

Aircraft-measured indirect cloud effects from biomass burning smoke in the Arctic and subarctic



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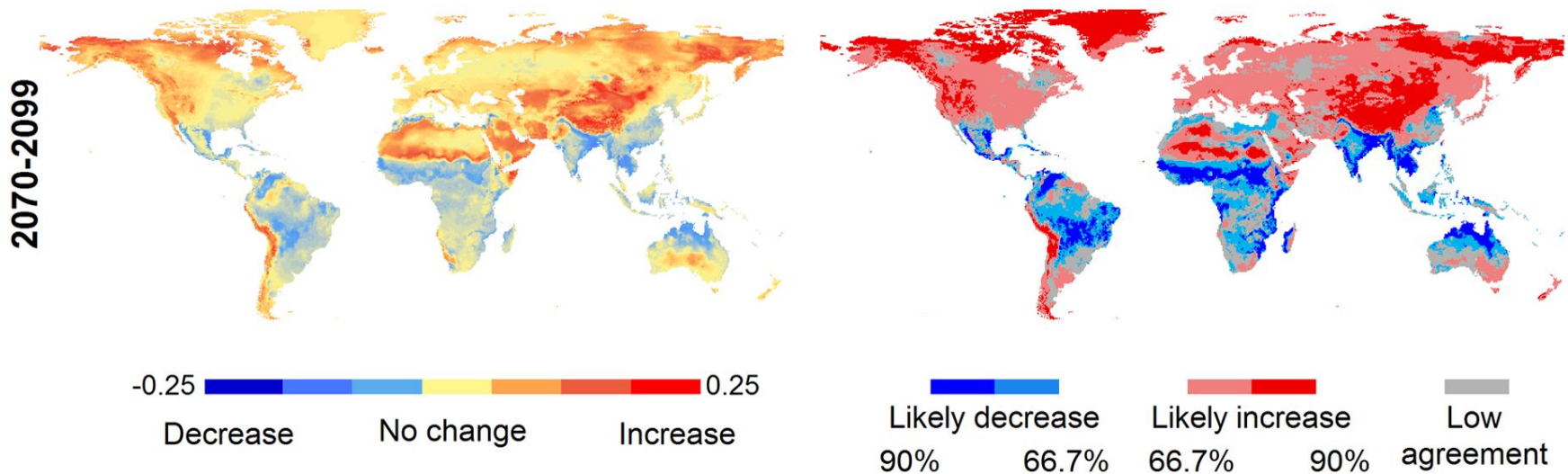


Smoke is increasing in the Arctic

(Warmer temperatures, longer fire seasons)

A. Modeled mean changes in fire probability

B. 16-model ensemble agreement



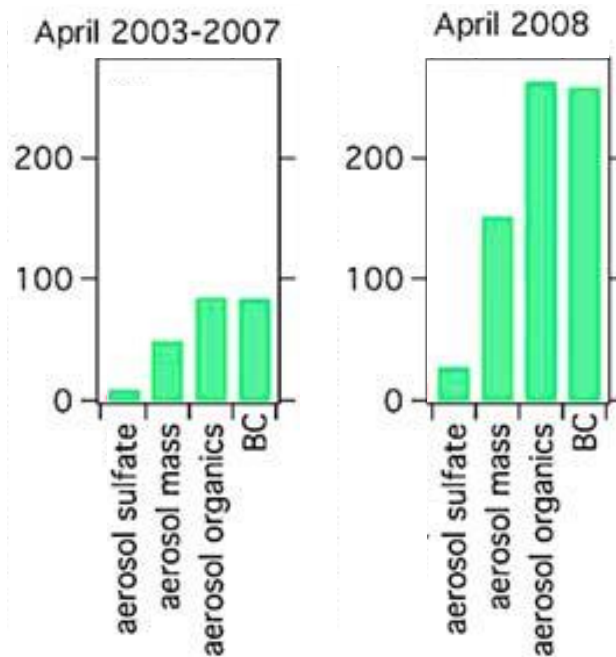
Moritz et al. (2012)

Balshi et al. (2009): Boreal wildfires in North America may double or triple

Smoke can double Arctic haze

Haze layer

Smoke enhancement
Background burden (%)



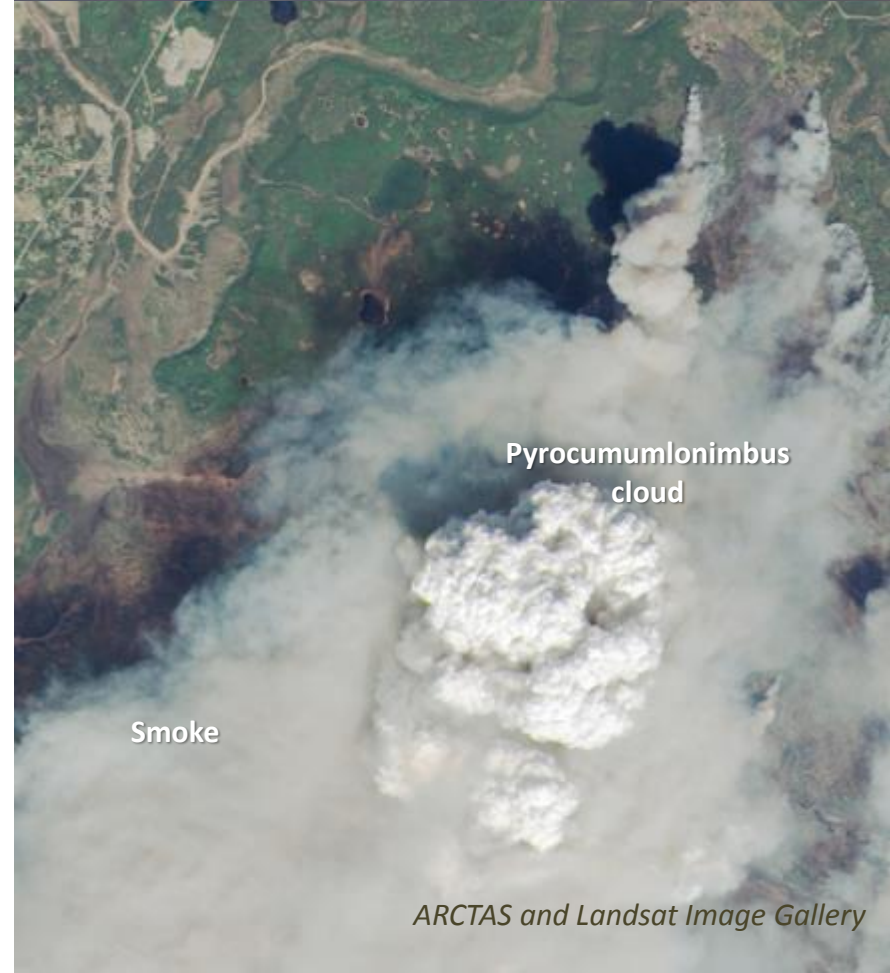
Modeled aerosol concentrations in the Arctic.

