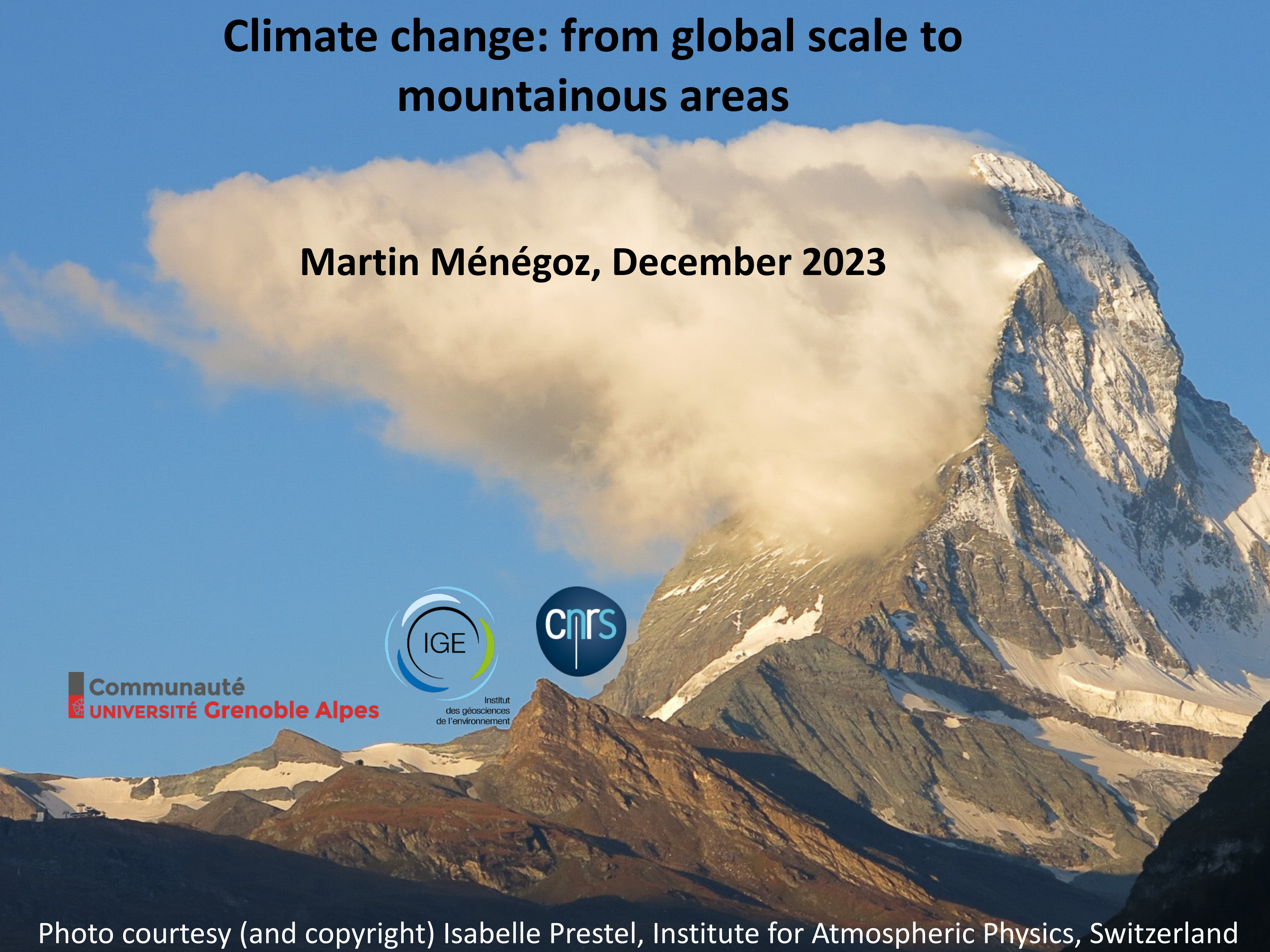
Climate change: from global scale to mountainous areas

Martin Ménégoz, December 2023



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IGE Institut des géosciences de l'environnement
cnrs

Quiz

We are now at around +1.1°C globally compared with ~1850. Current policies to reduce greenhouse gas emissions will bring us to...

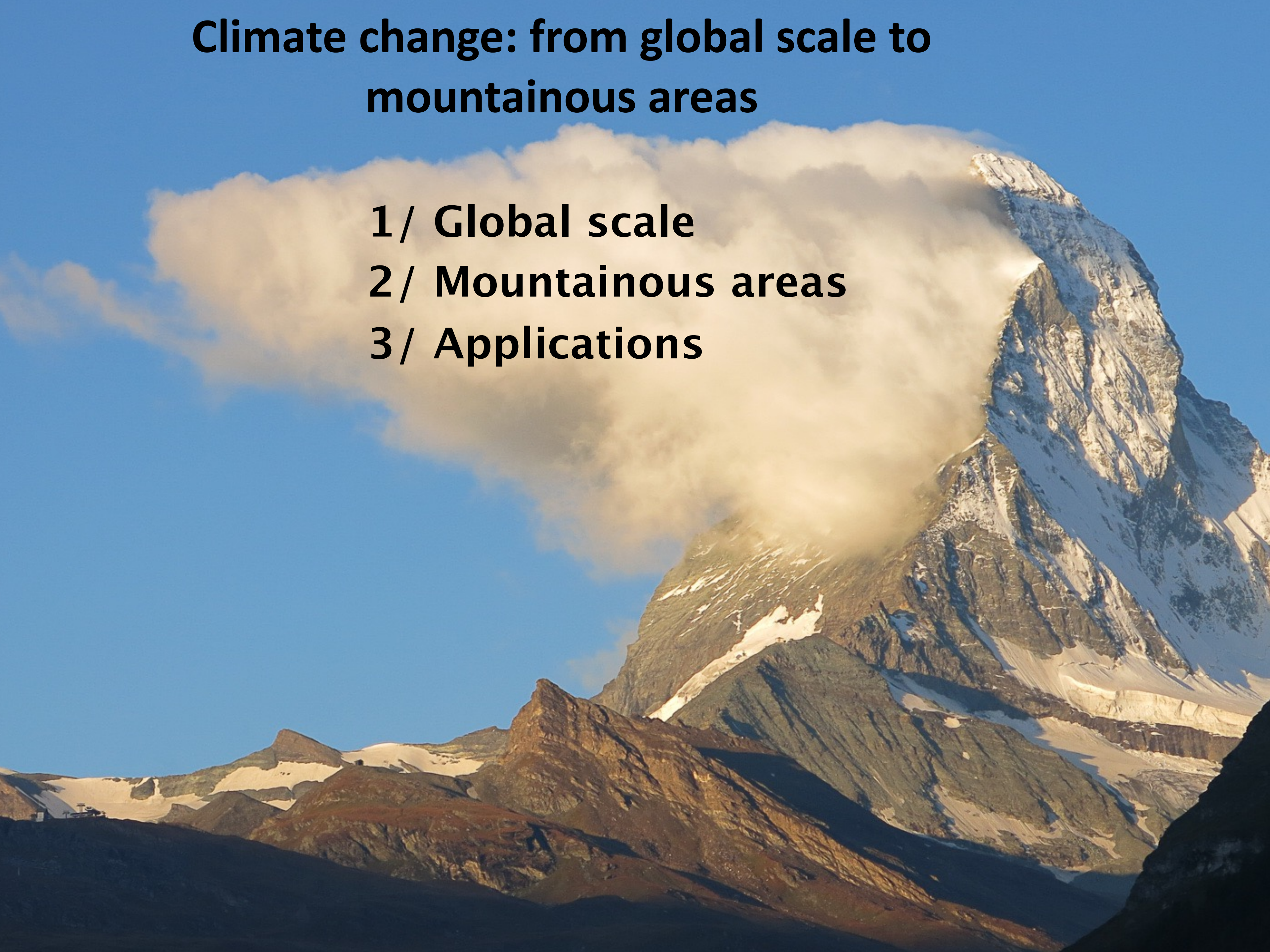
a) ... 4.9°C (between 4.3 and 5.6°C)
b) ... 3.2°C (between 2.2 and 3.5°C)
c) ... 2.5°C (between 1.7 and 2.9°C)

If we manage to reduce instantaneously anthropogenic CO2 emissions to zero at global level, ...

a) ... the global average temperature will return to pre-industrial levels in ~30 years.
b) ... the temperature will rapidly stabilise around the level reached at the time of "net zero".
c) ... the Earth will continue to warm for ~50 years, by a further 0.5°C or so.

Depending on the scenario, the estimation of the glacier mass change in the Alps between 2000 and 2100 is...

a) -33 to -62%
b) -82 to -96%
c) +24% (gain) to -37% (loss)

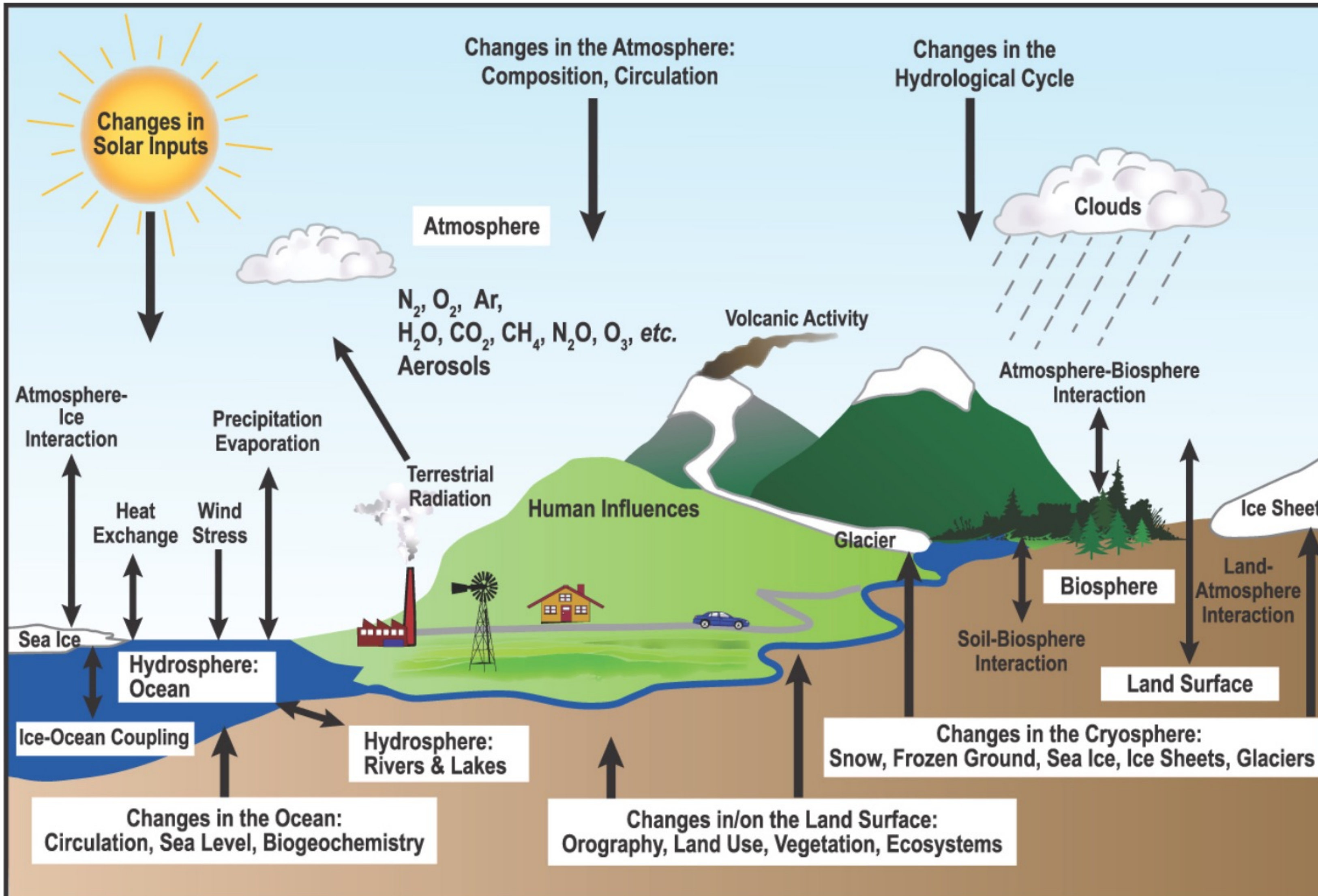

Climate change: from global scale to mountainous areas
1/ Global scale
2/ Mountainous areas
3/ Applications

Climate change: from global scale to mountainous areas

1/ Global scale

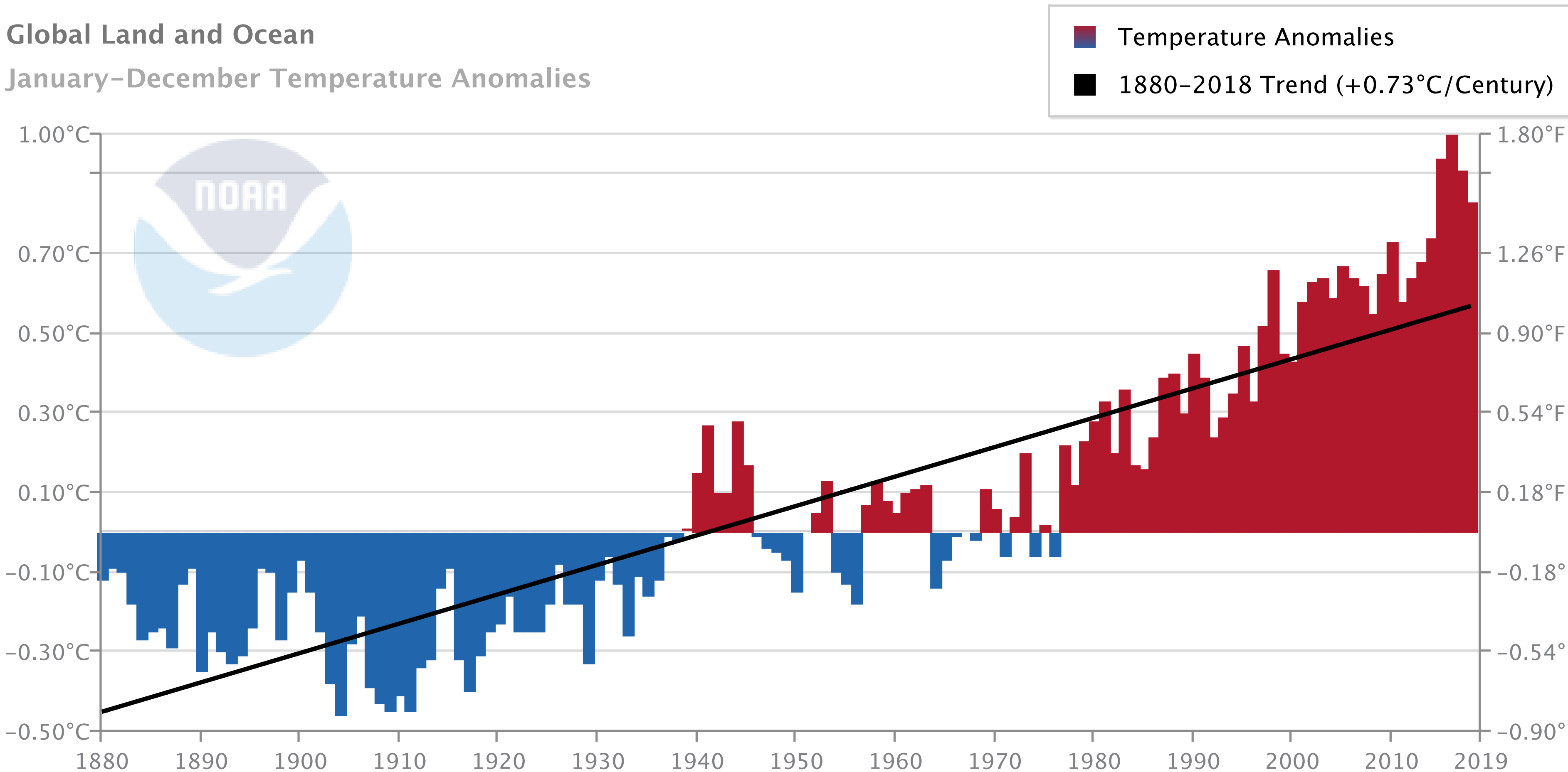
The climate system

Ocean <-> Atmosphere <-> continental surfaces <-> other components

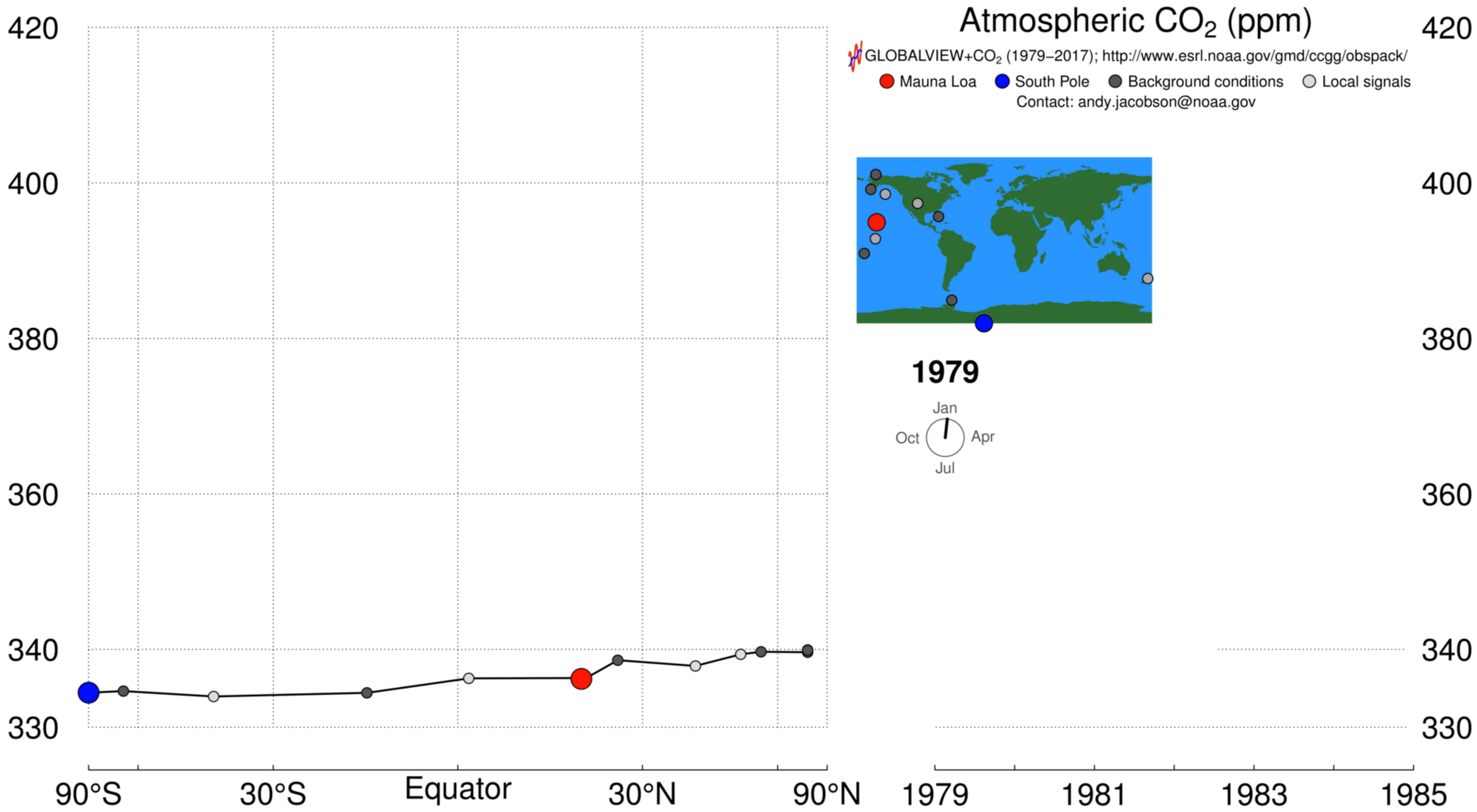


Source : IPCC AR4 (2007) FAQ 1.2 Fig. 1.

A significant global warming…



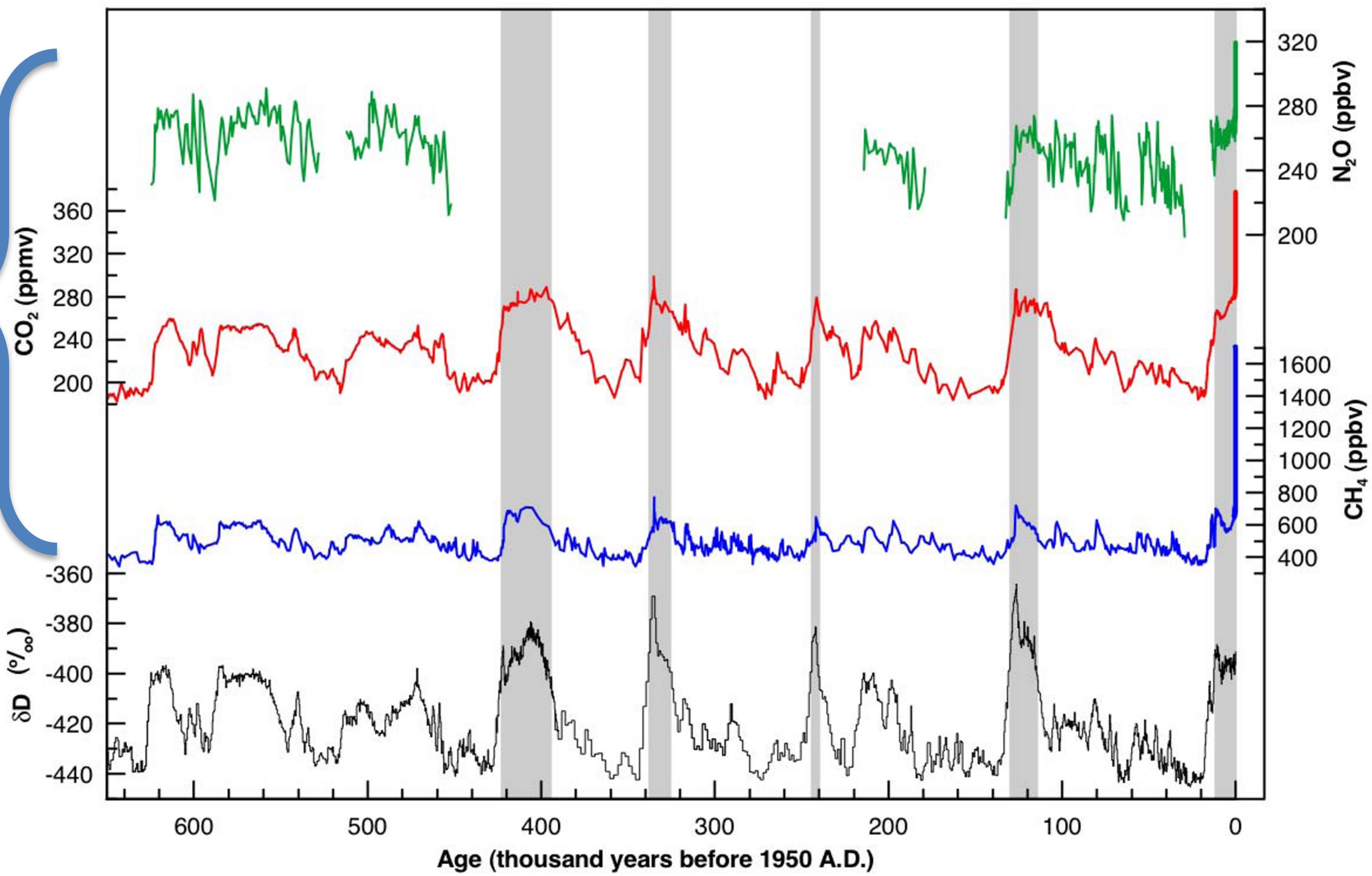
Observing the concentration of carbon dioxide in the atmosphere



