Mountain Weather and Climate in a Warmer World

¿

A focus on elevation-dependent warming and precipitation changes

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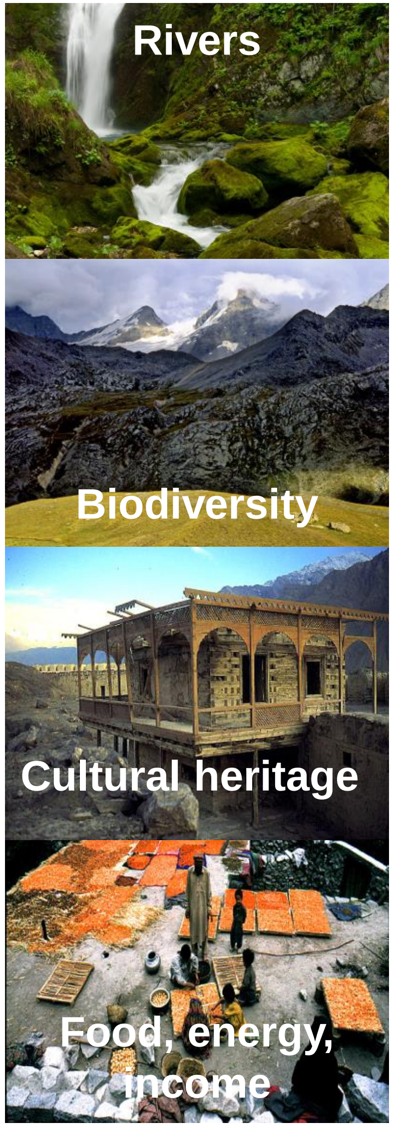
Consiglio Nazionale delle Ricerche

Context: Why mountains?

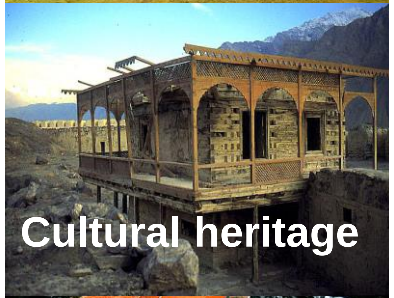


- Mountains occupy about **one-quarter of the Earth's land surface and are home to ~20% of the world's population** → **mountains are globally distributed and are transnational**

- **Mountains are storehouse of biological diversity and endangered species: they support about 25% of the terrestrial biodiversity and half of the world's biodiversity hot spots are concentrated in mountains** → **mountains are biodiversity hot-spots**

- **32% of protected areas worldwide are in mountains**

Context: Why mountains?



- The influence of mountains extends far beyond their ranges: they **provide goods and services** to over half the global population – making them not only crucial for people living in mountains, but also for those living downstream → **what happens in the mountains does not stay in the mountains**

  - **Provisioning services (water, food, energy, timber)**
  - **Regulating services (mountain water cycle and regional feedbacks, modulation of runoff regimes, mitigation of the risks from natural hazards, water storage,)**
  - **Cultural services** (cultural heritage and intrinsic spiritual values for humanity, aesthetic value, recreation, diversity of cultures)

The importance of mountains

1992 - **Rio de Janeiro Earth Summit, Chapter 13 of Agenda 21** confirmed the need for sustainable development in mountain regions, given mountains' crucial role as sources of water, energy, biodiversity, minerals, forest products and agricultural products.

2001- International programs of **FAO** (focus on mountains) and **IGBP (**Report 49)

2002- **Declaration of the International Year of Mountains by the United Nations**

2002 - **Johannesburg World Summit on Sustainable Development,** underlines that specific actions to be taken for the preservation and sustainable development of mountain regions

2008 - Mountain ecosystems were identified in 2008 report **of the General Assembly of the United Nations** (UN, A/Res/62/196, 2008) as key indicators of such effects of climate change, especially in terms of vulnerable resources like biodiversity and water.

2019 – Chapter 2 of the IPCC SROCC Report dedicated to «**high mountain areas**»: «this chapter assesses new evidence on observed recent and projected changes in the mountain cryosphere as well as associated impacts, risks and adaptation measures related to natural and human systems»

Mountain regions are highly sensitive to climate and environmental changes (including water and air pollution, changes in land use, alien species), with common and context-specific manifestations of these changes

- Ecosystem functions and services
- Water quality and quantity
- Food production
- Economic growth

It is essential to monitor the mountain environment, to better understand the drivers of the observed changes and to estimate the response of mountains to future climate conditions

- Cryosphere (glaciers, snow, permafrost)
- Changes in biodiversity
- Changes in mountain ecosystems

Research needs

Better understand key processes and mechanisms in mountain environments

- Measurement data (in-situ and EO) and their integration
  - Improving and homogenizing observations, designing proper metadata on existing observations

- Model simulations
  - Increase the spatial resolution, improve the parameterizations, implement modelling chains, **to test and improve our understanding of the physical processes that drive the climate system, identify feedbacks, predict future changes**

Handle (and possibly reduce) uncertainties in both observations and models

Observations

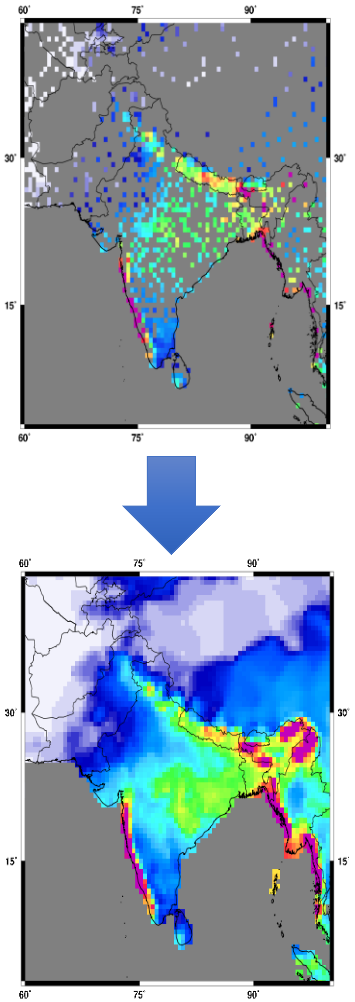
In-situ stations

- Characterization of the local conditions
- Long temporal coverage
- Unevenly distributed, mainly in the valleys and lowland areas, leading to a bias toward the lower elevations

Interpolated (gridded) datasets

- Gridding: reduces biases arising from the irregular station distribution and is essential for the analysis of regional trends
- Poor spatial coverage and high sparseness of the underlying stations →source of uncertainty when interpolating grid point values from the nearest few available stations.

GPCC raw



GPCC interpolated

Observations

Satellite data

- Spatially-complete coverage of climate variables estimates
- They do not extend back beyond the 1980s → are becoming suitable for assessing long-term trends and for climatological studies.
- Problems in measuring accurately some variables (eg snow or precipitation in some regions)

Merged in-situ and satellite Datasets

Reanalyses (use data assimilation techniques to keep the output of a numerical model close to observations)

- Global & continuos data
- Climate trends obtained from reanalyses should be regarded with caution, since continuous changes in the observing systems and biases in both observations and models can introduce spurious variability and trends into reanalysis output.

Models

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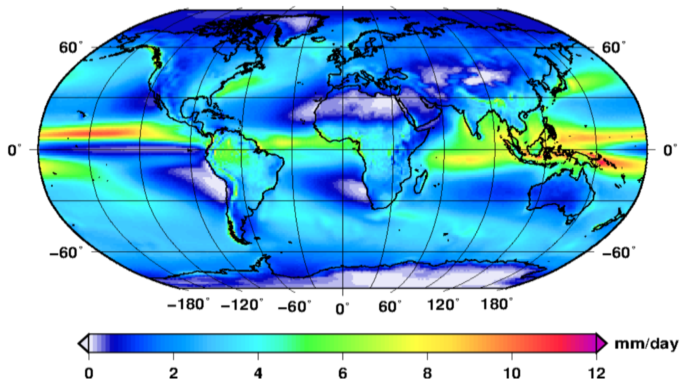
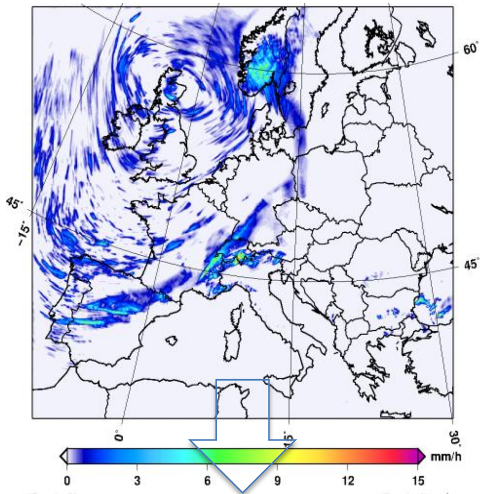
GLOBAL CLIMATE MODELS



REGIONAL CLIMATE MODELS



ECO-HYDROLOGICAL MODELS

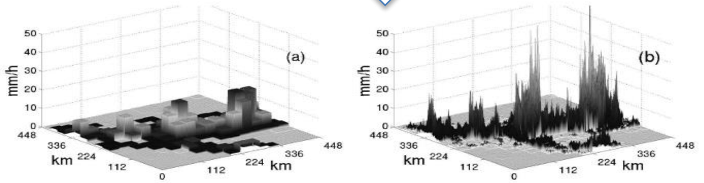


FIG. 10. (a) A snapshot of the forecasted rain field obtained from the LAM forecast and (b) one example of a downscaled field obtained by application of the RainFARM. The vertical scale indicates precipitation intensity (mm h^{-1}) and it is the same for the two fields.

FURTHER STATISTICAL/STOCHASTIC DOWNSCALING

Model uncertainties/weak points

- **Hydrological processes are often only crudely represented in the models**

- Future changes in some components, such as **precipitation**, **evapotranspiration**, **runoff**, and **precipitable water content** are not captured in detail and are affected by large uncertainties

- Detailed changes, especially in the te**rrestrial components of the hydrological cycle**, are largely uncertain or are not tackled at all (groundwater, snowmelt, permafrost hydrology, and wetlands)

- Certain **anthropogenic influences** are generally not considered (irrigation, dams, river regulation, and agricultural land use changes and management).

Model uncertainties/weak points

e.g. **Precipitation**

- Need to **parameterize** the large-scale effects of the sub-grid processes. Parameterizations are often tuned to obtain a representation of the present climate closest to reality. Parameterized processes include radiation, heat transfer, cloud microphysics, the boundary layer and deep convection (the choice of the convective scheme is crucial for precipitation simulations)

- **Grid resolution** (the effects of regional forcing not well represented)

- **Aerosol particles** (on short time scales)

Models

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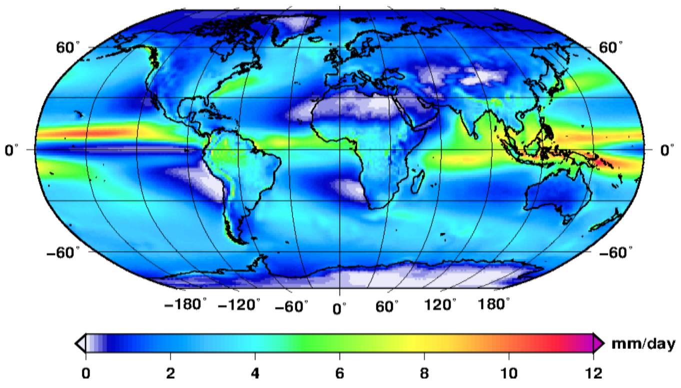
Examples taken from studies on EDW and precipitation

GLOBAL CLIMATE MODELS



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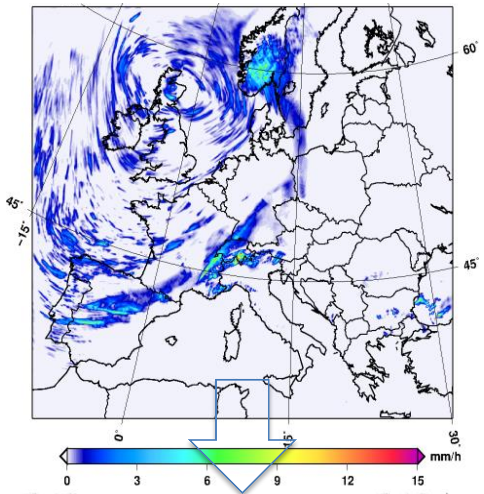

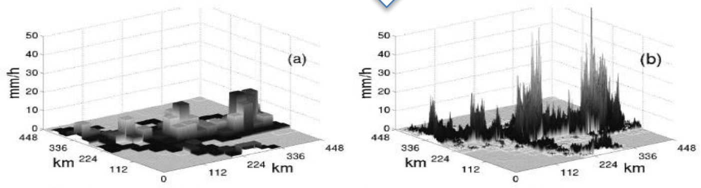

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FURTHER STATISTICAL/STOCHASTIC DOWNSCALING

ECO-HYDROLOGICAL MODELS

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Elevation-Dependent Warming

- Definition, importance and implications

- Difficulties arise from:
  - ✓ **Sparseness or lack of long-term observations** in the mountains, especially at very high elevations.
  - ✓ **Lack of consistency in the methods used to quantify EDW** (time periods examined, stations compared, elevational range selected, temporal resolution of the data)
  - ✓ **Enhanced warming is usually occurring in response to many climate variables** which are correlated with each other and give rise to feedback mechanisms

