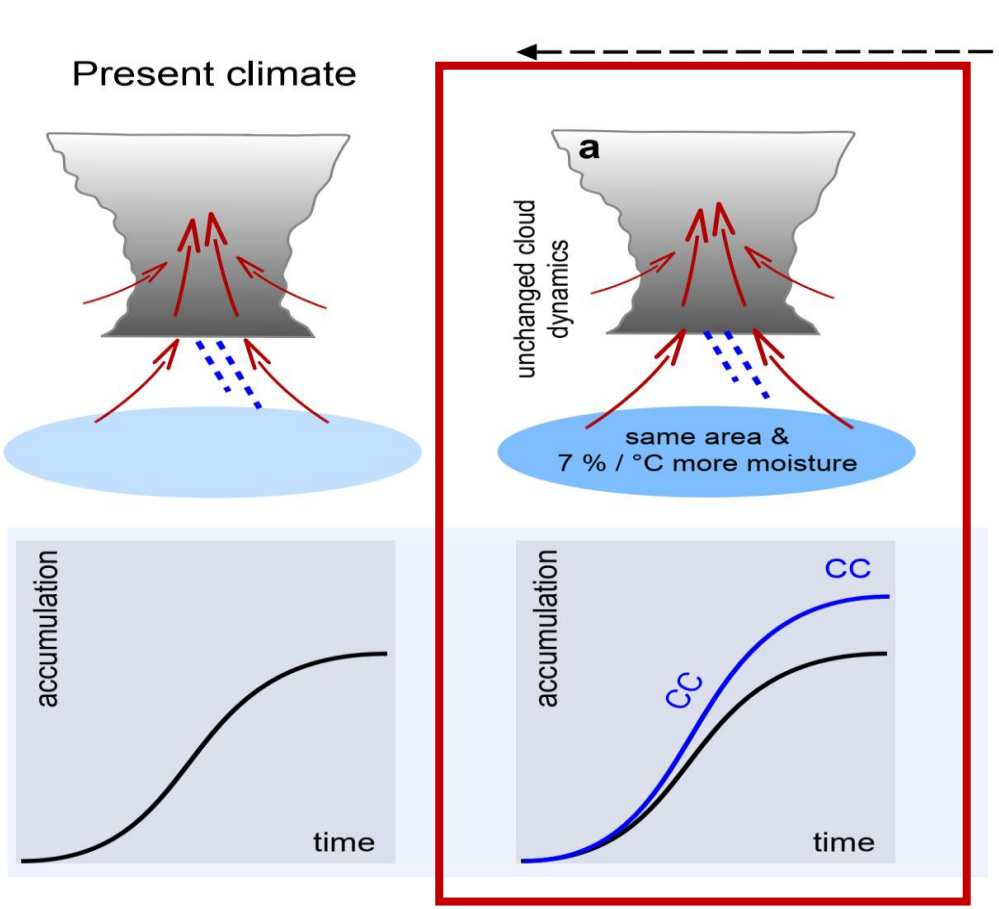
Koninklijk Nederlands
Meteorologisch Instituut
*Ministerie van Infrastructuur en Waterstaat*

# Convective systems and climate change in observations and model simulations using pseudo global warming

Geert Lenderink

Hylke de Vries, Erik van Meijgaard, Wim de Rooy, Bert van Ulft, Rob Groenland, Hayley J Fowler

# Rainfall in convective clouds and climate change

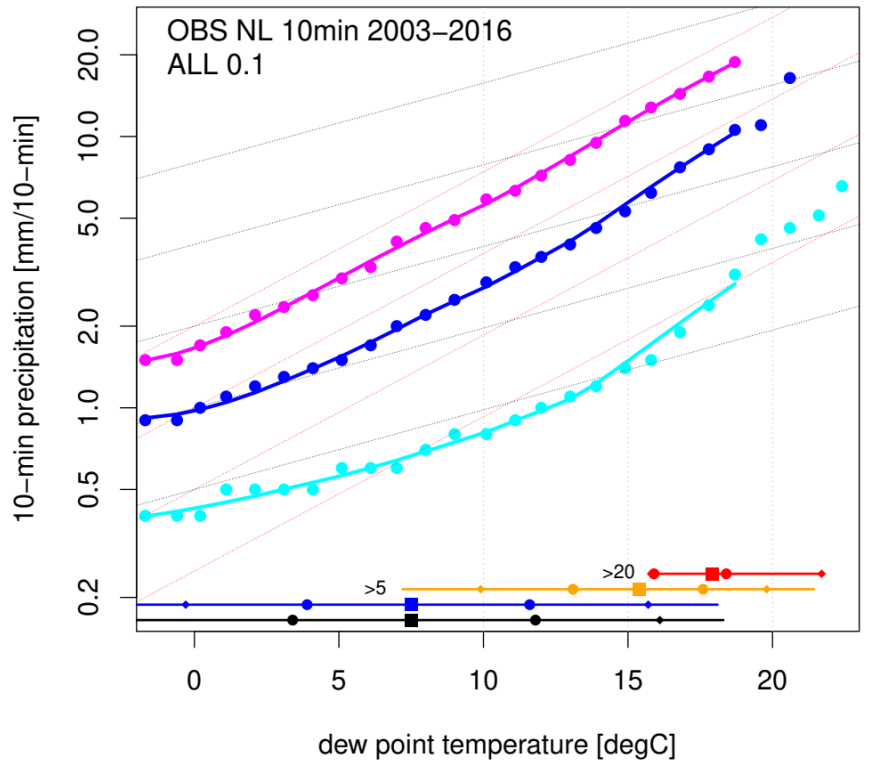



The common assumption

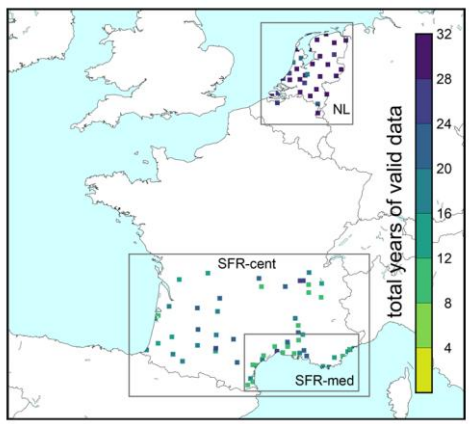
Everything scales with the Clausius-Clapeyron rate (CC)