Modified from Warneke et al. (2010).

Smoke affects Arctic cloud:

- Lifetime
- Precipitation
- Albedo
- Downwelling longwave radiation

e.g., Earle et al., 2011; Jouan et al., 2012; Lance et al., 2011; Lindsey and Fromm, 2008; Rosenfeld et al., 2007; Tietze et al., 2011



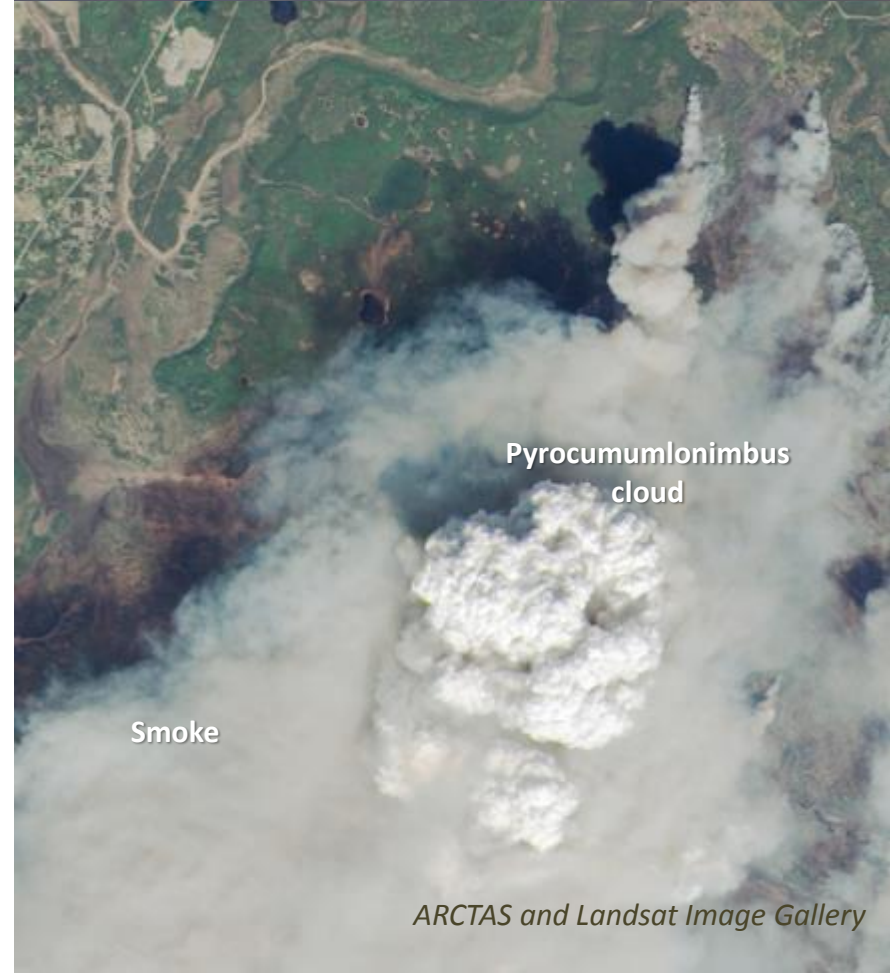
Smoke affects Arctic cloud:

- Lifetime
- Precipitation
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How to quantify?

- Sampling constraints
- Uncertain/non-linear meteorological and surface impacts

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Observations to quantify ACIs



Remote sensing



Surface measurements



Aircraft

Observations to quantify ACIs



Remote sensing

*Best way to observe global trends;
Challenges with co-location of clouds/aerosols, spatial biases*



Surface measurements



Aircraft

Observations to quantify ACIs



Remote sensing



Surface measurements



Aircraft

Best way to accurately quantify the albedo effect

Observations to quantify ACIs



Remote sensing



Surface measurements



Aircraft

Aerosol Cloud Interactions (ACI) (a.k.a. indirect effects, IE):

$$ACI = \frac{1}{3} \frac{d \ln N_{liq}}{d \ln BB_t}$$

N_{liq} = cloud droplet number, r_e = cloud droplet effective radius, LWP = liquid water path, BB_t = a biomass burning tracer

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(if every aerosol nucleated a cloud droplet)

