Invigoration of deep convection in polluted environments: myth or reality?

Wojciech W. Grabowski

Mesoscale and Microscale Meteorology Laboratory

NCAR, Boulder, Colorado, USA
Results to be discussed are from two papers:


“Flood or Drought: How Do Aerosols Affect Precipitation?”
Flood or Drought: How Do Aerosols Affect Precipitation?

Rosenfeld et al. Science, 2008
“Flood or Drought: How Do Aerosols Affect Precipitation?”
Cloud buoyancy: the potential density temperature

$$\Theta_d = \Theta (1 + \epsilon q_v - q_c - q_p)$$

$$\epsilon \approx 0.6$$

$q_v$ – water vapor mixing ratio
$q_c$ – cloud condensate mixing ratio
  (small fall velocity; $\sim$cm/s)
$q_p$ – precipitation mixing ratio
  (large fall velocity; $\sim$m/s)
Condensation: the impact on latent heating exceeds vapor/condensate effects:

\[ \Theta_d = \Theta (1 + \varepsilon q_v - q_c) \]

\( \delta q \) – change of vapor mixing ratio

\[ \delta \Theta_d \sim \delta \Theta + \Theta \delta q \]

\[ \delta \Theta \sim L_v/cp \ \delta q \sim 2 \cdot 10^3 \ \delta q \quad L_v \sim 2 \cdot 10^6 \text{ J/kg} \]

\[ \Theta \ \delta q \sim 3 \cdot 10^2 \ \delta q \]
Liquid condensate freezing: the impact of latent heating approximately balances loading effect:

\[ \Theta_d = \Theta (1 + \varepsilon q_v - q_c) \]

\[ \delta q \sim \frac{L_f}{c_p} \delta q \sim 3 \cdot 10^2 \delta q \quad L_f \sim 3 \cdot 10^5 \, J/kg \]

\[ \Theta \delta q \sim 3 \cdot 10^2 \delta q \]
Condensate off-loading: $q_c$ is converted into $q_p$, $q_p$ falls out:

$$\Theta_d = \Theta (1 + \varepsilon q_v - q_c - q_p)$$
Rosenfeld et al. mechanism: freezing of liquid condensate carried through the 0 degC level:

\[ \theta_d = \theta (1 + \varepsilon q_v - q_c) \]

- Latent heating increases buoyancy...
- But condensate loading reduces buoyancy
Rosenfeld et al. mechanism: freezing of liquid condensate carried through the 0 degC level:

\[ \theta_d = \theta (1 + \varepsilon q_v - q_c) \]

latent heating increases buoyancy… …but condensate loading reduces buoyancy

The two almost perfectly balance each other, thus off-loading is the key. Does it work?
Finite supersaturation impacts $\Theta$, $q_v$, and $q_c$:

$$\Theta_d = \Theta (1 + \epsilon q_v - q_c)$$

Comparing $\Theta_d$ with finite supersaturation and bulk $\Theta_d$ (i.e., $S=0$), $\Theta_d^b$:

$$\theta_d^b \approx \theta_d + \Delta q \frac{L}{c_p} \left( \frac{p_o}{p} \right)^{R_d/c_p} (1 + \epsilon q_v - q_c)$$

the amount of water vapor that needs to condense to bring the air back to saturation

Grabowski and Jarecka JAS 2015
Comparing $\Theta_d$ with finite supersaturation and bulk $\Theta_d$ (i.e., $S=0$), $\Theta_d^b$:

10% supersaturation reduces buoyancy by several tenth of 1K…
“Flood or Drought: How Do Aerosols Affect Precipitation?”
So it seems that documenting aerosol effects of deep convections should be relatively simple in observations…

However, there are two key problems:

- Correlations between aerosol and convection do not imply causality: aerosols and meteorology can co-vary.

- Atmospheric observations may not be accurate enough to exclude meteorological factors.
Observations: correlation does not imply causality!

