Climate change in the High Mountain Asia simulated with CMIP6 models

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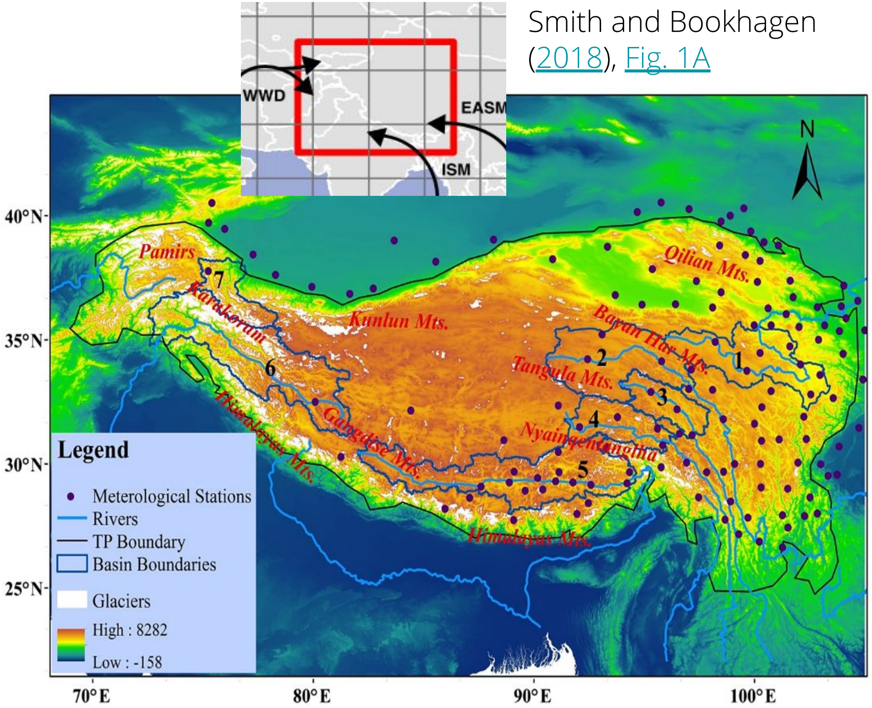
1. Introduction

High Mountain Asia (HMA): Introduction

- The Tibetan Plateau (TP): world's highest plateau (average elevation 4000m) ➝ influence on regional and global climate (e.g., Kutzbach et al., 1993)
- Water supply of over 1.4 billion living downstream (e.g. Immerzeel et al., 2012)
- Climatic regimes:
  - winter westerly disturbances (WDs)
  - Indian / East Asian summer monsoon
- Warming over the HMA and TP (Liu et al., 2000; Wang et al., 2008) -> impacts on permafrost (Yang et al., 2010), glaciers (Yao et al., 2007), water resources (e.g. Immerzeel et al., 2010), etc.
- Contrasted trends for precipitation and snow cover (Kang et al., 2010)
- Lack of observations: western part and high elevation

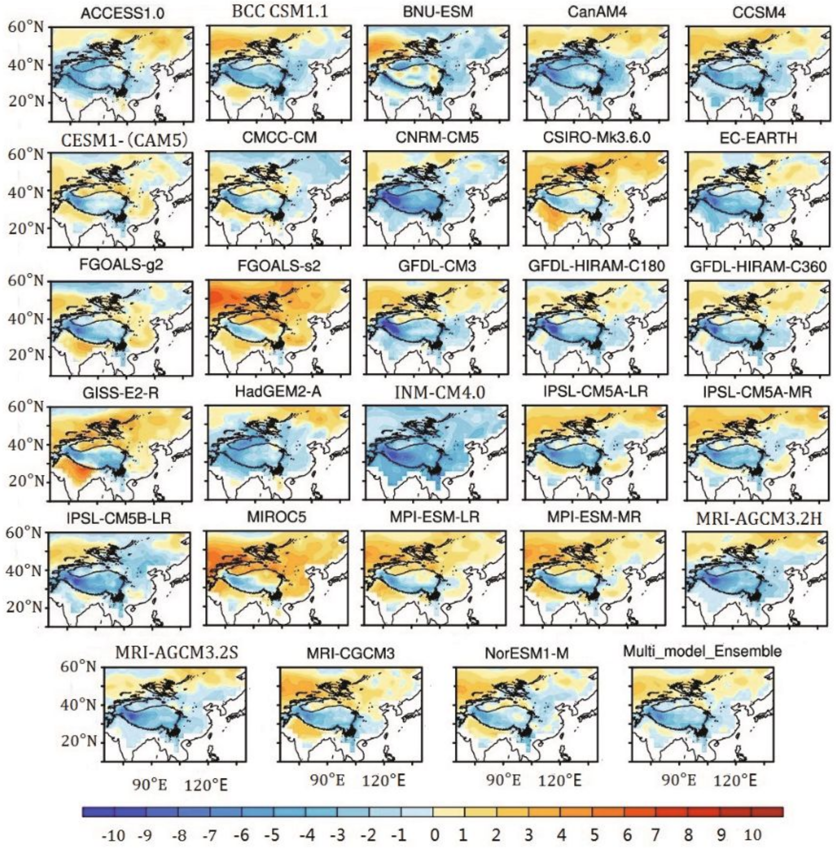


Smith and Bookhagen (2018), Fig. 1A

Li et al. (2018), Fig. 1

Use of GCMs (even if coarse spatial resolution ~50-300km) provides a coherent picture of the large-scale temporal and spatial patterns of key variables at a regional scale !

"Cold bias" over Tibetan Plateau



CMIP5 cold bias
(Chen et al., 2017; Fig 2)

- Cold biases in models from first AMIP experiments over HMA and TP (Mao and Robock, 1998)
- Possible explanations: excess precipitation (Lee & Suh, 2000), snow–ice albedo issues (Su et al., 2013), cold biases in T500 due to smoothed topography (Boos and Hurley, 2013), snow cover parameterization and boundary layer (Chen et al., 2017), lack of high-elevation observation stations in the CRU (Gu et al., 2012), etc.

