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## **Virtual Neanderthals : a study in agent-based modelling Late Pleistocene hominins in western Europe**

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The software and data used in this research is credited according to the guidelines given at GitHub, the data storage and versioning service<sup>48</sup>.

### Paleoclimate data sets

- NOAA, National Climatic Data Center: Paleoclimatology data: <http://www.ncdc.noaa.gov/paleo/model.html> (accessed 29 May 2013, verified 17 September 2017).
- WorldClim – Global Climate Data – Past conditions: <http://www.worldclim.org/past> (verified 17 September 2017).
- PMIP – Paleoclimate Modelling Intercomparison Project Phase II: <http://pmip2.lsce.ipsl.fr/> (verified 17 September 2017).
- CCSM – Community Climate System Model, a Global Climate Model (Wikipedia entry): [http://en.wikipedia.org/wiki/Community\\_Climate\\_System\\_Model](http://en.wikipedia.org/wiki/Community_Climate_System_Model) (verified 17 September 2017).
- MIROC3.2 (Model for Interdisciplinary Research on Climate) – model information: [http://www-pcmdi.llnl.gov/ipcc/model\\_documentation/MIROC3.2\\_medres.htm](http://www-pcmdi.llnl.gov/ipcc/model_documentation/MIROC3.2_medres.htm) (verified 17 September 2017).

### Topographical data sets

- VTP – Undersea Terrain Elevation (Bathymetry) – model description: <http://vterrain.org/Elevation/Bathy/> (verified 17 September 2017).
- World Map of Carbonate Rock Outcrops v3.0, [http://web.env.auckland.ac.nz/our\\_research/karst/](http://web.env.auckland.ac.nz/our_research/karst/), accessed 17 September 2013. Data is available as shape files (verified 17 September 2017).

### Software tools used in this study

- SAM – Spatial Analysis in Macroecology, v4.0: <http://www.ecoevol.ufg.br/sam/> (verified 17 September 2017).
- Repast Symphony, version 2.2: <https://repast.github.io/download.html> (accessed 17 November 2016, verified 17 September 2017).
- IBM SPSS Statistics - <http://www-01.ibm.com/software/analytics/spss/downloads/> (verified 17 September 2017).

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## APPENDIX 1: ABBREVIATIONS

### Abbreviations

Abbreviation	Meaning
<b>ABMS</b>	Agent-Based Modelling and Simulation
<b>ABM</b>	Agent-Based Model(ing), can also be found under the terms Agent-Based Computational Modelling, Agent-Based Social Simulation, Multi-Agent systems, Distributed Artificial Intelligence, and Swarm Intelligence.
<b>ABS</b>	Agent-Based System.
<b>AMH</b>	Anatomically Modern Human(s).
<b>BP</b>	Before Present, where present is defined as 1950.
<b>CLIMAP</b>	Climate Map.
<b>FR</b>	Foraging range: The total area of land over which a hominin group moves and from which resource materials are taken in one year. This is equal to the <i>annual range</i> , the area that is covered for subsistence purposes in a complete year (MacDonell 1995).
<b>GARP</b>	Genetic Algorithm for Rule-Set Prediction.
<b>HS</b>	HomininSpace: The <i>Hominini</i> tribal level is today the scientific identification of humans and their ancestors as separated from the great apes, with which they form the family taxonomic unit of <i>Hominidae</i> (Wood and Richmond 2000). In popular language this is anglicized to hominins. Space is the natural living dimension for individuals. Both the simulation research methods as well as archaeological excavations add their own temporal dimension to the usage of space. The generalized nature of the implementation of the system (without the specialized datasets that mark the case study for Neanderthals) suggests the name HomininSpace (no italics) for a simulation system that models hominin behaviour in the landscape and that is validated against archaeological data concerning hominin presence and absence. HomininSpace is the designation for the complete modelling and simulation system with associated documentation that has been developed in the context of the study described in this thesis.
<b>IBM</b>	Individual-Based Modelling.
<b>ka</b>	Kilo-Annum (thousand years) ago.
<b>kya</b>	Kilo (thousand) years ago.
<b>LP</b>	Late Pleistocene (versus Middle Palaeolithic). The Late Pleistocene is defined as the period from 126 ka up to 11.7 ka. It starts with the Eemian (MIS 5e) and ends with the Holocene ( <a href="http://quaternary.stratigraphy.org/majordivisions/">http://quaternary.stratigraphy.org/majordivisions/</a> , <a href="http://www.stratigraphy.org/index.php/ics-chart-timescale">http://www.stratigraphy.org/index.php/ics-chart-timescale</a> , accessed 15 January 2018). Since the simulations in this study all end at 50 ka, the final part of the Late Pleistocene is not included in this research.
<b>MAS</b>	Multi-Agent Systems.
<b>MAXENT</b>	Maximum Entropy.
<b>MH</b>	Mid-Holocene point in time (~6 ka), reconstructed as very warm compared to current day temperatures.
<b>My</b>	Million Years.
<b>Mya</b>	Million Years Ago.
<b>LGM</b>	Last Glacial Maximum (~21 ka).
<b>LMP</b>	Late Middle Palaeolithic.
<b>LUP</b>	Late Upper Palaeolithic.
<b>PMIP</b>	Paleoclimate Modeling Intercomparison Project.
<b>SAM</b>	Spatial Analysis in Macroecology.

