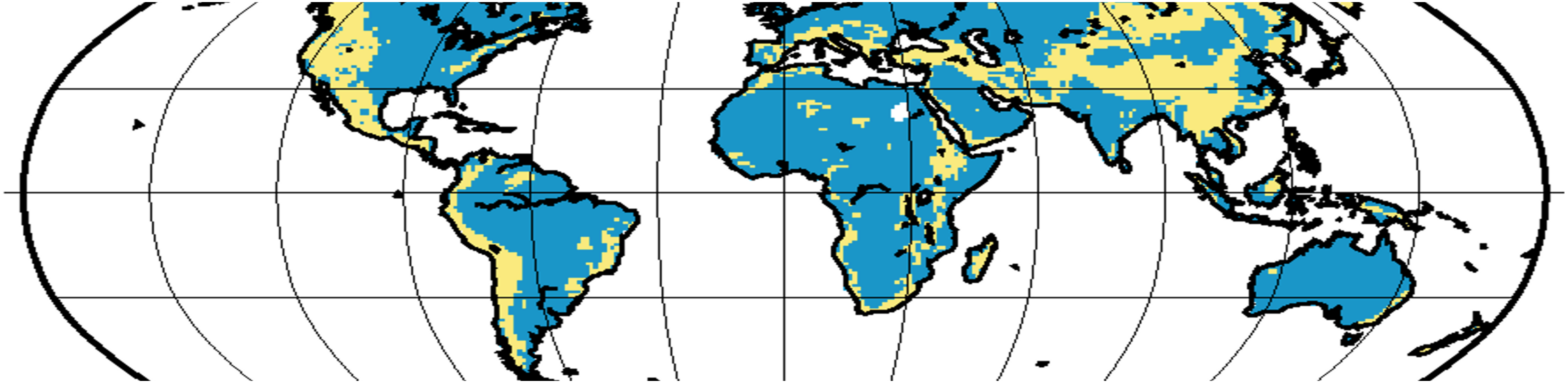

Climate change in mountains around the globe: Elevation dependencies and contrasts to adjacent lowlands

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Introduction

Mountain regions show **distinct and complex characteristics in temperature and precipitation**, which could depict a different **climate and consequent climate change** as compared to low elevation regions, beyond differences due to the geographical position of each site.

Systematic changes in temperature trends with height have been defined as **elevation dependent warming** (Pepin et al. 2015). Despite theoretical arguments as to why high elevations should warm more rapidly than lowlands, **the analysis of past observations has given equivocal results**, in part because of the lack of high elevation stations.

Fewer studies were dedicated to investigate precipitation in mountain regions as compared to adjacent lowlands.

The aim of this work is to **assess elevation dependencies of past temperature and precipitation trends (post 1900) at the global scale** using a) station observations, b) gridded datasets with complete global coverage (CRU, GISTEMP, GPCC, ERA5) and c) climate model simulations (CMIP5).

Elevation dependent climate change

Temperature: Mountain landscapes have distinct characteristics which can lead to **warming** patterns stratified according to elevation (Figure 1):

1. Presence of **snow** and/or **ice**
2. Distinct changes in **vegetation** with height – treeline/tundra transition (albedo changes).
3. **Frequent cloud cover** (forming on mountain slopes)
4. **Reduced water vapour** in air (reduced DLR)
5. **Low temperatures**
6. **Clear air and lack of aerosols** (reduced solar dimming)

Precipitation: Mountains also greatly influence **precipitation**, which may then show a different change at high elevation as compared to adjacent lowlands:

1. **Orographic** enhancement
2. Cross-summit (windward to leeward) **redistribution of water vapour** and leeside evaporation
3. Orographic **convection** (pre-conditioning and lifting)
4. Interaction with **global circulation** and its changes

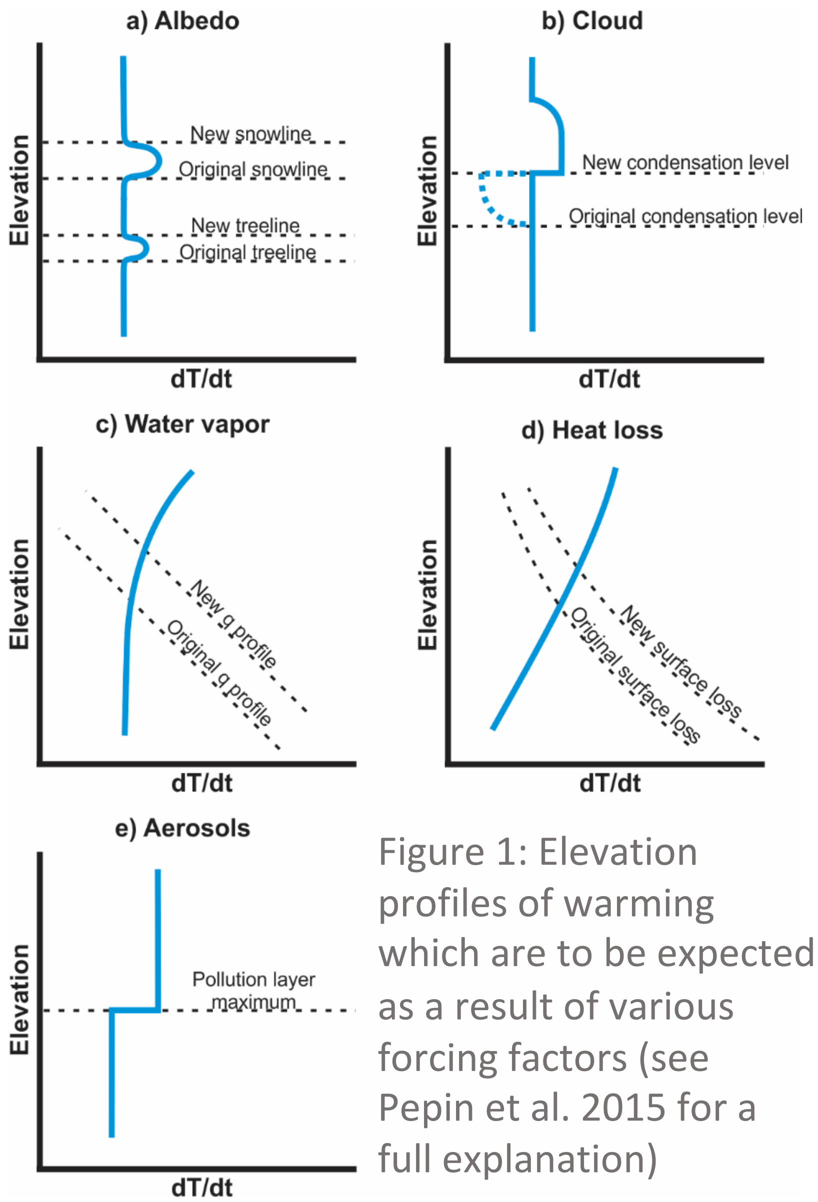


Figure 1: Elevation profiles of warming which are to be expected as a result of various forcing factors (see Pepin et al. 2015 for a full explanation)

