THE ALLERÖD/YOUNGER DRYAS BOUNDARY

Jan Mangerud

University of Bergen
Department of Geology, Sec. B
Allegt. 41
N-5007 Bergen
Norway

ABSTRACT. From former cirque glaciers in western Norway, it is calculated that the summer (1.May to 30.September) temperature dropped 5-6°C during less than two centuries, probably within decades, at the Alleröd/Younger Dryas transition, some 11,000 years ago. From the same data the Younger Dryas summer temperature is estimated to have been 8-10°C lower than at present, and from fossil ice wedges the mean annual temperatures 13°C lower than at present in the same area. The amplification of the climatic change in western Europe at the Alleröd/Younger Dryas transition appears due to a step function in the change in the path of the North Atlantic Current.

INTRODUCTION

During the Alleröd Chronozone, 11,800 to 11,000 years ago, western Europe approached the present day environmental and climatic situation, after having suffered the last glacial maximum some 20,000 to 18,000 years ago. However, the climatic deterioration 11,000 years ago led to nearly fully glacial conditions on this continent for some few hundreds of years during the Younger Dryas. This change is completely out of phase with the Milankovitch (orbital) forcing as this is understood today, and therefore its cause is of major interest.

Since the Alleröd/Younger Dryas boundary is well inside the period of radiocarbon dating, it is also of great interest as a model for the mode of response, time lags, and feedback mechanisms of different biota, glacial systems, periglacial features, etc., to this type climatic change, which in Europe was very similar to the onset of a glaciation, even though the forcing was different.

In this paper I will describe some of the geological records of this boundary. Description of other features, and some more general considerations, are recently given by the NATO/NSF working group (Mangerud et al., 1986b), and other abstracts in that volume. Finally, I provide some speculations on the cause of the Younger Dryas.

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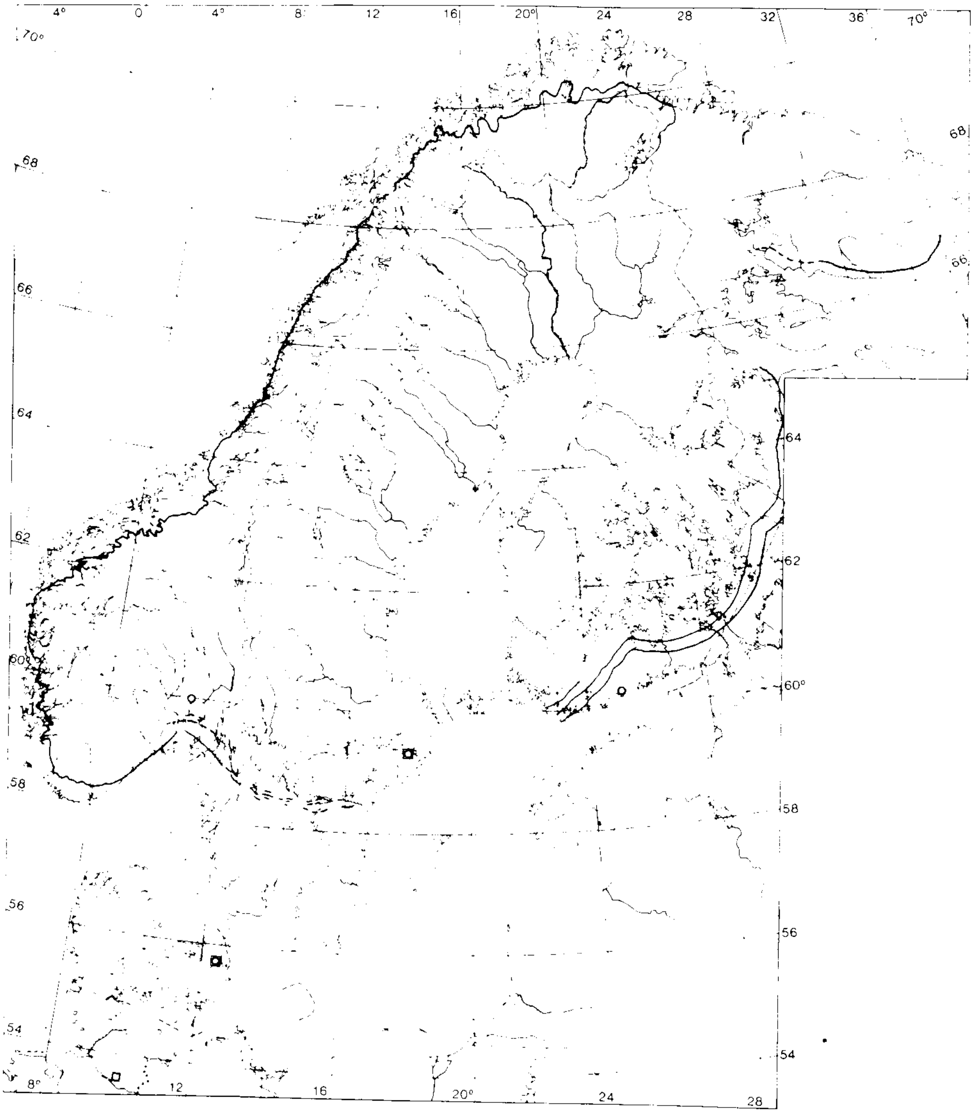

Figure 1. Map of Younger Dryas end moraines around the Scandinavian Ice Sheet. Compiled from various sources.