**Bioclimatic parameters**

<b>Bioclimatic parameters</b>	BIO1 = Annual Mean Temperature BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)) BIO3 = Isothermality (BIO2/BIO7) (* 100) BIO4 = Temperature Seasonality (standard deviation *100) BIO5 = Max Temperature of Warmest Month BIO6 = Min Temperature of Coldest Month BIO7 = Temperature Annual Range (BIO5-BIO6) BIO8 = Mean Temperature of Wettest Quarter BIO9 = Mean Temperature of Driest Quarter BIO10 = Mean Temperature of Warmest Quarter BIO11 = Mean Temperature of Coldest Quarter BIO12 = Annual Precipitation BIO13 = Precipitation of Wettest Month BIO14 = Precipitation of Driest Month BIO15 = Precipitation Seasonality (Coefficient of Variation) BIO16 = Precipitation of Wettest Quarter BIO17 = Precipitation of Driest Quarter BIO18 = Precipitation of Warmest Quarter BIO19 = Precipitation of Coldest Quarter
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**Biome (Mega) classifications**

<b>Original biome classification</b>	<b>Mega-biome classification</b>
Tropical evergreen broadleaf forest Tropical semi-evergreen broadleaf forest Tropical deciduous broadleaf forest and woodland	Tropical forest
Warm-temperate evergreen broadleaf and mixed forest Warm-temperate evergreen broadleaf forest Warm-temperate rainforest Wet sclerophyll forest	Warm-temperate forest
Cool evergreen needle leaf forest Cool mixed forest Cool-temperate rainforest Cool-temperate evergreen needle leaf and mixed forest Temperate evergreen needle leaf forest Temperate deciduous broadleaf forest	Temperate forest
Cold deciduous forest Cold evergreen needle leaf forest	Boreal forest
Temperate sclerophyll woodland and scrubland Temperate evergreen needle leaf open woodland Tropical savanna Temperate deciduous broadleaf savanna	Savanna and dry woodland
Tropical xerophytic scrubland Temperate xerophytic scrubland Tropical grassland Temperate grassland Steppe Xerophytic woods/scrub Temperate grassland and xerophytic scrubland	Grassland and dry scrubland
Desert	Desert
Graminoid and forb tundra	Dry tundra
Cushion-forb tundra (cushion forb, lichen and moss tundra) Erect dwarf-shrub tundra	Tundra

## Appendices

Low and high shrub tundra Prostrate dwarf-shrub tundra Tundra Alpine grassland	
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(taken from <http://pmip2.lsce.ipsl.fr/>, accessed 24 May 2013 (Harrison and Prentice 2003)).