  - ✓ **Uncertainties in model simulations**

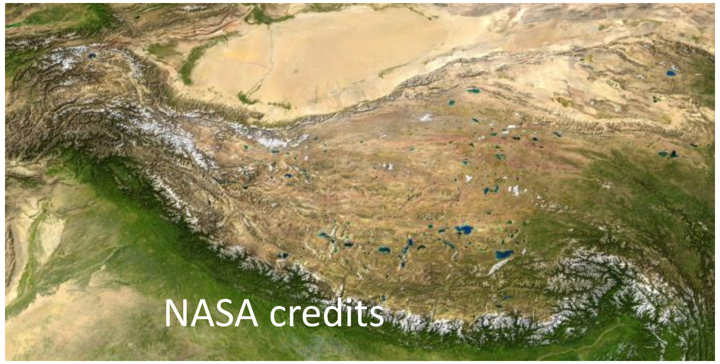
Elevation-Dependent Warming

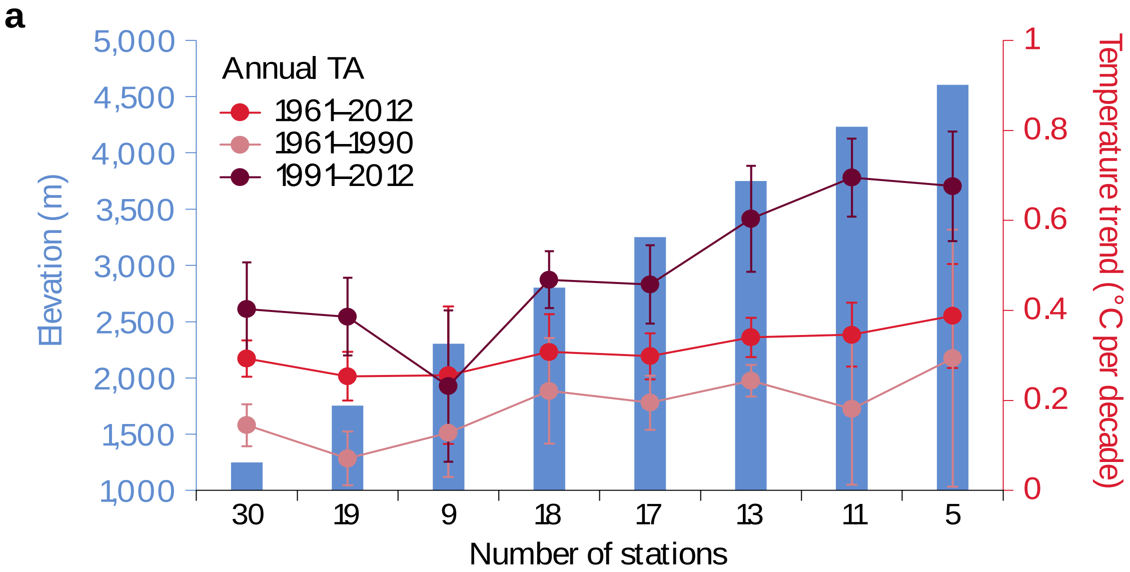
What we know from observations?

A majority of studies based on observations suggests that warming is more rapid and intense at higher elevations; however, a number of studies shows no relationship or a more complex situation (e.g. no linear relationship)

Pepin et al. Nature Climate Change 5, 424–430 (2015) doi:10.1038/nclimate2563

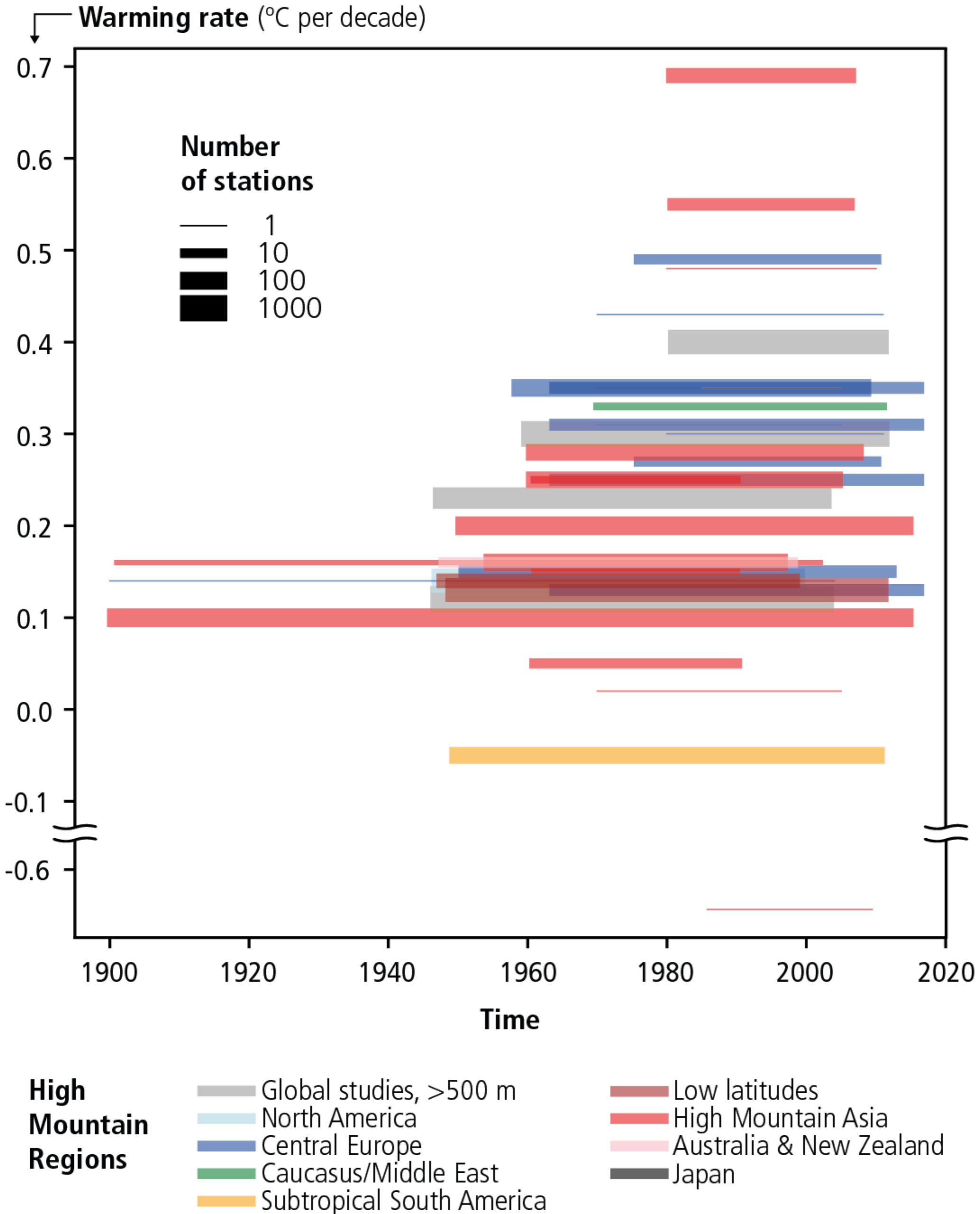
Tibetan Plateau- Himalayas





Between 1991 and 2012 temperature has increased at a rate of 0.7 °C/decade above 4.000 m compared to 0.3-0.4°C/decade below 2500 m

Elevation-Dependent Warming



Synthesis of trends in **mean annual surface air temperature in mountain regions**, reported in 40 studies based on 8703 observation stations in total (partly overlapping).

- *Each line refers to a warming rate from one study, averaged over the time period indicated by the extent of the line.*
- *Colors indicate mountain region, and line thickness the number of observation stations used.*

Average warming rate in mountains: 0.3°C/decade (to be compared to the globally averaged warming rate of 0.2°C/decade)

IPCC SROCC, 2019

Elevation-Dependent Warming

What about model simulations?

- Observational studies are in general in smaller agreement with each other than model simulations
- Most models integrate trends over a long time period (typically up to the end of the 21st century) when EDW may become more widespread than it has been so far.
- Models are widely used to understand the EDW underlying mechanisms

What drives EDW?

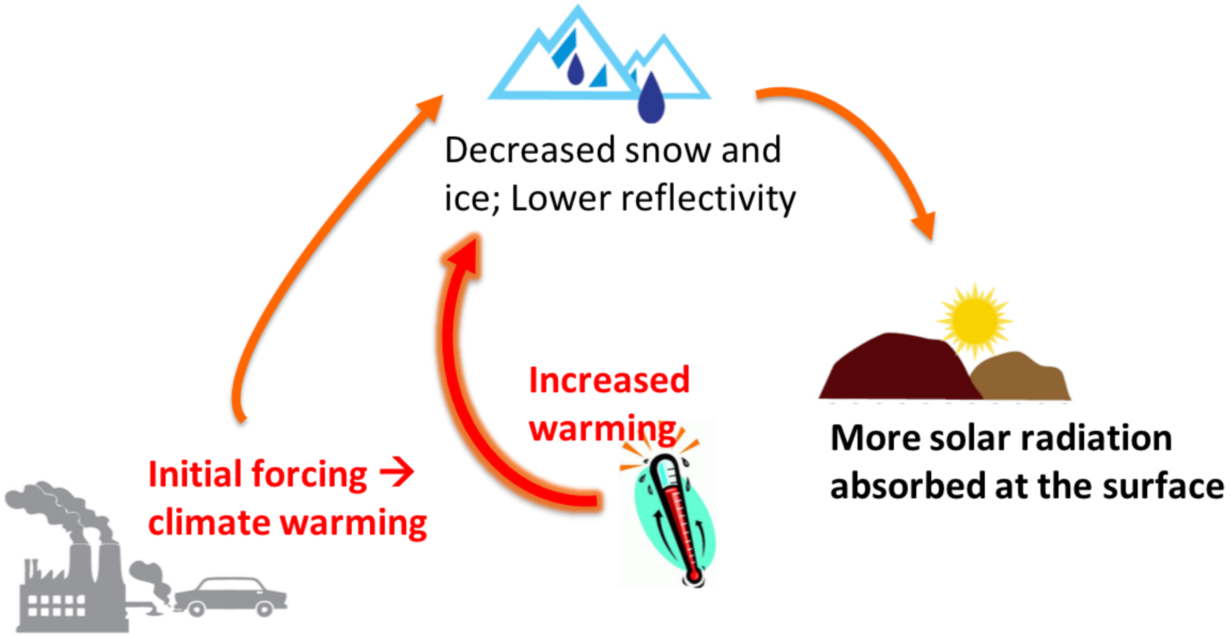
Snow-ice albedo feedback

Cloud cover

Water vapour modulation of longwave heating

Absorbing Aerosols

A mix of the mechanisms above

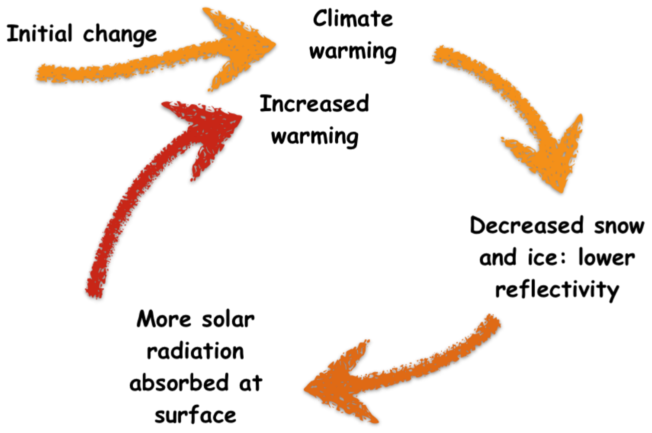


FEEDBACKS

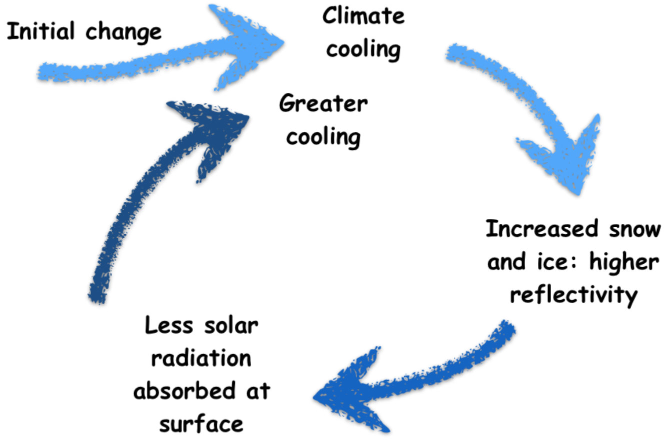
Broadly, a feedback occurs when the input is modified by the output of a process.

A positive feedback amplifies changes in the direction they start. With climate, that means a positive feedback amplifies a change.
Feedback acting to resist changes are called negative feedbacks. A negative feedback tends to push the system back to its original state: a stabilizing force.

Ice-albedo feedback: Warming melts snow, the darker surface beneath absorbs more solar radiation and warms more, which causes melting more snow and causes more warming.