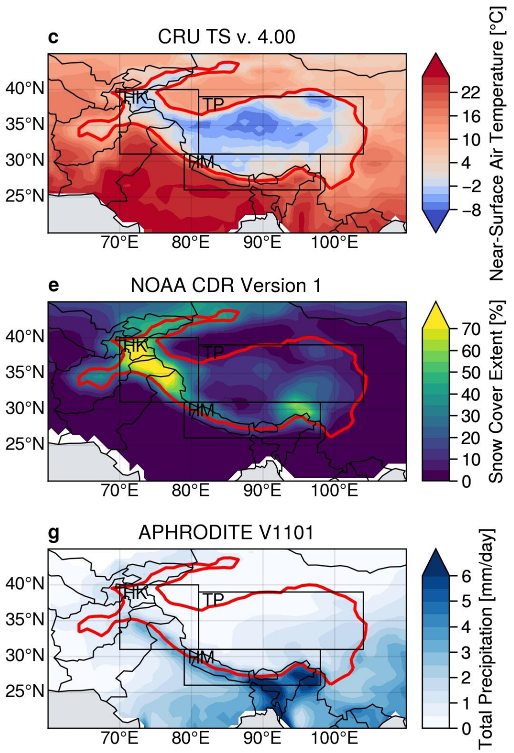
Our study

1. Biases in CMIP6 for near-surface air temperature, total precipitation and snow cover extent?
2. What are the links between the model biases?
3. Do the model biases impact the trends?
4. Projections over the next century?

2. Data and methods

Data and methods

- 26 CMIP6 GCMs simulations for historical period 1979-2014
- 10 CMIP6 models for the future projections: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (O'Neill et al., 2016)
- Observations: CRU (Harris et al., 2014), NOAA CDR (Robinson et al., 2012), APHRODITE (Yatagai et al., 2012) and GPCP (Adler et al., 2016)
- Reanalyses: ERA-Interim (Dee et al., 2011) and ERA5 (Hersbach et al., 2020)
- Domain: High Mountain of Asia (HMA) including the Tibetan Plateau (TP), with elevation higher than 2500 m.asl (red contour)
- 3 subdomains (> 2500 m.asl): Hindu-Kush Karakoram (HK), Himalaya (HM) and Tibetan Plateau (TP)
- Seasons: winter DJFMA (WDs) and summer JJAS (Asian summer monsoon)

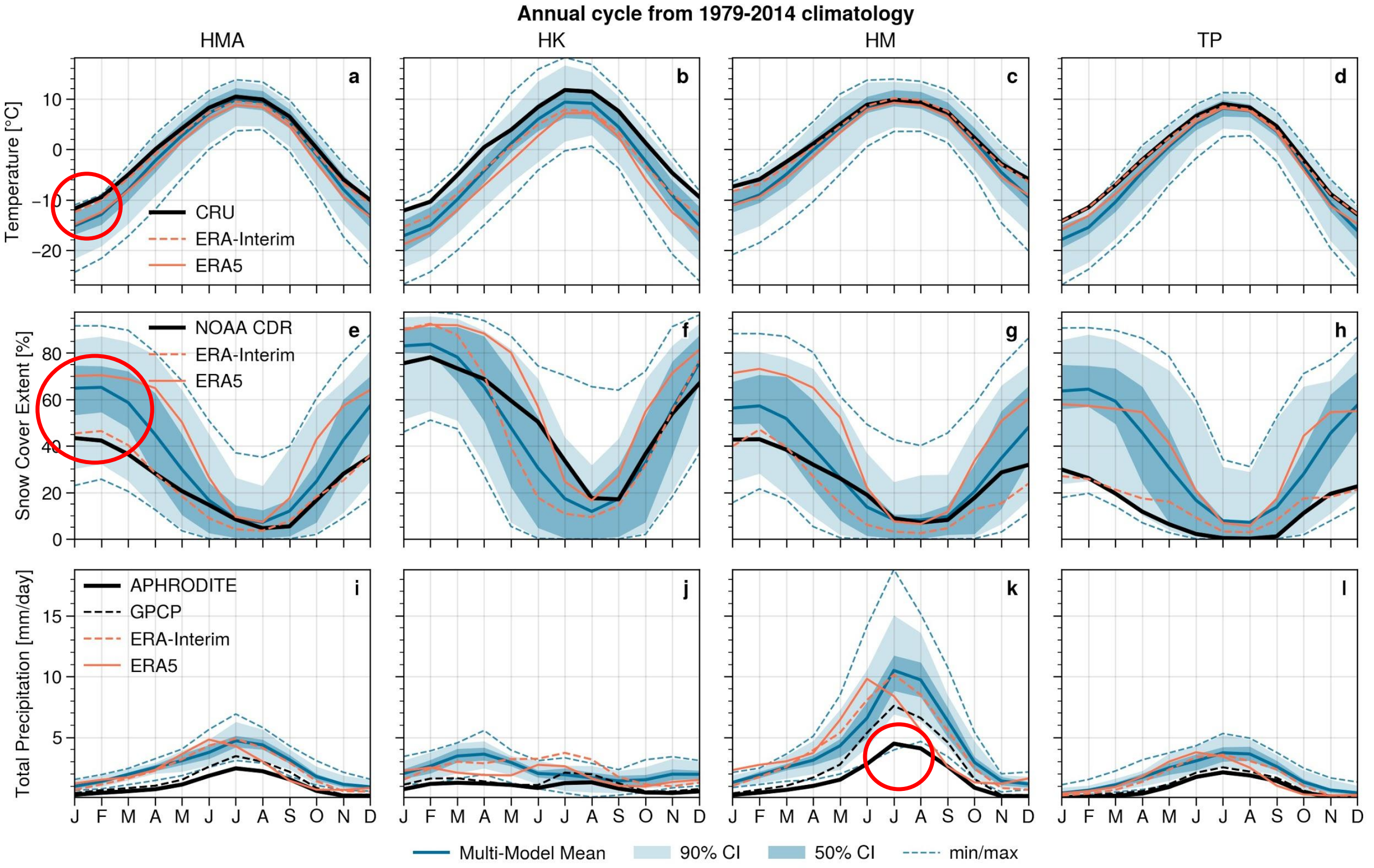


Annual climatologies (1979-2014)

