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Natural climatic variability and the Norse settlements in Greenland

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Abstract A multi-millennial simulation with the CSIRO Mark 2 coupled global climatic model has been used to determine whether climatic conditions approximate to those experienced by the medieval Norse settlers in Greenland could be identified. The aim of this analysis was to see whether such conditions could be replicated by the natural climatic variability in this unforced simulation, in order to counteract claims that the current observed global warming is merely another example of this type of climatic regime. This view has been expressed in the media in an attempt to refute the existence of a CO_2-induced global warming. A 291-year period of above-average temperature followed by a 41-year cooler period were identified in one millennium of the simulation, and subsequently used as an analogue of conditions representative of the time of the Norse settlements. Considerable interannual variability existed in both these periods, but with noticeable positive and negative surface temperature anomalies in the warm and cold periods respectively. Thus the warm period was not a time of uniform benign conditions. Above-average precipitation was also associated with the warm period, and these climatic conditions would have enhanced pasture growth and hay production (the only crop the Norse produced) thereby sustaining the livelihood of the Norse Greenlanders. The climatic conditions associated with the cold period in the model were probably sufficient to limit the survival prospects of the settlers, especially when other, probably more critical, deleterious factors are taken into account. The temperature anomalies replicated in the simulation are similar to the limited proxy data, but may be smaller in magnitude: nevertheless they appear to be sufficiently large to have affected the viability of the Norse Greenlanders.

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After considering possible climatic mechanisms that could have contributed to these warm and cold periods it was concluded that they are simply a consequence of stochastic influences generated by nonlinear processes in the simulation. Thus this simulation provides no support for the contention that the current global warming is a manifestation of conditions prevailing during the Norse settlements in Greenland.

1 Introduction

Both the founding of the Norse settlements in Greenland around AD 984 and their subsequent disappearance by the end of the fifteenth century have frequently been discussed as examples of historical events that may demonstrate the influence of environment and climate on human societies (McGovern 1991, 2000; Buckland et al. 1996; Barlow et al. 1997). The occurrence of the initial colonisation has been cited as circumstantial evidence for a mild climatic phase in the region of western Greenland around the end of the tenth century and has helped to give rise to the concept of the so-called "Medieval Warm Period". One of the proponents of this concept was Lamb (see e.g. 1965) who provided a comprehensive analysis of the climatic data available at that time. He suggested that during the MWP temperatures in many parts of the world were 1 K to 2 K above present values. Other perspectives on the validity of this suggestion have been provided by Hughes and Diaz (1994) and Ogilvie and Farmer (1997). See also Ogilvie et al. (2000). More recently, the case for the influence of climate on events in Norse Greenland has been popularized by Diamond (2005).

In spite of all the research which suggests that the concept of a globally warm "Medieval Warm Period" is at best, simplistic, at worst, erroneous, there now appears to be a widely accepted view, particularly in the general media, that the MWP was a time when global climate was as warm or warmer than at present. A disturbing consequence of this view is that it has been used as an argument to bolster the claim that current global warming is just another example of a natural variation in climate such as occurred in medieval times. The Greenland Norse would no doubt be quite surprised to learn that their settlements have become an issue in the politics of greenhouse science.

Clearly, the circumstances surrounding the establishment and subsequent demise of the Greenland Norse settlements must be seen primarily in the context of political and economic factors, even if the natural environment also played a part. The Scandinavian expansion that manifested itself in the "Age of the Vikings" (ca. AD 870 to 1100) had begun long before this and is associated with a variety of political, economic and social factors (see e.g., Foote and Wilson 1980). The resulting Viking raids over much of Europe and elsewhere went hand-in-hand with trading and settlement and resulted in the colonisation of Iceland, Greenland and the attempted colonisation of the New World.

Greenland was settled by the Norse from Iceland (Barlow et al. 1997). The attraction of Greenland was that it offered the opportunity to attain prestige associated with land holdings, as well as trade from furs and walrus ivory (Dugmore et al. 2007). The Norse established two settlements on the west coast of Greenland in sheltered fjords. These were known as the Western settlement (64° N) and the Eastern settlement (61° N), with respective populations of about 1,000 and 4,000.

Compared to the native Inuit, life was more marginal for the Norse Greenlanders, even though they survived 500 years, as they failed to adopt the hunting and survival techniques of the former, while seeking to maintain a farming culture based on pasture (Buckland et al. 1996; Dugmore et al. 2007). Climatic conditions played an important role in the life of the Norse Greenlanders because of the necessity of harvesting sufficient hay to permit their farm animals to survive over winter. Dugmore et al. (2007) have discussed the implications of interannual climatic variations on hay production and the consequent requirements for the over-wintering of the stock. In addition, climate affected the ability of the Norse to catch seals, which formed a major part of their diet. For instance, McGovern (1991) estimates a factor of six variation in seal catches in southern Greenland for the recent period 1954–1975 attributable to climatic fluctuations alone.

However, climate was only one of the possible factors, and probably not the most critical one, contributing to the eventual demise of the Norse Greenlanders. The following is a list of possible reasons why the settlements ultimately failed, (Buckland et al. 1996; Barlow et al. 1997; Dugmore et al. 2007; McGovern et al. 2007).

(i) Norse impact on the environment
(ii) Climatic variability
(iii) Decline in contact and trade with Norway.
(iv) Increase in hostile contact with the Inuit.
(v) The conservative outlook of the Norse.
(vi) Probable inbreeding given the size and isolation of the two populations.
(vii) Plague, reducing the manpower below critical levels.

The basic issue to be considered in this paper is how important were climatic fluctuations in determining the establishment, survival and ultimate demise of the Norse settlements in Greenland? These climatic influences have to be weighed against the other factors listed above in the critical question concerning what caused the demise of these settlements. This question has also been discussed by Buckland et al. (1996) and Barlow et al. (1997), with the former concluding “Norse society in the early fourteenth century had created a disastrous vulnerability to any curtailment in growing season and pasture productivity”, thereby emphasising the sensitivity to climatic fluctuations.

