Modelling climate and vegetation interactions Application to the study of paleoclimates and paleovegetations

Dissertation présentée par Alexandra-Jane Henrot en vue de l'obtention du grade de Docteur en Sciences

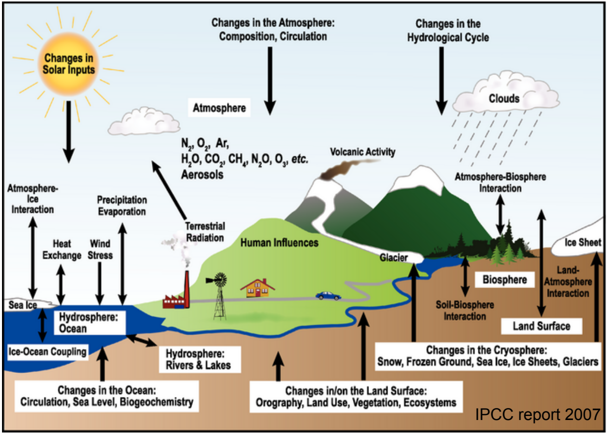
promoteur : G. Munhoven, co-promoteur : L. François

Liège, le 15 décembre 2010

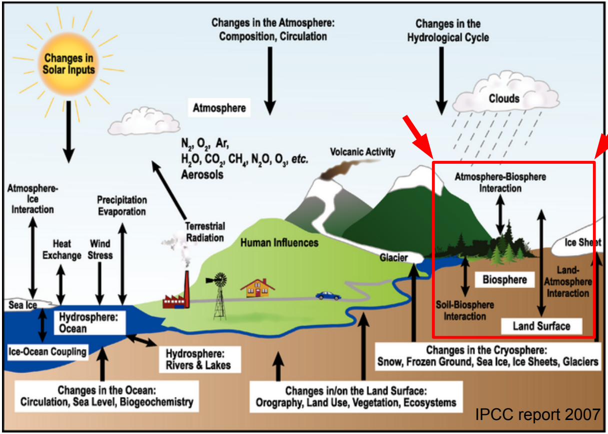
Summary

- Modelling climate and vegetation interactions
- The Planet Simulator and CARAIB models
- Application 1: the Last Glacial Maximum
- Application 2: the Middle Pliocene
- Application 3: the Middle Miocene
- General conclusions and perspectives

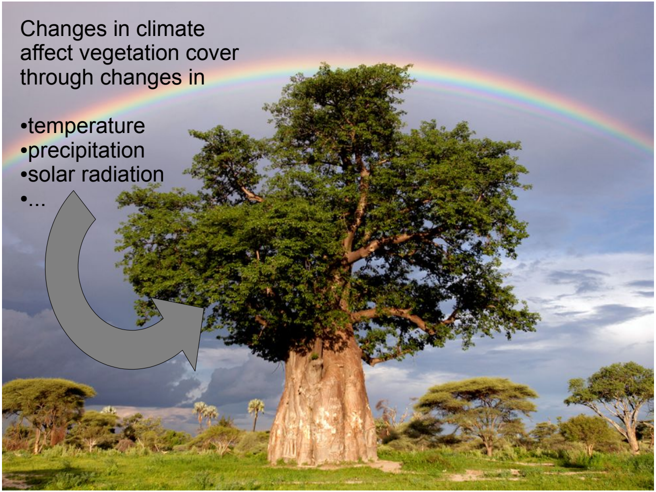
Climate system: processes and interactions between the components of the climate system



The atmosphere and the terrestrial biosphere: a coupled system interacting on a large range of time scales

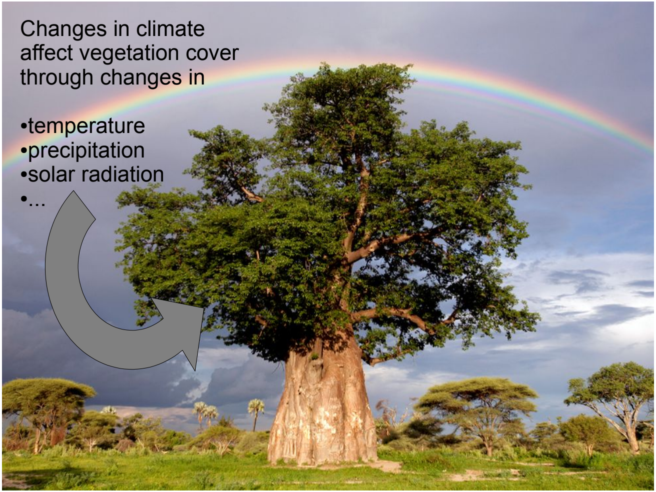


Climate and vegetation interactions: biophysical processes



Vegetation = "crystallised, visible climate" (Köppen, 1936)

Climate and vegetation interactions: biophysical processes



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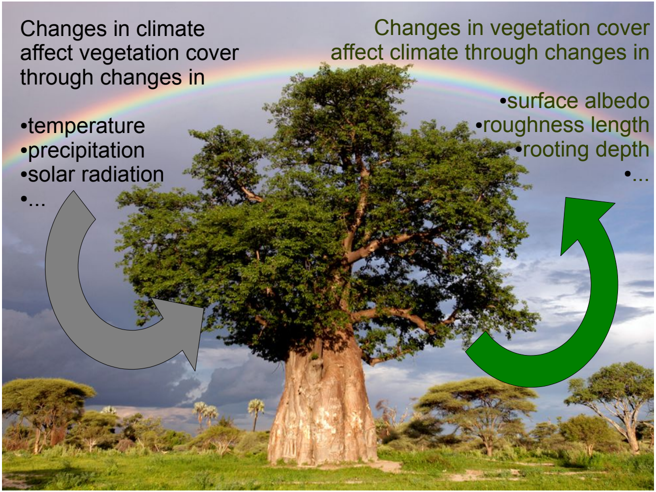
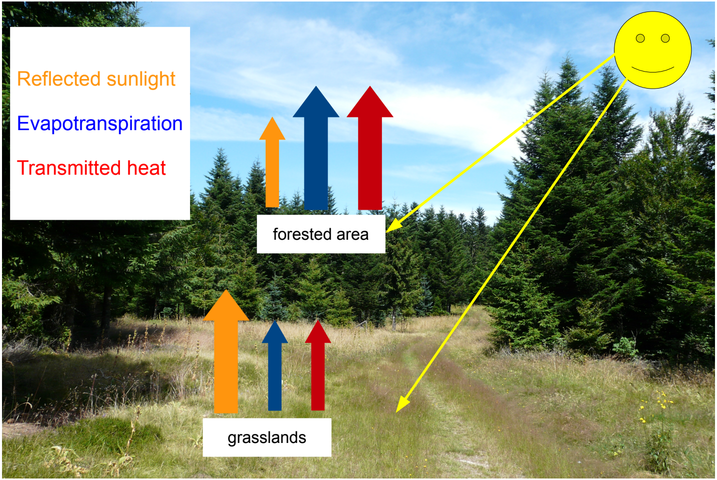
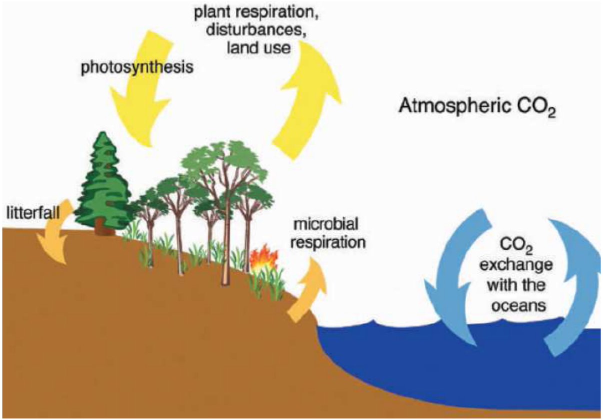


Vegetation impacts on climate: biophysical processes



Climate and vegetation interactions: biogeochemical processes



Foley et al., 2003

Modelling the climate and vegetation interactions

Recent efforts have been made to

- develop realistic climate and vegetation **models**,
- incorporate the two-way climate-vegetation interactions into **coupled climate-vegetation models**,
- model **past** climate and vegetation changes and better forecast near-**future** climate and vegetation changes.