Methods: Mountain definition

Defining mountain climate is a challenging task, partly also because of the many approaches adopted in selecting mountains. Here we define mountains using the **K1 definition of Sayre (2018)**: It is based on creating 6 mountain classes using a combination of **absolute elevation, slope and relative relief**. For this analysis all six K1 classes have been combined to create one mountain class.

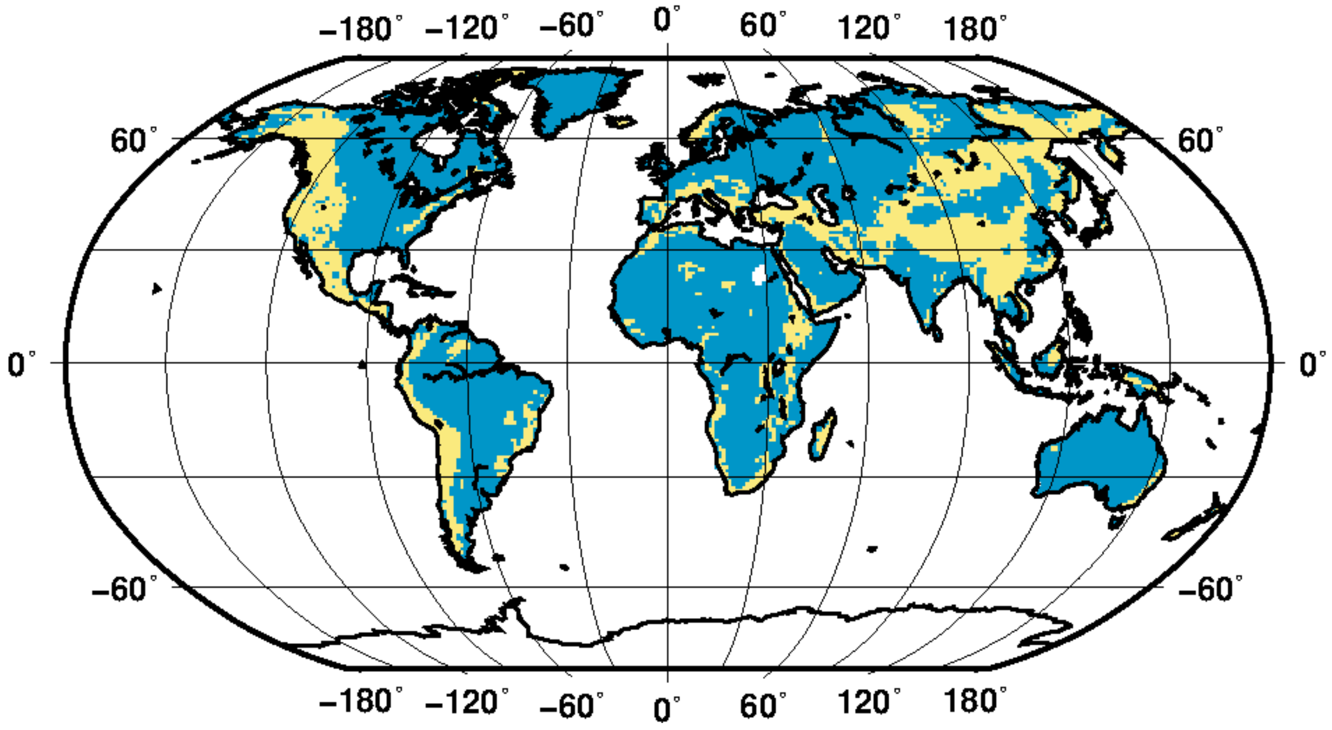


Figure 2: Map showing the global definition of K1 mountain zones (yellow), lowland (blue) and adopted latitudinal bands

Case	Elevation	Slope	Relative Relief	Area million km²	% land surface
1	>4500 m	NA	NA	1.8	1.2
2	3500-4599m	NA	NA	2.7	1.8
3	2500-3499m	NA	NA	6.9	4.7
4	1500-2499m	>3.5%	NA	5.3	3.6
5	1000-1499m	>8.75% OR >300m		6.2	4.2
6	300-999m	NA	>300 m	13.0	8.8
			Total	35.9	24.3

Table 1: Definition of K1 mountains (Sayre et al. 2018).

Methods: station observations, gridded datasets and models

STATION OBSERVATIONS

Previous studies have used various combinations of station observations to analyse elevational patterns in warming. However the **skewed distribution of stations with a majority towards lower elevations** is a source of uncertainty. Here we perform a comprehensive meta-analysis of past studies on temperature and precipitation both for mountain regions, and comparative lowland regions (where a distinct comparison exists). Studies were obtained from a literature analysis performed in the recent IPCC Special Report on Oceans and Cryosphere (SROCC, Hock et al. 2019), which covered both temperature and precipitation.

GRIDDED DATASETS

To compare station trends with regional/global mean values we also calculate trends in mean annual temperature and precipitation from gridded global datasets (ERA5, CRU, GISTEMP and GPCC) and an ensemble mean of historical simulations from CMIP5 global climate models (ENSMEAN), all re-gridded at 1˚ lat-lon spatial resolution. **These datasets have the advantage of covering all mountain and lowland regions**.

Temperature and precipitation anomalies are expressed using the 1986-2005 reference period. Trends are calculated for 1900-2018, 1940-2018, 1960-2018 and 1980-2018 for mountain and lowland areas separately.

Temperature: Station observations

Our meta-analysis of temperature trends based on stations includes 57 studies using different regions, different time periods, and different numbers of stations. Figures 3 and 4 show mean temperature trend magnitudes (as measured by OLR gradient) reported in the literature for various mountain regions across the globe plotted against the mean year of the record.

