CLIMATE CHANGE SCENARIOS: COMPARISONS OF PALEORECONSTRUCTIONS WITH RECENT TEMPERATURE CHANGES

M. V. SHABALOVA* and G. P. KÖNNEN

Royal Netherlands Meteorological Institute (KNMI), P.O. Box 201, 3730 AE De Bilt, the Netherlands

Abstract. Paleoclimatic reconstructions for the Mid-Holocene, Eemian, Mid-Pliocene and the Last Glacial Maximum are used to test the paleoanalog hypothesis and develop a regional climate change scenario based on a linear scaling by one parameter – the mean Northern Hemispheric temperature change with respect to present, ΔT_{NH}. The empirical verification of the paleoanalog hypothesis is extended to a cold epoch for zonal means and to regional distributions of temperature in warm epochs. The best agreement among the scaled paleoanomalies from different epochs is obtained if the seasonal temperature anomalies are scaled with ΔT_{NH} of the corresponding season. Preferential areas are identified where the paleoanalog hypothesis works relatively well; these areas coincide with the areas of the most pronounced warming. It is shown that the geographical distributions of the winter temperature anomalies over land in the paleodata are similar to those in the 1980–1990 period. From the three warm epochs, a paleodata-based scenario is deduced for the spatial distribution of temperature in a future climate, on the scale of continents. The conditions under which scenarios based on paleodata can be applied are discussed.

1. Introduction

As an alternative to GCM-simulations (IPCC, 1990), the paleoanalog method is sometimes applied to produce climate forecasts of an anthropogenically warming Earth (IPCC, 1990; Giorgi and Mearns, 1991; Budyko *et al.*, 1992; Shabalova and Selyakov, 1993). The basic assumption of this method is that the globally averaged mean annual temperature, being an integral energy characteristic of the planet, is the key climate parameter that determines uniquely the large scale structure of an equilibrium climate realization (Budyko *et al.*, 1978; Budyko and Izrael, 1991). Given the present climate, this assumption implies that in first approximation anomalies of temperature in a warmer or cooler climate should exhibit a unified structure if they are scaled with the value of global temperature change. If this paleoanalog hypothesis verifies, paleoclimatic reconstructions of past warm or cold epochs may under certain conditions be used to get a notion of future regional climatic change, at least for the equilibrium case.

So far the paleoanalog hypothesis has been tested empirically only for zonal mean temperatures of various warm epochs (Budyko and Izrael, 1990; Hoffert and Covey, 1992), and for some individual regions (Shabalova and Selyakov, 1993).

* Permanent affiliation: State Hydrological Institute, 199053, 2-nd Line, 23, St.-Petersburg, Russia.

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Direct verification of the hypothesis for spatial temperature distributions or for other elements has not been carried out, although GCM equilibrium simulations suggest a proportionality of the amplitude of some regional climate characteristics to the value of global warming, ΔT_g (IPCC, 1990, p. 157). In this paper the empirical verification of the paleoanalog hypothesis is extended to regional distributions of seasonal temperatures and different scaling parameters are tested. From the paleoreconstructions of three warm epochs, a paleoanalog-based scenario is deduced for the spatial distribution of temperature in a future equilibrium climate, on the scale of continents. It is shown that in winter the anomaly patterns in the warm 1980–1990 period have a similar structure over land.

The results of this paper rely heavily on the reliability of the Russian paleoreconstructions. Since the literature about this is not easily accessible to non-Russian readers, the next section summarizes the Russian work on paleoreconstructions. In section 4 the actual tests of the paleoanalog hypothesis on several levels is described and the anomalies in the 1980–1990 period are analyzed. Section 5 discusses under what conditions the anomaly patterns may be used as a climate change scenario and section 6 summarizes our conclusions.

2. Russian Paleoclimatic Reconstructions

In past years, much attention in Russia has been given to the climatic reconstructions for the Mid-Holocene (5–6 kyr B.P.; global warming ~1 °C) Eemian (120–125 kyr B.P. (stage 5e); ~2 °C), Mid-Pliocene (3.3–4 Myr B.P.; ~4 °C) and Last Glacial Maximum (18–20 kyr B.P.; Northern Hemisphere summer warming ~−5 °C) (Barash, 1971, 1985, 1988; Barash *et al.*, 1980, 1983, 1987; Velichko, 1985, 1988, 1989; Velichko *et al.*, 1983, 1984, 1992, 1993; Zubakov and Borzenkova, 1988, 1990; Borzenkova, 1990, 1990a, 1992). A separate list of references refers to the Russian sources. Reconstructions of more distant periods like the Eocene (48–45 Myr B.P.; global warming ~10 °C), Maastrichtian (70–66 Myr B.P.; ~7 °C) or Santonian-Coniacian (88–92 Myr B.P.; ~10 °C) climatic optima are also performed (Borzenkova, 1992; Velichko and Chapaluga, 1987; Yasomanov, 1978; Krashennikov and Basov, 1985; Vakhrameev, 1988), but for the present study they cannot be used either because of their current lack of spatial details or because of the geographical incompatibility with the present epoch. The reliability of paleoclimatic data has been discussed extensively in CLIMAP (1976, 1984), Velichko (1985), Martinson *et al.* (1987) and Crowley and North (1991). The interpretation of the data in terms of temperature and precipitation distributions is done by Borzenkova (1992). Her summer and winter maps of reconstructed temperature distributions of the Mid-Holocene, Eemian and Mid-Pliocene were recently published also in English (Borzenkova *et al.*, 1992). In these reconstructions, the sea water temperatures in the Mid-Holocene are based on data by Barash *et al.* (1987), Duplessy *et al.* (1981) and Balsam (1981) for the North Atlantic; Nesteroff (1983) for the Mediterranean; Taira (1979) and Pletnev (1985) for the Pacific. The sea water temperature reconstruction for the Eemian is based on CLIMAP data (1984) supplemented with data by Barash *et al.* (1983), Barash *et al.* (1987), Blum (1982), Blum *et al.* (1987), Nikolaev (1986), Nikolaev *et al.* (1983), Dansgaard and Duplessy (1981) and Labeyrie *et al.* (1987). The data indicate that the Mid-Holocene ocean was slightly warmer than present (see also Lutaenko (1993) and Yafeng (1993)), with a higher sea level; the same holds for the Eemian.

For the Southern Hemisphere (SH) temperature reconstruction of the Eemian, Borzenkova (1992) assumed a synchronous warming in both hemispheres during the isotopic stage 5e. However, Crowley (1990) and Imbrie *et al.* (1992) present evidence of a time lag of about 5 kyr in the occurrence of the maximum of warming in oceanic site RC11–120, 44 S. It is not clear whether this feature is characteristic for the whole Southern Ocean, because other SH deep-sea records from SPECMAP Archive, e.g. site RC13-228 (22 S) or RC12–294 (37 S) exhibit a warming which is in phase with the Northern Hemisphere (NH). An out-of-phase warming of the poleward Southern Ocean would imply that Borzenkova overestimates the global temperature in the Eemian by some tenths of a degree. The magnitude of the reported time lag has still to be confirmed, as the accuracy of the high-resolution deep-sea chronology is a few kyrs for the Eemian (Martinson *et al.*, 1987).

The actual Borzenkova's maps show patterns on the scale of continents. Although the original data are highly unevenly distributed over the globe with relatively few sea points, it is claimed that the combination of volume and intrinsic uncertainty of the data indicate that for the Northern Hemisphere patterns of that scale can be resolved successfully, at least over land areas. The present analysis of the divergence of the scaled paleodata (Section 4, Figures 4, 5) supports this claim.

3. Data Processing

The present work used the digitized paleoclimatic reconstructions of winter and summer temperatures of the Mid-Holocene, Eemian, Mid-Pliocene and the Last Glacial Maximum by Borzenkova (1992). These are gridded data over the whole globe of the temperature difference δT with present (1951–1980), with a resolution 10 degrees in latitude and 20 degrees in longitude. For the various epochs, the mean global temperature anomaly, ΔT_g, and the mean Northern Hemisphere (NH) temperature anomalies ΔT_{NH} for summer (JJA) and winter (DJF) were calculated by averaging the points (see Table I); no distinct annual variation in ΔT_g was found. For the Last Glacial Maximum, only summer temperature anomalies for the Northern Hemisphere are available.