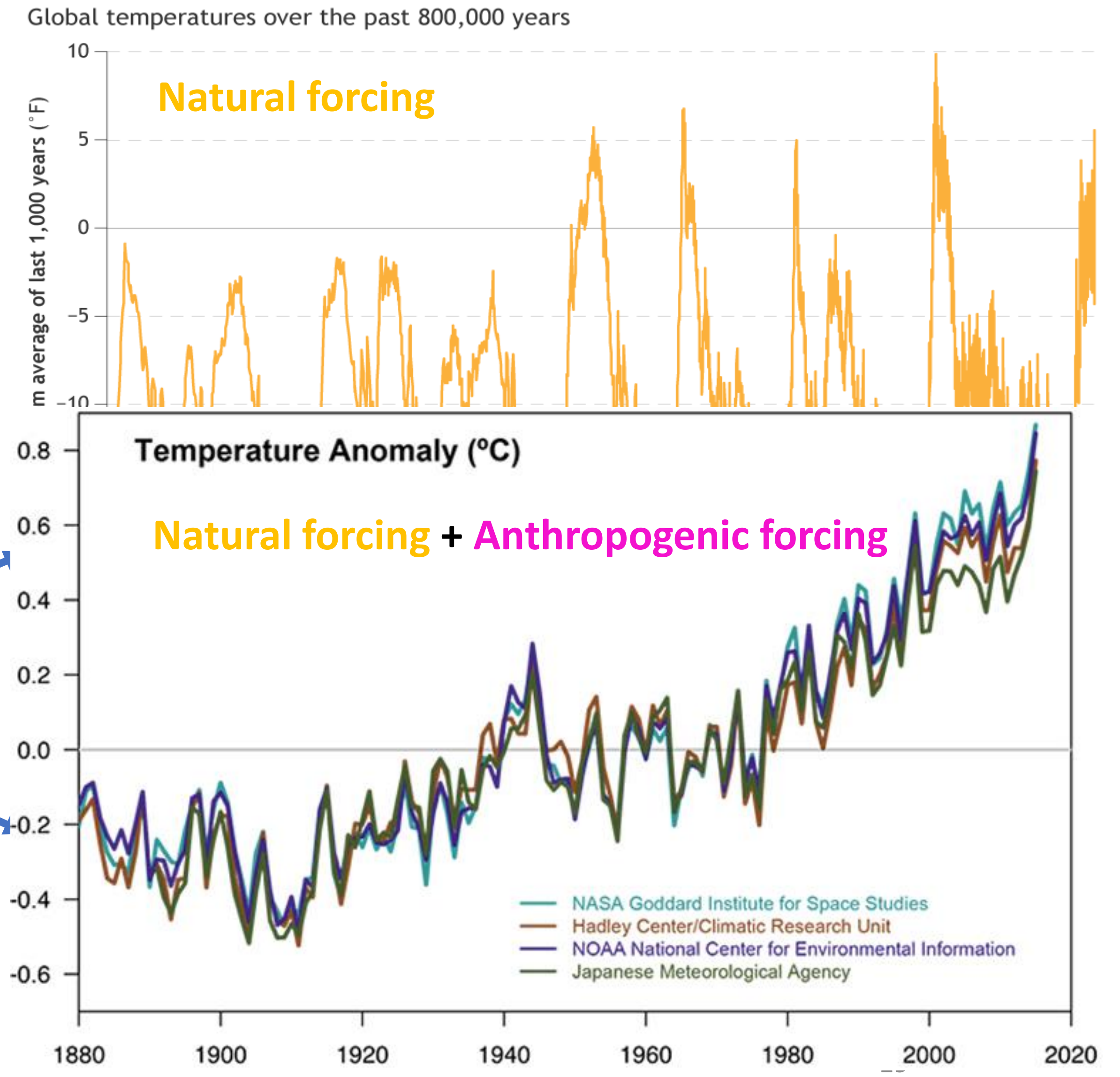


Ice-albedo feedback: Cooling increases snow, which reflects solar radiation and increase cooling which increases reflection causing more cooling

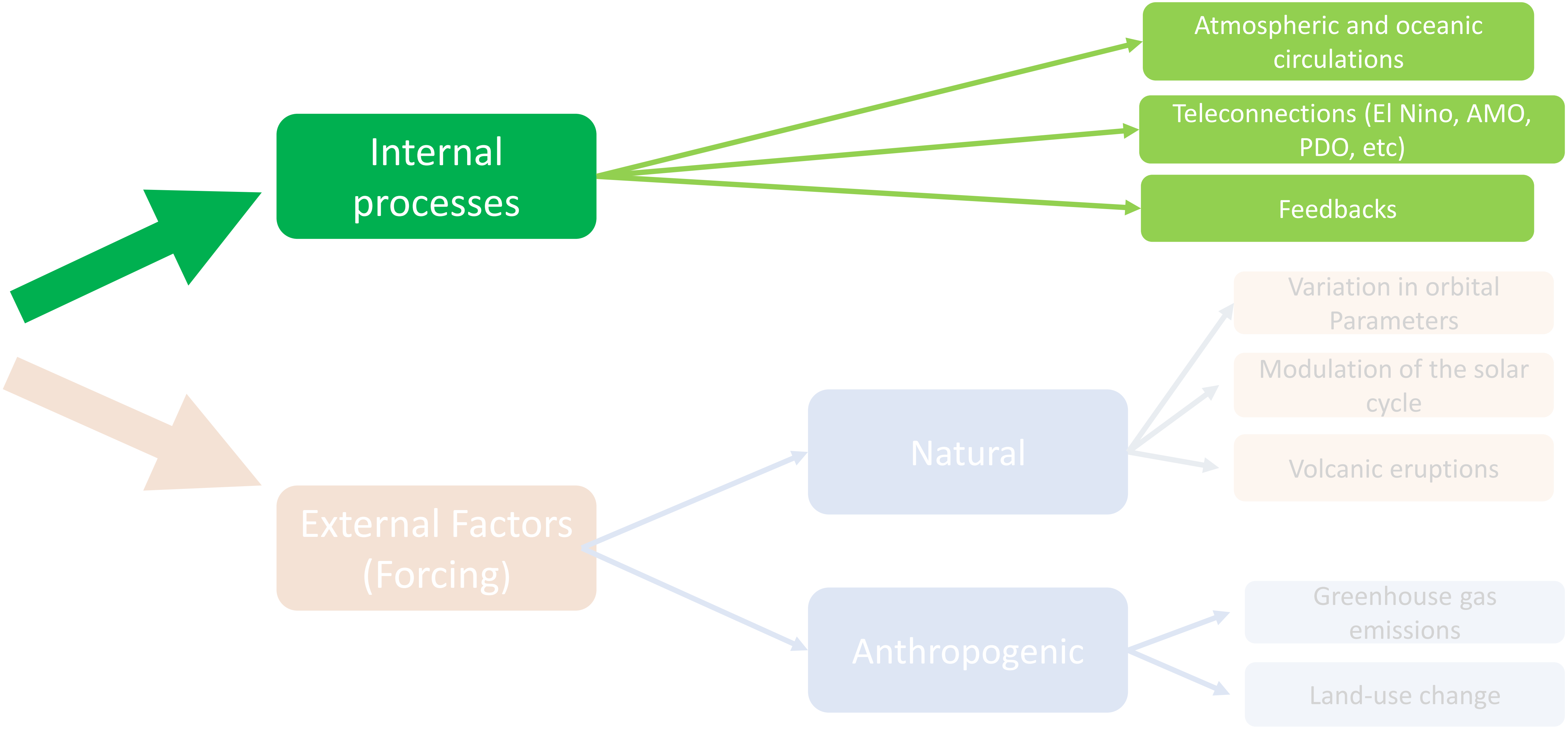


Why does climate change?

External Factors
(Forcing)



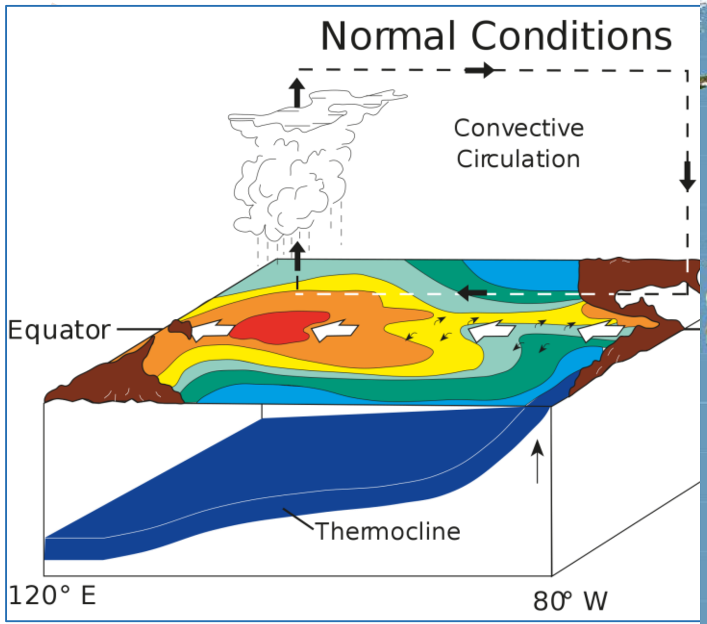
Climate variability and change

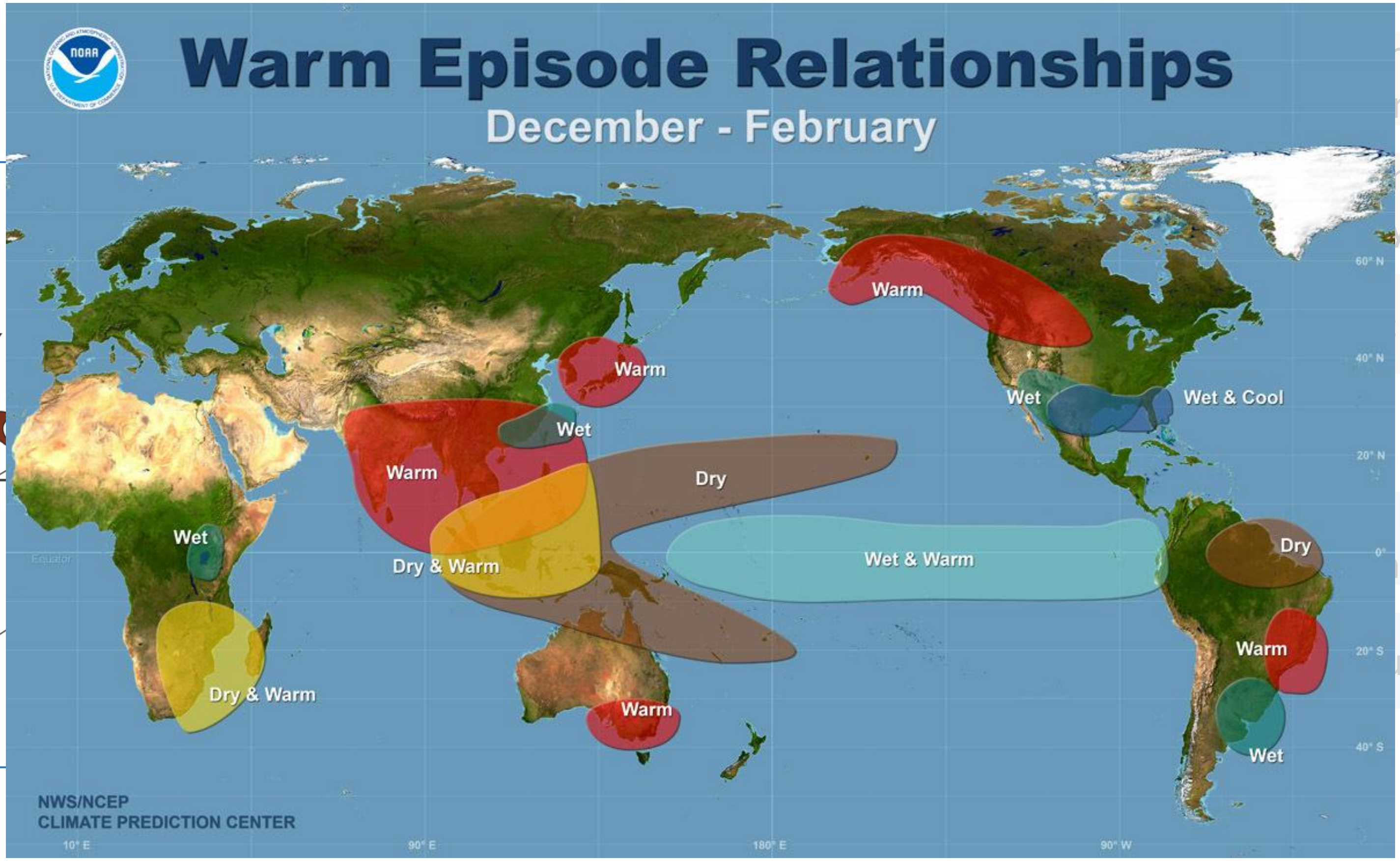


Climate variability and change

Internal processes

- Atmospheric and oceanic circulations
- Teleconnections (El Nino, AMO, PDO, etc)
- Feedbacks





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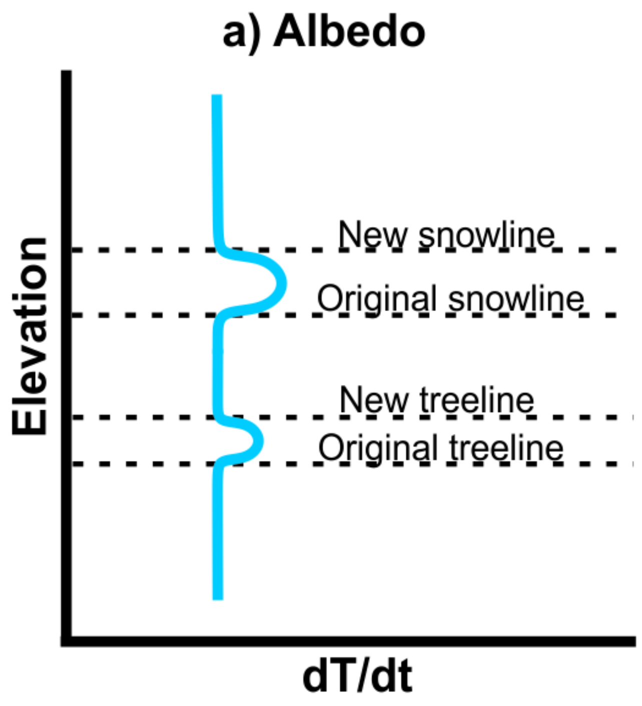
Hypotheses and Mechanisms for EDW

Snow albedo and vegetation feedbacks

The snow-albedo feedback is relevant in the mountain regions **where the seasonal timing of snow cover varies with elevation** (maximum warming rates occur near the annual 0°C isotherm).

