Earth – Evolution
at the dry limit

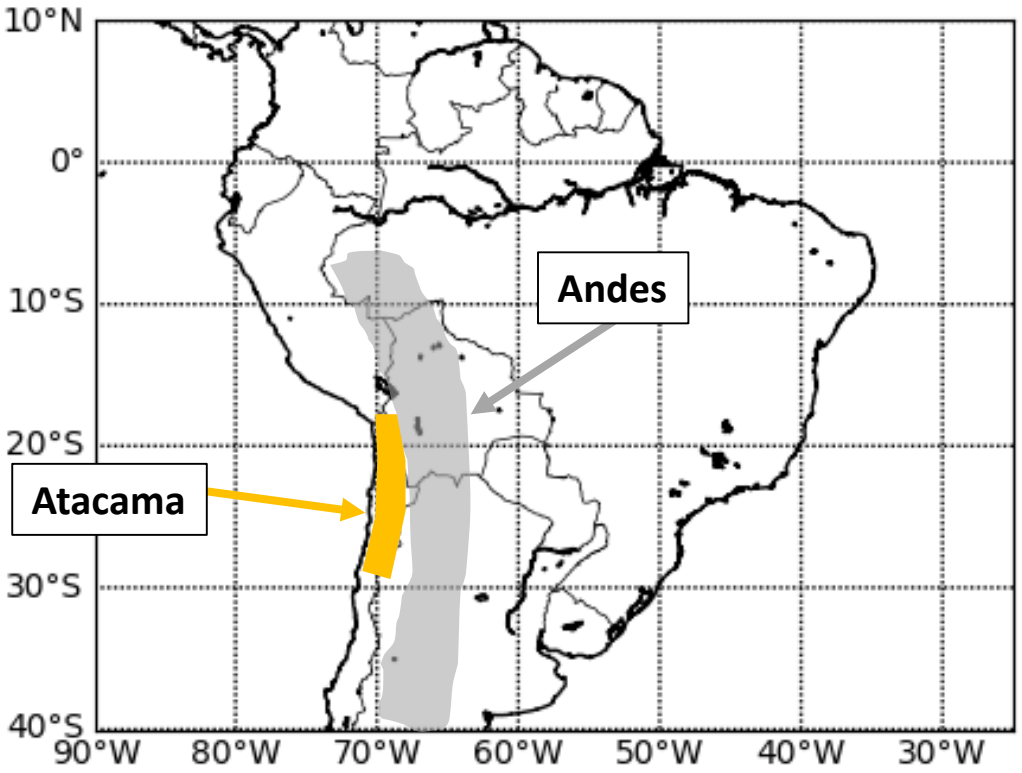
Paleo-climate shifts in the Atacama Desert from PMIP4 simulations

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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



Introduction

- **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?

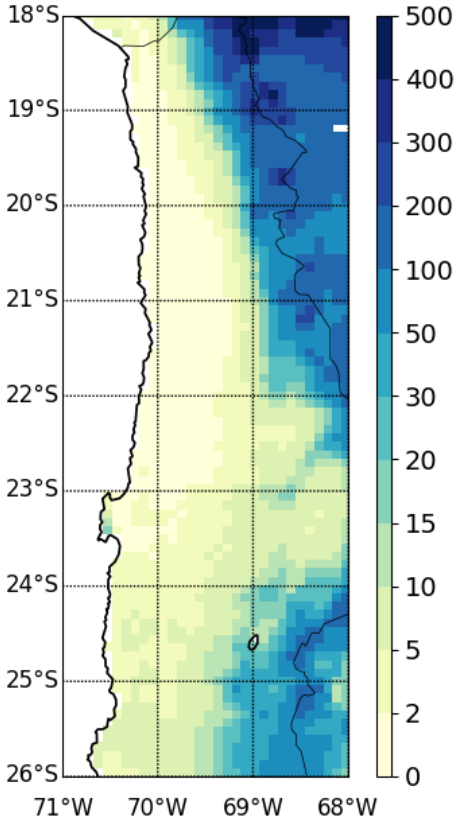


Fig. 1: Simulated mean annual rainfall [1] (in mm/year) as obtained from a WRF simulation forced with ERA-Interim

Data and Methods

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List of analysed CMIP6-PMIP4 Models

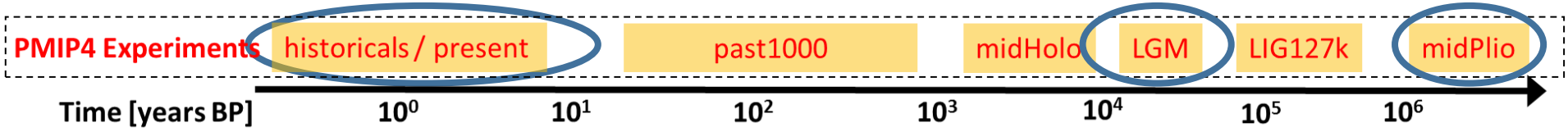
Model name	Institution	Acronym
ACCESS-ESM1-5	CSIRO	ACC
AWI-ESM-1-1-LR	AWI	AWI
CESM2	NCAR	CESM2
CNRM-CM6-1	CNRM-CERFACS	CNRM
FGOALS-f3-L	CAS	FGOAf
FGOALS-g3	CAS	FGOAg
GISS-E2-1-G	NASA-GISS	GISS
INM-CM4-8	INM	INM
IPSL-CM6A-LR	IPSL	IPSL
MIROC-ES2L	MIROC	MIROC
MPI-ESM1-2-LR	MPI-M	MPI
NESM3	NUIST	NESM3

Data and Methods

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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

Data and Methods

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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**

Historicals - Rainfall

- **Hyper-arid conditions simulated realistically by several PMIP4 models**

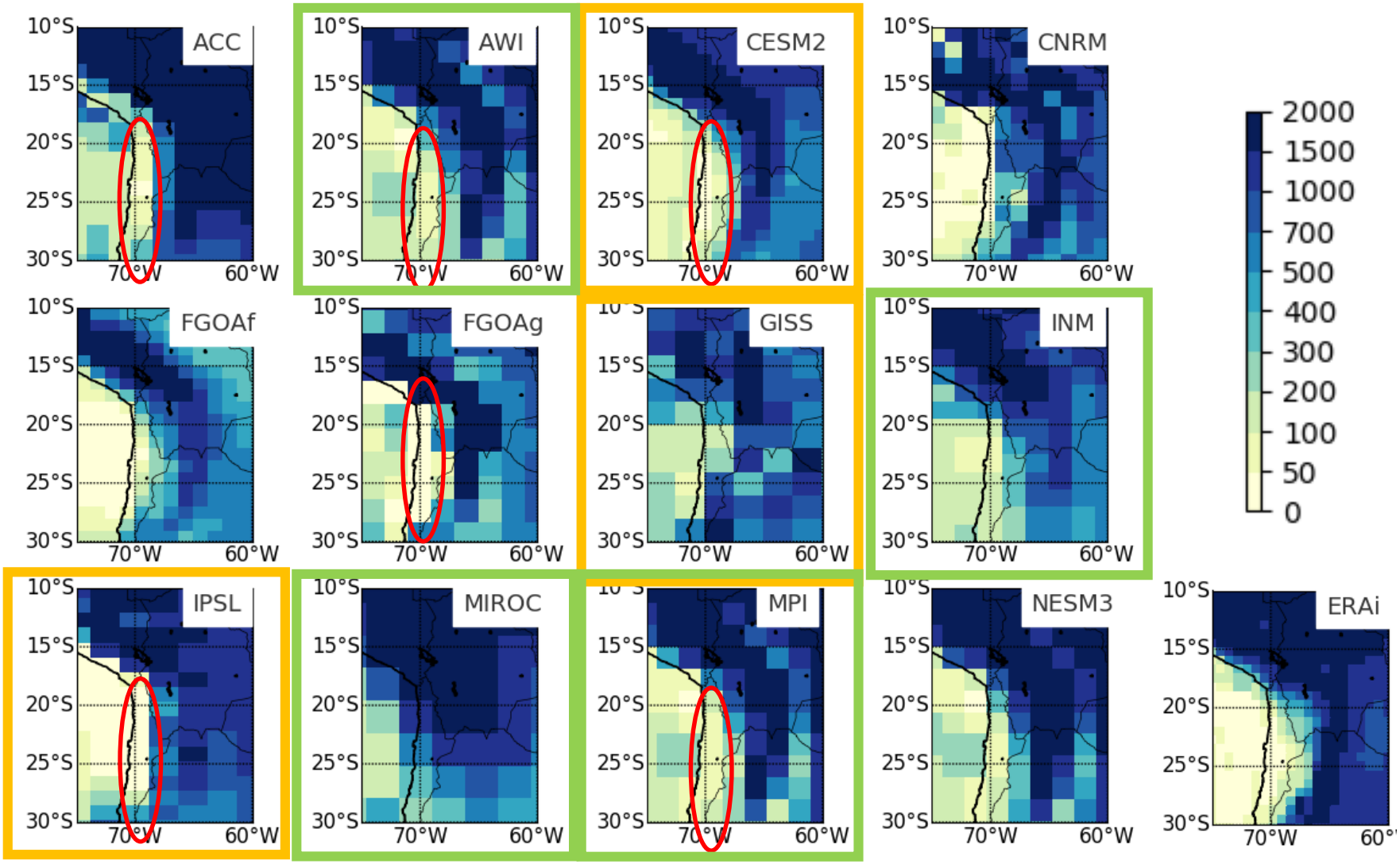
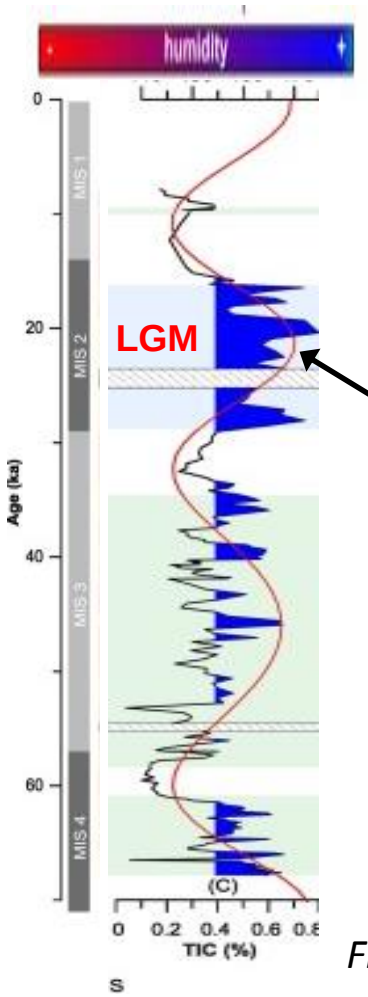


