We would like to acknowledge the time and effort that Editor Dr. Helen McGregor, 2k Special Issue Data Review Team, and the two anonymous reviewers have put into assessing the previous version of the manuscript. We have provided the responses to each of the editors' and reviewers' comments below. These are shown in blue italics. At the end of this document, we also provide a version of the manuscript where all changes are marked in yellow.

We look forward to hearing from you in due time regarding our resubmission and to respond to any further questions and comments you may have.

On behalf of the authors,

Kristina Seftigen

Dr Helen McGregor

Regarding your request for clarification on the referee #1 comment:
"Sec./Fig. S1: I'm a bit lost here. How can the annual mean be overestimated if all monthly means are underestimated?" All that is required is to clarify that the data in Fig. S1b are from southern Scandinavia (not stated in the caption or text as far as I can tell).
Response: done

In addition, in response to Referee #2's point 1., I encourage you to consider adding to the methods the more specific context your provide in your response (text could be inserted around the callout for Figure S3). Although the use of TRW to moisture balance is discussed in general terms in the introduction the additional text in the methods will assist readers to recognise the importance of the data presented in Figures S3 and S6.
Response: thank you for this suggestion. The text is now added (lines 122-137).

Referee #1
In general I find some formulations too strong and not fully supported by the presented analysis. This is in particular the case for formulations of over/underestimation and biases in the model output in comparison to the SPEI reconstruction. When comparing two non-perfect representations of a variable these terms are in my view only justified if one also includes observational data or if there is compelling evidence that one of the two is a better representation of physical reality. At most parts of the manuscript suggests that the proxy reconstruction is an accurate representation and the discrepancy is mainly due to an inability of the GCMs to reproduce these features. A better way would be, to just state a difference in variability, possibly followed by an assessment of both representations. The authors state in lines 561-562, that it is not possible to attribute the disagreements between the reconstruction and the models to one side. This is in disagreement with the rest of the paper, which blames the models. A reasonable formulation is found in lines 544-547 and I would have liked to see similar remarks earlier in the text.

This can probably be easily resolved by reformulating certain statements. In the current form, I found it widely irritating while reading. Some examples of statements which I find too strong (there might be others) are:

- l. 19-20, l. 315-318, l. 460-465 and l. 532-533: I would like to see a critical assessment of the variability of the SPEI reconstruction and a deeper comparison to the expected time-scale depended variability, also from observational data. Just comparing the model output to the

reconstruction is in my view not enough to conclude a bias on the model-side.

- l. 22-23, l. 520-522: The formulation implies, that a positive correlation on multidecadal scales is also found from observational evidence. This is not provided in the manuscript, but is crucial to determine if the mismatch between proxies and models is mainly due to GCMs deficiencies. Thus, much of the paragraph l. 518-526 is formulated with a bias towards a correct representation in the proxy reconstruction. The fact, that the multi-decadal variability is much stronger in the reconstructions can have many reasons (some of which are also discussed in the manuscript), but to claim a bias in the models from this fact alone is a bit strong.

Response: we agree with the reviewer that some of the statements are perhaps formulated too strong. Following the reviewer suggestions we have now reformulated some of the text. Rather than attributing the mismatch to either of the datasets, sect. 3 and 5 are now more focused on describing the inconsistencies in the model and proxy records. Possible causes of the disagreement are briefly discussed in the final sect. 'summary and discussions'. The abstract has been rephrased accordingly.

- l. 215-216: It is not immediately clear, which period is the validation and which is the calibration period.

Response: We have used a split period calibration/validation procedure, which means that both the early (1901-1948) and the late (1949-1995) periods have been used for calibration and validation. A more detailed description of the calibration/validation scheme (l.198-202) is now provided.

- Fig 3: It would be nice to include (at least for the high-frequency part) observations into this plot, to be able to judge both the proxy and the model performance. In Fig. 3 (d), adding the markers to the legend would make it more intuitive to read, especially for monochromatic prints.

Response: Thank you for the suggestion. We have now provided observational data in the comparison. Also, the legend in fig. 3d is changed as suggested.

- Fig 4.: I found it a bit confusing that the order of the columns does not correspond to the order in which the variables are discussed in the text. I would recommend adjusting the order accordingly.

Response: Order revised

- Repeatedly the formulations seem to imply that hydroclimate and temperature/ precipitation are independent variables which one can "contrast" or "compared" (e.g. l. 227). While the first is rather a combination of the two and thus one is not comparing them, but rather investigating, which factor is more dominating.

Response: Agreed, the text is now revised.

- As a reader who is not familiar with SPEI it is hard to follow what this variable does and what it's dependencies are. I would have liked to see the formula that is used in this study, possibly in the Supplementary Material.

Response: Thank your for this suggestion. A more detailed description of the SPEI computation, as well as some technical notes on the use of the SPEI R package, are now provided in the supplementary materials.

- l. 235-236: While the two time series are coming from different data sets they might still share common signals and might not be totally independent. Given the rather low r2 of 0.2, one could also argue that the low-frequency variability of the SPEI index, which is a combination of precipitation and temperature, is simply dominated by the temperature component, which would lead to similar multi-decadal variability with ScandT14.

Response: We thank the reviewer for his/her comment. We however argue that one would expect the two reconstructions ScandH17 and ScandT14 to be anti-correlated in the decadal/lower frequencies (warm decades -> dry decades), would the low-frequency portion of the reconstructed SPEI series be dominated by a temperature component. Interestingly, this is not the case. We have showed in the manuscript that a precipitation signal dominates the high-frequency portion of the TRW variability. Theoretically one would therefore expect the decadal variability to also be driven by changes in rainfall rather than temperature. However, we cannot rule out that there might be a frequency dependent sensitivity of the proxy data to climate and that the influence of temperature could increase towards lower frequencies of the spectra. We have now discussed this issue in lines 581-584.

- l. 309/310: A reference to the Supplementary Material Sec. S1 could strengthen this claim, even though it only applies to the inter-annual time scale.
Response: done.

- Sec. 4: I found the title misleading, as the only external forcing discussed is volcanic eruptions, while other forcings like solar variability are not mentioned. Please revise the title.

Reply: the header is now revised to 'The role of volcanic forcing'

- l. 432 ff: I found this paragraph a bit confusing. While it begins with comparison of temperature and precipitation the results are about temperature and SPEI. As SPEI is a mixed variable, which also includes temperature, it is not clear, how one can draw a connection to a T-precip relationship. In general, it seems like SPEI and precipitation are used interchangeable here, which they are not.

Response: The SPEI and precipitation have here been used interchangeable because there is presently no high-resolution, fully independent proxy reconstruction of rainfall available for the region. Also, we show that the SPEI variability is dominated by a precipitation signal in the region (Fig. S5). However, we agree that some of the readership might find this section a bit confusing. We have therefore revised the text (l444-467), to be more focused on the role of temperature in regional hydroclimate. We have also added two new plots to the supplementary materials (Fig. S9), that are more closely exploring the association between simulated SPEI, temperatures and rainfall across different frequency bands.

- l. 448 ff: Can you quantify the relationship between ScandH17 and ScandT14? While the multi-decadal co-variability is clearly visible by eye this is not the case for the interannual values. In both cases it would be nice to have quantified values (including significance).

Reply: done (l.453 and l.458).

- Sec./Fig. S1: I'm a bit lost here. How can the annual mean be overestimated if all monthly means are underestimated?

Reply: We are not sure that we understand the referees' comment. Fig S1b is based on model data from southern Scandinavia, where many of the models underestimate the annual rainfall (blue areas in fig. S1a).

Technical Corrections

- 387 [. . .] superior [to] TRW [. . .]

Reply: corrected

Referee #2

1. The growth of tree-ring width (TRW) may be limited by the shortage of water. However, does the TRW positively and linearly depend on soil mositure/ precipitation? Can TRW proxies reflect floods/extreme wetness, especially when the study region is not arid?

Response: We thank the reviewer for taking time to review our manuscript and providing us with a number of valuable and insightful comments and suggestions. We understand that the use of TRW data from moist and cool Scandinavia in moisture/rainfall reconstructions might appear controversial to some readers. After all, the developments of moisture sensitive TRW data have traditionally been restricted to lower latitude arid and semi-arid regions, with only a few exceptions for the northern European sector. Yet, we argue that moisture stressed trees do grow in these high-latitude environments and tree-ring chronologies with moisture sensitivity can be developed, at least if species and sites are carefully selected, which has also been proven by a number of recent studies (Helama & Lindholm, 2003; Wilson et al., 2012; Cook et al., 2015 etc.). In our study, we have almost exclusively used TRW data from sites with shallow and well-drained soils - that is, sites where the growth of vegetation is clearly affected by the amount of available moisture. We have therefore been able to build chronologies that are positively and more strongly correlated with moisture availability than with temperature variability, which is demonstrated in figs S3 and S6 in the supplementary materials.

2. I see you have another field hydrological reconstruction over Fennoscandia based on much more proxy records. Have you compared this reconstruction with that one over Scandinavia? Is there any difference for the northern part?

Response: yes, in Seftigen et al. (2014) we have used a denser tree-ring network to provide a field reconstruction over much of Fennoscandia. In that study the tree-ring data from the northernmost parts of Fennoscandia were mostly negatively correlated with available moisture and therefore we used it indirectly to reconstruct soil moisture availability, by considering the importance of surface temperature in determining the land surface heat flux, evapotranspiration and consequently the water balance. Mixing tree-ring data with different signals for reconstruction purposes is however not always straightforward, and as the main aim of the current study was to provide as robust and reliable reconstruction for the region we decided to only retain tree-ring data from moisture stressed sites, where the tree-growth is positively related to drought. As is shown in the manuscript fig 1, these sites are mainly located in southern Sweden. Comparing the current reconstruction with the 2014 reconstruction would yield basically the same results over southern Sweden, as the two reconstructions share more or less the same set of predictors in this region. The only difference would be that the current reconstruction contains more low-frequency information than the 2014 reconstruction (see sect. 2.2 in the manuscript). We have not compared the new

reconstruction with the previous one over northern Sweden, simply because the signal of the new reconstruction is confined to southern and central Scandinavia (see fig. 1).

3. The comparison between the reconstruction and the simulations is interesting. However some conclusions, from my point of view, are too strong. For example, "We find simulated interannual components of variability to be overestimated, while the multidecadal/longer timescale components generally are too weak." I supposed the conclusion is drawn from the lines from 307-322. As far as I understand, the TRWs tend to have red biased spectra, please see the papers from Franke et al. (2013) and Bunde et al. (2013). So, is it possible that the TRW-based reconstruction overestimated low-frequencies? If that is the case, then the following conclusions are not solid. Especially," Weak multidecadal variability in models also implies that inference about future persistent droughts and pluvials based on the latest generation global climate models will likely underestimate the true risk of these events."
Response: We agree that some of the statements were made a bit too strong – it is true that we are currently unable to identify the precise origin of the mismatch. We have now revised the manuscript to be more focused on highlighting the discrepancies in the datasets rather than drawing any conclusion about the source for the mismatch (see response to referee #1).

2k Special Issue Data Review Team

(1) Expand the "Data Availability" section to include a Data Citation or URLs to the primary output of this study (regional SPEI nested reconstruction (ScandH17) and the 100-year smooth and estimate uncertainty).

(2) Add Data Citations or URLs (in addition to publication citations) for each of the 27 tree-ring chronologies used in this study to Table II (we note that Table II includes only 25 entires). For those raw data not already in a persistent public repository, submit the essential metadata along with the chronology itself and add the corresponding Data Citation (or URL) in Table II. The archived data must contain the modified chronologies as they were re-processed and used in this study (newest signal-free standardization; adjusted to reduce variance bias). The 'Updated by Seftigen et al. 2015' revisions should be publicly archived and the 'Seftigen et al. 2015' datasets should also be archived.

