UAB
Universitat Autònoma de Barcelona

MAGIC
Major Atmospheric Gamma Imaging Cerenkov Telescopes

# Impact of Climate Change on the MAGIC and CTAO-N sites


Markus Gaug

Universitat Autònoma de Barcelona and IEEC-CERES

markus.gaug@uab.cat

Alessandro Longo, Stefano Bianchi , Lluís Font,
Sofia Almirante, Harald Kornmayer, Michele Doro, Alexander Hahn,
Oscar Blanch, Wolfango Plastino, Daniela Dorner

# Introduction

- Climate change can be assessed by:
  - Simulations (“Global Climate Models” GCM, e.g., the “Coupled Model Intercomparison Project” CMIP6 model family, on which IPCC reports are based)
  - Global Data Assimilations Systems (DAS)
  - Long weather data series
  - Combinations (simulations and DAS validated on ground)

- For the latter, see *C. Haslebacher, et al. A&A 665 (2022) A149*

*(Impact of climate change on site characteristics of eight major astronomical observatories using high-resolution global climate projections until 2050. Projected increase in temperature and humidity leads to poorer astronomical observing conditions)*

- Mainly, changes of temperature and specific humidity (through the Clausius-Clapeyron relationship) are detected; hence hampered operation conditions and increased PWV.

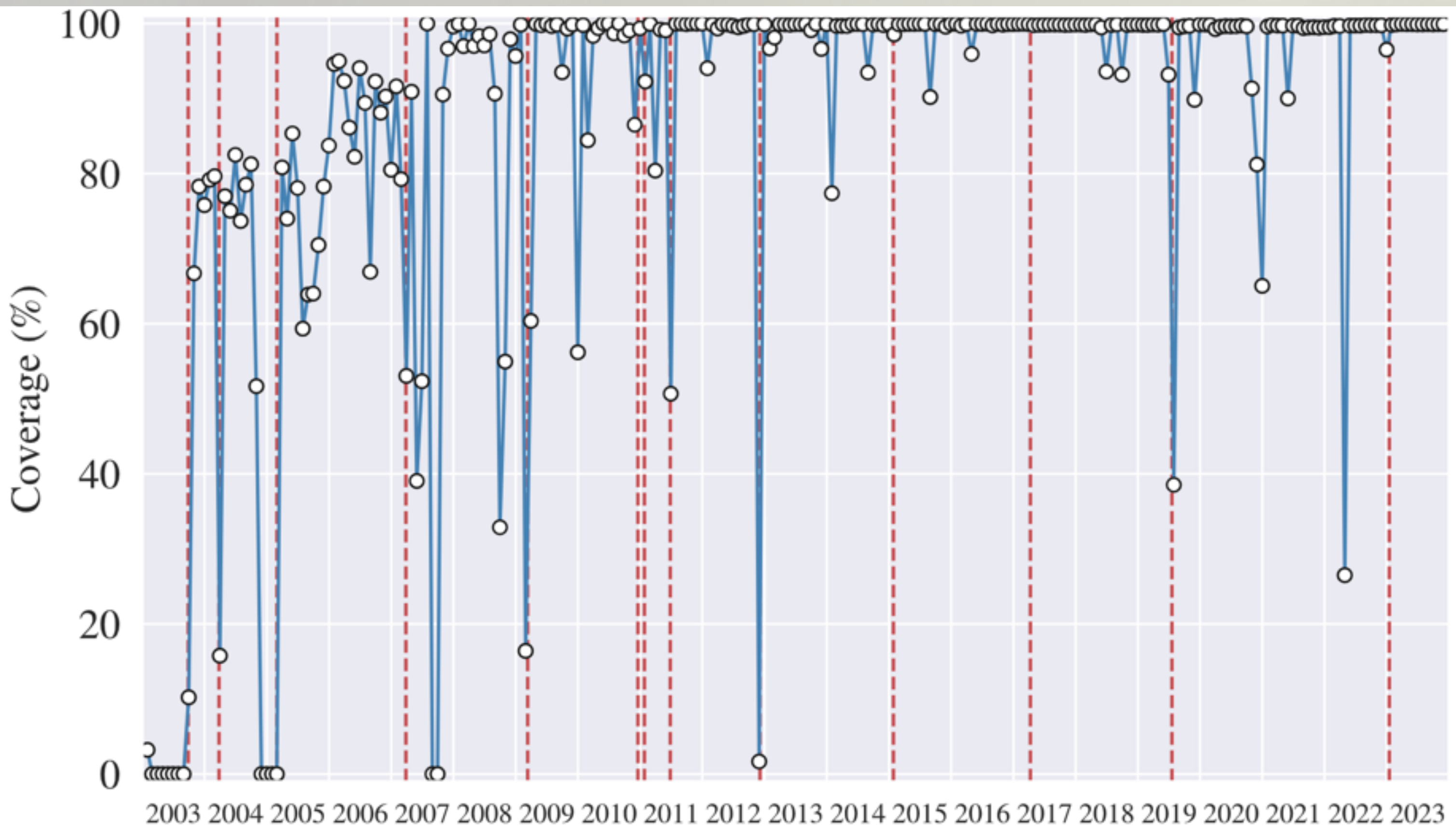
# MAGIC Weather Station

- 20 years of MAGIC weather station data acquired and analyzed


- One entry every 2 minutes, except for wind gust evaluated every 2s
  - temperature
  - relative humidity
  - barometric pressure
  - wind speed (incl. wind speed peak and average wind)
  - wind direction (incl. prevalent wind direction)

# Weather Data Analysis

- 3 different models were bought from Reinhardt GmbH over time:
  – MWS5, MWS-55V and MWS 5MV

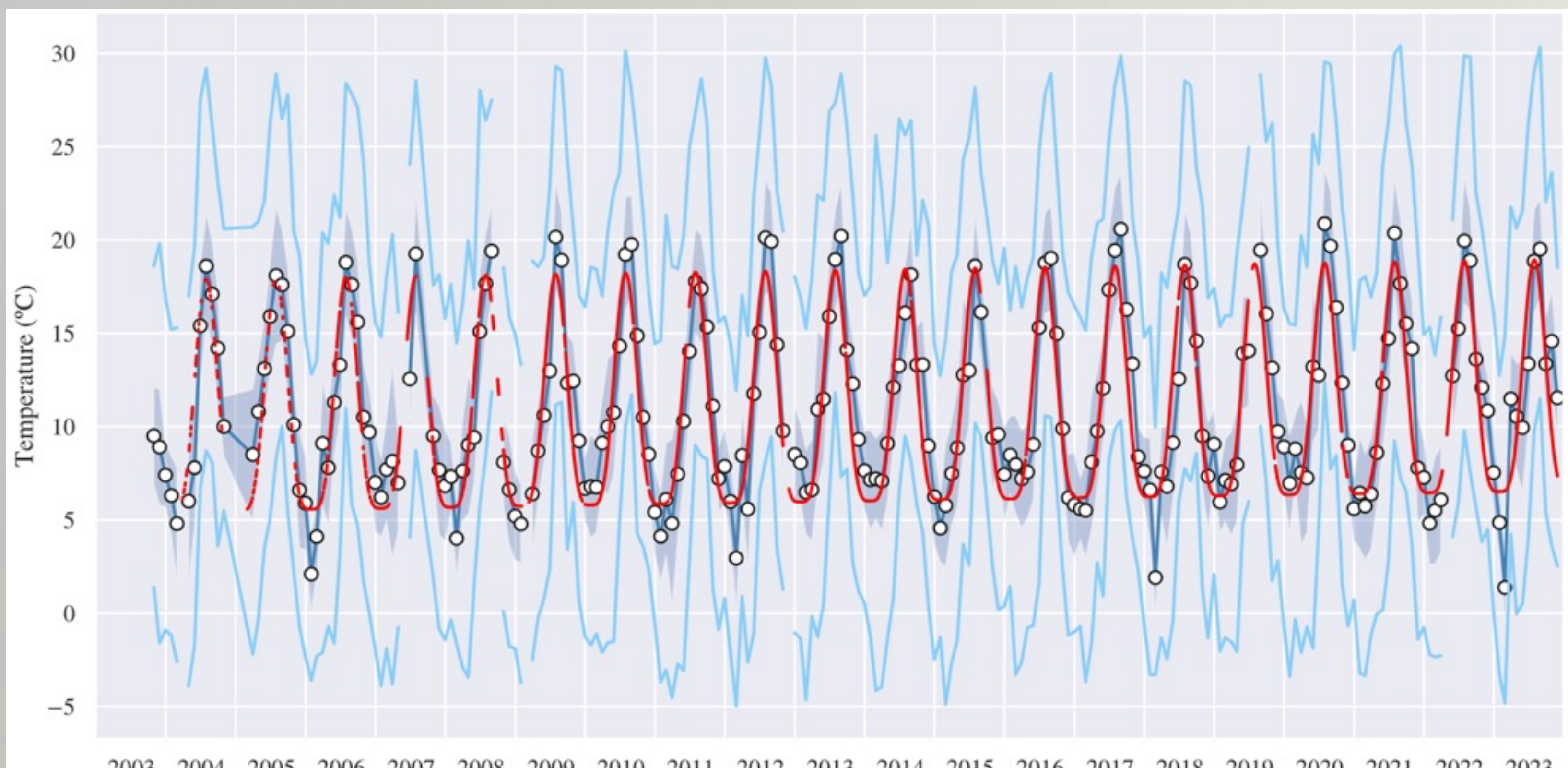


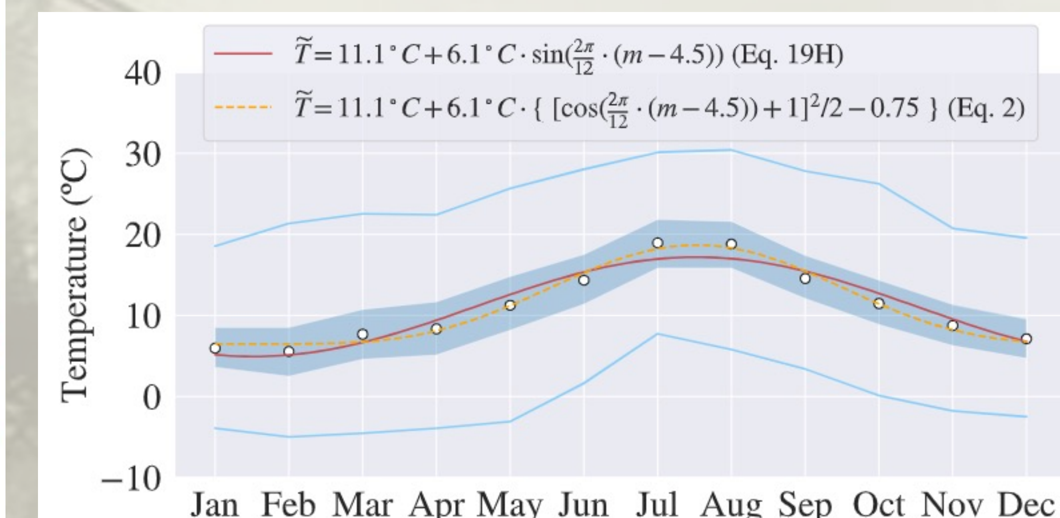

| Date | Comments |
|---|---|
| 2003-09-27 | Installation of model MWS5 on lightning rod |
| 2004-03-26 | Relocation to final site |
| 2005-03-01 | Exchange to a new unit, old was kept as spare. |
| 2007-03-28 | Wind vane bent, replacement by new MWS 5MV |
| 2009-03-12 | Short circuit on board, damaged wind cups, replacement by MWS 5MV |
| 2010-12-19 | Replacement by repaired and calibrated MWS5 |
| 2011-01-26 | Replacement by repaired and calibrated MWS 5MV |
| 2011-06-27 | Replacement by repaired and calibrated MWS 5MV |
| 2012-12-05 | Humidity drift detected, replacement by repaired and calibrated MWS 5MV |
| 2015-01-27 | Humidity sensor broken, replacement by calibrated spare MWS 5MV |
| 2017-04-10 | Replacement by new MWS 55V |
| 2019-07-20 | Defective memory card, replacement by repaired and calibrated MWS 5MV |
| 2023-01-16 | After a gradual increase of lowest humidities had been observed, the station was sent for inspection to the provider and replaced by a repaired and calibrated MWS 55V. |

- Turned out to be not the most robust choice, but this had unexpected positive effects!

