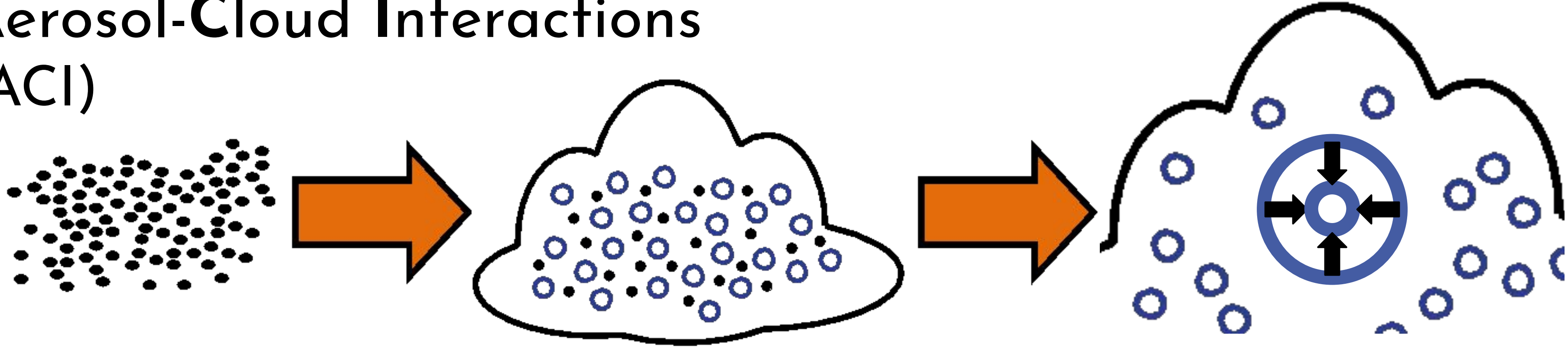
Using Non-Linear Models to Study Aerosol-Cloud Interactions in the Southeast Pacific

Andrew Jesson, Peter Manshausen, Alyson Douglas, Duncan Watson-Parris, Yarin Gal, Philip Stier

University of Oxford

UNIVERSITY OF OXFORD

Aerosol-Cloud Interactions (ACI)



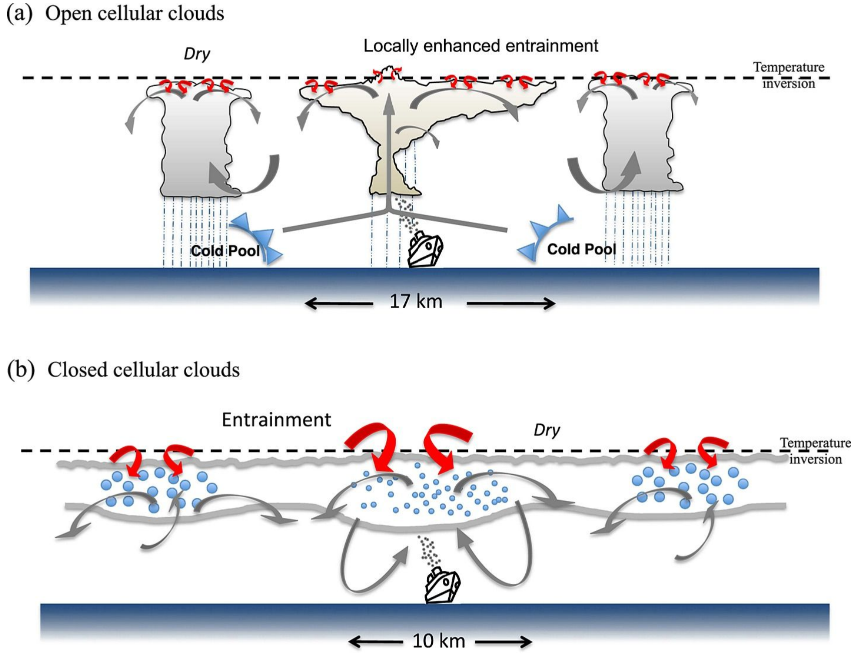
Aerosol is emitted into the atmosphere and enters a cloud

