Using uncertainty-aware machine learning models to study aerosol-cloud interactions

Maëlys Solal, Andrew Jesson, Yarin Gal, Alyson Douglas

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Motivation

Aerosol-cloud interactions are a main sources of uncertainty of global climate models

- **Climate change** is one of the major challenges of our time
- We use **climate models** are used to understand future projections due to climate change
- But their predictions come with **uncertainties**, arising from being unable to explicitly model small-scale interactions, such as **aerosol-cloud interactions** [1 2]

1. Olivier Boucher et al. "Clouds and Aerosols". In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Ed. by T.F. Stocker et al. Cambridge University Press, 2013, pp. 571–658.
2. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Ed. by V. Masson-Delmotte et al. Cambridge University Press, pp. 3–32

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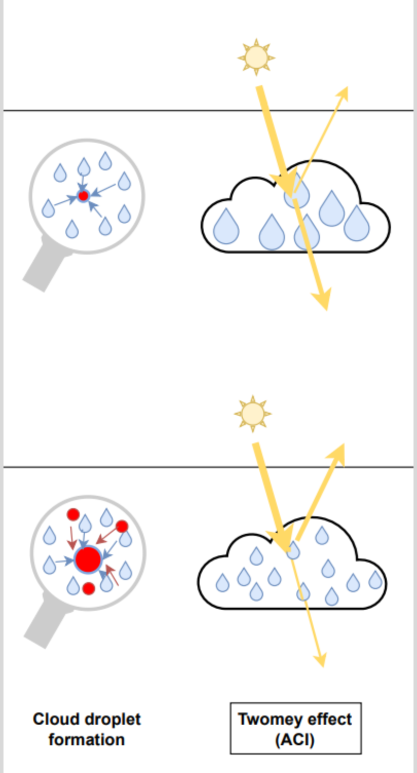
Aerosol-Cloud Interactions (ACI)

Use causal ML to estimate ACI and compare these estimates to that of global climate models



Twomey effect (ACI)

- Aerosol (in the form of pollution) enters the atmosphere, eventually interacts with a cloud, leading to ACI [3]

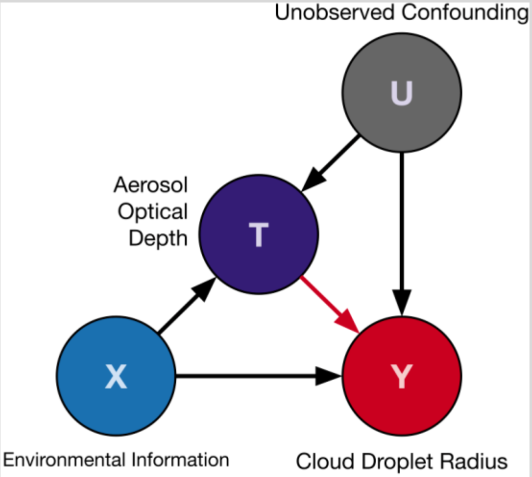
1. Aerosol particles activating as cloud droplet nuclei
2. Increasing the number of cloud droplet within the cloud
3. Reducing the mean radius of cloud droplet
4. Increasing the cloud's brightness
5. Cloud reflecting more incoming sunlight

- ACI are a net cooling process, and offset some fraction of warming due to greenhouse gases

3. Twomey, S. J. A. E. "Pollution and the planetary albedo." Atmospheric Environment (1967) 8.12 (1974): 1251-1256.

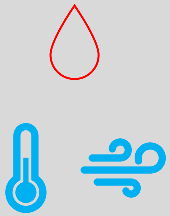
Methods

Reframe the problem of ACI as a treatment and outcome with confounding



1. Causal graph of ACI

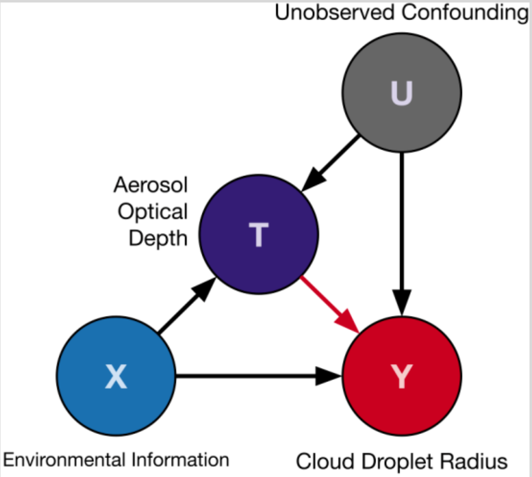
- **Treatment T**: aerosol optical depth (a proxy for aerosol)
- **Outcome Y**: cloud droplet radius
- **Measured confounding X**: meteorological proxies (e.g. temperature, winds, humidity)
- **Unmeasured confounding U** (e.g. humidity causing aerosol swelling and altering cloud properties)