# Long-term temperature trends

- Significant temperature increase of 0.55 ± 0.07(stat.) ± 0.07(syst.) ºC/decade




- Construct a profile likelihood

$$\mathcal{L} = \prod_{i=0}^{N} \mathcal{N}(t_i, \mu_i(b, \vec{v}; x_i), \sigma_0)$$

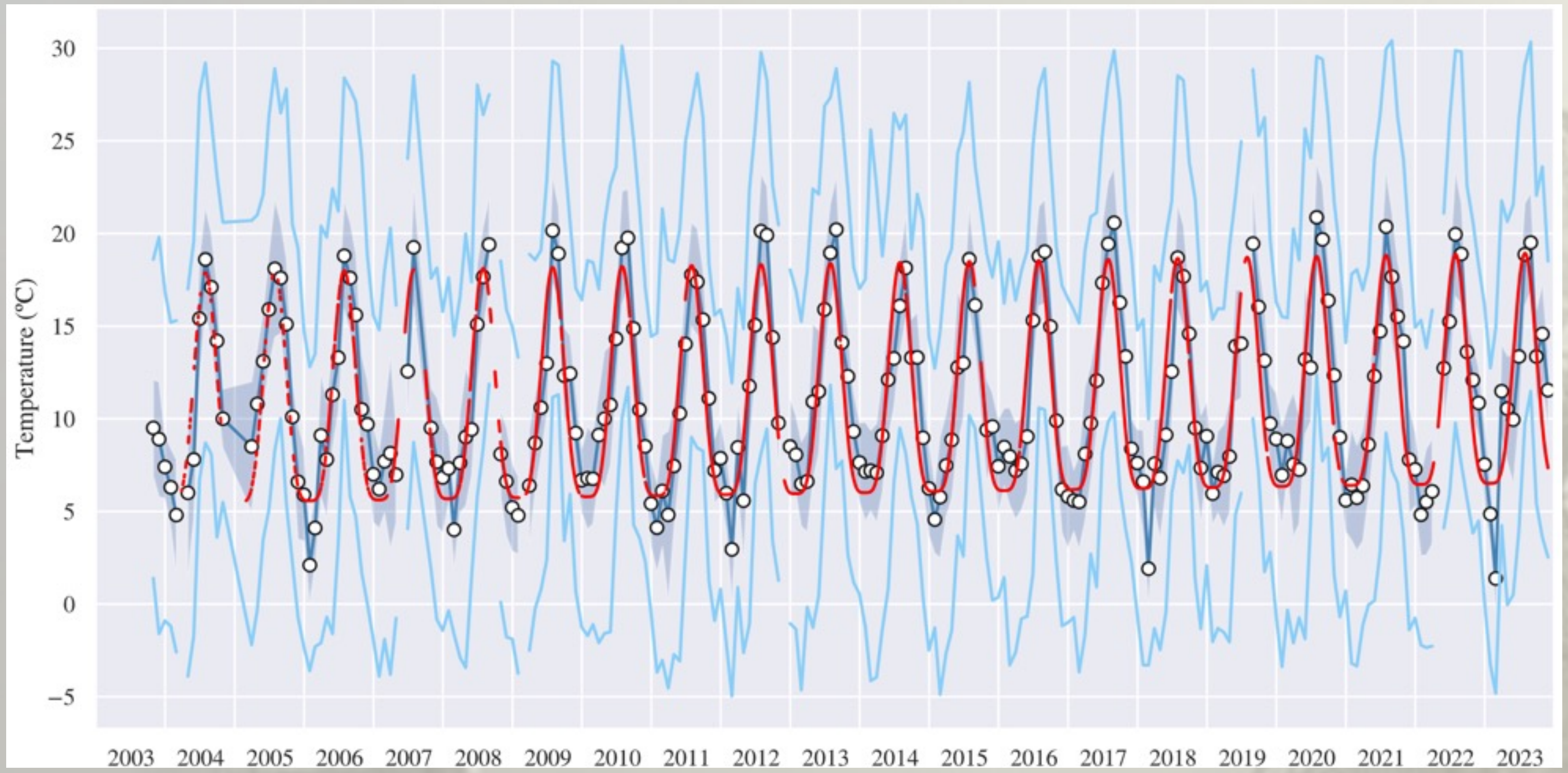
- Expectation values:

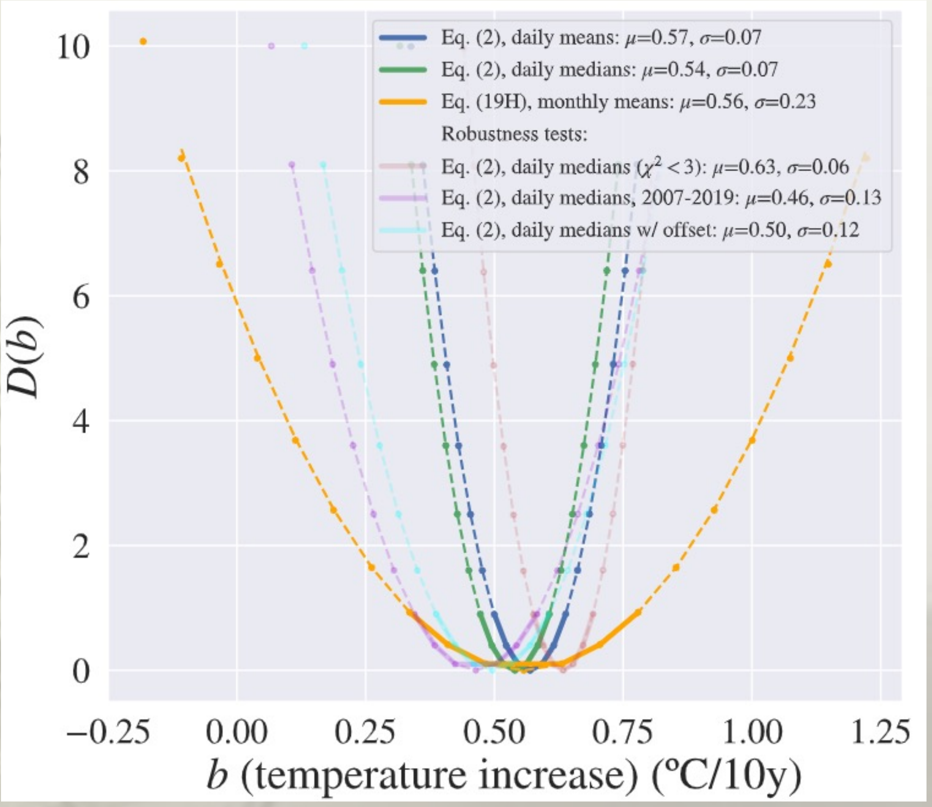
$$\mu_i = a + \frac{b}{120} \cdot x_i + \\ + \frac{C}{2} \cdot \left( \left( \cos\left( \frac{2\pi}{12} \cdot (x_i - \phi) \right) + 1 \right)^2 - \frac{3}{2} \right)$$

M. Gaug et al., “Impact of Climate Change on the MAGIC and CTAO-N Sites”, AtmoHEAD2024, 17.07.2024

# Long-term temperature trends

- Significant temperature increase of 0.55 ± 0.07(stat.) ± 0.07(syst.) ºC/decade



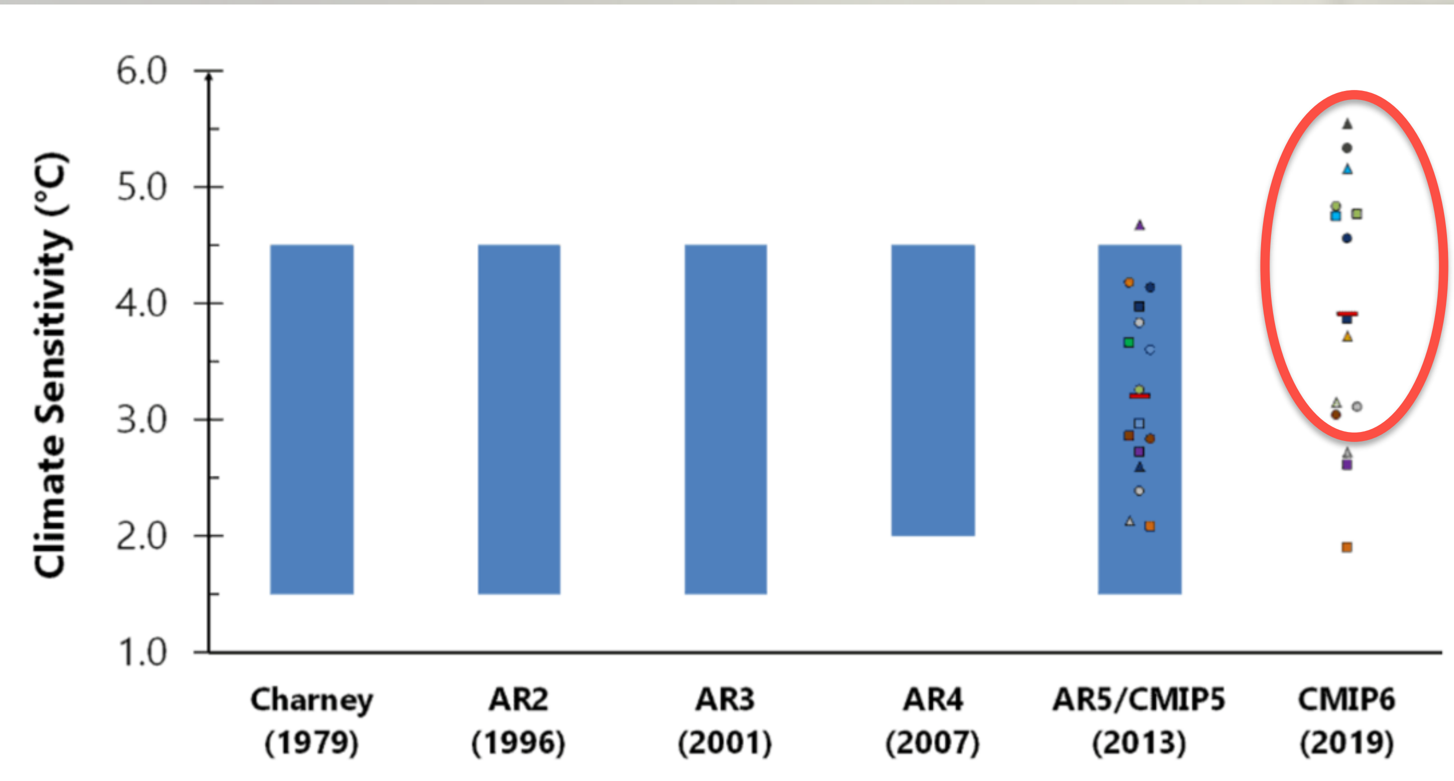




- Larger than found in the simulations: Haslebacher et al. find (0.09-0.24) ºC/decade for historical (NOT) data until 2014 and (0.3-0.5)ºC/decade from simulations for 2015-2050) for the ORM.

