Using causal inference to investigate aerosol influences on the diurnal temperature range

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Motivation

- Diurnal temperature range (DTR):
  $DTR_{day} = Tmax_{day} - Tmin_{day}$
- **DTR impacts human** (e.g., mortality [1]) and **natural health** (e.g., crop yields, vegetation growth [2])
- **Global** mean DTR **decreasing, but European trend reversed** in the 1990s ([3], compare Fig. 1)
- **Changes in anthropogenic aerosol emissions proposed as a driver** of this observed variability [4,5]
- **Anthropogenic contribution is difficult to quantify** due to large uncertainties in climate models ([5,6,7,8], see Fig. 1 and 2)
- Here: use of **novel causal inference methods to investigate aerosol-related drivers** of European Summer (MJJA) DTR

→ **Research Question:** Are aerosols a driver of European Summer DTR?

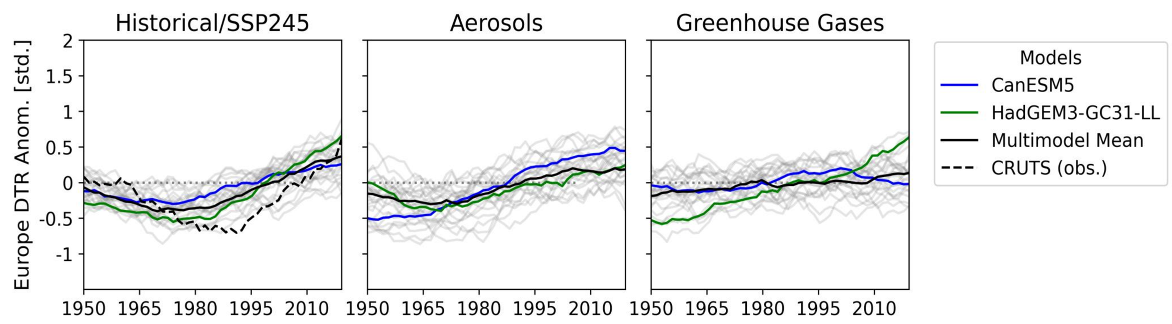

Fig. 1: Observed (CRUTSv4.06 [12]) and modelled European Summer DTR anomalies (rel. to 1950-2020) for CMIP6 historical/SSP245- (ALL) and single-forcing (aerosols and greenhouse gases) simulations [9,10,11].

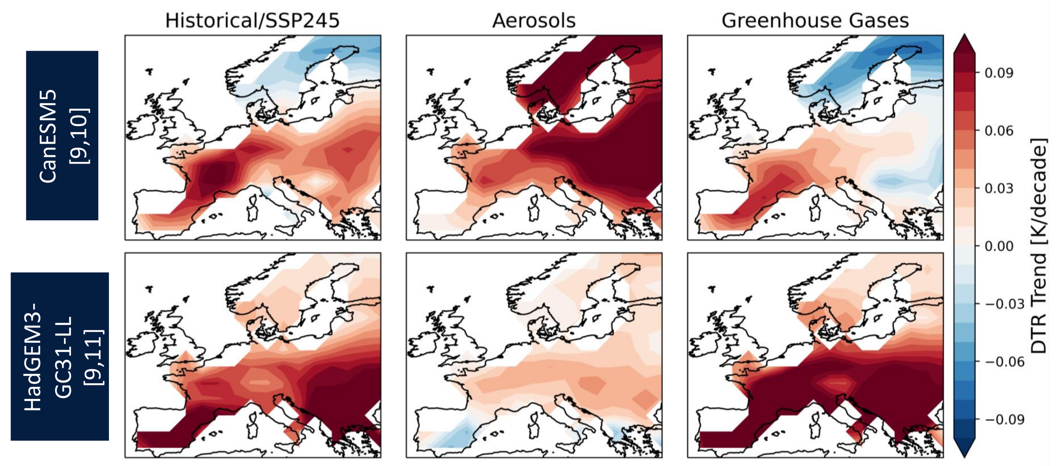

Fig. 2: European Summer DTR trends (1950-2020) for CMIP6 historical/SSP245 (ALL) and single-forcing (aerosols and greenhouse gases) simulations [9].