EVIDENCE

The Scandinavian Ice-sheet

At the time of the Alleröd/Younger Dryas transition, the Scandinavian ice-sheet was still a major element in the climate system. The record from the Younger Dryas is distinct, consisting of ice-marginal deposits that are mapped nearly continuously around Scandinavia (Fig. 1) (e.g. Andersen, 1981), showing that the climate turned to a more glacial regime in both the continental climate area of USSR/Finland and the oceanic climate area of Western Norway. This suggests that lower summer temperatures, and not increased winter precipitation, was the climatic factor that determined the major pattern of glacial response. Superimposed on this major trend are smaller variations, e.g. an amplification of the re-advance in Western Norway compared to the easterly areas, due to higher winter precipitation along the western flank of the ice-sheet, and topographical and glaciological factors (Mangerud, 1980). The re-advance also caused a relative rise in sea level in Western Norway through the combination of increased gravitational attraction and a halt in glacio-isostatic uplift (Anundsen, 1985). Concerning the northern limit for the Younger Dryas glacial response, it may be mentioned that in Svalbard (78°N) a re-advance for one valley glacier is also stratigraphically demonstrated (Mangerud et al., 1985; Elgersma and Helliksen, 1986).

Permafrost

Evidence of permafrost during the Alleröd is not known from Europe. From the Younger Dryas, ice wedge casts are found in the entire area from Finland to NW Germany, and frost cracks are found in the Netherlands (Maarleveld, 1976; Larsen et al., 1984). The main requirements for formation of ice-wedges are permafrost, and some extremely low temperatures during the winter. Mean annual temperatures are below -6°C in areas where they form today (Pewe, 1966). For Germany, this would mean an annual temperature 15°C lower than today. The permafrost in the mentioned area was probably due to cold NE-winds, especially during the winters. These winds may partly have been caused by the high pressure over the Scandinavian ice-sheet. However, as a topographical element, the ice-sheet did not change much from the Alleröd to the Younger Dryas, and the NE-winds can therefore not be merely a feedback result of increased size of the ice-sheet.

We (Larsen et al., 1984) have earlier pointed out that Younger Dryas ice-wedge casts are missing along the western coast of Norway, except in the far north, and have attributed this to the snow cover during winter. Later I have found one cast in a former shore-line on the island of Vigra, in a position where the snow must have blown off the ground during formation. With the assumptions given above, this suggests a Younger Dryas annual temperature 13°C lower than today in Western Norway.

Cirque glaciers

Cirque glaciers provide a simpler system for paleoclimatic reconstructions than larger glaciers (Sutherland, 1984). Distinct end moraines of Younger Dryas age that allow precise reconstruction of each individual glacier, are common both in the British Isles (Sissons, 1980a, b) and along the coast of Norway outside the Scandinavian icesheet (Andersen, 1975; Larsen et al., 1984). We (Mangerud et al., 1979; Larsen et al., 1984) cored a lake at Krakenes in western Norway which was fed by a stream from a cirque glacier. The sediment sequence proved that no glacier existed in the cirque during the Alleröd, and that the cirque glacier was formed at the Alleröd/Younger Dryas transition.

Rates of change. A cirque glacier starts to form when the climate passes certain thresholds. The geological signal is therefore generally of an on-off type, and rates of climatic deterioration are impossible to determine. One way of solving this would be to investigate when glaciers were formed at different elevations, because glaciers would form first at higher elevations, and progressively later in lower terrain. We have not yet had time to pursue this idea, however we tried a different approach; in the lake at Krakenes we (Larsen et al. 1984) found indication of a climatic deterioration in the pollen record from a level corresponding to 50-180 years before the start of glacio-lacustrine sedimentation. In another lake we (Kristiansen, Mangerud and Lömo, manuscript in preparation) found that the pollen influx (production) of *Betula* decreased faster as a response to the climatic deterioration than the composition of the vegetation. The difference in response time is estimated as maximum 100 years. However, both in that pollen diagram, as in most others from western Norway, the Alleröd/Younger Dryas transition is seen as one steep step. As a first approximation, I conclude that in this area the full amplitude of change, from the warmest Alleröd to the coldest Younger Dryas, occurred as one step within less than two centuries; possibly within some few decades.

