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

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

- **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)
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

Annual climatology bias of Near-Surface Air Temperature (1979-2014)

- CRU
- Multi-Model Mean
- BCC-CSM2-MR
- BCC-ESM1

CAS-ESM2-0
- Mean bias: -1.9 °C

CESM2
- Mean bias: -2.6 °C

CESM2-FV2
- Mean bias: -2.2 °C

CESM2-WACCM
- Mean bias: -0.7 °C

CESM2-WACCM-FV2
- Mean bias: -7.3 °C

CNRM-CM6-1
- Mean bias: -9.8 °C

CNRM-CM6-1-HR
- Mean bias: -6.3 °C

CNRM-ESM2-1
- Mean bias: -8.5 °C

CanESM5
- Mean bias: -4.2 °C

GFDL-CM4
- Mean bias: -4.4 °C

GISS-E2-1-G
- Mean bias: -1.0 °C

GISS-E2-1-H
- Mean bias: -1.7 °C

HadGEM3-GC31-LL
- Mean bias: -0.9 °C

HadGEM3-GC31-MM
- Mean bias: -2.1 °C

IPSL-CM6A-LR
- Mean bias: -1.9 °C

MIROC-ES2L
- Mean bias: 1.9 °C

MIROC6
- Mean bias: 0.6 °C

MPI-ESM1-2-HR
- Mean bias: -1.1 °C

MPI-ESM1-2-LR
- Mean bias: -0.2 °C

MRI-ESM2-0
- Mean bias: -2.9 °C

NorESM2-LM
- Mean bias: -3.3 °C

SAM0-UNICON
- Mean bias: -1.7 °C

TaiESM1
- Mean bias: -0.9 °C

UKESM1-0-LL
- Mean bias: 2.5 °C
Bias spatial correlation

<table>
<thead>
<tr>
<th></th>
<th>Annual spatial correlation of bias over HMA from 1979-2014 climatology</th>
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</thead>
<tbody>
<tr>
<td>tas normalized bias</td>
<td>-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</td>
</tr>
<tr>
<td>tas bias / snc bias</td>
<td>-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</td>
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<td>tas bias / pr bias</td>
<td>-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</td>
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<td>snr bias / pr bias</td>
<td>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</td>
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<tr>
<td>tas bias / elevation</td>
<td>-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</td>
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<tr>
<td>snr bias / elevation</td>
<td>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</td>
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<tr>
<td>pr bias / elevation</td>
<td>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</td>
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- Significant negative correlations between tas and snc biases
- **Less obvious for pr** (\(\text{APHRODITE underestimate solid precip}\) -> 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) /

- 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
Bibliography
References


Adler, Robert; Wang, Jian-Jian; Sapiano, Matthew; Huffman, George; Chiu, Long; Xie, Ping Ping; Ferraro, Ralph; Schneider, Udo; Becker, Andreas; Bolvin, David; Nelkin, Eric; Gu, Guojun; and NOAA CDR Program (2016). Global Precipitation Climatology Project (GPCP) Climate Data Record (CDR), Version 2.3 (Monthly). National Centers for Environmental Information. https://doi.org/10.7289/V56971M6


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Robinson, David A.; Estilow, Thomas W.; and NOAA CDR Program (2012): NOAA Climate Data Record (CDR) of Northern Hemisphere (NH) Snow Cover Extent (SCE), Version 1. NOAA National Centers for Environmental Information. https://doi.org/10.7289/V5N014G9


Supplementary materials
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<td>r1i1p1f2</td>
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Historical bias analysis

Annual climatology bias of Snow Cover Extent (1979-2014)

- NOAA CDR
- Multi-Model Mean
- 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
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MIROC-ES2L

- MIROC6
- MPI-ESM1-2-HR
- MPI-ESM1-2-LR
- MRI-ESM2-0

NorESM2-LM
SAM0-UNICON
TaiESM1
UKESM1-0-LL

Bias (model-obs) of Snow Cover Extent (%)

Annual climatology bias of Total Precipitation (1979-2014)

- APHRODITE
- Multi-Model Mean
- 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

Bias (model-obs) of Total Precipitation (mm/day)
## Bias spatial correlation (GPCP)

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

| 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  | -0.34 | -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 | -0.36 | -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  | -0.03 | -0.33 | -0.02 | -0.08 | -0.2  | -0.08 | -0.21 | 0.1   | 0.02  | 0.07 | 0.15  | -0.05 | -0.07 | 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  | 0.21 | 0.7   | 0.45 | -0.22 | -0.02 | -0.18 | -0.01 | -0.26 | -0.36 | -0.25 | 0    | -0.05 | -0.01 | -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 | -0.41 | -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 | 0.05 | 0.37  | 0.05 | -0.27 | -0.03 | -0.26 | -0.04 | -0.32 | -0.44 | -0.3  | -0.18 | -0.24 | -0.28 | -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

Observations and multimodel mean (first realization) seasonal trends (1979-2014)

Observation DJFMA

Multimodel DJFMA

Observation JJAS

Multimodel JJAS

Legend:
- tas trends (°C/dec)
- snc trends (%/dec)
- pr trends (mm/day/dec)