Importantly, it is necessary to distinguish between climatic fluctuations over Greenland and separately over the northern hemisphere or the globe. Estimates of the temperature fluctuations over the northern hemisphere for the last 2,000 years are presented in Fig. 2 of Jones and Mann (2004). These indicate a temperature anomaly of about −0.2 K for the first millennium, with the anomaly attaining about −0.4K during the Little Ice Age (LIA). As such this figure does not support the existence, at least for the northern hemisphere as a whole, of the MWP. Jones and Mann (2004), see also Hughes and Diaz (1994), provide an extensive discussion concerning the lack of evidence for a MWP. There is also a similar question concerning the basis for the LIA. This was not simply a period of below average temperatures, universal across the globe. There were regional temperature variations and episodes of both positive and negative temperature anomalies. See the extensive discussion on the LIA in Iceland and surrounding regions by Ogilvie and Jonsson (2001) and the review of by Jones and Mann (2004).

On the basis of a very careful analysis of proxy data Osborn and Briffa (2006) found "evidence for intervals of significant warmth in the northern hemisphere within the so-called MWP and for significantly colder intervals during the so-called LIA period". Note, they were not discussing conditions averaged over the northern hemisphere. Specifically, for the west Greenland region they show multi-decadal to centennial temperature fluctuations for the interval AD 800 to 2000.

Proxy estimates of temporal variability of temperature over Greenland (Dansgaard et al. 1975; Jennings and Weiner 1996) indicate the occurrence of decadal or longer positive and negative temperature fluctuations during the MWP. The amplitude of these time-smoothed fluctuations is about ±1 K. Importantly, this indicates, as might be expected, that the MWP was not a time of uniform positive temperature anomalies in Greenland. Nevertheless, Dahl-Jensen et al. (1998) have derived a remarkably smooth curve of temperature anomalies for Greenland for the last two millennia that suggests a +1 K anomaly around AD 1000 and a −1 K anomaly around AD 1600.

Despite the disparity of views regarding the occurrence or otherwise of the MWP, it seems plausible to assume that at least Greenland experienced a slight warming for a period of some centuries. This does not imply a uniform positive temperature anomaly for this period. The evidence, Dansgaard et al. (1975) and Osborn and Briffa (2006), indicates alternating positive and negative temperature anomalies over such a period, but presumably with an overall positive bias.

The above assumption will be used as the working hypothesis for this paper. In this context the output from a 10,000-year simulation with the CSIRO Mark 2 coupled climatic model for unforced conditions has been analysed to explore a range of climatic factors relevant to the climate of Greenland. The objective is to determine to what extent natural climatic variability could have been an issue in the demise of the Norse settlements.

A number of simulations have explored aspects of climate over the past millennium (Collins et al. 2002; Zorita et al. 2004; Goosse et al. 2005; Hunt 2006), but to the author's knowledge only one simulation has specifically investigated Arctic conditions relevant to the Greenland Norse issue (Goosse and Renssen 2003). They used a rather simple coupled model, with an arbitrary correction to the precipitation rate to reduce climatic drift. They presented results only for annual mean surface temperature for the past millennium. Over the Arctic they concluded that centennial-scale variability was primarily attributed to external forcing with natural variability having a smaller role. Specifically over Greenland their simulation showed less agreement with observations.

2 Model description and experimental details

The CSIRO Mark 2 coupled global climatic model was used to generate the data sets used in this paper. The model consists of atmospheric, oceanic, biospheric and sea-ice components, as described by Gordon and O'Farrell (1997). The horizontal resolution of the model is based on the R21 spectral formulation, implying gridboxes spaced at 5.625° longitudinally and 3.25° latitudinally, giving a total of 3,584 gridboxes per vertical level distributed over the global surface.

The atmospheric and oceanic components interact via radiative and heat fluxes and dynamical processes at the oceanic surface for each model timestep of 20 min. The widely used flux correction technique (Sausen et al. 1988) was applied to couple these two components. These corrections vary monthly, but being invariant from year-to-year do not influence interannual variability and thus the simulated climate.

The atmospheric model has nine vertical levels, diurnal and seasonal variability, a mass flux convection scheme, semi-Lagrangian water vapour transport, gravity wave drag and a cloud parameterization based on relative humidity. The oceanic model is based on version 2 of the Modular Ocean Model of the Geophysical Fluid Dynamics Laboratory, with temperature and salinity grid points corresponding to those used in the atmospheric model. The oceanic model has 21 vertical levels and realistic bottom topography. An eddy-induced advection scheme was implemented thus enabling the background diffusivity to be set to zero. Wind forcing of the upper three oceanic levels is crudely represented by setting a minimum lower limit to the vertical diffusivity, see Hirst et al. (2000) for further details. The biospheric scheme has a number of different soil and plant types, with the latter's properties varying on a monthly timescale. A rather simple two-layer soil moisture formulation is used. Thermal processes determine the growth and decay of sea ice, while dynamical processes can cause thinning or compaction of the ice. The sea ice can also be transported by oceanic currents or wind forcing.

The present simulation was initiated from a previous 1,000-year simulation of the model; hence all climatic variables were fully developed. The model was run out for 10,000 years for present climatic conditions, using an atmospheric CO_2 concentration of 330 ppm. No external forcing such as solar perturbations, volcanic forcing or changes in greenhouse gas concentrations were permitted during the model run. Thus, all climatic perturbations obtained are attributable to naturally occurring climatic variability generated solely by processes internal to the simulated climatic system.

The simulation does not represent a progression through the Holocene, but 10,000 years of climatic fluctuations representative of current conditions.

All results presented here have been restricted to a single millennium of the simulation, years 9,001–10,000. This is an arbitrary choice; results for other millennia are very similar except for outlier events specific to a given millennium. The choice of a single millennium for analysis is appropriate given that the MWP and LIA were effectively limited to the last millennium.

3 Simulated Greenland climatology

A brief summary of the simulated surface temperature and precipitation for Greenland is presented here to establish the verisimilitude of the model for this region.

In Fig. 1 the annual mean surface temperature for the Greenland region averaged over years 9,001 to 10,000 of the simulation is illustrated. Given the fairly low horizontal resolution of the model the orography over Greenland is highly smoothed, hence the lowest observed temperatures over the peak of the Greenland ice sheet cannot be expected to be simulated. Consequently, the minimum simulated temperature in Fig. 1 is 250 K compared with an observed value of 240 K (Putnins 1970).

