The Future of (Very) Large Hail Globally: Application of AR-CHaMo to the CMIP6 Ensemble

Francesco Battaglioli [1,2] **, Pieter Groenemeijer** [3,1] **, Tomas Pucik** [3] **, Mateusz Taszarek** [4]

[1] *European Severe Storms Laboratory (ESSL), Wessling, Germany*
[2] *ESSL Services GmbH, Wiener Neustadt, Austria*
[3] *European Severe Storms Laboratory Science & Training, Wiener Neustadt, Austria*
[4] *Adam Mickiewicz University Laboratory, Poznan, Poland*

"**AR-CHaMo is a comprehensive statistical framework** for estimating the frequency of SCS hazards on a **global scale** (lightning, **hail ≥ 2 cm, hail ≥ 5 cm**, tornado ≥ (E)F1, convective wind gusts ≥ 25 m/s) across forecasting and **climate** timescales (both in the past and in the **future**)."

- Global climatology of hail ≥ 2 cm, hail ≥ 5 cm using ERA5 ✅
- Global trends of hail ≥ 2 cm, hail ≥ 5 cm using ERA5 ✅
- Future trends of hail ≥ 2 cm, hail ≥ 5 cm using CMIP6 ❌

How will the **frequency and severity of hail change** according to the RCP58.5 scenario (at +1.5°C, +2.0°C and +3.0°C) **across the globe**?

Hail ≥ 5 cm ERA5 climatology (1950-2023)

Nature Geoscience, accepted
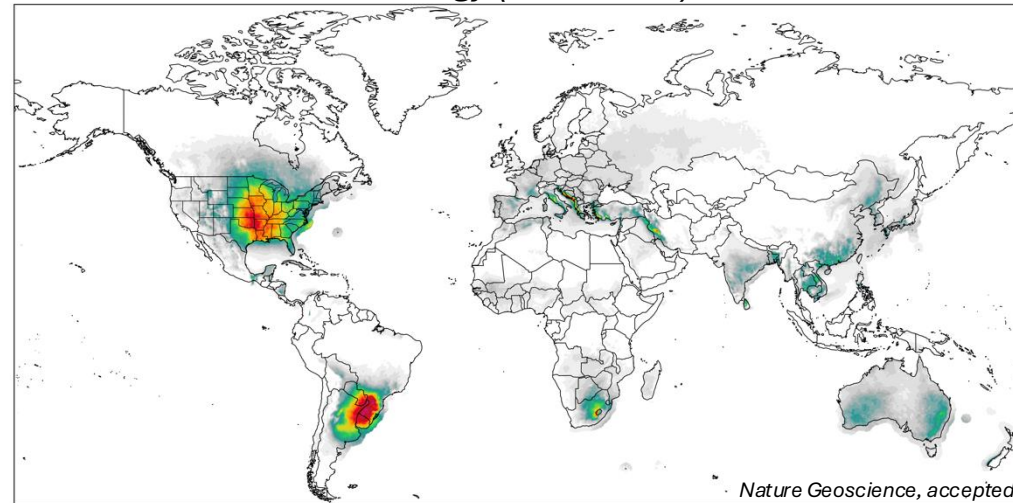
Hail ≥ 5 cm ERA5 trends (1950-2023)

Nature Geoscience, accepted
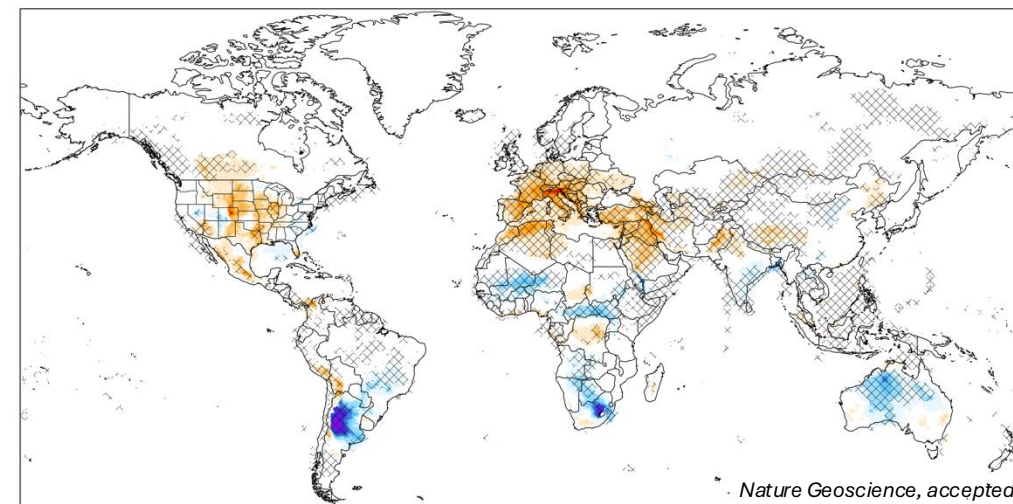
5576163 Lightning observations
4937 Very large hail reports

Training data:
2008-2020 – Europe

Training data:
2008-2020 – U.S.

Training data:
2012-2019 – AUS

Lightning model

Most Unstable Lifted Index
RH between 500 and 850 hPa
Most Unstable Mixing Ratio
Convective Precipitation
Land Sea Mask

Very Large Hail model

Most Unstable CAPE above -10°C
Most Unstable Effective Bulk Shear
Mixed Layer Mixing Ratio
Mixed Layer Lifting Condensation Level

Apply AR-CHaMo to
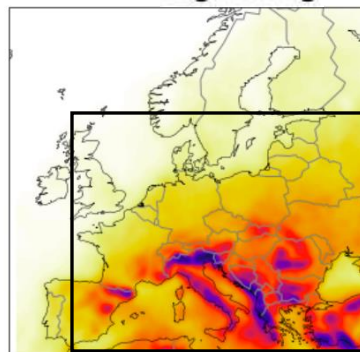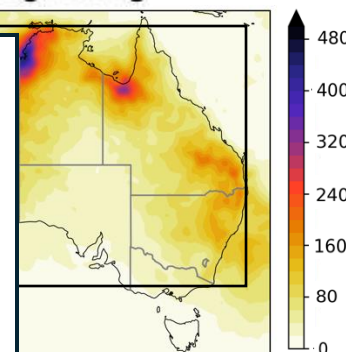**81206400000** vertical profiles
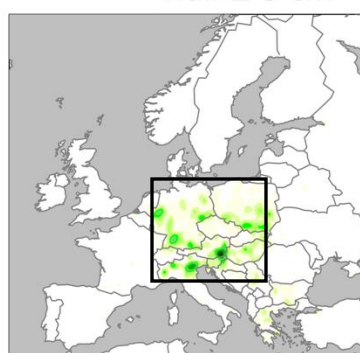
Probability of hail ≥ 5 cm
based on DLS and WMAX
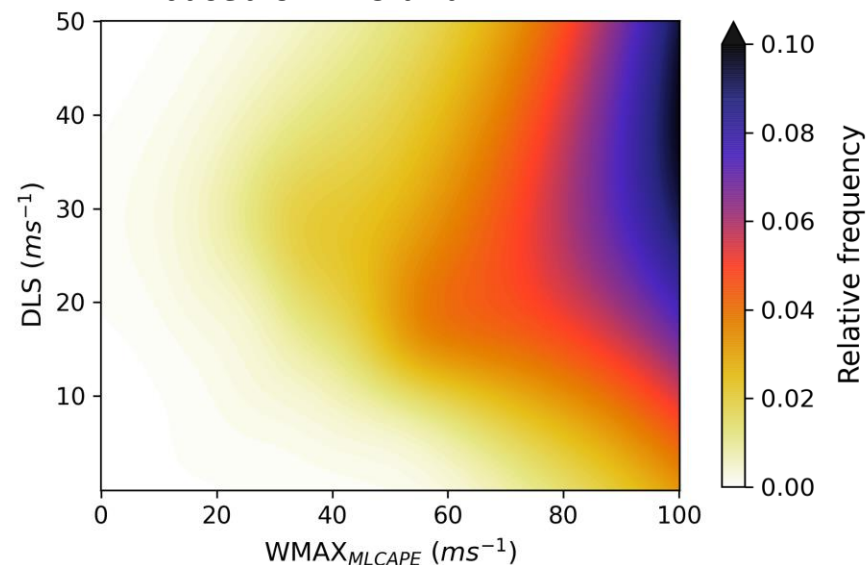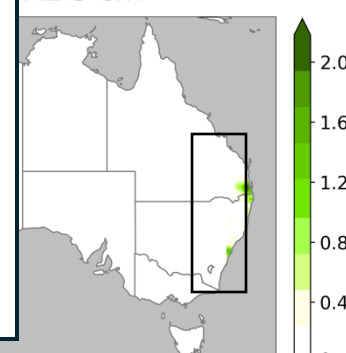
ERA5 reanalysis   **ERA5 reanalysis**   **ERA5 reanalysis**