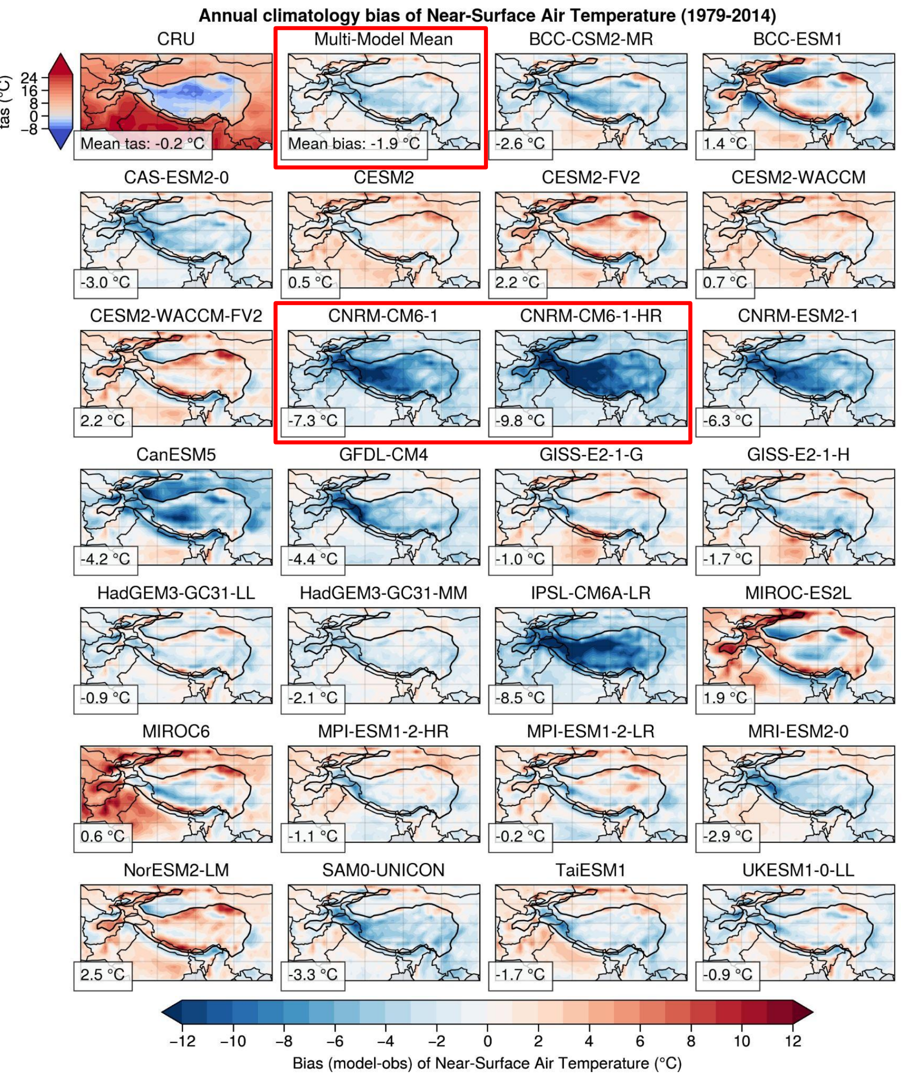
3. Historical bias analysis

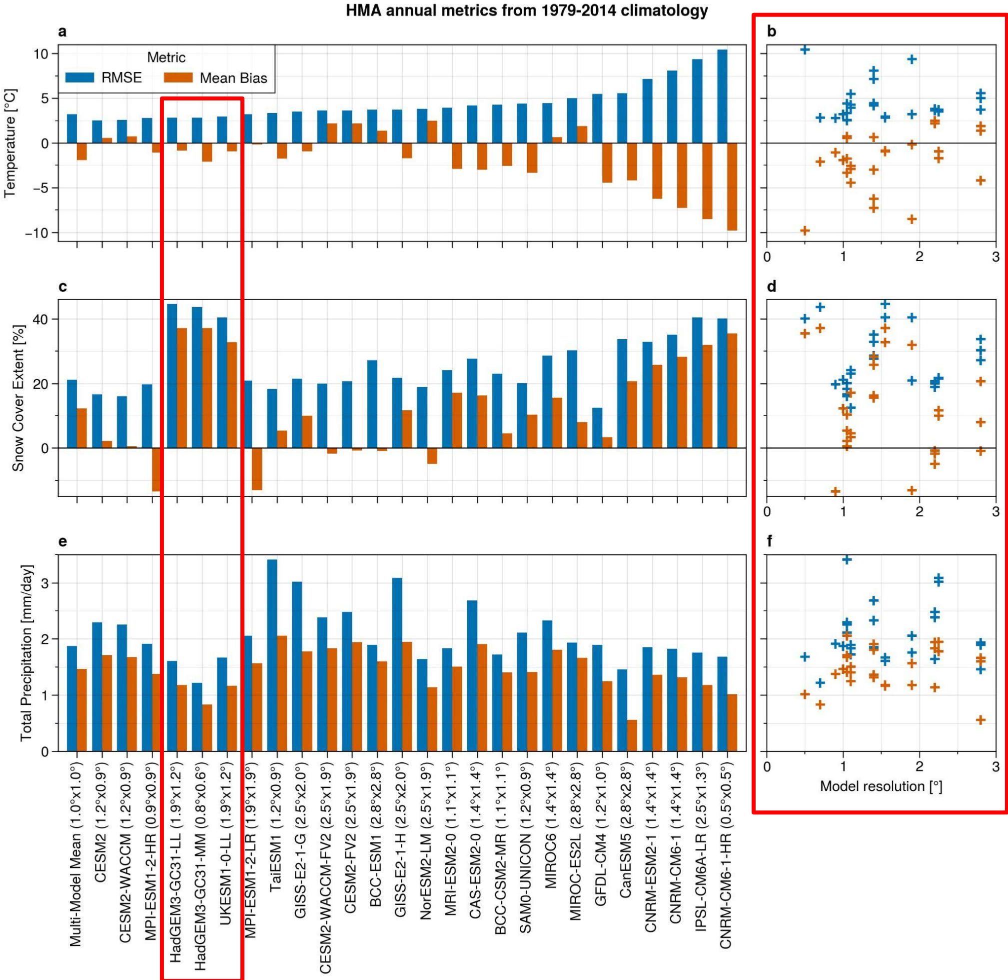
tas, snc and pr annual cycles

- stronger biases in winter for tas (~2/3°C) and snc (~20%) over HMA
- large snc spread -> difficulty to simulate snc in complex topography areas
- ERA5 bias similar to models -> no assimilation >1500m (Orsolini et al., 2019)
- pr obs lower than models -> snow undercatch issues by rain gauge (e.g. Jimeno-Saez et al., 2020)