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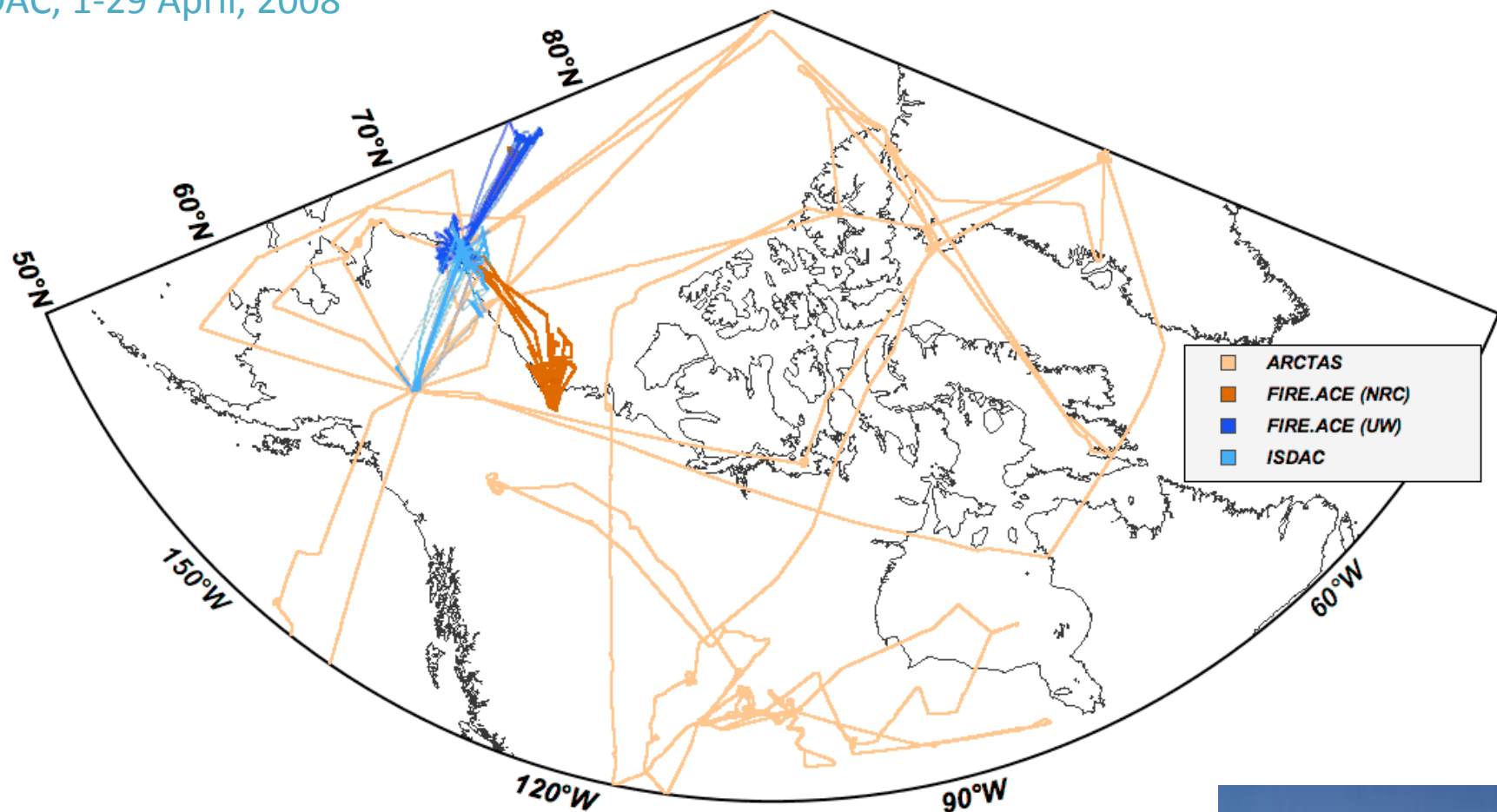
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All studies can be confounded by meteorology

