TWO-DIMENSIONAL MODELLING OF PAST AND FUTURE CLIMATE CHANGE AND COMPARISON WITH PMIP SIMULATIONS

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1. Introduction

Future climate change on timescales of 100-1000 years has generated a great deal of interest. For use in assessing the radiological performance of a deep repository for radioactive waste, there is also interest in the investigation of future climate change over much longer time periods, i.e. the next 100 ka. General circulation models (GCMs) are highly complex which makes them computationally intensive to run and hence unsuitable for long-term experiments. Two-dimensional statistical dynamical climate models, which have a simpler structure, require considerably less computing time and are therefore more suitable for long experiments.

2. The LLN-2D model

A zonally-averaged two-dimensional climate model developed at Louvain-la-Neuve, Belgium (LLN-2D) has been used to investigate climate change over the last 125 ka and the next 150 ka (Burgess, 1998). The model is described in detail by Gallée *et al*. (1991).

Important features of LLN-2D are listed below:

* Zonally and sectorally averaged.
* Northern Hemisphere only (global version under development).
* Zonal bands with 5° north-south resolution.
* Seven surface types or sectors: snow-covered land, snow-free land, open ocean, sea-ice, and the Greenland, Fennoscandian and Laurentide ice sheets.
* Forced by orbitally-induced changes in insolation and atmospheric CO_2

Table 1 Details of the LLN-2D simulations shown here.

SIMULATION	TIME PERIOD	CO_2 FORCING
LQ2	122 ka BP - 0	CO_2 concentrations from Jouzel *et al.* (1993) Vostok chronology
NAT	0 - 150 ka AP	Regression-predicted natural CO_2 concentrations
AN1	0 - 150 ka AP	NAT + Sundquist (1990) low anthropogenic scenario, decay to natural levels by 30 ka AP. Initial CO_2 concentration: 360 ppmv
AN7	0 - 150 ka AP	As AN1 but decay to natural levels by 150 ka AP
AN8	0 - 150 ka AP	NAT + Sundquist (1990) high anthropogenic scenario, decay to natural levels by 150 ka AP. Initial $C0_2$ concentration: 760 ppmv

3. Future Scenarios

Nine LLN-2D simulations were carried out to provide an envelope of possible future climate conditions for the next 150 ka. Figure 1 shows CO_2 forcing and simulated Northern Hemisphere (NH) ice volume from four of the simulations (see Table 1).

* The AN scenarios predict an initial reduction in NH ice over the first 5 ka.
* NH ice is almost non-existent in the first 50 ka in AN1, AN7 and AN8, whereas NAT indicates a gradual build-up of ice over this period.
* A cold period occurs at around 58 ka AP in NAT, in AN1 and AN7 this period is delayed by ~5 ka and is not as extreme. This cold period occurs only briefly in AN8.
* A second, more extreme, cold period occurs at around 110 ka AP. It is most extreme in AN1.

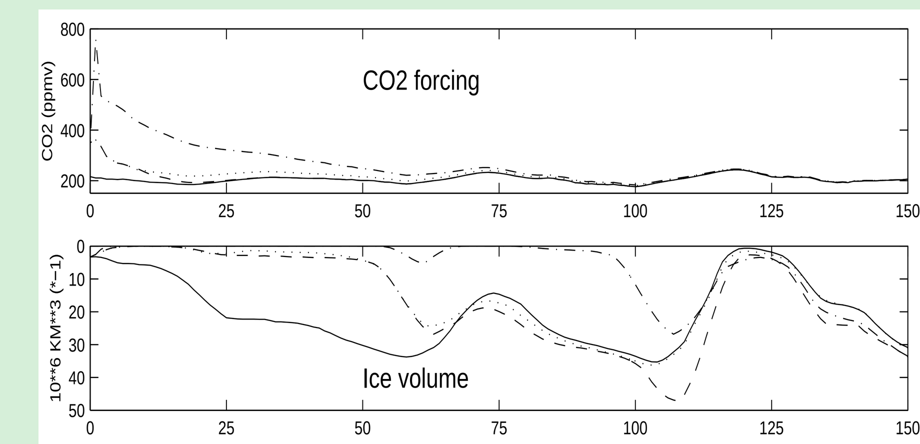

Figure 1 Future CO_2 concentrations and NH ice volume for the next 150 ka AP. NAT = solid line, AN1 = dashed line, AN7 = dotted line, AN8 = dot/dash line.

