Evidence for the climate during the Late Maunder Minimum from proxy data and model simulations available within KIHZ

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Summary

The knowledge constructed within the project „Klima in Historischen Zeiten“ (KIHZ) about the Late Maunder Minimum (LMM), based upon corals, lake and marine sediment records, ice cores and speleothems, is reviewed. The data are compared to a simulation with the climate model ECHO-G. It is found that the LMM was an event of global scale, with a cooling on the entire Northern hemisphere and in the tropics, while a weaker warming may have taken place on the Southern Hemisphere. The model results are mostly consistent with the empirical evidence. However, the empirical data is not very conclusive so that any claims that the dynamics behind the simulated LMM would equal the dynamics of the real event should be considered with care.

1 Prologue

The reconstruction and analysis of past climate variations from various archives has turned out to be a somewhat cumbersome exercise, simply because of the uncertainties in the transfer functions and dating of the proxy data. In an attempt to overcome this obstacle, which is to some extent not only due to scientific problems but has also something to do with the social exchange among different disciplines and subdisciplines, it was agreed to pool all knowledge about the Late Maunder Minimum (LMM), 1675-1710. Thus, the different groups within the KIHZ project (Klima in historischen Zeiten) were asked to come up with their best guesses concerning the state during the LMM period, relative to a the reference “normal” 1550 -1800, and its uncertainty both in the physical interpretation and the dating. Of course, in most cases, proxy data are not available for the entire 1550-1800 interval, so that compromises have to be made, by using as much as is available within that interval.

The results of this exercise are compared with an extended "forced" simulation with the state-of-the-art climate model ECHO-G (see also von Storch, 2002). This model was exposed to time-dependent solar output, volcanic aerosol loads in the atmosphere and greenhouse gas concentrations. During the model years 1675 -1715 a marked cool anomaly emerged during winter. The cooling in Europe is consistent with historical evidence but little is known outside Europe. Therefore the comparison with estimates from the various archives is hoped to support, or falsify the model -based hypothesis of global cooling.

The choice of the time intervals – 1675-1710 as "LMM" and 1550-1675, 1710-1800 as reference "normal" – is somewhat arbitrary. The interval 1675 -1710 is suggested by the work about the LMM in Europe. Since proxy data are better in describing relatively small variations relative to a "normal", we agreed on the 1550-1675, 1710-1800 as a reference "normal" for two reasons. First, the end point is motivated by the request of having no significant contamination by anthropogenic climate change, which may have begun sometimes in the 1850s. Second, the empirical data should be compared with the model output. The model was spun up with modern conditions and forcing beginning in 1450. By 1550 the model had about equilibrated, so that its output may be representative for pre-industrial forcing conditions.

The purpose of this paper is *not* to offer a complete overview of all available material. Instead it is the result of an ad-hoc working group of paleoclimatologists and modelers to systematically compare what is available within the project. As such the present paper represents a snapshot of how a joint view of historical past emerges within the group by bringing together the different disciplines. Important elements of this joint work is the mutual agreement about comparable dating and comparable informational content in the proxy data (e.g., temperature – where, which season, smoothed over how many years?) and their uncertainties. Likely, in a few years, this joint construction of the past will comprise much more archives, methods and disciplines. The purpose of this paper is to further this development.

2 Review of present knowledge

The term "Late Maunder Minimum" (LMM) refers to the coldest phase of the so-called 'Little Ice Age' with marked climatic variability over wide parts of Europe. Especially extreme values of temperature and precipitation over decades make the LMM an outstanding climatic period.

It coincided with a reduced solar and an enhanced volcanic activity, as well as a low number of sunspots. Estimates of the reduction of solar irradiance are in the order of 0.2 to 0.4% relative to present levels (e.g. Lean and Rind 1998; 1999). Solar activity during the LMM was near its lowest levels within the past 8000 years (Lean and Rind 1999) and the UV irradiance was reduced as well (Lean et al. 1995).

Most of the authors dealing with LMM, e.g. in Frenzel (1994), report cold winters in that period. The winter of 1685 was the most severe in Europe with an anomaly from -4.5 to -5 K (Lindgren and Neumann 1981).

In general, winter cooling was pronounced in western and central Europe. In northwest Europe, small anomalies prevailed, but the south-eastern regions experienced strong cooling: no mild or normal winters were recorded. In all other regions strong winters were much more frequent than usual. The springs in that time period were the coldest of the last 500 years in north-western, central and eastern Europe.

The summers were characterized by mostly cool summers: Mean summer temperatures of the Northern Hemisphere from 1691-1700 were with -0.7 K anomaly (relative to 1961-90) the lowest of the last millennium (Jones et al., 1998). At the same time variability was enhanced during summer with great regional differences. For instance the hottest summer in the period of 1480-1800 occurred in Hungary during the LMM (Racz 1994). In France and Switzerland more cool and cold summer than warm and hot occurred, but normal summers dominated. Briffa (1998) found summers wetter and cooler in western, central and eastern Europe. In northwestern and central Europe more cool summers than usual were observed. No hot summers were experienced on the British Islands. Also autumn conditions varied across Europe, with normal to slightly cooler conditions in northwest Europe, Switzerland and France.

In the following some results of investigations for distinct regions are listed exemplary.

- The annual *Central England* temperature (Lamb (1982) and Manley (1974)) from 1690-99 was –1.5 K relative cooler compared to the period 1920-1960. The coldest winter from 1659-1979 was winter 1684 with an anomaly of –5.2 K relative to the mean of 1850-1950. Winter 1695 was –3.3 K colder than that mean value. Summers of 1674, 1675, 1694,1695 were with –1.5 K anomaly the second to fifth coldest summer of 1659-1997.

- In *Germany* all seasons had negative temperature anomalies. The years 1684-1700 were coldest (Glaser 2001).

- During the LMM the frequency of strong winters, as reflected in sea ice conditions of the *Baltic Sea*, were increased (Figure 1, Koslowski and Glaser, 1999).

- The winter mean temperature value for 1683-1700 in *Zürich* was 1.5 K lower than the mean of 1900-60, whereas greatest differences, of 2.2-2.7K, were experienced in March (Pfister, 1999).

- In *Lisbon* there were six winters with snowfall: 1680, 1684, 1693, 1699, 1703, 1704, while within 1954-94 only once (1954) snow occurred. Grove and Conterio (1994) found only for 1983 reports for a strong cooling in the eastern and central

Mediterranean. In Italy, climate during the LMM was found to be mostly normal (Camuffo and Enzi, 1994).

- Ogilvie (1994) found evidence that the winter half years (October to April) of 1680, 1688, 1690, 1695, 1699 were very cold in *Iceland*.

- Also for the Far East, some evidence for a cooling during the LMM has been found. Arakawa (1957) notes that freezing of Lake Suwa (36 °N, 138°E) during the winters 1680/1 to 1719/20 was considerably earlier than before and after. However, the data base for this statement is rather weak. In China, a cool period was identified to appear between 1650 and 1700, with a temperature drop of about 0.5K (Wang and Wang, 1990. Quansheng et a., 2002).

A detailed review paper on the LMM has been carefully prepared by Luterbacher (2001).

Figure 1: Ice winter Index after Koslowski and Glaser (1999); grey: Index, blue:20 year mean, red: 5 year mean.

