Lessons learned from field campaigns on shallow clouds

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Themes

• $N_a - N_d$ [aerosol concentration – cloud droplet concentration]
  – Five decades of evidence linking cloud droplet concentration with aerosol concentration

• **Light precipitation sensitivity to $N_d$**
  – Drizzle common in the cloud-capped PBL, esp. over ocean
  – Consistent indication that Sc clouds with same amount of condensate precipitate less readily when they have larger $N_d$
  – Unclear from field data about susceptibility of precip. in Cu

• **Importance of cloud dynamical responses**
  – Are polluted Cu clouds more vigorous?
  – Cloud top entrainment
Recent MBL Cloud focused field programs
**FIRST INDIRECT EFFECT**

- Lower albedo
- Macrophysically identical clouds
- Fewer larger drops
- Higher albedo
- More smaller drops

**SECOND INDIRECT EFFECT**

- Lower albedo
- Macrophysically different clouds
- More efficient precipitation
  - More LWC depletion
  - Less cloud cover/longevity
- Higher albedo
- Less efficient precipitation
  - Less LWC depletion
  - More cloud cover/longevity
Key physical processes: Stratocumulus

- Large scale subsidence
- Evaporative cooling
- Latent heating
- Longwave cooling
- Solar heating
- Drizzle
- Surface fluxes energy & moisture

Turbulent mixing

Sea surface

FREE TROPOSPHERE

BOUNDARY LAYER
$N_a-N_d$ relationship

• Formalized as the ACI metric:

$$ACI = \frac{\partial \ln N_d}{\partial \ln N_a}$$

— where $N_a$ usually refers to as the concentration of accumulation mode aerosol particles.

• More complex relationship known as cloud droplet concentration closure (whereby entire CCN spectrum or size distribution/composition is specified, along with updraft speed statistics)

• Consequences for cloud albedo first proposed by Twomey (1974, 1977)
- First $N_d$ closure experiments by Twomey and Warner (right)
- Revisited in the 1990s (Martin et al. 1994, below)
  - Linear relationships for low $N_a$
  - "saturation" effect at larger $N_a$


Cloud droplet concentration closure

- Excellent closure in small Cu and Sc
- Activation largely a solved problem

Figure 2. Aerosol-CDNC closure: predicted versus observed droplet concentration. Observed values use method 1 screening (see text) for adiabaticity. The short-dashed line represents an unweighted least squares linear fit to the data in log-log units. The long-dashed line represents a fit to the data when method 2 screening is used. The solid line represents perfect model-observation agreement. The term “cloud base” reiterates that observations used in this plot were generally taken in adiabatic regions within 100 m of cloud base.

ACI

• More recently (2000s) attention has turned to evaluation of Twomey effect on cloud radiative properties, e.g. using ACI metrics:

\[ ACI_\tau = \left( \frac{\partial \ln \tau}{\partial \ln N_a} \right)_{LWP} \]

– where \( N_a \) usually refers to as the concentration of accumulation mode aerosol particles.

• Discrepancies between aircraft (e.g. Painemal and Zuidema values close to Twomey expectations) and remote sensing estimates that are often lower (see McComiskey et al. 2012) – scale issues?


Light precipitation sensitivity to $N_d$

First quantitative measurements in Sc. clouds (Brost et al. 1982)

Precipitation increases strongly with cloud top height in warm precipitating trade cumulus (Byers and Hall 1955)
Precipitation “susceptibility” metric

Analogous to albedo susceptibility, precipitation susceptibility expresses sensitivity of precipitation rate to cloud droplet concentration:

\[
R'_0 = -\frac{d \ln R}{d \ln N_d}.
\]  

(14.4)

\(R'_0\) expresses the relative change in precipitation \(R\) for a relative increase in \(N_d\) in warm clouds. The minus sign is applied so that a positive \(R'_0\) will reflect the conventional wisdom that for warm rain, \(R\) and \(N_d\) are negatively correlated.

Precipitation both macrophysically and microphysically controlled

Precip. susceptibility decreases with cloud thickness in marine Sc

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Brenguier and Wood [FIAS, 2009]

Terai et al. [Atmos. Chem. Phys. 2012]
Cloud macrophysical responses: ship tracks are useful control experiments for aerosol influences on clouds

- LWC reductions in some ship tracks (see also Coakley and Walsh 2002)

- Effect likely related to increased entrainment caused by (a) TKE invigoration due to drizzle suppression; (b) reduced cloud drop sedimentation (Ackerman et al. 2004, Bretherton et al. 2007)

Chen et al. (Atmos. Chem. Phys., 2012)
Light precipitation drives cloud transitions

DYCOMS-2 Field Campaign
Stevens et al. (2005, BAMS)
Cloud effects on aerosols

Observations of the Geographical Variation of Cloud Nuclei

S. Twomey and T. A. Wojciechowski
Naval Research Laboratory, Washington, D.C.
(Manuscript received 16 December 1968)

ABSTRACT

Airborne measurements at flight level of cloud nuclei have been carried out during approximately 100,000 mi of flight over wide areas of the world. A thermal diffusion chamber was used to obtain cloud-nuclei spectra which present the concentration of active nuclei as a function of supersaturation over the range of supersaturation of interest in cloud formation. The results confirm previous conclusions that continental air masses are systematically richer in cloud nuclei and indicate that the median of cloud nuclei over the open ocean is reasonably predictable and varied little from region to region. Over continents the median spectrum does not seem to vary greatly even when North America was compared to Africa and Australia; however, the variability about the median is much greater over land when compared to ocean areas. The results indicate that the lifetime of cloud nuclei, at least over the oceans, is about 3 days. The results require a widespread and relatively uniform source of cloud nuclei both over the oceans and over the land, and it is indicated that the sources of nuclei are not largely dependent on industrial or other man-made pollution.

