be possible to add to figure 1 a picture of the study site and possibly a picture of one disc collected by the authors?
In this study area, we can only use cores from living trees and discs (usually fragments of them) of a few dead Pinus koraiensis trees for several reasons. First, due to high humidity in summer (in the forest the air humidity during the summer is close to 100%) wood decomposes very quickly, so it is very difficult to find a well-preserved dead tree. Secondly, the old wooden buildings are completely absent. Finally, sub-fossil trees are extremely rare and are found only in one location within the study area – not far the NSA. Therefore, taking into account the maximum age of Pinus koraiensis trees and the rate of wood decomposition, we believe that the maximum length of chronologies can be about 600-700 years. We are currently collecting additional data in order to increase the length of the chronologies (especially for the NSA, where the chronology is relatively short). We've added this information to the Discussion.
We think it's a good idea to add some photos, we added two to Figure 1, and will add more in the Supplement.

2) Could all the samples collected be crossdated?
Yes, this is possible and makes sense if we want to obtain a regional chronology. In our case, we decided that it would be better if we make separate chronologies for each site. First, the reference years important for crossdating at different points often do not coincide. Second, tree ring data from trees in a closed canopy forest is usually “noisy” due to relationships between trees. Therefore, crossdating such data from remote locations is a rather difficult task. In general, the result of crossdating all data will be less accurate than crossdating data from individual sample sites (we tried it).

3) This concern has already been raised by other referees, but it would really useful to have more details about the detrending method used by the authors. Age-dependent spline smoothing is a very general description. The author should keep in mind that Science should always be reproducible and in this respect providing sufficient details for the reader to understand how the analyses were performed is really important.
Could the authors let us know the reasons that led them choose this particular method over other methods such the negative exponential method for instance?
To be more precise, in ARSTAN we used a 60-years low-pass filter for smoothing. We added this information to our manuscript.
As for the choice of a specific detrending method. When a tree grows alone (without interaction with other trees, for example, at the top of a high mountain), then its growth, both in height and in diameter, is well described by an S-shaped curve: at first tree growth is relatively slow, then it accelerates, and finally it slows down again. In this case, a negative exponential curve is good

choice for detrending. However, if a tree grows in a closed canopy stand (like all trees in our study), then it usually has several abrupt growth increases (so-called “releases”), after which growth slows down. Therefore, in this case, the cubic smoothing line is better suited. We have added a short explanation to the manuscript.

4) How did you aggregate the detrended series together? Did you use the Tukey’s Robust Mean or simply averaged the detrended series together?
This is also done in ARSTAN. By default, ARSTAN uses robust mean and we use it. One can also choose the arithmetic mean, but we don't think anyone is changing this option (since using robust mean is integral part of ARSTAN). To be more precise, we have added information about robust mean to the manuscript.

5) Did the authors account for variance changes resulting from changing sampled replication?
As one of the descriptions of the ARSTAN says, the index values (obtained as a result of standardization) are unitless, with a nearly stable mean and variance, allowing indices from numerous trees to be averaged into a site chronology. We think this is also true for changing sampled replication; ARSTAN has no additional settings for this.

6) Overall I think that the section “Tree-Ring Chronology development” could be expanded slightly and should contain more details.
We have expanded this section in accordance with your comments.

7) Lines 132-1322, the author state: “A correlation analysis was used to evaluate the relationships between the ring-width index and observed monthly climate records from the previous June to the current September”
Did the authors used bootstrapped correlations functions? Again, additional details would be most welcome.
Indeed, treeclim uses bootstrapping to test for significant correlations and there are several different options for that. We’ve added clarifying information to the manuscript.

8) I concur with the other referee that, using the residual chronology to perform climate reconstruction is a little bit unusual... Have the author at least tried to perform the precipitation reconstructions using the standard chronologies? Do the reconstructions have some predictive skills? One compromise could be to present the “residual reconstructions” in the main manuscript and to present the “standard reconstructions” in the supplementary material.
Of course, we tried to reconstruct precipitation using both residual and standard chronologies. In general, standard chronologies had a lower sensitivity and correlated worse with precipitation (after comments from previous reviewers, we added to Supplement a figure similar to Figure 4, but for the standard chronologies). Predictive skills of the residual chronologies also were better. In addition, for standard chronology CSA we got CE < 0 and so we cannot use it for precipitation reconstruction in this particular case.
We think it is a good idea to add "standard reconstructions" to the Supplement. We've added standard chronologies for three sample sites and two reconstructions - for SSA and NSA.

9) Unless I missed something, I was not able to locate the error bars in the plots displaying the reconstructions. The authors should keep in mind that trees are not perfect rain gauges. The method used to reconstruct precipitation variability also comes with limitations. Therefore paleoclimatic reconstruction should always come with uncertainty estimates. I would also

invite the author to describe in the method section how they computed the uncertainties of the reconstructions.

We have added uncertainty bans to Figures 5 and 6; estimated as twice the standard error of prediction (±2σ) (Wilks, 1995)

10) Figure 3: I would not reconstruct precipitation for the sections of the chronologies having an EPS below 0.85.

Corrected.

11) Figure 3, 5, and 6: Whenever possible I would encourage the authors to use the exact same scale for the Y axis.

In Figure 3, we changed the "Y" axes so that they became same for all graphs (all three sample sites). In Figures 5 and 6, we made the same "Y" axes for SSA and CSA, but did not change the axis for NSA, since for this site we reconstructed precipitation for a much longer season (March-July) than for the other two points. Accordingly, if we make the same "Y" scale on the graphs with reconstructions, then the reconstructions for SSA and CSA will look flat.

12) There is something odd in the Table 2. RE and CE are replaced by E and E.

Corrected (also something odd happened with DW)

13) I do also have a few concerns about the authors' conclusions regarding the linkages with ENSO and PDO...

The author didn't find any significant relationships with the NINO3, NINO4, NINO3.4 and SOI indexes, yet they hypothesize that the periodicities detected by the wavele analyses are related to ENSO. . . How can the authors be sure that the 3 years cycle is related to ENSO? It could be something completely different. I am not sure that the evidence currently presented by the authors support their conclusions.

Providing more details regarding the influence of ENSO on Far East Russia would be also be welcome. If I am not mistaken, so far the authors only cited one reference (Byshev et al., 2014). Does it mean that no other study attempted to investigate the influence of ENSO on Far East Russia's climate?

Indeed, we found no significant correlations between our reconstructions and the ENSO indices. Of course, having received such results, we began to think about what caused them (since, as we assumed, there should be some relationships between precipitation and ENSO and PDO). We analyzed the relationship between the ENSO and PDO indices by instrumental records and found that if we consider the entire period of the summer monsoon, then significant correlations can be found, but if we consider only the first part of the monsoon, then there are no significant correlations. Therefore, the influence of ENSO and PDO (also AO) actually exists, but we do not detect it in our reconstructions, since we are reconstructing precipitation for the first part of the summer monsoon. The only possible evidence of this effect that we have obtained is the cycles identified using wavelet analysis. We agree with you, even though these cycles are similar to the influence of ENSO and PDO, it could be something completely different. Therefore, we changed the phrases about the effect of oscillations in the conclusion so that it sounds not like a proven fact, but like our assumption.

We also cite Ponomarev et al, 2015 (Features of climate regimes in the North Asian Pacific). Of course, we were looking for works where the influence of ENSO and other oscillations on the studied region would be investigated, but practically nothing was found. There are separate studies for other parts of the Russian Far East, but this is a huge territory (the distance between the southern and northern points is about 4000 km) and the climate in different parts is completely different. Therefore, yes, we cannot cite other works, at least we could not find them.

List of relevant changes made in the manuscript

Lines 19-20. Sentence “Our reconstructions have 3, 15 and 60 year periods and corresponds to influence of the El Niño-Southern Oscillation and Pacific Decadal Oscillation on the region’s climate and relevant processes, respectively.” changed: “Our reconstructions have 3, 15 and 60-year periods, which suggests the influence of the El Niño-Southern Oscillation and Pacific Decadal Oscillation on the region’s climate and relevant processes.”

Figure 1. Added photo of one of the sample sites and a wood sample from a dead tree. Photos description added to the Figure caption: “…(b) Korean pine-broadleaved forest at the SSA site in late spring; tallest conifer trees are Korean pine. (c) Wood sample obtained from dead Korean pine tree.”

Line 106. Sentence “All samples were collected from old-growth trees in natural Korean pine-broadleaved forests.” changed: “All samples were collected from old-growth trees in natural closed-canopy Korean pine-broadleaved forests.”

Table 1 caption changed: “The sampling information and descriptive statistics of the residual chronologies. MS – mean sensitivity, SD – standard deviation, AC1 – first-order autocorrelation, EPS – expressed population signal.” Values of Skew and Kurtosis changed, added note “Note: * – before/after filtering outliers in the beginning of the chronologies (where EPS < 0.85), see Supplement, Fig. S2 and S3 for the details.”