(3) Add a Data Citation for the ScandT14 reconstruction (Fig 7a). If the data have not previously been deposited in a public data repository, then submit the essential metadata along with the time series itself and add the corresponding Data Citation and publication citation to the caption for Fig 7.
Response: The ScandT14 reconstructions will be made available through the NOAA paleoclimate database, and citation will be added to the paper. Metadata, including all new chronologies, re-processed chronologies as well as the new ScandH17 reconstruction (smoothed and raw), will be added to supplementary materials.

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Hydroclimate variability in Scandinavia over the last millennium - insights from a climate model-proxy data comparison

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Abstract

The integration of climate proxy information with General Circulation Model (GCM) results offers considerable potential for deriving greater understanding of the mechanisms underlying climate variability, as well as unique opportunities for out-of-sample evaluations of model performance. In this study, we combine insights from a new tree-ring hydroclimate reconstruction from Scandinavia with projections from a suite of forced transient simulations of the last millennium and historical intervals from the CMIP5 and PMIP3 archives. Model simulations and proxy reconstruction data are found to broadly agree on the modes of atmospheric variability that produces droughts/pluvials in the region. Despite these dynamical similarities, large differences between simulated and reconstructed hydroclimate time series remain. We find that the GCMs simulated multidecadal/longer hydroclimate variability is systematically smaller than the proxy based estimates, whereas the dominance of GCM simulated high-frequency components of variability is not reflected in the proxy record. Furthermore, the paleoclimate evidence indicates in-phase coherencies between regional hydroclimate and temperature on decadal time-scales, i.e. sustained wet periods have often been concurrent with warm periods and vice versa. The CMIP5/PMIP3 archive suggests, on the other hand, out-of-phase coherencies between the two variables in the last millennium. The lack of adequate understanding of mechanisms linking temperature and moisture supply on longer time scales has serious implications for attribution and prediction of regional hydroclimate changes. Our findings stresses the need for further paleoclimate-data model intercomparison efforts to expand our understanding of the dynamics of hydroclimate variability and change, to enhance our ability to evaluate climate models, and to provide a more comprehensive view of future drought and pluvial risks.

1. Introduction

Among the current key priorities in climate research is a more comprehensive understanding of changes in regional- to continental-scale hydroclimate in response to rising levels of atmospheric greenhouse gases on time scales ranging from decades to centuries (Wu et al., 2013; Hegerl et al., 2015). Delineating the role of internal variability and natural forcing, and its contribution to the anthropogenically forced twentieth century climate (Zhang et al., 2007; Sarojini et al., 2016), is immensely important for attributing past and predicting future trajectories in the hydrological cycle, and for strategic approaches to adaptation and planning. Sparse observational evidences limits possibilities of providing tight constraints on the long-term behavior of the climate system. The longest instrumental records (~150-200 years) are too short to fully sample modes of variability that are either rare or occur on multidecadal-to-centennial timescales. This motivates the development of paleoclimatic proxy reconstructions, which extends the observational baseline into the longer spectrum of climate variability and provides a framework to consider both internal and forced climate changes.

Considerable advancements have recently been made in developing tree-ring estimates of late Holocene hydroclimate variability across Scandinavia (Seftigen et al., 2014; Cook et al., 2015). Being located in the high-latitude boreal zone, Scandinavia is well suited for dendroclimatological studies and has a long tradition of climate and environmental research using tree-ring data (Linderholm et al., 2010). The use of tree-ring proxy evidence to study natural hydroclimate variability has however long been secondary when compared to the scientific attention focused on providing local/regional reconstructions (Gunnarson et al., 2011; Esper et al., 2012; McCarroll et al., 2013; Linderholm et al., 2014) and methodologies (Björklund et al., 2012; 2014) to study temperature variability over the last several millennia. Much of the tree-ring research at moisture-limited sites have until recently been limited to a handful of exploratory papers (Helama and Lindholm, 2003; Linderholm et al., 2004; Jönsson and Nilsson, 2009; Drobyshev et al., 2011; Seftigen et al., 2013) that generally develop one or few chronologies to provide local precipitation/drought histories. These studies, together with a steadily growing collection of high-latitude moisture sensitive tree-ring records (e.g., Seftigen et al., 2015), now serves as a basis for new possibilities to expand the detail and accuracy with which the history of Northern European moisture conditions can be described.

A recent milestone in the field include the development of the “Old World Drought Atlas” ("OWDA", Cook et al., 2015), a set of tree-ring reconstructed year-to-year maps that provide temporal *and* spatial details of droughts and wetness in the last millennium across Europe,

337 including Scandinavia. The OWDA has been used to elucidate hydroclimatic blueprints of the
338 Medieval Climate Anomaly (MCA, ~1000-1200 CE). Aligning with prior findings (Helama et
339 al., 2009), the atlas reveals the occurrence of so-called megadroughts in large portions of
340 continental north-central Europe and southern Scandinavia during the MCA period.
341 Interestingly, MCA and other "Old World" droughts seem to coincide with the timing of
342 some severe and persistent droughts documented in the climate history of North America.
343 While this suggests the presence of some common driving mechanisms across the North
344 Atlantic, being possibly related to variations in the Atlantic Ocean SST or/and the North
345 Atlantic Oscillation (Feng et al., 2011; Oglesby et al., 2012), the cause of these megadroughts
346 remains to be an open question.

347 While the proxy reconstructions undoubtedly play a pivotal role in unraveling
348 statistical qualities of past climate, they are, alone, not able to provide a comprehensive view
349 of the underlying physics governing the climate system. The forced-transient simulations over
350 the last millennium from fully coupled general circulation models (GCMs) (Taylor et al.,
351 2012) therefore offer an important complementary approach to the empirical analyses of
352 proxy estimates. Paleoclimate reconstructions provide an observational basis that spans
353 beyond current climate conditions that were used in developing and tuning such numerical
354 models, thus allowing for out-of-sample evaluations of the models' predictive power. The
355 models, on the other hand, can be used to explore the dynamics that have driven climate
356 variability in the past.

357 This paper builds on previous tree-ring analyses (Seftigen et al., 2014; 2015) and
358 aims at employing a paleoclimate-data model comparison framework to further explore the
359 drivers and dynamics of drought/pluvials across Northern Europe. We analyze an ensemble of
360 six state-of-the-art GCMs from the Past Model Intercomparison Phase 3 (Schmidt et al., 2011
361 - PMIP3) and the Coupled Model Intercomparison Phase 5 (Taylor et al., 2012 - CMIP5) and
362 compare them to a new regional tree-ring-based proxy reconstruction of drought and wetness,
363 spanning the last millennium of the Common Era (CE). A combined data approach is used to
364 (1) evaluate to what extent the GCMs are capable in reproducing the key features of the
365 paleoclimate record, and (2) to estimate the role of external forcing versus internal variability
366 in driving the hydroclimatic changes regionally. The relative contribution of changes in
367 rainfall and surface temperature at inter-annual and decadal/longer time-scales to regional
368 hydroclimate patterns is also briefly explored, and the ability of the CMIP5/PMIP3 models to
369 simulate the mechanisms by which the regional hydroclimate is constrained by these two
370 variables are evaluated. The collective proxy-model data assessment will help to increase our

understanding of decadal/longer climate dynamics in regions and to evaluate the ability of the state-of-the-art GCMs to simulate realistic future hydroclimatology regionally and across a variety of different timescales.

The paper is structured as follows. Sect. 2 reviews the methods and describes the paleoclimate and CMIP5/PMIP3 datasets. Subsequent analyses concentrates on comparing the GCM simulations with the proxy based hydroclimate reconstructions (sect. 3), and delineating the role of external (sect. 4) and internal (sect. 5) sources of variability over the last millennium. The principal results and the implication of this study are discussed in sect. 6.

2. Data and methods

2.1 CMIP5/PMIP3 simulations

Simulations with six models (CESM1, CCSM4, IPSL-CM5A-LR, MIROC-ESM, MPI-ESM-P, BCC-CSM1-1) contributing to the Coupled and Paleo Model Intercomparison Projects Phases (CMIP3/PMIP3) (Schmidt et al., 2011; Taylor et al., 2012) have been used (Table I). The analyses were restricted to models that have available complete monthly precipitation and temperature variables spanning the last millennium (850-1849 CE) through historical (1850-2005 CE) time intervals. The six millennium simulations were forced with reconstructed solar, volcanic, greenhouse gas (GHG) and aerosol forcing, and partly land use changes, whereas the historical simulations included natural and anthropogenic forcing (Schmidt et al., 2011; Taylor et al., 2012). Except for CESM1, the analyses were limited to the first r1i1p1 ensemble member. Supplementary information (sect. S1, Fig. S1) provide an evaluation of six selected model rainfall and temperature simulations against instrumental reference data focusing on the northern European sector.

2.2. Proxy data

The use of annually resolved tree-ring series in the study of past hydroclimate variations has traditionally been confined to lower-latitude arid and semi-arid region, with only a few exceptions for the northern European sector. This is because the influence of moisture on tree-growth generally decreases and is successively replaced by sensitivity to warm-season temperature towards northern, cooler and wetter environment. Nevertheless, a growing body of research (e.g., Helama and Lindholm, 2003; Wilson et al., 2012; Seftigen et al., 2013) has established the potential to develop moisture-sensitive tree-ring chronologies in high-latitude environments if a careful selection of species and sites is made. Building upon these findings,

we here analyse an existing network (Seftigen et al., 2014; 2015) of 25 *Pinus sylvestris* L. tree-ring width chronologies from across a number of dry sites in southern Scandinavia (Fig. 1). The collected trees have typically been growing on well-drained soils or steep south-facing slopes with warm and sunny exposure. Thus low soil moisture availability during the growing season has been shown to be the most common growth-limiting factor in the tree-ring network (Fig. S3 and S6).

The start dates of the chronologies varied across the collection, ranging from 532 to 1790 CE (Table II). All chronologies extended at least to year 1995. In order to reduce the risk of natural/anthropogenic disturbance signal from inflicting non-climate noise upon the reconstruction, the tree-ring data has been standardized in previous research (Seftigen et al., 2014) by using a flexible "data-adaptive" method of standardization (Cook et al., 1995). This has limited the degree to which longer-timescale climate information can be extracted. Therefore, rather than using the already available hydroclimate reconstruction provided in Seftigen et al. (2014), we have here re-processed the TRW collection with the newest signal-free (SF) method of standardization (Melvin and Briffa, 2008), which has the capacity of preserving long-term variability due to climate changes. The standardization was performed with the ARSTAN software (Cook and Krusic, 2005). Chronologies combining living and historical/subfossil material were standardized with a regional curve standardization (RCS) approach (Briffa et al., 1992), applying a single RCS curve without any pith-offset adjustments to detrend all series. To avoid spurious growth trends in the resulting RCS chronologies stemming from a modern sample bias (Briffa and Melvin, 2011), tree-ring datasets based only on living trees were standardized using the SF method in combination with an age-dependent smoothing spline applied individually to each series. Prior to the standardization, the modern chronology data were high-pass filtered and subsequently grouped by means of a S-mode principal component analysis over the common interval (1792 – 1996 CE). The resulting eigenvector loadings are provided in supplemental material (Fig. S2) and describe the major modes of high-frequency variability within the multiple modern chronologies composing the dataset. The subdivision of the chronologies essentially identified an east-west pattern, broadly corresponding to sub-regional differences in topography and climate across the study domain. This suggested that the sub-regional tree-growth coherence at high frequencies was driven by climate. Hence, it would be rational to expect a common, climatically induced, growth variability also at the medium-frequency time scales, while any disparities in the sub-regional tree-growth signal are likely mostly non-climatic in origin (i.e. local site management practices, stand dynamics or other 'random' site-specific disturbances).