Li et al. (*Nature Geo* 2011) show correlation between clouds and aerosols over ARM SGP site; they say in the abstract:

“…precipitation frequency and rain rate are altered by aerosols”

(Varble *JAS* 2018 shows that aerosols and meteorology co-vary at SGP!)

Storer et al. (*JGR* 2014) show correlation between aerosol and tropical convection over Atlantic; they say in the abstract:

“These observations suggest that convective invigoration occurs with increased aerosol loading, leading to deeper, stronger storms in polluted environments”
Observations show correlations, but it is difficult (impossible?) to deduce causality using observations... 

Models are perfect tools to consider causality, but they have to be used carefully...

- single-cloud short simulations are inappropriate (spin-up problem);
- inability to separate physical impact from different flow realizations.
Example of a good application of a numerical model:

**Aerosol-cloud-precipitation effects over Germany as simulated by a convective-scale numerical weather prediction model**

A. Seifert¹, C. Köhler¹,², and K. D. Beheng³

¹Deutscher Wetterdienst, Offenbach, Germany  
²Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany  
³Karlsruher Institut für Technologie, Institut für Meteorologie und Klimaforschung, Karlsruhe, Germany

*Correspondence to:* A. Seifert (axel.seifert@dwd.de)

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Revised: 5 December 2011 – Accepted: 8 January 2012 – Published: 16 January 2012
Fig. 1. COSMO-DE model domain, with insertions of coverage of the German radar composite (grey), and the three evaluation subdomains with the model orography.

Table 3. Experiments performed for this study. The data can be accessed from DWD using the database IDs given here for individual experiments and years.

<table>
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<th>No.</th>
<th>ID in database 2008</th>
<th>ID in database 2009</th>
<th>ID in database 2010</th>
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<th>IN</th>
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<td>one-moment</td>
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</tbody>
</table>
Fig. 9. Box-whisker plot of relative change of 12-h accumulated area-averaged precipitation of JJA 2008–2010. Shown are anomalies relative to the mean of Exps. 1–6. The precipitation data has been averaged over either one of the three subdomains. The bottom and top of the boxes are the lower and upper quartiles, the line near the middle of the boxes is the median, whiskers are the 5th and 95th percentiles and the stars represent the mean value.
“…CCN and IN assumptions have a strong effect on cloud properties, like condensate amounts of cloud water, snow and rain as well as on the glaciation of the clouds, but the effects on surface precipitation are—when averaged over space and time—small…”

Fig. 9. Box-whisker plot of relative change of 12-h accumulated area-averaged precipitation of JJA 2008–2010. Shown are anomalies relative to the mean of Exps. 1–6. The precipitation data has been averaged over either one of the three subdomains. The bottom and top of the boxes are the lower and upper quartiles, the line near the middle of the boxes is the median, whiskers are the 5th and 95th percentiles and the stars represent the mean value.
Observations show correlations, but it is difficult (impossible?) to deduce causality using observations...

Models are perfect tools to consider causality, but they have to be used carefully...

- single-cloud short simulations are inappropriate (spin-up problem);
- inability to separate physical impact from different flow realizations.
Because of the nonlinear fluid dynamics, separating physical impacts from the effects of different flow realizations (“the butterfly effect”; Ed Lorenz) is nontrivial.

**Traditional approach:** parallel simulations with different microphysical schemes or scheme parameters

The separation is traditionally done by performing parallel simulations where each simulation applies modified model physics.

Evolution of cloud cover in 5 simulations of shallow cumulus cloud field. The only difference is in random small temperature and moisture perturbations at t=0.
Separation of physical impacts from different flow realizations: three 24-hr simulations with CCN of 100, 1000, and 3000 per cc.