Causal Inference

Causal Discovery using PCMCI+ algorithm [13,14,15]:

- Reconstruct an underlying time-dependent system $X_t = (X_t^1, \ldots, X_t^n)$ described through the structural causal model (SCM)

$$X_j(t) := f_j(pa(X_j(t)), U^j(t)) \overset{\text{if linear}}{=} \sum_{X_i(t-l) \in pa(X_j(t))} \alpha_{X_i,X_j,l_i} \times X_i(t-l_i) + U^j(t) \text{ for j} \in [1:n]$$

where f_j is linear function, $pa(X^j_t)$ the direct causal parents and U^j_t an independently distributed noise variable

- $\alpha_{xi,xj,li}$ describes the direct (linear) causal effect of X_i on X_j at lag l_i

Causal Effect Estimation [14,16]:

- Total linear causal effect $\beta_{x,y}$ of X on Y estimated through Wright's method:

$$\beta_{X,Y} = \sum_{\substack{\text{causal}\\ \text{paths}\\ \text{from } X \text{ to } Y}} \prod_{\substack{\text{link } X_i \to X_j\\ (\text{lag } l_i)\\ \text{in path}}} \alpha_{X_i,X_j,l_i}$$

Discovered Causal Graph

Displayed Processes [22,23,24]:
(1) Aerosol cloud interactions (ACI)
(2) Blocking of incoming solar shortwave (SW) radiation
(3) Incoming SW radiation warming surface temperature during day
(4) Non-radiative cloud processes (e.g., precipitation) cooling the surface
(5) Blocking of outgoing longwave (LW) radiation warming at night
(6) Aerosol radiative interactions with SW (ARI)
(7) ARI with outgoing LW radiation
(8) Tmin and Tmax influencing each other, i.e., autocorrelation
(9) Cooling during a clear night (confounding due to coarse temporal resolution)