Therefore, in order to remove or minimize undesirable non-climatic noise upon our dataset, modern tree-ring series were first merged group-wise as identified by the first four principal components and subsequently detrended as four separate 'batches' using the SF method. The standard version of the resulting tree-growth indices were subsequently separated and averaged for each site to produce individual site chronologies. This procedure enabled us to retain any shared, sub-regional, growth-forcing signal while removing site-specific medium- to high-frequency noise.

Final data were adjusted to reduce the variance bias stemming from varying sample size trough time (Frank et al., 2006). The resulting chronologies were truncated where the Expressed Population Signal (EPS) (Wigley et al., 1984) dropped below the 0.85 threshold, or, in case of the longer chronologies, at year 1000 CE. The median segment length (MSL) of all the chronologies (Table II) ranged between 74 and 357 years, and the median MSL across all sites was 197 years. Although a precise quantification of returned frequency variance in the final SF detrended tree-ring chronologies was not straightforward, the median MSL suggested that it should be possible to use the network to reconstruct climate variability at time scales up to ~200 years.

2.3. Regional hydroclimatology

The CMIP5/PMIP3 inter-model spread in spatial resolution and sophistication of soil moisture schemes makes meaningful inter-model comparison difficult. To bypass some of these challenges, the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2013) was used to characterize the regional hydroclimatology across the study domain. The SPEI, a commonly used metric of soil moisture balance, has successfully been used as a target variable in several prior tree-ring reconstructions (e.g., Seftigen et al., 2014; 2015). The index is not a state variable but rather an offline metric of the surface moisture balance that can be consistently derived across models and therefore provide standard measure of hydroclimatic variability across GCMs. The computation of the index is based on normalized monthly climatic water balance, i.e. cumulative precipitation minus potential evapotranspiration (PET), summed over multiple time scales and computed as standard deviations with respect to long-term mean (Vicente-Serrano et al., 2010). The PET was here estimated with the Thornthwaite approach (Thornthwaite, 1948). The method requires surface temperature and latitude data only, and has therefore frequently been used for PET computations over the historical period. Moreover, the choice of methods is motivated by the larger confidence that is placed on GCM simulations of temperature compared to other

variables (vapor pressure, wind speed, net radiation, etc.) that are required for more physically based parameterizations of PET. At each grid point, model SPEI were derived from estimated PET and simulated rainfall over the past1000 and historical periods and then standardized against the 1901-2005 normalization period using the SPEI R package version 1.6 (Vicente-Serrano et al., 2010).

The proxy dataset was generated by a point-by-point regression (PPR) methodology that was applied to the TRW network to produce a SPEI reconstruction spanning the past millennium. The climate field reconstruction method is based on principal component regression procedure using the TRW chronologies as potential predictors to develop a set of nested multivariate stepwise regression models (see Cook et al., 1999 for details). Here we employed the same calibration/validation scheme, predictor selection and pre-processing steps as previously described in Seftigen et al. (2015). We performed a full period calibration over the 1901-1995 period of TRW/climate data overlap. A conventional split period calibration/validation procedure was additionally performed for an independent validation of the SPEI estimate, by splitting the full calibration period into two periods of roughly equal length (1901-1948 and 1949-1995 periods) and computing/comparing validation metrics over both periods. Each nest was centered and scaled to have the same mean and variance as the observational data in the calibration period. The instrumental SPEI target field for the reconstruction was computed from the CRU TS 3.22 (Harris et al., 2014) 0.5° latitude x 0.5° longitude gridded rainfall and temperature datasets over the southern portion of Scandinavia (55° - 65° N and 5° - 30° E) (Fig. 1), using the same conventions as described above. Simple correlation analysis conclusively demonstrated a short-term early summer moisture sensitivity of the TRW records over most of the study domain (Fig. S3). Based on these findings, we selected June SPEI, aggregated over a 2-month time scale, as the target season data for the reconstruction. A final regional time series was averaged from grid points where the calibration regression models explained at least 20% of instrumental variance and the reduction of error (RE) and coefficient of efficiency (CE) (National Research Council, 2006) verifications metrics exceeded the generally accepted threshold value of zero across all nests (N = 521 grid points). The mean tree-ring hydroclimate reconstruction (henceforth ScandH17) and the corresponding instrumental target dataset are shown in Fig. 1, and a validation of the reconstruction against 20th century instrumental data that have been withheld from the calibration is provided in supplementary materials (Fig. S4). Results are variable depending on the calibration/validation period used; the validation/calibration statistics are generally stronger for the 1901-1948 period and substantially weaker for the 1949-1995 period. The

most recent and well-replicated nests (mid-1600s to present) are generally explaining the greatest amount of instrumental variance (R^2 > 40% for the majority of the grid points). A loss of grid cells with declining proxy availability and a drop in reconstruction skill is occurring prior to the late-1400s and subsequently in the 1200s. Point-wise correlation with gridded instrumental SPEI dataset shows that ScandH17 is representative for a larger area in southern and central Scandinavia with a correlation 'hot spot' exceeding 0.6 (Fig. 1).

2.4. Analyses

The new proxy-based reconstruction was used to assess the temporal evolution of droughts and pluvials over the last millennium and to elucidate the mechanisms that govern hydroclimate changes in the northern European sector ranging from interannual to multidecadal time scales. We briefly analyze the relative role of temperature (which modulates potential evapotranspiration) and precipitation (which supplies moisture) in regional hydroclimate variability (sect. 5). We use the last-millennium and historical CMIP5/PMIP3 simulations of temperature and precipitation. As there are no independent, annually resolved, proxy reconstructions of rainfall variability currently available for the region, we only included temperature estimates in the analyses of ScandH17. For this purpose, the previously published Linderholm et al. (2014) (hereafter ScandT14) summer temperature reconstruction was used. The two reconstructions ScandH17 and ScandT14 share no common predictors and are thus fully independent, which ensures that any circular statement in the comparison can be ruled out. The ScandT14 record is based on tree-ring maximum density (MXD) and blue intensity data from central-northern Scandinavia and is in terms of signal strength and preserved multi-centennial scale variability one of the best temperature reconstructions currently available for the region.

Furthermore, we extended our analyses to the model domain using the methodology of paleoclimate data-model comparison. There were three main components to the combined approach. Firstly, we evaluated the consistency in various datasets and assessed whether the CMIP5/PMIP3 simulations have similar statistical properties as the reconstruction (sect. 3). Spectral and spectral coherency analyses were performed in two ways. The first is the multi-taper approach (Thomson, 1982) based on 4 tapers, where a Monte-Carlo procedure is used to estimate phase 95% confidence limits. We also used the wavelet cohere analyses available in the Grinsted et al. (2004) MATLAB package to assess the frequency dependent relationships and phasing between various datasets.

Secondly, we used the Superposed Epoch Analysis (SEA) (Haurwitz and Brier, 1981) to evaluate the influence of volcanic aerosol forcing on hydroclimate, temperature and precipitation of the Scandinavian region at inter-annual time scales (sect. 4). For the last millennium, monthly mean volcanic forcing series were obtained from three different sources: Gao et al. (2008), Crowley and Unterman (2013) and Sigl et al. (2015) datasets. We note that the former two forcings have been used as the boundary conditions for the last millennium CMIP5/PMIP3 simulations. The length of the proxy and model data allowed us to include sets of the 20 largest eruptions since 1100 CE (Table III) from the annual forcing series to assess the mean response. For each series and eruption, anomalies for ten post-eruption years were computed relative to a five-year pre-eruption mean. The confidence intervals around the composite responses were determined using a Monte Carlo block resampling (N = 10 000) of the actual event year windows (see Adams et al., 2003 for details).

Thirdly, we evaluated the skill of the models to represent the dynamics that drive the variability in hydroclimate of the Scandinavian region by establishing a link between simulated and reconstructed SPEI series and fields of mean sea level pressure (MSLP) over the Atlantic-European sector (sect. 5). Grid point correlations were computed to assess the spatial features and the strength of the teleconnections patterns over the modern era (1950-2005 CE). The analysis was also extended over the last millennium (1000-1849 CE) to investigate the nature of teleconnection stability without the influence of anthropogenic forcing. The gridded monthly instrumental HadSLP2 dataset spanning 1850-present (Allan and Ansell, 2006) was used for comparison with observed and proxy-based estimates of hydroclimate.

3. Modeled and reconstructed hydroclimate series

The regional warm season hydroclimate variability averaged across the six CMIP5/PMIP3 models together with the new ScandH17 proxy reconstruction over the last millennium are shown in Fig. 2a-b. Individual model SPEI time series are displayed in Fig. 2c-h. All data have been normalized and centred over the common interval from 1000 to 1995 CE, since this first joint proxy-model comparison focuses on the common relative changes rather than on the magnitude and the absolute values. A simple visual comparison reveals that the models and the reconstruction have generally little agreement in the variance structure and trends. The reconstruction is dominated by a large decadal-to-multidecadal variability while the multimodel mean is relatively flat at these time scales. There are some common features in some of the GCMs and the proxy datasets though (Fig. 2c-h), e.g., the drying in the 19th

568 century, but these are rare when the full millennium is considered and are likely occurring by
569 chance. The historical interval in the proxy record is characterized by a drought in the mid-
570 1800s and a gradual increase in wetness over the 20th century, while, with the exception of
571 short dry episode in the early-1900s, there is no long-term trend in the multimodel mean over
572 the modern era.

573 The very low correlation at inter-annual time scales is to be expected, as the internal
574 variations in the various records represent different realizations of the climate system, which
575 is to a very large extent chaotic at that time scale. The response of each ensemble member to a
576 strong external forcing applied to the model would nevertheless ideally agree (i.e. external
577 punctual perturbations such as volcanic eruptions could induce a coherent short-term
578 response, see sect. 4). Averaging across models or over multiple ensemble members will
579 reduce the contribution from stochastic variability so that the remaining signal can come
580 closer to the model response to external forcing. The comparison between ScandH17 and the
581 multimodel assemble mean reveal, however, no statistically significant agreement between
582 the series, neither on the interannual nor on decadal timescales, suggesting that the simulated
583 hydroclimate changes are not strongly tied to exogenous forcing. Moreover, we found no
584 statistically significant correlation between the different ensemble members in the same
585 model (CESM1) (Fig. 2c), which is the only model providing multiple ensemble members
586 (the only difference among these being the air temperature at the start of each ensemble
587 member (Otto-Bliesner et al., 2016) over the historical and past millennium intervals). The
588 poor overlap between CESM1 ensemble members as well as the individual GCM simulations
589 over the past millennium (despite the use of largely similar forcing series to drive the
590 simulations) is indicative of a larger contribution from internal variability on simulated
591 drought/pluvial occurrence than from changes in exogenous forcing.

592 We compare the spectral properties of the six individual CMIP5/PMIP3 models to
593 the ScandH17 reconstruction and observational data, which allows for a general evaluation of
594 potential frequency biases. Results indicate that the underlying spectrum of reconstructed
595 hydroclimate variability is significantly redder on decadal-centennial timescales than
596 indicated by the simulated SPEI (Fig. 3a and 3d), as has previously been noted (Ault et al.,
597 2012; Ault et al., 2013). In contrast, more hydroclimate variance is concentrated on
598 interannual timescales in the CMIP5/PMIP3 archive than in ScandH17 reconstruction. At
599 frequency bands < 8 years, the power spectral range of most models is systematically above
600 the confidence interval of ScandH17. We also consider the agreement between simulated,
601 reconstructed (ScandT14) and instrumental temperature data in terms of their spectral

properties (Fig. 3b). Although the degree of agreement is higher than for hydroclimatology and most models lie within the reconstruction confidence bands (see also sect. S2 supplementary materials), there are some models that have more variance than the reconstruction at periods < 10 years.