Lines 123-124. Changed to “Chronologies were developed using ARSTAN (Cook, 1985). To remove non-climatic and tree-age related growth trends, individual series were detrended prior to standardization with spline smoothing (60-years low-pass filter). This detrending method was chosen because trees in a closed canopy forest usually have several abrupt growth increases (Altman et al. 2020), and they are clearly visible in our raw ring width data. Chronologies computations were done by means of a biweight robust mean estimation. As a result, we obtained standard and residual chronologies for each sample site. Compared to residual chronologies (Table 1), standard chronologies (Supplement, Fig. S4) had lower sensitivity (0.210, 0.192 and 0.196 for SSA, CSA and NSA, respectively) and had a weaker correlation with precipitation (Supplement, Fig. S5). Therefore, we used residual chronologies for precipitation reconstruction.”

Lines 132-133. Sentence “A correlation analysis was used to evaluate the relationships between the ring-width index and observed monthly climate records from the previous June to the current September.” changed: “A correlation analysis (static bootstrapped correlation function) was used to evaluate the relationships between the ring-width index and observed monthly climate records from the previous June to the current September.”

Table 2. Fixed table header (RW, CE, DW).

Figure 2. The scale of the “Y” axes is made the same for (a)-(c) and (d)-(f).

Figure 5. Added uncertainty bands for the reconstructions, information of the bands placed in the Figure caption: “Uncertainty bands (grey areas) estimated as twice the standard error of

prediction (±2σ) (Wilks, 1995).” Precipitation reconstructions made for the sections of the chronologies having an EPS > 0.85.

Figure 6. **Figure 5.** Added uncertainty bands for the reconstructions, information of the bands placed in the Figure caption: “Uncertainty bands (grey areas) estimated as twice the standard error of prediction (±2σ).”

Lines 383-384. Sentence “Cycles of about 15 and 60 years reflect the influence of PDO variability, which has been found at 15-25 yr. and 50-70 yr. cycles (Ma, 2007).” changed: “Cycles of about 15 and 60 years may reflect the influence of PDO variability, which has been found at 15-25 yr. and 50-70 yr. cycles (Ma, 2007).”

Line 384. Added new sentences: “These results will be more accurate when we collect additional data, and chronologies will be expanded. It should be noted, that in this study area, we can only use cores from living trees and discs of dead *Pinus koraiensis* trees for several reasons. First, due to high humidity in summer wood decomposes very quickly, so it is very difficult to find a well-preserved dead tree. Secondly, the old wooden buildings are completely absent. Finally, sub-fossil trees are extremely rare and are found only in one location within the study area not far the NSA. Therefore, taking into account the maximum age of *Pinus koraiensis* trees and the rate of wood decomposition, we believe that the maximum length of chronologies can be about 600-700 years.”

Lines 394-395. Sentence “The wavelet analysis of the reconstruction identifies cycles related to the processes influenced by the El Niño-Southern Oscillation and Pacific Decadal Oscillation.” changed: “The wavelet analysis of the reconstruction identifies cycles possibly related to the processes influenced by the El Niño-Southern Oscillation and Pacific Decadal Oscillation.”

References section. Added new reference: Altman, J. 2020. Tree-ring-based disturbance reconstruction in interdisciplinary research: Current state and future directions. Dendrochronologia 63, 125733. https://doi.org/10.1016/j.dendro.2020.125733.

Tree-ring based spring precipitation reconstruction in the Sikhote-Alin Mountain Range

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Abstract. Here, we present precipitation reconstructions based on tree rings from *Pinus koraiensis* (Korean pine) from three sites placed along latitudinal (330 km) gradient in Sikhote-Alin mountains, Russian Far East. The tree-ring width chronologies were built using standard tree-ring procedures. We reconstructed the April-June precipitation for the southern Sikhote-Alin (SSA), March-June precipitation for the central Sikhote-Alin (CSA) and March-July precipitation for the northwestern Sikhote-Alin (NSA) over the 1602 to 2013, 1804 to 2009 and 1858 to 2013, respectively. We found that an important limiting factor for Korean pine growth was precipitation within the period when the air current coming from the continent during the cold period is replaced with the impact of the wet ocean air current. We identified common wet years for SSA, CSA and NSA occurred in 1805, 1853, 1877, 1903, 1906, 1927, 1983, 2009 and common dry years occurred in 1821, 1869, 1919, 1949 and 2003. Our reconstructions have 3, 15 and 60-year periods, which suggests the influence of the El Niño-Southern Oscillation and Pacific Decadal Oscillation on the region's climate and relevant processes. Despite the impact of various global processes, the main contribution to precipitation formation in study area is still made by the Pacific Ocean, which determines their amount and periodicity.

1 Introduction

Water resources are a crucial driving force behind the development of human society (Vorosmarty et al, 2010). The hydrological regime depends directly on the precipitation regime, which forms as a result of the interactions among various global climate processes. The intensification of the global hydrological regime is drawing attention and becoming a crucial topic in regard to the analysis and forecasting of impacts of global changes (Allen and Ingram, 2002; Dai et al., 1998; Gedney et al., 2006; Hintington, 2008; Yang et al., 2003; Li et al., 2008; Shamov, 2010).

Dendrochronology is a widespread method for reconstruction of past climate processes with the high spatiotemporal resolution at the century to millennial scale (Corona et al.; Popa and Bouriaund, 2014; Kress et al., 2014; Lyu et al., 2016).

Dendrochronological studies in Northeast Asia are mostly concentrated in the northeast China, Mongolia, Korean Peninsula and Japanese archipelago (Chen et al., 2016; Chen et al., 2012; Li et al., 2013; Liu et al., 2009; Liu et al., 2013). The southern Russian Far East, however, remains a blind spot in terms of dendrochronological and overall paleoclimatological studies despite its large area of about 1.5 million square kilometers. There are only few available studies, for example, e.g. from the Sakhalin Island (Wiles et al., 2014), the Kuril Islands (Jacoby et al., 2004), and the Primorsky Region (Ukhvatkina et al., 2018) and they purely focused on temperature reconstruction.

No studies, however, have been conducted in this region on the dependency of the annual radial growth width on precipitation amount. The nearest precipitation reconstructions that were carried out were in Inner Mongolia (Liu et al., 2009; Chen et al., 2012; Liu et al., 2004), parts of China further to the south and the Korean Peninsula (Chen et al., 2016). These reconstructions mainly focused at the interrelation between the summertime precipitation amount and plant growth, which is quite justified since virtually all of Northeast Asia is exposed to the monsoon impact to some extent and the maximum precipitation amount is often registered in the second half of the summer. At the same time, the Southern Far East is characterized by a seasonal division in the summer monsoon impact degree: the first stage of the Far Eastern summer monsoon lasts from April to June, while the second stage lasts from July to September (Mezentseva and Fedulov, 2017). The first summer monsoon stage is a very cold and wet sea air current, which is intermittent with the impact of air masses coming from Central Asia, and the second stage is a warm wet sea air current with abundant precipitation (Mezentseva and Fedulov, 2017). Thus, most of the studies analyze the second stage of the monsoon impact and tend to overlook the importance of the spring-to-early-summer precipitation abundance in the region. The issue of what determines the nature of precipitation occurrence during the spring-to-early-summer period and how the presence of dry and wet years affects the growth and development of plants during this season remains unstudied. Another unstudied issue is the importance of the precipitation abundance during the second monsoon phase in terms of the growth and development of woody plants.

As the analysis of modern global meteorological trends clearly shows recently, the Far Eastern region is characterized by increasing variability in temperature and precipitation, which leads to a higher frequency of extreme hydrological events (Gartsman, 2008; Dobrovolsky, 2011; Khon and Mokhov, 2012; Dai et al., 2009; Huntington, 2008; Liu et al., 2003a; Milly et al., 2002; Ukhvatkina et al., 2018; Altman et al., 2018). Therefore, the issues of hydrological regime changes are of great importance for humankind and nature (Shamov et al., 2014).

The main objectives of this study are (1) to develop and compare the tree-ring-width chronology for three points in the southern part of the Russian Far East; (2) to analyze the regime of precipitation variation during past centuries in the southern part of the Russian Far East and compare it with neighboring territories; and (3) to analyze the periodicity of climatic events and their driving forces.

