The Past and Future Mass Balance of Himalayan Glaciers

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Objectives

- Modelling Mass Balance of glaciers to understand the drivers of past changes and hydrological implications.

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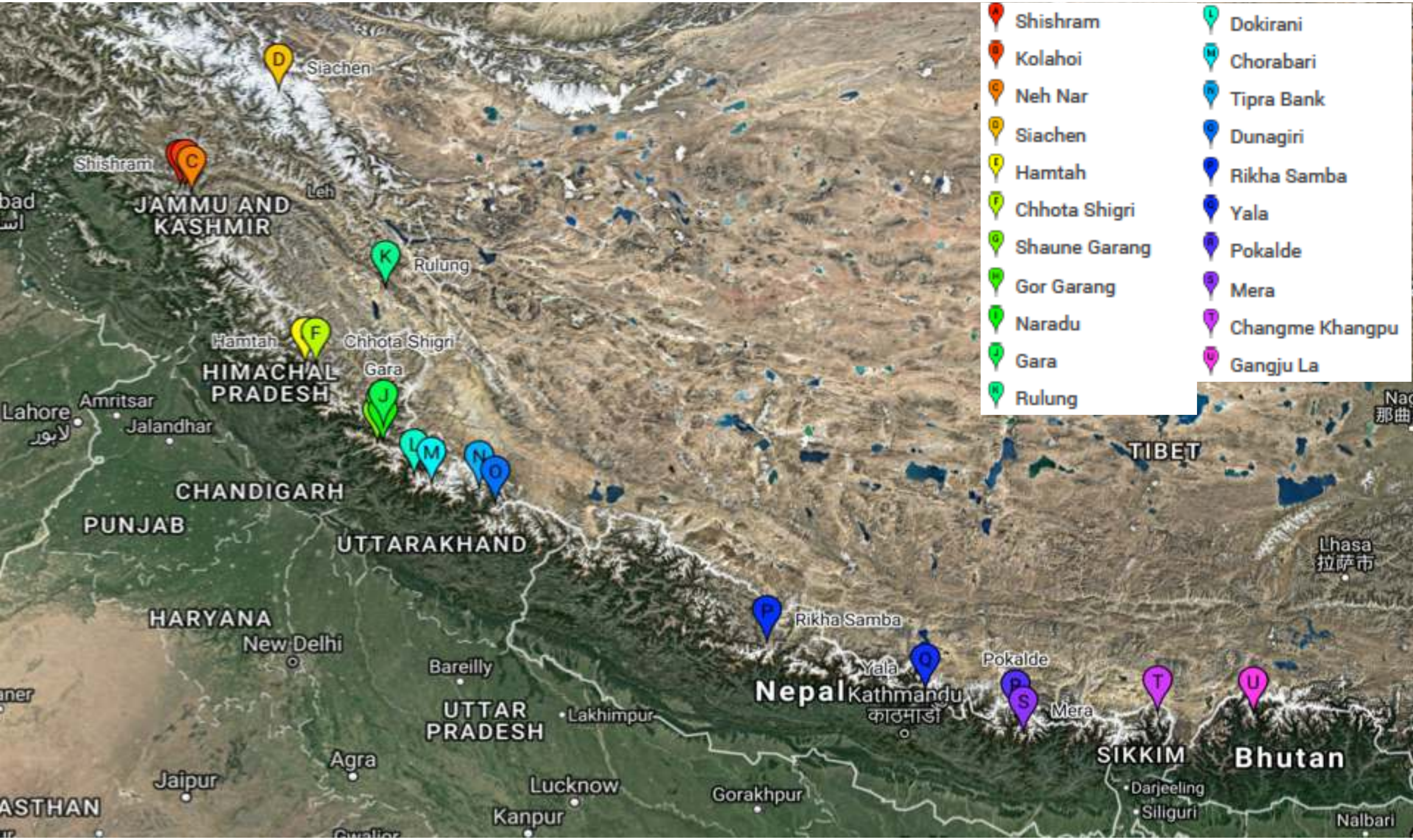
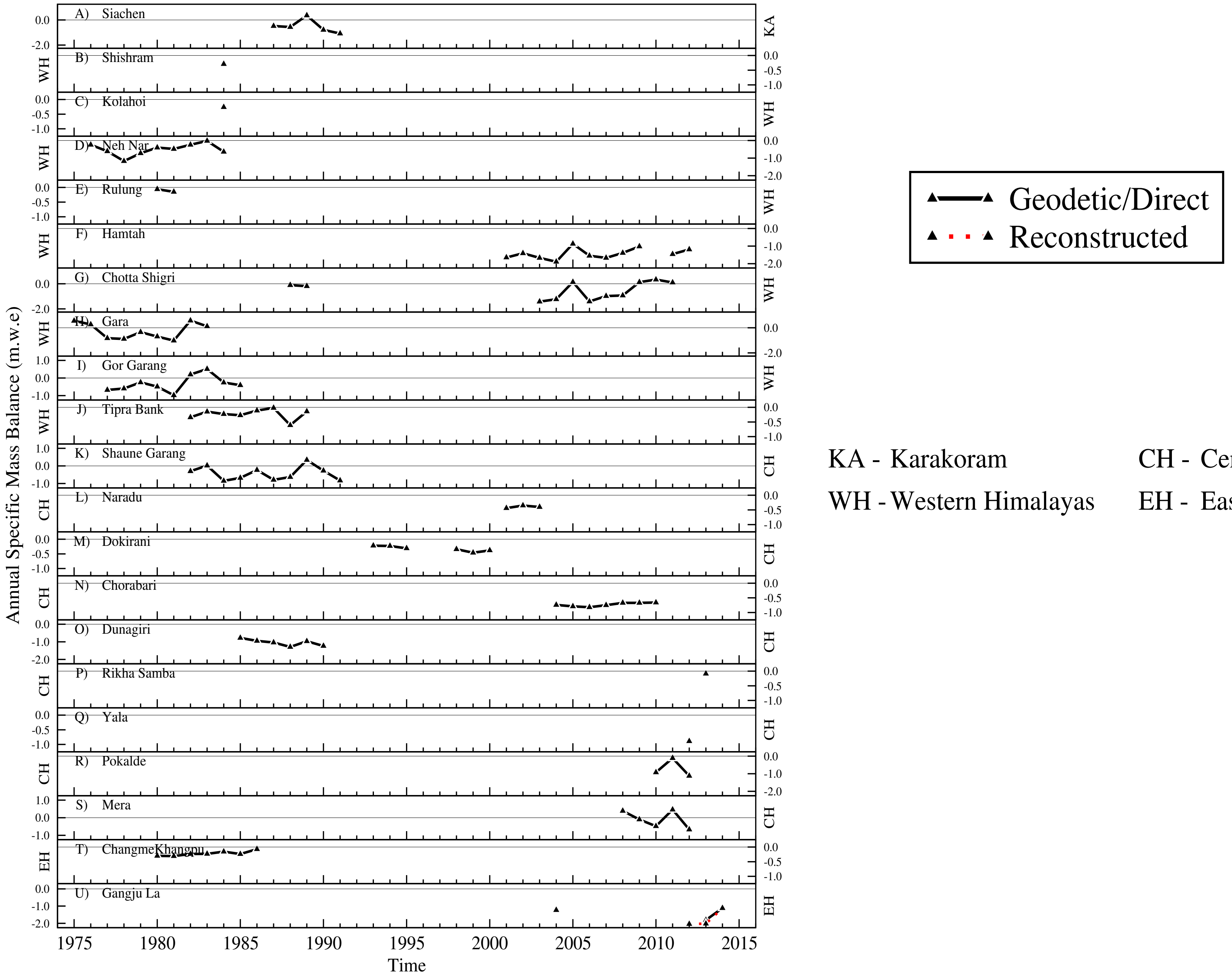
- Modelling Mass Balance of glaciers to understand the drivers of past changes and hydrological implications.
- Model future changes to glacier mass balance in the Himalayas.

Location of Chosen Glaciers



Observed Annual Specific Mass Balance – Himalayan Glaciers



KA - Karakoram

WH - Western Himalayas

CH - Central Himalayas

EH - Eastern Himalayas

Datasets

- Meteorological Data
  - ECMWF Reanalysis (2.5°x2.5° resolution) for
    - Monthly mean Temperature
    - Fixed fields: Orography
  - GPCC data for precipitation (2.5°x2.5°)
    - Monthly Precipitation
  - Coupled Model Intercomparison Project (CMIP5)
    - Monthly Datasets – Temperature, Precipitation
    - Fixed fields: Orography
    - Models: CCSM4, CMCC-CM, CMCC-CMS, CNRM-CM5, CSIRO-Mk3-6-0, FGOALS-g2, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-R, HadGEM2-CC, HadGEM2-ES, MPI-ESM-LR, MPI-ESM-MR

Mass Balance Model

$$b = c - a + R$$

Specific Mass Balance

Accumulation

Ablation

Refreezing

Mass Balance Model

$$b = c - a + R$$

Specific Mass Balance *Accumulation* *Ablation* *Refreezing*

Accumulation: $c = \delta_m P_m \begin{cases} \delta_m = 1, T_m < T_{snow} \\ \delta_m = 0, T_m \geq T_{snow} \end{cases}$ where P_m = Monthly Precipitation

T_m = Monthly Temperature

T_{snow} = Snow Temperature

Mass Balance Model

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P_m = Monthly Precipitation

T_m = Monthly Temperature

T_{snow} = Snow Temperature

Ablation: $a = f_{snow/ice} T_m^+ n$ where

$f_{snow/ice}$ → Degree day factor of snow/ice

T_m^+ → Positive Monthly Temperature

Mass Balance Model

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Refreezing: $R = -0.69 T_a + 0.0096$ T_a → Annual Mean Temperature

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T_m^+ →Positive Monthly Temperature

Refreezing: $R = -0.69 T_a + 0.0096$ T_a →Annual Mean Temperature

Area Averaged Specific Mass Balance

$$B = \frac{\sum_{i=0}^{n} b_i S_i}{\sum_{i=0}^{n} S_i}$$

Where, S = Surface area of glacier

n = number of elevation bands

Mass Balance Model

Calculating Temperature at Glacier site (from Reanalysis):

$$T = T_{ERA} + lr_{ERA}\left(h_{\max} - h_{ERA}\right) + lr\left(h - h_{\max}\right)$$

Where, T_{ERA} = Temperature from ERA-40 from the observed period

lr_{ERA} = Statistical Lapse Rate

lr = Lapse rate along the glacier surface

$h_{\max}$ = Highest altitude of the glacier

h_{ERA} = Altitude of the ERA grid cell containing the glacier

h = Average altitude of the elevation band

Calculation of Precipitation at Glacier site (from Reanalysis):