Fig.2: Mean annual rainfall (mm/year) in PMIP4 models (historicals) and in ERA-Interim; green boxes: LGM experiments available; yellow boxes: midPloicene experiments available

LGM



- **Climate record from Northern Atacama indicate substantially more rainfall during the Last Glacial Maximum**

→ **Analysis of PMIP4 experiment LGM**

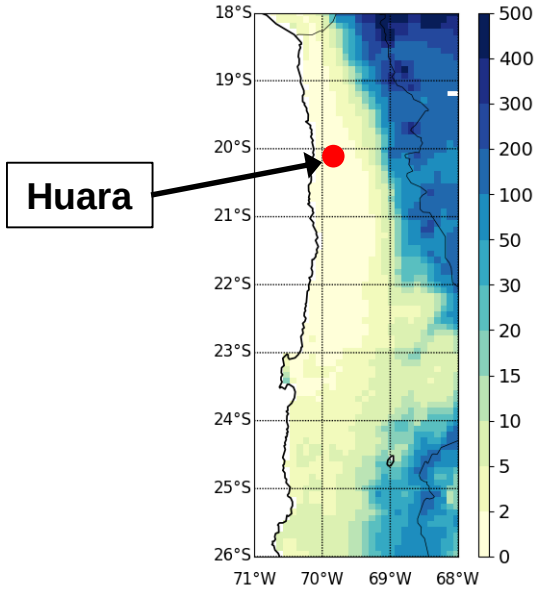
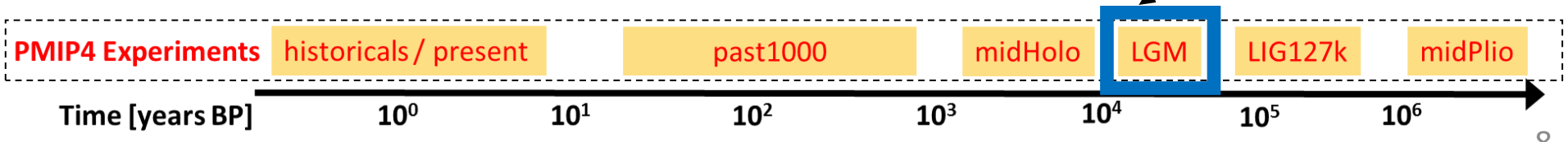


Fig. 3: Huara climate record [4]



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)

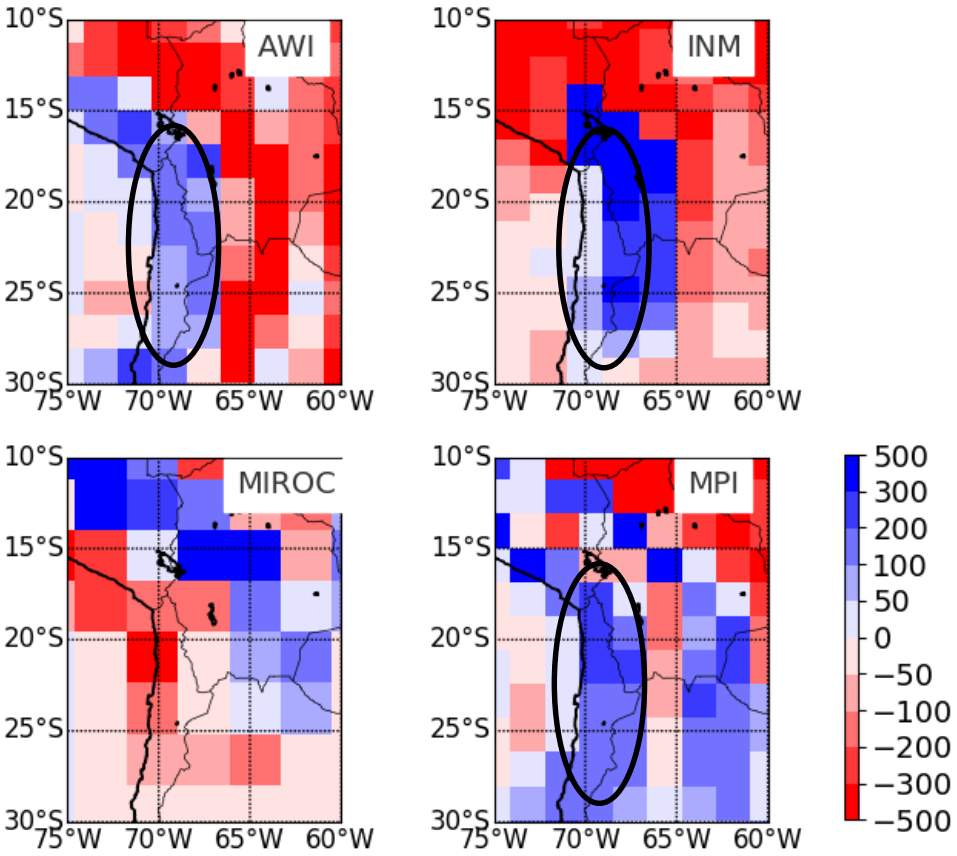


Fig. 4: LGM minus historicals for mean annual rainfall (in mm/year) in four PMIP4 models