Spatial biases and metrics





Bias spatial correlation

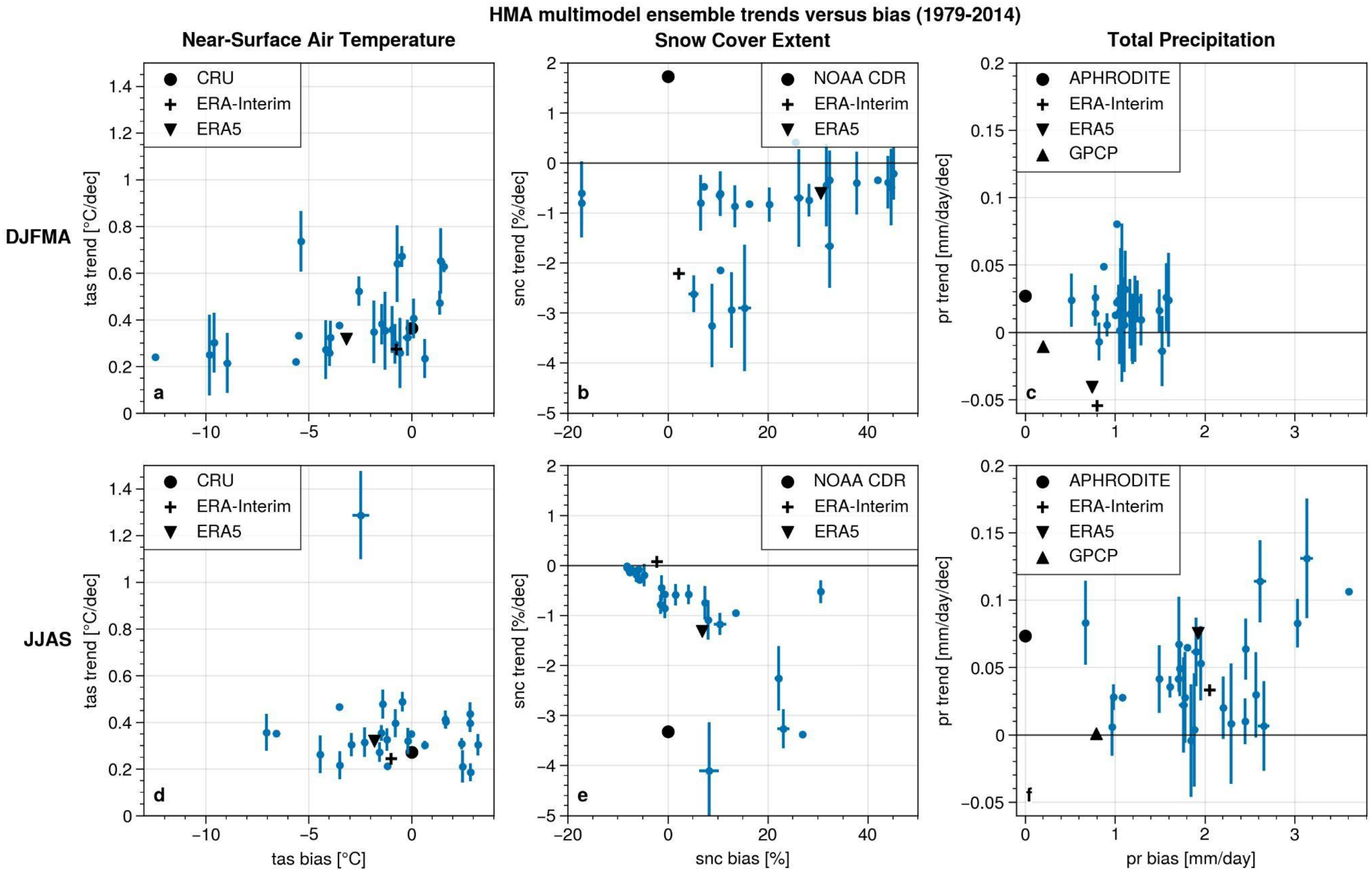
Annual spatial correlation of bias over HMA from 1979-2014 climatology