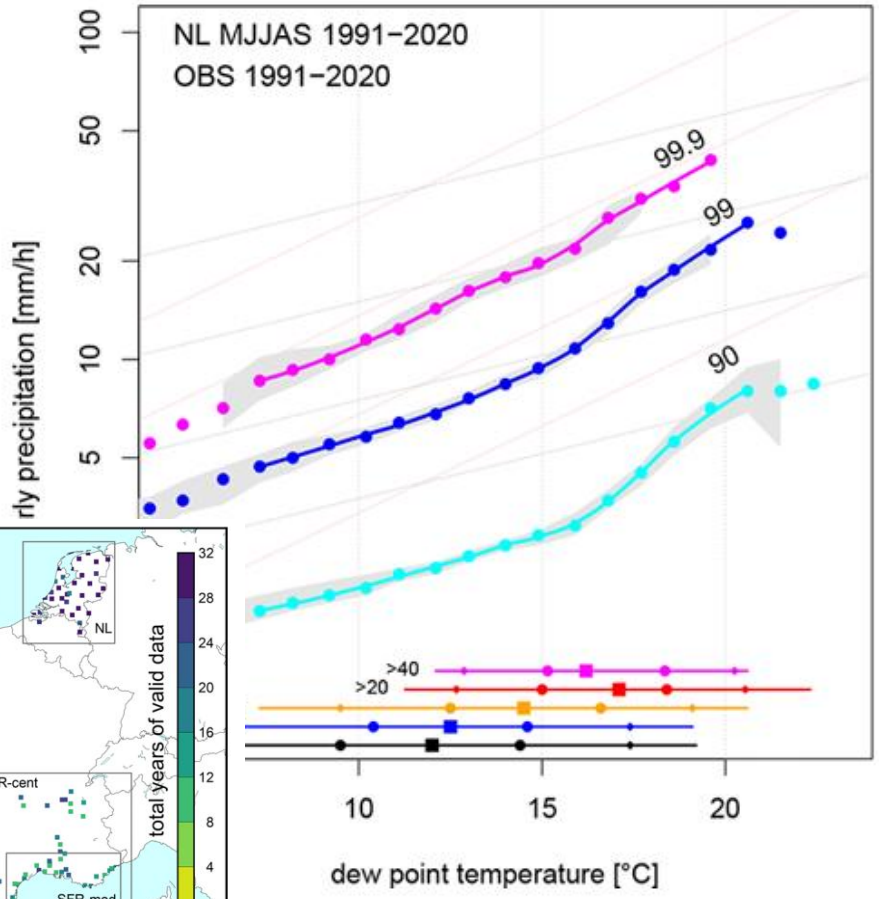
**The IPCC mantra**

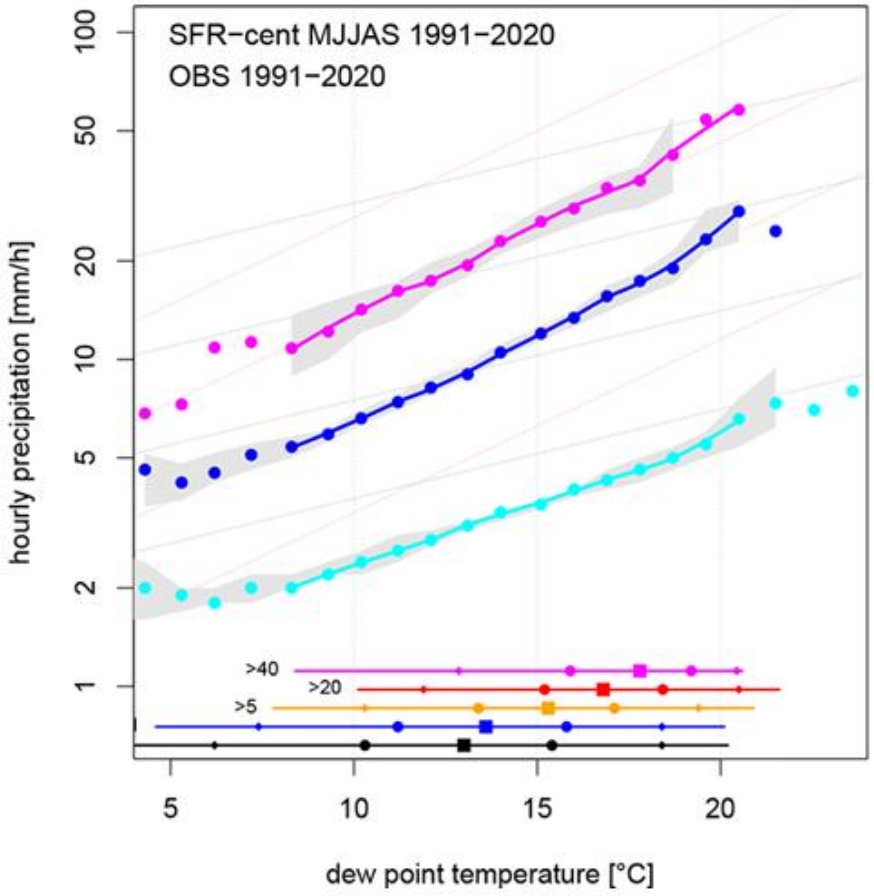
BUT: Observed 10-min rainfall extremes show 2CC across a ~ 20-degree temperature range (a ~10-fold increase in intensity)



# Evidence for universality: hourly extremes in NL and France



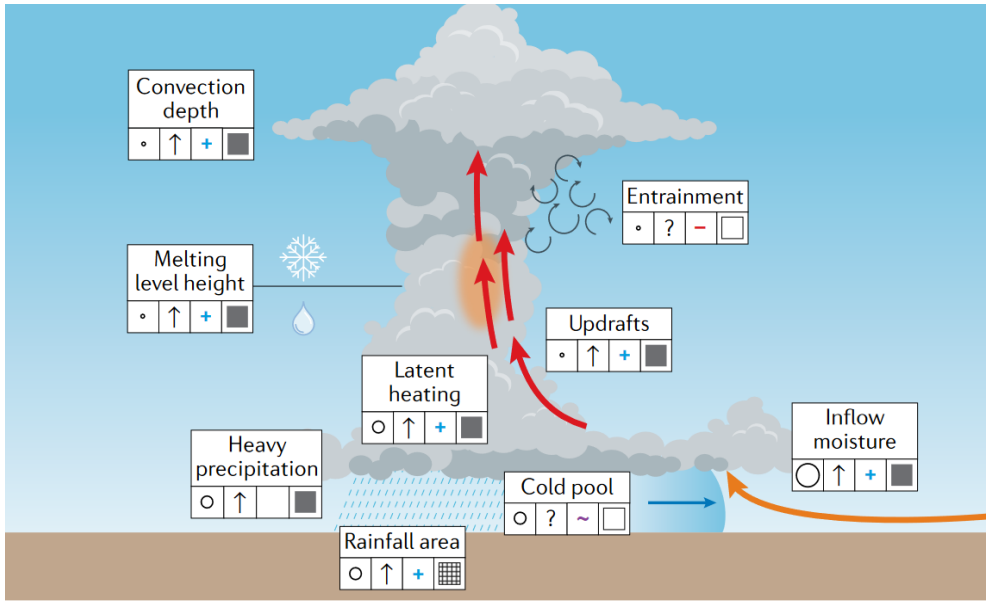




Quite some confusion in the literature because of different "temperature" measures, co-variations with lapse rate and difference between climate change and present-day

Lenderink et al. HESS, 2025 and a number of earlier papers

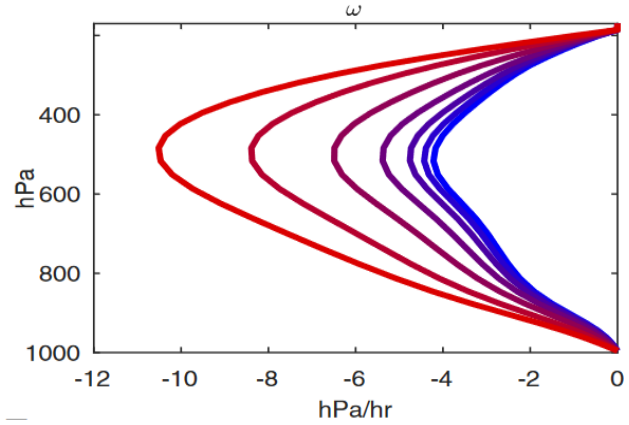
# Feedback processes due to latent heat release

Latent heat release leads to stronger updrafts in the cloud




Fowler et al. Nature Reviews, 2021

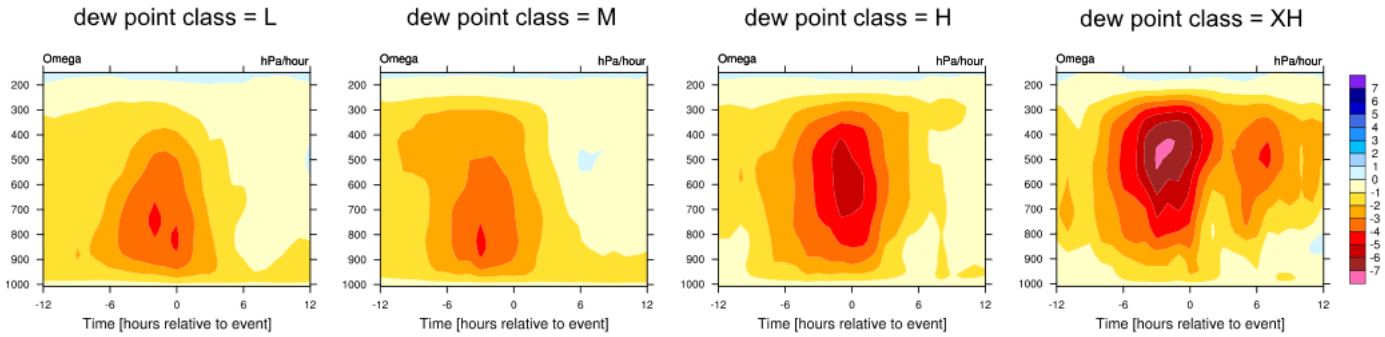
Latent heat release leads to upward (quasi-geostrophic) large-scale motions