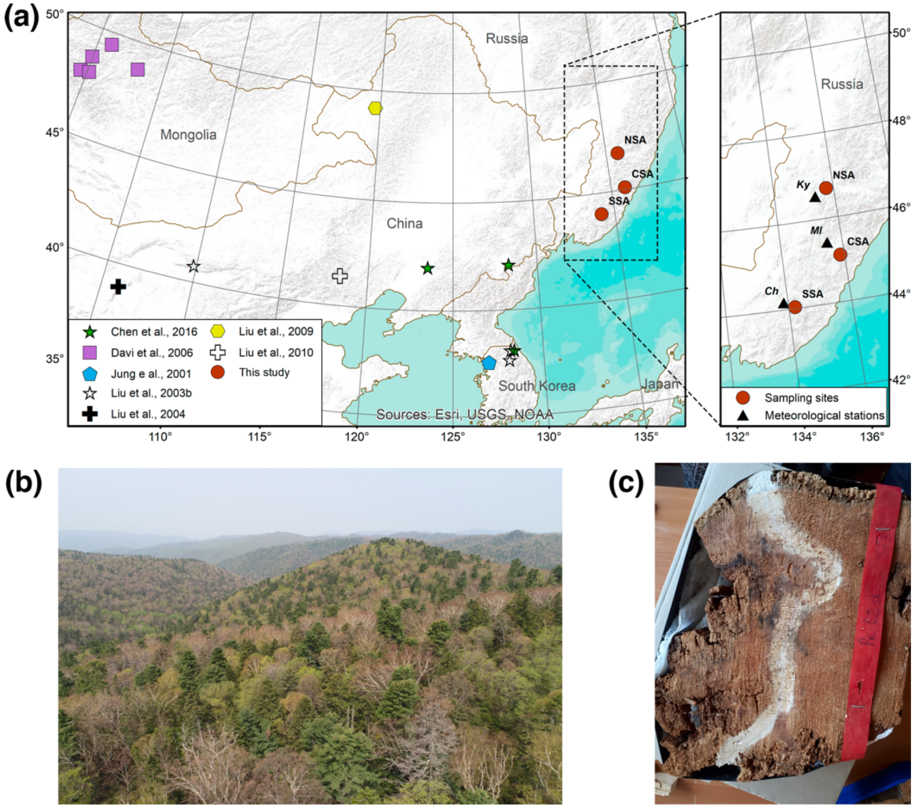

Figure 1: Location of the study area. (a) Location of the sample sites of this study and nearest study areas with precipitation reconstructions in continental Northeast Asia. SSA, CSA and NSA are the southern, central and north-western Sikhote-Alin Mountains, respectively; Ch, Ml and KY are the Chuguevka, Melnichnoe and Krasniy Yar meteorological stations, respectively. Basemap: Esri. "Topographic" [basemap]. Scale Not Given. "World Topographic Map". June 14, 2013. http://www.arcgis.com/home/item.html?id=30e5fe3149c34df1ba922e6f5bbf808f. (April 07, 2020). (b) Korean pine-broadleaved forest at the SSA site in late spring; tallest conifer trees are Korean pine. (c) Wood sample obtained from dead Korean pine tree.

2 Materials and methods

2.1 Study area

The study area is located in northeast Asia and includes three points located in the southern, central and north-western parts of the Sikhote-Alin Mountain Range, Southeastern Russia (Fig. 1). The first point was the Verkhneussuriysky Research Station (SSA) of the Federal Scientific Center of the East Asia terrestrial biodiversity Far East Branch of the Russian Academy of Sciences (Fig. 1), which is along the western side of the south Sikhote-Alin mountain range. The second point was in the central part of the Sikhote-Alin Nature Reserve (CSA) (Fig. 1), which is approximately 220 km northwest of SSA. The third point (NSA) was in the valley of the Bikin River on the western side of the Sikhote-Alin mountain range, approximately 200 km northwest of CSA and 330 km north of the SSA. Geographical coordinates and other characteristics of the studied locations are given in Table 1.

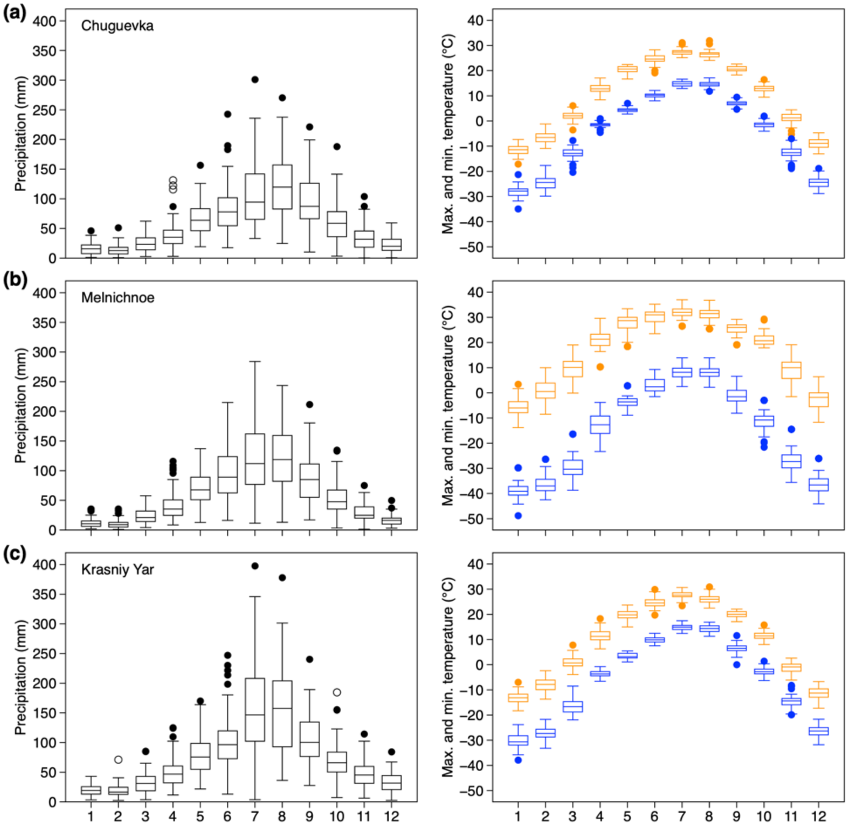

Figure 2: Monthly total precipitation, minimum and maximum temperature at (a) Chuguevka (1936-2004), (b) Melnichnoe (1941-2009), and (c) Krasniy Yar (1940-2013) meteorological stations.

The SSA, CSA and NSA are characterized by a monsoon climate with relatively long, cold winters and warm, rainy summers (Fig. 2, Fig. S1). The average annual air temperatures are 0.9 °C for SSA, 0.2 °C for CSA and 0.8 °C for NSA. January is the coldest month (average minimum temperatures are -35.8 °C, -38.5 °C and -30.5 °C for SSA, CSA and NSA, respectively), and July is the warmest month (average maximum temperatures are 27.4 °C, 31.8 °C and 27.6 °C for SSA, CSA and NSA, respectively). In general, most of the precipitation falls in the summer period. The precipitation amount during coldest months, i.e., previous November to current February/March was 10-13% (13-17%) (Fig. S1). The driest areas are at the southern point (SSA) and central point (CSA), where the annual precipitation reaches approximately 700 mm. Higher precipitation is seen at the northwestern point – NSA (ca. 900 mm).

Korean pine-broadleaved forests are the main forest vegetation type in the Sikhote-Alin mountain range of the southern Russian Far East. This area is the northeastern limit of the range of Korean pine-broadleaved forests, which are also found in northeastern China (the central part of the range), on the Korean peninsula, and in Japan. The Sikhote-Alin Mountains are among the few places where significant areas of old-growth Korean pine-broadleaved forests remain.

All samples were collected from old-growth trees in natural closed-canopy Korean pine-broadleaved forests. All trees were located in places where the direct anthropogenic impact and human economic activity were absent for at least 300 to 500 years (for details see Altman et al., 2018; Omelko et al., 2018).

Table 1. The sampling information and descriptive statistics of the residual chronologies. MS – mean sensitivity, SD – standard deviation, AC1 – first-order autocorrelation, EPS – expressed population signal.

	SSA	CSA	NSA
Elevation (m a.s.l.)	700-850	650	250
Latitude (N)	44°01’32’’	45°06’05’’	46°41’47’’
Longitude (E)	134°13’15’’	135°52’56’’	135°45’54’’
living/dead trees	25/20	77/0	34/0
Time period / length (years)	1451-2014 / 563	1678-2009 / 331	1748-2013 / 264
MS	0.253	0.267	0.274
SD	0.387	0.234	0.234
AC1	0.601	0.771	0.726
*R*bt	0.691	0.685	0.646
EPS>0.85 / length (years)	1602-2014 / 412	1804-2009 / 205	1858-2013 / 155
Skew	0.402/0.234*	0.991/0.434	0.348/0.099
Kurtosis	0.537/-0.087*	3.673/0.524	0.649/-0.059

Note: * – before/after filtering outliers in the beginning of the chronologies (where EPS < 0.85), see Supplement, Fig. S2 and S3 for the details.

2.2 Tree-ring chronology development

The data collection was carried out on permanent sample plots from 2010 to 2016 (Table 1). Two increment cores were extracted from living trees (then we used the one with the highest number of tree rings) and one core from dead trees at the breast height. In addition, in SSA discs from dead trees were collected (one disc per tree). Together we collected 156 wood samples (136 cores and 20 discs) from 156 trees. In the laboratory, all tree-ring samples were mounted, dried and progressively sanded to a fine polish until individual tracheids within annual rings were visible under the microscope according to standard dendrochronological procedures (Fritts, 1976; Cook and Kairiukstis, 1990). The cores were measured using the semi-automatic Velmex measuring system (Velmex, Inc., Bloomfield, NY, USA) with a precision of 0.001 mm. We firstly cross-dated ring-sequences visually and consequently the COFECHA program (Holmes, 1983) was used to check the accuracy of the cross-dated measurements. Chronologies were developed using ARSTAN (Cook, 1985). To remove non-climatic and tree-age related growth trends, individual series were detrended prior to standardization with spline smoothing (60-years low-pass filter). This detrending method was chosen because trees in a closed canopy forest usually have several abrupt growth increases (Altman et al. 2020), and they are clearly visible in our raw ring width data. Chronologies computations were done by means of a biweight robust mean estimation. As a result, we obtained standard and residual chronologies for each sample site. Compared to residual chronologies (Table 1), standard chronologies (Supplement, Fig.