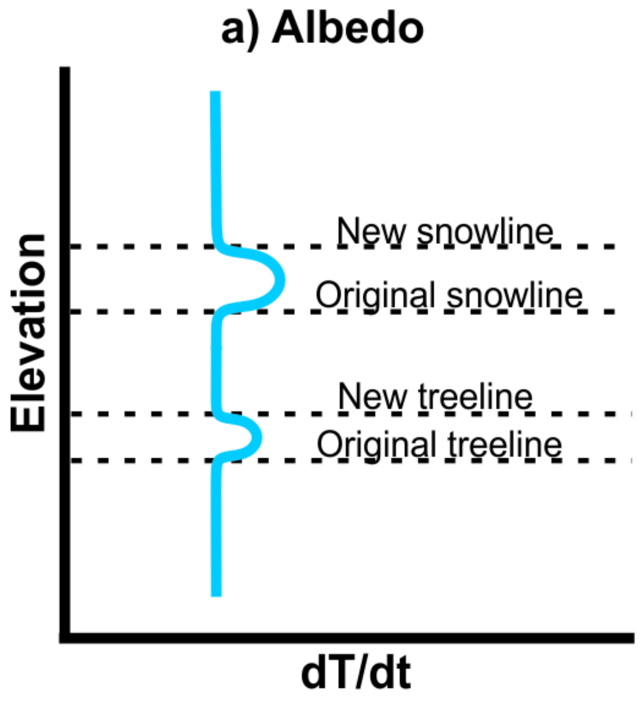


Increases in the surface absorption of incoming solar radiation around the retreating snow line, causing enhanced warming at that elevation. As the current snowline is expected to migrate upslope as global temperatures rise this effect will extend to increasingly higher elevations

A similar process is expected to result from an upslope migration of the **tree-lines**

Hypotheses and Mechanisms for EDW

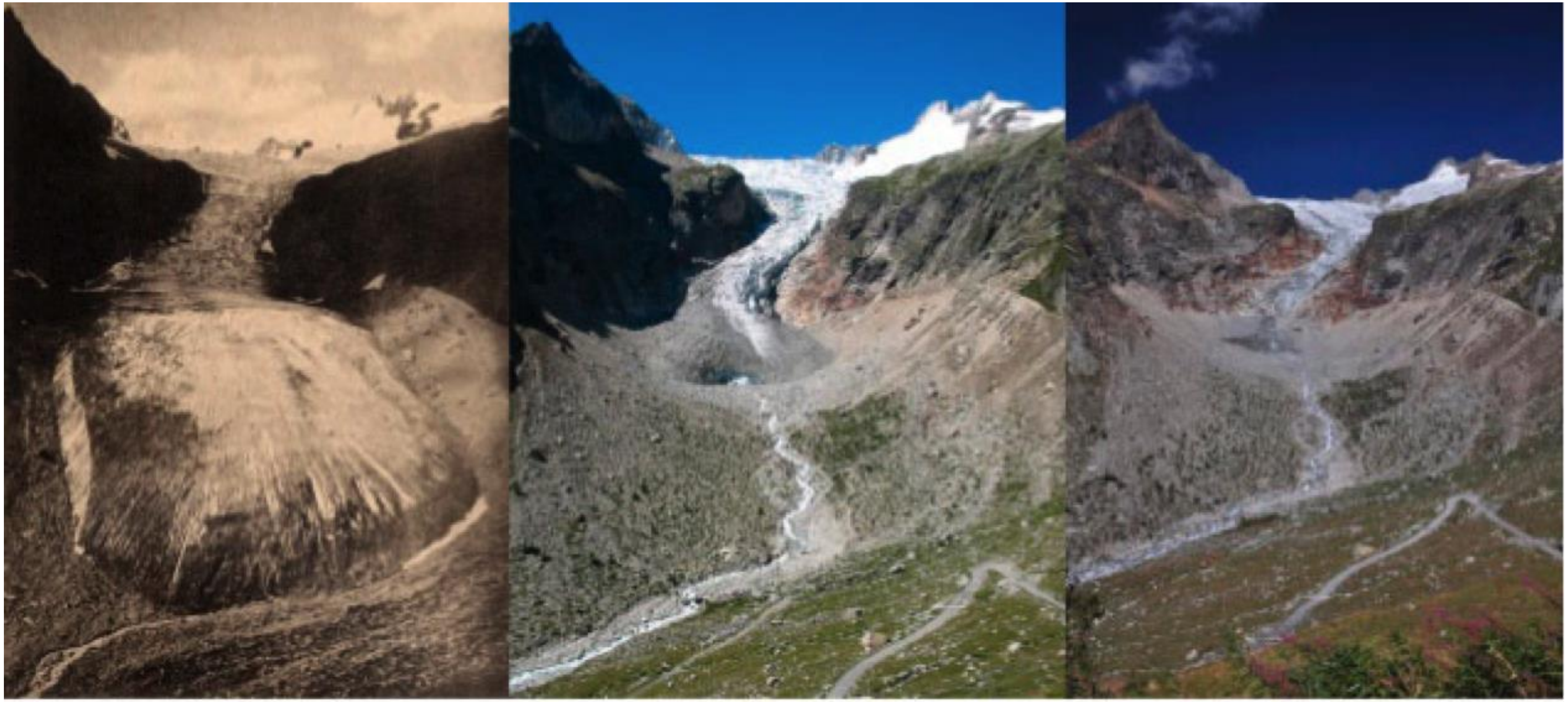
Snow albedo and vegetation feedbacks



The snow-albedo feedback has a stronger influence on maximum than minimum temperatures because of the increase in absorbed solar radiation

Dependence on soil moisture: if the increased surface shortwave absorption is balanced by increases in sensible heat fluxes (latent heat fluxes) the response will be more prominent in T max (T min)

Retreating glaciers



1897 (f. Druetti) | 2005 (f. L. Mercalli) | 2012 (f. L. Mercalli)

Are a consequence and a cause of increased warming in mountains

Retreating glaciers

Rhône Glacier, Switzerland

Painting by Caspar Wolf (1735-1783

Retreating glaciers

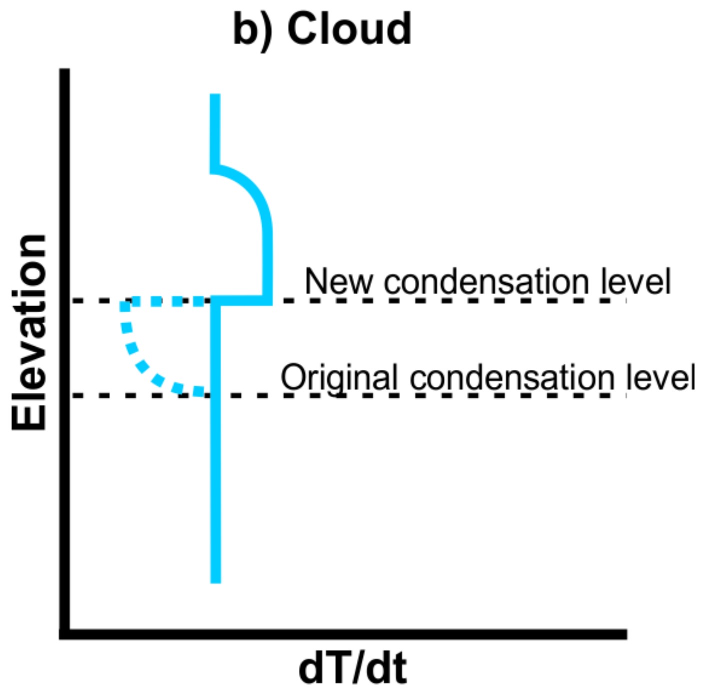
Fradusta, Pale di San Martino, Trentino

Snow at ground melts in advance

Threat to downstream water availability

Hypotheses and Mechanisms for EDW

Clouds



Changes in cloud cover and cloud properties affect

- **SW and LW** radiation → **surface energy budget**
- **Warming rates in the atmosphere through condensation**

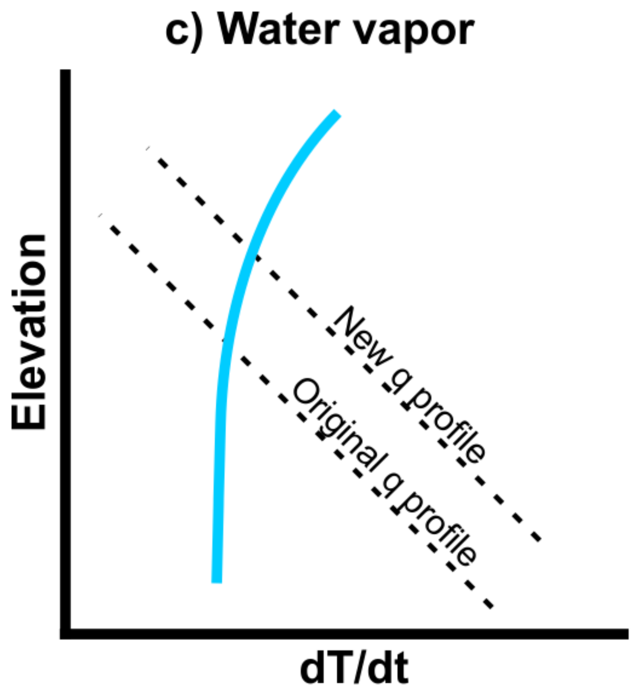
A band of enhanced warming caused by latent heat release is expected near the condensation level

If the condensation level rises then a band of reduced warming would occur immediately below the cloud base, with enhanced warming above

For the Tibetan Plateau between 1961 and 2003 increasing low level clouds at night has caused minimum temperatures to increase

Hypotheses and Mechanisms for EDW

Water vapour and radiative fluxes



Key processes that are expected to lead to an elevation-dependent warming include:

i) **the sensitivity of DLR to specific humidity (q)**

→ **i) DLR increases with increasing q. The relationship is non-linear and exhibits higher sensitivities for lower q (q < 2.5 g/kg) as those found in high-elevated regions**

i) **the relationship between temperature and OLR**

→ **An increase in OLR will result in a larger temperature change at lower temperatures**

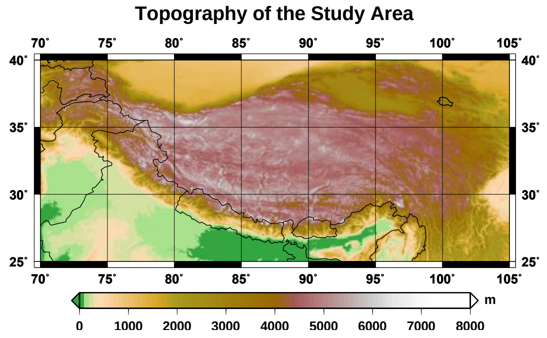
Elevation-Dependent Warming - Himalayas

A model study, EDW in the Himalayas/Tibetan Plateau

Palazzi, E., Filippi, L. & von Hardenberg, J. Clim Dyn (2017) 48: 3991.
doi:10.1007/s00382-016-3316-z

Model ID	Res. (Lon x Lat)	# Grid points (HKKH-TP)
CCSM4	1.25 x 0.9	435
CESM1-BGC	1.25 x 0.9	435
CESM1-CAM5	1.25 x 0.9	435
bcc-csm1-1-m	1.125 x 1.125	434
MRI-CGCM3	1.125 x 1.125	434
CNRM-CM5	1.40625 x 1.40625	275
MIROC5	1.40625 x 1.40625	275
ACCESS1-0	1.875 x 1.25	247
ACCESS1-3	1.875 x 1.25	247
HadGEM2-CC	1.875 x 1.25	247
IPSL-CM5A-MR	2.5 x 1.25874	180
INM-CM4	2 x 1.5	180
CSIRO-Mk3-6-0	1.875x1.875	152
NorESM1-M	2.5x1.89474	120
GFDL-CM3	2.5x2	112
GFDL-ESM2G	2.5x2	112
GFDL-ESM2M	2.5x2	112
GISS-E2-H	2.5x2	112
GISS-E2-R	2.5x2	112
IPSL-CM5A-LR	3.5x1.89474	80
IPSL-CM5B-LR	3.75x1.89474	80
MIROC-ESM-CHEM	2.8125x2.8125	65
MIROC-ESM	2.8125x2.8125	65
bcc-csm1-1	2.8125x2.8125	65
BNU-ESM	2.8125x2.8125	65
CanESM2	2.8125x2.8125	65
FGOALS-g2	2.8125x3	65

CMIP5 models and study area



ETOPO1 NOAA Global Relief Model (~0.008°)

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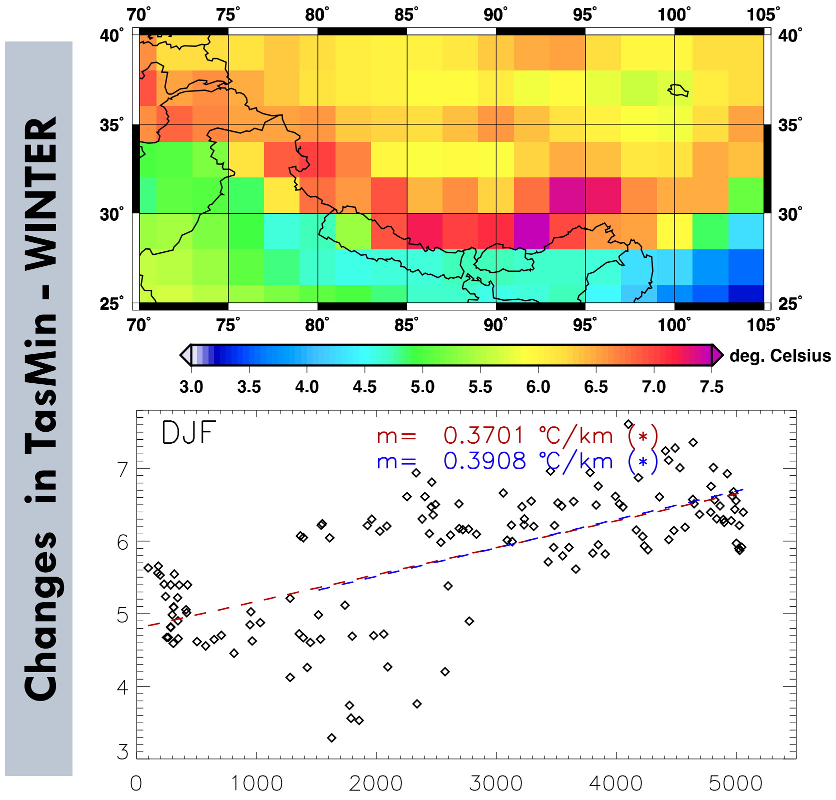
METHODOLOGY FOR EDW ASSESSMENT



1. Calculate temperature trends (°C/year or °C/decade or so) or temperature changes (difference between two long-term climatologies)
   Example in the left: <2071–2100> - <1971-2000> in the RCP 8.5 scenario, minimum temperature, winter