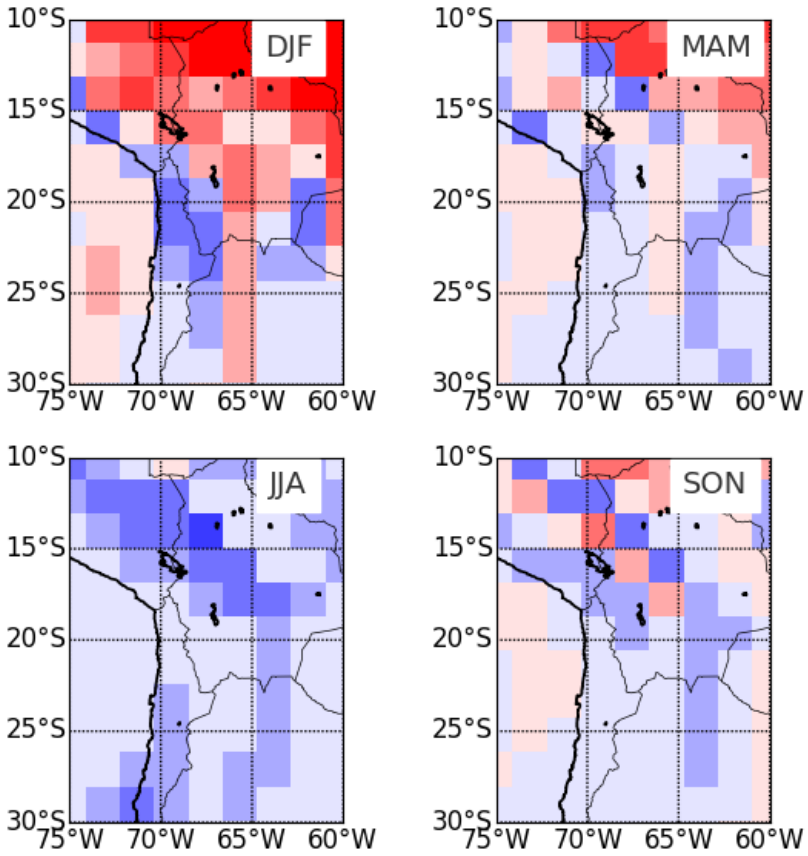


Fig. 5: LGM minus historicals for mean seasonal rainfall (in mm/season) in MPI

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)**

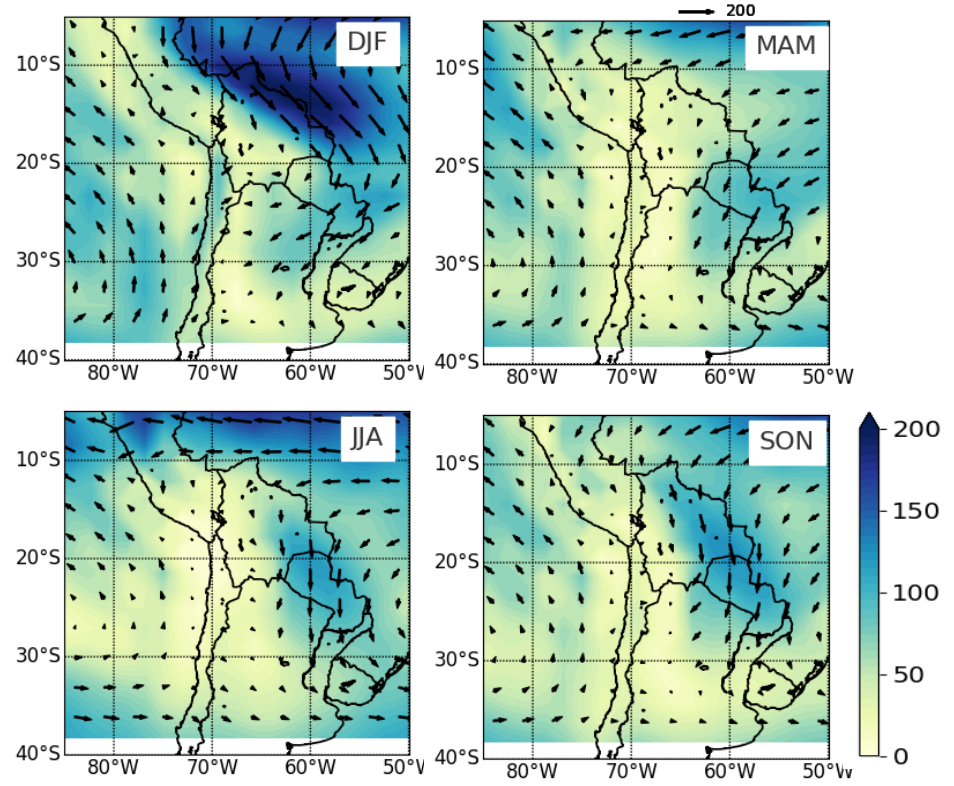


Fig. 6: Seasonal moisture flux (arrows and shading, in kg/(m·s)) in MPI-historicals

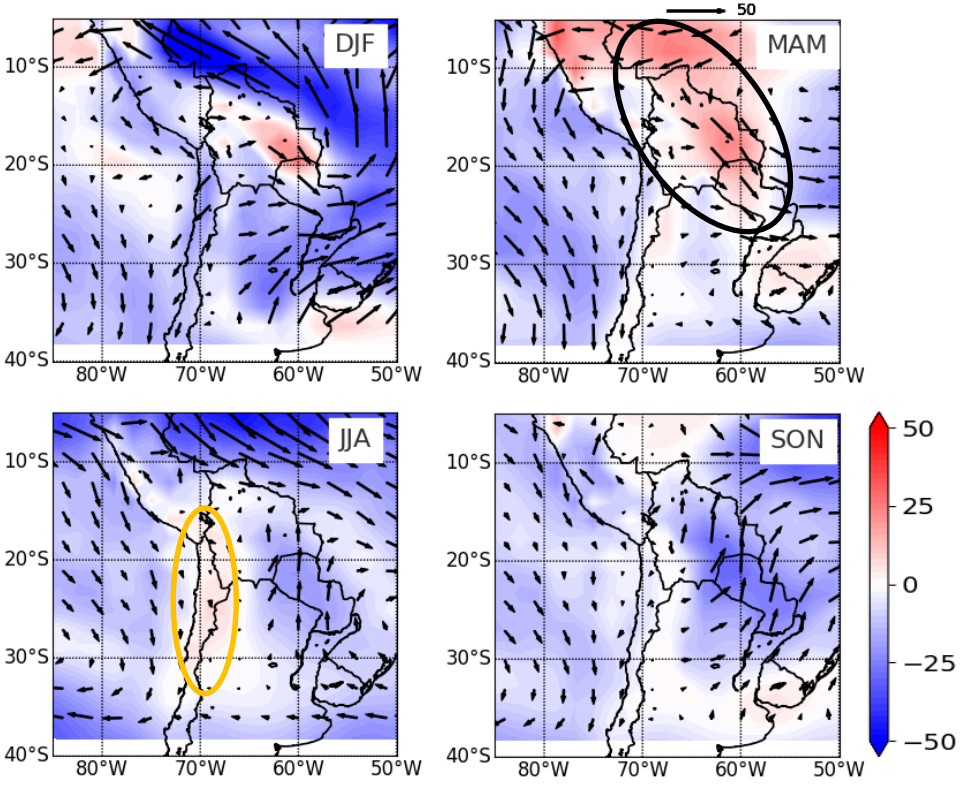


Fig. 7: LGM minus historicals for seasonal moisture flux (arrows and shading, in kg/(m·s)) in MPI

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)

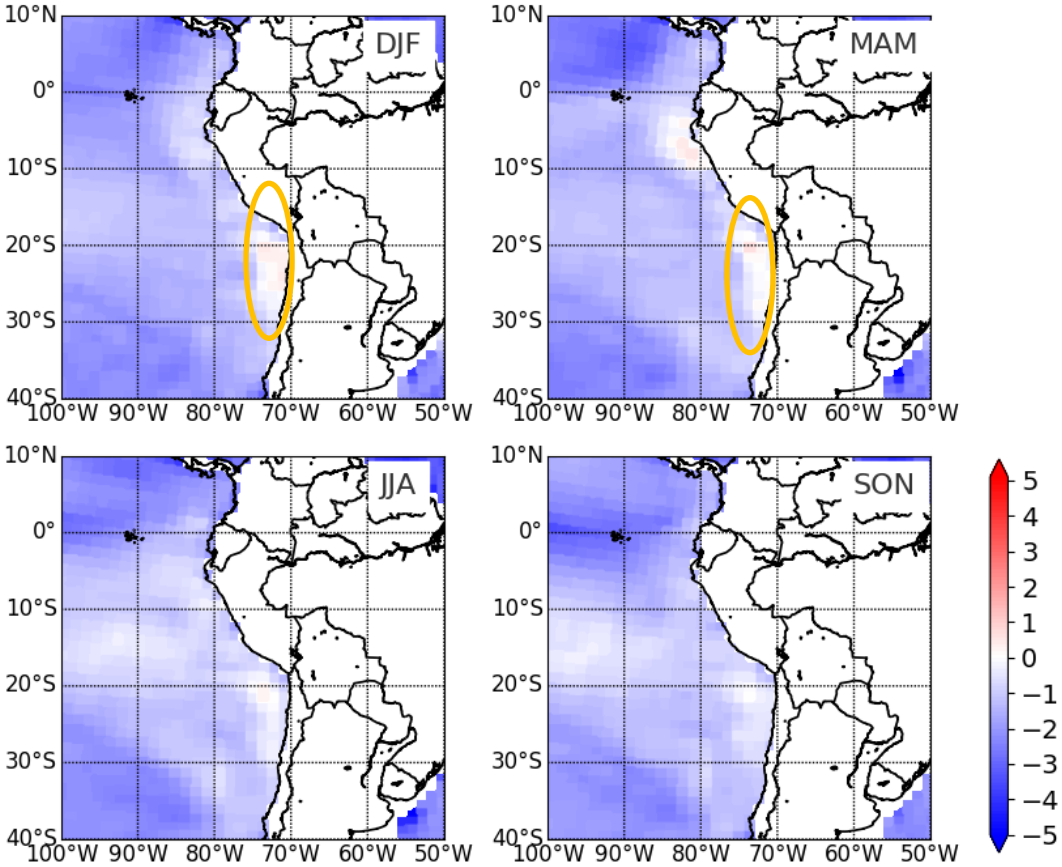


Fig. 8: LGM minus historicals for seasonal SST (in °C) in MPI

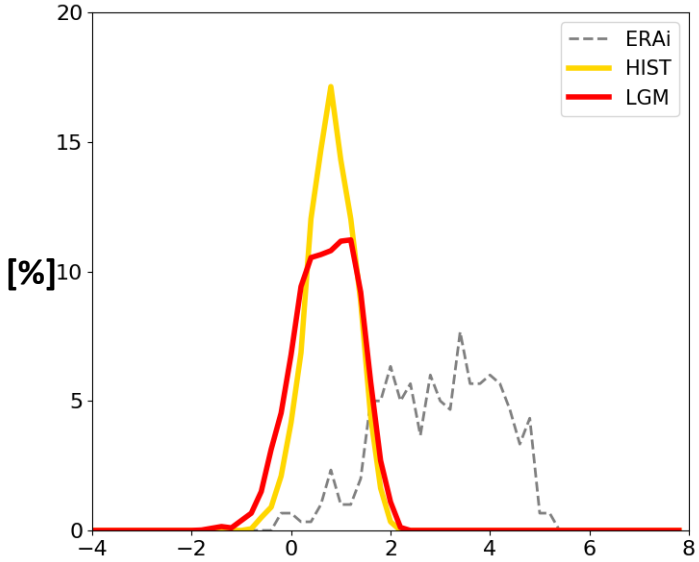


Fig. 9: Histograms of SST difference (in °C) between tropical West Pacific and tropical Central-East Pacific in ERA-Interim, MPI-historicals and MPI-LGM