More recent studies tend to produce stronger gradients (illustrative of increased warming rates over recent decades). There is a wide range of magnitudes within and between continents, and it is not clear that one mountain region is warming much faster than others.

Few studies use distinct paired comparisons (within a region). In all cases but one **the mean high elevation warming rate is more rapid than the mean low elevation trend.**

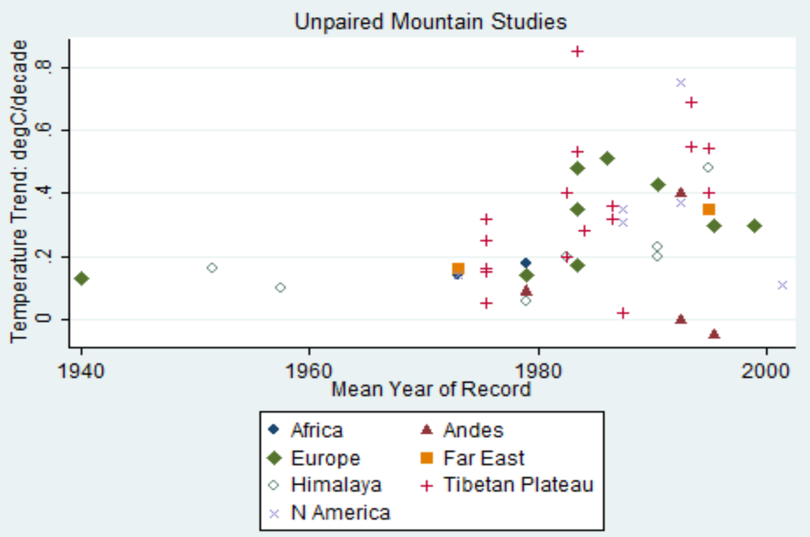


Figure 3 - Temperature trend magnitude vs the mean year of the record for 57 mountain studies reported in SROCC (IPCC, 2019).

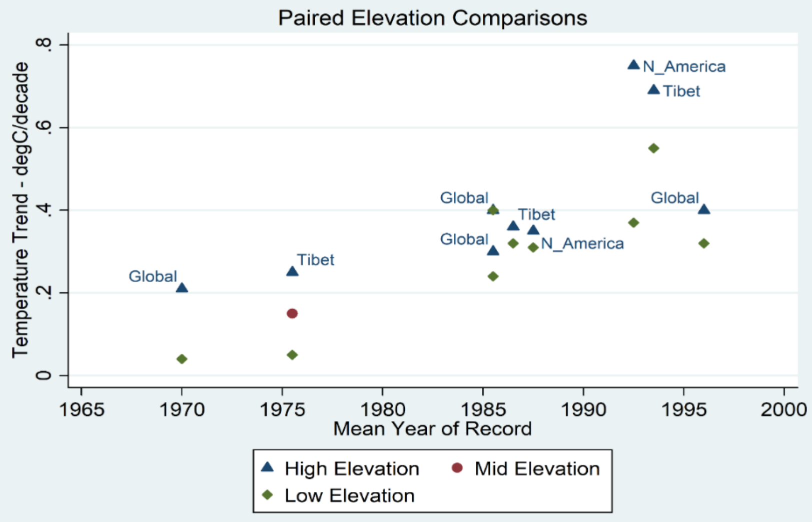


Figure 4 - Paired high/low elevation temperature trend magnitudes (within specific regions) vs mean year of record.

Temperature: Station observations

When a global comparison of temperature trends for all high elevation/mountain regions vs all adjacent low elevation regions (unpaired and not taking geography into account) is performed, **there is no significant difference in the mean trend magnitudes for high vs low elevation regions as a whole** (high/low elevation = **0.268 vs 0.289˚C**/decade (p=0.80)) – Figure 5a.

For paired comparisons, the mean high elevation rate is **+0.412˚C/decade** as opposed to **+0.289˚C/decade** for adjacent low elevation regions (p=0.077) – Figure 5b.

In summary, **enhanced warming with elevation is shown in most paired station studies within regions, but not on a global scale when high and low elevation stations are amalgamated.**

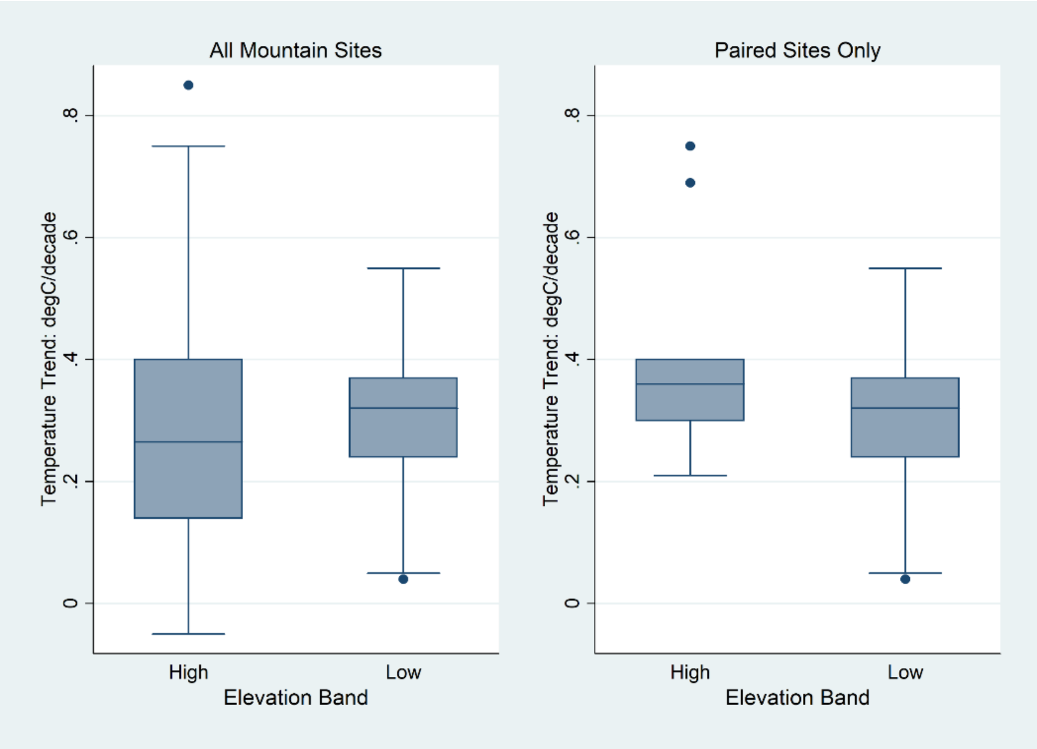


Figure 5: Boxplots showing distribution of trend magnitudes (all periods) for mountain stations vs lowland stations: left) all studies, right) paired studies (within a region) only.