Ice core observations

Greenhous gases

Température

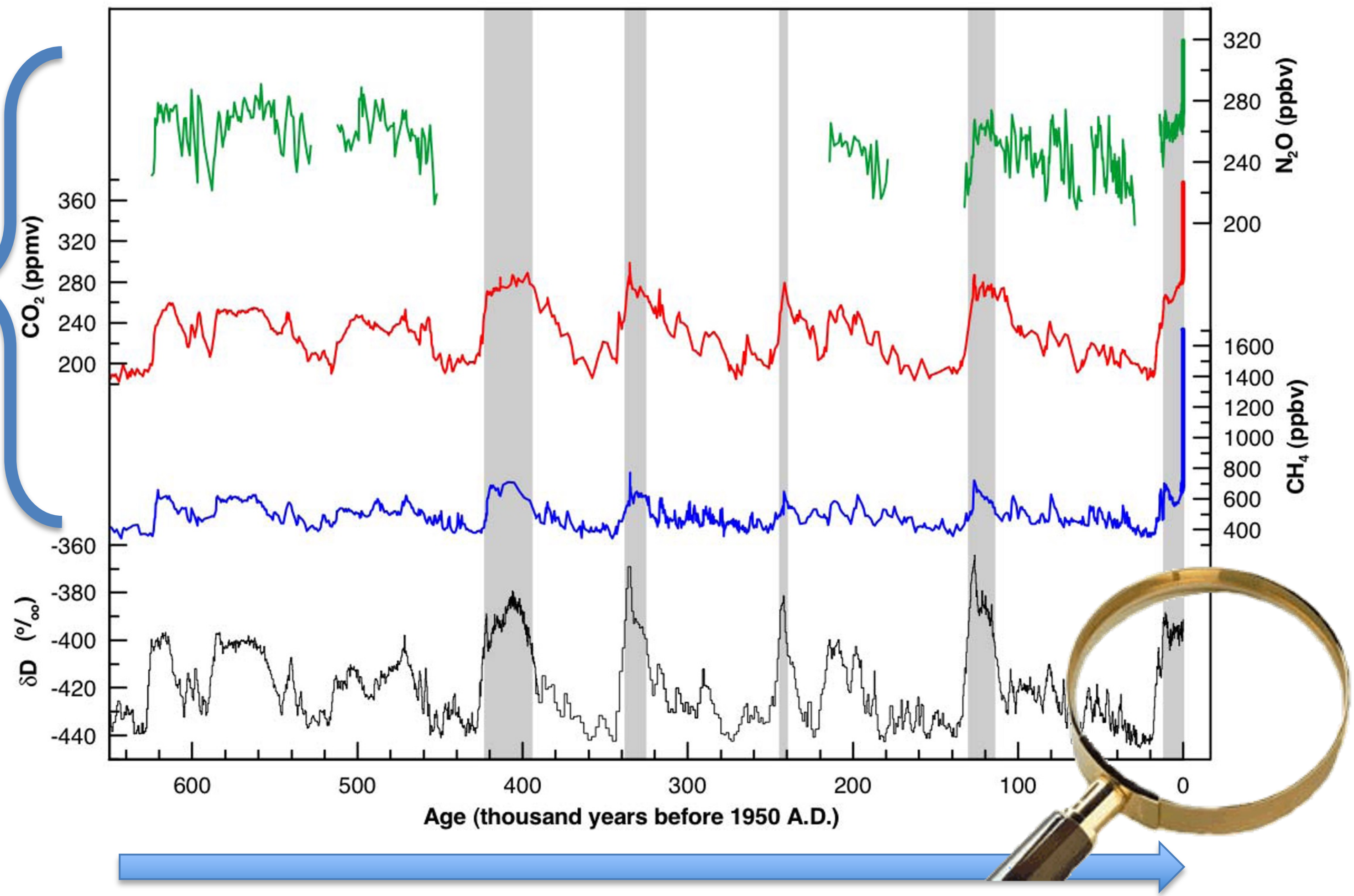


800 000 years

Ice core observations

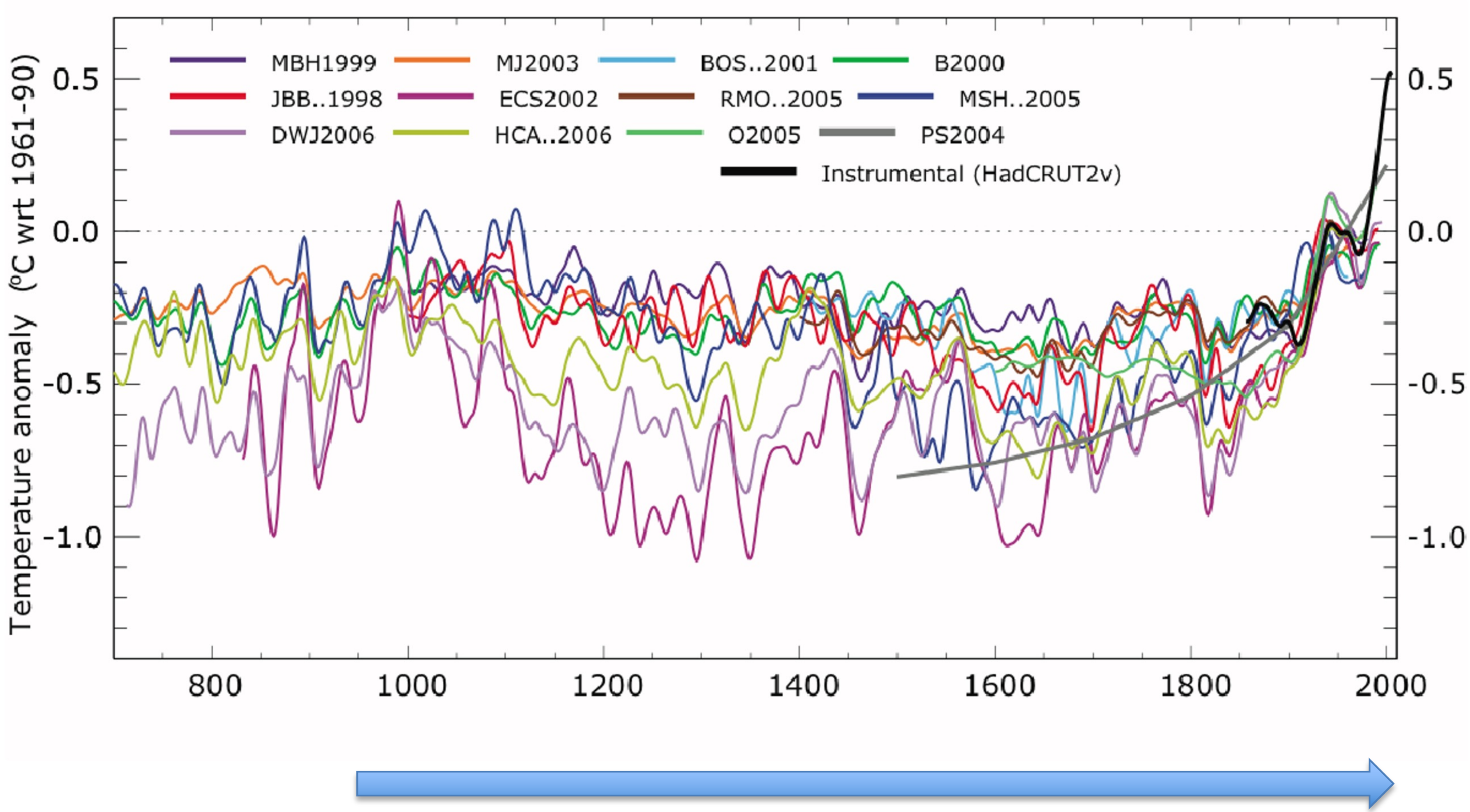
Greenhous gases

Température



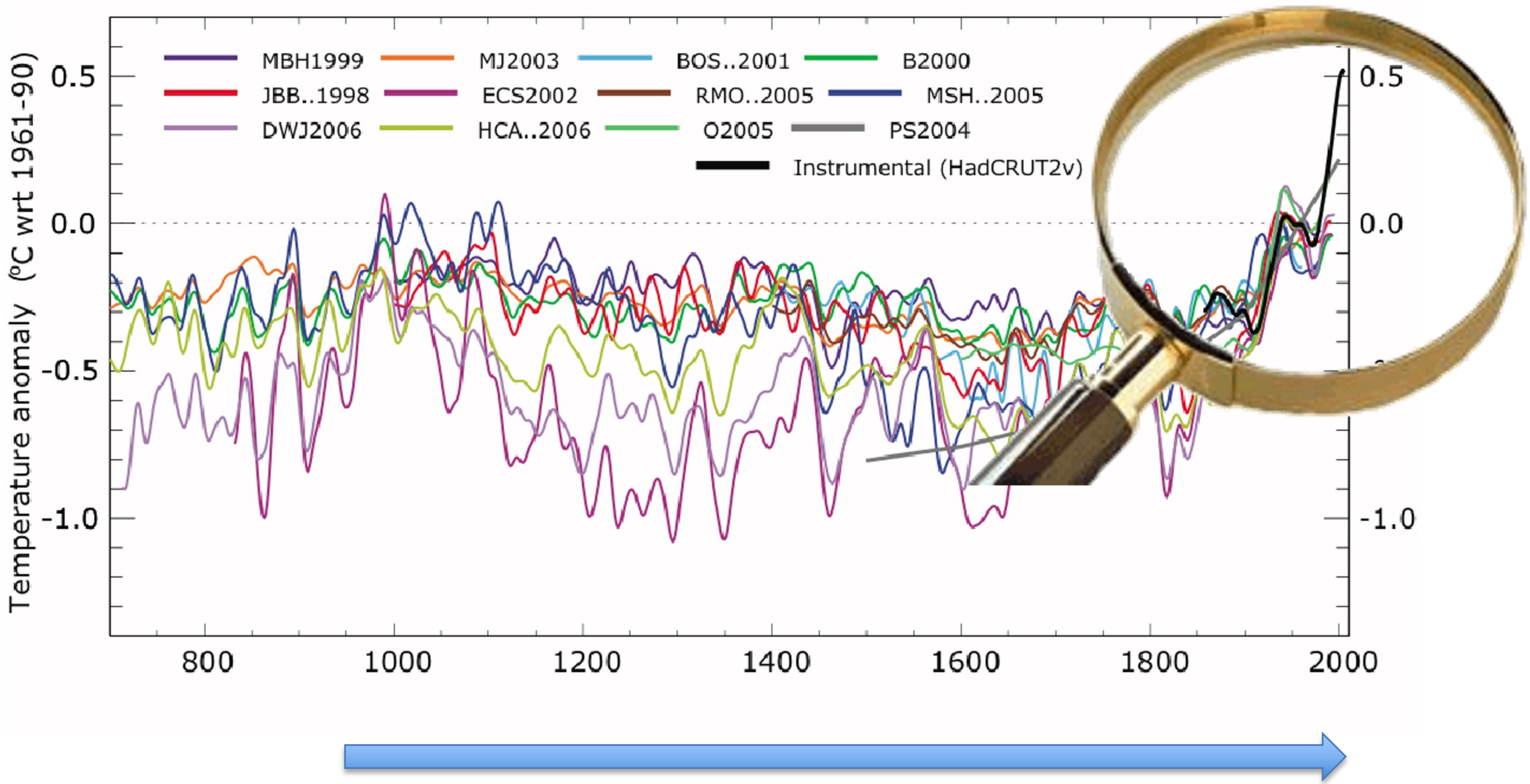
800 000 years

Last millenium observations of temperature



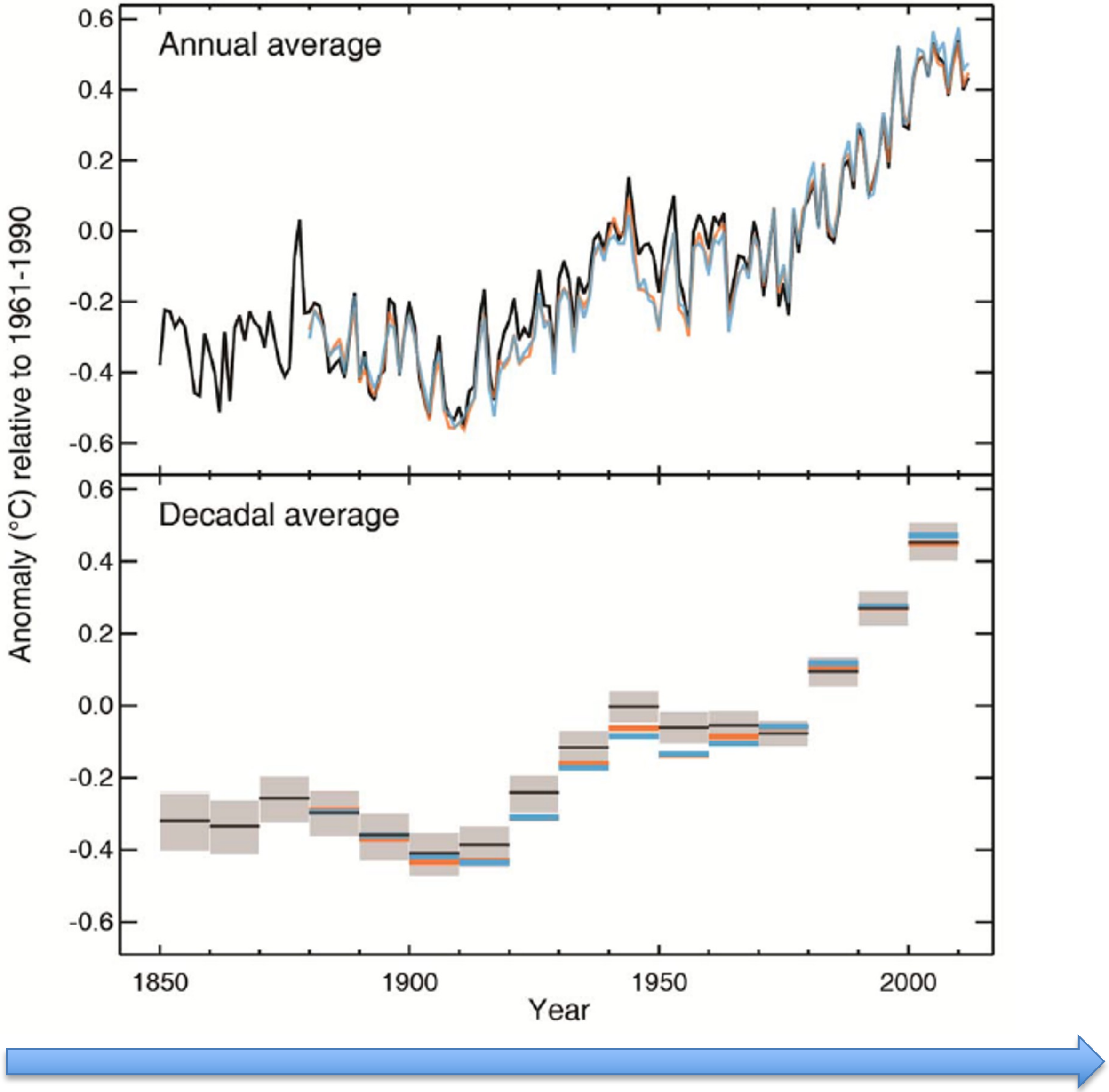
1000 years

Last millenium observations of temperature



1000 years

Observation: global temperature



150 years

Definitions

Climate = Mean state + climate variability

Climate variability = internal variability + external forcings

External forcings = anthropogenic forcings + natural forcings

Natural variability = natural forcing + internal variability

Definitions

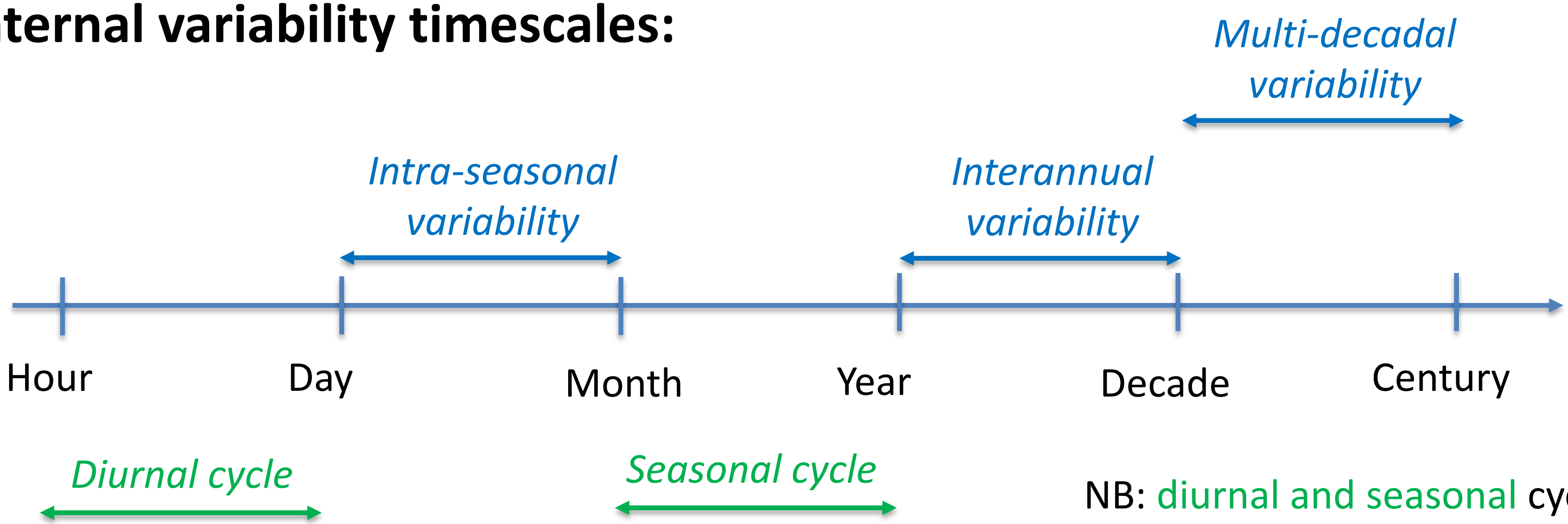
Climate = Mean state + climate variability

Climate variability = internal variability + external forcings

External forcings = anthropogenic forcings + natural forcings

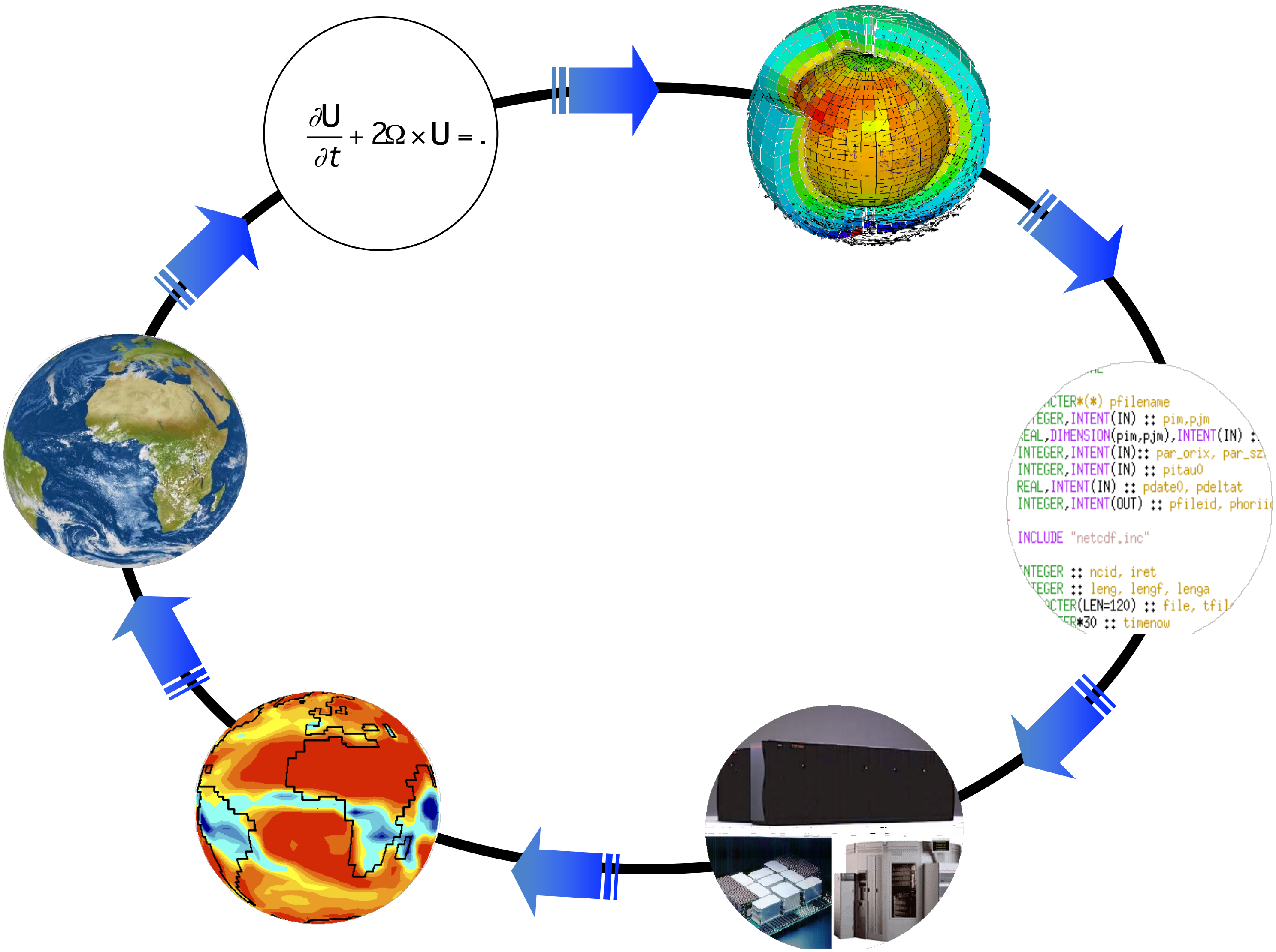
Natural variability = natural forcing + internal variability

Internal variability timescales:



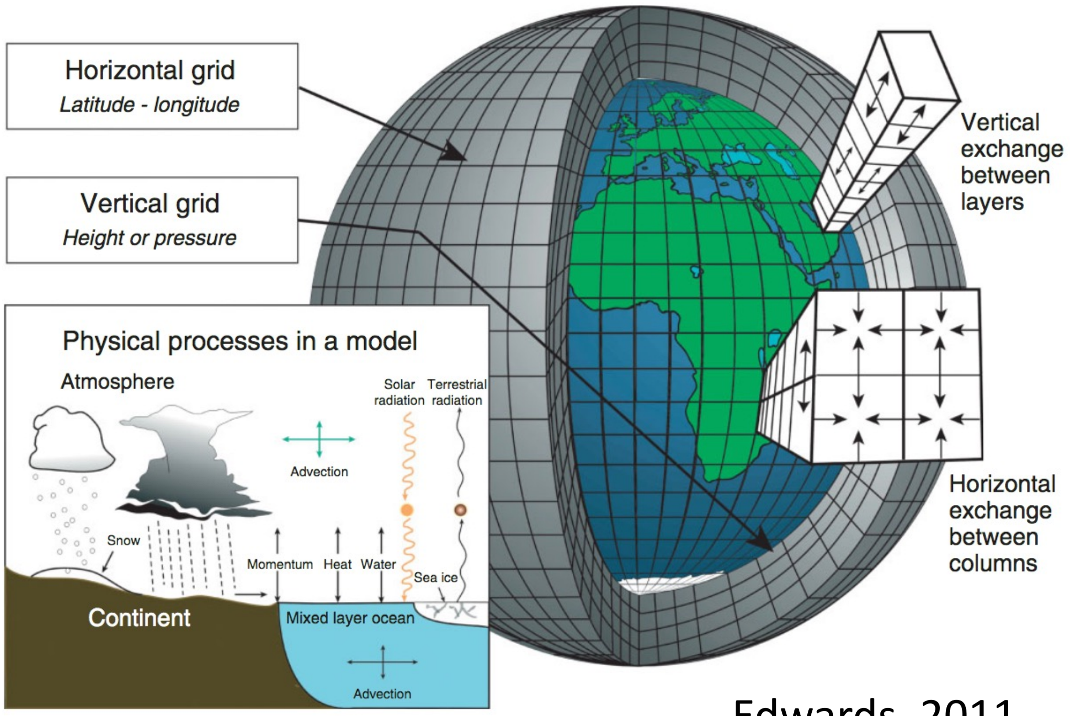
NB: diurnal and seasonal cycles are not internal variability

Model developments



Model developments

- Space (x,y,z) and time (t) discretisation
- 3D resolution of dynamical processes (u,v, and tracers)
- 1D physical scheme : surface energy balance, radiative transfert, thermal conduction in the ground…
- Sub grid-scale parametrisations: cloud fraction, snow cover fraction, atmospheric convection, etc…



Edwards, 2011

Model developments

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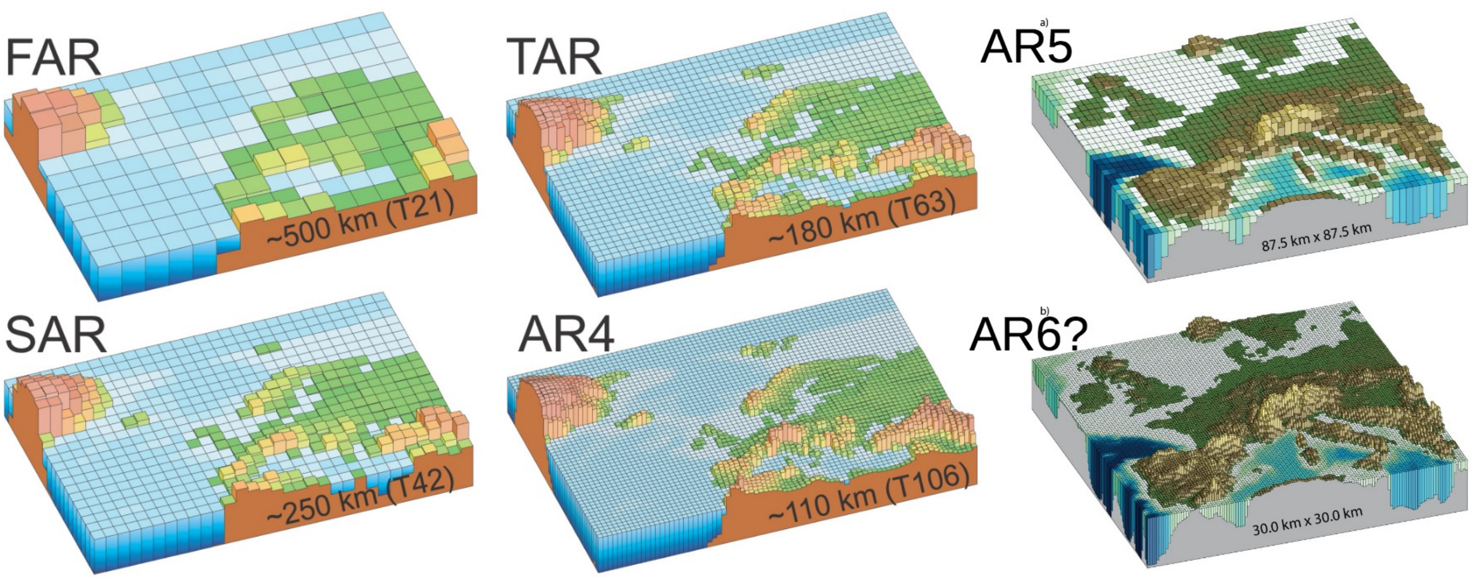
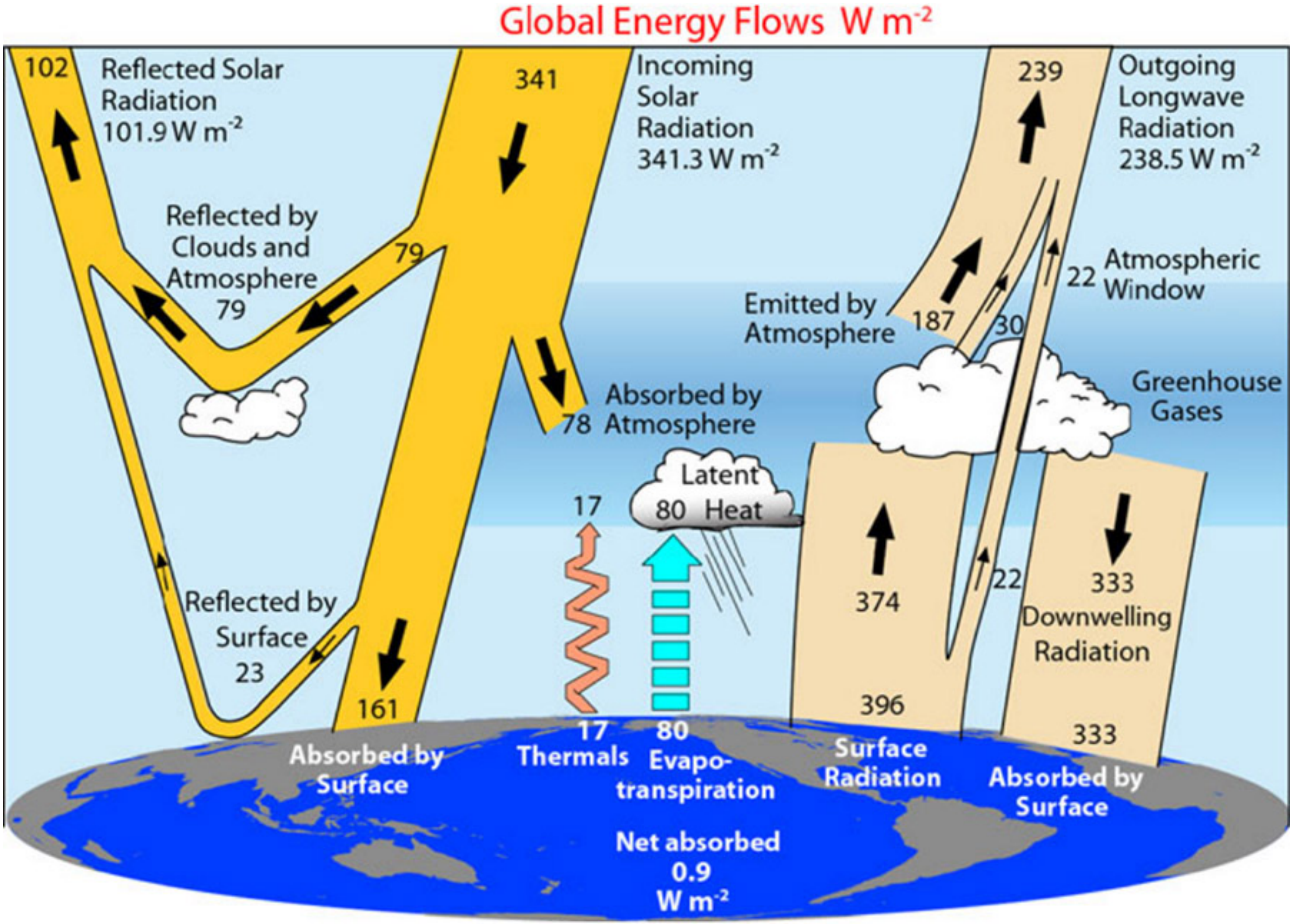
Grille typique des modèles lors des rapports successifs du GIEC
(1991, 1995, 2001, 2007, 2013, 202?)

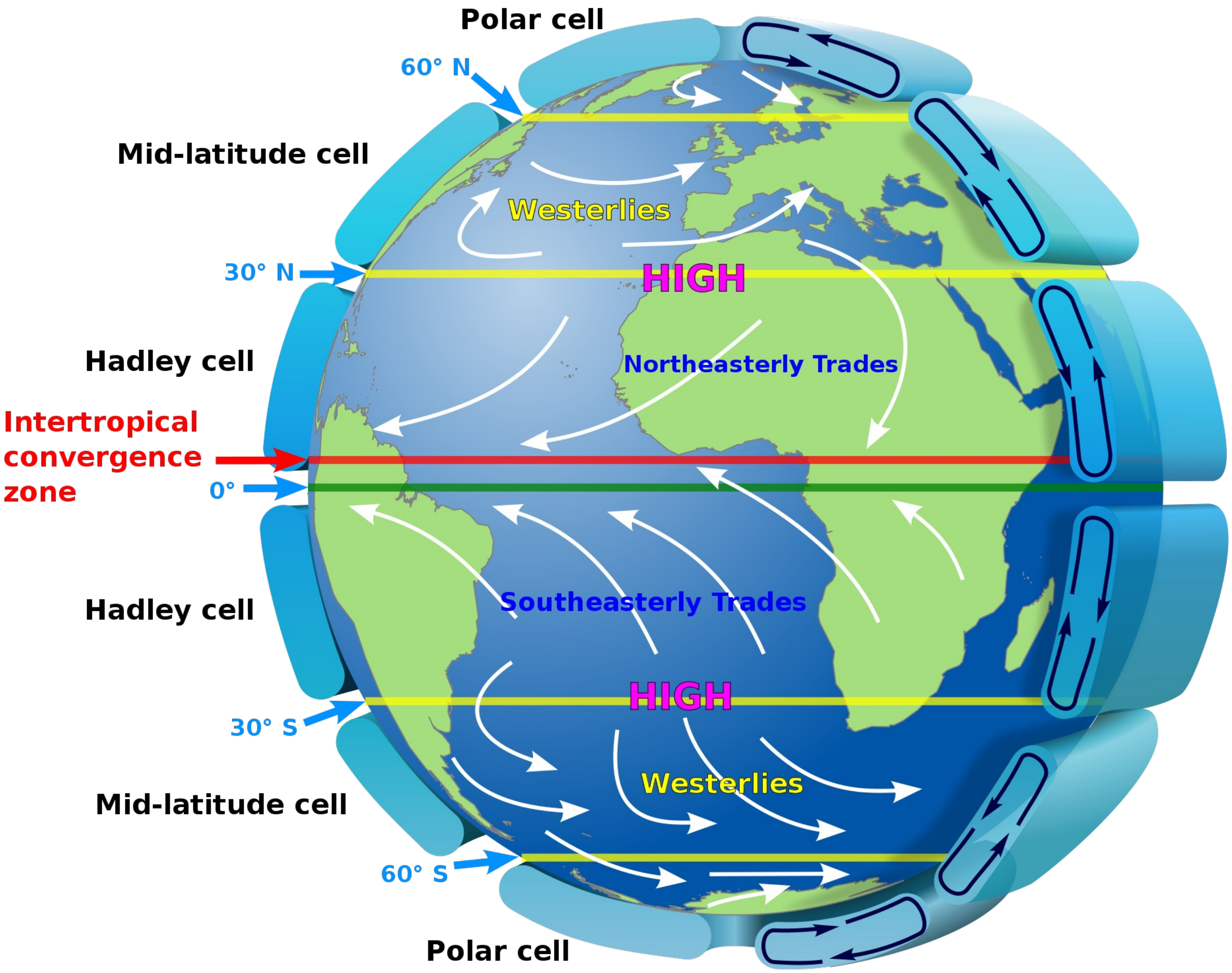


Source : IPCC AR4 (2007) Fig. 1.4 et AR5 (2013) Fig 1.14.