2. Calculate the relationship (assuming a linear regression) between temperature changes and elevations and quantify EDW through the slope of the **linear regression**

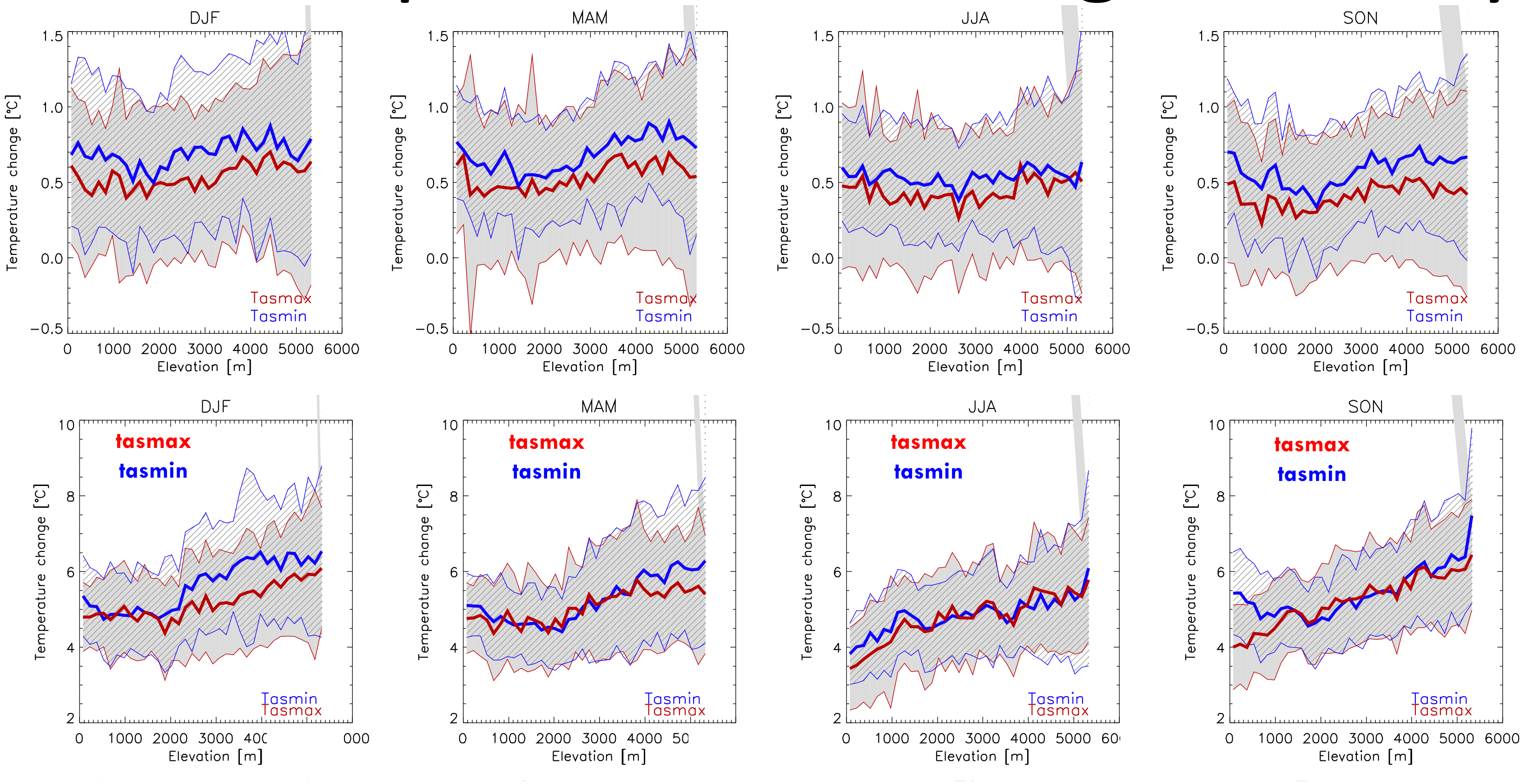
Elevational gradient of warming rate

Δtasmin/Δz

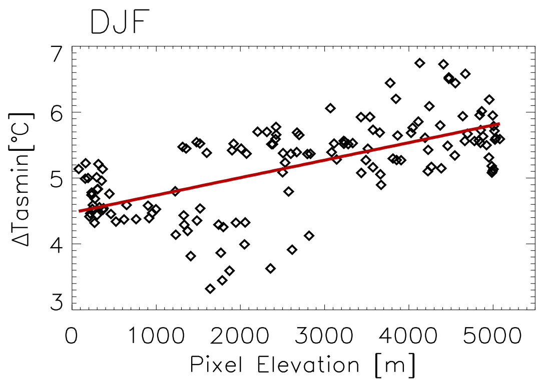
Elevation-Dependent Warming - Himalayas

historical

Scenario RCP 8.5



1871-2000	DJF	MAM	JJA	SON
Hist				
tasmin	0.0135	0.0348	0.0106	0.0173
tasmax	0.0262	0.165	0.0154	0.0164
1971-2100	**DJF**	**MAM**	**JJA**	**SON**
Scenario RCP 8.5				
tasmin	0.3701	0.2803	0.2807	0.2789
tasmax	0.2635	0.2231	0.3816	0.4584



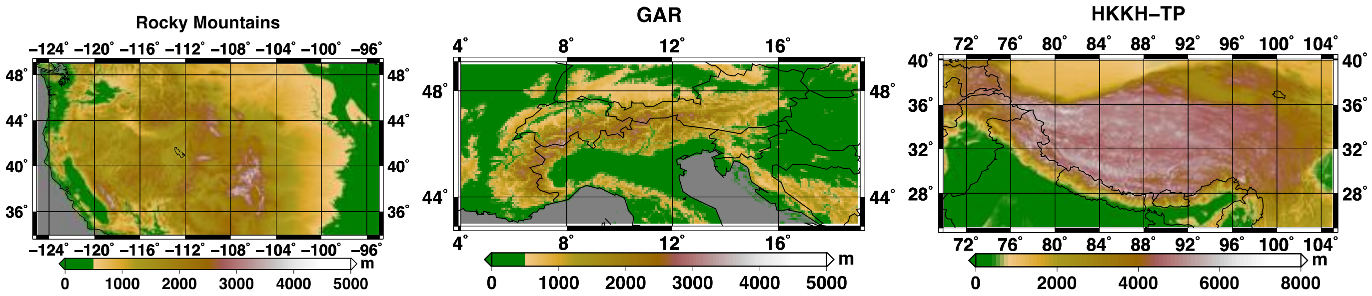
Elevation-Dependent Warming - Himalayas

Possible EDW drivers -1

- Temperature change at the surface is primarily a response to the energy balance → factors that increase the net flux of energy to the surface would lead to EDW
- We consider other model variables simulated by the GCMs whose change may be related to the temperature change and to its dependence on elevation

• Δalbedo • Δhuss • Δrlds • Δrsds	Change in	Albedo near-surface specific humidity surface downward longwave radiation surface downward shortwave radiation
• $\Delta huss/huss_0$ • $\Delta rlds/rlds_0$ • $\Delta rsds/rsds_0$	Normalized change in	near-surface specific humidity surface downward longwave radiation surface downward shortwave radiation

Elevation dependent warming

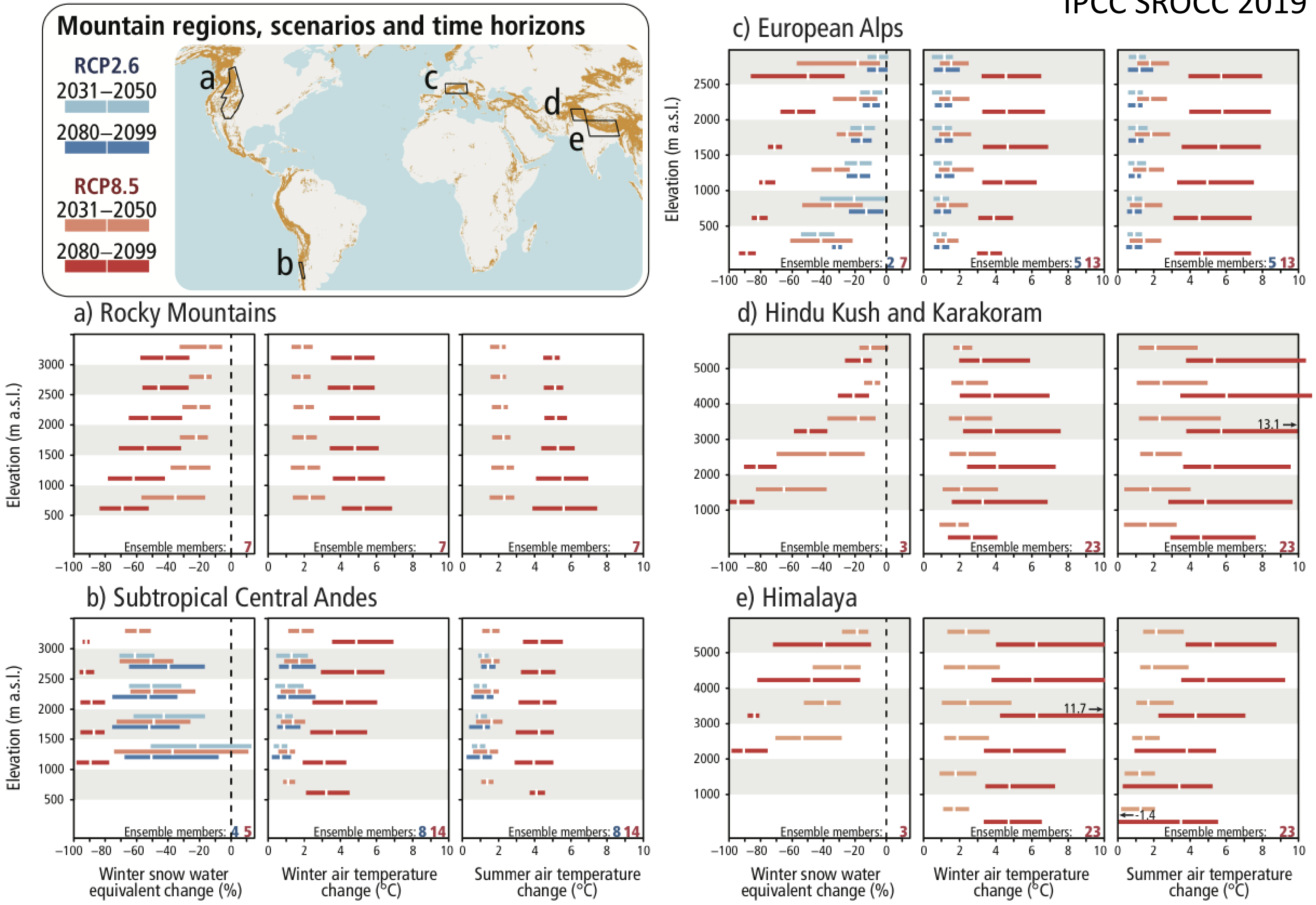


- The region which is found to be more prone to EDW is the HKKH-TP
- The season showing the most striking evidence of EDW in all regions is Autumn

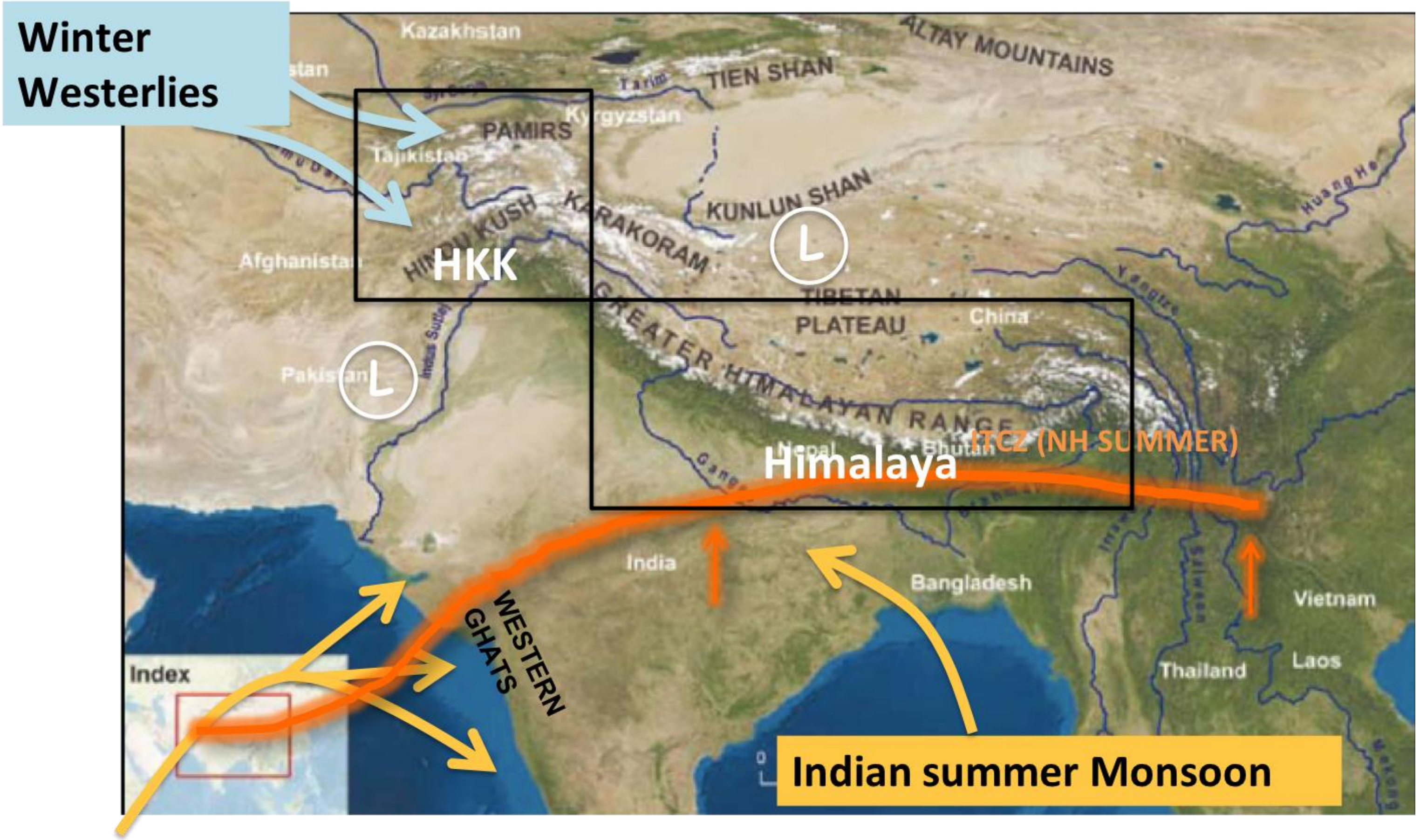
Autumn is a “transition season” between snow-free and snow-covered areas. **Climate warming is delaying the onset of snow cover at low and mid altitudes and this trend is expected to continue in the future, involving higher elevations.** Therefore, larger snow free areas are expected in autumn. (**Albedo change is the most important EDW driver in this study**)