Temperature: Gridded datasets

To partly overcome the bias caused by the uneven distribution of stations, it is helpful to examine global gridded datasets. The table summarises the mean temperature trends for K1 mountain/lowland pixels in several global gridded datasets: spatial analysis of ground observations (CRU, GISTEMP) model based reanalysis (ERA5) and model (CMIP5 ENSMEAN).

Blue cells (dark blue significant at $p<0.05$) show areas where mountain trends are **weaker** than lowland trends.

Pink cells (dark pink significant at $p<0.05$) show areas where mountain trends are **stronger** than lowland trends.

Overall:
There is a **predominance of weaker mountain trends**, suggesting that warming in mountains is less than the latitudinal mean in lowlands.

There is a **slight tendency for this to be reversed in the most recent period**, suggesting that the classic EDW pattern (enhanced at high elevations) is perhaps emerging but only recently.

There are **large inconsistencies and discrepancies between datasets**.

Obs. gridded datasets CRU		Trends are in °C/100y					
		Global	60S-30S	30S-0	0-30N	30N-60N	60N-90N
Mountain/Lowland	1900-2018	1.02/0.97	0.72/0.81	0.65/0.65	0.69/0.74	1.20/1.28	1.53/1.38
	1940-2018	1.51/1.53	1.00/1.22	0.91/1.05	1.06/1.26	1.76/1.94	2.29/2.10
	1960-2018	2.38/2.31	1.37/1.40	1.31/1.48	1.86/1.97	2.63/2.73	4.00/3.83
	1980-2018	2.76/2.63	1.58/1.55	1.28/1.63	2.26/2.21	3.15/3.09	4.42/4.62
GISTEMP							
		Global	60S-30S	30S-0	0-30N	30N-60N	60N-90N
Mountain/Lowland	1900-2018	1.12/1.17	1.00/0.91	1.00/1.21	0.84/0.88	1.20/1.26	1.52/1.58
	1940-2018	1.67/1.80	1.15/1.26	1.24/1.55	1.31/1.52	1.87/2.03	2.29/2.39
	1960-2018	2.58/2.63	1.53/1.55	1.71/1.99	2.09/2.24	2.83/2.91	3.93/4.04
	1980-2018	3.00/2.97	1.56/1.59	1.71/1.95	2.60/2.69	3.35/3.33	4.43/4.76
ERA5							
		Global	60S-30S	30S-0	0-30N	30N-60N	60N-90N
Mountain/Lowland	1980-2018	3.37/3.18	1.65/1.39	2.28/2.06	2.93/3.12	3.84/3.47	4.26/5.23
Global climate models							
CMIP5 ENSMEAN		Global	60S-30S	30S-0	0-30N	30N-60N	60N-90N
Mountain/Lowland	1900-2018	0.84/0.89	0.64/0.58	0.73/0.73	0.68/0.80	0.83/0.89	1.38/1.46
	1940-2018	1.30/1.35	0.85/0.74	1.01/1.01	1.01/1.18	1.37/1.50	2.11/2.22
	1960-2018	2.42/2.48	1.37/1.25	1.79/1.83	1.94/2.14	2.65/2.91	3.50/3.76
	1980-2018	3.88/3.77	1.56/1.50	2.30/2.34	3.03/3.18	4.42/4.71	6.04/6.17

Table 2: Mean mountain/lowland temprature trends (°C/century) for various gridded datasets, time periods and latitudinal bands

Temperature: Case studies

Key mountain regions were analysed in comparison to adjacent lowland surroundings: the Andes, Rockies, Tibetan plateau, Greater Alpine Region (GAR).

Several of them **show distinct differences (p<0.05)** in temperature trends vs lowland surroundings but patterns vary by dataset and region.

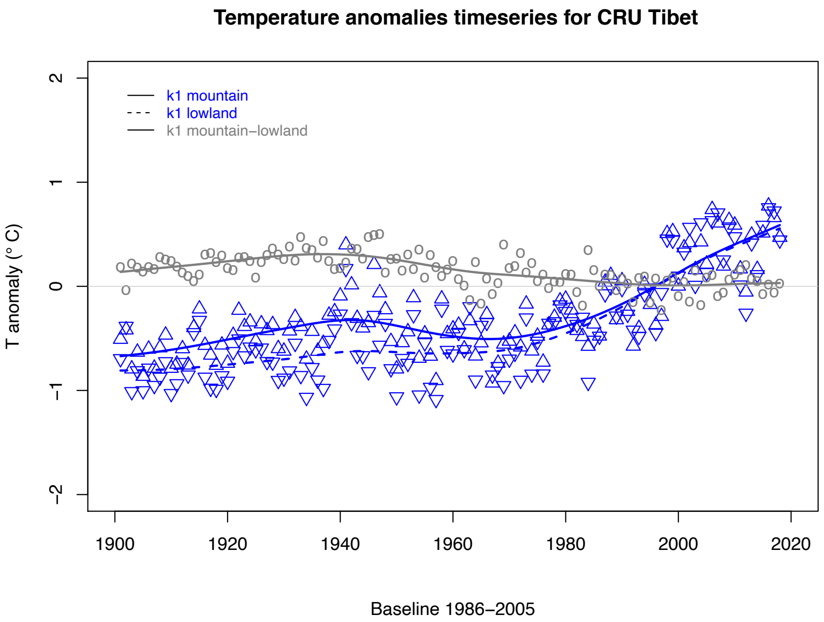
Tibetan plateau: less warming than surr. (CRU, GISTEMP, ENSMEAN), in 1900- and 1940-2018. **As in lat-band.**

Andes: less warming in gridded obs. (CRU 1980-2018, GISTEMP 1940-2018) but more warming in models (ENSMEAN, all periods). **As in lat-band (~).**