$$P = k_p \times P_{ERA}[1 + d_{prec}(h - h_{\max})]$$

Where, k_p = Precipitation coefficient

P_{ERA} = Monthly precipitation in GPCC

d_{prec} = Precipitation gradient

Mass Balance Model

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lr_{ERA}

lr

f_{snow}

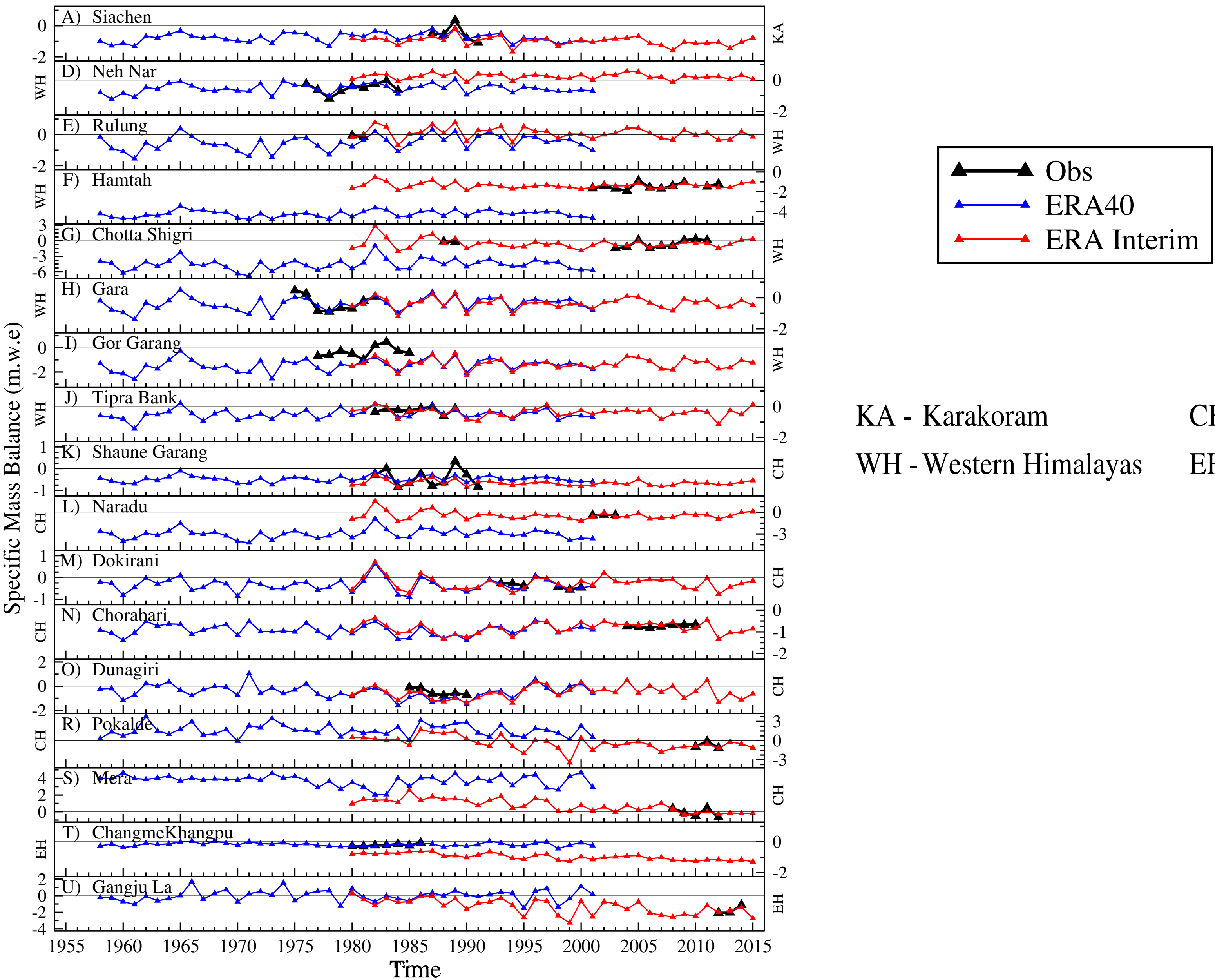
f_{ice}

k_p

d_{prec}

T_{snow}

Observed and Modelled Annual Specific Mass Balance Himalayan Glaciers



KA - Karakoram

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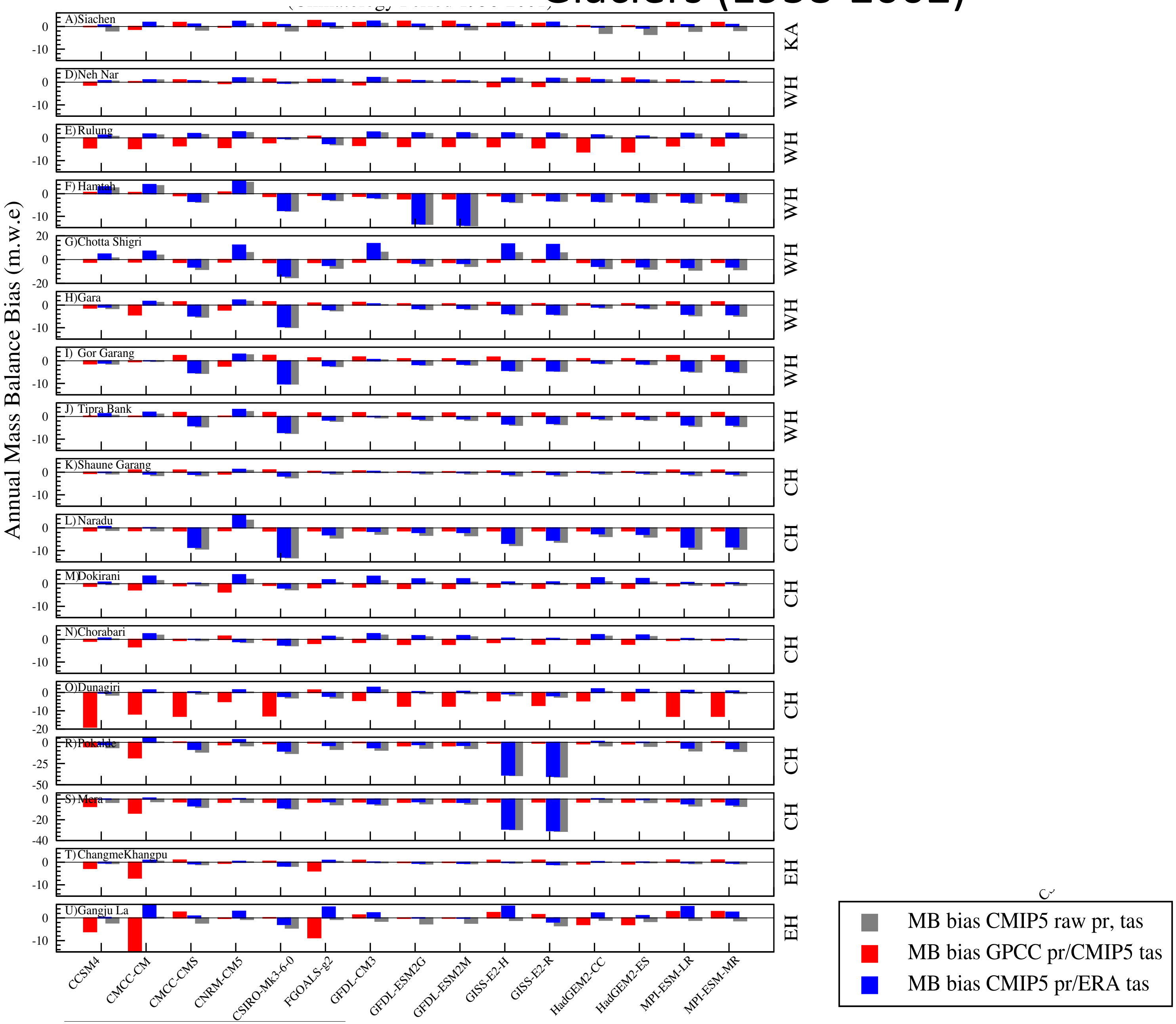
Biases of Climatology of Modelled Annual Mass Balance of Himalayan Glaciers (1958-2002)



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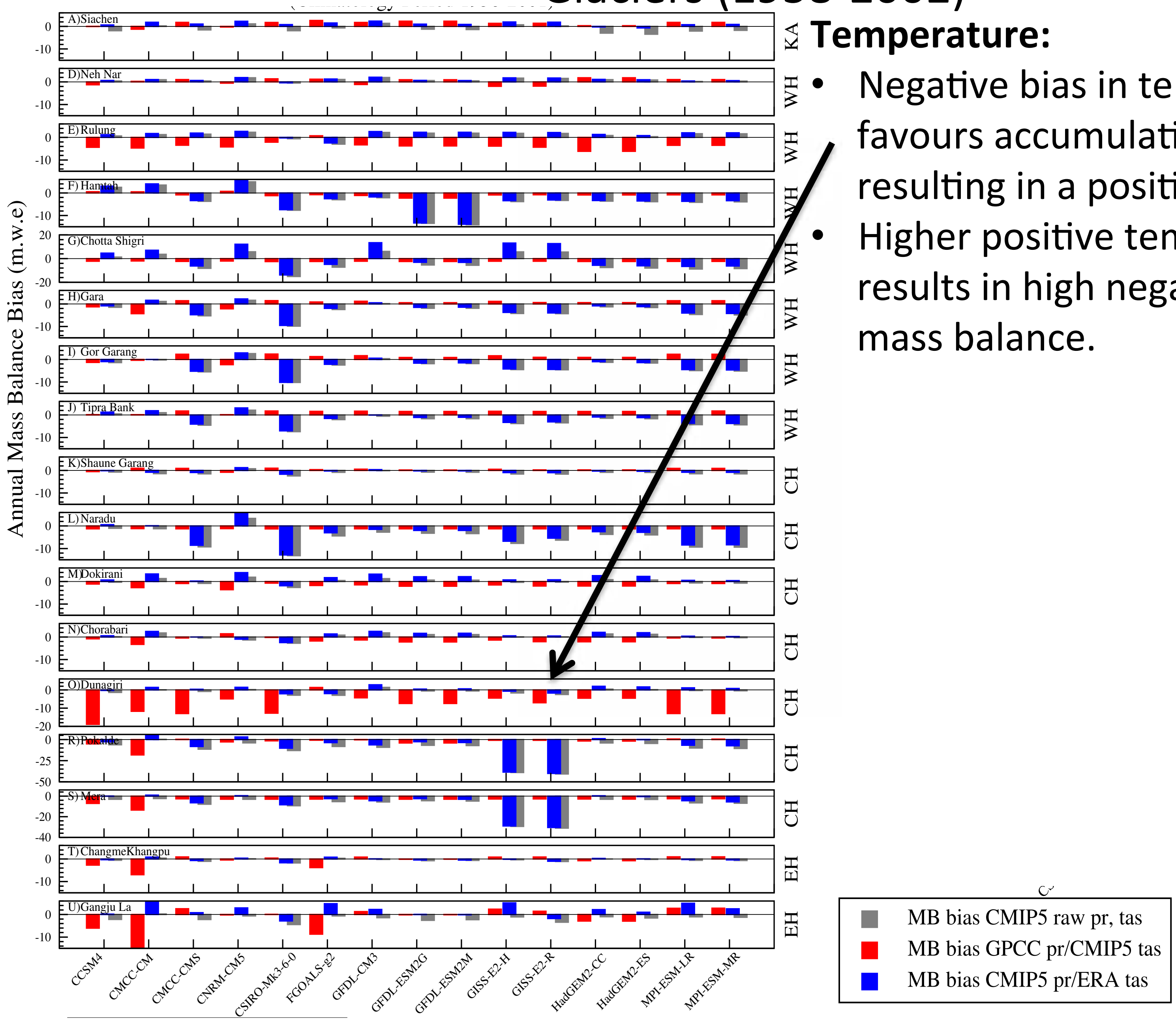

Temperature:

- Negative bias in temperature favours accumulation and refreezing resulting in a positive bias.
- Higher positive temperature bias results in high negative bias of the mass balance.

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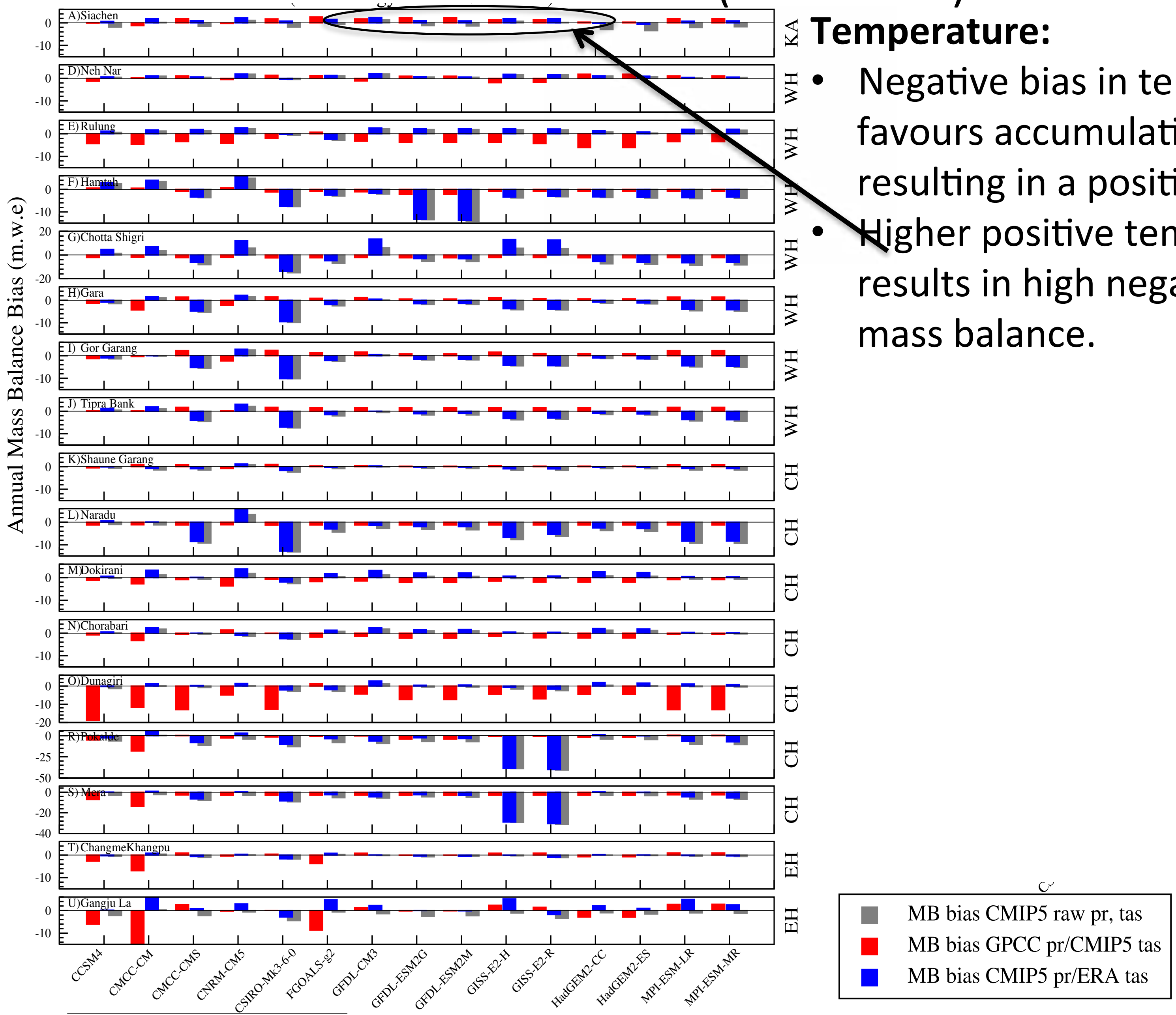

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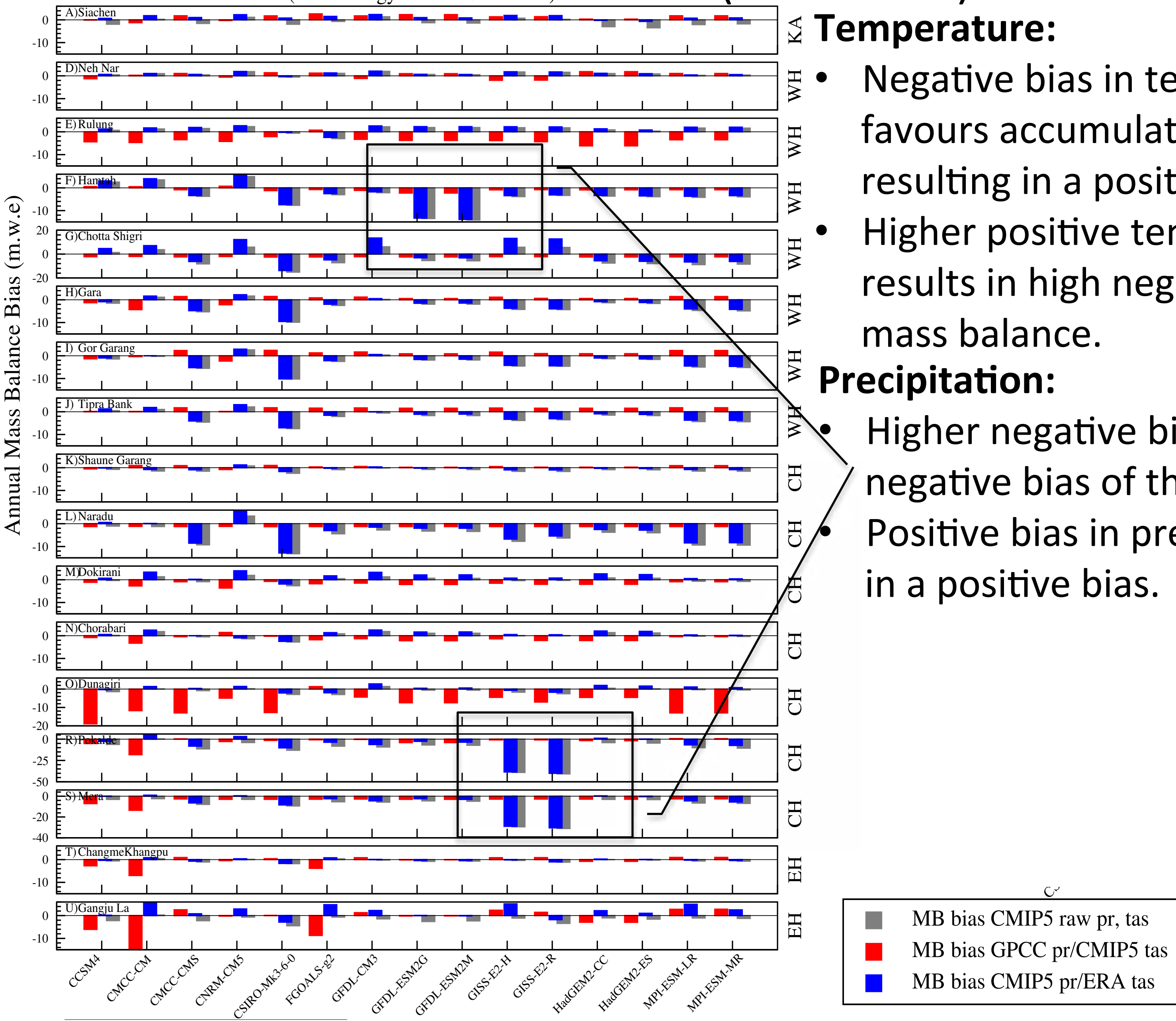

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Precipitation:

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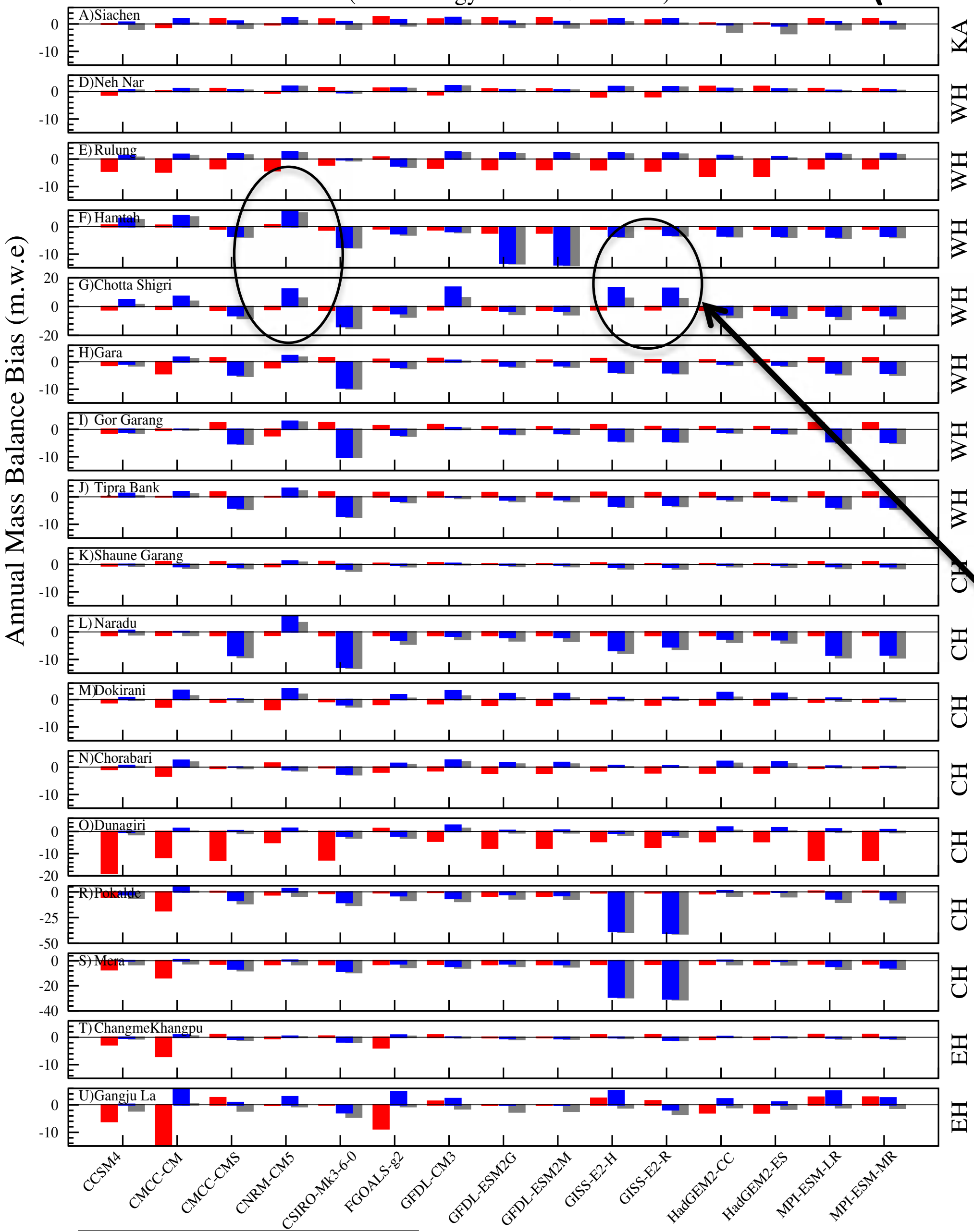

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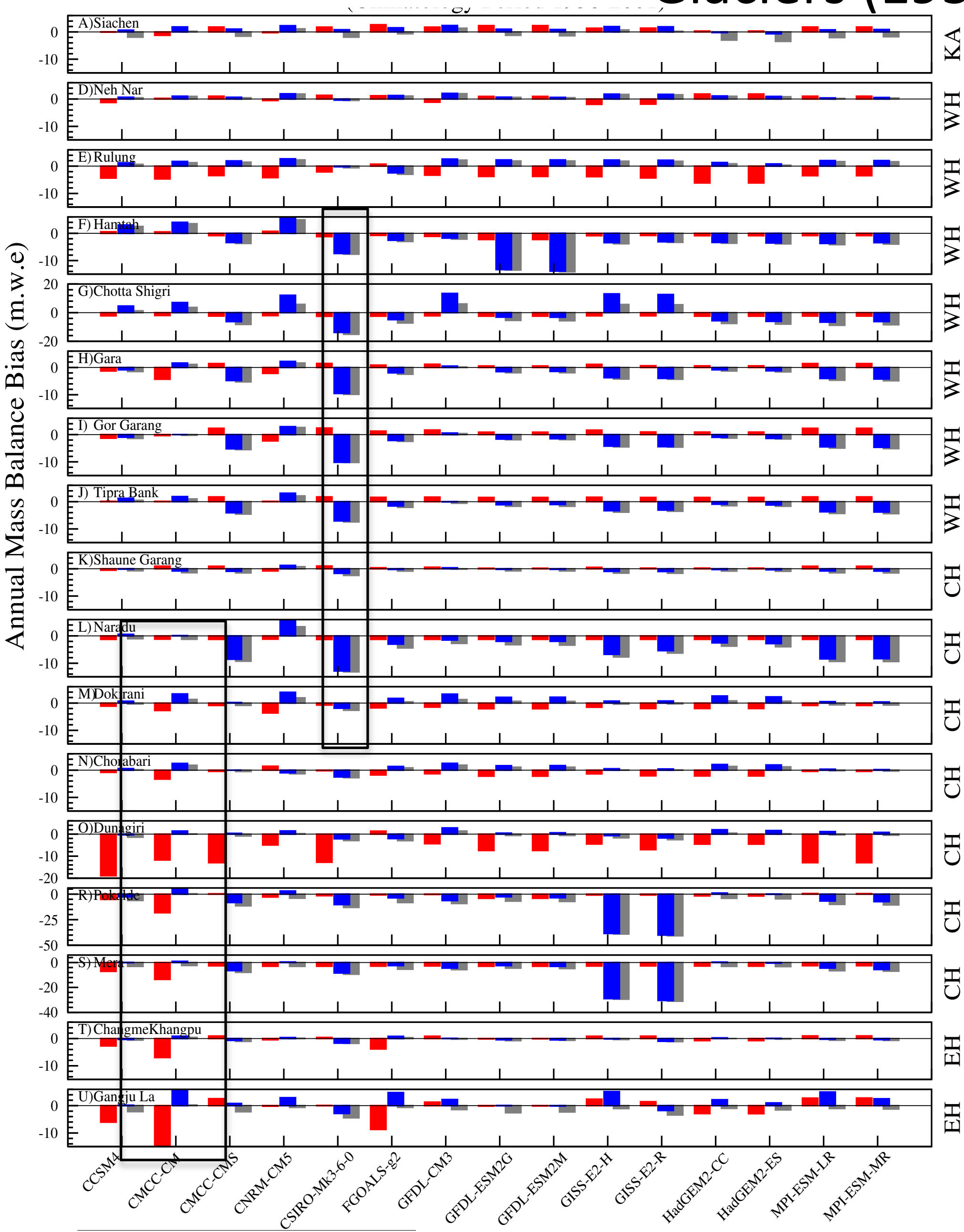

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Precipitation:

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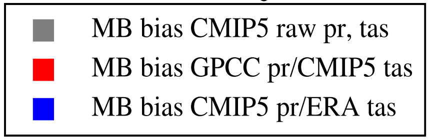
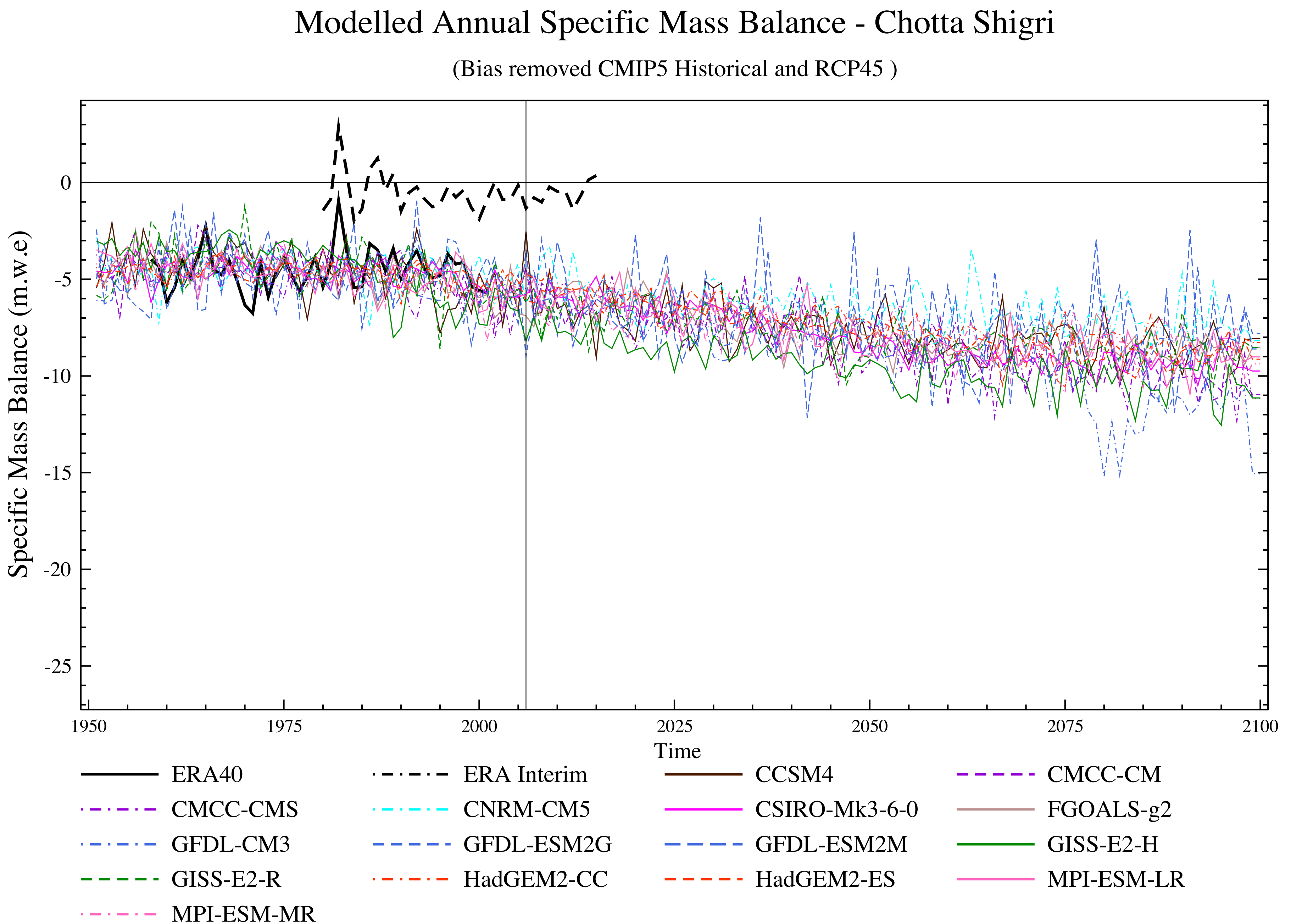
- Positive bias in precipitation results in a positive bias.

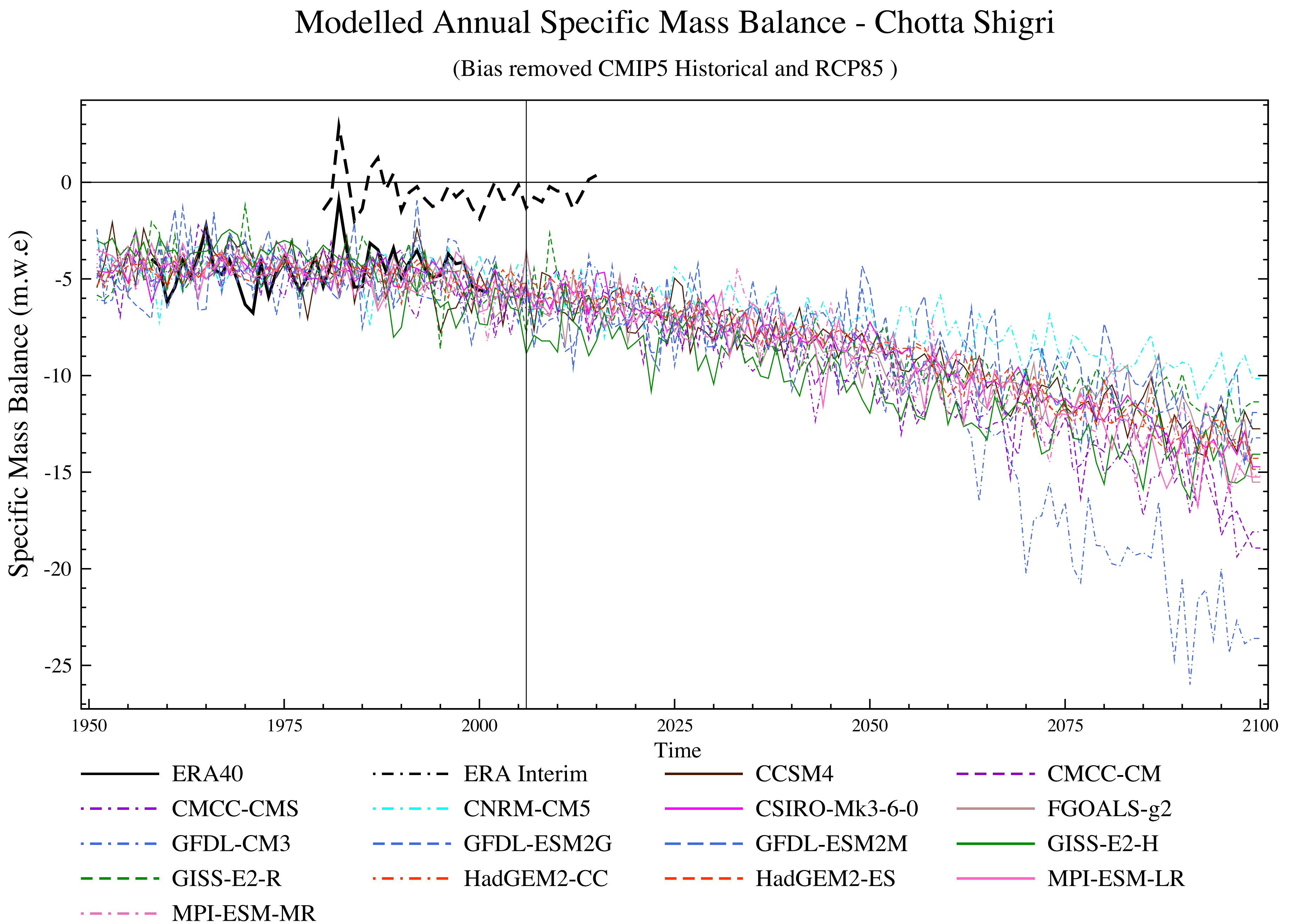
- Larger bias due climate variables of many models for particular glacier.
- Few models with large bias for many glaciers.