The differences between NAT and AN simulations indicate that the timing and intensity of glacial-interglacial cycles can be altered by anthropogenically enhanced CO_2 concentrations. The scenarios indicate that the future development of ice sheets is very sensitive to the choice of CO_2 scenario.

4. The PMIP models

The GCMs used in this comparison all come from the Palaeoclimate Modelling Intercomparison Project (PMIP, Joussaume and Taylor, 1995), further details of the models are given in Table 2. The GCMs follow the standard PMIP boundary conditions shown in Table 3.

Table 2 Details of the PMIP models used in the comparison, with the LLN-2D model included for reference.

Model	Resolution	Solar constant (Wm^{-2})	CO_2 (ppm)	Ocean model
LMD5	sin(latitude) x 5.6°	1365	Standard PMIP values	50m mixed layer ocean model
GENESIS2	Prec. 3.75° x 3.75° Temp. 2° x 2°	1365	Standard PMIP values	50m mixed layer ocean model
UGAMP	2.8° x 2.8°	1365	Standard PMIP values	Mixed layer ocean model
CCM1	4.5° x 7.5°	1365	0 ka BP (cal): 330 21 ka BP (cal): 191	50m mixed layer ocean model
CCM3	2.8° x 2.8°	1365	0 ka BP (fix): 355 6 ka BP (fix): 288	Slab ocean model
LLN-2D	5° latitude zonal bands	1368	0 ka BP: 280 6 ka BP: 263 21 ka BP: 191	Mixed layer model

LMD5: Laboratoire de Meteorologie Dynamique, France
GENESIS2: Pennsylvania State University, USA
UGAMP: Universities Global Atmospheric Modelling Project, UK
CCM1/CCM3: Community Climate Model, USA
'cal' = calculated SST, 'fix' = fixed SST.

Table 3 PMIP standard boundary conditions

Period	SST	Insolation	CO_2 concentration (ppm)
0 ka BP	Present-day	Present-day	345 (fix/cal)
6 ka BP	Present-day	6 ka BP value	280 (fix)
21 ka BP	CLIMAP (1981) reconstruction	21 ka BP value	200 (fix); 246.4 (cal)