## APPENDIX 2: SUPPLEMENTARY MATERIALS

HomininSpace consist of a computer application, associated input files, simulation results and documentation. This thesis describes the study in which the HomininSpace simulation system was developed and with this thesis come Supplementary Materials, both in the appendices and in separate files collected on a single DVD disk. The content of this DVD is listed in Table 56. Furthermore this appendix contains the posters that were presented at conferences and which are referred to in this work. Such materials are normally not easily accessible and therefore included here. All materials available on the DVD are also accessible online, via a service made available by the Data Archiving and Networked Services (DANS): <https://doi.org/10.17026/dans-28h-bysx>. Data has been submitted using the online archiving system EASY, upon which data is archived according to the guidelines of the international Data Seal of Approval, the ICSU-WDS, and the NESTOR seal for Trustworthy Digital Archives. Moreover, the metadata fields in EASY comply with the guidelines of the Dublin Core standard<sup>49</sup> ensuring future availability.

### Contents of the HomininSpace data disk

The Table 56 lists the items on the disk that accompanies this study. Bold face headers are the names of directories on the disk, starting at the root. The actual filenames as included on the disk are given in italics.

**Table 56: Contents of the HomininSpace disk.**

<b>\Documentation</b>	
<i>HomininSpace ODD.docx / .pdf</i>	The Overview, Design and Details document for the HomininSpace model and simulation system.
<i>HomininSpace – checkpoint database.docx</i>	Document describing the construction of the checkpoint database. Provides also reasons to include or exclude individual sites.
<i>HomininSpace – thesis.docx / .pdf</i>	This thesis.
<i>Climate reconstruction - Fulco Scherjon - labreport.docx</i>	Documentation on the use of SAM and related files.
<i>HomininSpace_GE.kmz</i>	Google Earth input file with all checkpoints.
<i>HomininSpace - user manual 1.6.docx / .pdf</i>	User manual describing the most common actions within the simulation system, including input and output data formats.
<b>\Analysis</b>	
<i>Analysis results plots [scenario].pdf</i>	Graphical output of the statistical analysis, including correlation figures. For each scenario.

<sup>49</sup> See [http://easy.dans.knaw.nl/doc/pdf/DEP\\_All\\_other\\_disciplinesUK.pdf](http://easy.dans.knaw.nl/doc/pdf/DEP_All_other_disciplinesUK.pdf), verified 26 March 2018.

	<i>AllData.csv</i>	File with all simulations from all scenarios.
	<i>Batchresults_[scenario].txt</i>	Results for all simulations from a scenario. One file for each scenario.
	<i>[Correlation output]</i>	For each scenario files with correlation data for the Standard set, the Evolved set and the combined set with all simulations.
	<i>Top10 parametervalues.csv</i>	Overview of the best 10 simulations for each scenario.
<b>\Model Data</b>		
	<i>Neandertal sites – north west Europe.xlsx</i>	All checkpoints with associated intervals. Database with dating information for Neandertal sites for the simulation area. Also includes a list of MIS 6 sites (used for starting populations) and pure information points (that just register presence, but since no exact dating information is known, these are not used in validation of the results). Contains all checkpoints, monitoring checkpoints and starting locations of initial population groups.
	<i>SAM Grid a_1_12.txt</i>	Input grid cells.
	<i>Bintanja2008.txt</i>	Reconstructed temperature and sea level values.
	<i>HomininSpace Climate Grid.txt</i>	Climate data per grid cell.
	<i>HomininSpace Checkpoint List.txt</i>	The actual input file with the checkpoint information. Derived from the Neandertal sites Excel file.
<b>SAM input files</b>		
	<i>Etopo1_bedrock.zip</i>	Bedrock height values for selected area, XYZ format input file.
	<i>alt_2-5m_bil.zip</i>	Worldclim.org input files, ecological data for current and past climates in high resolution (2.5 arc minutes).
	<i>bio_2-5m_bil.zip</i>	
	<i>wc_2_5m_CCSM_21k_bio.zip</i>	
	<i>wc_2_5m_MIROC3.2_21k_bio.zip</i>	
<b>\Source code</b>		
	<i>Workspace\HomininSpace</i>	Source Code which provides the Java source code of the HomininSpace modelling framework. This is a Repast workspace and contains next to the source also administrative files.
<b>\Scripts for statistical analysis</b>		
	<i>Batch analysis HS results.R</i>	R script for statistical analysis of the combined simulation result files.
	<i>Batch print HS results.R</i>	R script to generate images that are used in the statistical analysis.
	<i>Analysis draw faces.R</i>	R script to generate the Chernoff faces of the top 10 scoring individuals.