Elevation-Dependent Warming

IPCC SROCC 2019



Precipitation in the HKK-Himalaya



- *Palazzi, E., J. von Hardenberg, and A. Provenzale. 2013. Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios, J. Geophys. Res. Atmos., 118, 85–100. 14.*
- *Palazzi, E., Von Hardenberg, J., Terzago, S., Provenzale, A. Precipitation in the Karakoram- Himalaya: a CMIP5 view, Climate Dynamics, Vol 45, pp. 21-45, DOI: 10.1007/s00382-014- 2341-z, 2015.*
- *Filippi, L., Palazzi, E., von Hardenberg, J. & Provenzale, A. 2014. Multidecadal Variations in the Relationship between the NAO and Winter Precipitation in the Hindu-Kush Karakoram. Journal of Climate (2014). doi:10.1175/JCLI-D-14-00286.1,*

Hindu-Kush Karakoram (vs Himalayas)

- ✓ Climate: not dominated by the summer monsoon

- ✓ Precipitation: concentrated in late-winter and spring, carried on broad scale western weather patterns originating in the Mediterranean/Atlantic regions

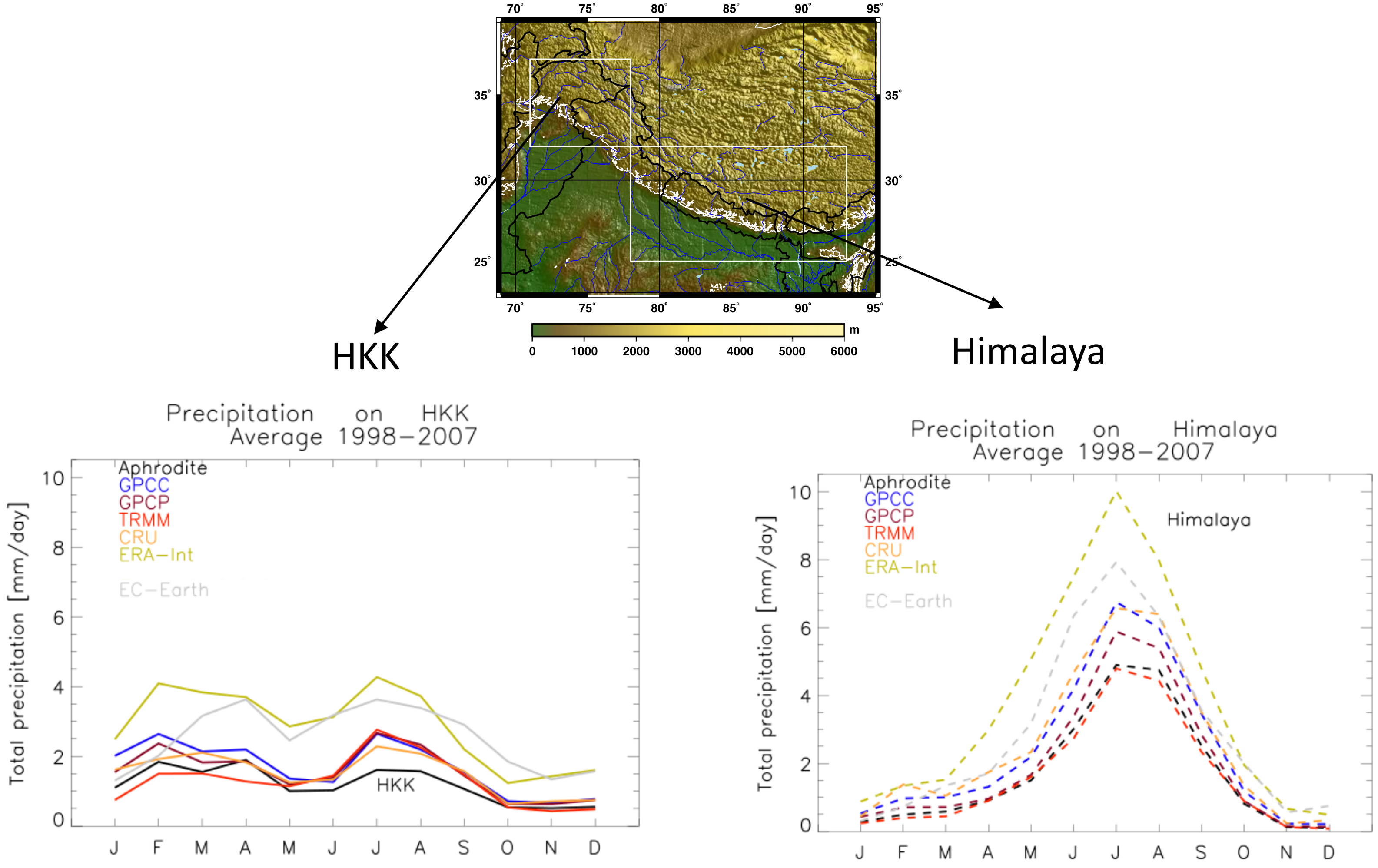
- ✓ Moisture sources and transport of humidity towards the Karakoram

- ✓ Pattern of climatic change in Karakoram
  - ✓ stable/slightly advancing glaciers (Hewitt, 2005; Bishop et al., 2008; Hewitt, 2011; Gardelle et al., 2012; Sarikaya et al., 2012) vs overall retreating glaciers in the Himalaya (Kääb et al. 2012; Bolch et al. 2012).
  - ✓ Decreasing trends in summer temperatures, increasing trends in winter precipitation.

Need of treating the HKK and the Eastern Himalayas separately, owing to the different circulation patterns, seasonal precipitation amounts, glacier behavior.

Precipitation in the HKK-Himalaya

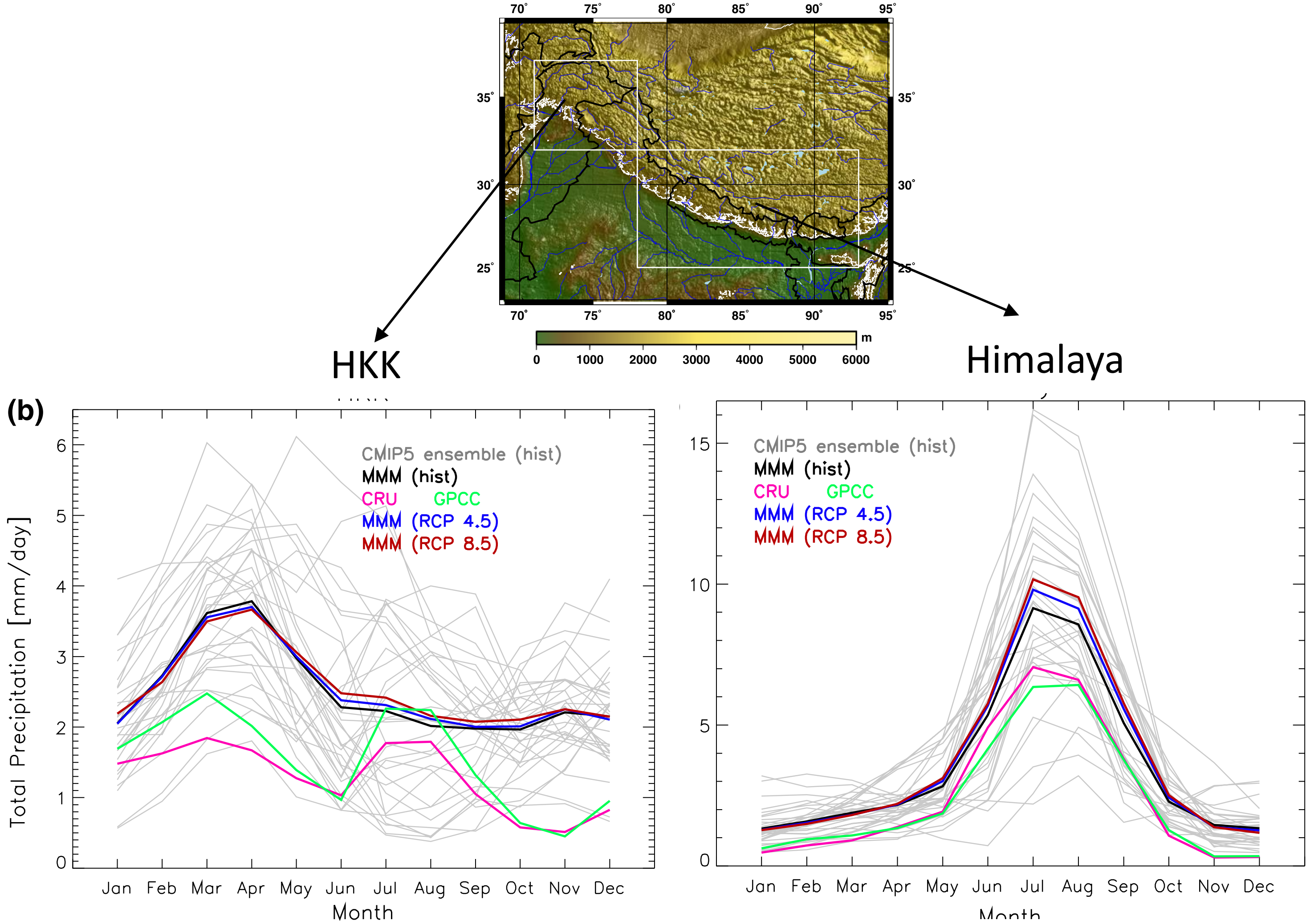
CMIP5 Multi-model ensemble



Palazzi, E., J. von Hardenberg, and A. Provenzale. 2013. Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios, J. Geophys. Res. Atmos., 118, 85–100. 14.

Precipitation in the HKK-Himalaya

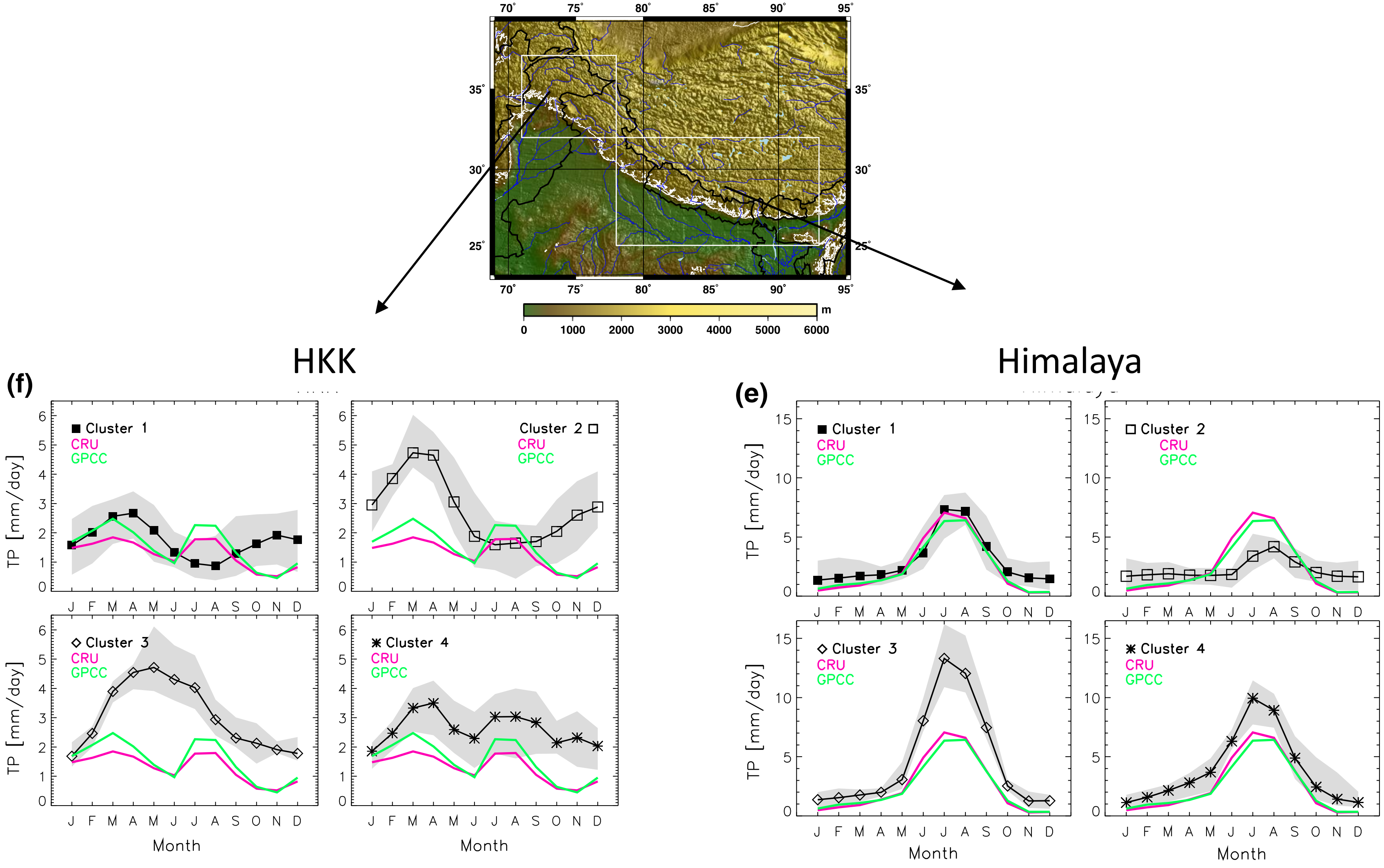
CMIP5 Multi-model ensemble



Palazzi E., J. von Hardenberg, S. Terzago, A. Provenzale. 2014. Precipitation in the Karakoram-Himalaya: A CMIP5 view, Climate Dynamics, doi: 10.1007/s00382-014-2341-z