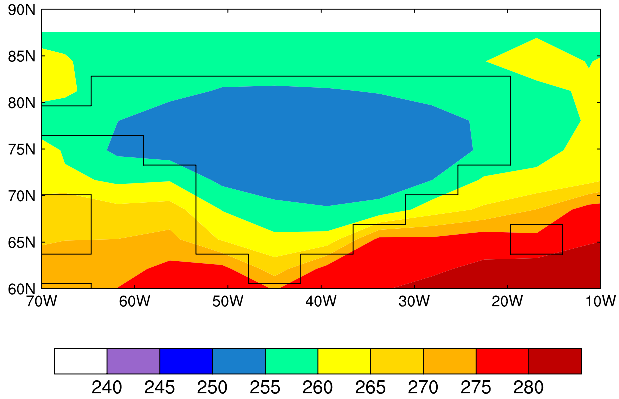


Fig. 1 Climatological distribution of the annual mean surface temperature for the Greenland region based on years 9,001–10,000 of the simulation. The *colour bar below the figure* gives the temperature in K

Nevertheless, the latitudinal variation of the surface temperature is basically replicated, especially in southern Greenland, which is the region of interest here.

The seasonal cycle of surface temperature for a model gridbox (65° N, 50° W), near the Western settlement site, is shown in Fig. 2 (results for the Eastern settlement (61° N, 45° E were very similar). Temperatures over individual years range from about 250 K to 283 K for the 20-year period illustrated. Since this was a "warm phase" of the simulated Greenland climate (see below), there are a number of years in Fig. 2 where the minimum winter temperature was well above 250 K. The time series in Fig. 2 agrees reasonably well with observations for a site north of the gridbox used here (Hanna and Valdes 2001). In Fig. 2 the observed maximum temperatures exhibited rather little interannual variability in contrast to the minimum values. The brevity of the summer period with temperatures above freezing point in Fig. 2 is particularly noteworthy, and emphasises the extreme environmental conditions the Greenland Norse experienced.

Annual mean precipitation, averaged over years 9,001 to 10,000 of the simulation, is shown in Fig. 3 for the Greenland region. It has the same broad characteristics

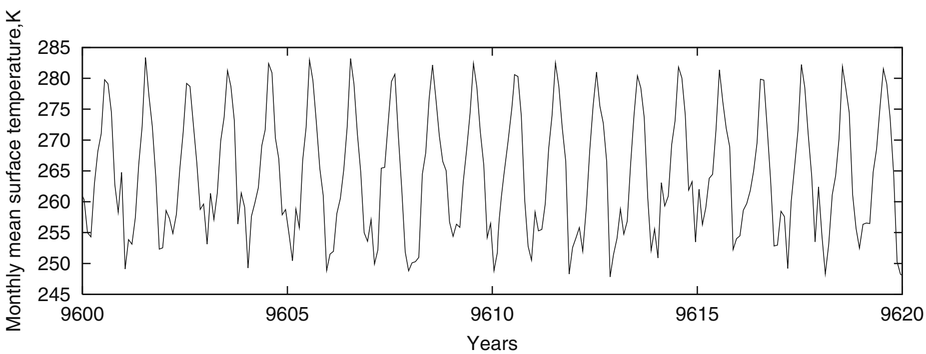


Fig. 2 Seasonal cycle of the surface temperature from a 20-year sample of the simulation for a model gridbox (65° N, 50° W)

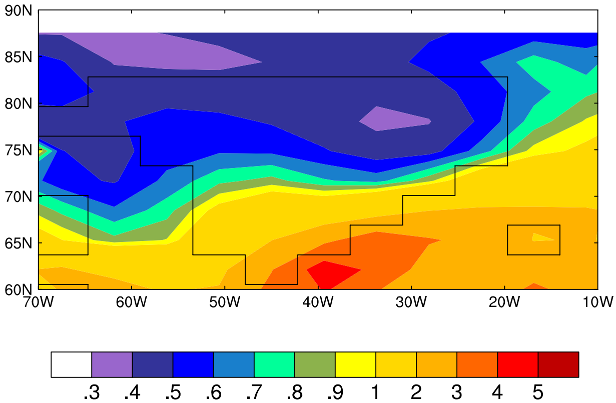


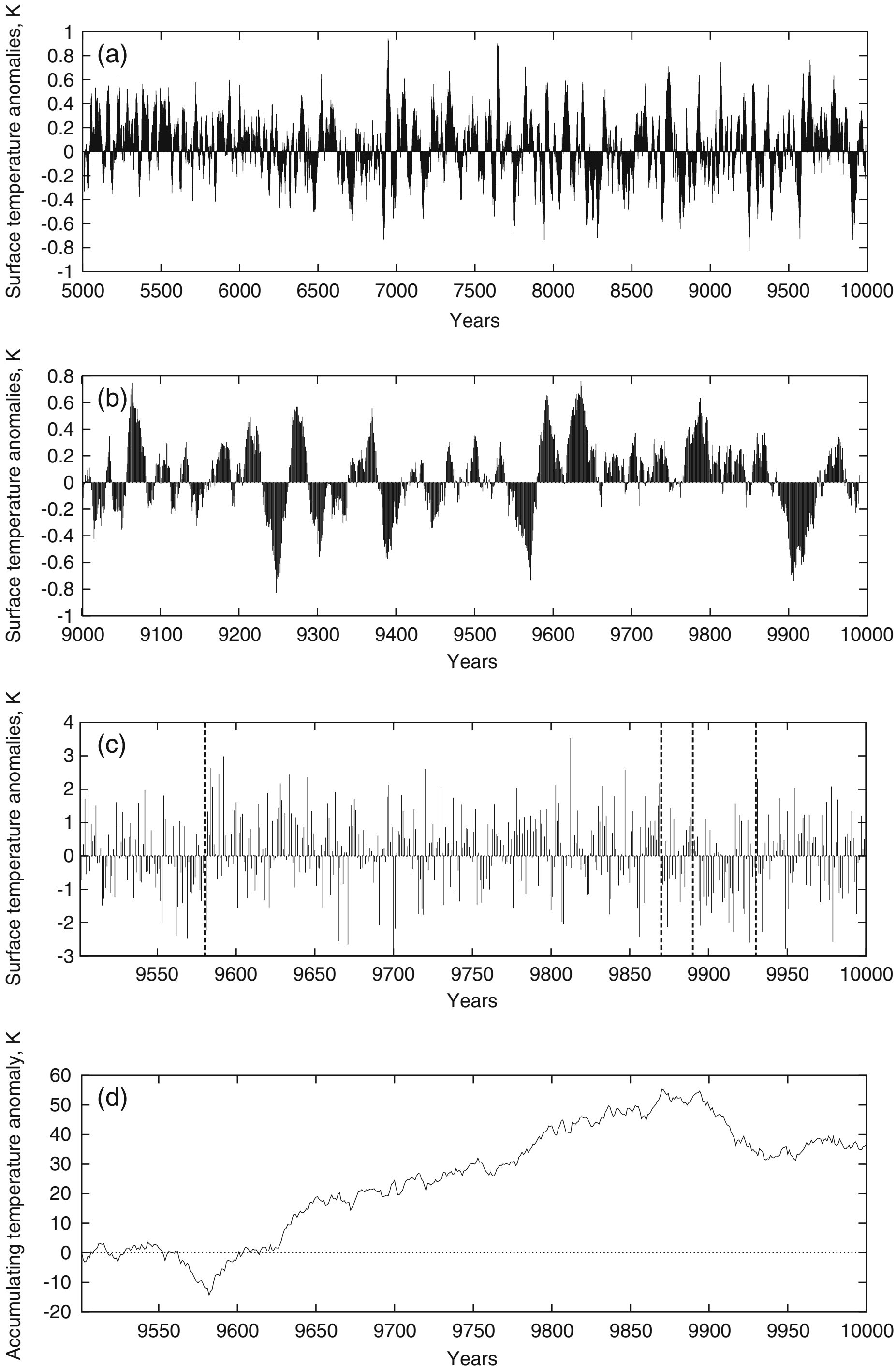
Fig. 3 Climatological distribution of the annual mean precipitation for the Greenland region based on years 9,001 to 10,000 of the simulation. The *colour bar below the figure* gives the precipitation in mm/day. Note the scale change above 1 mm/day