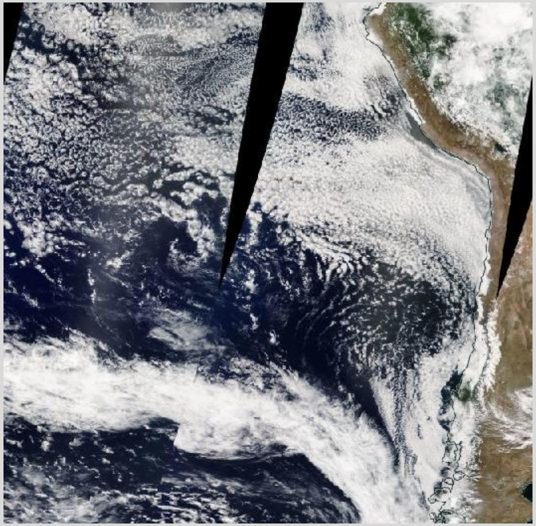
Note: **confounding variables** have an impact on the results of a statistical test but are not the variables that causal inference is studying

Methods

Use satellite data from the Atlantic and the Pacific



1. Causal graph of ACI

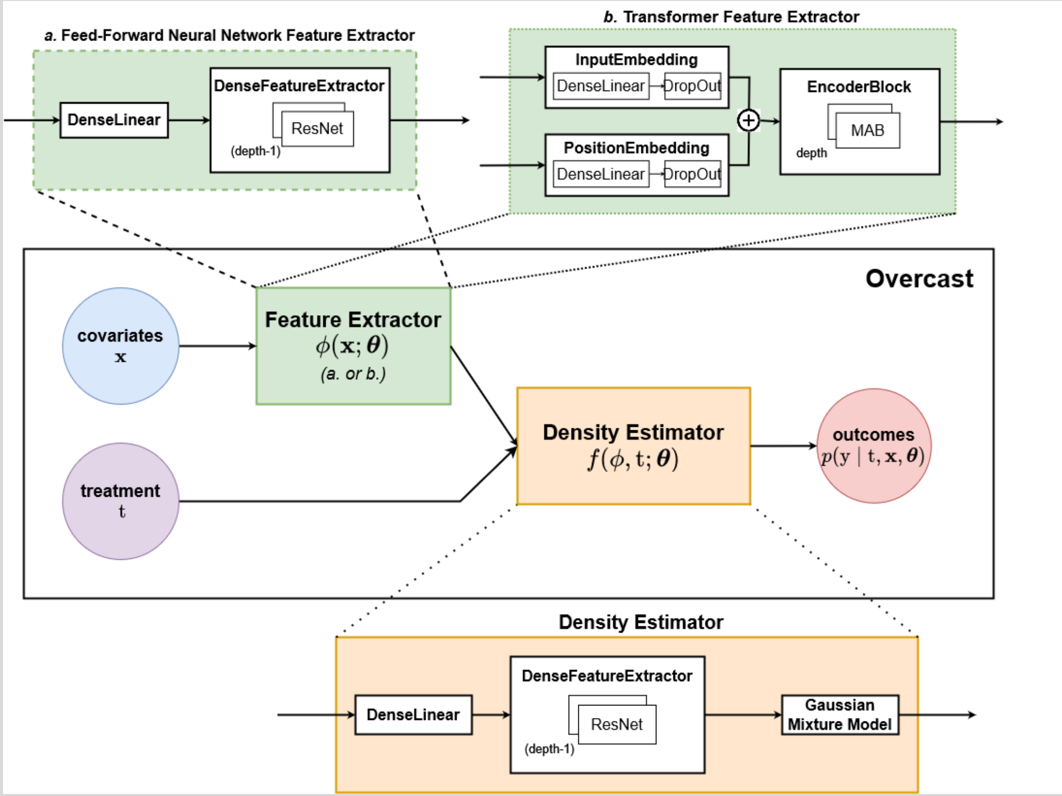


2. Satellite data from the Atlantic and the Pacific

Methods

Use uncertainty-aware ML model to identify the treatment effect

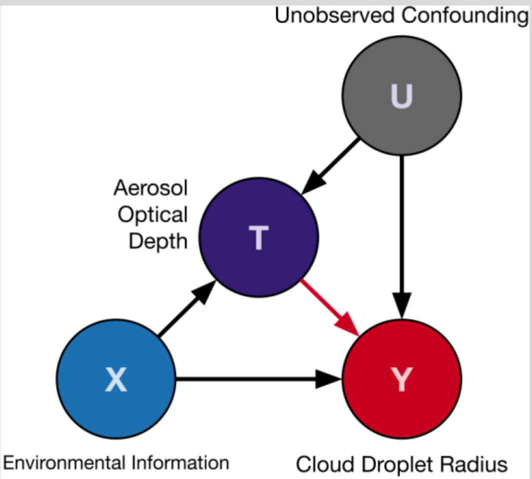
- Overcast is used to identify the conditional average potential outcome (CAPO) from the observational distribution