Mean annual number of hail ≥ 5 cm events

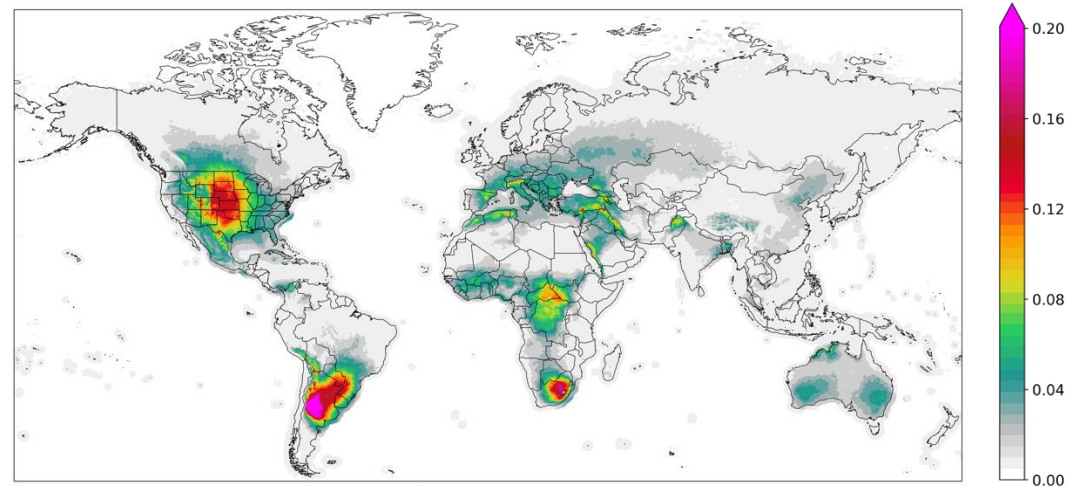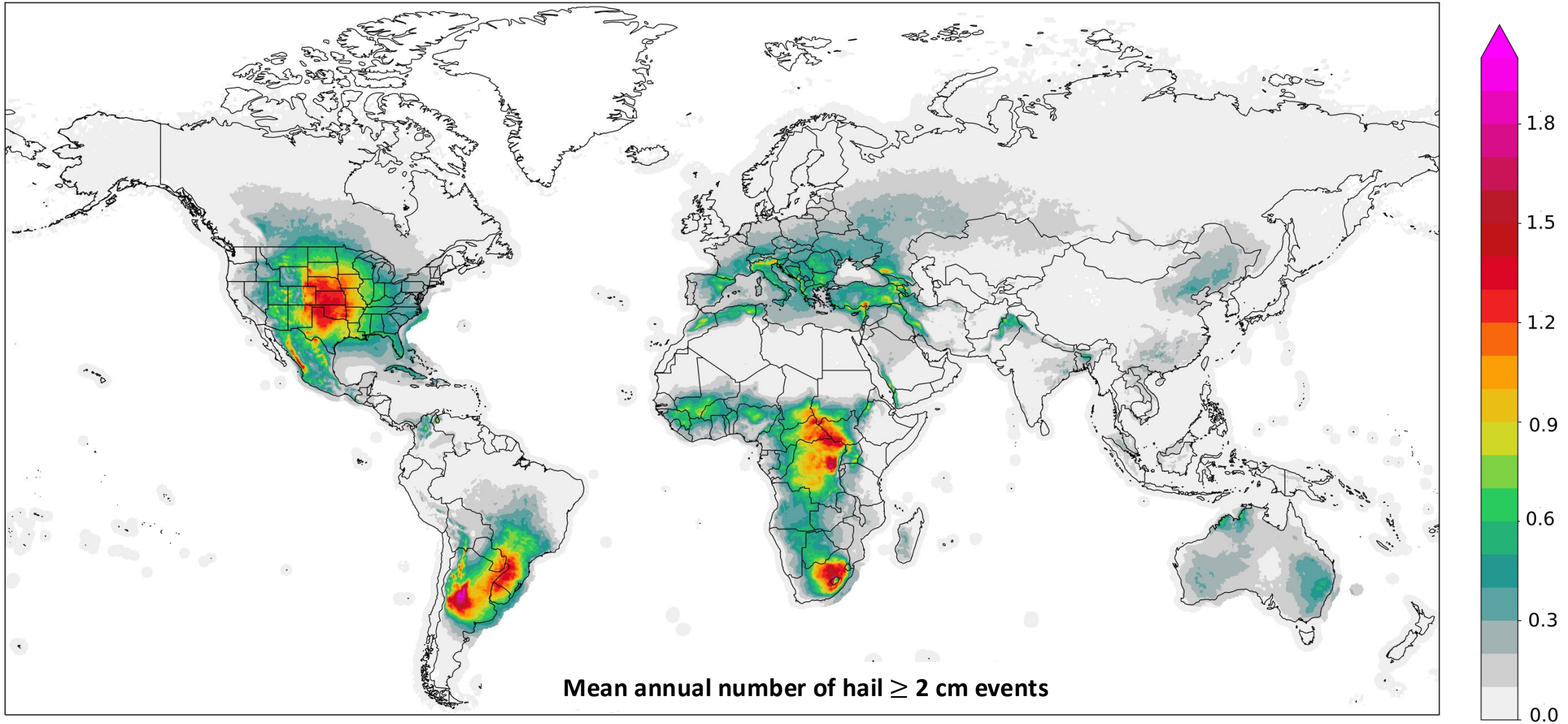*Nature Geoscience, accepted*
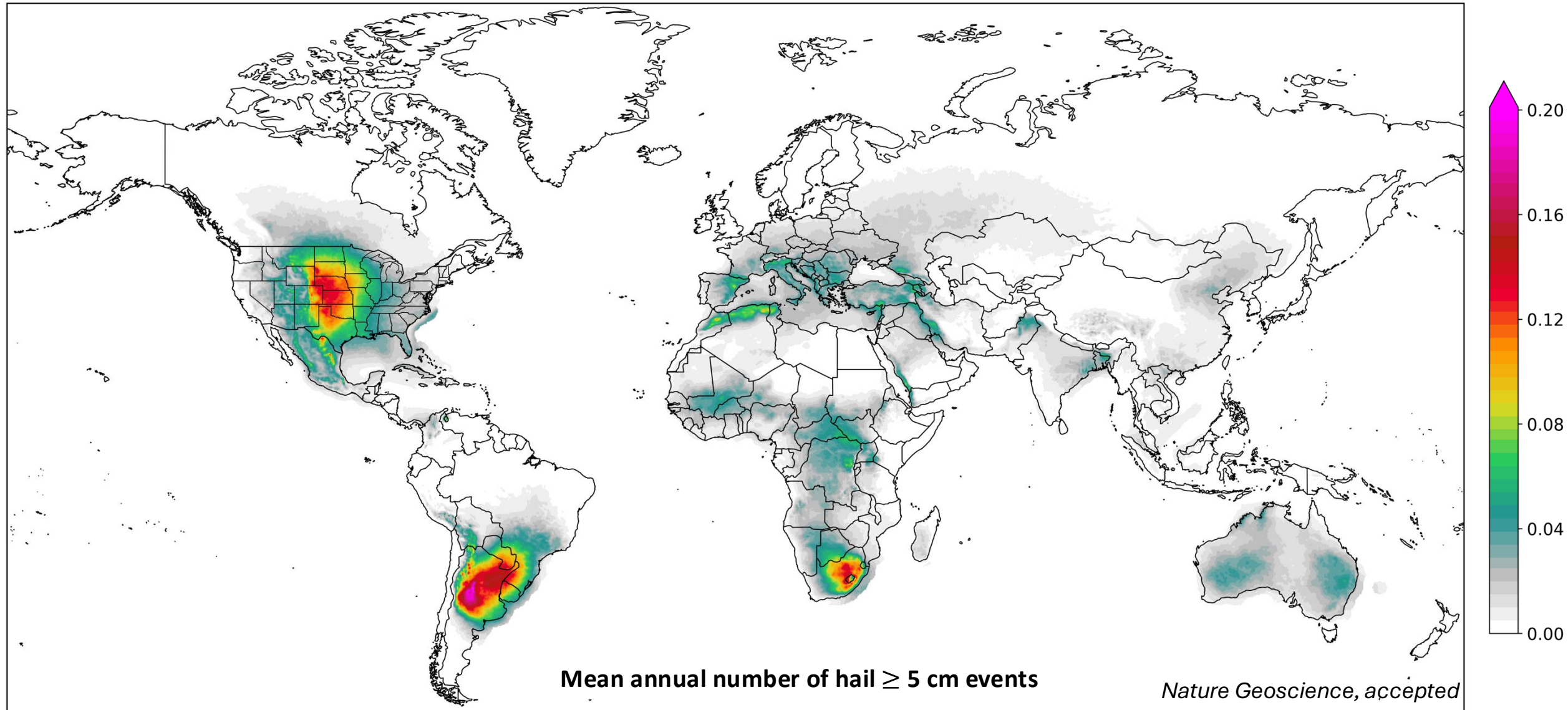
1. **Calculate AR-CHaMo lightning, hail ≥ 2 cm and hail ≥ 5 cm predictors** from model-level data on 5 CMIP6 models.