Precipitation in the HKK-Himalaya

CMIP5 Multi-model ensemble



Palazzi E., J. von Hardenberg, S. Terzago, A. Provenzale. 2014. Precipitation in the Karakoram-Himalaya: A CMIP5 view, Climate Dynamics, doi: 10.1007/s00382-014-2341-z

Precipitation in the HKK-Himalaya

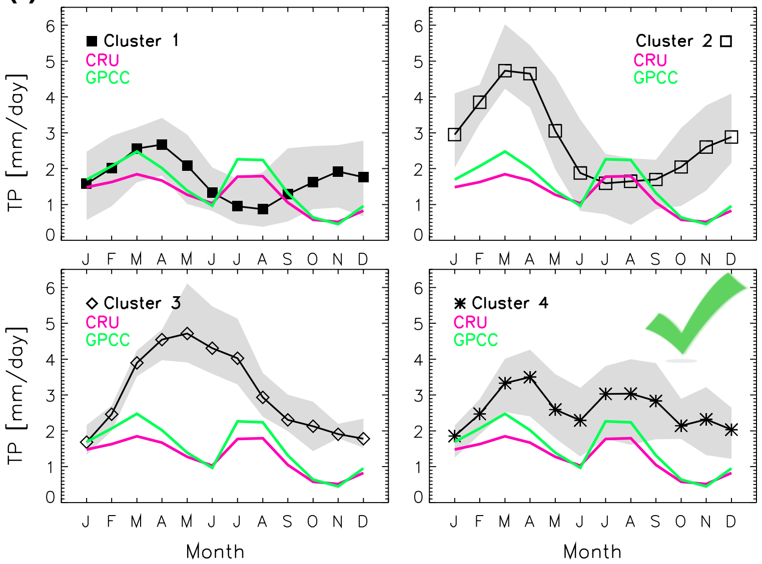
CMIP5 Multi-model ensemble

Higher resolution GCMs

Aerosol particles and their (indirect) effect - included

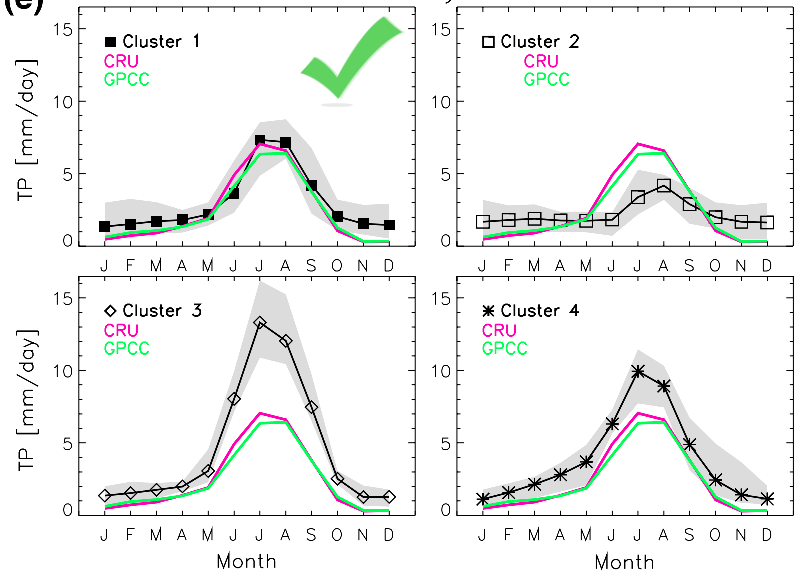
HKK

(f)



Himalaya

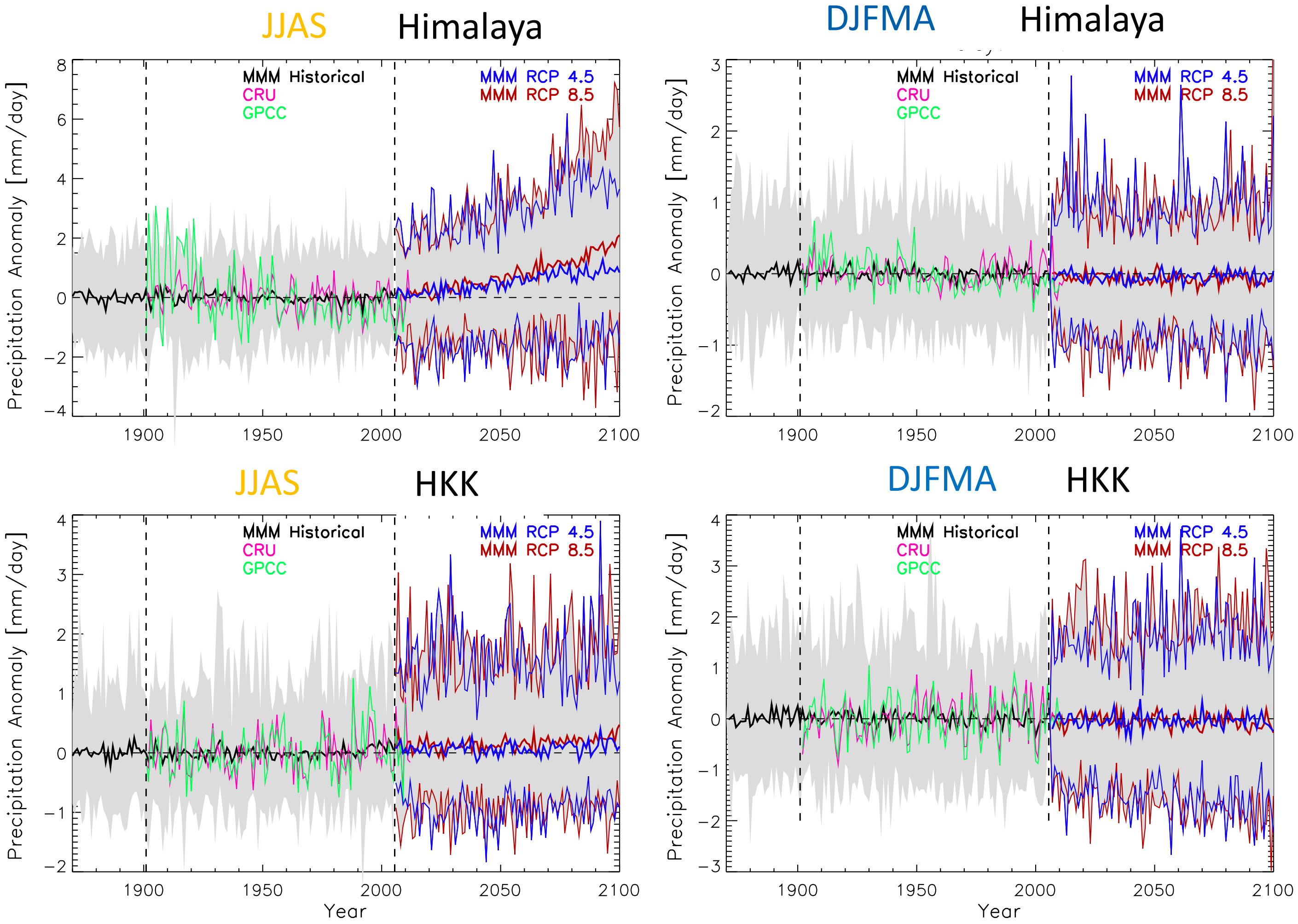
(e)



Palazzi E., J. von Hardenberg, S. Terzago, A. Provenzale. 2014. Precipitation in the Karakoram-Himalaya: A CMIP5 view, Climate Dynamics, doi: 10.1007/s00382-014-2341-z

Precipitation in the HKK-Himalaya

CMIP5 **Multi-model** ensemble



Palazzi E., J. von Hardenberg, S. Terzago, A. Provenzale. 2014. Precipitation in the Karakoram-Himalaya: A CMIP5 view, Climate Dynamics, doi: 10.1007/s00382-014-2341-z

Uncertainty in model simulations

Sources of uncertainty in (global and regional) model simulations :

- **Internal variability**

- **Modelling uncertainty**

- **Scenario uncertainty**

Uncertainty in model simulations

Sources of uncertainty in GCM and RCM simulations :

- **Internal variability**
  - Initial condition uncertainty

Variability that is **unforced** by natural or anthropogenic forcings, but **generated internally in the climate system**. Beyond a few years, this is unpredictable.

- **Modelling uncertainty**

- **Scenario uncertainty**

Uncertainty in model simulations

Sources of uncertainty in GCM and RCM simulations :

- **Internal variability**
  - Initial condition uncertainty
- **Modelling uncertainty**
  - Structural uncertainty
  - Parametric uncertainty
- **Scenario uncertainty**

Variability that is **unforced** by natural or

Structural uncertainty → from different ways to approximate the climate system when building a model.
Parametric uncertainty → model parameters that control unresolved processes can take a range of plausible values.

Sampled by multi-model 'ensembles' (e.g. CMIP5)

Uncertainty in model simulations

Sources of uncertainty in GCM and RCM simulations :

- **Internal variability**
  - Initial condition uncertainty
- **Modelling uncertainty**
  - Structural uncertainty
  - Parametric uncertainty
- **Scenario uncertainty**

Variability that is **unforced** by natural or

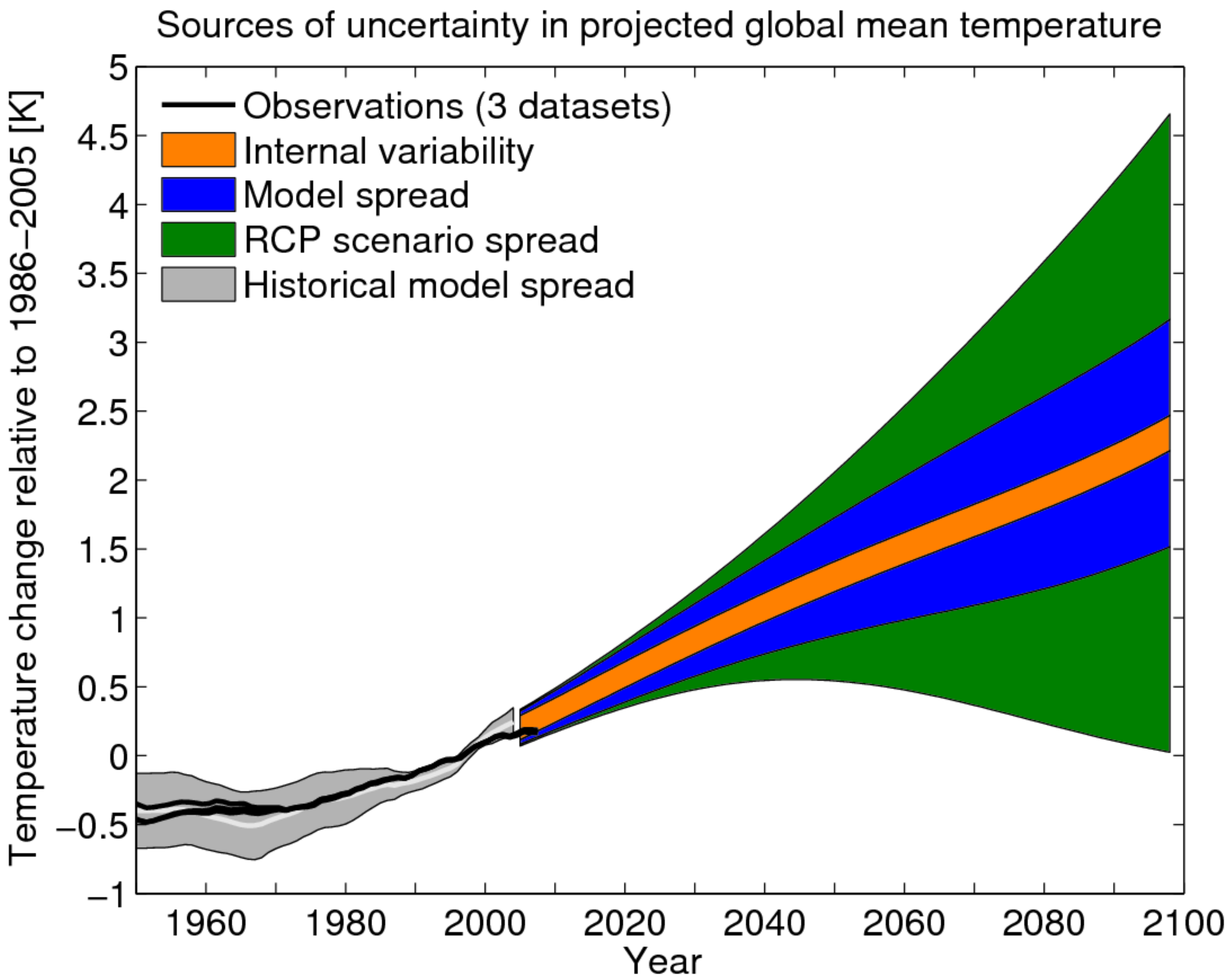
Structural uncertainty → from different ways to approximate the climate system when building a model.
Parametric uncertainty → model parameters that control unresolved processes can take a range of plausible values.

The uncertainty in **global socio-economic development and associated** greenhouse gas and aerosol **emissions**.