The mean zonal NH temperature anomalies dT were calculated with a resolution of 10 degrees of latitude. The values of the local seasonal temperature anomalies δT and the zonal ones dT were scaled (divided) by ΔT_g or another appropriate parameter of Table I. Shared patterns in $\delta T/\Delta T_g$ or $\delta T/\Delta T_{NH}$ could be detected

TABLE I

Temperature difference with respect to the norm period (1951–1980), °C

	ΔT_g	ΔT_{NH}		$\Delta T_{NH}(land)$		$\Delta T_{NH}(ocean)$	
		summer	winter	summer	winter	summer	winter
Mid-Pliocene	3.7	3.2	4.4	3.0	5.5	3.3	3.7
Eemian	1.8	1.5	2.0	1.7	2.7	1.4	1.5
Mid-Holocene	1.0	0.9	1.1	1.0	1.4	0.8	0.9
LGM	–	–4.7	–	–6.8	–	–2.6	–
1980's	0.23	0.13	0.28	0.23	0.55	0.06	0.10

ΔT_g – global mean temperature;
ΔT_{NH} – Northern Hemisphere seasonal temperature;
$\Delta T_{NH}(land)$ – land only, $\Delta T_{NH}(ocean)$ – ocean only.

by averaging the results of the different epochs and comparing the average with the mean deviation that follows from the fields of the individual epochs.

Current temperature anomalies δT (1980–1990; reference period 1951–1980) together with standard deviations are obtained from World Climate Disk (1992). According to this database, the last decade 1980–1990 was very warm, with a global mean annual temperature ΔT_g of 0.23 °C over the 1951–1980 normal (see also IPCC, 1992). The seasonal warming in Northern Hemisphere ΔT_{NH} was about 0.3, 0.2, 0.1 and 0.1 °C over the normal for winter, spring, summer and autumn respectively. Over the NH extratropical ocean the temperature anomaly $\mathrm{d}T$ was almost zero in each season. Over land, the mean NH warming $\Delta T_{NH}(land)$ was 0.55 °C in winter and in other seasons less.

4. Scaled Temperature Distributions

Figure 1 shows for the past three warm epochs the scaled difference in zonal mean summer and winter temperatures with present, as a function of latitude ϕ. In Figure 1a, the scaling in each epoch is done with ΔT_g of that epoch (see also Hoffert and Covey, 1992; and Budyko and Izrael, 1990); in Figure 1b the scaling is done with ΔT_{NH}, which is seasonally dependent (Table I). Also depicted is the universal paleo-warming curve of Hoffert and Covey (1992):

$$\mathrm{d}T/\Delta T_g = 3.21 \sin^4(\phi) + 0.36, \tag{1}$$

based on the data from the same three warm epochs as in Figure 1.

The summer points in Figure 1a are mostly below the universal curve (Equation (1)) and the winter points above it. Figure 1b demonstrates that a better agreement is obtained if the scaling factor ΔT_g in Equation (1) is replaced by seasonally dependent parameter ΔT_{NH}. The new scaling reduces the residual variance σ^2 of

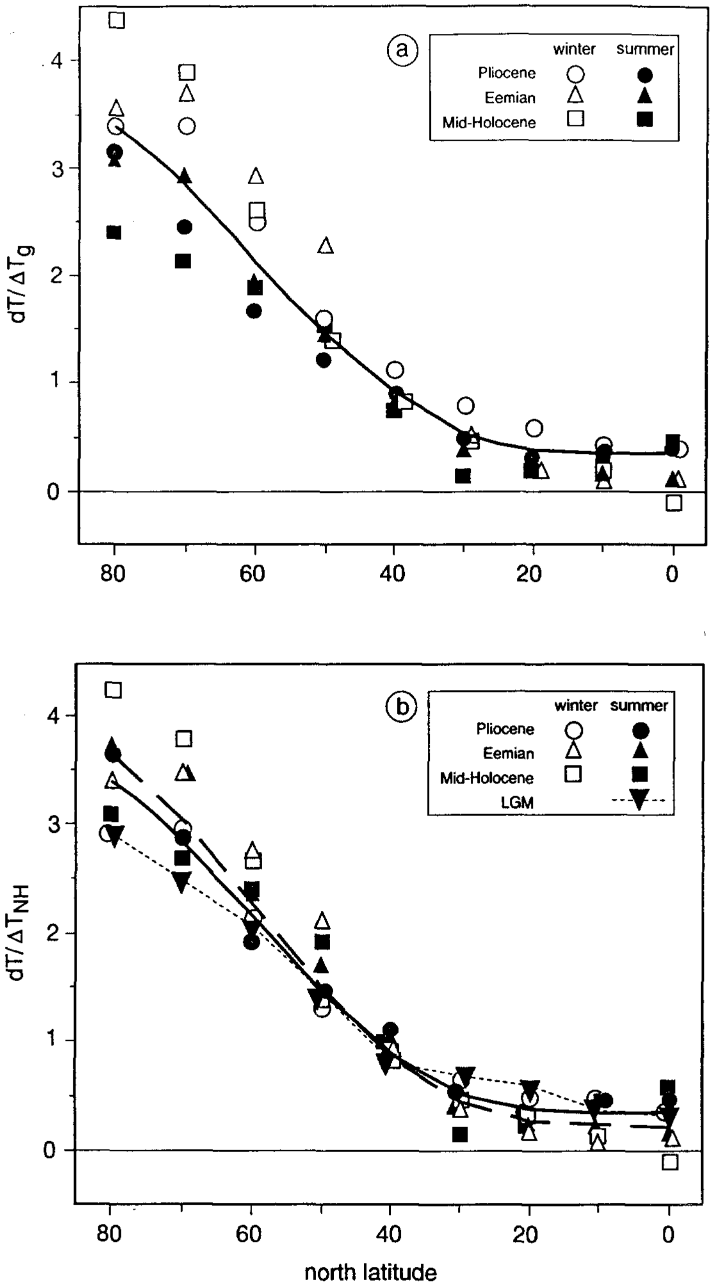

Fig. 1. *Top:* Mean zonal warming dT (reference period 1951–1980) for winter and summer of three warm epochs, scaled with the mean global warming ΔT_g of the corresponding epoch; *Bottom:* Mean zonal warming dT for winter (DJF) and summer (JJA) of three warm epochs and the Last Glacial Maximum (LGM), scaled with the mean Northern Hemisphere seasonal warming ΔT_{NH} of the corresponding epoch. The universal warming curve suggested by Hoffert and Covey (1992) is shown as a solid; the modified curve from Equation (2) is dashed.

the points by 40%. Another 20% reduction of σ^2 can be obtained by replacing Equation (1) by

$$dT/\Delta T_{NH} = 3.6\sin^4(\phi) + 0.28 \quad (2)$$

Both the curves of Equation (1) and Equation (2) are depicted in Figure 1b.

In Figure 1b, the summer points of the Last Glacial Maximum (LGM) have also been included (both dT and ΔT_{NH} are negative). Despite the fact that the range of ΔT_{NH} (Table I) is very large, the latitudinal dependencies of $dT/\Delta T_{NH}$ are similar for all past epochs, including the cold one. Hence, although the causes of the climate fluctuations of the four epochs are different (Crowley, 1990), the agreement in Figure 1b suggests that for mean latitudinal values and scaling with ΔT_{NH} the paleoanalog hypothesis holds for warm climates, as well as for cold epochs. On the other hand, due to the presence of the large asymmetric ice sheet in LGM the distribution of cooling along the zonal belt at high latitudes was very inhomogeneous. Thus, on the regional level, the scaled temperature anomalies $\delta T/\Delta T_{NH}$ from Last Glacial Maximum are incomparable with those of the warm epochs.

In equilibrium state, the latitudinal warming of land and ocean should be similar. Even in equilibrium conditions, however, $\Delta T_{NH}(land)$ averaged over summer and winter is larger than $\Delta T_{NH}(ocean)$, because of the predominant presence of land in higher latitudes. Equation (2) indicates that for a pure equilibrium and averaged over the seasons $\Delta T_{NH}(land) = 1.2\Delta T_g$ and $\Delta T_{NH}(ocean) = 0.9\Delta T_g$. This agrees with paleoreconstructions (see Table I).

Figure 2 compares the zonally averaged warming of 1980's with the scaled paleodata. In terms of latitudinal means, the current winter warming (Figure 2a) goes roughly in the line with paleodata except for very high latitudes. However, Figure 2c shows that the signal mainly originates from land, as is to be expected in the current transient situation.

