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Cloud cover feedback moderates Fennoscandian summer temperature changes over the past 1000 years

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Key Points:

- Over recent decades, Northern Fennoscandian summer temperatures have increased little, compared to those of the Northern Hemisphere.
- Cloud cover plays an important role in controlling temperature. Summers with more cloud cover are cooler and those with less are warmer.
- During hemispheric warm periods, northern cloud cover increases, cooling regional temperature, the opposite is true during cool periods.

Abstract

Northern Fennoscandia has experienced little summer warming over recent decades, in stark contrast to the hemispheric trend, which is strongly linked to greenhouse gas emissions. A likely explanation is the feedback between cloud cover and temperature. We establish the long- and short-term relationship between summer cloud cover and temperature over Northern Fennoscandia, by analysing meteorological and proxy climate data. We identify opposing feedbacks operating at different timescales. At short timescales, dominated by internal variability, the cloud cover-temperature feedback is negative; summers with increased cloud cover are cooler and sunny summers are warmer. However, over longer timescales, at which forced climate changes operate, this feedback is positive, rising temperatures causing increased regional cloud cover and *vice versa*. This has occurred both during warm (Medieval Climate Anomaly and at present) and cool (Little Ice Age) periods. This two-way feedback relationship therefore moderates Northern Fennoscandian temperatures during both warm and cool hemispheric periods.

Plain Language Summary

Temperatures have increased globally over recent decades, strongly linked to increases in greenhouse gasses. However, over Northern Fennoscandia summer temperatures have increased little over this period, although this region should be strongly affected by global warming. We suggest that changes in summer cloud cover, driven by global temperature changes, are responsible for this moderation of temperatures. This is happening now, and during past episodes of climate change. We produce a new reconstruction of summer cloud cover for this region and compare it to existing temperature reconstruction to establish the relationship between temperature and cloud cover. We find that over short timescales, increased cloud cover leads to cooler temperatures and *vice versa*. However, over longer timescales (decades to centuries) we find that increased global temperature lead to increased northern cloud cover, which reduces local temperatures (the medieval period and at present). The opposite being true in globally cool periods, such as the Little Ice Age. These finding are important as they help to explain the feedback relationship between cloud cover and temperature, which is one of the major uncertainties in modelling future climate. Our data also confirm models of climate that suggest a poleward movement of storm tracks during recent warming.

1 Introduction

Recent increases in global temperatures have been linked to the anthropogenic release of long-lived greenhouse gases (IPCC, 2013). As these gases are well-mixed in the atmosphere, they have a direct influence on the world-wide energy balance. However, at regional scales, feedbacks operate amplifying or moderating temperature responses to global forcing, leading to regionally enhanced or dampened changes. At high latitudes feedbacks tend to amplify the magnitude of temperature response, and model projections suggest enhanced temperature increases over regions such as Fennoscandia (IPCC, 2013). However, the instrumental records show that since AD1859, summer (June-August) temperatures over northern Fennoscandia have increased little, when compared to Northern Hemisphere trends (Osborn & Jones, 2014). A possible explanation for the weaker regional response to hemispheric and global-scale forced warming is the feedback relationship between temperature and cloud cover.

At present cloud cover, and especially low cloud cover, represents the single greatest uncertainty in modelling future climate (Bony et al., 2006; Boucher et al., 2013). Both climate models and observations suggest that with global warming there may be a poleward migration of the storm tracks leading to higher levels of cloud cover in high-latitude regions such as Northern Fennoscandia (Bender et al., 2012; Boucher et al., 2013; Norris et al., 2016). Clouds have an important and complex feedback relationship with surface temperature (Boucher et al., 2013). There is a negative feedback, reflecting shortwave radiation back into space, and a positive feedback, retaining longwave radiation close to Earth's surface (Hartmann et al., 1992). Resolving the feedback relationships between temperature and cloud cover is critical to understanding past and future climatic change (Boucher et al., 2013)

Over short timescales, it is possible to define the feedback relationship using ground and satellite data. Defining the relationship between temperature and cloud cover over the longer timescales, at which both naturally and anthropogenically forced changes occur, is much more problematic and requires reliable data for both variables. There is a strong history of reconstructing annual summer temperature over Northern Fennoscandia (e.g. Esper et al., 2012; McCarroll et al., 2013) and the Northern Hemisphere (e.g. D'Arrrigo et al., 2006; Moberg et al., 2005; Shi et al., 2013;

Christiansen & Ljungqvist, 2012), and a number of robust millennial length reconstructions are available.

