Final Draft
of the original manuscript:

Gagen, M.; Zorita, E.; McCarroll, D.; Young, G.H.F.; Grudd, H.; Jalkanen, R.; Loader, N.J.; Robertson, I.; Kirchhefer, A.:

Cloud response to summer temperatures in Fennoscandia over the last thousand years

In: Geophysical Research Letters (2011) AGU

DOI: 10.1029/2010GL046216

Cloud response to summer temperatures in Fennoscandia over the last thousand years.

Mary Gagen[1*], Eduardo Zorita[2], Danny McCarroll[1], Giles H. F. Young[1], Håkan Grudd[3], Risto Jalkanen[4], Neil J. Loader[1], Iain Robertson[1], Andreas Kirchhefer[5]

----

[1]Department of Geography, Swansea University, UK. [2]Department of Palaeoclimate, Institute for Coastal Research, Helmholtz-Zentrum Geesthacht, Germany. [3]Department of Physical Geography and Quaternary Geology, Stockholm University 106 91 Stockholm, Sweden. [4]Rovaniemi Research Unit, The Finnish Forest Research Institute, Rovaniemi, Finland., [5]Department of Arctic and Marine Biology, University of Tromsø, Tromsø, Norway .

Abstract

Cloud cover is one of the most important factors controlling the radiation balance of the Earth. The response of cloud cover to increasing global temperatures represents the largest uncertainty in model estimates of future climate because the cloud response to temperature is not well-constrained. Here we present the first regional reconstruction of summer sunshine over the past millennium, based on the stable carbon isotope ratios of pine treerings from Fennoscandia. Comparison with the regional temperature evolution reveals the Little Ice Age (LIA) to have been sunny, with cloudy conditions in the warmest periods of the Medieval at this site. A negative shortwave cloud feedback is indicated at high latitude. A millennial climate simulation suggests that regionally low temperatures during the LIA were mostly maintained by a weaker greenhouse effect due to lower humidity. Simulations of future climate that display a negative shortwave cloud feedback for high-latitudes are consistent with our proxy interpretation.

1. Introduction and background

Cloud cover is one of the most important factors controlling the radiation balance of the Earth because clouds modulate the surface temperature response to external forcing, partly by reducing shortwave radiation (sunshine) received at the ground surface. The response of cloud cover to increasing global temperatures represents the largest uncertainty in model estimates of future climate (IPCC, 2007; Trenberth and Fasullo 2009; Clement et al., 2009) because the cloud response is not well-constrained in General Circulation Models (GCMs) (Bony et al., 2006; Soden et al., 2006, Dai et al., 2006). Clouds may diminish in the tropics (a positive feedback) and increase at high-latitudes (a negative feedback) under 21st century warming but with a wide range of spatial responses (Trenberth and Fasullo 2009; Soden et al., 2006). Recent attempts to better constrain model uncertainties by analyzing instrumental cloud cover data (Clement et al., 2009; Lindzen et al., 2009) are burdened by the limited length of the observational record. Records of sunshine hours, which are inversely related to cloud cover data, suffer from similar constraints. Inter-annual weather variability, and the limited length of cloud records, confound analysis of the forcing-and-response relationship, over the last few decades.

In the context of future climate change it is the sustained, long-term, response of cloud cover to changes in temperature that is of interest, because clouds will modulate the radiative perturbation caused by increasing greenhouse gases into the 21st century. A new millennial length treering stable carbon isotope ($\delta^{13}C$) series from Finland is interpreted here as a record of summer near-ground solar radiation and calibrated using local records of summer sunshine hours. When compared with the regional temperature history, based on treering densities, this new proxy record offers the chance to critically reduce the uncertainties in the cloud response to temperature anomalies.