S4) had lower sensitivity (0.210, 0.192 and 0.196 for SSA, CSA and NSA, respectively) and had a weaker correlation with precipitation (Supplement, Fig. S5). Therefore, we used residual chronologies for precipitation reconstruction.

2.3 Climate data

Monthly precipitation and temperature were obtained from the Chuguevka meteorological station (44°09’05” N, 133°52’10” E) for SSA, from the Melnichnoe meteorological station (45°26”06” N, 135°31’27” E) for CSA and from the Krasniy Yar meteorological station (46°32’27” N, 135°21’29” E) for NSA; the available periods of monthly data for the stations are 1936-2004, 1941-2009 and 1940-2013, respectively. The sampling sites are located 31, 45 and 30 km from the weather stations of SSA, CSA and NSA, respectively (Fig. 1).

2.4 Statistical analyses

A correlation analysis (static bootstrapped correlation function) was used to evaluate the relationships between the ring-width index and observed monthly climate records from the previous June to the current September. We used a traditional split-period calibration/verification method to explore the temporal stability and reliability of the reconstructions (Fritts, 1976; Cook and Kairiukstis, 1990). Pearson’s correlation coefficient (r), R squared (R^2), the reduction of the error (RE), the coefficient of efficiency (CE), and the product means test (PMT) were the tools used to verify the results. Analyses were carried out in R (R Core Team, 2019) using treeclim package (Zang and Biondi, 2015) and STATISTICA (StatSoft®) software.

We used runs analysis (Dracup et al., 1980) on the reconstructions to study extreme dry and wet events. Empirical thresholds for the dry and wet events were defined as 25th and 75th percentiles of instrumental measurements of precipitation for the periods 1936-2004, 1941-2009 and 1940-2013 for Chuguevka (SSA), Melnichnoe (CSA) and Krasniy Yar (NSA), respectively. Low-frequency time series variations in reconstructed precipitation were summarized with moving averages (5-year).

Since the study area is located on the western coast of the Pacific Ocean at the boundary of the zone of influence of tropical cyclones (Altman et al., 2018), we tried to find correlations between our precipitation reconstructions and El Niño-Southern Oscillation (ENSO, Allan et al., 1996; Allan, 2000) indexes (SOI, NINO3, NINO4, NINO3.4) and Pacific Decadal Oscillation (PDO, Mantua and Hare 2002) index. We also tried to find a correlation between the precipitation reconstructions and Arctic Oscillation (AO), which affects the climate of the Northern Hemisphere. Additionally, we looked for correlations between the reconstructions and the Palmer Drought Severity Index (PDSI), which is used to describe the moisture environment (Palmer, 1965; Dai et al., 2004). All correlation analyzes were performed using the KNMI Climate Explorer (http://climexp.knmi.nl).

Periodicity of reconstructed series at the three points was investigated using a wavelet analysis with the significance estimation of the identified periods using the methodology of Torrence and Compo (1998). The computing environment used for the calculations was built on the basis of the Python programming language and scientific computing packages: NumPy, SciPy and waipy. The function «Morlet» was used as the mother wavelet.

3 Results

3.1 Climate-radial growth relationship

The full length of the tree-ring chronologies spanned from 1451 to 2014 for SSA, from 1678 to 2009 for CSA and from 1748 to 2013 for NSA (Fig. 3). Reliable period of chronologies (EPS > 0.85) was identified from AD 1602 to 2014 (9 trees; Fig. 3a) for SSA, from AD 1804 to 2009 for CSA (6 trees; Fig. 3b) and from AD 1858 to 2013 for NSA (11 trees; Fig. 3c). The mean correlation between trees (*R*bt), mean sensitivity (MS) and expressed population signal (EPS) were calculated to evaluate the chronology quality (Fritts, 1976, Cook and Kairiukstis, 1990) (Tab.1). EPS indicates the extent to which the sample size is representative of a theoretical population with an infinite number of individuals. A level of 0.85 in EPS is considered to indicate a satisfactory quality of the chronology (Wigley et al., 1984). The statistical characteristics of the chronologies are listed in Table 2.

Table 2. Calibration and verification statistics of the reconstruction equations for the common periods 1936-2004 and 1941-2009.

Calibration	R	R^2	Verification	RE	CE	RMSE	DW
SSA							
Whole period (1936-2004)	0.670	0.460	–	–	–	–	–
1936-1971	0.755		1972-2004	0.392	0.368	5.511	1.78
1972-2004	0.611		1936-1971	0.368	0.303	6.067	1.85
CSA							
Whole period (1941-2009)	0.651	0.452	–	–	–	–	–
1941-1975	0.661		1976-2009	0.409	0.302	3.842	2.018
1976-2009	0.650		1941-1975	0.302	0.182	5.237	2.016
NSA							
Whole period (1940-2013)	0.690	0.465	–	–	–	–	–
1940-1977	0.750		1978-2013	0.316	0.303	4.690	2.237
1978-2013	0.590		1940-1977	0.426	0.392	4.726	2.100

All three created chronologies show substantially better correlations with precipitation than with temperatures (Fig. 4). In terms of precipitation, there is an identifiable and significant spring-to-early-summer period common to all three study sites. For instance, in the SSA case, the growth of Korean pine is positively related to precipitation during April-June of the current year (Fig. 4a), in the case of CSA the growth is positively related to precipitation during April-June of the current year (Fig. 4c), and in the case of NSA the growth is positively related to precipitation during previous June, September and December, and also March-July (except May) of the current year (Fig. 4e). Based on the results of the analysis of the precipitation correlation with individual months, we tried to select combinations of months that give the highest correlation.

In the SSA case it is the period from April to June (correlation 0.67), in the CSA case it is the period from March to June (correlation 0.65) and in the NSA case it is the period from March to July (correlation 0.69) (Fig. 4a, c, e).

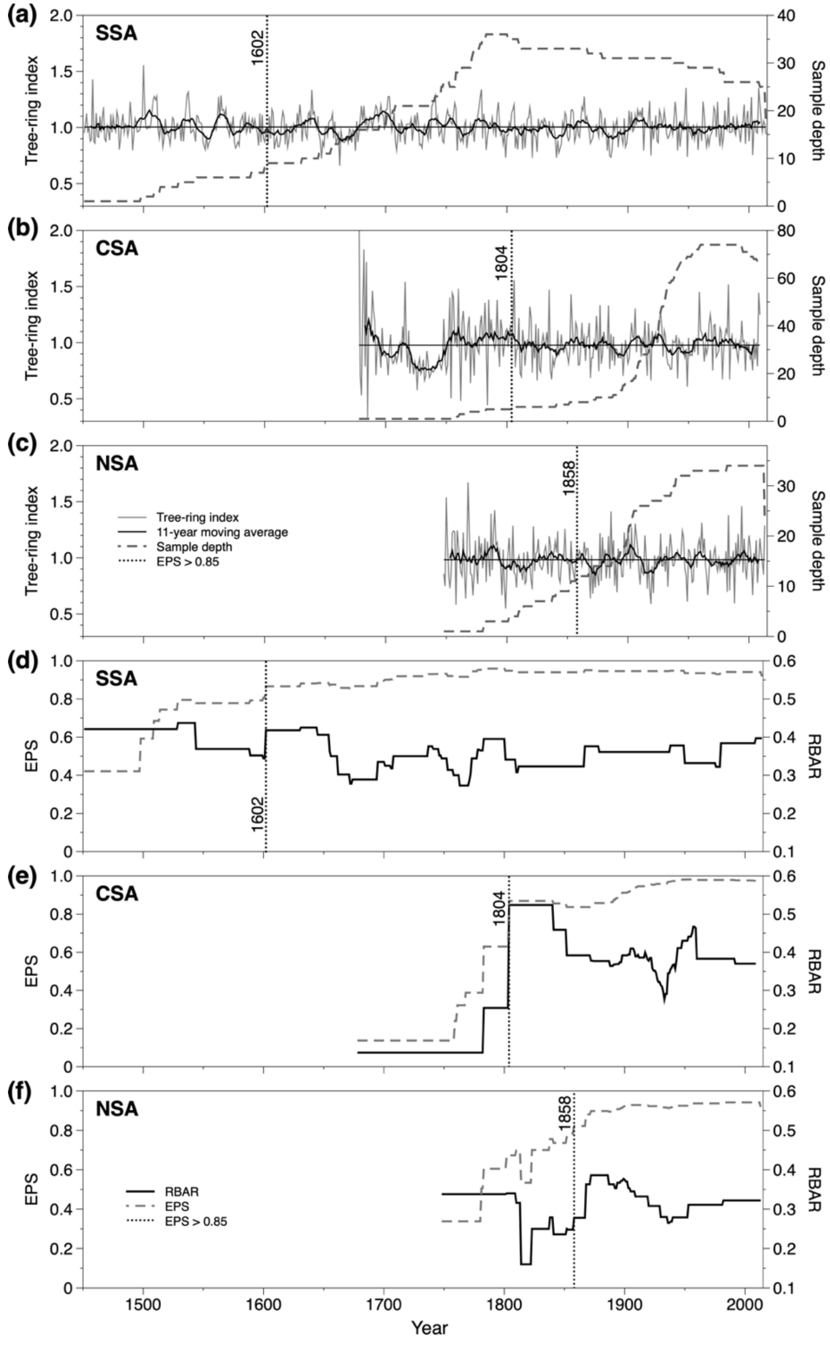

Figure 3: Variations in the tree-ring width chronologies and sample depth (a-c), expressed population signal (EPS) and average correlation between all series (RBAR) (d-f).