**Aerosol–Cloud Interaction in Deep Convective Clouds over the Indian Peninsula Using Spectral (Bin) Microphysics**

Gayatri et al.  
*JAS* 2017

Maps of accumulated rainfall:

- (a) 100
- (b) 1000
- (c) 3000

![Graphs showing accumulated rainfall](image-url)
Novel modeling methodology: *the piggybacking*


Daytime convective development over land: A model intercomparison based on LBA observations

By W. W. GRABOWSKI1*, P. BECHTOLD2, A. CHENG3, R. FORBES4, C. HALLIWELL4, M. KHAIROUTDINOVA5, S. LANG6, T. NASUNOB7, J. PETCH8, W.-K. TAO6, R. WONG8, X. WU9 and K.-M. XU3
Simulations with double-moment bulk microphysics of Morrison and Grabowski (*JAS* 2007, 2008a,b):

\[ N_c, q_c \] - cloud water
\[ N_r, q_r \] - drizzle/rain water
\[ N_i, q_{id}, q_{ir} \] - ice

Important differences from single-moment bulk schemes:

1. Supersaturation is allowed.
2. Ice concentration linked to droplet and drizzle/rain concentrations.
Simulations with double-moment bulk microphysics of Morrison and Grabowski (*JAS* 2007, 2008a,b):

PRI: pristine case, CCN of 100 per cc
POL: polluted case, CCN of 1,000 per cc

The same ice initiation for POL and PRI

Piggybacking: D-PRI/P-POL: PRI drives, POL piggybacks
D-POL/P-PRI: POL drives, PRI piggybacks

Five-member ensemble for each
Lognormal single-mode CCN distribution:

\[
f_d = \frac{dN_a}{dr_d} = \frac{N_t}{\sqrt{2\pi} \ln \sigma_d r_d} \exp\left[-\frac{\ln^2(r_d/r_{d0})}{2 \ln^2 \sigma_d}\right]
\]

\(r_d\) is the dry aerosol radius

\(N_t\) is the total aerosol number

\(\sigma_d\) is the standard deviation

\(r_{d0}\) is the geometric mean radius of the dry particles

PRI, pristine: 100 mg \(^{-1}\)

POL, polluted: 1000 mg\(^{-1}\)

2.0

0.05 \(\mu\)m

as in Morrison and Grabowski (JAS 2007, 2008a)
Fig. 2. Albedo at hours (top)–(bottom) 2, 6, and 10 for two simulations from (left) D-PRI and (right) D-POL ensembles.
POL drives,
PRI piggybacks

PRI drives,
POL piggybacks
Comparing buoyancy between driving and piggybacking sets (hour 6):

$1 \text{ K} \approx 0.03 \text{ m s}^{-2}$

at 9 km (-27 degC)

(Rosenfeld et al. mechanism...)
Comparing buoyancy between driving and piggybacking sets (hour 6):

\[ 1 \text{ K} \approx 0.03 \text{ m s}^{-2} \]

**POL has slightly less buoyancy than PRI...**
Comparing buoyancy between driving and piggybacking sets (hour 6):

$1 \text{ K} \approx 0.03 \text{ m s}^{-2}$

at 3 km (9 degC)
Comparing buoyancy between driving and piggybacking sets (hour 6):

1 K ≈ 0.03 m s\(^{-2}\)

POL can have more buoyancy than PRI...
Hour 6, $z = 3 \text{ km (9 degC)}, \text{ points with } w > 1 \text{ m/s, } Q > 1 \text{ g/kg}$

activated CCN

All CCN is activated even for the strongest updrafts...

updraft velocity

supersaturation

Supersaturations are large, especially in PRI
\[ \theta_d = \theta(1 + \varepsilon q_v - q_c - q_r - q_{id} - q_{ir}) \]

Comparing \( \Theta_d \) with finite supersaturation and \( \Theta_d \) at \( S=0, \Theta^b_d \)

Impact of finite supersaturations on cloud buoyancy in deep convection
solid lines: driving set
dashed lines: piggybacking set
Impact on the cloud dynamics!
This can be shown by looking at the updraft statistics (no time to show that, see Grabowski and Morrison *JAS* 2016).

