Paleo-climate shifts in the Atacama Desert from PMIP4 simulations

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Introduction

- This study is part of the Collaborative Research Center 1211 “Earth – Evolution at the dry Limit” (https://sfb1211.uni-koeln.de/)
- Focus Area: Atacama Desert at Central West coast of South America
Atacama is considered to be the driest Desert on Earth
Hyper-arid conditions with mean annual rainfall less than 2mm/year (Fig. 1) in modern climate
Climate records: hyper-aridity interrupted by more pluvial phases in the past

Research questions:
- Can we identify observed past climate shifts in global and regional climate models?
- What are the key drivers for these climate shifts?

Fig. 1: Simulated mean annual rainfall [1] (in mm/year) as obtained from a WRF simulation forced with ERA-Interim
### Data and Methods

#### List of analysed CMIP6-PMIP4 Models

<table>
<thead>
<tr>
<th>Model name</th>
<th>Institution</th>
<th>Acronym</th>
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<tr>
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<td>NESM3</td>
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Data and Methods

Analysed PMIP4 Experiments

- **Historicals**: ensemble mean over all available realisations; 1990-2014
- **LGM**: Last Glacial Maximum; all available model years; 21 ka
- **midPlio**: midPliocene-eoi400; all available model years; 3.2 Ma

Reanalysis Data

- **ERA-Interim (ERAi)**; 1990-2014; 0.75°x0.75° resolution

Downscaling

- Selected Experiments are downscaled with the Weather Research and Forecasting Model WRF
- 10km x 10km horizontal resolution
Variable list

- **Rainfall**: mean annual and mean seasonal rainfall
- **Moisture flux**: integrated water vapor flux between 1000hPa and 700hPa
- **SST Sea Surface Temperature**: 
  (i) local SST
  (ii) SST difference between tropical West Pacific and tropical Central-East Pacific (as a proxy for ENSO)
- **Troughs**: mid-tropospheric (500hPa) trough points using the detection method from [2]
- **Cutoff lows**: mid-tropospheric (500hPa) cutoff lows as in [3]
- **Bolivian High**: 200hPa geopotential height; summer
Hyper-arid conditions simulated realistically by several PMIP4 models

Fig.2: Mean annual rainfall (mm/year) in PMIP4 models (historicals) and in ERA-Interim; green boxes: LGM experiments available; yellow boxes: midPliocene experiments available
LGM

- Climate record from Northern Atacama indicate substantially more rainfall during the Last Glacial Maximum
- Analysis of PMIP4 experiment LGM

Fig. 3: Huara climate record [4]
LGM - Rainfall

- Increased mean annual rainfall in three out of four models (Fig. 4)
- Due to data availability focus on MPI
- More rainfall in MPI in all four seasons (Fig. 5)

**Fig. 4:** LGM minus historicals for mean annual rainfall (in mm/year) in four PMIP4 models

**Fig. 5:** LGM minus historicals for mean seasonal rainfall (in mm/season) in MPI
LGM – Moisture flux

- Deceleration of SASM circulation (Fig. 7, DJF)
- SASM-like circulation signal in autumn (Fig. 7, MAM)
- Delayed onset of SASM in LGM ???
- Slightly stronger eastward moisture flux into the Atacama in winter (Fig. 7, JJA)

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**Fig. 6**: Seasonal moisture flux (arrows and shading, in kg/(m·s)) in MPI-historicals

**Fig. 7**: LGM minus historicals for seasonal moisture flux (arrows and shading, in kg/(m·s)) in MPI
LGM - SST

- Generally colder SSTs throughout the year (Fig. 8)
- Slight warming at the Atacama coast in summer and autumn (Fig. 8)
- Tropical west-to-east SST gradient underestimated in MPI (Fig. 9)
- Only small SST gradient changes in LGM (Fig. 9)

**Fig. 8:** LGM minus historicals for seasonal SST (in °C) in MPI

**Fig. 9:** Histograms of SST difference (in °C) between tropical West Pacific and tropical Central-East Pacific in ERA-Interim, MPI-historicals and MPI-LGM
MPI-historicals – Troughs

- Trough frequency over land masses overestimated in MPI (Fig. 10, contours)
- Strength of troughs captured well in MPI (Fig. 10, shading)

**Fig. 10:** Seasonal number (contours, in number per decade) and strength (shading, in gpm/°lon) of trough points in ERA-Interim (left) and MPI-historicals (right)
LGM – Troughs and cutoff lows

- More and stronger troughs in LGM (Fig. 11)
- More cutoff lows in all seasons (Fig. 12)
- These results agree to findings for PMIP3 models [3]
A climate record, which is currently dated, indicates that onset of hyper-aridity was after the Pliocene (not published yet).

Much moister conditions prior that onset.

Analysis of PMIP4 experiment midPliocene.
midPliocene - Rainfall

- Increased mean annual rainfall obtained by CESM2 only (Fig. 13)
- Mostly due to more rainfall in summer (DJF) and autumn (MAM) (Fig. 14)

→ Focus on CESM2 and on these two seasons in the following slides

Fig. 13: midPliocene minus historicals for mean annual rainfall (in mm/year) in three PMIP4 models

Fig. 14: midPliocene minus historicals for mean seasonal rainfall (in mm/season) in CESM2
midPliocene – Moisture flux

- Moisture flux associated with South American Summer Monsoon (SASM) slightly overestimated by CESM2 (Fig. 15)
- SASM-related moisture flux increased in midPliocene (Fig. 16)
- Stronger inflow of moisture from Pacific (Fig. 16), probably associated with ...