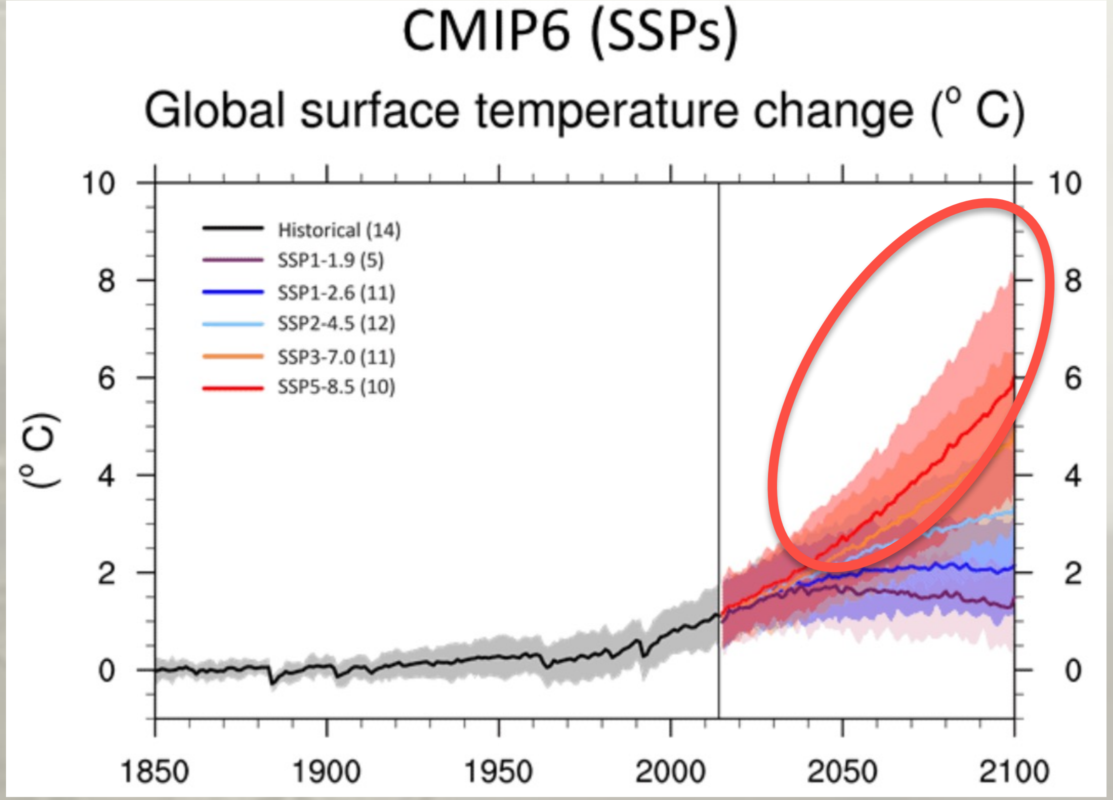
- *May have to do with uncertainties (errors) in Equilibrium Climate Sensitivity (ECS)*

# Long-term temperature trends

- Significant temperature increase of 0.55 ± 0.07(stat.) ± 0.07(syst.) °C/decade




*Manuel Schlund (DLR)*
https://ukesm.ac.uk/climate-sensitivity-in-cmip6-causes-consequences-and-uses/

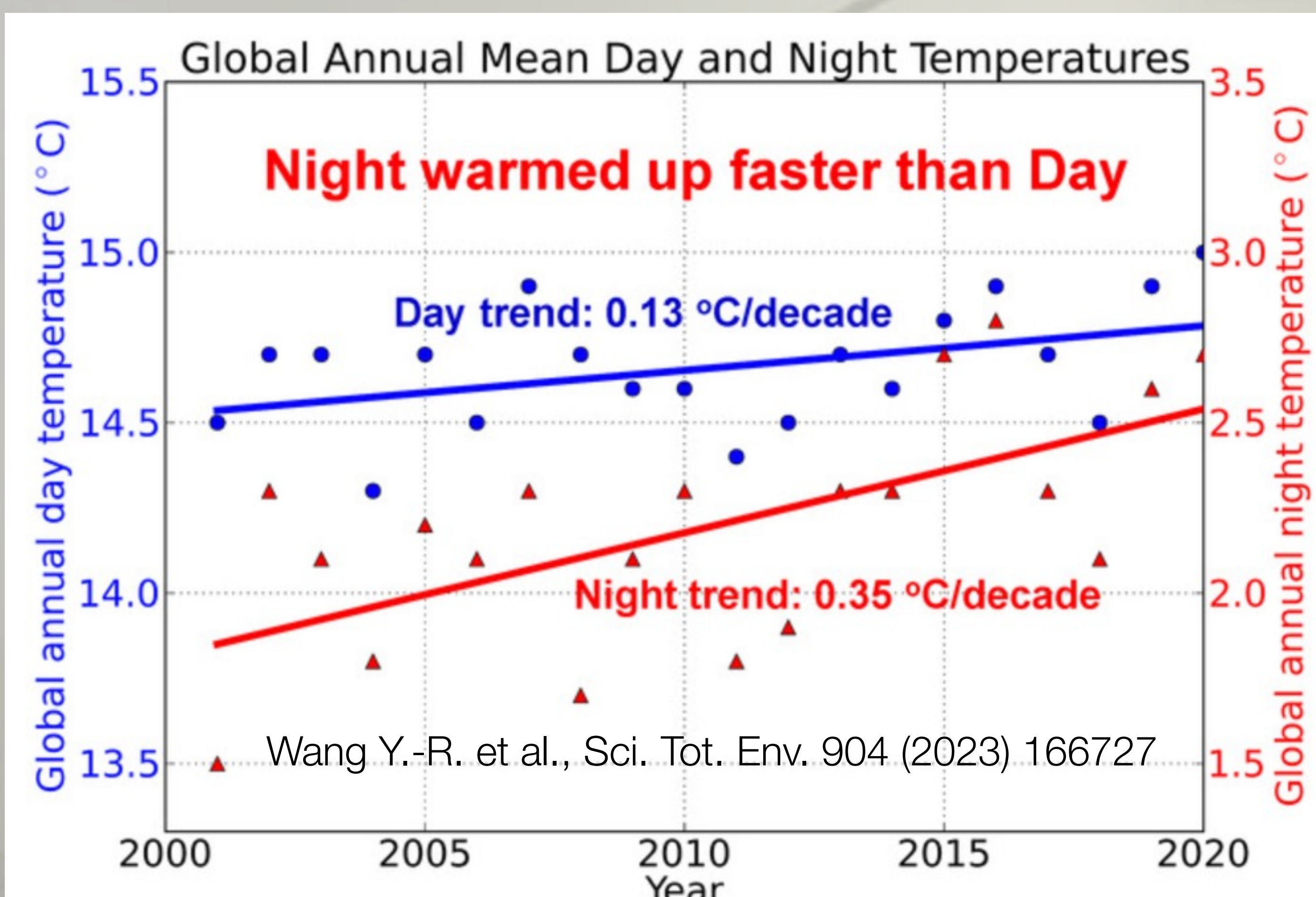


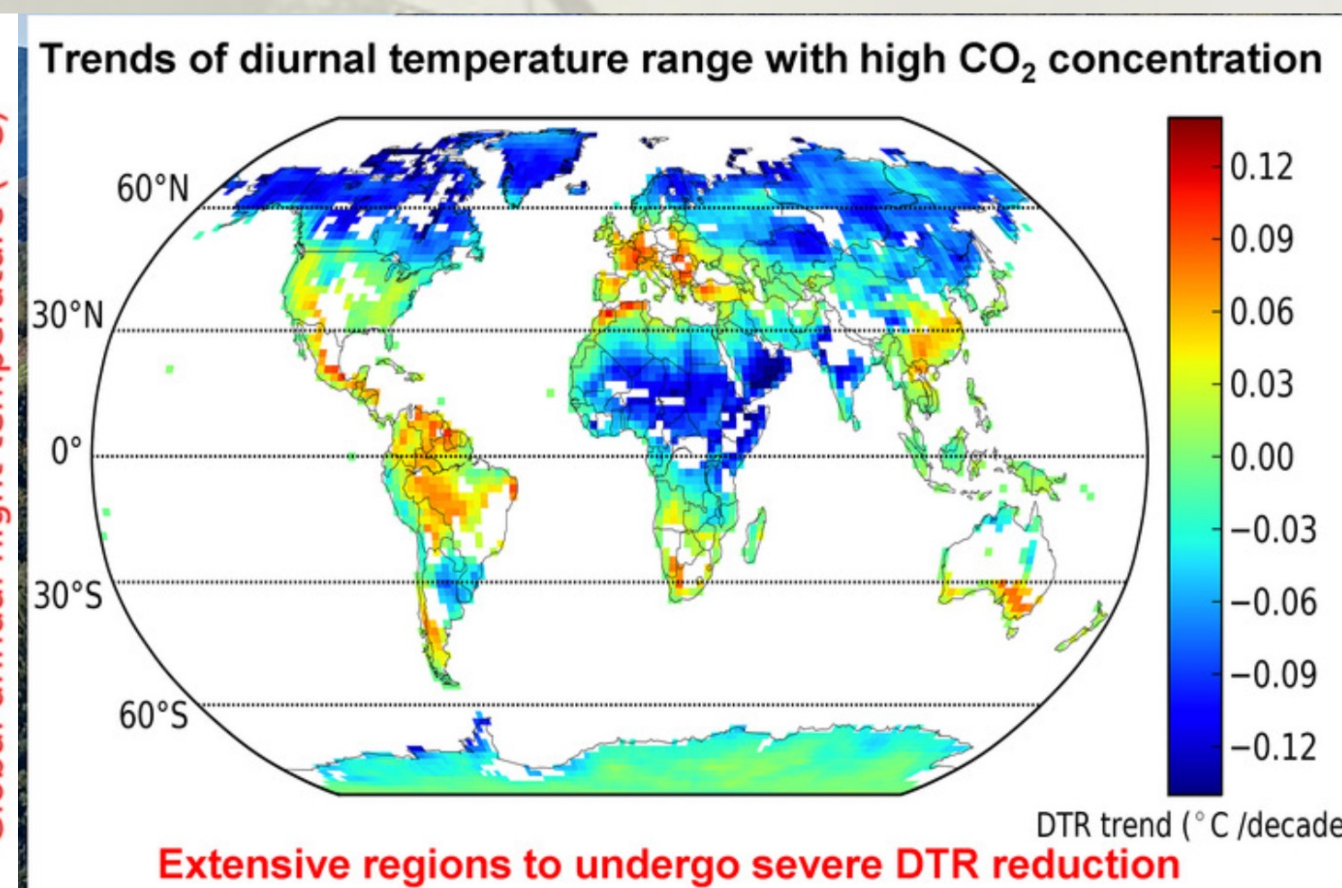

*Erich Fischer (ETH)*
https://ukesm.ac.uk/climate-sensitivity-in-cmip6-causes-consequences-and-uses/

- New models correct a (previously overestimated) negative feedback from super-cooled liquid clouds. ECS comes out higher (or even much higher).

# Diurnal temperature Ranges (DTR)

- Diurnal temperature ranges are defined as daily temperature maximum minus minimum.
- DTR decreased world-wide during the past 20 years
- Future regional increases predicted (drying of surface veg.)



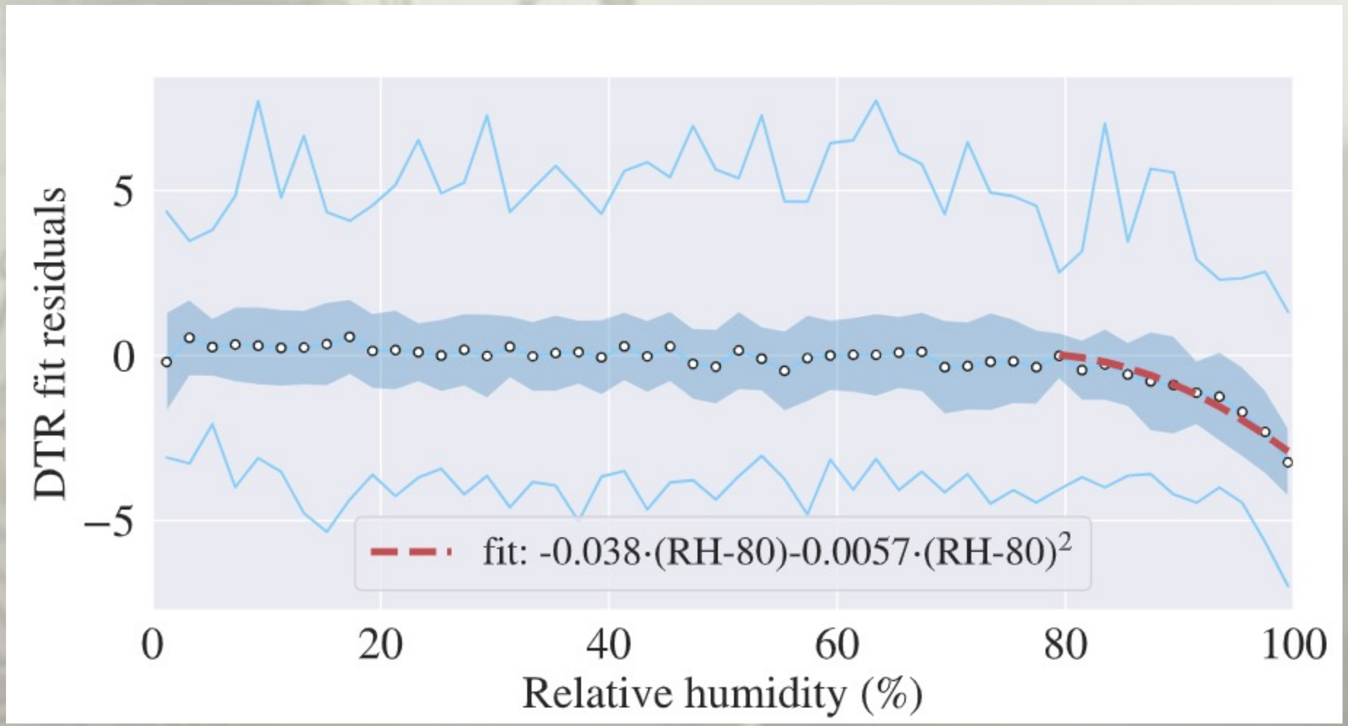

2021-2050 DTR trends projected by CMIP6

# Diurnal temperature Ranges (DTR)

- Diurnal temperature ranges are defined as daily temperature maximum minus minimum.
- "Days" redefined to start and end at 8 am…