	<i>Climate calculations.xlsx</i>	Example calculations of secondary biomass.
	<i>HomininSpace Population Calculator.xlsx</i>	Interactive tool to see the effect on population structure of different parameters.
<b>\Output data</b>		
Files with batch simulation results		
	<i>Summed data only.xlsx</i>	Excel sheet containing the summed results for all output variables for all relevant simulations for all scenarios.
	<i>HS Logfile 2018-11-29 0045.txt</i>	Example log file.
Movies with screen captures of running simulations		
	<i>1.888.579.450 8-10-2013 50.avi</i>	
	<i>1.888.579.450 9-10-2013 50.avi</i>	
	<i>1.888.579.450 22-10-2013 50.avi</i>	
	<i>1.888.579.450 23-10-2013 50.avi</i>	
<b>\Review by Iza Romanowska</b>		
	<i>HomininSpaceComments.docx</i>	Word document with the source code review results.
	<i>Re HomininSpace et al (email 2016-12-11).txt</i>	Verbatim email text with the overall impression and review results.
	<i>Earlier emails.txt</i>	Email exchange about the review.
<b>\Applications</b>		
Tools used in the framework or during development		
	<i>Quickview</i>	Installation file for Quickview (needed to capture and view simulation movies).
	<i>Repast</i>	Installation files for Repast 2.2.
	<i>SAM</i>	Installation files for SAM 4.0 + documentation.



Poster: *Neandertals on the move. Or not.* – ESHE 2015

# NEANDERTALS ON THE MOVE. OR NOT.

A multi-parameter investigation of mobility types in the deep past

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Figure 1 - HomininSpace: deconstructing the Neandertal model