Within the cloud, aerosol acts as a cloud condensation nuclei, increasing the number of cloud droplets

As the number of cloud droplets increases, the mean droplet radius (r_e) decreases

Twomey, 1974

ACI are a heterogeneous effect…



Chen et al. 2015

The magnitude and sign of the effect are heavily dependent upon the local environment surrounding the cloud

Douglas & L'Ecuyer 2019

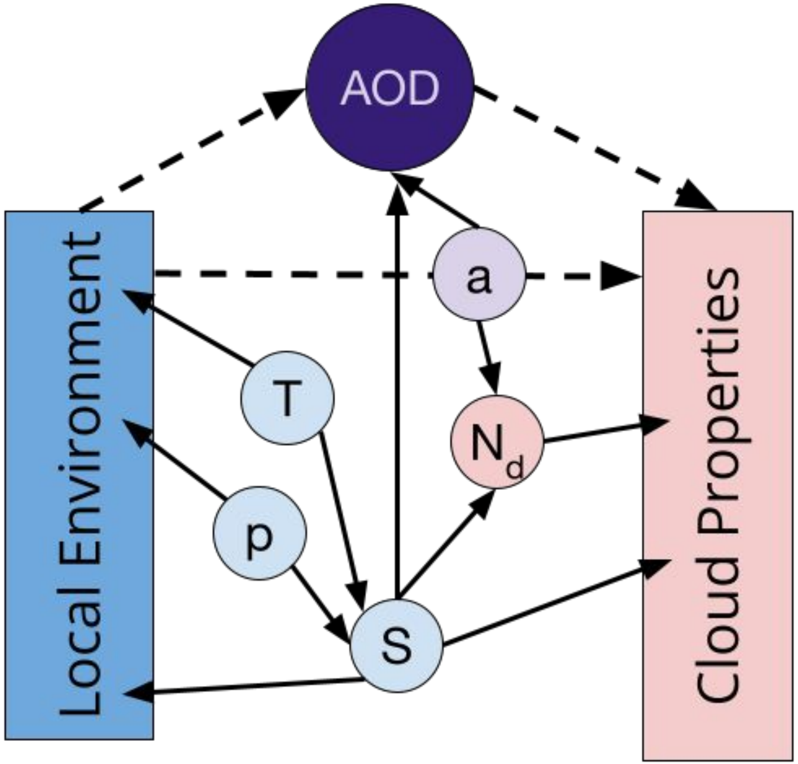
Aerosol can act to decrease r_e (as expected) or increase r_e due to environmental interactions

Stevens & Feingold 2009

Observing ACI using satellites leads to a confounding problem

1. Only observe aerosol optical depth (AOD, colored regions) in cloud free scenes
2. AOD itself is a proxy for the aerosol concentration
3. AOD is affected by nearby clouds and the local environment

Open cell marine stratocumulus and aerosol optical depth over the southeast Pacific as captured by the Aqua satellite on October 15, 2021



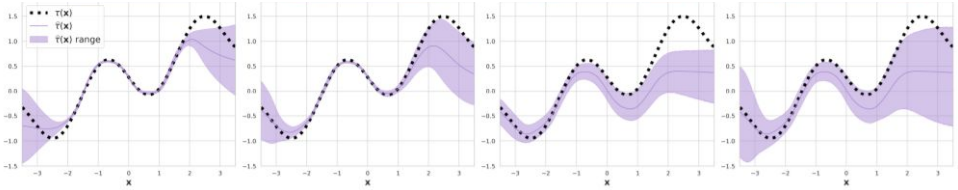
From a causal point-of-view, the environment acts as a confounding influence on ACI, which is itself a heterogeneous effect due to its modulation by the environment

To evaluate ACI as a function of the environment while accounting for confounding relationships we employ two non-linear, causal models