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Aims of the present work

Modelling climate and vegetation interactions

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- with the climate model **Planet Simulator** and the vegetation model **CARAIB** interacting through an equilibrium coupling procedure.
- Study the joint evolutions of climate and vegetation during three past periods: the Last Glacial Maximum, the Middle Pliocene and the Middle Miocene.

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Models

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Earth System Model of Intermediate Complexity (EMIC)

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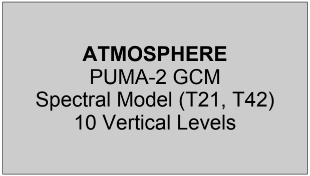

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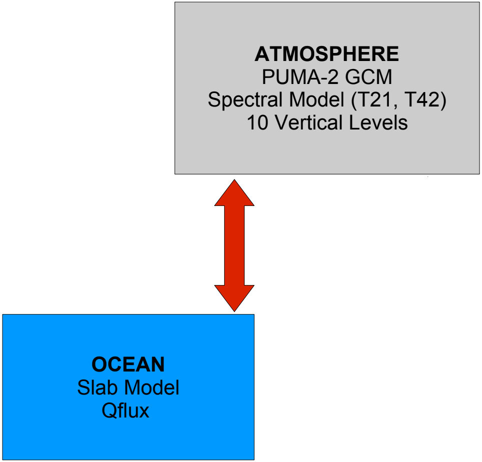

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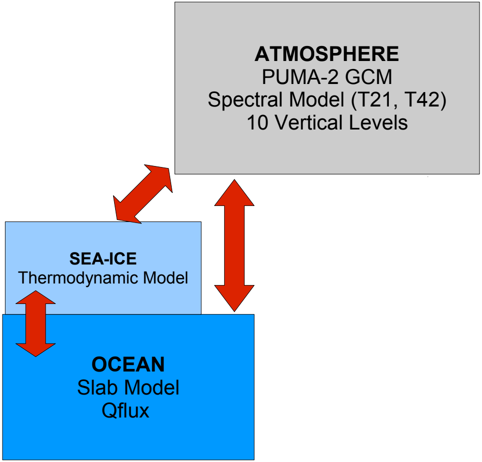

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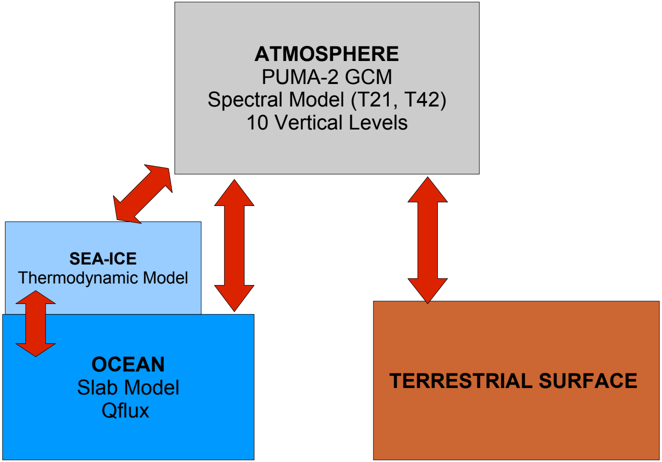

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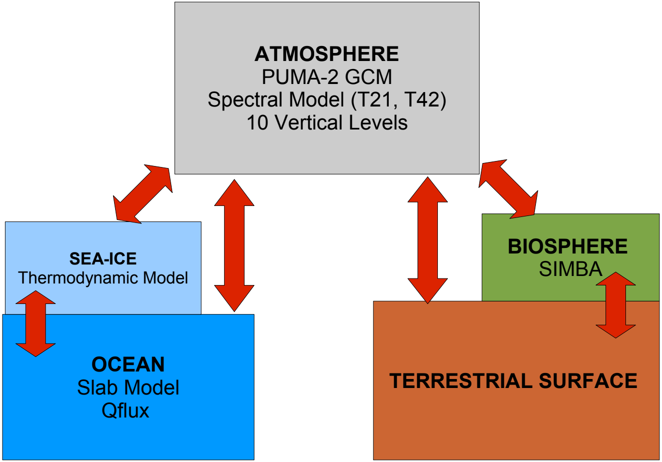

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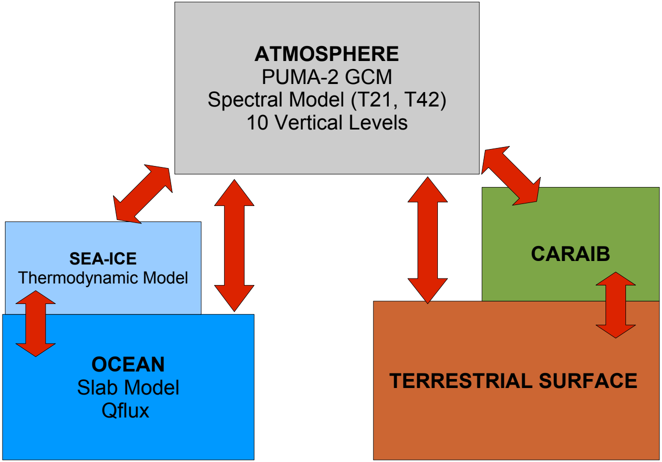
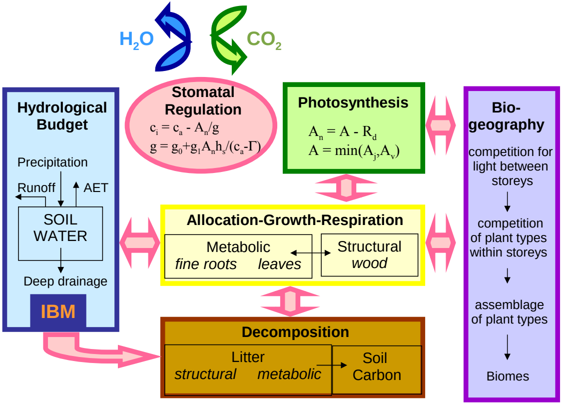


The CARAIB model (CARbon Assimilation In the Biosphere)

Dynamic Global Vegetation Model (DGVM)