GAR: more warming in ERA5 (1980-2018) and less warming over longer periods (1940-2018, GISTEMP and ENSMEAN). **As in lat-band (~).**

Rockies: no significant differences with surroundings. **Not as in lat-band.**

Note: Results are reported in terms of temperature ***anomaly*** *wrt the* ***1986-2005*** *average temperature.*



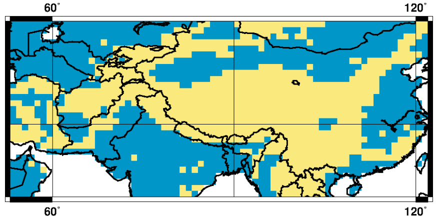
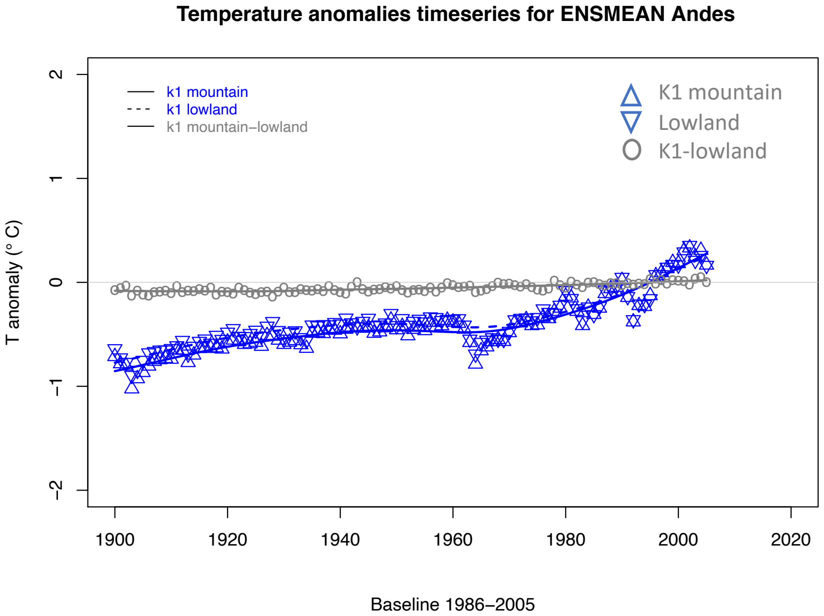


Figure 6 - Top: Tibetan plateau K1 area. Left: anomaly time series for mountain vs lowlands (CRU)



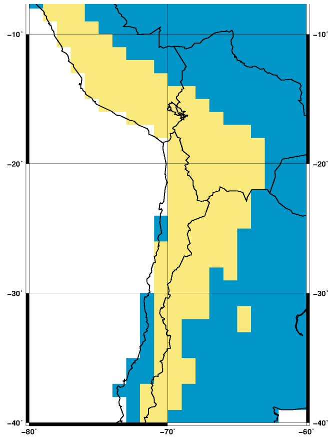


Figure 7 - Top: Andes K1 area. Left anomaly time series for mountain vs lowlands (ENSMEAN)

Precipitation: Station observations

Extension of the meta-analysis to consider precipitation has proved to be **challenging** because of **fewer studies** in the literature. Changes are also expressed both as absolute and percentage change and the two are difficult to compare. Further problems with in-situ precipitation measurements at high elevations (e.g. snow) should also be considered.

Studies were separated into relative and absolute precipitation change groups. **No clear patterns arise from the meta-analysis** (figure 9), with a clear lack of studies extending over long term (>50 years).

Even given this paucity, visually joining the two groups of studies (figure 10), suggests that no linear trend can be identified. It is likely that there is oscillation in trend magnitudes depending on the period considered.

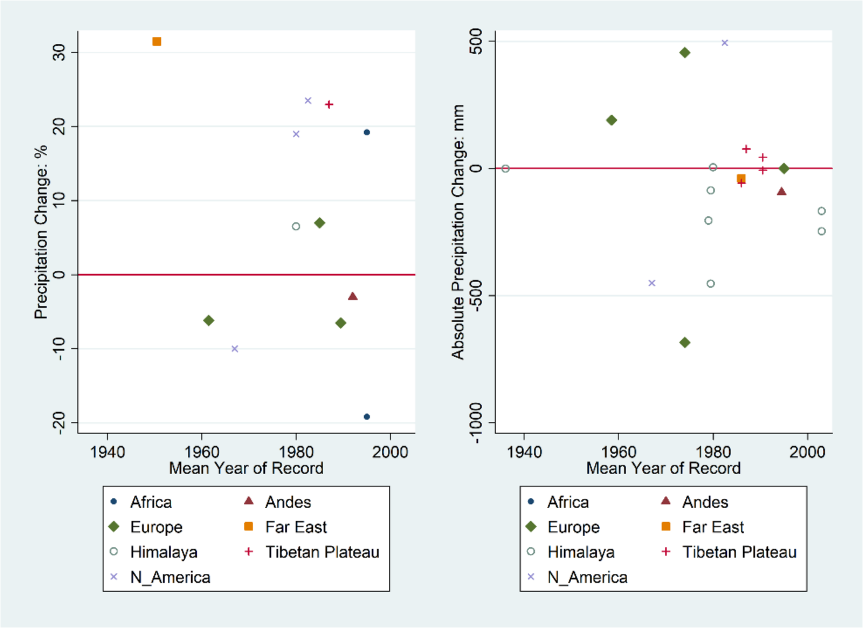


Figure 9: Precipitation change vs mean year of record for studies in mountain regions. Studies adopting relative (%, left) and absolute (right) precipitation change were reported separately.