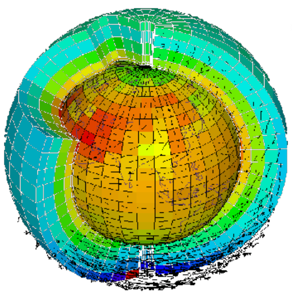
Global annual estimation of the atmospheric energy balance,
Source : Kiehl et Trenberth (1997)

Atmospheric circulation



https://en.wikipedia.org/wiki/Atmospheric_circulation

Climate versus meteorological forecast: Same models in different configurations



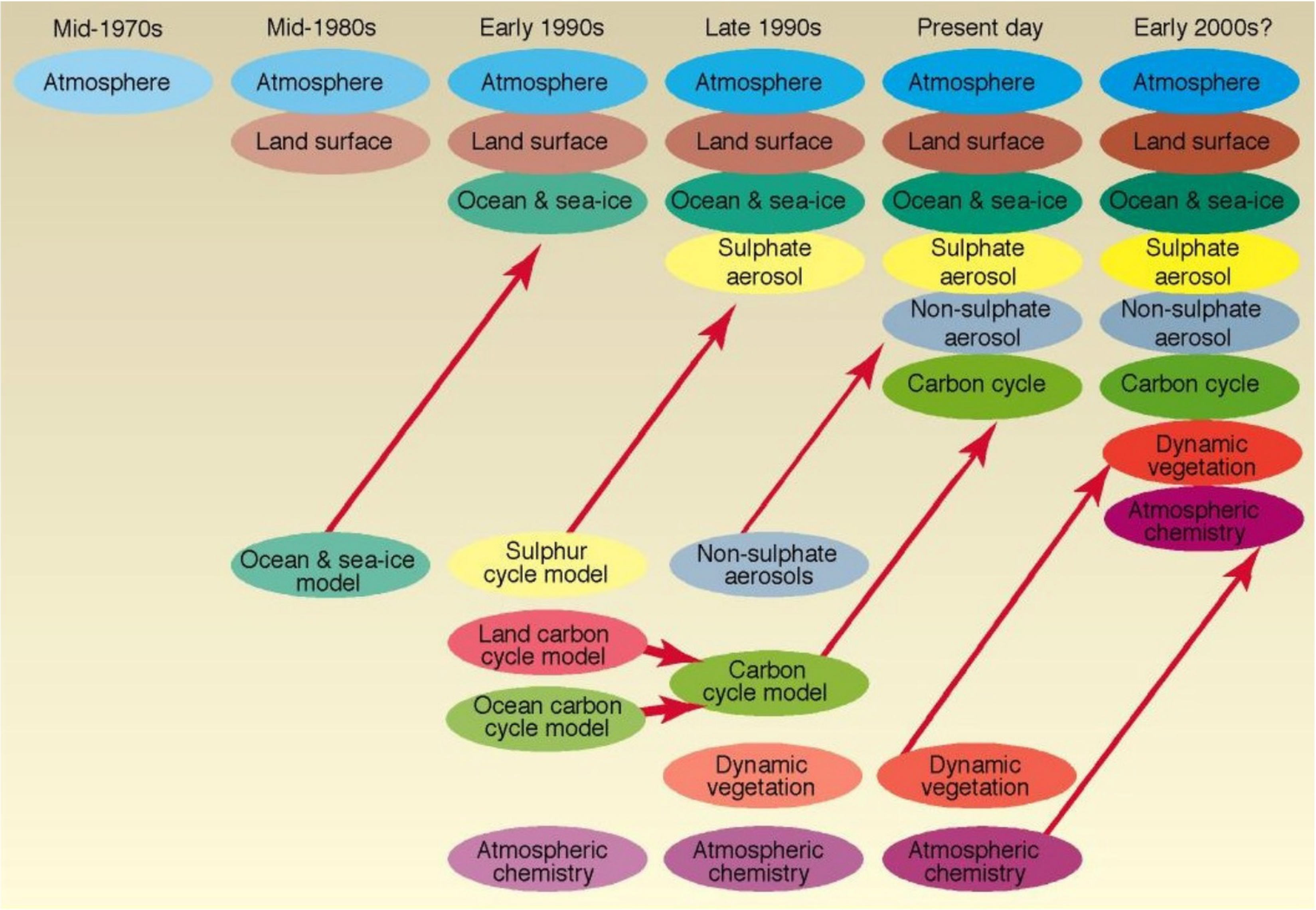
Climate:

- Long experiments (several decades)
- Dependency to **boundary conditions**

Meteorological forecasts:

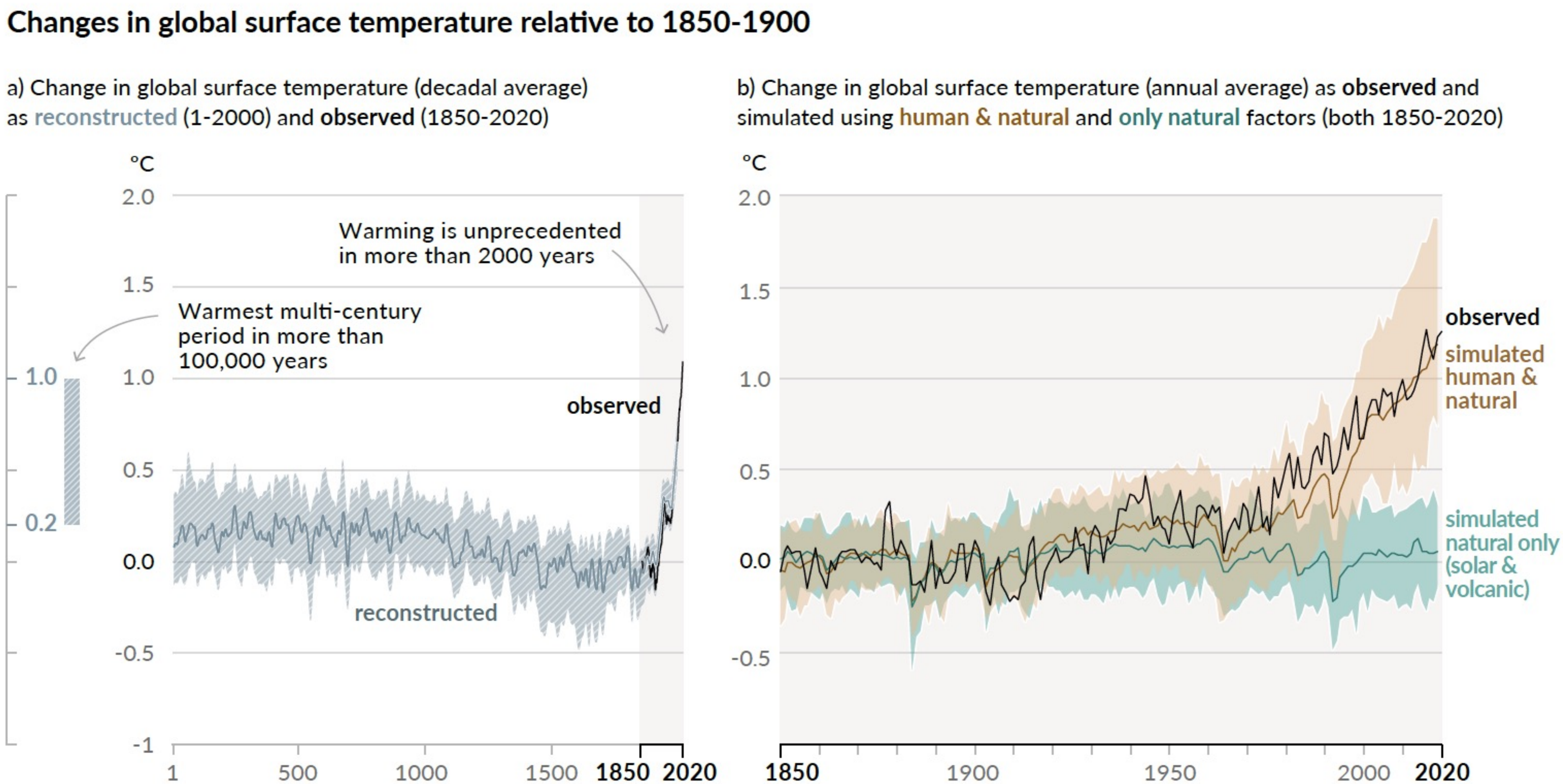
- Short simulations (several days)
- Dependency to **initial conditions**

From AOGCMs to ESMs



Source : IPCC TAR (2001), Fig. TS Box 3.

AOGCMs are used
-> to estimate the climate response to anthropohenic forcings

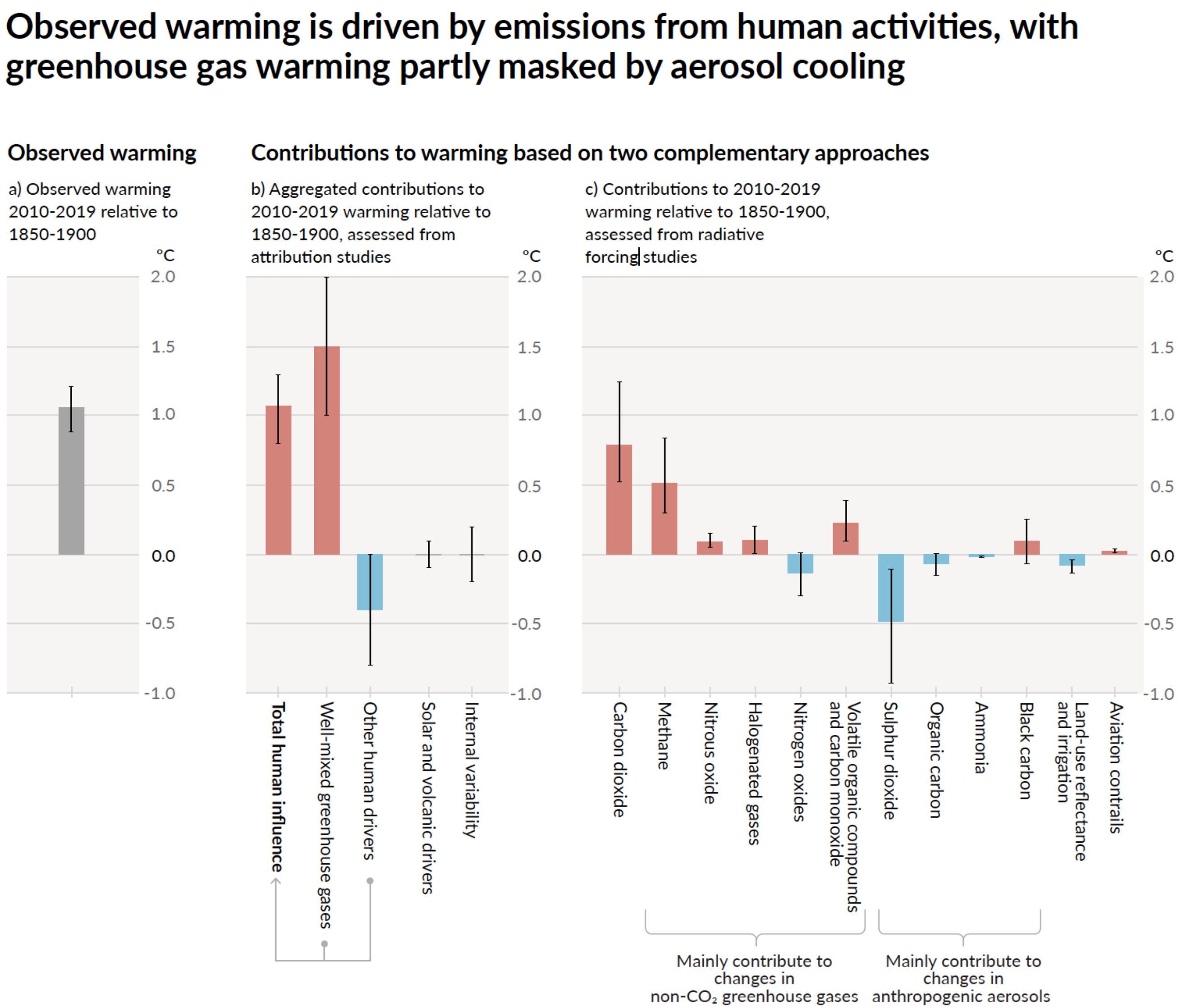


IPCC, AR6

AOGCMs are used

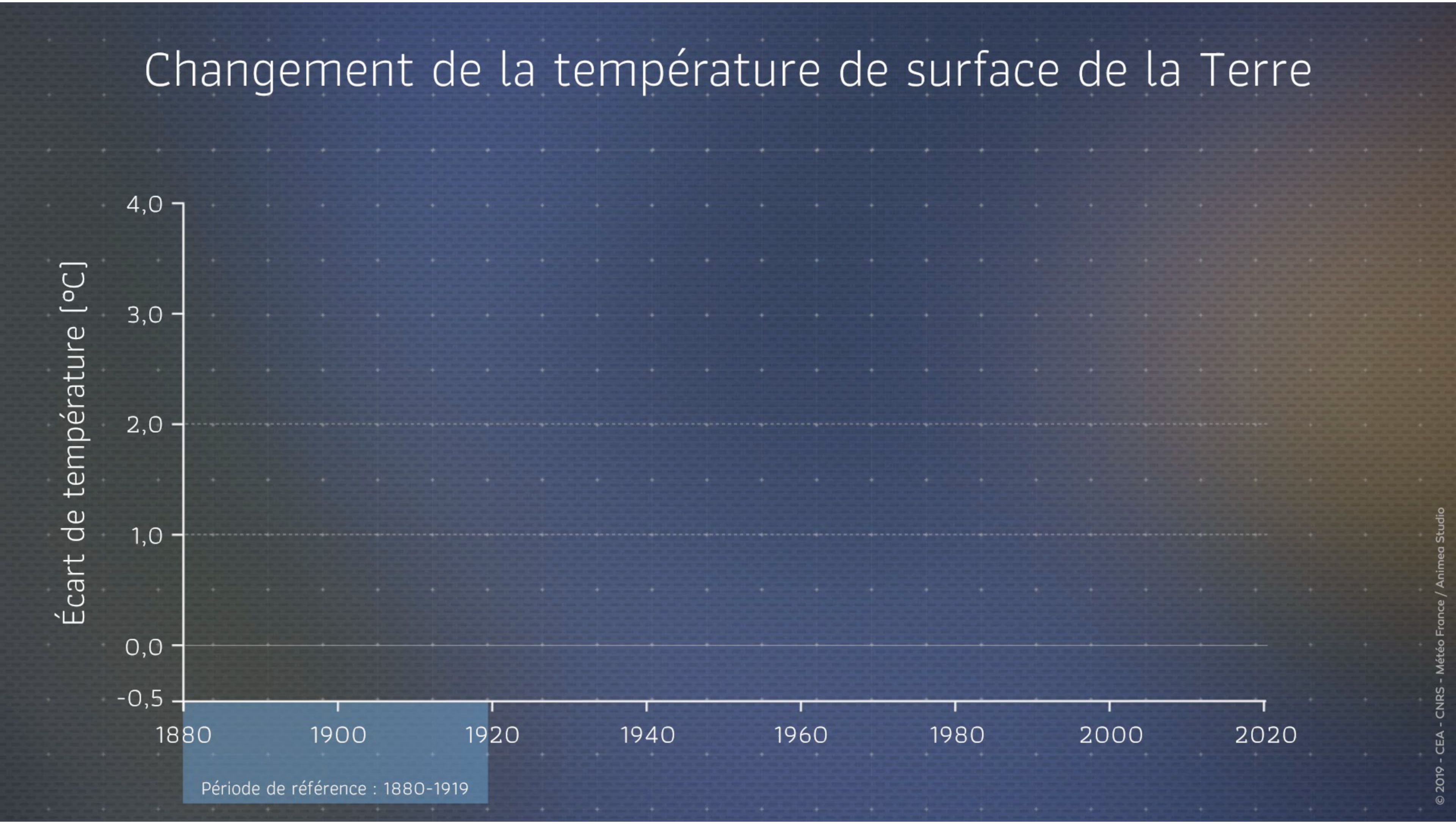
-> to estimate the climate response to anthropohenic forcings

-> to disentangle the imprints of the different forcings

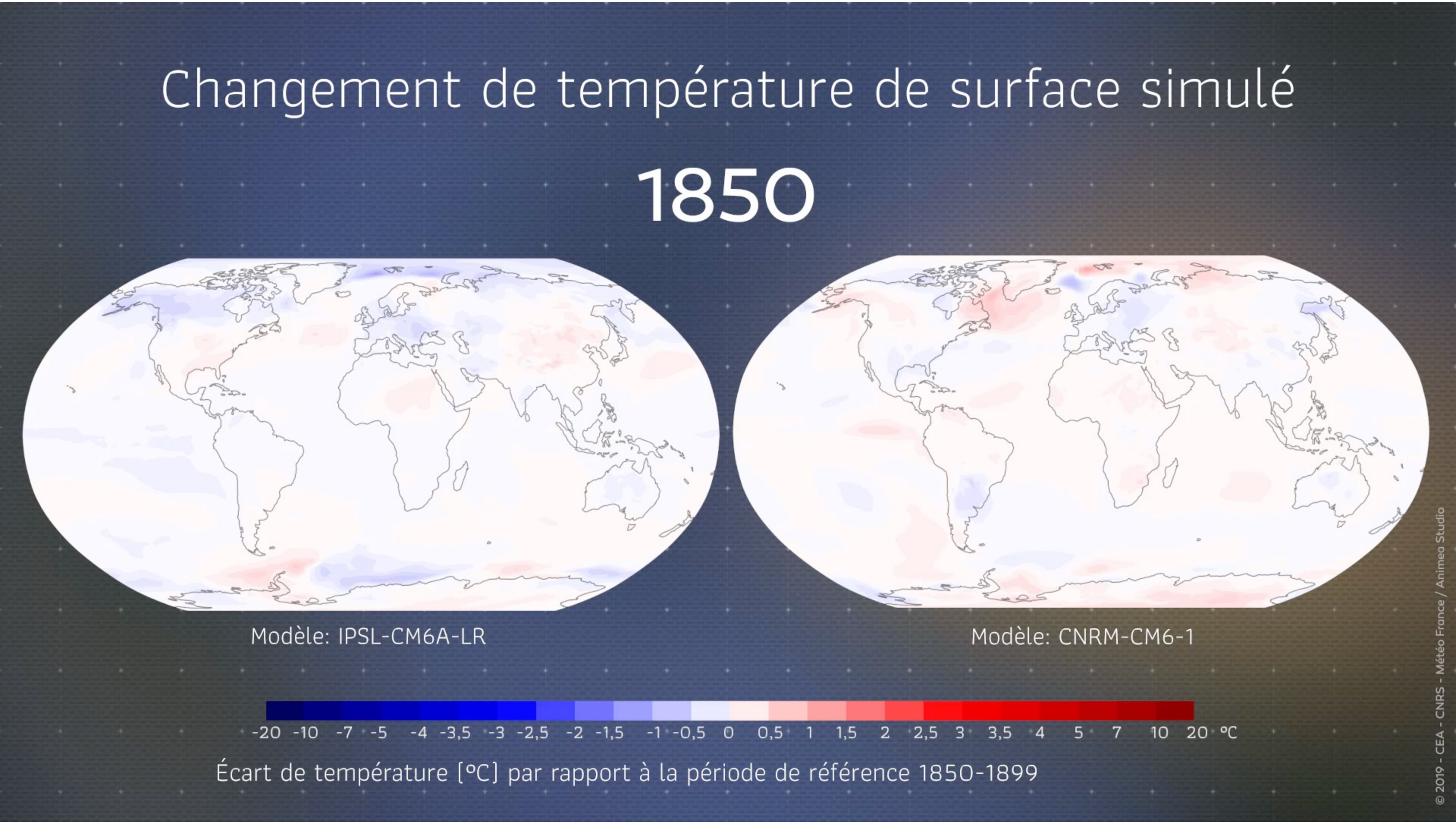


IPCC, AR6

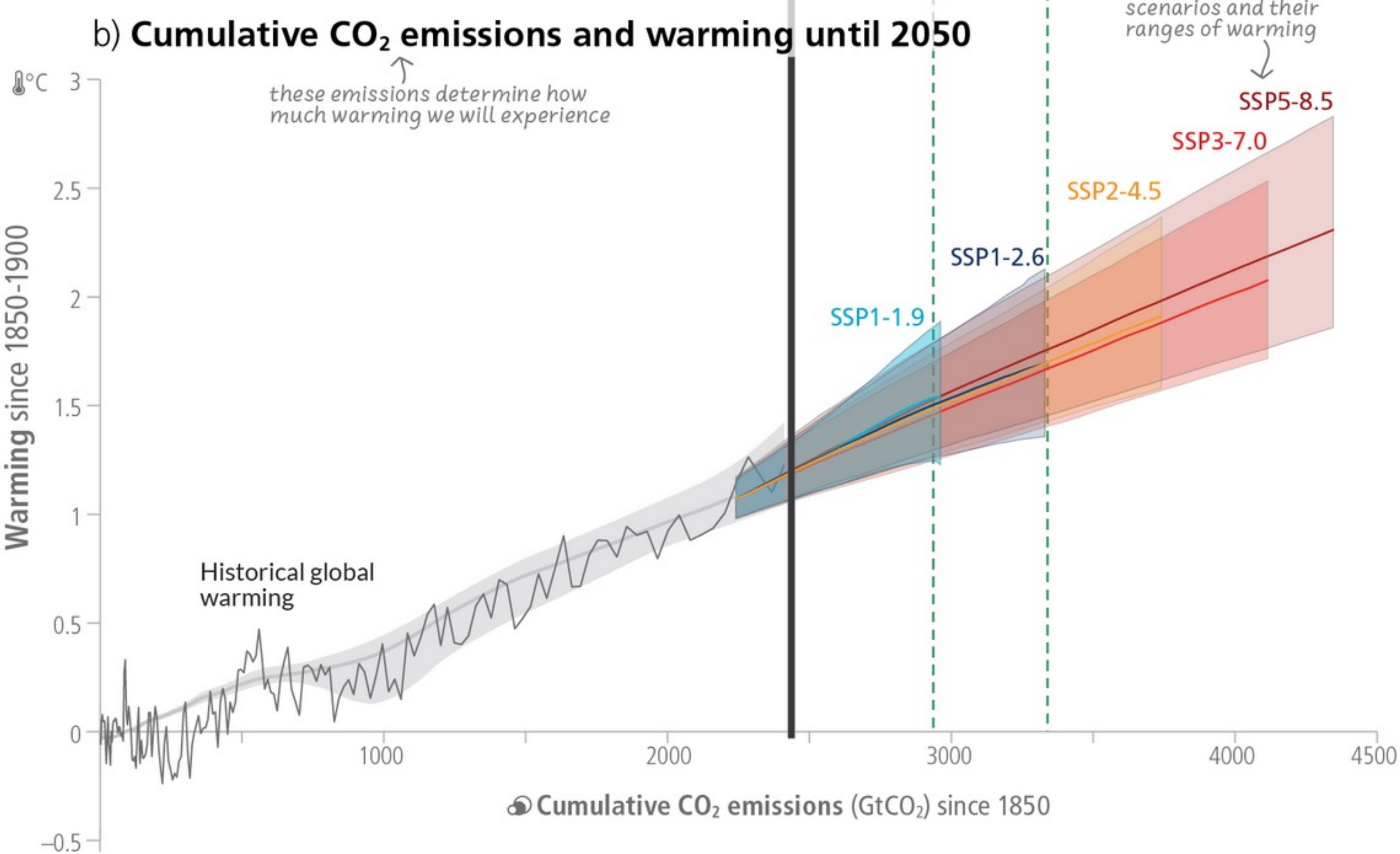
Simulating global annual temperature changes



Simulating global annual temperature changes

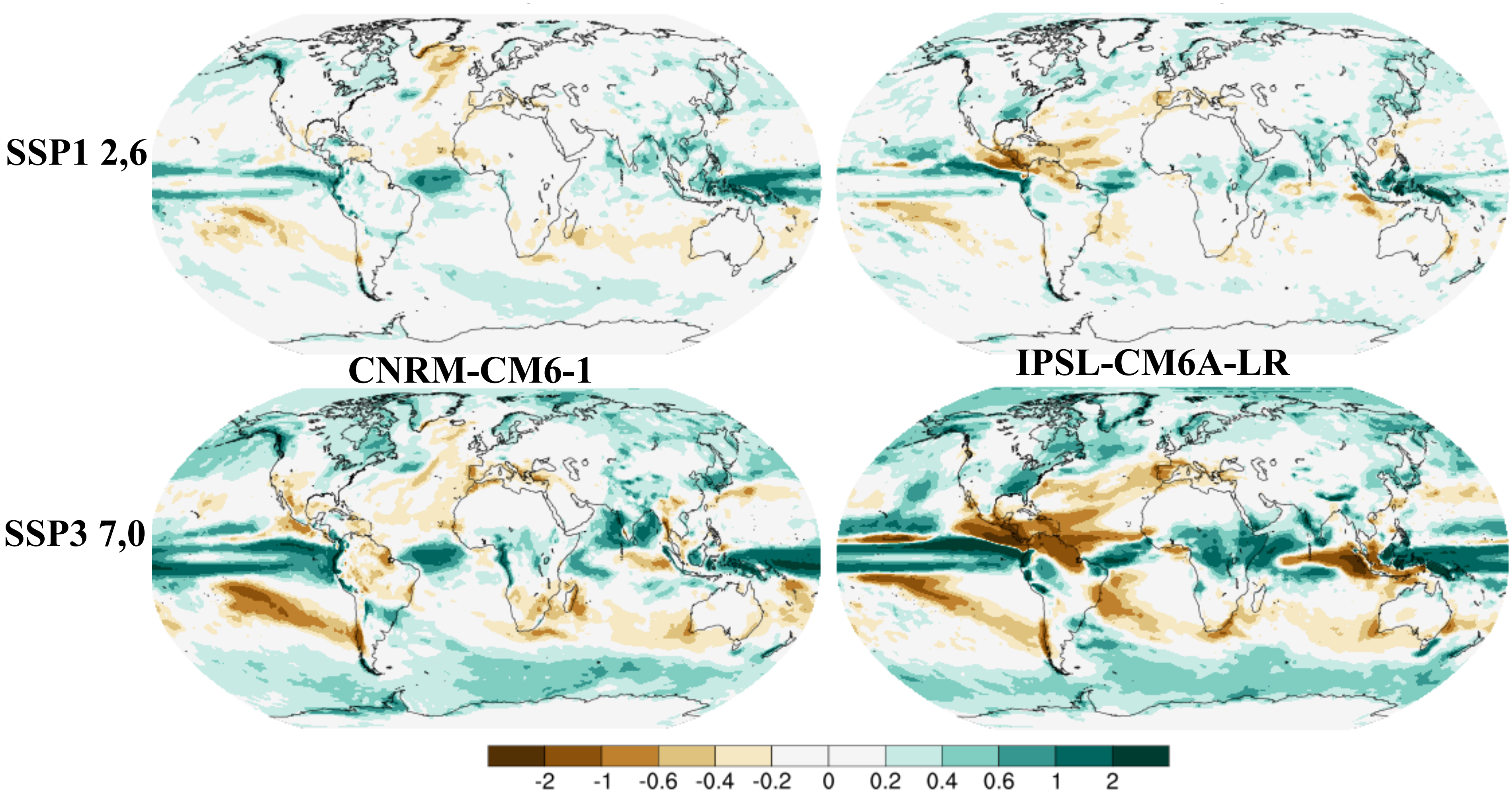


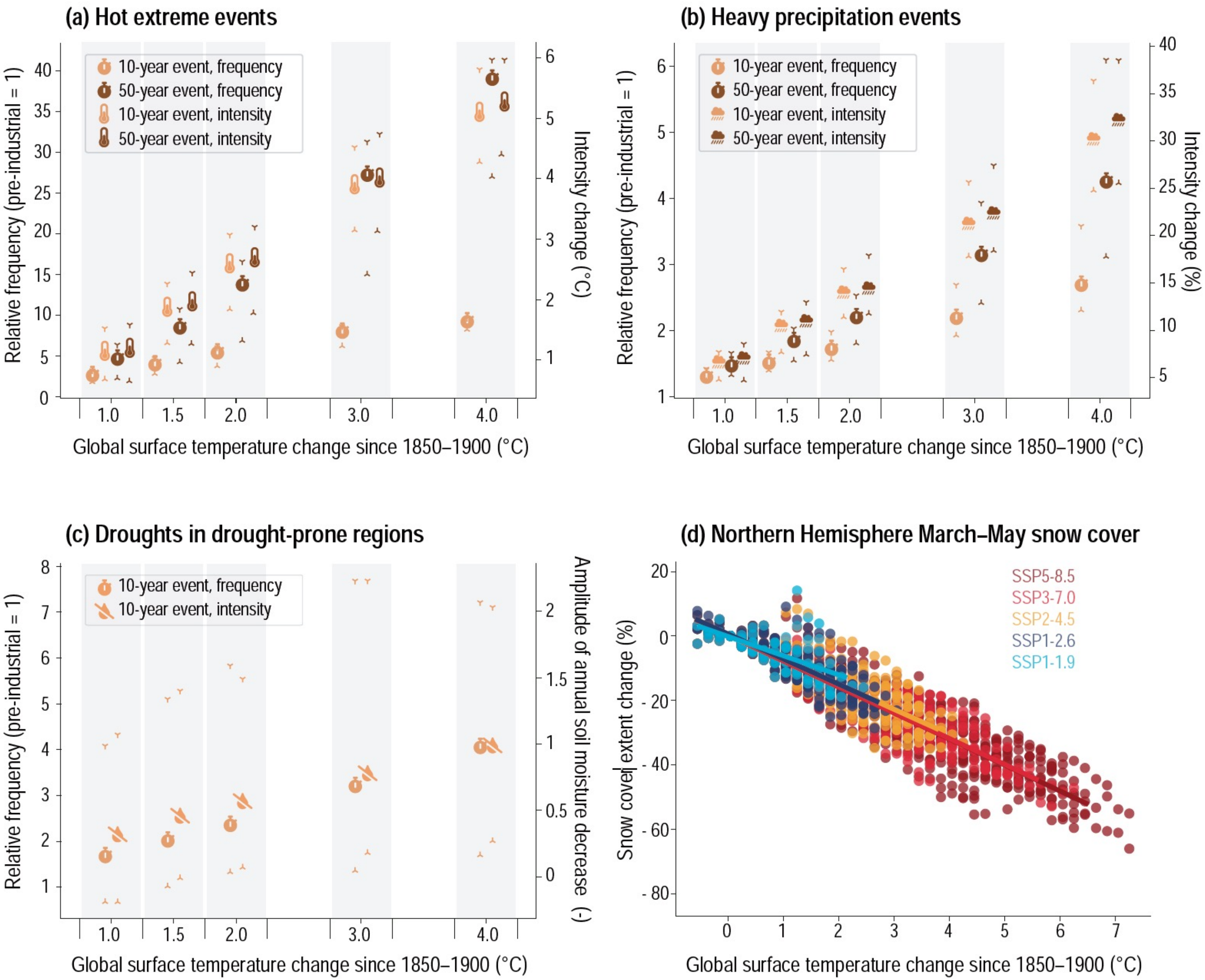
Every ton of CO_2 adds to global warming