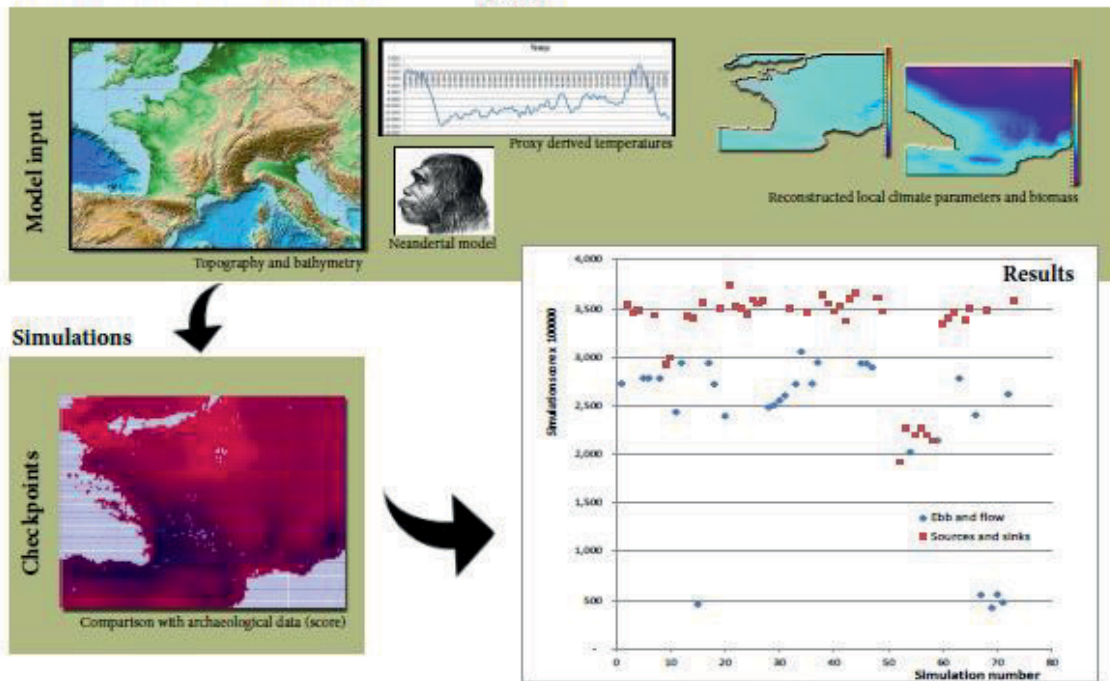
## HomininSpace

The aim of the HomininSpace modelling and simulation system is to model, as realistically as possible, past hominin movement and persistence through time, in a changing ecological and geographical environment. Key characteristics are:

- Agent-based model (ABM);
- Fluctuating carrying capacity as key attractor;
- Parameterized and spatially explicit reconstructed paleo-environment;
- Year-by-year demographic model;
- Comprehensive database of archaeological checkpoints in space and time.

Hypothesis testing is done by comparing simulation results of hominin group presence in different scenarios against the archaeological record (stimulation score). Results illustrate the effects of different parameters when reconstructing hominin behavior in the past (Figure 1). Both "ebb and flow" and "sources and sinks" mobility types have been used to explain the Neandertal record of presence and absence (Roebroeks *et al.* 2011) and have been implemented within the HomininSpace simulation system.

## Model



## Conclusion: Sources and sinks mobility matches archaeology best

Comparing the archaeology with the results for the two mobility types suggest that the "sources and sinks" model matches the archaeological record best. Competition for available resources is a major factor influencing mobility strategies. Possible explanations why the "sources and sinks" model scores higher and increases population levels consistently:

- When resources become scarce, hominins can sometimes survive, albeit at very low densities;
- During ebb and flow movement, groups will all converge on areas with high productivity;
- Sink populations will utilize the environment optimally, by being forced to use resources from areas that flow groups do not enter or leave when conditions become less favorable.

The implemented "sources and sinks" mobility model explains how repeated regional extinction could have been an important factor in the demography of Neandertals. The underlying results also illustrate some of the advantages of ABM over other types of modelling.

### Selected references

Roebroeks, E., E. M. van der Plicht, and J. Desnues. 2015. Modelled atmospheric temperatures and global sea levels over the period 100,000 years before present. *Quaternary Science Reviews* 115: 1–12.  
 Roebroeks, E., M. van den Bergh, S. L. Van der Meulen, and J. Desnues. 2011. Climatic and environmental changes in the last glacial period: A review. *Journal of Human Evolution* 61: 1–12.  
 Roebroeks, E., and J. Desnues. 2015. The Neandertal record: A review. *Journal of Human Evolution* 89: 1–12.  
 Roebroeks, E., and J. Desnues. 2015. The Neandertal record: A review. *Journal of Human Evolution* 89: 1–12.  
 Roebroeks, E., and J. Desnues. 2015. The Neandertal record: A review. *Journal of Human Evolution* 89: 1–12.





# HOW (NOT) TO MODEL NEANDERTAL EXTINCTION

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Figure 1 - Unequal chances for Neanderthals.