MPI-historicals – Troughs

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

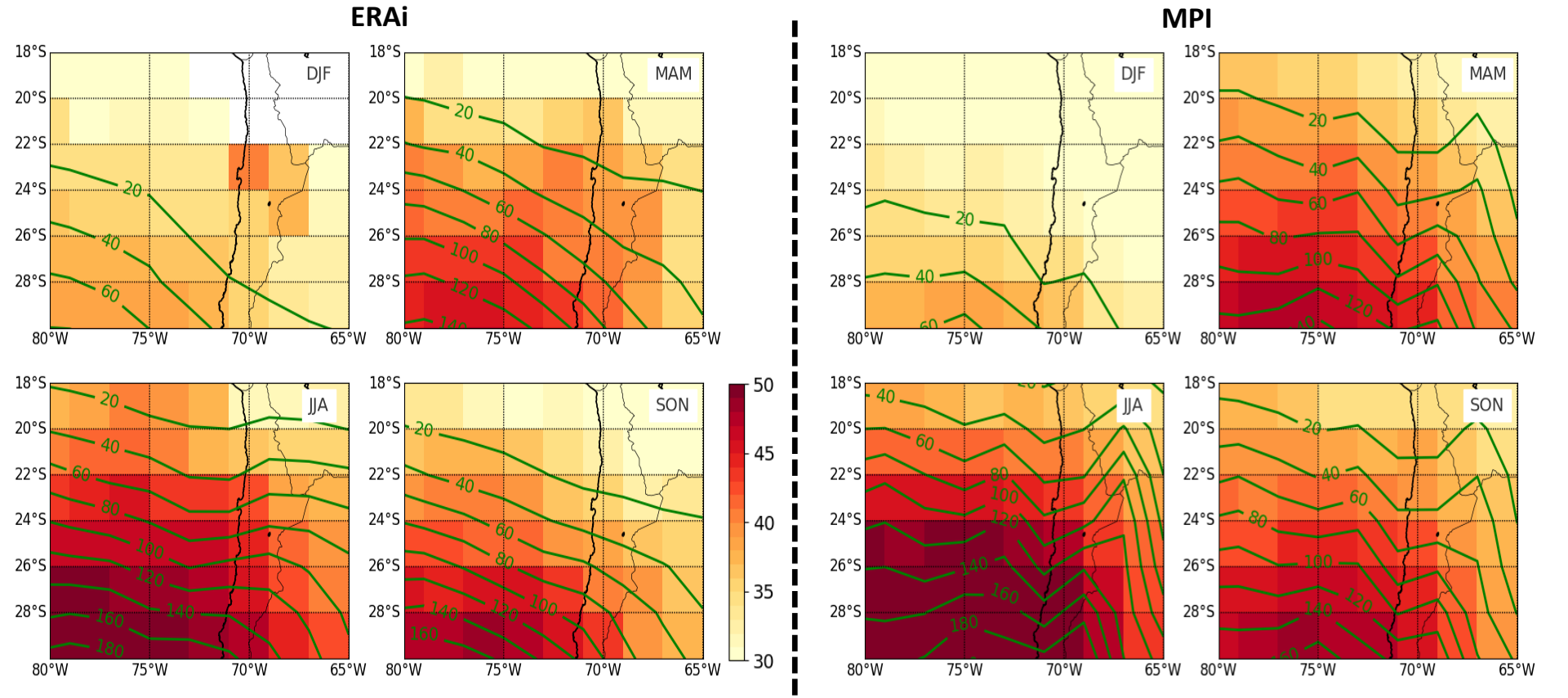


Fig. 10: Seasonal number (contours, in number per decade) and strength (shading, in gpm/°lon) of trough points in ERA-Interim (left) and MPI-historicals (right)

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]

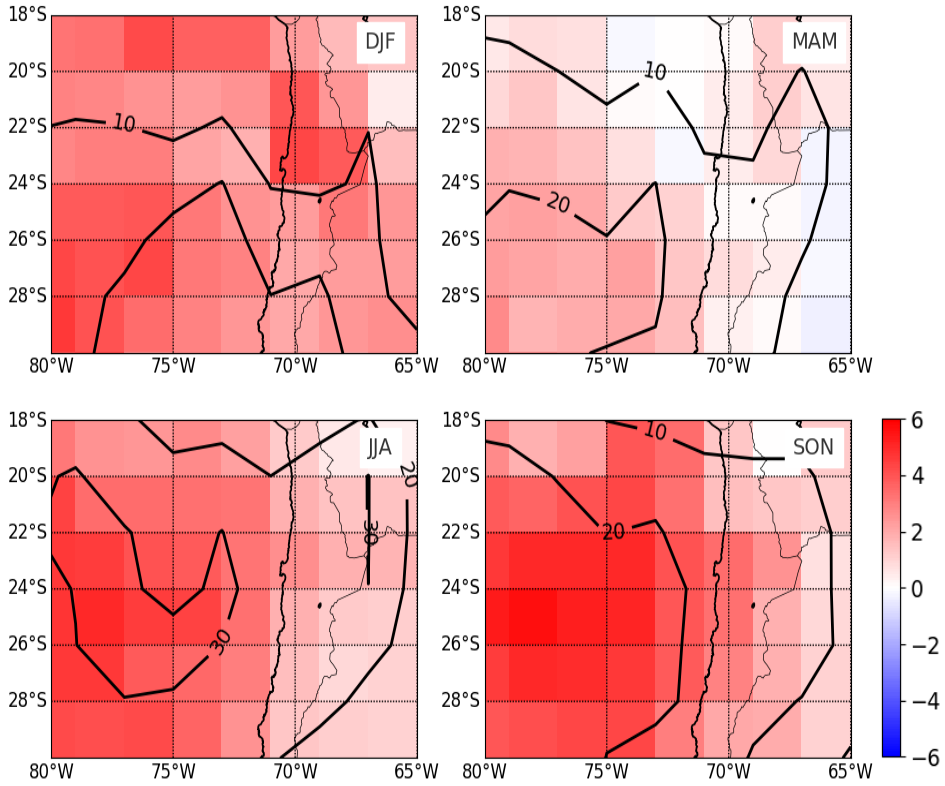


Fig. 11: LGM minus historicals for number (contours, in number per decade) and strength (shading, in gpm/°lon) of trough points in MPI

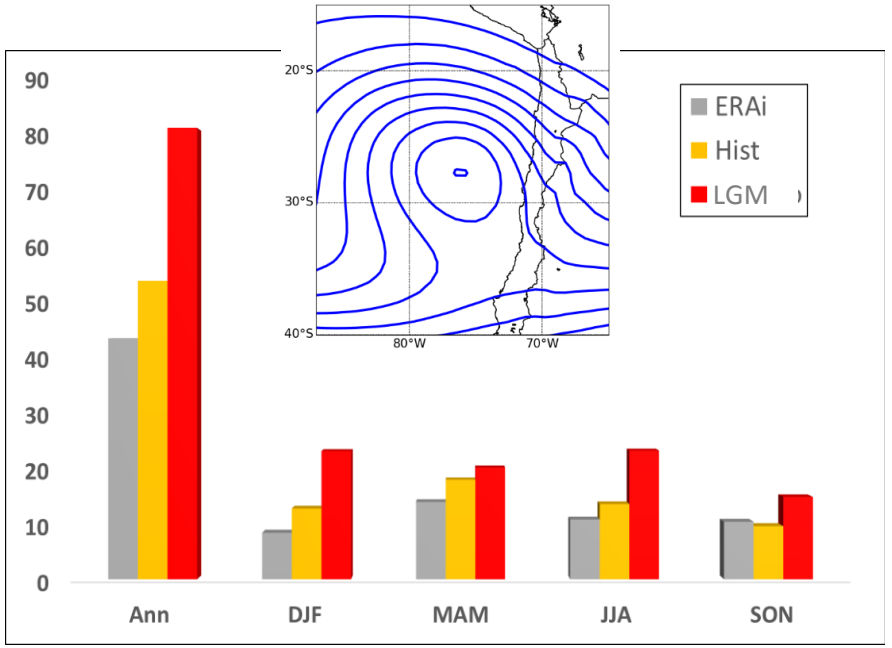


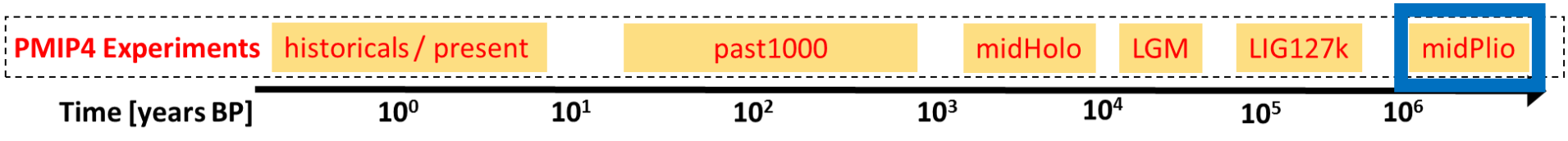
Fig. 12: Annual and seasonal number of cutoff lows in ERA-Interim, MPI-historicals, and MPI-LGM (in number per decade)

midPliocene

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- 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

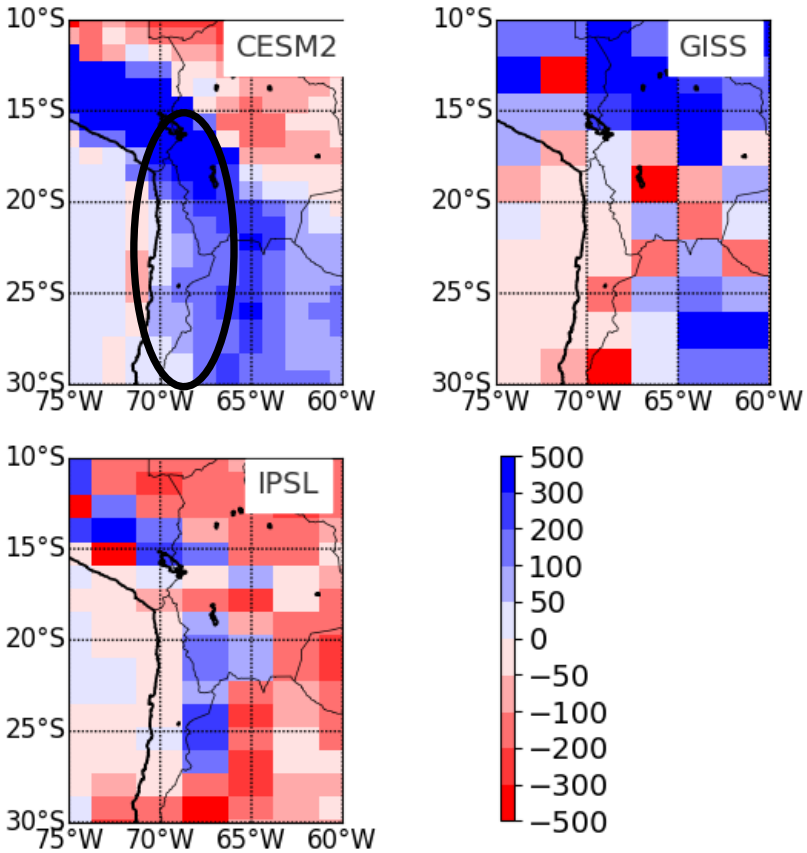


Fig. 13: midPliocene minus historicals for mean annual rainfall (in mm/year) in three PMIP4 models