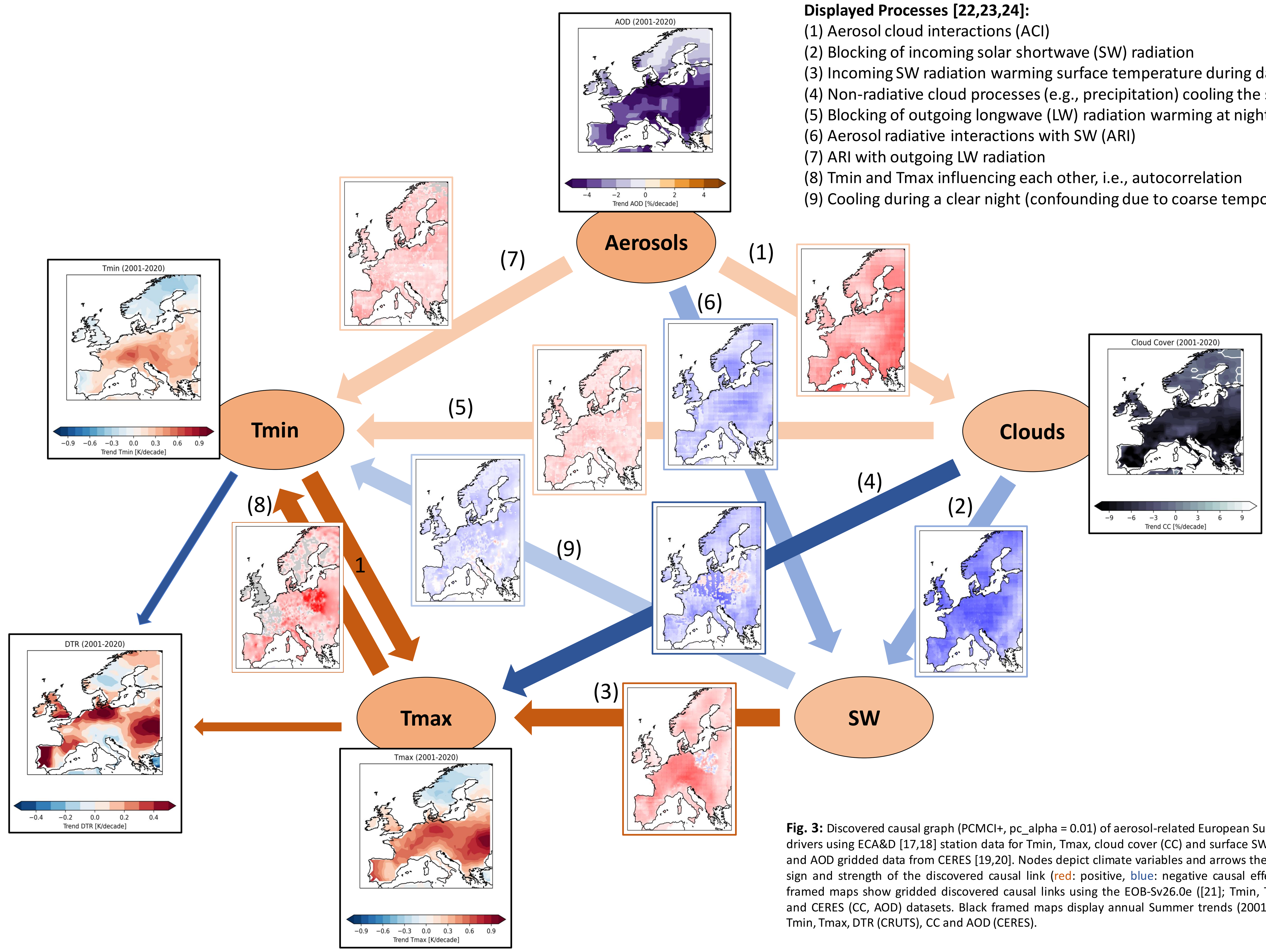

Fig. 3: Discovered causal graph (PCMCI+, pc_alpha = 0.01) of aerosol-related European Summer DTR drivers using ECA&D [17,18] station data for Tmin, Tmax, cloud cover (CC) and surface SW radiation and AOD gridded data from CERES [19,20]. Nodes depict climate variables and arrows the direction, sign and strength of the discovered causal link (red: positive, blue: negative causal effect). Color framed maps show gridded discovered causal links using the EOB-Sv26.0e ([21]; Tmin, Tmax, SW) and CERES (CC, AOD) datasets. Black framed maps display annual Summer trends (2001-2020) for Tmin, Tmax, DTR (CRUTS), CC and AOD (CERES).