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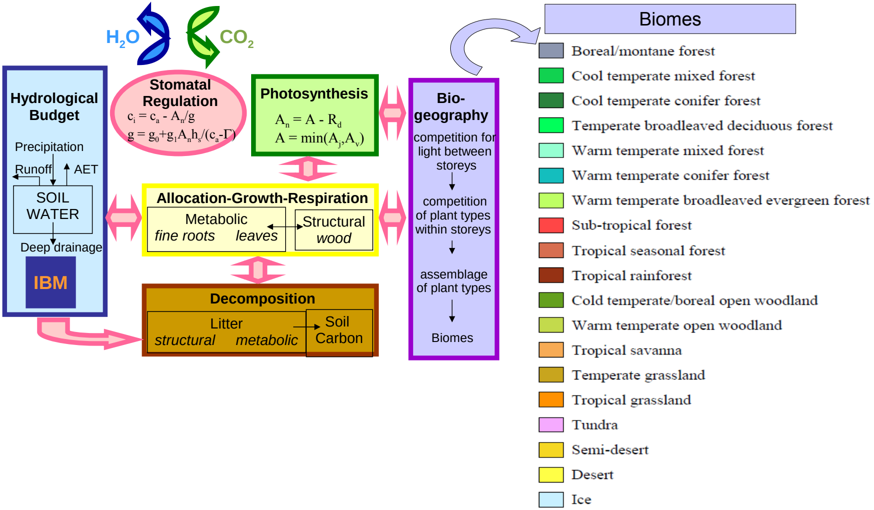
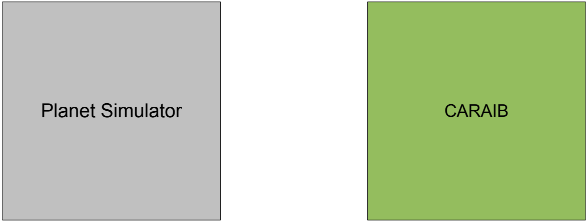


Interactions between the models



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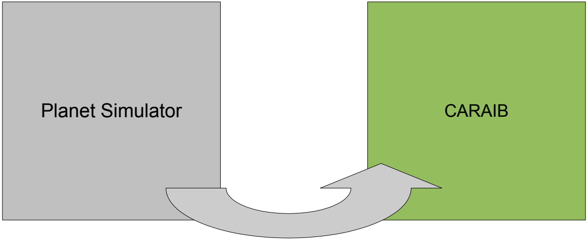
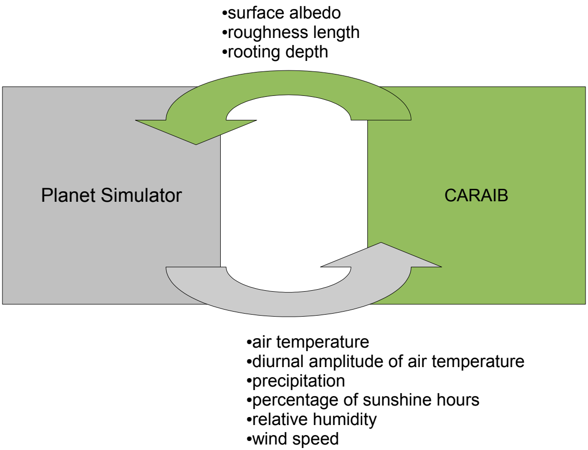
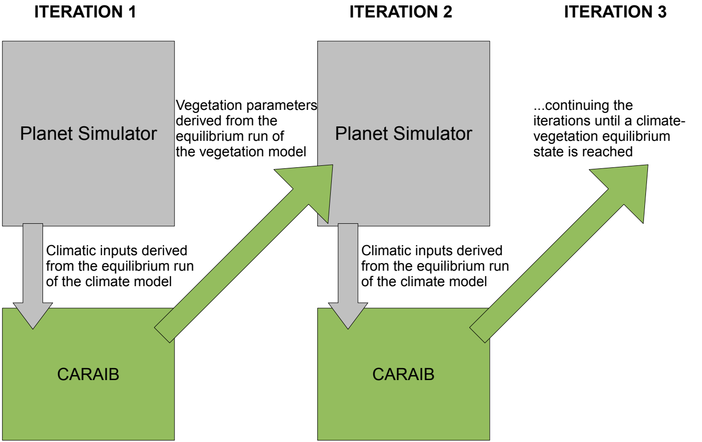


- air temperature
- diurnal amplitude of air temperature
- precipitation
- percentage of sunshine hours
- relative humidity
- wind speed

Interactions between the models



Asynchronous equilibrium coupling of the Planet Simulator and CARAIB models

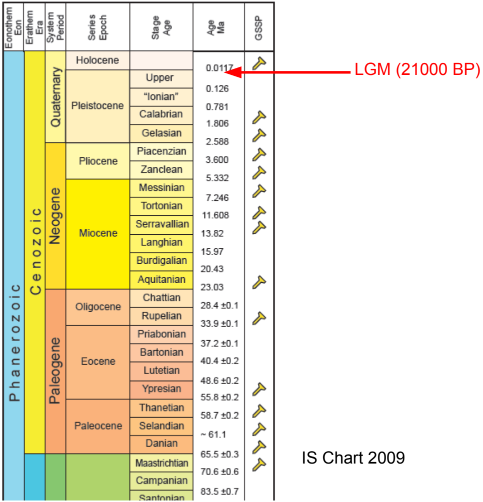


Applications

1. The Last Glacial Maximum
2. The Middle Pliocene
3. The Middle Miocene

Application 1. The Last Glacial Maximum

The Last Glacial Maximum



IS Chart 2009

Simulation experiments

Land surface cover change implications on LGM climate?

⇒ Series of sensitivity experiments with the Planet Simulator in order to analyse and isolate the climatic impacts of:

- the expansion of ice sheets,
- the modification of the topography on land,
- the reduction of the vegetation cover,
- the lowering of the atmospheric carbon dioxide concentration (from 280ppmv during the preindustrial time to 200ppmv at the LGM).

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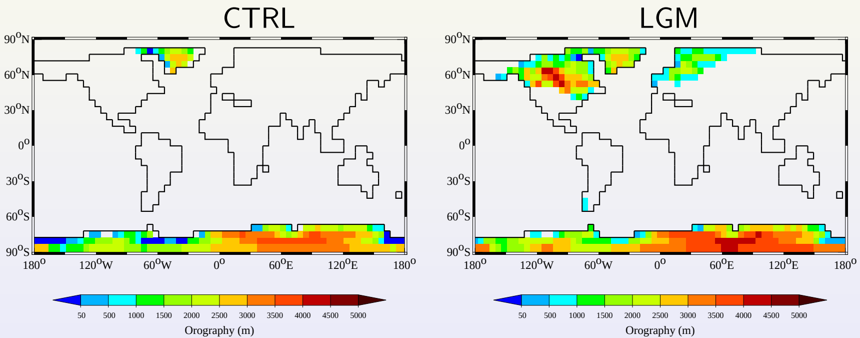
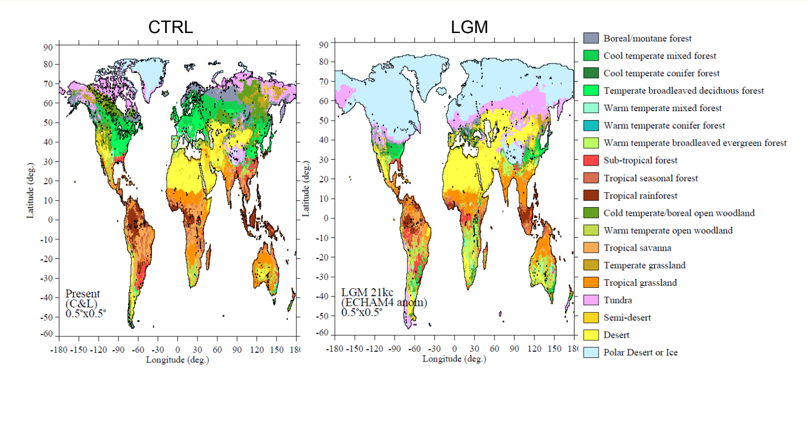
Land-sea distribution and topography over the ice sheet mask for the CTRL and the LGM configurations