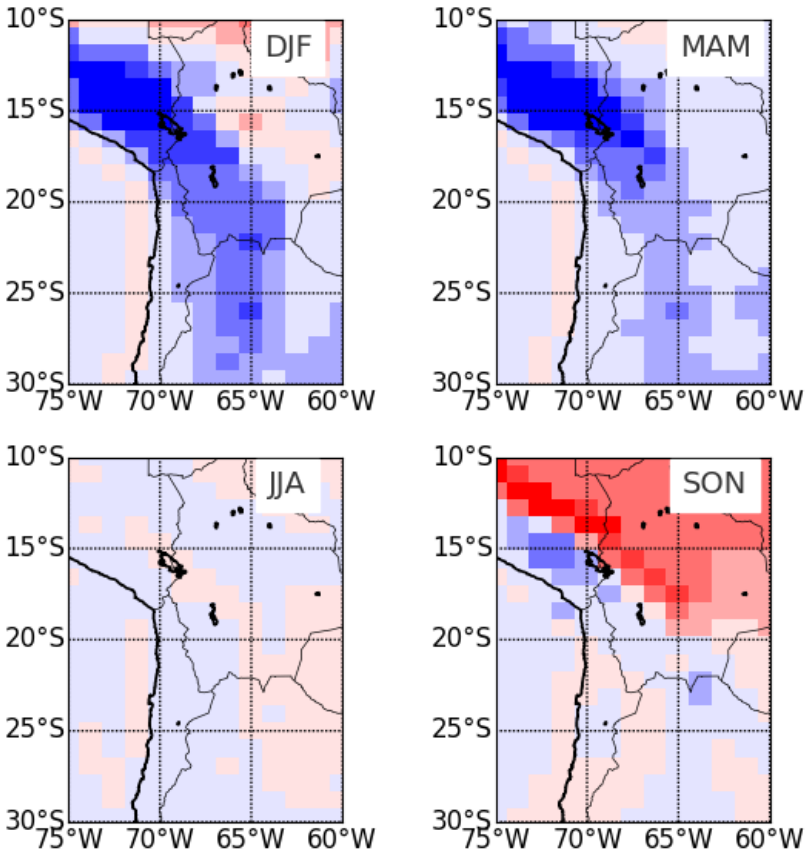


Fig. 14: midPliocene minus historicals for mean seasonal rainfall (in mm/season) in CESM2

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 …**

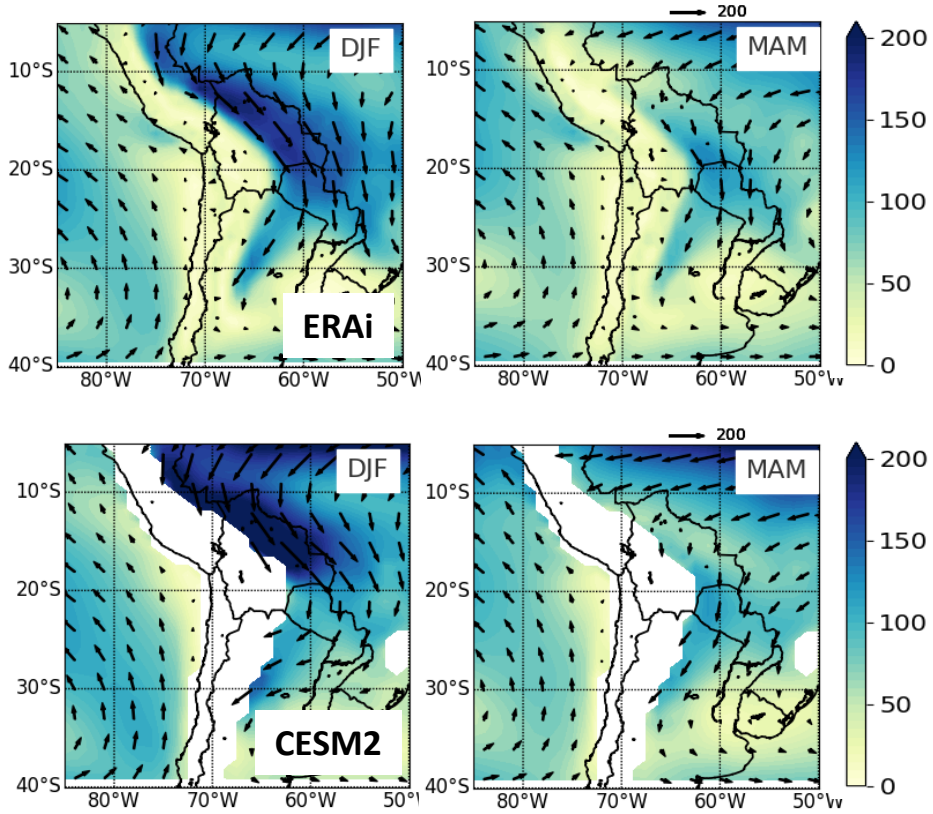


Fig. 15: Seasonal moisture flux (arrows and shading, in kg/(m·s)) in ERA-Interim (upper row) and in CESM2-historicals (lower row)

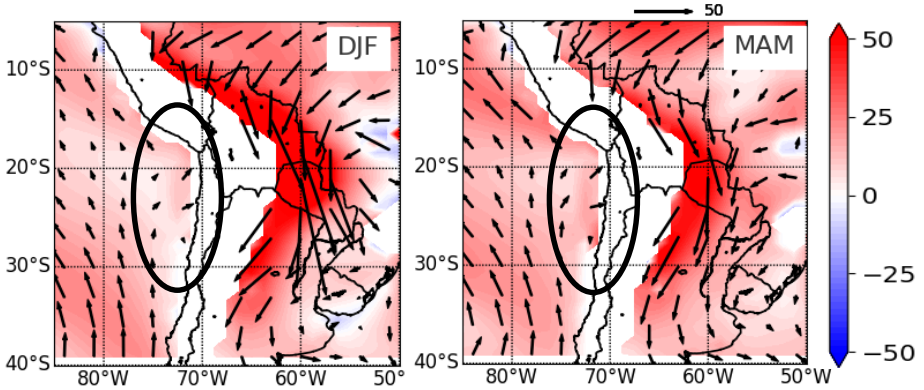


Fig. 16: midPliocene minus historicals for seasonal moisture flux (arrows and shading, in kg/(m·s)) in CESM2

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 ?