2. **Identify warming windows** (24 years) at +**1.5°C, +2.0°C and +3.0°C** for each model compared to the historical run.

3. **Apply ERA5-trained AR-CHaMo** to the historical run (1980-2014) and SSP58.5 (2015-2100) scenario of CMIP6 models. *Models often have problems in Africa.*

4. **Calculate ratio** between mean annual **historical** frequency and each **warming period** (+1.5°C, +2.0°C and +3.0°C) frequency for every CMIP6 model.

5. **Apply ratio to ERA5 baseline** and obtain future hail ≥ 2 cm, hail ≥ 5 cm occurrence at +1.5°C, +2.0°C and +3.0°C.

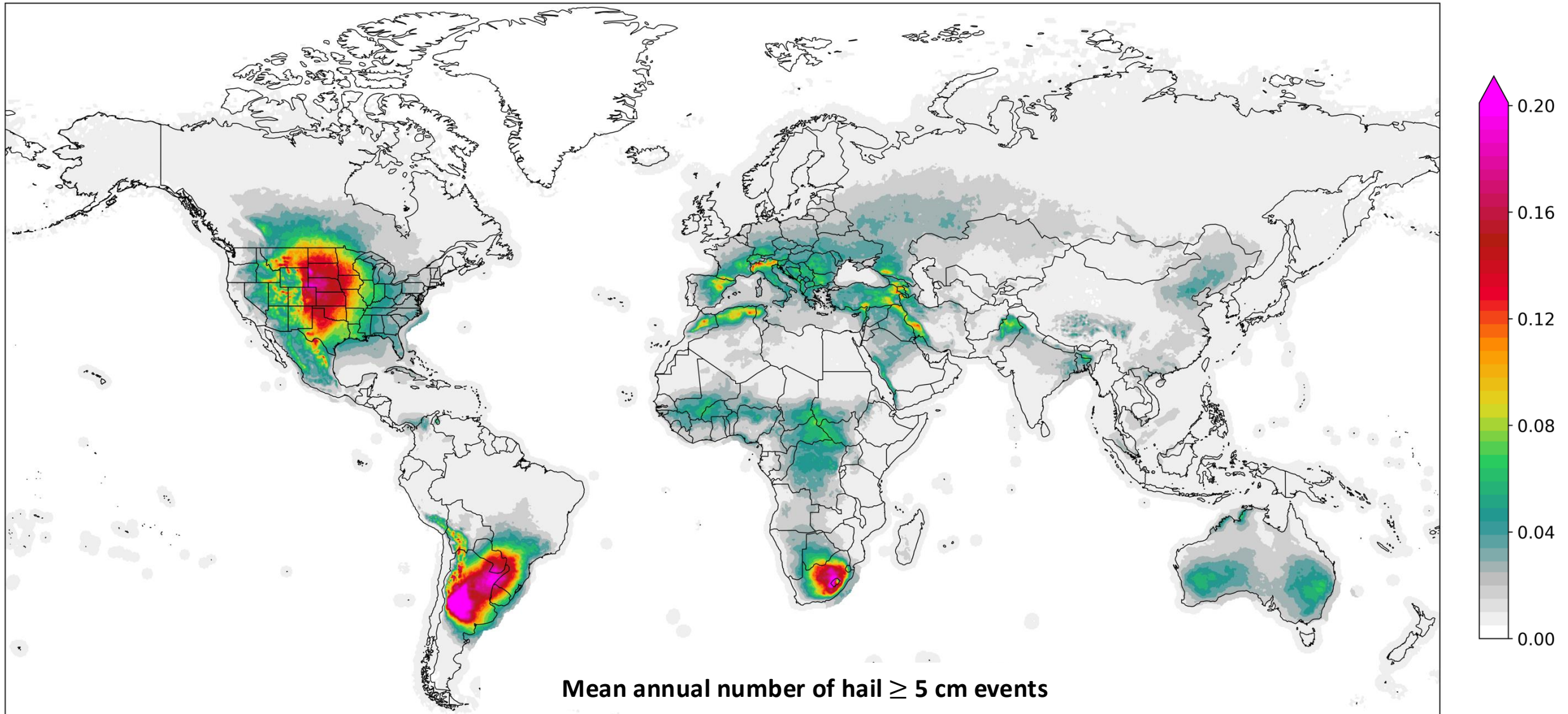6. **Calculate multi-model mean** for hail ≥ 2 cm and hail ≥ 5 cm.

Lepore et al. 2021	1.5°C	2°C	3°C
BCC-CSM2-MR	2032	2042	2065
CNRM-CM6-1	2027	2042	2058
CNRM-ESM2-1	2032	2045	2064
CanESM5	2011	2024	2040
MIROC6	2040	2051	2076
MPI-ESM1-2-LR	2037	2048	2071
MRI-ESM2-0	2025	2038	2064

