# Estimation of the spectral aerosol optical depth from broadband surface radiation measurements and quantification of the direct aerosol effect in Germany

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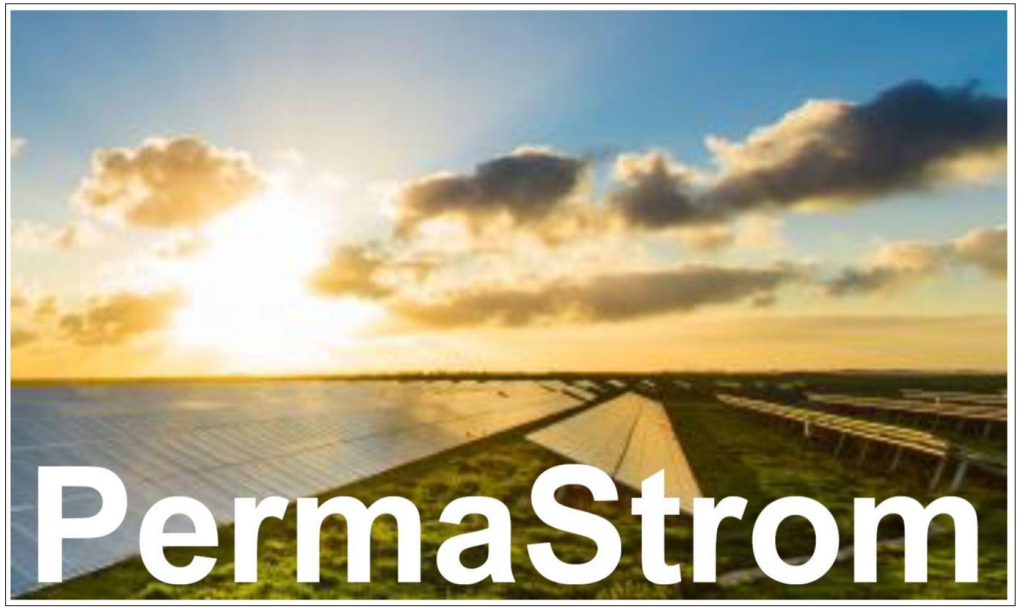
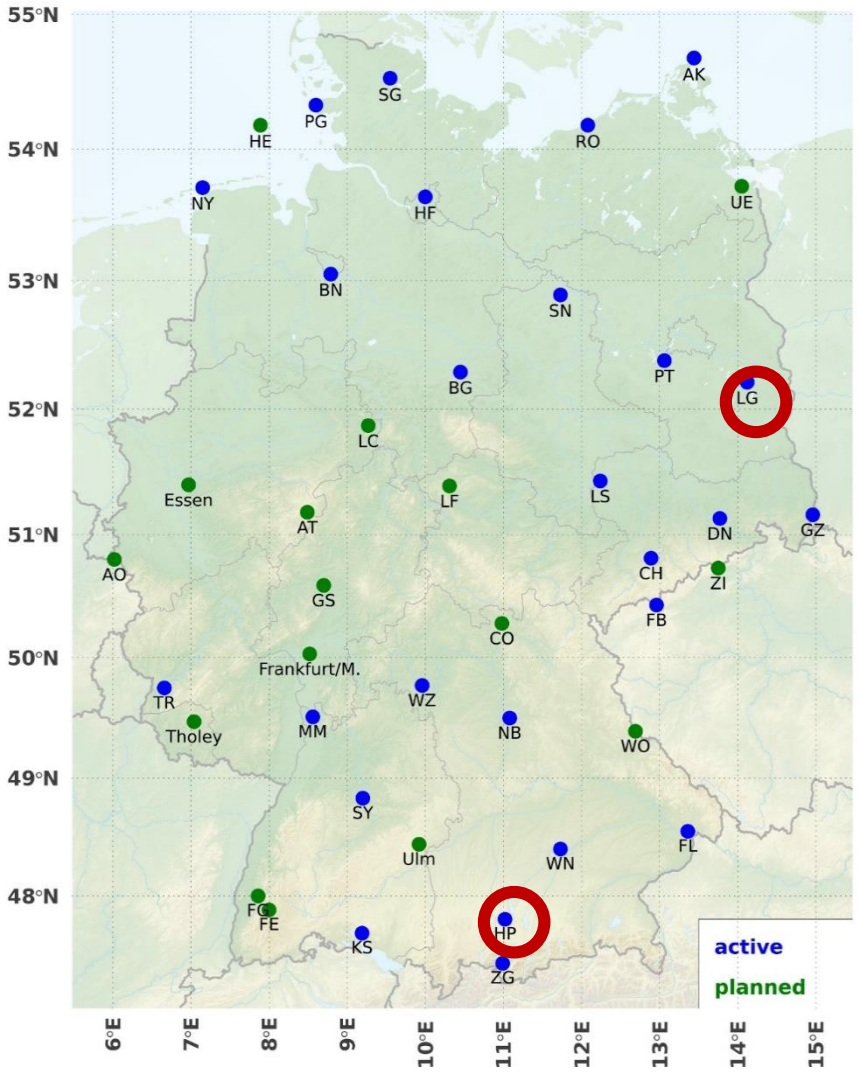
EMS – 2022 Bonn