2. Materials and methods

We developed a reconstruction of mean summer sunshine hours based on treering $\delta^{13}C$ ratios from Scots pine (*Pinus sylvestris* L.) at a site known as Laanila, in the northern Boreal forest zone of Finnish Lapland (Table Supporting Material 1). A modern $\delta^{13}C$ chronology (AD 1740-2001) from this site has been described previously (Gagen et al., 2007) and was built from living trees. Here we extend the Laanila $\delta^{13}C$ series to AD 886 using sub-fossil trees preserved in lakes. Both $\delta^{13}C$ chronology sections are unusually well replicated with a minimum of five trees (see Table Supporting Material 1). Trees were processed in offset 5-year blocks such that the final chronology represents a 9-year centralized moving average built from eight overlapping cohorts (Figure 1 and Figure Supporting Material 2). Since the offset in absolute $\delta^{13}C$ values between trees is often large, compared to the inter-annual variability, absolute $\delta^{13}C$ was fixed by sampling a much larger number of trees at the join-points between cohorts. Methodological details are given in the Supporting Material. We compare our $\delta^{13}C$ series to a reconstruction of past April-August temperatures based on a maximum latewood density (MXD) record from Torneträsk (Figure 2) in northern Sweden, ~400km west from Laanila (Grudd et al., 2008).

The influence of climate on carbon isotope fractionation in trees is well understood (Farquhar et al., 1982) and the perturbing effect of tree age has less influence on $\delta^{13}C$ than it has on other treering parameters, so that low-frequency climate information can be retained with less uncertainty (Gagen et al., 2007) providing the offset between trees is addressed. Over the industrial period (since AD 1850), trees have been exposed to large changes in the amount and isotopic composition of atmospheric CO_2, for which corrections are necessary (Saurer et al., 1997; McCarroll et al., 2009). Prior to this, treering $\delta^{13}C$ records changes in the internal concentration of CO_2 (c_i) in the leaves or needles, reflecting the balance between stomatal conductance to incoming CO_2 and photosynthetic assimilation rate (Farquhar et al., 1982; McCarroll and Loader 2004).

At cool, moist sites the dominant control over c_i is assimilation rate which can be limited either by enzyme activity, and thus photon flux, or by enzyme production, and thus leaf temperature (Beerling 1994). At Laanila summer temperatures are too high for this latter mechanism to be important (Luoma 1997) and experimentation with *Pinus sylvestris* in eastern Finnish Lapland confirms that growing-season sunlight, not leaf temperature, explains 90% of photosynthetic rate variations (Hari et al., 1981). Experimental evidence also suggests that tree leaf temperature is highly stable across a very wide geographical area (Helliker and Richter 2008) such that temperature limitation of c_i is unlikely to be the norm.

The potential for treering $\delta^{13}C$ from Boreal sites to thus record sunny summers has recently been identified (Gagen et al., 2007; McCarroll et al., 2003; Young et al., 2010). Boreal treering $\delta^{13}C$ results often correlate as well with instrumental summer temperatures as with records of sunshine hours or percentage cloud cover over the 20th Century, due to the co-variance of the two climate variables at high frequency but $\delta^{13}C$ based temperature reconstructions tend to fail against long instrumental temperature records (Young et al., 2010; Hilasvuori et al., 2009) at multi decadal timescales. The assumption that the strong co-variance between summer sunshine and temperature seen in the calibration period is stationary at multi-decadal timescales, seems to be invalid and treering $\delta^{13}C$ chronologies from high latitude tree line sites are better interpreted as records of summer sunshine or cloudiness (Young et al., 2010; McCarroll et al., 2003). If the relationship between temperature and cloud cover has varied through time, $\delta^{13}C$ series from northern Boreal pine will track variations in summer sunshine not temperature (Young et al., 2010).

Meteorological records, available from the Finnish Meteorological Institute's Sodankylä station, 150km south of Laanila (see Table Supporting Material 1), reveal that summer sunshine hours and summer temperature correlate highly ($r = 0.72$) between AD 1958 and 2001. In the common period, the correlations between Laanila $\delta^{13}C$ and summer sunshine hours and temperature are comparably high (Table 1). Correlations between the Laanila $\delta^{13}C$ series and summer % cloud cover (AD 1908-2001) are also strong but weaker than those between $\delta^{13}C$ and temperature/sunshine hours (Table 1). The correlations with cloud cover also appear to be somewhat less time stable which may be a reflection of notorious error in cloud cover measurements (Dai et al., 2006).