Large-scale omega in different warming experiments

Nie et al. PNAS, 2018

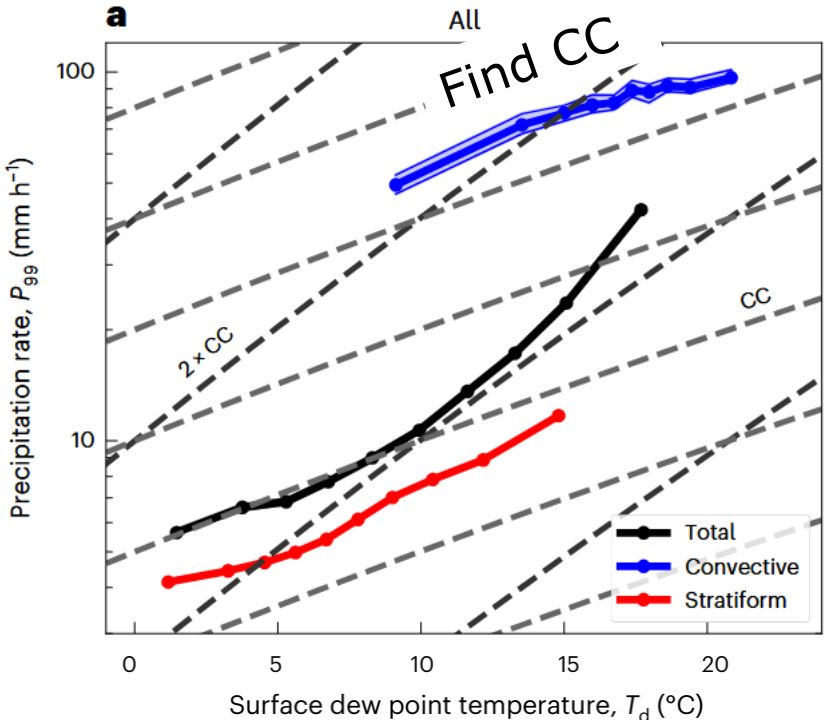
High resolution "re-analysis" for observed extremes




Lenderink et al. JCLI, 2017

# Some controversy about convective versus stratiform precipitation

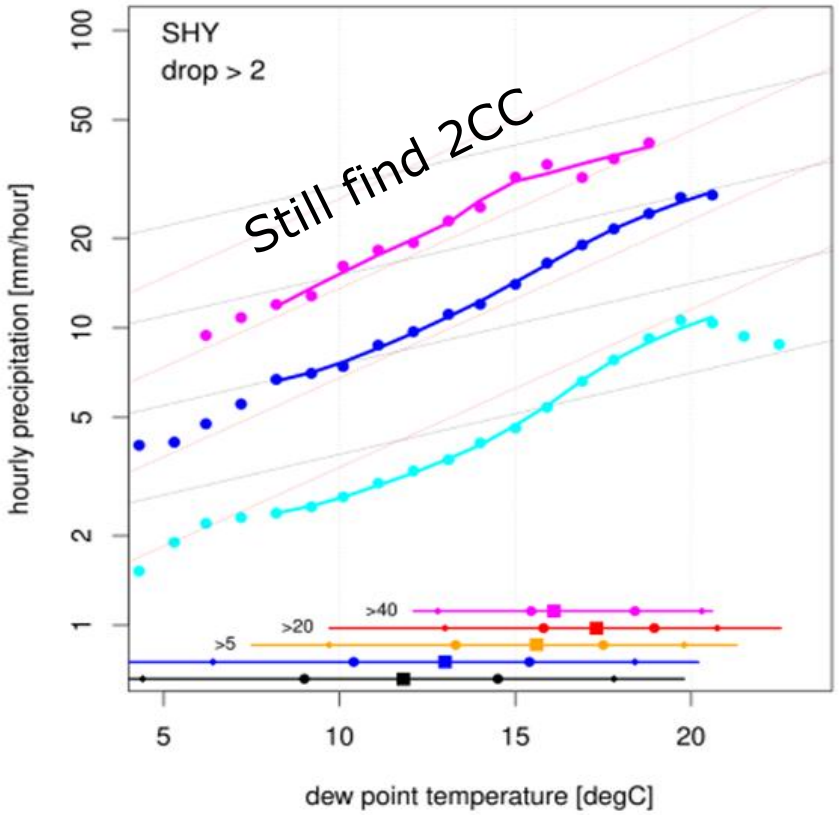
Lightning as indicator of **convection**



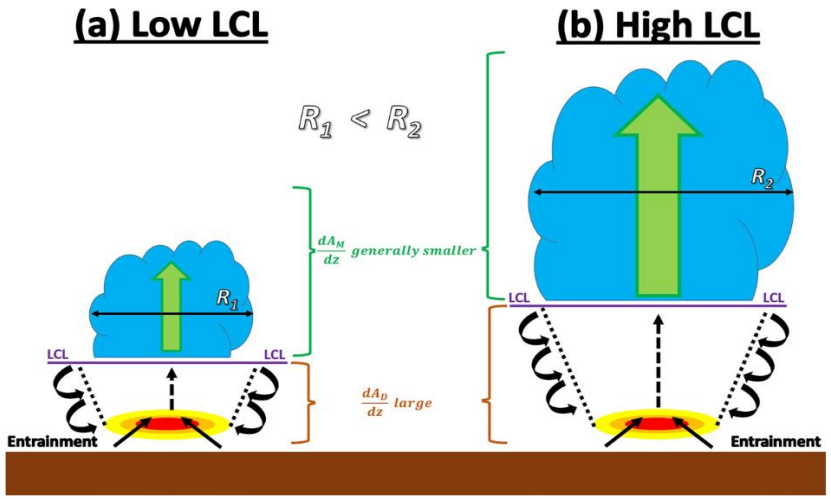

(Da Silva and Haerter, NGS, 2025)

But lightning basically conditions on strong vertical motions

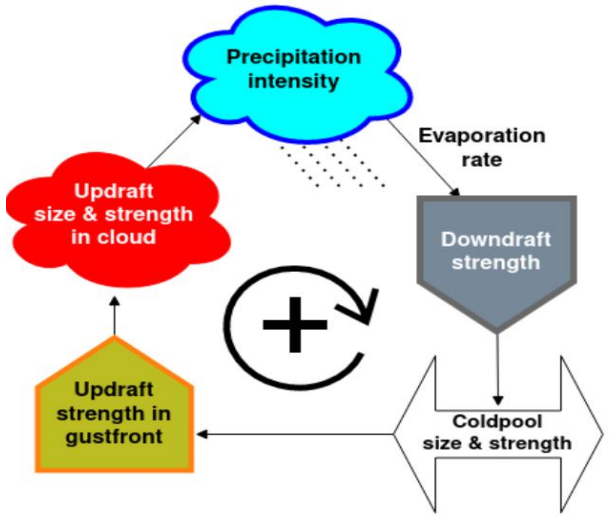
Temperature drop "cold pools" as indicator of convection



# Dependencies on relative humidity




Lower RH -> higher LCL -> broader thermals at LCL (Mulholland et al GRL, 2021)



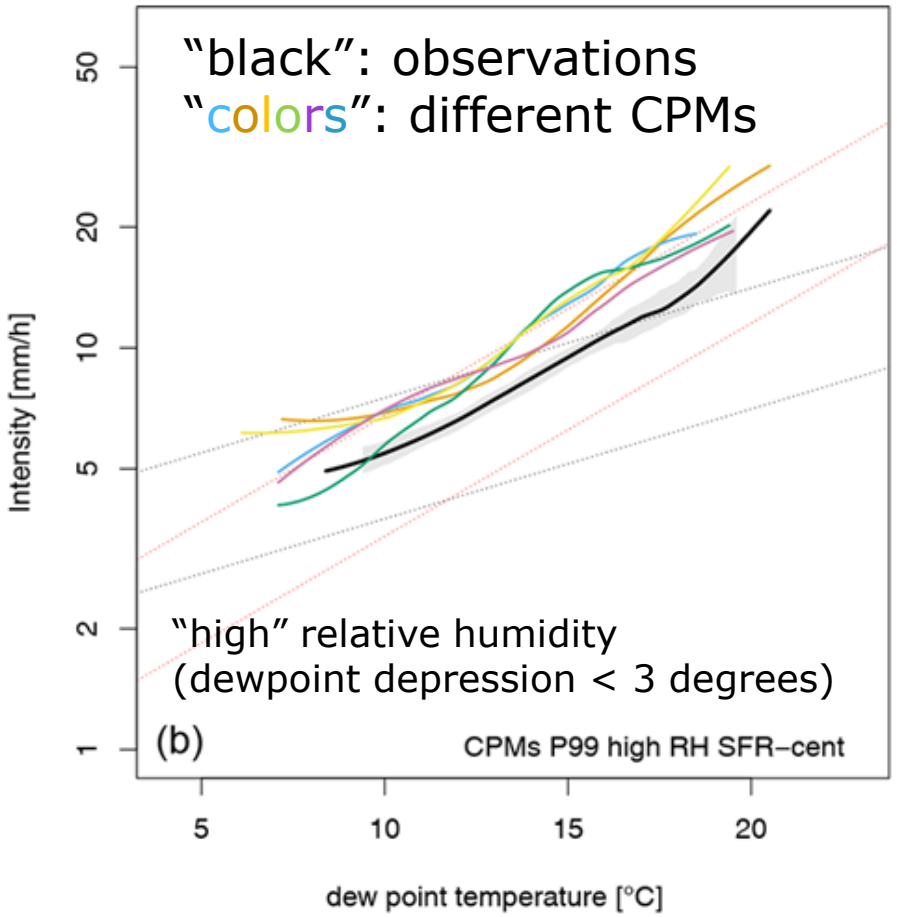

Lower RH -> more evaporation of rain -> stronger cold pool dynamics (Lochbihler et al. JAMES, 2021)