Modelled Historical and RCP4.5 Projections



Modelled Historical and RCP8.5 Projections



Conclusion

- Very few glaciers with long record of mass balance observations are available for the Himalayas
- Glaciers with longer record of mass balance observations are better for modeling
- Model errors in precipitation are larger than temperature errors affecting mass balance calculations
- The RCP8.5 scenario shows a comparatively larger loss of ice mass at the end of century than RCP4.5

THANK YOU

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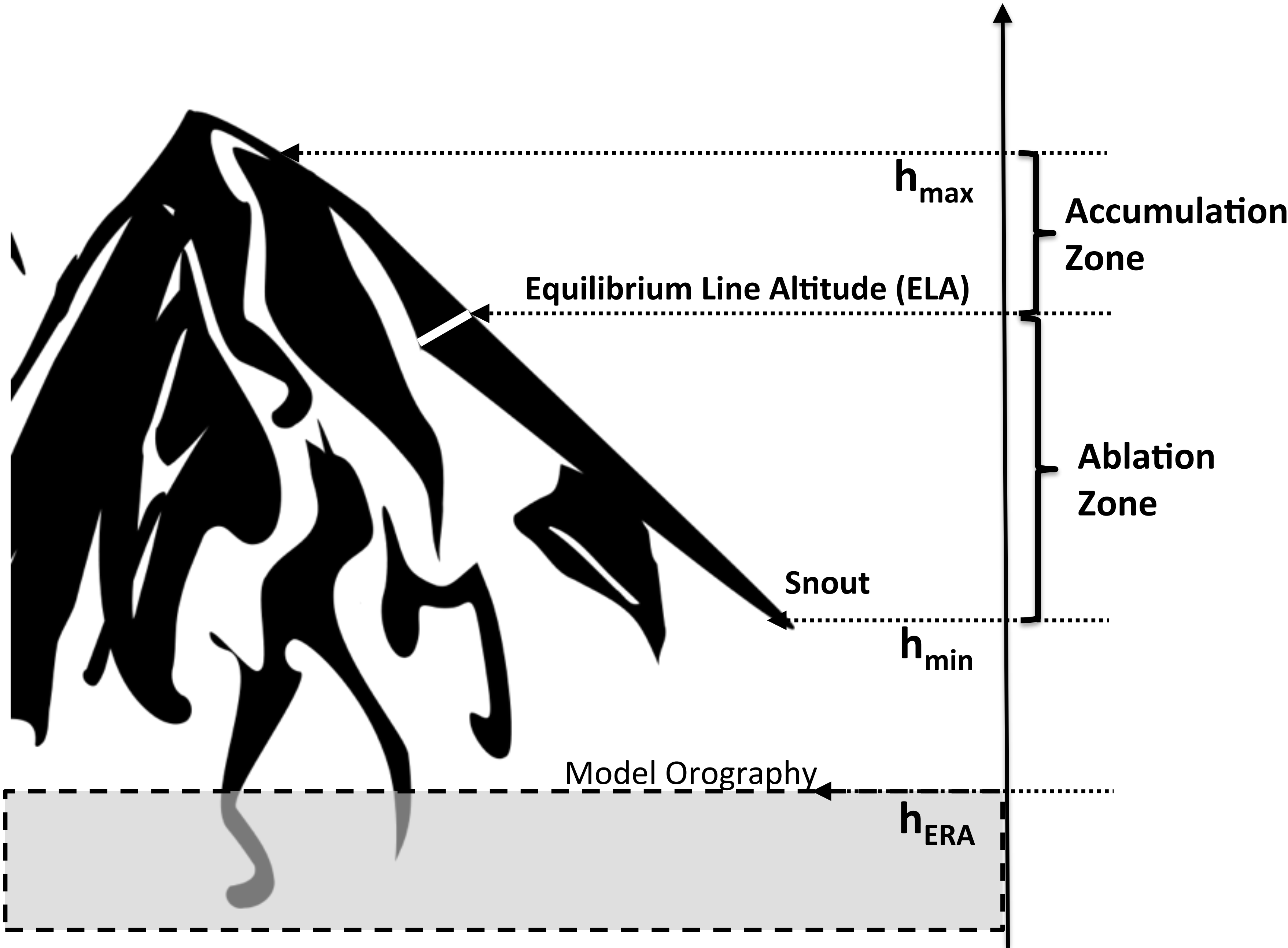
McCarty Glacier - Alaska

Data Survey

- Individual glacier details such as Location, elevation, surface area, Mass Balance time series, changes are sourced from Glacier Atlas of India, INSTAAR Occasional paper no 55 and journal publications.

S. No	Glacier	hmin (m)	hmax (m)	hmean (m)	area (sqkm)	starting year	ending year	Tot. Years	Source	Region
A	**Siachen**	2800	7600	5200	647.3	1987	1991	5	Bhutiyani 1999	KA
B	**Shishram**	3740	4900	4320	9.9	1984	1984	1	INSTAAR/OP-55	WH
C	**Kolahoi**	3690	5000	4345	11.9	1984	1984	1	INSTAAR/OP-55	WH
D	**Neh Nar**	3920	4925	4422.5	1.7	1980	1984	5	INSTAAR/OP-55	WH
E	**Rulung**	5660	6090	5880	0.947	1980	1981	2	Srivastava et al 1999b	WH
F	**Hamtah**	4000	5000	4500	3.3	2001	2012	11	S.S.Dutta et al 2009	WH
G	**Chotta Shigri**	4050	6263	5156.5	8.75	1988	2011	11	Glacier Atlasof India	WH
H	**Gara**	4700	5600	5150	2.02	1975	1983	9	Glacier Atlasof India	WH
I	**Gor Garang**	4750	5400	5075	5.76	1977	1985	9	INSTAAR/OP-55	WH
J	**Tipra Bank**	3070	5730	4400	7	1986	1988	3	INSTAAR/OP-55	WH
K	**Shaune Garang**	3840	5360	4600	4.94	1982	1990	9	INSTAAR/OP-55	CH
L	**Naradu**	4395	5400	4920	4.56	2001	2003	3	Koul & Ganjoo 2010	CH
M	**Dokirani**	3890	5990	4940	8.75	1993	2000	6	Glacier Atlasof India	CH
N	**Chorabari**	3850	6420	5070	6.66	2004	2010	7	Dobhal et al 2013	CH
O	**Dunagiri**	3970	5150	4560	2.56	1986	1990	5	INSTAAR/OP-55	CH
P	**Rikha Samba**	5392	6476	5800	5.37	2013	2013	1	Sanjaya et al 2016	CH
Q	**Yala**	5094	5749	5250	2.5	2012	2012	1	Sanjaya et al 2016	CH
R	**Pokalde**	5430	5690	5625	0.1	2010	2012	3	P.Wagnon et al 2013	CH
S	**Mera**	4940	6420	5615	5.1	2008	2012	5	P.Wagnon et al 2013	CH
T	**ChangmeKhangpu**	5080	5520	5300	4.5	1981	1986	6	INSTAAR/OP-55	EH
U	**Gangju La**	4900	5200	5050	0.29	2012	2014	3	Phantsho et al 2016	EH
KA - Karakoram, WH - Western Himalayas, CH - Central Himalayas, EH - Eastern Himalayas										

Glacier Terminology

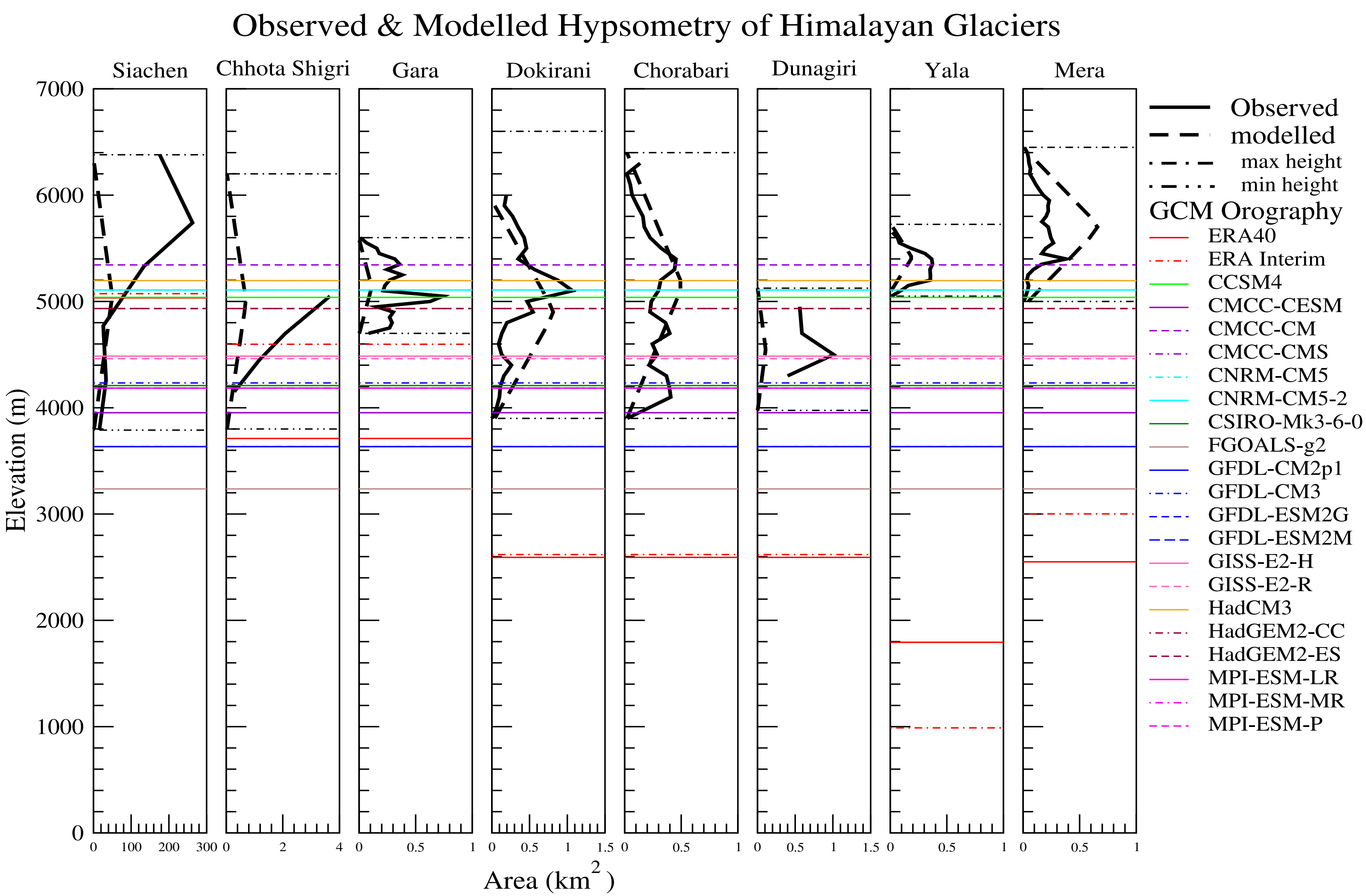


Modelling Hypsometry

Not all the glaciers have observed hypsometry

Triangle Method : mountain glaciers (Raper and Braithwaite 2006)