## If you handicap the competition, do not be surprised to win...

We analysed existing simulation models for Neanderthal demise. Each of the models assumes a large difference between Neanderthals and AMH (Fig. 1). Evidently, under such conditions the replacement of Neanderthals by AMH is inevitable (Fig. 2). Each model we looked at implements an unsubstantiated (relative) handicap for Neanderthals:

- increasing mortality rates for Neanderthals [6], and decreasing rates for AMH [1];
- decreasing growth rates for Neanderthals, but increasing rates for AMH (due to differences in technological development [3,4,5,7] or in social organization [2]).

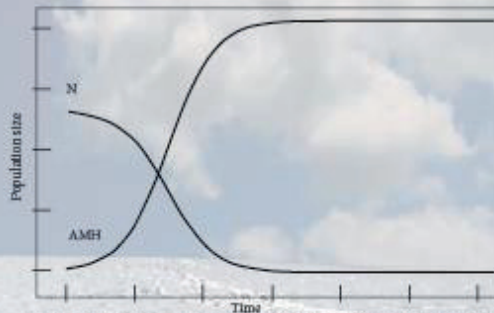


Figure 2 - The inevitable result: replacement of N by AMH (figure adapted from [7]).

Reference	Handicap (assumptions)	Results	Model type
Zubrow 1989 [4]	Seemingly small but effectively large demographic differences, with lower birthrate for N.	Large discrepancies in mortality and life expectancy, with an increment in N mortality of 1-2 % leading to extinction within as little as 30 generations.	population model
Horan et al. 2005 [2]	Increasing social organisation for AMH.	Unavoidable replacement of N by AMH after varying amount of years.	mathematical
Flores 2011 [3] Flores 1998 [7] Murray 2004 [5]	Higher mortality rate for N	N are replaced by AMH (model implemented by Murray 2004). Flores 2011 uses the computed similitude from [7] to calculate diffusion coefficients.	nonlinear mathematical model
Gilpin et al. 2016 [4]	Lower cultural level interacting with population size.	Replacement of larger N population by AMH.	mathematical
Sorensen 2011 [6]	1% reduction in death during childbirth and in death by hunting incidences between AMH and N.	Population growth amongst AMH despite adverse climatic conditions ~45 kya.	mathematical

### Conclusion: How to model Neanderthals?

We introduce a conservative model which assumes no difference between N and AMH and uses only population size. This null model suggests that stochasticity and allele effects (i.e., populations at low numbers are affected by decreasing growth rates) might have been sufficient for the Neanderthals to have gone extinct (Fig. 3).

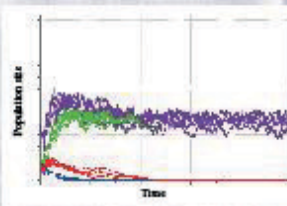


Figure 3 - Preliminary results for different population sizes of N, including allele effects. Green and Blue illustrate critical population sizes, where Purple represents survival and Red extinction levels.

#### References

- [1] ...
- [2] ...
- [3] ...
- [4] ...
- [5] ...
- [6] ...
- [7] ...



The research was supported by the Netherlands Organisation for Scientific Research (N.W.O. VIDI Grant 016.144312) (KV) and the N.W.O. Spinoza program (PS).

### Comparing past climate models: CCSM versus MIROC

The LGM period is part of the focus of the Paleoclimate Modeling Intercomparison Project (PMIP, [Joussaume and Taylor 1995](#)) which is an international effort to evaluate models using widely varying climate conditions. Climate for this defining period in the past has been extensively documented using a diverse array of paleo-climate proxy data sets and is used to calibrate (new) climate models. The LGM climate differs significantly from today and can be interpreted as an extreme climate anomaly for which there is no present day analogue and which is difficult to reconstruct in simulations, but for which the major forcing factors are relatively well known. The LGM is a severe glacial period with changes in greenhouse gases, sea level and ice sheets. As such, climate parameters can be used to model extreme climate changes ([Prentice \*et al.\* 2000](#)). Due to the fact that conditions for the LGM are well studied, results from simulations including this period can be compared against other modelling results ([Otto-Bliesner \*et al.\* 2006](#)) and thus the dataset as a whole gains in confidence.