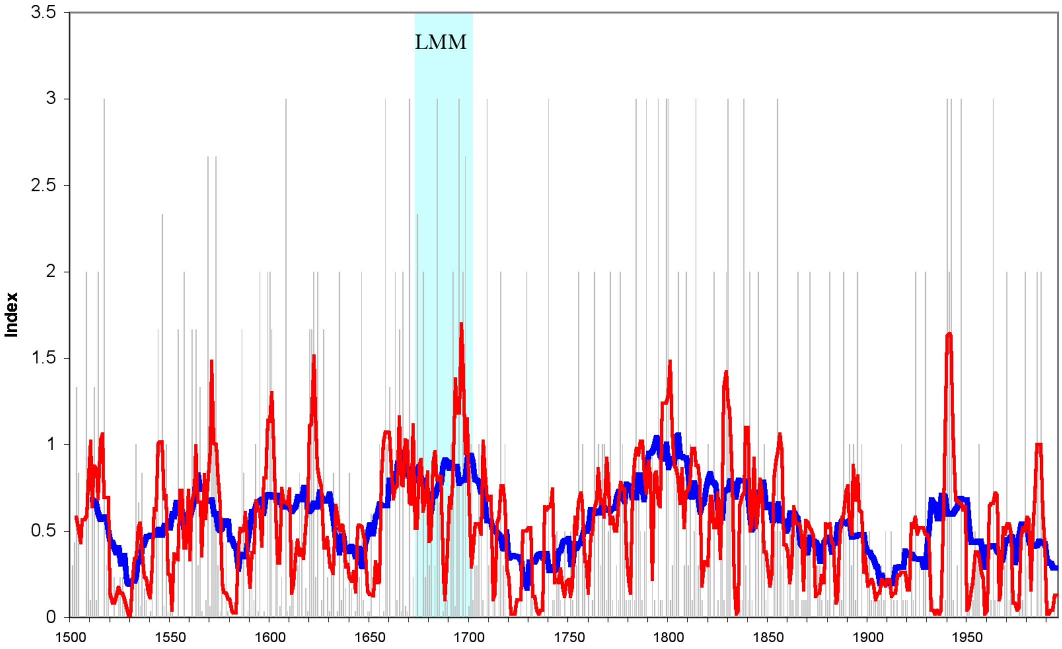
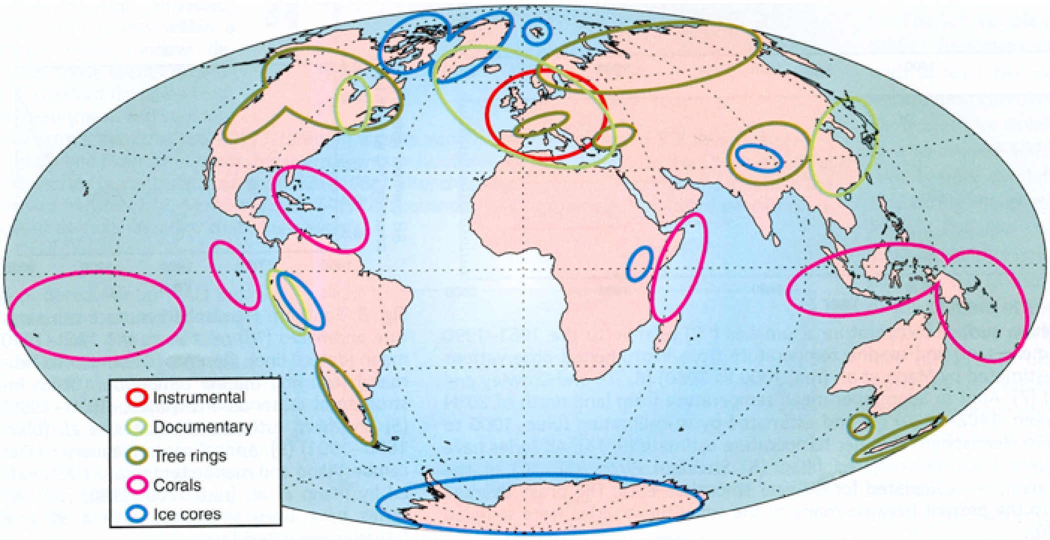


Figure 2 – Global map of the main regions with annually resolving proxy data for pre-1750 temperatures. From Jones et al., 2001.



3 Evidence from archives about the climate during the Late Maunder Minimum (LMM)

Various proxies reflect past variations of mainly air and sea surface temperature, precipitation and wind directions. Figure 2 sketches broadly the main areas, and types of proxies, from which annually resolving reconstructions of temperatures seem to be possible. The project KIHZ is engaged in many of these areas, working in corals, marine and lake sediments and ice cores. In the following a summary of the available data, and their informational content for the Late Maunder Minimum (LMM, 1675-1710) is given.

We present not only that material, which provides relatively well defined estimates about the LMM climate anomaly, both in terms of quantative change and timing, but also evidence which is not really useful, because of too uncertain timing (marine sediments) or because of contaminations of the climate signal with other, non-climatic factors (speleothems).

3.1 Corals

Within KIHZ a coral from the lagoon of Ifaty off southwest Madagascar in the Mozambique Channel was examined (Zinke, J., 2001). The core is 406 cm long and was sectioned into 3mm thick slabs. The coral slabs were X-rayed and reveal a very clear annual density banding.

A high-resolution profile for stable isotope analysis was drilled along the growth axis to avoid sampling artifacts. Subsamples were drilled at a distance of 1 mm for the years 1995-1920 and 2 mm for the older part of the core. The growth rate of the coral averages 10 mm/year, so that the 1 or 2 mm sample spacing provides approximately monthly or bimonthly resolution, respectively. Average precision is ±0.08‰ for ^{18}O or about 0.5K

The stable isotopic composition of coral skeletons reflects a combination of sea surface temperatures (SST) and δ^{18}O of seawater (salinity). In regions with relatively constant hydrological balance coral δ^{18}O records can provide SST variations, with positive δ^{18}O values indicating cooler and negative values warmer SST. Thus, the strong seasonal cycle in δ^{18}O was used to develop the chronology of the coral core. The most positive δ^{18}O values were assigned to August 15 of each year, which on average is the coldest month. The timing of the coldest month varies for about 1-2 months between the years, thus this approach creates a time-scale error of about 1-2 months in any given year.

Seasonal and annual mean SST‘s were estimated from the entire δ^{18}O record on the basis of two calibration data sets:

- 1^{o}x1^{o} gridded NCEP-AOI-SST available for 1982-present (Reynolds and Smith, 1994) and