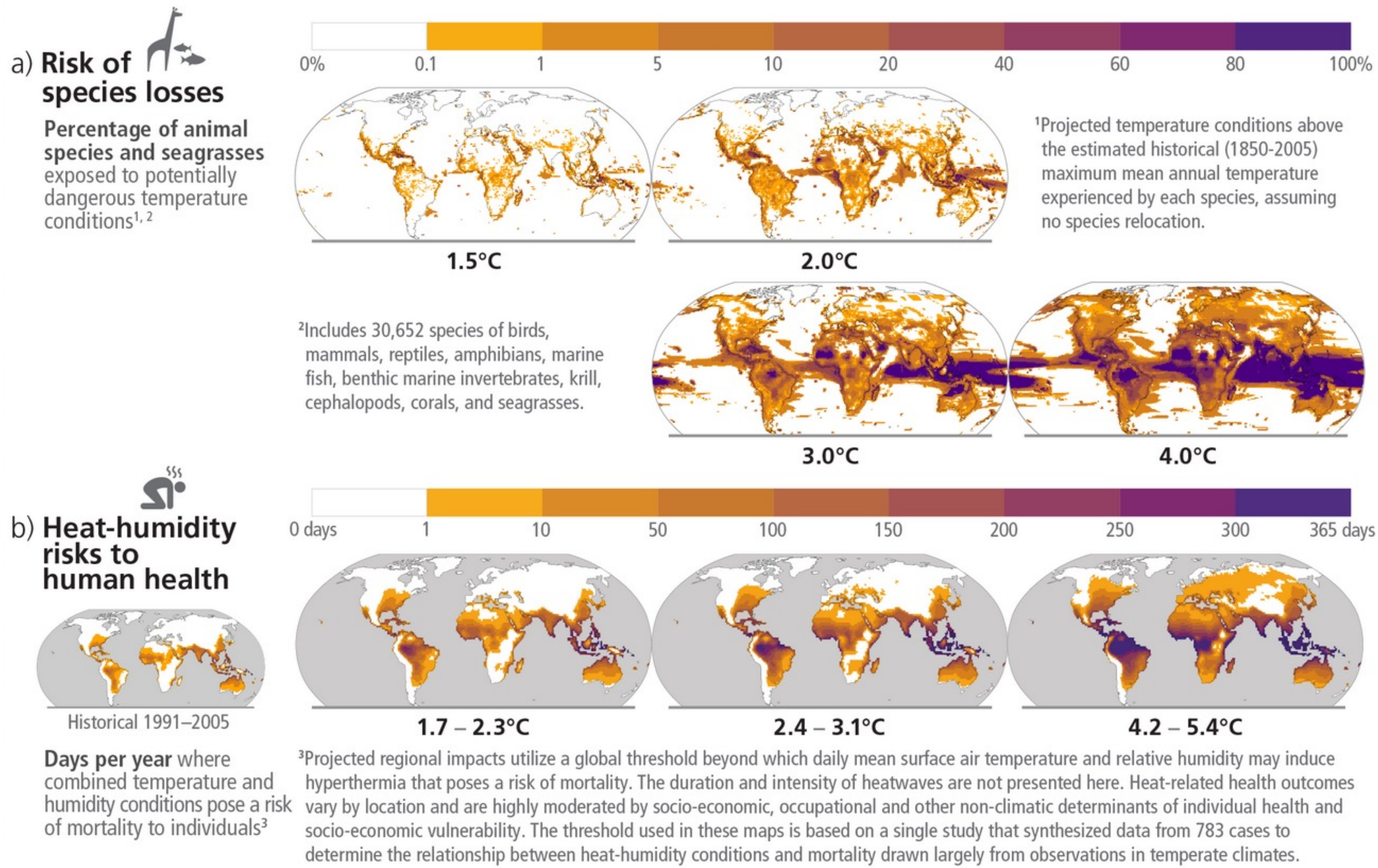
IPCC, Synthesis report (2023)

Precipitation changes from 1981-2010 to 2071-2100 (mm.day-1)





IPCC, Synthesis report (2023)



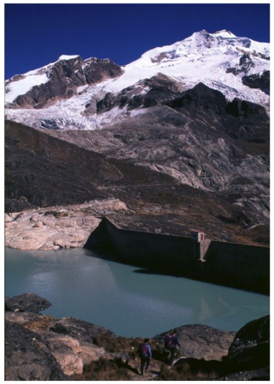
IPCC, Synthesis report (2023)

Climate change: from global scale to mountainous areas

2/ Mountainous areas

- **Water resources**

-> drinkable water, irrigation, hydroelectricity

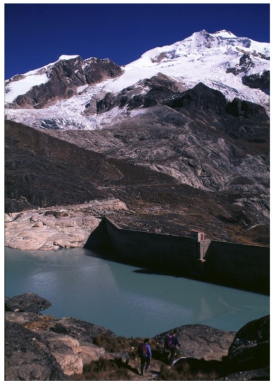


Glacier Zongo, Bolivie
@P. Wagnon

- **Water resources**

-> drinkable water, irrigation, hydroelectricity

- **Tourism**



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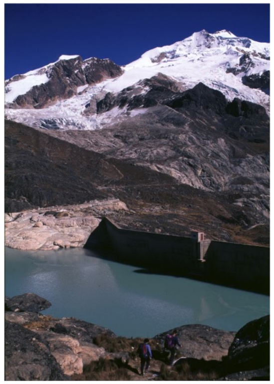

Glacier Zongo, Bolivie
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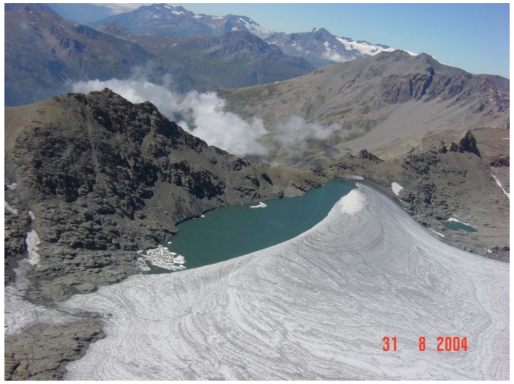
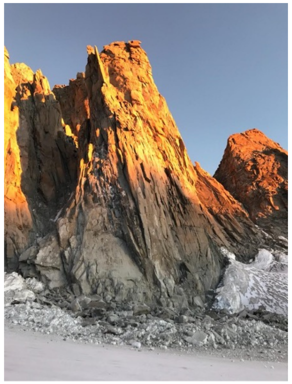
- **Tourism**

- **Glaciological risks and rock collapse**



Glacier de Rochemelon, @
B. Laili, 2004.



Trident du Tacul,
2018. @P. Gourdin

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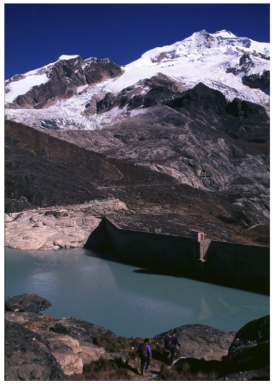

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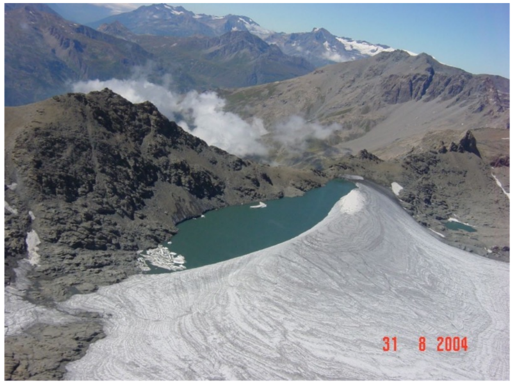

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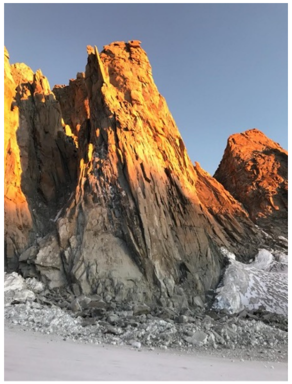


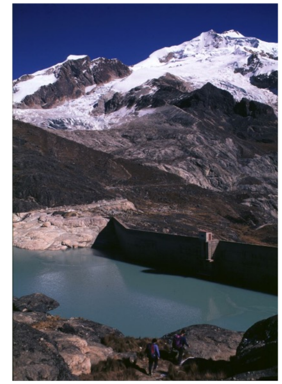
Trident du Tacul,
2018. @P. Gourdin

- **Extreme events more intense and more frequent (floods, dry and warm events)**

Flood, Manali, India, 2018, @Daily Star

- **Water resources**

-> drinkable water, irrigation, hydroelectricity



Glacier Zongo, Bolivie
@P. Wagnon

- **Tourism**

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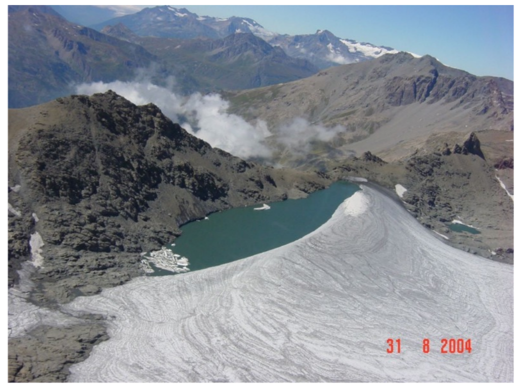
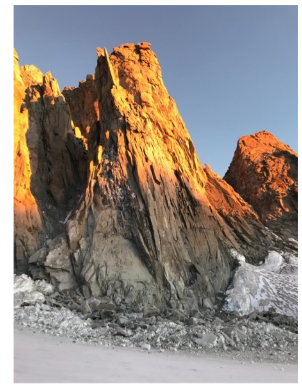


Glacier de Rochemelon, @ B. Laili, 2004.



Trident du Tacul, 2018. @P. Gourdin

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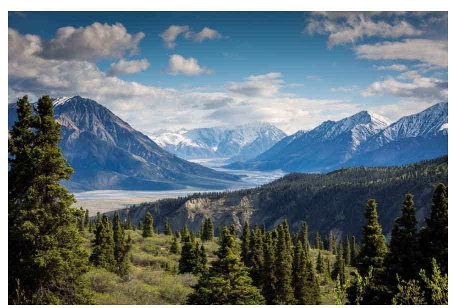
Flood, Manali, India, 2018, @Daily Star

- **Biodiversity changes**



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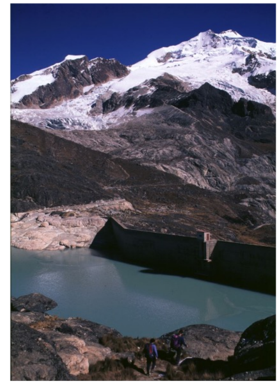
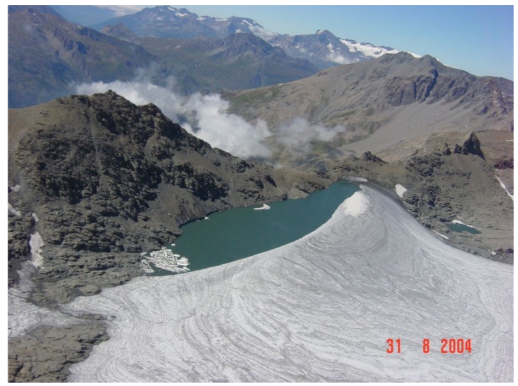


Glacier Zongo, Bolivie
@P. Wagnon

- **Tourism**

- **Glaciological risks and rock collapse**



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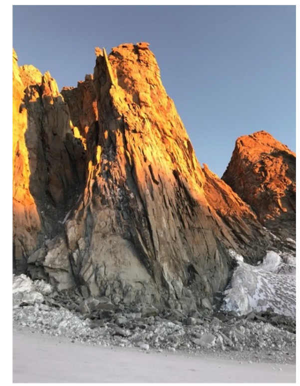


Trident du Tacul,
2018. @P. Gourdin

- **Extreme events more intense and more frequent (floods, dry and warm events)**

Flood, Manali, India, 2018, @Daily Star

- **Biodiversity changes**

- **Sea level rise (+3mm/year)**

-> glaciers (30%), ice sheets (30%), thermal dilatation (30%) from 1980

Climate modelling over mountain -> tricky!!!

Credit CHRISTOPH HORMANN / SCIENCE PHOTO LIBRARY

Clouds: one of the complex point in models

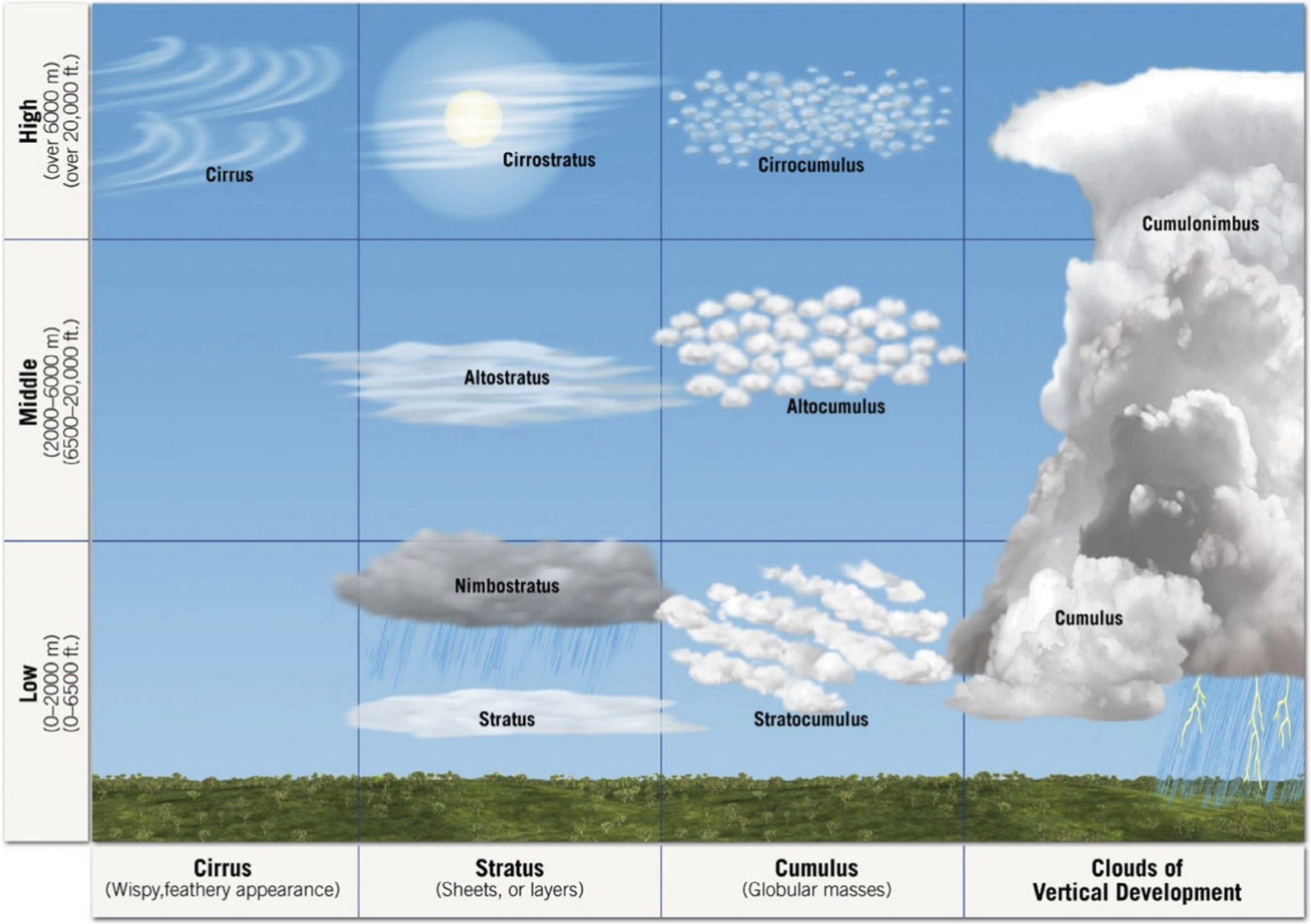
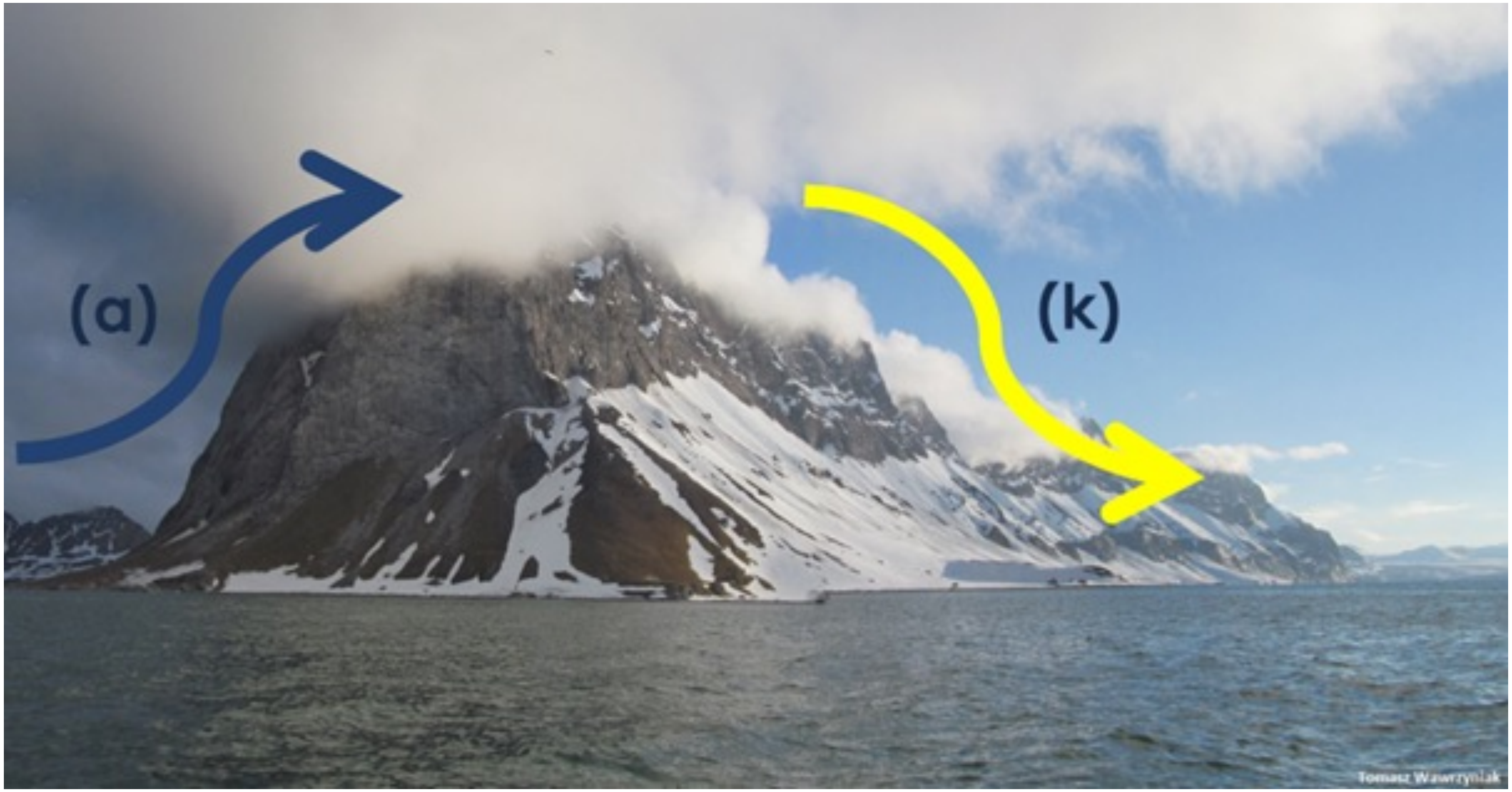


Figure 1 Ten major cloud types. Reproduced from Lutgens et al., 2016. http://www.pearsonhighered.com/bookseller/product/Atmosphere-An-Introduction-to-Meteorology-The-Plus-MasteringMeteorology-with-eText-Access-Card-Package/9780321984425.page

In mountains, it's even more complex!



Orographic clouds and foehn processes
(source: https://polarpedia.eu)

In mountains, it’s even more complex!

(source: wikipedia)

In mountains, it’s even more complex!

(source: wikipedia)

In mountains, it's even more complex!

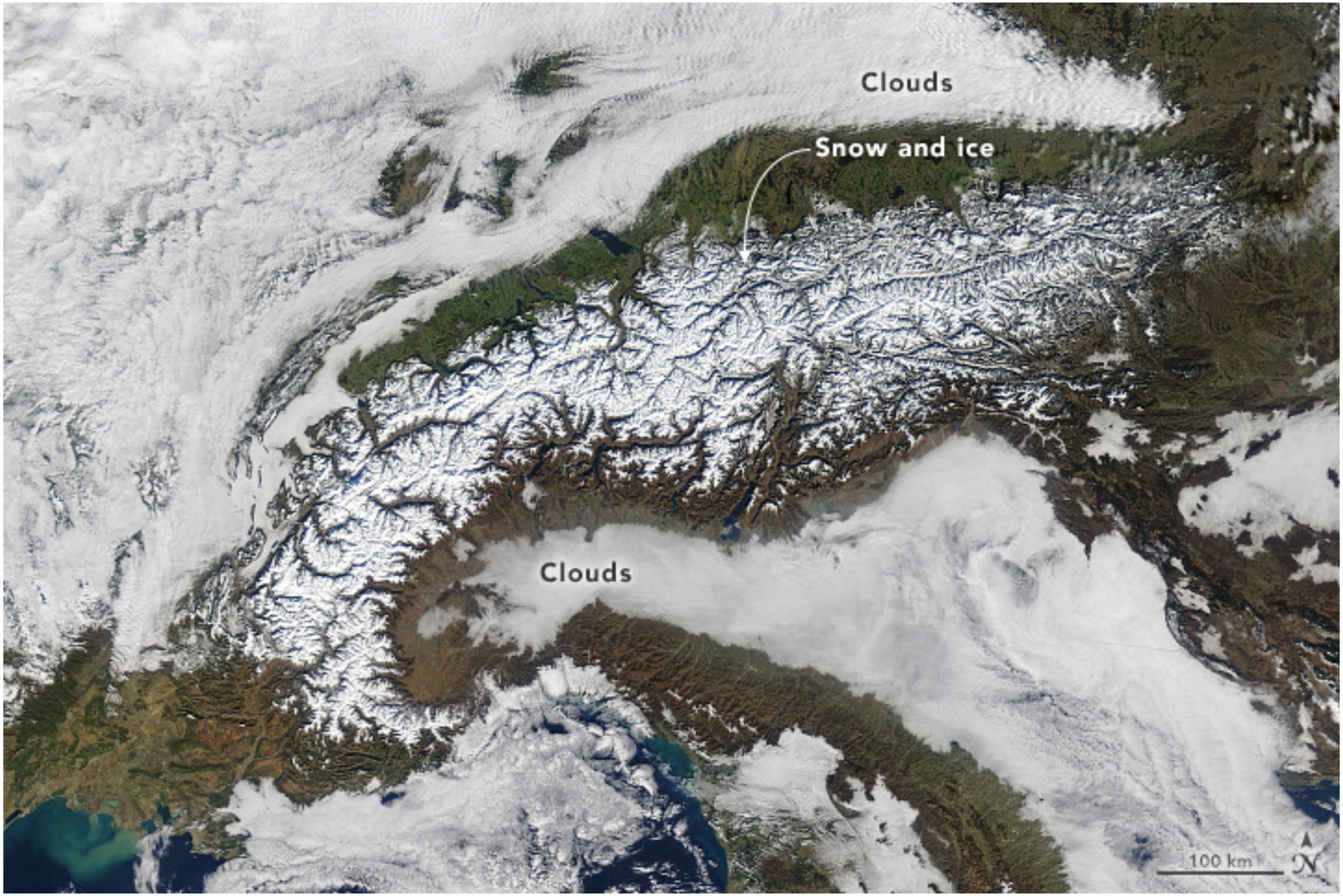
Photo courtesy (and copyright) Isabelle Prestel, Institute for Atmospheric Physics, Switzerland

In mountains, it’s even more complex!

Summer cumulonimbus in French Alps
Crédit : Laurence Martin via twitter
@meteocentreisere

Sea-cloud in Chamonix
Credit : Daniel Simpson

How to simulate the snow cover in mountainous areas?



Credits: Nasa

How to simulate aire pollution trapped in the valleys?

Winter atmospheric pollution in the Alps

Elevation-dependant warming?

