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Express Letter

Permafrost as a critical factor in paleoclimate modelling: the Younger Dryas case in Europe

H. Renssen [a,*], R.F.B. Isarin [a], J. Vandenberghe [a], M. Lautenschlager [b], U. Schlese [b]

[a] *Netherlands Centre for Geo-ecological Research (ICG), Faculty of Earth Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1085, NL-1081 HV Amsterdam, The Netherlands*

[b] *Deutsches Klimarechenzentrum (DKRZ), Bundesstrasse 55, D-20146 Hamburg, Germany*

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Abstract

Simulations with an atmospheric climate model of the Younger Dryas climate, a distinct cooling event around 12 kyr cal B.P., were compared with temperature reconstructions based on fossil plant data. In one experiment we forced the model to maintain a wet and frozen soil at high latitudes to reproduce the effect of permafrost in the model. This measure resulted in a climate similar to the reconstructions with a depression of the summer temperatures in Eurasia by 4–8°C and an increase in precipitation. This suggests that permafrost may have played a more important role in driving paleoclimates (such as the Younger Dryas climate) than believed until now. This calls for re-evaluation of (paleo)climate simulations in which permafrost was not explicitly included.

Keywords: climate change; general circulation models; simulation; Younger Dryas; permafrost; Europe

During the last glacial–interglacial transition (15–10 kyr cal B.P.) the climate experienced an initial warming phase, followed by a return to glacial conditions during the Younger Dryas (YD) [1]. This period may hold clues to the sensitivity of the climate system to the various external and internal forcing factors [2]. An important tool to evaluate the effect of such forcing factors is the comparison of climate model results with paleodata. Here we apply this method to investigate the role of permafrost (i.e. a permanently frozen soil) as a defining factor within the climate system during cold periods.

The YD is most clearly registered in the geological archive of the North Atlantic region. For instance, numerous terrestrial multi-proxy records in Europe point to a summer cooling of 3–6°C compared to today [3,4] (see Fig. 1a). Reconstructions with a regional coverage from other regions are rare, although valuable attempts were published for central Asia [5]. In Fig. 1 we compare reconstructions based on paleodata with results of experiments performed with the ECHAM4 atmospheric GCM in T42 resolution (~2.8° latitude–longitude) [6]. This model is capable of simulating

* Corresponding author. Tel.: +31-20-4447357; Fax: +31-20-6462457; E-mail: renh@geo.vu.nl

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the present-day climate to a reasonable degree (within ± 2°C of observations in the study area [6]). Experiment YD1 describes the model's response to the following changes to modern boundary conditions (prescribed in control experiment CTR): a cooled ocean surface [7,8], additional ice sheets in North America and Scandinavia [9], lowered concentrations of greenhouse gasses [10], YD vegetation parameters [11,12] and insulation at 12 kyr cal B.P. [13] (see Table 1 for further information). The effect of most of these individual boundary conditions was explored in an earlier study [8].

The summer temperatures in experiment YD1 are clearly inconsistent with reconstructed values in continental Europe, as a warming of 2°C compared to CTR is simulated, instead of a 3–6°C cooling (see Fig. 1b). Apparently, these high temperatures in YD1 are the effect of the 12 kyr cal B.P. summer insulation, which was 40 W/m^2 more than today at 50°N [8,13]. In YD1 the high temperatures over land cause a strong thermal gradient between the continent and the cold Atlantic Ocean. Over the cold ocean the air descends and induces a relatively high air pressure with a maximum over Ireland (4 hPa higher in YD1 than in CTR). This high pressure acts as an atmospheric 'blocking', which effectively deviates North Atlantic storms to a more northernly or southerly path, thus reducing summer precipitation in Western Europe. Simulations on the YD with other GCMs produce similar results, suggesting that the outcome is not an artifact of the ECHAM model [14]. Instead, it is likely that in experiment YD1 a forcing factor is missing that affects the energy balance by not compensating for the surface heating.

This missing factor may be the effect of permafrost. There is ample geological evidence that permafrost existed in Europe during the YD [15]. In present-day permafrost environments, a high soil water table is a common feature during summer, since the surplus of melt water cannot drain through the impermeable ground ice [16]. This abundance of soil water implies a relatively high latent heat flux in summer, which tempers the heating of the air. In contrast, in YD1 melt water