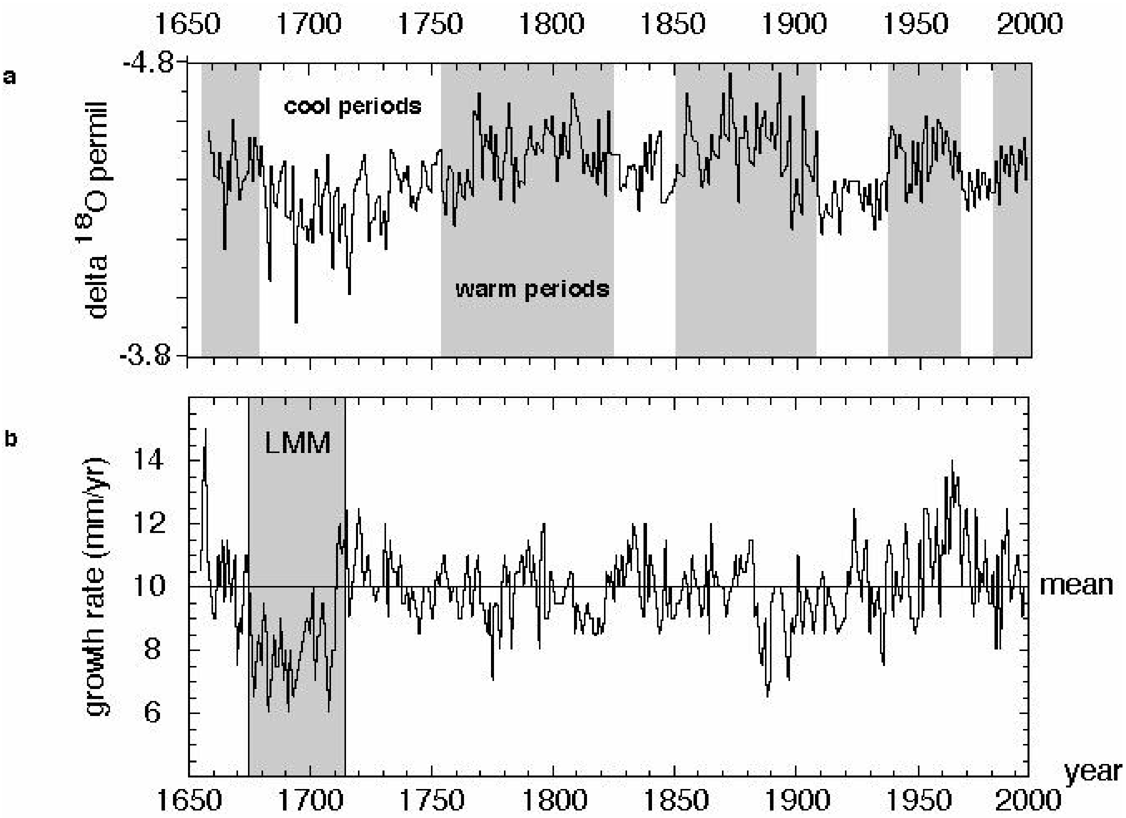
  1^{o}x1^{o} gridded GISST 2.3b for monthly mean temperatures dating back to 1871 prepared by Rayner et al. (1996). We used the period from 1982-present as the calibration interval.

The best fit for linear regressions between annual mean coral δ^{18}O and the NCEP-AOI-SST is SST = 2.061 – 5.298 δ^{18}O (r=0.9). For GISST 2.3b we obtained SST = 9.191 – 3.708 δ^{18}O (r=0.78). The mean square error for the estimated annual mean SST is 0.1K and 0.13K for NCEP-AOI-SST and GISST2.3b. In order to validate the coral-δ^{18}O-temperature calibrations we compared late 19th and early 20th century annual mean SST derived from GISST 2.3b with the coral data. The coral record successfully captures the general trend in GISST 2.3b for the 20th century.

The 338 year coral record displays marked positive and negative δ^{18}O shifts during certain time periods (Fig. 3). The most positive excursion coincides with the Late Maunder Minimum of solar forcing which extends from 1675-1715. During the LMM, coral growth rates are the lowest of the entire record (Fig. 3).

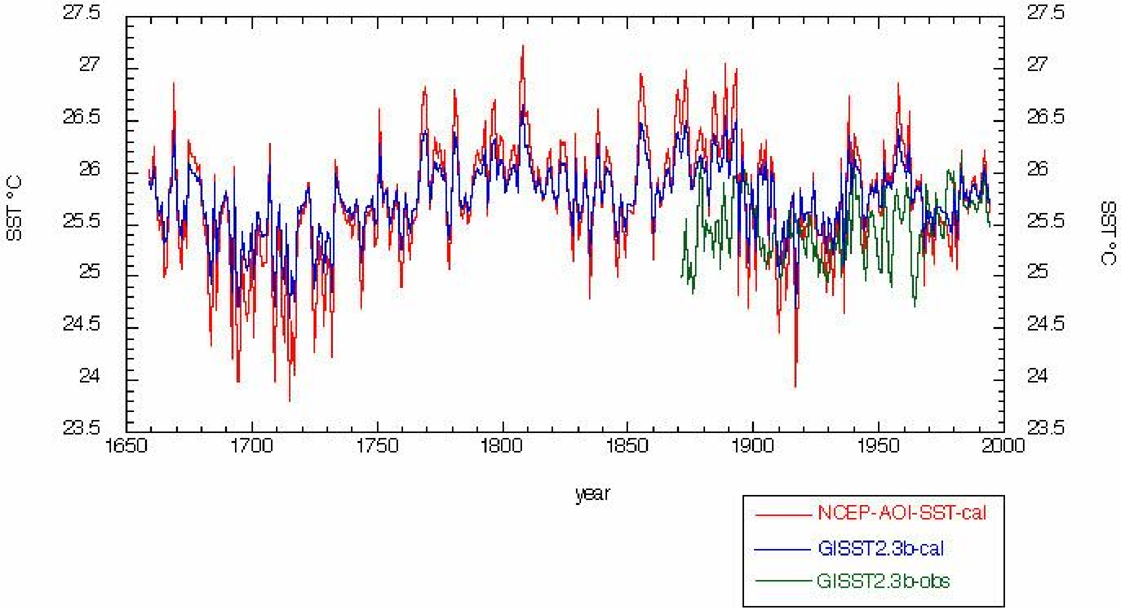
The comparison of calculated annual mean SST during the LMM (1670-1710) with the preceding (1658-1669) and following periods (1711-1730) suggests that the mean SST was 0.4 K cooler in the former and similar in the latter period (Fig. 3). During the time interval from 1730-1800 a warming in annual mean SST of about 0.4 K is observed reaching values similar to the period from 1658-1669. Compared to the present (1980-1995), the annual mean SST during the LMM was about 0.3K cooler. Interannual SST variability is strongly enhanced during the LMM in comparison with the recent time interval. This also holds for the preceding and following reference periods as well as all cool episodes (1820-1850, 1890-1930).

Figure 3 - The 338 year record of variations in mean annual coral $\delta^{18}O$ (a) and annual coral growth rate (b).



SSTs in DJFM during the LMM were on average 0.6K cooler than during the preceding interval from 1658-1669 and warmer by about 0.5K than the following period (1711-1730). The average SST's between 1730-1800 were 0.3 K cooler than during the period between 1658-1669. SSTs in JJAS during the LMM were on average 0.2K cooler than between 1658-1669 and warmer by about 0.05K than between 1710-1730. The average SST's between 1730-1800 were 0.6 K warmer than during the LMM.

Figure 4 – The reconstructed 338 year record of variations in sea-surface temperatures as inferred from the 1982-95 annual mean $\delta^{18}O$ -SST calibration equations using SST observations from NCEP-AOI-SST (Reynolds and Smith, 1994; red) and GISST 2.3b (Rayner et al., 1996; blue). Observed SST based on GISST 2.3b is shown for comparison (green).



Several previous studies with corals have established growth conditions as far back as the LMM. These studies are relevant for

- Galapagos (E-Pacific, 1°S, 90°W, Dunbar et al., 1994): 367 years of coral $\delta^{18}O$ and $\delta^{13}C$ records from 1587-1953, with annual resolution. The intervals 1660-1680, 1710-1800 and 1870-1895 were found warmer than "normal", whereas the intervals 1600-1660, 1680-1700 (LMM) and 1800-25 were cooler than on average. $\delta^{18}O$ is about 0.1-0.15‰ heavier during the LMM than between 1660-70 and 1705-1750 and thus indicates a *cooling of 0.5-0.75K*. The coral growth rates during the LMM were reduced, but increased after the LMM (1700 -1730).
- New Caledonia (SW-Pacific, 22°S, 166°E, Quinn et al., 1998): 335 years of coral $\delta^{18}O$ and $\delta^{13}C$ records from 1657-1952, with seasonal resolution. The records describe a brief interval of modest cooling in the late 17th century, with an annual mean *SST about 0.2-0.3K cooler* between 1680-1740 than between 1660-1680 and 1740-1750

- Great Barrier Reef (SW-Pacific, 10°S-23°S, 150°E, Hendy et al., 2002): 420 years composite record of 8 corals of coral δ^{18}O, Sr/Ca and U/Ca from 1565-1988, with a 5-year resolution. SST were *0.3K cooler* between 1565-1700 than the long term average.
- Puerto Rico (Caribbean Sea, 18°N, 67°W; Winter et al., 2000; Watanabe et al., 2001): 313 years of coral growth from 1685-1998, four high-resolution windows of δ^{18}O, δ^{13}C. The window from 1700-1705 shows a *2K cooling compared to the present* and warmer SST of about 0.9K from 1780-1785 and 1810-1815.