- Allows to account for unobserved confounding through the parameter Λ



3. Uncertainty-aware ML model (Overcast) [4]

4. Andrew Jesson et al. Scalable sensitivity and uncertainty analysis for causal-effect estimates of continuous-valued interventions. October 2022.

Methods



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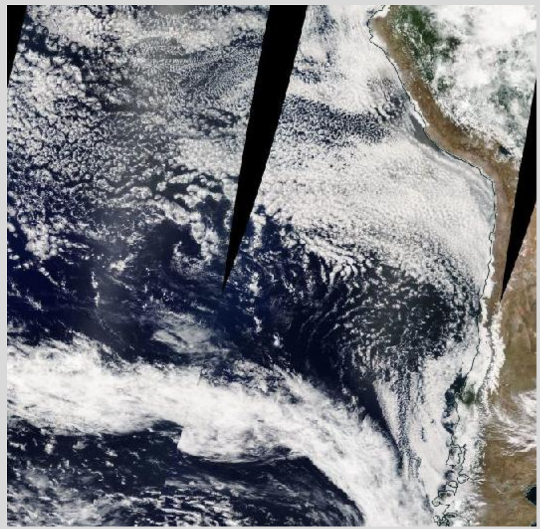

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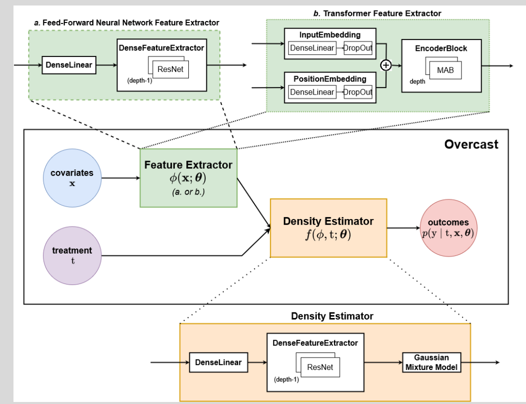
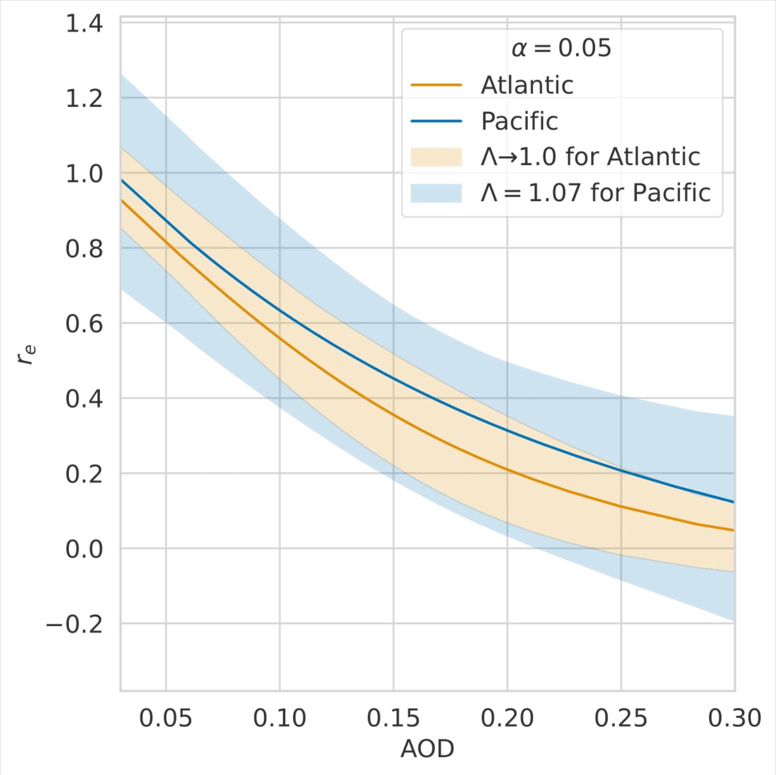