NRC FIRE.ACE, 1-29 April, 1998 ; UW FIRE.ACE, 19 May - 24 June, 1998

ARCTAS-A 1-19 April; -CARB 29 June; -B 1-13 July, 2008

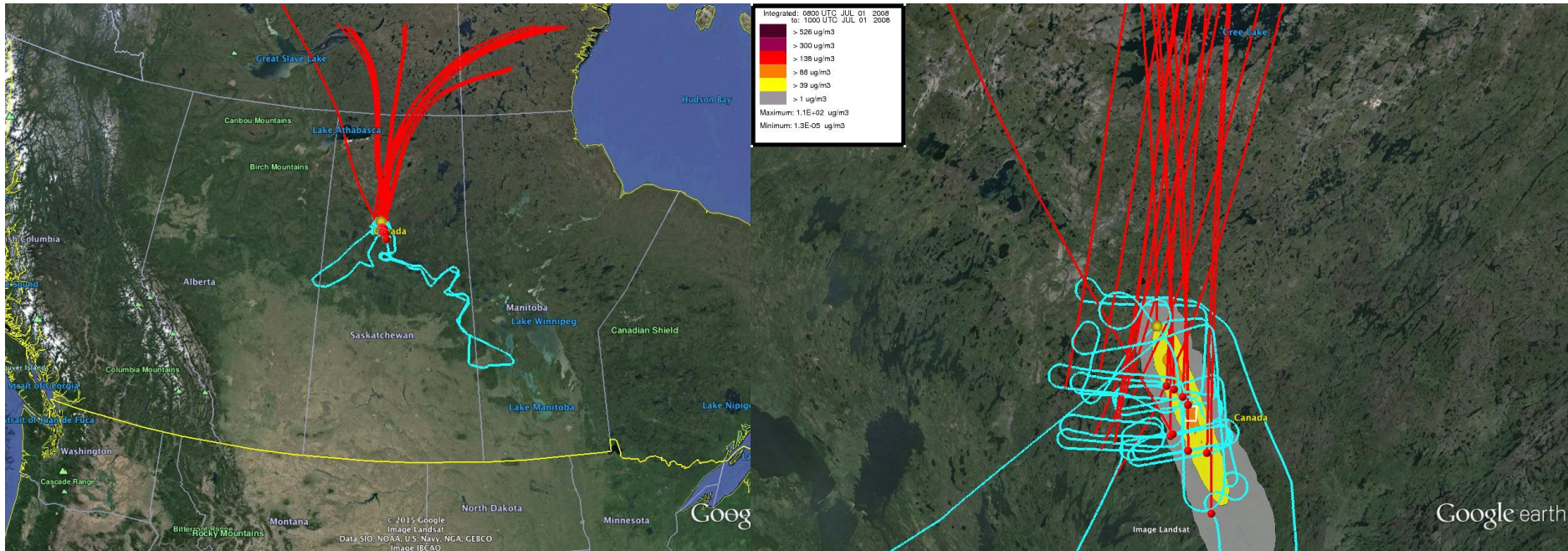
ISDAC, 1-29 April, 2008



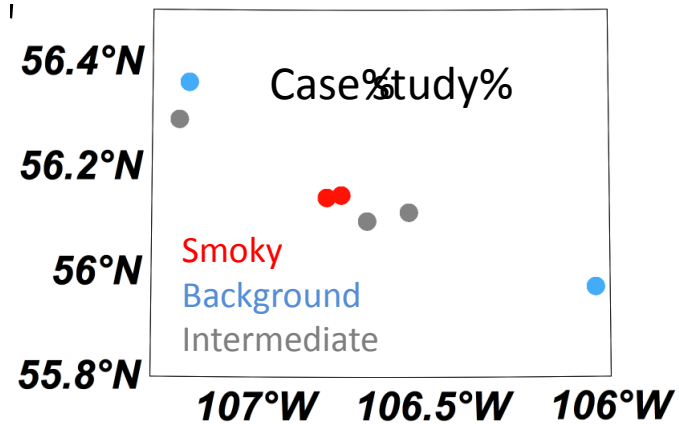
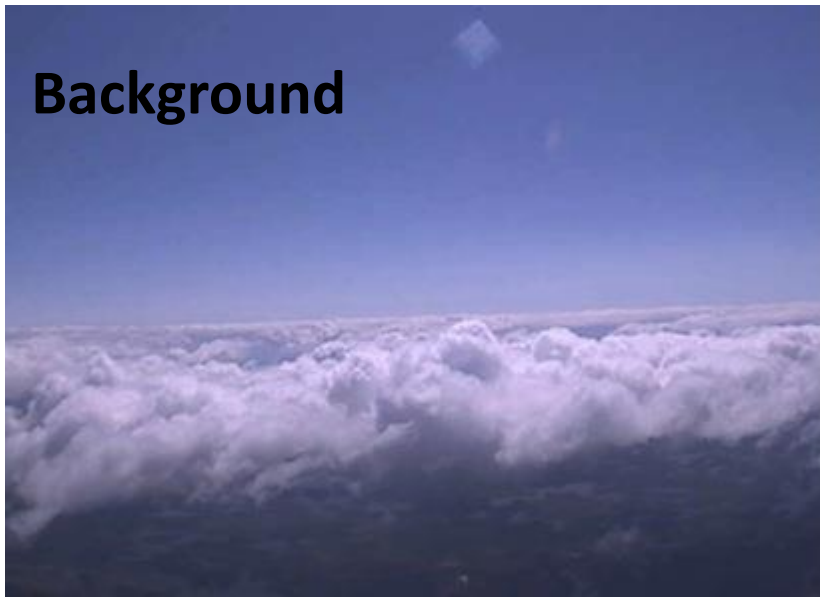
Sampling locations



Case Study Day: July 1, 2008 (ARCTAS-B)



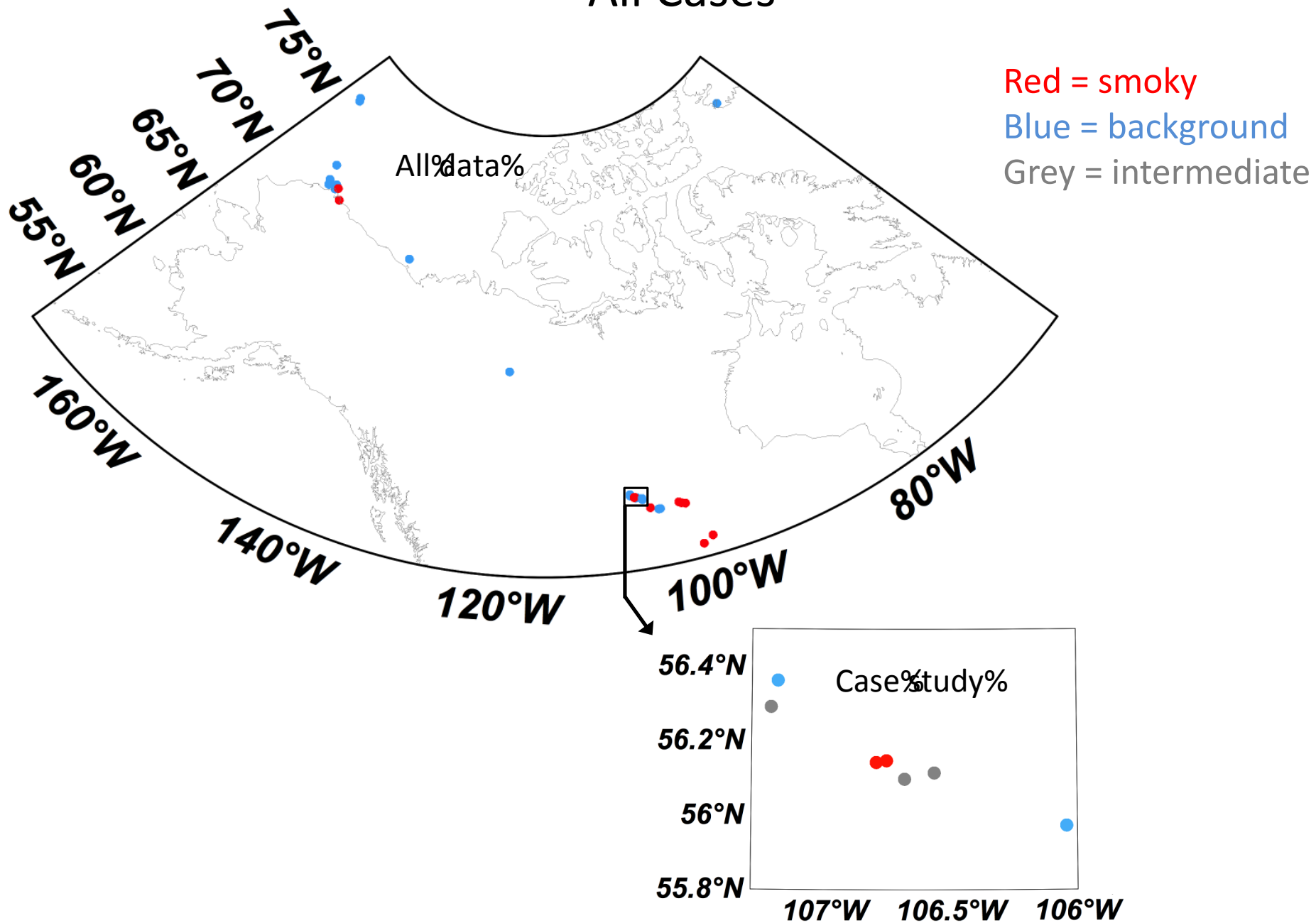
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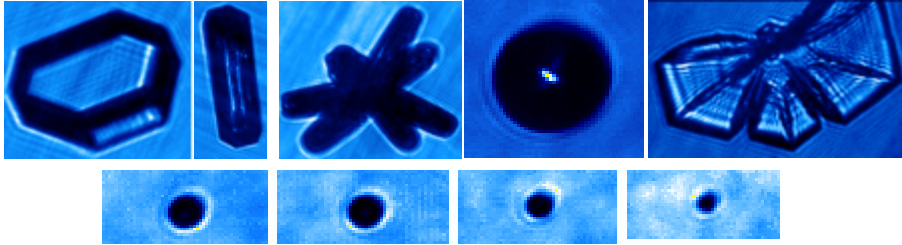
Conditions were atypical compared to the Arctic...