Mean annual number of hail ≥ 5 cm events (MIROC6+ERA5) 2064-2088

Mean annual number of hail ≥ 2 cm events

Mean annual number of hail ≥ 5 cm events

Mean annual change in hail ≥ 2 cm events

Mean annual change in hail ≥ 2 cm events

Mean annual change in hail ≥ 2 cm events

Mean annual change in hail ≥ 5 cm events
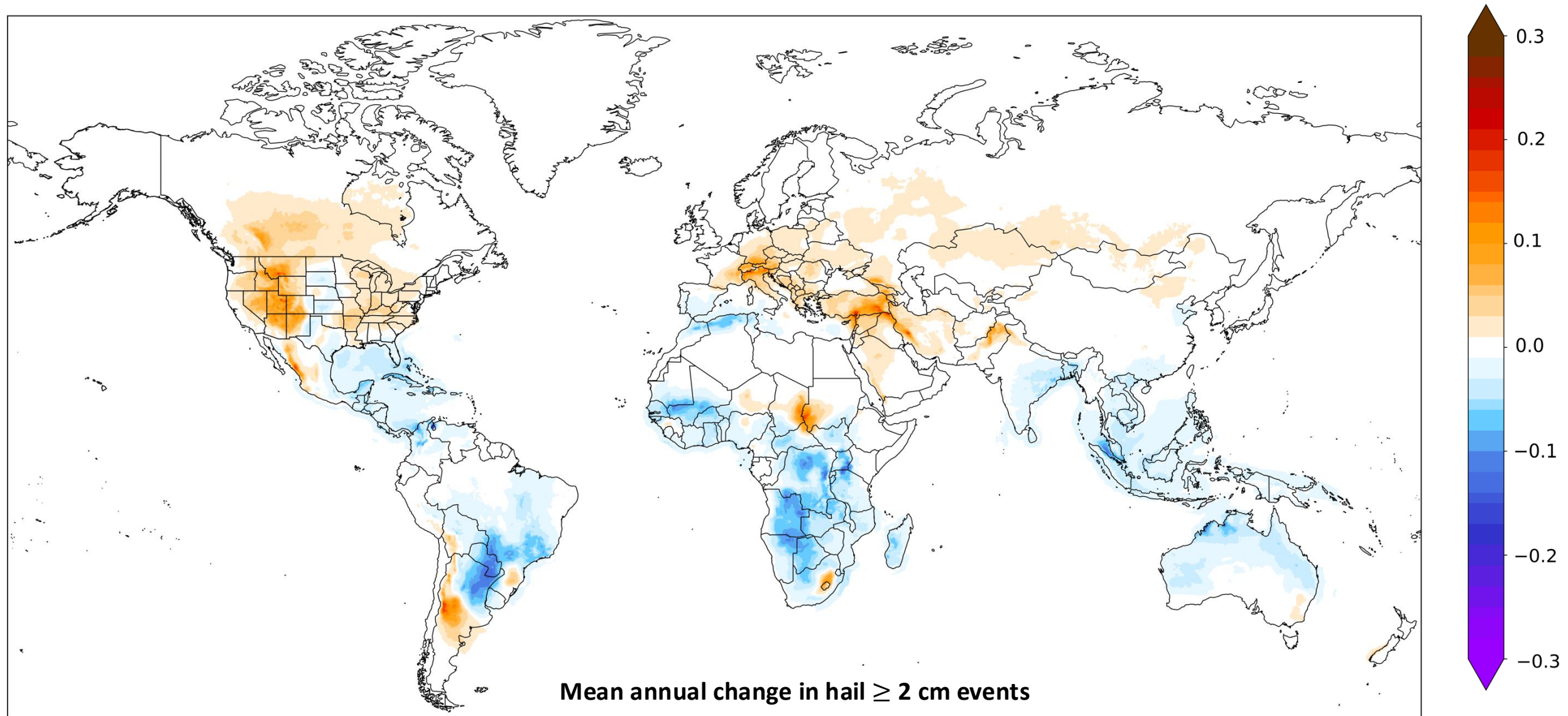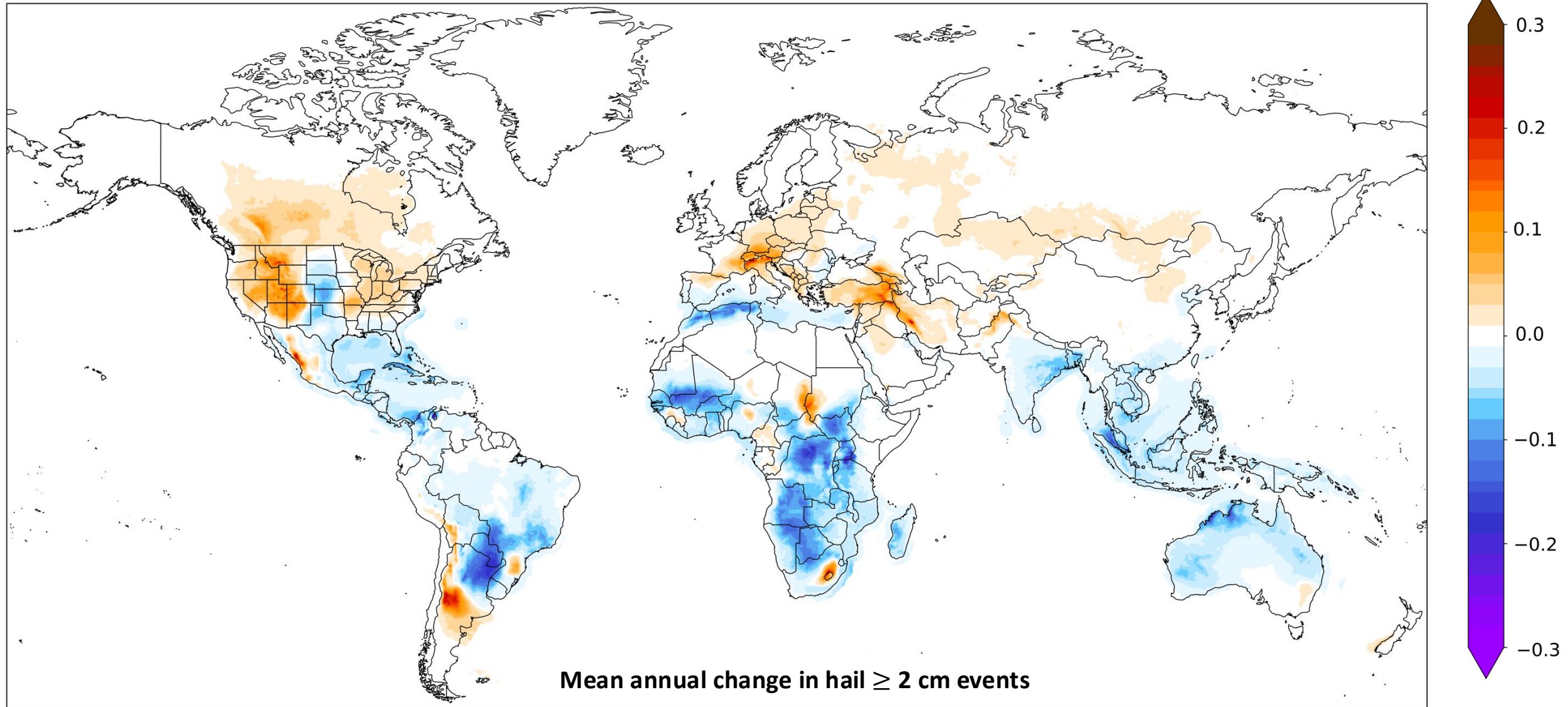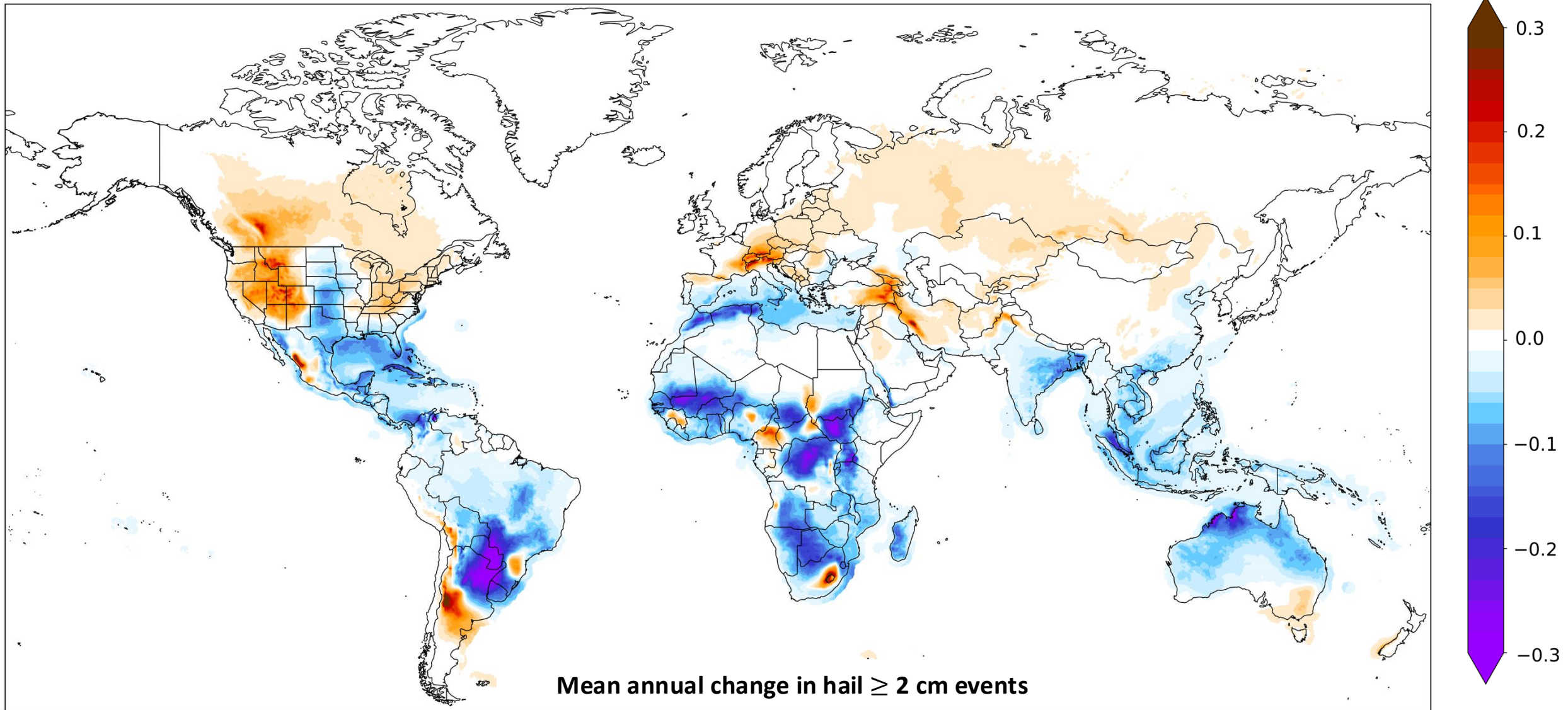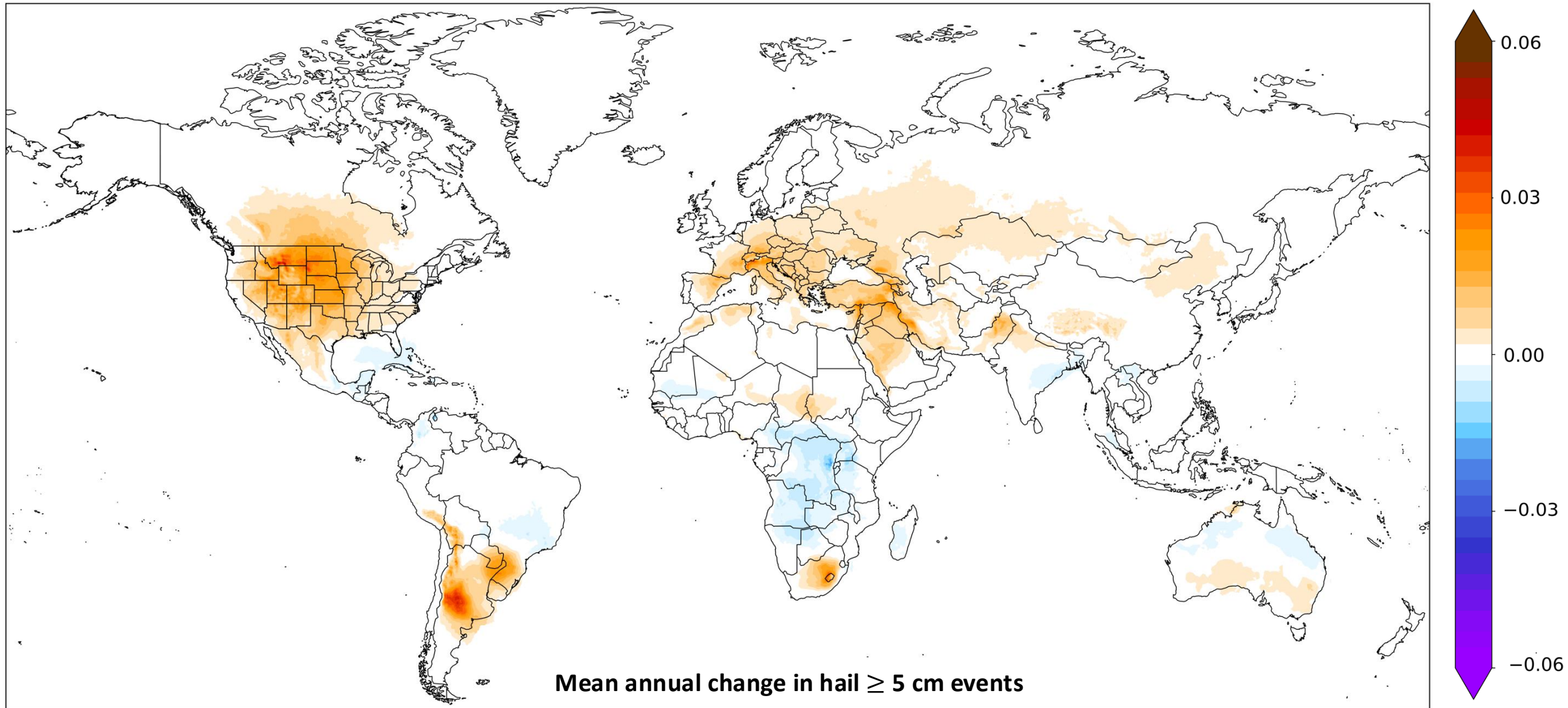
Hail ≥ 5 cm +2.0°C absolute change