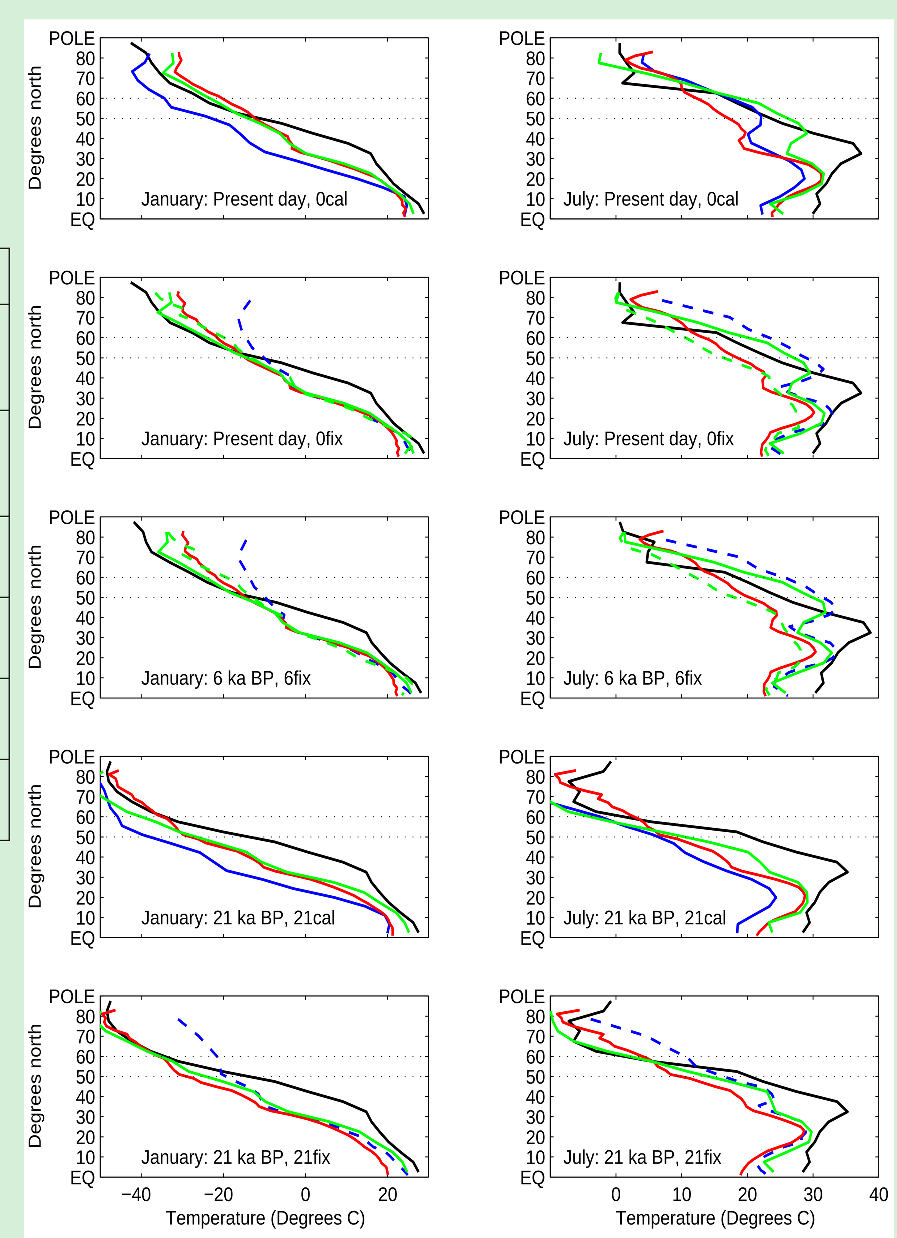

Figure 2 Comparison of Northern Hemisphere LLN-2D and PMIP zonal temperature (land only) for January and July, 0, 6 and 21 ka BP.

5. Comparison of LLN-2D and PMIP zonal temperature

Zonal mean temperature over land was calculated for all the PMIP models and plotted against LLN-2D zonal land temperature (see Figure 2).

* For January present-day, LLN-2D is warmer than the GCMs between ~20-40° N. Agreement between LLN-2D and most of the PMIP models improves north of 50° N.
* For present-day July there is reasonable agreement north of ~40° N. The main area of disagreement in July (for all three time-slices) is that LLN-2D is much warmer over most of the subtropics, especially ~30 to 40° N.
* The 6 ka BP response is similar to the present-day fix response
* For 21 ka BP, agreement between the models is similar to, but slightly worse than, present-day.

6. Comparison of LLN-2D and PMIP zonal precipitation

Zonal mean precipitation (mm/day) over land and ocean was calculated for both LLN-2D and the PMIP models (see Figure 3).

* For present-day January, LLN-2D is within the range of PMIP model estimates at most latitudes. However, at ~20°N, LLN-2D is wetter than most of the PMIP models.
* For present-day July, LLN-2D is within the range of PMIP models at most latitudes. The exception is at ~10° N where LLN-2D is considerably drier than most of the PMIP models.
* For 21 ka BP, agreement is not as good. In January, LLN-2D is the wettest at most latitudes.
* For 21 ka BP July, LLN-2D is wetter than most PMIP models north of 40° N and for the fix case, much drier between 10-20° N.

It should be noted that LLN-2D precipitation is based on the seasonal cycle of observed precipitation from the Jaegar (1976) climatology. Thus, precipitation at 6 and 21 ka BP is only a modification of present-day values.