Amplitude of change. Cirque glaciers can climatically be characterized by one single parameter; the equilibrium line altitude (ELA)-the altitude of the boundary between the area of net yearly accumulation, and the area of net ablation. A map of the ELA for present-day glaciers in Norway is given by Östrem and Liestöl (1964), from which we calculated the present day ELA at Krakenes to 900m a.s.l. (Fig. 2). The Younger Dryas ELA could also be precisely determined from 14 reconstructed glaciers (Larsen et al., 1984) to 180m a.s.l., that is 700m lower than today. So far we have not been able to directly determine the ELA for the Alleröd, because we have not yet identified a cirque glacier that survived the Alleröd. As an approximation we have used the lowering of the tree-limit, since the ELA and tree-limit today are roughly parallel. This method suggests an Alleröd ELA of 600m a.s.l., a result that appears slightly too low from other considerations. These results give a lowering of the ELA of at least 400m at the Alleröd/Younger Dryas boundary (Fig. 2) in western Norway.

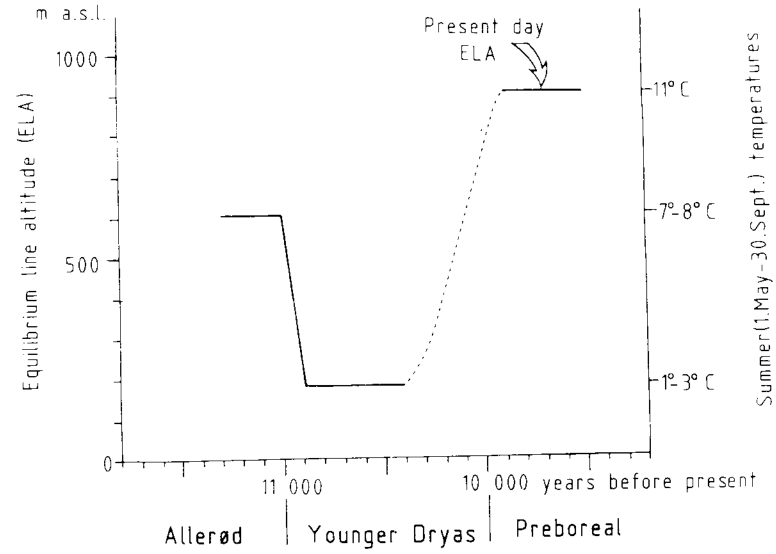

Figure 2. Variation of the equilibrium line altitude (ELA) for cirque glaciers in western Norway for the period 11,500 to 9000 years ago. For simplicity the present day ELA is plotted at 9500 Years B.P., as that certainly is close to the correct value. At the right axis the ELA variations are translated to summer temperatures, under certain assumptions discussed in the text.

The next step will be to translate the ELA changes to more direct climatic parameters. In Fig. 3 we have plotted the winter accumulation versus summer temperatures at the equilibrium line for present day glaciers in Norway and Svalbard. We have also plotted present day summer temperatures and winter precipitation for the cirques around Kraknes that housed the Younger Dryas glaciers. The idea is that the climatic conditions for the Younger Dryas glaciers were similar to the conditions for glaciers in this area today. Before comparing it should be mentioned that present-day precipitation for the Younger Dryas cirque glacier sites probably is underestimated, because the local precipitation is lower at the recording stations than beneath the high-walls in the cirques. However, even with that caution it appears evident from the plot that the Younger Dryas winter precipitation could not have been much lower than today. One may also argue that with the much colder climate a significant higher precipitation was unlikely, leading to the conclusion that winter precipitation was of the same order as today. With that assumption Fig. 3 suggests that the Younger Dryas summer temperature was 8-10°C lower than today. Extending that assumption also to the Alleröd (Fig. 2), the conclusion is that the summer (1.May to 30.September) temperature dropped 5-6°C during less than two centuries around 11,000 years ago.