As a further test of the paleoanalog hypothesis, Figure 3 compares the current and past zonally averaged winter warming over land. Here, as scaling parameter $\Delta T_{NH}(land)$ was applied instead of ΔT_{NH}. Figure 3 shows that the distribution of $dT/\Delta T_{NH}(land)$ of 1980's agrees with paleodata, particularly with the Eemian.

Poleward of 70 N the 1980's winter warming (Figures 2a, 3) is much smaller than that derived from the paleodata or predicted by GCMs. This discrepancy can be explained by the influence of the Arctic, which is the most inertial component of climatic system in the NH. Since in modern epoch there is little evidence of a changing sea-ice condition in high latitudes (IPCC, 1990), it can be supposed that the Arctic retards the warming poleward of 80 N. In the 0–60 N zone, the latitudinal amplification of winter warming is well pronounced, in accordance with both the paleoclimatic data and GCM's equilibrium runs.

No agreement is present in the 1980's summer warming and the paleodata, not even over land (Figures 2b, d); the land warming of the 1980's summer does not show any sign of northward latitudinal amplification. This is probably related with

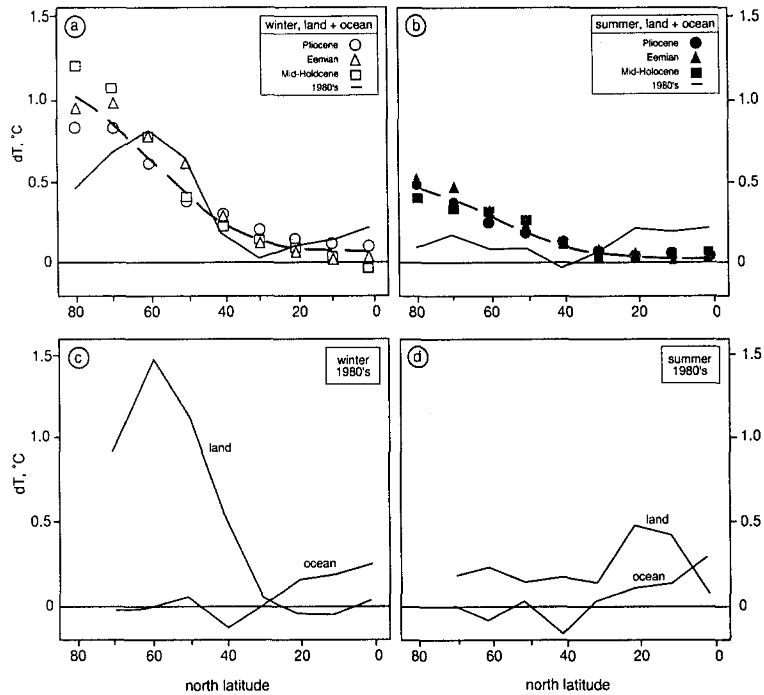

Fig. 2. Mean zonal warming dT of the 1980–1990 period (reference period 1951–1980). In the upper graphs, the paleodata and the universal warming curve (Equation (2)) are also shown, multiplied by the mean NH warming ΔT_{NH} of the 1980's (0.13 °C for summer and 0.28 °C for winter). The lower graphs separate the warming dT into warming over ocean and land.

the inertia of the Arctic sea-iceas which reduces the role of the sea-ice albedo-temperature feedback in the current summer warming. The tropical land area in summer shows an excess warming (Figure 2d). This may also be regarded as a transient effect, caused by the change in hydrological cycles in that season.

The current warming over the ocean is small and differs largely from the paleodata. A remarkable feature in Figures 2c, d is the warming of the 1980's over ocean in tropics. One explanation may be the decadal variability in the ocean circulation; another is an early signal of the greenhouse warming, caused by the relative shallowness of the tropical ocean in combination with the water vapour feedback (Raval and Ramanathan, 1989) and cloud feedback (Tselioudis *et al.*, 1993). The effects of these feedbacks are discussed in the next section.

Figures 4–5 show for winter and summer the geographic distributions of the averaged scaled temperature anomalies t ($t = \overline{\delta T / \Delta T_{\mathrm{NH}}}$) of the three warm epochs and the deviation in the field. The deviation r has been calculated by

$$r^2 = \frac{\sum_{i=1}^{N} (t_i - t)^2}{N} \tag{3}$$

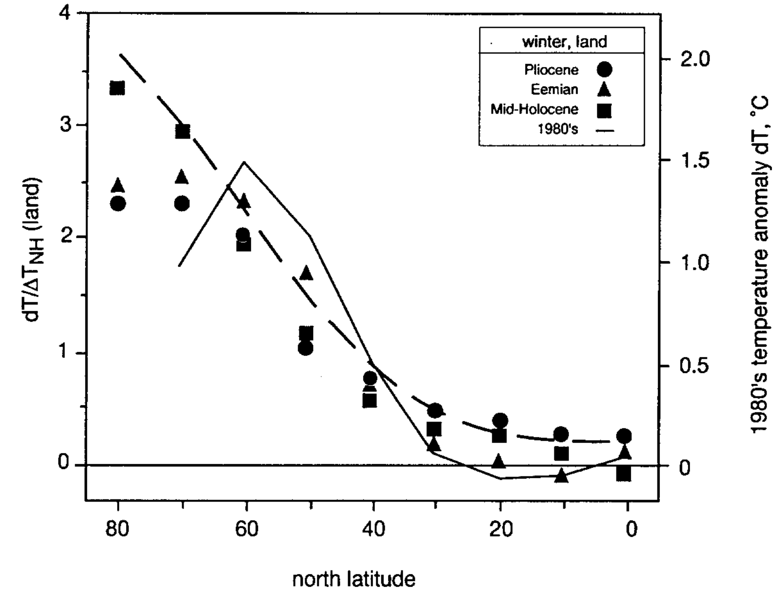

Fig. 3. Mean zonal winter warming over land dT (reference period 1951–1980), scaled with the mean NH winter warming over land ΔT_{NH}(*land*) for three warm epochs and the 1980–1990 period. The dashed line is the universal curve from Equation (2).

where t_i represents $\delta T/\Delta T_{\mathrm{NH}}$ for each epoch in a grid point and $N = 3$. Hence, r represents the divergence in the scaled data of the three epochs.

In the winter map (Figure 4), a marked non-homogeneity in t occurs in high latitudes, with an amplified warming over northern Canada and Asia. A pronounced relatively cold tongue with a large r extending over the Northern Atlantic near Scandinavia; this particular region will be discussed in the next section. The summer temperature anomaly distribution (Figure 5) is smoother than the winter distribution and the Atlantic tongue is absent. For the summer, the largest r is in northern Siberia and is caused by relatively small values of $\delta T/\Delta T_{\mathrm{NH}}$ of the Mid-Holocene. This may be related to the lack of effective regression of the sea-ice boundary in that epoch as compared to the other epochs and consequently a less effective poleward temperature amplification by the sea-ice albedo-temperature feedback.

In a recent publication by Stouffer *et al.* (1994) the regression coefficient of local temperature against the mean global temperature was calculated for observed mean annual time series for the 1881–1990 period. The resulting geographic distribution of the regression coefficient corresponds to the scaled temperature distributions of Figures 4–5. A comparison of the map by Stouffer *et al.* (1994) with ours indicates that the proportionality coefficient between the regional and global annual warming in contemporary climate is of the same order of magnitude as it was in the past.

