Natural Laboratories for Aerosol Cloud Interactions

Andrew Gettelman (NCAR), Matthew Christensen (Oxford)

Micael Cecchini, Jan Cermak, Guy Dagan1, Michael Diamond, Alyson Douglas, Graham Feingold, Franziska Glassmeier, Tom Goren, Jennifer Griswold, Daniel Grosvenor, Ed Gryspeerdt, Jim Haywood, Ralph Kahn, Zhanquing Li, Luiz Machado, Florent Malavelle, Greg McFarquhar, Johannes Mulmenstadt, Sandip Pal, Anna Possner, Adam Povey1, Johannes Quaas, Danny Rosenfeld, Anja Schmidt, Roland Schrodner, Armin Sorooshian, Odran Sourdeval, Philip Stier, Velle Toll, Minghuai Wang, Duncan Watson-Parris, Robert Wood, Masaru Yoshioka, Tianle Yuan

September 25th 2016 South Sandwich Islands (NASA Worldview)

What is a ‘Natural Laboratory’?
AKA: ‘Opportunistic Experiment’

Anomalous Cloud Lines[1]

JOHN H. CONOVER

Air Force Cambridge Research Laboratories, Bedford, Mass.

(Manuscript received 22 March 1966, in revised form 29 July 1966)

3. Interpretation

Possible causes of the anomalous lines involve a) aircraft condensation trails, b) missile trails, c) smoke screens from ships, d) convection induced by certain temperature patterns in the sea, and e) the effluents from ships. The last appears to be the most reasonable,

a) Cloud lines distort in relation to the large scale cloud which is at low-levels.

b) Due to their speed, one end of the missile trail should not appear significantly different from the other end.

c) Smoke screens of this size cannot be generated, nor would they be in locations where these lines are found.

d) Sharp discontinuities in SST are not prevalent except on the edges of major ocean currents. Furthermore, cloud lines formed over a line of warm water would not be expected to show a difference in age from one end to the other.

One of the first satellite images of a ship track

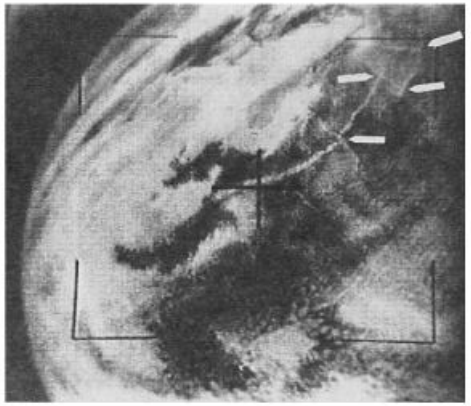
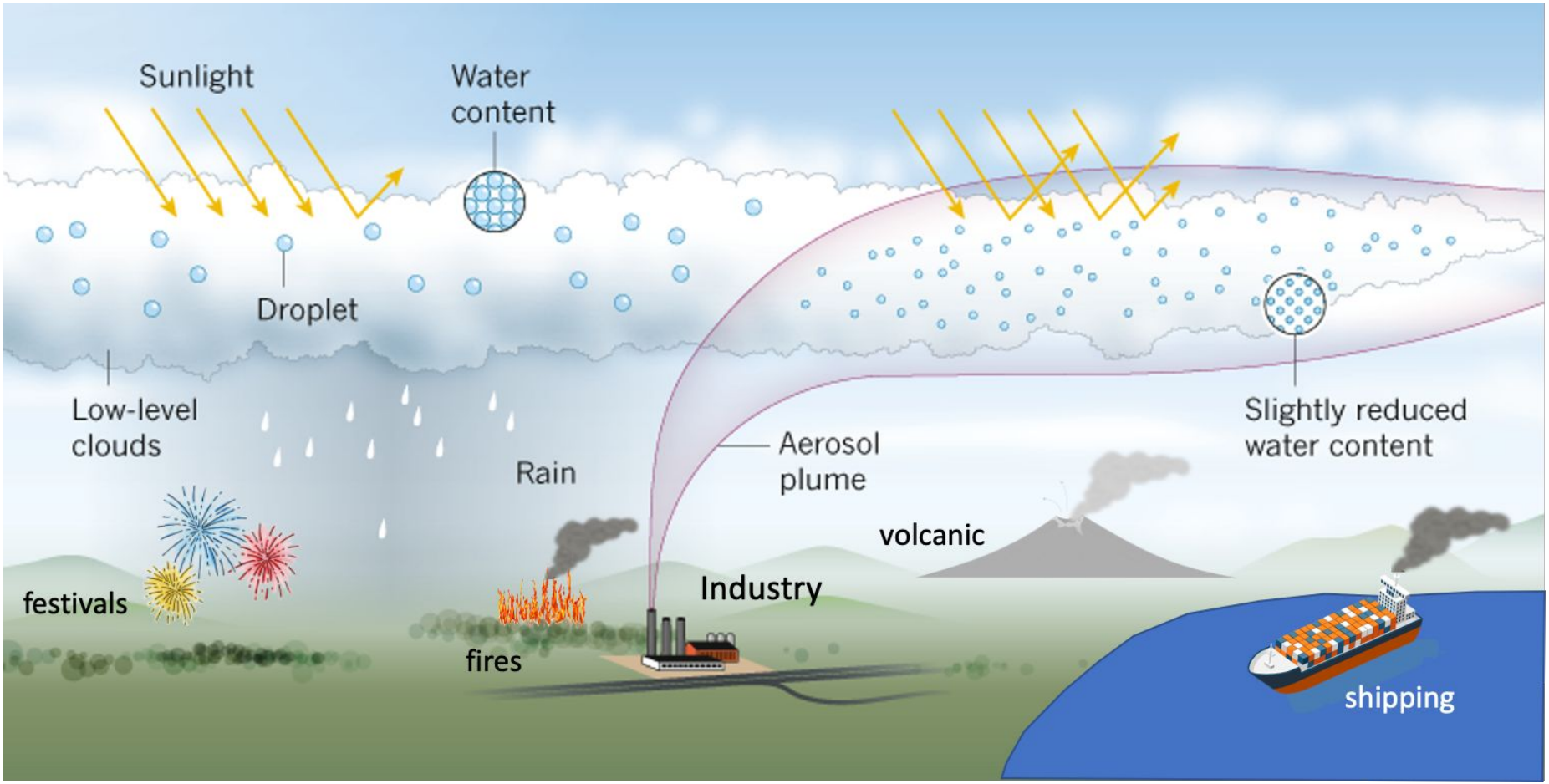