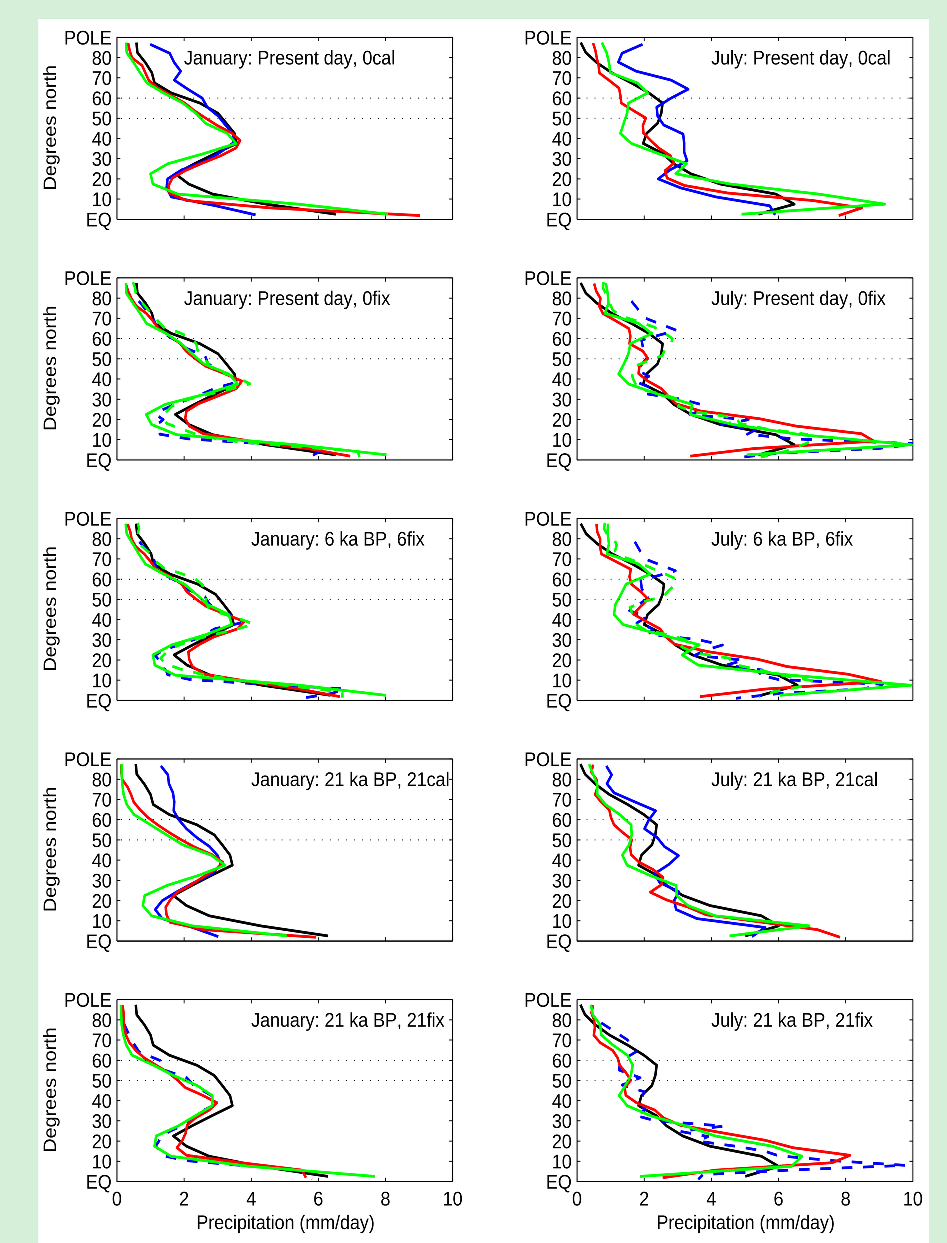

Figure 3 Comparison of Northern Hemisphere LLN-2D and PMIP zonal precipitation (land + ocean) for January and July 0, 6 and 21 ka BP.

7. Downscaling methodology

The sectoral nature of LLN-2D means that it is not possible to get direct estimates of long-term climate change at the regional scale (e.g. the British Isles). Downscaling methodologies developed for use with GCMs cannot be used with 2D models. Therefore a downscaling methodology, using a rule-based approach, was developed (Burgess, 1998).

Indices of English climatic states during the Late Quaternary were compared with various LLN-2D model outputs from the LQ2 simulation. These model timeseries were used to define critical thresholds of zonal climatic parameters that coincide with local changes in climatic state. Figure 4 illustrates the procedure for assignment of Central England climatic states from LLN-2D output. Once climatic states are defined, temperature and precipitation values can be assigned using present-day climate analogue states, identified using the Koppen-Trewartha system (Rudloff, 1981).