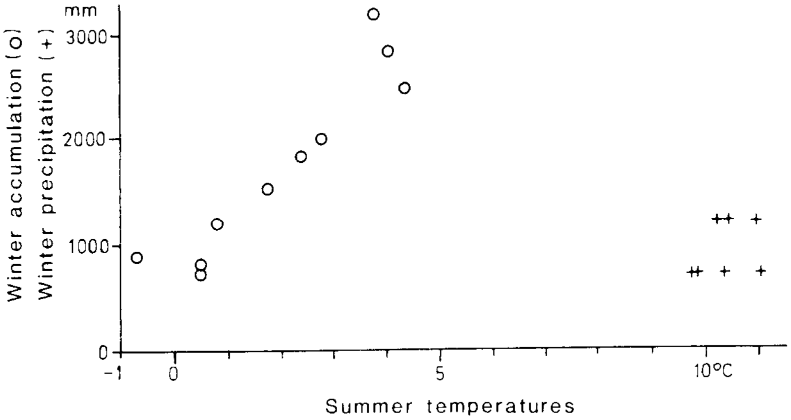

Figure 3. Circles: Measured winter accumulation versus summer temperatures at the equilibrium line (ELA) at present day glaciers in Norway and Svalbard. Winter accumulation is close to winter precipitation, since hardly any melting takes place during winter. However, in cirques winter accumulation is normally larger than the precipitation, because snow blows in from adjacent areas.
Crosses: Present day summer temperatures and winter precipitation in the cirques that housed the Younger Dryas glaciers. If the main pattern of the climate was the same during the Younger Dryas as today, the crosses should match the circles, and the relative difference in summer temperature and/or winter precipitation can be read. Constructed from Figs. 13 and 14 in Larsen et al.(1984).

THE CAUSE FOR THE YOUNGER DRYAS

In the following I will list some facts and thoughts on the Alleröd-Younger Dryas shift, without reaching a final conclusion.

1. The North Atlantic Ocean Current and the atmospheric circulation in the area are dynamically linked in a way that a change in either will cause a change in the other.

2. Following the work of Ruddiman and McIntyre (1973, 1981), the simplified path of the North Atlantic Current can be considered, on the time scale we are discussing here, as having a hinge east of North America (Lowe and Gray, 1980). The current may turn north of the British Isles into the Norwegian Sea, as it does today, and where it has a sector of freedom. It may also turn south, passing Portugal like the present day Canary Current, where it also has a large open sector for variations. The important point is that surface currents hitting the coast of Europe are forced either to the north or to the south. The mentioned hinge thus has sectors of continuous variations, but with one major step. Due to its heat transport, the North Atlantic Current is a major element in the climate of Europe, and a change in the form of a step

function of the current will probably cause a step in climatic change. Superimposed on the change of the path of the current, might be more gradual changes in its surface temperature, and volume of water.

3. During the Alleröd a branch of the North Atlantic Current entered the Norwegian Sea (Ruddiman and McIntyre, 1973, 1981). Jansen and Bjorklund (1985) and Jansen (this volume) demonstrated that this was only a narrow current in the extreme eastern part of the Norwegian Sea, while Mangerud (1977) showed that it was a warm surface current with the characteristics of the present day Atlantic Water, but which ended far south of present northern limit of Atlantic Water. However, Vorren et al. (1978, 1984) found evidence of warming as far north as Troms (70°N), and Jansen (this volume) concluded that no deep water was formed in the area during the Alleröd, implying that the current continued north along the Norwegian coast, as a progressively diluted and cooled surface and intermediate water mass.

I make the point that during the Alleröd, the Atlantic Current was in a very sensitive position; a minor change in its direction would, as a step function, move the flow of warm water from the coast of Norway towards the coast of Portugal, causing a sudden and large climatic deterioration in western Europe.

4. Because of the major climatic signal in Europe and the North Atlantic, and apparently small changes if any elsewhere in the world, the cause for the cooling has also been sought in this area. Point 1 supports this idea. Possibly a major outflow of icebergs between Iceland and Greenland, as postulated but not proven (Mercer, 1969; Ruddiman and McIntyre, 1981), was a strong enough driving force to the change. I have, however, two objections (Points 5 and 6 below) against searching for the ultimate cause only in the North Atlantic area.

5. The large Alleröd/Younger Dryas amplitude in Western Europe is, according to Points 2 and 3 above, due to an amplification caused by a geographical pattern. Thus the large signal is in itself not an argument for the location of the cause. In this "chicken and egg problem" it is just as probable that a minor change in atmospheric circulation initially caused a small shift of the North Atlantic current, and that the major climatic change was a feedback result of that change. Adjustment in atmospheric circulation to changing ice-sheet configuration (Ruddiman and McIntyre, 1981), or change in atmospheric CO_2 content (Berger and Killingley, 1982) have been proposed as possible initial causes.

6. Simply by common sense, I have often maintained that the Younger Dryas cannot be an exclusively European event. Even if the cause should be some "random" physical process within this area, the amplification led to such major changes in both atmospheric and oceanic circulation within a significant enough portion of the earth's surface that it had to cause some kind of change (cooler, warmer, drier, moister climate) in other areas. For a long time many scientists have also claimed to have found climatic changes which correspond in time to the Younger Dryas (refs. in e.g. Broecker et al., 1985). An extremely interesting task now would be to separate which changes are direct responses to the ultimate forcing of the North Atlantic changes, and which are "only" responses to the amplification in the North Atlantic.

7. Obviously the relative timing of events is important for solving many of the involved problems. We are therefore investigating volcanic ash beds from this period, that can be traced both in continental and marine sequences. Fortunately such ash beds occur both within and just after the Younger Dryas (Mangerud et al., 1984, 1986a).

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