Table II presents for a number of large areas northward of 35 N the paleowarming for summer and winter and current (1980–1990) winter warming. Like in Figure 3,

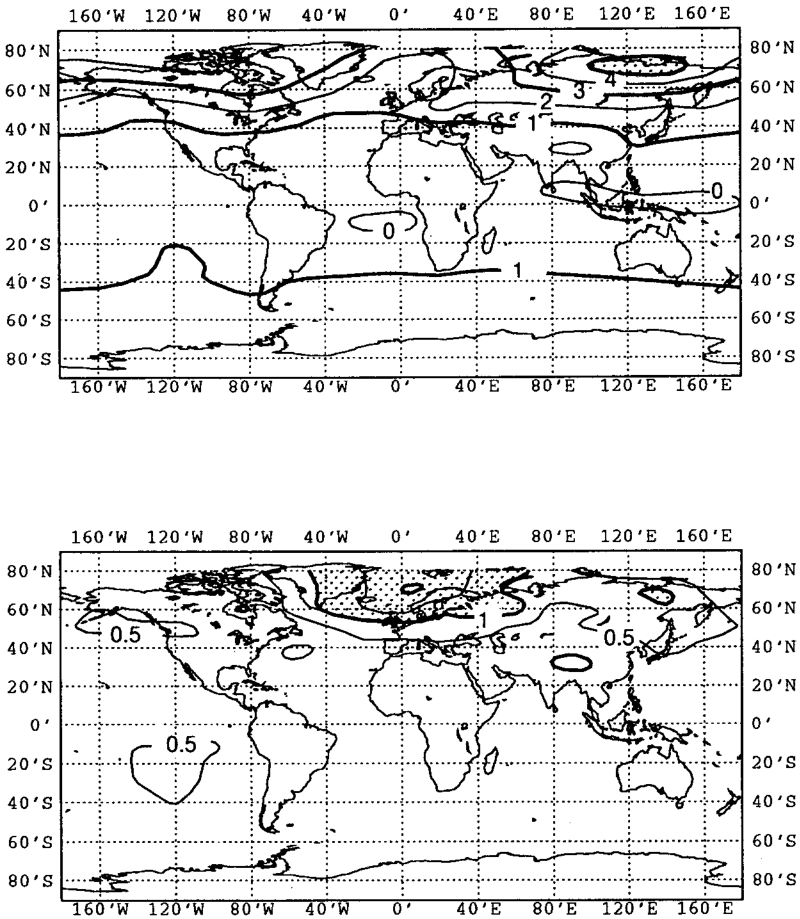

Fig. 4. Scaled winter temperature rise t (top) and deviation r (bottom) as deduced from the average of the paleoclimatic data of three warm climates (°C). For one degree of Northern Hemisphere winter warming, the isolines of t represent the local response in temperature δT in centigrades. Contour intervals are 1 °C (top) and 0.5 °C (bottom). Areas where δT is larger than 5 °C (top) or the deviation r is larger than 1 °C (bottom) are stippled. For the definition of r, see Equation (3).

the temperatures are scaled with $\Delta T_{\mathrm{NH}}(land)$. The summer data of the 1980's are not included since they disagree with the paleodata even for zonal means (Figure 2). Detailed maps of seasonal δT for the recent decade were published in the IPCC update (1992). Table II shows that the areas with the largest winter warming in the 1980's and in past epochs are the same. This holds particularly for the northern regions with a continental climate (areas 1–5). However, the scaled temperature rise in the 1980's is systematically higher than that in the paleodata, by a factor of about 1.5. The explanation is that part of the continents is influenced by the ocean, whose temperature remained unchanged in the 1980's (Figure 2). As a consequence, the value of $\delta T_{\mathrm{NH}}(land)$ for the 1980's is smaller than it would

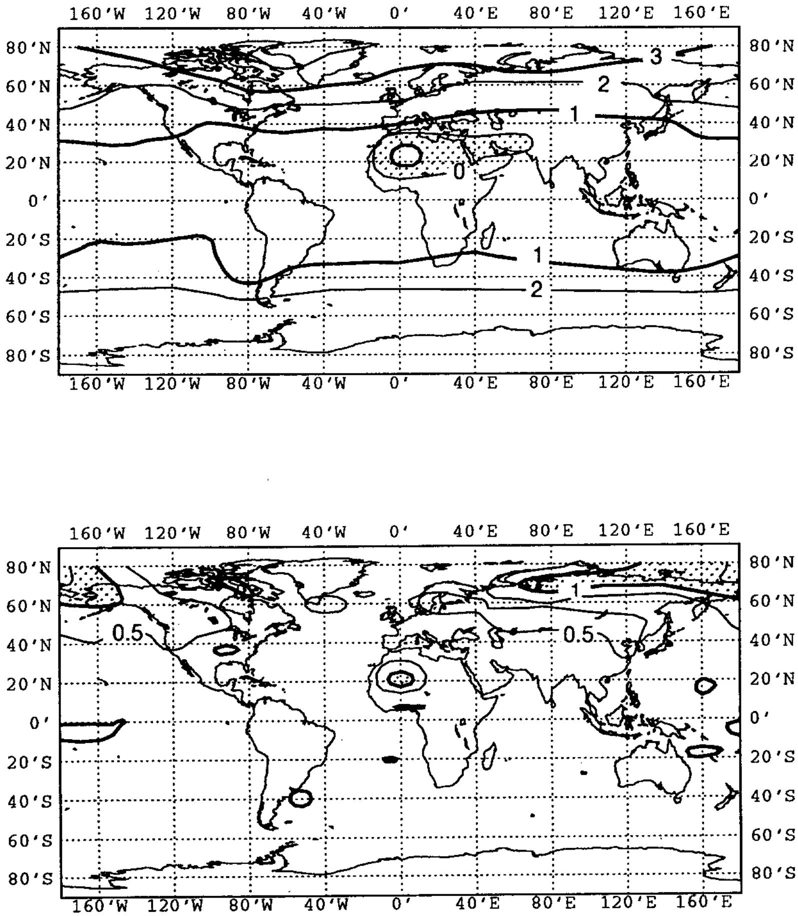

Fig. 5. As in Figure 4, but for summer. Cooling area (top) and areas with a deviation r larger than 1 °C (bottom) are stippled.

have been in the presence of ocean heating (in equilibrium), and hence the scaled temperature rise of the 1980's is relatively high. The same explanation applies to the difference between the zonal data in Figure 3.

In the regions with the most pronounced warming (areas 1–5) the scaled temperature rises of the 1980's are very similar. The difference in signals in these areas is smaller than to be expected from the signal to noise ratios of Table II. The reason for the similarity is the large spatial temperature correlation in high latitudes (Vinnikov *et al.*, 1990), especially for 10-years means. This spatial correlation results also in a strong correlation between δT in these areas and $\Delta T_{\mathrm{NH}}(land)$ since the latter is strongly determined by warming at high latitudes (see also Figure 3). This implies that the signal to noise ratio (t/σ) for the scaled anomalies of 1980's is actually higher than $\delta T/\sigma$ in Table II suggests.

TABLE II

Estimates of scaled temperature change from normals t ($t = \overline{\delta T / \Delta T_{\rm NH}(land)}$ based on paleoclimatic data from three epochs and on current (1980–1990) anomalies. r is a characteristic deviation of the paleodata (Equation (3)). For the modern epoch the ratio of signal to noise ($\delta T/\sigma$) is presented, where δT is the absolute value of the anomaly and σ is the standard deviation in the temperature for 11-year means

	Region	Paleowinter		Paleosummer		Winter 1980's	
		t	r	t	r	t	$\delta T/\sigma$
1.	Alaska 70–60 N; 160–130 W	2.2	0.4	2.3	0.8	3.8	3.7
2.	Canada 70–55 N; 130–90 W	1.9	0.4	2.5	0.5	3.1	2.6
3.	Northern Siberia 75–60 N; 80–140 E	3.0	0.6	2.6	0.8	3.4	3.1
4.	Central Siberia 60–45 N; 80–140 E	1.6	0.5	1.7	0.6	2.7	3.4
5.	Central Russia 75–50 N; 40–80 E	1.9	0.6	2.3	0.7	2.6	2.0
6.	Middle Asia 50–35 N; 40–80 E	0.8	0.3	0.7	0.6	1.4	2.6
7.	Central America 45–35 N; 100–85 W	0.8	0.3	1.1	0.2	0.7	1.0
8.	Europe 60–45 N; 0–40 E	1.0	0.5	1.4	0.4	0.7	1.0
9.	Mediterranean 45–30 N; 10 W–40 E	0.5	0.3	0.5	0.4	0.0	–
10.	Scandinavia 75–60 N; 0–40 E	1.2	1.0	2.2	0.4	–0.2	1.0

In Table II the divergence of the paleodata r (Equation (3)) is also included. The ratio t/r is a measure for the validity of the paleoanalog hypothesis. The Table indicates that $t/r > 1$ in all regions considered and that it ranges up to about 5 in areas with the largest paleowarming. This verifies the paleoanalog hypothesis at a regional level; for regions with a clear warming the hypothesis also verifies for the current transient winter-season warming.

