Emergent Constraints for Aerosol Indirect Effect

Minghuai Wang
School of Atmospheric Sciences, Nanjing University
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Uncertainties in radiative forcing come primarily from aerosol radiative forcing.
Climate Models: indispensable tools for studying aerosol climate effects, but with limitations in representing aerosol-cloud interactions.
Observations are critical for evaluating and improving climate models.
Direct constraints on model states are inefficient for constraining aerosol indirect forcing

Lee et al., 2016, PNAS

- Constraining CCN in current climate does not necessarily narrowing the estimate of aerosol indirect forcing
Emergent constraints

- Definition: Physically explainable empirical relationship between characteristics of the current climate and long-term climate prediction that emerge in collections of climate model simulations (Klein and Hall, 2015, Curr. Clim. Change Rep.)

- Three types of emergent constraints:
  - Potential emergent constraints (simple relationship)
  - Promising emergent constraints (physical basis for relationship)
  - Confirmed emergent constraints (physical understanding is credible)
Emergent constraints in climate feedback studies

**Snow-albedo feedback**

- **Predictor**: albedo change from seasonal cycle
- **Predictand**: albedo changes from climate change

Hall and Xu, 2006, GRL

**Cloud feedback**

- **Predictor**: lower tropospheric mixing over oceans
- **Predictand**: climate sensitivity

Sherwood et al., 2014, Nature
\( S_{\text{POP}} \): An emergent constraint for aerosol cloud lifetime effects of aerosols

\[ S_{\text{POP}} = -\frac{d\ln\text{POP}}{d\ln\text{AI}} \]

POP: Probability of precipitation (raining clouds divided by all clouds)
AI: Aerosol Index

M. Wang et al., 2012, *GRL*

- Predictor: \( S_{\text{POP}} \) from the present-day climate
- Predictand: Liquid water path change in response to CCN changes from PI to PD (cloud lifetime effects of aerosols)
Physically explainable: Both $S_{POP}$ and $\lambda$ strongly depends on the relative role of autoconversion in rain formation.

$S_{POP}$: promising emergent constraint or confirmed emergent constraint?
The 3rd AeroCOM indirect effect intercomparison project

- Main objective: To study cloud lifetime effects of aerosols in global aerosol-climate models, especially those used in CMIP5 (led by Steve Ghan and Minghuai Wang)

- Model runs: two runs (5 years each), All_2000 (PD, present day) and All_1850 (PI, pre-industrial)

- Participants: CAM5.3 and its variants (5 versions); ETH-ECHAM6-HAM2; SPRINTARS; HadGEM3-UKCA; ModelE2-TOMAS; GFDL AM3

Publications: two papers published (S. Zhang et al., 2016, ACP; S. Ghan et al., 2016, PNAS); several are in preparation (E. Gryspeerdet et al, 2016; M. Wang et al., 2016; ...)
Regime dependence of cloud lifetime effects (as a function of w500)

\[ \text{dlnLWP} = \frac{(PD - PI)}{PI} \]

\[ \text{dlnCCN} = \frac{(PD - PI)}{PI} \]

Zhang S., M. Wang, et al., 2016, ACP
Emergent constraints for other changes?

\[
\frac{d \ln \overline{R}}{d \ln \overline{E}} = \left[ \frac{d \ln \overline{C}}{d \ln \overline{N_d}} + \frac{d \ln \overline{R_c}}{d \ln \overline{N_d}} \right] \left( \frac{d \ln \overline{L}}{d \ln \overline{N_d}} - \frac{d \ln \overline{r_e}}{d \ln \overline{N_d}} \right) \frac{d \ln \overline{N_d}}{d \ln \overline{CCN}} \frac{d \ln \overline{CCN}}{d \ln \overline{E}}
\]

Ghan, Wang M., et al., 2016@PNAS
**$S_{POP}$**: a better metric for constraining cloud water response to aerosols than $S_R$

$S_{POP} = -d\ln POP / d\ln AI$

$S_R = -d\ln R / d\ln AI$  
(Feingold and Seibert, 2009)

$S_{POP}$: rain frequency susceptibility

$S_R$: rain susceptibility
Discrepancy in observational estimates of $S_{POP}$

Wang et al., 2012, GRL

\[ S_{POP_{-AT}} = - \frac{d \ln \text{POP}}{d \ln \text{AT}} \]

Mann et al., 2014, JGR

\[ S_{POP_{-CCN}} = - \frac{d \ln \text{POP}}{d \ln N_{CCN}} \]

Terai et al., 2015, JGR

\[ S_{POP_{-CDNC}} = - \frac{d \ln \text{POP}}{d \ln CDNC} \]
$S_{POP_{-}CDNC}$ vs. $S_{POP_{-}AI}$

$S_{POP_{-}CDNC}$ is substantially larger than $S_{POP_{-}AI}$, which can be explained by the weak dependence of CDNC on AI.

\[
S_{POP_{-}AI} = -\frac{\partial \ln POP}{\partial \ln AI} = \frac{\partial \ln CDNC}{\partial \ln AI} \cdot \frac{\partial \ln POP}{\partial \ln CDNC} = S_{POP_{-}CDNC} \cdot \frac{\partial \ln CDNC}{\partial \ln AI}
\]
Constraints from both $S_{\text{POP_CDNC}}$ and $S_{\text{POP_AI}}$

![Graph showing the relationship between $S_{\text{POP_CDNC}}$ and $S_{\text{POP_AI}}$ with various symbols representing different datasets.](image-url)
Summary

- Emergent constraints provides a way to constrain aerosol indirect forcing that is based on physical understanding and interpretation.
- Rain frequency susceptibility ($S_{POP}$) is shown to be a promising emergent constraint for cloud lifetime effects of aerosols.
- Further work is needed to better quantify observational uncertainties and to develop new emergent constraints on multiple processes for different cloud regimes.
Thanks!

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• Univ. of Wyoming: X. Liu; UMBC: Z. Zhang
Relative changes in CCN vs. relative changes in LWP: \((PD-PI)/PI\)

The response in LWP to a given CCN perturbation in CAM5 is about 3 times that in the MMF.

\[ Y = 0.11 \times X + 0.01 \]

\[ Y = 0.30 \times X + 0.04 \]
A new observable based on NASA A-Train satellites

- Rain frequency susceptibility to aerosol loading

\[ S_{\text{pop}} = -\frac{d\ln \text{POP}}{d\ln \text{AI}} \]

POP: Probability of precipitation (raining clouds divided by all clouds)
AI: Aerosol Index

- \( S_{\text{pop}} \) includes information about aerosols, clouds, and precipitation
- \( S_{\text{pop}} \) is easy to calculate (e.g., \( S_R \), \( R \) is rain rate)
The Multi-scale Aerosol-Climate Model

CAM5 with modal aerosols
Two-moment microphysics

SP-CAM5

(M. Wang et al., 2011a@GMD; 2011b@ACP)

CRM cloud/precipitation statistics used for cloud processing of aerosols
Published estimates of aerosol indirect effects

Source: Lohmann et al., 2010
Expressing indirect forcing in terms of liquid water path sensitivity

Value at $\lambda=0.04$ provides estimate of indirect forcing given change in CCN