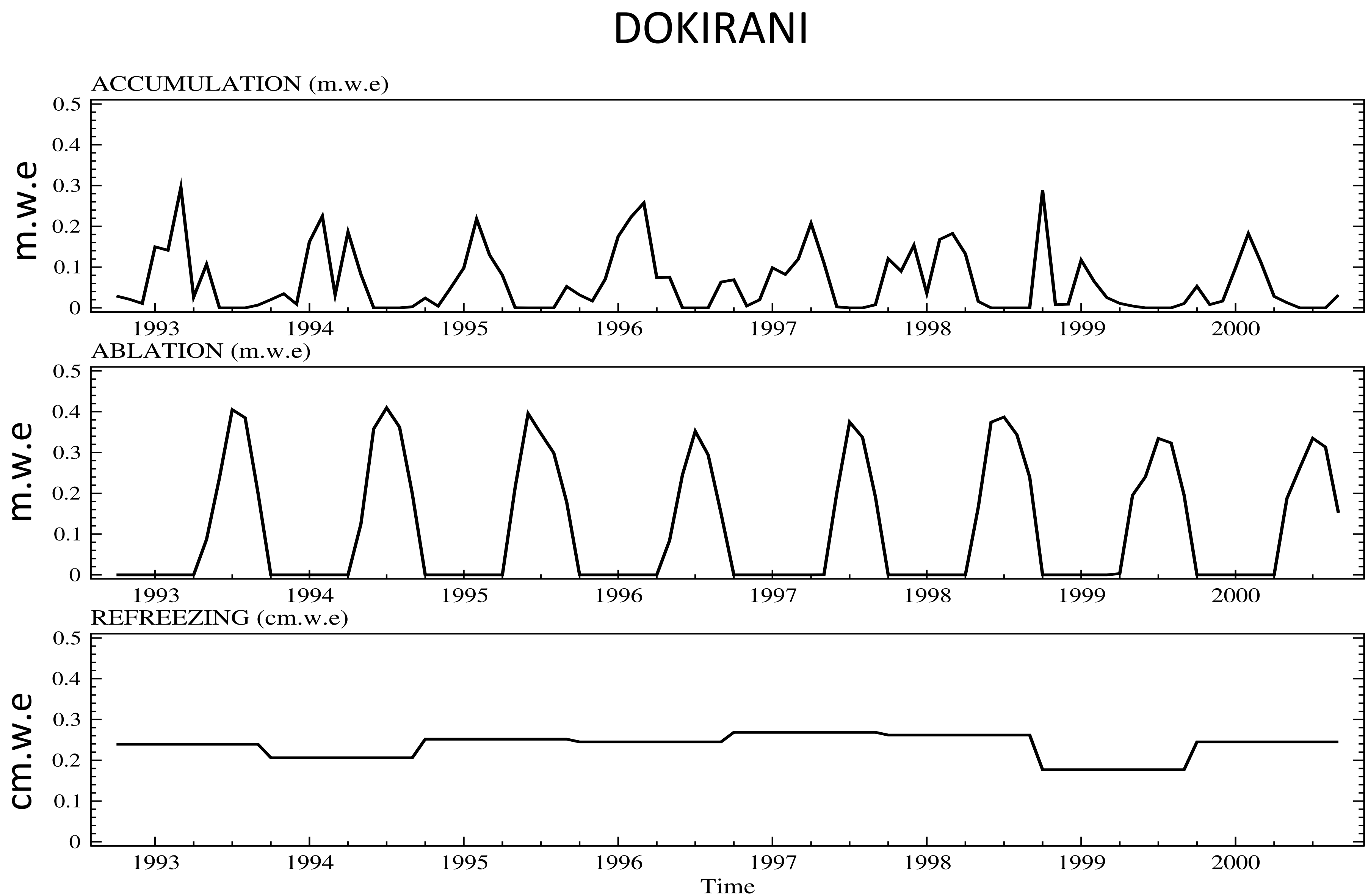
Parabola Method : ice caps, ice sheets

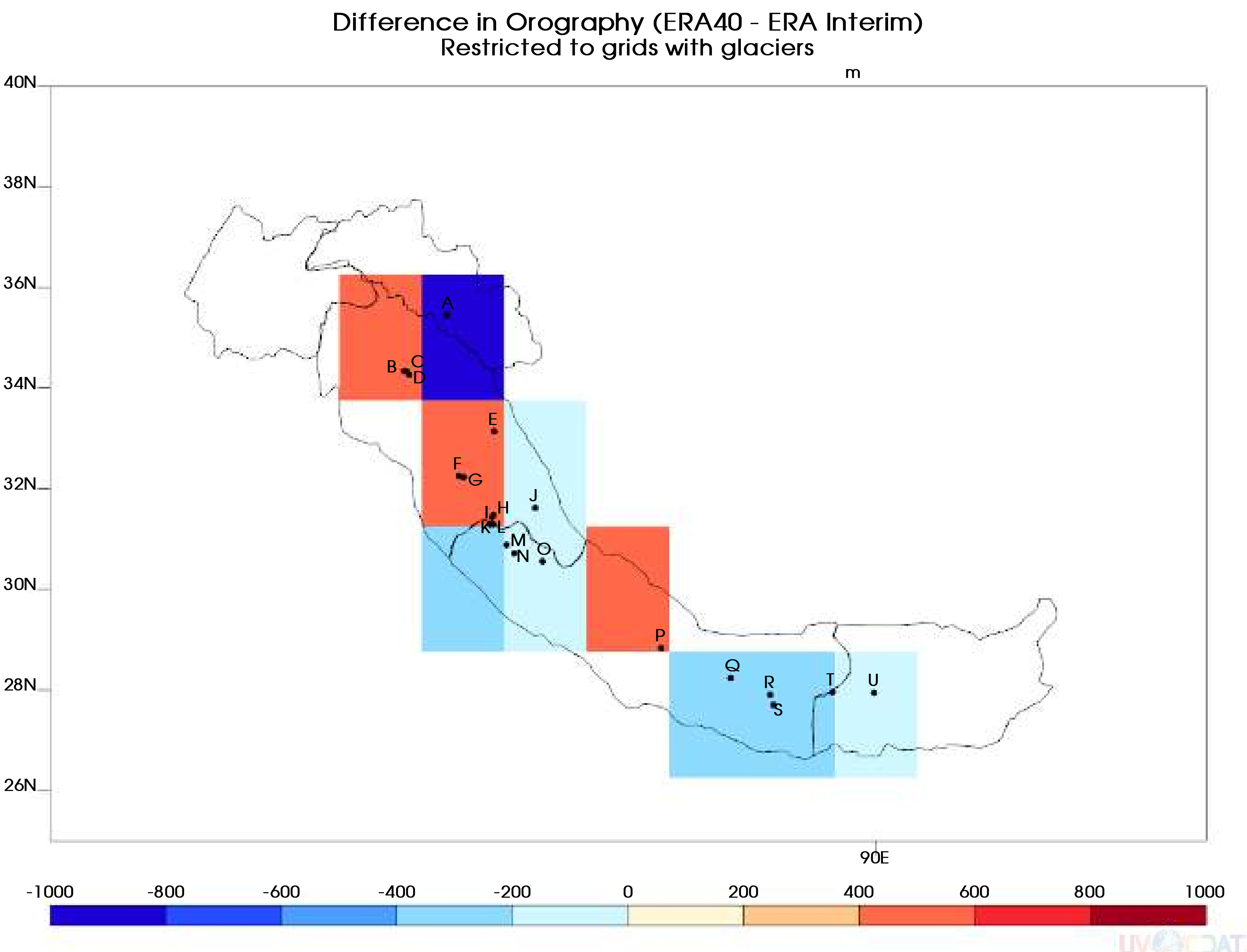


Mass Balance Model Parameters

Parameter	Parameter name	Parameter range
lr_{ERA}	Statistical lapse rate	-0.01 to 0.002
lr	Normal lapse rate	-0.01 to 0.002
f_{snow}	Degree day of snow	2 to 8
f_{ice}	Degree day of ice	4 to 12
k_p	Precipitation coefficient	0.1 to 20
d_{prec}	Precipitation gradient	0.0 to 0.9
T_{snow}	Temperature of snow	0.0 to 2.0

Area Averaged Monthly contribution of Mass Balances

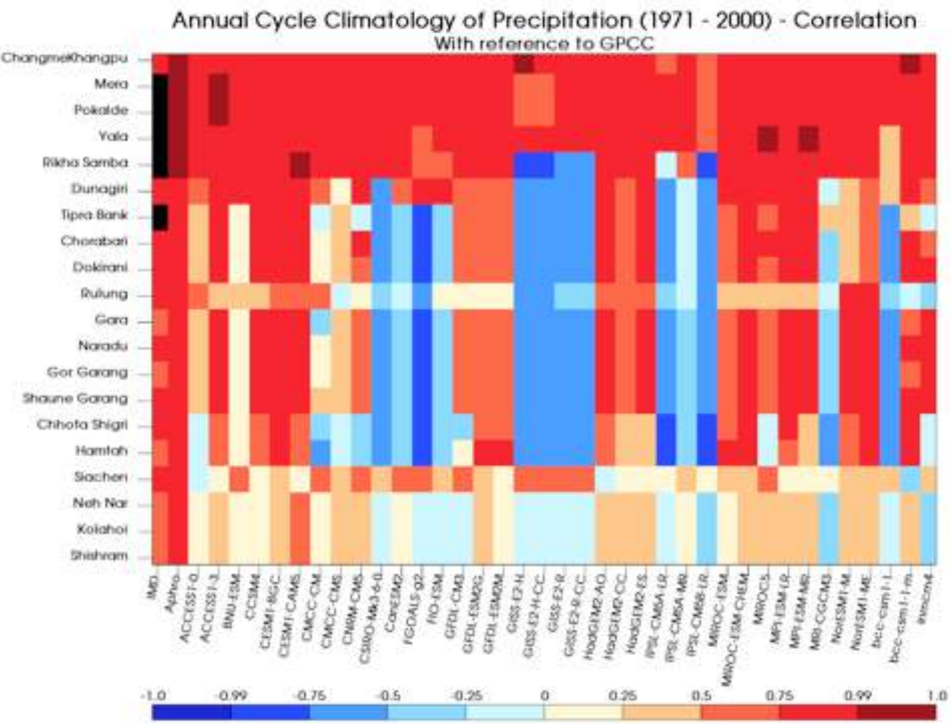


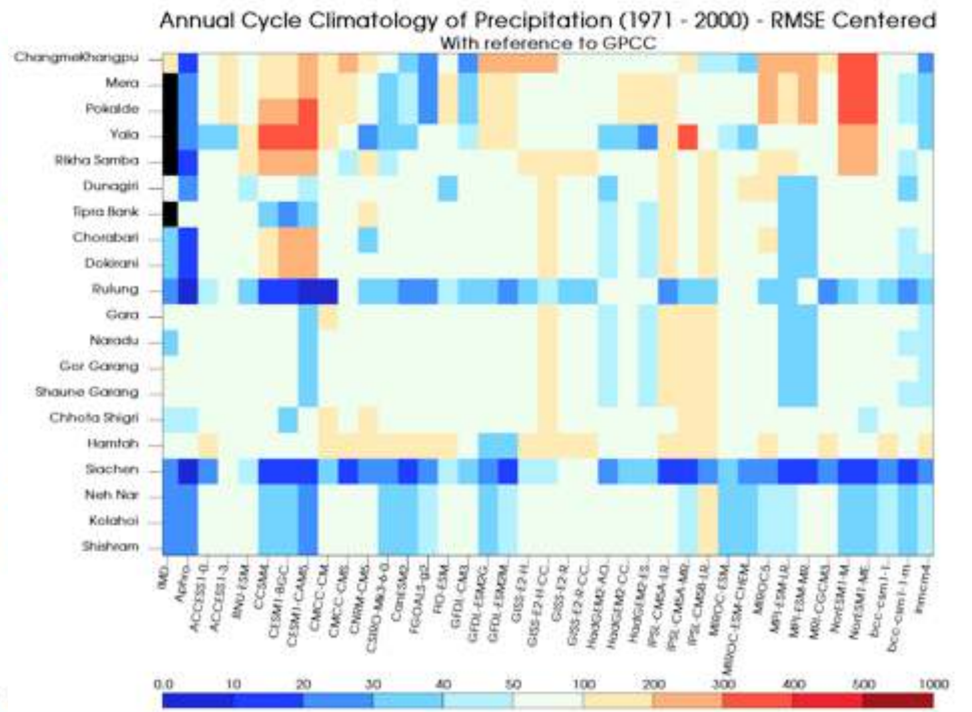


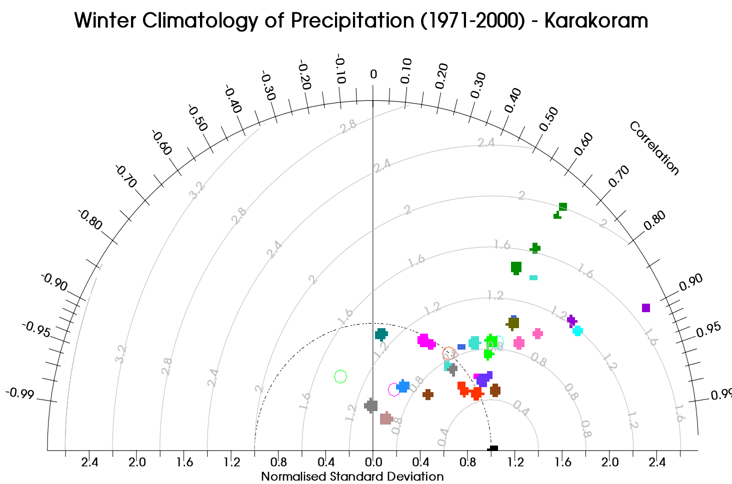
Difference in Orography (ERA40 - ERA Interim)
Restricted to grids with glaciers
m
40N
38N
36N
34N
32N
30N
28N
26N
90E
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
-1000
-800
-600
-400
-200
0
200
400
600
800
1000

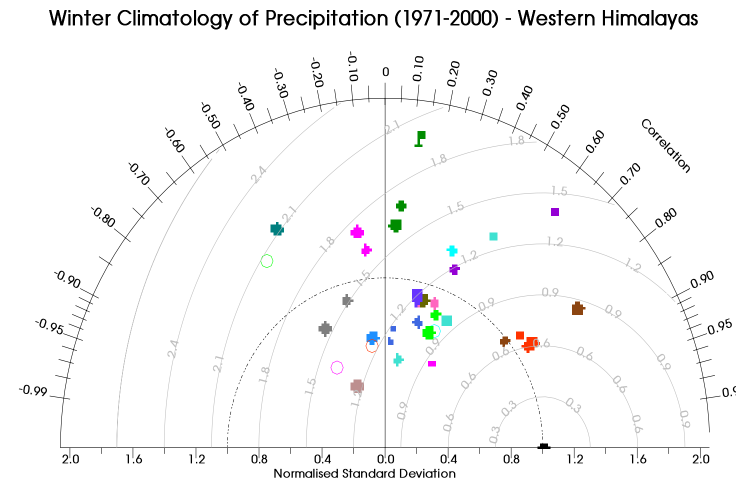
Selection of CMIP5 models

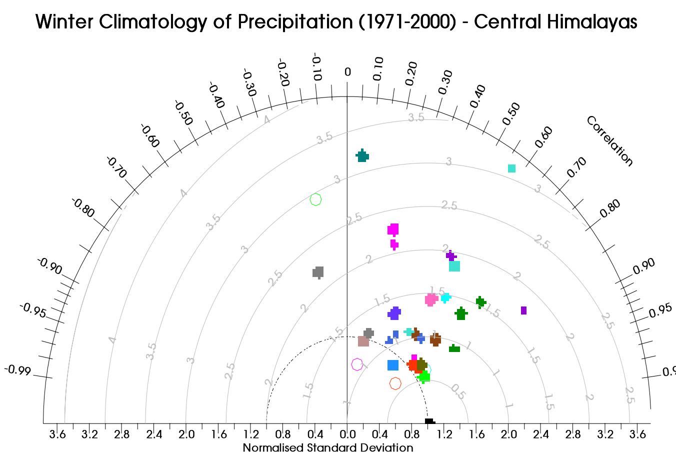
We have to examine carefully three statistical properties viz Correlation, Root Mean Square Error (RMSE) and Standard Deviation (SD).
If the Correlation is high and RMSE is low, we can say the model is good as the SD is a trigonometric function of those two.