FIG. 5. Crossing curved anomalous lines. Arrows point to the most prominent crossings. Case 7.

TIROS VII: Television Infrared Observational Satellite camera

First successful weather satellites


Sunlight
Water content
Droplet
Low-level clouds
Rain
Aerosol plume
Slightly reduced water content
volcanic
festivals
Industry
fires
shipping

Different types of Natural Laboratories (or ‘opportunistic experiments’)

- Ship emissions (42 papers; satellite=28, LES=4 , in situ =6)
- Industrial sources (14 papers)
- Volcanoes (11 papers)
  - Kilauea (Hawai’i), Ambrym (Vanuatu) , Holuhraun 2014-2015 (Iceland)
- Fires (7 papers)
- Hemispheric differences (2 papers)
- Long Term Trends (4 papers)
- Weekly cycle (2 papers)
- Particular events
  - Beijing Olympics, Great Recession,
  - COVID-19 [several papers in process]

ACPC Natural Laboratories Review

April 2020: ACPC low cloud project decided that there was a lot to be learned from synthesizing work on natural laboratories for aerosol cloud interactions.

A project to develop a review paper was initiated

Aerosol, **C**loud, **P**recipitation & **C**limate (ACPC) Working Group

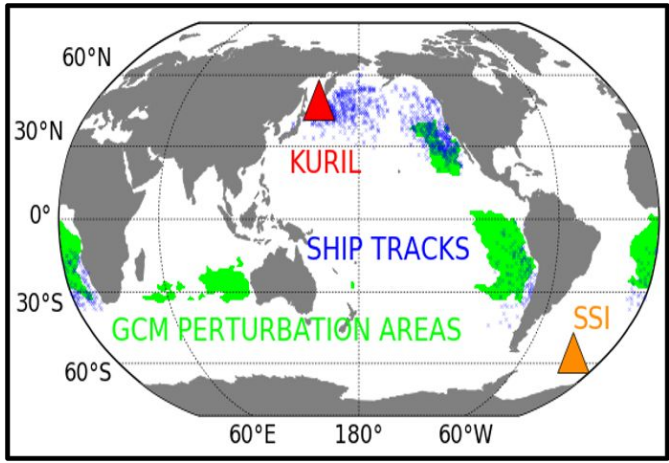
ACPC is a joint initiative of the International Geosphere–Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP), developed through the cooperation of the IGBP's Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS) and International Global Atmospheric Chemistry (IGAC) and WCRP's Global Energy and Water Cycle Experiment (GEWEX) .

Natural Laboratories Review: Scope/Vision

Bring together in a common framework different ‘natural laboratories’ of anthropogenic aerosol impacts on clouds, especially the microphysical effect of aerosols on clouds

1. A review/summary paper on different laboratories and what we have learned from them using models and observations. Include a synthesis and next steps.

2. A Table and Database of different natural laboratories
where, when, data sources, where studied. Links to associated emissions and observations datasets



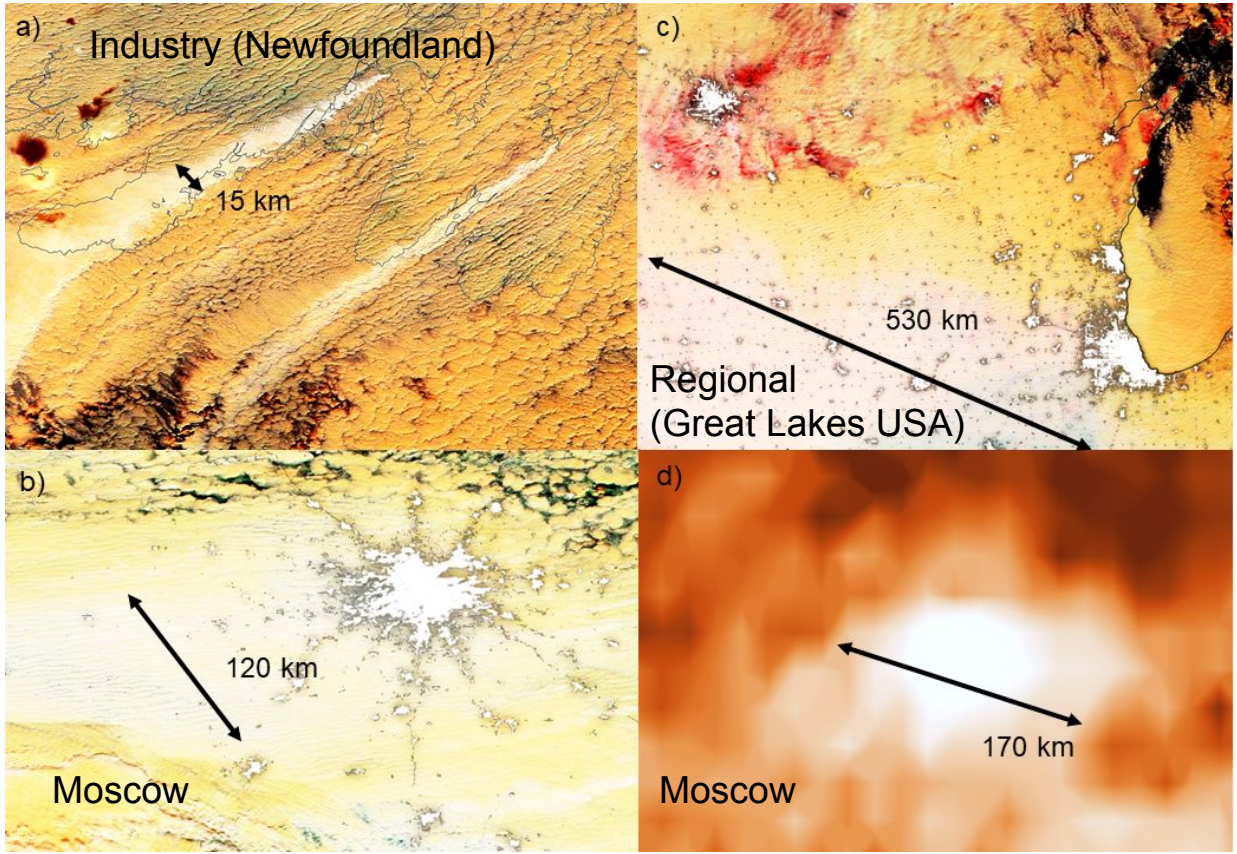
Pollution track database (Toll et al. 2019): https://researchdata.reading.ac.uk/208/