Regarding temperature, significant months for the SSA are February to April (positive correlation) and June, July (negative correlation) (Fig. 4b). For the CSA there is a positive significant correlation with the temperatures during the March and April (Fig. 4d). For the NSA the temperature shows positive yet significant correlations with the previous June, September, November and December period, and negative correlations with the June and July of the current year (Fig. 4f).

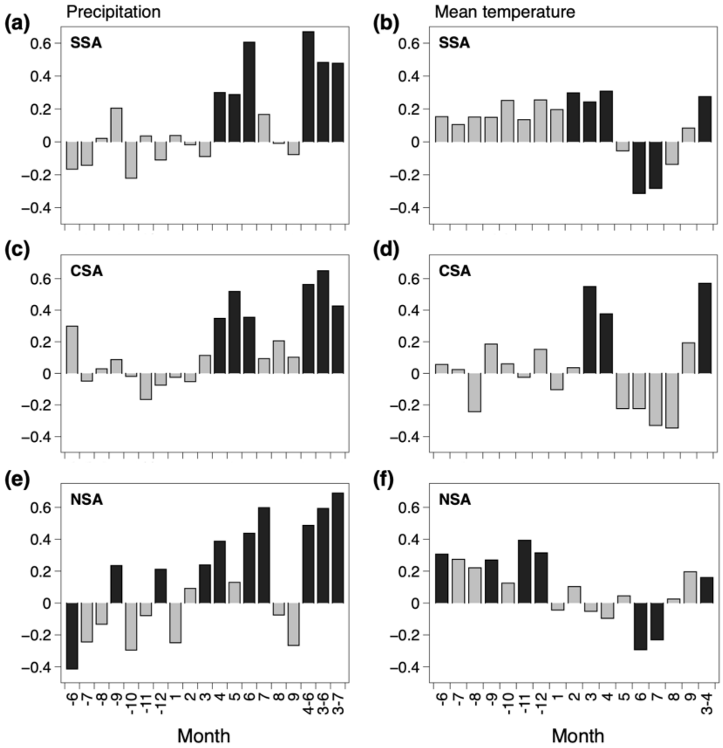

Figure 4: The correlation between the meteorological data (total precipitation and mean temperature) from Chuguevka meteorological station and SSA tree-ring width index (a, b), Melnichnoe meteorological station and CSA tree-ring width index (c, d), Krasniy Yar meteorological station and NSA tree-ring width index (e, f). Black bars denote significant values ($\alpha = 0.01$).

3.1 Precipitation reconstructions

Based on the analytical results, we created a linear regression equation to reconstruct the aggregate precipitation amount during April to June for SSA, March to June for CSA and March to July for NSA. The transfer function was as follows:

$Y_{SSA} = 333.00X_p - 141.77$ ($N = 45$, $R = 0.67$, $R^2 = 0.46$, $R^2_{\text{adj}} = 0.42$, $F = 25.9$, $p < 0.001$),

$Y_{CSA} = 259.72X_p - 21.46$ ($N = 68$, $R = 0.65$, $R^2 = 0.45$, $R^2_{\text{adj}} = 0.43$, $F = 18.8$, $p < 0.001$),

$Y_{NSA} = 526.93X_p - 89.67$ ($N = 37$, $R = 0.69$, $R^2 = 0.47$, $R^2_{\text{adj}} = 0.45$, $F = 36.6$, $p < 0.001$),

where Y_{SSA}, Y_{CSA} and Y_{NSA} is the April-June (for SSA) or March-July (for CSA) or March-June (for NSA) precipitation and X_p is the tree-ring index of the Korean pine chronology for each point at year p. The comparison between the reconstructed and observed mean growth season temperatures during the calibration period is shown in Fig. 5a, c, e. The cross-validation test yielded a positive RE and CE, confirming the predictive ability of the model (Table 2).

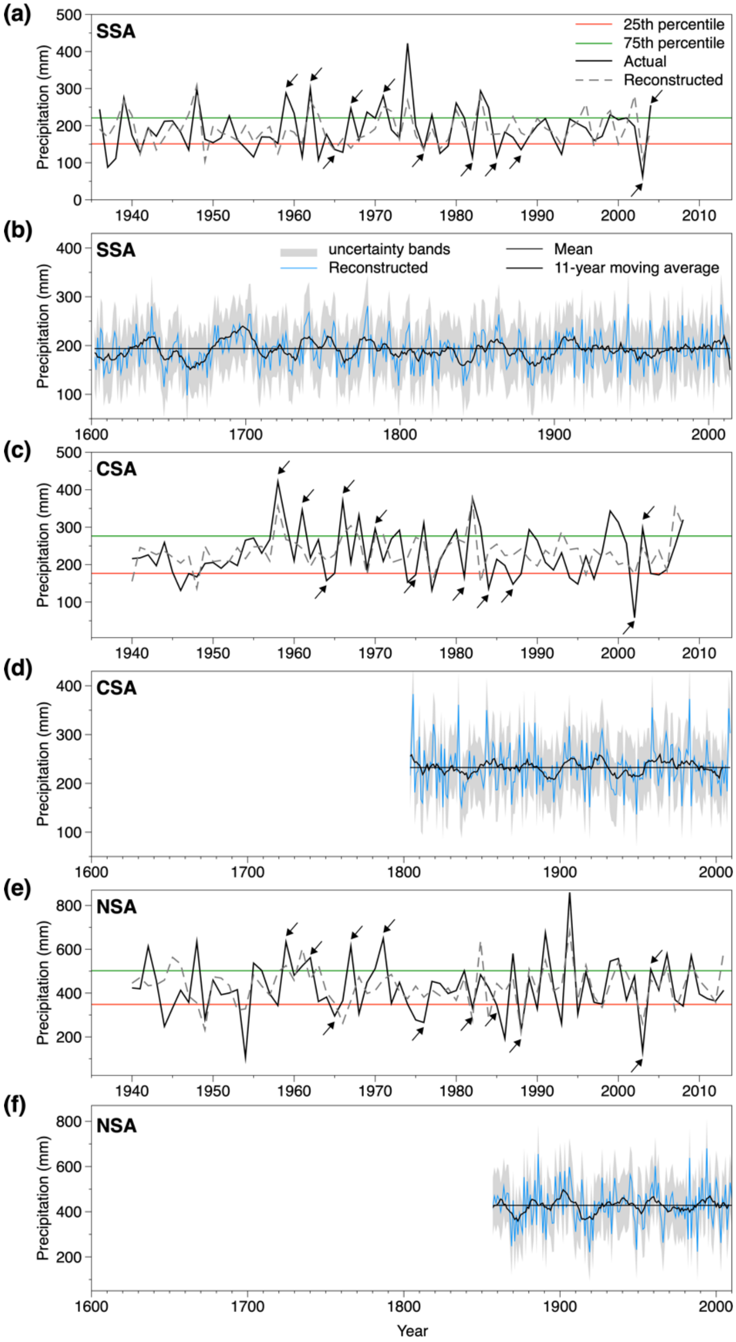

Figure 5: Actual and reconstructed precipitation for the SSA (a, b), CSA (c, d) and NSA (e, f). Uncertainty bands (grey areas) estimated as twice the standard error of prediction ($\pm 2\sigma$) (Wilks, 1995). Arrows indicate common extreme wet and dry years in instrumental data (values above 75th and below 25th percentiles of measurements, respectively).

The correlation between the precipitation reconstructions was significant at all three points yet varied as follows: 35% in the case of CSA-NSA, 22% in the case of NSA-SSA and 44% in the case of CSA-SSA. Correlation between the weather stations being as follows: CSA-NSA - 0.46, NSA-SSA - 0.43 and CSA-SSA - 0.64.