Mean annual change in hail ≥ 5 cm events

Mean annual change in hail ≥ 5 cm events
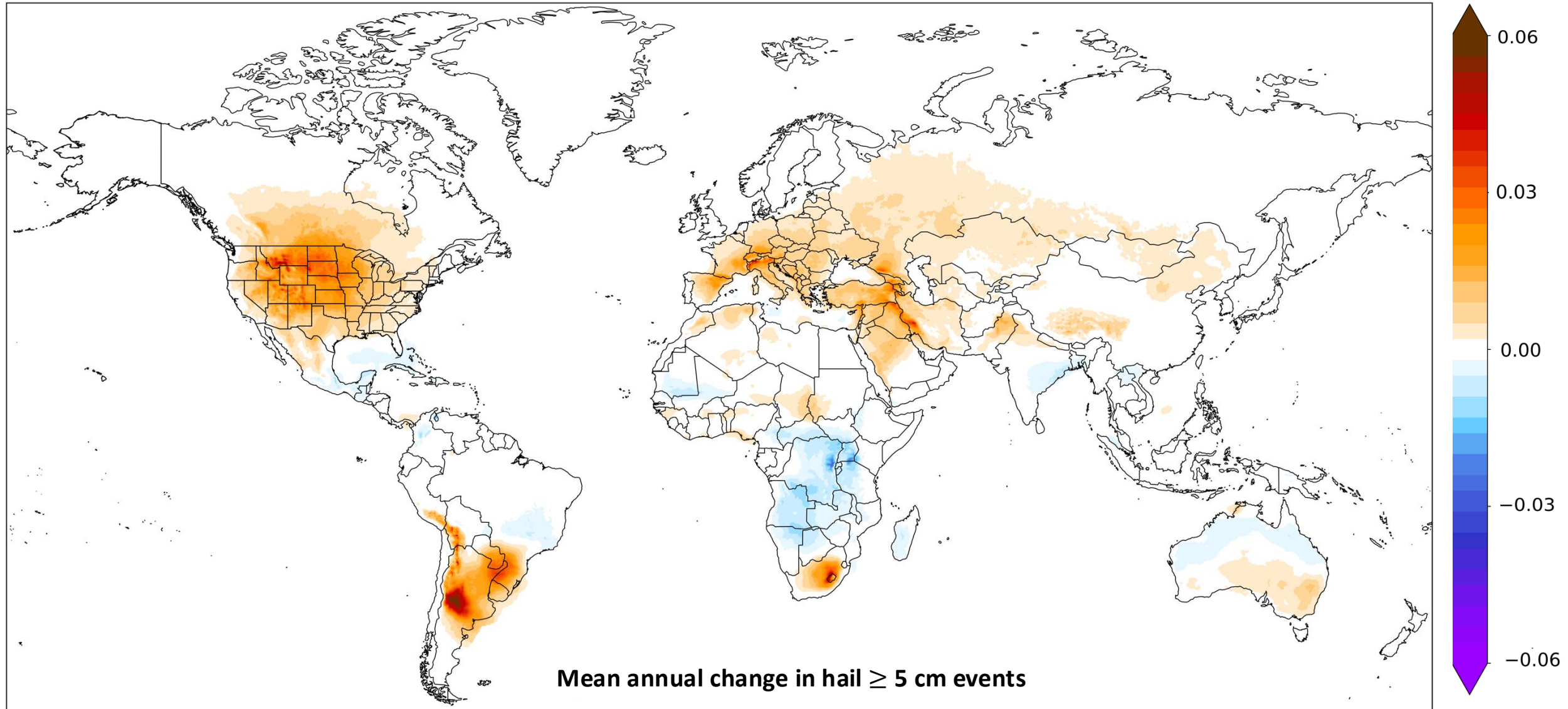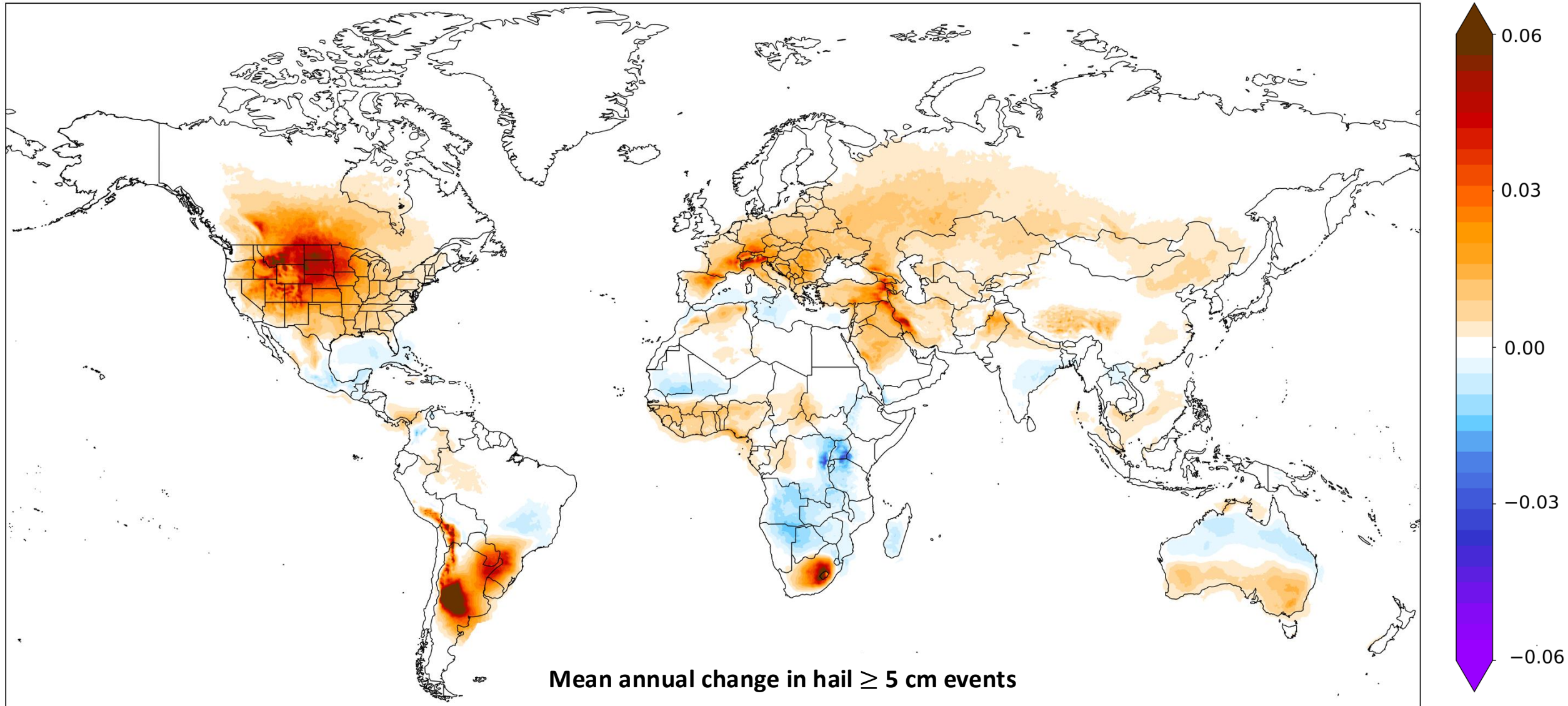
Hail ≥ 5 cm +3.0°C relative change