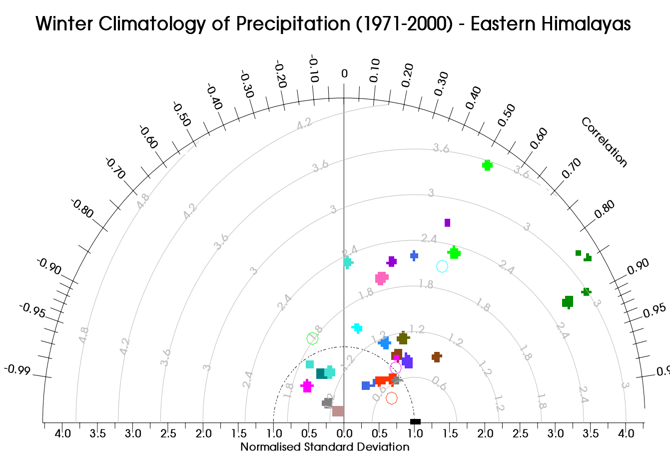


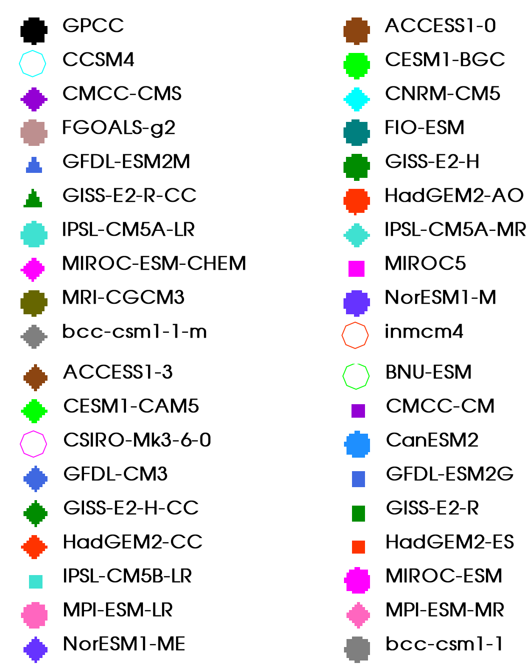




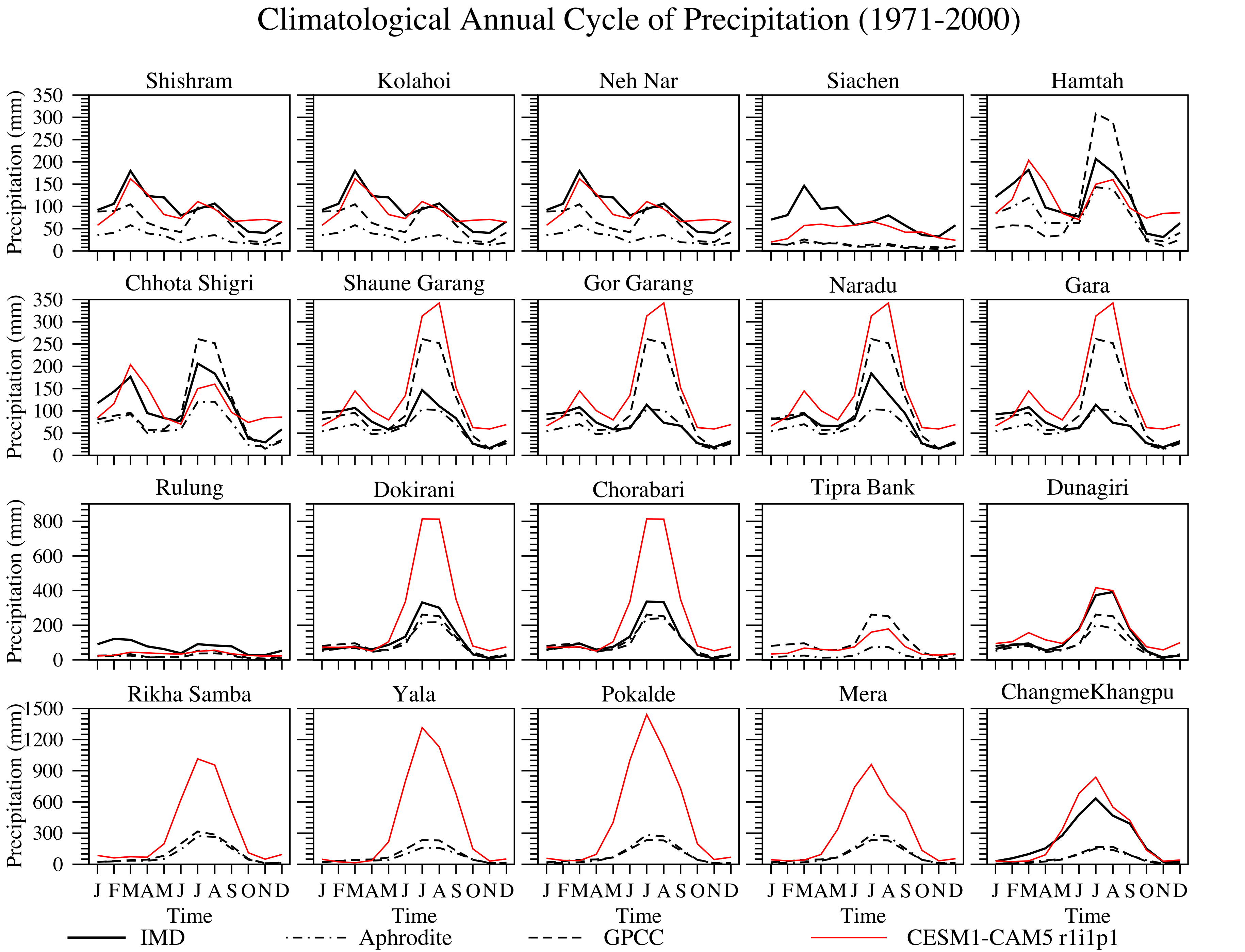




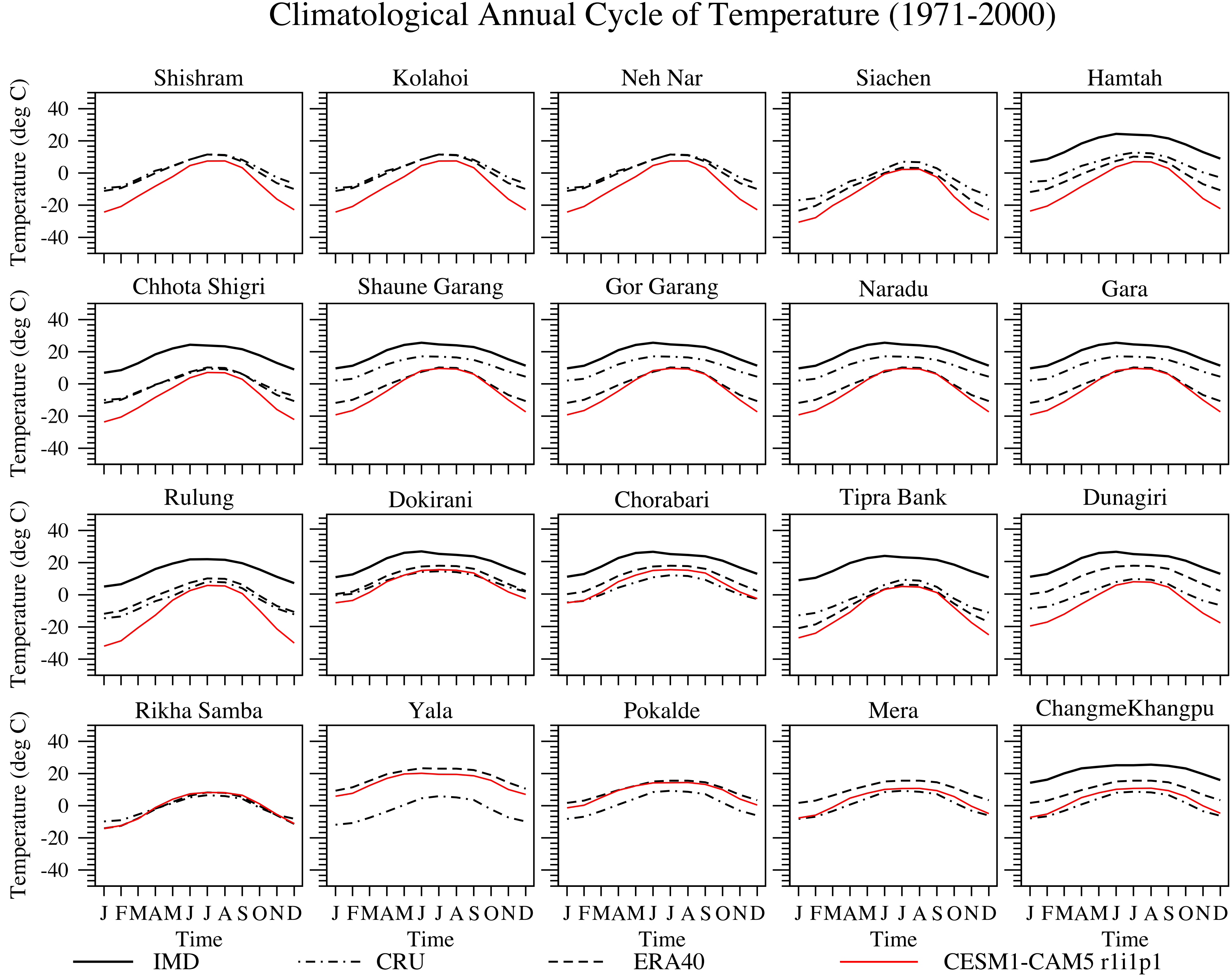




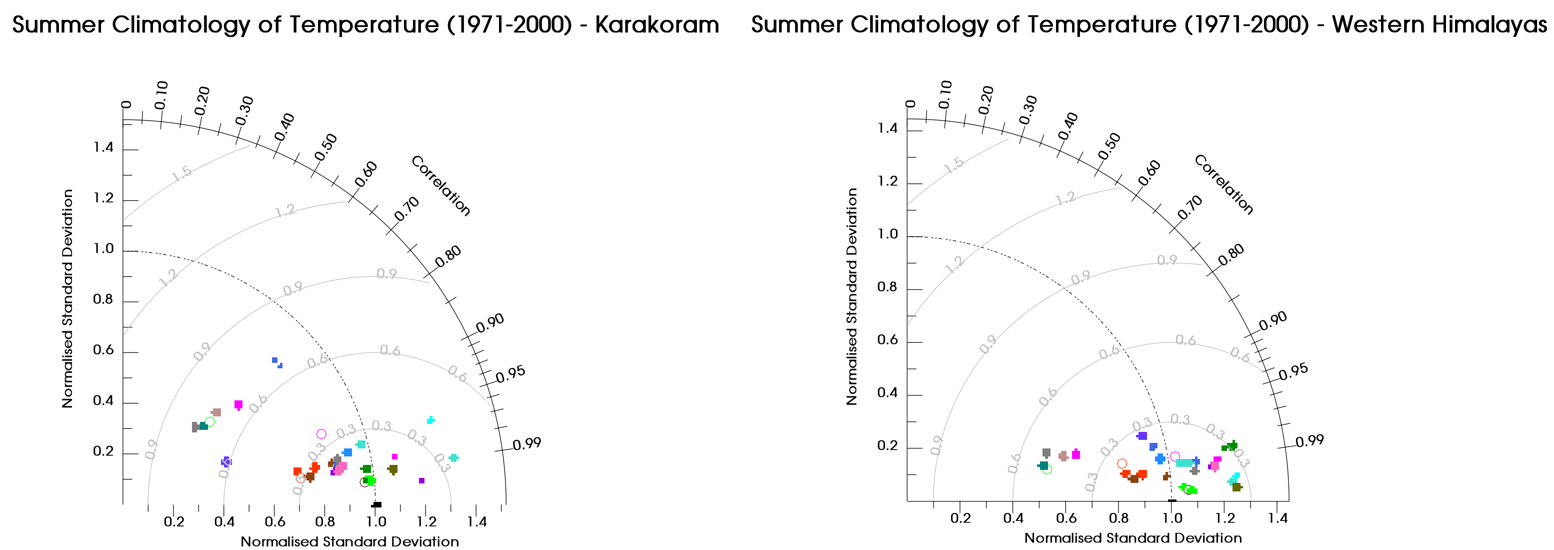
Region wise seasonal climatology of precipitation of all models with reference to reanalysis dataset (CMIP5 vs GPCC)

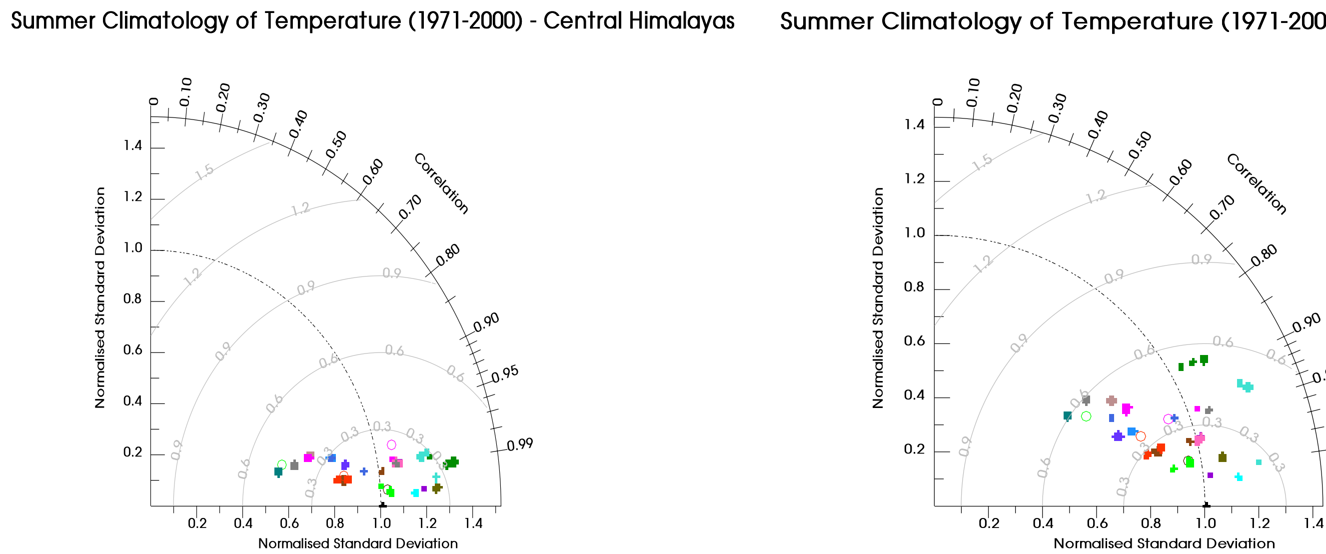


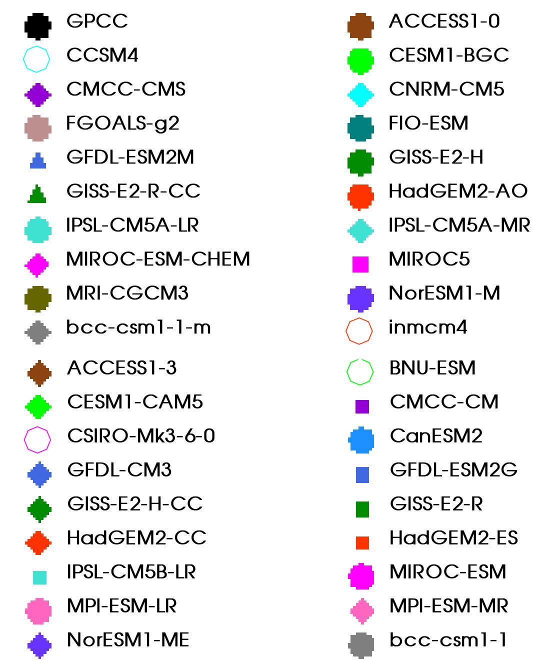
Climatological Annual Cycle of Precipitation (1971-2000)
Shishram
Kolahoi
Neh Nar
Siachen
Hamtah
Chhota Shigri
Shaune Garang
Gor Garang
Naradu
Gara
Rulung
Dokirani
Chorabari
Tipra Bank
Dunagiri
Rikha Samba
Yala
Pokalde
Mera
ChangmeKhangpu
Precipitation (mm)
J F M A M J J A S O N D
Time
IMD
Aphrodite
GPCC
CESM1-CAM5 r1i1p1



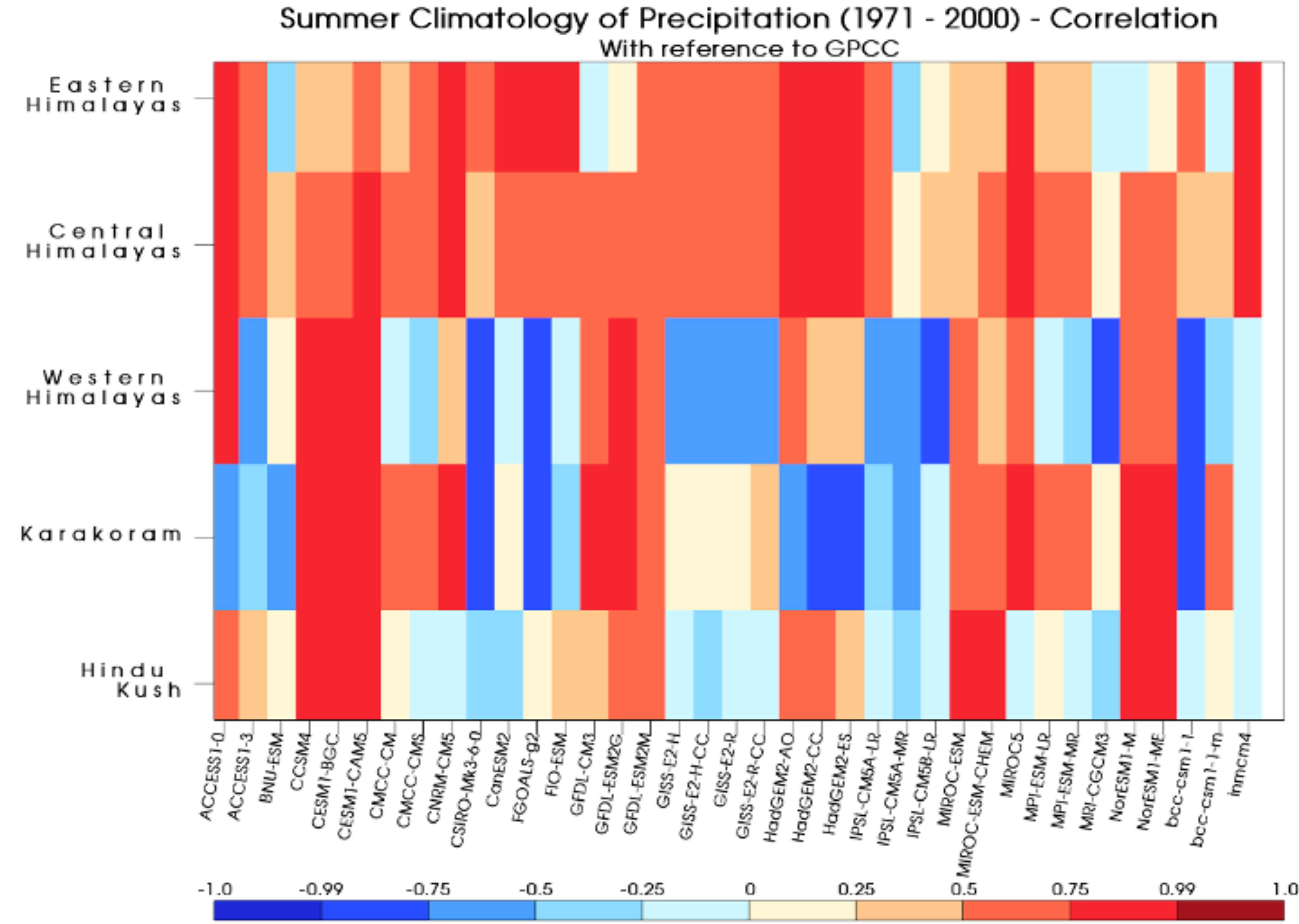
Climatological Annual Cycle of Temperature (1971-2000)
Shishram
Kolahoi
Neh Nar
Siachen
Hamtah
Chhota Shigri
Shaune Garang
Gor Garang
Naradu
Gara
Rulung
Dokirani
Chorabari
Tipra Bank
Dunagiri
Rikha Samba
Yala
Pokalde
Mera
ChangmeKhangpu
Temperature (deg C)
40
20
0
-20
-40
J F M A M J J A S O N D
Time
IMD
CRU
ERA40
CESM1-CAM5 r1i1p1