5. Discussion

Figure 1 shows that the paleoanalog hypothesis holds for zonal means in warm and cold epochs and Figures 4–5 together with Table II show that this hypothesis verifies for several regions in the zonal belts, although not everywhere. The maps 4–5 agree satisfactorily with those generated by GCMs for the equilibrium climate with enhanced CO_2 (IPCC, 1990). Agreement is also found between the current transient winter warming over land (see also IPCC update, 1992) and the paleotemperature distributions in warm epochs.

Although the mechanisms causing the climate fluctuations in the past may be different and differ also from that of the current warming, the resulting spatial temperature distributions are suprisingly similar. Also, the average structure of the warming of different epochs resembles that of the GCM equilibrium runs by Wetherald and Manabe (1975), Manabe and Wetherald (1980) and Hansen *et al.* (1984). These experiments show only little difference in spatial distribution of temperature and several other climate elements, although the warming is induced by such diverse mechanisms as increasing either CO_2 or solar radiation. It is also known (Wigley *et al.*, 1986) that the latitudinal and seasonal patterns over land of the early 20th century warming are remarkably similar to the patterns predicted by the equilibrium response GCM study of Manabe and Stouffer (1979, 1980) for quadrupling of CO_2 concentration. These similarities support the idea that the general circulation adjusts itself to give a similar response to different forcings. Note, however, that a change in CO_2 concentration is a common feature of climatic change for epochs we considered, including the current one: since the preindustrial era the CO_2 concentration in the atmosphere rose by about 60 ppm (20%) with an increase of about 15 ppm in a period 1980–1990 (IPCC, 1990).

The change in greenhouse gases concentration is regarded as a main mechanism for climate change in Mid-Pliocene (Budyko, 1986; Crowley, 1991; Van der Burgh *et al.*, 1993) and a significant climate forcing in Eemian and Mid-Holocene (Hansen *et al.*, 1984; Pisias and Shackleton, 1984; Kerr, 1984). Although recent results by Lorius *et al.* (1993) and GRIP Members (1993) support the role of astronomical forcing as the initial cause of the Pleistocene interglacial-glacial transitions, the strong correlation between CO_2 and isotopic temperature in ice-core records from both ice caps (e.g., 0.81 for the extended Vostok record (Jourzel *et al.*, 1993)) indicates that changing CO_2 levels is a significant amplifying factor in glacial-interglacial transitions. Partly due to this amplification a relatively weak fluctuation in global orbital forcing (< 0.7 Wm^{-2} for annual mean) could ultimately result in a change of global temperature by about 6 °C. During the Last Glacial Maximum, the orbital insolation distribution was quite similar to present (Wigley *et al.*, 1986) but the cold conditions maintained, not only because of the inertia of the ice cap, but also because of the reduced CO_2 concentration (Delmas *et al.*, 1980; Broccoli and Manabe, 1987); multivariate analysis performed by Lorius *et al.* (1990, 1993) showed that about half of the temperature change during last glacial-interglacial cycle could be attributed to the greenhouse effect.

Another evidence of the significant role of CO_2 in Pleistocene climate transitions is the broadly parallel behavior between the Northern and Southern Hemispheres throughout the Holocene (see Pittock and Salinger, 1991), since this parallelism can be understood from the role of CO_2 in the spatial homogenizing of the nonuniform orbital forcing. With respect to the Eemian, the terrestrial and most deep-sediment data from both hemispheres also show the synchronous warming, with an exception of high southern latitudes, where a time lag of a few thousand years was recently recognized (Crowley, 1990; Imbrie *et al.*, 1992). The existence of the asynchronous behavior has still to be confirmed because the uncertainty in a high resolution chronology for the Eemian is close to the magnitude of the reported time lag (Martinson *et al.*, 1987).

In the Eemian and Mid-Holocene the CO_2 concentrations were virtually the same as in the preindustrial period, but the sea levels were higher than present. This fact indicates that the ice coverage was considerably reduced (e.g., Mercer, 1978; Gallee *et al.*, 1993). The resulting ice albedo-temperature feedback, together with the surface albedo-temperature feedback resulting from the increase of precipitation in subtropical deserts (Petit-Maire, 1989) could maintain the warmer-than-present Earth conditions at a relatively low CO_2 level.

Thus, even taken individually, each of the three warm periods may be considered as an approximate equilibrium analog for the future climate. But if the periods are taken together, the data indicate the existence of regions with good and poor agreement between the different epochs (Figures 4–5; Table II). We suppose that the regions with good agreement (small divergence in paleodata) present the typical structure of regional equilibrium warming, while poor agreement (large divergence) indicates the regions which are sensitive to the difference in analogs. A reason for this can be either a difference in sea ice boundary conditions in past epochs or a difference in oceanic circulation (Broecker *et al.*, 1985; Broecker and Denton, 1989).

The North Atlantic (NA) region is characterized by a large divergence r, if compared with other areas in the same zonal belt (Figure 4). From paleoclimatic records it is known that this particular region is a very specific one characterized by a high instability in climate (Dansgaard *et al.*, 1993; Alley *et al.*, 1993). Even at the culmination of the last interglacial, the climate in the NA region was able to fluctuate very rapidly. The mechanism of such rapid climate fluctuations is not well understood. As a complex nonlinear system, the climate in NA region might be very sensitive to a small forcing (Palmer, 1993) and might even have a multimodal steady state (Held, 1993). Therefore, this specific region is very difficult for prediction of any sort. Figure 4 shows that the paleoanalog hypothesis fails for the northern NA in winter. The relative divergences r/t in the regional winter temperature change for the land areas influenced by the NA (Europe and Scandinavia) are still relatively high but less than unity; in summer r/t in these regions is low ($r/t < 0.5$, Table II).

In tropics the relative divergence in the paleodata r/t exceeds amply 100% while the absolute values of r are small. This is caused by the fact that the signals themselves are very small. Since the reconstructed values in the tropical areas are close to the detection limit of geologic data, the high values of relative divergence r/t in tropics does not contradict with paleoanalog hypothesis.

The discrepancy in distributions of zonal temperature anomalies between past warm epochs and modern one (Figures 2–3, Table II) is a clear signature of the transient nature of current climate change when the response to the radiative forcing appears firstly over the least inertial component of the climatic system. The characteristic relaxation times of different land areas and of the ocean mixed layer (see also Harvey and Schneider, 1985; Wigley and Schlesinger, 1985) as a response to the insolation forcing were calculated by Byutner and Shabalova (1985) from the amplitude and phases in the annual cycle of surface temperatures. Although the characteristic time scale of greenhouse forcing is larger than the period of seasonal oscillations, the latter encompasses about half of the quasihomogeneous layer of the ocean. Thus, on a time scale of decades, the relative characteristics of inertia can serve as a guide estimation for consideration of greenhouse gases-induced climatic change. The typical relaxation times calculated by Byutner and Shabalova (1985) differ by an order of magnitude for ocean and land as a whole and by a factor of 2–4 for different land areas, being the smallest in the inner continental regions.

In qualitative agreement with this result, the NH warming of 1980's is small northward of 70 N, moderated by the inertial Arctic, and well pronounced over land as a whole in comparison with the ocean (Figure 2). Table II indicates that the largest land warming of 1980's occurs over inner parts of continents, while it is low in the maritime areas. The strong negative correlation between snow cover extend and air surface temperature as observed by Karl *et al.* (1993) provides experimental evidence for the contribution of the albedo-temperature feedback to the current warming over high-latitude land. Figure 2 gives evidence of the role of different inertia of tropical and extratropical oceans, as the 1980's warming over the tropical ocean with shallow mixed layer is accompanied with an absence of warming over deeply mixed high-latitude ocean (Schneider, 1994). The radiative warming over the ocean in tropics could have been amplified by the water-vapour feedback which is most effective over the low-latitude ocean (Raval and Ramanathan, 1989). Additionally, according to Tselioudis *et al.* (1993), there is a strong feedback between surface temperatures and low-level cloudiness which is positive in tropics and changes its sign in higher latitudes ($\varphi \geq$ 50 N) where it becomes much stronger over ocean than over land. This feedback could contribute to the observed contrast in zonal temperature anomalies of the 1980's by amplifying the warming over tropical ocean and compensating for the possible radiative warming over the high-latitude ocean.

Prior to using paleodata as a scenario for the regional distribution of temperature in a future climate, two assumptions should be tested. The first is that the regional anomaly patterns produced by global warming are in first approximation independent of the cause of warming; the second is that the regional structure will also appear in a transient situation. Concerns about the validity of these assumptions were expressed by Crowley (1990).