3. Uncertainty-aware ML model (Overcast)

Estimating Λ

We believe the uncertainty range for Λ=1.07 allows to cover the possible variation in ACI due to confounding effects

- **Theoretically**: Λ allows to derive confidence intervals dependent on the influence of confounding
- **In practice:** we contrast two regions known for their ACI with different environmental drivers of confounding effects to estimate a reasonable value for Λ
- **Λ=1.07** is selected as the uncertainty bounds (blue) cover the entire ignorance region of the Atlantic predictions (orange)

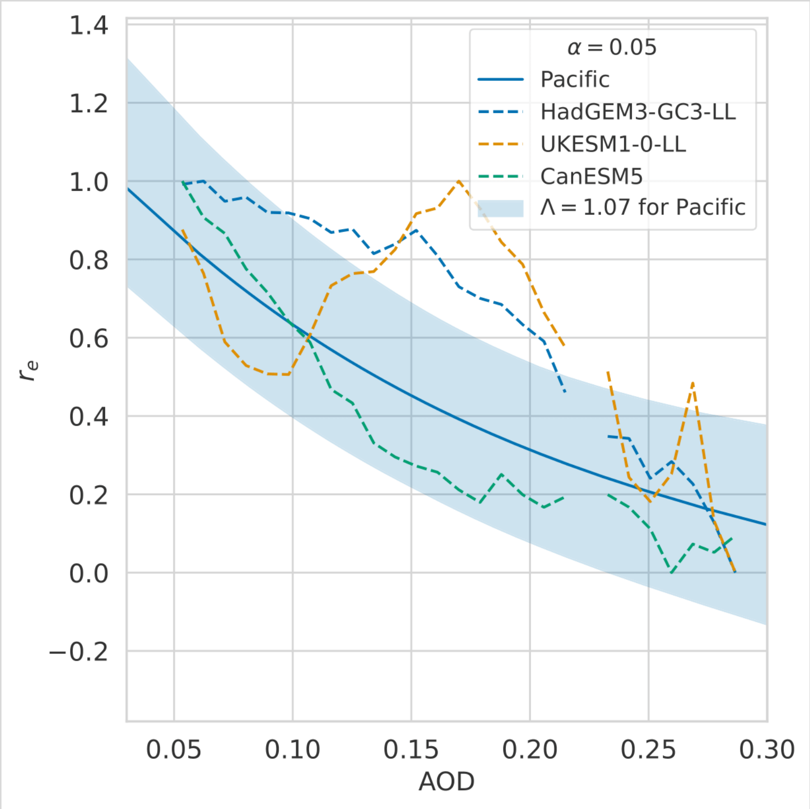


Dose-response curves: plausible ranges of effects of aerosols on cloud droplet radius in the Atlantic and the Pacific

Results

Trained ML models use real, observed relationships and consider environmental context and confounding to derive uncertainty bounds

- We judge how well climate models (dashed lines) recreate this observed trend, by seeing if their responses lie within our derived intervals (shaded blue)
- We find that CanESM5 simulates ACI better than the two other models
- Cooling effect due to ACI would offset approximately half of the warming due to greenhouse gases

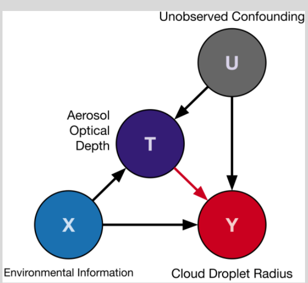


Comparison with Earth System Models

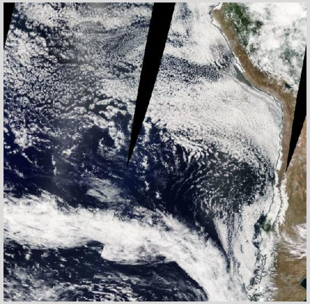
Take-home message

ML methods offer viable ways to judge how well models reproduce climate processes such as the effects of aerosols on cloud droplet radius

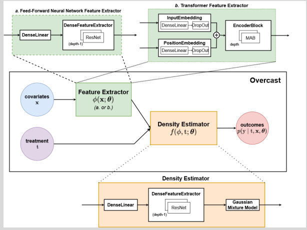
1. Domain knowledge



2. Data



3. ML model and knowledge



References

1. Olivier Boucher et al. “Clouds and Aerosols”. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Ed. by T.F. Stocker et al. Cambridge University Press, 2013, pp. 571–658.
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