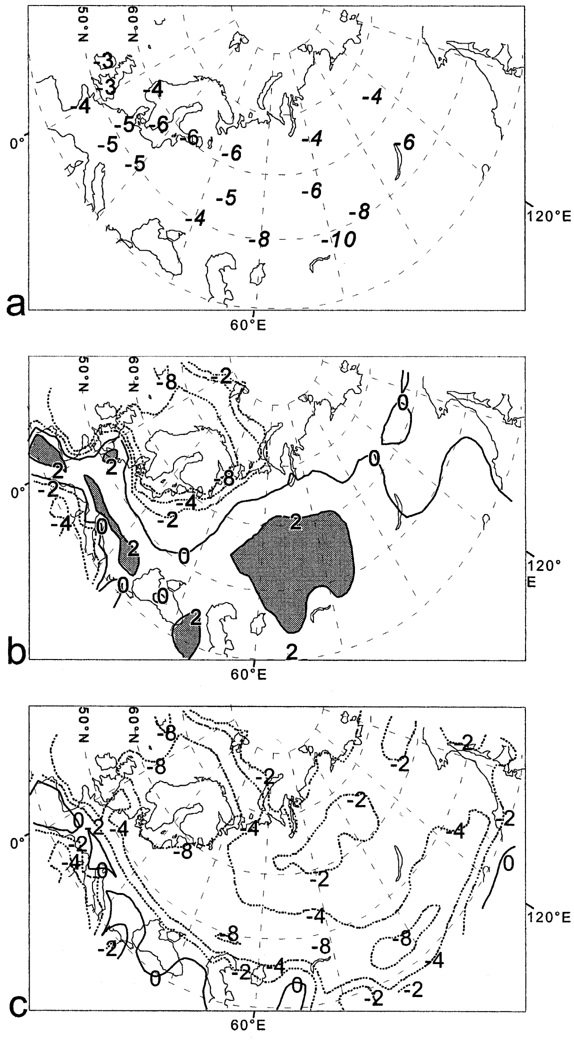

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Fig. 1. YD summer temperatures in Eurasia. a: Reconstructed YD minimum mean July temperature differences (°C) from the present, based on paleobotanical data. Straight figures are derived from over 300 sites (see [3]). Italic figures are derived from [5]. The uncertainty for these reconstructions is estimated at ± 1–2°C [3]. b: Simulated mean June–July–August surface temperature anomalies (YD1−CTR) in °C. Contours at −8, −4, −2, 0 and 2°C. Anomalies > 2°C are shaded. In CTR the 'interseasonal' standard deviation for JJA is between 1 and 1.5°C in the study area (based on 14 JJA seasons). c: As in (b), but for YD2−CTR. The negative anomalies in Europe are statistically significant (95% level) using Student's *t*-test [23].

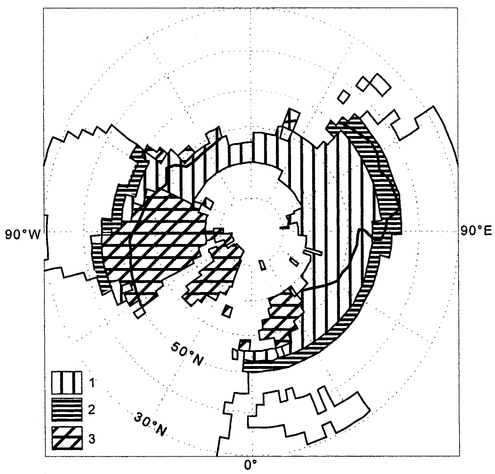

Fig. 2. Permafrost distribution (1 = continuous, 2 = discontinuous/deep seasonal frost, 3 = ice sheets) during the YD (following [15,24–26]). For grid cells with 1 or 2, we fixed in YD2 the soil humidities at field capacity and the soil temperatures at sub-zero values in the lower two soil layers (below 1.2 m depth [17]). This measure was taken to reproduce a so-called 'active layer' [16]. The thick line represents a mean annual temperature of 0°C in the lowest soil layer in CTR and approximates the modern southern limit of permafrost.

is removed quickly (within 2 months after first melting) due to the relatively simple soil hydrology within the ECHAM4 model [6,17]. In YD1 the combination of this fast runoff with reduced summer precipitation led to unrealistically dry soils in Europe, implying that most of the available solar energy is available for heating of the air. Indeed, from previous sensitivity experiments with GCMs it is known that dry soils lead to high surface temperatures and to low precipitation at extratropical latitudes [18].

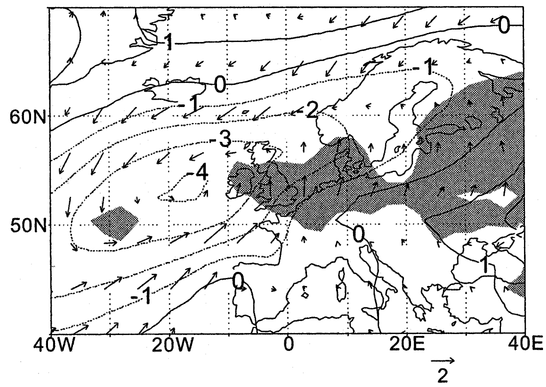

Fig. 3. Simulated mean June–July–August anomalies (YD2−YD1) in: mean sea level pressure (contours in hPa), surface winds (arrow for scale in m/s) and precipitation (shading denotes > 0.5 mm/d).