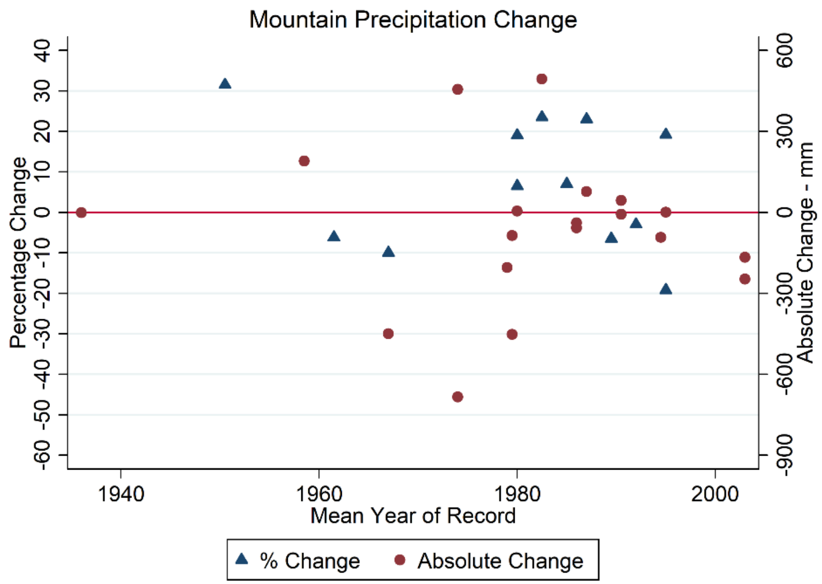


Figure 10: As in Figure 9 but with the two groups plotted together (only visually, no scaling).

Precipitation: Gridded datasets

As for temperature, the table summarises mean precipitation trends for K1 mountain/lowland pixels in several global gridded datasets: spatial analysis of ground observations (CRU, GPCC), model-based reanalysis (ERA5) and model (CMIP5 ENSMEAN),.

Blue cells (dark blue significant at p<0.05) show areas where mountain trends are **weaker** (more drying/less wetting) than lowland trends.

Pink cells (dark pink significant at p<0.05) show areas where mountain trends are **stronger** (more wetting/less drying) than lowland trends.

Overall:
There is a **consistent picture from the CRU and GPCC data sets.**

There is a **clear predominance of weaker or more negative mountain trends at mid-latitudes in both hemispheres**, with precipitation in mountain regions decreasing more (60S-30S) or increasing less (30N-60N) than lowland regions (increasing).

There is a **tendency for a shift in trends in the most recent period**, with a loss of many significant mountain/lowland differences in mid-latitudes and/or a change of sign in the K1-lowland gradient (see ERA5).

There are **less inconsistencies and discrepancies between datasets as compared to temperature**.

Obs. gridded datasets CRU		Trends are in mm/year/100y					
		Global	60S-30S	30S-0	0-30N	30N-60N	60N-90N
Mountain/Lowland	1900-2018	14/22	-3/58	20/32	-6/-12	18/33	32/39
	1940-2018	7/17	-58/42	6/29	3/-33	11/43	25/36
	1960-2018	18/-18	-104/14	-30/8	23/-8	3/43	23/40
	1980-2018	30/71	-186/-64	22/63	109/122	4/50	67/62
GPCC							
		Global	60S-30S	30S-0	0-30N	30N-60N	60N-90N
Mountain/Lowland	1900-2018	5/13	-26/46	5/7	-16/-19	15/32	20/38
	1940-2018	11/18	-51/69	9/9	-21/-38	24/49	38/69
	1960-2018	7/17	-63/71	-4/5	6/-15	13/39	26/42
	1980-2018	22/61	-68/12	-19/60	42/87	26/36	53/81
ERA5							
		Global	60S-30S	30S-0	0-30N	30N-60N	60N-90N
Mountain/Lowland	1980-2018	-115/-107	-155/-192	-167/-188	-186/-127	-110/-76	75/39
Global climate models							
CMIP5 ENSMEAN		Global	60S-30S	30S-0	0-30N	30N-60N	60N-90N
Mountain/Lowland	1900-2018	-4/0	-15/5	-3/-9	-30/-9	1/6	25/21
	1940-2018	-1/6	-9/20	-16/-19	-23/4	4/13	43/37
	1960-2018	26/30	-8/24	10/-13	22/41	22/34	79/74
	1980-2018	70/65	-17/6	-1/-21	113/122	63/70	137/103

Table 3: Mean mountain/lowland precipitation trends (mm/year/century) for various gridded datasets, time periods and latitudinal bands

Precipitation: Case studies

As for temperature, **key mountain regions** were analysed in comparison to adjacent surroundings: Andes, Rockies, Tibetan plateau, Greater Alpine Region (GAR).

Several of them **show significant K1-lowland differences (k1-lowland)** in precipitation trends for high elevations vs lowland surroundings.

Tibetan plateau: no consistency among periods and datasets. **As in lat-band (?).**

Andes: negative K1-lowland difference (decreased orographic gradient) in all obs. datasets and periods (p<0.05 CRU 1900-2018) (Figure 12), but positive (increased orographic gradient) for ENSMEAN. **As in lat-band.**

GAR: negative K1-lowland difference (decreased orographic gradient) for 1900- and 1960-2018 but positive (increased orographic gradient) for 1940- and 1980-2018 consistently among all datasets (<0.05 ENSMEAN). **Not as in lat-band.**

Rockies: negative K1-lowland difference (decreased orographic gradient) in all datasets and periods (<0.05 ENSMEAN, <0.10 CRU) – Figure 11. **As in lat-band**.