# Broadband Radiation Network

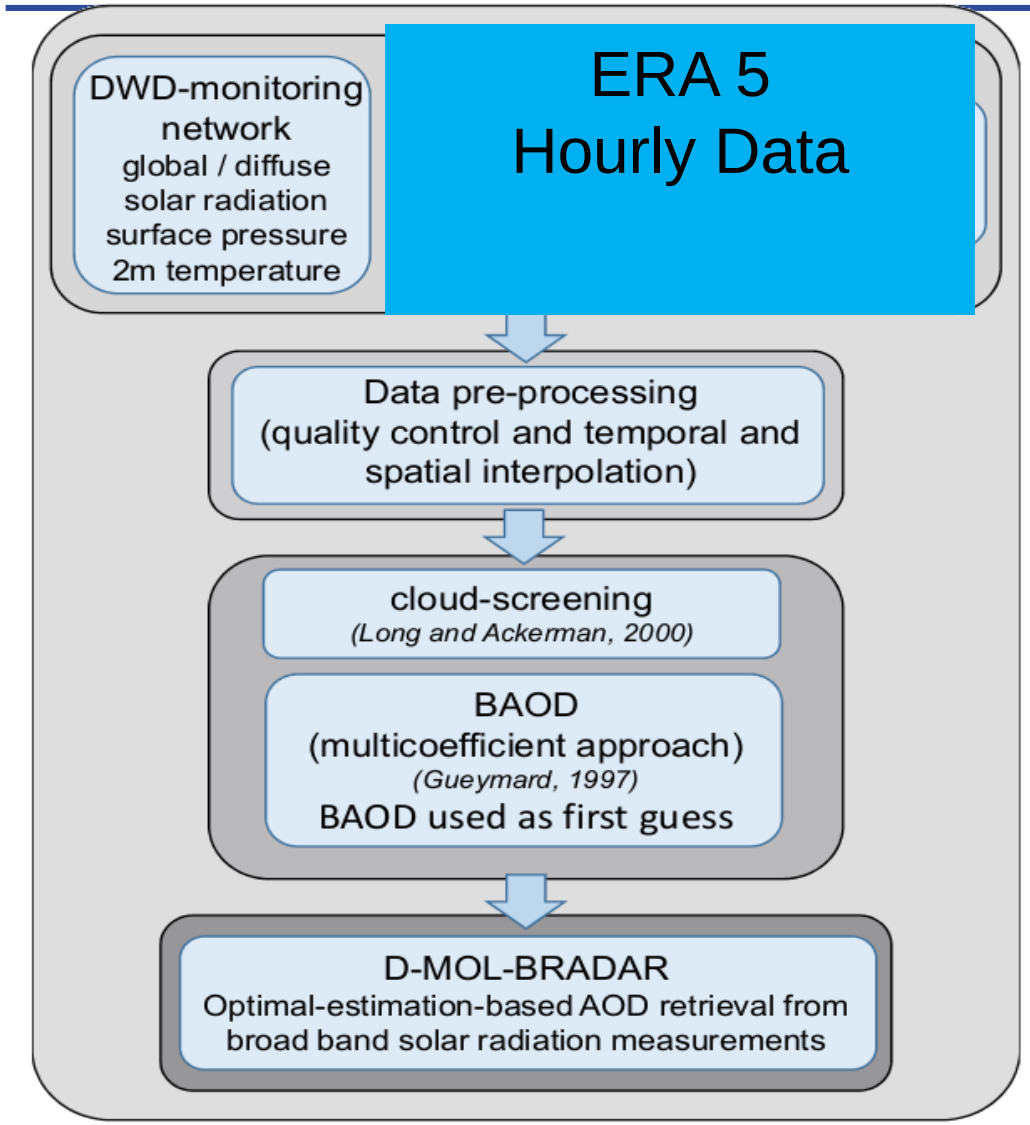


- First Station 1937, since 1993 (1min)
- ~ 30 active stations, 12 in planning
  - 24 used in this study (2008 – 2021)
- Each station is equipped with 2 secondar standard Kipp&Zonen CM11 / CM21 Pyranome