- Smoke was:
 - highly concentrated (2000-3000 particles cm^{-3})
 - fresh (hours old)
- Clouds had low LWC (median 0.02 g m^{-3})

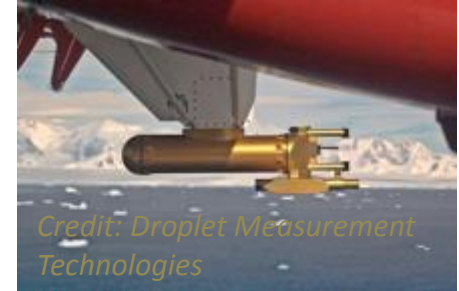
All Cases



Focus on liquid phase clouds



CPI images



CAPS-CAS
instrument

Cloud presence:

- $LWC > 0.01 \text{ g m}^{-3}$ (from CAPS-CAS or FSSP measurements)

Phase:

- FIRE.ACE/ISDAC: Cloud particle imager (CPI) roundness criterion + ice water content values
- ARCTAS: Temperatures $> 0^{\circ}\text{C}$

Air mass classification – ARCTAS

Background



Biomass burning



- In-cloud

- CO < 123 ppbv
- CH₃CN < 0.14 ppbv

- Near-cloud

- Submicron-SO₄²⁻ < 0.3 μg m⁻³
- BC < 0.12 μg C m⁻³

- In-cloud

- CO > 175 ppbv
- CH₃CN > 0.2 ppbv

Air mass classification – FIRE.ACE/ISDAC

Background



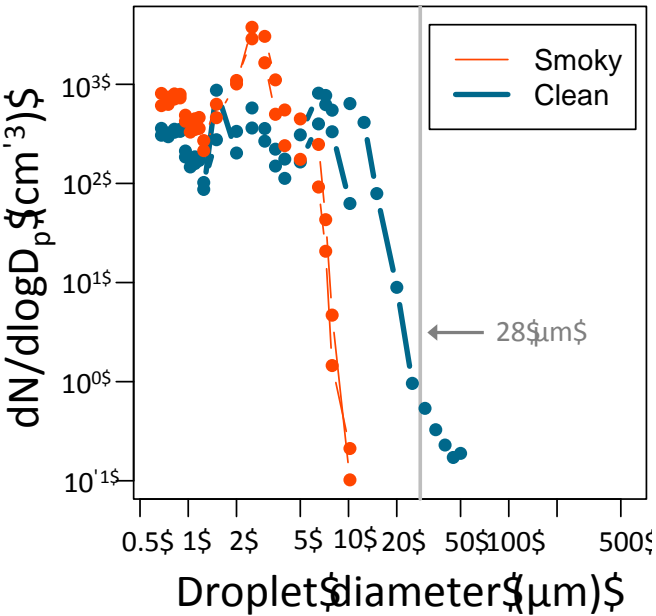
- Near-cloud PCASP aerosol concentrations ≤ 127 particles cm^{-3}

Biomass burning

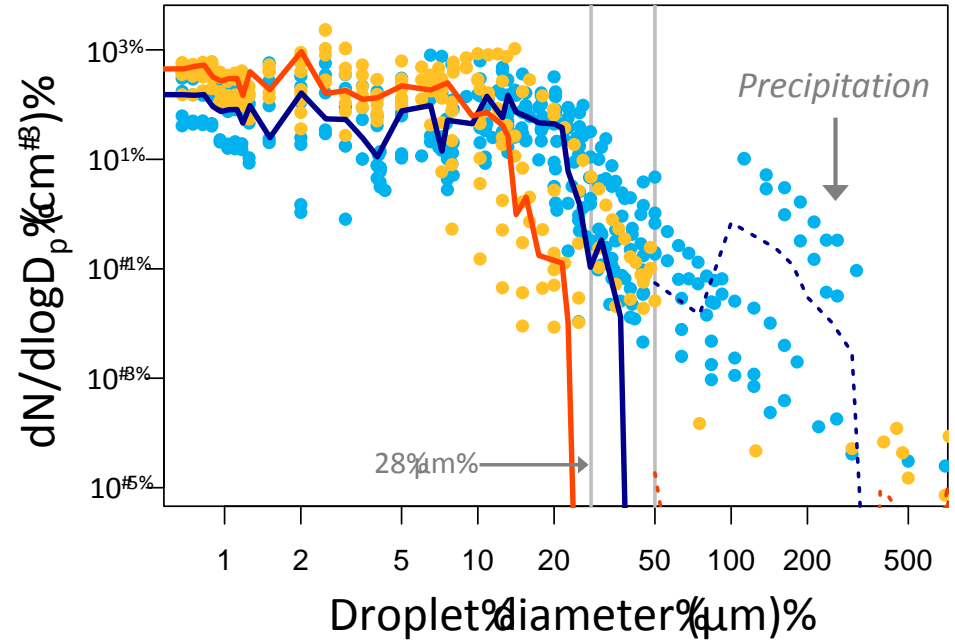


- ISDAC: Single Particle Mass Spectrometer
- FIRE.ACE: No chemical data; not included