It has become possible to produce reliable reconstructions of regional cloud cover, using stable carbon isotopes ($\delta^{13}C$) from tree rings (Gagen et al., 2011a; Young et al., 2010; Helama et al., 2018). The method works well using high latitude conifers, where carbon isotope fractionation is dominated by photosynthetic rate rather than stomatal conductance, and therefore is mainly controlled by photosynthetically active radiation (PAR) and linked strongly to the amount of summer sunshine, and thus cloud cover. The relationship with cloud cover is therefore not direct and is complicated by factors such as diffuse radiation being more effective for plant photosynthesis. However, when a single, well replicated, measure of tree-ring $\delta^{13}C$ is compared average summer sunshine or cloud cover, the relationship is strong and consistent through time (Young et al., 2012; Loader et al., 2013). This methodological advance allows us to examine the relationship between summer temperature and cloud cover over Northern Fennoscandia over the last 1000 years. We combined millennial length, well replicated, $\delta^{13}C$ series from three locations across northern Fennoscandia: Forfjord, Norway (Young et al., 2010; 2012); Torneträsk, Sweden (Loader et al., 2013); and Laanila, Finland (Gagen et al., 2011a) (Figure S1), to produce a new reconstruction of regional cloud cover. We use this new cloud cover reconstruction in conjunction with regional temperature reconstructions and meteorological data for both cloud cover and temperature to understand the complex and important relationship between cloud cover and temperature over a millennial timescale.

2 Methods

2.1 Data

To determine the relationship between cloud cover and temperature over both long and short timescales, we used both meteorological and proxy climate data.

2.1.1 Meteorological Data

2.1.1.1 Cloud Cover

Records of cloud cover for Northern Fennoscandia (c. N 65.0° to 70.0°, E 10.0° to 30.0°) are available from ground and satellite data. A number of ground based series stretch back to the nineteenth century (Tuomenvirta et al., 2001). Records of cloud cover measured by satellite, since AD1983, are available from the International Satellite Cloud Climatology Project (ISCCP) (Schiffer & Rossow, 1983). Ground and satellite cloud cover measurements match well over the period of overlap (Figure S2).

2.1.1.2 Temperature

Long instrumental records are relatively abundant for this region and gridded data products, are also available. We use the gridded data produced by the Climatic Research Unit (CRU), as they clearly represent the grid boxes under analysis. The mean of the four equal area adjacent 5°x5° boxes (centred on N 67.5°, E 12.5°; N 67.5°, E 17.5°; N 67.5°, E 22.5°; N 67.5°, E 27.5°) were used to represent temperature of Northern Fennoscandia (Osborn & Jones, 2014; Jones et al., 2007). We also use temperature records from the same four meteorological stations used to derive our cloud cover composite (Figure S1), to compare directly the signal contained in tree ring $\delta^{13}C$ for temperature and cloud cover. For hemispheric temperature, we also used data produced from the CRU, CRUtemp4v Northern Hemisphere temperatures (Osborn & Jones, 2014).

To compare Northern Fennoscandian temperature to those of the Northern Hemisphere values we scaled Northern Fennoscandian to those for the Northern Hemisphere over the period AD1859-1980. Recent temperature increase was calculated by showing mean temperatures since AD1981 as the difference from the AD1859–1980 mean.

2.1.2 Proxy Data

2.1.2.1 Isotopes

$\delta^{13}C$ measured from cellulose extracted from *Pinus sylvestris* L. tree rings, were used as a proxy for summer cloud cover. Data from three locations (Forfjord, Torneträsk and Laanila (Figure S1)) extending back over the past millennium were used (Young et al., 2010; 2012; Loader et al., 2013; Gagen et al., 2011a).

2.1.2.2 Proxy Temperature Data

Two regional (Esper et al., 2012; McCarroll et al., 2013) and four hemispheric reconstructions (D'Arrrigo et al., 2006; Moberg et al., 2005; Shi et al., 2013; Christiansen & Ljungqvist, 2012) of temperature were used to analyse the long term cloud cover-temperature relationship. To look at periods of divergence between temperature and cloud cover, both series were z-scored over the common period. $\delta^{13}C$ values were then subtracted from the temperature values to indicate positive (cool/clear) and negative values (warm/cloudy) conditions. To compare regional and hemispheric temperature reconstructions, individual series were z-scored over the common period (AD1000–1973) and combined by taking the mean. This mean was then z-scored over the same common period.

2.2 Combining Data

2.2.1 Cloud Cover and Temperature

Meteorological cloud cover and temperature composites (c. N 65.0° to 70.0°, E 10.0° to 30.0°) were produced using data collected at four climate stations (Figure S1). The monthly values were composited by taking the mean of the deviations from the climate normal period AD1961–1990. This method has the dual advantages of, retaining the original units, while allowing the mean of discontinuous data sets to be reliably established (Jones et al., 2012).

2.2.2 Isotopes

To produce a regional tree ring $\delta^{13}C$ chronology for the past millennium, we combined three exiting, published, chronologies from northern Fennnoscandia. These three millennial records of tree-ring $\delta^{13}C$ were produced using slightly differing methodologies (Young et al., 2012; Loader et al., 2013; Gagen et al., 2011a; 2011b). The Forfjord chronology was constructed entirely using annual values from individual trees. Torneträsk was constructed using annual values from individual trees, annually pooled values from multiple trees, and temporally pooled values from individual trees (Loader et al., 2013). Laanila comprises temporally pooled values from individual trees; while a shorter Laanila chronology stretching back to AD1652 (Gagen et al. 2007), comprises annual values from individual trees.