	BCC-CSM2-MR	BCC-ESM1	CAS-ESM2-0	CESM2	CESM2-FV2	CESM2-WACCM	CESM2-WACCM-FV2	CNRM-CM6-1	CNRM-CM6-1-HR	CNRM-ESM2-1	CanESM5	GFDL-CM4	GISS-E2-1-G	GISS-E2-1-H	HadGEM3-GC31-LL	HadGEM3-GC31-MM	IPSL-CM6A-LR	MIROC-ES2L	MIROC6	MPI-ESM1-2-HR	MPI-ESM1-2-LR	MRI-ESM2-0	NorESM2-LM	SAM0-UNICON	TaiESM1	UKESM1-0-LL
tas normalized bias	−0.26	0.14	−0.31	0.06	0.22	0.07	0.22	−0.74	−1	−0.64	−0.43	−0.45	−0.1	−0.18	−0.09	−0.21	−0.87	0.19	0.07	−0.11	−0.02	−0.3	0.25	−0.34	−0.2	−0.1
tas bias / snc bias	**−0.51**	**−0.45**	**−0.21**	−0.02	**−0.29**	0.01	**−0.29**	**−0.5**	**−0.39**	**−0.47**	**−0.53**	**−0.4**	**−0.36**	**−0.35**	**−0.28**	**0.16**	**−0.62**	**−0.71**	**−0.58**	0.09	**−0.23**	**−0.16**	**−0.25**	**−0.18**	−0.09	**−0.17**
tas bias / pr bias	−0.09	**−0.22**	−0.08	**−0.18**	**−0.21**	**−0.19**	**−0.22**	0.02	−0.05	−0.02	**0.16**	**−0.16**	**−0.11**	−0.04	−0.04	−0.07	0.02	−0.07	0.02	**−0.37**	**−0.35**	**−0.24**	**−0.26**	**−0.12**	**−0.14**	−0.02
snc bias / pr bias	**0.18**	**0.48**	**0.41**	**−0.22**	−0.05	**−0.18**	−0.04	**−0.23**	**−0.38**	**−0.23**	−0.06	0.04	−0.02	0.03	0.05	−0.04	0.06	0.01	**−0.31**	**−0.12**	0.1	**−0.22**	**0.13**	0.1	0.01	−0.03
tas bias / elevation	**−0.41**	−0.04	**−0.36**	**−0.28**	−0.09	**−0.26**	−0.1	**−0.56**	**−0.66**	**−0.55**	**−0.32**	**−0.37**	**−0.34**	**−0.43**	**−0.16**	−0.09	**−0.63**	**−0.28**	**−0.52**	**−0.3**	**−0.21**	**−0.42**	−0.05	**−0.45**	**−0.34**	**−0.12**
snc bias / elevation	**0.63**	**0.5**	**0.5**	**0.53**	**0.46**	**0.51**	**0.44**	**0.54**	**0.67**	**0.53**	**0.5**	**0.45**	**0.46**	**0.5**	**0.47**	**0.32**	**0.56**	**0.41**	**0.56**	**0.22**	**0.24**	**0.44**	**0.29**	**0.48**	**0.39**	**0.49**
pr bias / elevation	**0.18**	**0.43**	**0.12**	**−0.13**	0.07	**−0.12**	0.07	**−0.15**	**−0.31**	**−0.13**	−0.05	−0.08	**−0.19**	**−0.18**	0.01	**−0.28**	−0.06	0.03	−0.05	−0.01	**0.15**	0.01	−0.01	−0.03	**−0.12**	0.01

- Significant negative correlations between tas and snc biases
- Less obvious for pr (/!\ APHRODITE underestimate solid precip /!\ -> more negative correlation)
- Correlations between tas/snc biases with elevation -> difficulty representing physical processes at high elevation?

Are trends impacted by overall biases?

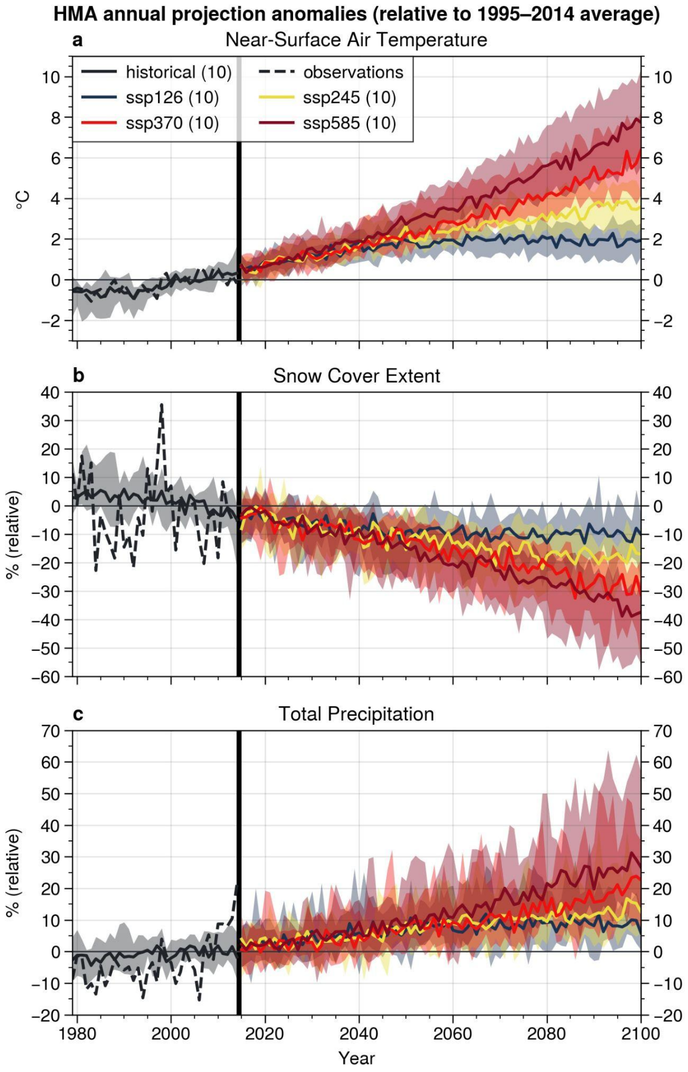
Historical trends analysis



- No obvious link between model biases and trends
- Some strongly biased models have trends close to observations
- On the contrary, some models with little bias have very different trends
- Except for snow cover in summer -> very small snow cover