Uncertainty in model simulations

Sources of uncertainty in GCM and RCM simulations :

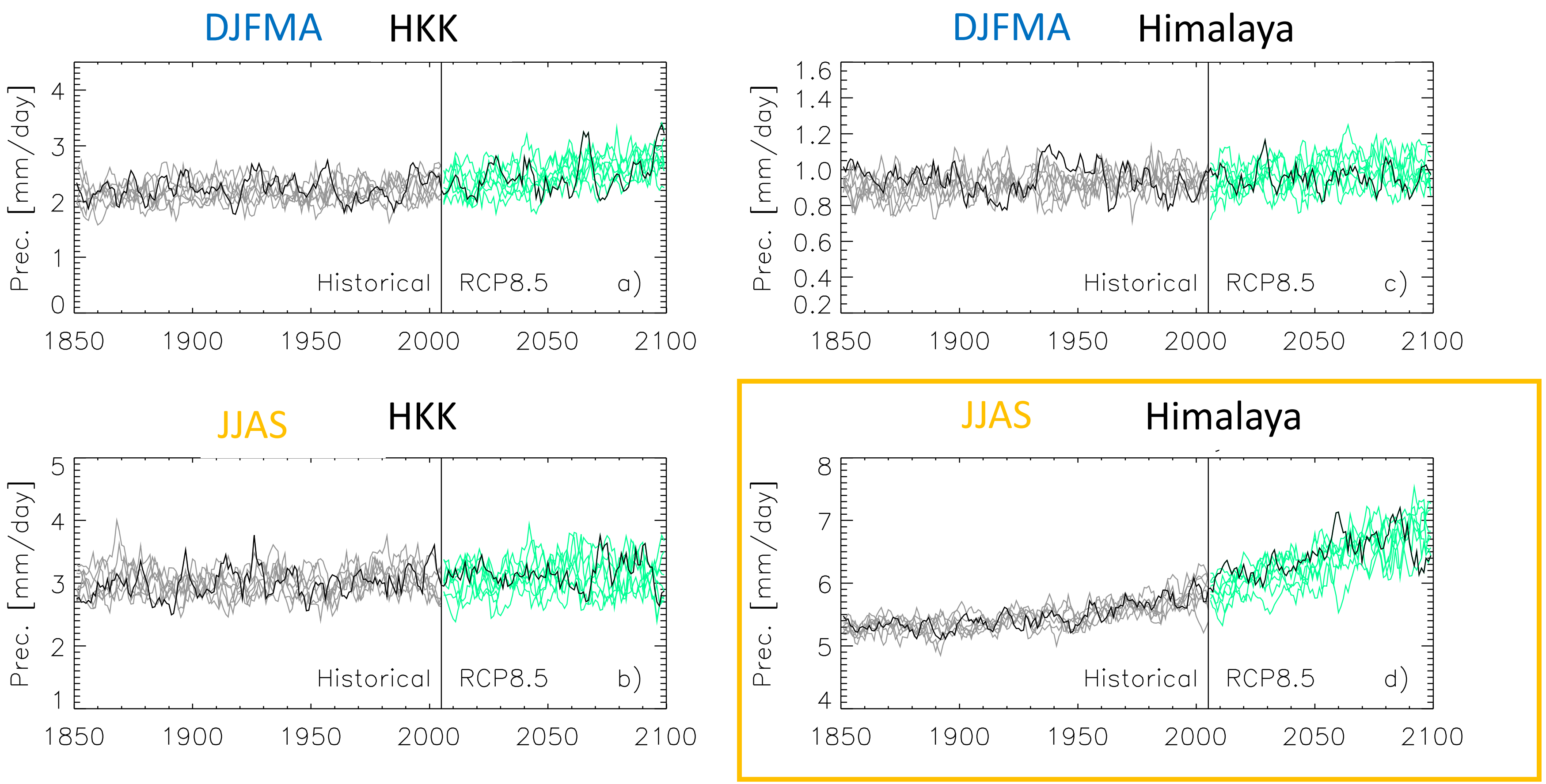
- **Internal variability**
  - Initial condition uncertainty
- **Modelling uncertainty**
  - Structural uncertainty
  - Parametric uncertainty
- **Scenario uncertainty**



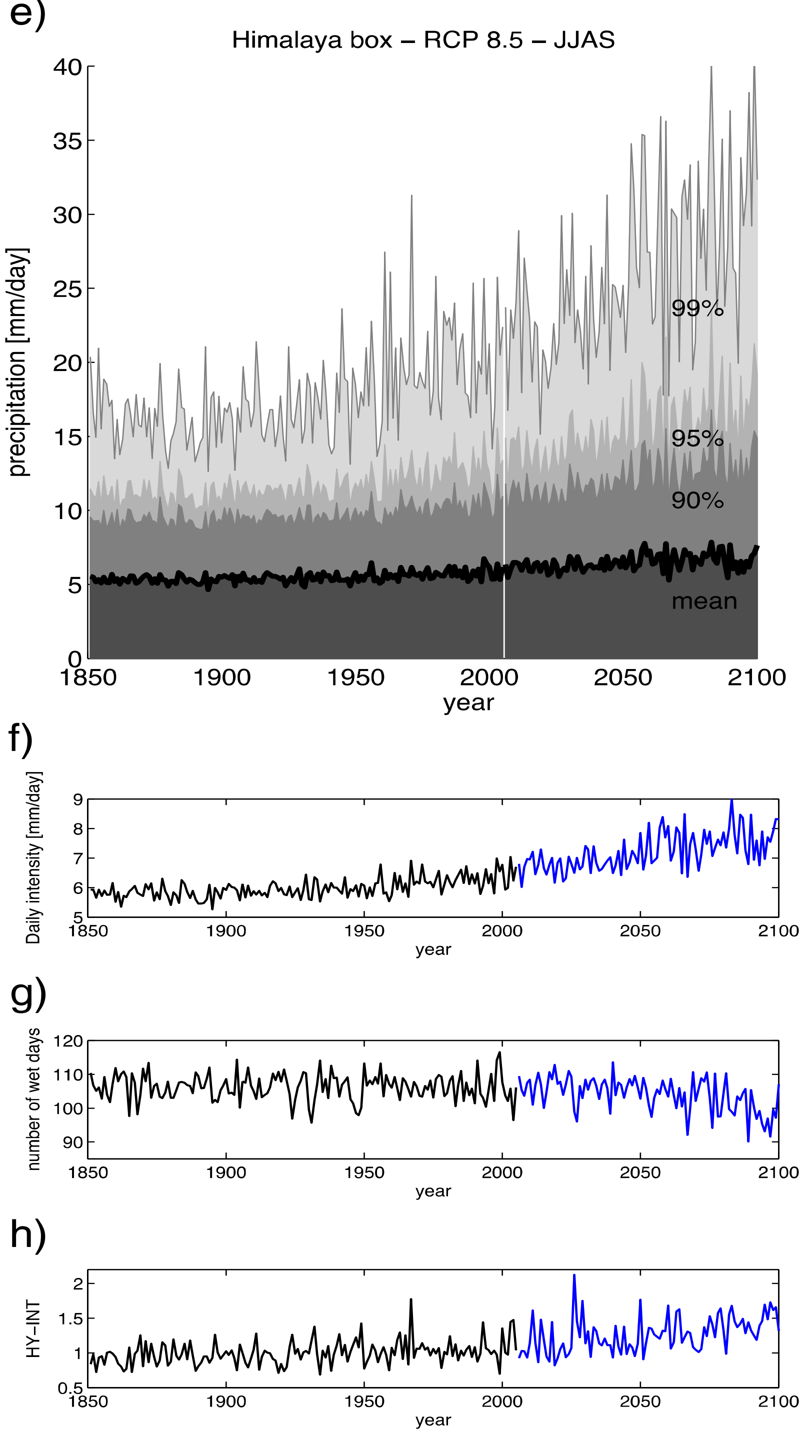
Precipitation in the HKK-Himalaya

Multi-member ensemble (EC-Earth)

CMIP5 Multi-member ensemble



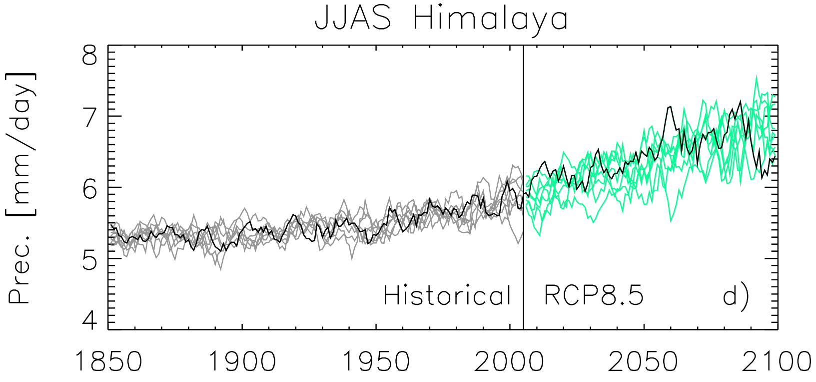
Palazzi, E., von Hardenberg, J., & Provenzale, A. (2013). Precipitation in the hindu-kush karakoram himalaya: Observations and future scenarios. JGR Atmospheres, 118(1), 85-100.



The increasing trend in summer precipitation over the Himalaya is associated with an increasing trend in precipitation extremes.

- **Increase in daily precipitation intensity**
- **Decrease in the number of wet days**
- **Increase in HY-INT**

Trend toward more episodic and intense monsoonal precipitation.

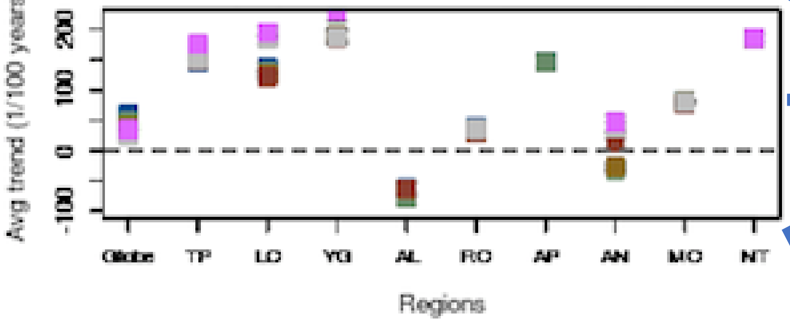


Elevation dependent change in precipitation extremes

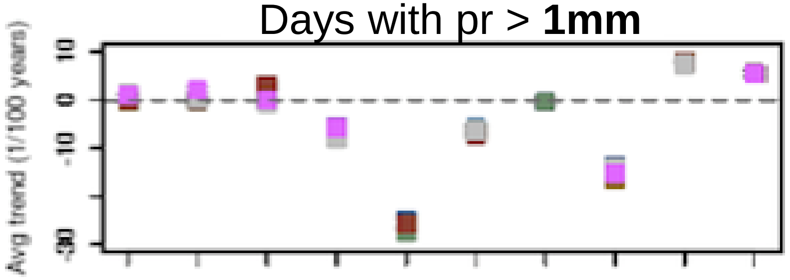
Ensemble mean of all CMIP5 models: 2006-2100 trends of hydroclimatic extremes in mountain regions (RCP 8.5)

Paper in preparation

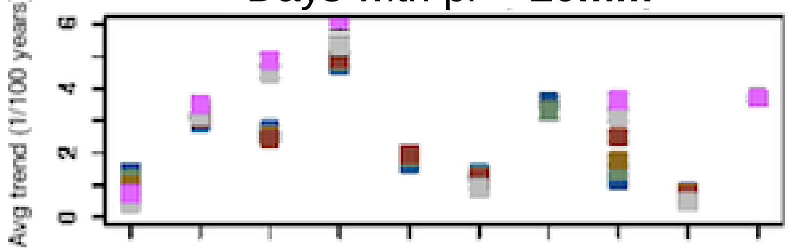
Annual total precipitation in wet days



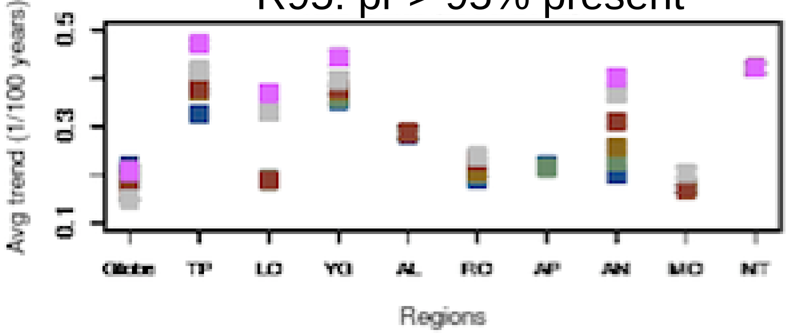
Days with pr > **1mm**



Days with pr > **20mm**



R95: pr > 95% present



- **more days with very intense precipitation**
- **much more precipitation above present 95%.**
- **strong elevation amplification (+50/100% comparing very high vs low elevations)**

Future Needs

- To improve knowledge of mountain temperature trends and (elevation-dependent) climate change and their controlling mechanisms through

    - **Improved observations**
    - **Satellite data**
    - **Model simulations** (both global and fine-scale regional climate model simulations and statistical/Stochastic downscaling methods useful to increase the spatial detail)

Future Needs - Observations

- The surface in-situ climate **observing network needs to be expanded**
  - **to cover data poor regions (high-altitude areas, e.g., above 4000 m, are heavily under-sampled; the tropics)**
  - **to include more variables (humidity, radiation, clouds, precipitation, soil moisture, snow cover, besides minimum and maximum temperature)**.

- Targeted field campaigns should be performed in areas where the climate change signal is expected to be strongest (**including transects across tree-lines and snow-lines, near the 0°C isotherm, e.g. for EDW studies**)

Mountains → should also be regarded as an opportunity to develop new research approaches

- The spatial heterogeneity of the mountains generates methodological challenges for Earth observation (cloudiness, shadows, etc.)

- Mountain areas represent an important opportunity to
  - **Develop more robust approaches of study and to integrate different kinds of observations**
  - **Improve model simultions**

Thank you for your attention