2.2.2.1 Annual Isotope Data

Annual data from the three locations are available for the period AD1652–2002 (Figure S1 and S3), there is a significant match between the three series ($P<0.001$). The series were z-scored and the mean was taken to produce an annual series from AD1652–2002. This mean, over the period AD1890–2002, was used for calibration purposes.

2.2.2.2 Non-Annual Isotope Data

Prior to AD1652 no annualised data are available for the Laanila site, while both the Forfjord and Torneträsk are comprised of annually resolved values. Combining the three isotope series involved four steps. Firstly, the Forfjord and Torneträsk series were degraded to the same temporal resolution as the Laanila series, by treating each series with a 9-year Gaussian filter. Secondly, the annualised series from Forfjord and Torneträsk were subtracted from their respective filtered series and averaged, to create a high frequency data set. Thirdly, a mean was taken of the Laanila and the filtered Forfjord and Torneträsk series to create a low frequency composite. Fourthly, the high frequency series created in step two was added to the low frequency series created in step four, producing a composite series combining low frequency data from Laanila, Forfjord and Torneträsk and the high frequency data from Forfjord and Torneträsk (Figure S4).

2.3 Calibration

Climate calibration was carried out using standard methods for annual proxy data (NRC, 2006). Both the proxy and climate data were divided into two parts (AD2002–1946 and AD1945–1890). Calibration was undertaken over each periods, and then verified using the other period. Three statistics were calculated for each pair of calibrations and verifications: the squared correlation coefficient (R^2); the reduction of error (RE); and the coefficient of efficiency (CE).

2.4 Reconstruction

Reduced major axis regression (RMA), often referred to as variance scaling, was used to reconstruct cloud cover from the $\delta^{13}C$ data. The method scales the proxy to the mean and variability of the climate target over the instrumental period, giving a more realistic reconstruction of climate variability than ordinary least squares (OLS) regression.

2.5 Scaling versus Regression and Extreme Value Capture Tests

A problem with RMA regression is that there is an inevitable increase in error compared to an OLS reconstruction, as the increase in variance inevitably increase the error (McCarroll et al., 2015). If the proxy relationship with climate is not sufficiently strong, the result will be a reconstruction which is scaling noise, rather than signal and the predictive skill of the reconstruction will fall below zero. A simple metric, R^2_{vs} (R^2 variance scaled), was proposed to determine this (McCarroll et al., 2015). When the correlation between proxy and climate falls below r = 0.5, R^2_{vs} will fall below zero, the predictive skill of the reconstruction will be less than that of the mean climatology over the calibration period.

An extreme value capture (EVC) test (McCarroll et al., 2015) is used to establish whether the correct values are being pushed to the extreme by RMA regression. The test determines whether the increase in error, inevitable when scaling, is sufficiently counterbalanced by a more effective expression of the extreme values.

2.6 Uncertainties

A typical approach is to use two standard errors (2SE) of the prediction (c. 95% confidence interval). However, this does not quantify uncertainty relating to changes in sample depth and coherence prior to the instrumental period. Adding a measure of uncertainty based upon series coherence goes some way towards resolving this problem; but if this figure merely added to the 2SE it will tend to exaggerate uncertainty (McCarroll et al., 2013), as the 2SE of the calibration also encompasses an element of this uncertainty. We therefore use the 2SE of the regression equation as a base error throughout the reconstruction, adding to this the 95% confidence interval of the coherence between the three series, in units of cloud cover, where and by the amount it exceeds 2SE (Figure S5).

3 Results

3.1 Meteorological temperature

Data, calculated using regional gridded temperature and hemispheric temperatures (Osborn & Jones, 2014), shows that while mean annual and summer Northern Hemispheric temperatures have increased considerably since records began, the increase of mean annual and especially mean summer Northern Fennoscandia temperature has been very modest. Northern Fennoscandia summer temperature rise since AD1859 is only 14.05% of that of the Northern Hemisphere mean (Figure 1), while the annual increase is less than a third (25.8%).

3.2 Meteorological temperature and cloud cover

Summer monthly mean cloud cover has a strongly negative relationship with summer mean temperature ($r = -0.80$, $P<0.001$), explaining 64% of the variability in summer temperature variability (Figure S6). Therefore, during the summer months (June–August), when skies are clear, summers are warm and when cloud cover increases summers become cooler. When estimated by linear trend there has been an increase of 4.5% in observed summer cloud cover over the twentieth century ($r = 0.2$, $P<0.5$). Temperature over the same period has increased but by only c. 1°C, and since AD1930 — in marked contrast to the hemispheric trend — temperature has not increased at all (linear trend –0.5°C). From the available meteorological, satellite and model simulation data (Bony et al., 2006; Norris et al., 2016), there is also evidence that cloud cover over Fennoscandia may have increased with hemispheric temperature.