A linear regression model was used to reconstruct summer sunshine hours (Table Supporting Material 2) at Sodankylä using the Laanila $\delta^{13}C$ series as the predictor (Figure 2 and Supporting Material). The calibration of the Laanila $\delta^{13}C$ record, to estimate Sodankylä sunshine hours, was accomplished using ordinary least squares regression, whereby the annual Laanila $\delta^{13}C$ record (Gagen et al., 2007) was used as predictor and the Sodankylä sunshine hours meteorological record as predictand. The target meteorological variable was mean daily sunshine hours averaged over July-August and the calibration period was dictated by the available data at Sodankylä (AD 1958-2001). Diagnosis of the regression residuals indicated that they were not significantly serially correlated (Table Supporting Material 2). To obtain the reconstruction of the meteorological variable throughout the series length, the same regression slope and intercept as obtained in the annually measured calibration period were applied to the regression model used to develop the 9-year smoothed reconstruction. The uncertainty bounds for the whole period were estimated assuming the same lag-1 autocorrelation of the regression residuals as obtained in the calibration, and assuming that the sampling procedure of the $\delta^{13}C$ record is indeed equivalent to a 9-year running average smoothing (Briffa et al., 2002).

3. Results and discussion

The Laanila summer sunshine reconstruction contrasts markedly with the Torneträsk growth season temperature reconstruction (Figure 2). The two proxy records are sensitive to slightly different parts of the growing season and we make the assumption that the relationship between April-August climate (Torneträsk reconstruction) and July-August (Laanila) would be the same in the past as now (highly correlated). The coldest century of the LIA in the Torneträsk reconstruction (17th), which is supported by other evidence to suggest cold summers at this time across the region (Gouirand et al., 2007), is also the sunniest century.. During the warmest phase of the Medieval at Torneträsk (AD 950 – 1100), $\delta^{13}C$ values were low, suggesting unusually cloudy summers. This presents a picture of a negative cloud feedback at this latitude.

An explanation requires the regionally cool periods of the LIA to have also experienced enhanced summer sunshine. Support for a sunny Little Ice Age in Northern Fennoscandia is provided by past glacial dynamics in northern Sweden (Holmlund et al., 1996), which suggest low precipitation. A further $\delta^{13}C$ series is also available from the Atlantic side of the Scandes Mountain range at Forfjorddalen in Norway (Young et al., 2010). Laanila and Forfjorddalen are on opposite sides of the Scandes and thus do not correlate well at high frequency. However they do show a similar response to the LIA with high $\delta^{13}C$ values also at Forfjorddalen (Young et al., 2010).

According to our interpretation summer temperature and summer sunshine in Fennoscandia co-vary at interannual timescales. This is supported by the station data and by the plausible physical reasoning that at this location less cloud cover causes higher temperatures at inter-annual timescales. However, at multidecadal timescales, the proxy records indicate that cloud cover may change as a response to temperature variations caused by external forcing. This time-scale dependent behavior is reproduced in a millennial simulation with the global atmosphere-ocean model ECHO-G (see Supporting Material for model details) (von Storch et al., 2004; Zorita et al., 2005). Figure 3 displays the multidecadal evolution of the simulated summer temperature, incoming radiation, and specific humidity, over Fennoscandia. The modeled inter-annual variations of Fennoscandian incoming shortwave radiation (“sunshine”) and temperature are positively correlated ($r = 0.47$, similar to the observed correlation), but the multi-decadal evolutions of incoming shortwave radiation and temperature are different. Although the Late Maunder Minimum (AD 1680-1710) is a period of weak external solar irradiance, stronger downwelling solar radiation at the surface is indicated over Fennoscandia, indicative of sunnier weather. Markedly lower temperatures are partly due to the lower atmospheric water content, which causes a diminished greenhouse effect (reduced incoming infrared radiation). Thus, at longer time scales, regional surface solar radiation and regional temperature can be decoupled due to the other factors becoming important at these time scales.