With respect to the first assumption, we already noted that GCM simulations show that whatever the cause of the warming, there are broad similarities in the patterns of climatic change. Also, we indicated the similarity in structure of the 1980–1990 winter warming and the paleodata at least in several regions; empirical studies by Wigley *et al.* (1980) and by others (see the review by Giorgi and Mearns, 1991) of warm years from instrumental record as well as the study by Stouffer *et al.* (1994) indicate that even in the individual year the temperature anomaly patterns over land are similar.

The second assumption is not generally valid. However, as reported by IPCC (1990, p. 156), the patterns of equilibrium and transient climate change derived from the high resolution models are similar. This suggests that the influence of the transient nature of the present and future climate is not so critical as a whole (except for some particular regions). This argument is in line with the agreement which we find between the recent transient warming over land (Table II from present paper; IPCC, 1992; Wigley *et al.*, 1980; Jager and Kellogg, 1984) and the paleoreconstructions. On the one hand, the asymmetry of current climate change between ocean and land is the clear indication of the transient nature of current warming resulting from the difference in thermal inertia of these two components of climatic system, but on the other hand, the recent winter warming over the least inertial extratropical land areas does agree with equilibrium paleodata. Our conclusion is, that Figures 4–5 can be interpreted as an equilibrium paleodata-based scenario of climate change, whereas for the intracontinental land areas in the NH extratropics a reasonable regional climate change scenario for winter could be produced even in a transient situation by using only one parameter – mean NH temperature change over land – together with scaled paleoanomalies.

Although the paleoanalog hypothesis has been tested at various levels in this paper, we are well aware that this does not prove the validity of the paleoanalog method as a real forecast method. A climate change projection based on paleoreconstructions should rather be considered as a scenario, and quoting Wigley *et al.* (1986), "scenarios are not meant to be a prediction of future climate, rather they are meant to be internally consistent pictures of a plausible future climate".

6. Conclusions

The comparison of the paleoreconstructions of temperature in various epochs and the temperature anomalies in the 1980–1990 period leads to the following conclusions:

First, for zonal means in NH the paleoanalog hypothesis verifies:

1. in warm epochs for individual seasons – if paleodata are scaled with the NH mean temperature anomaly ΔT_{NH} of the corresponding season;
2. in a cold epoch for summer – if the same scaling is applied;
3. in transient situations for the current (1980–1990) winter warming over land – the mean NH winter temperature anomaly over land $\Delta T_{\mathrm{NH}}(\mathit{land})$ is the appropriate scaling factor.

Second, a warmer Earth results in a preferential temperature distribution. This supports the paleoanalog hypothesis on a regional level. When there are strong regional forcings, like an instability of ocean currents or the presence of large ice sheets, the paleoanalog hypothesis on a regional level is violated.

Third, an equilibrium climate change scenario can be produced by considering the scaled temperature anomalies averaged over three epochs (Figures 4–5) and multiplying them by the projected mean hemispheric seasonal temperature rise, ΔT_{NH}. In transient situations like the present one, a reasonable scenario of the future temperature distributions in the intracontinental areas in winter can be obtained in a similar way but using the multiplication with the projected winter temperature rise over land, $\Delta T_{\mathrm{NH}}(land)$.

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References

Alley, R. B. *et al.*: 1993, 'Abrupt Increase in Greenland Snow Accumulation at the End of the Younger Dryas Event', *Nature* **362**, 527.

Balsam, W. H.: 1981, 'Late Quaternary Sedimentation in the Western North Atlantic: Stratigraphy and Palaeoceanography', *Palaeogeogr. Palaeoclim. Palaeoecol.* **35**, 32.

Barash, M. S.: 1971, 'The Vertical and Horizontal Distribution of Planktonic Foraminifera in Quaternary Sediments of the Atlantic Ocean', in Funnel, B. M., and Riedel, W. R. (eds.), *The Micropaleontology of Oceans*, Cambridge Univ. Press, 433.

Borzenkova, I. I.: 1992, *The Changing Climate during the Cenozoic*, Hydrometeoizdat, St. Petersburg, p. 247 (in Russian).

Borzenkova, I. I., Zubakov, V. A., and Lapenis, A. G.: 1992, 'Reconstructions of Global Climate of the Past Warm Epochs', *Soviet Meteorol. Hydrol.* **8**, 19.

Broccoli, A. J. and Manabe, S.: 1987, 'The Influence of Continental Ice, Atmospheric CO_2 and Land Albedo on the Climate of the Last Glacial Maximum', *Clim. Dyn.* **1**, 87.

Broecker, W. S. and Denton, G. H.: 1989, 'The Role of Ocean-Atmosphere Reorganizations in Glacial Cycles', *Geochim. Cosmochim. Acta* **53**, 2465.

Broecker, W. S., Peteet, D. M., and Rind, D.: 1985, 'Does the Ocean-Atmosphere System Have More than One Stable Mode of Operation?', *Nature* **315**, 21.

Budyko, M. I.: 1986, *The Evolution of the Biosphere*, D. Reidel en Co., Dordrecht, Holland, p. 460.

Budyko, M. I. and Izrael, Y. A.: 1990, 'Expected Climate Change', in MacCracken, M., Hecht, A., Budyko, M., and Izrael, Y. (eds.), *The Prospects for Future Climate, US/USSR Report on Climate and Climate Change*, Levis Inc. Publ., p. 267.

Budyko, M. I. and Izrael, Y. A.: 1991, *Anthropogenic Climate Change*, Univ. of Arizona Press, Tucson, p. 277.

Budyko, M. I., Vinnikov, K. Ya., Drozdov, O. A., and Efimova, N. A.: 1978, 'Future Climate Change', *Izv. AN SSSR, Ser. geogr.* **6**, 5 (in Russian).

Byutner, E. K. and Shabalova, M. V.: 1985, 'Seasonal Course of Temperature of Surface Air Layer with Variations of Stratospheric Transparency', *Soviet Meteorol. Hydrol.* **6**, 5.

CLIMAP Project Members: 1976, 'The Surface of the Ice Age Earth', *Science* **191**, 1131.

CLIMAP Project Members: 1984, 'The Last Interglacial Ocean', *Quat. Res.* **21**, 123.

Crowley, T. J.: 1990, 'Are There any Satisfactory Geologic Analog for a Future Greenhouse Warming?', *J. Clim.* **3**, 1282.

Crowley, T. J.: 1991, 'Modeling Pliocene Warmth', *Quat. Sci. Rev.* **10**, 275.

Crowley, T. J. and North, G. R.: 1991, *Paleoclimatology*, Oxford Univ. Press, Clarendon Press, Oxford, p. 360.

Dansgaard, W. and Duplessy, J.-C.: 1981, 'The Eemian Interglacial and Its Termination', *Boreas* **10**, 133.

Dansgaard, W. *et al.*: 1993, 'Evidence for General Instability of Past Climate from a 250 kyr Ice Record', *Nature* **364**, 218.

Delmas, R., Ascencio, L.-M., and Legrand, M.: 1980, 'Polar Ice Evidence that Atmospheric CO_2 20,000 Yr BP Was 50% of Present', *Nature* **284**, 155.

Duplessy, J.-C. *et al.*: 1981, 'Deglacial Warming of the Northeastern Atlantic Ocean: Correlation with the Paleoclimatic Evolution of the European Continent', *Palaeogeogr. Palaeoclim. Palaeoecol.* **35**, 121.

Gallee, H., Berger, A., and Shackleton, N. J.: 1993, 'Simulation of the Climate of the Last 200 kyr with the LLN 2D-Model', in Peltier, W. R. (ed.), *Ice in the Climate System*, NATO ASI Series **I 12**, Springer, Berlin, 329.

Giorgi, F. and Mearns, L. O.: 1991, 'Approaches to the Simulation of the Regional Climatic Change: A Review', *Rev. Geophys.* **29**, 191.

GRIP Members: 1993, 'Climate Instability during the Last Interglacial Period Recorded in the GRIP Ice Core', *Nature* **364**, 203.

Hansen, J. E. *et al.*: 1984, 'Climate Sensitivity: Analysis of Feedback Mechanisms', in Hansen, J. E. and Takahashi, T. (eds.), *Climate Processes and Climate Sensitivity* **5**, AGU, Washington D.C.

