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

LAUREN ZAMORA
Smoke is increasing in the Arctic
(Warmer temperatures, longer fire seasons)

A. Modeled mean changes in fire probability

B. 16-model ensemble agreement

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

Moritz et al. (2012)
Smoke can double Arctic haze

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
- Albedo
- Downwelling longwave radiation

How to quantify?

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

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
Observations to quantify ACIs

Remote sensing
Surface measurements
Aircraft
Observations to quantify ACIs

Remote sensing

Surface measurements

Aircraft

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

Best way to accurately quantify the albedo effect
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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Max. = 0.33
(if every aerosol nucleated a cloud droplet)

$N_{liq} = \text{cloud droplet number}$,  $r_e = \text{cloud droplet effective radius}$,  $LWP = \text{liquid water path}$,  $BB_t = \text{a biomass burning tracer}$
Observations to quantify ACIs

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

\[
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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
ISDAC, 1-29 April, 2008

Sampling locations

Convair-580

NASA’s DC8

Zamora et al. (in press) ACP
Case Study Day:
July 1, 2008 (ARCTAS-B)
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July 1, 2008 (ARCTAS-B)

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\(^{-3}\))
Zamora et al. (in press) ACP
Focus on liquid phase clouds

Cloud presence:
• LWC > 0.01 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°C
Air mass classification – **ARCTAS**

**Background**
- In-cloud
  - CO < 123 ppbv
  - CH$_3$CN < 0.14 ppbv
- Near-cloud
  - Submicron-SO$_4^{2-}$ < 0.3 μg m$^{-3}$
  - BC < 0.12 μg C m$^{-3}$

**Biomass burning**
- In-cloud
  - CO > 175 ppbv
  - CH$_3$CN > 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:**

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:**

Zamora et al. (in press) ACP
Multi-campaign assessment: ACI = 0.16 (95% CI range 0.14-0.17)

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)

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

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

Zamora et al. (in press) ACP
Multi-campaign assessment: $ACI = 0.16$ (95% CI range 0.14-0.17)

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

Subarctic: $\sim 2-4$ W m$^{-2}$ in radiative forcing in unbroken homogeneous cloud conditions; Impact would be less in the Arctic due to higher surface albedo
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)
Many small summertime background particles:

- By condensation, may increase diluted smoke volume up to ~1-10%

- Are hygroscopic and can be surface active
  \[(\text{Lathem et al., 2013; Lawler et al., 2014; Zhou et al., 2001; Lohmann and Leck, 2005})\]

- 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 ~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 ~2-4 W m$^{-2}$)

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