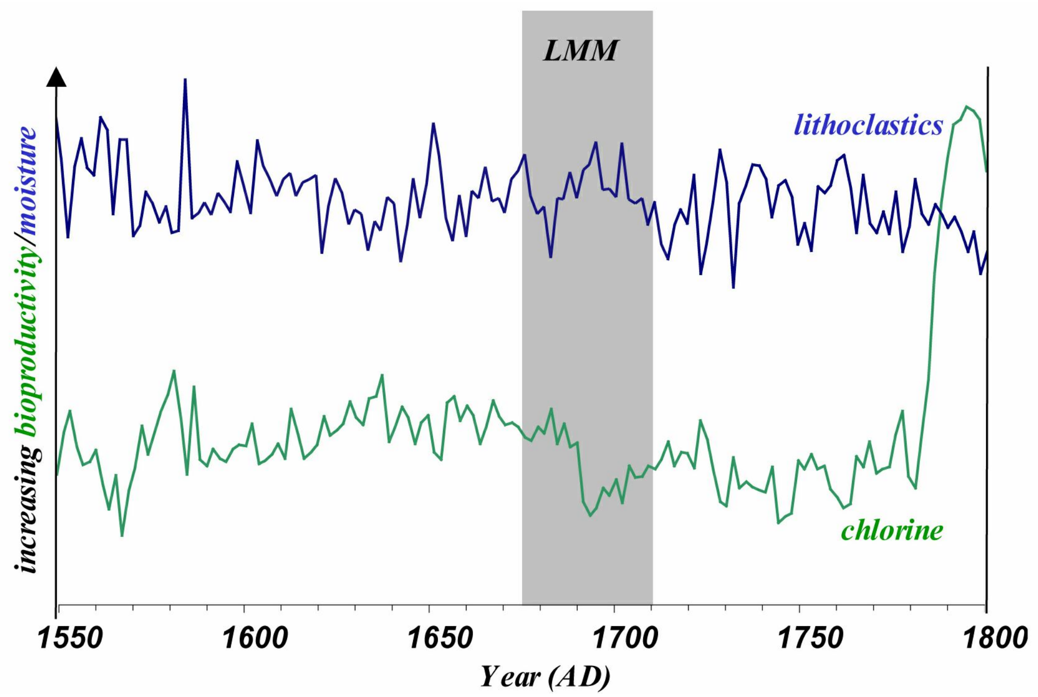
3.2 Marine Sediments

Laminated marine sediments have been recovered from the Peruvian shelf about 100 km west off Lima (Dullo et al., 2000). Oceanography off the coast of Peru and the climate of the region are fundamentally linked to ENSO variability. The nutrient-rich upwelling waters make the Peruvian shelf the world's most bioproductive marine environment supplying organic matter as photosynthesis pigments to the sediments. When trade winds weaken, upwelling is blocked by the advection of backflushing warm surface water from the western Pacific. Marine bioproductivity is strongly reduced and moisture is transported towards South America, bringing extensive rainfall into some regions of the arid to hyper-arid coastal deserts. With the run-off, lithoclastic matter is flushed via rivers into the sea. The sediments have been analysed with respect to tracers of primary production (chlorines) and lithoclastic sedimentation (Rein & Sirocko, in press). Together they describe the paleo - El Niño/La Niña modes of ENSO: Lithoclastics are more abundant during El Niño years, whereas bioproductivity is stronger in between (La Nina).

The dating of the uppermost sediments in core 106KL is based on two AMS - ^{14}C ages (1000 ±30 BP, 1305 ±25 BP; Rein, unpubl. data) and lead isotopes (Suckow, unpubl. data). A reservoir correction of 800 years was used for the correction and calibration of radiocarbon ages. This reservoir age is supported by lead isotopes for the topmost dating. Lead isotopes were also used to narrow down the calibrated age of the younger sample to 1790 ±20 cal AD. The calibrated age of the older dating is 1425 +15/ -10 cal AD. The remaining dates have been set by linear interpolation.

The lithoclastic sedimentation during the LMM is about average compared to the reference period. The frequency and intensity of EL Nino events as indicated by peaks in the lithoclastics (Figure 5) did not significantly change. Although lithoclastic sedimentation prior to 1450 AD was partly more variable, it was generally on a lower level. That means that the reference period and the LMM were wetter than the time before the Little Ice Age. Bioproductivity has been further reduced during the LMM although the time 1400-1790 AD, as a whole, including the reference period, is characterized by strongly reduced bioproductivity compared to the centuries before and two decades following (Rein, unpubl. data). The LMM is one of three periods of minimum bioproductivity (fig. 5) during the last millenium. Beside a decadal deterioration around 1565 AD, another extended period of reduced bioproductivity prevailed in the middle of the 18th century. As mentioned above high frequency bioproduction variability depends on ocean circulation (ENSO) but mid - to long-term reduced bioproductivity is related to lower sea-surface temperatures (Rein et al, unpubl. data).

Figure 5 Marine bioproductivity (chlorines) and continental moisture (lithoclastics) recorded in laminated sediments from the El Niño region off the coast of Peru.



deMenocal et al. (2000) found evidence for a strong cooling (-1 to –2 K relative to 1550-1800) for the West African coast in a core drilled at about 20 °N, 18°W, concurrent with a SST anomaly of –0.5 to –1 K derived from material at Bermuda Rise.

3.3 Lake Sediments

A new composite profile (cores HZM41 & HZM42) of mainly varved sediments from Lake Holzmaar (Germany) has been analyzed. Dating is accurate within ±15 years. The following properties have been determined:

- Magnetic susceptibility is a good approximation for clastic input into the lake basin. Lower values, as found during the LMM (Figure 6) thus possibly indicate reduced erosion in the catchment of the lake.

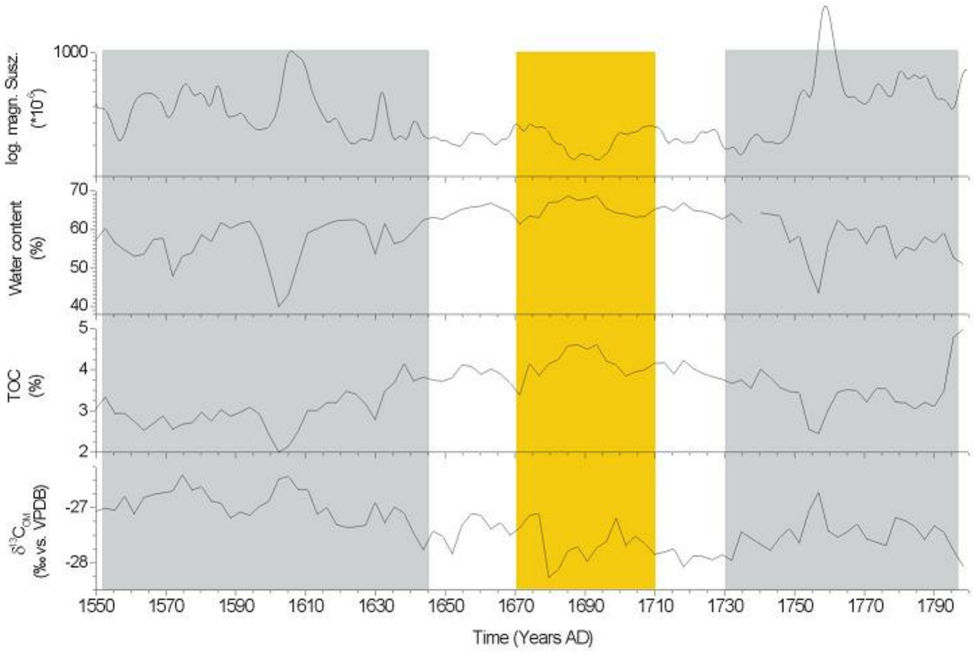
- Contents of water and total organic carbon (TOC) in the sediments can be related to higher primary production in the lake. However, these parameters are subject to a concentration effect when clastic input is reduced.