Harvey, D. L. D. and Schneider, S. H.: 1985, 'Transient Climate Response to External Forcing on 10^0–10^4 Year Time Scales. Part 1: Experiments with Globally Averaged, Coupled, Atmosphere and Ocean Energy Balance Models', *J. Geophys. Res.* **90**, 2191.

Held, I. M.: 1993, 'Large-Scale Dynamics and Global Warming', *Bull. Amer. Met. Soc.* **74**, 228.

Hoffert, M. I. and Covey, C.: 1992, 'Deriving Global Climate Sensitivity from Palaeoclimate Reconstructions', *Nature* **360**, 573.

Imbrie, J., Boyle, E. A., Clemens, S. C., Duffy, A., Howard, W. R., Kukla, G., Kutzbach, J., Martinson, D. G., McIntyre, A., Mix, A. C., Molfino, B., Morley, J. J., Peterson, L. C., Pisias, N. G., Prell, W. L., Raymo, M. E., Shackleton, N. J., and Toggweiler, J. R.: 1992, 'On the Structure and Origin of Major Glaciation Cycles. 1. Linear Responses to Milankovich Forcing', *Paleoceanogr.* **7**, 701.

Intergovernmental Panel on Climate Change (IPCC): 1990: *Climate Change, The IPCC Scientific Assessment*, Houghton, J. T., Jenkins, G. J., and Ephraums, J. J., (eds.), Cambridge University Press, p. 365.

Intergovernmental Panel on Climate Change (IPCC): 1992, *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment*, Houghton, J. T., Callander, B. A., and Varney, S. K. (eds), Cambridge Univ. Press, p. 200.

Jager, J. and Kellogg, W. W.: 1984, 'Anomalies in Temperature and Rainfall during Warm Arctic Seasons', *Clim. Change* **5**, 39.

Jouzel, J. *et al.*: 1993, 'Extending the Vostok Ice-Core Record of Palaeoclimate to the Penultimate Glacial Period', *Nature* **364**, 407.

Karl, T. R., Groisman, P. Ya., Knight, R. W., and Heim, R. R.: 1993, 'Recent Variation of Snow Cover and Their Relation to Precipitation and Temperature Variations', *J. Clim.* **6**, 1327.

Kerr, R. A.: 1984, 'Carbon Dioxide and the Control of Ice Ages', *Science* **223**, 1053.

Labeyrie, L. D., Duplessy, J.-C., and Blanc, P. L.: 1987, 'Variations in the Mode of Formation and Temperature of Oceanic Deap Waters over the Past 125,000 Years', *Nature* **327**, 477.

Lorius, C., Jouzel, J., and Raynaud, D.: 1993, 'Glacial-Interglacials in Vostok: Climate and Greenhouse Gases', *Glob. Planet. Change* **7**, 131.

Lorius, C., Jouzel, J., Raynaud, D., Hansen, J., and Le Treut, H.: 1990, 'The Ice-Core Record: Climate Sensitivity and Future Greenhouse Warming', *Nature* **347**, 139.

Lutaenko, K. A.: 1993, 'Climatic Optimum during the Holocene and the Distribution of Warm-Water Mollusks in the Sea of Japan', *Palaeogeogr. Palaeoclim. Palaeoecol.* **102**, 273.

Manabe, S. and Stouffer, R. J.: 1979, 'A CO_2 Climate Sensitivity Study with a Mathematical Model of a Global Climate', *Nature* **282**, 491.
Manabe, S. and Stouffer, R. J.: 1980, 'Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration in the Atmosphere', *J. Geophys. Res.* **85**, 5529.
Manabe, S. and Wetherald, R. T.: 1980, 'On the Distribution of Climate Change Resulting from an Increase in CO_2 Content of the Atmosphere', *J. Atm. Sci.* **37**, 99.
Martinson, D. G., Pisias, N. G., Hays, J. D., Imbrie, J., Moore, T. C., and Shackleton, N. J.: 1987, 'Age Dating and the Orbital Theory of the Ice Age: Development of a High-Resolution 0 to 300,000-Year Chronostratigraphy', *Quatern. Res.* **27**, 1.
Mercer, J. H.: 1978, 'West Antarctic Ice Sheet and CO_2 Greenhouse Effect. – A Threat of Disaster', *Nature* **271**, 321.
Nesteroff, W. D.: 1983, 'Evolution Climatique de la Méditerranée Orientale au cours de la Dernière Déglaciation', in *Paleoclimatic Research and Models*, D. Reidel Publ. Co., Brussels, 81.
Palmer, T. N.: 1993, 'A Nonlinear Dynamical Perspective on Climate Change', *Weather* **48**, 314.
Petit-Maire, N.: 1989, 'Interglacial Environments in Presently Hyperarid Sahara: Paleoclimatic Implications', in Leinen, M. and Sarnthein, M. (eds.), *Palaeoclimatology and Palaeometeorology: Modern and Past Patterns of Atmospheric Transport*, Kluwer, Dordrecht, 637.
Pisias, N. G. and Shackleton, N. J.: 1984, 'Modelling the Global Climate Response to Orbital Forcing and Atmospheric Carbon Dioxide Change', *Nature* **310**, 757.
Pittock, A. B. and Salinger, M. J.: 1991, 'Southern Hemisphere Climate Scenarios', *Clim. Change* **18**, 205.
Raval, A. and Ramanathan, V.: 1989, 'Observational Determination of the Greenhouse Effect', *Nature* **342**, 758.
Schneider, S. H.: 1994, 'Detecting Climatic Change Signals: Are There Any "Fingerprints"?', *Science* **263**, 341.
Shabalova, M. V. and Selyakov, K. I.: 1993, 'A Model of the Variation of Regional Climatic Characteristics Based on Paleoclimatic Data', *Russian Meteorol. Hydrol.* **7**, 25.
Stouffer, R. J., Manabe, S., and Vinnikov, K. Ya.: 1994, 'Model Assessment of the Role of Natural Variability in Recent Global Warming', *Nature* **367**, 634.
Taira, K.: 1979, 'Holocene Migrations of the Warm Water Front and Sea-Level Fluctuations in the North-Western Pacific', *Palaeogeogr. Palaeoclim. Palaeoecol.* **28**, 197.
Tselioudis, G., Lacis, A. A., Rind, D., and Rossow, B.: 1993, 'Potential Effect of Cloud Optical Thickness on Climate Warming', *Nature* **366**, 670.
Van der Burgh, J., Visscher, H., Dilcher, D. L., and Kurschner, W. M.: 1993, 'Paleoatmospheric Signatures in Neogene Fossil Leaves', *Science* **260**, 1788.
Velichko, A. A.: 1988, 'Late Pleistocene Spatial Paleoclimatic Reconstructions', in *Late Quaternary Environments of the Soviet Union*, Univ. Minnesota Press, Minneapolis, 261.
Velichko, A. A.: 1989, 'Evolutionary Analysis of the Contemporary Landscape of the Earth and Prognosis', *Quatern. Internat.* **1**, 1.
Velichko, A. *et al.*: 1992, *Atlas of the Paleoclimates and Paleoenvironment of the Northern Hemisphere (Late Pleistocene and Holocene)*, Budapest.
Velichko, A. *et al.*: 1993, 'Greenhouse Warming and the Eurasian Biota: Are There Any Lessons from the Past?', *Glob. Planet. Change* **7**, 51.
Vinnikov, K. Ya., Groisman, P. Ya., and Lugina, K. M.: 1990, 'Empirical Data on Contemporary Global Climate Changes (Temperature and Precipitation)', *J. Clim.* **3**, 662.
Wetherald, R. T. and Manabe S.: 1975, 'The Effect of Changing the Solar Constant on the Climate of a General Circulation Model', *J. Atm. Sci.* **32**, 2044.
Wigley, T. M. L., Jones, P. D., and Kelly, P. M.: 1980, 'Scenarios for a Warm, High-CO_2 World', *Nature* **283**, 17.
Wigley, T. M. L. and Schlesinger, M. E.: 1985, 'Analytical Solution for the Effect of Increasing CO_2 on Global Mean Temperature', *Nature* **315**, 649.
Wigley, T. M. L., Jones, P. D., and Kelly, P. M.: 1986, 'Empirical Climate Studies', in Bolin, B. *et al.* (eds.), *The Greenhouse Effect, Climate Change, and Ecosystems, SCOPE* **29**, John Wiley, New York, 273.