Cloud ‘Tracks’ Across Scales

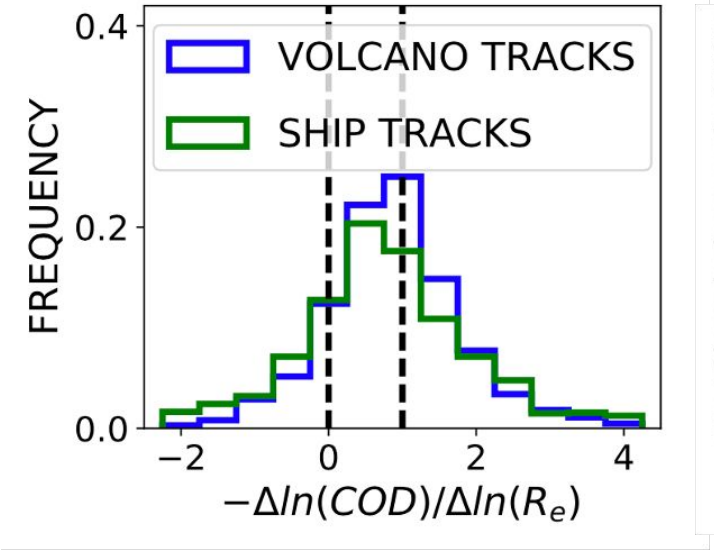
A-C: MODIS daytime near-infrared composite satellite images (sensitive to Re)

D: AVHRR Re

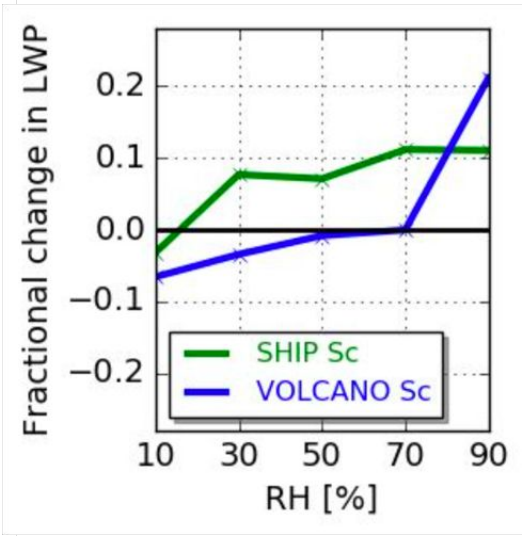
Velle Toll



Ship and Volcano Track Responses



Response to meteorology



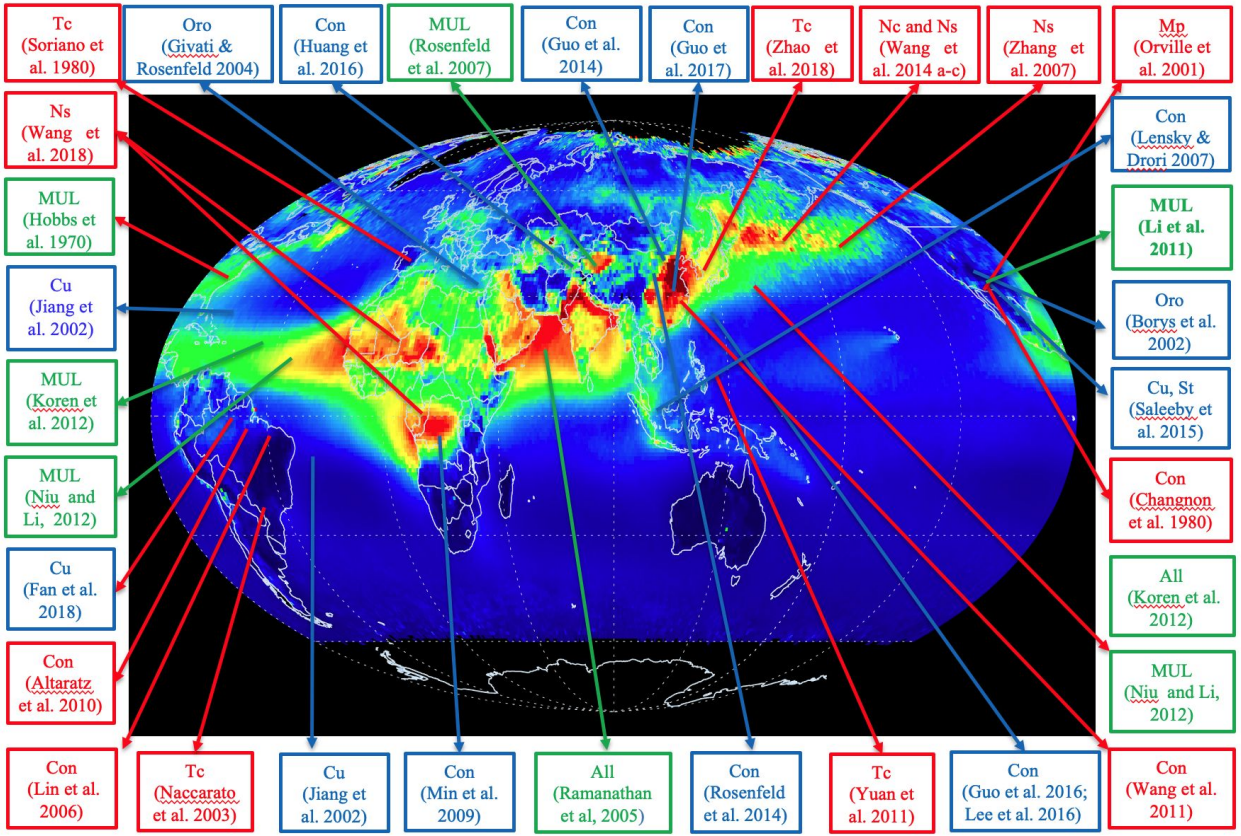
Toll et al. (2017)