- Reduction of $\delta^{13}C$ values during the LMM suggests a massive disturbance of the lake ecosystem. The isotope reaction is possibly an effect of a reduced growing season due to an extension of winterly ice cover or cooler summer temperatures. However, the abrupt isotope reaction at 1675 can also be interpreted as a nonlinear response of the composition of the algal community.

- The diatom species *Aulacoseira subarctica* was abundant during the LMM, while it did not occur during the reference period (Kumke et al., this volume). The present-day occurrence of this diatom is restricted to northern or alpine lakes. Conditions under which this species lives include low light supply as under ice cover and turbulent waters.

- Available evidence from Lake Holzmaar sediment converge into a *LMM scenario characterized by cooler and dryer winters and temperate to cooler summers in Europe*. Effects for the lake are the reduction of clastic input, a shortening of the growing season for lacustrine algae due to the extension of the lake`s winterly ice cover and moderate summer water temperatures.

Figure 6 - Proxies from lacustrine sediments of Lake Holzmaar: magnetic susceptibility, water content, TOC and $\delta^{13}C$ (from top to bottom.


log. magn. Susz. (*10^{-6})
1000
Water content (%)
70
60
50
40
TOC (%)
5
4
3
2
$\delta^{13}C_{OM}$ (‰ vs. VPDB)
-27
-28
1550
1570
1590
1610
1630
1650
1670
1690
1710
1730
1750
1770
1790
Time (Years AD)

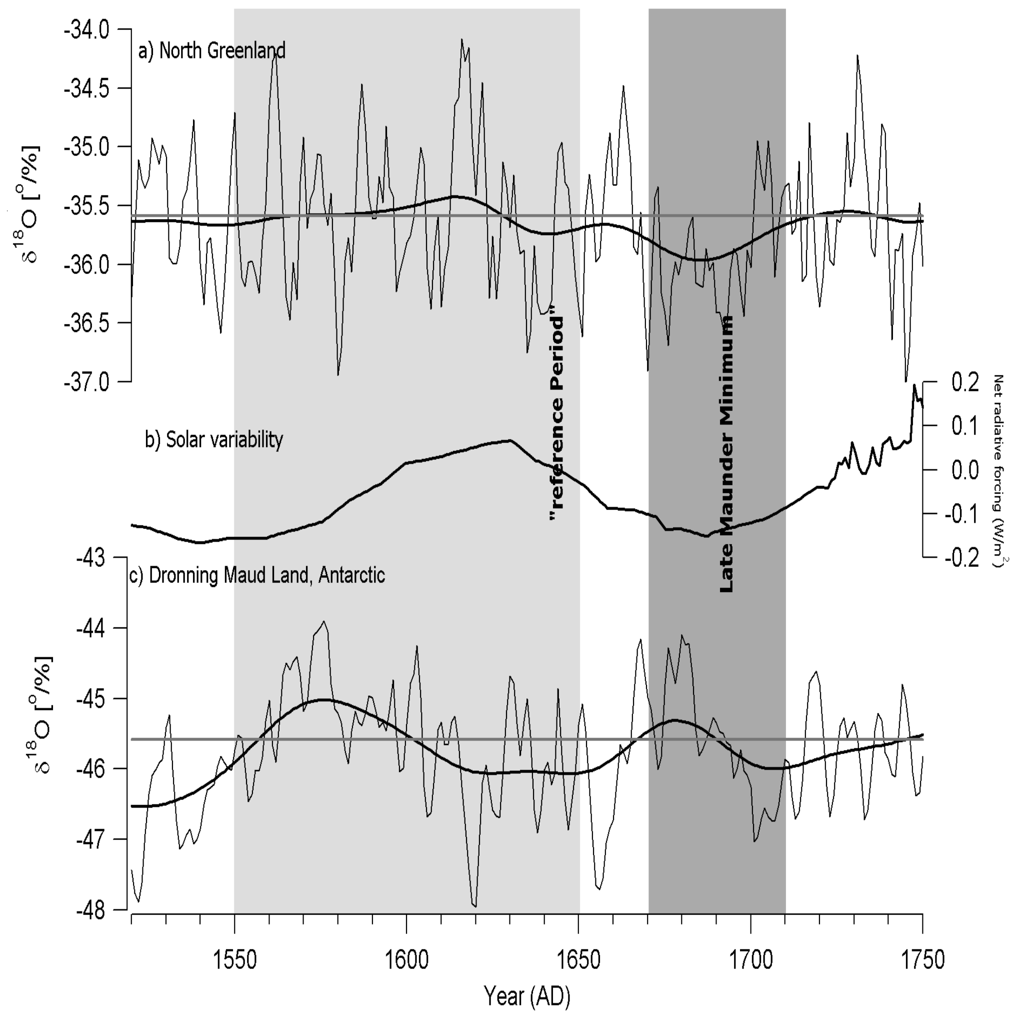


Figure 7

a) Stacked isotope record from five North-Greenland ice cores (Schwager, 2000)

b) Reconstruction of solar variability, deduced from ^{10}Be measurements (Crowley, 2000)

c) Stacked isotope record from three ice cores from Dronning Maud Land, Antarctica (Graf et al., in press)

All the data sets cover the time span over 1520-1750 year (AD). The thin lines represent annual data sets, the thick grey lines the average of the "reference period" 1550-1650 and the black thick lines a smoothed records using a running binominal filter.

3.4 Ice Cores

Five ice cores from the North-Greenland-Traverse (Schwager, 2000) and three ice cores from the inland ice plateau of Dronning Maud Land in the Atlantic sector of Antarctica (Graf et al., in press) were evaluated for their isotopic ($\delta^{18}O$) content (Figure 7). From these records stable isotope temperature time series covering the last 500 -1000 years were estimated for each region. The ice cores have been dated with an accuracy better than 3 years over the last 500 years by a combination of age markers (volcanic horizons in continuous sulfate and electrical conductivity), annual layer counting in high resolution density measurements, continuous flow analysis and Ca^{2+} and NH_4^+-stratigraphies.

The long-term variations of $\delta^{18}O$ in North Greenland indicate several persistent cold periods during the 14th, 15th, 17th and the first half of the 19th century (Schwager, 2000). Furthermore, for the period 1610 -1850 the isotope record shows a significant correlation with the low-frequency variability of the total solar irradiance (Fischer et al. , 1998). During the Late Maunder Minimum the stacked $\delta^{18}O$ profile from North Greenland shows an anomaly of about -0.4‰. Using the spatial $\delta^{18}O$ temperature gradient in recent firn of 0.64‰/°C (Fischer et al., 1995), this anomaly is equivalent to a cooling of about 0.6K compared to the “reference period” from 1550 -1650.