**solid lines:** driving set

**dashed lines:** piggybacking set
Lognormal double-mode CCN distribution:

\[
f_d = \frac{dN_a}{dr_d} = \frac{N_t}{\sqrt{2\pi} \ln\sigma_d r_d} \exp\left[-\frac{\ln^2(r_d/r_{d0})}{2\ln^2\sigma_d}\right]
\]

- \( r_d \) is the dry aerosol radius
- \( N_t \) is the total aerosol number
- \( \sigma_d \) is the standard deviation 2.0
- \( r_{d0} \) is the geometric mean radius of the dry particles 0.05 + 0.01 \( \mu \)m

**PRI, pristine:** 100 + 500 mg\(^{-1}\)  
**POL, polluted:** 1000 + 5000 mg\(^{-1}\)

as in Morrison and Grabowski (*JAS* 2007, 2008a)
Hour 6, $z = 3$ km ($9 \text{ degC}$), points with $w > 1$ m/s, $Q > 1$ g/kg

Not all CCN is activated even for the strongest updrafts...

Supersaturations are smaller now, but still up to several percent...
Smaller difference between POL and PRI for upper-tropospheric anvils...

POL minus PRI still significantly larger when POL is driving...
The piggybacking methodology allows confident assessment of the impact of cloud microphysics on cloud simulation.

Piggybacking clarifies the dynamic basis of convective invigoration in polluted environments.

POL versus PRI simulations with 2-moment bulk scheme:

- small modification of the cloud dynamics in the warm-rain zone due to differences in the supersaturation field, \( \sim 10\% \) more rain in polluted cases;

- significant *microphysical* impact on convective anvils.
Can the impact of aerosols on deep convection be isolated from the effects of meteorology in atmospheric observations?

Wojciech W. Grabowski

National Center for Atmospheric Research, Boulder, Colorado, USA

“Flood or Drought: How Do Aerosols Affect Precipitation?”
Are atmospheric observations accurate enough to exclude meteorological factors?
Daytime convective development over land: A model intercomparison based on LBA observations

By W. W. GRABOWSKI¹*, P. BECHTOLD², A. CHENG³, R. FORBES⁴, C. HALLIWELL⁴, M. KHAIROUTDINOV⁵, S. LANG⁶, T. NASUNO⁷, J. PETCH⁸, W.-K. TAO⁶, R. WONG⁸, X. WU⁹ and K.-M. XU³
The argument:

If there are other factors that affect convection ("meteorology"), then the impact can be wrongly interpreted as aerosol effects…

The modeling idea:

Compare simulations with and without changes in the environment ("meteorology") in which convection develops. The changes are small and thus difficult to detect in observations:

- additional forcing
- modified surface fluxes
- modified temperature profile
- modified RH profile

simulations with the two aerosol modes (more realistic?)
\[ w = w_o \sin\left(\pi \frac{z}{L}\right) \]

\[ 0 < z < L \]

\[ w_o = 0.5 \text{ cm/s} \quad L = 10 \text{ km} \]

vertical: 0.5 cm/s over 5 km

horizontal: 0.5 m/s over 500 km
...small but noticeable impact on cloudiness...
…a significant impact on surface precipitation...

So if you did not know about the ascent, you may attribute the change to aerosols!...
...the impact on CAPE and CIN is insignificant ...
Global Atmospheric Research Program (GARP) -
Atlantic Tropical Experiment (GATE)

June 15, 1974 to September 23, 1974
Project Location: Atlantic Ocean
Grabowski et al. (*JAS* 1996, 1998a,b)
GATE sounding and surface precipitation data
Observations alone cannot provide support for the convection invigoration in polluted environments. The key issue is that correlations between modified aerosols and modified clouds seen in observations do not imply causality.

Separation of aerosol impact from the impacts of meteorology (e.g., different advective tendencies of temperature and moisture that drive cloud dynamics) is virtually impossible using current measurement capabilities.
I strongly believe that the convection invigoration is a myth, at least in the way it is presented in papers by Danny Rosenfeld and his entourage (e.g., Rosenfeld et al. *Science* 2008, Fan et al. *Science* 2018).

Only time will tell who is right and who is wrong…