Quince

Quantifying Ignorance in Individual-Level Causal-Effect Estimates

Jessen et al. 2021

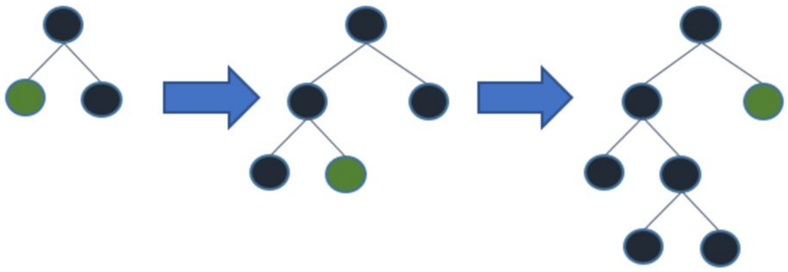


(a) similarity (b) overlap (c) context (d) unified

Neural network that accounts for how ignorance (from known and unknown sources) can alter the treatment effect

Causal Forest

EconML



Creating decision trees using random splits in the training data in order to derive a treatment effect

Features

Relative humidity at 700 mb
Relative humidity at 850 mb
Estimated Inversion Strength (EIS)
Sea Surface Temperature (SST)
Vertical winds at 500 mb (w_{500})

From NASA MERRA-2 and NOAA Climate Data Record

Treatment*

Aerosol Optical Depth

$AOD > \langle AOD \rangle \rightarrow 1$

$AOD < \langle AOD \rangle \rightarrow 0$

Predicted Outcomes

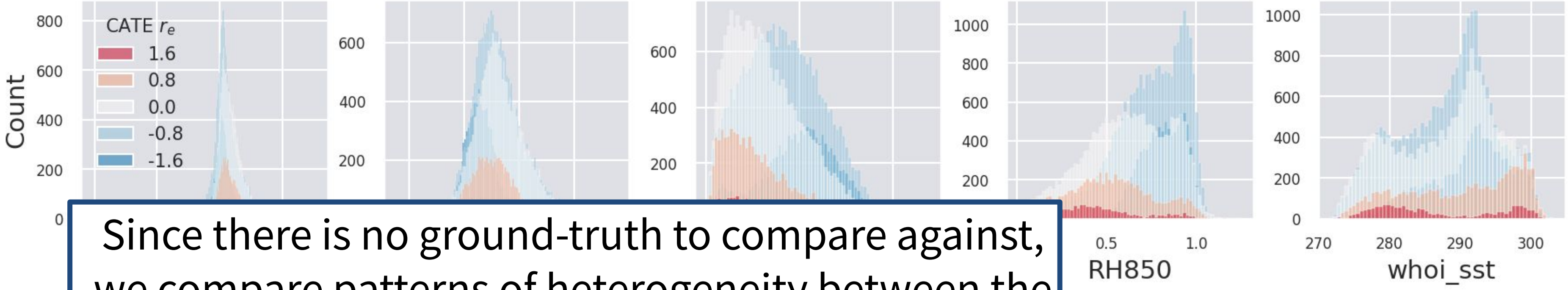
Mean droplet radius r_e*
Cloud fraction
Cloud optical depth
Cloud liquid water content

From NASA Aqua Satellite

*Must convert AOD to categorical in order to derive a treatment effect

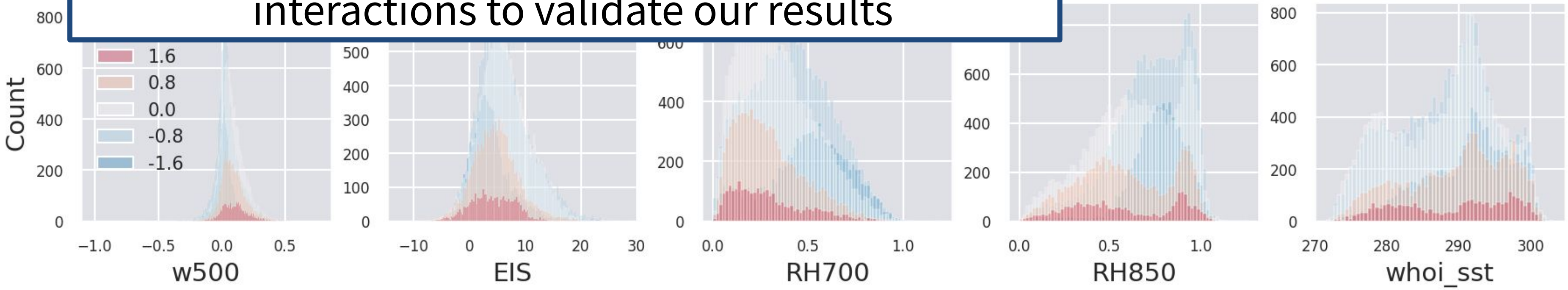
**Only showing results for the effects on mean droplet radius r_e