Case study:



Multi-campaign assessment:

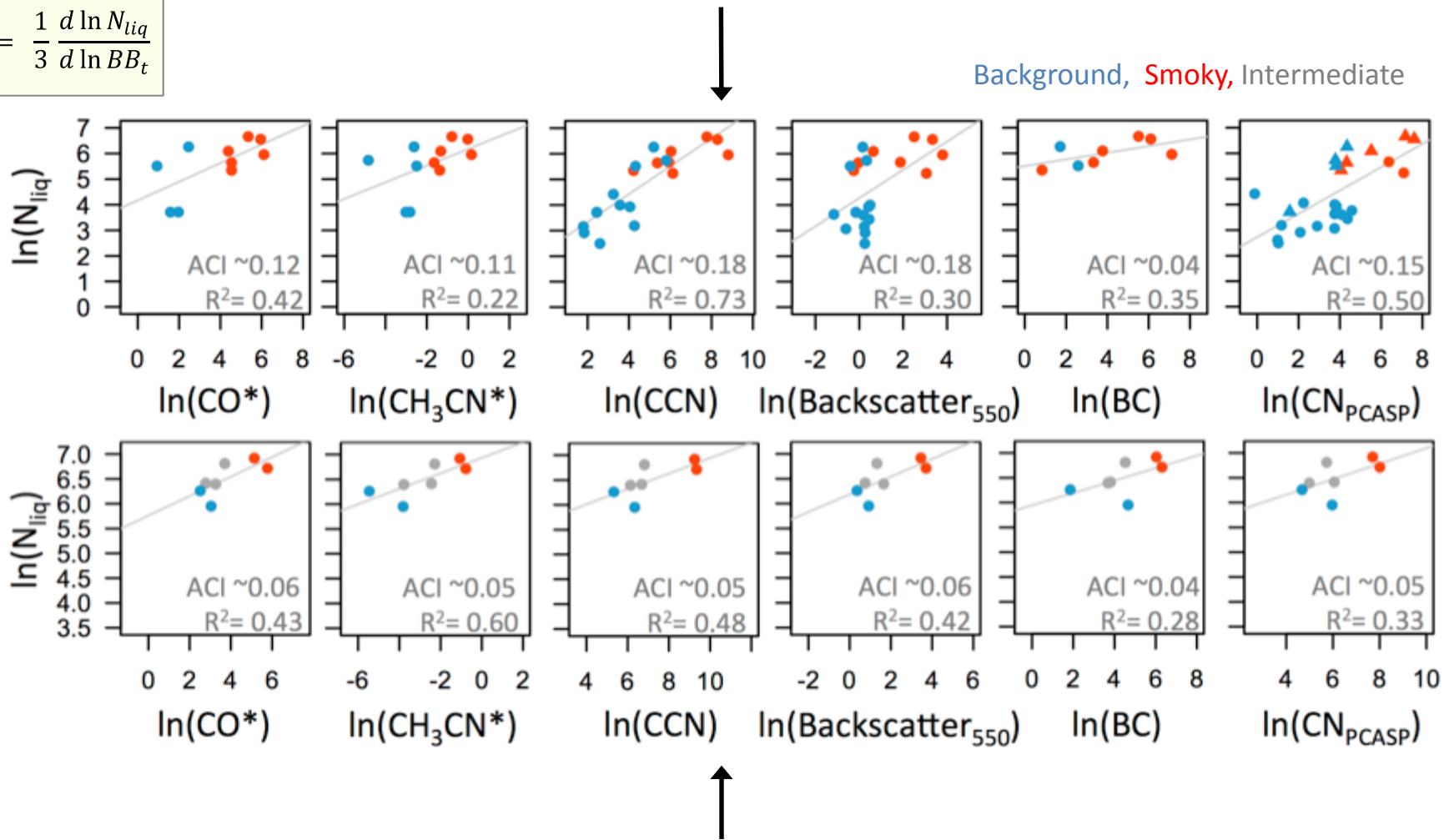


Distributions suggest that smoke may lower the probability of precipitation

Median cloud droplet radius in smoky clouds was ~50% smaller in both assessments

Multi-campaign assessment: ACI = 0.16 (95% CI range 0.14-0.17)