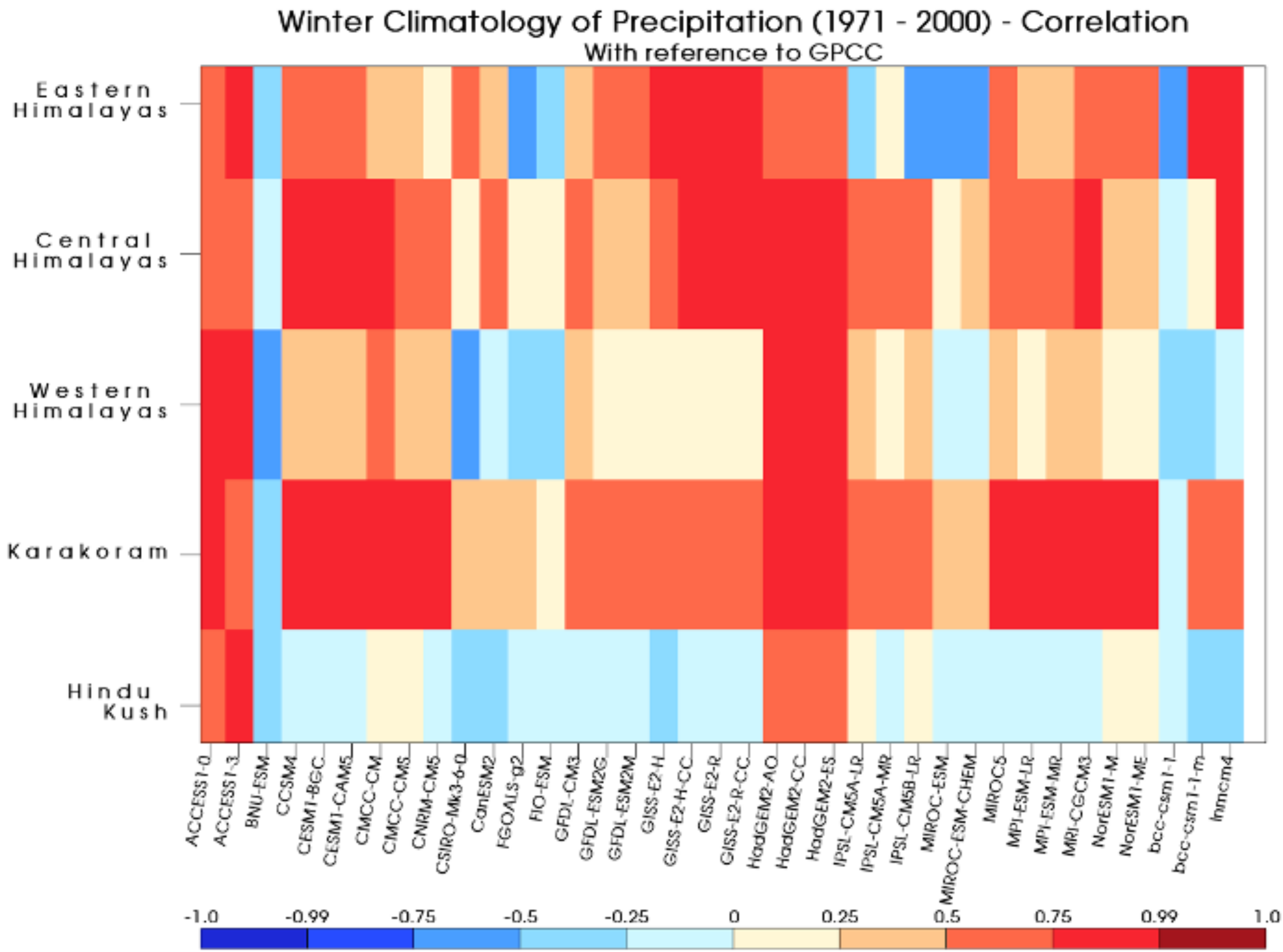




Region wise seasonal climatology of temperature of all models with reference to reanalysis dataset (CMIP5 vs ERA40)

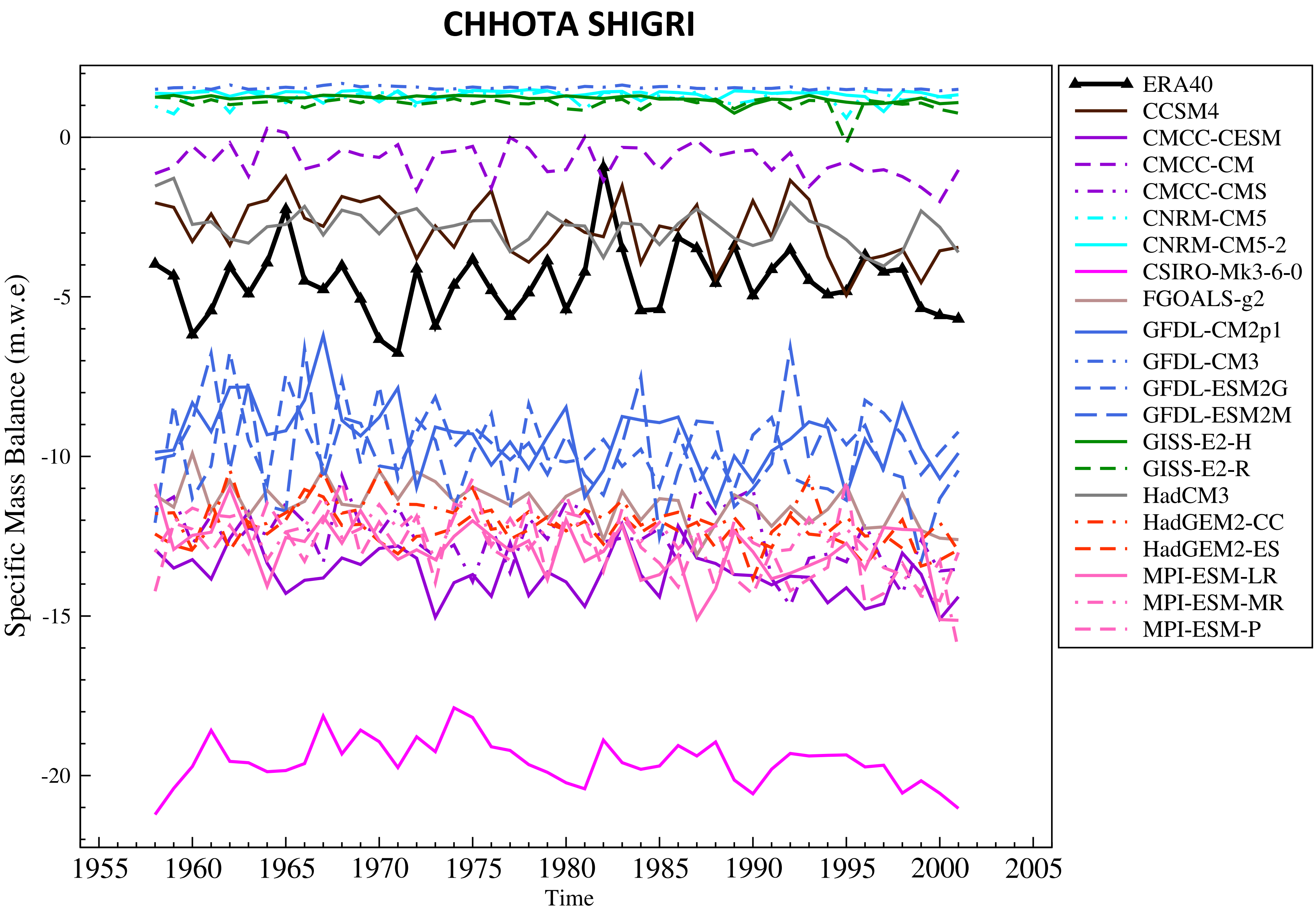


Summer Climatology of Precipitation (1971 - 2000) - Correlation
With reference to GPCC
Eastern Himalayas
Central Himalayas
Western Himalayas
Karakoram
Hindu Kush
ACCESS1-0
ACCESS1-3
BNU-ESM
CCSM4
CESM1-BGC
CESM1-CAM5
CMCC-CM
CMCC-CMS
CNRM-CM5
CSIRO-Mk3-6-0
CanESM2
FGOALS-g2
FIO-ESM
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
GISS-E2-H
GISS-E2-H-CC
GISS-E2-R
GISS-E2-R-CC
HadGEM2-AO
HadGEM2-CC
HadGEM2-ES
IPSL-CM5A-LR
IPSL-CM5A-MR
IPSL-CM5B-LR
MIROC-ESM
MIROC-ESM-CHEM
MIROC5
MPI-ESM-LR
MPI-ESM-MR
MRI-CGCM3
NorESM1-M
NorESM1-ME
bcc-csm1-1
bcc-csm1-1-m
inmcm4
-1.0
-0.99
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
0.99
1.0

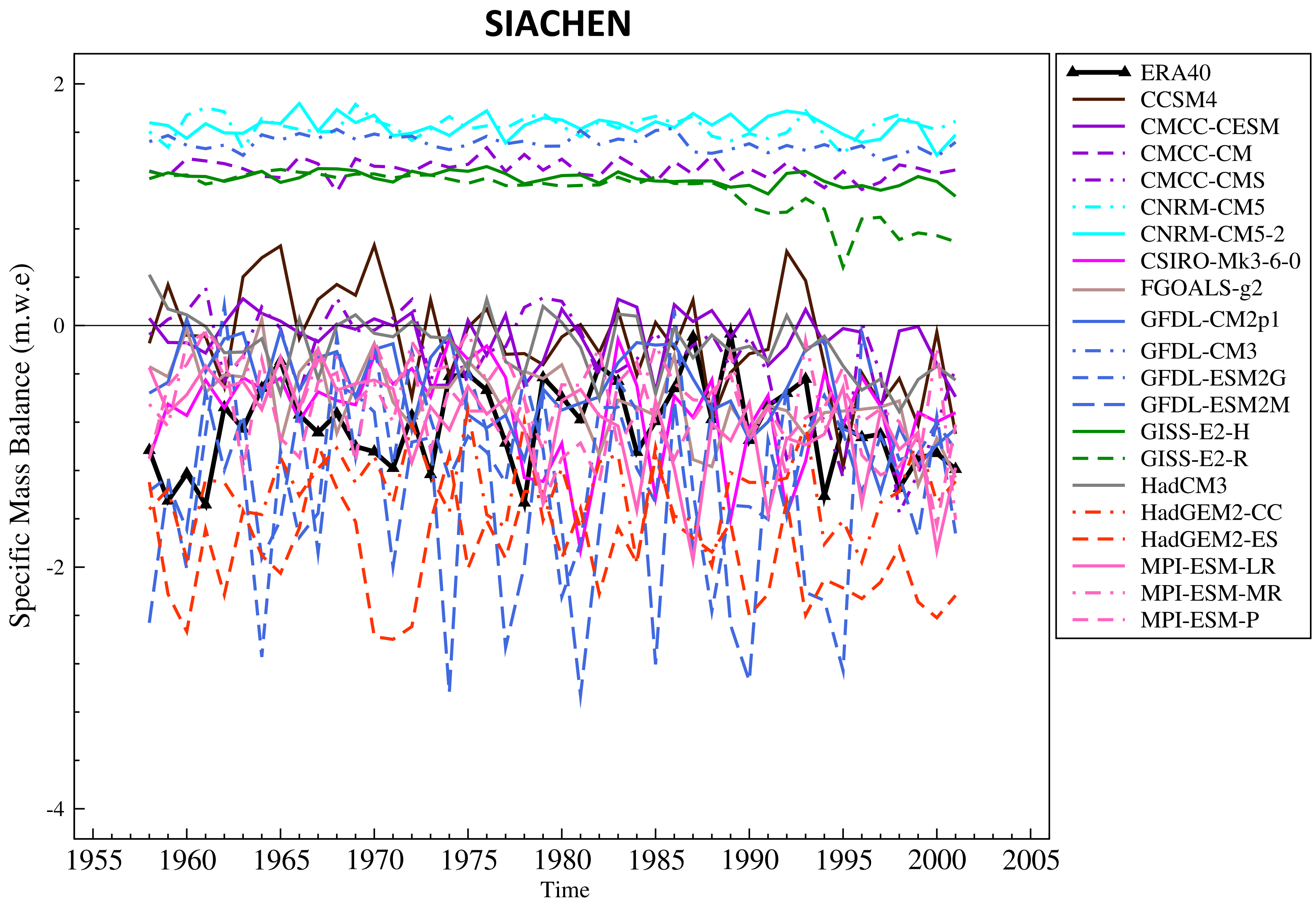


Winter Climatology of Precipitation (1971 - 2000) - Correlation
With reference to GPCC
Eastern Himalayas
Central Himalayas
Western Himalayas
Karakoram
Hindu Kush
ACCESS1-0
ACCESS1-3
BNU-ESM
CCSM4
CESM1-BGC
CESM1-CAM5
CMCC-CM
CMCC-CMS
CNRM-CM5
CSIRO-Mk3-6-0
CanESM2
FGOALS-g2
FIO-ESM
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
GISS-E2-H
GISS-E2-H-CC
GISS-E2-R
GISS-E2-R-CC
HadGEM2-AO
HadGEM2-CC
HadGEM2-ES
IPSL-CM5A-LR
IPSL-CM5A-MR
IPSL-CM5B-LR
MIROC-ESM
MIROC-ESM-CHEM
MIROC5
MPI-ESM-LR
MPI-ESM-MR
MRI-CGCM3
NorESM1-M
NorESM1-ME
bcc-csm1-1
bcc-csm1-1-m
inmcm4
-1.0
-0.99
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
0.99
1.0