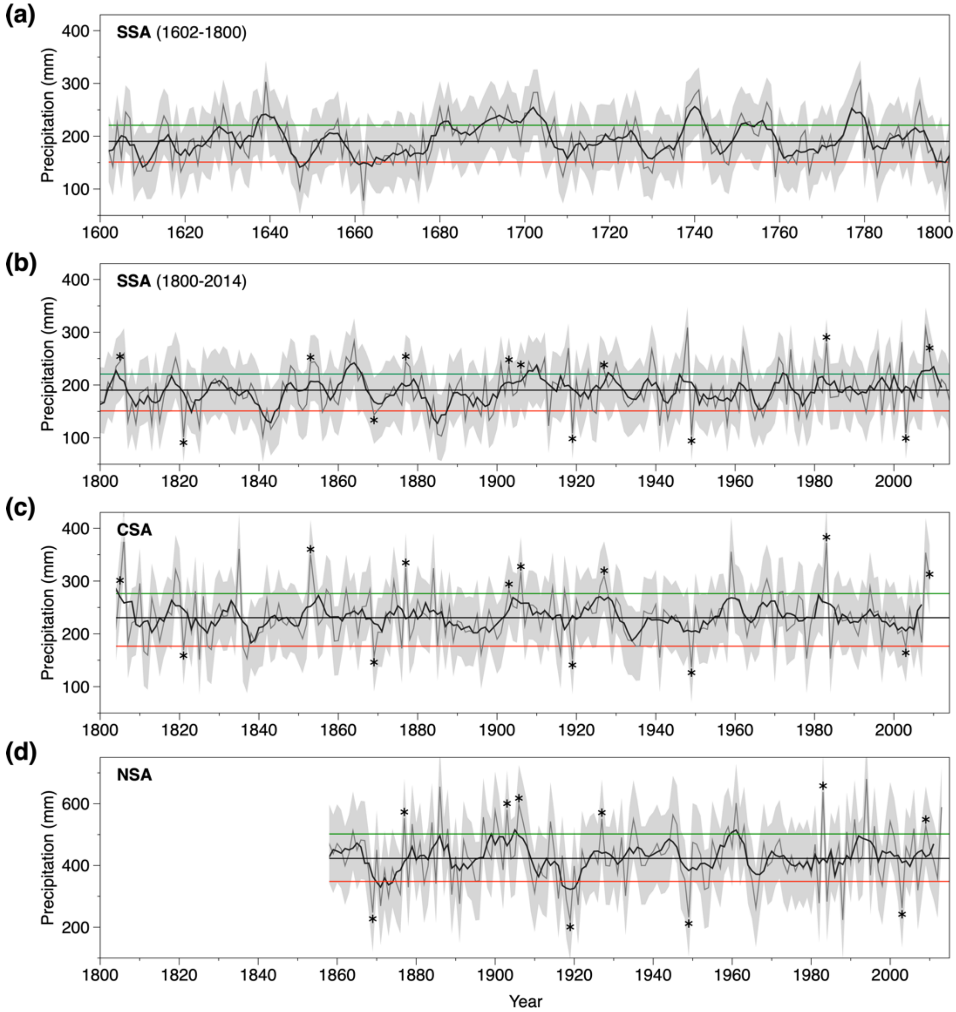

Figure 6: Extreme wet and dry years for SSA (a), CSA (b) and NSA (c). Gray lines indicate reconstructed precipitation values, bold black lines are the 5-year moving average; horizontal solid black lines are mean values of the instrumental data, red and green dashed horizontal line is empirical thresholds of 25th and 75th percentile of the instrumental data, respectively. Uncertainty bands (grey areas) estimated as twice the standard error of prediction (±2σ). Asterisks indicates common extreme wet and dry years for all three reconstructions, common period from 1800.

3.1 Precipitations variations to each point and its periodicity

The reconstructed sum of the April-June (SSA), March-July (CSA) and March-June (NSA) precipitation variations and its 11-year moving average are shown in Fig. 5b, d, f. The mean value of the reconstructed precipitation was 190 mm (SD ±34 mm) for SSA, 232 mm (SD ±55 mm) for CSA and 348 mm (SD ±56 mm) for NSA. We defined the wet and dry years for each reconstruction and also common wet and dry years (Fig. 6). Additionally, we verified the identified wet and dry years for the relevant data period (Fig. 5a, c, e).

Table 3. Characteristics of drought events (DE) and wet events (WE) identified based on the precipitation reconstructions.

Characteristic	SSA	CSA	NSA
DE number	57	18	23
Mean interval between DE (years)	6.8±5.8	11.2±8.0	6.1±5.4
Max. interval between DE (years)	31	32	19
Driest year (precipitation, mm)	1662 (77.7)	1949 (136)	1919 (221)
DE duration: duration/number of DE	1/49, 2/4, 3/4	1/16, 2/2	1/20, 2/3
DE frequency in 17th, 18th, 19th, 20th century	18, 16, 20, 14	-, -, 10, 9	-, -, -, 14
WE number	49	23	25
Mean interval between WE (years)	7.2±6.3	9.0±7.0	6.0±4.8
Max. interval between WE (years)	29	32	20
Wettest year (precipitation, mm)	1948 (309)	1959 (421)	1994 (680)
WE duration: duration/number of WE	1/23, 2/12, 3/7, 4/4, 5/1	1/16, 2/7	1/23, 2/2
WE frequency in 17th, 18th, 19th, 20th century	23, 25, 15, 27	-, -, 13, 15	-, -, -, 18

The April-June reconstruction for SSA from 1602 to 2014 contains 57 drought events and 47 wet events (Table 3). The percentage of droughts with a duration of more than 1 year is 14%, while the proportion of wet events with a duration of more than one year is 49%. The longest droughts are three-year events in 1647-1649, 1728-1730, 1843-1845 and 1885-1887. The frequency of dry years is highest in the 19th century. The frequency of wet events is maximum in the 20th century. A 5-year moving average of the reconstruction demonstrates multi-annual to decadal variation in April-June precipitation and suggests prolonged wet and dry events, most of them were in 17th and 18th centuries. The driest 5-year reconstructed period is 1883-1887 (128 mm). The wettest 5-year reconstructed period is 1748-1942 (256 mm).

The March-June reconstruction for CSA from 1804 to 2009 contains 18 drought events and 23 wet events. The proportion of wet events with a duration of more than 1 year is 11%, while the proportion of wet events with a duration of more than one year is 44% and this is 4 times more than for dry events. Two-year drought events were in 1811-1812 and 1836-1837. Two-year wet events were in 1805-1806, 1819-1820, 1853-1854, 1926-1927, 1967-1968, 1971-1972 and 2008-2009. The frequency of wet and dry years in the 19th and 20th century is similar. A 5-year moving average of the reconstruction do not reveal prolonged dry events. There is only one wet 5-year reconstructed period from 1802-1806 (285 mm).

The March-July reconstruction for NSA from 1858 to 2013 contains 23 drought events and 25 wet events. Two-year drought events were in 1875-1876, 1918-1919 and 1953-1954. Two-year wet events were in 1906-1907 and 1945-1946. Since the reliable reconstruction interval (EPS> 0.85) starts from 1858, there are insufficient data to compare the frequency of dry and wet years in different centuries. A 5-year moving average reveal several prolonged wet and dry events. The driest 5-year reconstructed period is 1917-1921 (323 mm) and the wettest 5-year reconstructed period is 1903-1907 (515 mm).

Common wet years for SSA, CSA and NSA were identified in following years: 1877, 1903, 1906, 1927, 1983 and 2009 (Fig. 6). For SSA and CSA common wet years were additionally identified in 1805, 1853. Common dry years for SSA, CSA and

NSA occurred in 1869, 1919, 1949 and 2003; for SSA and CSA there is one more common dry event in 1821. We did not identify common wet and dry events with a duration of more than one year.