In the period between AD 1600 and 1700 (approx.) the simulated shortwave radiation does not diverge as clearly from the simulated temperature as the Laanila $\delta^{13}C$ record does from the temperature reconstruction. Furthermore, in contrast to the proxy correlation between sunshine and temperature, the correlation between model shortwave radiation and temperature over the whole millennium at multidecadal timescales is close to zero. The time evolution of the modeled surface solar radiation is dependent on the representation of the regional details in the coarse-resolution global model and on the parametrizations of cloud microphysics, which are still imperfect in climate models. Therefore, a close quantitative agreement over the last centuries between modeled radiation and the Laanila record cannot be expected for one particular model. Nevertheless, the model results do provide a plausible mechanistic explanation for multidecadal-scale decoupling of regional summer temperature and incoming shortwave radiation in spite of their coupling at inter-annual time scales. This behavior represents a target for the forthcoming simulations of the past centuries in the next IPCC report, particularly if further sunshine proxy records can be retrieved from other sites worldwide. As an illustration of this type of combined proxy-model analysis, Figure 3 also presents deviations of incoming shortwave radiation in nineteen future climate model simulations from the IPCC AR4 archive, driven by the scenario SRES A2. Although the noisier regional long-term trends are not as consistent through time, most models do show less incoming shortwave radiation than present in the high-latitude zonal average and thus are consistent with the palaeo interpretation of an anticorrelation between temperature and shortwave radiation, in this region, at long time scales.

4. Conclusions

Under the assumption that the cloud response at high latitudes is driven by the mean near-surface temperature, it would be expected that the behavior of cloud cover in a warmer future climate should be opposite to that of the Late Maunder Minimum. If, as indicated by the Laanila summer sunshine reconstruction, cloud cover was less in colder periods, and therefore incoming shortwave radiation greater, cloud cover at this latitude in a warmer climate should be higher and therefore incoming shortwave radiation less than at present. Most future climate simulations from the IPCC AR4 suite do display this behavior.

Treering stable carbon isotope ratios from both northern Finland and northern Norway indicate a negative shortwave cloud feedback in this high-latitude region in summer in the LIA with the Laanila series presented here also showing a negative feedback in the Medieval, in line with model findings for the 21st century (Trenberth and Fasullo, 2009). We hypothesize that information on past changes in sunshine could be extracted from treerings in other areas where assimilation rate, rather than stomatal water regulation, dominates the $\delta^{13}C$ signal, which includes many tropical regions. Treering $\delta^{13}C$ may thus provide a critical test of the ability of climate models to deal with the most uncertain feedback mechanism that still hampers accurate future climate projections (Bony et al., 2006).

Acknowledgements

We thank Kevin Anchukaitis, Anders Moberg and Valerie Trouet for critical comment on the manuscript and the Millennium consortium for support. This research was funded by the European Union Millennium project (017008). MG is supported by a Research Councils United Kingdom Fellowship. NJL is supported by the British Natural Environment Research Council. Tarmo Aalto, Pekka Närhi and Reino Vierelä are thanked for field sampling and dating. Thanks to Nicola Jones for help with figures.

References

Beerling, D. J. (1994), Predicting Leaf Gas-Exchange and Delta-C-13 Responses to the Past 30000 Years of Global Environmental-Change, *New Phytologist*, *128*(3), 425-433.

Bony, S., et al. (2006), How well do we understand and evaluate climate change feedback processes?, *Journal of Climate*, *19*(15), 3445-3482.

Briffa, K. R., T. J. Osborn, F. H. Schweingruber, P. D. Jones, S. G. Shiyatov, and E. A. Vaganov (2002), Tree-ring width and density data around the Northern Hemisphere: Part 1, local and regional climate signals, *Holocene, 12*(6), 737-757.