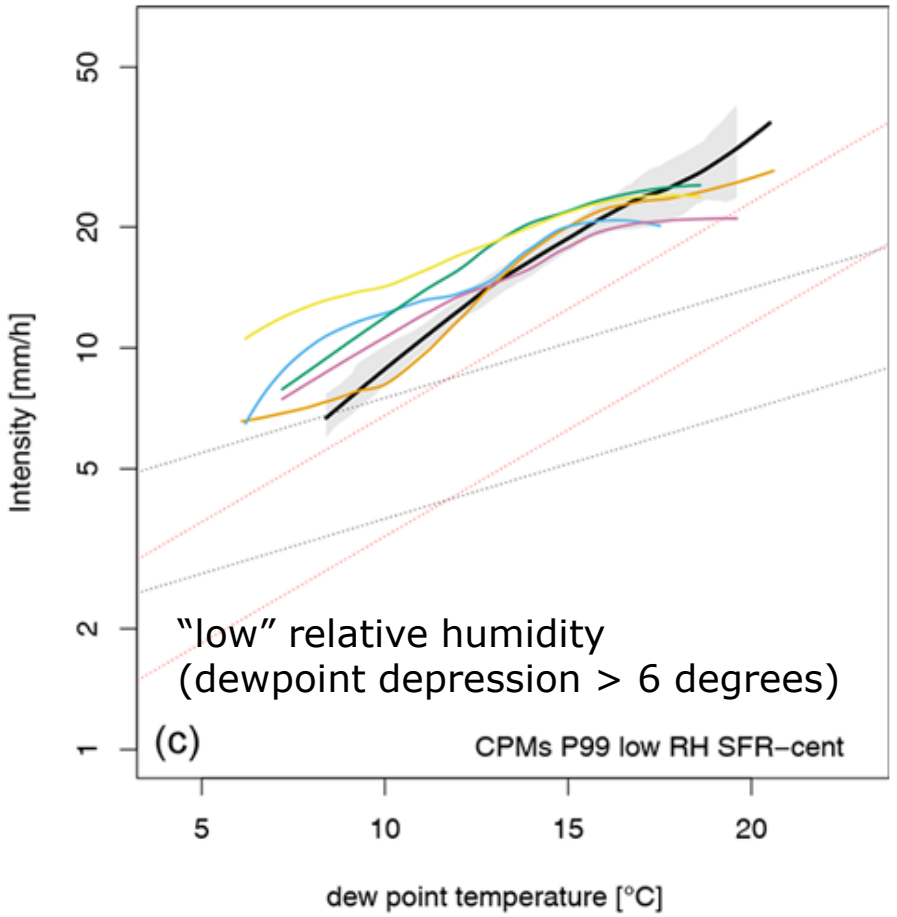
**Cold Pool Dynamics Shape the Response of Extreme Rainfall Events to Climate Change**

Kai Lochbihler[1,2], Geert Lenderink[1], and A. Pier Siebesma[1,2]

# CPMs: Scaling “high” relative humidity versus “low” relative humidity

CPM: convection permitting model @ 2.5 km



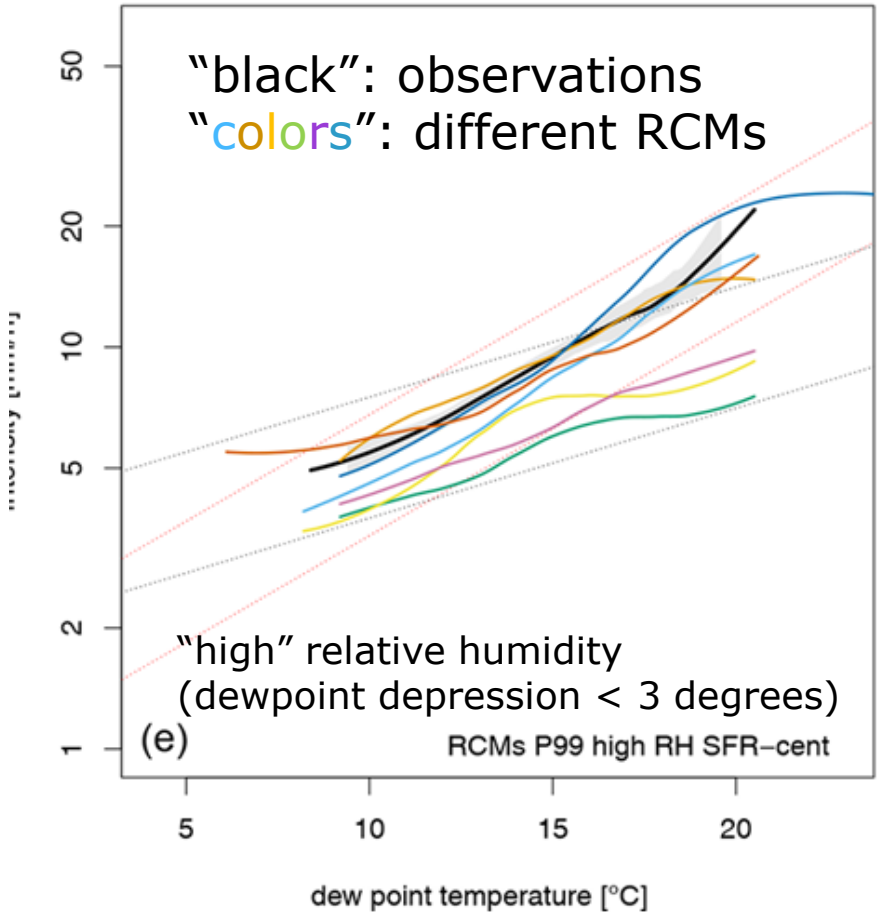

Low versus high RH

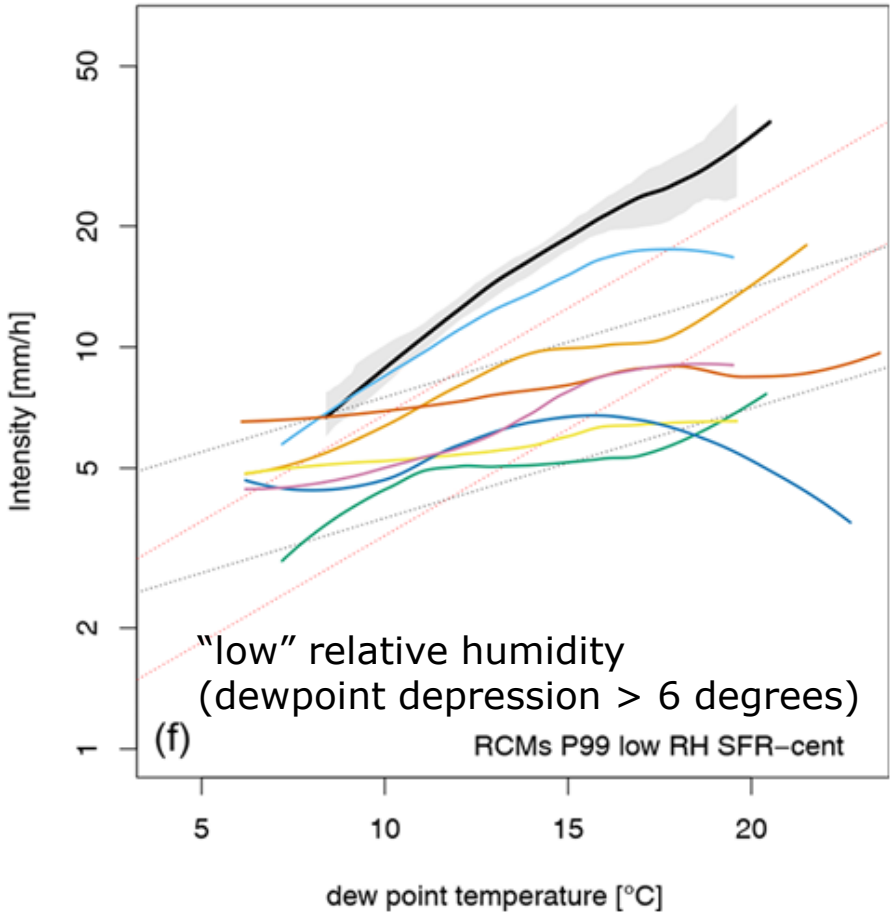
- Less frequent rain, but more intense rain at low RH
- Both follow ~2CC
- CPMs are quite good at capturing dependency at low and high RH