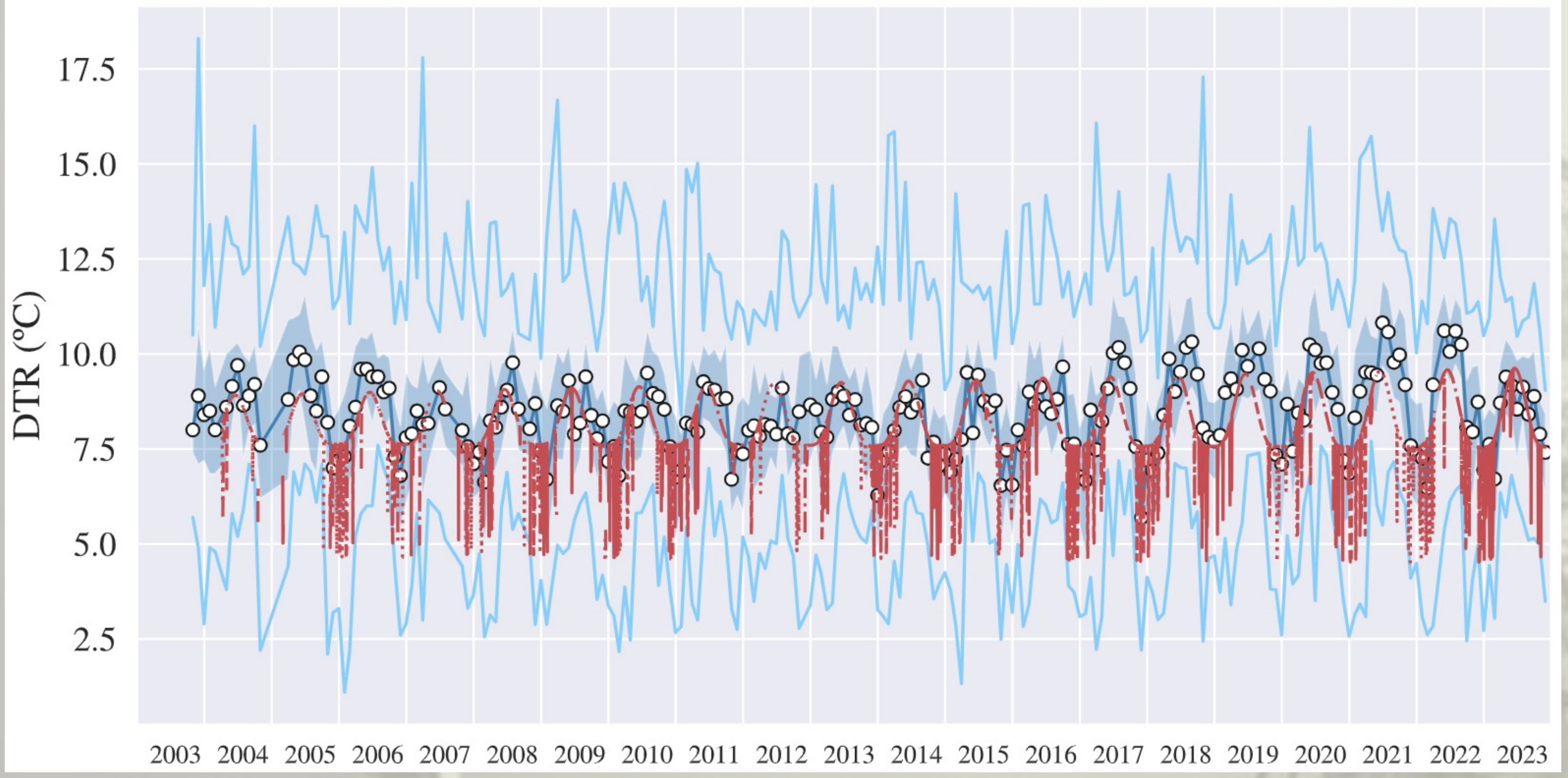
- Needed to perform some rolling averages to get rid of sensitivity to temperature resolution!

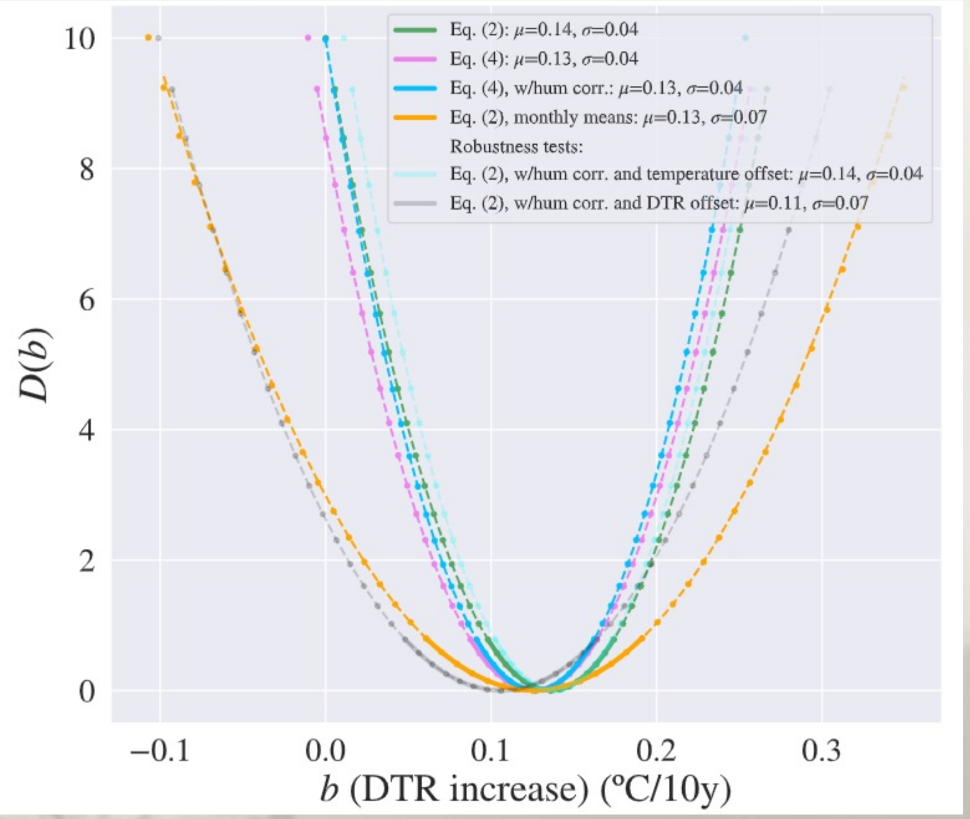
- Seasonal fit corrections for high humidity (treated separately):



# Diurnal temperature Ranges (DTR)

- Significant DTR increase of 0.13 ± 0.04(stat.) ± 0.02(syst.) ºC/decade



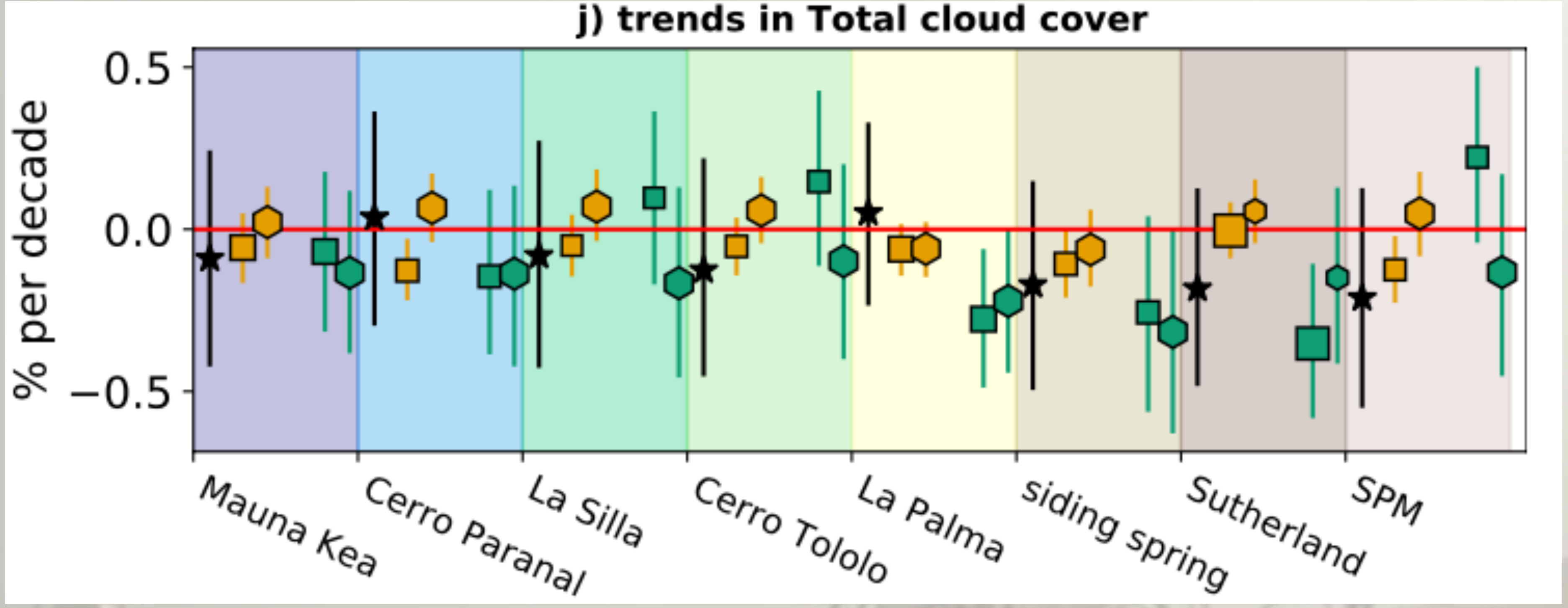

- Accompanied with increase of seasonal oscillation amplitude

- Positive trend predicted from simulations (Expósito et al.) for mountainous areas of Canaries caused by decrease in soil moisture and a slight reduction in cloud cover.
- Reference article (Future Projections of Temperature and Precipitation in the Canary Islands)