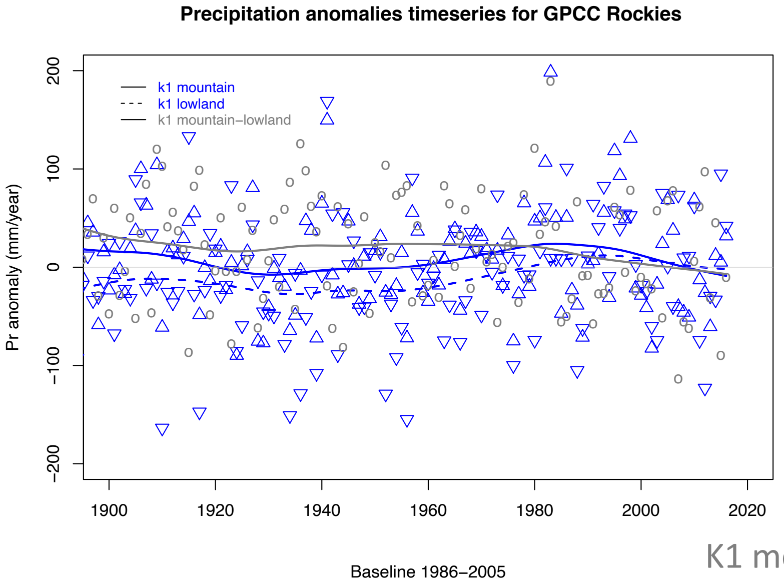
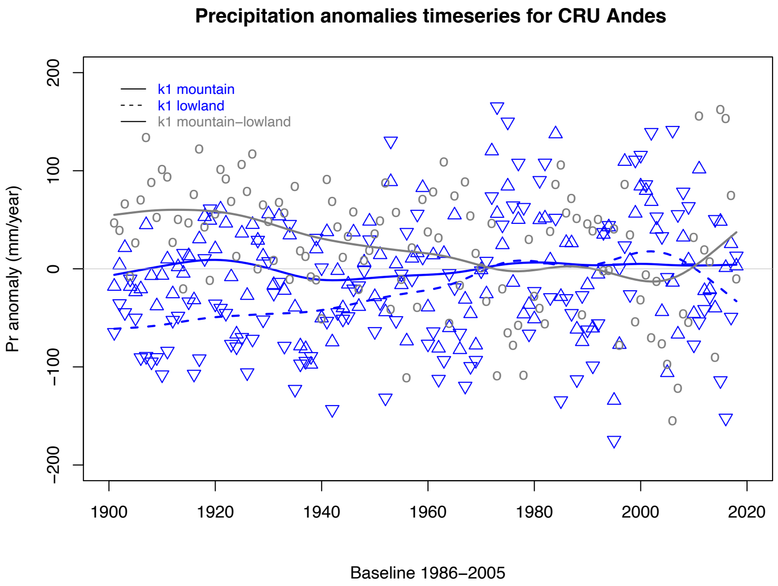


Figure 11 - Left: precipitation anomaly time series for mountain vs lowlands in the Rockies (GPCC)

K1 mountain △
Lowland ▽
K1-lowland ○



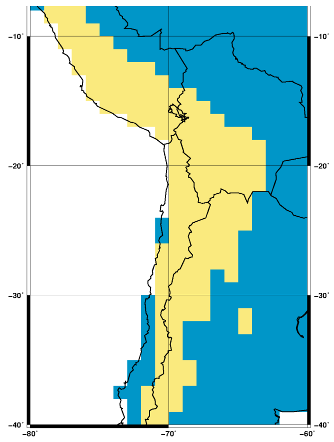


Figure 12 - Top: Andes K1 area. Left: precipitation anomaly time series for mountain vs lowlands (CRU)

Seasonal dependency

Individual seasons show differences in K1 and lowland trends that can consistently contribute to yearly-average trends or compete to cancel it. The seasonal dependence is much larger in precipitation. In some cases, a clear picture emerges.

As an example, Figure 13 shows seasonal timeseries in the 60S-30S latitude band over 1900-2018. The K1-lowland difference is controlled by a steady K1 timeseries and positive lowland trend in SON and DJF, by a negative K1 trend and positive lowland trend in MAM and by almost no trends in JJA. This leads to a consistent **reduction of the K1-lowland difference (decreased orographic gradient)**. This situation is similar also in the CRU datasets.

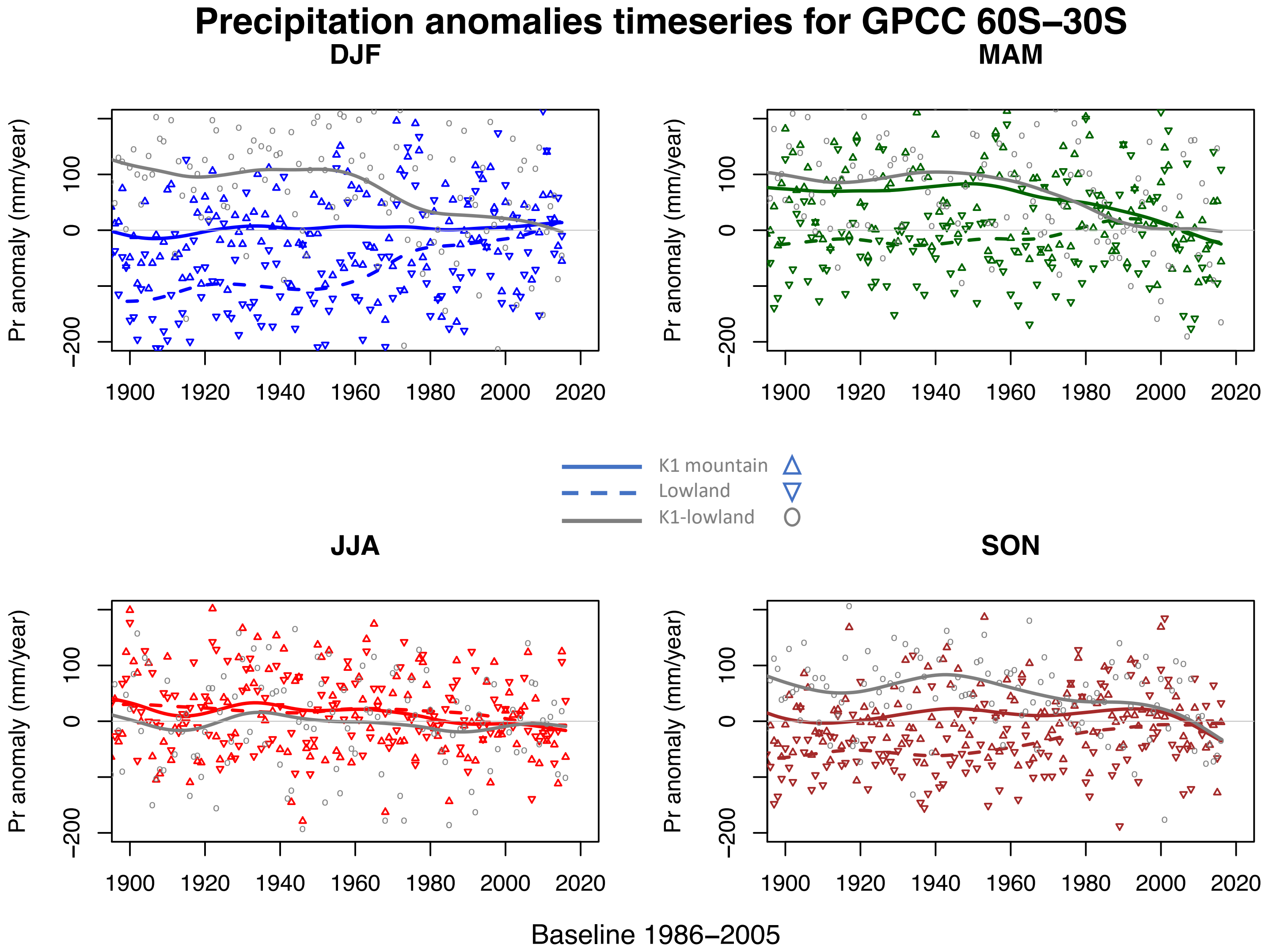


Figure 13 – Mountain vs lowland precipitation timeseries in the 60S-30S band over individual seasons (GPCC dataset).