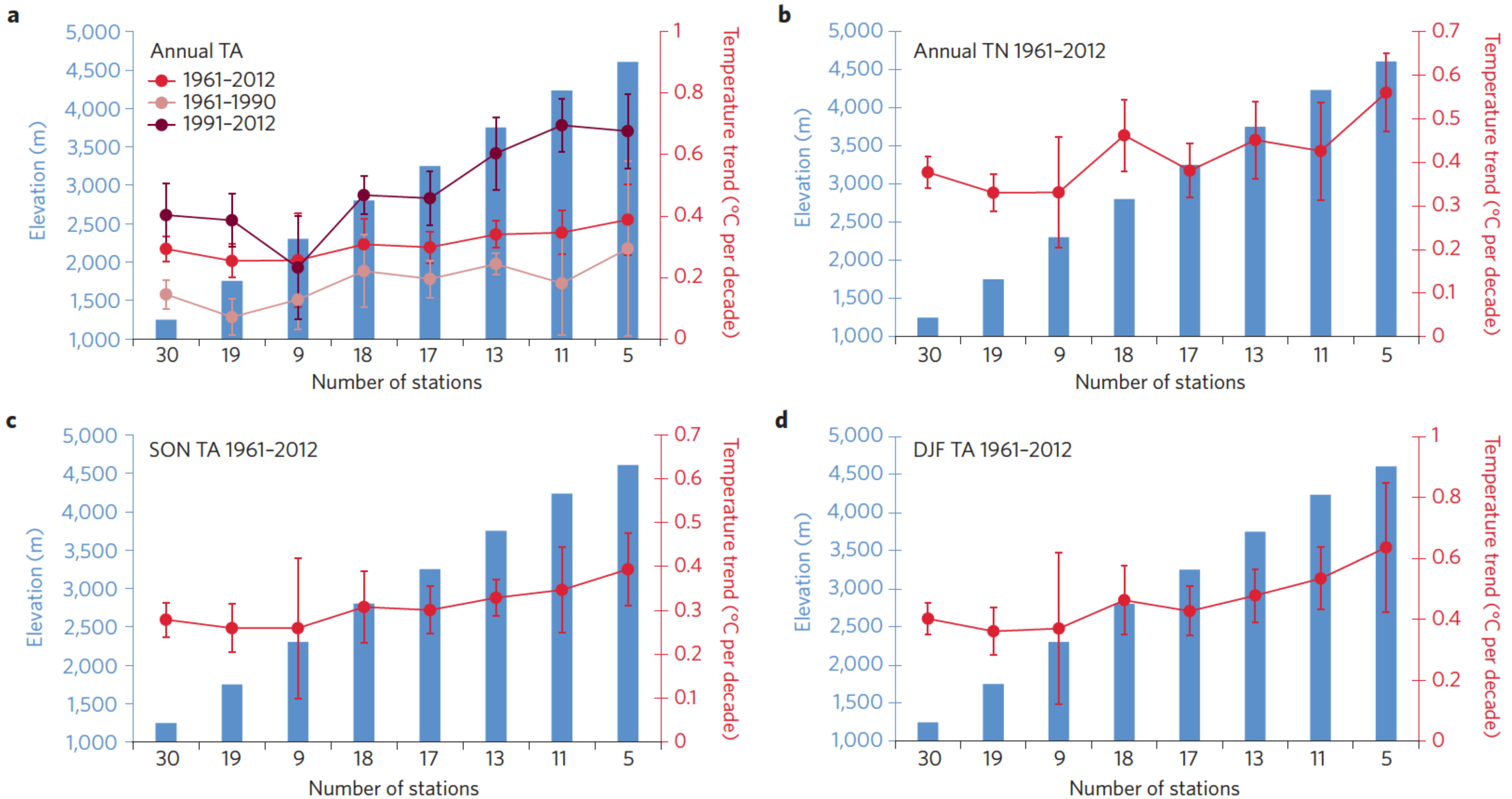
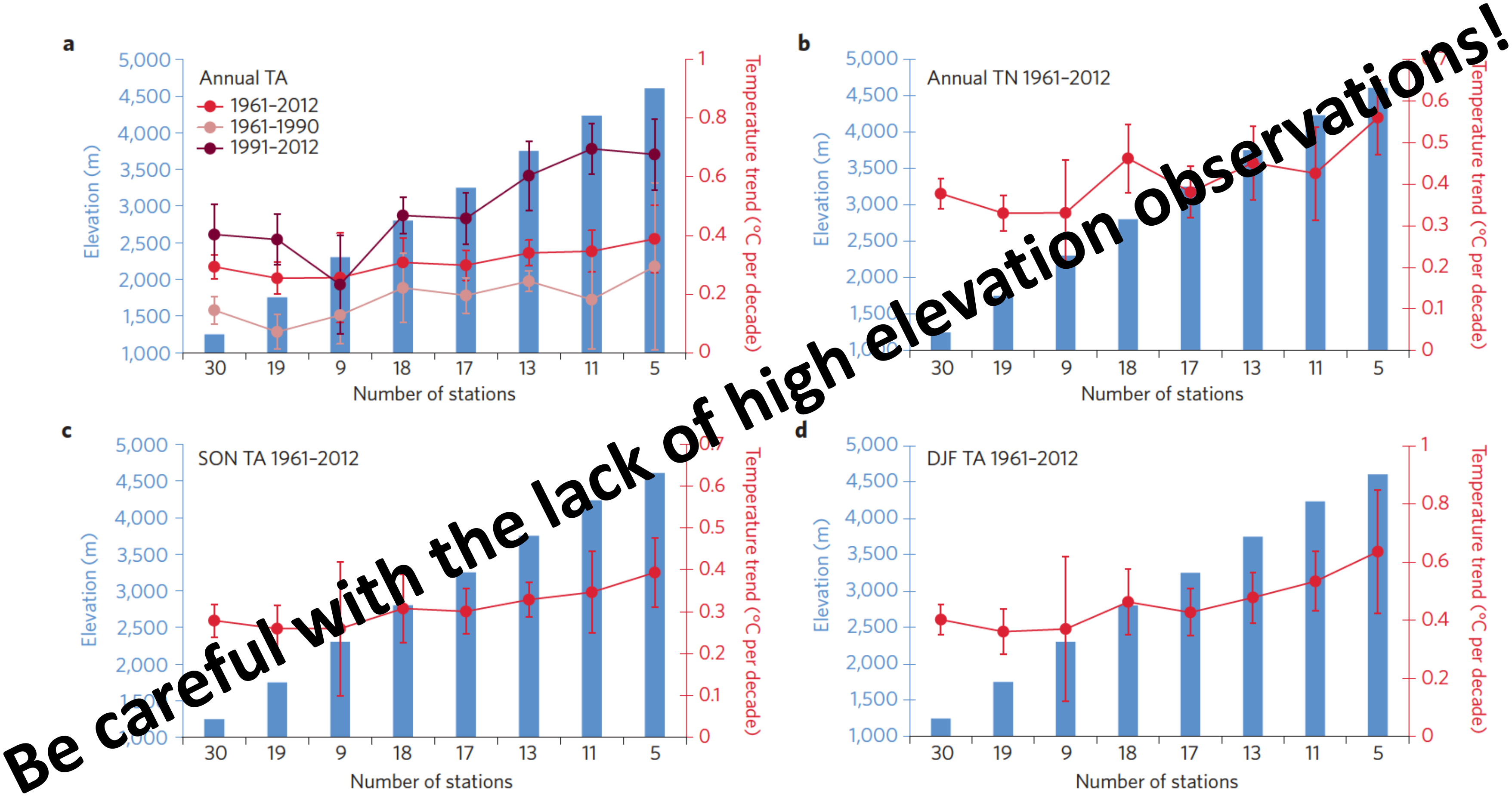


Figure 1 | Elevation-dependent warming over and around the Tibetan Plateau. a, Annual mean surface air temperature (TA) over 3 time periods. **b**, Annual mean minimum temperature (TN) from 1961–2012. **c**, Mean autumn (September–November, SON) surface temperature from 1961–2012. **d**, Mean winter (December–February, DJF) surface temperature from 1961–2012 . Bars represent elevation and trend magnitude is plotted on the *y* axis according to the 8 elevation ranks of 122 stations. The presentation format is similar to ref. 76 for ease of comparison. Error bars are based on 95% confidence intervals around the mean. The vertical scale for winter warming rate (**d**) and annual warming rate (**a**) have been adjusted to reflect the more rapid warming.

Pépin et al., 2015

Elevation-dependant warming?



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Pépin et al., 2015

Elevation-dependant warming? Which mecanisms?

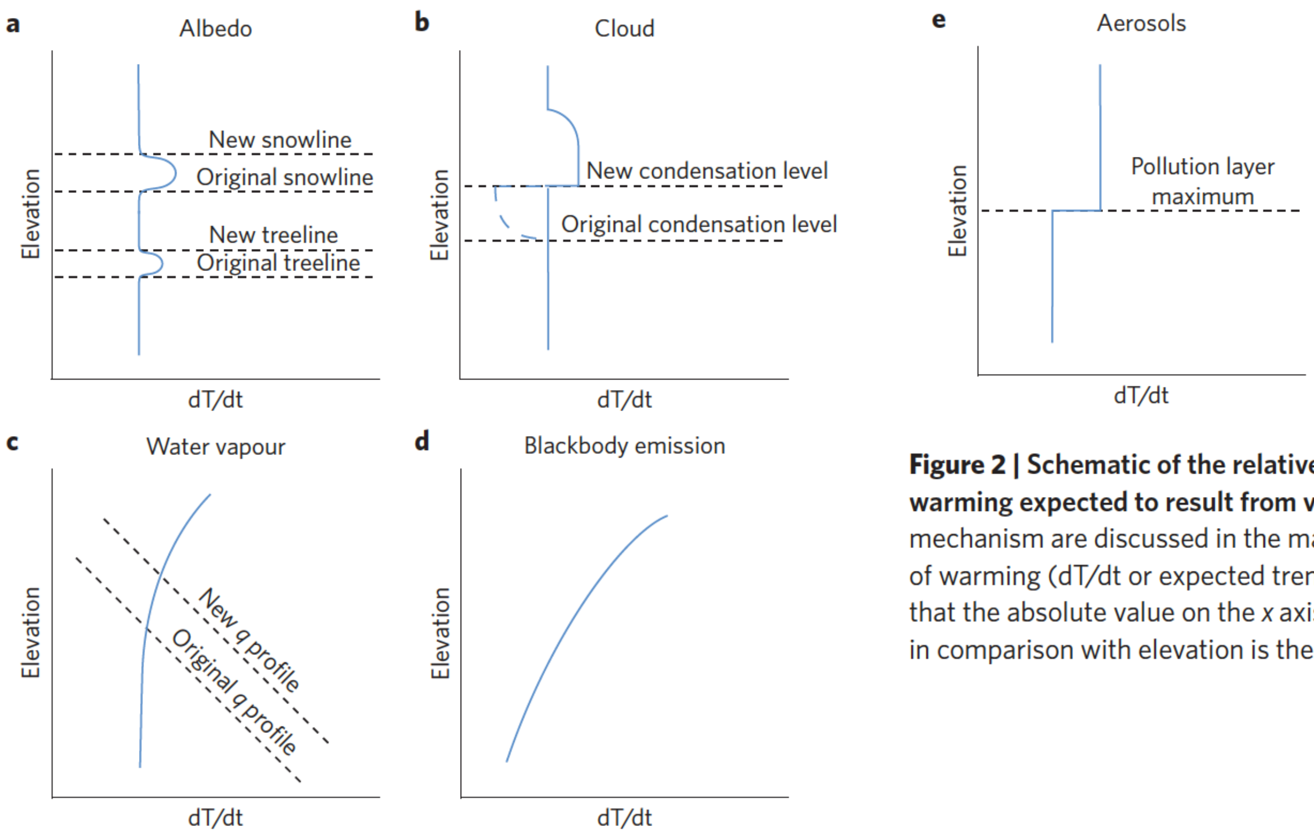


Figure 2 | Schematic of the relative vertical profile in atmospheric warming expected to result from various mechanisms. The details of each mechanism are discussed in the main text. The *x* axis represents the rate of warming (dT/dt or expected trend magnitude). The curves are relative in that the absolute value on the *x* axis is unimportant; the shape of the signal in comparison with elevation is the principal focus.

Pépin et al., 2015

GCMs biases in HMA in current climate models

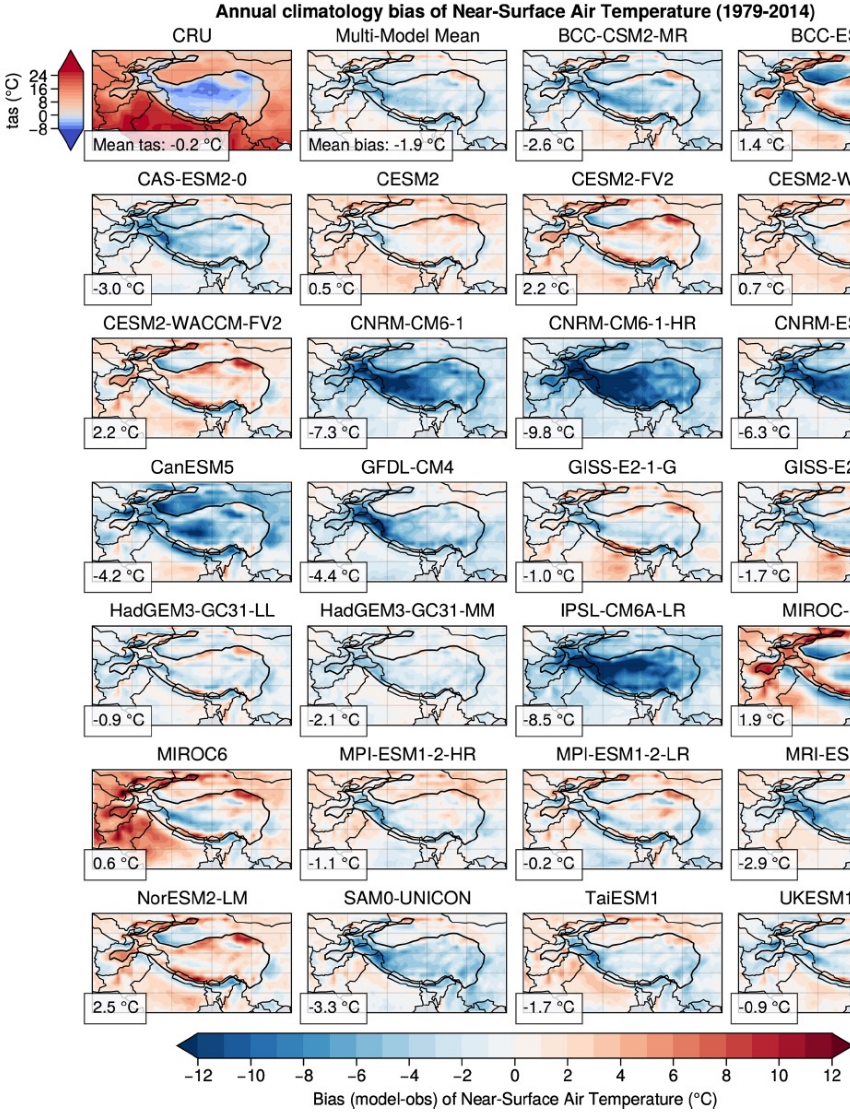


Figure 3. Annual bias (model minus observation) computed over 1979–2014 for temperature, except the top left panel that shows the climatology estimated from the CRU observation, used as the reference for the bias computation. The panel located at the right side of the CRU observation shows the bias of the multimodel mean based on the 26 models shown in the figure. The black contour shows the political frontiers and the bold black line the HMA domain located above 2500 m a.s.l., for which the spatial average of the bias is given in the bottom left of each panel.

Lalande et al., 2021

GCM biases in HMA: seasonal contrasts

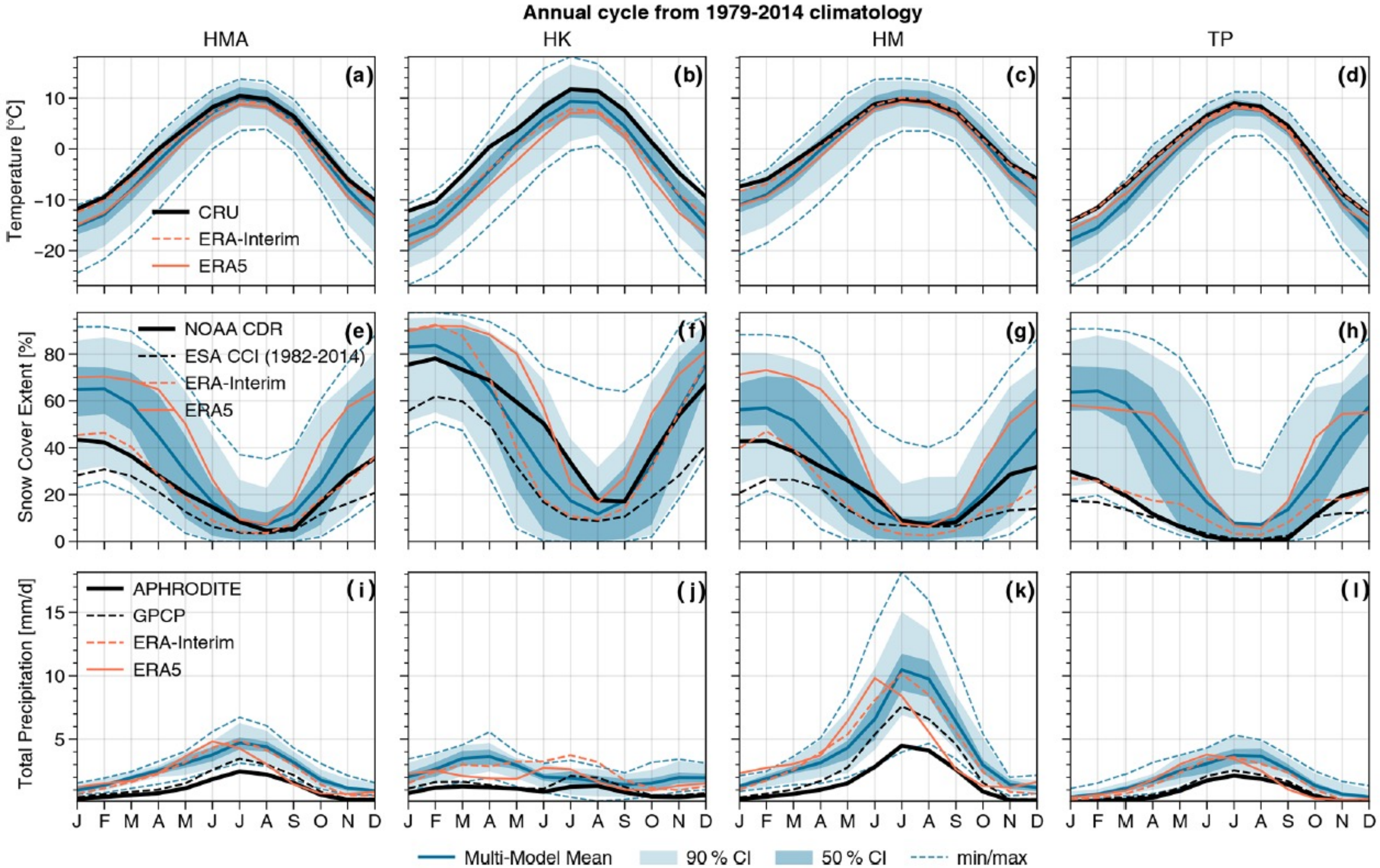


Figure 2. 1979–2014 climatology of the annual cycle of temperature **(a–d)**, snow cover **(e–h)** and precipitation **(i–l)** averaged over HMA **(a, e, i)** HK **(b, f, j)** HM **(c, g, k)** and TP **(d, h, l)**, excluding the surface area located below 2500 m a.s.l. (red contours in Fig. 1). The multimodel mean (dark blue line) is shown with the 50 % confidence interval (CI, dark blue shading), the 90 % CI (light blue shading) and the minimum and maximum (dashed blue lines) of the ensemble. The black curves correspond to the observational datasets: CRU, NOAA CDR and APHRODITE, respectively, for temperature, snow cover and precipitation. The ERA-Interim and ERA5 reanalyses are shown, respectively, with the dashed and solid orange curves. GPCP and ESA CCI datasets are also shown for snow cover and precipitation respectively (dashed black line). The ESA CCI covers only the 1982–2014 period.

Lalande et al., 2021

HMA trends: model and observations

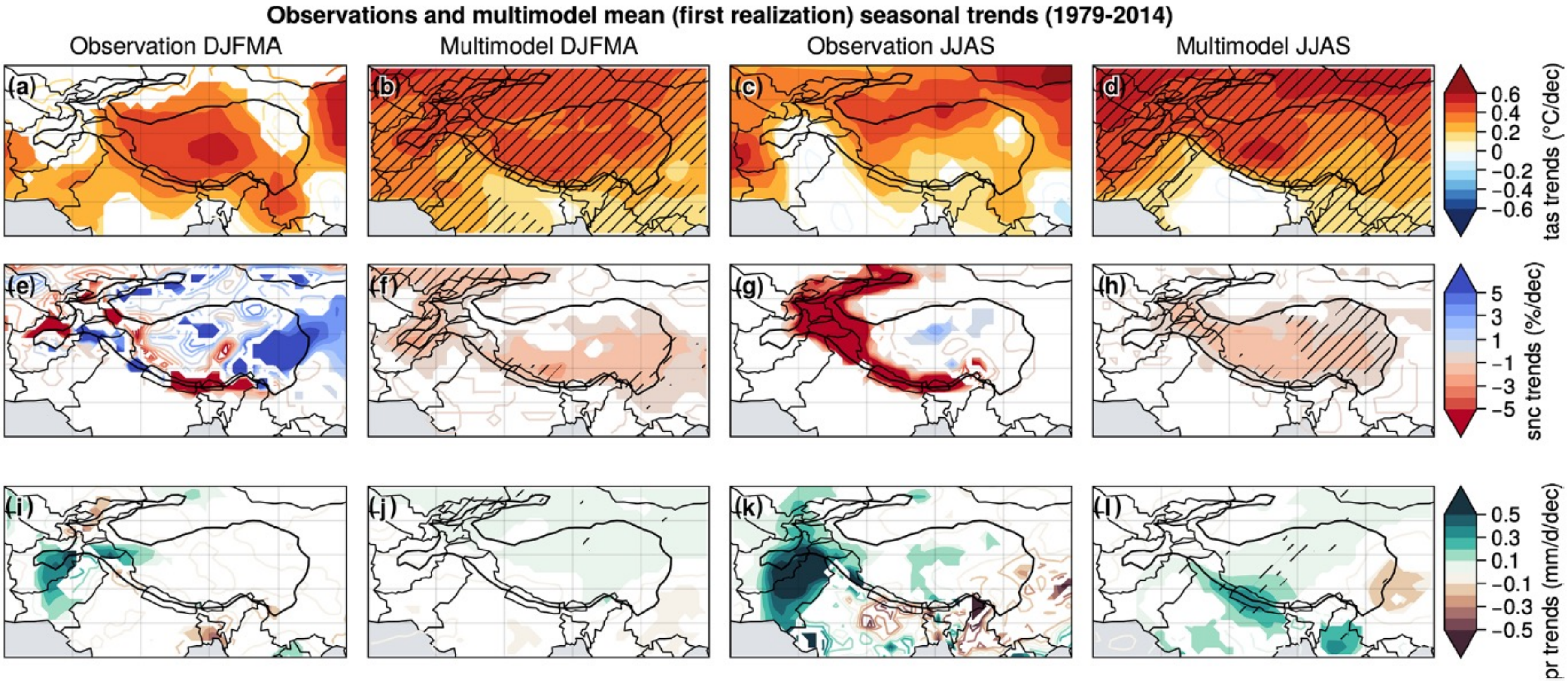
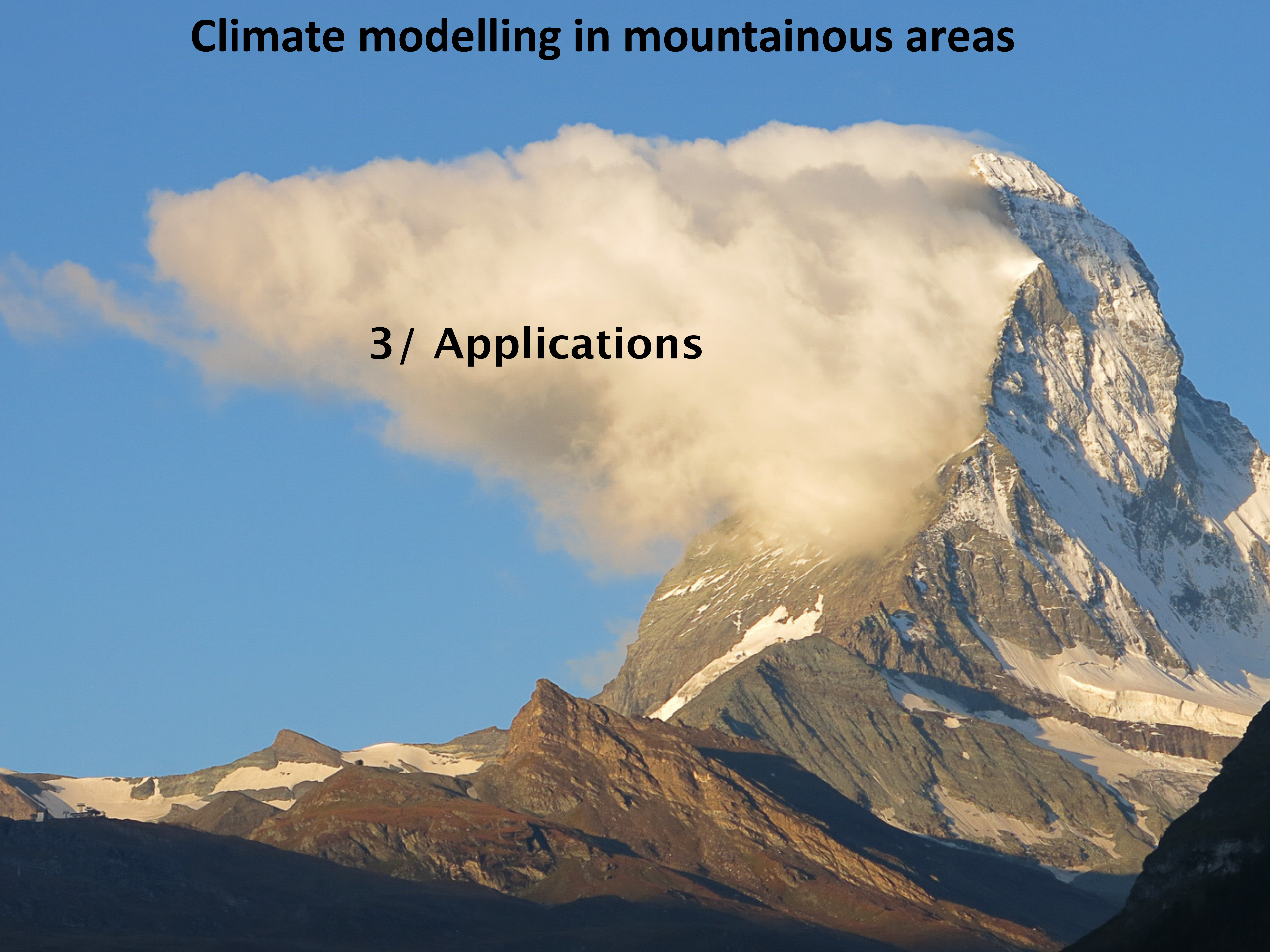


Figure 7. DJFMA (left) and JJAS (right) trends computed over 1979–2014 for temperature **(a–d)**, snow cover **(e–h)** and precipitation **(i–l)**. CRU temperature, NOAA CDR snow cover and APHRODITE precipitation observation trends (DJFMA: **a, e, i** and JJAS: **c, g, k**) are compared to the multimodel mean computed with the first realization for each model (DJFMA: **b, f, j** and JJAS: **d, h, l**). Contours are used for non-significant trends, shading for significant trends (p value > 0.05) and hatching for points where $> 80\,\%$ of the models agree on the sign of the trend.