*F. J. Expósito et al. Journal of Climate, 28 (2015) 7846.*

# Diurnal temperature Ranges (DTR)

- Significant DTR increase of 0.13 ± 0.04(stat.) ± 0.02(syst.) ºC/decade



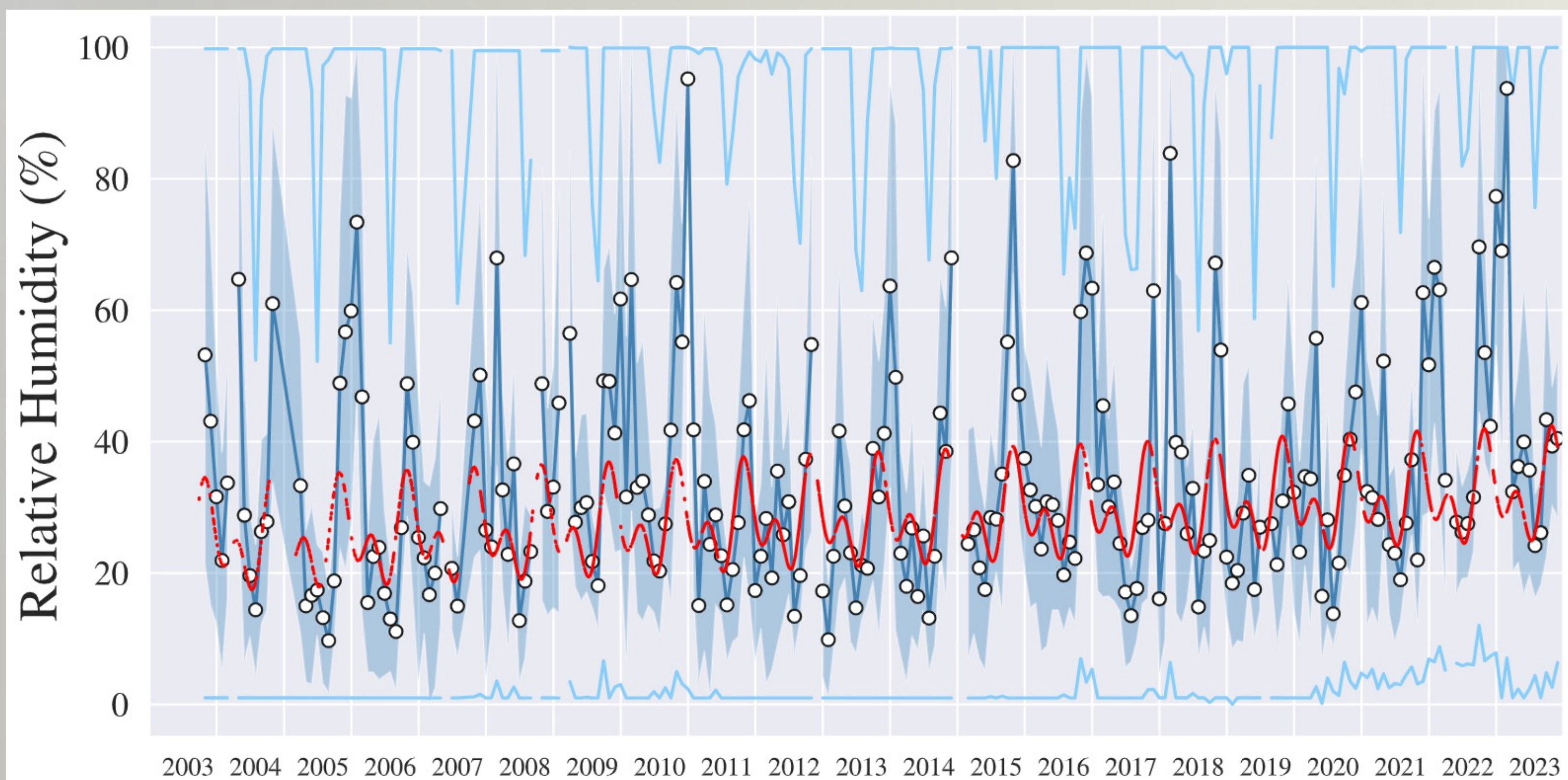

*C. Haslebacher, et al. A&A 665 (2022) A149*

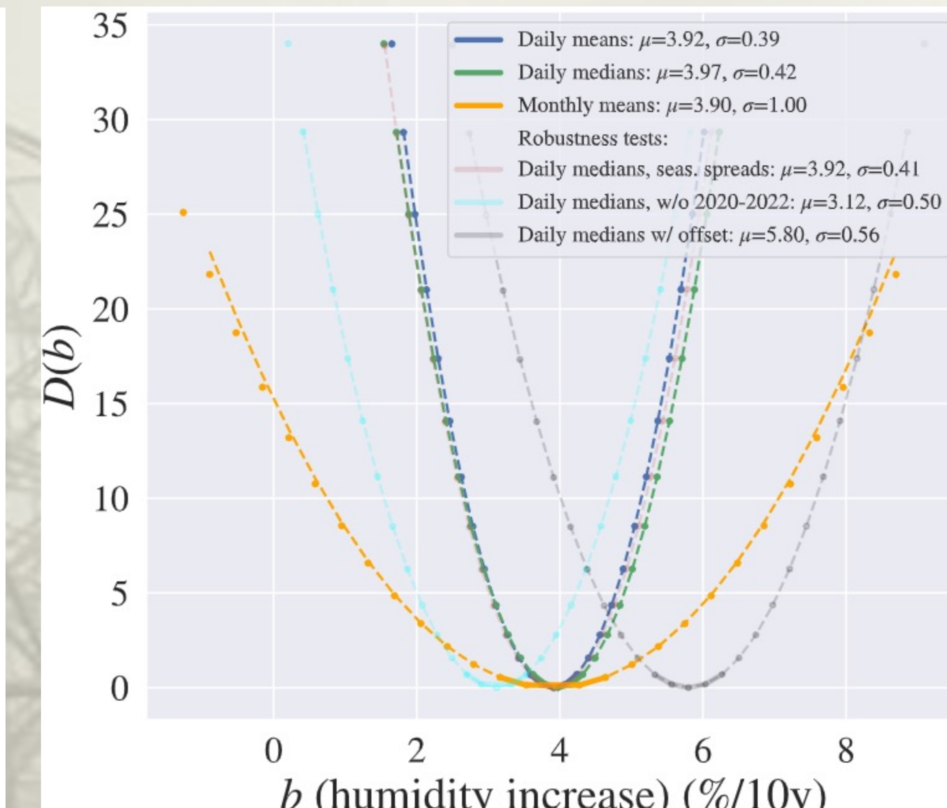
- Positive trend predicted from simulations (Expósito et al.) for mountainous areas of Canaries caused by decrease in soil moisture and a slight reduction in cloud cover.

- Reference article (Future Projections of Temperature and Precipitation in the Canary Islands)
  *F. J. Expósito et al. Journal of Climate, 28 (2015) 7846.*

# Long-term behaviour of relative humidity

- Significant increase of RH (without rain) 4.0±0.4(stat.)±1.1(syst.)%/decade



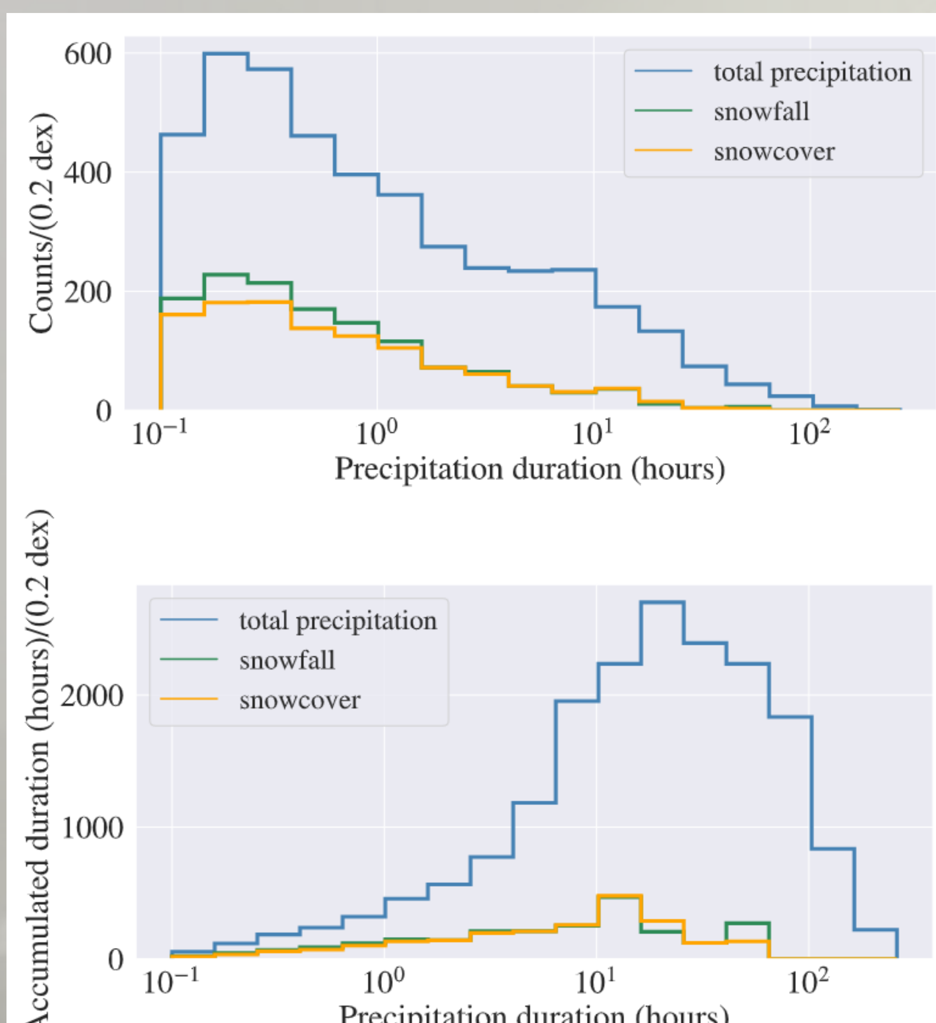




- Positive trend predicted from simulations (Haslebacher et al.) due to higher evaporation rates of sea water, which affect island observatories (Mauna Kea, OMR) in a different way than mainland ones.

- Reference article (climate projections until 2050 for 8 major observatories)
  *C. Haslebacher, et al. A&A 665 (2022) A149*

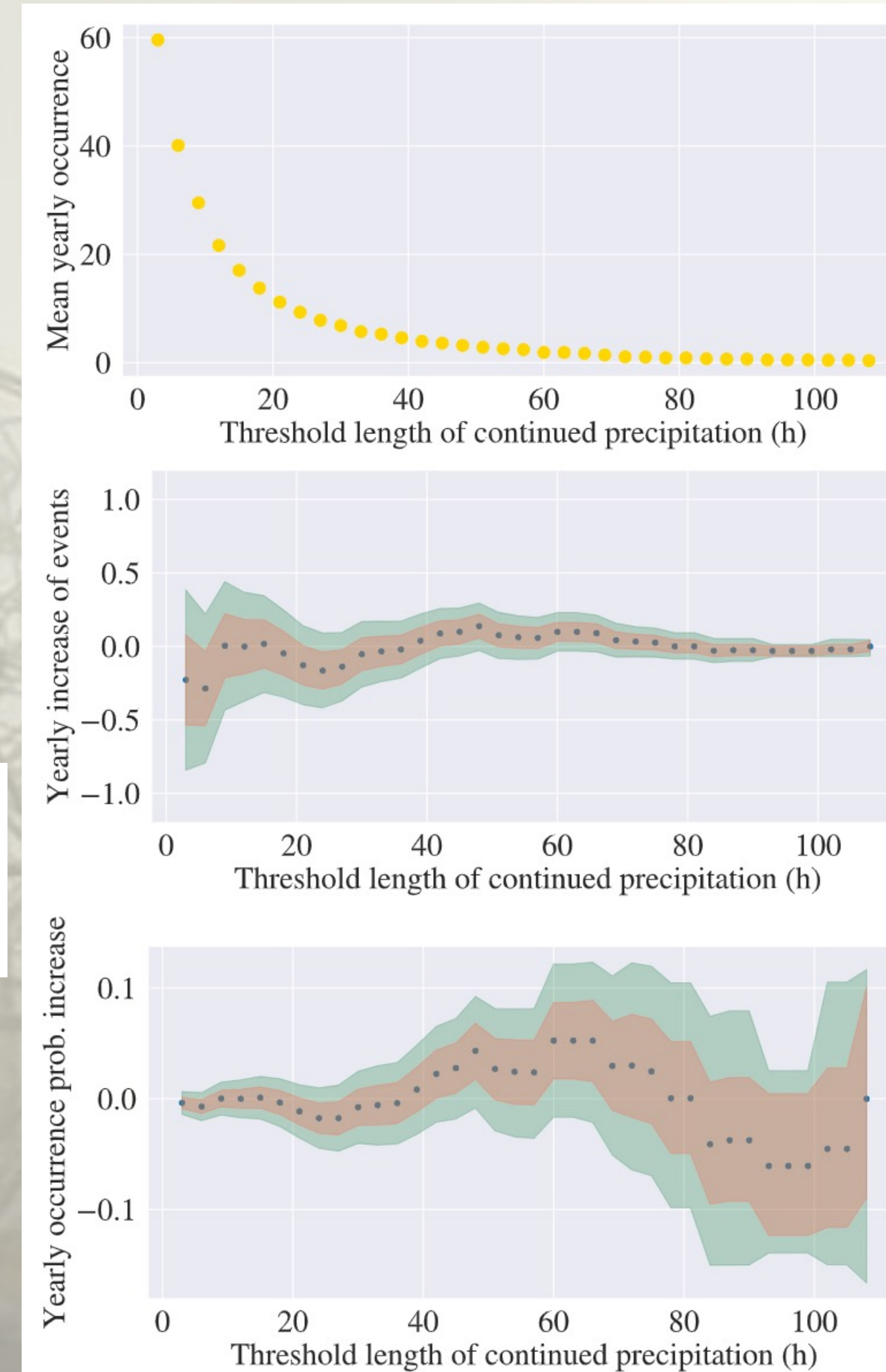
# Long-term behaviour of precipitation

- Precipitation is dominated by long rains.
- No significant increase of precipitation over time observed