N. America:
+10-70%

Europe:
+30-60%

Tropical belt:
?

Argentina:
+0-50%

S. Africa:
+0-20%

S. Autralia:
+20-40%
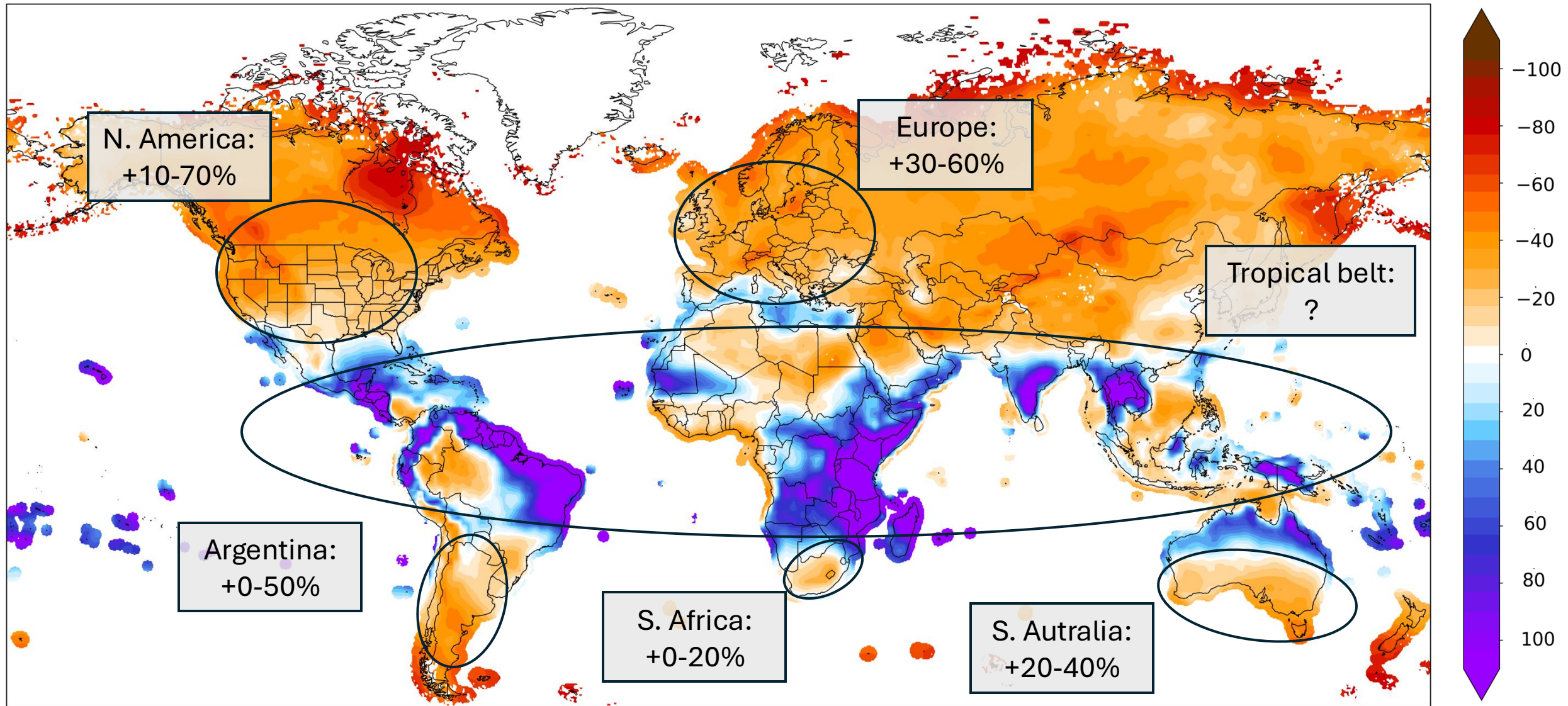
ERA5 (1950 – 2023)
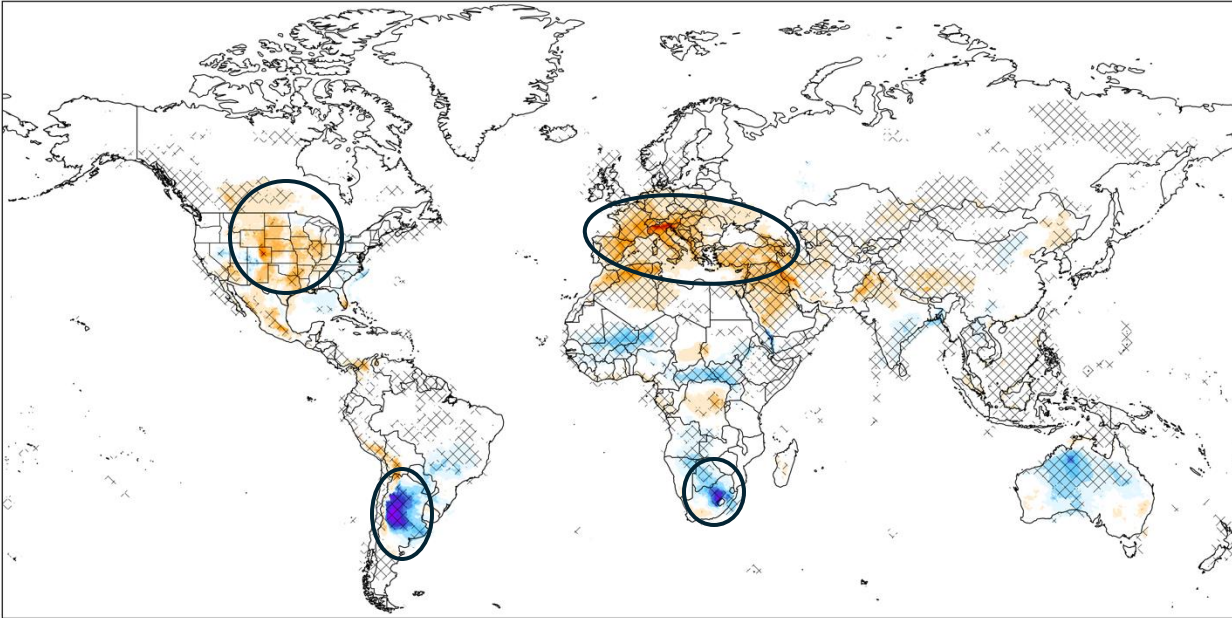
CMIP6 (3° warming)