Henrot et al., 2009

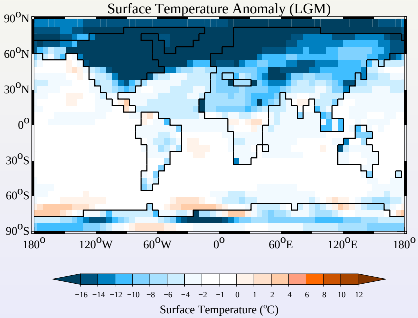
Vegetation cover changes: CARAIB biome distributions for the CTRL and the LGM experiments



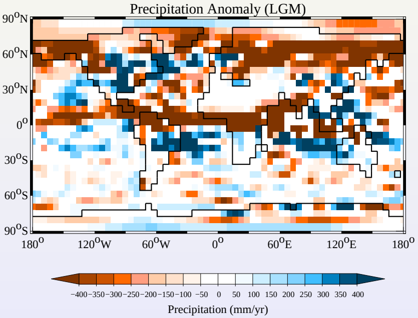
Henrot et al., 2009

Surface temperature and precipitation anomalies for the LGM experiment with all the boundary condition changes

-5.2°C

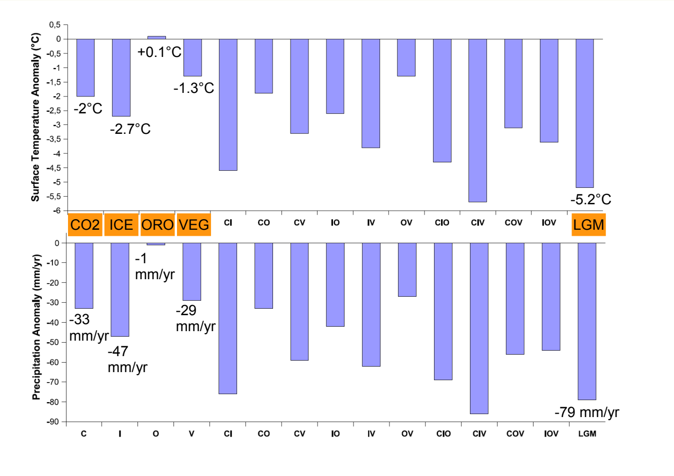


-79 mm/yr

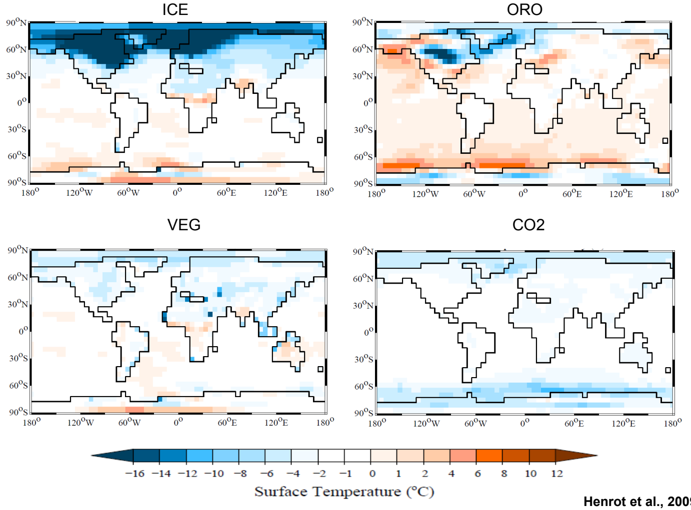


Henrot et al., 2009

Surface temperature and precipitation differences for the series of sensitivity experiments

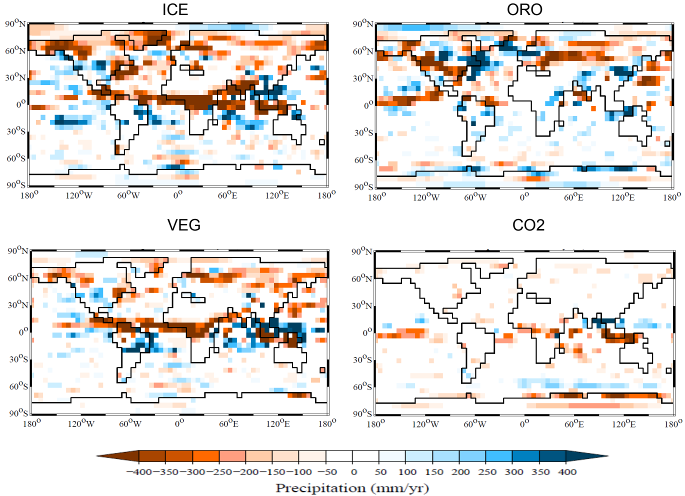


Impacts on surface temperature



Henrot et al., 2009

Impacts on precipitation



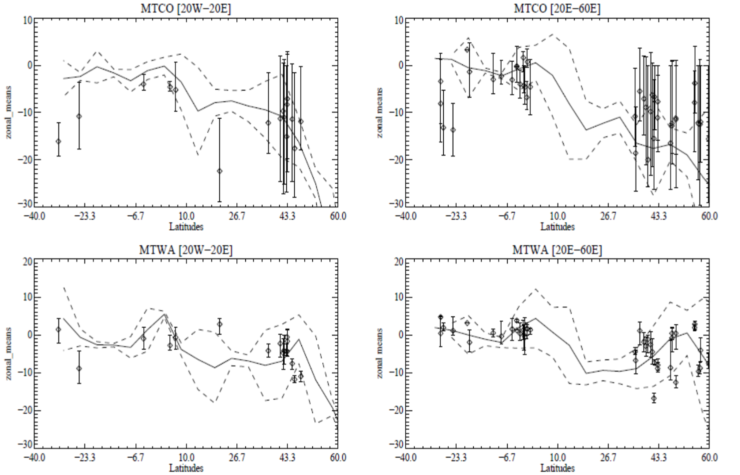
Henrot et al., 2009

Comparison to the results of previous modelling studies

Simulation	Global ΔT	ICE+ORO	CO_2	VEG
This study	-5.2°C	-2.6°C	-2°C	-1.3°C
Jahn et al., 2005	-5.1°C	-3°C	-1.5°C	-0.7°C
Ganopolski, 2003		-3°C	-1.2°C	-0.6°C
PMIP1	-2 to -6°C*			
PMIP2	-3.6 to -5.7°C*			

*(no vegetation change considered)

Consistency with paleo data



Henrot et al., 2009

Last Glacial Maximum results

Our results highlight

- the dominant cooling and drying effect of the ice sheet expansion on the LGM climate,
- the large changes that occured in the vegetation cover at the LGM: expansion of desert and grassland ecosystems at the expense of forest ecosystems,
- the contribution of the vegetation cover change to the maintaining of cold and dry climatic conditions at the LGM.