as the observed values (Bromwich et al. 2001), with the maximum occurring in the southeast of Greenland. Time series of simulated monthly total precipitation (not shown) revealed marked interannual variability for the selected gridbox used above, with exceptional peak values of about 7 mm/day. Annual mean totals for this gridbox had similar values and temporal variability to those observed (Hanna and Valdes 2001).

4 Temporal variability of the simulated Greenland climate

The essential question of concern here is whether surface temperature variations can be found in the simulation that replicate the assumed extended, benign, initial conditions experienced by the Norse settlers in Greenland, together with a subsequent climatic deterioration? If so, are these temperature variations of sufficient magnitude to be a critical factor in the demise of the Norse? The ice-core temperatures of Dansgaard et al. (1975) indicate band-passed temperature fluctuations of about ±1 K in Greenland, while Dawson et al. (2003) show air temperature fluctuations of up to ±5 K, although very few values exceed ±3 K as shown in scatterplots (their Fig. 6). Thus, in the present simulation perturbations similar to these raw fluctuations need to be identified for the unforced conditions used in the simulation.

Model results will be presented primarily for the gridbox at 65° N, 50° W, assumed to be representative of conditions near the Western settlement site. Figure 4 is intended to provide an overall perspective of annual mean surface temperature anomalies for this gridbox. Thus in Fig. 4a temperature anomalies smoothed with a 20-year running mean are shown for the last 5,000 years of the simulation. This reveals alternating episodes of positive and negative anomalies that attain a magnitude of about 0.8 K. There is an extended episode between years 5,000 to 6,300 where primarily positive anomalies prevail. A more consistent episode of positive anomalies occurs from about year 9,600 to 9,900, followed by a brief, but relatively intense episode of negative anomalies. It is these latter episodes that have been selected for analysis as being representative of a "benign" climatic interval followed by a climatic deterioration similar to that presumably experienced by the Norse. The


(a)
Surface temperature anomalies, K
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500
10000
Years
(b)
Surface temperature anomalies, K
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
9000
9100
9200
9300
9400
9500
9600
9700
9800
9900
10000
Years
(c)
Surface temperature anomalies, K
4
3
2
1
0
-1
-2
-3
9550
9600
9650
9700
9750
9800
9850
9900
9950
10000
Years
(d)
Accumulating temperature anomaly, K
60
50
40
30
20
10
0
-10
-20
9550
9600
9650
9700
9750
9800
9850
9900
9950
10000
Years

◀ **Fig. 4** Annual mean surface temperature anomalies at a model gridbox (65° N, 50° W). **a** Temperature anomalies for years 5,001 to 10,000 after smoothing with a 20-year running mean. **b** Expanded view of **a** for years 9,001 to 10,000 of the simulation. **c** Unsmoothed temperature anomalies for years 9,501 to 10,000 of the simulation. **d** Accumulating temperature anomalies commencing from year 9,501. The warm period is defined for years 9,580 to 9,870 and the cold period for years 9,890 to 9,930 by the two sets of *dashed vertical lines* in **c**

brevity of the period associated with the climatic deterioration is, of course, much shorter than that attributed to the LIA. This difference is not a critical issue here as it is the difference in the climatic regimes simulated by the model that are of interest rather than a precise replication of the (poorly known) climatic details.

A clearer indication of the temperature anomalies associated with the selected intervals is given in Fig. 4b, which shows that, even for these smoothed anomalies, there was not a simple, multi-century benign climatic phase, which is in agreement with observations (Dansgaard et al. 1975; Osborn and Briffa 2006).

In Fig. 4c unsmoothed annual mean surface temperature anomalies are illustrated for the last 500 years of the simulation. This shows more realistically the temperature regime as regards interannual variability, magnitude, sign and persistence of the temperature anomalies. These anomalies exceeded ±1 K very frequently, and excursions of ±2 K were not uncommon.

For the purposes of subsequent analysis, years 9,580 to 9,870 (291 years), and years 9,890 to 9,930 (41 years) were defined to be warm and cold periods respectively—these periods can be clearly identified in Fig. 4b. It is important to note that while positive temperature anomalies prevailed in the warm period, negative anomalies, usually rather small, also occurred, with the reverse situation applying during the cold period. This mixture of opposite signed anomalies is to be expected as a consequence of naturally occurring climatic variability in an unforced simulation, such as that under consideration here. A multi-century, or even multi-decadal, episode of solely positive temperature anomalies, such as might be expected to have existed during the greater part of the Norse settlement in the popular imagination, would require very specific external forcing of the climatic system. The mean temperature anomaly over the warm period was 0.231K, that over the cold period being −0.498 K. For individual 50-year samples within the warm period mean positive anomalies of about 0.5 K were attained. The reality of the warm period is demonstrated clearly in Fig. 4c, where the accumulating annual mean surface temperature anomalies commencing from year 9,501 are illustrated. This shows that despite the present of negative anomalies in the warm period this was a time of overall warmth.