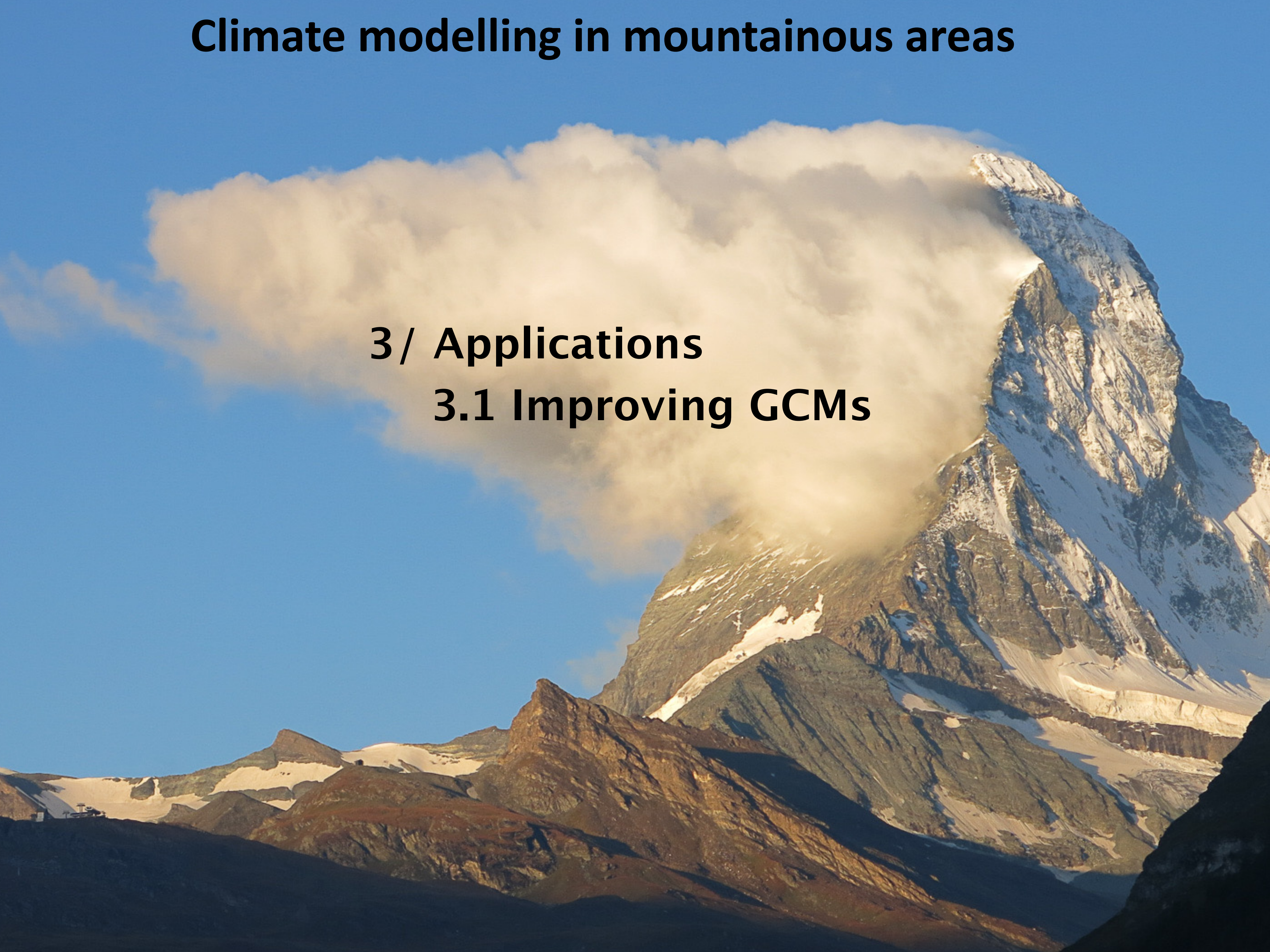
Lalande et al., 2021

Climate modelling in mountainous areas



3/ Applications

Climate modelling in mountainous areas

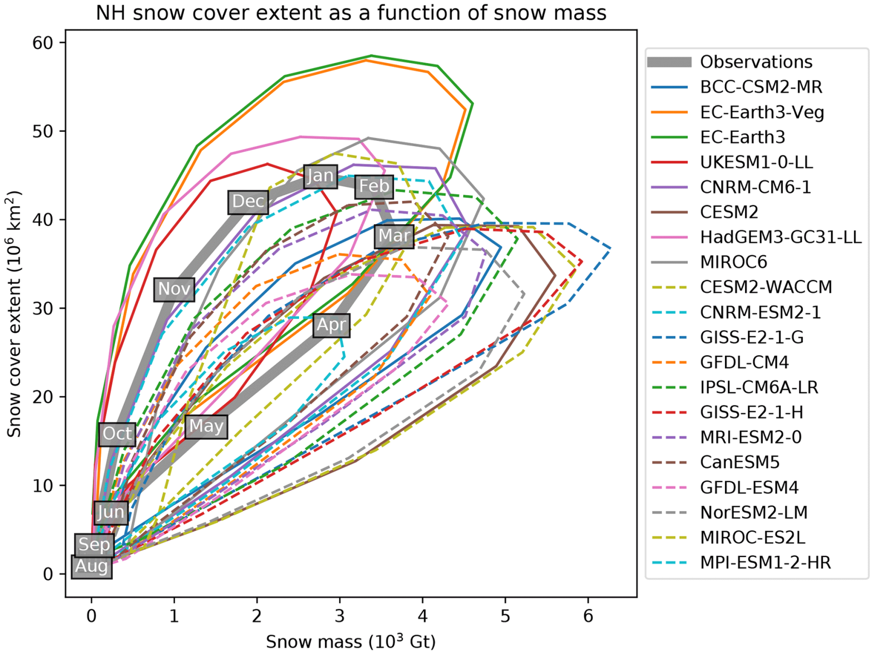


3/ Applications

3.1 Improving GCMs

Improving GCMs:

Example: subgridscale representation of the snow cover area

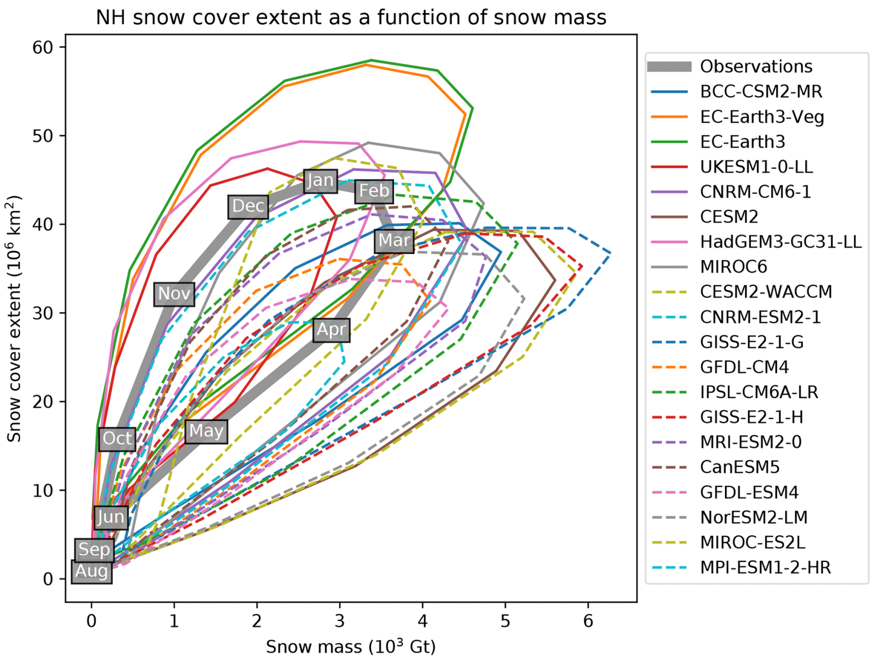


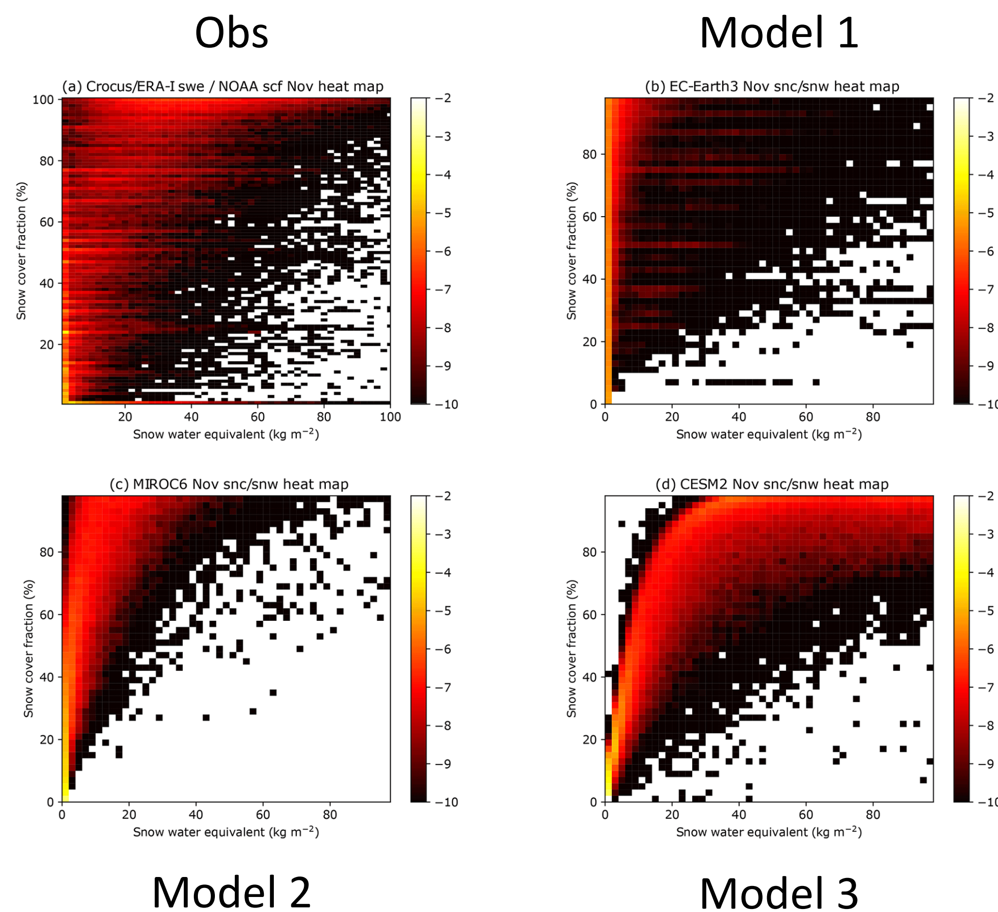
Snow cover fraction as a function of the snow depth.

Mudrick et al., 2020

Improving GCMs:

Example: subgridscale representation of the snow cover area



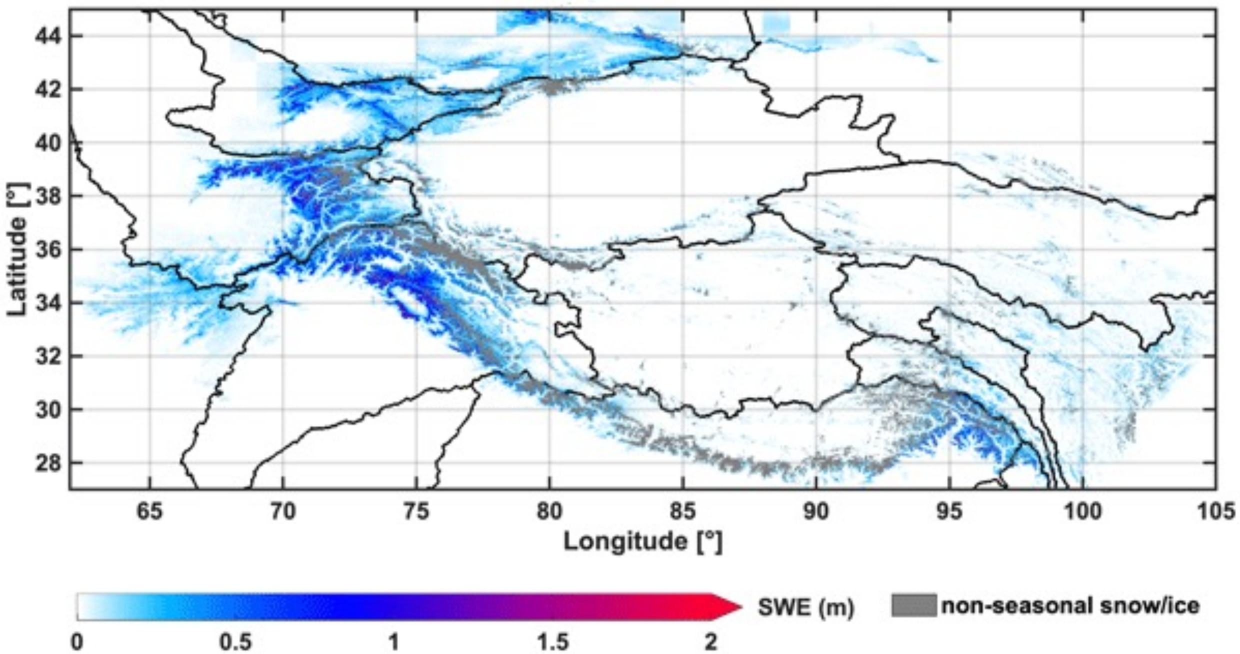


Snow cover fraction as a function of the snow depth.
-> Should depend on the topography!

Mudrick et al., 2020

Improving GCMs:

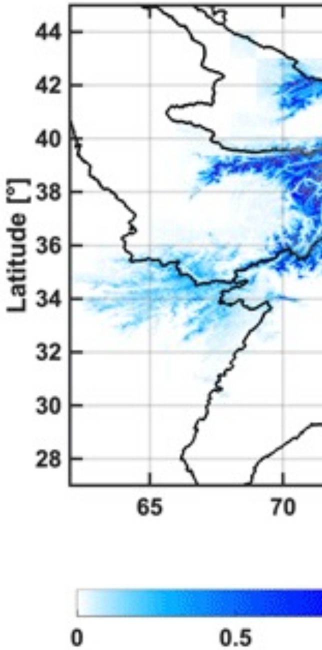
Example: subgridscale representation of the snow cover area

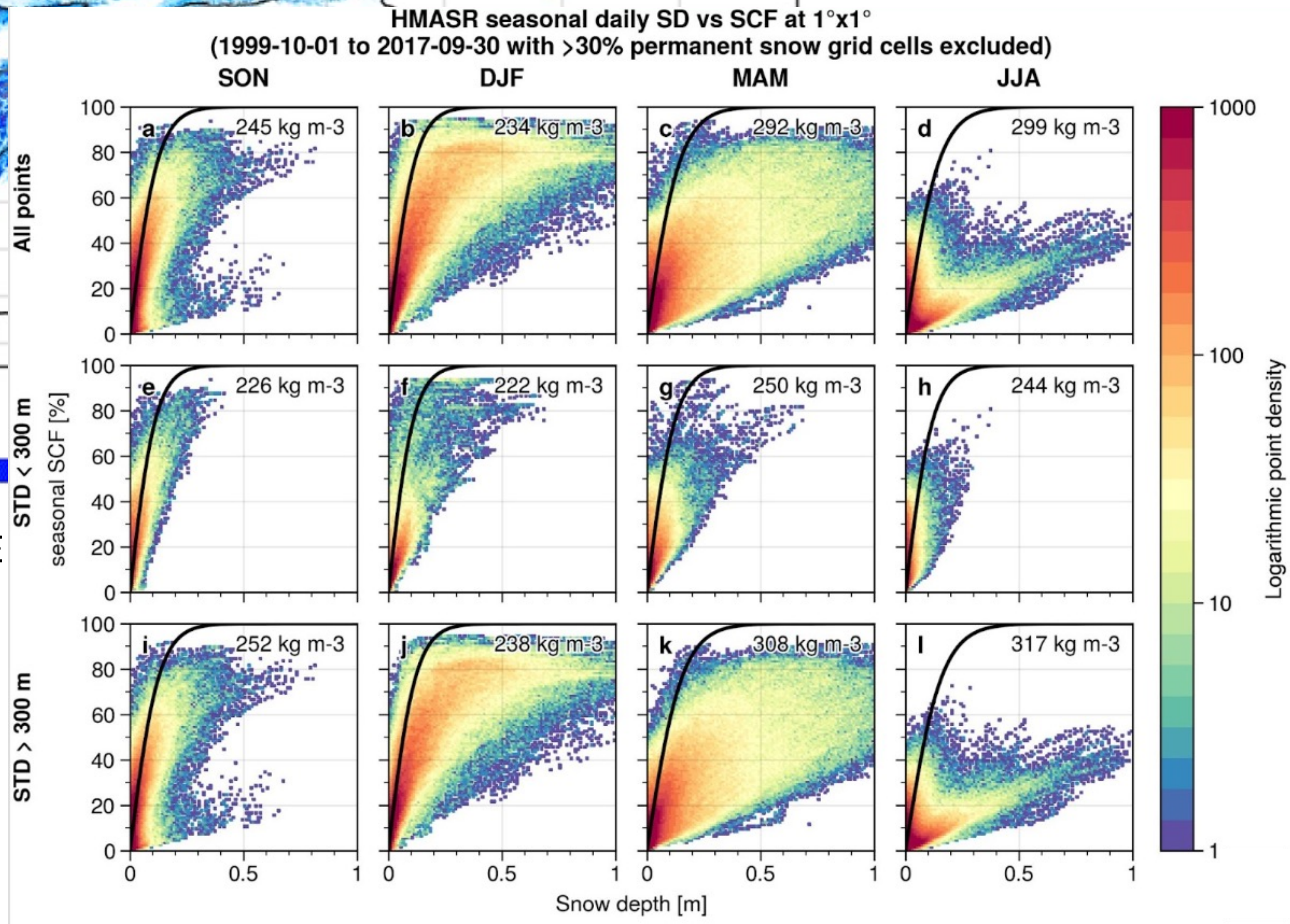


HMASR SCF/SWE reanalysis
(Liu et al., 2021)

Improving GCMs:

Example: subgridscale representation of the snow cover area





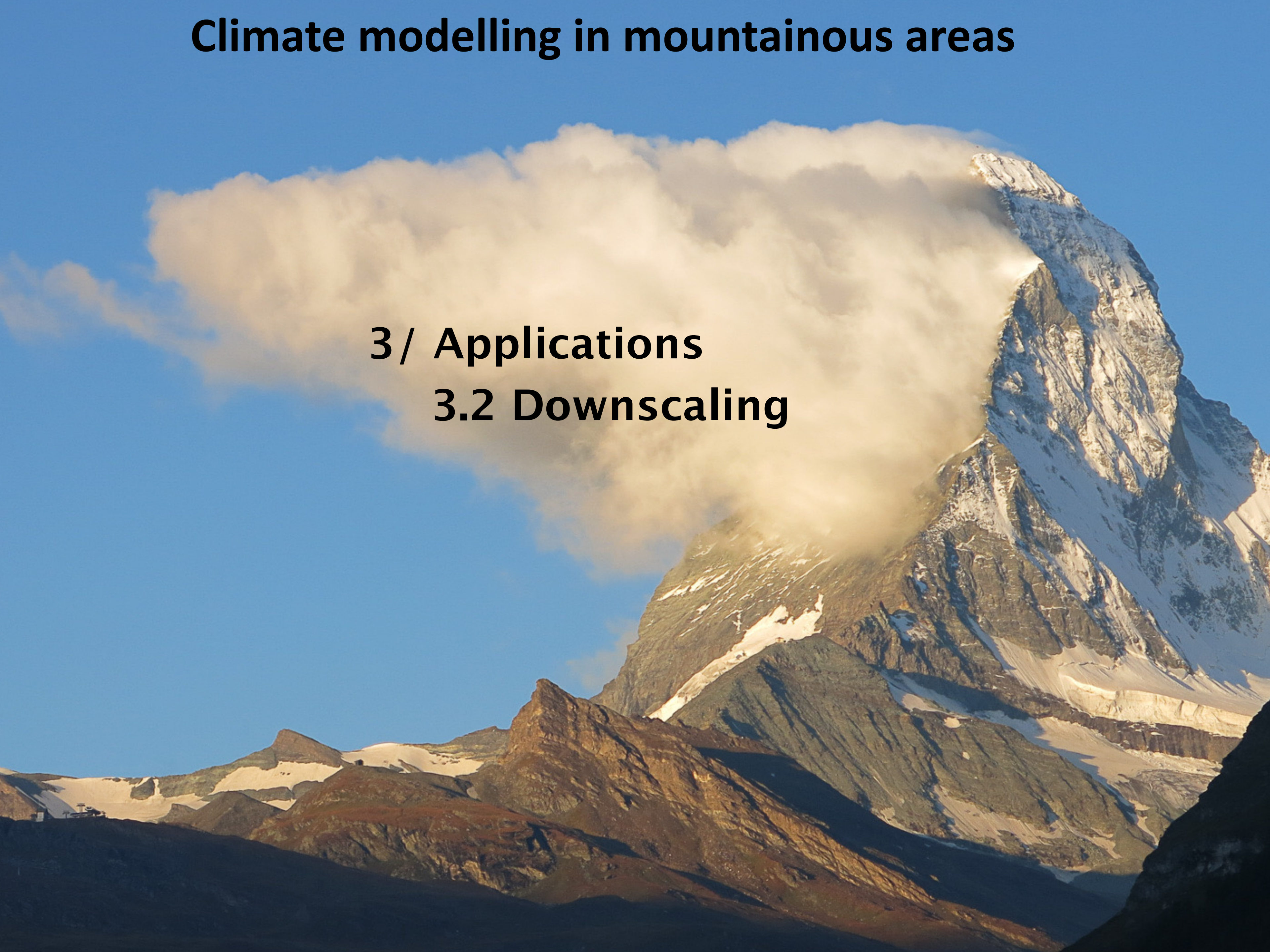
HMASR SCF/SWE (Liu et al., 2021)

Lalande et al., 2023

Climate modelling in mountainous areas

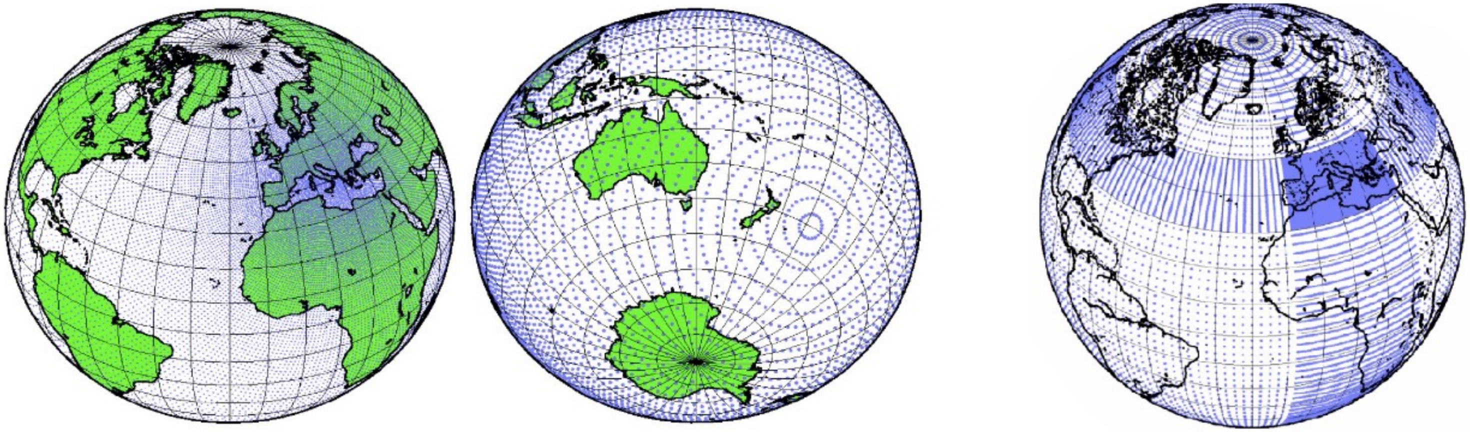
3/ Applications

3.2 Downscaling



Dynamical downscaling

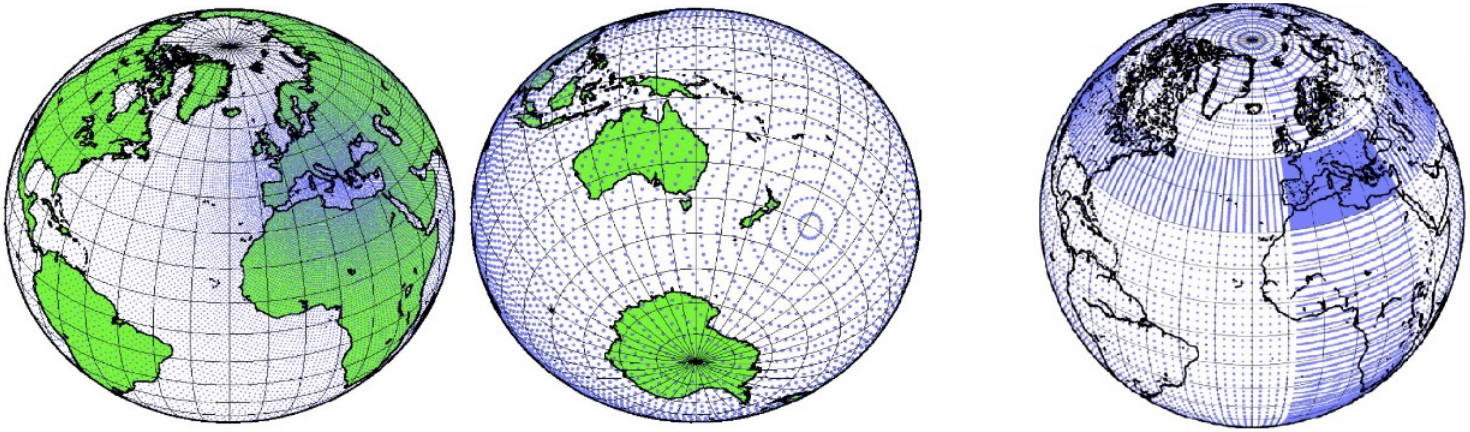
Stretched grid in GCMs
(e.g. LMDZ, ARPEGE)



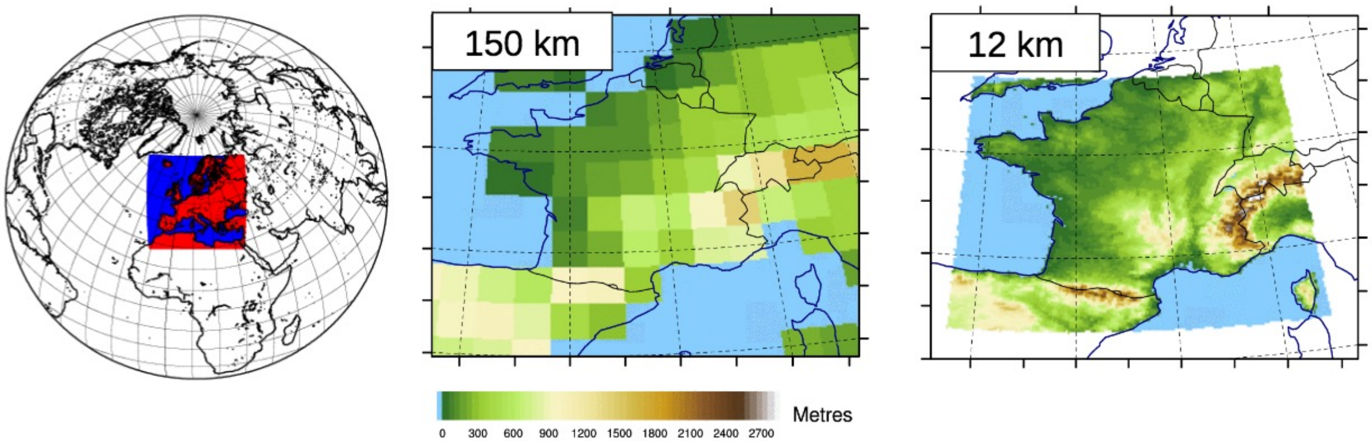
Courtesy B. Pohl, C. Cassou, J. Cattiaux

Dynamical downscaling

Stretched grid in GCMs
(e.g. LMDZ, ARPEGE)

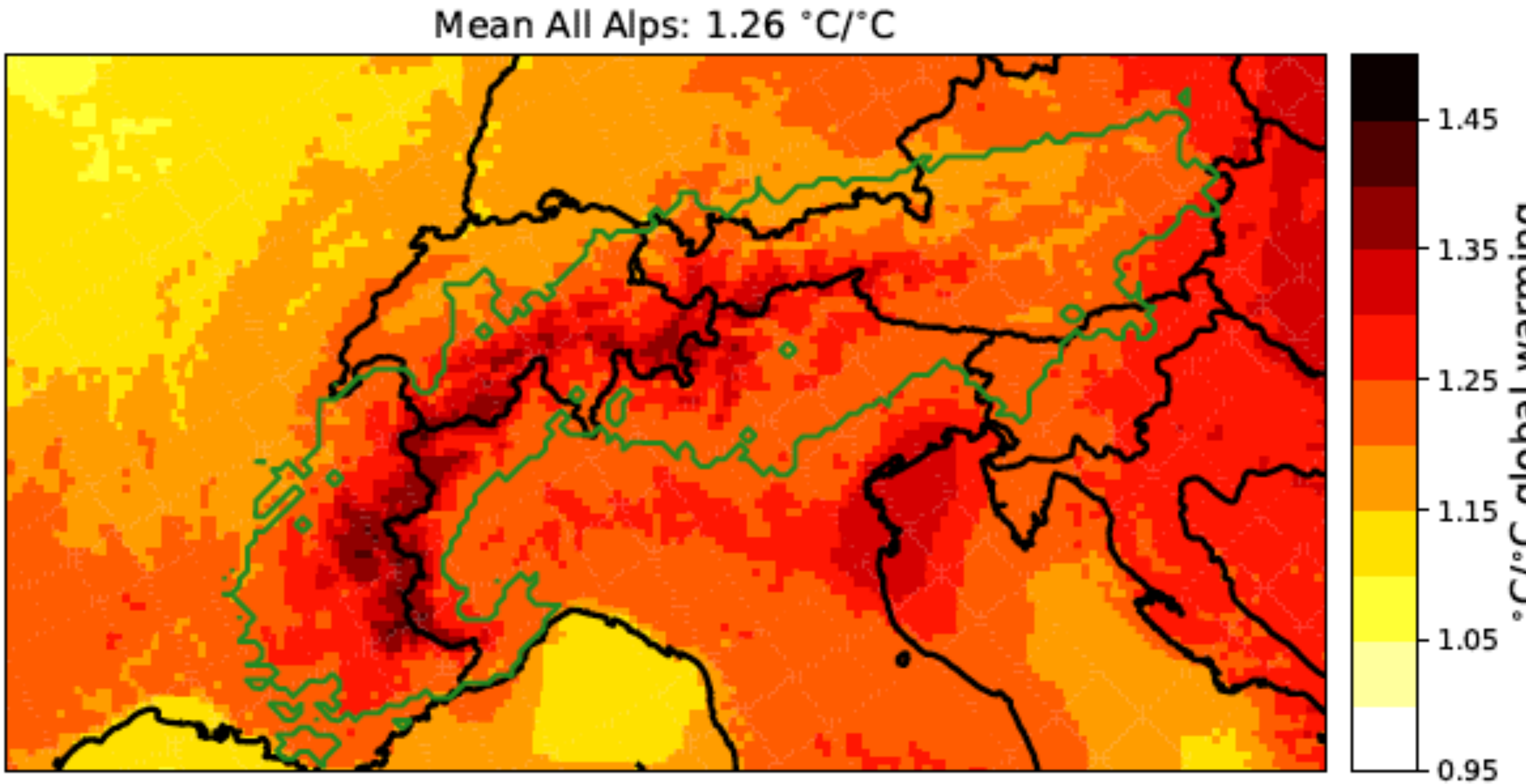


Regional Climate Models
(RCMs, limited area models)