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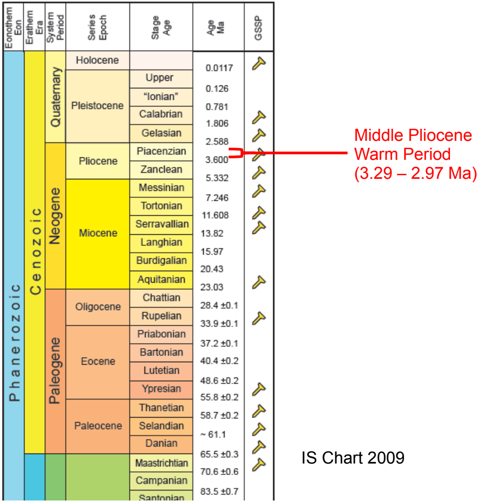
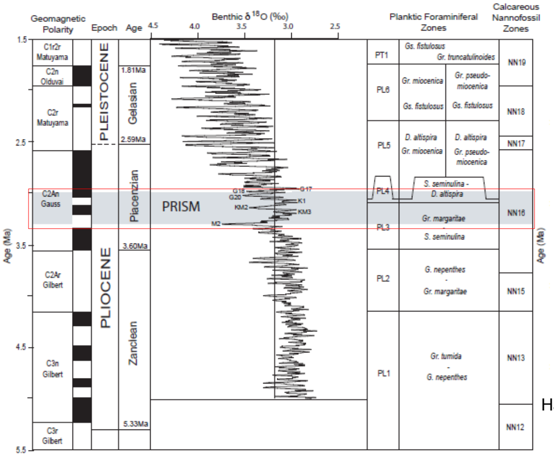
Application 2. The Middle Pliocene

The Middle Pliocene



IS Chart 2009

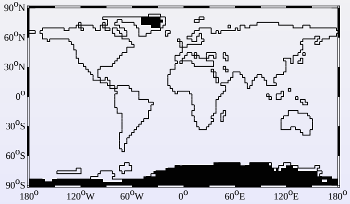
The MPWP: an analogue for the climate of the twenty-first century?

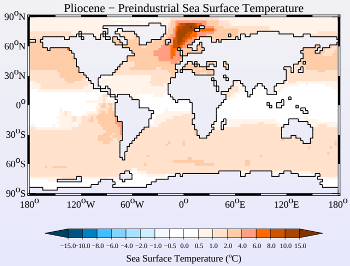


Haywood et al., 2010

PRISM 3D boundary conditions for the MPWP

MPWP simulation experiment	
Orbital configuration	present-day
CO_2	405 ppmv
Topography	PRISM3D
Land-sea and land-ice masks	PRISM3D
SSTs and sea-ice	PRISM3D
Vegetation cover	PRISM3D (BIOME4)





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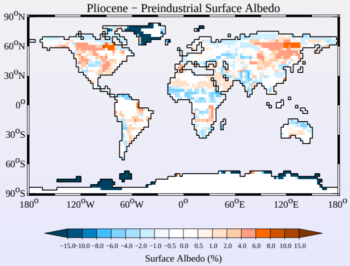
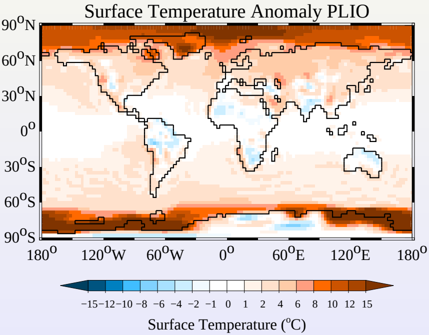
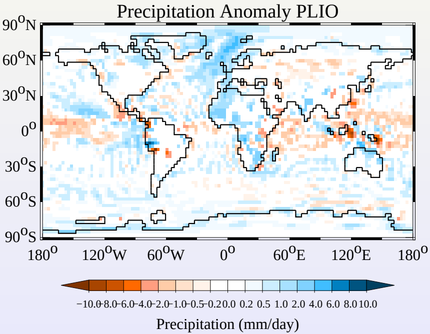


MPWP annual mean surface air temperature and precipitation anomalies simulated by the Planet Simulator

+2.2°C



+0.11mm/day

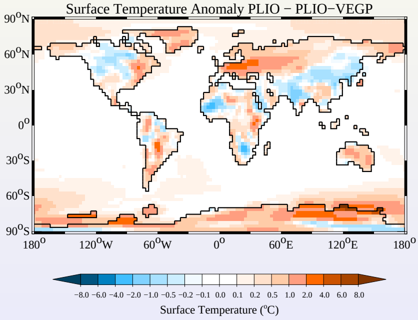


Comparison to the results of previous modelling studies

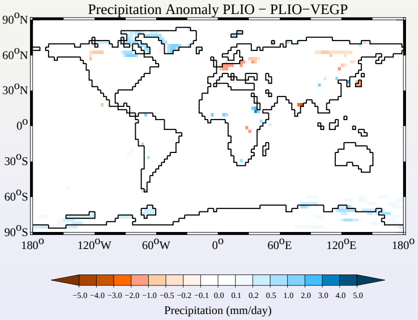
Simulation	Global ΔT	Global ΔPRC	PRISM version
This study	+2.2°C	+3.5%	PRISM3D
Haywood et al., 2000	+1.9°C	+4%	PRISM2
Haywood and Valdes, 2004	+3°C	+6%	PRISM2
Jiang et al., 2005	+2.6°C	+4%	PRISM2

Effect of the PRISM3D vegetation on the MPWP climate

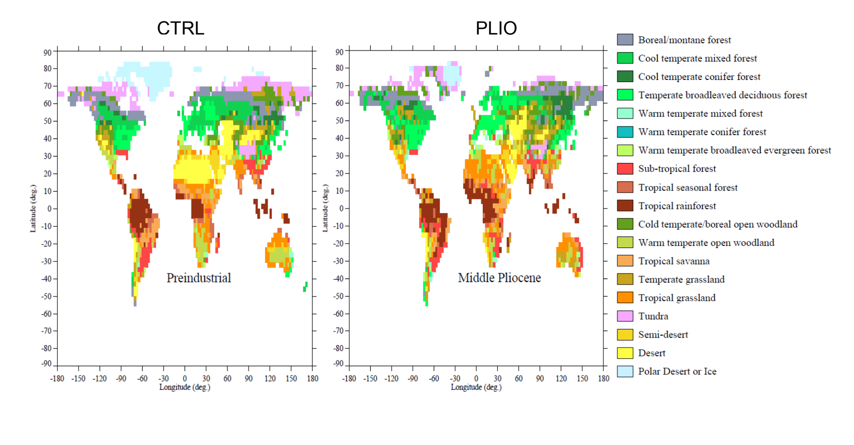
$+0.16°C$



$+0.005mm/day$



CARAIB biome distributions for the preindustrial and the Pliocene experiments



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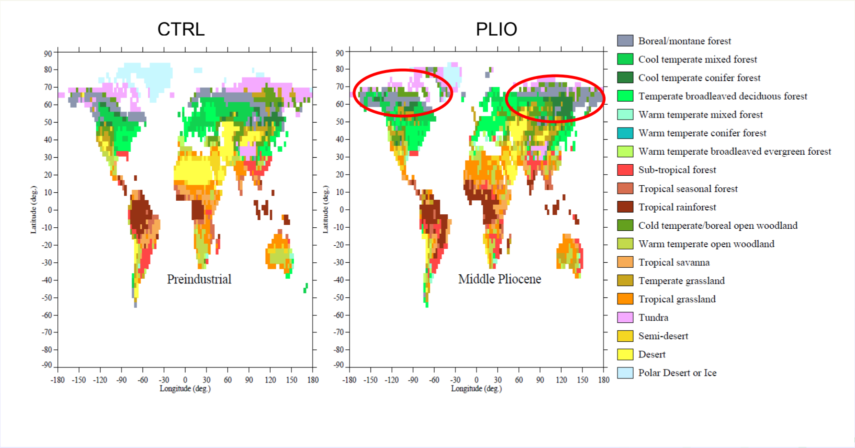