-> All available models are kept for projections

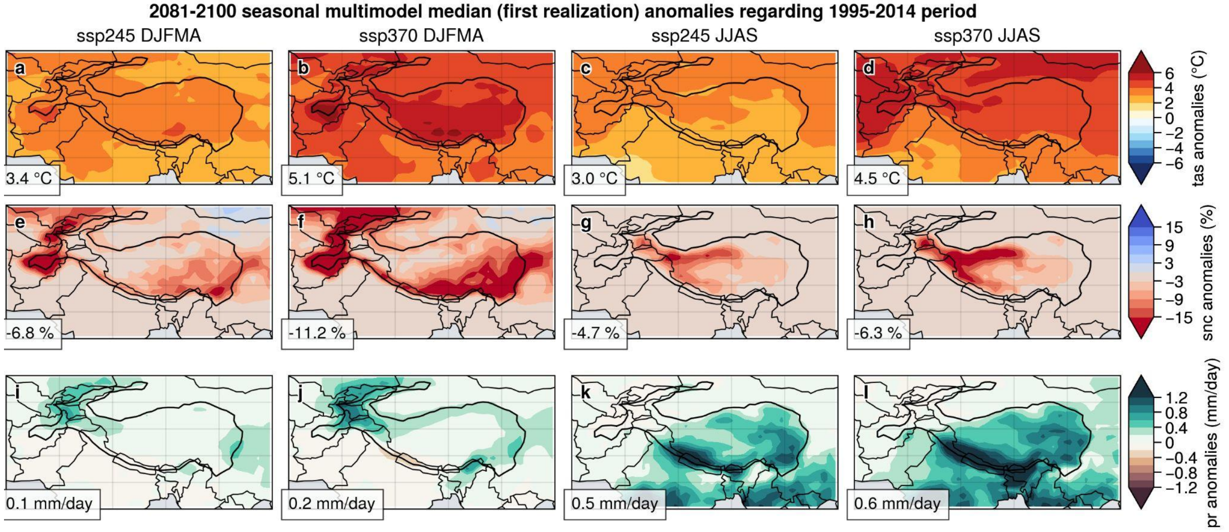
4. Projections



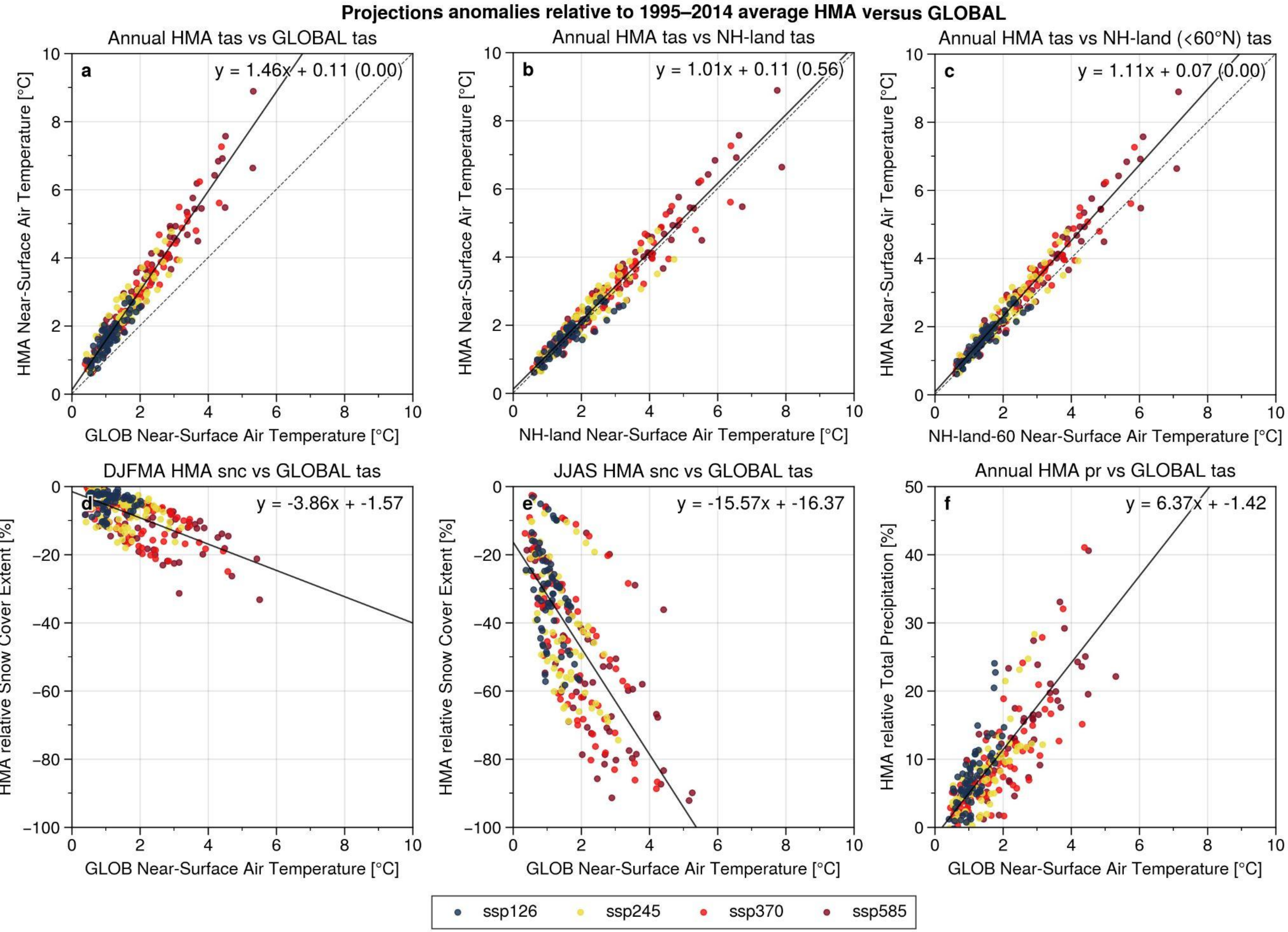
Projections

- annual median 2081-2100 with respect to 1995-2014 average:
  - tas: 1.9 [1.2 to 2.7] °C (SSP1-2.6) to 6.5 [4.9 to 9.0] °C (SSP5-8.5)
  - relative snc: -9.4 [-16.4 to -5.0] % (SSP1-2.6) to -32.2 [-49.1 to -25.0] % (SSP5-8.5)
  - relative pr: 8.5 [4.8 to 18.2] % (SSP1-2.6) to 24.9 [14.4 to 48.1] % (SSP5-8.5)

- snc and pr models variability underestimated?