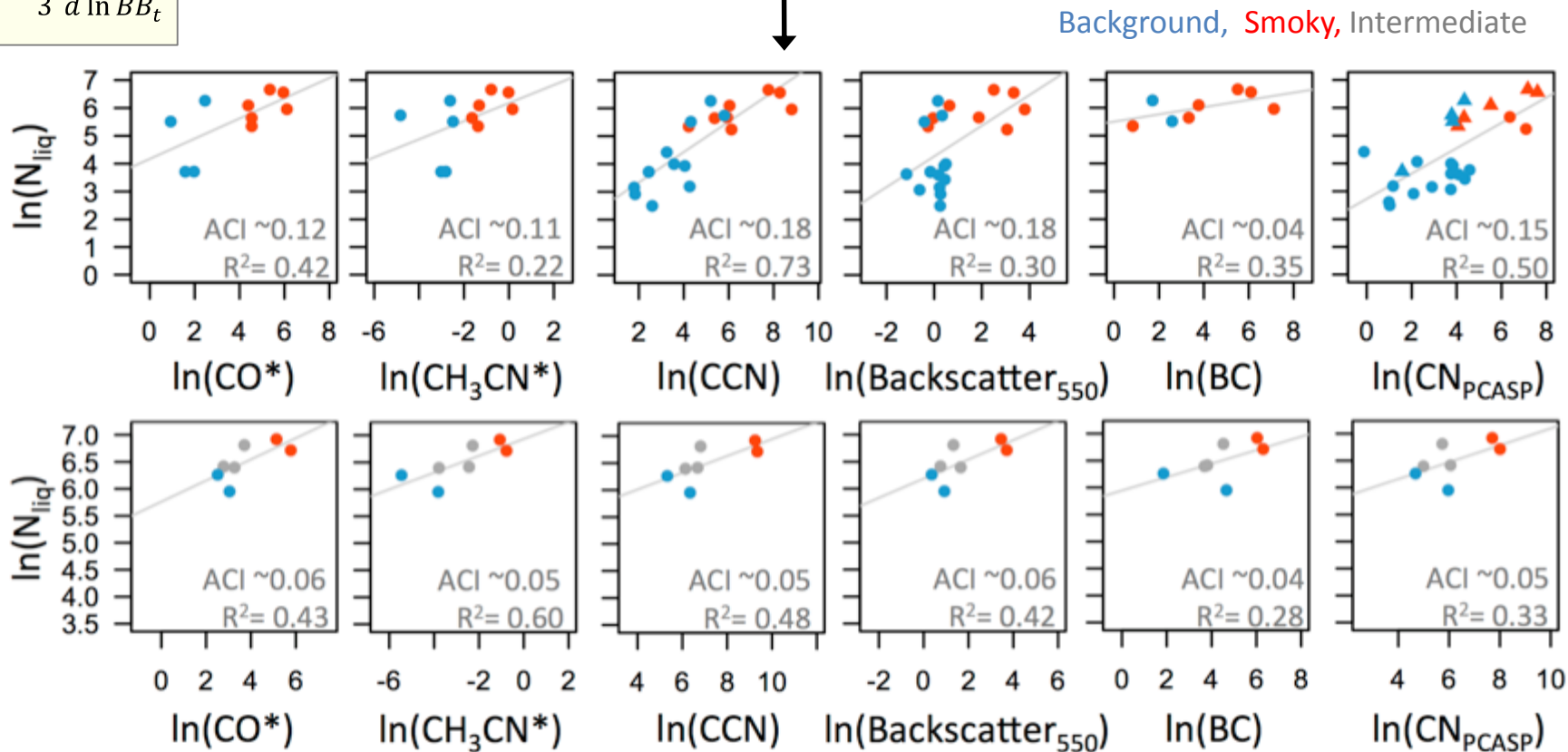
$$ACI = \frac{1}{3} \frac{d \ln N_{liq}}{d \ln BB_t}$$



Subarctic case study: ACI = 0.05 (95% CI range 0.04-0.06)

Multi-campaign assessment: $ACI = 0.16$ (95% CI range 0.14-0.17)

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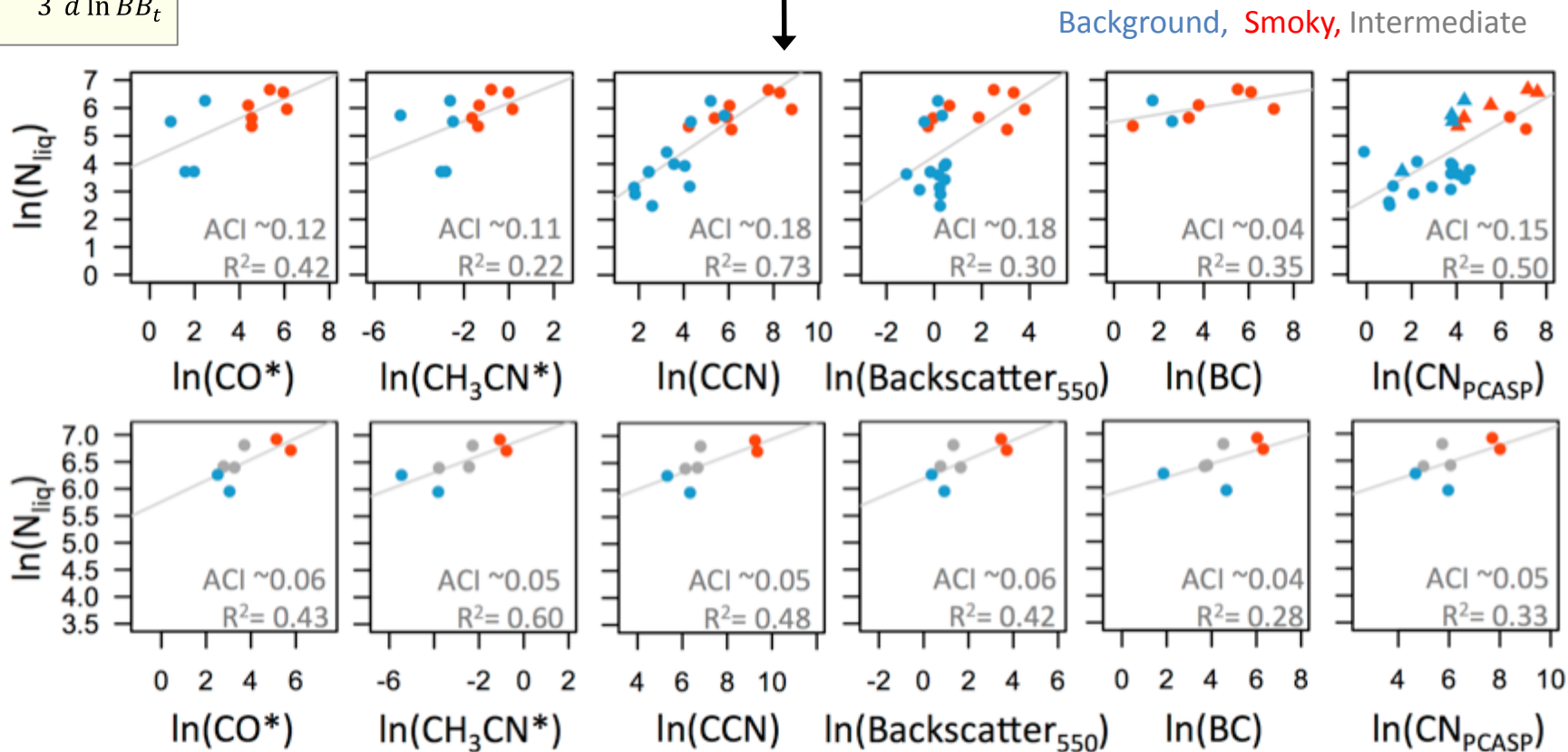