# Broadband AOD 550nm Retrieval



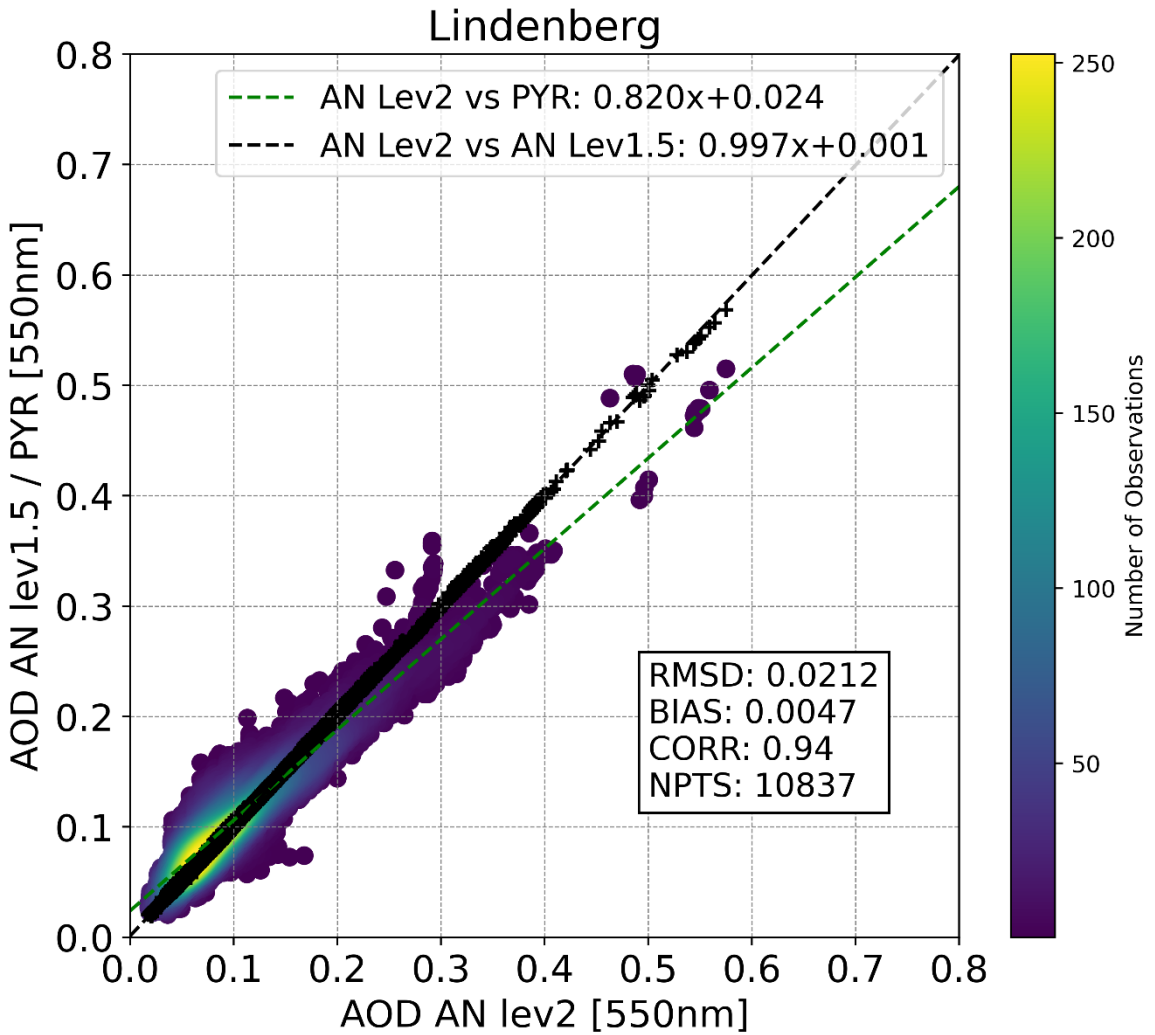


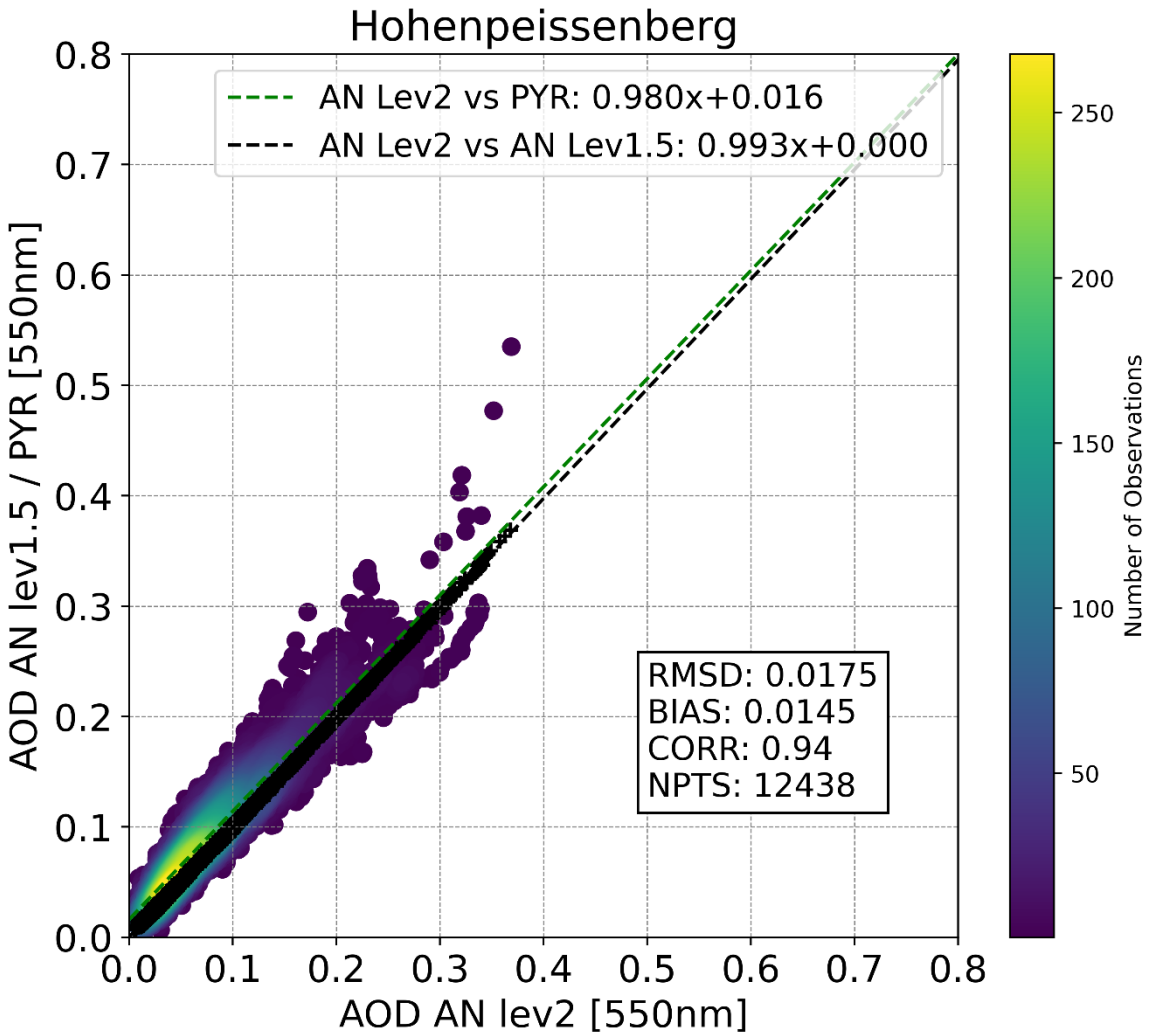

**D-MOL-BRADA:**
Optimal estimation-based algorithm to retrieve the AOD at 550nm from global and diffuse surface radiation observations.
As a forward model we use the radiative transfer code MOMO (matrix-operator model).

$$F(a_{AB}, a_{wa}, a_{sa}, \mathrm{H_2O}, \mathrm{O_3}, \mathrm{p}, \mathrm{sza}) = \mathrm{G}, \mathrm{D}, \mathrm{I}$$

# Broadband AOD 550nm Retrieval vs AERONET





# Method: Estimation of the Direct Aerosol and Cloud Effect



## Direct Aerosol Radiative Effect (D-ARE)

## Cloud Radiative Effect (CLE)

1. **Global horizontal irradiance for atmospheric gas extinction** ($GHI_{sim(gas)}$)

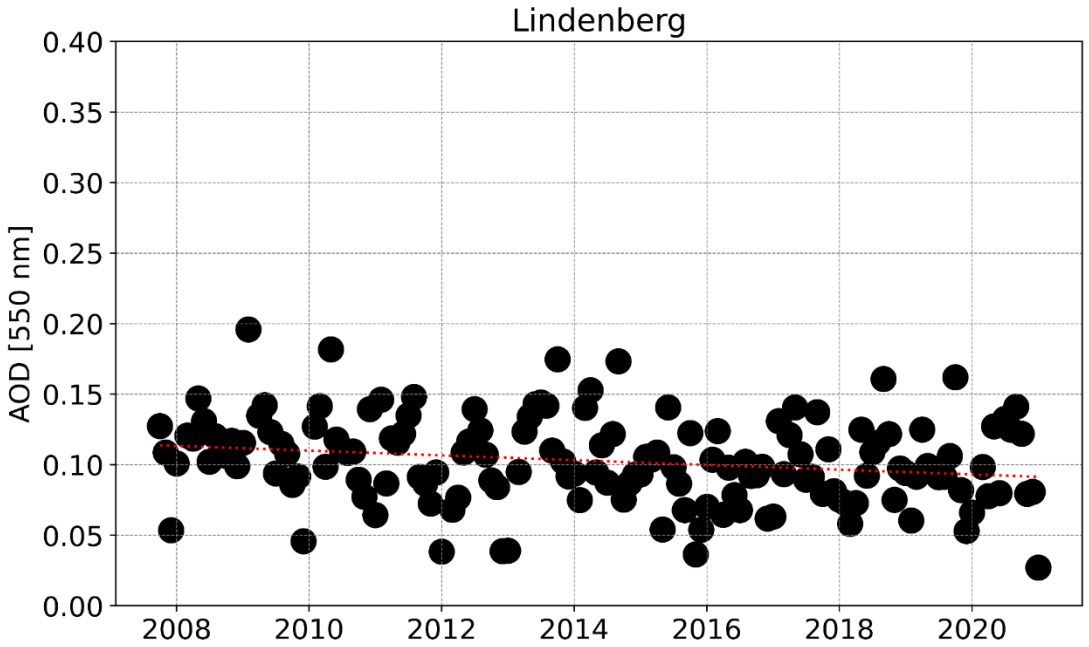
   (ERA5 data are used for water vapor and ozone concentration)

2. **Global horizontal irradiance for atmospheric gase and Aerosol extinction** ($GHI_{sim(gas+\ aerosol)}$)
   - Daily mean AOD (-> retrieved from braodband measurements)
   - Cloudy days an AOD average from the last 10 days with valid clear sky measurements is used

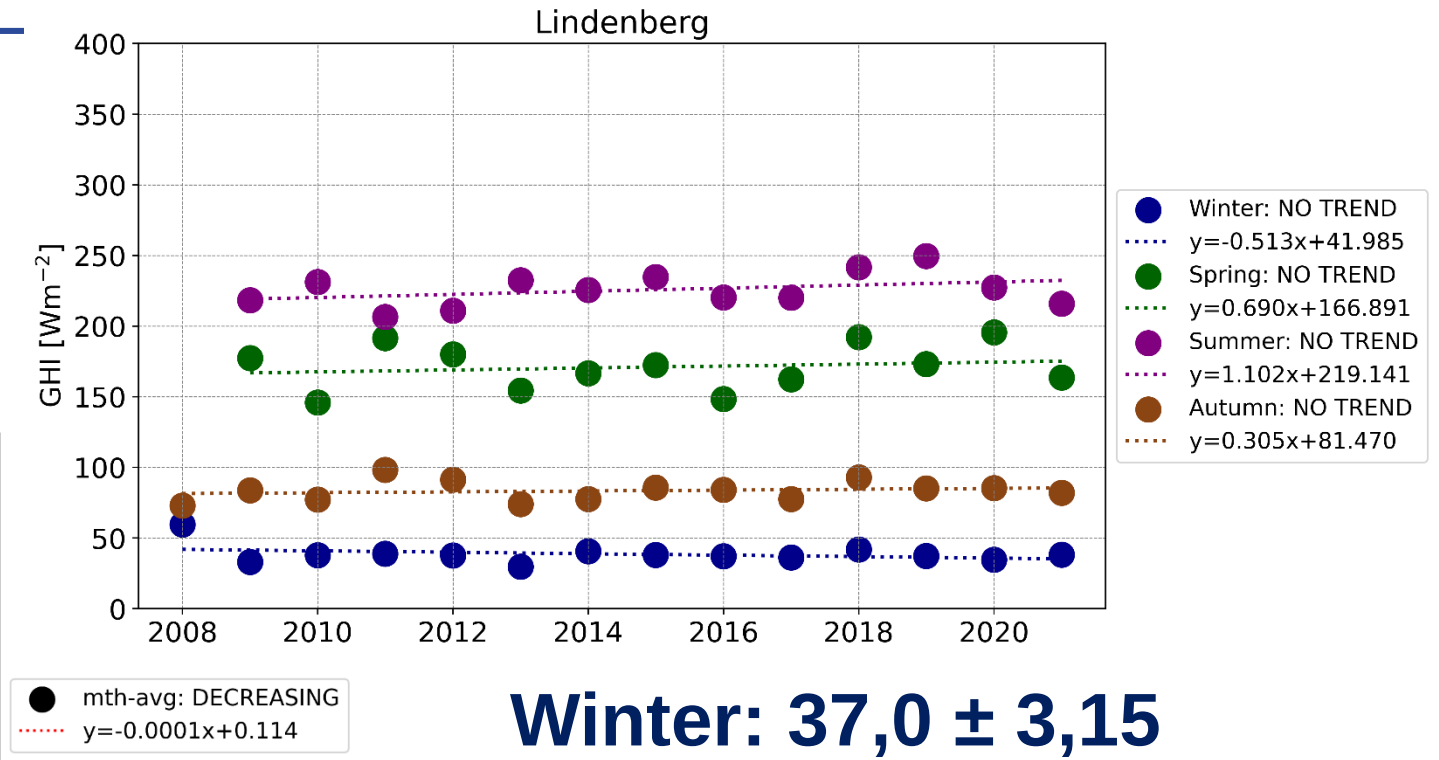
$$\mathbf{D\text{-}ARE = GHI_{sim(gas+\ aerosol)} - GHI_{sim(gas)}}$$