$$p_i = p_A + \alpha \cdot \left(i - \frac{N+1}{2}\right)$$

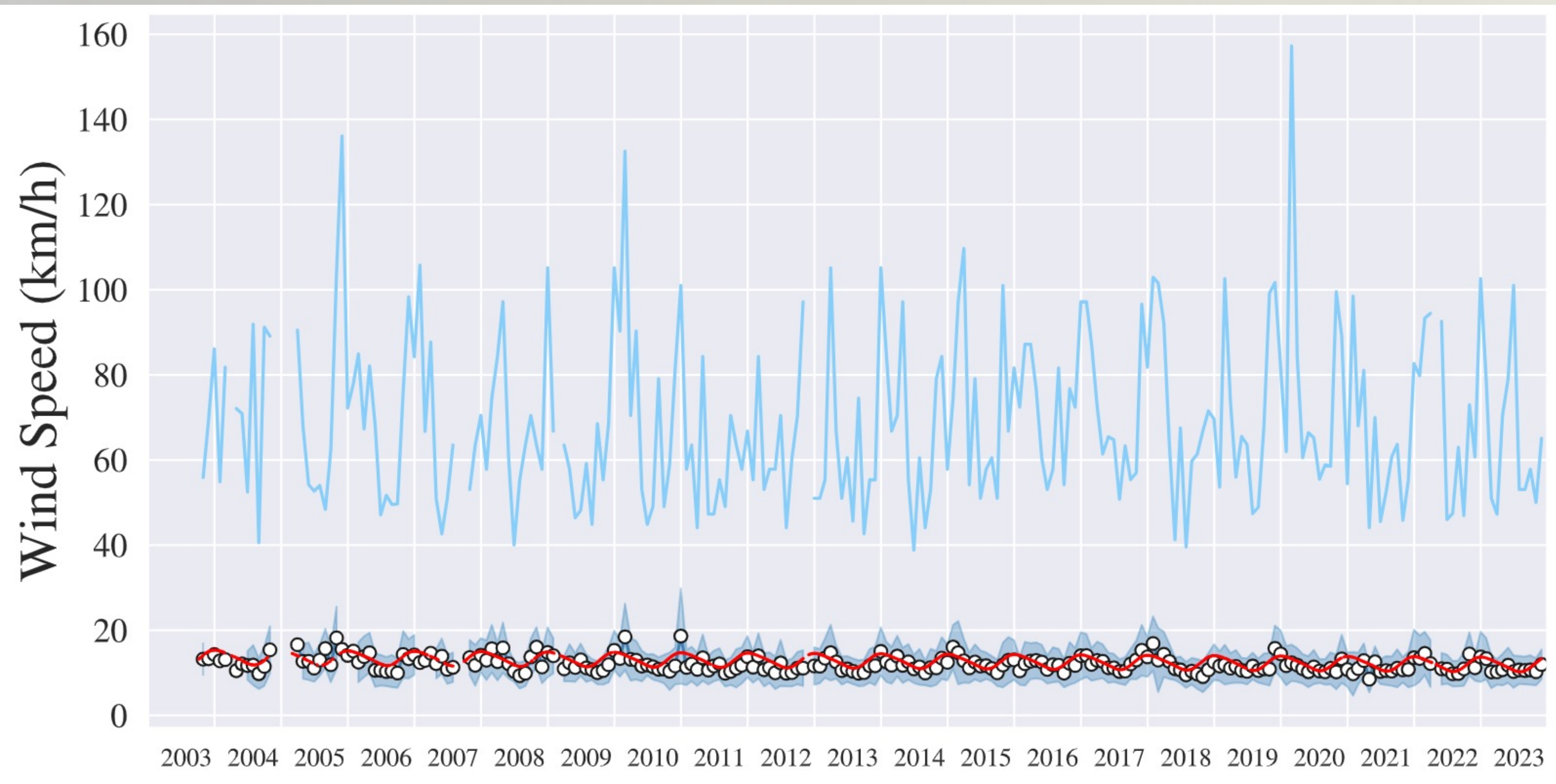
$$\ln(\mathcal{L}) = \sum_{i=0}^{N-1} \left(-p_A - \alpha \cdot i + \alpha \cdot \frac{N+1}{2}\right) \cdot w_i + \\ + k_i \cdot \ln\left[\left(p_A + \alpha \cdot i - \alpha \cdot \frac{N+1}{2}\right) \cdot w_i\right]$$

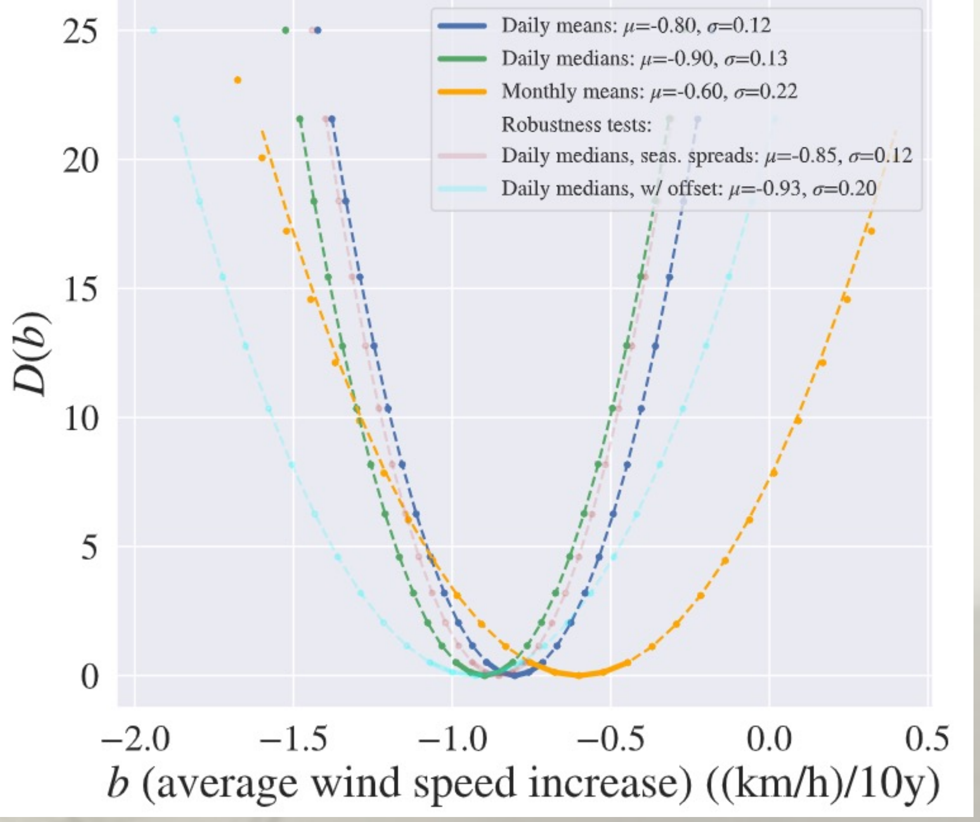



M. Gaug et al., “Impact of Climate Change on the MAGIC and CTAO-N Sites”, AtmoHEAD2024, 17.07.2024

# Long-term behaviour of trade winds

- Significant decrease of trade winds 0.85±0.12(stat.)±0.07(syst.)(km/h)/decade.