Quince



Since there is no ground-truth to compare against, we compare patterns of heterogeneity between the models and use expert knowledge of the possible interactions to validate our results

Causal Forests

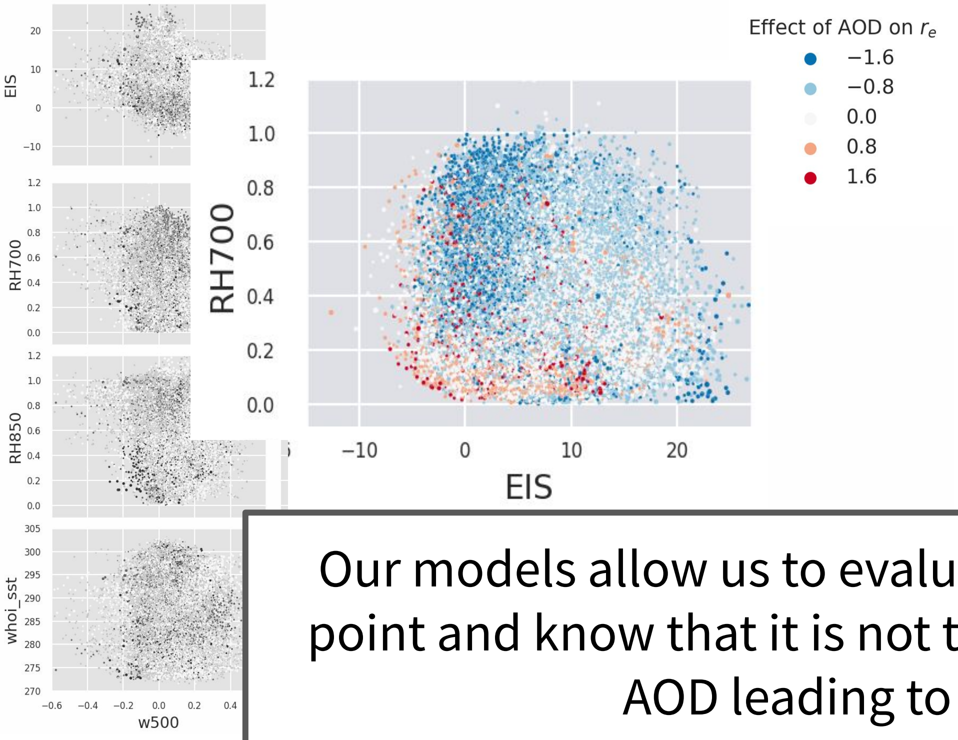


Evaluating the heterogeneity of ACI

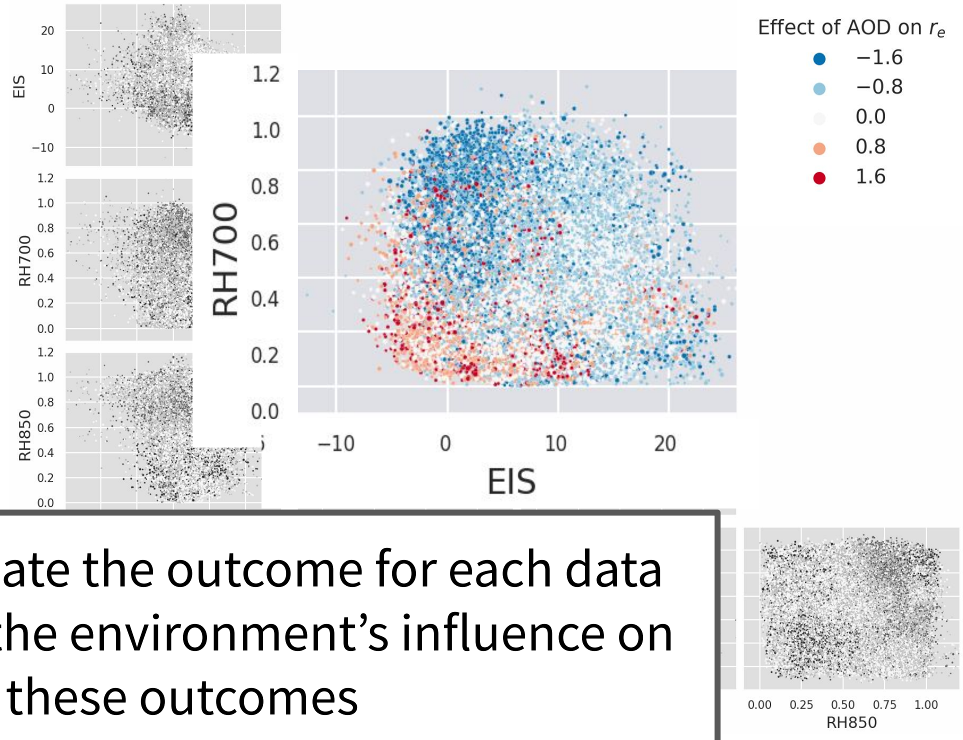
Quince

Causal Forests

Quince



Causal Forests



Our models allow us to evaluate the outcome for each data point and know that it is not the environment's influence on AOD leading to these outcomes

	Average Treatment Effect (ATE) of Above vs. Below Average AOD on r_e		
	Train (60%)	Validate (20%)	Test (20%)
Quince	-0.429	-0.413	-0.452
Causal Forest	-0.328	-0.325	-0.359

- Models agree on magnitude size (±.1) and sign (an increase in AOD decreases r_e)
- ATE remain consistent across the validation and test datasets
- The ATE is dependent upon the limit set for AOD binarization; must explore how this limit affects results
- Must also tune to increase the models' R^2 values (0.23, 0.21 for Quince and CF)

Conclusions

- Non-linear, causal models provide a unique perspective on confounding, heterogeneous effects like those of satellite observed aerosol on cloud properties
- Quince and causal forest reveal how the local environment can induce a range of effects, from reversing the effect (increasing the re) in dry, unstable environments to invigorating the effect in moist, unstable environments
- We can bypass the lack of ground-truth by comparing models and their derived heterogeneity across different environments