Lenderink et al. HESS, 2025

# RCMs: Scaling “high” relative humidity versus “low” relative humidity

RCM: regional (convection parameterized) climate model @ 12 km




Low versus high RH

- Less frequent rain, but more intense rain at low RH
- Both follow ~2CC
- RCMs are quite bad, in particular for low relative humidity

Lenderink et al. HESS, 2025

# **P**seudo **G**lobal **W**arming and Future Weather

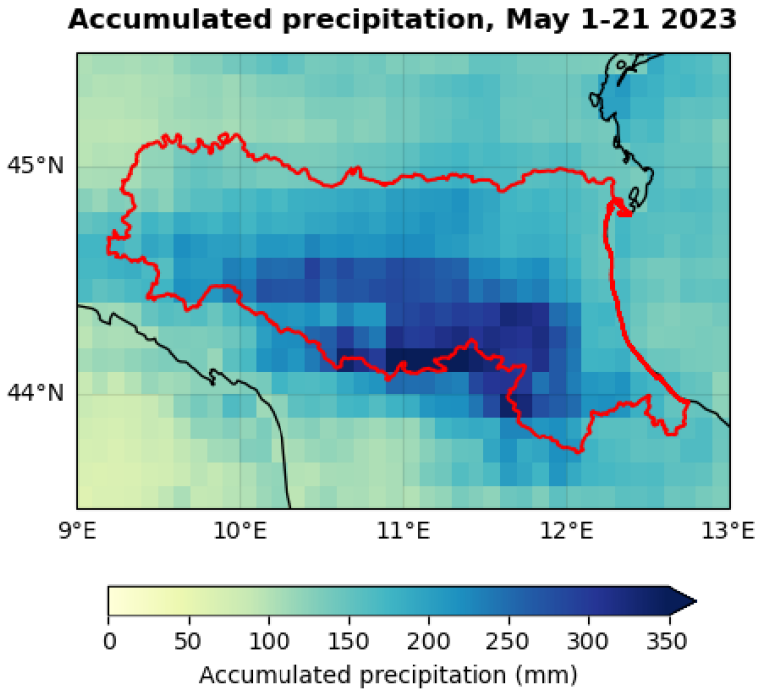
- PGW: Repeat present-day weather or climate using perturbed boundaries
- Perturbation derived from global climate models (warmer, more moisture, small circulation change)
- High signal-to-noise: very effective way to cover a large part of systematic (forced) climate change effects

- Future weather system:
  - Simulate present-day extreme using NWP technique
  - Re-simulate the event using PGW (-1.5, 1.5 and 2 times 3 degrees warmer climate)
  - Systems runs daily in ensemble model (in total 75 days each day)

# Rainfall extremes and climate change: spring 2023 Italy

**Italy's deadly floods are yet another example of climate change extremes, experts say**

**Were Italy's devastating floods really caused by climate change? This new study suggests not**



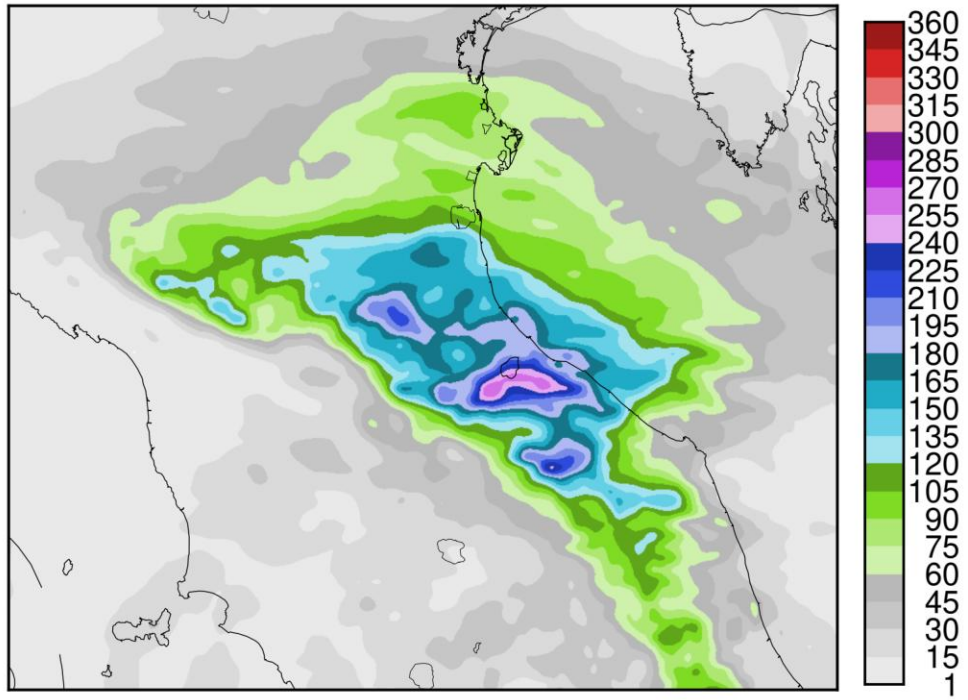



The floodwaters were so high, firefighter and coastguard helicopters were needed to rescue some residents who climbed onto rooftops of three-story buildings to avoid drowning. — Copyright AP Photo/Luca Bruno

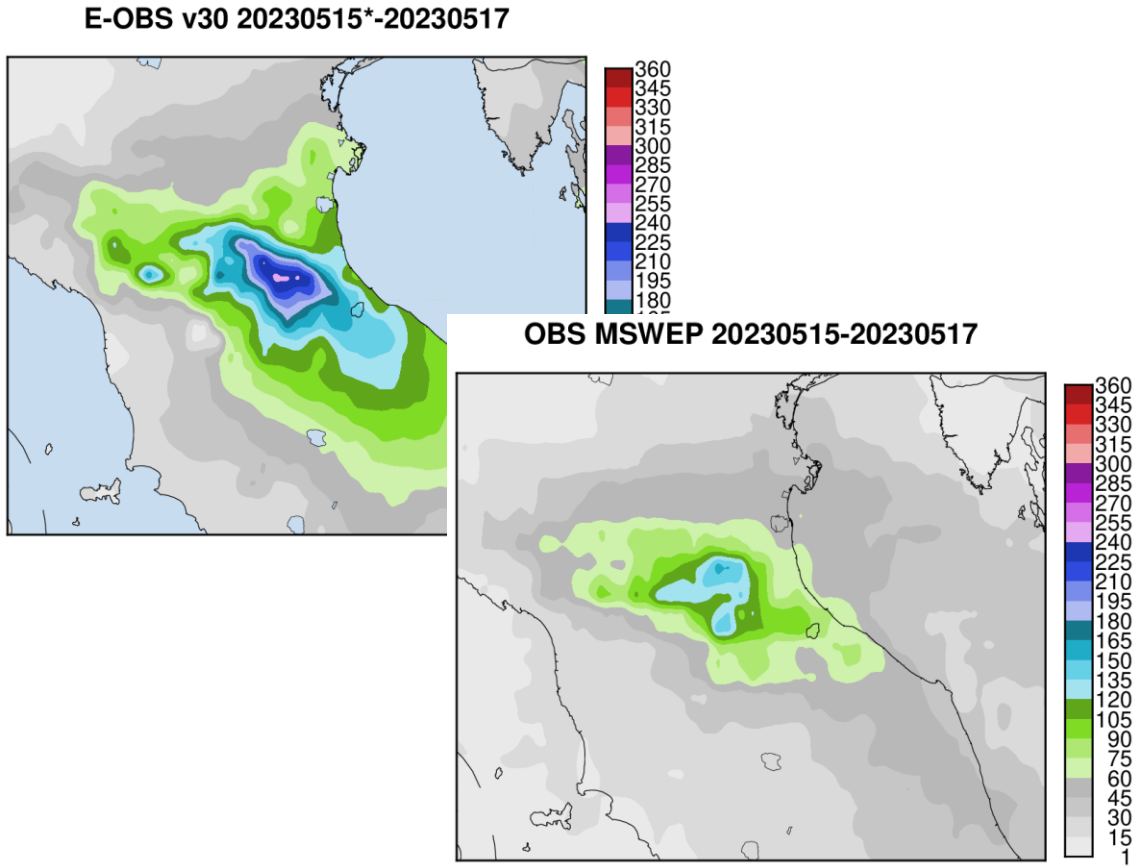
Analysis of 21-day precipitation change in RCMs
Based on a probabilistic top-down approach