To test the effect of permafrost in the model, we conducted two sensitivity experiments with an identical design as YD1, but with a forced frozen soil in grid cells for which periglacial evidence exists (see Figs. 1c and 2). In the first sensitivity experiment - a 5-year run of which the results are not shown - we prescribed a frozen soil in the first time step only. After 2 years the temperatures of all five model soil layers [17] reached values of more than 0°C and soil humidity remained low. This result is expected, since the primary cause for permafrost initiation is still not included and thus the model could not maintain the introduced 'YD permafrost'. Therefore, a second sensitivity experiment was set up, YD2, in which we forced the model to maintain a frozen soil by fixing the temperature of the lower two soil layers at below

Table 1
Design of discussed experiments

	CTR	YD1	YD2
Ocean surface conditions	0 k	YD (Northern Atlantic+Northern Pacific)	YD (Northern Atlantic+Northern Pacific)
Ice sheets	0 k	12 k	12 k
Insulation	0 k	12 k	12 k
CO_2(ppm)/CH_4(ppb)/N_2O (ppb)	353/1720/310	246/500/265	246/500/265
Vegetation	0 k	12 k	12 k
Soil conditions	0 k	0 k	'YD permafrost'

'k' denotes kyr cal B.P. The length of the experiments is 16 (CTR) or 12 (YD1 and YD2) annual cycles, of which we discarded the first 2 years to account for spin-up. Results shown are based on averages of 14 (CTR) and 10 (YD1 and YD2) summers. Ocean surface conditions as described in [8]. See Fig. 2 for explanation on 'YD permafrost'

0°C throughout the experiment. Moreover, in grid cells with YD permafrost (see Fig. 2) we fixed the soil humidity at field capacity to prescribe a high water table. These measures imply a somewhat exaggerated moisture source. It is important to stress again that experiment YD2 is intended as a sensitivity analysis to study the first order effect on the model climate if permafrost would have been present. In this respect the design of YD2 (i.e. with a fixed wet and frozen soil) is comparable with that of other paleoclimate sensitivity studies (e.g., with ice sheets of various sizes). Still, it is good to realize that YD2 represents a forced response to the prescribed soil conditions.

In the YD2-result (Fig. 1c) the European summer temperatures agree very well with the reconstructed values in Fig. 1a. However, the YD summer cooling as reflected in some records from Southern Europe [19] is not reproduced. It is noteworthy that the prescribed soil conditions in YD2 affect the atmospheric circulation in the model. Over the Atlantic the air pressure in YD2 is up to 4 hPa lower, effectively removing the blocking found in YD1 (Fig. 3). This new pressure distribution induces relatively frequent southwestern winds over Western Europe in YD2, transporting moist maritime air to the continent and enhancing precipitation. The unlimited evaporation of soil water over grid cells with prescribed 'permafrost' increases the humidity of the air, thus stimulating further precipitation. The increase in precipitation replenishes the soil moisture content at this latitude, which would effectively reinforce the above processes. As expected, the YD2 results for the winter are similar to those of YD1 (i.e. within 2°C in Europe), indicating that the prescribed soil conditions have little effect on climate during winter. It should be noted that the frozen soil conditions in our YD2-experiment are not sustainable in Eurasia west of 110°E, as a downward net surface heat flux of 2–5 W/m^2 is simulated (not shown). East of 110°E this flux is negligible (< 1 W/m^2).

Assuming that YD2 gives a first order effect of permafrost, our results suggest that this could be an essential factor to the YD climate. The experiments indicate that without a fixed wet and frozen soil, summer temperatures would rise to values even above the modern ones. This conclusion is supported by the agreement between temperature reconstructions from Asia and our YD2 results (compare Fig. 1a and c). Moreover, the noted increase in precipitation in YD2 is in agreement with studies on lake levels and other proxies, suggesting that the early YD was a humid phase in Western Europe [20].

Additional experiments should be designed to find the actual cause of the YD cooling and the subsequent formation of permafrost, as our inferences give no answer to the question under what climate conditions permafrost was formed and maintained. There is evidence that permafrost disappeared from the Northwestern European plains during the first warm phase of the deglaciation ($\sim$14.5 kyr cal B.P.) [21]. Consequently, a very cold phase early in the YD must have initiated permafrost formation in Western Europe. Indeed, geological evidence suggests that the first phase of the YD was the coldest part [1,20,22].

We have shown that the incorporation of a simple parameterization of permafrost in a YD climate simulation substantially improves the agreement with paleodata. This finding implies that cold climate simulations without a permafrost parameterization should be re-evaluated. The anomalously warm climate simulated over Europe in other paleoclimate model studies (e.g., in experiments on the last glacial maximum) may be due to the absence of such a parameterization. Our results indicate that it may be important to include realistic permafrost in climate models.

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