HMA versus global



- HMA is warming faster as the rest of the world ?
- 10% faster... compared to NH (without Arctic)
- ~ 4% relative snc loss per 1°C GSAT in winter (linear)
- In summer almost all snc disappear in worst scenario (not linear)
- ~ 6 % relative more pr per 1°C GSAT

Take-home message

Take-home message

- Multimodel analysis with 26 CMIP6 GCMs over HMA
- CMIP6 annual multimodel biases (more pronounced in winter for tas and snc):
  - cold bias of -1.9 [-8.2 to 2.9] °C
  - snc overestimated 12 [-13 to 43] % (or 52 [-53 to 183] % relative)
  - pr overestimated 1.5 [0.3 to 2.9] mm.day-1 (or 143 [31 to 281] % relative) /!\ obs /!\
- No obvious link between biases and trends -> biased models seems able to reproduce past trends
- Models resolution doesn’t seem to improve performances! Additional improvements in parameterizations seems essential!
- Other variables might be involved... (cloud cover, aerosols, boundary layer, T500,...)
- Annual projections (2081-2100 with respect to 1995-2014 average with 10 GCMs):
  - median warming from 1.9 °C to 6.5 °C
  - relative median snc decrease from -9.4 % to -32.2 %
  - relative median pr increase from 8.5 % to 24.9 %

Future work

Implementation of a snow cover parameterization taking into account the variation of subgrid topography in LMDZ

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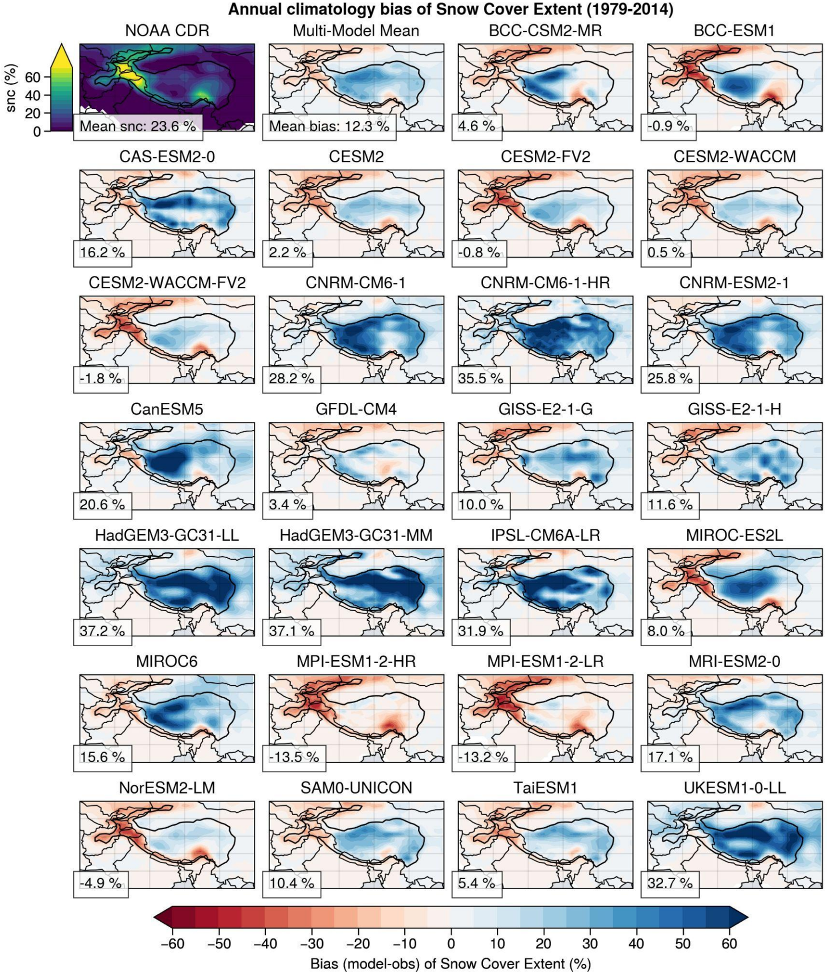
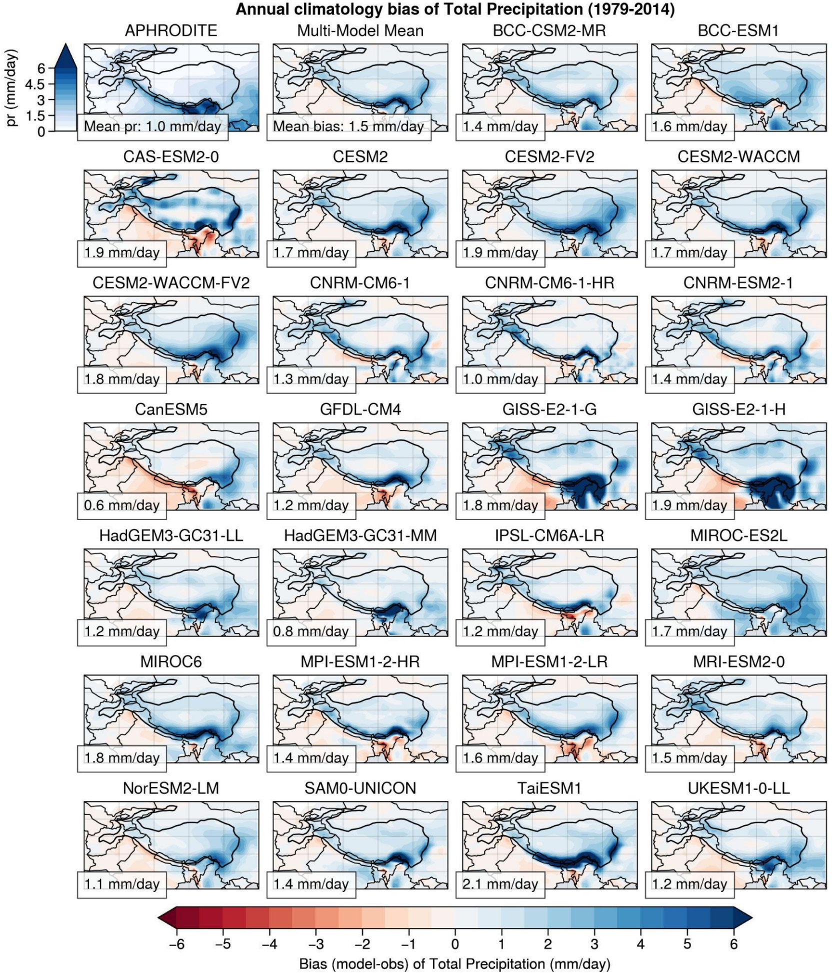
Supplementary materials