- Cloud albedo effect ratio similar in both ship and volcano tracks. (Ship tracks: effective Radius ΔRe = -22%; and Cloud Optical Depth ΔCOD ≃ +36%).
- Liquid water path (LWP) increases as *free-troposphere humidity* increases similarly for both ship and volcano tracks.

Precipitation Sensitivity

Precip Sensitivity to Aerosols, depends on Regime

Lee et al 2019, JGR



Cloud	All cloud types	Thundercloud	Mixed-phase cloud	Orographic cloud	Cumulus	Nimbostratus	Stratus	Convective clouds
Acronym	All	Tc	Mp	Oro	Cu	Ns	St	Con

Review Timeline/Progress

- Developed outline with co-authors
- Data collection: Preliminary database
- Now: analysis/synthesis, working on draft
- Goal: Submit and Report by April 2021 ACPC meeting

Want to help? Let us know.

Still happy to engage others and add co-authors. Unpublished modeling estimates based on existing models are probably fine (e.g.: Shipping emissions effects).

Database

Data collection with type, location, regime, highlights

Quantitative estimates:

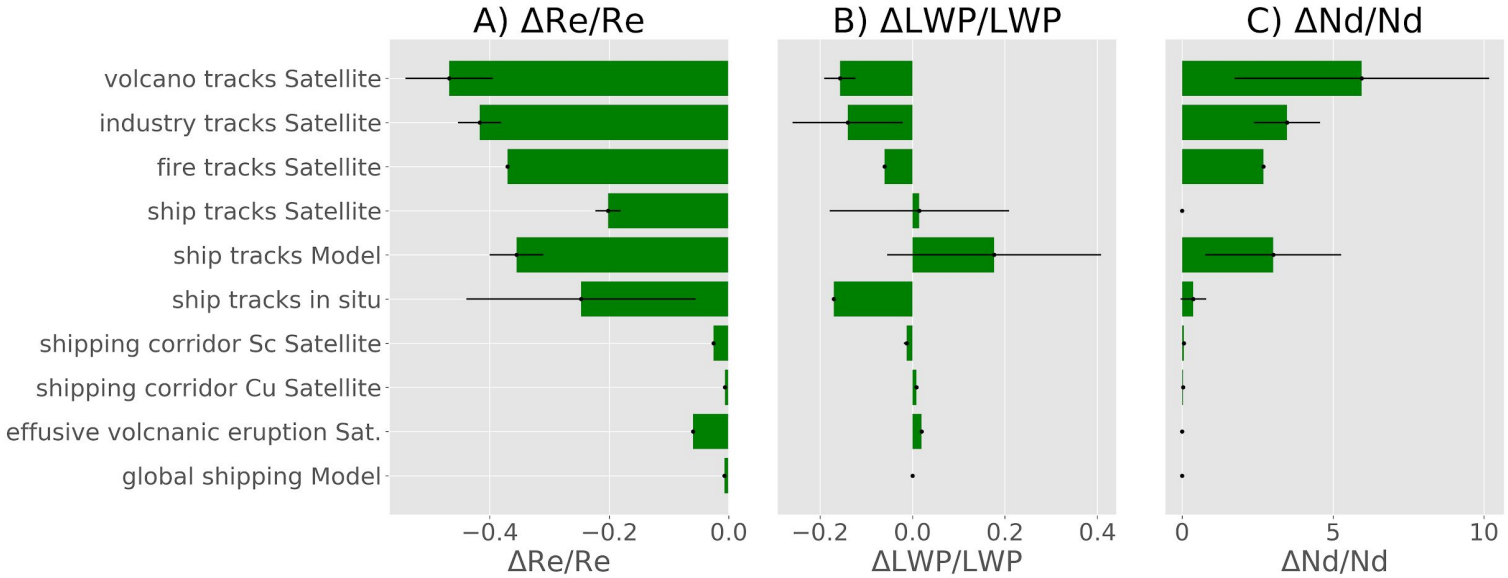
- ERF (W/m2)
- Freq
- CldFrc
- $\Delta\tau/\tau$
- $\Delta A/A$
- $\Delta Nd/Nd$
- $\Delta Re/Re$
- $\Delta LWP/LWP$
- $\Delta Height/Height$