Subarctic case study: **ACI = 0.05** (95% CI range 0.04-0.06)

Case study: competition for water vapor limits droplet formation, cloud albedo effect

Multi-campaign assessment: $ACI = 0.16$ (95% CI range 0.14-0.17)

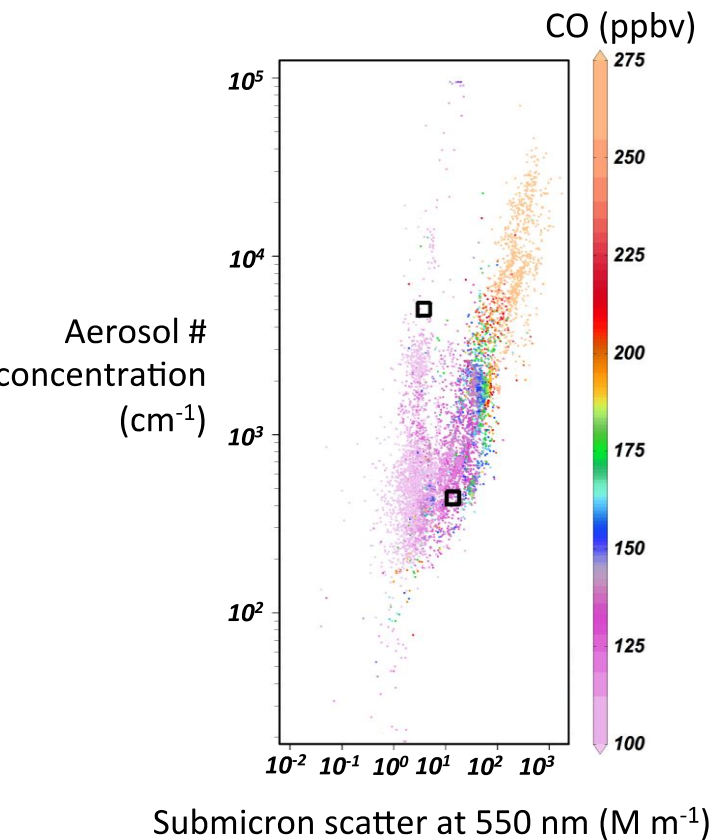
$$ACI = \frac{1}{3} \frac{d \ln N_{liq}}{d \ln BB_t}$$



Subarctic case study: **ACI = 0.05** (95% CI range 0.04-0.06)

Subarctic: ~2- 4 W m⁻² in radiative forcing in unbroken homogeneous cloud conditions;
Impact would be less in the Arctic due to higher surface albedo

ARCTAS-B
> 3 nm diam.

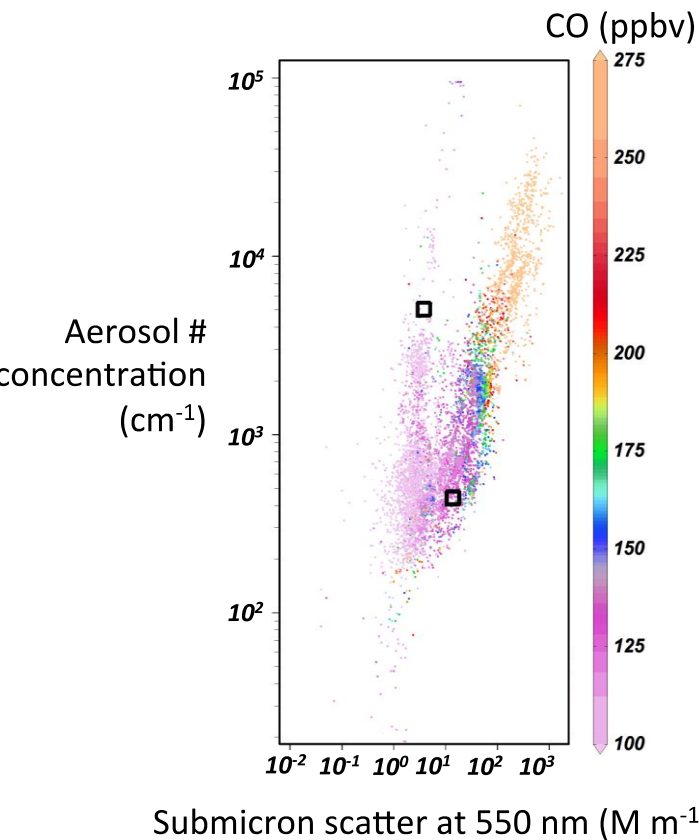


Many small summertime background particles that can condense on larger particles like smoke:

(Engvall et al., 2008; Leaitch et al., 2013; Tunved et al., 2013)

- By condensation, may increase diluted smoke volume up to ~1-10%
- Are hygroscopic and can be surface active
(Latham et al., 2013; Lawler et al., 2014; Zhou et al., 2001; Lohmann and Leck, 2005)

ARCTAS-B
> 3 nm diam.



Many small summertime background particles:

- By condensation, may increase diluted smoke volume up to ~1-10%
- Are hygroscopic and can be surface active
(Lathem et al., 2013; Lawler et al., 2014; Zhou et al., 2001; Lohmann and Leck, 2005)

- Are these particles surfactants?
- In dilute smoke, could they modify smoke CCN characteristics and cause deviations from the linear ACI model?

Conclusions



- 1) Smoke reduced median cloud droplet size by $\sim 50\%$, suggesting potentially strong second indirect effects on precipitation
- 2) Multi-campaign analysis ACI estimates ~ 0.16 out of max. possible 0.33
- 3) We observed that water vapor competition reduced cloud albedo effect in the case study to only 0.05 (associated reductions in subarctic summertime radiative flux for low and homogeneous cloud cover estimated at between $\sim 2-4 \text{ W m}^{-2}$)

Could the numerous small summertime background aerosols deposit onto dilute smoke and alter CCN properties?