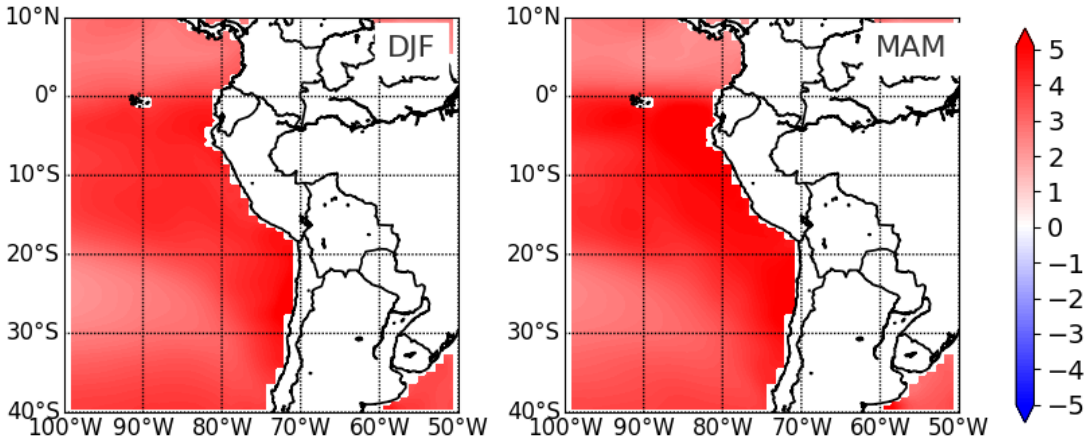


Fig. 17: midPliocene minus historicals for seasonal SST (in °C) in CESM2

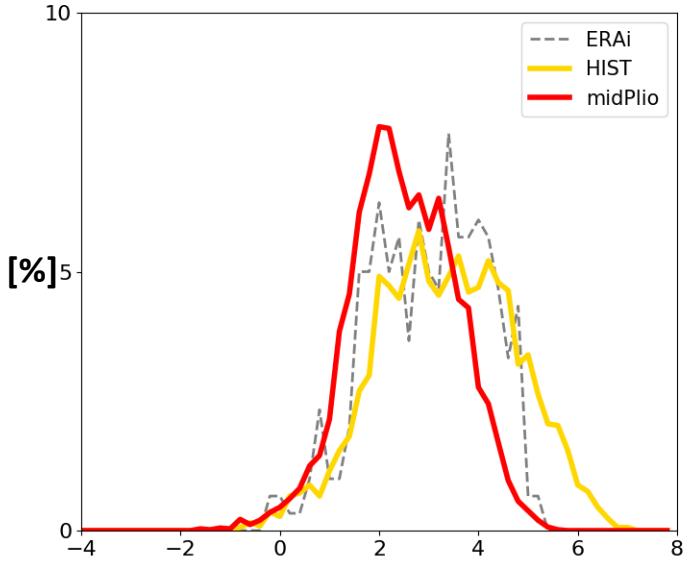
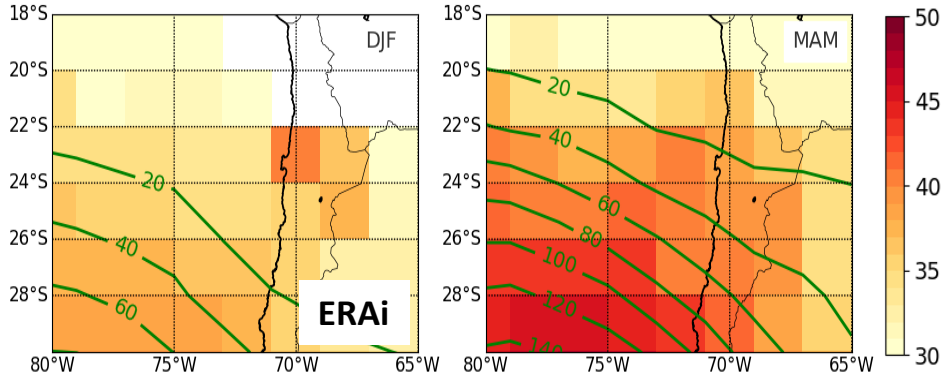


Fig. 18: Histograms of SST difference (in °C) between tropical West Pacific and tropical Central-East Pacific in ERA-Interim, CESM2-historicals, and CESM2-midPliocene

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)



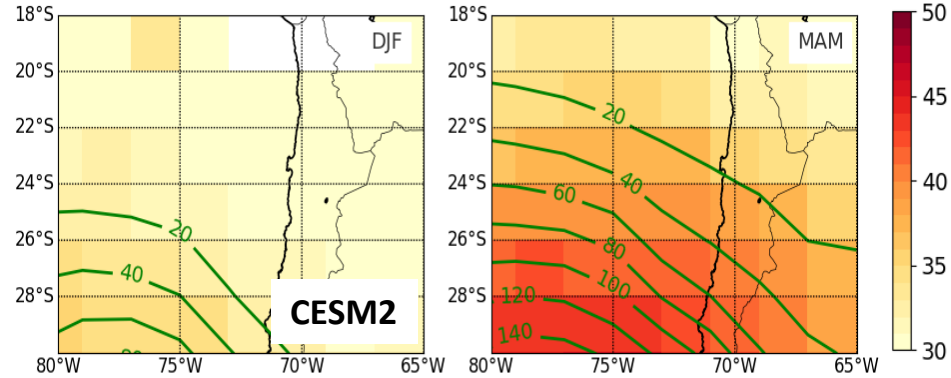


Fig. 19: Seasonal number (contours, in number per decade) and strength (shading, in gpm/°lon) of trough points in ERA-Interim (upper row) and CESM2-historicals (lower row)

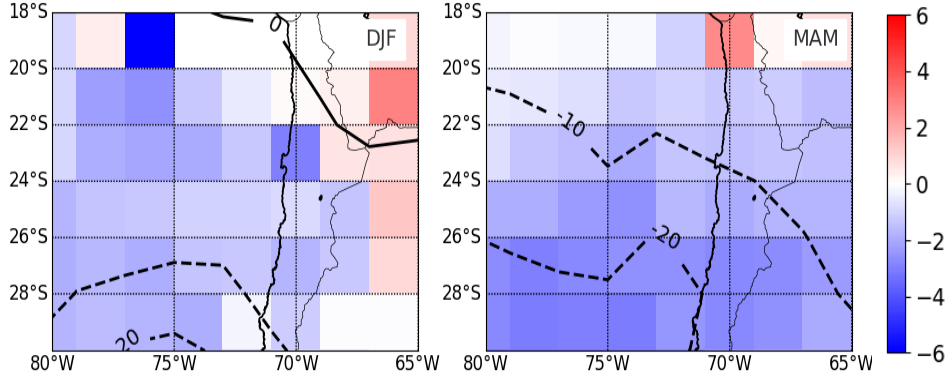


Fig. 20: midPliocene minus historicals for number (contours, in number per decade) and strength (shading, in gpm/°lon) of trough points in CESM2

midPliocene – Cutoff lows

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

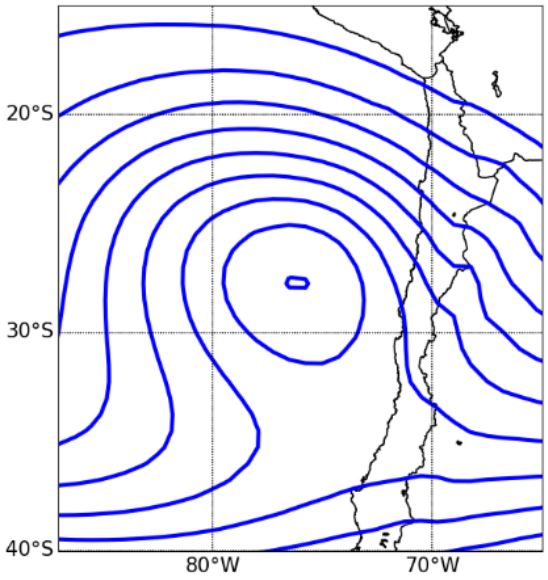


Fig. 21: Cutoff low off the coast of the Atacama Desert

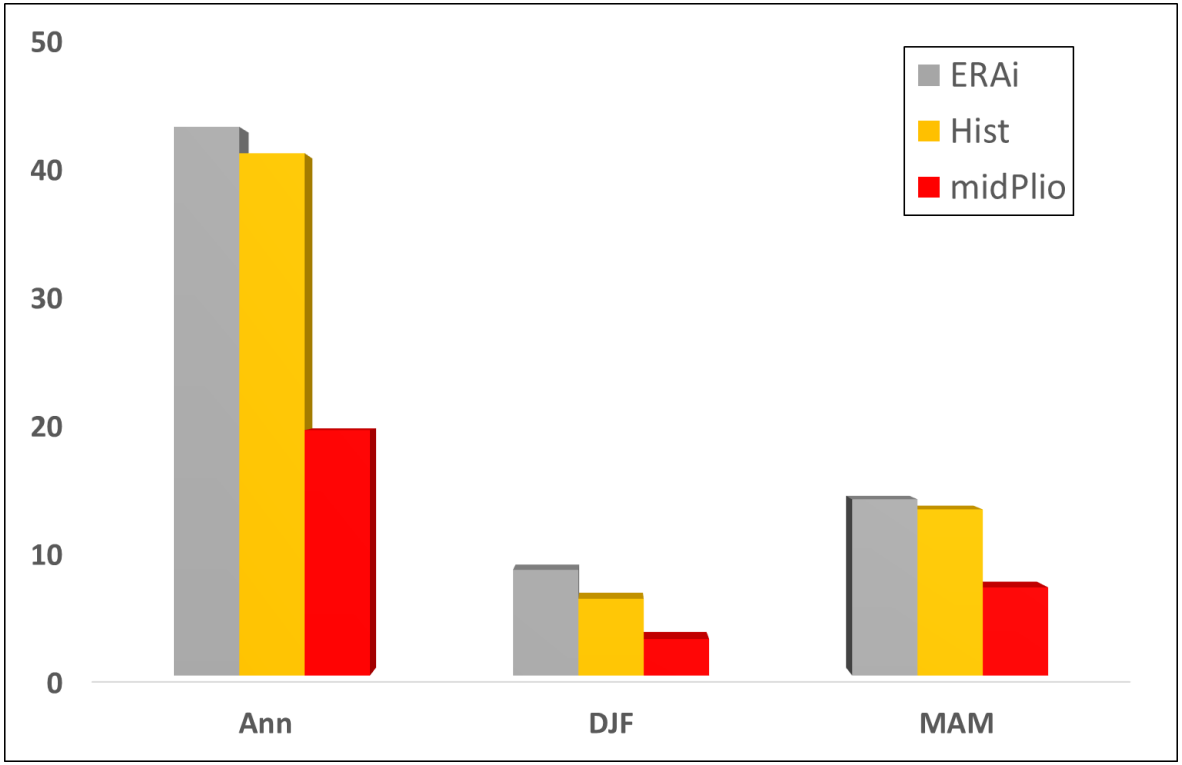


Fig. 22: Annual and seasonal number of cutoff lows in ERA-Interim, CESM2-historicals, and CESM2-midPliocene (in number per decade)

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_{Hist})
  (ii) MPI-LGM r1, 25 model years (WRF_{LGM})
- Double one-way nesting
- 1.875° → 50km → 10km

Downscaling – Rainfall in LGM

- Rainfall overestimated in WRF_{HIST} (Fig. 23)
- Nevertheless, hyper-aridity and rainfall gradients captured by WRF_{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)