Table 1. Warm liquid cloud responses and radiative effects in anthropogenic and natural laboratories. Effective radiative forcing by aerosol cloud interactions

Author/Year	Laboratory	Location	Methods	Regime/Type	Scale	Highlight/Conclusions	Responses ERF (W/m2)	Freq	CldFrc	$\Delta\tau/\tau$	$\Delta A/A$	$\Delta Nd/N$	$\Delta Re/Re$	$\Delta LWP/LV$	$\Delta Height/Heig$	Full reference
Bai et al., 2020	long-term trend	global oceans, p	Satellite			large drop in cloud droplet nubmer concentrations in response to aerosol reduction, but not cloud fraction.										Bai, H., Wang, M., Zhang, Z., & Liu, Y. (2020). Synergetic satellite trend analysis of aerosol and warm cloud properties over ocean and its implication for aerosol–cloud interactions. Journal of Geophysical Research: Atmospheres, 125, e2019JD031598. https://doi.org/10.1029/2019JD031598
Berner et al. (2015)	ship tracks		Model	LES		ship tracks in roll clouds (orientation between rolls and plume constrain track width)										Berner, A. H., Bretherton, C. S., and Wood, R.: Large eddy simulation of ship tracks in the collapsed marine boundary layer: a case study from the Monterey area ship
Bowley et al. (1967)	ship tracks		Satellite			further evidence of "anomalous cloud lines" following first sighting by Conover (1966) and link to stable synoptics										Bowley, C. J., 1967: Comments on Atmospheric Requirements for the Genesis of Anomalous Cloud Lines. J. Atmos. Sci., 24, 596–597, https://doi.org/10.1175/1520-0
Campmany et al (2009)	ship tracks	Globe	Satellite			small frequency of occurrence		0.0002								
Cermak & Knutti	Beijing Olympics	China	Satellite	Aerosol only (should this count?)		Small effect detected with neural net that accounts for met., but meteorology swamps effect size										Cermak, J., & Knutti, R. (2009). Beijing Olympics as an aerosol field experiment. Geophysical Research Letters, 36(10), L10806.
Chen et al. (2014)	ship tracks	Multiple basins	Satellite			cloud dimming in 30% of ship tracks										
Chen et al. (2015)	ship tracks	Multiple basins	Satellite			MISR enhanced cloud top divergence in ship tracks										
Cherian and Quaas (2020)	trend	North America, I	Satellite			Trends in AOD and Nd largely consistent, not for L and f; Constraints on CMIP5 and CMIP6										Cherian, R., and J. Quaas, Trends in AOD, clouds and cloud radiative effects in satellite data and CMIP5 and CMIP6 model simulations over aerosol source regions,
Cherian et al. (2014)	trend	Europe	Surface radiation			Emergent constraint for CMIP5 models	-1.3 Wm-2									Cherian, R., J. Quaas, M. Salzmann, and M. Wild, Pollution trends over Europe constrain global aerosol forcing as simulated by climate models, Geophys. Res. Lett.,
Christensen and Stephens (2012)	ship tracks	Multiple basins	Satellite			drizzle suppression in ship tracks in closed cell clouds										
Christensen and Stephens 2011	ship tracks	East Pacific	Satellite			Ship tracks in open cells large reponses	12			0.13		-0.18	-0.05	0.006		Christensen, M. W., and G. L. Stephens (2011), Microphysical and macrophysical responses of marine stratocumulus polluted by underlying ships: Evidence of cloud deepening, J. Geo
Christensen and Stephens 2011	ship tracks	East Pacific	Satellite			Ship tracks in closed cells weak responses	59			0.83		-0.21	0.39	0.15		Christensen, M. W., and G. L. Stephens (2011), Microphysical and macrophysical responses of marine stratocumulus polluted by underlying ships: Evidence of cloud d
Christensen et al. (2009)	ship tracks	East Pacific	Satellite			TERRA and AQUA differences of same tracks										
Christensen et al. (2014)	ship tracks	Multiple basins	Satellite			warm vs mixed phase cloud comparisons										
Coakley and Walsh (2002)	ship tracks	East Pacific	Satellite			first study to demonstrate LWP decreases (although Ackerman et al. 1999 inferred weak LWC decreases from MAST...)				0.08		-0.24	-0.175			*J. A. Coakley Jr., C. D. Walsh: Limits to aerosol indirect radiative effect derived from observations of ship tracks, J. Atmos. Sci. 59, 668 (20*
Coakley et al. (2000)	ship tracks	East Pacific	Satellite			ship tracks are rare and predominantly occur in low-lwl coupled clouds										Coakley, J. A., and Coauthors, 2000: The Appearance and Disappearance of Ship Tracks on Large Spatial Scales. J. Atmos. Sci., 57, 2765–2778, https://doi.org/10.1
Conover (1966)	ship tracks		Satellite													Conover, J. H., 1966: Anomalous Cloud Lines. J. Atmos. Sci., 23, 778–785, https://doi.org/10.1175/1520-0469(1966)023<0778:ACL>2.0.CO;2.
Diamond et al. (2020)	shipping corridor	South East Atlar	Satellite	Sc	Morning climatology	Strong cloud brightening from Twomey effect	-6.56		0.8809	0.0213	0.0163	0.0724	-0.0261	-0.0057		Diamond, M. S., Director, H. M., Eastman, R., Possner, A., & Wood, R. (2020). Substantial Cloud Brightening From Shipping in Subtropical Low Clouds. AGU Advanc
Diamond et al. (2020)	shipping corridor	South East Atlar	Satellite	Sc	Afternoon climatology	Offsetting Twomey and negative LWP effects	-2.4		0.913	0.0058	0.0072	0.0522	-0.0252	-0.02		Diamond, M. S., Director, H. M., Eastman, R., Possner, A., & Wood, R. (2020). Substantial Cloud Brightening From Shipping in Subtropical Low Clouds. AGU Advanc