4. The role of volcanic forcing

Large explosive volcanic eruptions are an important natural radiative forcing mechanism at timescales ranging from seasons to decades (Shindell et al., 2004; Gleckler et al., 2006). The imposed perturbation on the climate system by such events will depend on the nature of the eruption, the magnitude of change in the energy entering the earth's atmosphere, the background climate and internal variability, latitude and season. Analysis of observational data (Shindell et al., 2004), tree-ring records (D'Arrigo et al., 2013) and model simulations (Anchukaitis et al., 2010) indicate a considerable spatial variability in the dynamical response of the climate system to volcanic forcing, with some regions experience surface and tropospheric cooling effects and other regions showing no significant change or even warming effect. Here, we assess the magnitude and timing of Scandinavian summer temperature, rainfall and hydroclimate response to short-term radiative cooling due to volcanic aerosols.

A peak cooling is observed one year after the eruption, both in ScandT14 and in the CMIP5/PMIP3 composite average, for all the three forcings considered (Fig. 4). In addition, there is a significant cooling in the year of the event for the Crowley and Unterman (2013) and Sigl et al. (2015) lists. ScandT14 reveal a marginally greater cooling (2.0 °C, mean of the three event lists) than the model average (1.8 °C) one year after the eruption. Remarkably, there is a high degree of similarity in the proxy and in the GCMs not only in terms of the signal timing and the magnitude of the cooling response, but also the rate of recovery. A complete recovery after the volcanic cooling is found two years after the eruption, independent of the forcing list. These results are generally consistent with prior studies (Fischer et al., 2007; Jones et al., 2013; McCarroll et al., 2013) highlighting the importance of explosive volcanism as an external driver of Northern European temperature variability. They also provide a relevant test of the model to radiation perturbations. The agreement between the model simulations and proxy data demonstrates the credibility of the models.

Existing research on the response of high-latitude rainfall and hydroclimate to volcanism is limited (in part because high resolution moisture sensitive proxy records are sparse or unavailable). Fischer et al. (2007) found a weak tendency to drying conditions over

southern/central Scandinavia in the summer of year 0 and year 1 after the eruption. Circulation changes to the surface cooling were shown to modulate the directly forced response. On continental and global scales, both observational and modeling studies have found a decrease in precipitation (Iles et al., 2013) and streamflow (Iles and Hegerl, 2015) in response to large explosive eruptions, particularly in climatologically humid regions (Carley and Gabriele, 2014). The short-term drying is caused by a reduction in incoming solar radiation reaching the surface, which reduces evaporation, whilst the widespread cooling stabilized the atmosphere and lowers its water holding capacity (Bala et al., 2008). Here, we apply SEA on ScandH17 and simulated SPEI and precipitation to examine the influence of volcanism on Scandinavian moisture availability. A statistically significant reduction in simulated rainfall is observed for all event lists, ranging between the year of the event (Crowley and Unterman, 2013 dataset) and up to two years (Sigl et al., 2015 dataset) following the eruption. We find, however, that the precipitation signal is less consistent across the six CMIP5/PMIP3 models than the cooling effect observed in the simulated temperature series.

The SEA on SPEI time series reveals a statistically significant drying after large volcanism. However, the response is more muted than the response of temperature and rainfall separately. Moreover, the agreement between proxy data and the model composite average is weak and there are large inconsistencies between the different forcing records. ScandH17 show a progressive transition from wet conditions in the event year and preceding years to dryer conditions in the consecutive years with significant dry anomalies five (Crowley and Unterman, 2013 dataset) and seven years (Sigl et al., 2015; Gao et al., 2008 datasets) after the perturbation. For the CMIP5/PMIP3 multimodel multi-eruption average, only the fifth year after the eruption (Crowley and Unterman, 2013 list) is found to be significantly drier than the adjacent years.

The observed weak influence of volcanic forcing on the hydroclimate of the region can be explained by various factors. For example, our results reveal that GCM simulated post-volcanic cooling remains significant for about two years and matches the timescale of the post-volcanic rainfall decrease. Since the SPEI accounts for both supply and demand changes, the net effect would be such that the temperature-driven PET decrease counter a substantial fraction of the precipitation-driven drying, thus producing SPEI values near neutral. Furthermore, the muted response of ScandH17 may arise from autocorrelated biological memory in the TRW data (Esper et al., 2015). The high year-to-year persistence may bias its ability to estimate the abruptness and severity of climatic extremes caused by volcanic

cooling. The tree-ring MXD and the blue intensity parameters have, in contrast, been suggested to be superior to TRW for recording short term climate perturbations (Wilson et al., 2016), which is likely the reason why the response of ScandT14 is more immediate than that of ScandH17.

5. Internal sources of variability

If the regional hydroclimate variability is indeed dominated by internally generated stochastic components of variability (see sect. 3), atmospheric circulation changes can be the key process shaping regional patterns of moisture availability. Advancing our understanding of the range, stability and strength of teleconnection behavior (defined here as the correlation between hydroclimate and MSLP over the Atlantic-European sector) and its coupling to regional hydroclimate would provide an improved understanding of drought/pluvial dynamics and associated uncertainty. In this section, we first explore major modes of atmosphere variability that impact summertime northern European hydroclimatology. We also assess more extensively the contribution of atmospheric processes (and possible land-atmosphere interactions) by investigating the couplings between hydroclimate and arguably the two most critical variables of the terrestrial climate and the hydrological cycle: precipitation and temperature.

To determine the role of teleconnections, correlation of MSLP fields with the hydroclimatic variables over the recent 50 years of the post-industrial era were computed. Results are shown in Fig. 5. As expected, we find that atmospheric dynamics have a significant role in climate variability in the region: a strong correlation with regional hydroclimate is found when MSLP in concurrent months (i.e. May-June) is considered. The results show that the proxy based and CMIP5/PMIP3 simulated dynamics are largely consistent with those in the instrumental record, indicating that both the proxy and the models contain to some degree realistic teleconnections. A consistent feature across the datasets is a tripole structure that would favor increased moisture supply into the Scandinavian region. The structure is characterized by anomalous cyclonic conditions across Scandinavia and high-pressure systems extending over Iceland-Greenland and, albeit less pronounced, over European Russia - Central Asia. Out of the six CMIP5/PMIP3 models, MIROC-ESM is the one showing the largest discrepancy with the major spatial features of the observed correlation map, by failing to reproduce the anti-cyclonic pattern over Iceland-Greenland. Additionally, MIROC-ESM and also CCSM4 show a meridional and zonal shift of the European Russia - Central Asia high-pressure structure towards the Mediterranean region.

Atmospheric circulation has been identified as key contributor to recent changes in the climate of Europe in both summer and winter (van Oldenborgh and Van Ulden, 2003; Jones and Lister, 2009). To assess the stationarity of observed MSLP patterns, the analysis was repeated for the pre-industrial last millennium (1000-1849 CE) period (Fig. 6). The exercise was restricted to five GCMs for which simulated MSLP was available for the pre-industrial era (BCC-CSM1-1 was not included). The simulated dynamical relationships were found to be largely stable for all five models, being consistent with observed correlations patterns in the modern era. This suggests a weak influence of anthropogenic forcing on the structure of the dynamical drivers of Scandinavian hydroclimate. In addition to raw data, correlation analysis with 10-year low-passed data was also completed for the pre-industrial period with the purpose to elucidate the drivers of multidecadal hydroclimate variability. We find similar, yet weaker, correlation patterns as compared to the high-frequency variations (results not shown).

Precipitation and temperature are the two key variables of the hydrological cycle. Assessing the relative contribution of these two variables to the surface moisture balance across various timescales, and the mechanisms that control and modulate it, is therefore of great interest to the study of regional processes on surface energy and water budgets. While past studies have investigated the relationship between temperature, moisture supply and drought in various regions on daily, seasonal and interannual timescales (Adler et al., 2008; Berg et al., 2015; Trenberth, 2011; Madden and Williams, 1978), the nature of concurrent multidecadal/ long-term relationship is still far from being clear. A join analyses of the new hydroclimate reconstruction with the recently published Linderholm et al. (2014- ScandT14) fully independent warm-season temperature record for Scandinavia is provided in Figs. 7 and 8, in conjunction with the CMIP5/PMIP3 simulations of temperature, rainfall and SPEI. On interannual timescales, five out of six GCMs show a significant ($p < 0.05$) negative association between simulated interannual temperature and rainfall, with correlation coefficients ranging between $r = -0.12$ and -0.29 (1000-2005 CE period). Moreover, all model show a strong negative (positive) correlation between temperature (precipitation) and SPEI in the last millennium, ranging between $r = -0.63$ and -0.80 ($r = 0.61$ and 0.84). Extending the analysis to the instrumental data, we find that the regional year-to-year variability in hydroclimate is more closely organized around changes in precipitation than changes in temperature (Fig. S5). In southern Scandinavia, weak negative correlations appear between temperature and rainfall (Fig. S5a), and temperature and SPEI (Fig. S5b). Over northern Scandinavia, the interannual correlations are not significant.

Turning to the tree-ring records, we find no significant relationship between ScandH17 and ScandT14 reconstructions on a year-to-year basis ($r = 0.01$ and $p = 0.8$ on first difference data, 1100-1995 CE period). The considerable distance separating the sampling sites of each tree-ring collection, and the fact that summer precipitation occurrence often depends on local processes and moisture fluxes could explain the lack of a shared annual signal. Notably, however, we find that the two reconstructions are mostly in phase on decadal and longer timescales ($r = 0.30$ and $p < 0.001$ on loess-smoothed data, 1100-1995 CE period) (Fig. 7), suggesting that the low-frequency temperature and hydroclimate variability is more spatially coherent. These results are corroborated by the cross-wavelet coherency analysis (Fig. 8a), revealing that the ScandH17 and ScandT14 reconstructions share significant ($p < 0.05$) in phase variance in multidecadal frequency throughout most of the last millennium. The coupling seems to arise from overlap in shared frequencies at wavelengths longer than ~ 50 years (c.f. Fig. 3). Interestingly, we find that the paleoclimatic evidence and the CMIP5/PMIP3 models portray a considerably different response of hydroclimate in Scandinavia to long-term temperature changes. While the proxy time series suggests that prolonged wet periods generally coincide with elevated temperatures, the majority of the CMIP5/PMIP3 models indicate that warm decades should have been dryer (Fig. 8b – h and Fig. S9).

Instrumental and paleoclimate evidence collectively suggest a time-dependent shift of the relationship between regional temperature and hydroclimate, which in turn implies that different mechanisms governing the climate system might be operating at high (interannual) and low (decadal/longer) frequencies, respectively. The previously discussed strong link between inter-annual regional hydroclimate variability and atmospheric pressure patterns indicates that atmospheric dynamics is likely a dominant driver of hydroclimate in the northern European sector on interannual basis. The inverse covariability between warm-season temperature and moisture supply, which is revealed by the instrumental record, may arise from synoptic-scale correspondence between reduced cloud cover/rainfall and increased incoming shortwave radiation warming the surface during clear sky conditions. In addition, soil moisture exert a strong influence on the allocation of available energy between latent and sensible heating, especially in the warm-season (Seneviratne et al., 2010). Reduced soil moisture, for example, is associated with reduced latent heat flux and thus increased sensible heating and higher air temperatures near the surface. Resulting positive feedbacks of a modified surface heat flux partitioning on cloud cover and radiation (Gentine et al., 2013) and

large-scale circulation (Haarsma et al., 2009) could further strengthen the influence of rainfall variability on the thermal climate.