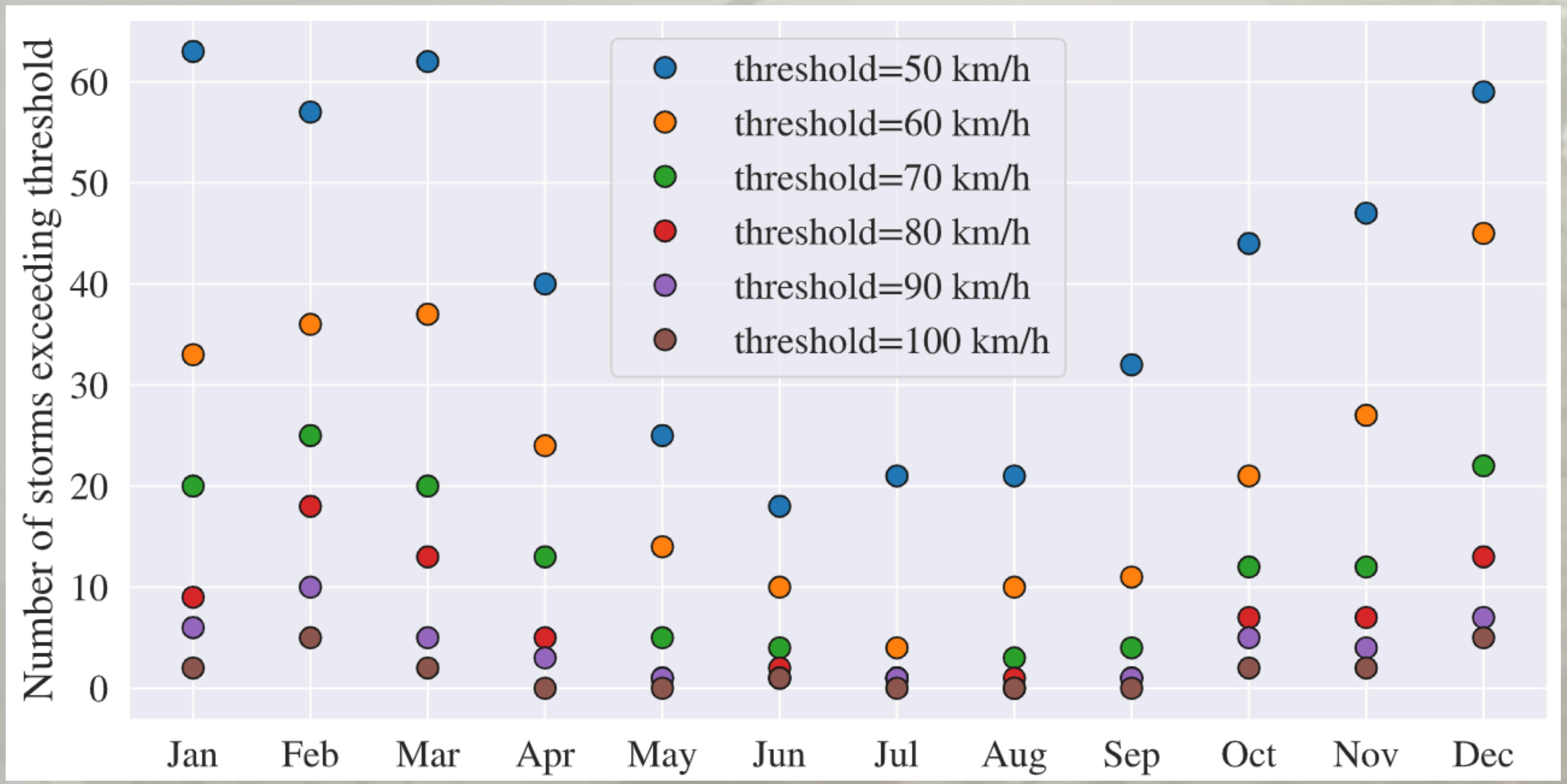



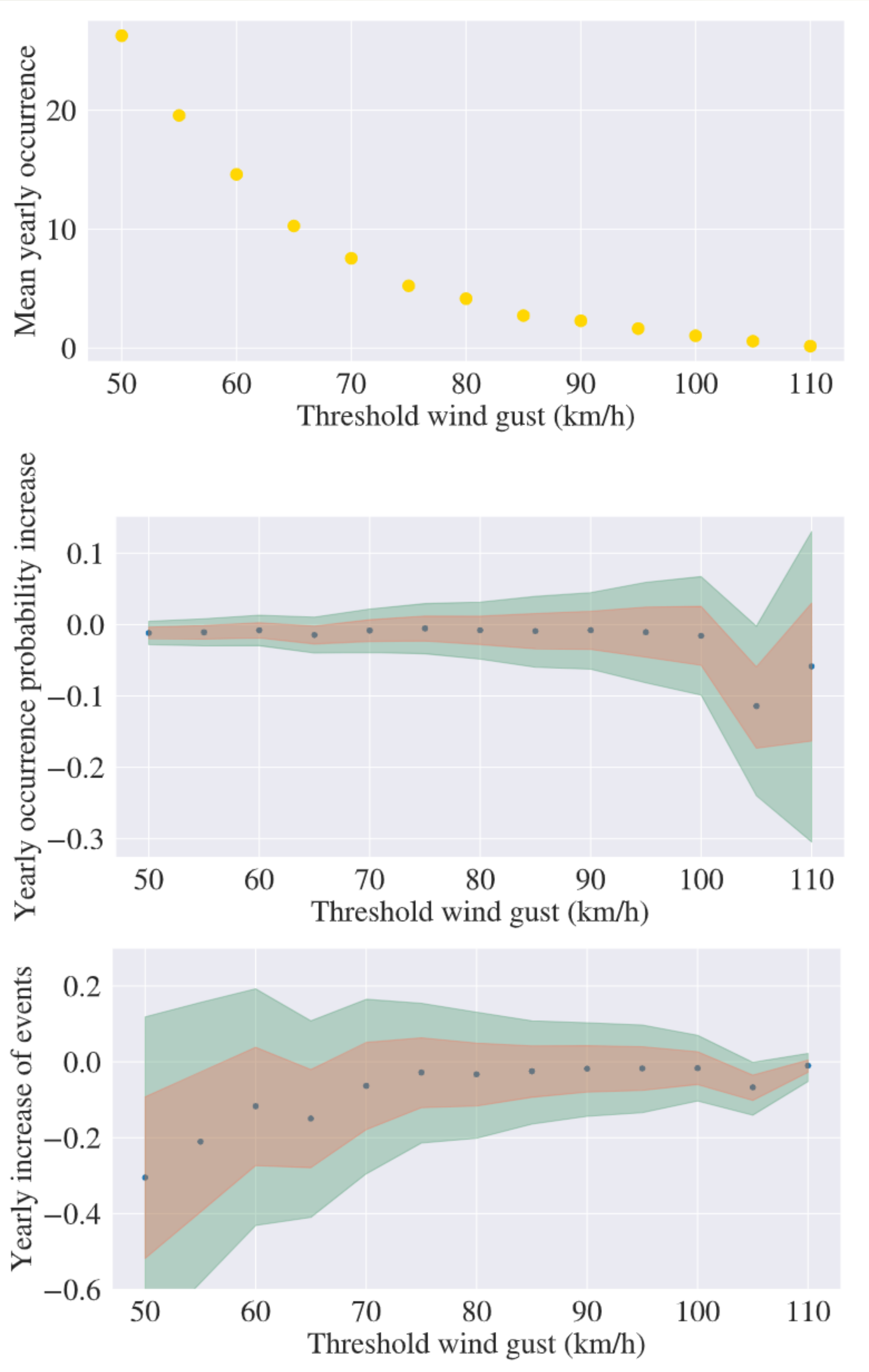

- Azorin-Molina et al. find decrease below the (first) inversion layer, but an increase above it for Izaña (Tenerife, 2400 m asl.). Apparent contradiction may be due to fact that MAGIC often lies below the second inversion layer.

- Reference article (wind speed variability over the Canary Islands)
  *C. Azorin-Molina et al. Climate Dynamics, 50 (2018) 4061.*

# Long-term behaviour of storms

- Storms occur predominantly in Winter.
- No significant increase or decrease of storm occurrence over time observed

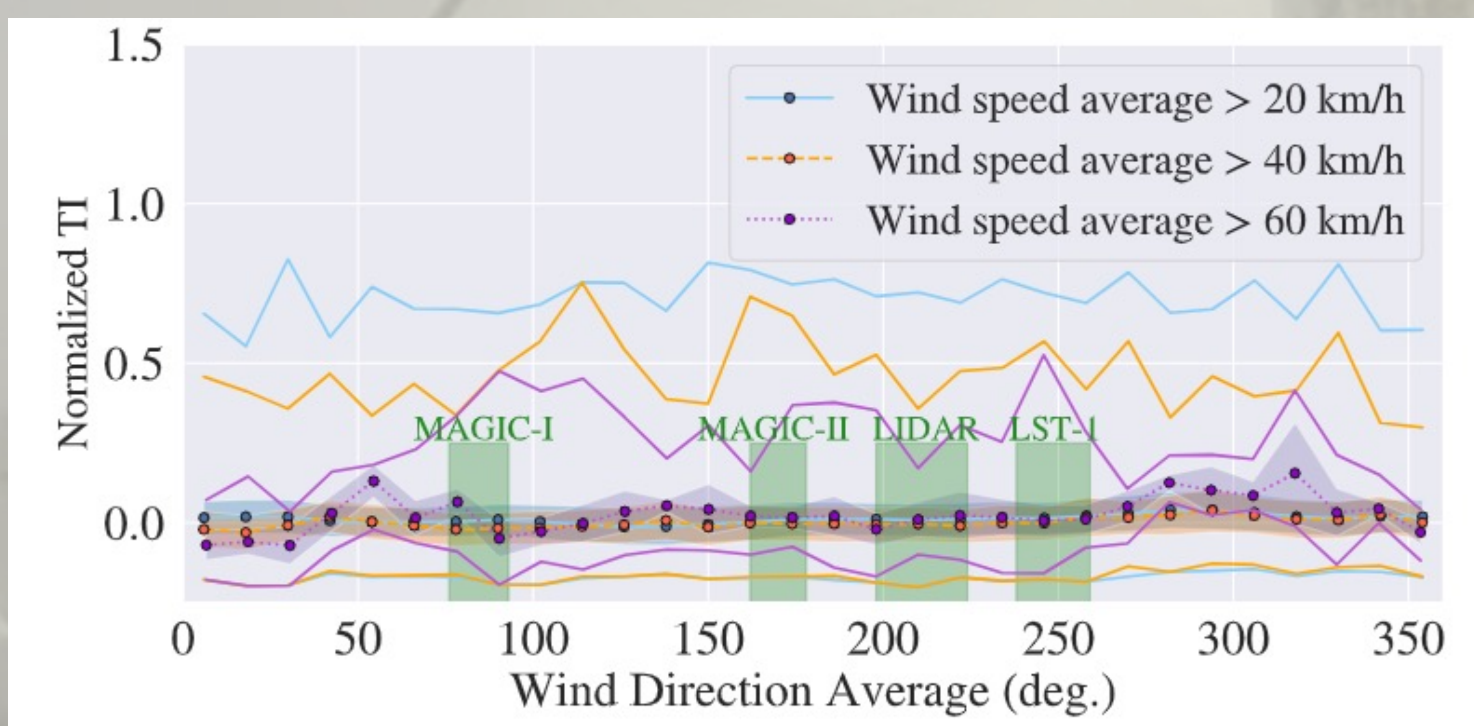


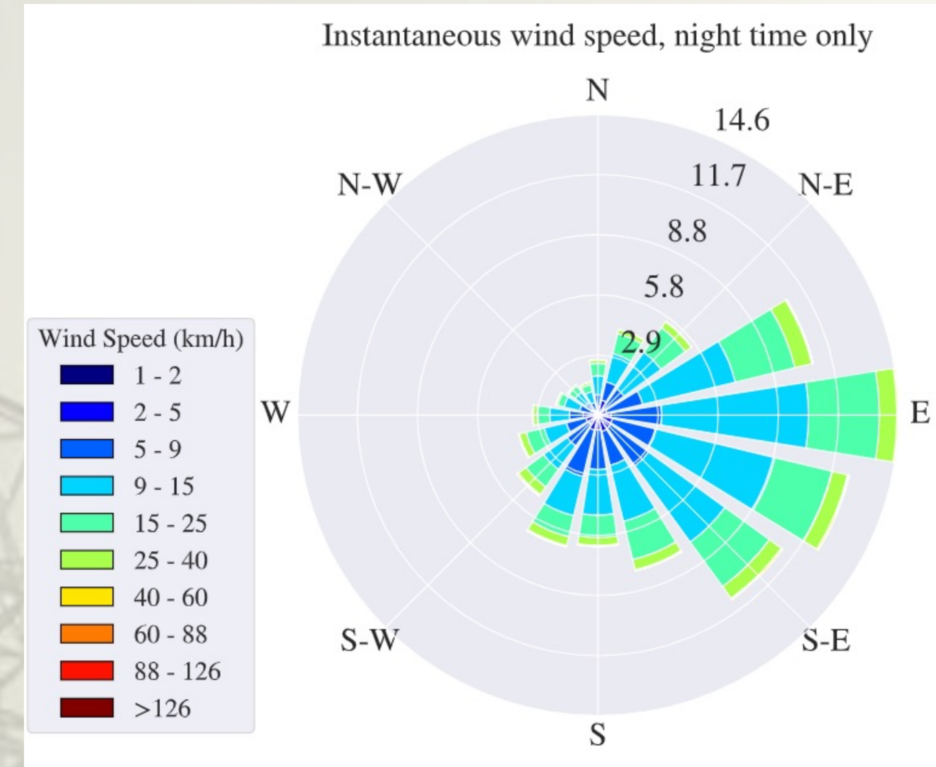



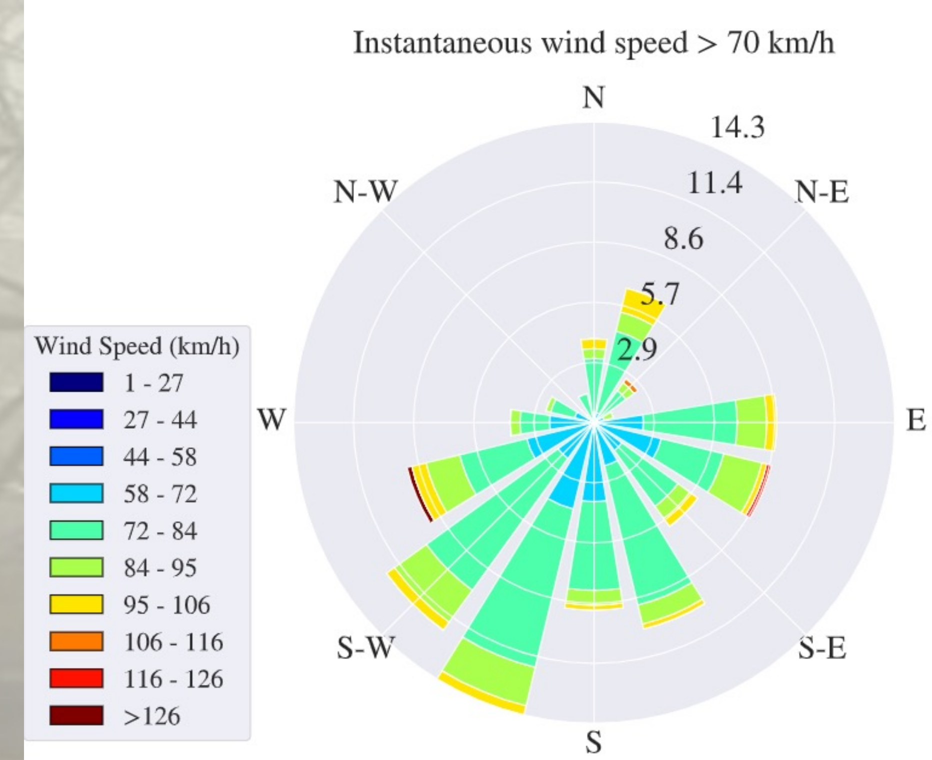

M. Gaug et al., “Impact of Climate Change on the MAGIC and CTAO-N Sites”, AtmoHEAD2024, 17.07.2024

# Long-term behaviour of storms

- Wind directions predominantly from East
- Storms blow from any direction (except from the 4th quadrant).
- No correlation of turbulence intensity (TI) with telescope and LIDAR dome shadows found.