Estimated Causal Effects and Trends

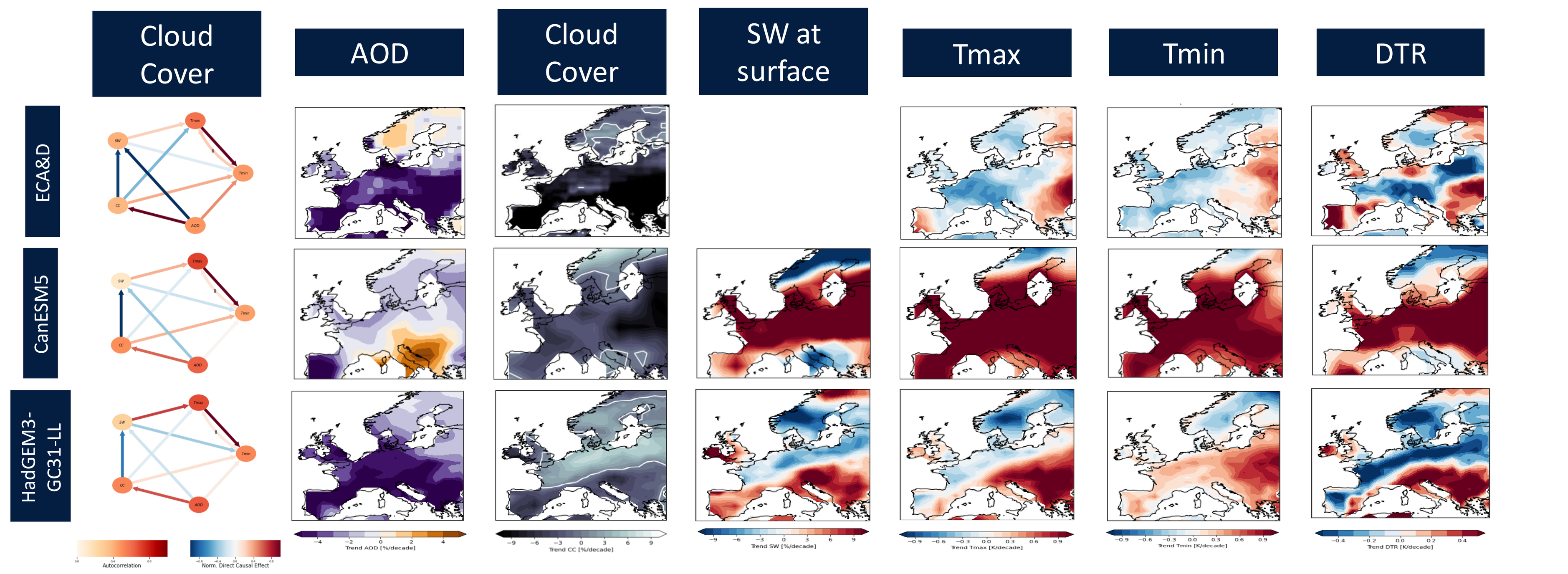

Fig. 4: Comparison of estimated causal effects (Wright) between observations and CMIP6 historical (ALL-forcing) simulations (CanESM5 and HadGEM3-GC31-LL). Additionally, European Summer trends (2001-2014) for AOD, CC, SW, Tmax, Tmin and DTR are shown.

Outlook

Effective Radiative Forcing Estimation of ACI and ARI impacts on Summer SW:

Using $\Delta AOD = AOD_{PD} - AOD_{PI}$ = [0.02;0.04] from [22] and estimated direct causal effects using observations for the causal graph displayed above we estimate:

ERF_{ACI-SW} = 0.56*-123.6 W/m² * [0.02;0.04] = [-2.8;-1.4] W/m²
ERF_{ARI-SW} = -64.7 W/m² * [0.02;0.04] = [-2.6;-1.3] W/m²

ERF estimates from [22]: ERF_{ACI} = [-2.65;-0.07] W/m² and ERF_{ARI} = [-0.71;-0.14] W/m²

BUT: Are causal effects constant in time and what does is mean for estimating ERF?

$$ERF_{ACI-SW} = \alpha_{AOD,CC,0} \cdot \alpha_{CC,SW,0} \cdot \Delta AOD = \frac{\delta CC}{\delta AOD} \cdot \frac{\delta SW}{\delta CC} \cdot \Delta AOD$$

$$ERF_{ARI-SW} = \alpha_{AOD,SW,0} \cdot \Delta AOD = \frac{\delta SW}{\delta AOD} \cdot \Delta AOD$$

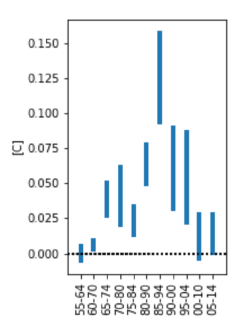

Fig. 5: $\alpha_{AOD,Tmin,0}$ for increasing 10-year slices between 1955 and 2014 for CanESM5 historical simulations.

Main Findings

- GHG not the only driver of DTR, **aerosols identified to impact European Summer DTR** through their direct (ARI) and indirect (ACI) effects
- Discovered causal graph agrees with literature
- **Estimated causal effects** for the discovered causal graph **agree in sign between observations and CMIP6 models**
- Differences in causal effect strength exist between models

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