3.3 Isotopic cloud cover calibration and reconstruction

The correlation between observed summer cloud cover and the $\delta^{13}C$ composite is strong (r = 0.75, P<0.001), and passes verification tests for climate reconstructions (Table S1 and Figure 2A & B). When temperature data from the same climate sations are used the relationship with $\delta^{13}C$ is still significant (r = 0.58, P<0.001), but considerably weaker and the relationship only passes the RE verification, failing the important CE test (Figure S7). The data $\delta^{13}C$ are therefore much more suitable for a palaeoclimatic reconstruction of past cloud cover variability than temperature. The relationship between cloud cover and our $\delta^{13}C$ composite is considerably higher than the threshold of r = 0.5, established by McCarroll et al. (2015) for RMA (scaling). The scaled data also much more efficient at capturing extreme values (12 out of 24) in the meteorological data, than regression (6 out of 24) (Figure S8). We therefore produced a reconstruction of summer cloud cover over Northern Fennoscandia from AD990-2002 using RMA regression (Figure 2A). The reconstruction shows considerable variability in cloud cover over the past 1000-years with a maximum in AD1017 (+12.98% ±7.43) and a minimum in AD1698 (-19.31% ±9.20). The decade with the highest cloud cover was the AD1490s (+3.35% ±7.43) and the sunniest decade was the AD1750s (-9.30% ±7.88). There were notable extended periods of high cloud cover in the 11^{th} century, the 14^{th} and 15^{th} centuries, and the 20^{th} century. There was a lengthy extended sunny period from AD1550 to AD1800. Our reconstruction also clearly shows that most of the past 1000 years has been sunnier than recent decades. All but one (AD1450) of the 10 sunniest years and calendar decades (AD1291–1300) and all of the sunniest 30-year periods, fall within the prolonged period of reduced cloud cover between c. AD1550 and 1800, which corresponds with the European Little Ice Age.

To analyse the long-term (millennial) relationship between temperature and cloud cover we compared our $\delta^{13}C$ composite with published records of temperature from proxy sources for both Northern Fennoscandia and the Northern Hemisphere. When compared with hemispheric reconstructions, used in the latest IPCC report (D'Arrrigo et al., 2006; Moberg et al., 2005; Shi et al., 2013; Christiansen & Ljungqvist, 2012) our proxy record of cloud cover shows clear periods of divergence (Figures 3 & S9). During three extended periods: AD990–1125, the latter stages of the Medieval Climate Anomaly (MCA); AD1575-1850, Little Ice Age (LIA); and since AD1900, there are large directional changes in Northern Fennoscandian cloud cover, in response to forced hemispheric temperature changes. This palaeoclimatic perspective shows that at multi-decadal and centennial timescales there is an anti-phase between summer temperature and the $\delta^{13}C$ composite, a positive relationship between hemispheric temperatures and Fennoscandian cloud cover. Therefore, the opposite of that observed from meteorological records (Section 3.1).

3.4 Comparison of reconstructed hemispheric and Northern Fennoscandian temperature

We also compared the temperature over Northern Fennoscandia with that of the Northern Hemisphere over the past millennium (Figure S10). This comparison shows that, while reconstructed temperatures trends over the past 1000 years follow a generally similar pattern, with warmer than average temperatures in the medieval period and at present, the magnitude of the changes is muted over Northern Fennoscandia. Indeed, there is little sign of the prolonged cool period between c. AD1525 and AD1850 often referred to as the LIA.

4 Discussion

The feedback relationship between cloud cover and temperature is extremely important over northern Fennoscandia as can be seen in Figure S6. In winter, it is positive, with low-level cloud cover acting to retain heat at the surface. However, during the growing season, the cloud cover-temperature relationship is a strongly negative one. Higher percentages of cloud cover lead to reduced summer temperatures and lower percentages increased temperatures. Cloud cover, therefore, plays an extremely important role in moderating surface temperature over northern Fennoscandia, especially during summer months.

In contrast, palaeocliomatic data clearly show that the long-term relationship between summer temperature and cloud cover is a positive one, in the opposite direction to that which operates over shorter timescales. During hemispheric periods of prolonged warmth (the medieval and at present) summer cloud cover increases, and during cool periods (c. AD1525-1850) summer cloud cover decreases. There are two possible explanations for this. Firstly, that during warm periods there is an increase in northern cloud cover, due to a northerly drift in the storm tracks. This hypothesis fits model projections and short-term studies from satellite data (Norris et al., 2016), which predict a poleward movement of the mid-latitude storm tracks in direct response to forced global warming, and by inference the opposite during cooler periods. Secondly, that during warm/cool periods the atmosphere has a lower/higher water holding capacity, which leads to higher/lower cloud cover. These two hypotheses are, of course, not mutually exclusive and can clearly operate at the same time. However, second hypothesis appears less likely than the first, as it is clear from the meteorological data that as there is not a significant increase in cloud cover during warm summers and also the position of the region means that it receives much of its precipitation from Atlantic frontal systems.