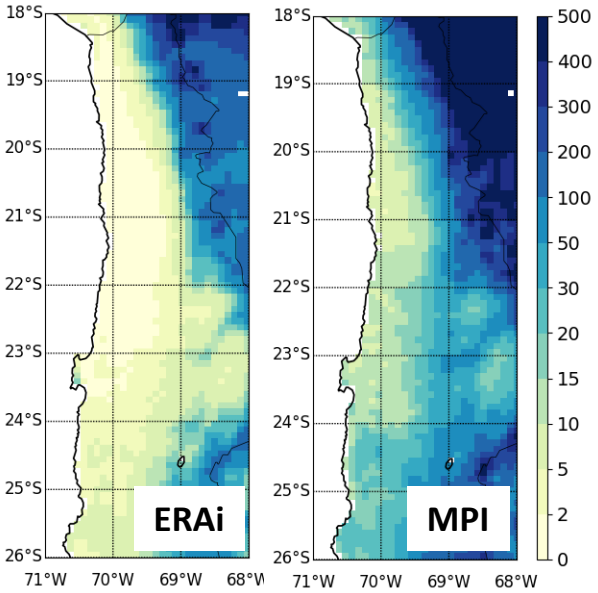


Fig. 23: Mean annual rainfall (mm/year) WRF_{ERAi} and in WRF_{Hist}

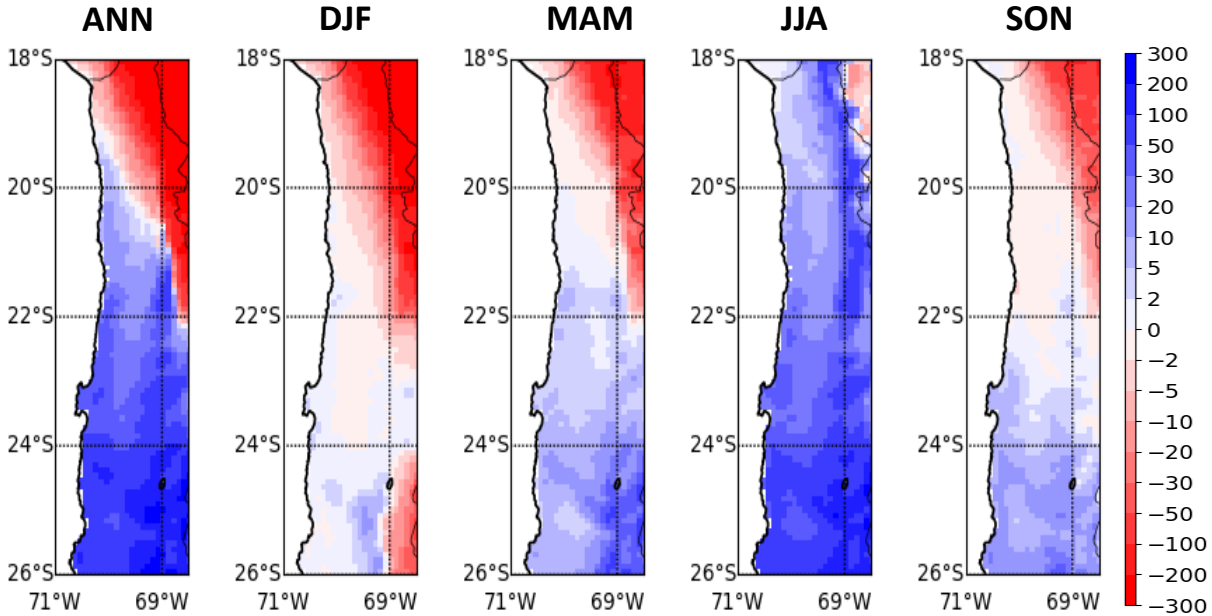


Fig. 24: WRF_{LGM} minus WRF_{HIST} for annual and seasonal rainfall (mm/year and mm/season)

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)**

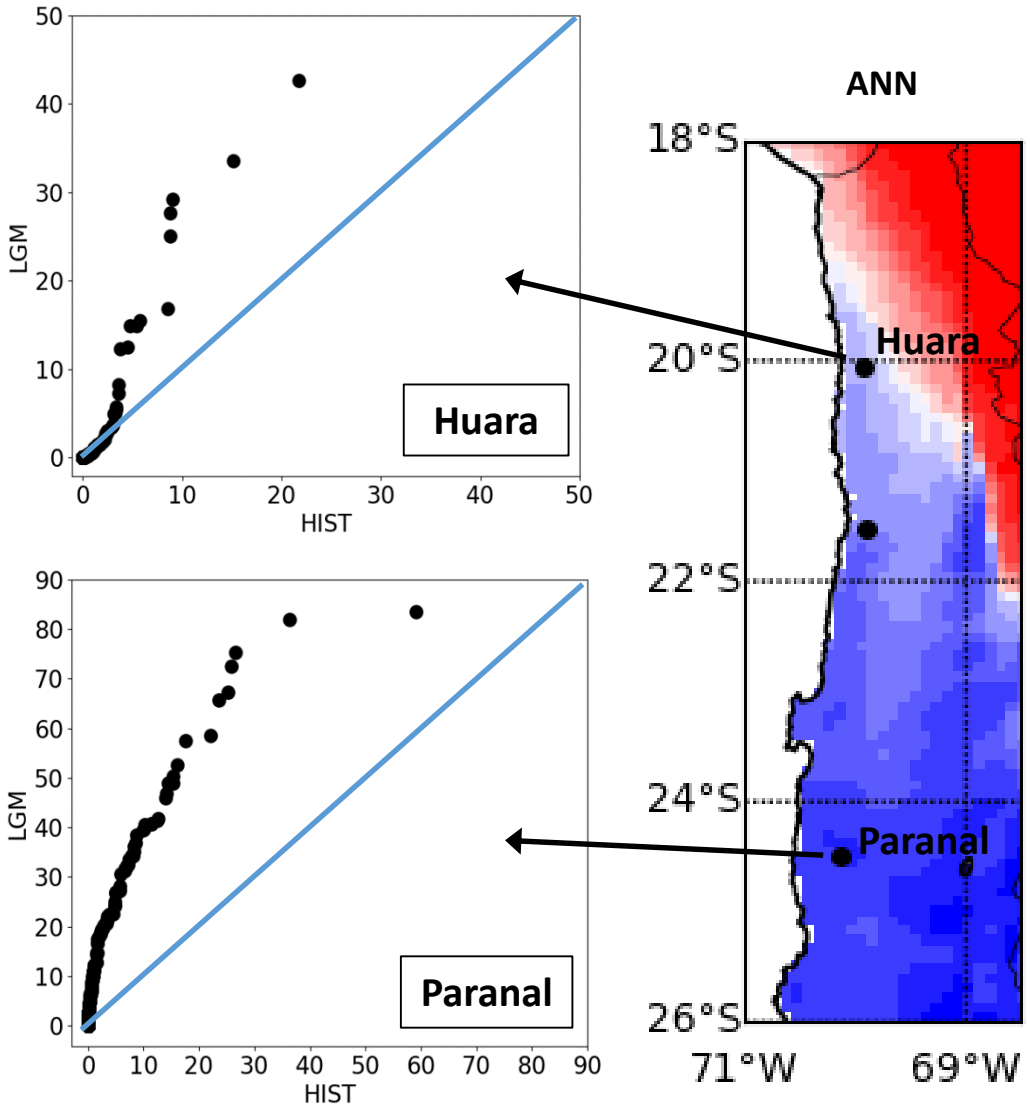


Fig. 25: Percentile-percentile plots for daily rainfall at Huara and Paranal, WRF_{LGM} vs WRF_{HIST}

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?

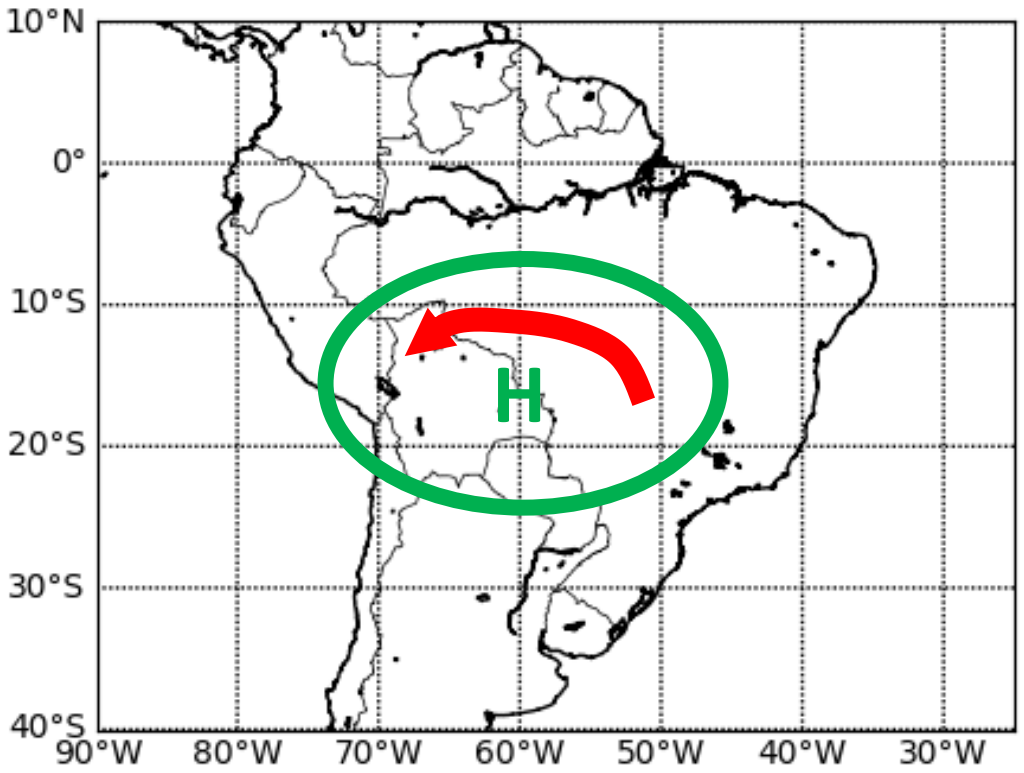


Fig. 26: Illustration of the Bolivian High and the associated upper-level easterlies at the Northern periphery