Diamond et al. (2020)	shipping corridor	South East Atlar	Satellite	Sc	Daily climatology	Cloud brightening from Twomey effect partially offset by LWP decrease, no clear cloud fraction change	-2.24		0.9258	0.0136	0.0129	0.062	-0.0256	-0.0129		Diamond, M. S., Director, H. M., Eastman, R., Possner, A., & Wood, R. (2020). Substantial Cloud Brightening From Shipping in Subtropical Low Clouds. AGU Advanc
Diamond et al. (2020)	shipping corridor	South East Atlar	Satellite	Cu	Morning climatology	No statistically significant changes			0.7451	0.0193	0.0154	0.0366	-0.0073	0.0148		Diamond, M. S., Director, H. M., Eastman, R., Possner, A., & Wood, R. (2020). Substantial Cloud Brightening From Shipping in Subtropical Low Clouds. AGU Advanc
Diamond et al. (2020)	shipping corridor	South East Atlar	Satellite	Cu	Afternoon climatology	Significantly significant cloud droplet increase but nothing else			0.7402	0.0066	0.0043	0.0215	-0.0057	0.0023		Diamond, M. S., Director, H. M., Eastman, R., Possner, A., & Wood, R. (2020). Substantial Cloud Brightening From Shipping in Subtropical Low Clouds. AGU Advanc
Diamond et al. (2020)	shipping corridor	South East Atlar	Satellite	Cu	Daily climatology	Overall effects much more highly uncertain than for Sc region	-0.83		0.7317	0.013	0.0079	0.0292	-0.0065	0.0086		Diamond, M. S., Director, H. M., Eastman, R., Possner, A., & Wood, R. (2020). Substantial Cloud Brightening From Shipping in Subtropical Low Clouds. AGU Advanc
Diamond & Wood (2020)	COVID	China	Satellite	Stratus/Sc	Regional	No detected aerosol/cloud effect despite huge NO2 drop										Diamond, M. S., & Wood, R. (2020). Limited Regional Aerosol and Cloud Microphysical Changes Despite Unprecedented Decline in Nitrogen Oxide Pollution During
Durkee et al. (2000)	ship tracks	East Pacific	satellite/sounding	(MAST)		MAST campaign statistics, ship tracks are ~7.3h old, 296km long					0.11				0.15	Durkee, P. A., and Coauthors, 2000: Composite Ship Track Characteristics. J. Atmos. Sci., 57, 2542–2553, https://doi.org/10.1175/1520-0469(2000)057<2542:CSTC>
Ebmeier et al. 2014	volcano tracks	Kilauea	Satellite			Enhancement of effective radius but not LWP downwind; includes control	10-45			0.23		-0.5				Ebmeier, S. K., Sayer, A. M., Grainger, R. G., Mather, T. A., and Carboni, E. (2014). Systematic satellite observations of the impact of aerosols from passive volcanic
Eyring et al 2007	shipping corridor	Global	Various			Review of ship emissions and radiative forcing, Section on clouds										*Eyring et al 2007, Atmos Environment, https://doi.org/10.1016/j.atmosenv.2009.04.059*
Ferek et al. (1998)	ship tracks	East Pacific	in situ		2 tracks sampled	CCN increase is responsible for track and associated with Reff reduction by ~50%							-0.5			*Ferek, R. J., Hegg, D. A., Hobbs, P. V., Durkee, P., and Nielsen, K. (1998), Measurements of ship–induced tracks in clouds off the Washington coast, J. Geophys. Re* .
Ferek et al. (2000)	ship tracks	East Pacific	in situ			drizzle reduction within ship tracks by 61% on average during MAST										Ferek, R. J., and Coauthors, 2000: Drizzle Suppression in Ship Tracks. J. Atmos. Sci., 57, 2707–2728, https://doi.org/10.1175/1520-0469(2000)057<2707:DSIST>2.0
Gasso (2008)	volcano tracks	South Sandwich	Satellite			liquid water content can decrease, increase or remain unchanged with respect to nearby unperturbed clouds										Gassó, S. (2008). Satellite observations of the impact of weak volcanic activity on marine clouds. Journal of Geophysical Research: Atmospheres, 113(D14).
Gettelman, Schmidt, & Kristjansso	volcano tracks	Europe	GCM													Gettelman, A., Schmidt, A. & Egill Kristjánsson, J. Icelandic volcanic emissions and climate. Nature Geosci 8, 243 (2015). https://doi.org/10.1038/ngeo2376
Goren and Rosenfeld (2014)	ship tracks		Satellite			long-lived ship tracks have substantial effect on cloud fraction of regional scales										
Gryspeerdt et al. (2019)	ship tracks	East Pacific	Satellite			SECA zone and meteorological impacts on ship track occurrence										
Gryspeerdt et al. (2019b)	volcano, shiptracks	Kilauea, global	Satellite			Weak Nd-LWP relationship in plume, shiptrack relation depends on background state										
Guo et al.,	industrial emission	China	surface observation			Impact of increasing anthropogenic emissions on light rain trend										*Guo, J., T. Su, Z. Li, T. Miao, J. Li, H. Liu, H. Xu, M. Cribb, P. Zhai, 2017, Declining frequency of summertime local-scale precipitation over eastern China from 1970–2010 and its potential link to aerosols, Geophy. Res. Lett., 1*
Hobbs et al. (2000)	ship tracks	East Pacific	in situ	average from diesel-powered ships		ship exhaust impacts cloud properties						0.97	-0.35			Peter V. Hobbs;Timothy J. Garrett; Ronald J. Ferek;Scott R. Strader; Dean A. Hegg; Glendon M. Frick; William A. Hoppel; Richard F. Gasparovic; Lynn M. Russell; D
Hobbs et al. (2000)	ship tracks	East Pacific	in situ	distillate fuel		ship exhaust impacts cloud properties						0.06	-0.04			Peter V. Hobbs;Timothy J. Garrett; Ronald J. Ferek;Scott R. Strader; Dean A. Hegg; Glendon M. Frick; William A. Hoppel; Richard F. Gasparovic; Lynn M. Russell; D
Hobbs et al. (1980)	coal power plant	Washington Stat	in situ	stratus		Large Nd effect in stratus, little effect in cumulus										Hobbs, P. V., Stith, J. L., & Radke, L. F. (1980). Cloud-Active Nuclei from Coal-Fired Electric Power Plants and Their Interactions with Clouds. Journal of Applied Mete