The long-term variations of $\delta^{18}O$ in Dronning Maud Land (DML) over the last 1000 years show remarkable features with a 350 -year period from 1180 to 1530 AD with decreasing $\delta^{18}O$ values and a return to the same values as prior to 1200 within a short 50 -year period (Graf et al., in press). The persistent cold periods of the “Little Ice Age” from North Greenland are not found in DML. The oxygen isotope ratio in DML during the Late Maunder Minimum reveals no deviation (+0.04‰) compared to the “reference period” from 1550-1650. However, during the Maunder Minimum we find a local $\delta^{18}O$ maximum around 1680 simultaneous to a minimum in North Greenland. This anomaly over the time span 1660-1700 amounts to 0.6 ‰ which is equivalent to a warming of about 0.8K using the spatial $\delta^{18}O$ temperature gradient in recent firn in DML of 0.77‰/°C (Graf et al., in press).

Thus, the ice core data provide evidence for a LMM -cooling in North Greenland and, at the same time, a warming in Antarctica.

3.5 Speleothems

Two sets of analyses of annual growth width of banded speleothems are available within the KIHZ data archive.

A small (35 mm high) stalagmite was collected from the cave Uamh an Tartair, part of the Cnoc nan Uamh cave system, in NW Scotland (Proctor et al., 2000) and examined for annual luminescent bands using standard UV microscopy techniques. It was continuously banded with a total of 1087 annual bands. No evidence of any hiatus was found, suggesting continuous growth. However a small uncertainty in counting was introduced by occasional double bands, implying a counting error of <20 years. Thus, the stalagmite was deposited over a period of 1087±20 years, from about 900 AD to the present. The thickness of the bands, i.e., the growth rate of the stalagmite, depends on annual precipitation, and to the hydrological situation, in particular vegetation.

The time series of normalized band width is shown in Figure 8. During the LMM conditions were near normal. An episode prior to the LMM, in the middle of the 17th century was likely wetter and/or cooler. Taking into account possible dating errors, the episode may have been somewhat earlier, but not later, in particular not during the LMM (1675-1710).

Stalagmites from caves in New Mexico (USA) have been examined (Polyak and Amserom, 2001). In this semi-arid region with seasonal precipitation, stalagmite growth is moisture limited. The stalagmite BC2 provides a continuous sequence of 292 bands and two U-series dates (1518 ± 13 and 1714 ± 50 years B.P.). After thicknesses of about 0.1 mm were found for the time until about 1650, an abrupt lowering at about 1650 indicates the beginning of *dry conditions during the LMM* until about 1720 (Figure 9). If this is a inhomogeneity in the data or a real signal remains to be seen.

Figure 8 - Evidence from speleothems.: NW Scotland: Normalized annual bandwidth. Error < 20 years. From Proctor et al. (2000).

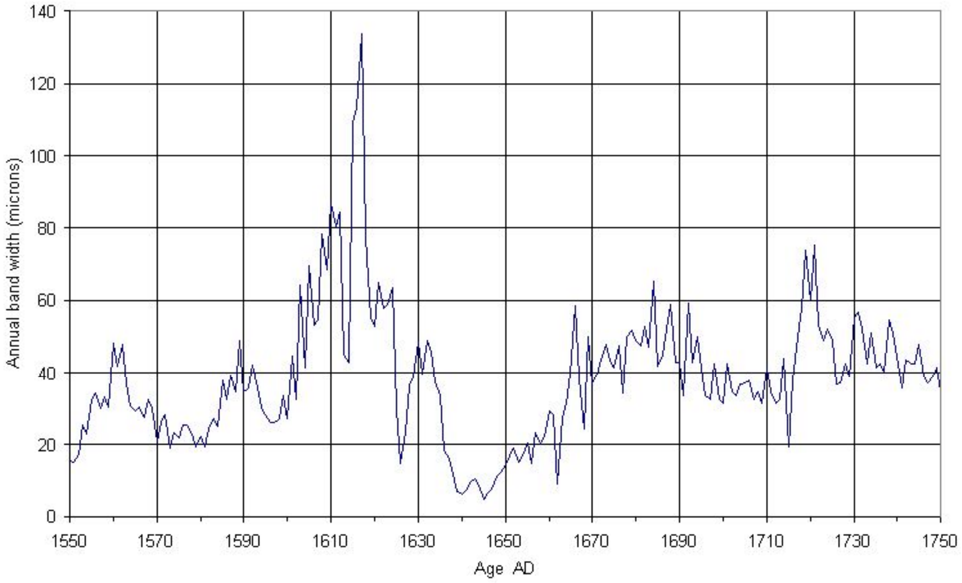
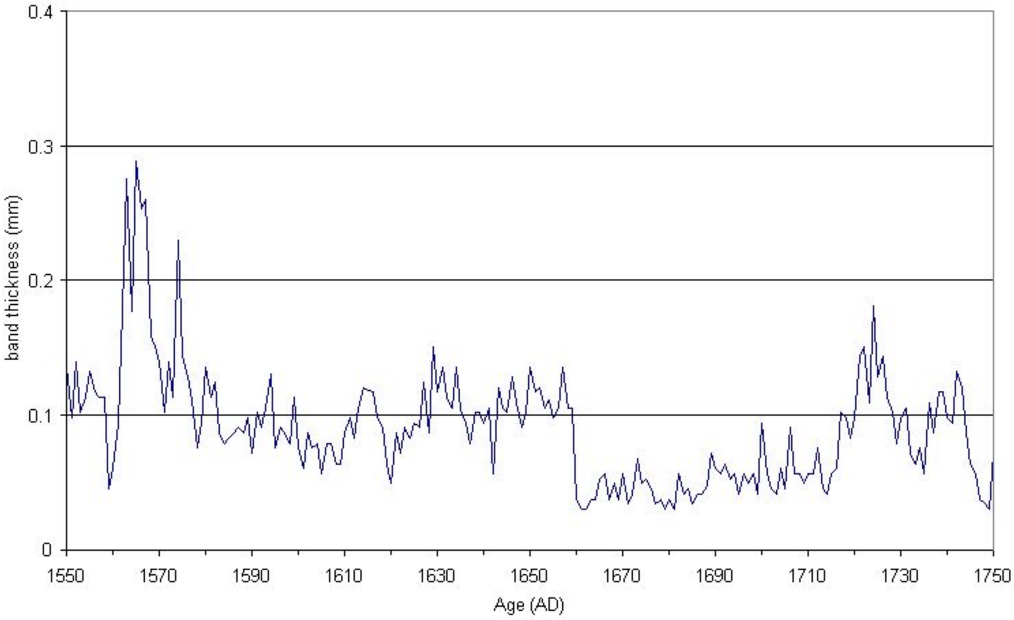


Figure 9 – Evidence from speleothems: Speleothem BC2 from New Mexico. Low values indicate dryness. From Polyak and Asmerom (2001)



4 Numerical model simulation of the LMM

As already mentioned in the Introduction, a simulation with a state -of-the-art climate model, ECHO-G, featuring a T30 atmospheric general circulat ion model (E CHAM4) and a T42 ocean model (HOPE -G). The simulation was extended over 450 years, with realistic time -dependent forcing of solar output, volcanic aerosol forcing and forcing due to greenhouse gases (von Storch, 2002). The resulting climate va riations reflect the influence of these “external” factors as well as the omnipresent interval variable, often called “climate noise” (von Storch et al., 2001).

In terms of temperature, the simulated temperatures during the period 1675 -1710 are rather cold, when compared to the anthropogenically undisturbed period 1550 -1800. The model output has been evaluated for the winter (DJF) season in some detail (von Storch, 2002), and it was found that the simulated temperature distribution in Europe was quite consistent with the historical evidence. The evidence outside Europe is sparse, but also these were mostly consistent with the model results. In the following we present global maps of seasonal means of air temperature (at the ground), precipitation and zonal wind in Northern Hemisphere winter (DJF). Results for the other seasons (MAM, JJA and SON) as well as annual results are given on the internet, http://w3g.gkss.de/staff/LMM/LMM-data.htm.