Clement, A. C., Burgman, R. & Norris, J. R. (2009), Observational and Model Evidence for Positive Low-Level Cloud Feedback. *Science*, *325,* 460-464.

Dai, A. G., T. R. Karl, B. M. Sun, and K. E. Trenberth (2006), Recent trends in cloudiness over the United States - A tale of monitoring inadequacies, *Bulletin of the American Meteorological Society*, *87*(5), 597.

Farquhar, G. D., M. H. Oleary, and J. A. Berry (1982), On the Relationship between Carbon Isotope Discrimination and the Inter-Cellular Carbon-Dioxide Concentration in Leaves, *Australian Journal of Plant Physiology*, *9*(2), 121-137.

Gagen, M., D. McCarroll, N. J. Loader, L. Robertson, R. Jalkanen, and K. J. Anchukaitis (2007), Exorcising the 'segment length curse': Summer temperature reconstruction since AD 1640 using non-detrended stable carbon isotope ratios from pine trees in northern Finland, *Holocene*, *17*(4), 435-446.

Gouirand, I., H. W. Linderholm, A. Moberg, and B. Wohlfarth (2008), On the spatiotemporal characteristics of Fennoscandian tree-ring based summer temperature reconstructions, *Theoretical and Applied Climatology*, *91*(1-4), 1-25.

Grudd, H. (2008), Tornetrask tree-ring width and density AD 500-2004: a test of climatic sensitivity and a new 1500-year reconstruction of north Fennoscandian summers, *Climate Dynamics*, *31*(7-8), 843-857.

Hari P, Hallman E, Salminen R, Vapaavuori E (1981) Evaluation of Factors Controlling Net Photosynthetic Rate in Scots Pine-Seedlings under Field Conditions without Water-Stress. *Oecologia*, *48,* 186-189..

Helliker, B. R., and S. L. Richter (2008), Subtropical to boreal convergence of tree-leaf temperatures, *Nature*, *454*(7203), 511-U516.

Hilasvuori, E., F. Berninger, E. Sonninen, H. Tuomenvirta, and H. Jungner (2009), Stability of climate signal in carbon and oxygen isotope records and ring width from Scots pine (Pinus sylvestris L.) in Finland, *Journal of Quaternary Science*, *24*(5), 469-480.

Holmlund, P. (1986), Mikkaglaciaren: Bed Topography and Response to 20th Century Climate Change, *Geografiska Annaler. Series A, Physical Geography*, *Vol. 68*(No. 4), pp. 291-302.

IPCC (2007), Climate Change 2007, IPCC fourth assessment report. The physical science basis. Retrieved from: <http://www.ipcc.ch/ipccreports/ar4-wg1.htm..

Lindzen, R. S., and Y. S. Choi (2009), On the determination of climate feedbacks from ERBE data, *Geophysical Research Letters*, *36*.

Luoma, S. (1997), Geographical pattern in photosynthetic light response of Pinus sylvestris in Europe, *Functional Ecology*, *11*(3), 273-281.

McCarroll, D., R. Jalkanen, S. Hicks, M. Tuovinen, M. Gagen, F. Pawellek, D. Eckstein, U. Schmitt, J. Autio, and O. Heikkinen (2003), Multiproxy dendroclimatology: a pilot study in northern Finland, *Holocene*, *13*(6), 829-838.

McCarroll, D., and N. J. Loader (2004), Stable isotopes in treerings, *Quaternary Science Reviews*, *23*(7-8), 771-801.

McCarroll, D., M. H. Gagen, N. J. Loader, I. Robertson, K. J. Anchukaitis, S. Los, G. H. F. Young, R. Jalkanen, A. Kirchhefer, and J. S. Waterhouse (2009), Correction of treering stable carbon isotope chronologies for changes in the carbon dioxide content of the atmosphere, *Geochimica et Cosmochimica Acta*, *73*(6), 1539-1547.

Saurer, M., Borella, S., Schweingruber, F., Siegwolf, R. (1997), Stable carbon isotopes in treerings of beech: climatic versus site-related influences., *Trees-Structure and Function*, *11*, 291–297.