Downscaling – Rainfall in LGM

- **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

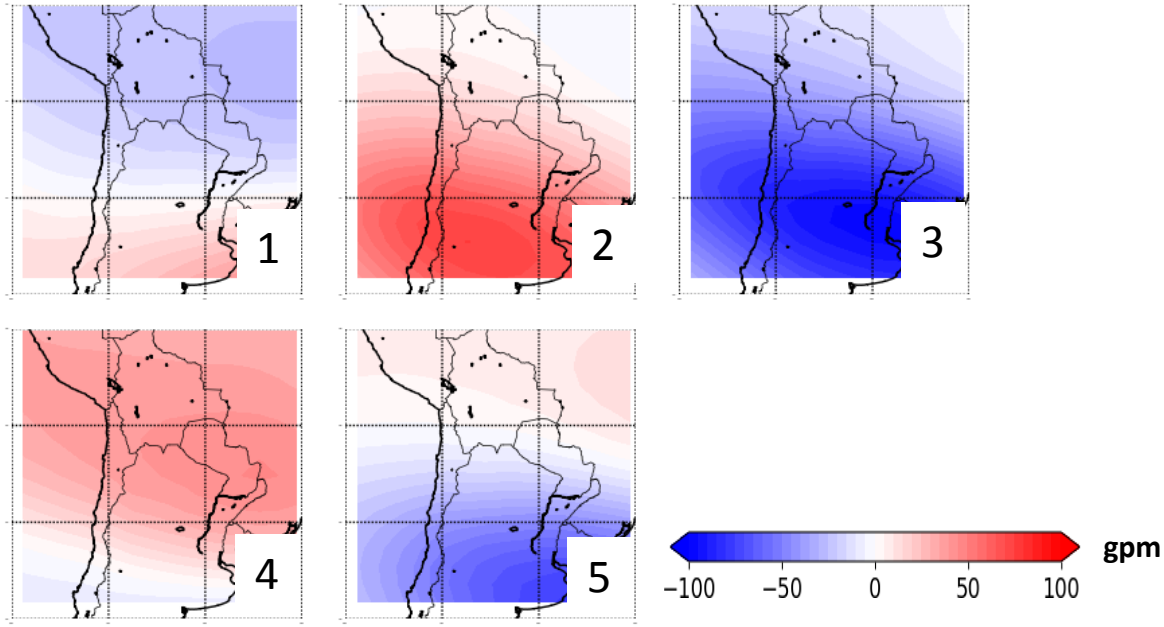


Fig. 27: circulation types as obtained by clustering for summer (DJF), shown as 200hPa geopotential height anomalies (in gpm)

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 …

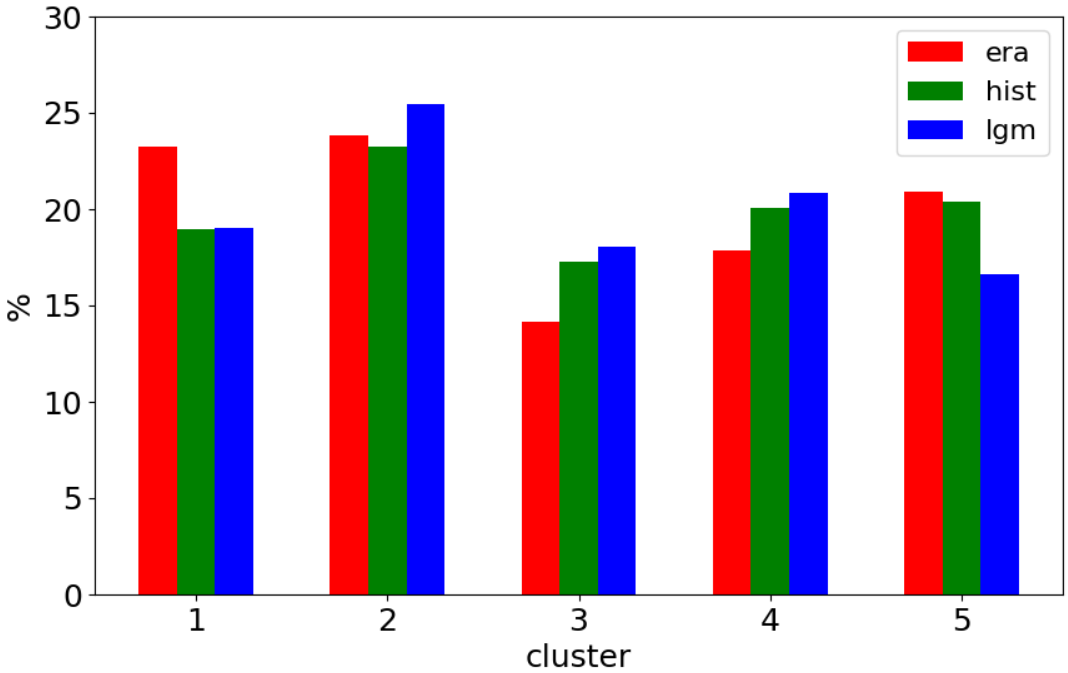


Fig. 28: Frequencies of occurrence of the five circulation types in ERA-Interim, MPI-historicals, and MPI-LGM

Downscaling – Rainfall in LGM

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

→ Rainfall decrease rather due to thermodynamic effects ?

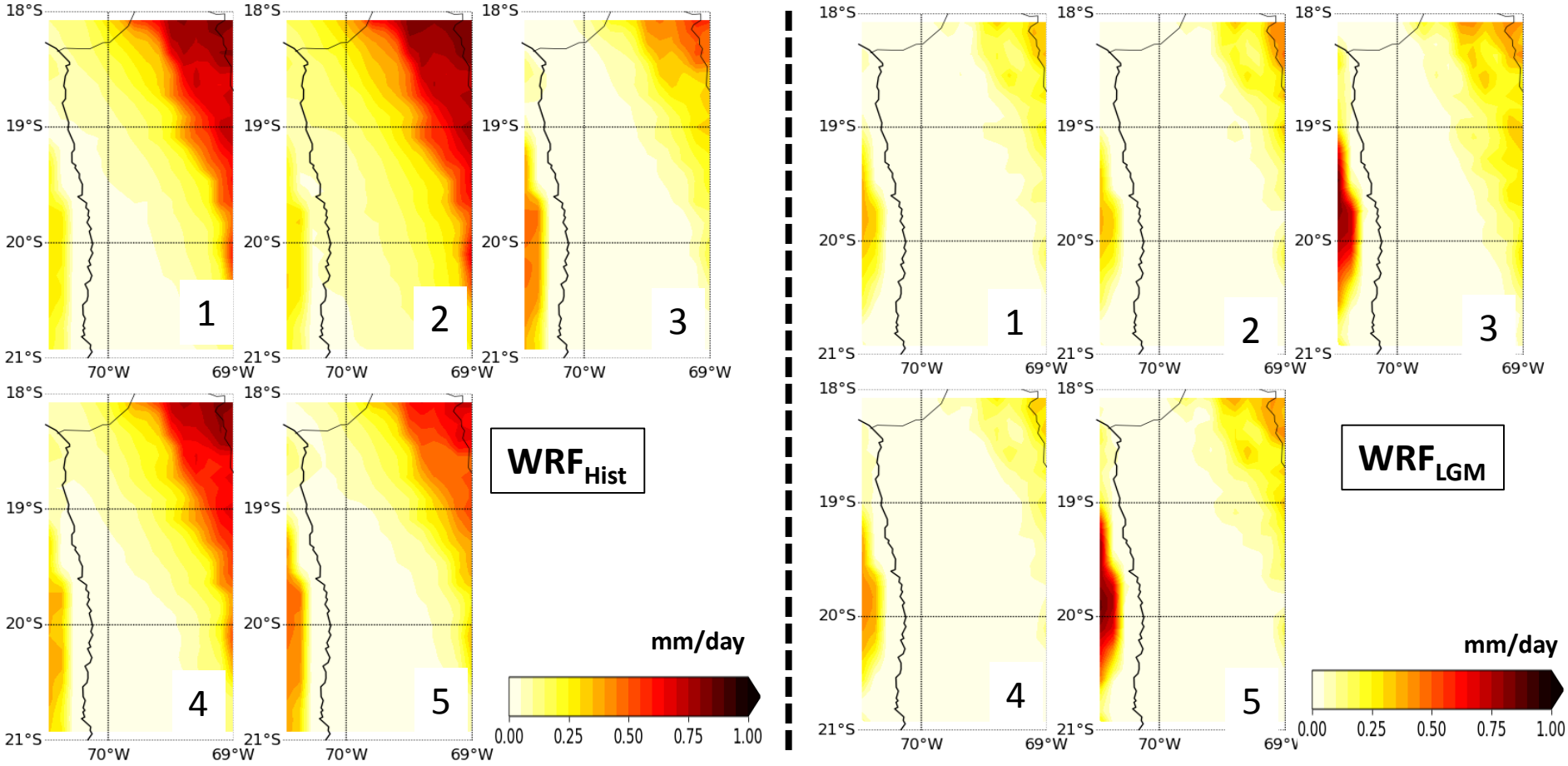


Fig. 29: Composite means of WRF-simulated rainfall in North Atacama for the five circulation types in WRF_{Hist} and WRF_{LGM}

Summary

Earth – Evolution at the dry limit

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**

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Earth – Evolution at the dry limit

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