$$\mathbf{CLE = GHI_{meas} - GHI_{sim(gas+\ aerosol)}}$$

# Results: Monthly Mean AOD




**mean: 0,11 ± 0,01**




**Winter: 37,0 ± 3,15**

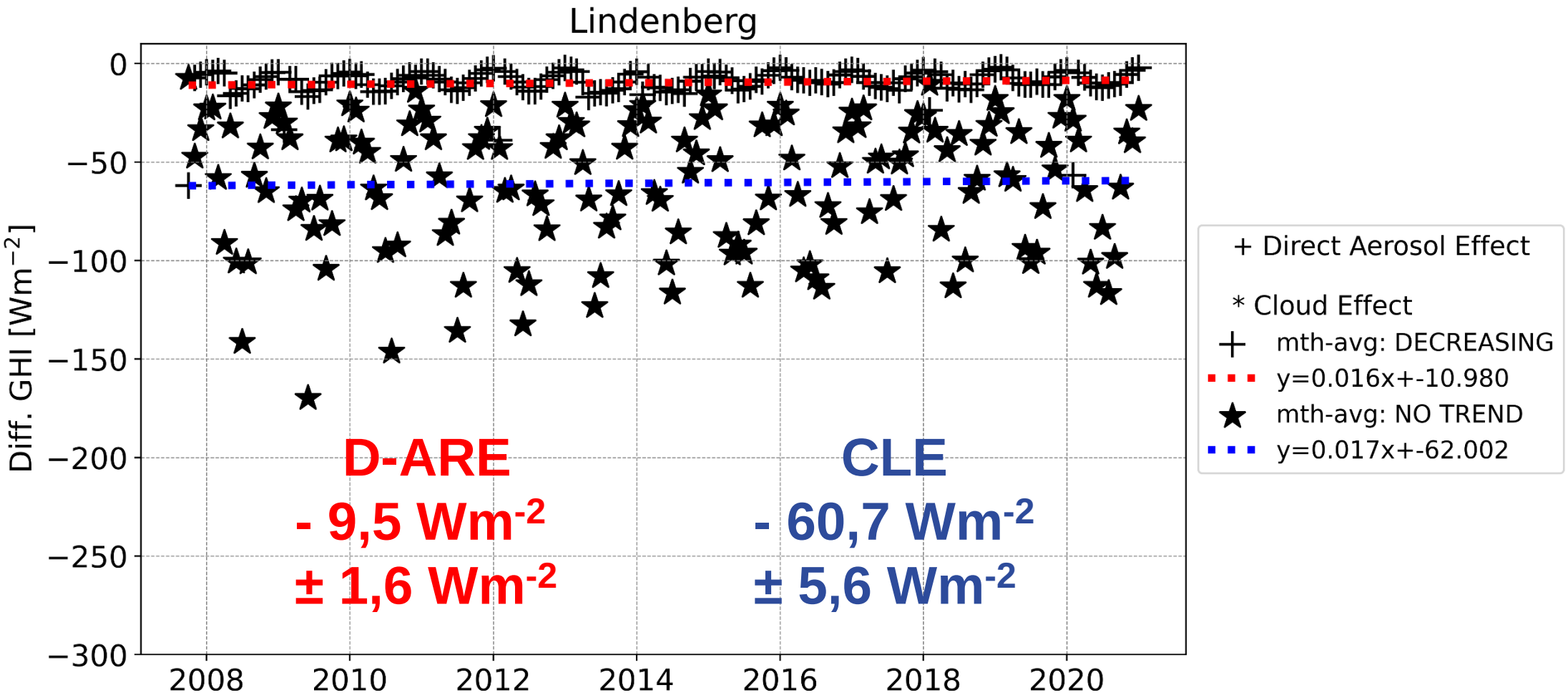
**Spring: 171,0 ± 16,25**

**Summer: 225,7 ± 12,20**

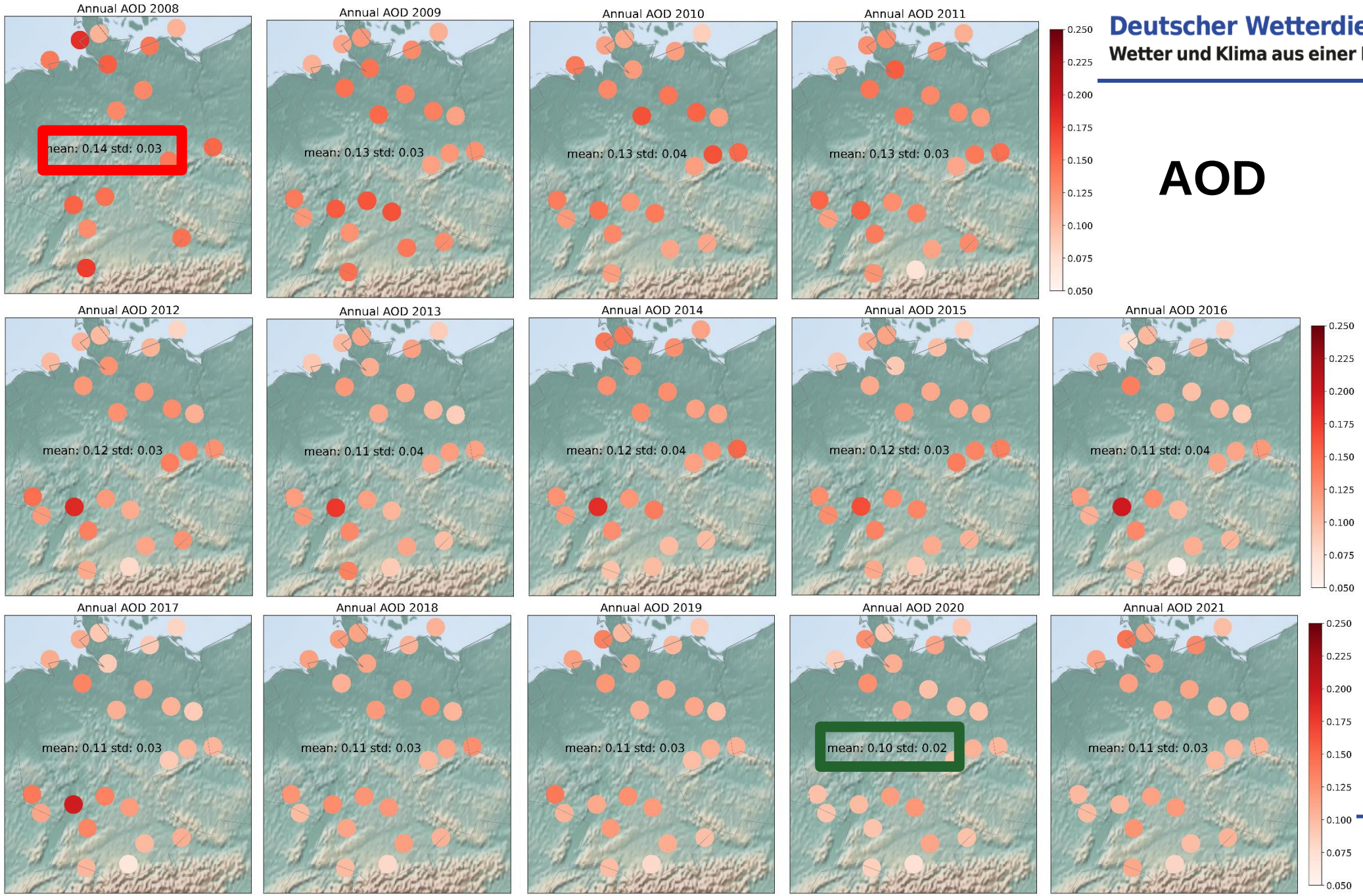
**Autumn: 84,3 ± 6,92**

# Results: Monthly Mean Direct Aerosol and Cloud Effect

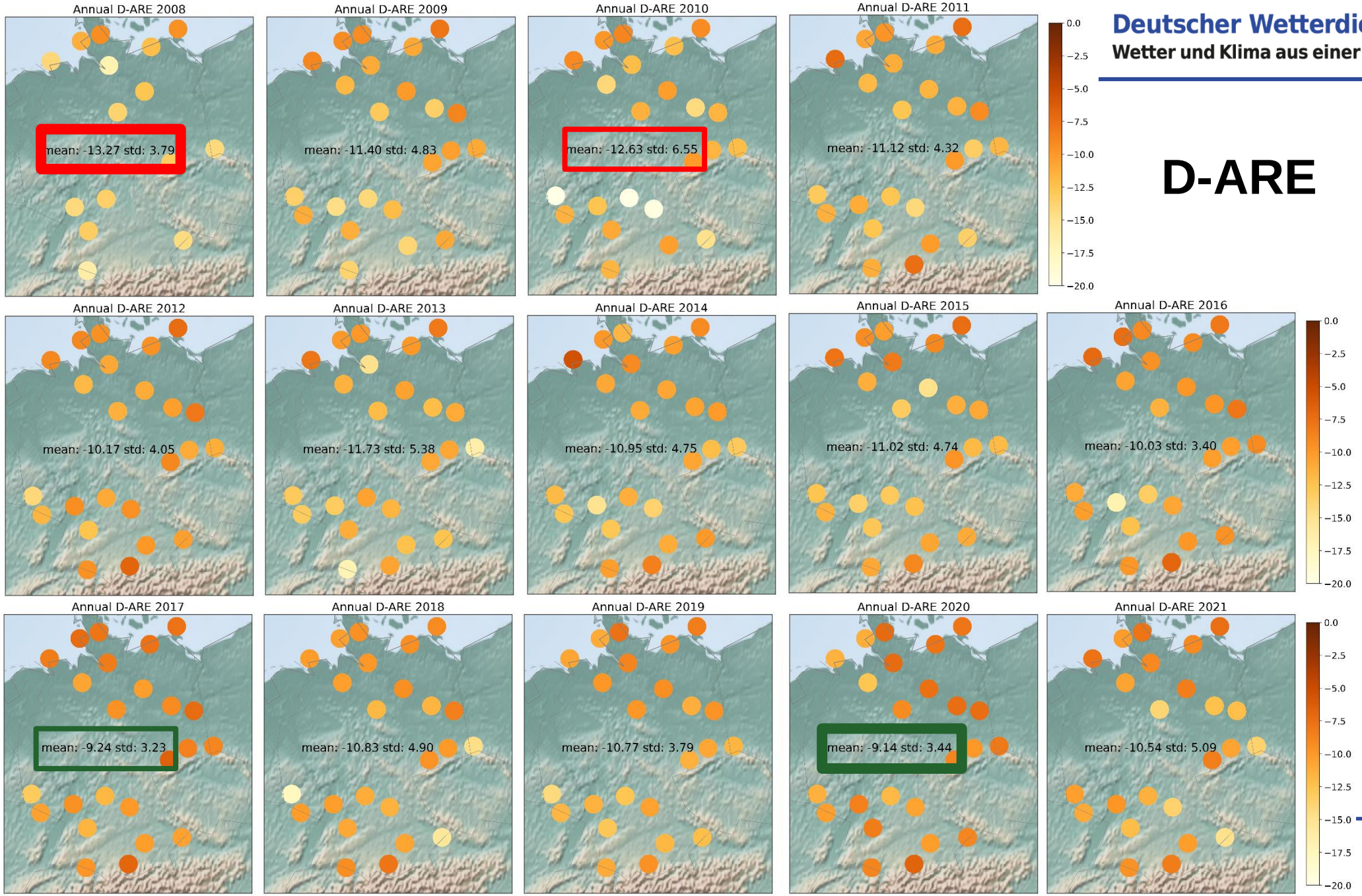




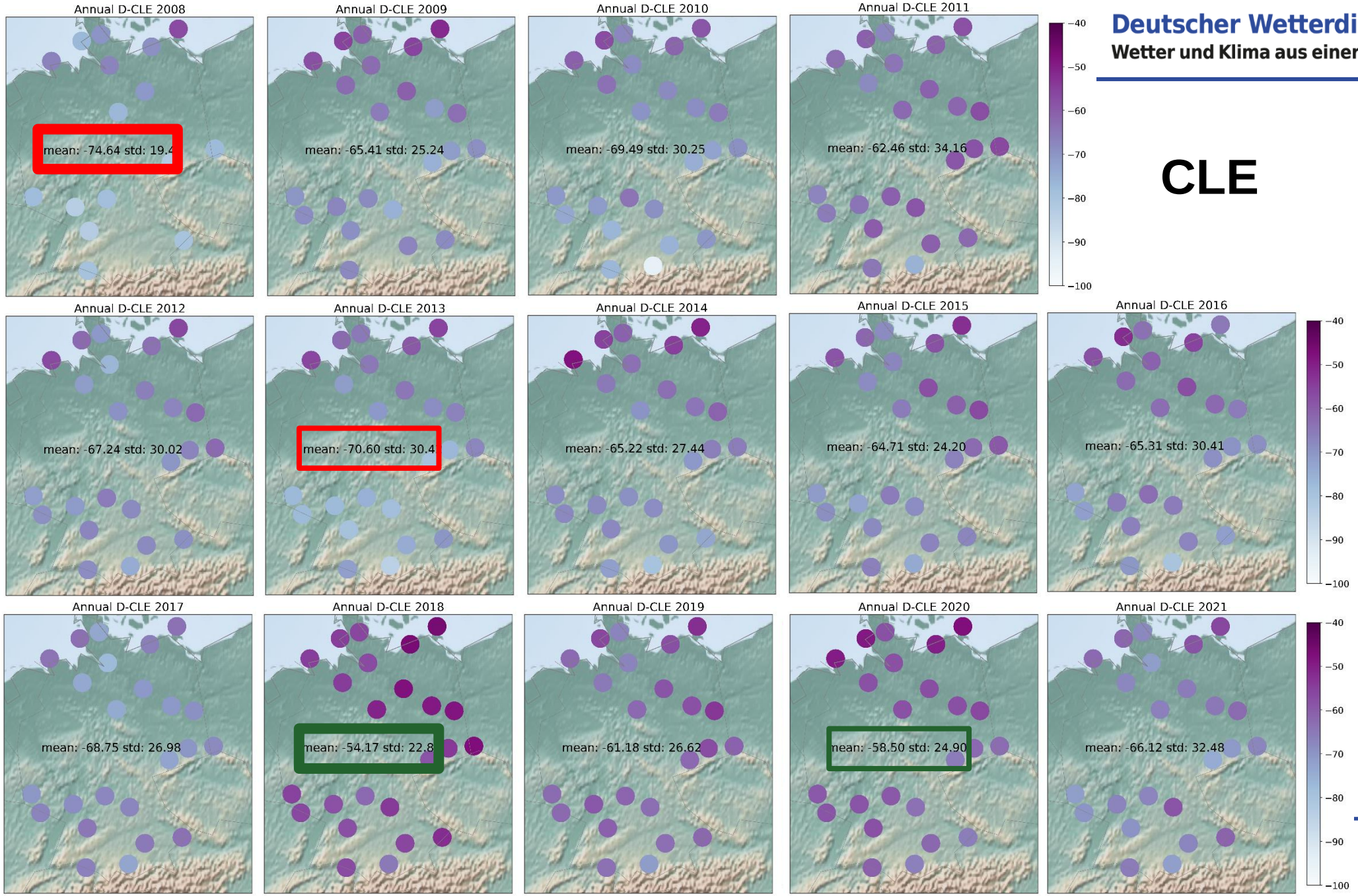
# AOD


Annual AOD 2008
mean: 0.14 std: 0.03
Annual AOD 2009
mean: 0.13 std: 0.03
Annual AOD 2010
mean: 0.13 std: 0.04
Annual AOD 2011
mean: 0.13 std: 0.03
Annual AOD 2012
mean: 0.12 std: 0.03
Annual AOD 2013
mean: 0.11 std: 0.04
Annual AOD 2014
mean: 0.12 std: 0.04
Annual AOD 2015
mean: 0.12 std: 0.03
Annual AOD 2016
mean: 0.11 std: 0.04
Annual AOD 2017
mean: 0.11 std: 0.03
Annual AOD 2018
mean: 0.11 std: 0.03
Annual AOD 2019
mean: 0.11 std: 0.03
Annual AOD 2020
mean: 0.10 std: 0.02
Annual AOD 2021
mean: 0.11 std: 0.03
0.250
0.225
0.200
0.175
0.150
0.125
0.100
0.075
0.050

# D-ARE

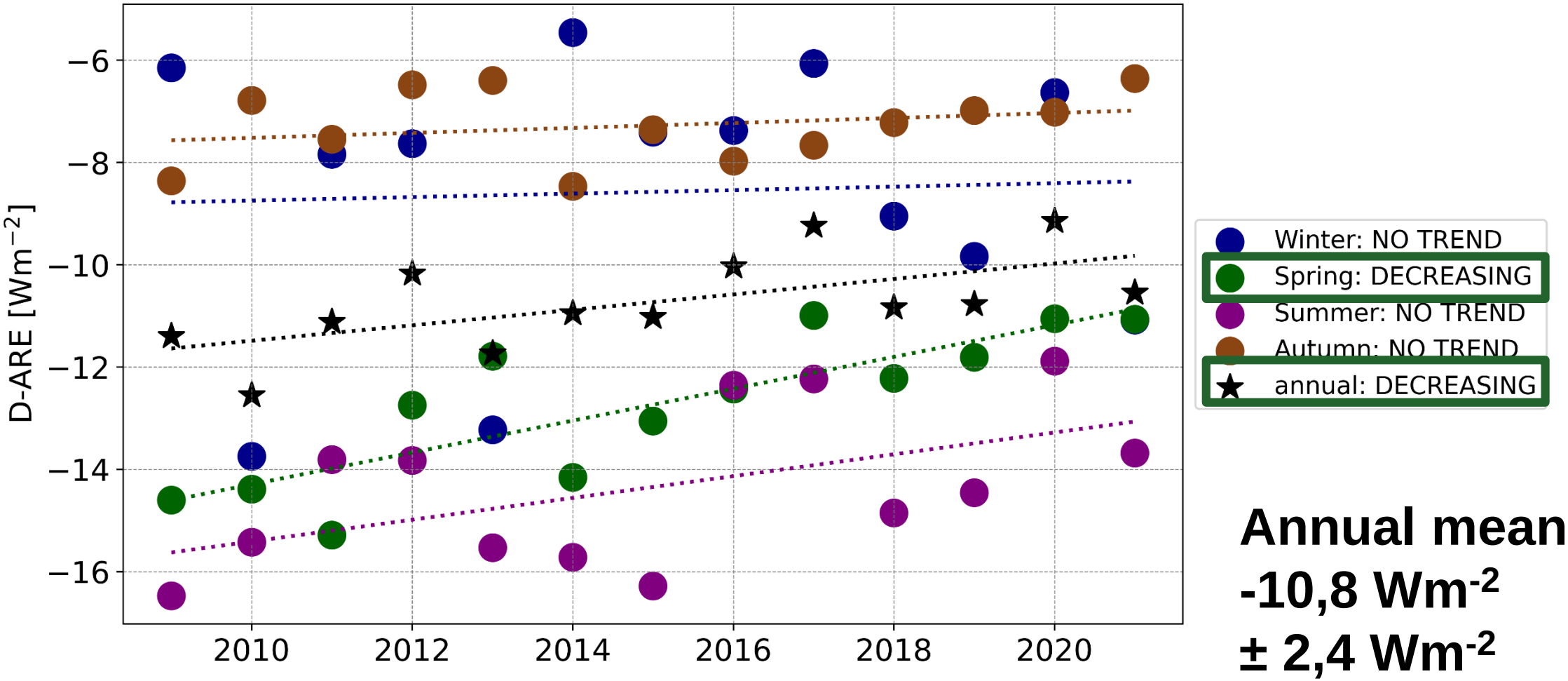

Annual D-ARE 2008
mean: -13.27 std: 3.79
Annual D-ARE 2009
mean: -11.40 std: 4.83