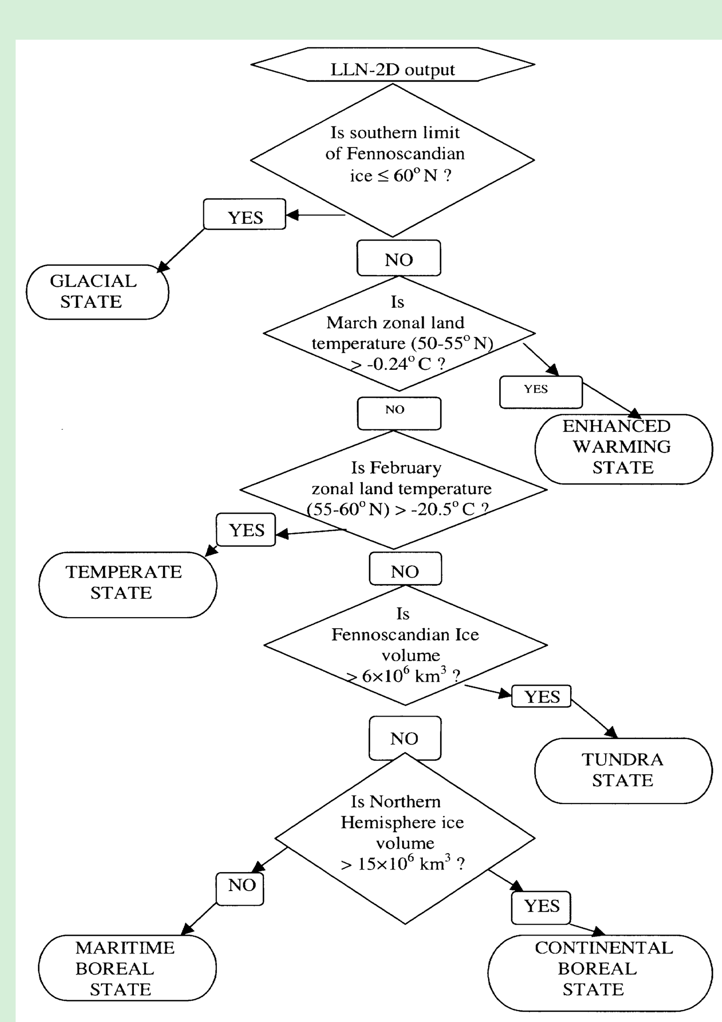

Figure 4 Overview of the rule-based downscaling procedure.

8. Evaluation of the downscaling results

Downscaled mean January and July temperature and precipitation for the past 25 ka, from LQ2 are plotted in Figure 5. Temperature and precipitation from the nearest GCM land grid box to central England were extracted from each of the PMIP models and are also plotted in Figure 5. Values during glacial times are taken as the means over tundra analogue stations, as no station observations were available over ice to form a separate climate analogue. Furthermore, Central England is likely to have been on the edge, rather than in the centre, of extensive glaciation and conditions may have fluctuated between glacial and tundra conditions. Thus variability is not indicated for these periods.

January temperature:

* For 0 and 6 ka BP, most of the PMIP values fall within one standard deviation (SD) of downscaled temperatures from LLN-2D.
* At 21 ka BP the range of estimates from the PMIP models is large and the downscaled LLN-2D temperature lies within the range of these estimates.

July temperature:

* The range of PMIP estimates at 0 and 6 ka BP is much larger for July than January and the GCM values do not fall within one SD of downscaled temperatures.
* The range of the PMIP estimates remains large at 21 ka BP, all GCM values are warmer than the downscaled LLN-2D values.

The validity of LLN-2D precipitation at 6 and 21 ka BP was questioned because of its dependence on present-day observed precipitation, see Panel 6. The downscaled precipitation values do not suffer from this problem as they are taken as the mean precipitation of the climate analogue stations which are selected on the basis of a temperature classification scheme (Burgess, 1998).

January precipitation:

* At 0 and 6 ka BP, the PMIP values all fall within one SD of the downscaled LLN-2D values.
* At 21 ka BP all PMIP models predict slightly higher precipitation than LLN-2D.