The positive association between temperature and SPEI that is found in the proxy records on decadal-to-multidecadal timescales could imply that the long-term regional hydroclimate variability is more sensitive to changes in moisture supply (precipitation) rather than to increased evaporative demand due to warming. It may also suggests that the regional moisture balance might be favored by the Clausius-Clapeyron relation (Allen and Ingram, 2002), prescribing an increase in rainfall and intensity of the hydrological cycle during warmer periods in the past millennium. This is generally referred to as 'wet-get-wetter'/'dry-get-dryer' mechanism and is attributed to thermodynamics processes (Held and Soden, 2006). In the absence of changes in atmospheric circulation, changes in net moisture supply with warming are related to change in moisture content of the atmosphere. It presupposes that existing circulations will transport more moisture into mesic regions of the globe (e.g., tropics and the mid- to latitudes of Northern Hemisphere), whilst dry regions (e.g., subtropics) will get even dryer, with the fractional change determined by Clausius-Clapeyron relation. In contrast to the proxy records, the model composite average reveals a twentieth-century temperature and rainfall increase yet little change in hydroclimate (Fig. 7b). The multimodel assessment implies that natural variability plays only a subsidiary role in recent changes and that forcing from anthropogenic greenhouse gases (GHG) may have played a more important role (as previously discussed, the effect of GHG-forcing on interannual teleconnection patterns in the modern era seems to be weak). Moreover, the absences of any significant trend in simulated SPEI series indicates that the gains in moisture from increased precipitation are large enough to compensate for any GHG-induced increase in PET in the post-industrial period.

6. Summary and discussion

This study presents the first comprehensive assessment of past variability and trends in hydroclimate of northern European sector over the last millennium of the Common Era along with interrelated variables: precipitation, which supplies moisture, and temperature, which modulates evapotranspiration. A combined approach comparing observational (both instrumental and proxy based) and model-based results is used for evaluation of simulated and real-world interannual-to-centennial climate variability and the underlying physics governing the climate system. A number of important finding emerge from the collective comparison:

[1] Models and proxy data are found to broadly agree on the modes of atmospheric variability (sect. 5) that produces droughts and pluvials in Scandinavia. Despite these dynamical similarities, large discrepancies between model simulations and the proxy reconstruction are shown to exist. The droughts and pluvials in the forced simulation are not temporally synchronous with those in the proxy record, nor do the GCM spectra agree with the proxy spectra on the amount of variance present on short and long timescales (sect. 3).

[2] The proxy data and the CMIP5/PMIP3 models reveal different effects of long-term temperature changes on summer hydroclimate in Scandinavia. According to the GCMs, prolonged droughts generally coincide with elevated temperatures. The proxy evidence, on the other hand, suggests that warm decades in the last millennium also tend to be wet decades. Although the precise reason for the model-proxy mismatch remains to be unraveled, our results suggests that spectral inconsistencies among the model and proxy datasets could be one possible explanation for the mismatch.

[3] There are considerable disagreements among hydroclimate features shown by the CMIP5/PMIP3 simulations (despite the use of largely similar forcing series) (sect. 3). Together, these results point to the possibilities of dominant influence of stochastic processes for the regional hydroclimate and/or deficiencies in the models to realistically represent relevant processes in reality.

Most notably we find clear inconsistencies between the paleoclimate record and the model spectra. At multidecadal/longer timescale there is more variability in the proxy data than in the models. In contrast, the dominance of GCM simulated interannual components of variability is not reflected in the proxy record. It is difficult to determine explicitly whether it is an external forcing or internal sources that drive the decadal and longer variance in the proxy reconstruction. Prior studies have highlighted the importance of external influences on regional climate variability at different timescales (e.g., Gleckler et al., 2006; Thiéblemont et al., 2015; Sigl et al., 2015). Although we find a short term response of regional hydroclimate to volcanic perturbations (sect. 4), multi-year anomalies in the proxy reconstruction do, however, not appear to correspond well with the epochs following the large volcanic eruptions (e.g., in the 1250s, 1450s and 1810s) used to force the models. Thus we cannot rule out that the variability in the reconstruction largely arise from internal sources of variation. Consequently, if the proxy-inferred decadal-to-multidecadal variability is accurate and if the variability is indeed largely unforced, then its magnitude is well beyond what any of the current generation global climate models are able to produce in the region. Underestimation of redness in the models on multidecadal/longer timescales, suggests the GCMs might be

lacking/underestimating processes important to the variability at these timescales. There are a number of recognized limitations relating to the dynamics that are relevant to the climatology of the North Atlantic-European sectors. One such example is that models have generally been unable to simulate low-frequency variability in the North Atlantic Oscillation (Osborn, 2004). They have also been shown to underestimate the periodicity of the Atlantic Multidecadal Oscillation (Kavvada et al., 2013), which has implications for the associated hydroclimate impact on neighboring continents (Coats et al., 2015). If, on the other hand, the proxy estimated multidecadal/longer variability in the last millennium is forced by exogenous mechanisms, then either 1) it is a forcing component that is largely missing in the CMIP5/PMIP3 models, alternatively, 2) it is a forcing component that generates a different long-term response in the models compared to the "proxy view" of regional hydroclimatology.

It is not possible to pinpoint which part of the disagreement between models and the proxy comes from uncertainties in the tree-ring reconstruction, deficiencies in the forcing series used to drive the models, or from deficiencies in the model. Our analyses have included precipitation simulation – a challenging variable for GCMs to simulate accurately. The coarse spatial resolution of the models gives only an approximate representation of the topographic features, which are important for regional hydroclimate. Another possibility is that the scale of the GCMs is unrepresentative of the point estimate provided by the ScandH17 reconstruction. On the other hand, the mismatch between grid box and point estimates is expected to reduce at longer timescales (Jones et al., 1997). There are also limitations of the tree-ring proxy and uncertainties in the interpretation of the data that cannot be ignored. Tree-rings and other biological archives may integrate climate conditions over multiple years (Zhang et al., 2015), which could potentially overestimating the ratio of low to high frequency variability (Franke et al., 2013). While we have been able to establish that prevailing summer moisture availability has been the main growth limitation of trees in the ScandH17 network on an interannual basis over the twentieth century (Figs. S3 and S6), we cannot verify the drought-tree growth model in the pre-instrumental era or across longer spectrum of variability. We are not able to rule out that there might have been climatic regimes in the past that would have caused dynamical shift in the tree growth response to climate, and potentially have called into question the uniformitarian paradigm traditionally applied in the field of dendroclimatology. These non-stationaries may include frequency dependent sensitivity of the proxy system to climate. While we are able to show that the year-to-year variability of growth is dominated by a moisture signal, the impact of growing season temperature on lower

frequency variations has yet to be established. In addition to these issues, there are also risks that less well know dynamics outside the climate system may introduce variability into the records at decadal/longer timescales. Advances in the mechanistic understanding of the various proxies and the processes through which they record environmental change, e.g., through development and refinement of process-based forward models (Tolwinski-Ward et al., 2011), is currently an emerging priority in the field.

The discrepancies in CMIP5/PMIP3 simulated and proxy reconstructed hydroclimate variability in the last millennium is an issue that must be addressed when assessing projections of future hydroclimate change. The lack of adequate understanding for mechanisms linking temperature and moisture supply on longer timescales has important implication for future projections. Weak multidecadal variability in models also implies that inference about future persistent droughts and pluvials based on the latest generation global climate models will likely underestimate the true risk of these events. Reconciliations for the apparent proxy – model mismatch will require efforts from the proxy, modeling and statistics groups, including additional proxy records and refined model simulations of hydroclimate variability in the last millennium, together with the development of alternative approaches for joint proxy-model assessments. Having here provided a first comparison of reconstructed and simulated hydroclimate for Scandinavia, our future efforts will include adaptions of the data assimilation approach to paleoclimate reconstruction. Such efforts hold promise for reducing the uncertainties associated with model physics, external forcings, and internal climate variability, and ultimately help to refine our view of past and future hydroclimate changes.

Data availability

The raw tree-ring data can be downloaded from the International Tree-Ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html) and the SAIMA Tree-Ring Data Bank (http://lustiag.pp.fi/Saima/dendrotieto.htm) (Table II). The CMIP5/PMIP3 climate model output can be obtained though the Earth System Grid - Center for Enabling Technologies (ESG-CET) portal (http://pcmdi9.llnl.gov/). The ScandT14 temperature reconstruction is archived through the NOAA paleoclimate database (citation added on publication). The ScandH17 reconstruction and standardized tree-ring chronologies are provided in the supporting information.

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Tables and figures

Table I. CMIP5/PMIP3 model description.

Model Name	**Resolution [Atmosphere]**	**Resolution [Ocean]**	**Reference**
CCSM4	192 x 288	384 x 320	Landrum et al. (2012)
CESM1	96 x 144	384 x 320	Lehner et al. (2015)
IPSL-CM5A-LR	96 x 96	149 x 182	Dufresne et al. (2013)
MIROC-ESM	64 x 128	192 x 256	Watanabe et al. (2011)
MPI-ESM-P	96 x 192	220 x 256	Jungclaus et al. (2014)
BCC-CSM1-1	64 x 128	232 x 360	Wu et al. (2014)

1186 **Table II:** Tree-ring network description.

Site	Coord.	Time coverage	Standardization method	MSL[3]	Source
Eastern Finland	61.87N, 28.90E	535 -2002 CE	RCS[1]	147 yrs	Helama et al. (2009) Online resource: http://lustiag.pp.fi/Saima/dendrotieto.htm Date access: January 2013
Gotland Sweden	57.49N, 18.41E	1127-2011 CE	RCS	130 yrs	Investigator: Schweingruber, F.H. Online resource: https://www.ncdc.noaa.gov/paleo/study/4427 Date access: January 2013 Updated in Seftigen et al. (2015)
Jondalen Norway	59.71N, 9.53E	1185 -2011 CE	RCS	165 yrs	Investigator: Briffa, K. Online resource: https://www.ncdc.noaa.gov/paleo/study/2826 Date access: January 2013 Updated in Seftigen et al. (2015)
Baljåsen Sweden	59.04N, 12.27E	1686-2002 CE	SF2[2]	174 yrs	Seftigen et al. (2015)
Björbo Sweden	60.27N, 14.44E	1450-2011 CE	SF	177 yrs	Investigator: Axelson, T. Online resource: https://www.ncdc.noaa.gov/paleo/study/2667 Date access: January 2013
Ekhultebergen Sweden	57.45N, 13.50E	1705-2008 CE	SF1	215 yrs	Seftigen et al. (2015)
Fårhagsberget Sweden	58.08N, 16.14E	1621-2011 CE	SF1	262 yrs	Seftigen et al. (2015)
Helvetets håla Sweden	57.14N, 16.14E	1691-2011 CE	SF1	255 yrs	Seftigen et al. (2015)
Halle-Vagnaren Sweden	57.17N, 15.17E	1718-2009 CE	SF3	186 yrs	Seftigen et al. (2015)
Hornslandet Sweden	59.01N, 11.08E	1590-2011 CE	SF1	270 yrs	Seftigen et al. (2015)
Korphålorna Sweden	61.43N, 17.00E	1790-2011 CE	SF1	199 yrs	Seftigen et al. (2015)
Myrkaby Sweden	57.45N, 15.23E	1669-2011 CE	SF2	294 yrs	Seftigen et al. (2015)
Nämndö Sweden	59.52N, 16.56E	1582-1995 CE	SF1	123 yrs	Investigator: Larsson, L. Online resource: https://www.ncdc.noaa.gov/paleo/study/3869 Date access: January 2013
Valekleven-Ombo Sweden	59.11N, 18.41E	1578-2011 CE	SF1	225 yrs	Seftigen et al. (2015)
Putbergen Sweden	58.37N, 14.32E	1734-2008 CE	SF1	188 yrs	Seftigen et al. (2015)
Salboknös Sweden	59.11N, 16.55E	1486-2011 CE	SF2	357 yrs	Seftigen et al. (2015)
Särö Sweden	61.92N, 11.93E	1712-2002 CE	SF3	176 yrs	Seftigen et al. (2015)
Sisshammer Sweden	59.46N, 14.54E	1661-2003 CE	SF	74 yrs	Investigator: Andreason, T. Online resource: https://www.ncdc.noaa.gov/paleo/study/2663 Date access: January 2013
Skärmarbodabergen Sweden	57.51N, 11.93E	1600-2002 CE	SF3	160 yrs	Seftigen et al. (2015)
Skitåsen Sweden	59.09N, 18.02E	1672-2011 CE	SF2	285 yrs	Seftigen et al. (2015)
Skuleskogen Sweden	59.26N, 15.07E	1448-2011 CE	SF	181 yrs	Seftigen et al. (2015)
Sörknatten Sweden	59.22N, 15.29E	1762-2009 CE	SF3	197 yrs	Seftigen et al. (2015)
Tjurhults mosse Sweden	63.06N, 18.29E	1655-2011 CE	SF2	268 yrs	Seftigen et al. (2015)
Tjusthult Sweden	58.55N, 12.27E	1681-2011 CE	SF1	221 yrs	Seftigen et al. (2015)
Tyresta Sweden	59.52N, 14.71E	1609-2010 CE	SF1	198 yrs	Linderholm and Molin (2005) Updated in Seftigen et al. (2015)

1187 [1] RCS: Regional Curve Standardization;

1188 [2] SF: Signal-Free Standardization. The number after the abbreviation indicates the PCA cluster number (Fig. S2);

1189 [3]MSL: Mean Segment Length.