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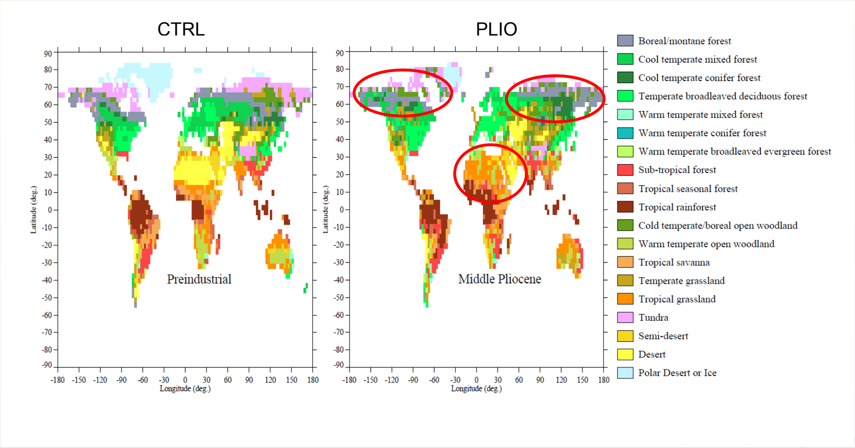

Middle Pliocene results

- Globally warmer and wetter than present-day climate conditions simulated for the Middle Pliocene
- Reduction of the latitudinal temperature gradient in good agreement with previous modelling studies (Haywood et al., 2009; Haywood and Valdes, 2004)
- Shift of boreal forest to higher latitudes and reduction of tundra and desert ecosystems in good agreement with previous vegetation reconstructions (Haywood and Valdes, 2006; Salzmann et al., 2008)
  $\Rightarrow$ Need for a more accurate comparison of climate and vegetation results with climate and vegetation modelling results or data-based reconstructions.

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Application 3. The Middle Miocene

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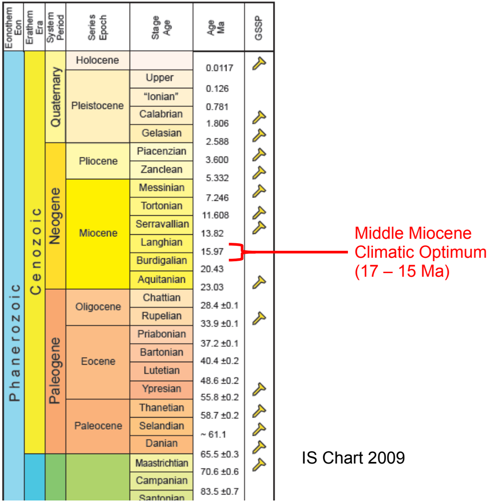
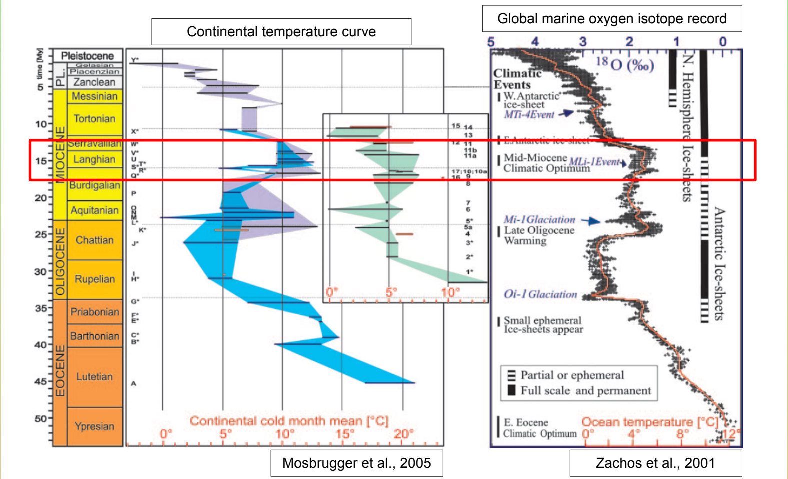


IS Chart 2009

The climatic optimum of the Middle Miocene



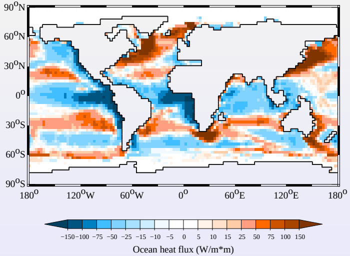
Simulation experiments and boundary conditions

Simulation	CO_2	Ocean	Ice	Topo	Veg
CTRL	280ppmv	PI	PI	PI	PI

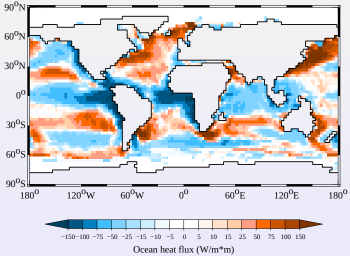
Simulation experiments and boundary conditions

Simulation	CO_2	Ocean	Ice	Topo	Veg
CTRL	280ppmv	PI	PI	PI	PI
MM1	280ppmv	**MM**	**MM**	PI	PI

Ocean heat transfer PI



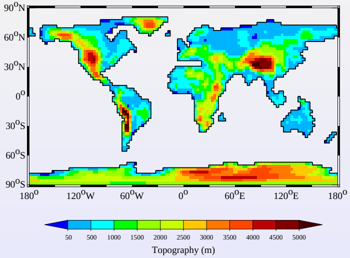
MM



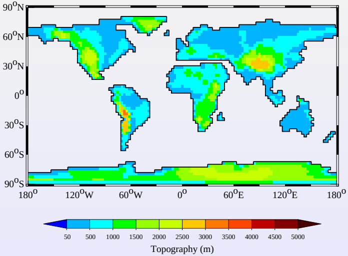
Simulation experiments and boundary conditions

Simulation	CO_2	Ocean	Ice	Topo	Veg
CTRL	280ppmv	PI	PI	PI	PI
MM1	280ppmv	MM	MM	PI	PI
MM2	280ppmv	MM	MM	**MM**	PI

Topography PI



MM



Simulation experiments and boundary conditions

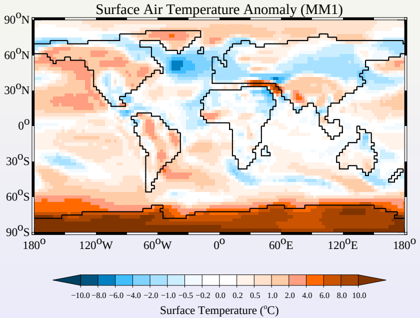
Simulation	CO_2	Ocean	Ice	Topo	Veg
CTRL	280ppmv	PI	PI	PI	PI
MM1	280ppmv	MM	MM	PI	PI
MM2	280ppmv	MM	MM	MM	PI
MM3	**200ppmv**	MM	MM	MM	PI
MM4	**500ppmv**	MM	MM	MM	PI