| Europe & Middle East | | | → | **High confidence** in climate trends | ← | USA Great Plains & Canada | | |
| **Europe & Middle East** ⬆ ERA5 CMIP6 ⬆ | | | | | | **USA Great Plains & Canada** ⬆ ERA5 CMIP6 ⬆ | | |
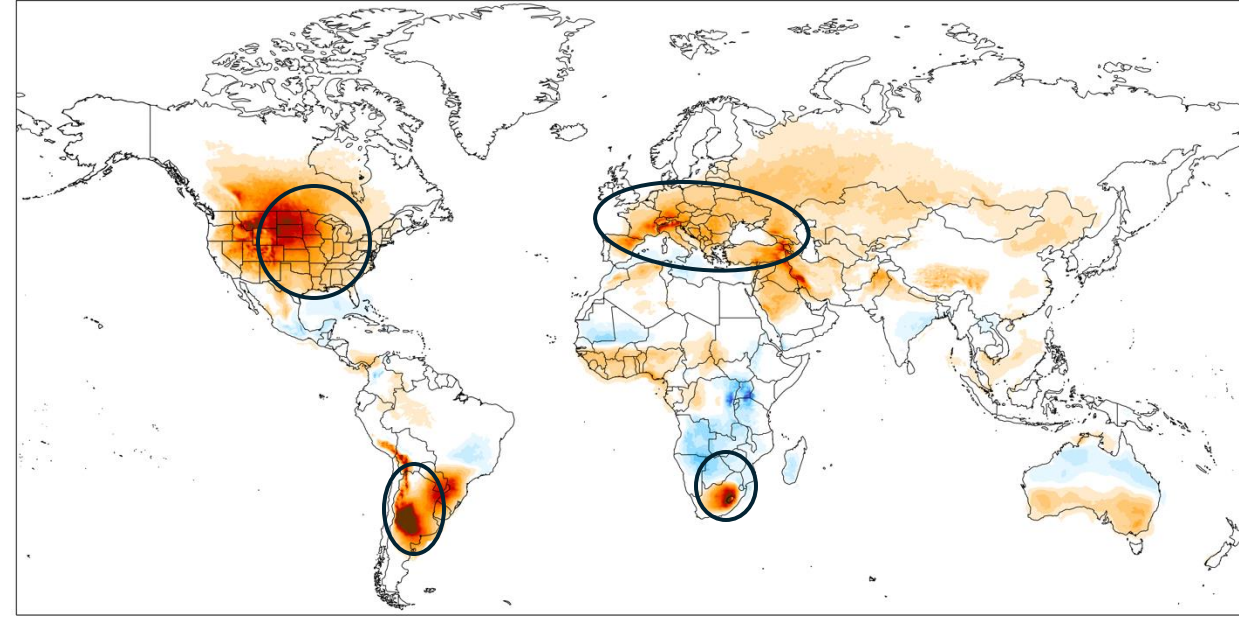
Europe & Middle East
⬆ ERA5 CMIP6 ⬆

→ **High confidence** in climate trends ←

USA Great Plains & Canada
⬆ ERA5 CMIP6 ⬆

Argentina
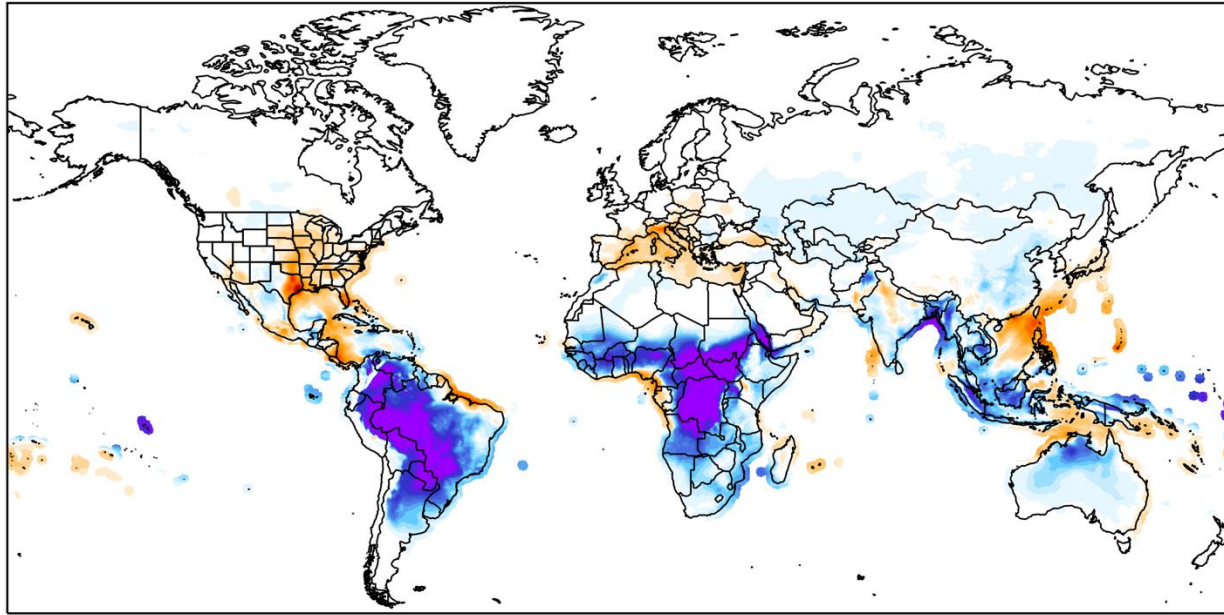⬇ ERA5 CMIP6 ⬆

→ **Low confidence** in climate trends ←

South Africa
⬇ ERA5 CMIP6 ⬆

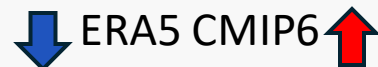# Past vs future trends – MU CAPE above -10°C

ERA5 Decadal Trends (1950-2023) in J/kg
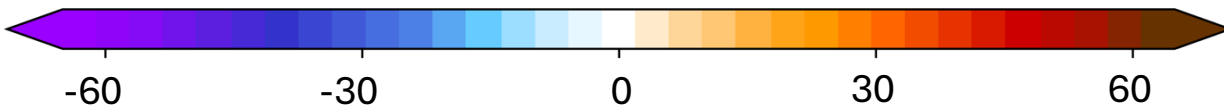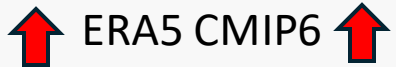
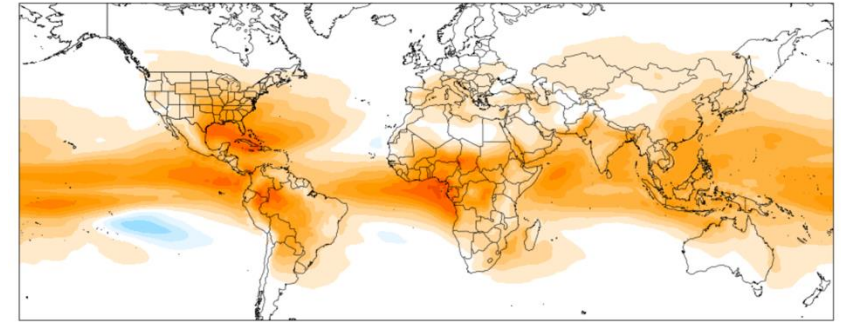**CMIP6 Ensemble-Mean Trends** in J/kg