Our results suggest that over Northern Fennoscandia, there may be a complex two-way relationship between surface temperature and cloud cover. The cloud cover-temperature feedback appears to operating in opposing directions over different timescales (Figure 4). Over short timescales, cloud cover imposes a negative feedback on regional temperature; cloudy summers with increased cloud are on average cooler and summers with less cloud cover are warmer. This relationship is clear from the meteorological records (Figure S6). Our data suggest however, that over longer time-scales, hemispheric temperature changes lead to directional changes in regional cloud cover (Figure 3). Over these time-scales, the feedback relationship appears to be a positive one: warm periods have increased cloud cover and cool periods less cloud cover (Figure 4). Over recent decades, anthropogenically forced global temperature rises appear to have led to an increase in regional cloud cover (Bender et al., 2012; Boucher et al., 2013; Norris et al., 2016). Our data suggest that such an increase in cloud cover should have a negative feedback effect on regional summer temperature (Figure S6), resulting in a muted temperature increase, relative to the rest of the hemisphere (Figure 1). The same dampening of regional temperatures can also be seen in the palaeoclimatic record (Figures S10). During the hemispherically warm Medieval (prior to c. AD1100), and cool LIA, c. AD1550–1850 (Matthews and Briffa, 2005) periods, directional changes in summer cloud cover have acted to moderate the degree of regional summer warming and cooling.

Our model (Figure 4) predicts that summer surface temperature changes over Northern Fennoscandia are moderated by the associated change in cloud cover. This can be tested by looking at both the meteorological and the palaeo data. Figure 1 clearly shows that summer temperatures over Northern Fennoscandia have risen very modestly when compared to Northern

Hemisphere changes. While Figure S10 places this clearly into the context of large-scale, long-term, forced climate change of the past millennium, showing that Northern Fennoscandian temperatures show lower long-term variability than Northern Hemisphere temperatures, especially in key periods of forced climate change the MCA, the LIA and the late twentieth century.

5 Conclusions

Measures of tree growth, including ring widths and maximum densities, provide some of the most powerful methods for reconstructing past summer temperatures at annual resolution over long timescales. Our results suggest that they can now be combined with stable carbon isotope ratios from suitable tree rings to produce parallel records of changes in summer sunshine and/or cloud cover, providing unique insights into the long-term relationship between cloud cover and temperature, which remains the greatest source of uncertainty in modelling the climate of the future.

While Northern Hemispheric temperature has shown substantial average increases over recent decades, the temperature of Northern Fennoscandia has remained fairy static. This can be linked to changes in summer cloud cover, especially when considered in the longer palaeoclimatic context. Over the past 1000-years as forced hemispheric temperatures have increased/decreased regional cloud cover has increased/decreased; leading to a moderating effect on regional temperatures.

Our observations, based on palaeoclimatic proxies, confirm what been suggested by climatic models, that increasing global temperature leads to increased cloud cover at high-latitudes. Our data also suggest that this is a two-way process, with warm conditions leading to increased cloud cover and cool conditions reduced cloud cover.

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The proxy data sets required to produce this research are archived on the NOAA Paleoclimatology Data Base at https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets. Climate data are available from the Climatic Research Unit at the University of East Anglia http://www.cru.uea.ac.uk/data and The Royal Netherlands Meteorological Institute (KNMI) Climate Explorer https://climexp.knmi.nl.

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Figure Captions

Figure 1. Comparison of CRUtemp4v (Osborn & Jones, 2014) Northern Hemisphere (NH, blue) and Northern Fennoscandian temperature (NF, red) annual and summer (June-August) means, over the common period AD1859-2017. NF values have been scaled to those for the NH over the period AD1859-1980 for comparison. Recent temperature increase was calculated by showing mean NH and NF temperature since AD1981 as the difference from the AD1859–1980 mean. The percentage of NF to the NH temperature increase, over the period since AD1981 arealso shown in the adjacent bar graphs.

Figure 2. (A) Percentage of summer cloud cover (as deviations from the AD1961-1990 mean) reconstructed from $\delta^{13}C$ composite (grey line) for the period AD990–2002, observed cloud cover AD1890–2002 (red line). The reconstruction was made using reduced major axis regression (variance scaling). (B) Scatter-graph for the squared correlation coefficient between observed summer cloud cover and reconstructed cloud cover. (C) Observed (red line) and reconstructed cloud (grey line) over the period for which meteorological cloud cover and the reconstruction overlap (AD1890–2002).