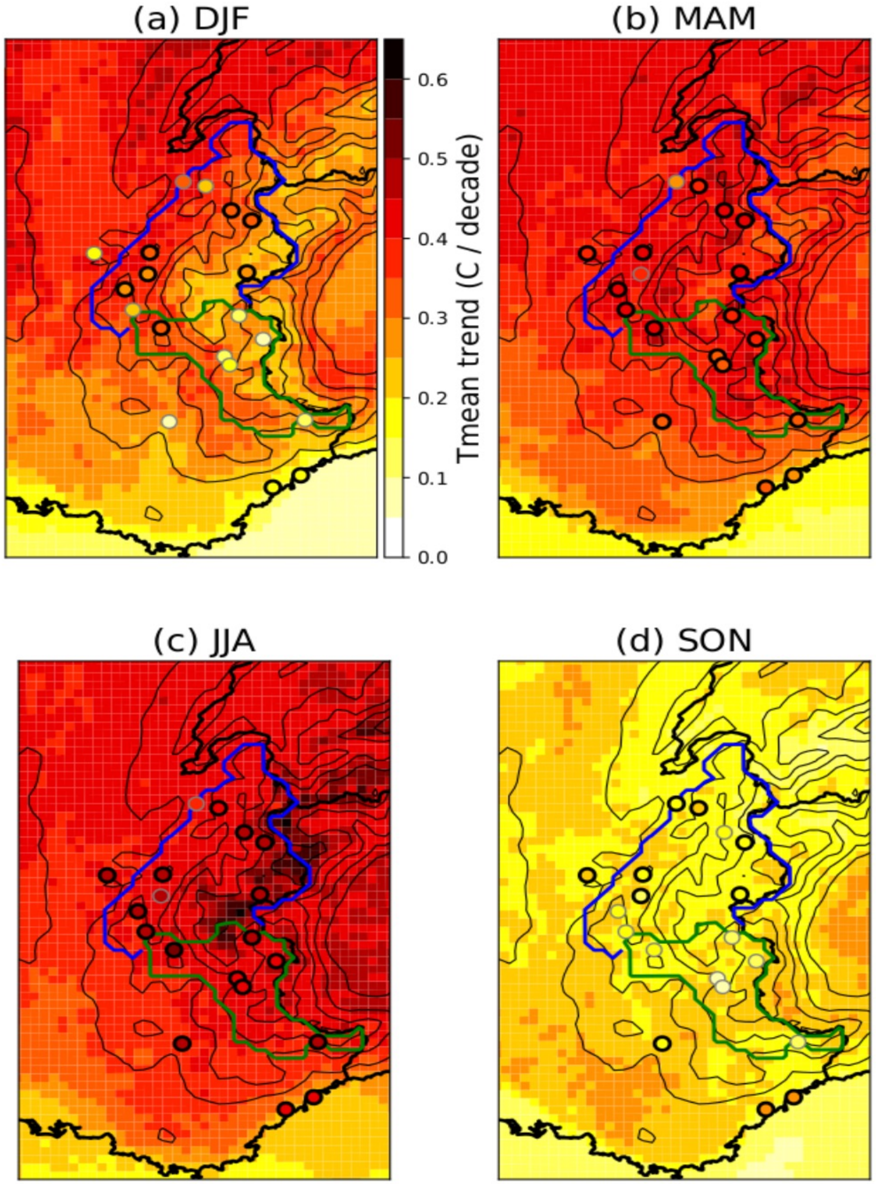
Courtesy B. Pohl, C. Cassou, J. Cattiaux

Temperature trend in the Alps



Temperature trend as a function of the global temperature change simulated with the regional model MAR over 1960-2100

Temperature trend in the Alps



Seasonal trends of temperature over 1959-2010, MAR model (shading) and Météo-France stations (dots)

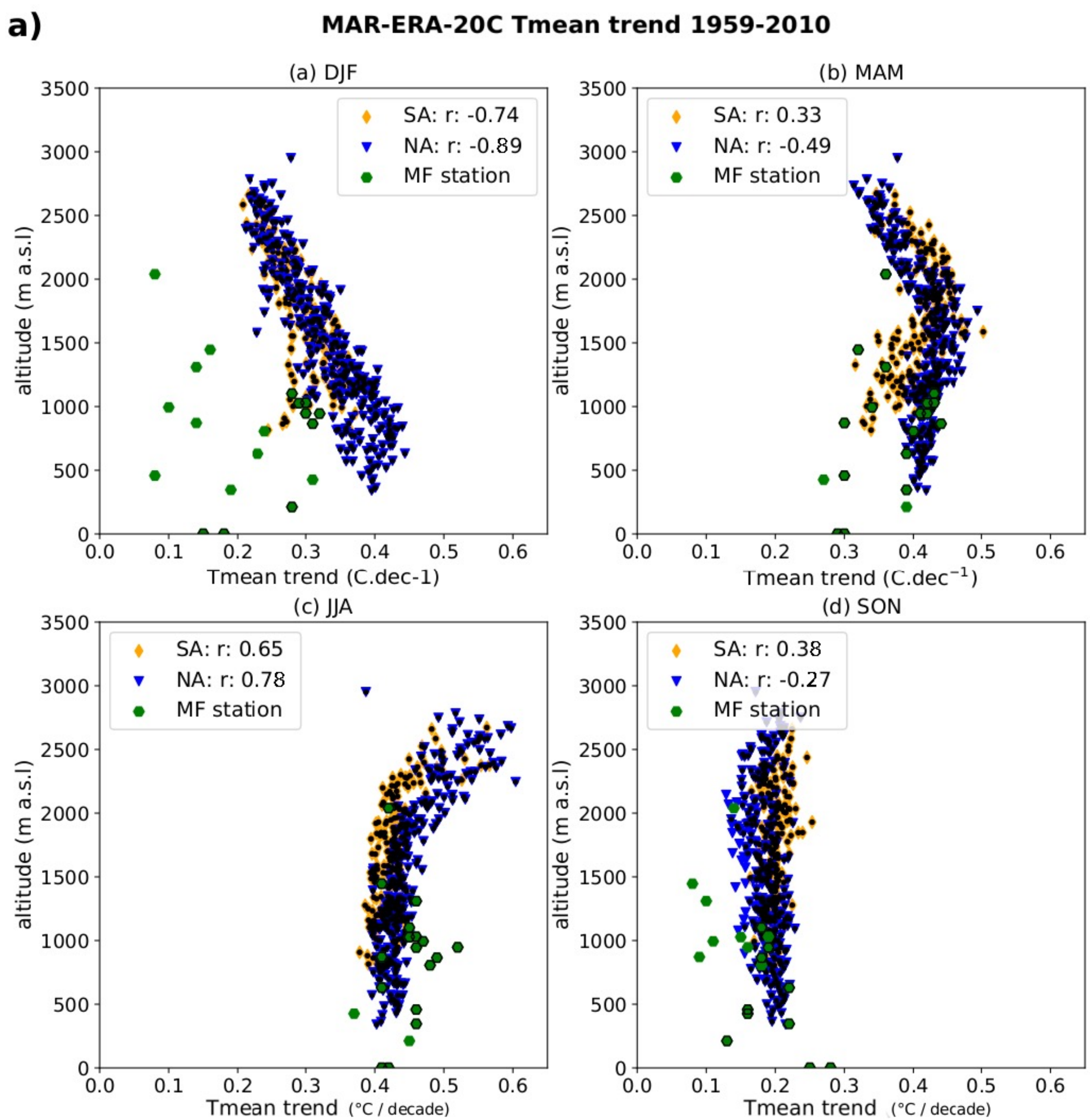
December-January-February (DJF)March-April-May (MAM)June-July-August (JJA) and September-October-November (SON).

Beaumet et al. (2021)

Temperature trend in the Alps (MAR, IGE)

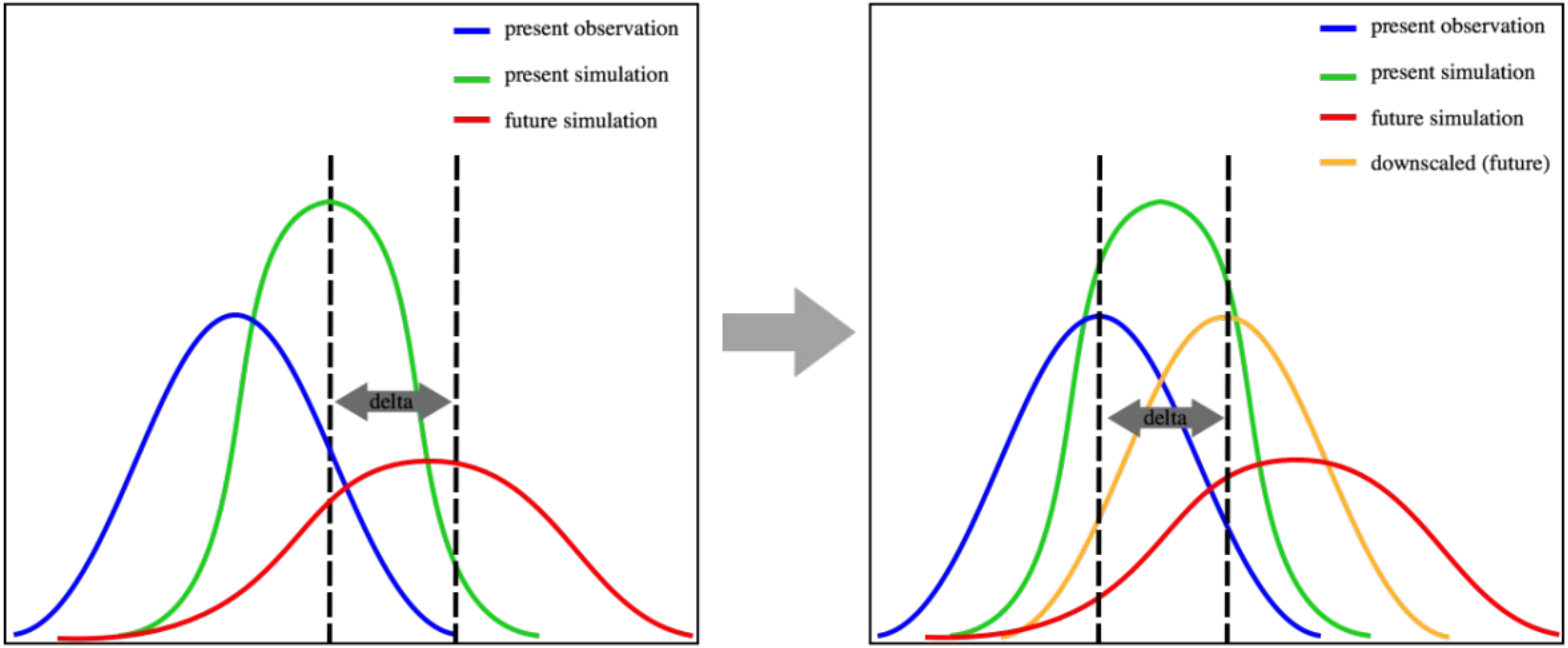
Warming in the French Alps over 1959-2010)

- **Seasonal contrasts**
- **Elevation dependency**



Beaumet et al., 2021

Statistical downscaling



https://rcmes.jpl.nasa.gov/content/statistical-downscaling

Statistical versus dynamical downscaling

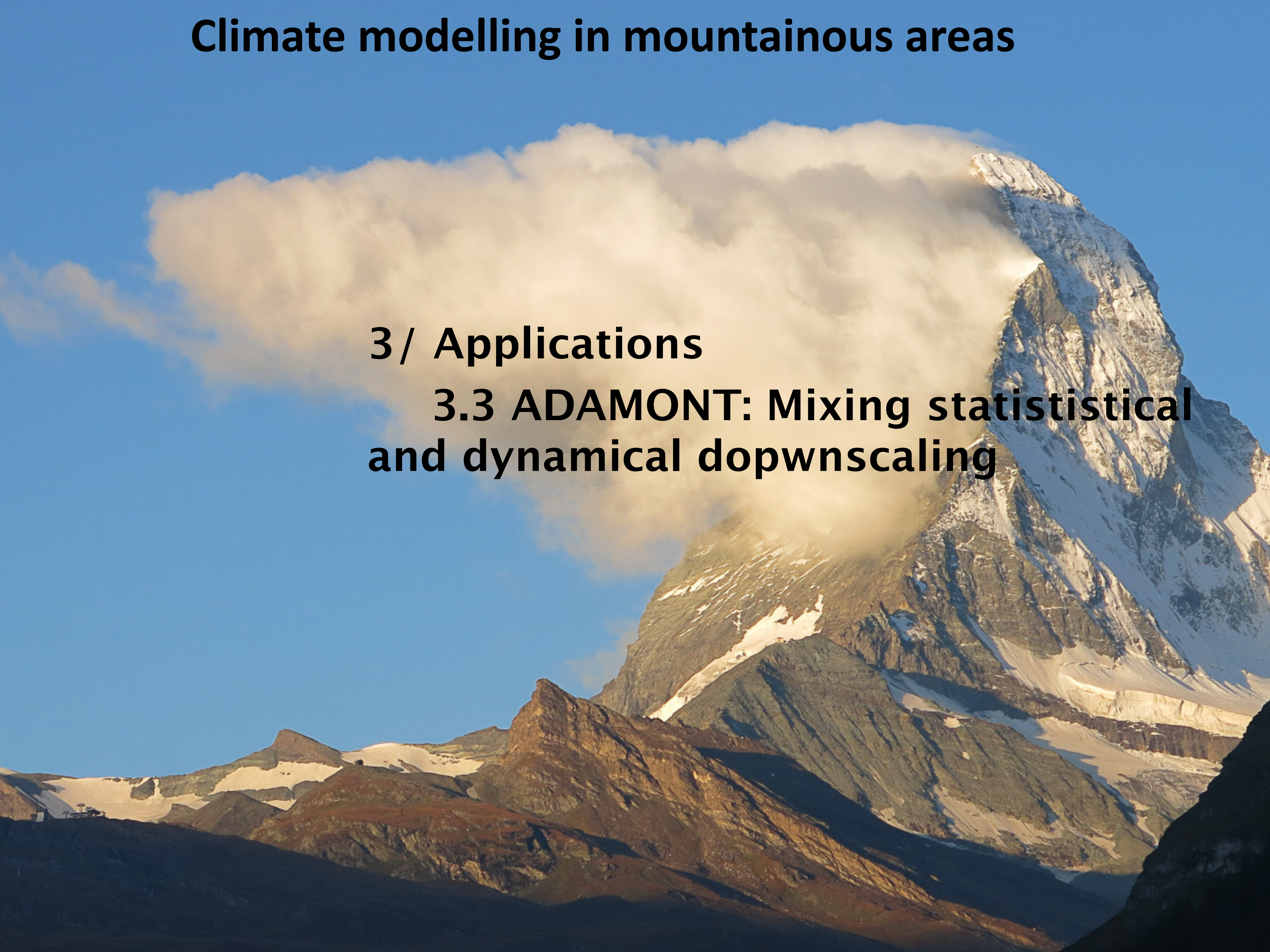
Dynamical	Statistical
Physical realism, catching feedbacks	Lack of physical realism
High computational cost, big data!	Low computational cost, possibility to produce large ensembles
RCMs reproduce a part of the GCMs biases trough lateral conditions	Biases and large scale - small scale teleconnections might be not stationnary
Spatial resolution still too coarse for mountainous areas	Possibility to get data at very local scale

Synthesis on the climat of HMA: https://www.encyclopedie-environnement.org/climat/glaciers-hautes-montagnes-asie-face-au-changement-climatique/

Climate modelling in mountainous areas

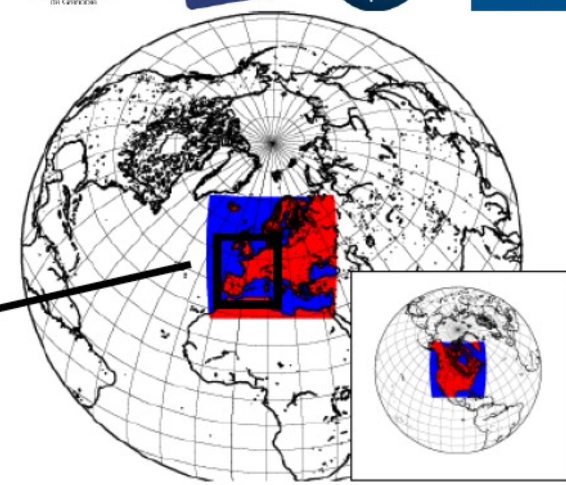
3/ Applications

3.3 ADAMONT: Mixing statististical and dynamical dopwnscaling

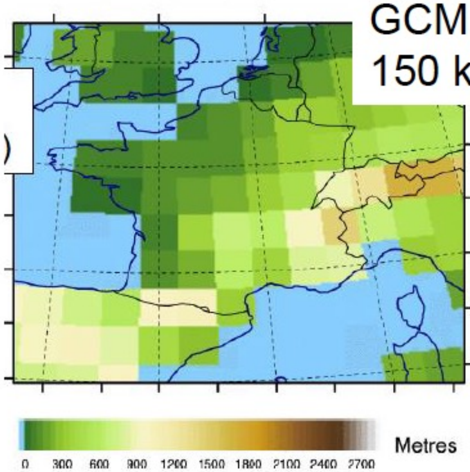


Future projections with ADAMONT

- Cascade de modèles et ajustements pour exploiter les projections climatiques à échelle mondiale et les appliquer aux territoires de montagne

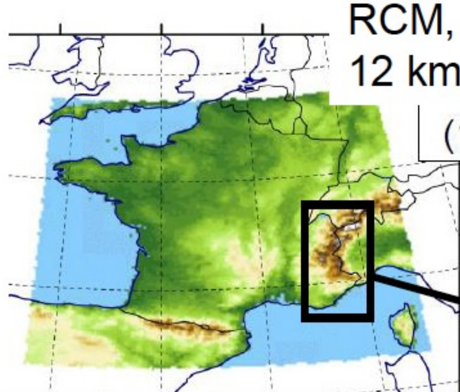


GCM, 150 km



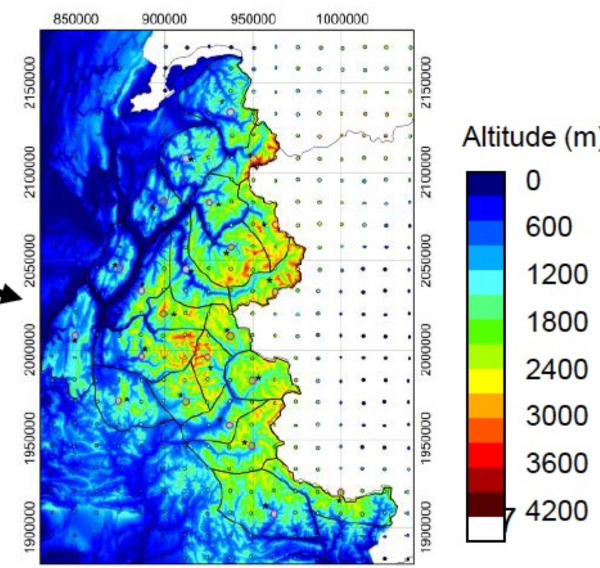
EUROCORDEX

RCM, 12 km



Modèle de climat régional (RCM)

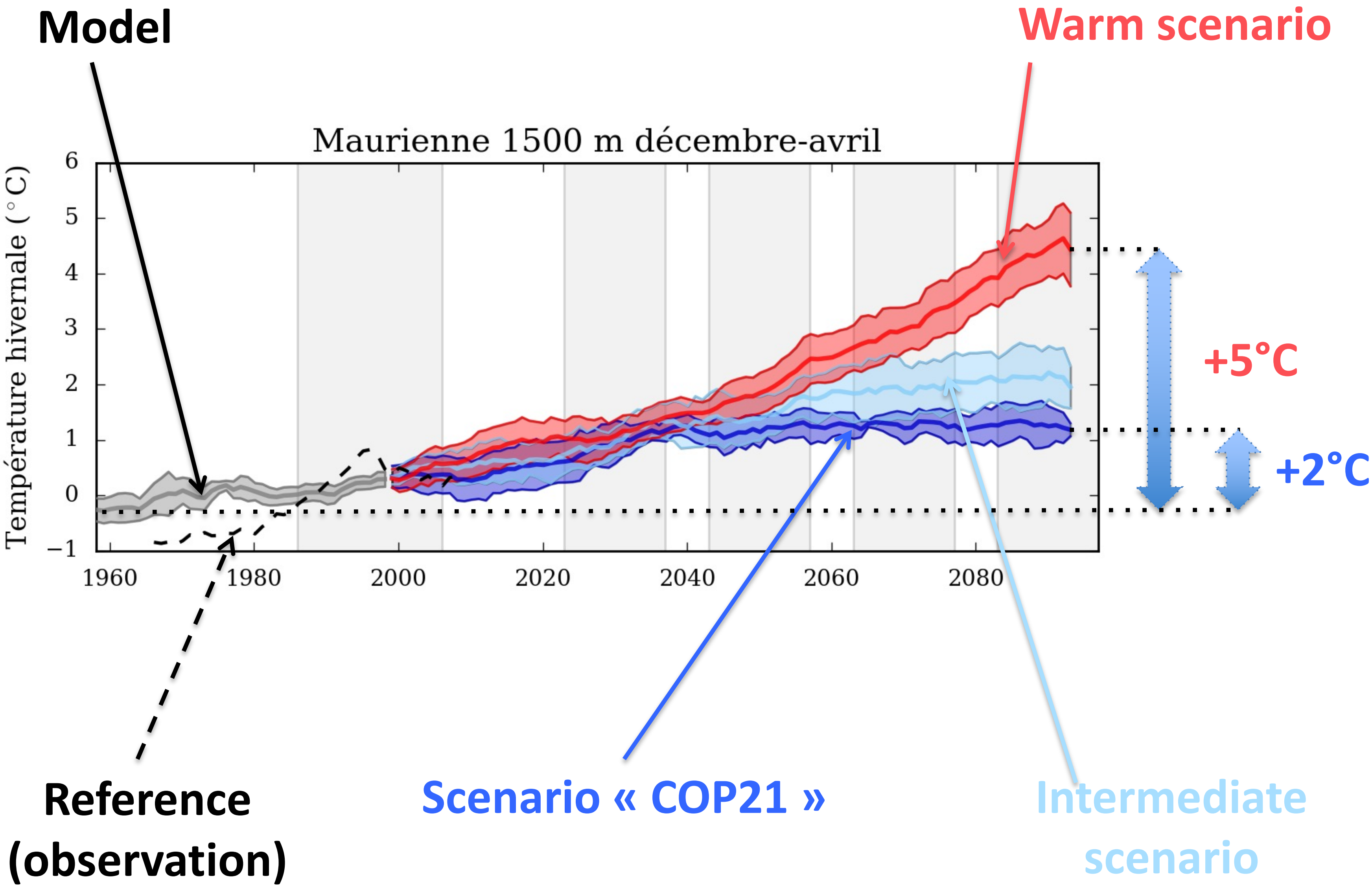
Ajustements statistiques, ADAMONT



D. Verfaillie, S. Morin, Météo-France

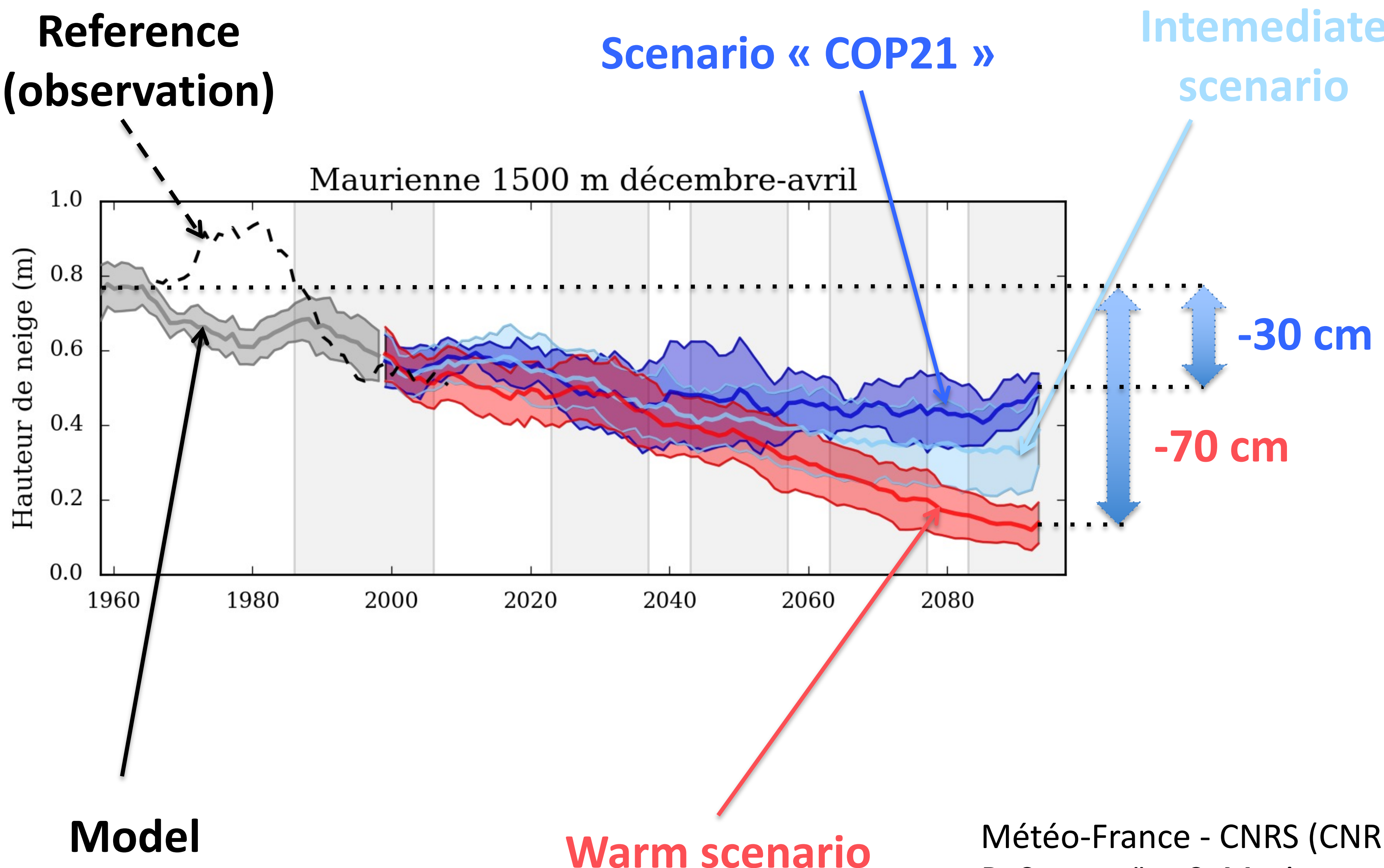
Verfaillie et al., 2017, Figure C. Cassou

Temperature observed and simulated at 1500m



Météo-France - CNRS (CNRM), R. Samacoïts, S. Morin

Snow depth observed and simulated at 1500m



Météo-France - CNRS (CNRM),
R. Samacoïts, S. Morin

ADAMONT: Advantages and drawbacks

-> Uncertainty assessed with ensemble experiments

-> Description of atmospheric and snowpack variables by massif and by altitude range.