+1.5°C

+2.0°C

+3.0°C

Southern Europe & E. USA
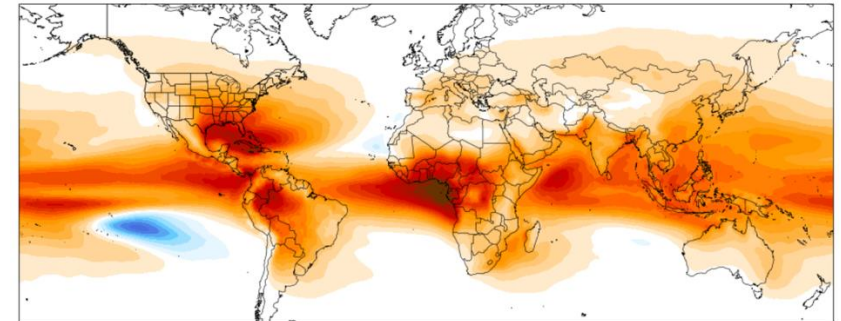↑ ERA5 CMIP6 ↑

South America & Africa
↓ ERA5 CMIP6 ↑
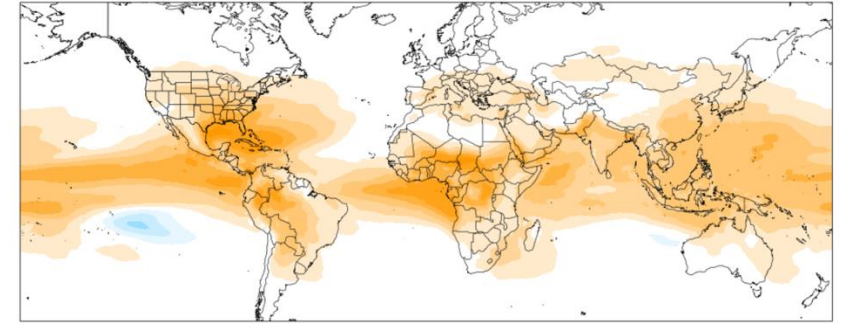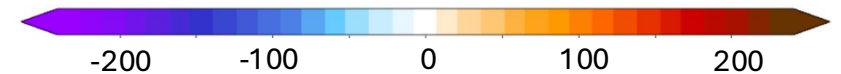
Past vs future trends – ML MIXR

ERA5 decadal trends (1950-2023) in g/kg
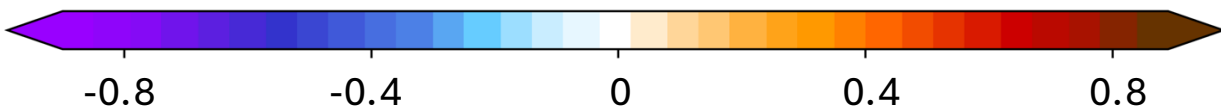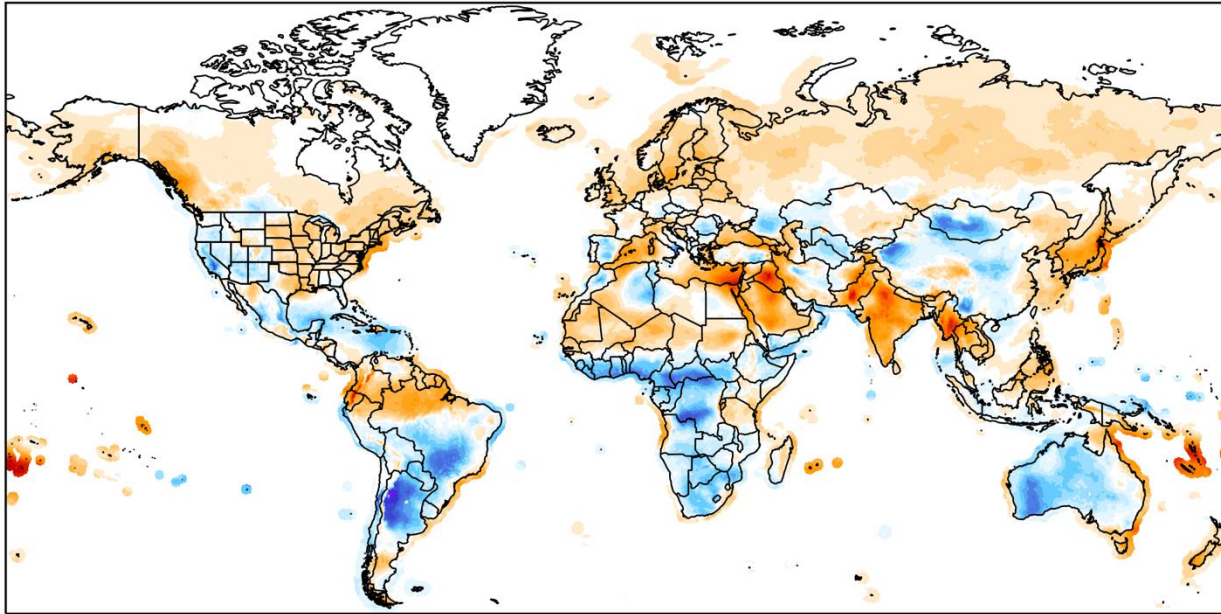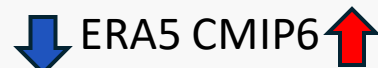
CMIP6 Ensemble-Mean Trends in g/kg

+1.5°C

+2.0°C

+3.0°C

Southern Europe & E. USA
⬆ ERA5 CMIP6 ⬆

South America & Africa
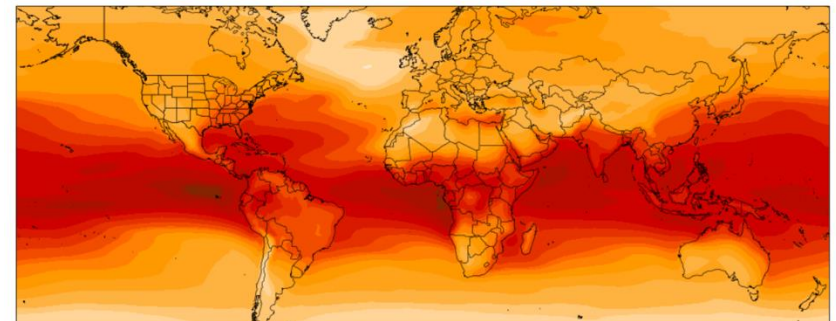⬇ ERA5 CMIP6 ⬆
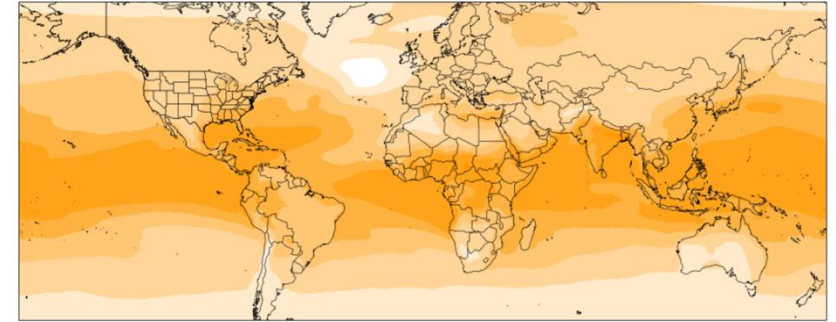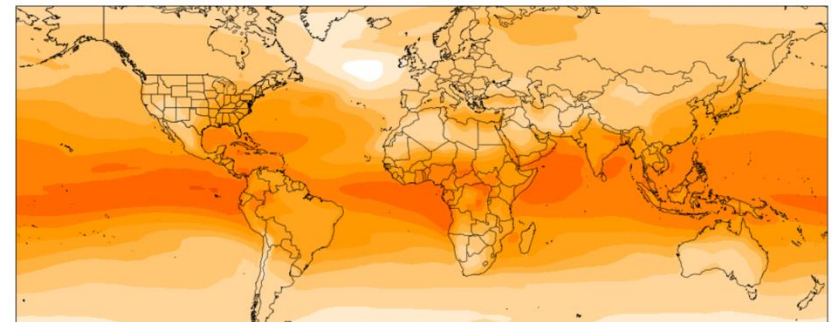
The AR-CHaMo now allows for a **continuous depiction** of the frequency of hail ≥ 2 cm and hail ≥ 5 cm **from the past (1950-2023) into the future (up to 2100).**

- **Hail ≥ 5 cm:** Widespread increase in all global hotspots e.g., North America, South America, South Africa and Europe.

- **Hail ≥ 2 cm:** Decrease in the USA Great Plains and the Mediterranean. Increases in Alps, W Argentina, South Africa. Widespread decreases elsewhere.

- **ERA5 vs CMIP6:** Large differences in magnitude and sign of trends due to different moisture and CAPE above -10°C trends. Uncertainty in the Southern Hemisphere!

Next up: Extension to tornadoes ≥ (E)F1 and convective wind gusts ≥ 25 m/s.

francesco.battaglioli@essl.org