Figure 3. To indicate periods of divergence between temperature and cloud cover, the z-scored stable carbon isotope chronology were subtracted from the z-scored NH temperature reconstructions (Moberg et al., 2005; Shi et al., 2013). Positive values indicate cool/clear and negative values warm/cloudy conditions.

Figure 4. The feedback relationship between temperature and cloud cover over short (unforced) and longer (forced) timescales. Over short timescales increased cloud cover reduces summer temperature. Over longer timescales increased temperatures result in a reorganisation of circulation and an increase in Northern Fennoscandian cloud cover.

Figure 1.

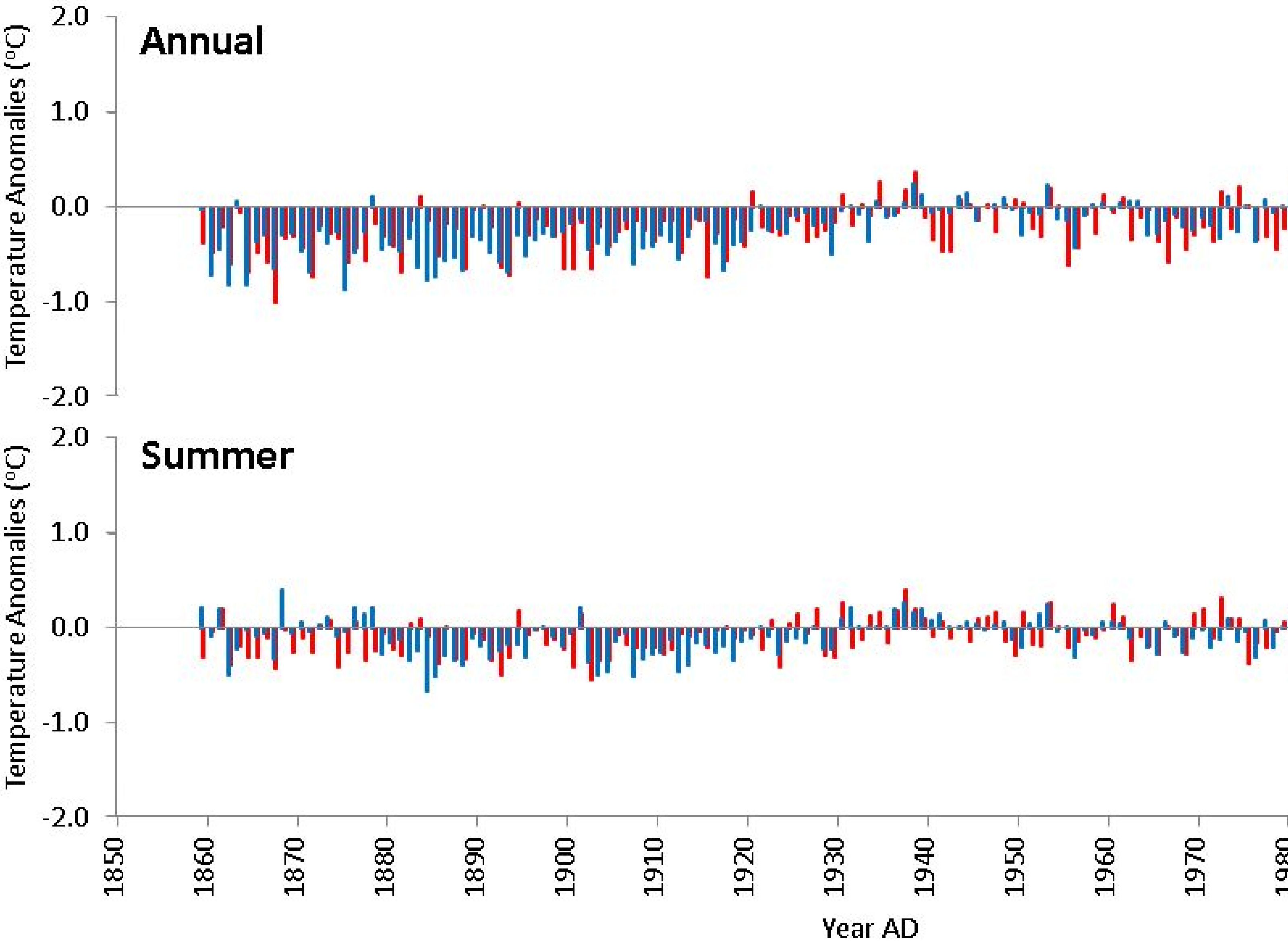
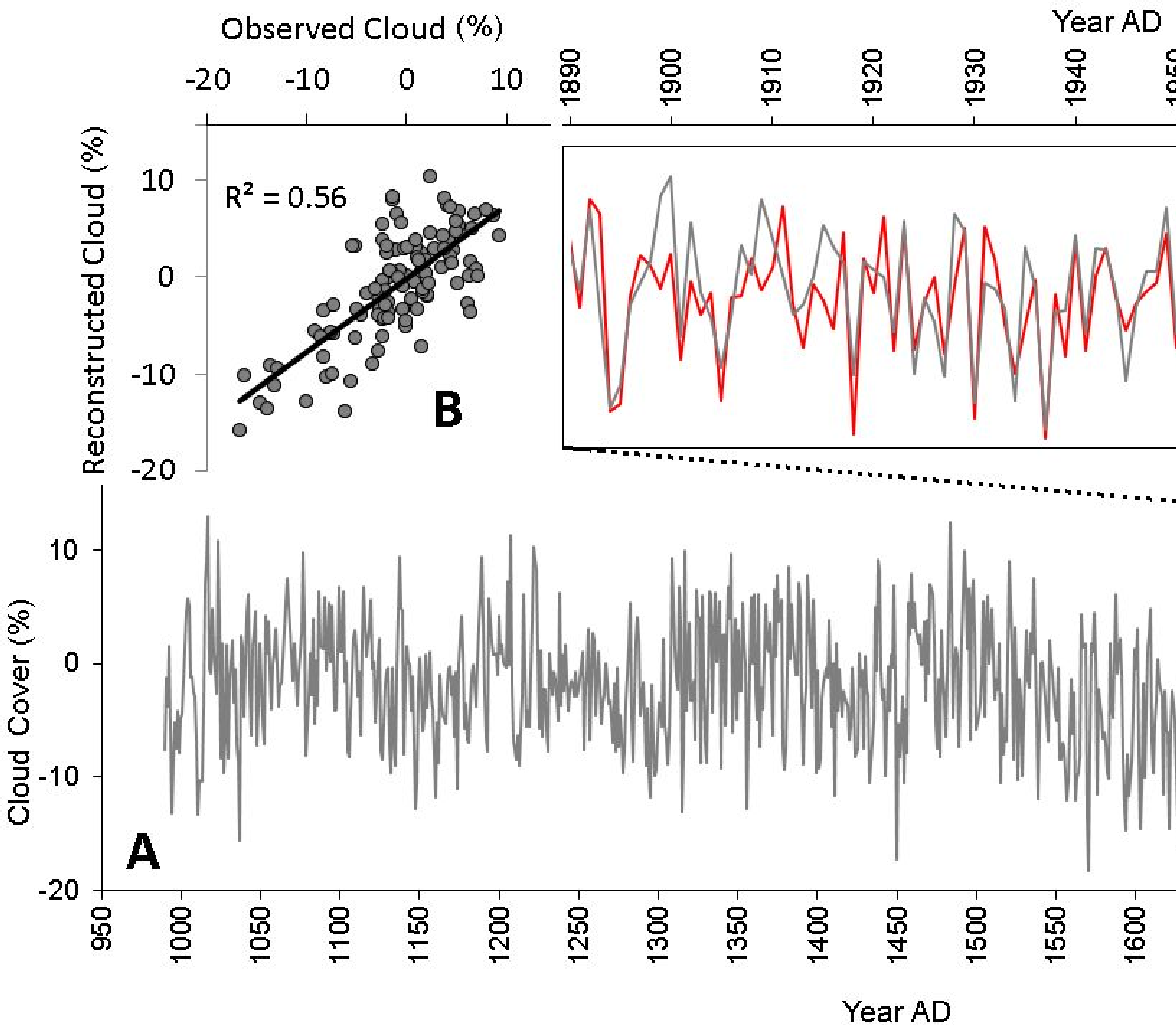