World Climate Disk, Global Climatic Change Data: 1992, Chadwyck-Healey, University of East Anglia.
Yafeng, S.: 1993, 'Mid-Holocene Climates and Environment in China', *Glob. Planet. Change* **7**, 219.
Zubakov, V. A., and Borzenkova, I. I.: 1988, 'Pliocene Paleoclimates: Past Climates as Possible Analogs of Mid-Twenty-First Century Climate', *Palaeogeogr. Palaeoclim. Palaeoecol.* **65**, 35.
Zubakov, V. A., and Borzenkova, I. I.: 1990, *Global Climate during the Cenozoic*, Elsevier Publ. Co., Amsterdam, New York, Oxford, Tokyo, p. 456.

References in Russian

Abramova, T. A.: 1985, 'Paleogeographical Conditions of the Aral-Caspian Region during the Late Holocene (According to Pollen Data)', in *Relief and Climate*, Moscow, 91.
Barash, M. C.: 1985, 'Reconstruction of the Quaternary Temperatures Using Planktonic Foraminifers Data', in *Methods of Reconstructions of Paleoclimates*, Nauka, Moscow, 134.
Barash, M. S.: 1988, *The Quaternary Paleoceanography of the Atlantic Ocean*, Nauka, Moscow, p. 272.
Barash, M. S., Kuptsov, V. M., and Oskina, N. S.: 1987, 'The Atlantic: The New Data about Chronology of Late Pleistocene and Holocene', *Bull. Quat. Study* **56**, 3.
Barash, M. S., Oskina, N. S., and Blum, N. S.: 1983, 'Quaternary Biostratigraphy and Surface Paleotemperatures by Means of Planktonic Foraminifers, Sites 516 and 518', *Init. Rep. DSDP* **72**, 849.
Barash, M. S., Oskina, N. S., and Ivanova, Y. I.: 1980, 'The Upwellings of African Coastal Waters in the Late Pleistocene Studied by the Data on Planktonic Foraminifers', *Oceanology* **20**, N1.
Bazarov, D. B.: 1986, *The Cenozoic of the Near-Baical Territory*, Nauka, Moscow.
Blum, N. S.: 1982, 'Paleotemperature Reconstructions in Different Regions of World Ocean for Pleistocene, Based on Planktonic Foraminifers Data', *Aftoreferat dissertatsii*, Moscow, p. 24.
Blum, N. S., Ivanova, Ye. V. and Os'kina, N. S.: 1987, 'Reconstructions of the Climatic Ocean Zonality (by Using Foraminifera Data)', in *Earth's Climate in the Geological Time*, Moscow, Nauka, 125.
Borzenkova, I. I.: 1987, 'The Features of Moisture Conditions over the Land in the Northern Hemisphere in the Geologic Past', *Meteorol. i Gidrol.* **10**, 15.
Borzenkova, I. I.: 1990, 'Moisture Conditions in the Arid Regions of the Northern Hemisphere during the Late Glacial-Holocene', *Izv. AN SSSR, Ser. Geogr.* **2**, 12.
Borzenkova, I. I.: 1990a, 'Fluctuations in the Moisture Conditions of the Sahara and the Adjacent Areas during the Past 20 kyr', *Izv. AN SSSR, Ser. Geogr.* **3**, 36.
Borzenkova, I. I. and Zubakov, V. A.: 1984, 'Climatic Optimum of the Holocene as a Model of Global Climate of the Early 21st Century', *Meteorol. i Gidrol.* **8**, 69.
Budyko, M. I., Borzenkova, I. I., Mezhulin, G. V., and Selyakov, K. I.: 1992, 'Future Climate Changes', *Izv. AN SSSR, Ser. Geogr.* **4**, 47.
Burashnikova, G. A., Muratova, M. A., and Suetova, I. A.: 1982, 'Climatic Model of the USSR Territory during Holocene Optimum', in *The Development of Nature over the USSR Territory in the Late Pleistocene and Holocene*, Nauka, Moscow, 245.
Khotinskyi, N. A. and Savina, S. S.: 1984, 'Paleoclimatic Maps of the USSR Territory in Boreal, Atlantic and Subboreal Periods of the Holocene', *Iz. AN SSSR, Ser. Geogr.* **4**, 18.
Klimanov, B. A.: 1982, 'Climate of the East Europe during Holocene Climatic Optimum (Pollen Data)', in *The Development of Nature over the USSR Territory in the Late Pleistocene and Holocene*, Nauka, Moscow, 251.
Kotljakov, V. M. *et al.*: 1988, 'Isotope Analysis of the Komsomolskaja Ice core From Antarctica', *Glaciolog. Mather.* **63**, 97.
Krashennikov, V. A. and Basov, I. A.: 1985, *Cretaceous Stratigraphy of the South Ocean*, Nauka, Moskow, p. 170.
Mamedov, E. D.: 1982, 'Pluvials and Arids in the Late Pleistocene and Holocene History of Deserts of the USSR and Adjacent Areas', in *The Development of Nature over the USSR Territory in the Late Pleistocene and Holocene*, Nauka, Moscow, 94.

Mamedov, E. D. and Trofimov, T. N.: 1986, 'Holocene Pluvial Lakes of the Caspian Sea Area', *Bull. Com. Stud. Quatern.* **55**, 102.

Murzaeva, V. E., Konopleva, V. I., Devyatkin, E. V., and Serebryany, L. R.: 1984, 'Pluvial Situations of the Late Pleistocene and Holocene in the Arid Zone of Asia and Africa', *Iz. AN SSSR, Ser. Geogr.* **4**, 15.

Nikolaev, S. D.: 1986, 'The Change of Temperature of the Oceans in Cenozoic (Based on Oxygen Isotope Data)', *Aftoreferat dissertatsii*, Moscow, p. 47.

Nikolaev, S. D., Nikolaev, B. I., and Blum, H. C.: 1983, 'Climate of the Pacific in Pleistocene (Mean Annual Temperature Fields 18 and 125 kyr ago)', in *The Nature of the Ocean*, Moscow, 257.

Pletnev, S. P.: *Stratigraphy of the Marine Sediments and Paleogeography of Japan Sea during the Late Pleistocene (by Using the Planctonic Foraminifera)*, Vladivostok, p. 112.

Vakhrameev, V. A.: 1988, *Jurastic and Cretaceous Floras and Earth's Climates*, Nauka, Moscow, p. 214.

Varushchenko, S. I., Varushchenko, A. N., and Klige, R. K.: 1989, *Fluctuations of the Caspian Sea and Closed Lake Basins during the Geologic Time*, Nauka, Moscow, p. 238.

Velichko, A. A.: 1985, 'Empirical Paleoclimatology (Methods and Uncertainty)', in *Methods of Reconstructions of Paleoclimates*, Nauka, Moscow, p. 7.

Velichko, A. A. and Chapaluga, A. L. (eds.): 1987, *Climates of the Earth in the Geological Past*, Nauka, Moscow, p. 225.

Velichko, A. A., Barash, M. S., Grichuk, V. P., Gurtovaja, E. E., and Zelikson, E. M.: 1984, 'Climate of Northern Hemisphere in the Last Mikulino Interglacial Epoch', *Iz. AN SSSR, Ser. Geogr.* **1**, 5.

Velichko, A. A., Grichuk, V. P., Gurtovaja, E. E., and Zelikson, E. M.: 1983, 'Paleoclimate of the USSR Territory in the Optimum of the Last (Mikulino) Interglacial', *Izv. AN SSSR, Ser. Geogr.* **6**, 30.

Velichko, A. A., Serebriannyi, L. R., and Gurtovaja, E. E. (eds.): 1985, *Methods of Reconstructions of Paleoclimates*, Nauka, Moscow.

Vipper, P., Dorofjuk, L. A., Meteltseva, E., and Sokolovskaya, V.: 1981, 'Paleogeography of the Holocene and the Upper-Pleistocene of Central Mongolia', *Izv. Akad. Nauk Est. SSR, Ser. Biol.* **30**, 74.

Yasomanov, N. A.: 1978, *Landscapes and Climates during Jurastic, Cretaceous and Palaeoneogene Epochs in the South of the USSR*, Nedra, Moscow, p. 223.

Yasomanov, N. A.: 1985, *Ancient Climates of the Earth*, Gidrometeoizdat, Leningrad, p. 292.

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