Simulation experiments and boundary conditions

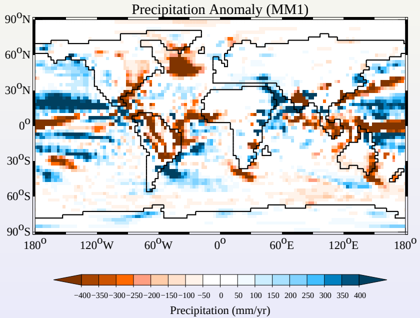
Simulation	CO_2	Ocean	Ice	Topo	Veg
CTRL	280ppmv	PI	PI	PI	PI
MM1	280ppmv	MM	MM	PI	PI
MM2	280ppmv	MM	MM	MM	PI
MM3	200ppmv	MM	MM	MM	PI
MM4	500ppmv	MM	MM	MM	PI
MM4-veg	500ppmv	MM	MM	MM	**MM**
MM2-veg	280ppmv	MM	MM	MM	**MM**

Impacts of Miocene oceanic conditions and land-sea distribution

+0.6°C



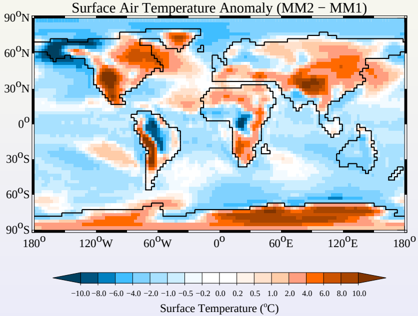
-5 mm/yr



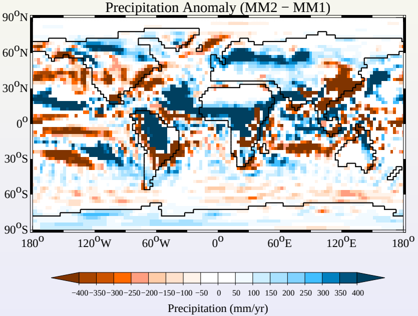
Henrot et al., 2010

Impacts of a lower topography on land

-0.3°C



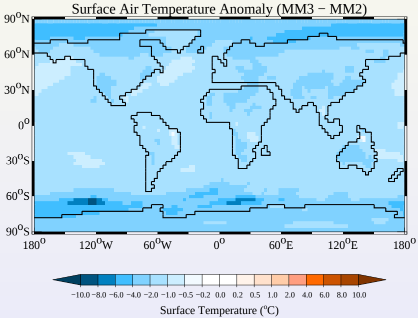
+25 mm/yr



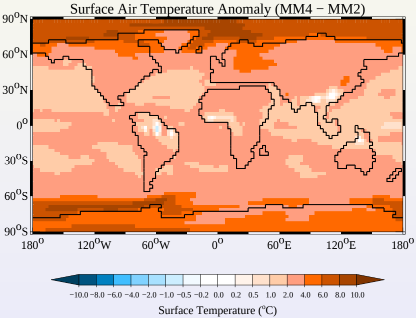
Henrot et al., 2010

Impacts of various CO_2 concentrations

-1.8°C (CO_2=200ppmv)

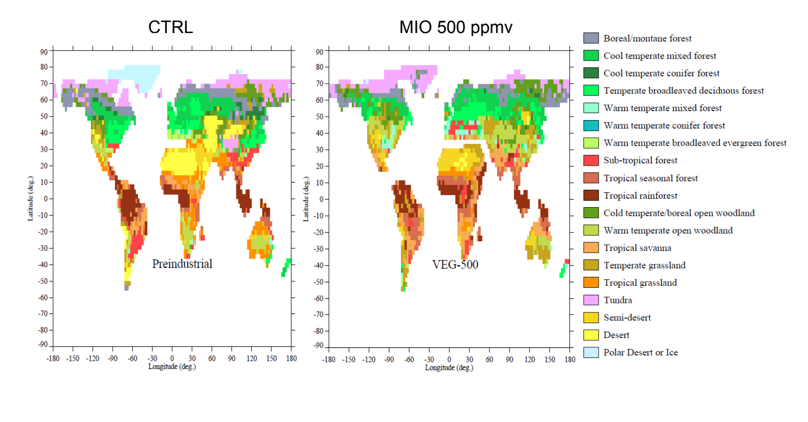


+2.6°C (CO_2=500ppmv)



Henrot et al., 2010

Response of vegetation to MMCO climate and high CO_2 concentration



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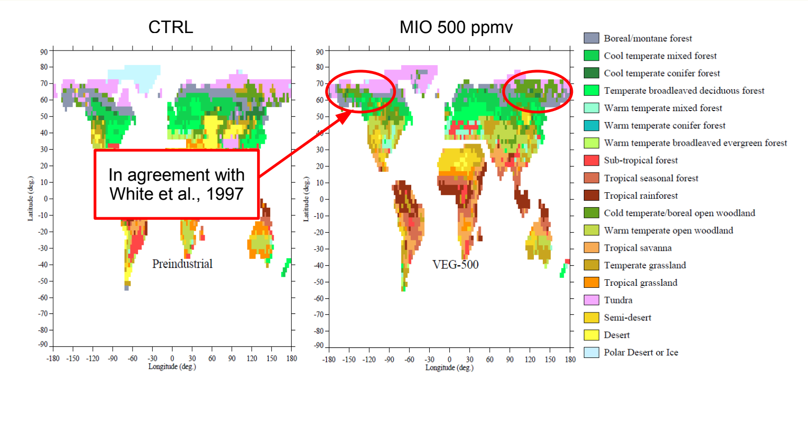

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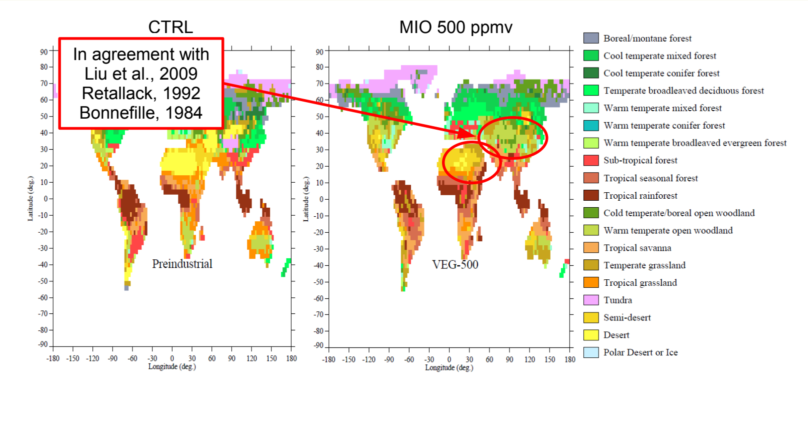