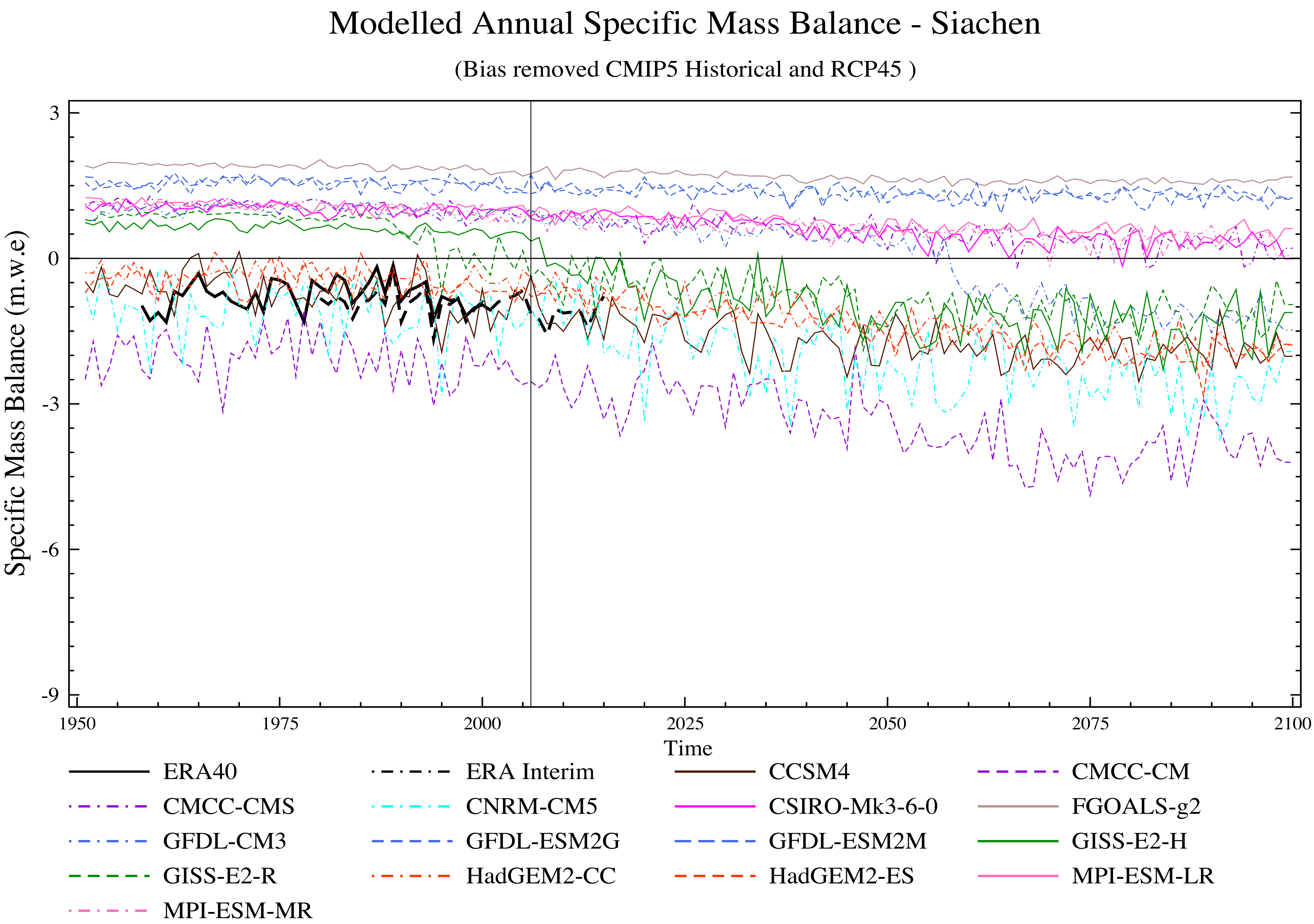
Modelled CMIP5 Historical Mass Balance

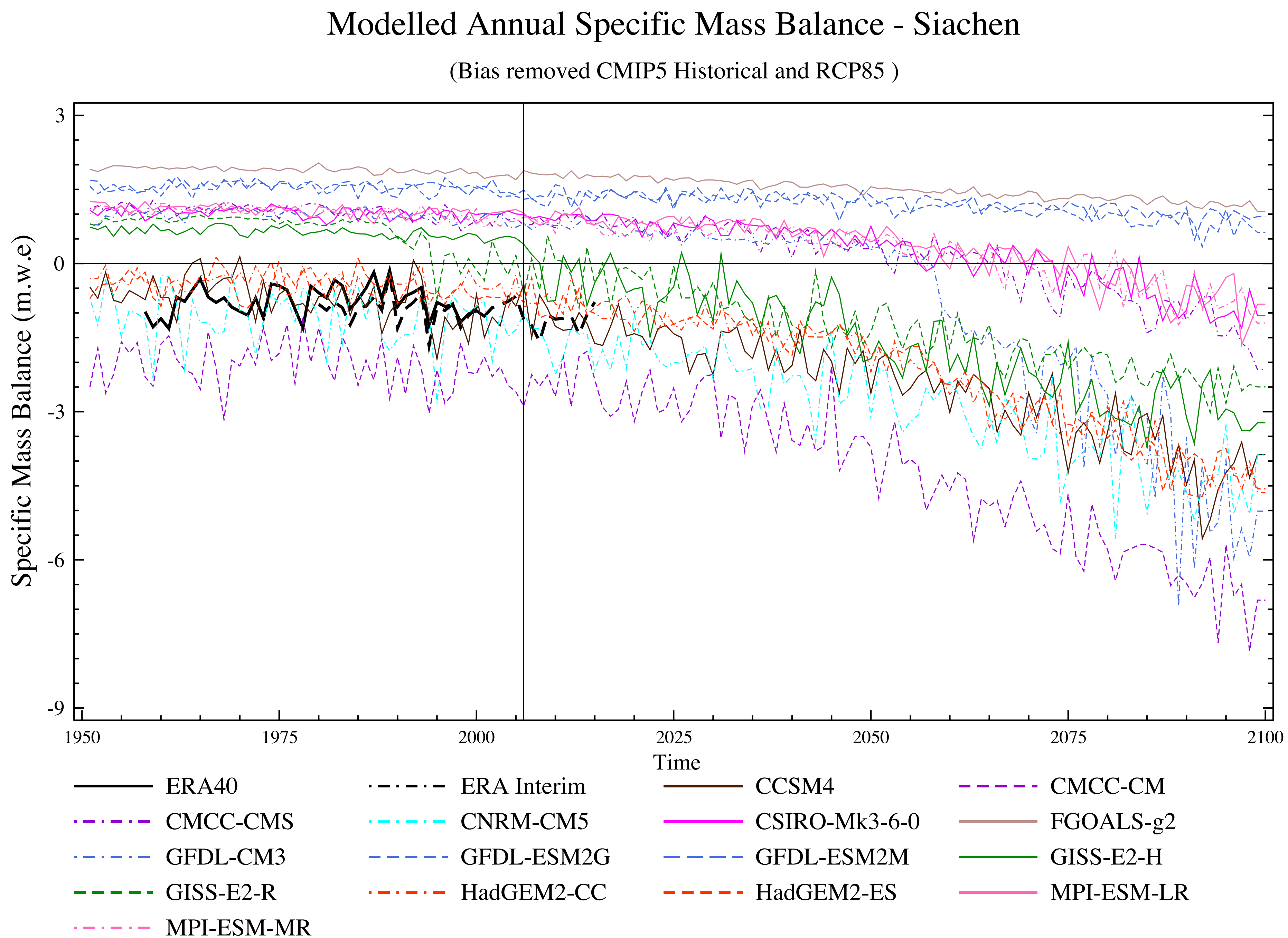


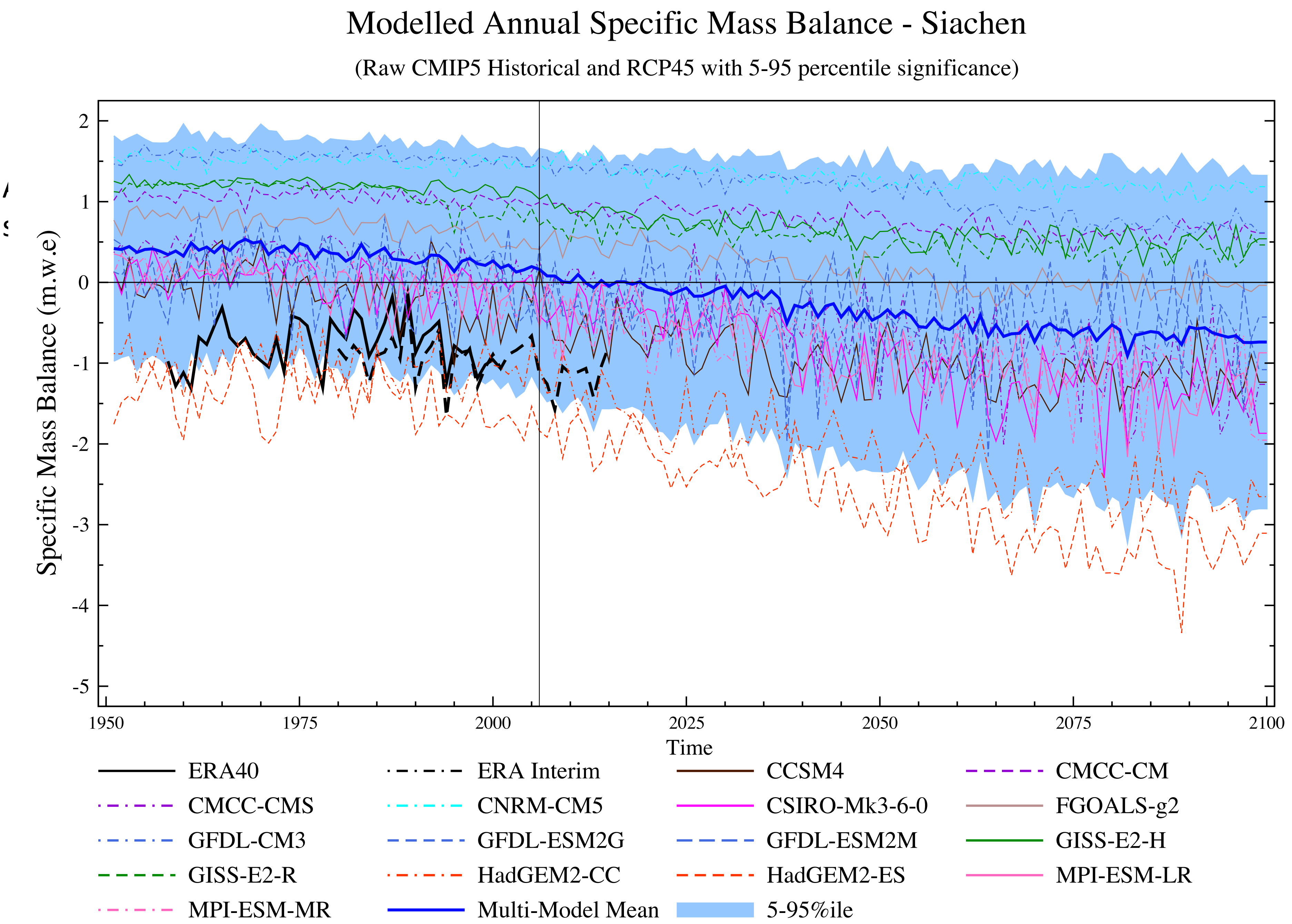
Modelled CMIP5 Historical Mass Balance



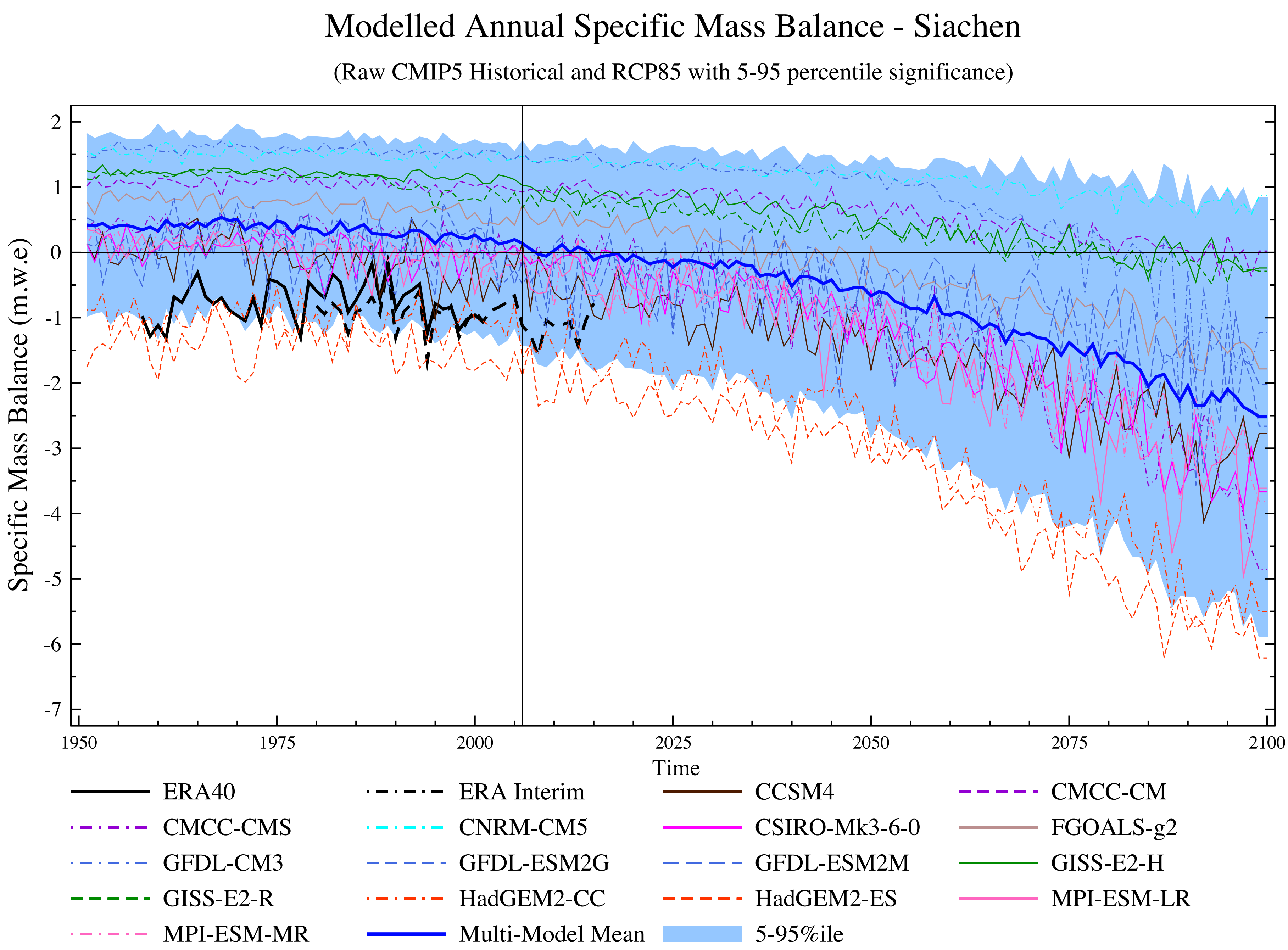
Modelled CMIP5 Historical and Future Projections




Modelled Annual Specific Mass Balance - Siachen
(Bias removed CMIP5 Historical and RCP85)
Specific Mass Balance (m.w.e)
3
0
-3
-6
-9
1950
1975
2000
2025
2050
2075
2100
Time
ERA40
ERA Interim
CCSM4
CMCC-CM
CMCC-CMS
CNRM-CM5
CSIRO-Mk3-6-0
FGOALS-g2
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
GISS-E2-H
GISS-E2-R
HadGEM2-CC
HadGEM2-ES
MPI-ESM-LR
MPI-ESM-MR



Modelled Annual Specific Mass Balance - Siachen
(Raw CMIP5 Historical and RCP45 with 5-95 percentile significance)
Specific Mass Balance (m.w.e)
2
1
0
-1
-2
-3
-4
-5
1950
1975
2000
2025
2050
2075
2100
Time
ERA40
ERA Interim
CCSM4
CMCC-CM
CMCC-CMS
CNRM-CM5
CSIRO-Mk3-6-0
FGOALS-g2
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
GISS-E2-H
GISS-E2-R
HadGEM2-CC
HadGEM2-ES
MPI-ESM-LR
MPI-ESM-MR
Multi-Model Mean
5-95%ile



Modelled Annual Specific Mass Balance - Siachen
(Raw CMIP5 Historical and RCP85 with 5-95 percentile significance)
Specific Mass Balance (m.w.e)
2
1
0
-1
-2
-3
-4
-5
-6
-7
1950
1975
2000
2025
2050
2075
2100
Time
ERA40
ERA Interim
CCSM4
CMCC-CM
CMCC-CMS
CNRM-CM5
CSIRO-Mk3-6-0
FGOALS-g2
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
GISS-E2-H
GISS-E2-R
HadGEM2-CC
HadGEM2-ES
MPI-ESM-LR
MPI-ESM-MR
Multi-Model Mean
5-95%ile