Annual D-ARE 2010
mean: -12.63 std: 6.55
Annual D-ARE 2011
mean: -11.12 std: 4.32
0.0
−2.5
−5.0
−7.5
−10.0
−12.5
−15.0
−17.5
−20.0
Annual D-ARE 2012
mean: -10.17 std: 4.05
Annual D-ARE 2013
mean: -11.73 std: 5.38
Annual D-ARE 2014
mean: -10.95 std: 4.75
Annual D-ARE 2015
mean: -11.02 std: 4.74
Annual D-ARE 2016
mean: -10.03 std: 3.40
Annual D-ARE 2017
mean: -9.24 std: 3.23
Annual D-ARE 2018
mean: -10.83 std: 4.90
Annual D-ARE 2019
mean: -10.77 std: 3.79
Annual D-ARE 2020
mean: -9.14 std: 3.44
Annual D-ARE 2021
mean: -10.54 std: 5.09

# CLE


Annual D-CLE 2008
mean: -74.64 std: 19.4
Annual D-CLE 2009
mean: -65.41 std: 25.24
Annual D-CLE 2010
mean: -69.49 std: 30.25
Annual D-CLE 2011
mean: -62.46 std: 34.16
Annual D-CLE 2012
mean: -67.24 std: 30.02
Annual D-CLE 2013
mean: -70.60 std: 30.4
Annual D-CLE 2014
mean: -65.22 std: 27.44
Annual D-CLE 2015
mean: -64.71 std: 24.20
Annual D-CLE 2016
mean: -65.31 std: 30.41
Annual D-CLE 2017
mean: -68.75 std: 26.98
Annual D-CLE 2018
mean: -54.17 std: 22.8
Annual D-CLE 2019
mean: -61.18 std: 26.62
Annual D-CLE 2020
mean: -58.50 std: 24.90
Annual D-CLE 2021
mean: -66.12 std: 32.48
−40
−50
−60
−70
−80
−90
−100