Temperature vs precipitation trends

For the three gridded observational datasets we can compare the temperature and precipitation trends for both lowland (left) and mountain (right) regions. All periods are included in the figures (not identified separately).

All temperature trends are positive. Most precipitation trends are positive, but there is some strong drying in ERA5.

The broad pattern is that **precipitation trends are independent of temperature trends**, although there **is slight tendency for areas warming more rapidly to be experiencing stronger trends in precipitation**. This relationship is **strongest in ERA5, and in the mountain regions**.

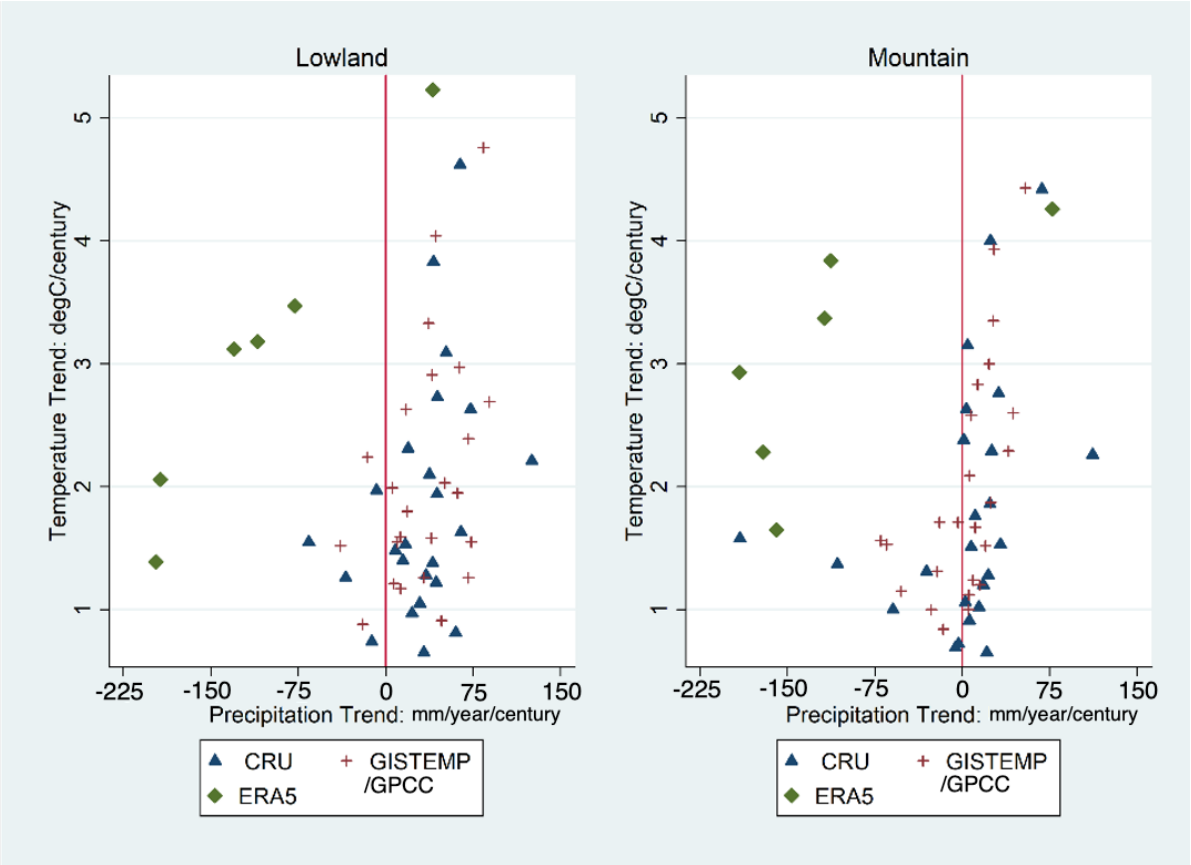


Figure 14: Temperature versus precipitation trends for all four periods in Table 3 (combined) for lowland (left) and mountain (right) regions for each gridded dataset.

Conclusions-1

- There are strong theoretical reasons why mountain areas may warm more rapidly than lowlands. Changing warming rates with height is named **elevation dependent warming (EDW).** Similarly, in some cases **one expects a different change (or trend) in mountain precipitation as compared to lowlands**.

- A meta-study of the literature shows **significantly more rapid warming at mountain stations** as compared to lowlands when only paired studies (same region, different elevations) are considered, whereas no difference is found at global scale between high- and low-elevation regions. **No clear results based on in-situ stations are found for precipitation.**

- Gridded datasets are used to compare mountain (K1) and lowland trends globally: **Mountain temperature trends are often weaker than lowland (i.e. no positive EDW).** Mountain precipitation trends are often **more negative/less positive than lowland especially at mid-latitudes,** whereas they tend to be **less negative/more positive at low latitude.**

- **Trends in temperature have accelerated over time, but more so in mountain regions**, meaning that there is a slight tendency for mountain trends to be stronger more recently. **A change in behaviour is also seen in precipitation in the most recent period, but with a loss of significance or a change in sign of the mountain-lowland differences**.

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Conclusions-2

- **On a local scale changes are inconsistent**, several individual mountain ranges show more/less warming and/or different precipitation changes than "adjacent lowlands".
- **Lack of stations at high altitude can negatively impact the analysis**. For both stations and gridded datasets, the definition of "adjacent lowlands" may influence the quantification of EDW and changes in precipitation.
- **Comparison between datasets shows discrepancies in temperature results,** whereas, perhaps surprisingly, **a better agreement is found for precipitation,** particularly at mid-latitudes.
- **Work is needed to understand differences between gridded datasets, station observations and model runs** (and among members of each category), if we are to have confidence in future predictions of elevation dependencies in temperature and precipitation.

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