July precipitation:

* At 0 and 6 ka BP, most PMIP model estimates are slightly drier than the mean LLN-2D downscaled value.
* At 21 ka BP, in contrast to January, LLN-2D is not the most extreme estimate, with PMIP estimates being both slightly wetter and drier than LLN-2D.

Raw LLN-2D values from the 50-55° N latitude band are also plotted in Figure 5 to investigate whether downscaling is beneficial.

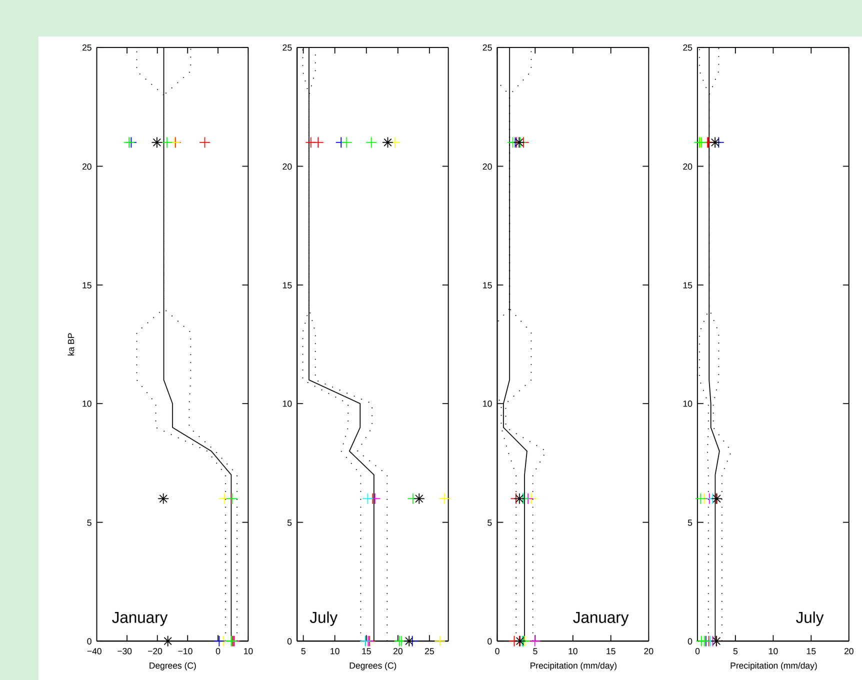

Figure 5 Downscaled temperature and precipitation from LLN-2D together with nearest land grid point values from the PMIP models and raw LLN-2D output (*).

* For temperature at 0 and 6 ka BP, downscaled values are much warmer than the raw values in January and colder in July.
* There is not much difference in the raw and downscaled January temperatures at 21 ka BP but downscaled July temperatures are colder.
* There is very little difference between the raw and downscaled values for precipitation.
* Thus downscaling increases the temperature change between 21 ka BP and 0/6 ka BP.

9. Conclusions

* Considering that the PMIP models all have similar boundary conditions and are therefore constrained to give similar results, the comparisons between LLN-2D and PMIP output are encouraging and support the use of the two-dimensional model for long simulations.
* There is little difference in either raw LLN-2D temperature or precipitation values at 50-55°N between the three time periods, indicating that LLN-2D has difficulties in representing the magnitude of change between glacial and interglacial periods at this latitude.
* The comparisons presented here indicate that downscaling LLN-2D output is desirable for temperature, but has little impact on precipitation values. However, because LLN-2D precipitation is constrained to present-day observed values, downscaling precipitation should provide estimates which are more consistent with the simulated temperature changes.

There are, however, a number of minor discrepancies between LLN-2D output and PMIP output. Possible causes of these discrepancies are listed below.

* There is no representation of variations within each 5° latitude band in LLN-2D.
* The monsoonal circulation is not represented in LLN-2D.
* There is no Southern Hemisphere in the LLN-2D model.
* LLN-2D uses quasi-geostrophic equations to calculate atmospheric dynamics, which are cruder and do not perform as well in the tropics as the primitive equations used by the GCMs (Gallée *et al.*, 1991).
* The comparisons between nearest grid box and downscaled values should be approached with care. GCMs are not generally considered to perform well at grid-box scale because of the parameterisation of small-scale processes.

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10. References

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