The maps shows the difference of the 1675-1710 and 1550-1800 time means. Because of the internal noise in the system, the difference maps reflect to some extent, or even entirely such random variations. The robustness of the signal was tested with a local t-test, assessing the chances that the mean difference 1675-1710 minus 1550-1800 may be due to random variations and a systematic effect. Significance levels of 99%, 95% and 90% are used, equivalent to a risk of an erroneous rejection of the null hypothesis of 1%, 5% and 10%. Maps of the risks are given on the internet address given above.

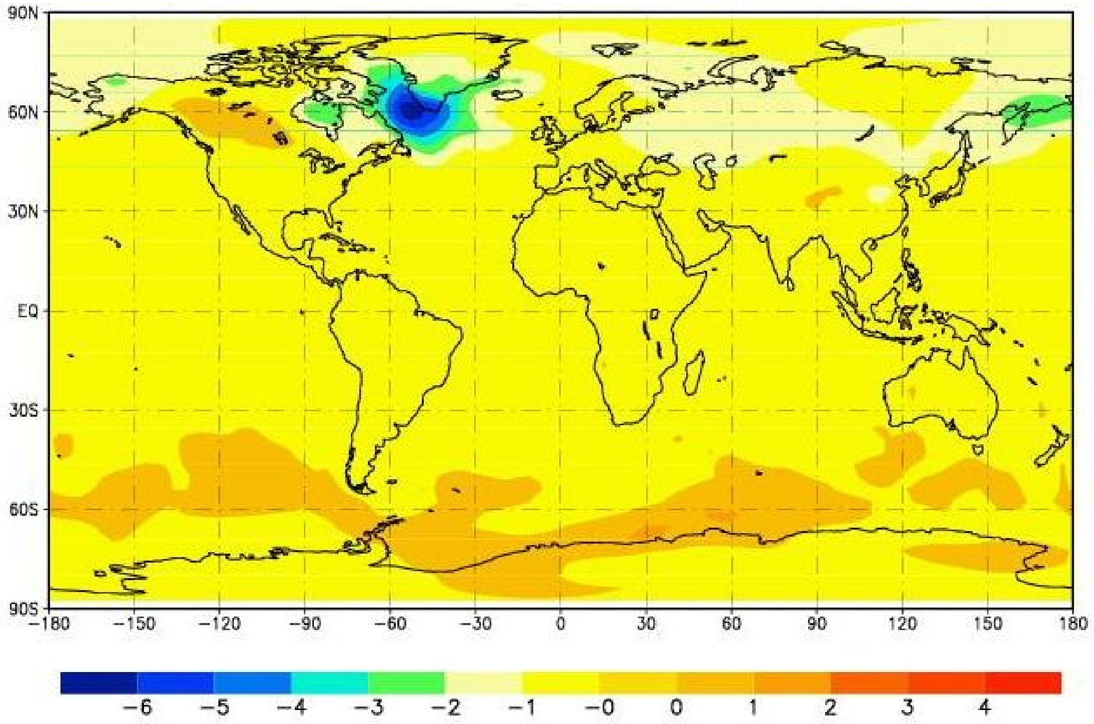
4.1 Air temperature

The DJF temperature map, displayed in Figure 10, are characterized by an almost global cooling. Only in the southern ocean and over Antarctica a warming is to be seen. In all seasons but northern summer (JJA), a pronounced cooling of minus two and more degree K is found in the Labrador Sea or in the Hudson Bay. Thus, the cooling found in DJF extends into the neighboring seasons, MAM and SON, but not into summer (JJA). The signal north of 30 ^{o}S is almost everywhere significant at the 95% level.

These results are by and large consistent with the historical record for Europe outlined in Section 2 and the evidence from Lake Holzmaar (Section 3.3). All seasons were found to be cooler than in the years before and after, but regional details like the warming in Hungary has not been reproduced. In fact, one would not expect a climate model to resolve such regional scale spatial differences (von Storch, 1995). Also the winter cooling reported by Ogilvie (1994) for Iceland and claimed by Arakawa (1957) for Japan are not in conflict with the model results. However, the evidence provided by the speleothem evidence in Scotland (Section 3.5) of almost normal temperatures is not consistent with the general impression of cooling in Europe during the LMM.

The coral data reported in Section 3.1 as well as the marine evidence off West Africa (Section 3.2) are consistent with the result that the cooling during the LMM was not confined to Europe or the north Atlantic sector, but was also felt throughout the tropics. The ice core evidence (Section 3.4) suggests an global out-of-phase link between Northern Greenland (cooling) and the Atlantic sector of Antarctica (slight warming), a feature also found in the model data.

Figure 10 – Simulated air temperature differences 1675-1710 minus 1550-1800 in DJF. Degree K.

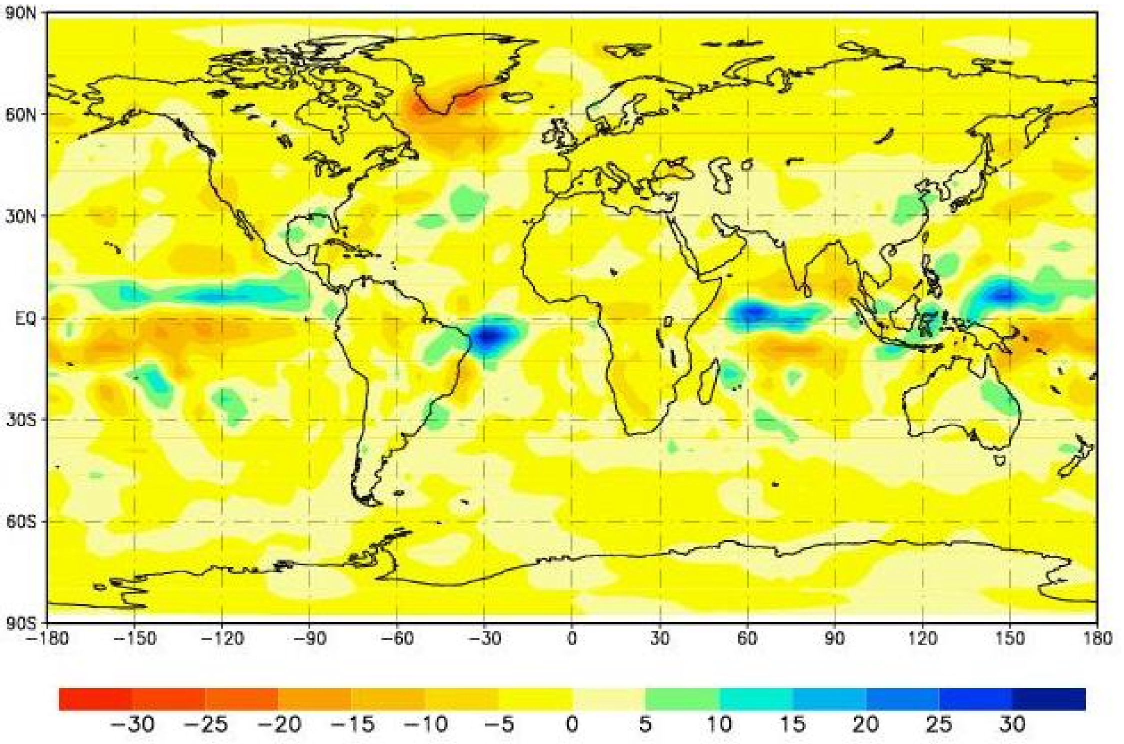


4.2 Precipitation

The DJF precipitation difference map is shown in Figure 11. Various patterns of increased and reduced precipitation are found, mainly in the tropics. However, most of these features can not be distinguished from the effect of random variations. Only the strong reduction of precipitation over the Labrador Sea and the Hudson Bay is strongly significant. A similar feature emerges in the other seasons. Also the DJF-intensification of the ITCZ north of the East Pacific equator is significant, albeit marginally (10%). In JJA and SON, the slight reduction of precipitation over the Artic is significant as well. Everything else can be explained with reasonable likelihood as result of averaging random variations. In particular, in Europe, where historical evidence is rich, no clear signal emerges. Also the Indian monsoon is not markedly affected in the model.