Soden, B. J., and I. M. Held (2006), An assessment of climate feedbacks in coupled ocean-atmosphere models, *Journal of Climate*, *19*(14), 3354-3360.

Trenberth, K. E., and J. T. Fasullo (2009), Global warming due to increasing absorbed solar radiation, *Geophysical Research Letters, 36*.

von Storch, H., E. Zorita, J. M. Jones, Y. Dimitriev, F. Gonzalez-Rouco, and S. F. B. Tett (2004), Reconstructing past climate from noisy data, *Science*, *306*(5696), 679-682.

Young, G. H. F., D. McCarroll, N. J. Loader, and A. Kirchhefer (2010), A 500-year record of summer near-ground solar radiation from tree-ring stable carbon isotopes, *The Holocene*, *20(3)*, 315-324

Zorita, E., J. F. Gonzalez-Rouco, H. von Storch, J. P. Montavez, and F. Valero (2005), Natural and anthropogenic modes of surface temperature variations in the last thousand years, *Geophysical Research Letters*, *32*(8).

Figure Captions

Fig 1. The δ^{13}C chronology from Laanila, centralised 9-year (thin blue) and 30-year (thick blue) moving averages. Standard deviation is also given (n = 5). An insert panel shows the simple linear correlation between daily summer sunshine hours at Sodankylä and the Laanila δ^{13}C chronology (1958-2001), both centralised 9-year moving averages.

Fig 2. Daily summer sunshine hours reconstructed from Laanila δ^{13}C 9-yr mean (dark blue) with uncertainty estimates (light blue), observed summer sunshine (July-August, 9-yr mean) (black) and April-August temperature reconstruction at Torneträsk (MXD) (pink). 30 year moving averages for the reconstructions are shown (thick blue and red lines respectively) and the LIA and MWP are indicated by dark grey shading. The mean for each series is indicated (black horizontal lines).

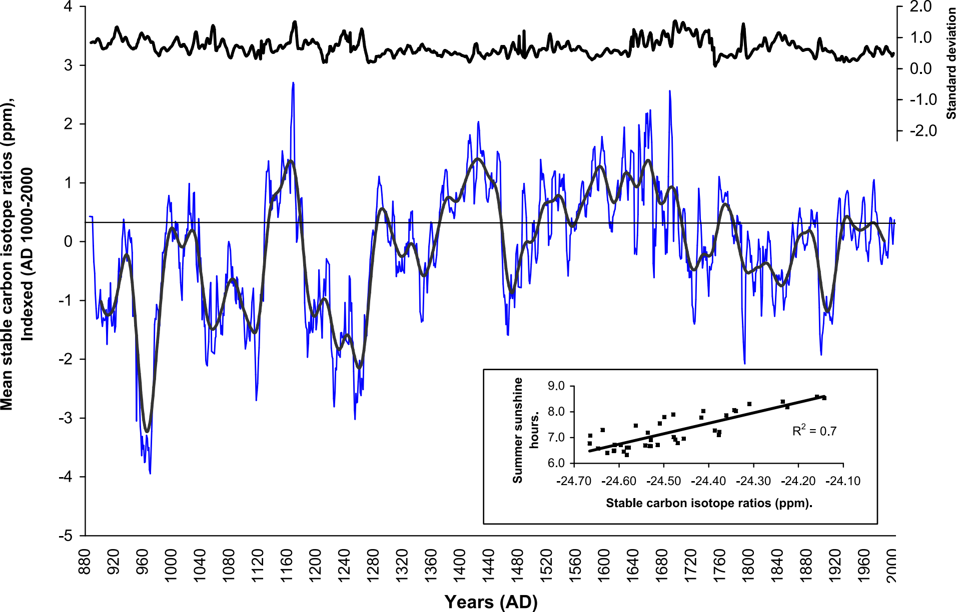
Fig. 3. ECHO-G GCM simulated time series (31-year running mean, anomalies from the 20th century mean) of, **A**. incoming shortwave surface(grey), incoming infrared surface (black) and total incoming (thick grey) surface radiation averaged over

Fennoscandia. **B**. Near-surface temperature (red) and specific humidity at 500 mb height (blue). **C**. IPCC AR41 models, scenario A2, downwelling shortwave radiation July-August, deviations from the 2000-2010 mean, zonal mean (60ºN - 80ºN) and **D**. for the Laanila region (20º-40ºW; 60º-70ºN), 21-year centralised moving average.