Kablick et al., 2019	fire tracks	Canada				Impact of smoke on pyra-Cb in boreal forest region of Canada										Kablick, P., et al., 2018, The Great Slave Lake pyroCb of 5 August 2014: Observations, simulations, comparisons with regula convection, and impact on
Jung et al. (2015)	sea salt (is this a n	NE Pacific	in situ	stratus		Impacts of giant salt particle seeding after release by a Twin Otter at tops of the cloud deck										Jung, E., Albrecht, B.A., Jonsson, H.H., Chen, Y.C., Seinfeld, J.H., Sorooshian, A., Metcalf, A.R., Song, S., Fang, M., Russell, L.M., 2015. Precipitation
Lauer et al 2007	global shipping	global	Model	low cloud	global								-0.00732			Lauer, A., Eyring, V., Hendricks, J., Jöckel, P., and Lohmann, U.: Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiat
Li et al., 2016	long-term trend	Asia	satellite and ground observations			A comprehensive review of studies on the impact of Asian aerosols on the long-term trends of various meteorological variables at varying time scales especially decadal trends										*Li, Z., et al., 2016: Aerosol and monsoon interactions in Asia, Rev. Geophys., 10.1002/2015 RG000500.*
Li et al., 2019	industrial emission	China	all types of observations			Survey and review on the impact of different types of aerosols on cloud and precipitation in China and around the world										*Li, Z., et al., 2019, East Asian Study of Tropospheric Aerosols and their Impact on Regional Clouds, Precipitation, and Climate (EAST-AIRCPC), J. Geo*
Lu et al 2008	biomass burning	South East Atlar	Satellite	Obs / models		Diurnal cycle in cloud adjustment response for Sc										Lu, Z., Liu, X., Zhang, Z., Zhao, C., Meyer, K., Rajapakshe, C., Wu, C., ... (2018). Biomass smoke from southern africa can significantly enhance the brightness of stratocumulus over the southeastern atlantic ocean. Proceedings of the National Academy of Sciences, 115(12), 2924–2929.
Mace and Abernathy 2016	volcano tracks	Kilauea	Satellite			Deeper clouds in Kilauea Plume										Mace, G. G., and A. C. Abernathy: "Observational Evidence for Aerosol Invigoration in Shallow Cumulus Downstream of Mount Kilauea." *Geophysical Research Lette*
Malavelle et al 2017	effusive volcanic	Holuhraun	Satellite			Nd response, no LWP response in MODIS							-0.06	0.02		Malavelle, Florent F., Jim M. Haywood, Andy Jones, Andrew Gettelman, Lieven Clarisse, Sophie Bauduin, Richard P. Allan, et al. "Strong Constraints on Aerosol–Clo
Mardi et al. 2018, 2019	biomass burning	Northeast Pacific	in situ			Lower CCN activation potential during wildfire periods; different chemical profile in clouds during wildfire periods; dust is entrained in wildfire plumes and evident in cloud water										Mardi, A.H., Dadashazar, H., MacDonald, A.B., Crosbie, E., Coggon, M.M., Aghdam, M.A., Woods, R.K., Jonsson, H.H., Flagan, R.C., Seinfeld, J.H., Mardi, A.H., Dadashazar, H., MacDonald, A.B., Braun, R.A., Crosbie, E., Xian, P., Thorsen, T.J., Coggon, M.M., Fenn, M.A., Ferrare, R.A., Hair, J.W., Woods, R.K., Jonsson, H.H., Flagan, R.C., Seinfeld, J.H., Sorooshian, A., 2018. Biomass Burning Plumes in the Vicinity of the California Coast: Airborne Characterization of Physicochemical Properties, Heating Rates, and Spatiotemporal Features. J Geophys Res-Atmos 123, 13560-13582.
Noone et al. (2000)	ship tracks		in situ			no discernable radiative effect of ship tracks in polluted boundary layers						0.08	-0.006			Noone, K. J., and Coauthors, 2000: A Case Study of Ship Track Formation in a Polluted Marine Boundary Layer. J. Atmos. Sci., 57, 2748–2764, https://doi.org/10.117
Peters et al. (2011)	shipping corridor	several?	Satellite													
Possner et al 2015	ship tracks	Europe	Model	regional model		fully parameterised model capable of reproducing realistic ship tracks						3	-0.4			Possner, A., Zubler, E., Lohmann, U., and Schär, C.: Real-case simulations of aerosol–cloud interactions in ship tracks over the Bay of Biscay, Atmos. Chem. Phys., 1
Possner et al 2017	ship tracks	Europe	Model			emission dilution contributed 47% to bias in SW CRE, while										Possner A., E. M. Zubler,U. Lohmann, and C. Schär (2016), The resolution dependence of cloud effects and ship-induced aerosol-cloud interactions in marine stratoc
Possner et al 2017	ship tracks	Arctic	Model	LES		increased ice water content in ship-perturbed mixed-phase clouds						2.13	-0.31	0.06		Possner, A., A. M. L. Ekman, and U. Lohmann (2017), Cloud response and feedback processes in stratiform mixed-phase clouds perturbed by ship exhaust, Geophys
Quaas (2015)	compilation					previous (less good) review attempt										Quaas, J., Approaches to observe effects of anthropogenic aerosols on clouds and radiation, Current Climate Change Reports, 1, 297-304, doi:10.1007/s40641-015-(
Quaas et al (2011)	weekly cycle	Europe	Satellite	Obs, surface obs		Discernible cycle in AOD and Nd, not in L and f										Quaas, J., O. Boucher, A. Jones, G. P. Weedon, J. Kieser, and H. Joos, Exploiting the weekly cycle as observed over Europe to analyse aerosol indirect effects in two
Rosenfeld (1999) Fires? It compa	fire tracks															
Russell et al. (2013)	ship tracks	East Pacific	in situ													Russell, L. M., Sorooshian, A., Seinfeld, J. H., Albrecht, B. A., Nenes, A., Ahlm, L., Chen, Y. C., Coggon, M., Craven, J. S., Flagan, R. C., Frossard, A. A., Jonsson, H