Annual
Summer
Temperature Anomalies (°C)
2.0
1.0
0.0
-1.0
-2.0
Year AD
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980

Figure 2.



Observed Cloud (%)
-20
-10
0
10
Reconstructed Cloud (%)
R² = 0.56
B
-20
Year AD
1890
1900
1910
1920
1930
1940
Cloud Cover (%)
10
0
-10
A
-20
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
Year AD

Figure 3.

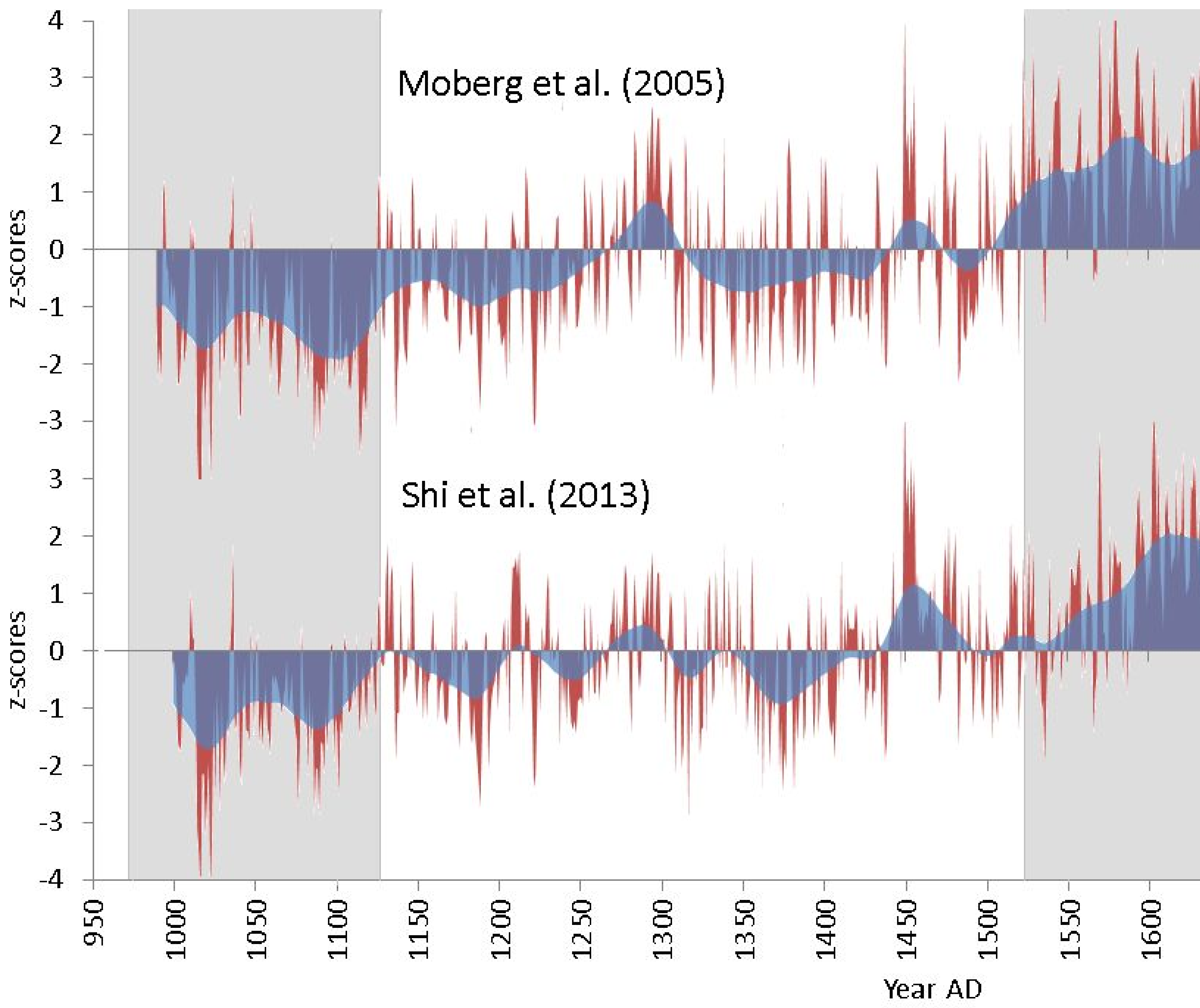
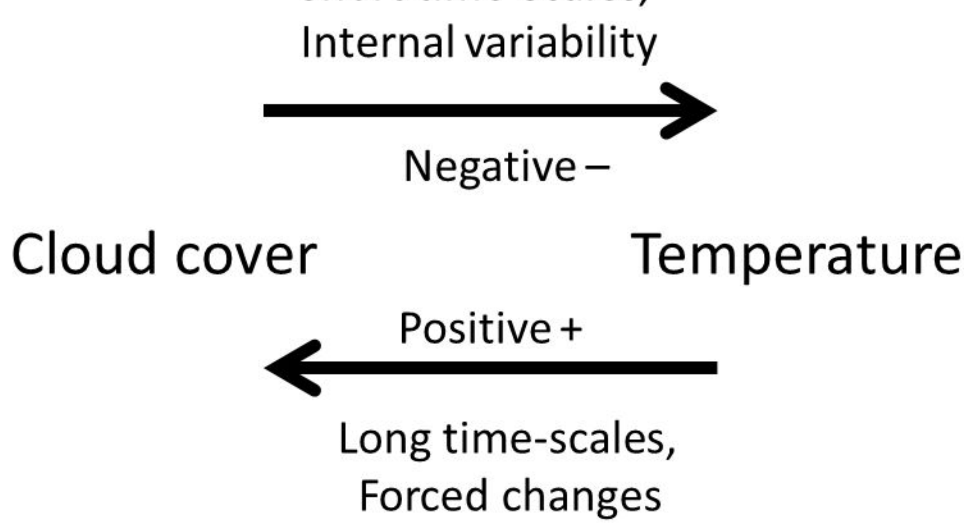

Moberg et al. (2005)
Shi et al. (2013)
z-scores
z-scores
Year AD
4
3
2
1
0
-1
-2
-3
3
2
1
0
-1
-2
-3
-4
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600

Figure 4.


Short time-scales,
Internal variability
Negative –
Cloud cover
Temperature
Positive +
Long time-scales,
Forced changes