Table III. Event years used in the Superposed Epoch Analysis (Fig. 4). The event lists are composed of the 20 strongest eruptions from each record.

Source	**Event years (CE)**
Gao et al. (2008) (sulfate aerosol > 15 Tg)	1167, 1176, 1195, 1227, 1258, 1284, 1328, 1452, 1459, 1584, 1600, 1641, 1719, 1783, 1809, 1815, 1831, 1835, 1991
Crowley and Unterman (2013) (AOD > 0.13)	1229, 1258, 1259, 1286, 1287, 1456, 1457, 1600, 1601, 1641, 1695, 1696, 1809, 1810, 1815, 1816, 1817, 1884, 1992
Sigl et al. (2015) (global forcing < 5.86 W/m^2)	1108, 1171, 1191, 1230, 1258, 1276, 1286, 1345, 1453, 1458, 1601, 1641, 1695, 1783, 1809, 1815, 1832, 1836, 1992

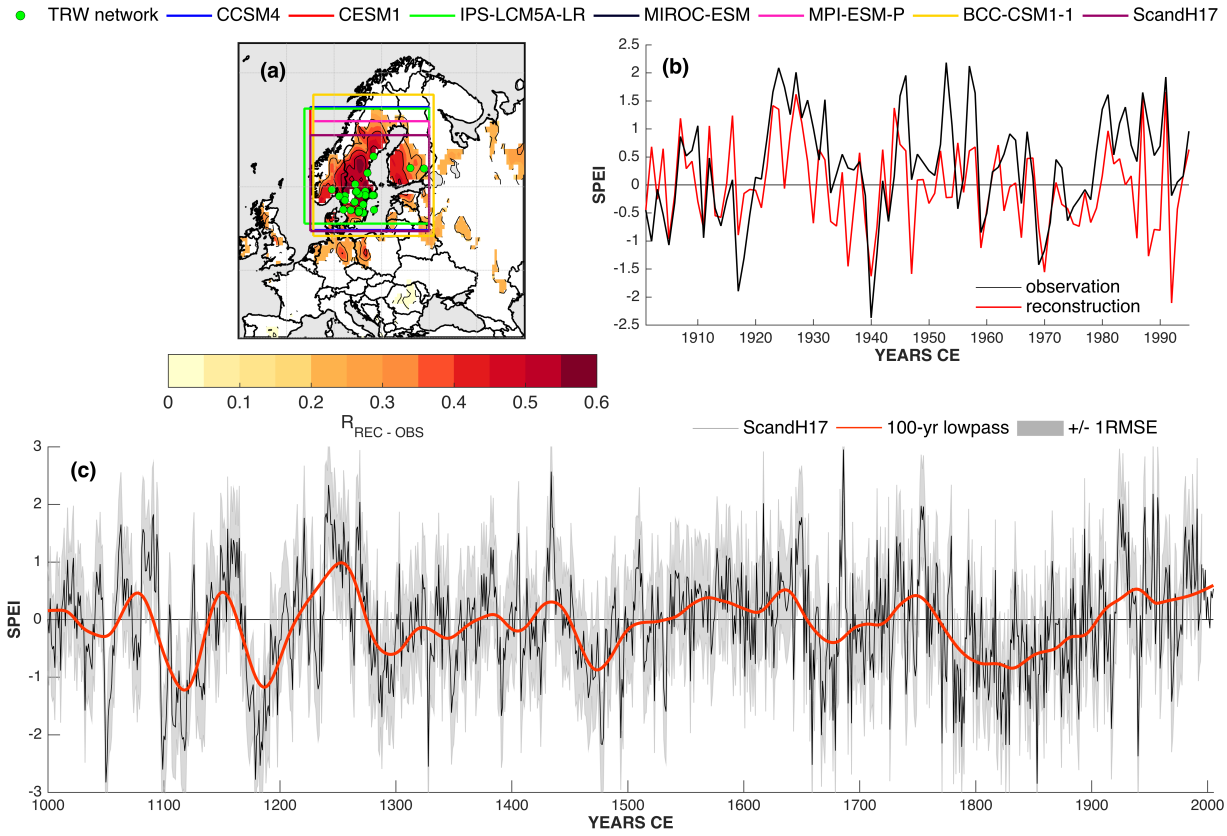

Figure 1: Average regional warm-season SPEI time series reconstructed from tree-rings. (a) Location of the tree-ring network used for regional reconstruction and the extent of the CMIP5/PMIP3 model precipitation and temperature grids used to derive regional SPEI estimates. Shaded contours display the correlation ($p < 0.1$) between the tree-ring reconstruction and fields of instrumental SPEI data over the 1901-1995 period; (b) average regional reconstructed and instrumental 20th century 2-month June SPEI; (c) average regional SPEI nested reconstruction, with the +/- 1RMSE of the regression equations outlined in grey shading. A smoothed version of the reconstruction using a 100-year loess smooth is shown in red. Reconstruction assessment metrics are provided in supplementary materials (Fig. S4).

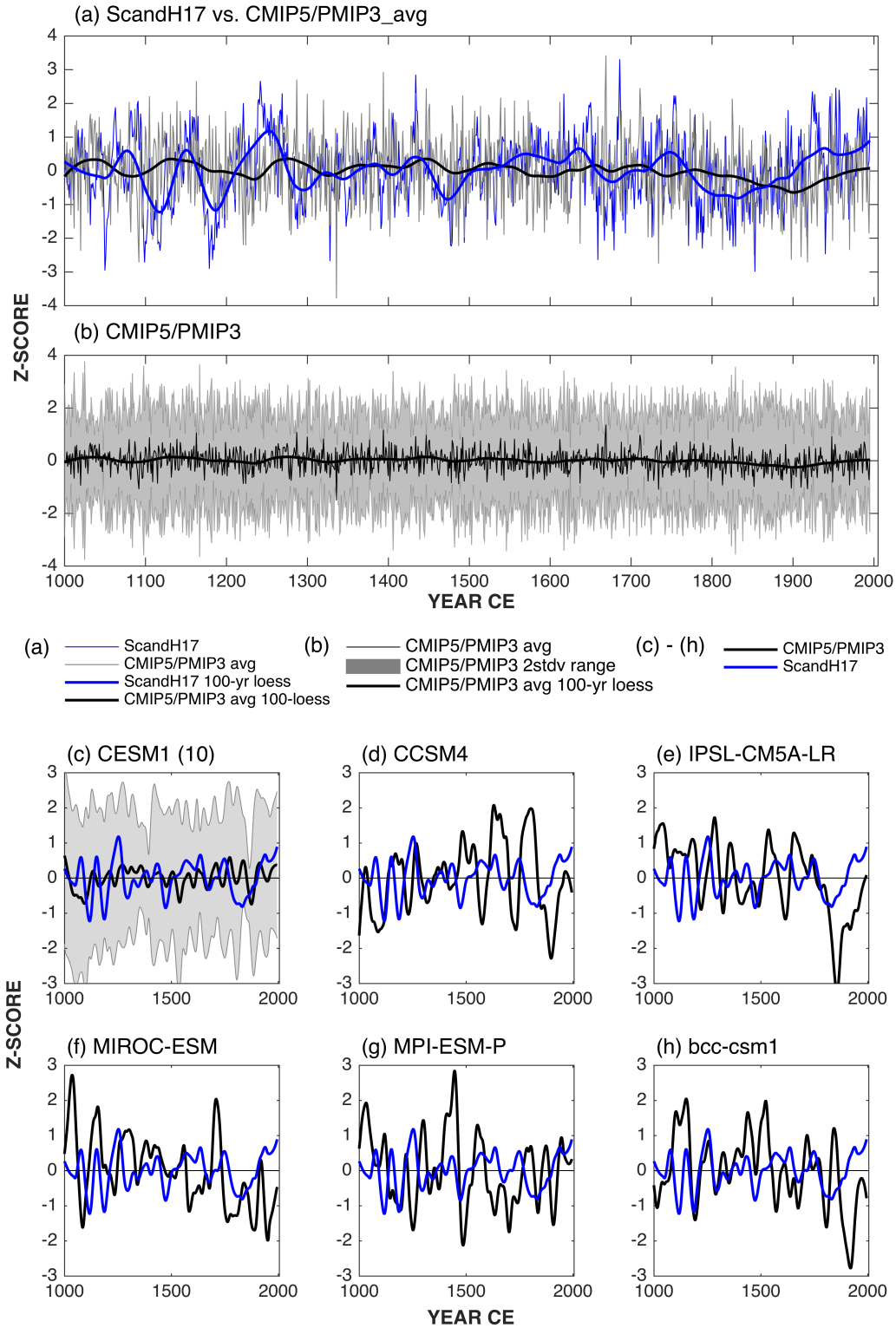

Figure 2: Comparison of reconstructed SPEI with forced model runs. (a) The reconstruction versus the mean of the six CMIP5/PMIP3 models transformed into standard normal deviates (z-scores) over the 1000-1995 CE period and smoothed with 100-year loess filter; (b) multimodel mean and the two standard deviation range (shading) of the six GCMs; (c) mean and two standard deviation (shading) of CESM1 ten smoothed and z-scored ensemble members (blue) together; (d) – (h) the

reconstruction (blue) versus individual model runs (black). All time series have been smoothed with 100-year loess filter and then z-scored over the 1000-1995 CE period.