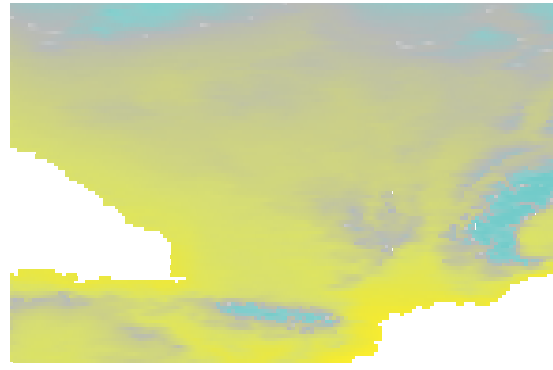
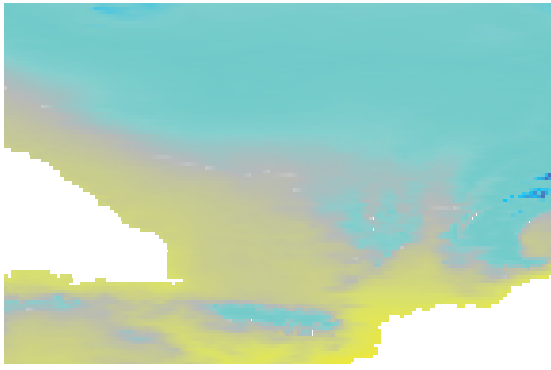
WorldClim provides two sets of data for the Last Glacial Maximum (LGM, around 21ka): the Community Climate System Model (CCSM) and the Model for Interdisciplinary Research On Climate (MIROC). Both are coupled general circulation models, with MIROC developed at the Center for Climate System Research (CCSR) at the University of Tokyo ([Hasumi and Emori 2004](#)) and CCSM designed at the University Corporation for Atmospheric Research (UCAR) ([Collins \*et al.\* 2006](#)). MIROC couples models for atmosphere, land, river, sea ice and ocean where CCSM couples models for land, sea-ice, ocean and atmosphere. MIROC is available upon request for collaborative researchers ([http://ccsr.aori.u-tokyo.ac.jp/~yangpeng/source\\_center.htm](http://ccsr.aori.u-tokyo.ac.jp/~yangpeng/source_center.htm), accessed 25 July 2013), where CCSM is actively developed into a successor named Community Earth System Model (CESM, <http://www2.cesm.ucar.edu/>, accessed 25 July 2013). Both are used primarily for future climate predictions, for instance by the Intergovernmental Panel on Climate Change (IPCC) ([Hamilton 2007](#)).

The reconstructed LGM environments from CCSM and MIROC are different. See Figure 94 for a visual comparison of the most relevant datasets. Especially temperatures as simulated by CCSM are generally lower than those from MIROC, but precipitation levels are also lower. These differences are likely to influence simulation results ([Olfert \*et al.\* 2011](#)). Both models are however among the best for modelling LGM circumstances ([Maris \*et al.\* 2012](#); [Otto-Bliesner \*et al.\* 2007](#)). Instead of averaging the results of the two models as done by [Waltari \*et al.\* \(2007\)](#), the underlying research uses one single model. CCSM has