**Fig. 15:** Seasonal moisture flux (arrows and shading, in kg/(m·s)) in ERA-Interim (upper row) and in CESM2-historicals (lower row)

**Fig. 16:** midPliocene minus historicals for seasonal moisture flux (arrows and shading, in kg/(m·s)) in CESM2
midPliocene – SST

- Substantially warmer SSTs in tropical and subtropical Southeast Pacific (Fig. 17)
- SST warming up to +5°C (Fig. 17), coincides with SST proxies [5]
- Tropical SST variability captured well by CESM2 (Fig. 18)
- Shift towards decreased tropical west-to-east SST gradient in midPlio (Fig. 18)

More frequent El Nino conditions?

Fig. 17: midPliocene minus historicals for seasonal SST (in °C) in CESM2

Fig. 18: Histograms of SST difference (in °C) between tropical West Pacific and tropical Central-East Pacific in ERA-Interim, CESM2-historical, and CESM2-midPliocene
midPliocene – Troughs

- Realistic representation of trough frequency in CESM2 (Fig. 19)
- Strength of troughs underestimated (Fig. 19)
- Less and weaker troughs in midPliocene (Fig. 20)

Fig. 19: Seasonal number (contours, in number per decade) and strength (shading, in gpm/°lon) of trough points in ERA-Interim (upper row) and CESM2-historicals (lower row)

Fig. 20: midPliocene minus historicals for number (contours, in number per decade) and strength (shading, in gpm/°lon) of trough points in CESM2
midPliocene – Cutoff lows

- Cutoff low (see Fig. 21) frequency simulated realistically in CESM2 (Fig. 22)
- Substantially less cutoff lows in midPliocene (Fig. 22)

**Fig. 21:** Cutoff low off the coast of the Atacama Desert

**Fig. 22:** Annual and seasonal number of cutoff lows in ERA-Interim, CESM2-historicals, and CESM2-midPliocene (in number per decade)
Downscaling

- PMIP4 models have a horizontal resolution of >100 km
- Complex topography of the Atacama Desert not captured realistically
- Some local processes not resolved adequately
- We plan to downscale an ensemble of PMIP4 models with WRF

- Finished WRF simulations:
  (i) MPI-historical r1, 1990-2014 (WRF\textsubscript{Hist})
  (ii) MPI-LGM r1, 25 model years (WRF\textsubscript{LGM})
- Double one-way nesting
- 1.875° → 50km → 10km
Downscaling – Rainfall in LGM

- Rainfall overestimated in WRF\textsubscript{HIST} (Fig. 23)
- Nevertheless, hyper-aridity and rainfall gradients captured by WRF\textsubscript{HIST} (Fig. 23)
- Annual rainfall decreases in Northeast Atacama in LGM, mostly due to less rain in summer (Fig. 24)
- Annual rainfall increases in West and South Atacama in LGM, mostly due to more rain in winter (Fig. 24)

Fig. 23: Mean annual rainfall (mm/year) WRF\textsubscript{ERAi} and in WRF\textsubscript{Hist}

Fig. 24: WRF\textsubscript{LGM} minus WRF\textsubscript{HIST} for annual and seasonal rainfall (mm/year and mm/season)
Downscaling – Rainfall in LGM

- North Atacama: not more but stronger rainfall events (Fig. 25, Huara)
- South Atacama: more and stronger rainfall events (Fig. 25, Paranal)

Fig. 25: Percentile-percentile plots for daily rainfall at Huara and Paranal, $WRF_{LGM}$ vs $WRF_{HIST}$
Downscaling – Rainfall in LGM

Driver:

- Rainfall increase probably associated to more and stronger troughs (see slide 13)
- What about the drying in Northeast Atacama?
- Associated to Bolivian High?

**Fig. 26:** Illustration of the Bolivian High and the associated upper-level easterlies at the Northern periphery
Clustering of daily 200hPa geopotential height fields of MPI for summer (DJF)

Five circulation types CTs (Fig. 27), e.g.:

CT2: southward displacement of the Bolivian High
CT4: strengthening of Bolivian High

Fig. 27: circulation types as obtained by clustering for summer (DJF), shown as 200hPa geopotential height anomalies (in gpm)
Downscaling – Rainfall in LGM

- Frequencies of occurrence of the circulation types captured well by MPI-historicals (Fig. 28)
- Only marginal changes in the frequencies of occurrence of the circulation types in MPI-LGM (Fig. 28)
- Upper-tropospheric circulation did not significantly change during the LGM, but ...

Fig. 28: Frequencies of occurrence of the five circulation types in ERA-Interim, MPI-historicals, and MPI-LGM
Downscaling – Rainfall in LGM

- particularly CT2 and CT4 associated to less rainfall in LGM (Fig. 29)

Rainfall decrease rather due to thermodynamic effects?

Fig. 29: Composite means of WRF-simulated rainfall in North Atacama for the five circulation types in WRF_{Hist} and WRF_{LGM}
Distinctly different key drivers for past pluvial phases in the Atacama Desert in PMIP4 models:

### LGM:
- Atmospheric circulation over the subtropical Southeast Pacific
- More and stronger troughs, more cutoff lows

### MidPliocene:
- Sea Surface Temperatures
- Distinctly warmer SSTs, shift towards more El Nino conditions

Downscaling enables to uncover local features of the climate change signals and to improve the process understanding.