# Simulation of one cut off low event with a CPM (HCLIM)
# Precipitation 15-17 May 2023 (most falling on 16th)

Modelled HCLIM @2.5km

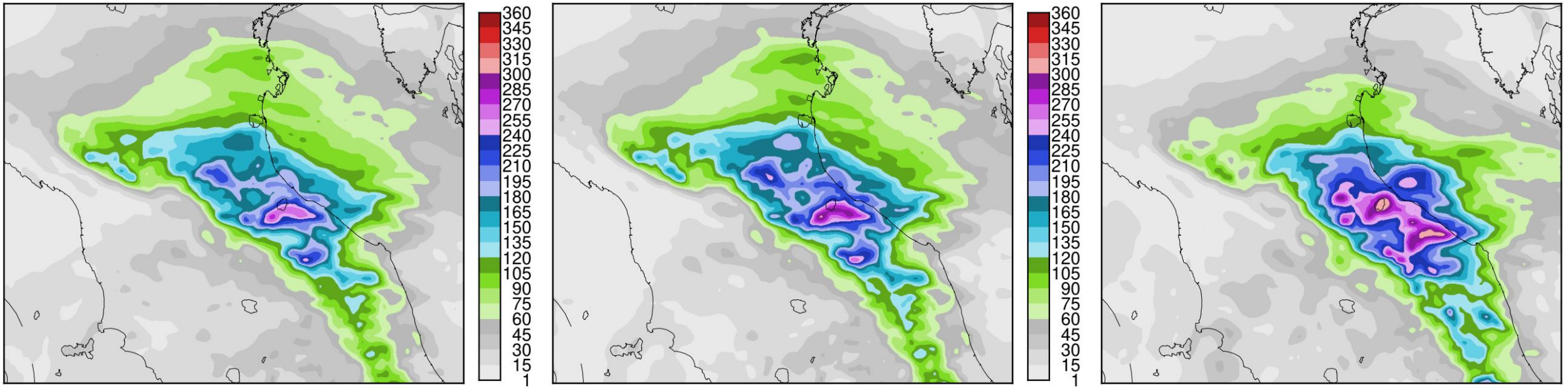



Present-day climate conditions



# With 1.5-degree global warming the event could look…

same overall change (10% increase) but different redistributions in space




Peaks lower relative change

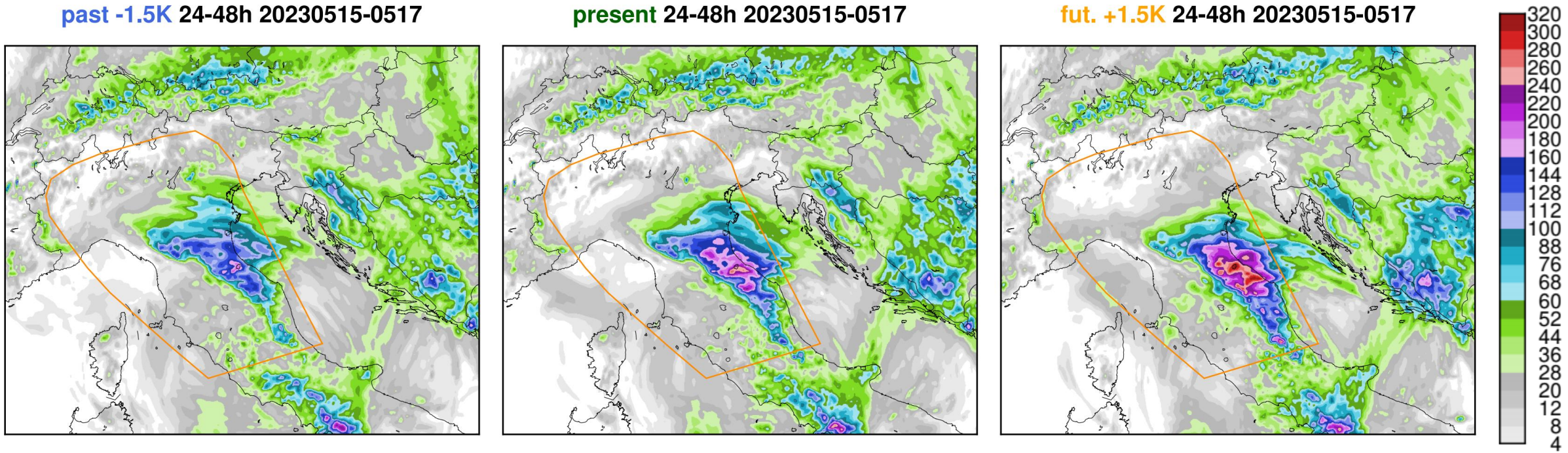
Peaks same relative change

Peaks larger relative change



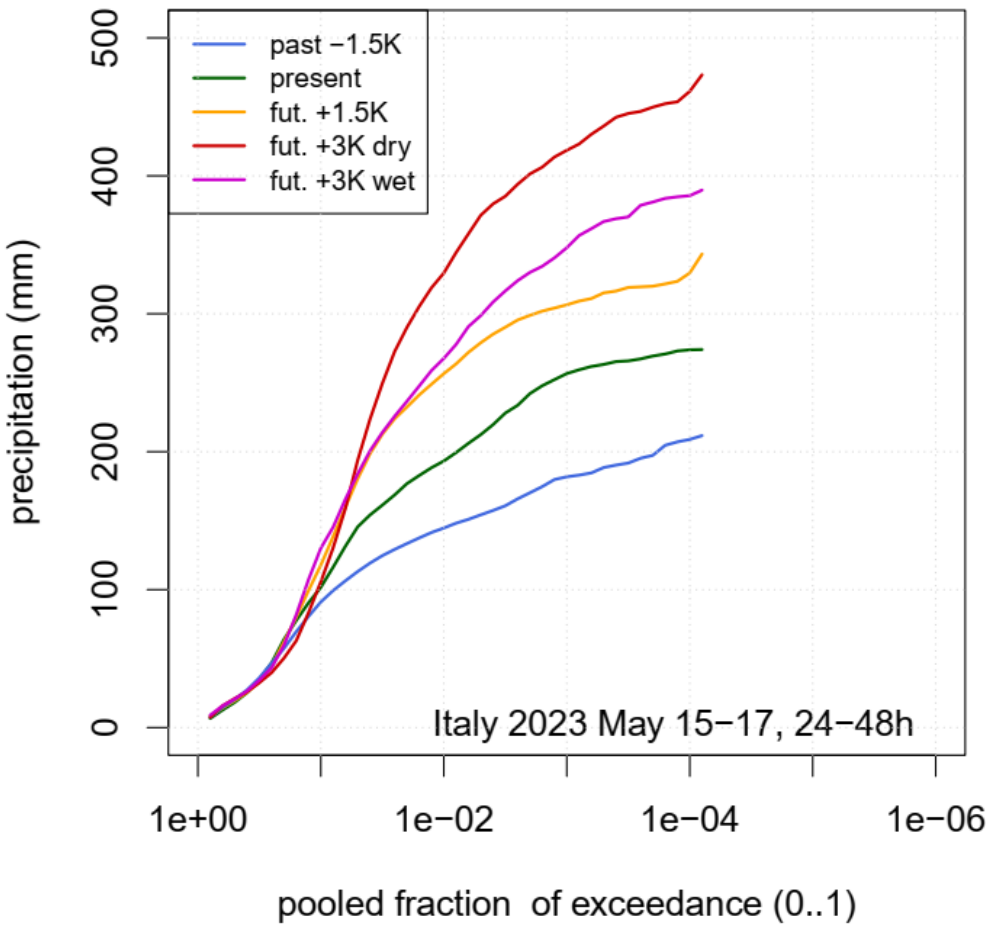
Lenderink et al. WACE 2025