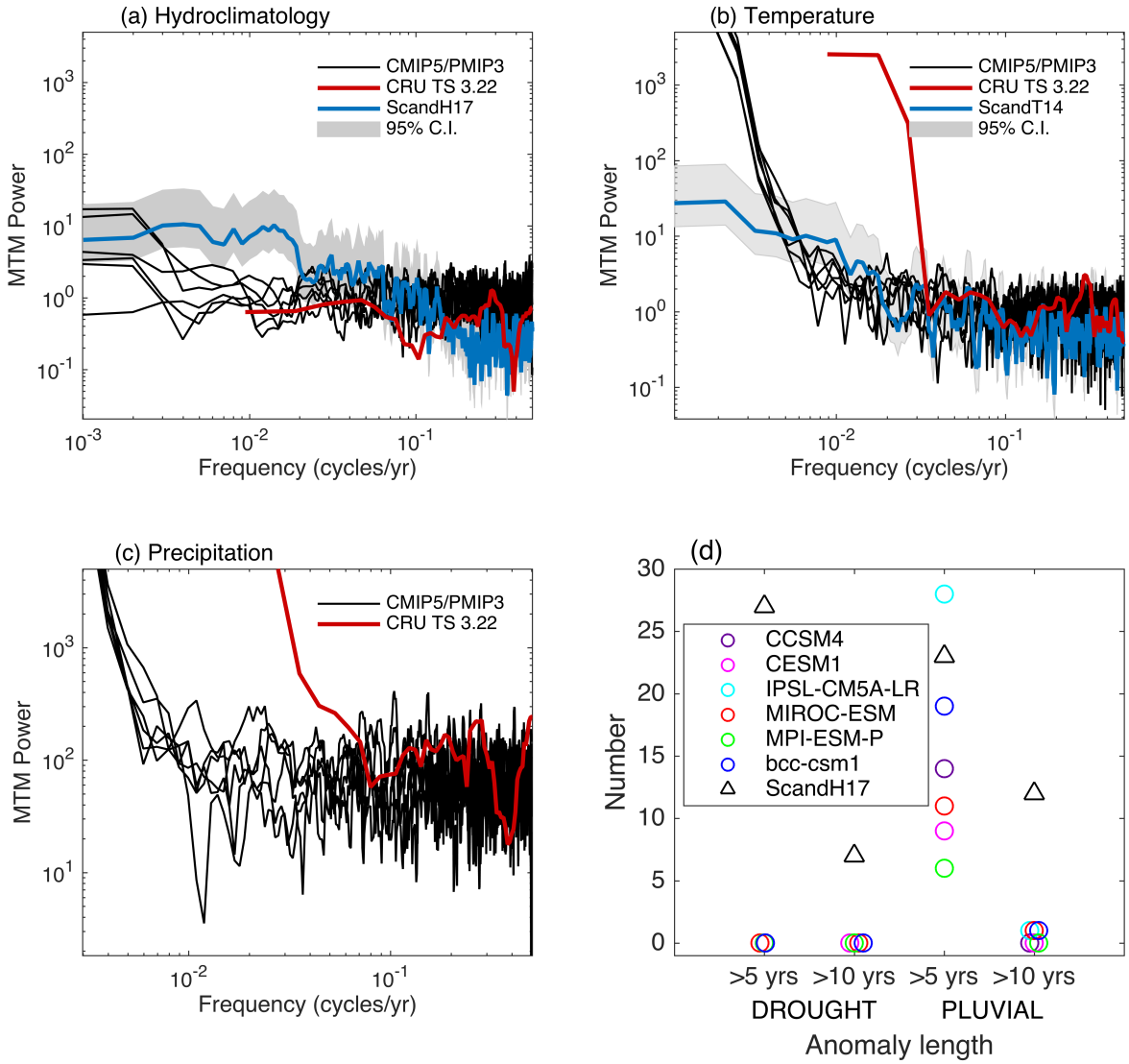

Figure 3: Spectral properties (multi-taper approach, 4 tapers) of (a) SPEI, (b) temperature and (c) precipitation over the common 1100-1995 period. For SPEI and temperature, the spectral properties of individual GCMs (r1i1p1 ensemble) are compared to those of the tree-ring ScandH17 and ScandT14 reconstructions and regionally averaged instrumental CRU TS 3.22 data. Shaded areas show the 95% confidence interval of the reconstruction spectra. (d) The number of droughts and pluvials in the reconstructed and simulated time series that are > 5 and >10 years in duration. Spectral properties of the individual models are provided in Fig. S7.

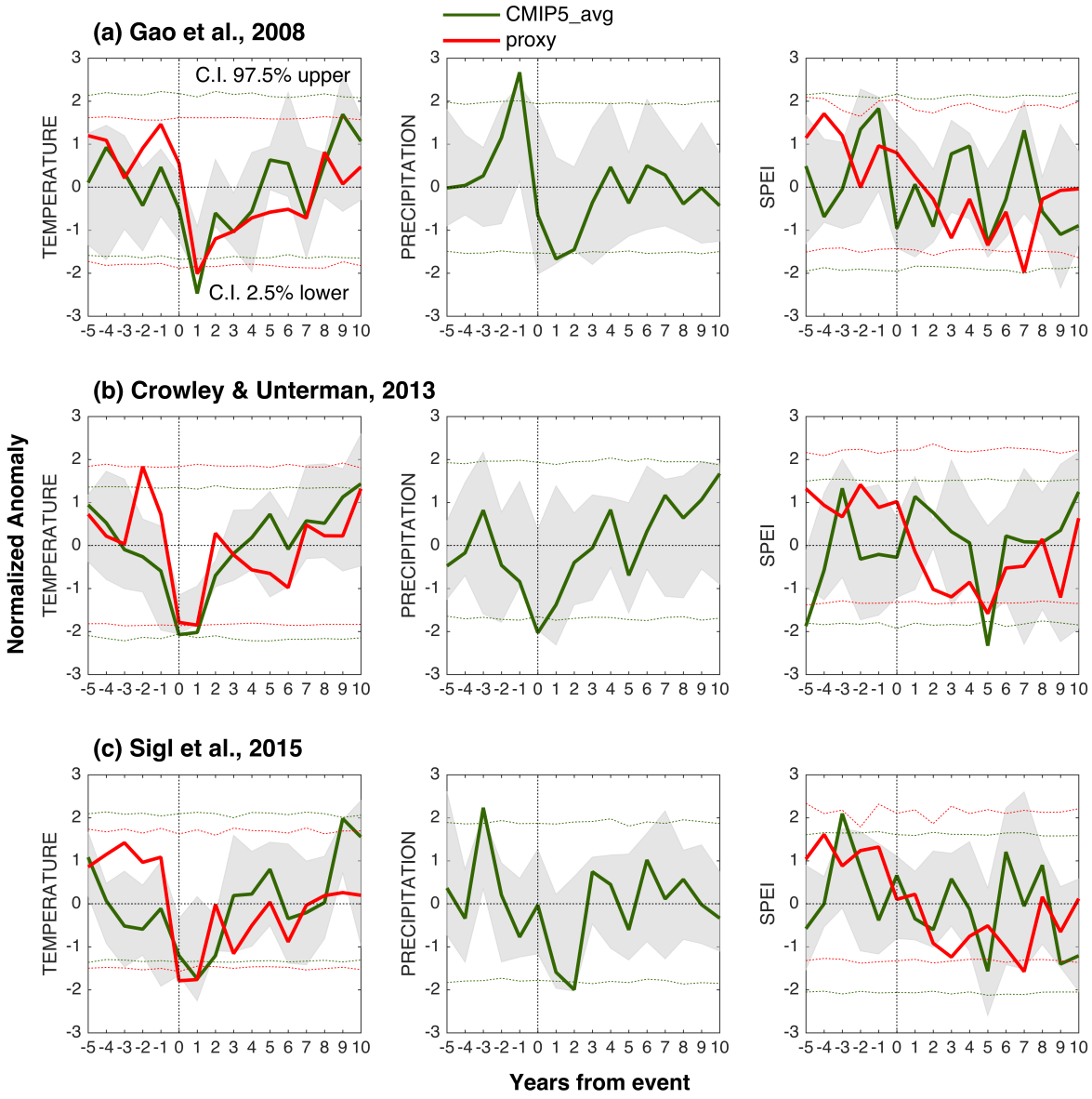

Figure 4: Modeled and reconstructed hydroclimate response to eruptions. Superposed epoch analysis using the 20 largest eruption years from the (a) Gao et al. (2008), (b) Crowley and Unterman (2013), and (c) Sigl et al. (2015). Table III lists the event years used in the analysis. Grey shading indicate the range of modeled hydroclimate response from the six GCMs. Confidence intervals (C.I.) are derived from bootstrap resampling (N = 10 000).

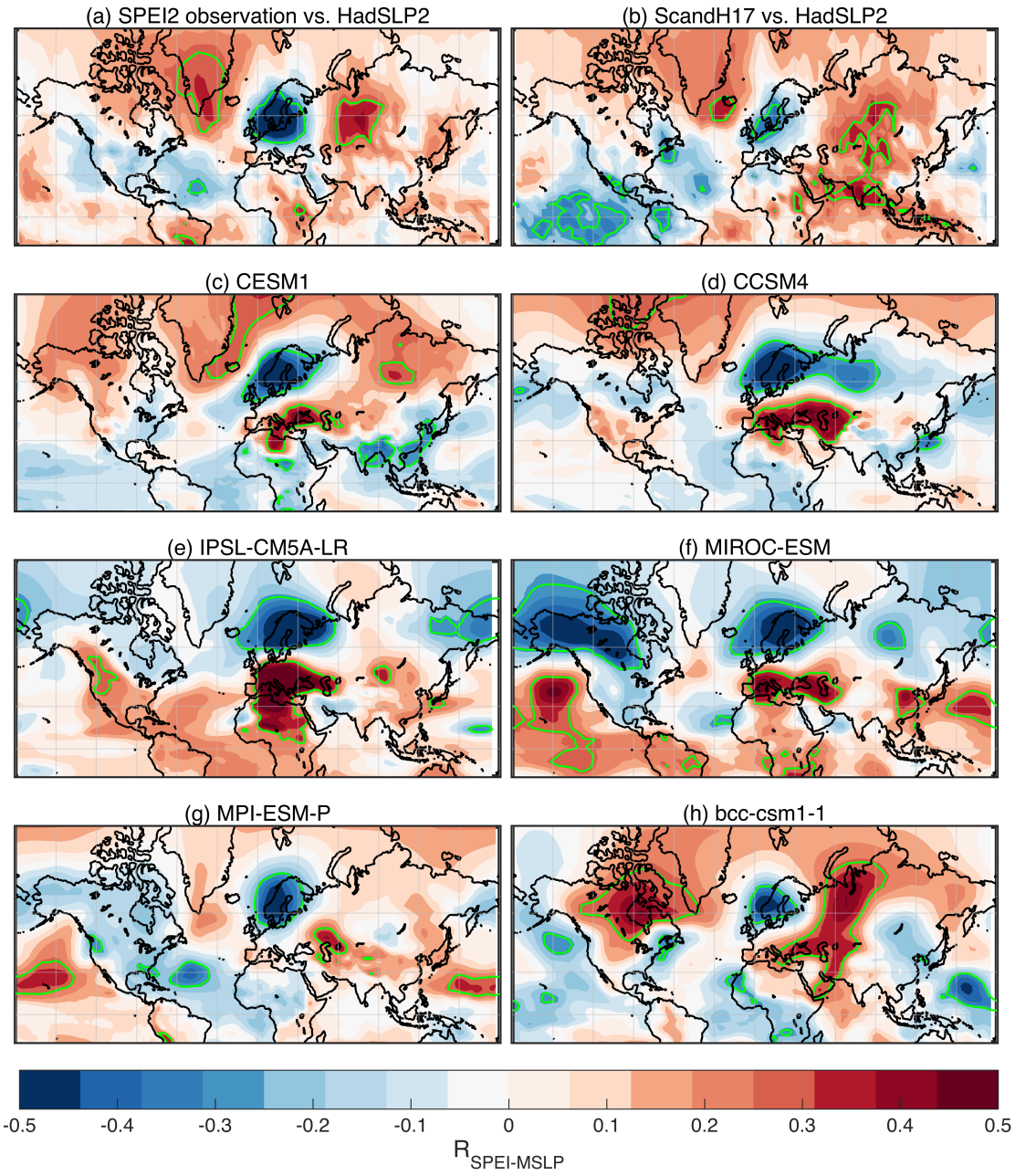

Figure 5: Spatial distribution of correlation coefficient of northern European warm season hydroclimate and mean sea level pressure (MSLP). Association between regional drought index and sea level pressure over the 1950-1995 period. (a) observational, (b) ScandH17, (c)-(g) model based results (including r1i1p1 ensemble only). Regions with significant ($p < 0.05$) correlations are outlined in green contours.