The temperature anomalies Fig. 4c are somewhat small compared with those given by Dawson et al. (2003). There are several possible causes for such discrepancies. Model limitations are always an issue, particularly using a single model gridbox (implying an area mean) to compare with a point measurement. There is also the possibility that some form of external forcing was associated with the MWP, and this would have been explicitly excluded from the present simulation. Dansgaard et al. (1975) note that there are problems relating the isotopic values from an ice core to temperature, in addition to issues regarding temporal resolution. Perhaps of more significance are the recent comments of White et al. (1997) who state "... the stable isotopic composition of Greenland snow is responding to regional climate change and not just local meteorological changes at the top of an isolated ice sheet”. In fact, as critically demonstrated by Newell and Zhu (1994), the Greenland snow could derive from water vapour transferred from oceans with quite different temperature and salinity values.

Returning to the interannual temperature fluctuations in Fig. 4c, these are similar to the isotopic variations shown by White et al. (1997) for Greenland that go back to about AD 1780. Sea salt concentrations in ice cores reported by Fischer and Mieding (2005) also indicate marked temporal variability. There is no reason to presume that the “benign” climatic conditions existing at the time of the Norse settlements in Greenland did not also involve such interannual variability. This variability might have been ameliorated somewhat in the sheltered fjords where the settlements were located, as mean summer temperatures were higher in the fjords compared with the outer coast. Norse activities were not confined to the fjords, as the hunting of seals and caribou was an important contribution to their diet.

Interannual temperature fluctuations must have had a major impact on Norse survival because of their influence on pastures and hay production. Hay was the only crop produced by the Norse, and was critical for the feeding of their sheep, goats and cows, which could be confined in byres for up to 9 months of the year. The sensitivity of hay production to temperature has been analysed in some detail by Bertgthorsson (1985) for Iceland. Presumably his analysis is also relevant to Greenland, where conditions are even more marginal. For a particular site in Iceland with an annual mean temperature of 3.2°C he shows that hay yield declined to 73% with a temperature drop of just 1°C, and increased to 124% for a rise of 1°C. This sensitivity of hay yield to temperature was exacerbated by the winter fodder requirements of the animals, which increased by about 12% when the annual mean temperature dropped by 1°C. Given the criticality of fodder supplies, and the apparent abundance of seals as a food source, it seems surprising that the Greenland Norse persisted with the maintenance of farm animals.

Since annual mean temperatures at coastal sites in west Greenland are (currently) at or below zero (Hanna and Valdes 2001), and have been at this level at least back to 1850 (Vinther et al. 2006), the hay yield there would be lower and even more sensitive to temperature than in Iceland. The severity of climatic conditions in Greenland is illustrated by Fig. 3 of Lefebre et al. (2005), who show observed June temperatures at an ice sheet site falling below freezing point for a 2 week period in 1991. Even allowing for the “benign” conditions during the time of the Norse settlements, the marginality of life there can be appreciated.

Relating the above variations in hay yield and fodder requirements to the annual mean temperature anomalies in Fig. 4c, see also the annual temperature cycles in Fig. 5, provides an indication of the problems facing the Norse settlers. Assuming that an anomaly of 0°C in Fig. 4c is representative of “acceptable” farming conditions, then it can be seen that for the warm period most years were near normal, with over 60 years having temperature anomalies greater than 1°C, and sometimes 2°C. These would presumably be particularly prosperous years. Nevertheless, there were numerous years (∼35) with anomalies below −1°C, which would have stressed the settlements. Barlow et al. (1997) suggest that there was sufficient resilience in the Norse community for a poor year to be compensated by the hunting of seals and caribou, provided that such a year was followed by a number of benign years in which

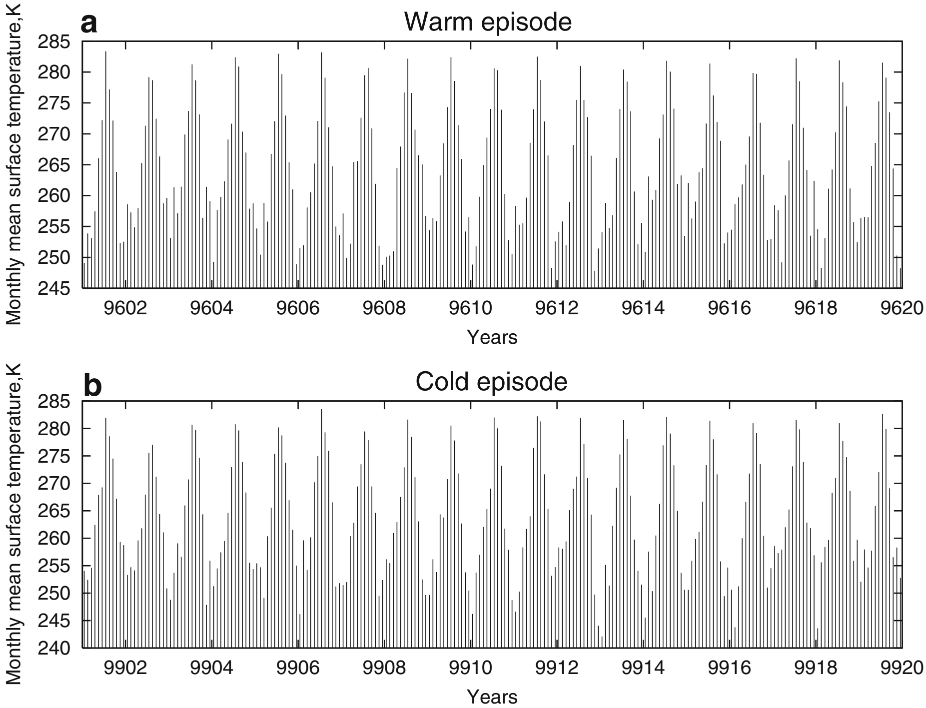


Fig. 5 Seasonal cycle of the surface temperature for 19-year periods for the warm and cold periods are illustrated in **a** and **b** respectively

livestock numbers could be rebuilt. Figure 4c suggests that this fortuitous situation prevailed for most of the warm period, but there were occasions around years 9,700, 9,760 and 9,810 when multiple years with negative temperature anomalies occurred. Such successions of years can also be seen in the proxy observations of Osborn and Briffa (2006) during the MWP for a west Greenland region. This may indicate that the Norse settlers were able to cope with rather more difficult climatic conditions than supposed by Barlow et al. (1997).