# 2023 spring Italy floods



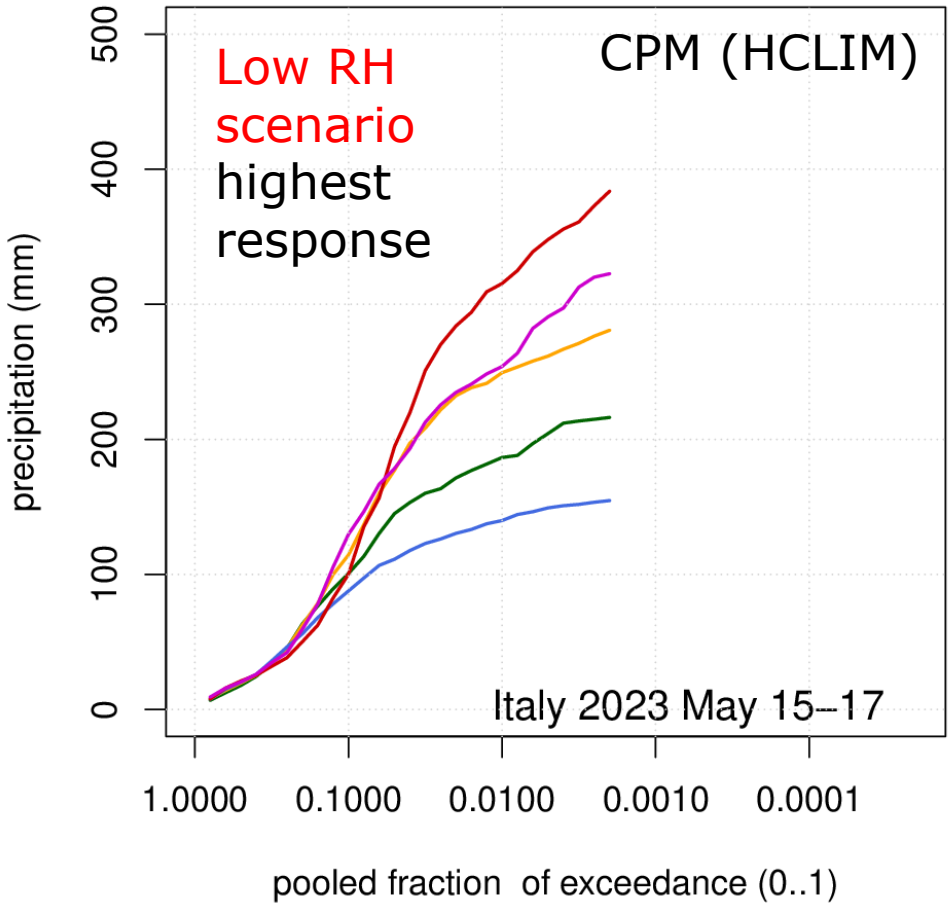

Plotted: ensemble max (3 members) of accumulated rainfall

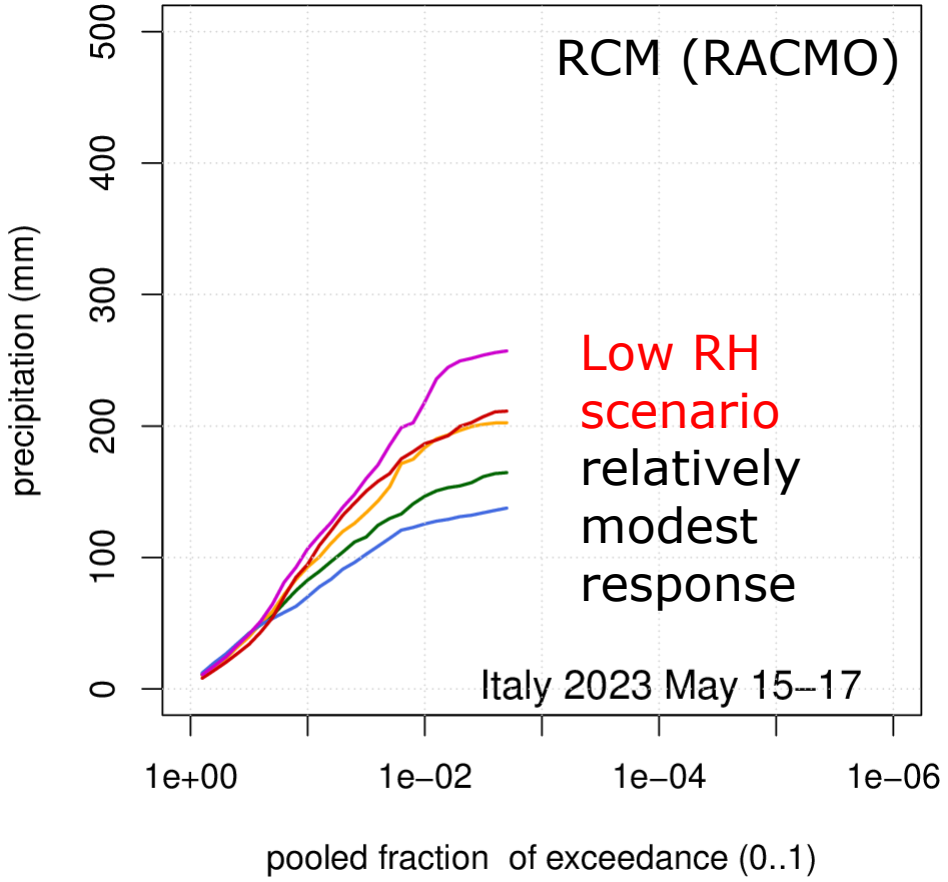
# Statistics spring Italy floods




- Rainfall over larger area increase with 4-6% per degree warming (confirming standard approaches)
- Rainfall in precipitation peaks increases with 10-17% per degree warming
- The “dry” future (strong soil drying in the future) increases the most

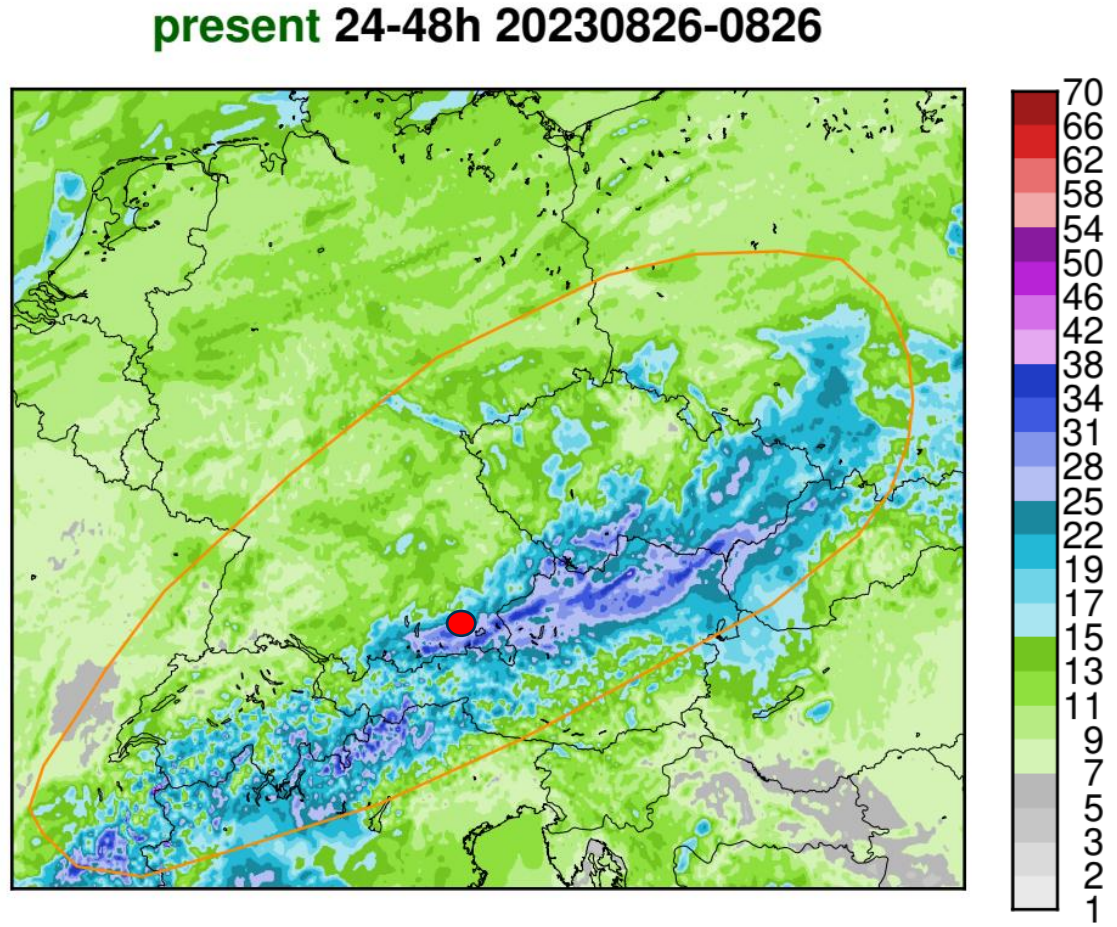
# HCLIM (12x12km re-gridded) versus RACMO (12 km parameterized convection model)