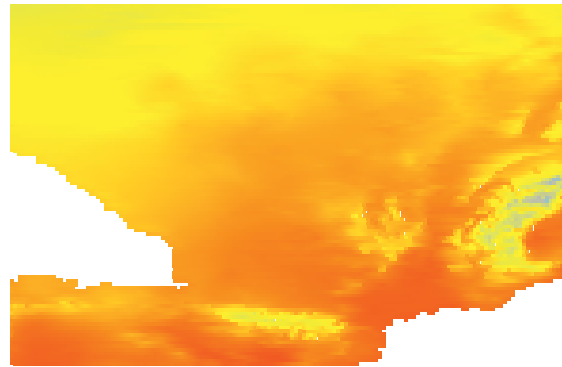
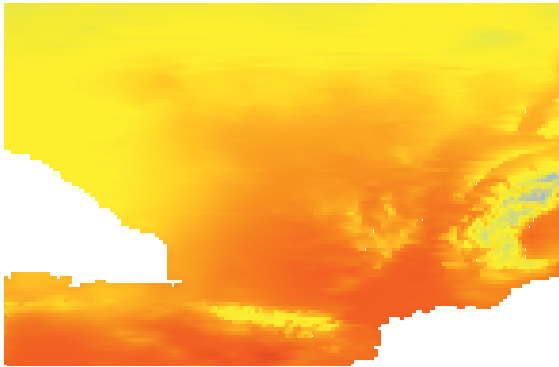
been selected due to the fact that the available data from MIROC were created using version 3.2 which contains an error in the land surface scheme. Correcting this error, as has been done in 3.2.2, would lower the temperature values ([Maris \*et al.\* 2012, 804](#)).

The chosen colour scheme for the temperature maps (values in Table 3) is constructed based on the colours used by The Weather Network (example in <http://scsjournal.files.wordpress.com/2011/11/the-weather-network.jpg>, accessed 21 July 2013). The colour scheme for the precipitation values is inspired by the Canadian weather reports (<http://scsjournal.wordpress.com/>, accessed 21 July 2013). Note that the temperature values in the WorldClim database must be divided by 10 to get degrees Celsius.

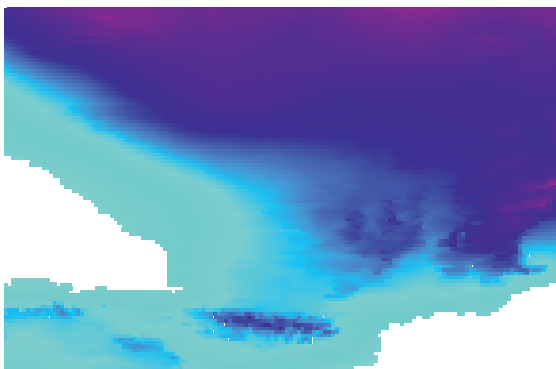




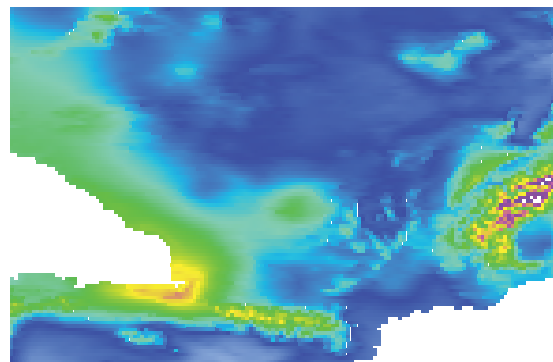
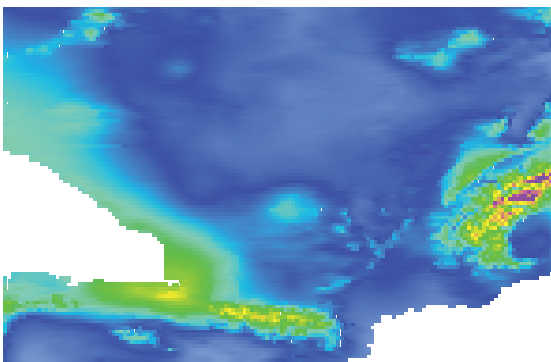
BIO1 = Annual mean temperature



BIO5 = Max temperature of the warmest month



BIO6 = Min temperature of the coldest month



BIO12 = Annual precipitation

**Figure 94: Overview of the results for the main biological values for CCSM (left) and MIROC climate models with unified colour coding schemes.**