Preliminary Meta Analysis

Preliminary analysis of 50 studies, maybe 15 studies with quantitative values



Still adding studies. Interesting commonalities (e.g., volcanoes more than shipping corridors)
Looking at systematic differences by regime, emission type, method

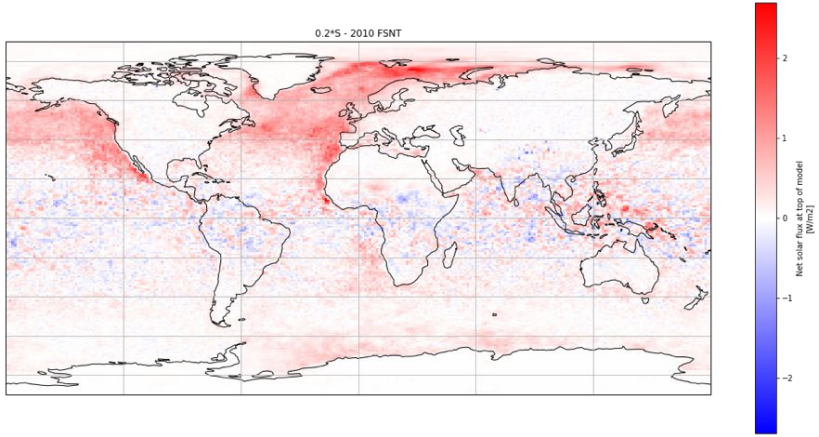
Unpublished and Emerging Analyses

We can probably add estimates even if they are not quite published

Examples with CAM6:

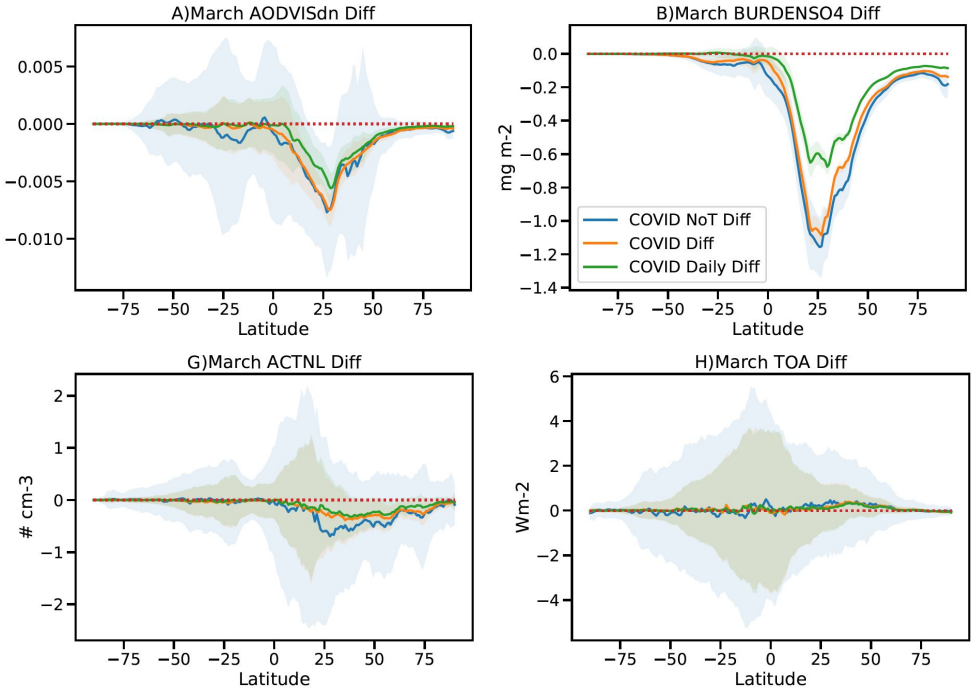
2020 Shipping Emissions Regulations

ERF for 80% Shipping Sulfur Reduction (+0.14 Wm^{-2})



COVID Aerosol Change Impacts

(Gettelman et al, in Prep)



Summary

- Natural Laboratories are experiments of opportunity that show clear sensitivity of cloud properties to aerosols
- Types: industrial emissions, volcanoes, ship tracks, regional emissions.
  - Even global perturbations: COVID emissions changes or long term trends
- Perhaps 50 or more studies looking at these events, but no meta-analysis
- Initial collection and synthesis of different studies indicates some interesting differences and commonalities.
- Quantitative information is available and this may be very useful to help understand and quantify ACI
- Join us! Happy to include emerging modeling work