# Results: Mean Seasonal Direct Aerosol Effect - Germany

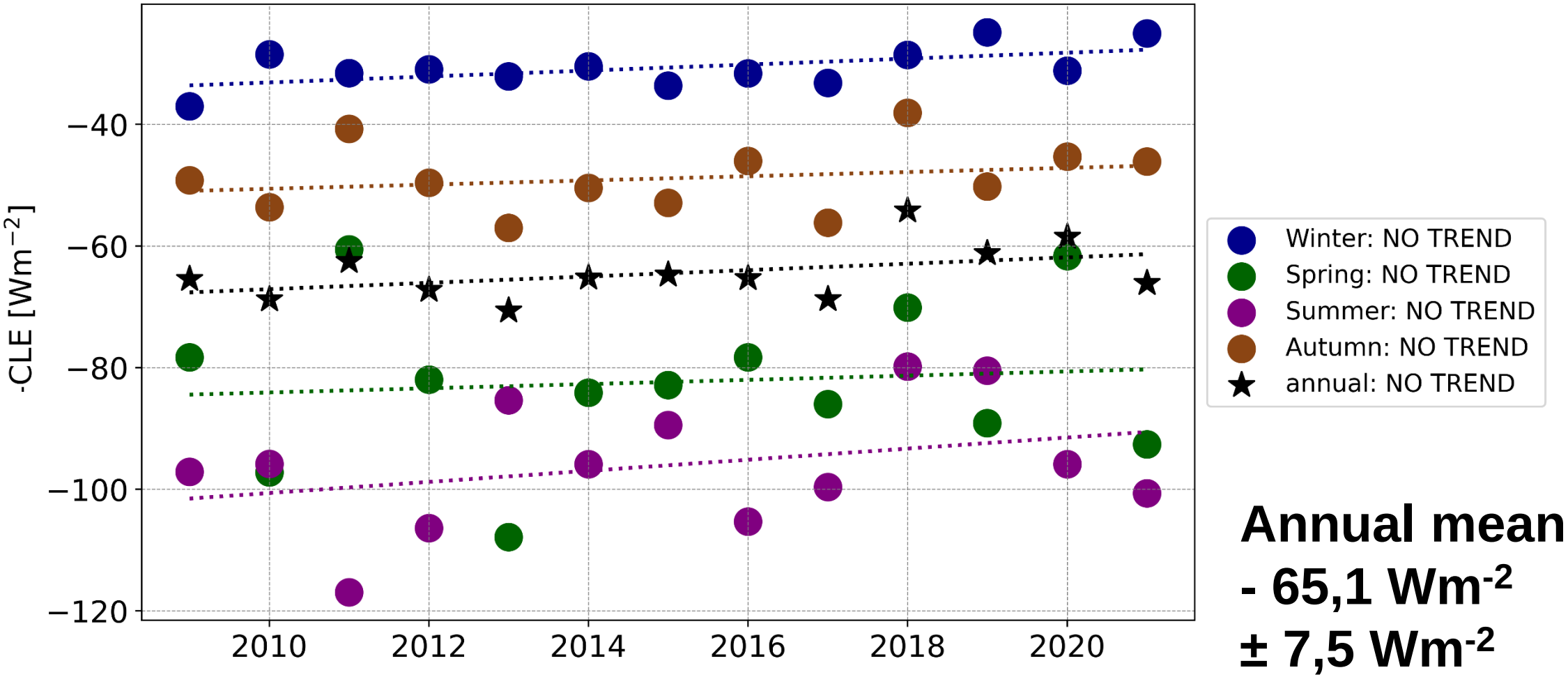





**Annual mean:**
**-10,8 Wm$^{-2}$**
**± 2,4 Wm$^{-2}$**

# Results: Mean Seasonal Cloud Effect - Germany

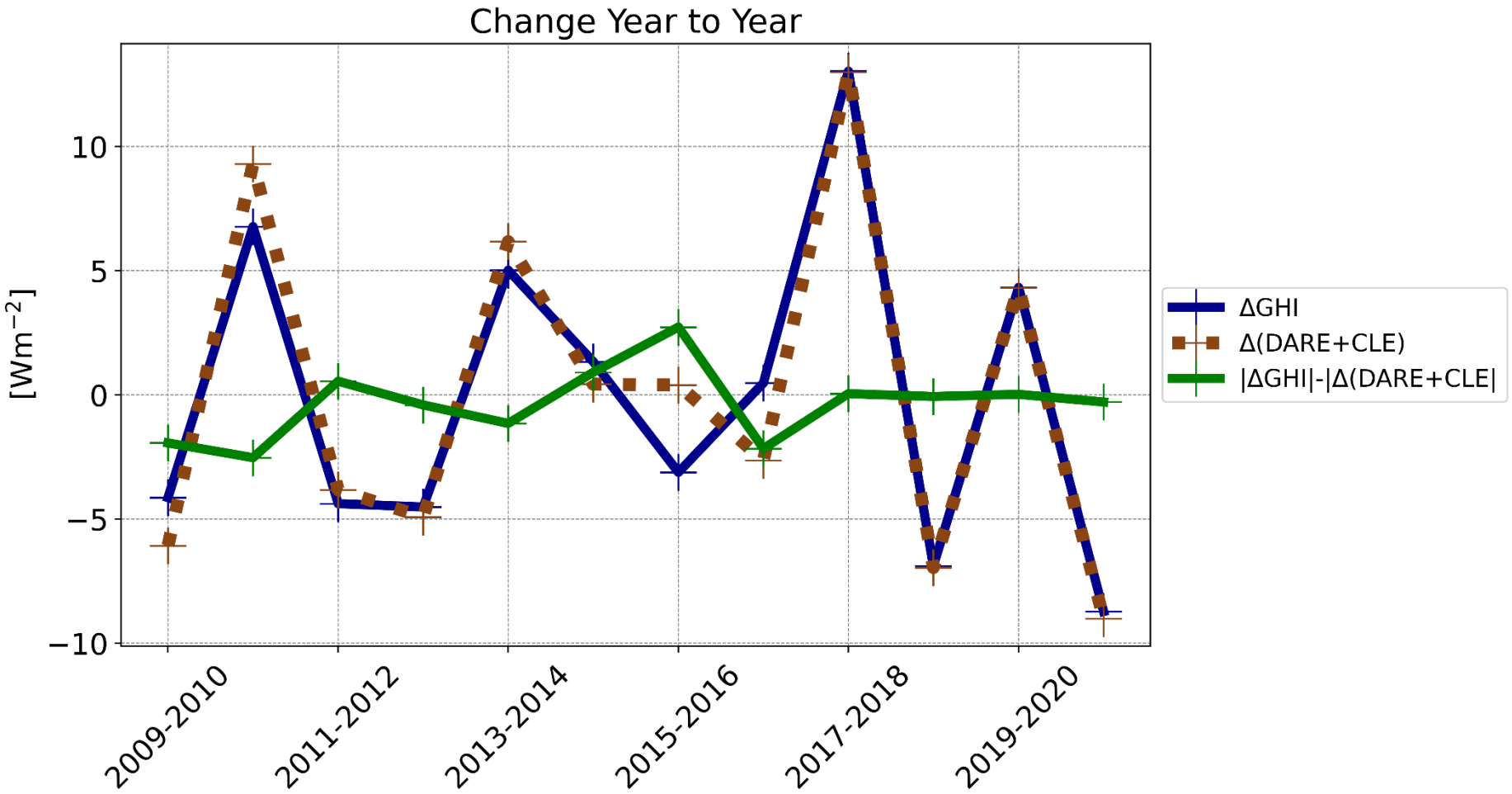





**Annual mean:**
**- 65,1 Wm$^{-2}$**
**± 7,5 Wm$^{-2}$**

# Results: Year to Year Change in GHI vs (D-ARI + CLE)





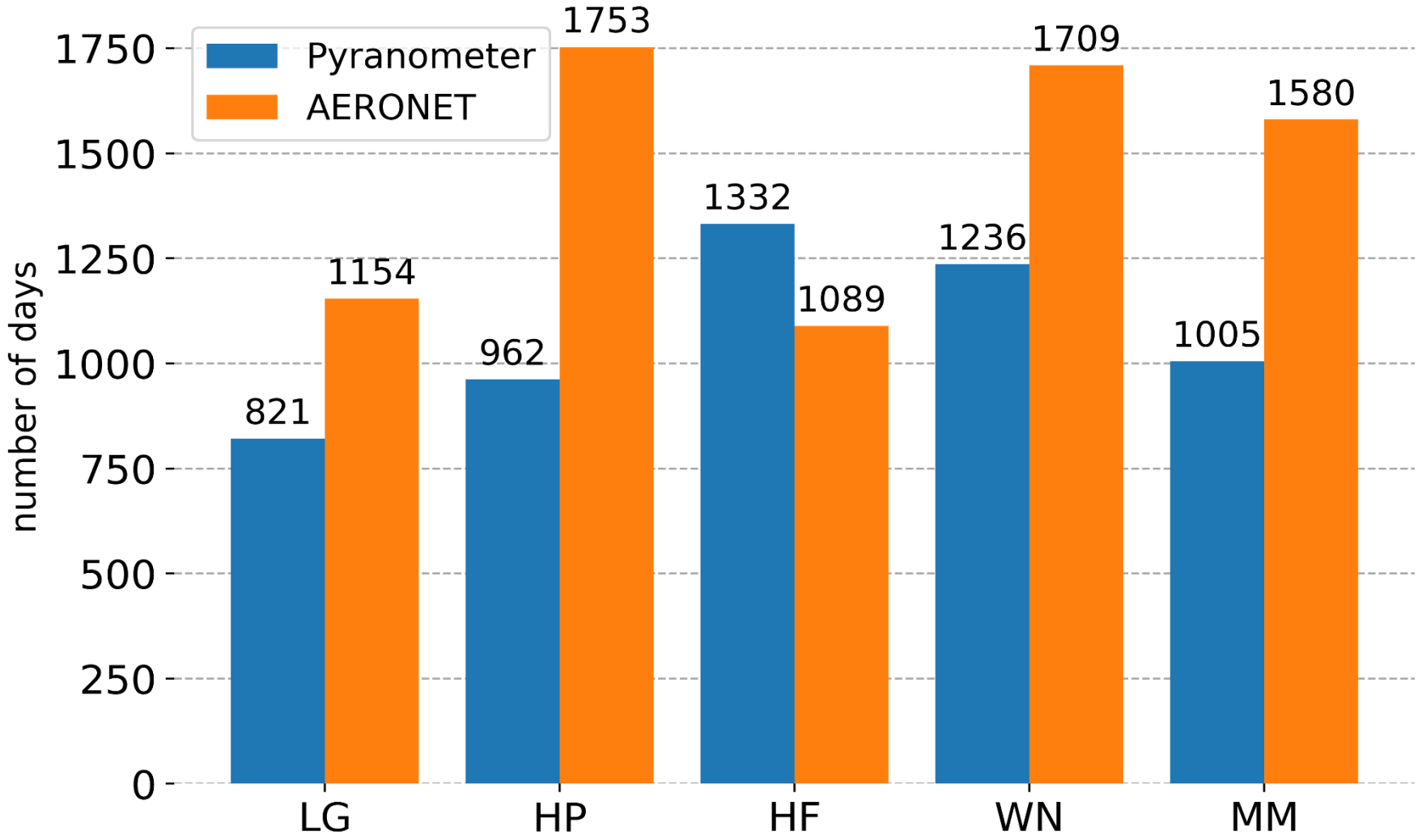
# Summary and Conclusions



- **Estimation of AOD from Broadband radiation is limited to a 99% cloud free atmosphere**
  - instrument is comparatively cheap
  - easy to operate and easy to service
  - high time resolution (1min)
- **The AOD estimated from Broadband radiation is in good agreement with AERONET AOD**