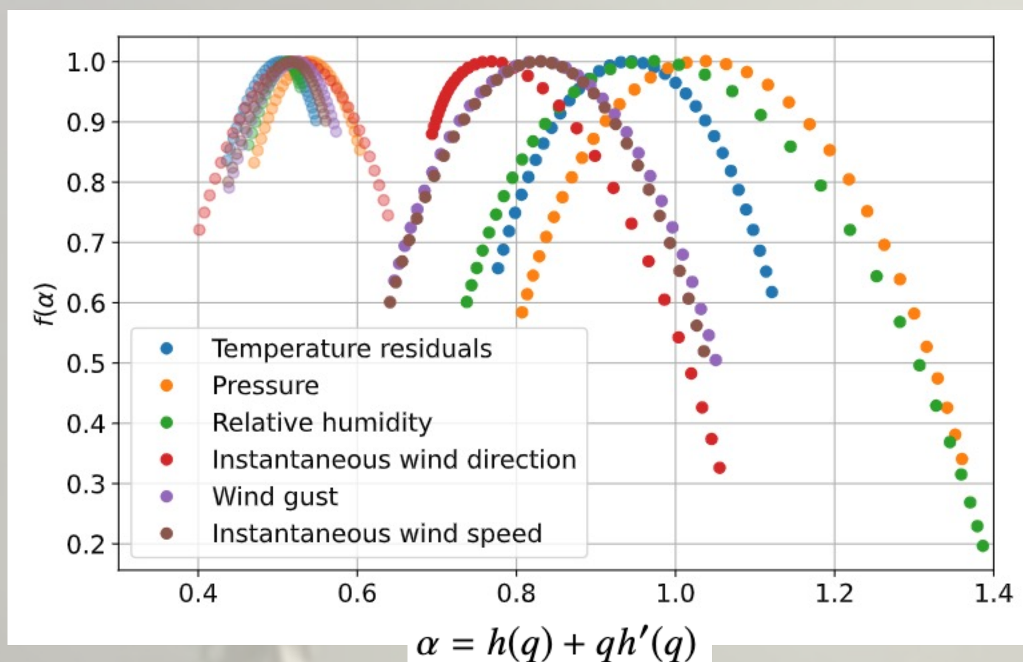


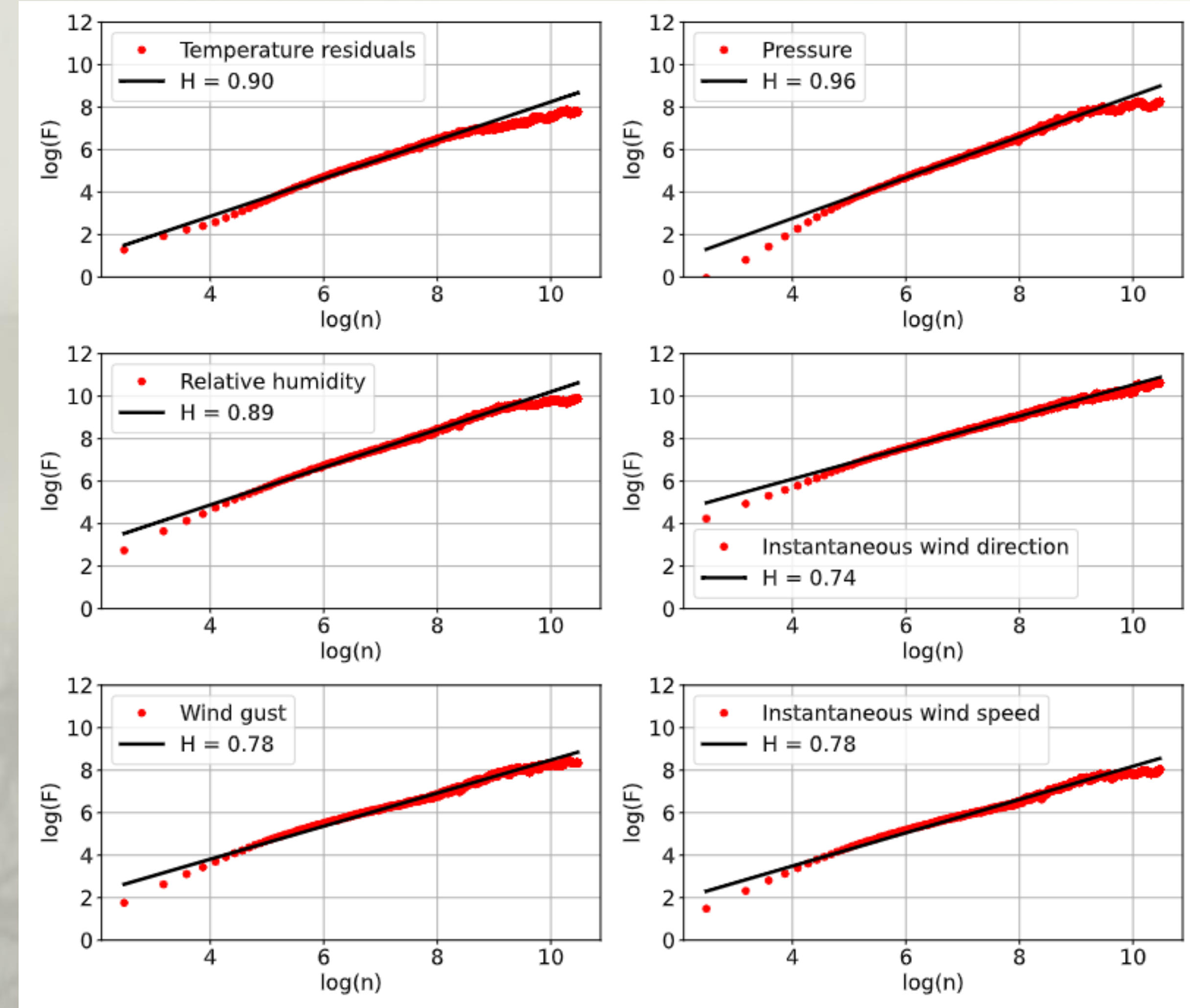



# Fractal behaviour of weather parameters

## Multi-fractal behaviour of all weather parameters.




- Fractality expressed in terms of the Hurst exponent H: $$F(n) = \left[\frac{1}{N_{\mathrm{tot}}}\sum_{s=1}^{N_{\mathrm{tot}}} RMS^2(n,s)\right]^{1/2}$$
- For different window widths $n$, a power-law spectrum is obtained: $$F(n) \sim n^H$$
- Multifractality is calculated at various orders $q$: $$F_q(n) = \left[\frac{1}{N_{\mathrm{tot}}}\sum_{s=1}^{N_{\mathrm{tot}}} [RMS^2(n,s)]^{q/2}\right]^{1/q} \sim n^{h(q)}$$

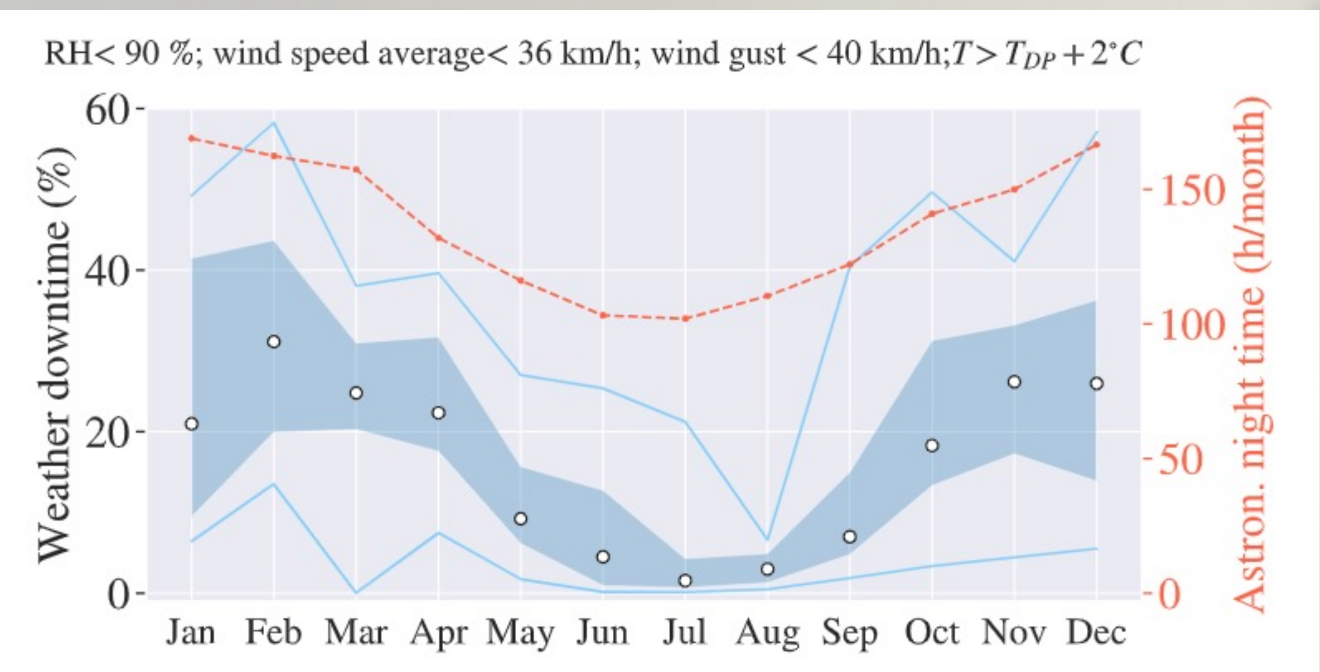
# Conclusions

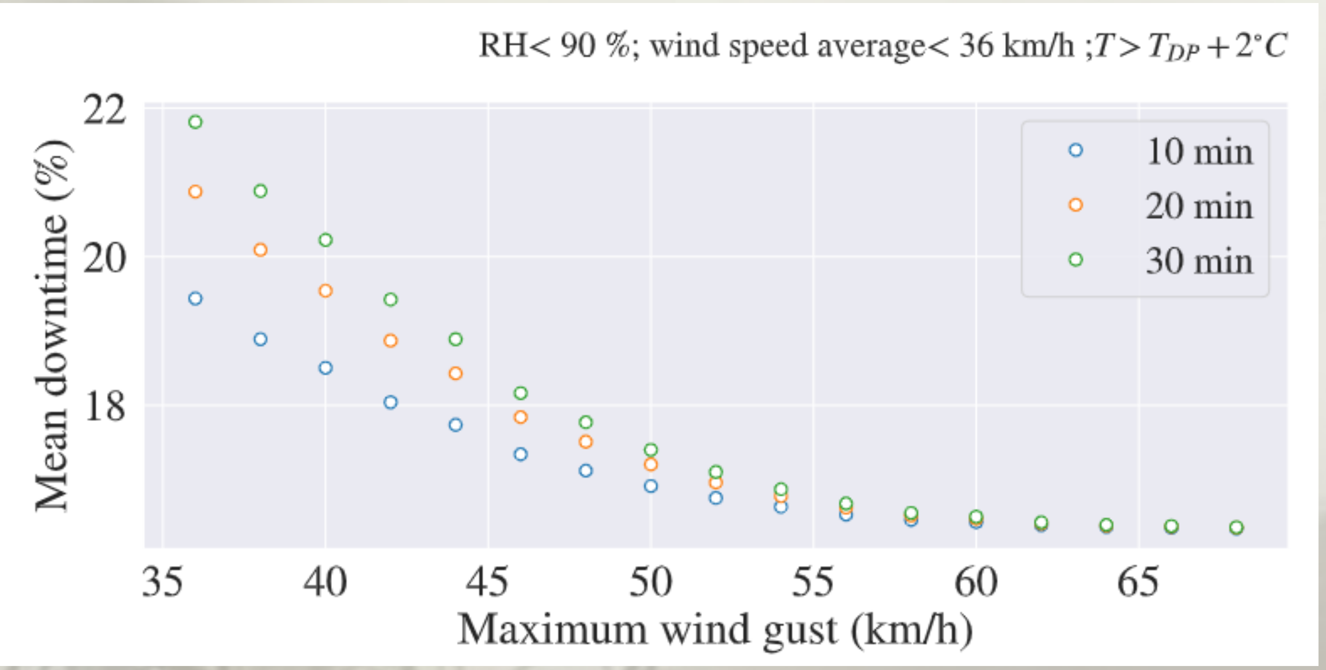
- A new weather data analysis with an emphasis on long-term (linear) change of weather parameters and robustness tests has been created.
- Code available under https://github.com/mgaug/WS-Analysis
- Observe significant long-term trends from 2003-2023 w.r.t. temperature, relative humidity and trade winds.
- In all cases, the effects are (slightly) stronger than anticipated
- Unless non-linear changes of behaviour occur (which depends on a number of tipping points, like the inversion of the Gulf Stream), no big effect on weather downtime is likely.

# Thanks

# Weather downtime

- No hints for degradation of weather downtime found.




- Shorter waiting times after wind gusts can improve downtime by 2-3%
- Robuster telescopes that withstand wind gusts <60 km/h allow to gain 3% observation time.

# Fairification of weather data and publication experience

- Weather data are published under the Findable, Accessible, Interoperable, and Reusable (FAIR) principles
- Data under: https://dx.doi.org/10.5281/zenodo.11279074.
(attached to community https://zenodo.org/communities/magictelescopes/)
- Analysis code under: https://github.com/mgaug/WS-Analysis
- Paper has been submitted to MNRAS.