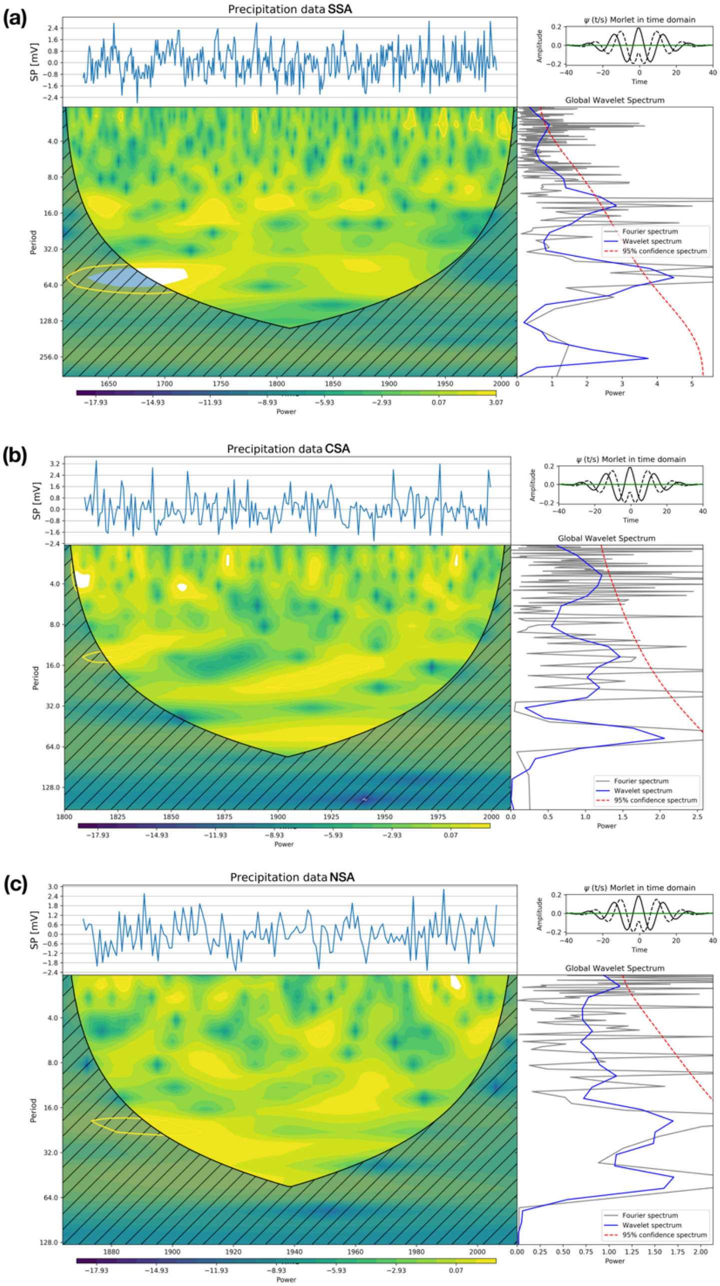

Figure 7: The wavelet power spectrum of the reconstructed precipitation at the SSA (a), CSA (b) and NSA (c); powers are given in log$_2$-scale. Significant are the periods that in the graph on the right intersect the dashed red region of significance (blue curve), constructed for a significance level of 0.05. At the top of the graph is a time series and to the right is the view of the used mother wavelet. By hatching on the wavelet transform graph (this graph is filled), the influence cone is indicated. Values falling into the

hatched region could be affected by the continuation of the signal due to its artificial periodization beyond the interval of its actual determination.

The wavelet analysis for the three points yielded the following results. In the case of SSA, a significant time-series periodicity component with a duration of 57 to 60 years was detected (Fig. 7a). This cycle (given the intensity of the conversion diagram's color filling (yellow and white) is expressed in the late 17th and early 18th centuries. Other noteworthy cycles were 12 to 15 and 2 to 3 years, which were also identified as significant. The former mostly took place until 20th century, and the latter was typical for 20th century. No significant cycles were detected for CSA and NSA; however, power graph shows that there is a tendency for existence of periodicity component of 58 to 60 years and 60 to 62 years for CSA and NSA, respectively (Fig. 7b, c). There were also identified periods of approximately 15 and 2 to 4 years for CSA and NSA, yet the periods themselves coincided in terms of duration with significant periods identified for SSA.

For all three sample points, we found significant ($p < 0.01$) correlations between the precipitation reconstructions and PDSI: $r = 0.276$ for SSA, 0.365 for CSA and 0.372 for NSA. However, we did not find any significant correlation between precipitation reconstructions and other climatic indices (NINO3, NINO4, NINO3.4, SOI, PDO and AO).

The precipitation reconstructions are significantly correlated with the CRU TS4.03 precipitation data (SSA: $r = 0.382$, $p < 0.05$; CSA: $r = 0.350$, $p < 0.05$; NSA: $r = 0.440$, $p < 0.001$). Spatial correlations between our precipitation reconstructions and the gridded precipitation data set (CRU TS4.03) reveal that our reconstructions, especially for NSA, have large-scale implications (Fig. 8).

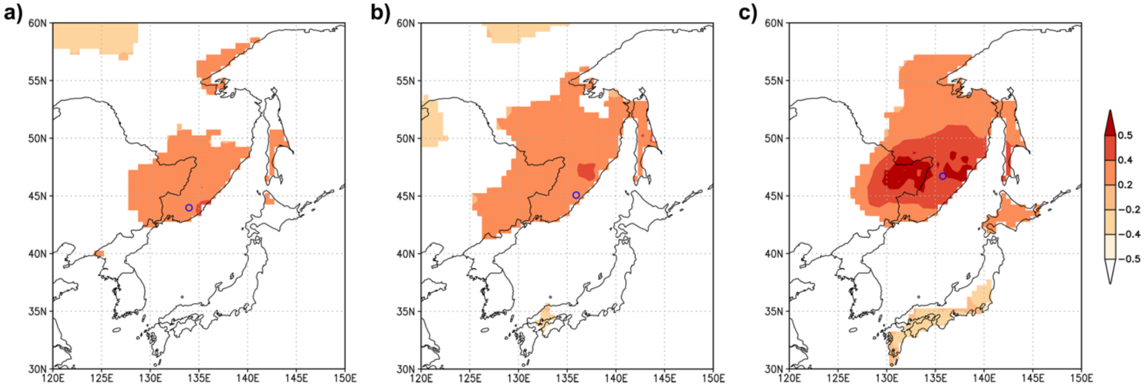

Figure 8: Spatial correlation pattern of gridded precipitation CRU TS 4.03 with the reconstructed precipitation using Climate Explorer website (http://climexp.knmi.nl): a) April-June (SSA), b) March-June (CSA) and c) March-July (NSA). The sample points are marked with circles. Analysis periods are 1936–2004, 1941-2009 and 1940-2013 for SSA, CSA and NSA, respectively.

4 Discussion

4.1 Climate-growth response

As the analytical results of the correlation between the tree growth and climate factors showed, the spring-to-early-summer precipitation played an important role in the growth of Korean pine at all study sites. As previous studies have shown, the growth of pines in Northeast Asia tended to be limited by a moisture deficit (Liu et al., 2003b, 2004; Gao et al., 2005; Li et al., 2006, 2007; Liang et al., 2007; Fang et al., 2009; Li et al., 2009a, b; Liu et al., 2009; Fang et al., 2010a, b; Chen et al., 2012). During springtime the moisture deficit is of great importance for plants, since it is exactly the period when their active growth began (Kozhevnikova, 2009).

Since a relatively small amount of precipitation falls during the cold months, precipitation at the beginning of the growing season is of great importance for plants. During the dry years, the periods in which trees were sensitive to precipitation (March to June, March to July and April to June in the cases of CSA, NSA and SSA, respectively) were characterized by the precipitation that amounted to up to 25% (CSA and NSA) and up to 32% (SSA) of the multiyear mean value (Fig. S1). During the wet years, the precipitation amounted to 181, 201 and 218% of the multiyear mean value for CSA, NSA and SSA, respectively. For instance, in the case of NSA, the March-July precipitation in the driest year was 106 mm, while that in the wettest year was 860 mm.

The months with significant precipitation-growth relationships belong to the first stage of the Far Eastern summer monsoon, which lasts on average from April to June (Mezentseva and Fedulov, 2017). This monsoon stage is a very cold wet sea air current, which is intermittent with the impact of air masses coming from Central Asia (Mezentseva and Fedulov, 2017). The variation in the significant months could be explained by their locations. April to June were significant months for the southernmost point (SSA), which completely coincides with the first monsoon stage (Sorochan, 1957; Lisogurskyi and Petrichev, 1980). The period between March and June was identified as the most important for the site located further east and being the nearest one to the shore (CSA), because for this point the influence of the oceanic current is longer and more pronounced. In the case of the inland part, located further west (NSA), March to July precipitation play the most important role as this area is more frequently exposed to the springtime arrival of southern wet air masses, and during summer the first (drier) monsoon stage is later replaced with the second stage (with abundant precipitation).

Growth-climate analysis identified the effect of temperature for different seasons at individual sites. Extreme temperatures are widely known to have a severe limiting impact on the growth of trees located at the boundary of their growth region (northern boundary of the distribution area and altitudinal forest limit) (Wison and Luckman, 2002; Körner and Paulsen, 2004; Porter et al., 2013; Yin et al., 2015; Ukhvatkina et al., 2018). At points where the ocean (monsoon) influence is stronger, the average temperatures of the early spring - February-April for the SSA and March-April for the CSA - become significant for plant growth. Moreover, for the relatively more north and closer to the coast point (CSA), the correlation is approximately two times higher than for the southern and remote from the ocean point (SSA). For the more continental point (NSA), the months of the previous season are significant, especially winter temperatures. One reason for this may be that low winter temperatures may lead to thicker snow cover, which melts far more slowly in spring (Zhang et al., 2015). If the vegetation period of the plant cannot begin at the end of March due to prolonged melting of snow, plant growth may be reduced. Also, although cambial activity stops in the winter, organic components are still synthesized by photosynthesis. Low temperatures may induce a loss of accumulated materials, which adversely affects growth (Zhang et al., 2015).

4.2 Analysis of spring precipitation reconstructions

Differences in correlation between precipitation reconstructions for SSA, CSA and NSA could be explained by several reasons. First, the months important for tree growth varied at all three points, with the weakest correlation of NSA-SSA coinciding with March-July being important for NSA and April-June being important for only SSA. Second, the weather pattern itself differed between sites. As numerous authors have noted (Kozhevnikova, 2009, Shamov, 2010, Shamov et al., 2014), highly rugged relief and meridional location of the main mountain range leads to high variability in climate parameters, especially precipitations (Sohar et al. 2017), even at small distances within the region.

Notably, although after 1950 the general direction of long-term trends of precipitation change at all three points tended not to coincide, the total fluctuation in the precipitation amount remained around the mean values. Smoother precipitation dynamics were registered after 1950s for VIS and CSA and 1960s for NSA, which generally coincide with the start of the active warming period in the region (Ukhvatkina et al., 2018, Mezentseva and Fedulov, 2017).