The model is not capable of reproducing regional-scale (< 10^7km^2) patterns in a realistic manner (Giorgi et al., 2001; von Storch, 1995), in particular when the precipitation is controlled by small-scale topography; therefore it is not surprising that the European details of the LMM in terms of precipitation are not reproduced. Also, the dryness derived from the New Mexico speleothem (Section 3.5) has no robust counterpart in Figure 11.

Figure 11 – Simulated precipitation differences 1675-1710 minus 1550-1800 in DJF. mm/ month.



4.3 Zonal wind

The zonal wind exhibited stable features only in the areas south of Greenland, where the climatological easterly winds are weakened, which may be associated with less cyclogenesis, and a band of westerly anomalies over the Southern ocean, i.e. a weakening of the “roaring forties”. Generally, the differences in the zonal wind are weak. Over Europe no stable pattern emerges; anomalous easterlies have been simulated only for summer (JJA), but are not statistically significant.

Very little evidence about wind fields has been extracted form the geological archives. One aspect was the reduced upwelling off the coast of Peru (Section 3.2) which would be associated with weakened easterlies, i.e. anomalous westerly winds. During JJA and DJF weak westerly anomalies are simulated, but they far from statistically significant (not shown). Of course, statistical significance is a matter of both, the strength of the signal and the number of available samples, so that a (so far unavailable) ensemble of simulation may eventually help to identify a weak but nevertheless stable signal in terms of ENSO characteristics.

4.4 Subsurface temperature

Finally, the simulated temperature in the ocean has been analyzed (Figure 12). At 100 m the global ocean does not exhibit systematic changes as in the air temperature (Figure 10). Some warming appears in the Southern Ocean as well as a marked, isolated cooling south of Greenland. At 800 m, most of the ocean is actually warmed, but the cooling south of Greenland is still visible. At 2100 m, the difference is rather small, as one would possibly expect because of the involved time scales.

5 Conclusions

A first attempt was made to collect the diverse evidence about the climate during the Late Maunder Minimum 1675 -1710 from a variety of proxy from the project “Klima in historischen Zeiten” (KIHZ). As a reference , the time interval 1550 -1800 was chosen, because this interval is not affected by anthropogenic warming, and fully covered by the climate model simulation.

So far, too often, proxy data are extracted and interpreted without consistency check with other proxy-data, both in terms of informational content as well as dating. In the present case, the different groups within KIHZ have tried to overcome these obstacles. As a result, the LMM emerges as a global phenomenon.

There is some consistency of the empirical evidence with the modeling results. that are responses to time dependent solar output, stratospheric aerosol load and greenhouse gas concentrations. Together, this suggests that similar dynamics are behind the real and the simulated LMM. However, this suggestion should be considered with caution until further analysis of the model data and comparisons with other proxy -data are completed.

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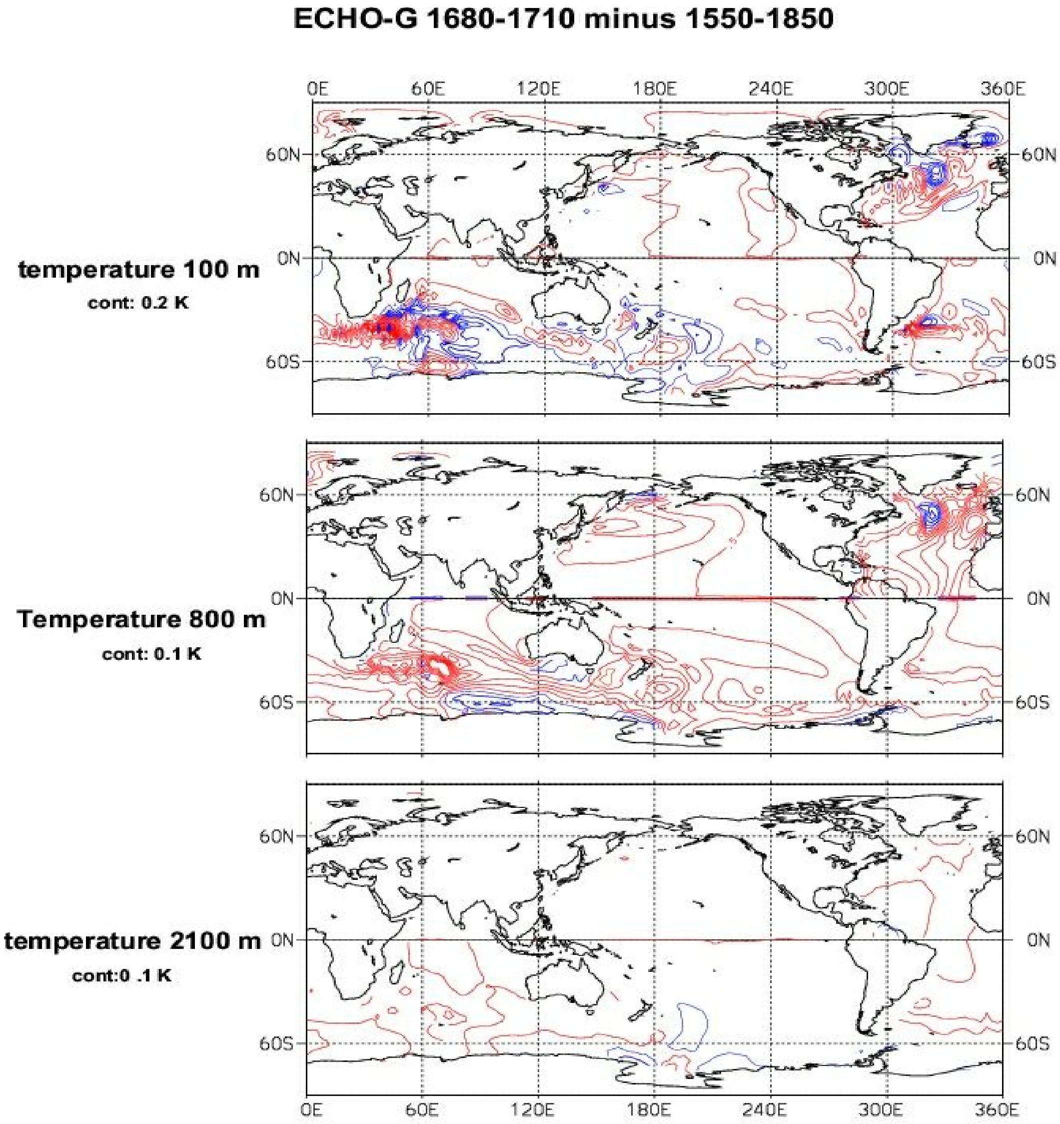
Key words: Late Maunder Minimum, proxy data, dating problems, climate modeling.

Figure 12: Temperature difference 1680 -1710 minus 1550 -1800 in the climate model at three levels: 100 m (below surface), 800m and 2100m. Contour lines 0.2 K (top) and 0.1 K middle and bottom panel). Blue lines represent negative temperature differences, red lines positive differences.



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