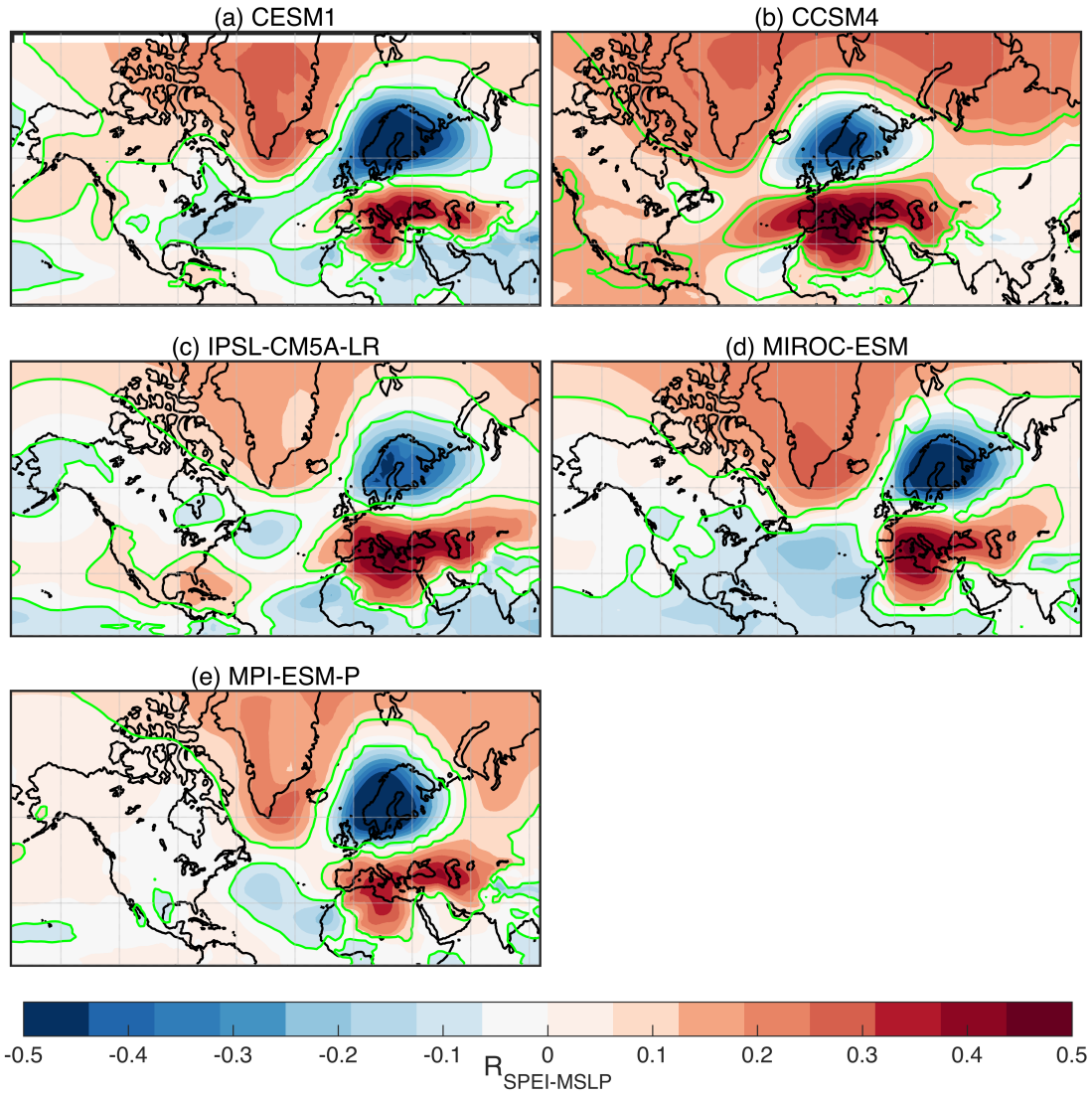

Figure 6: Spatial distribution of correlation coefficient of northern European warm season hydroclimate and mean sea level pressure (MSLP). Same as Fig. 5, but for the 850-1849 CE period.

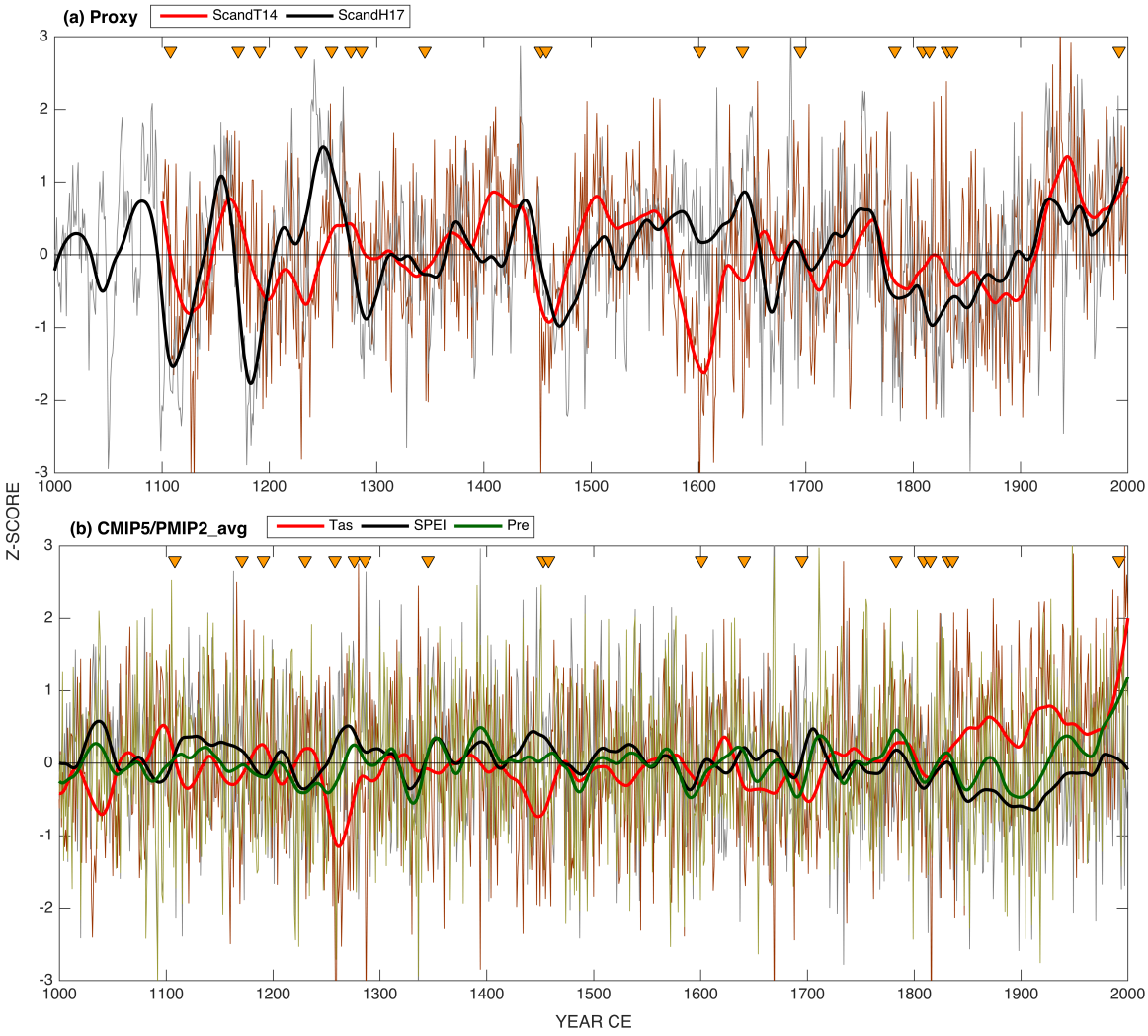

Figure 7: Time series of (a) ScandH17 and ScandT14, and (b) GCM (r1i1p1 ensemble) average temperature, precipitation and SPEI. Smoothed time-series using a 50-year loess filter are shown as thick lines. Individual model data are provided in supplementary material (Fig. S8). The years with volcanic eruptions from Table III are indicated by triangle glyphs.

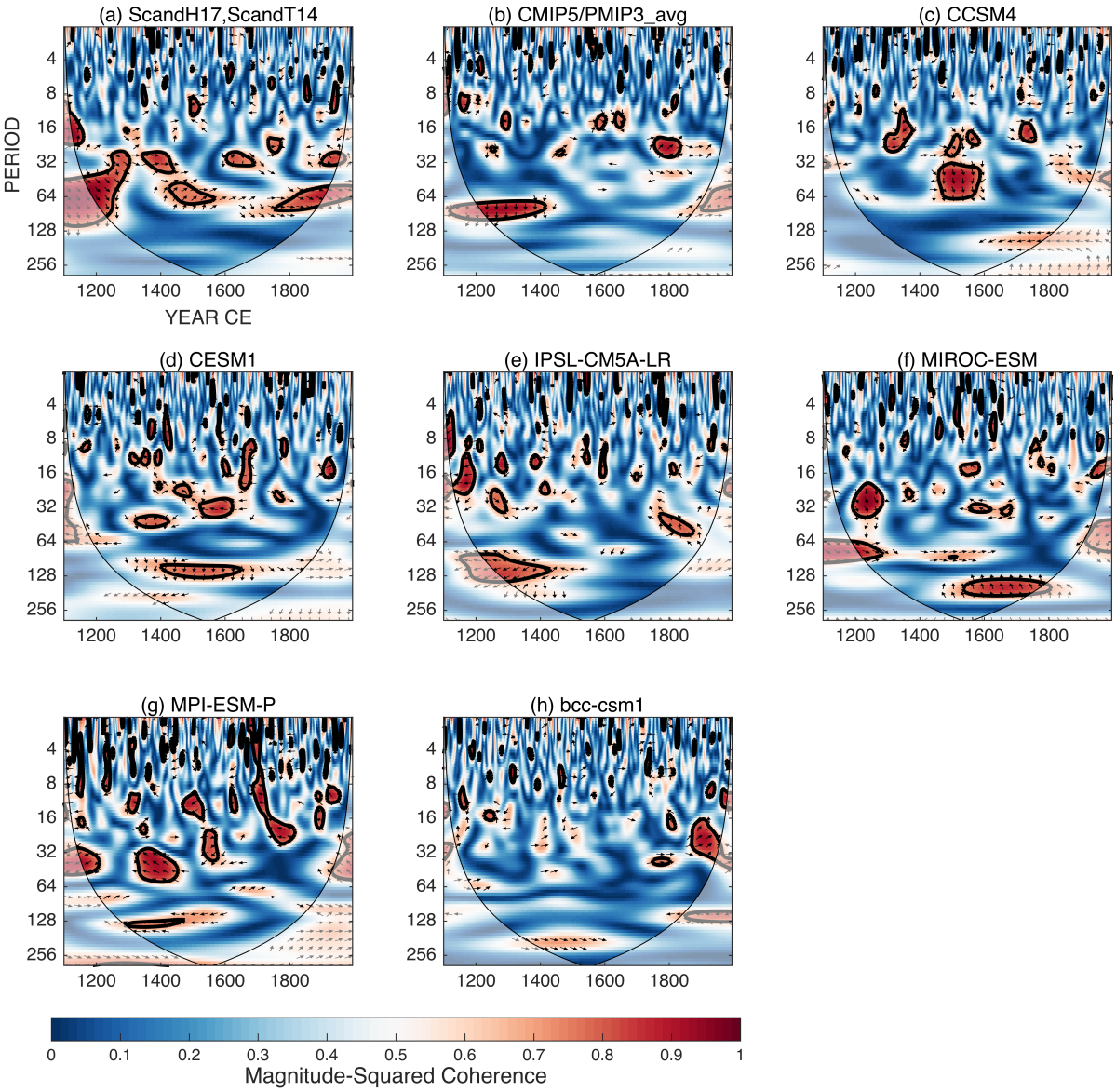

Figure 8: Squared wavelet coherence and phase between (a) ScandH17 and ScandT14, and (b) – (h) CMIP5/PMIP3 simulations of temperature and rainfall. The arrows indicate the relative phase relationship between two series; right (left) pointing arrow indicates in-phase (180 degrees out of phase) relationship. Significant coherence at 95% significance level is shown as thick contour.