The climatic deterioration associated with the cold period (years 9,890 to 9,930) is identified in Fig. 4c, with an initial period of about 30 years where temperature anomalies of about −1°C were dominant and very few years had positive anomalies. At later times temperature anomalies of −2°C occurred on a number of occasions, although there were also years with positive anomalies. The succession of continuous cold years in this period would have severely stressed the Norse settlers. More frequent ice conditions blocking the fjords would also have limited opportunities for seal hunting (Barlow et al. 1997). The increasing environmental degradation caused by the Norse farming activities, and more hostile encounters with the Inuit, would have accentuated the problems faced by the Norse, and, taken together with the deteriorating climatic conditions, the combination of these factors may have been sufficient to finalise their demise.

An additional view of the contrast in surface temperatures between the warm and cold periods is given in Fig. 5, where monthly mean total temperatures are displayed for 19-year sequences in each of these periods. The maximum temperatures were similar in July in both periods, nevertheless there were systematic differences. Taking 270 K as an arbitrary level there were 18 out of 19 years in the warm period in Fig. 5 where there were four consecutive summer months with temperatures above this value, as against only 13 years in the cold period. During winter there were only 10 years where a temperature below 250 K was attained in the warm period, but 17 for the cold period. In addition, in Fig. 5 there are four occasions in the cold period when temperatures below 245 K were reached, but no such occasions for the warm period.

Thus the cold period in the simulation experienced consistently more years with climatic conditions unfavourable to the survival of the Norse settlements. In reality, if daily temperatures had been available for this period from the simulation it is possible even more extreme disparities between temperatures for the warm and cold periods could be demonstrated.

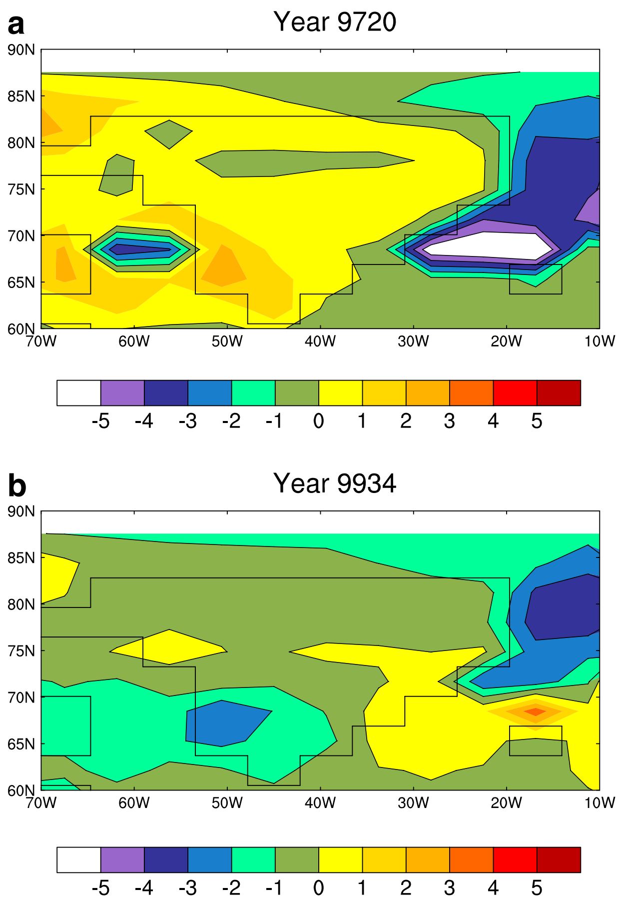


Fig. 6 Annual mean surface temperature anomalies for the Greenland region illustrating the differences between individual warm and cold extreme years. The *colour bars below the panels* are in K

An indication of the spatial characteristics and magnitude of annual mean surface temperature anomalies occurring over Greenland is given in Fig. 6. This shows positive temperature anomalies for year 9,720 in the warm period, and negative anomalies for year 9,934 in the cold period. The examples shown are not the most extreme cases during these periods, as the largest negative anomaly occurred in year 9,700 in the warm period. The maximum anomalies range from about +3 K in Fig. 6a to −3 K in Fig. 6b. The associated spatial patterns have large coherent scales, indicating sizeable synoptic systems, thus confirming that the use of a single model gridbox in the present analysis is not unrepresentative. Examination of an 8-year sequence of negative anomalies (years 9,909 to 9,916) revealed a wide range of spatial patterns, indicative of interannual variability. The marked contrast between the underlying climatic states implicit in Fig. 6 highlights the problems the Norse would have experienced with such variability.

As noted in the Introduction, the MWP was not a time of uniform, global warmth and noticeable spatial variations occurred, see the proxy reconstructions of Briffa et al. (2004). Spatial patterns associated with surface temperature anomalies averaged over selected years from the present simulation are presented in Figs. 3 and 5 of Hunt (2006). These illustrate the co-existence of positive and negative anomalies across the globe. Composites of global surface temperature anomalies (not shown) for the warm and cold periods over Greenland also revealed the simultaneous existence of regions of positive or negative anomalies. For example, the warm period was associated with positive anomalies over Europe and southern Asia and western North America, while the cold period revealed negative anomalies over all of North America and most of Asia, while Europe still experienced positive anomalies. There is no reason to suppose that the actual climate during the MWP did not also have a similar range of spatial variability.