  - small positive bias, underestimation for high AODs and small particles.
- **We found a decreasing trend in the D-ARE over Germany**
  - 10 stations in Spring, 7 stations in Summer and 4 stations in Autumn.
- **No trend was found on the CLE on short wave radiation.**
- **Changes in the GHI can not be fully described by changes in D-ARI and CLE**
  - Optical properties of aerosols may also have changed (size, SSA)
  - Changes in TCWV and other gases need to be considered (missing measurements)

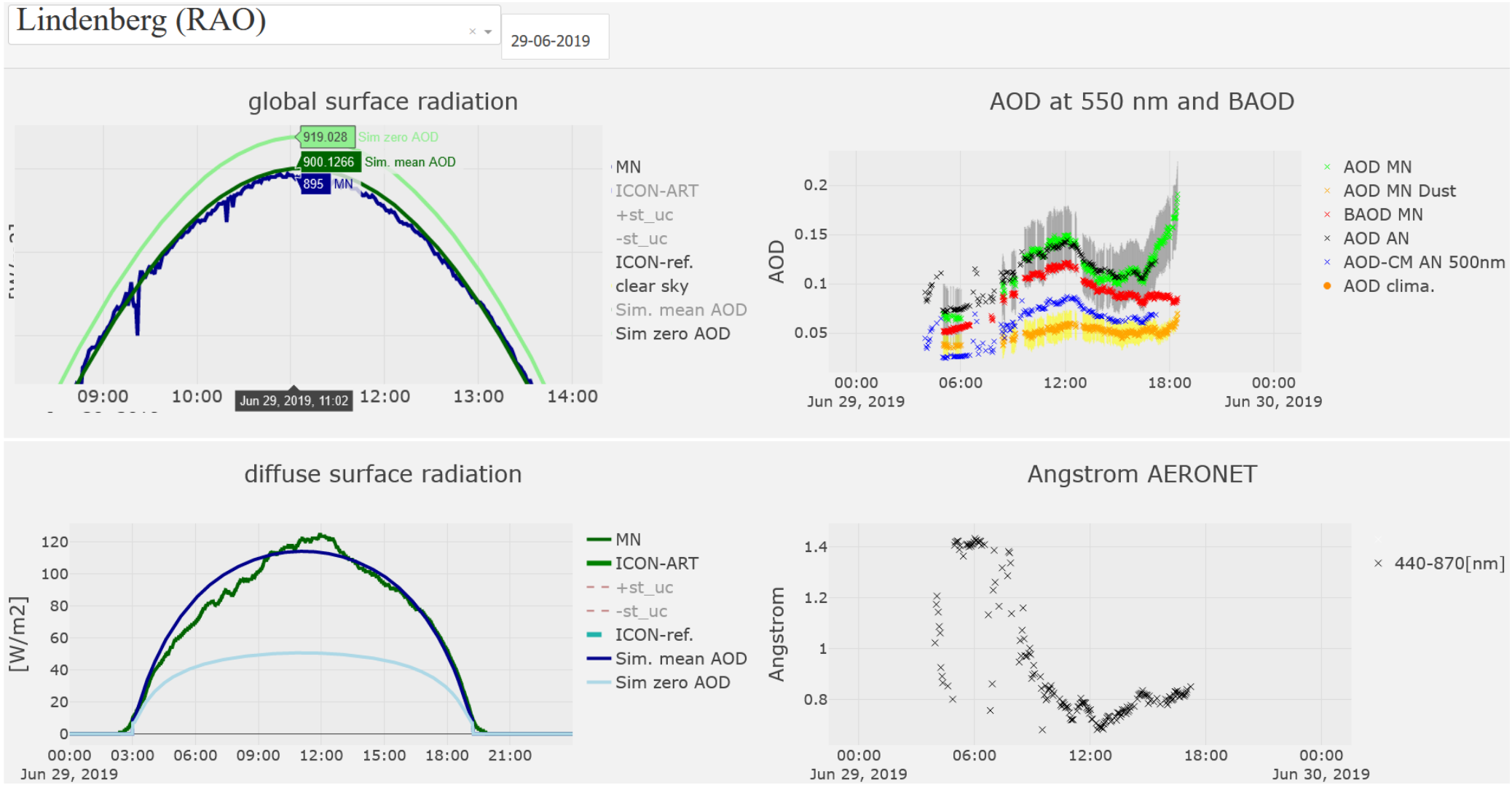
# Broadband AOD 550nm Retrieval vs AERONET





# Method: Estimation of the Direct Aerosol and Cloud Effect





# Results: Trend Analysis on the Seasonal Aerosol Effect