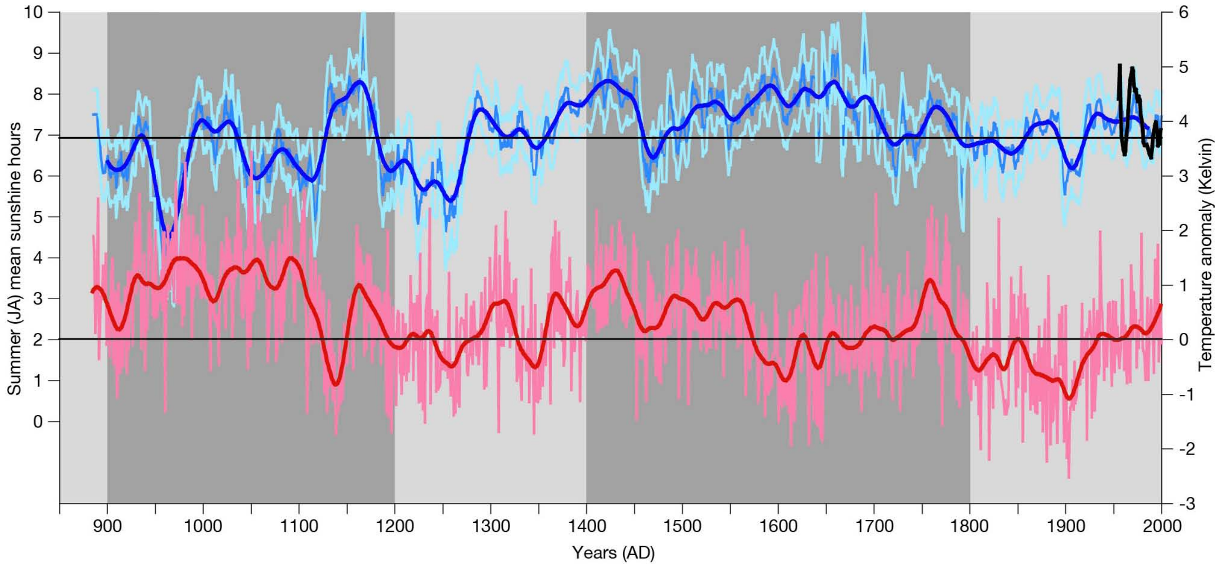
Tables

Table 1 – Correlations between Sodankylä climate and the Laanila δ13C series (9-year smooth), significance values ($P<0.05$, in bold) were estimated using Monte Carlo simulations for the 9-year smooth series. Simple linear correlations for the annual Laanila $\delta^{13}C$ series are shown in brackets. Statistical significance is not indicated for the correlations with sunshine data due to the low number of degrees of freedom, * = 2001-1958.