Besides temperature, precipitation, especially summer rainfall, was important for hay production in Greenland. The Norse apparently used irrigation, indicating the sensitivity of their agriculture to rainfall. Figure 7 illustrates the annual mean precipitation anomalies at the selected model gridbox for year 9,501 to 10,000 of the simulation. While there is noticeable interannual variability, the warm period had more positive and few negative anomalies than the cold period. The respective means over these two periods were 1.35 mm/day and 1.21 mm/day. Quite distinctive spatial anomaly patterns occurred over Greenland for the two periods, with the

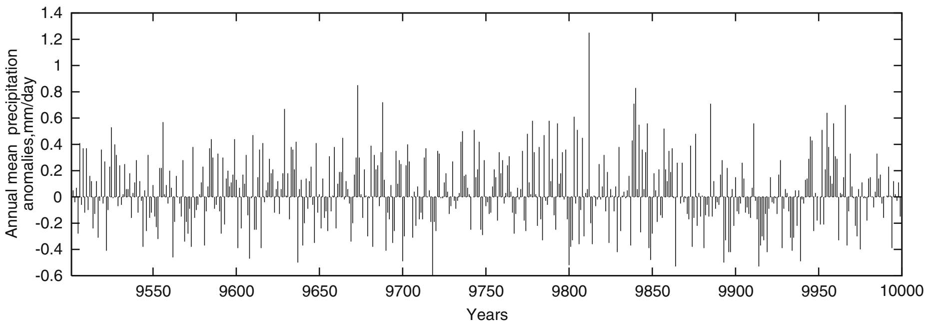


Fig. 7 Annual mean precipitation anomalies for the gridbox (65° N, 50° W) for years 9,501 to 10,000 of the simulation

largest anomalies concentrated in the southwest. Thus, the warm period was not only warmer but wetter, indicating better hay production. Over the last millennium of the simulation the correlation between precipitation and surface temperature was 0.35. This is in agreement with the general conclusion of Putnins (1970) that snowfall was higher in warmer years, as confirmed by plots of snowfall in the simulation (not shown).

The mean snow depths for the selected gridbox were 66.7 and 61.9 cm for the warm and cold periods respectively. The interannual variability of the snow depth ranged from 20 to 110 cm over the last 500 years of the simulation. While there was less snow during the cold period there was more variability, with a standard deviation of 17.6 cm compared to 15.9 cm for the warm period.

Sea-ice variations also impacted the Norse settlers, Ogilvie et al. (2000). Firstly, by blocking the entrance to the fjords where they lived and thus limiting their ability to catch seals, and, secondly, by creating hazards in travel to Norway. Time series of sea ice for a model gridbox west of the settlements indicated a mean ice thickness of about 0.6 m in March, but with an interannual variability from 0.4 to 1.0 m, with isolated extremes outside this range. Spatial plots of sea ice amount (not shown) revealed interannual variations of sea-ice on the east and west coasts, with the more extensive changes on the west coast. Sea-ice extent in March varied by several degrees of latitude, occasionally extending to 60° N. No obvious differences were apparent between the warm and cold periods. The low horizontal resolution of the model limited the detail of the ice perturbations that would have been important to the Norse.

Time series and spatial plots were made for surface pressure and surface winds over the Greenland-Iceland region. While there was much interannual variation, rather small (~1 mb pressure, ~10 to 30 cm/s wind) differences were noted between the warm and cold periods. Daily data capable of resolving individual synoptic features are probably necessary to clarify aspects such as changes in storminess between the two periods.

5 Possible mechanisms controlling long-term changes in Greenland climate

If climatic variability was a factor in the demise of the Norse settlers in Greenland, then temperature anomalies similar to those shown in Fig. 4c for the period 9,500 to 10,000 years presumably prevailed. The central issue then is what caused such anomalies?

A number of possibilities exist.

One possible contributor is ENSO given the widespread influence of this phenomenon. Jones and Mann (2004) discuss historical variations in ENSO, and the problems in obtaining definitive outcomes. Cobb et al. (2003) derived an ENSO time series extending from AD 930 to the present based on oxygen isotope cores from an island in the central tropical Pacific Ocean. This provides a local estimate of ENSO activity. Their results suggest La Nina conditions during the MWP and El Nino conditions for the LIA. In contrast, composites of annual mean global surface temperature anomalies for the individual warm and cold periods in the simulation indicate El Nino-type temperature anomalies for the former, and poorly defined La Nina anomalies for the latter.

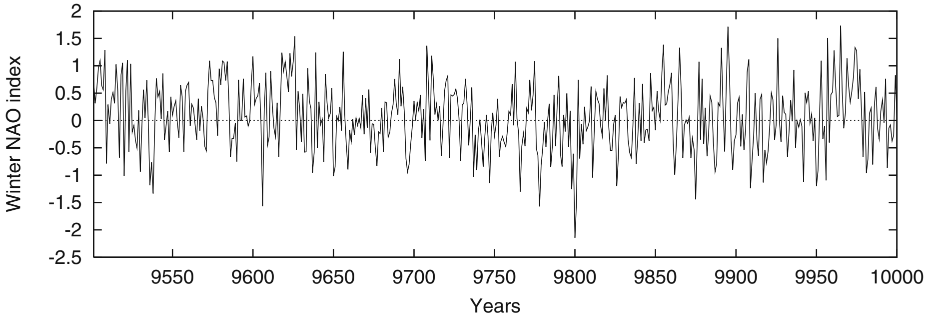


Fig. 8 The simulated winter North Atlantic Oscillation index for the period 9,501 to 10,000 years

However, Greenland is remote from tropical influences, and the correlation coefficient between NINO 3.4 sea surface temperature and surface temperature for the selected gridbox was only 0.14 over the last 5,000 years of the simulation. This correlation declined to 0.10 for the last 500 years of the simulation. A major reason for the low correlation was the high interannual variability of the Greenland temperature, see Fig. 4c, compared to the ENSO frequency.

Similarly, a low correlation (0.06) was obtained between the time series for the Pacific Decadal Oscillation and the surface temperature at this gridbox, indicating that it also did not influence Greenland climate.