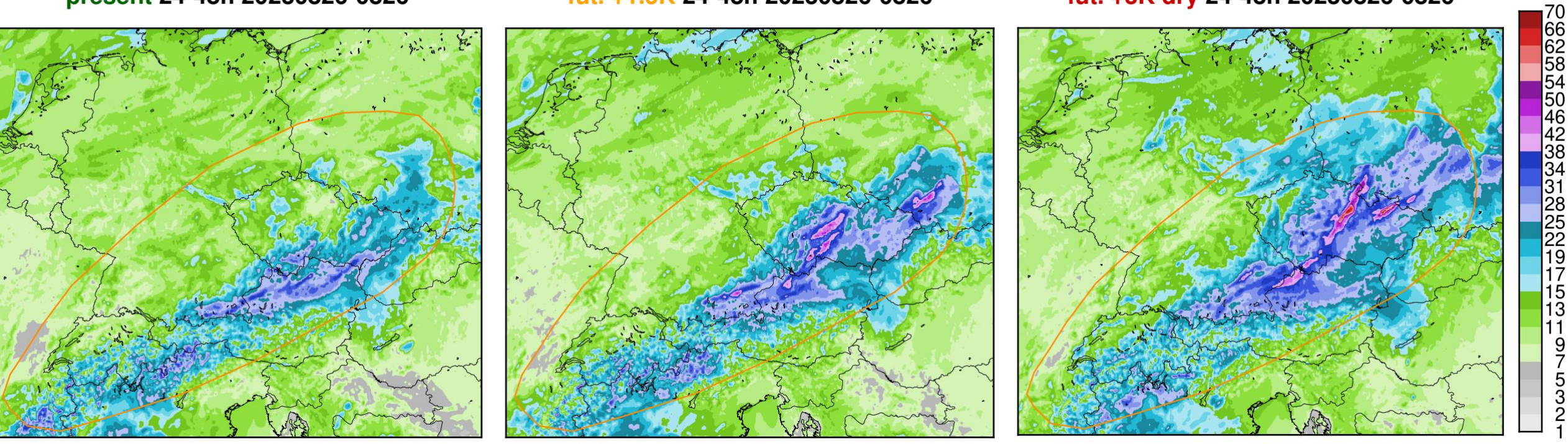
# Wind gusts for a super cell 26 August 2023

*Figure 12: Supercell in south-east Germany on 26-08-2023 obtained from: https://tegernseerstimme.de/das-tegernseer-tal-in-der-superzelle/*



# Maximum windgust from the system

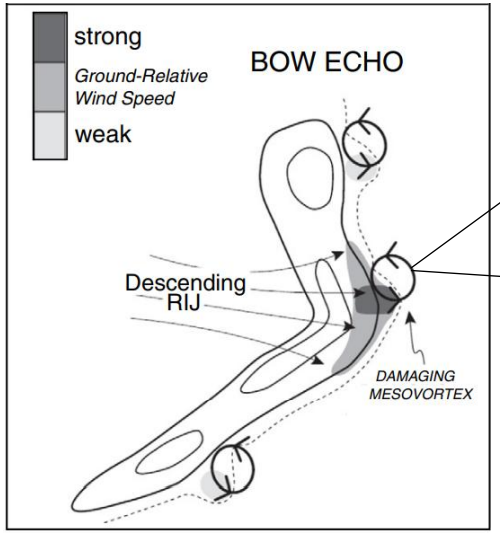
Low RH scenario highest response

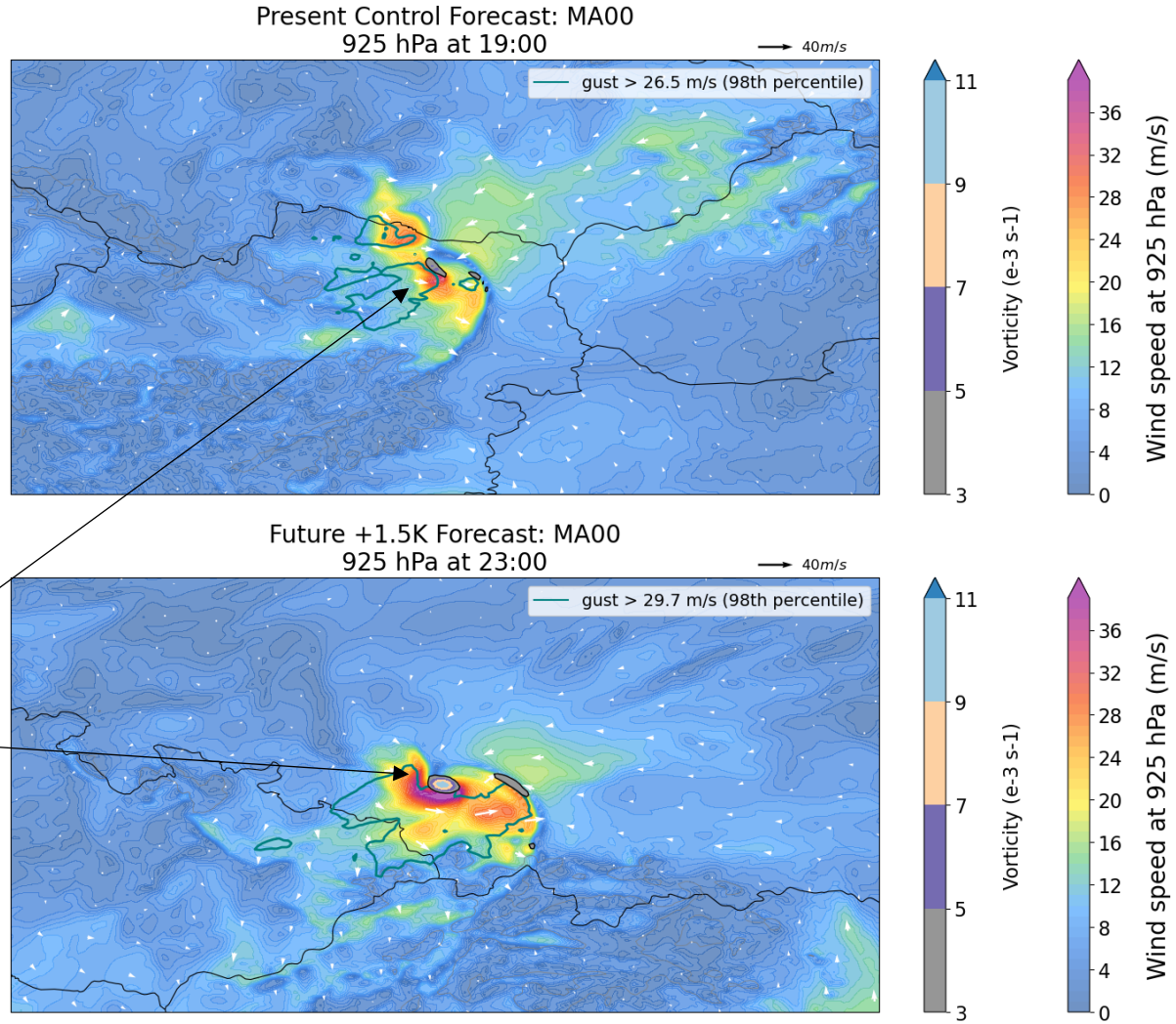



Plotted is the maximum over a 4-member ensemble

# Bow-echo: Mesovortex

- Significant increase in vorticity
  - 0.003 s-1 -> 0.009 s-1
- Strong apparent relation with gust
- Stronger vorticity correlates with stronger downward motions (rear inflow)




Jelle Verburg

# Summary

- Extreme rainfall observations reveal surprisingly regular dependencies on near surface humidity (for relatively uncomplex terrain) often at 2CC rates
- Climate change response of extreme rainfall may deviate substantially from humidity increase.
  - CHANGES IN MESOSCALE DYNAMICS MATTER MORE THAN COMMONLY THOUGHT
- Decreases in relative humidity could strongly impact future extreme rainfall (concentrating rainfall over smaller areas) and may also lead to stronger wind gusts
- Read more: Lenderink et al. Weather and climate extremes, 2025
  Lenderink et al. Hydrology Earth System Science, 2025