CMIP6 models

CMIP6 institute	CMIP6 model	Resolution (lonxlat)	Grid	Calendar	Member	SSP
BCC	BCC-CSM2-MR	1.1°x1.1°	gn	365_day	r1i1p1f1	
	BCC-ESM1	2.8°x2.8°				
CAS	CAS-ESM2-0	1.4°x1.4°	gn	365_day	r4i1p1f1	
NCAR	CESM2	1.2°x0.9°	gn	noleap	r1i1p1f1	
	CESM2-FV2	2.5°x1.9°				
	CESM2-WACCM	1.2°x0.9°				
	CESM2-WACCM-FV2	2.5°x1.9°				
CNRM-CERFACS	CNRM-CM6-1	1.4°x1.4°	gr	gregorian	r1i1p1f2	
	CNRM-CM6-1-HR	0.5°x0.5°				
	CNRM-ESM2-1	1.4°x1.4°				
CCCma	CanESM5	2.8°x2.8°	gn	365_day	r3i1p2f1	
NOAA-GFDL	GFDL-CM4	1.2°x1.0°	gr1	noleap	r1i1p1f1	
NASA-GISS	GISS-E2-1-G	2.5°x2.0°	gn	365_day	r1i1p1f1	
	GISS-E2-1-H					
MOHC	HadGEM3-GC31-LL	1.9°x1.2°	gn	360_day	r1i1p1f3	
	HadGEM3-GC31-MM	0.8°x0.6°				
IPSL	IPSL-CM6A-LR	2.5°x1.3°	gr	gregorian	r1i1p1f1	
MIROC	MIROC-ES2L	2.8°x2.8°	gn	gregorian	r1i1p1f2	
	MIROC6	1.4°x1.4°			r1i1p1f1	
MPI-M	MPI-ESM1-2-HR	0.9°x0.9°	gn	proleptic_gregorian	r1i1p1f1	
	MPI-ESM1-2-LR	1.9°x1.9°				
MRI	MRI-ESM2-0	1.1°x1.1°	gn	proleptic_gregorian	r1i1p1f1	
NCC	NorESM2-LM	2.5°x1.9°	gn	noleap	r2i1p1f1	
SNU	SAM0-UNICON	1.2°x0.9°	gn	noleap	r1i1p1f1	
AS-RCEC	TaiESM1	1.2°x0.9°	gn	noleap	r1i1p1f1	
MOHC, NIMS-KMA	UKESM1-0-LL	1.9°x1.2°	gn	360_day	r1i1p1f2	

Historical bias analysis





Bias spatial correlation (GPCP)

Annual spatial correlation of bias over HMA from 1979-2014 climatology

	BCC-CSM2-MR	BCC-ESM1	CAS-ESM2-0	CESM2	CESM2-FV2	CESM2-WACCM	CESM2-WACCM-FV2	CNRM-CM6-1	CNRM-CM6-1-HR	CNRM-ESM2-1	CanESM5	GFDL-CM4	GISS-E2-1-G
tas normalized bias	−0.26	0.14	−0.31	0.06	0.22	0.07	0.22	−0.74	−1	−0.64	−0.43	−0.45	−0.1
tas bias / snc bias	−0.51	−0.45	−0.21	−0.02	−0.29	0.01	−0.29	−0.5	−0.39	−0.47	−0.53	−0.4	−0.36
tas bias / pr bias	−0.03	−0.33	−0.02	−0.08	−0.2	−0.08	−0.21	0.1	0.02	0.07	0.15	−0.05	−0.07
snc bias / pr bias	0.21	0.7	0.45	−0.22	−0.02	−0.18	−0.01	−0.26	−0.36	−0.25	0	−0.05	−0.01
tas bias / elevation	−0.41	−0.04	−0.36	−0.28	−0.09	−0.26	−0.1	−0.56	−0.66	−0.55	−0.32	−0.37	−0.34
snc bias / elevation	0.63	0.5	0.5	0.53	0.46	0.51	0.44	0.54	0.67	0.53	0.5	0.45	0.46
pr bias / elevation	0.05	0.37	0.05	−0.27	−0.03	−0.26	−0.04	−0.32	−0.44	−0.3	−0.18	−0.24	−0.28

	GISS-E2-1-H	HadGEM3-GC31-LL	HadGEM3-GC31-MM	IPSL-CM6A-LR	MIROC-ES2L	MIROC6	MPI-ESM1-2-HR	MPI-ESM1-2-LR	MRI-ESM2-0	NorESM2-LM	SAM0-UNICON	TaiESM1	UKESM1-0-LL
tas normalized bias	−0.18	−0.09	−0.21	−0.87	0.19	0.07	−0.11	−0.02	−0.3	0.25	−0.34	−0.2	−0.1
tas bias / snc bias	−0.35	−0.28	0.16	−0.62	−0.71	−0.58	0.09	−0.23	−0.16	−0.25	−0.18	−0.09	−0.17
tas bias / pr bias	0.03	0.09	0.07	0.05	−0.12	0.15	−0.24	−0.32	−0.1	−0.25	−0.03	−0.08	0.05
snc bias / pr bias	−0.01	0.11	0.09	0.08	0.19	−0.38	−0.09	0.15	−0.23	0.27	0.13	0.02	0.02
tas bias / elevation	−0.43	−0.16	−0.09	−0.63	−0.28	−0.52	−0.3	−0.21	−0.42	−0.05	−0.45	−0.34	−0.12
snc bias / elevation	0.5	0.47	0.32	0.56	0.41	0.56	0.22	0.24	0.44	0.29	0.48	0.39	0.49
pr bias / elevation	−0.27	−0.17	−0.49	−0.22	−0.15	−0.2	−0.16	0.05	−0.17	−0.17	−0.15	−0.2	−0.15

Historical trends analysis