Jones and Mann (2004) suggest an extensive role for climatic variations associated with the North Atlantic oscillation (NAO), extending possibly to Greenland. In view of this, a more detailed analysis was undertaken of the simulated NAO. The NAO index for the last 500 years of the simulation is illustrated in Fig. 8. The NAO is defined here as the winter (JFM) surface pressure difference between the Azores and Reykjavik, Iceland. The mean values of the NAO time series over the warm and cold periods, defined in relationship to Fig. 4c, were virtually identical. A number of episodes with sustained positive values can be seen in Fig. 8 suggesting that the current extended positive phase of the observed NAO (Hurrell 1995) is not exceptional; see also the proxy reconstruction of the NAO by Cook et al. (2002). Hurrell (1995) noted that clearly defined surface temperature anomalies could be identified in a composite over the positive phase of the observed NAO extending from 1981 to 1993. In Fig. 9, composites of surface temperature for winter are shown for a positive phase (years 9,617 to 9,625 in the warm period) and a negative phase (years 9,917 to 9,921) of the NAO. The positive phase results in Fig. 9a agree remarkably well with the observations of Hurrell (1995) apart from the negative temperature anomalies extending too far westwards over North America. The negative NAO phase results in Fig. 9b are almost the reverse of those for the positive phase. However, examination of composites for other negative episodes suggests that this composite is not particularly stable, especially as regards temperature anomalies over North America. As a further check of the model's performance in high northern latitudes surface pressure anomalies were examined for positive and negative phases of the NAO (not shown). These agreed well with the observations presented by Thompson and Wallace (2001), with substantial changes in surface pressure being obtained over the North Atlantic region between the two phases.

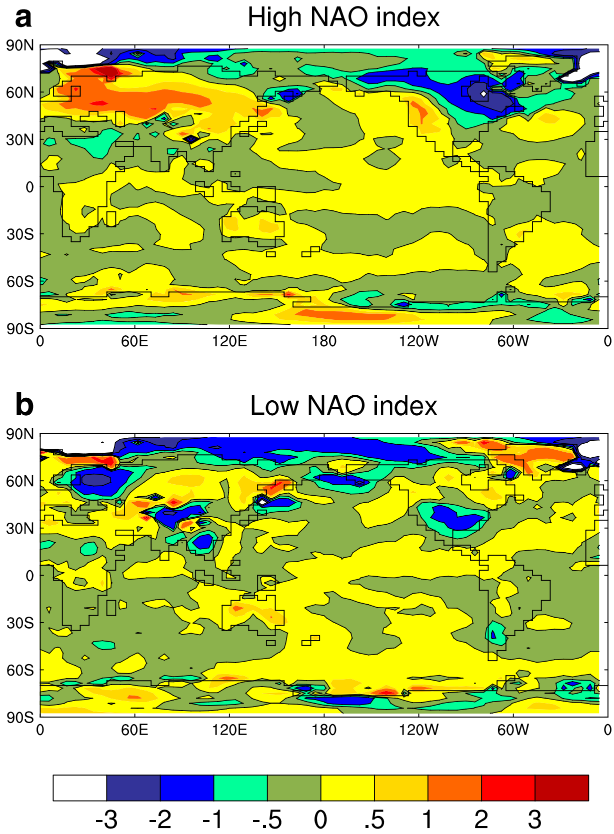


Fig. 9 The simulated surface temperature anomalies for winter (*JFM*) conditions for the Greenland region for a high NAO index period (years 9,617 to 9,625) and a low index period (years 9,917 to 9,921). The *colour bar below the figure* gives the temperature anomalies in K

Thus, the model simulated the basic characteristics of the observed climatology in this region for opposite phases of the NAO. Nevertheless, the correlation coefficient between the surface temperature for the selected gridbox and the NAO time series over the last millennium of the simulation was only 0.025, indicating that the NAO did not influence temperature conditions in the simulation in the region of the Norse settlements. This is despite the fact that in Fig. 9 opposite signed temperature anomalies can be seen over Greenland for the two phases of the NAO. The lack of stability of the temperature composites noted above would have been a contributory factor in this low correlation.

The simplest explanation for the extended warm and cold periods in Fig. 4 is stochasticism, i.e. random influences. In fact this can be the only explanation given the invariance of the model's boundary conditions. Even if a statistically significant correlation had been found between any of the above three Oscillations and the Greenland climate in the simulation, the temporal variations of the Oscillations in the model are still attributable to stochasticism.

In a wide-ranging series of analyses of the present simulation, stochastic influences have been deemed responsible for climatic anomalies associated with the MWP and LIA (Hunt 2006), climatic outliers (Hunt 2007), Maya droughts (Hunt and Elliott 2005), Mexican megadrought (Hunt and Elliott 2002) and other climatic features.

While the present simulation could not account for all the climatic anomalies associated with the MWP and LIA (Hunt 2006), these deficiencies may have been attributed to the omission of the impact of volcanic eruptions and varying concentrations of CO_2 in the atmosphere, as well as model limitations. These omissions may be responsible for the short duration of the cold period in Fig. 4c. Accepting this, the interannual and decadal variability in the temperature anomalies shown in Fig. 4c are representative of natural climatic variability, and thus attributable to stochasticism.

6 Conclusions

A number of factors, especially increasing attacks by the Inuit and isolation from Norway, as well as climatic variations, probably resulted in the demise of the Norse settlements in Greenland (Barlow et al. 1997). The analysis presented here suggests that natural climatic variability, as simulated in the CSIRO Mark 2 global climatic model, may have identified sufficiently large surface temperature anomalies which, when combined with the above factors, contributed to the termination of these settlements. The available proxy data are inadequate to quantify the magnitude and variability of the temperature anomalies occurring in Greenland over the duration of the settlements. If they were larger and more persistent than simulated here then presumably some form of external forcing of the climatic system would have been required. Despite this uncertainty, the range of temperature anomalies simulated between the warm and cold periods would seem to be sufficiently large to have impacted considerably the traditional activities the Norse needed for their survival. The simulation reveals that even the warm period was marked by noticeable interannual variability, and there is no reason to suppose that the Norse did not experience similar variability during the benign phase of the settlements. This indicates that the Norse had considerable resilience to short term climatic fluctuations, suggesting that when the climate did deteriorate around AD 1400 crisis conditions were created from which they were unable to recover. We may never know the true story.

The warm and cold periods identified in the simulation are attributed to stochastic influences, and no compelling support for the role for the various Oscillations discussed above was quantified. Given the temporal invariance of the model's boundary conditions, stochasticism is the fundamental source of all the climatic variability generated in the simulation.

Finally, if the above explanation is considered to be satisfactory, then no case exists for the so-called "climatic change deniers" who claim that the Norse settlements in Greenland are proof of previous climatic conditions that can explain the current observed global warming. They thus claim that there is no CO_2-induced greenhouse effect in operation and the present climatic state is just a repetition of these previous climatic conditions. The present simulation highlights the role of natural climatic variability in past climatic fluctuations, while other simulations indicate that such natural variability cannot account for the current global warming (Davies and Hunt 1994).

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