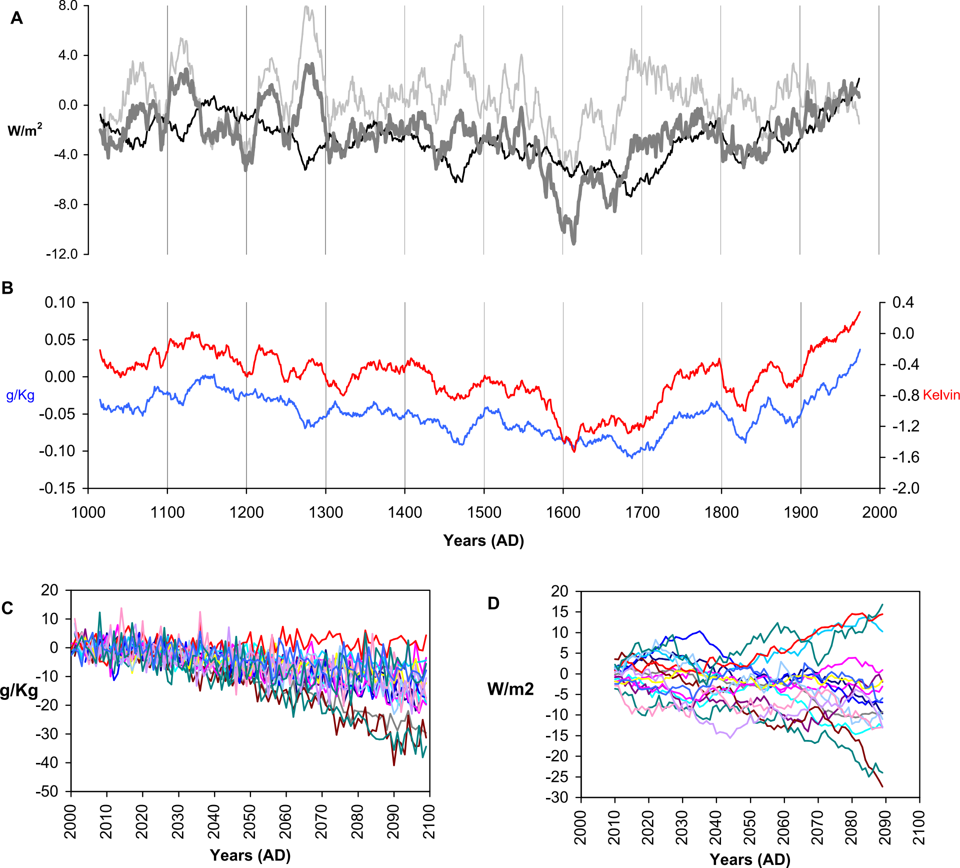
Laanila $\delta^{13}C$	Correlation (r =), Temp Sodankylä , (July-Aug)	Correlation (r=), % Cloud cover. Sodankylä , (July-Aug)	Correlation (r=), Sunshine Hours , Sodankylä , (July-Aug)
2001-1908	**0.61 (0.74)**	**-0.56 (-0.58)**	n/a
2001-1955	**0.82 (0.79)**	**-0.66 (-0.75)**	*0.84 *(0.74)
1954-1908	**0.67 (0.71)**	**-0.66 (-0.47)**	n/a



Mean stable carbon isotope ratios (ppm), Indexed (AD 1000-2000
Standard deviation
Years (AD)
4
3
2
1
0
-1
-2
-3
-4
-5
2.0
1.0
0.0
-1.0
-2.0
880
920
960
1000
1040
1080
1120
1160
1200
1240
1280
1320
1360
1400
1440
1480
1520
1560
1600
1640
1680
1720
1760
1800
1840
1880
1920
1960
2000
Summer sunshine hours.
Stable carbon isotope ratios (ppm).
9.0
8.0
7.0
6.0
-24.70
-24.60
-24.50
-24.40
-24.30
-24.20
-24.10
R^2 = 0.7



Summer (JA) mean sunshine hours
10
9
8
7
6
5
4
3
2
1
0
Temperature anomaly (Kelvin)
6
5
4
3
2
1
0
-1
-2
-3
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Years (AD)


A
8.0
4.0
0.0
W/m2
-4.0
-8.0
-12.0
B
0.10
0.05
0.00
g/Kg
-0.05
-0.10
-0.15
0.4
0.0
-0.4
-0.8 Kelvin
-1.2
-1.6
-2.0
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Years (AD)
C
20
10
0
-10
g/Kg
-20
-30
-40
-50
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Years (AD)
D
20
15
10
5
0
W/m2
-5
-10
-15
-20
-25
-30
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Years (AD)