- These results are sensitive to our chosen AOD threshold, future work should explore how increasing or decreasing this threshold alters the treatment effect

Jesson, Andrew, et al. “Using Non-Linear Causal Models to Study Aerosol-Cloud Interactions in the Southeast Pacific.” ArXiv:2110.15084 [Physics], Oct. 2021. arXiv.org, http://arxiv.org/abs/2110.15084.

References

Douglas, Alyson, and Tristan L'Ecuyer. "Quantifying variations in shortwave aerosol–cloud–radiation interactions using local meteorology and cloud state constraints." Atmospheric Chemistry and Physics 19.9 (2019): 6251-6268.

Jesson, Andrew, et al. "Quantifying Ignorance in Individual-Level Causal-Effect Estimates under Hidden Confounding." arXiv preprint arXiv:2103.04850 (2021).

Jesson, Andrew, et al. "Using Non-Linear Causal Models to Study Aerosol-Cloud Interactions in the Southeast Pacific." ArXiv:2110.15084 [Physics], Oct. 2021. arXiv.org, http://arxiv.org/abs/2110.15084.

Keith Battocchi, Eleanor Dillon, Maggie Hei, Greg Lewis, Paul Oka, Miruna Oprescu, Vasilis Syrgkanis. EconML: A Python Package for ML-Based Heterogeneous Treatment Effects Estimation. https://github.com/microsoft/EconML, 2019. Version 0.x.

Chen, Yi-Chun, et al. "Aerosol-cloud interactions in ship tracks using Terra MODIS/MISR." Journal of Geophysical Research: Atmospheres 120.7 (2015): 2819-2833.

Stevens, Bjorn, and Graham Feingold. "Untangling aerosol effects on clouds and precipitation in a buffered system." Nature 461.7264 (2009): 607-613.

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

UNIVERSITY OF OXFORD

OATML

iMIRACLI

FORCeS