drizzle helps control CCN and cloud microphysical variability in the MBL

- **Simple** budget model for CCN/$N_d$ in the MBL:

\[
\dot{N} = \dot{N}_{ent} + \dot{N}_{sfc} + \dot{N}_{coal}
\]

\[
N_{eq} = \frac{N_{FT} + \beta U^{3.41}}{Dz_i} \left( \frac{h k P_{CB}}{Dz_i} \right)
\]

- Assume constant FT aerosol conc.
- **Model** $N_d$ gradients mostly driven by precipitation sinks

Polluted shallow cumulus may have shorter lifetimes

Lessons

- $N_a-N_d$ relationships mostly an engineering rather than a science challenge
  - Scale effects important; updrafts important

- Observations show good evidence for aerosol-driven precipitation suppression, but also for precipitation-driven aerosol suppression
  - Together with “contamination” of the CCN signal by near-cloud radiative/swelling effects, results in major challenges in interpreting satellite aerosol-cloud relationships

- Cloud macrophysical responses to changing CCN can be observed but obtaining adequate controls is challenging
  - Ship track clouds can increase or decrease condensate in response to aerosol increases.
High resolution measurements of the EIL atop stratocumulus

Free troposphere

Entrainment Interfacial Layer (EIL)

Cloud layer

Large eddy scale $\ll$ EIL thickness

“nibbling rather than engulfment”

Katzwinkel et al. (BLM, 2011)
Entrainment in trade cumulus: new considerations

- Upward mass transport in cumulus clouds primarily balanced by near-cloud downdrafts
- Implications for species longevity in the trade Cu MBL, and for lateral entrainment

Jonker et al. (2008)

Heus et al. (2009)
New capabilities open new frontiers

• ARM Climate Research Facilities, especially new remote sensing and aerosol sampling suites, offer long-duration sampling of cloud physical and dynamical processes. New statistical approaches to cloud sampling. New permanent ARM site in the Azores.

• Need for more routine measurements over the remote ocean (e.g. NSF Ocean Observatories Initiative “super buoys”)

• Aircraft facilities now offer longer range (e.g. Global Hawk, HIAPER), unprecedented remote sensing

• **Big capabilities** ⇒ **need big thinking**
Where new field observations can help

• Factors controlling cloud top entrainment in stratocumulus and cumulus.
  – Role of shear and evaporative cooling uncertain.
  – Need to exploit new measurements approaches, both in-situ (very high resolution measurements) and remote sensing (new Doppler radar and lidar approaches)

• Microphysical impacts (both CCN and ice formation) on marine low clouds over the extratropical oceans
  – IN remain poorly understood and measured
  – Role of aerosol in influencing extratropical cloud regimes (e.g. open/closed cells, collapsed boundary layers)
  – Aerosol transport mechanisms to the remote ocean
  – What controls cloud droplet concentration over the extratropical oceans?
Stratocumulus cloud thickness

Data are from the published literature and available datasets from recent stratocumulus field campaigns (Nicholls and Leighton 1986; Boers and Krummel 1998; Miles et al. 2000; Pawlowska and Brenguier 2003; Comstock et al. 2004; vanZanten et al. 2005; Wood 2005a; Lu et al. 2007; McFarquhar et al. 2007; Lu et al. 2009; Wood and coauthors 2011)
What remains to be done?

• Understanding of entrainment and key processes affecting it remains poor
  – New measurement techniques required
  – Large eddy models do not yet explicitly model entrainment

• Large scale model treatments of low clouds are improving but low cloud feedback not narrowing significantly. Why?

• Aerosol impacts on Sc and (perhaps as importantly) Sc impacts on aerosols are not well known
Shallow, well-mixed STBL

Deep, cumulus-coupled STBL
Differences in precipitation "efficiency" between continental and marine clouds

A STUDY OF CONVECTIVE PRECIPITATION BASED ON CLOUD AND RADAR OBSERVATIONS

By Louis J. Battan and Roscoe R. Braham, Jr.

University of Chicago

(Manuscript received 6 March 1956)

ABSTRACT

Observations of precipitation and cloud-top height in the central United States and in the Caribbean area, obtained from radar-equipped airplanes, have been analyzed in terms of the fraction of clouds of a given height which contains precipitation. These data are compared with observations of a similar type taken by Braham, Reynolds and Harrell in New Mexico. It is concluded that the condensation-coalescence process can account for the formation of precipitation in convective clouds in all three regions but in varying proportions of clouds.

Fig. 6. Percentage of cumuli with precipitation as function of cloud-top height and temperature for three different geographical regions (lower part of diagram). Schematic clouds in upper part of diagram fall in height categories where 20 per cent were observed to contain precipitation echoes.

Canonical profiles

Albrecht et al. (J. Geophys. Res., 1995)
Entrainment interfacial layer