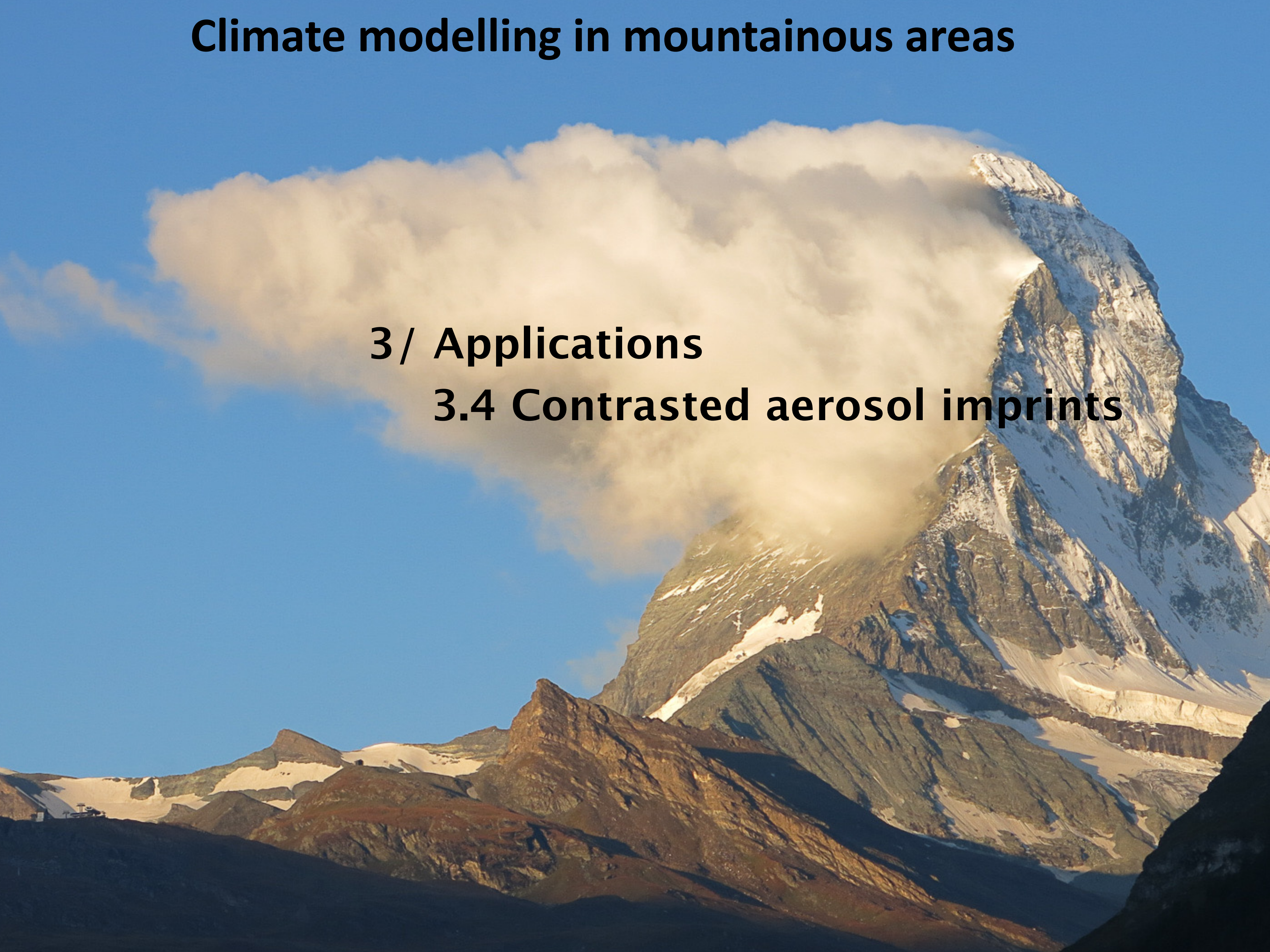
-> no local physical feedbacks

-> local aerosol forcing in the atmosphere and on the snow poorly represented

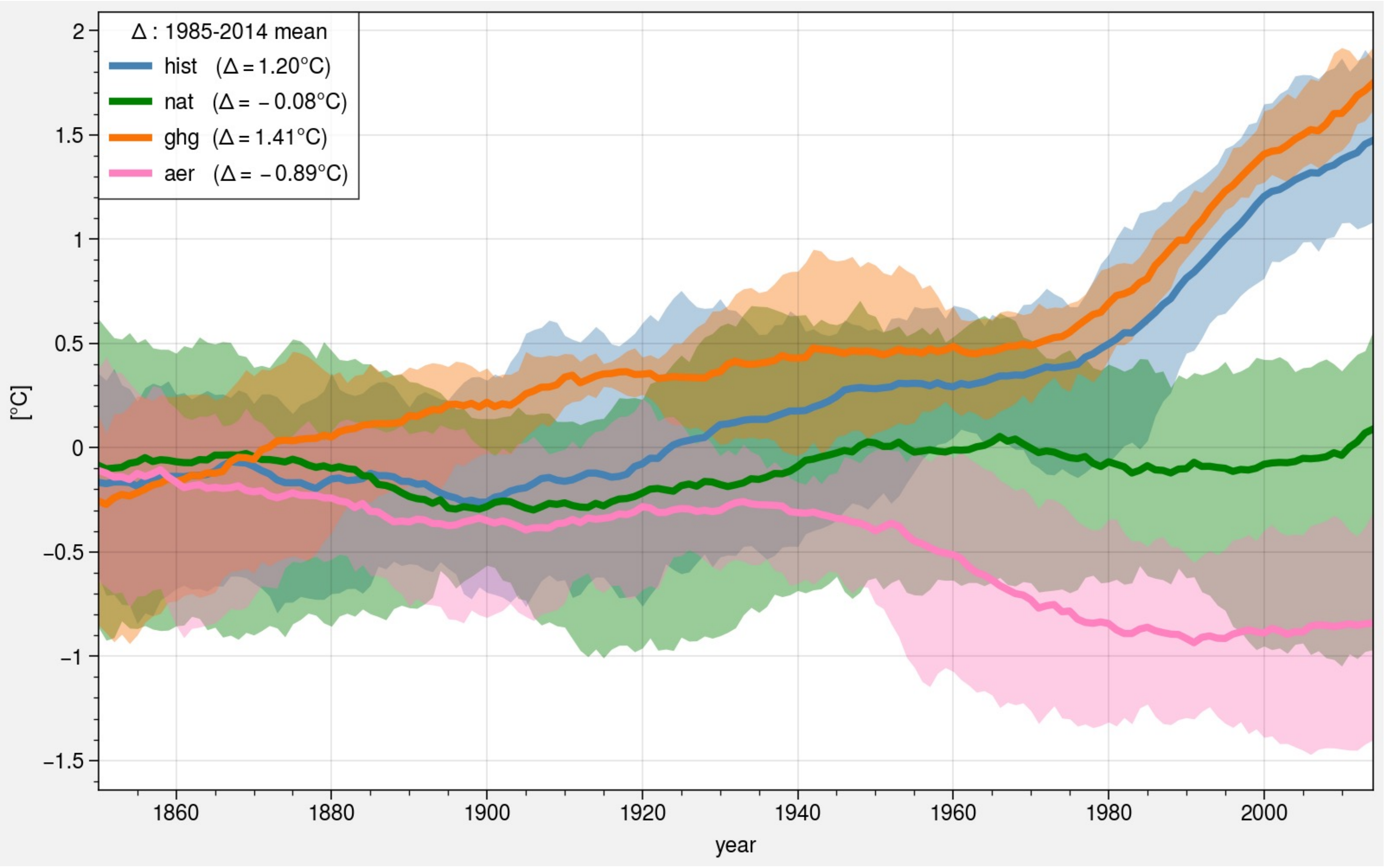
Climate modelling in mountainous areas

3/ Applications

3.4 Contrasted aerosol imprints

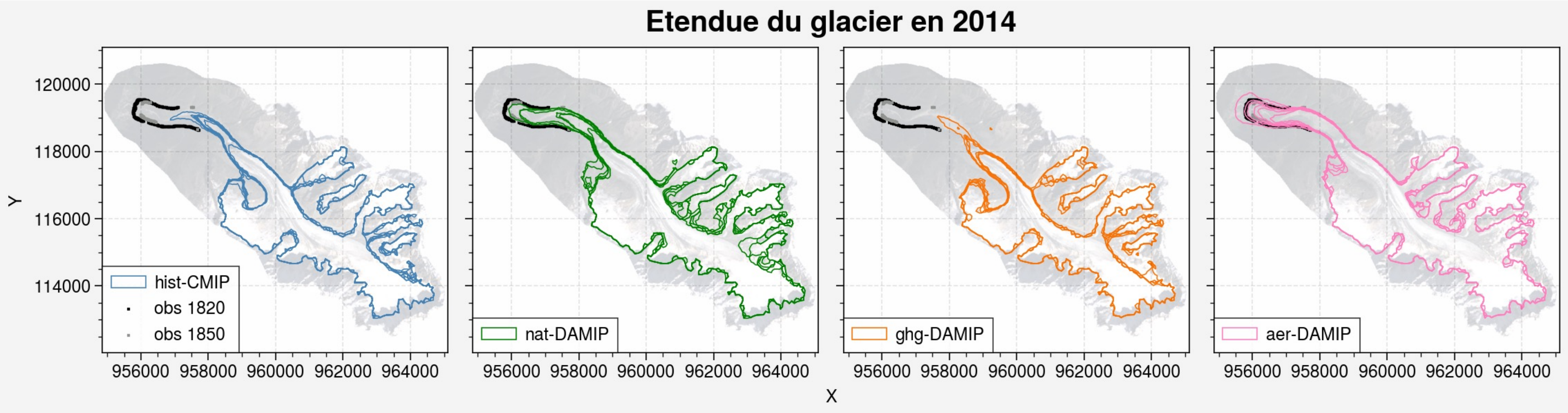


Atmospheric aerosols cool the climate…



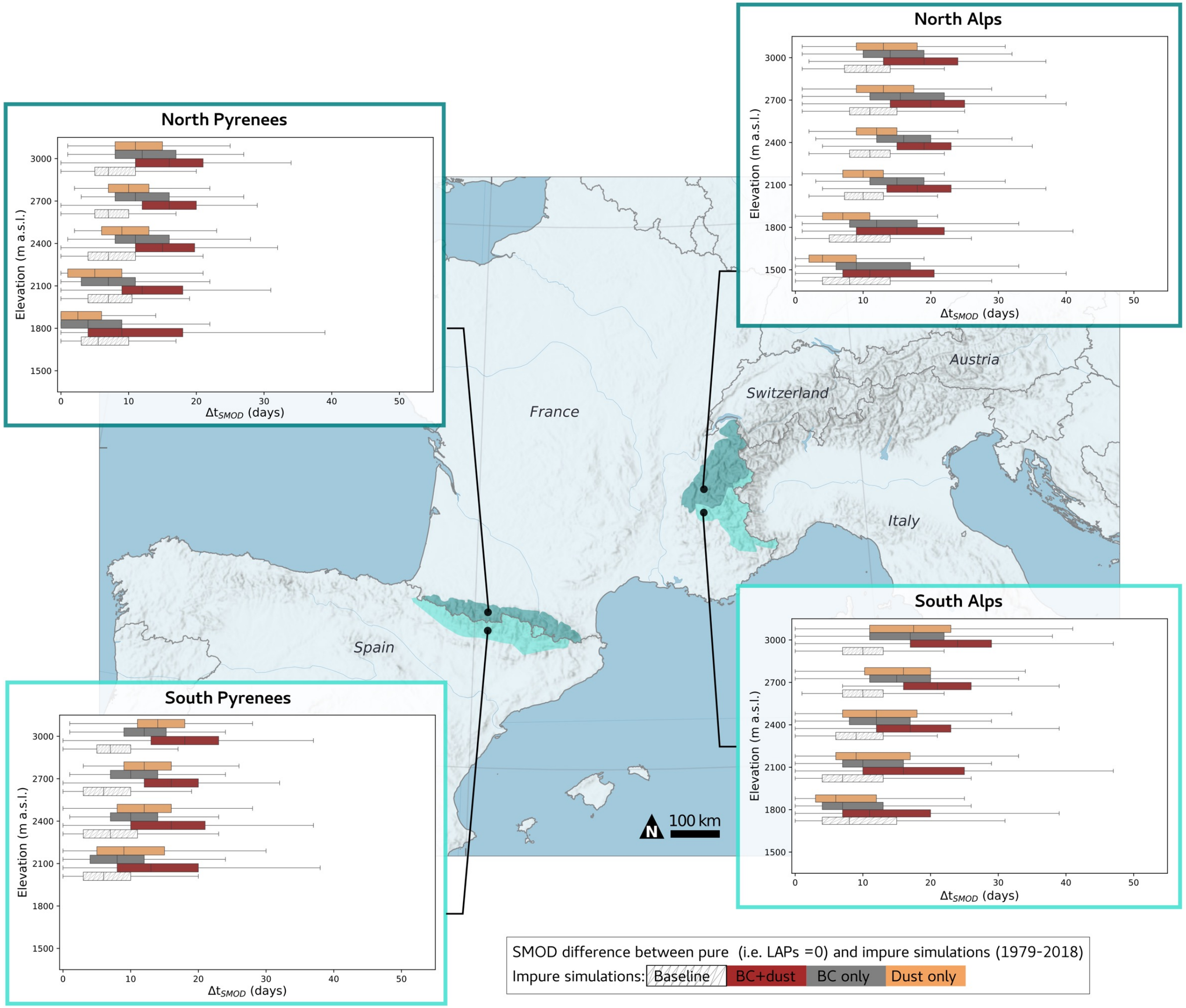
Bias-corrected temperature at Chamonix estimated from historical GCM experiences, including only natural forcings (nat), only greenhouse gases (Ghgs), only aerosols (aer). Clauzel et al., 2023.

Atmospheric aerosols cool the climate…



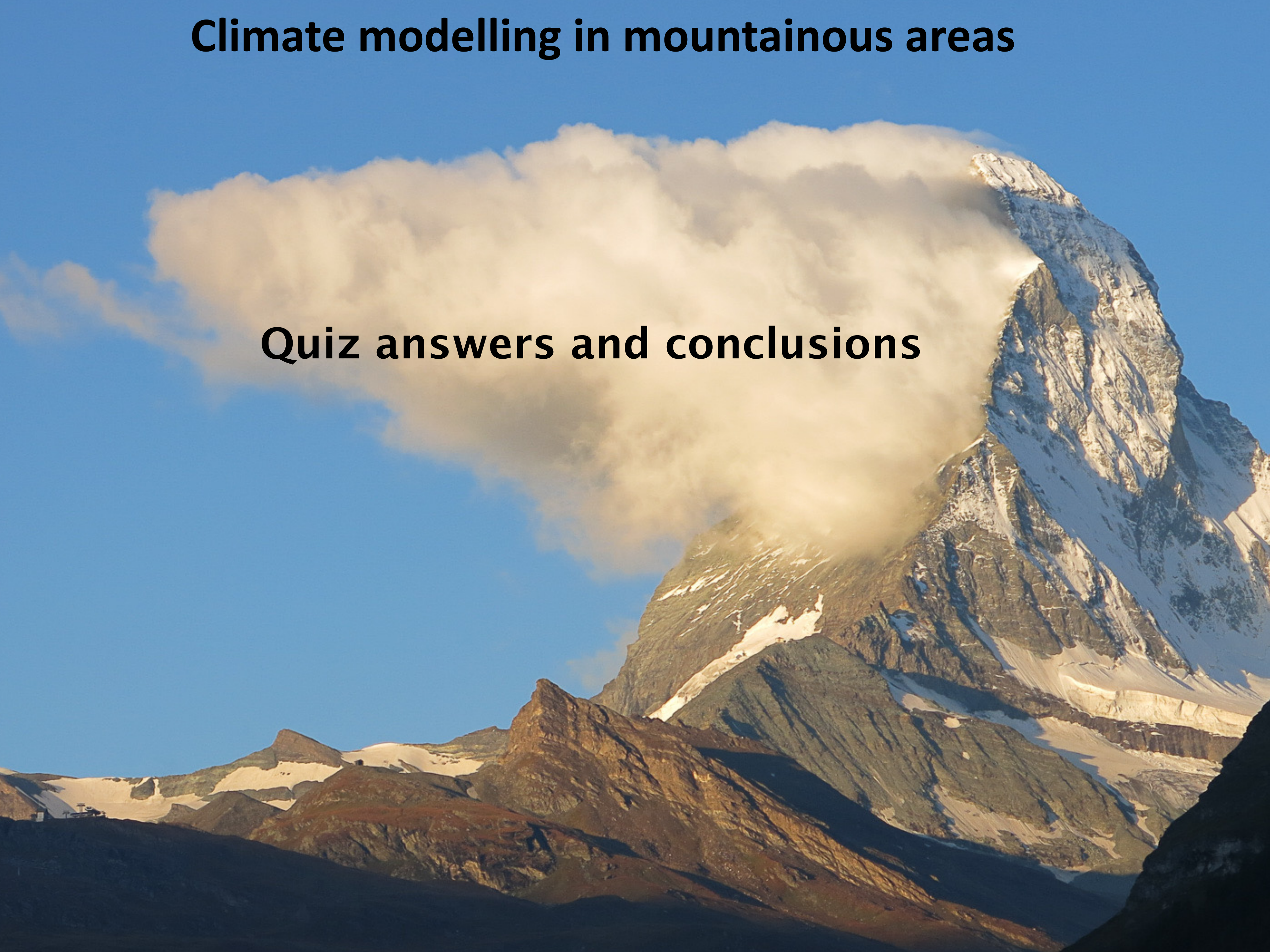
Surface of the Argentière glacier simulated with ELMER-ICE, forced by historical GCM experiments, including only natural forcings (nat), only greenhouse gases (Ghgs), only aerosols (aer). Clauzel et al., 2023.

Aerosols deposited onto the snow increase melting...



Decrease in ground snow duration (days) induced by particle deposition (Reveillet et al., 2022)

Climate modelling in mountainous areas



Quiz answers and conclusions

Quiz

We are now at around +1.1°C globally compared with ~1850. Current policies to reduce greenhouse gas emissions will bring us to...

a) ... 4.9°C (between 4.3 and 5.6°C)
b) ... 3.2°C (between 2.2 and 3.5°C)
c) ... 2.5°C (between 1.7 and 2.9°C)

If we manage to reduce instantaneously anthropogenic CO2 emissions to zero at global level, ...

a) ... the global average temperature will return to pre-industrial levels in ~30 years.
b) ... the temperature will rapidly stabilise around the level reached at the time of "net zero".
c) ... the Earth will continue to warm for ~50 years, by a further 0.5°C or so.

Depending on the scenario, the estimation of the glacier mass change in the Alps between 2000 and 2100 is...

a) -33 to -62%
b) -82 to -96%
c) +24% (gain) to -37% (loss)

Quiz

We are now at around +1.1°C globally compared with ~1850. Current policies to reduce greenhouse gas emissions will bring us to...

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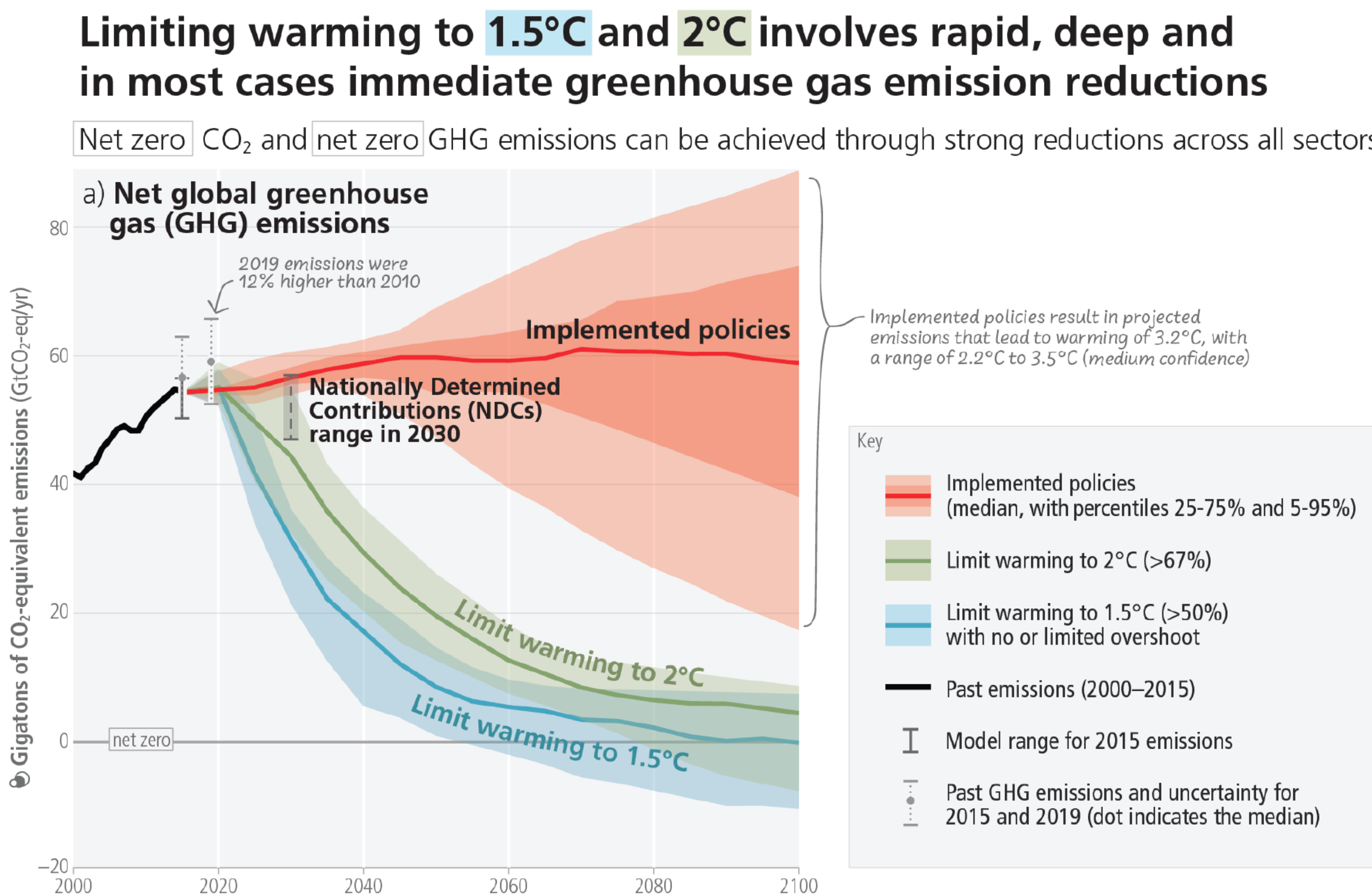

IPCC, Synthesis report (2023)

Quiz

If we manage to reduce instantaneously anthropogenic CO2 emissions to zero at global level, ...

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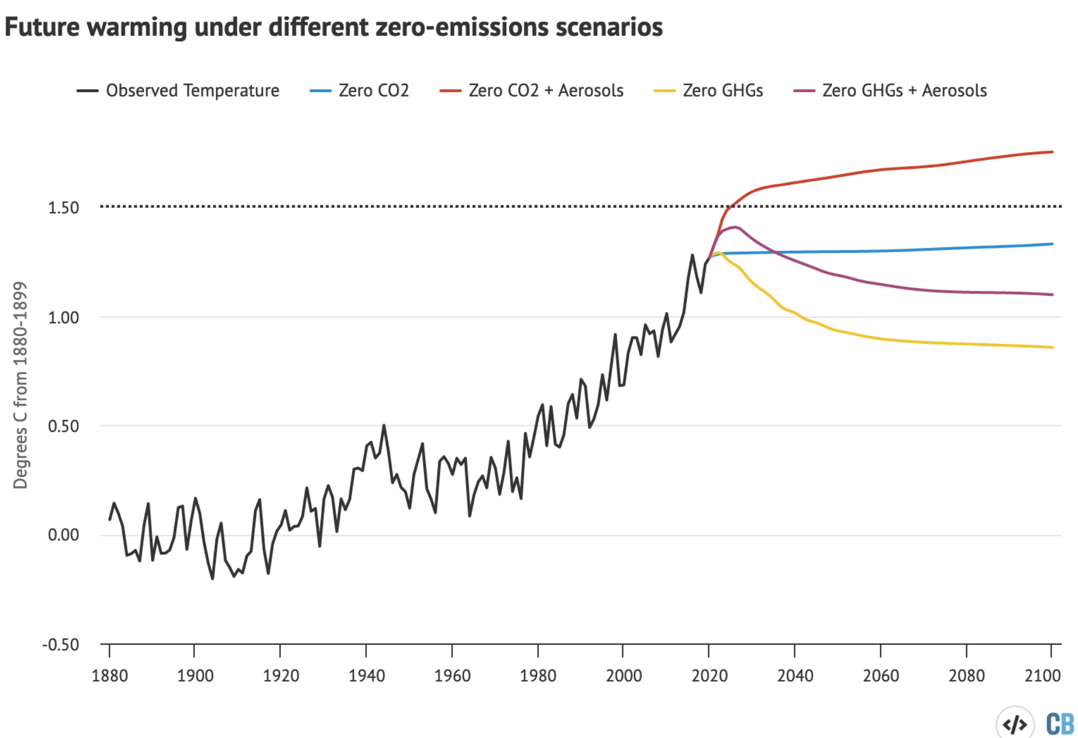


Projected global surface temperature changes under zero CO2 emissions (blue line), zero CO2 and aerosol emissions (red), zero GHG emissions (yellow) and zero GHG and aerosol emissions (purple). Chart by Carbon Brief using Highcharts, adapted from Figure 1.5 in the IPCC SR15. Historical warming values (black) and combination with model simulations are estimated using the methods described in the first figure.

Tricky question!
Ocean heat released should be compensated by CO2 uptake by land surfaces and oceans. But we should also consider the non CO2 GHGs (warming) and aerosol (cooling)

https://www.carbonbrief.org, adapted from IPCC SR15

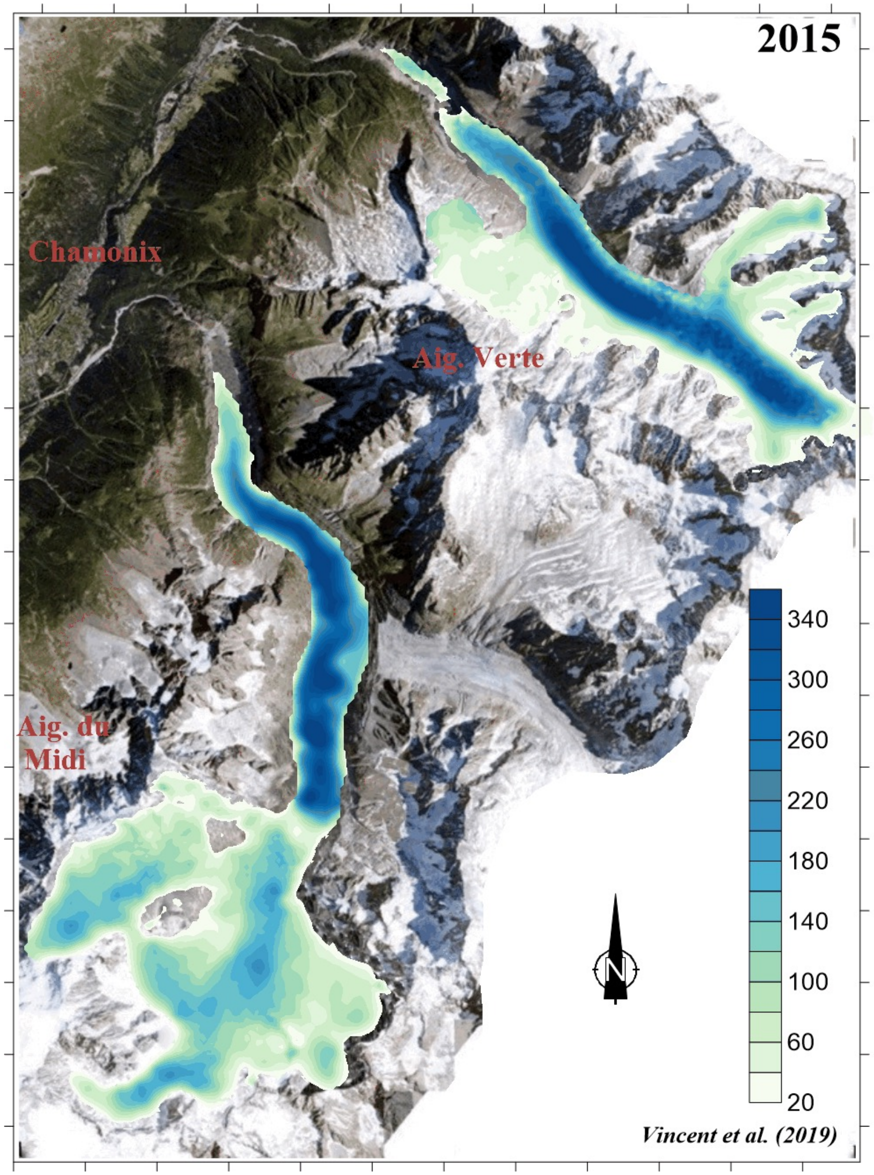
Quiz

Depending on the scenario, the estimation of the glacier mass change in the Alps between 2000 and 2100 is...

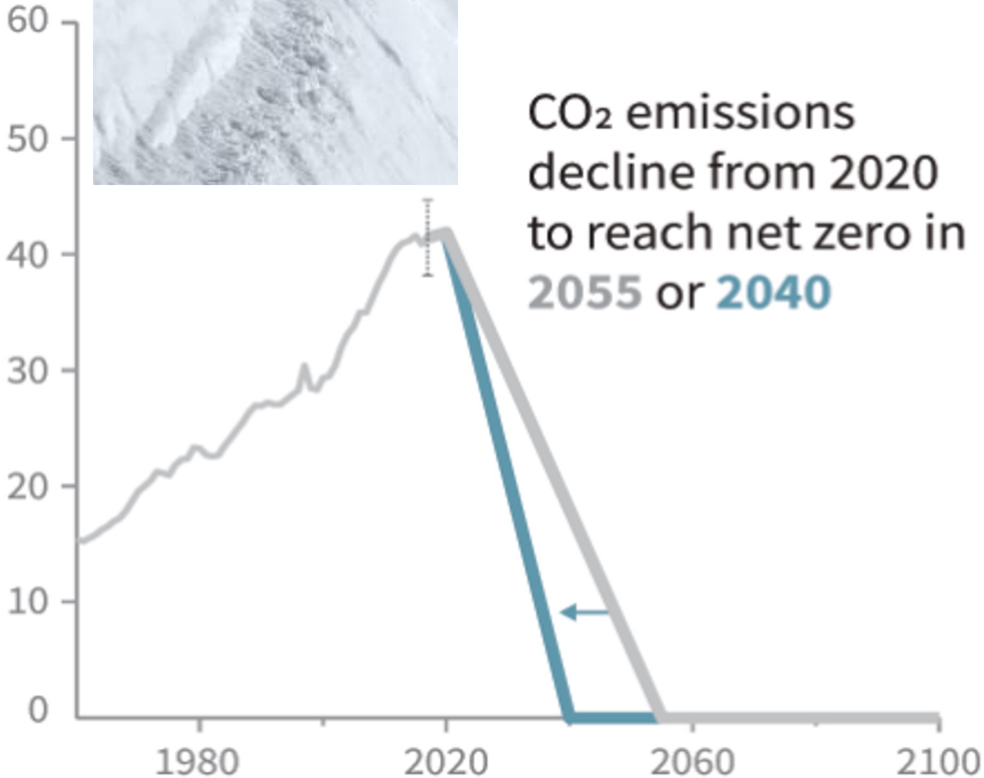
~~a) -33 to -62%~~

b) -82 to -96% (Huss et al., 2012)

~~c) +24% (gain) to -37% (loss)~~



The more we are waiting, the steeper will be the slope…



Schematic scenarios for net global CO2 emissions (GtCO2/year)

Thanks!!!

Your turn to play:

https://github.com/mmenegoz/climate_HMA_course/tree/M2_climat_2023