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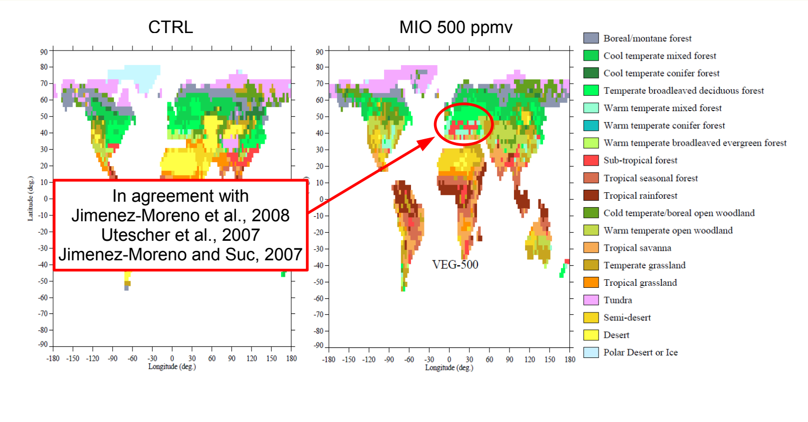
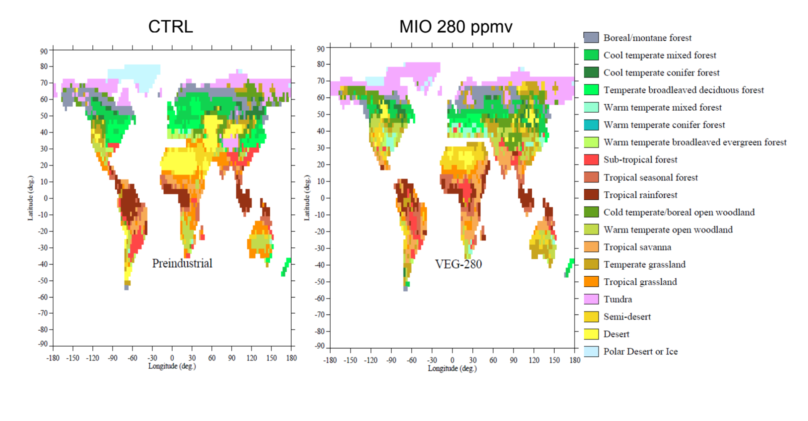


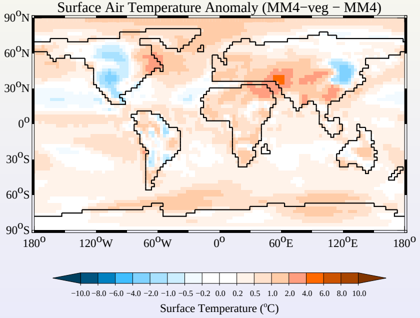
Henrot et al., 2010

Response of vegetation to MMCO climate and low CO_2 concentration

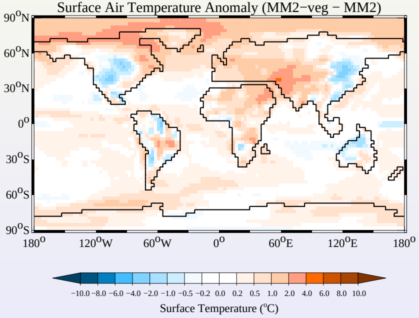


Vegetation feedback under different CO_2 concentrations

$+0.5°C$ (CO_2=500ppmv)



$+0.4°C$ (CO_2=280ppmv)



Comparison to the results of previous modelling studies

Simulation	CO_2	Global ΔT
This study	280ppmv	+0.7°C (including vegetation changes)
This study	500ppmv	+3.4°C (including vegetation changes)
Tong et al., 2009	355ppmv	+0.6°C
Tong et al., 2009	700ppmv	+2.9°C
You et al., 2009	700ppmv	+3.5°C

Middle Miocene climate results

Our results indicate that

- an increase of atmospheric CO_2 concentration, higher than the present-day one, is necessary to warm significantly the climate at the MMCO.

In agreement with paleo-atmospheric CO_2 reconstructions from stomatal frequency analysis suggesting more than 500 ppmv of CO_2 during the MMCO (Kürschner et al., 2008).

However, the required warming may be due to processes not considered in our setup (e.g. full oceanic circulation, other greenhouse gases such as CH_4).

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Other mechanisms to consider:

- the reduction of the topography on land
  - induces significant temperature increases on the continents,
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- under warmer and more humid conditions
  - warm forest types expand at middle latitudes,
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The vegetation produced under high CO_2 concentration is in better agreement with proxy-based vegetation reconstructions.

The vegetation feedbacks at 500 and 280 ppmv are comparable in terms of magnitude.

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- Improvement of the Planet Simulator model (oceanic circulation, atmospheric trace gases, ...).
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MERCI !

Global PFTs classification (15 types)

GLOBAL PFT CLASSIFICATION

Subtropical PFT thresholds are defined according to present distribution in south-eastern Asia and North America

1 C3 grass
all C3 herbaceous plants
2 C4 grass
all C4 herbaceous plants
3 Needleleaved evergreen boreal/temperate cold
Cupressaceae, Juniperus, Juniperus communis (BAG4)
Abies (BAG 5)
Picea abies, Pinus, Pinus sylvestris (BAG 6)
4 Needleleaved evergreen temperate cool
Abies Alba, Taxus (BAG 2)
Chamaecyparis; Picea omorika, Pseudotsuga menziesi, Sequoia sempervirens, Thuja orientalis, Tsuga diversifolia
5 Needleleaved evergreen temperate dry warm
Cedrus, Pinus halepensis, Pinus pinaster (BAG 1)
Cupressus, Libocedrus, Tetraclinis
6 Needleleaved evergreen temperate perhumid warm
SUB-TROPICAL: Sciadopitys, Cathaya, Keteleeria, Taiwania, Torreya, Athrotaxis
7 Needleleaved summergreen boreal/temperate cold
Larix decidua (BAG 7)
8 Needleleaved summergreen temperate warm
SUB-TROPICAL : Taxodium, Glyptostrobus
9 Broadleaved evergreen temperate dry warm
Olea eur, Pistacia, Phillyrea, Quercus ilex, Quercus suber (BAG 8)
Arbutus, Dalbergia, Ocotea, Quercus troyana
10 Broadleaved evergreen temperate perhumid warm
SUB-TROPICAL : Alangium, Castanopsis, Fatsia japonica, Gordonia, Lindera, Magnolia virginiana, Neolitsea, Reevesia, Sassafras, Symplocos yunnanensis, Persea indica
11 Broadleaved summergreen boreal/temperate cold
Alnus, Alnus glutinosa, Corylus avellana, Quercus, Quercus robur, Populus, Tilia (BAG 12)
Betula, Salix (BAG 13)
12 Broadleaved summergreen temperate cool
Acer campestre, Carpinus betulus, Fagus sylvatica, Tilia platyphyllos (BAG 10)
Acer, Fraxinus excelsior, Tilia cordata, Ulmus (BAG 11)
Aesculus rubicunda, Populus cathayana, Quercus castaneaefolia, Quercus lobata, Tilia japonica, Tilia platyphyllos, Ulmus davidiana
13 Broadleaved summergreen temperate warm
Castanea, Juglans, Ostrya, Quercus pubescens (BAG 9)
Craigia, Diospyros lotus, Halesia, Liquidambar formosana, Quercus benthamii
14 Broadleaved raingreen tropical
Acacia, Bursera, Dendropanax, Gironniera, Punica
15 Broadleaved evergreen tropical
Annona, Bombax, Bursera, Cassine, Cupania, Monotes, Sterculia, Zenkerella