Most of the studies available from China, South Korea or Japan (Gao et al., 2013; Liu et al., 2004; Liu et al., 2003a; Chen et al., 2012; Chen et al., 2016; Sakashita et al., 2016) were aimed at precipitation reconstructions during the summertime monsoon period and rarely covered the spring-to-early-summer period. Thus, comparing our spring-to-early-summer precipitation reconstruction with generally available summer-time monsoon period (June to August) is not suitable as these two periods featured entirely different weather patterns (Mezentseva and Fedulov, 2017). The only available spring-to-early-summer precipitation reconstruction was carried out at the inland part of Northeast Asia, in the Inner Mongolia (Liu et al., 2004). The distance between our study area and that point is more than 2400 km (Fig. 1), and, in addition Inner Mongolia's climate features much higher degree of continentality (Liu et al., 2009). Thus, comparing our results with other available precipitation reconstruction(s) is not suitable. Therefore, it was deemed practically impossible to assess the reliability of our reconstructions based on a comparison with the reconstructions for adjacent areas. Hence, we decided to conduct only a qualitative analysis of the wet and dry period coincidences with other reconstructions.

We compared the data obtained with the identified wet/dry periods in terms of precipitation from the previous October to the current September, which were studied by Chen et al. (2016) for the southern part of northeast China (Changbai Mt., Qainshan Mt.) and the northern part of South Korea. Chen et al. (2016) identified several dry periods between 1833 and 1862, 1911 and 1925 and 1964 and 1987, The dry period of 1833 to 1862 (Chen et al., 2016) coincided with the period of 1841 to 1845 (SSA). According to numerous studies, this period coincided with the historical records on severe draughts during the 1840s in Northeast China (Lui et al., 2010, Lui et al., 2009, Chen et al., 2016), Mongolia (Davi et al., 2006) and Korea (Jung et al., 2001; Liu et al., 2003b, Cook et al., 2010). The identified dry period of 1911 to 1925 (Chen et al., 2016) coincided with the period of 1918 to 1922 (NSA), also 1919 is a common dry year for all three reconstructions. The dry period of 1964 to 1987 (Chen et al., 2016), however, did not coincide with the data obtained in our work but seen as a clear trend in SSA and NSA reconstructions. Critically, according to the state record data (Forest complex of the Russian Far East…, 2008), the clearly identified in all three reconstructions dry year 2003 coincided with the peak in the number of spring-time fires observed in the studied region.

For the wet periods, in the case of adjacent regions, the years identified were between 1863 and 1879, 1884 and 1898, 1934 and 1963 (Chen et al., 2016). The first of these periods coincides with the wet period of 1862-1866 (SSA), the last of these periods coincides with the wet period of 1960-1964 (NSA). At the same time, the periods from 1869 to 1873 and from 1882 to 1886 were dry periods for NSA and SSA, respectively. Such noncoincidence of wet periods could be explained by the fact that the (spring-to-early-summer) season analyzed in our study did not coincide with the compared season, which included the season of the monsoon's maximum impact (last October to current September). Furthermore, the compared regions were located in more inland areas, where the monsoon's effect during the spring-to-early-summer period was less obvious and overlapped with the impact of the continent (Gao et al., 2013; Liu et al., 2004; Liu et al., 2003b, Chen et al., 2012, Chen et al., 2016).

4.3 Links to global climate processes

Significant correlation between precipitation reconstructions for all three points and PDSI showed the importance of moisture sufficiency for the growth of Korean pine, which was also confirmed by other studies (Yu et al., 2013; Wang et al., 2016). Simultaneously, the studied region had no reported general trend towards more severe droughts, which has been globally observed since the 1950s (Dai, 2011).

At the same time, we did not find significant correlations between our precipitation reconstructions and the SOI, NINO3, NINO4, NINO3.4, PDO, and AO indices. In order to understand the reason for this, we tried to find correlations between these indices and instrumental measurements of precipitation for three different periods - from April to June (the first phase of the summer monsoon), from July to September (the second phase of the summer monsoon) and from April to September (entire summer monsoon period). We found significant correlations between the indices and precipitation; however, they appear only when we take into account the entire summer monsoon period, and not its first or second phase separately (Table S1). In particular, we found significant ($p < 0.05$) correlations between precipitation in Chuguevka (SSA) and SOI, NINO3.4 and PDO indices ($r = 0.351$, -0.399 and -0.331, respectively), precipitation in Melnichnoye (CSA) (CSA) and PDO index ($r = -0.419$), precipitation in Krasny Yar (NSA) and AO index ($r = 0.267$).

The influence of ENSO appears only for the southernmost point. According to the instrumental data during the El Niño period in the southern part of the Russian Far East the winter monsoon became stronger, while the summer monsoon became weaker (Bishev et al., 2014). Weakening of the summer Far Eastern monsoon, which brings wet air and precipitation, led to the decrease in river water volume (Bishev et al., 2014; Ponomarev et al., 2015). The PDO influence appears for Chuguevka (SSA) and Melnichnoe (CSA). During the positive PDO phase, precipitation decreases as in the case of El Niño. For the northernmost point, only the influence of AO turned out to be significant. During the positive AO phase, moist air penetrates further north and as a result, the amount of precipitation increases. Thus, despite the fact that the distance between the SSA and NSA sites is relatively small (about 330 km), the influence of ENSO in PDO along the gradient formed by these sites weakens and for the northern point we found significant correlation only with AO. This is consistent with the earlier results (Altman et al., 2018), where it was shown that in this region the influence of tropical cyclones decreases relatively rapidly northward.

Therefore, the oscillations influence on the climate of sample points within the region of study, but we cannot find correlations with the precipitation reconstructions, since the reconstruction period covers only part of the summer monsoon period. An indirect confirmation of this is the results of the wavelet analysis, which revealed cycles of about 3, 15 and 60 years. As it appears, quasi-cyclic short-term frequency (about 3 years) may be associated with ENSO, which is a variability with a 2 to 2.5-year frequency coupled with a low-frequency component of 2.5 to 7 years (Allan et al ., 1996; Bridgman and Oliver, 2006; Gaire at al., 2017). Cycles of about 15 and 60 years may reflect the influence of PDO variability, which has been found at 15-25 yr. and 50-70 yr. cycles (Ma, 2007). These cycles are significant for SSA and marginally significant for CSA and NSA. Most likely, this insignificance of cycles is explained by the fact that reconstructions of precipitation for CSA and NSA are much shorter than reconstruction for SSA. These results will be more accurate when we collect additional data, and chronologies will be expanded. It should be noted, that in this study area, we can only use cores from living trees and discs of dead *Pinus koraiensis* trees for several reasons. First, due to high humidity in summer wood decomposes very quickly, so it is very difficult to find a well-preserved dead tree. Secondly, the old wooden buildings are completely absent. Finally, sub-fossil trees are extremely rare and are found only in one location within the study area not far the NSA. Therefore, taking into account the maximum age of *Pinus koraiensis* trees and the rate of wood decomposition, we believe that the maximum length of chronologies can be about 600-700 years.

Thus, features of distribution and amount of precipitation were likely to be determined by a combination of the impacts of various air currents, which caused frequent change and large differences in the precipitation amount on a year-to-year basis. However, the main contribution to the precipitation is still made by the impact of the Pacific Ocean.

5 Conclusions

The results of this study show that the radial growth of Korean pine is greatly limited by precipitation during the early and middle parts of the growing season in the Sikhote-Aline area. Based on this, we first created three precipitation reconstructions for the southern (April to June), central (March to June) and northwestern (March to July) parts of the Sikhote-Aline covering past 412, 205 and 162 years, respectively. Our precipitation reconstruction records fill the knowledge gap in the existing reconstructions for Northeast Asia and provide first evidence of past precipitation variability over large area of Russian Far East. The wavelet analysis of the reconstruction identifies cycles possibly related to the processes influenced by the El Niño-Southern Oscillation and Pacific Decadal Oscillation. We also found that precipitation at different parts of the Sikhote-Alin is to some extent influenced by different oscillations (ENSO and PDO for the southern part, PDO for the central part and AO for the northwestern part), which is probably one of the important reasons for the climate features of these parts. Thus, our results enable better understanding of future climatic trajectories in Northeast Asia.

Data availability. All tree-ring chronologies used in this paper will be uploaded to the International Tree-Ring Databank.

Author contributions. OU and AO designed the research; OU, AO and DK performed analyses; OU, AO and JA wrote the paper; OU, AO, AZ, ET and JA contributed to data collection.

Competing interests. The authors declare no competing interests.

Acknowledgments. This work was supported by the Russian Foundation for Basic Research (grant numbers 18-04-00120, 18-04-00278), JA was supported by Research Grants 17-07378S and 20-05840Y of the Czech Science Foundation, LTAUSA19137 (program INTER-EXCELLENCE, subprogram INTER-ACTION) provided by Czech Ministry of Education, Youth and Sports, MSM200051801 of the Czech Academy of Sciences, and long-term research development project RVO 67985939 of Institute of Botany of the Czech Academy of Sciences.

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