Precipitation as a driver of cloud droplet concentration variability along 20°S

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Photograph: Tony Clarke, VOCALS REx flight RF07
Radiative impact of cloud droplet concentration variations

Satellite-derived cloud droplet concentration $N_d$ and albedo enhancement (fractional).

How do we explain this pattern?

low level wind

$\bullet$ 0.05 SO$_2$ emission TgS yr$^{-1}$
$\bullet$ 0.2
$\bullet$ 0.5

George and Wood, Atmos. Chem. Phys., 2010
Aerosol (D>0.1 μm) vs cloud droplet concentration (VOCALS, SE Pacific)

see also...
Twomey and Warner (1967)
Martin et al. (1994)
Screen to remove heterogeneous clouds by insisting on $\text{CF}_{\text{liq}} > 0.6$ in daily L3.
Prevalence of drizzle from low clouds

Drizzle occurrence = fraction of low clouds (1-4 km tops) for which $Z_{\text{max}} > -15 \text{ dBZ}$

Simple CCN budget in the MBL

\[ \dot{N} = \left[ \dot{N} \right]_{\text{ent}} + \left[ \dot{N} \right]_{\text{sfc}} + \left[ \dot{N} \right]_{\text{coal}} + \left[ \dot{N} \right]_{\text{dry dep}} \approx 0 \]

Model accounts for:
- Entrainment
- Surface production (sea-salt)
- Coalescence scavenging
- Dry deposition

Model does not account for:
- New particle formation – significance still too uncertain to include
- Advection – more later
Production terms in CCN budget

\[
\left[ \dot{N} \right]_{\text{ent}} = \frac{w_e (N_{FT} - N)}{Z_i}
\]

\[
\left[ \dot{N} \right]_{\text{sfc}} = \frac{\beta U_{10}^{3.41}}{Z_i}
\]

- Entrainment rate
- FT Aerosol concentration
- MBL depth
- Wind speed at 10 m
- Sea-salt parameterization-dependent constant

We use Clarke et al. (J. Geophys. Res., 2007) at 0.4% supersaturation to represent an upper limit.
Loss terms in CCN budget: (1) Coalescence scavenging

\[
\left[ \dot{N} \right]_{coal} = -KNP_{CB} \frac{h}{z_i}
\]

Comparison against results from stochastic collection equation (SCE) applied to observed size distribution

\[ \dot{N} \approx -\pi E_0 N \int_0^{\infty} r^3 w_T n(r) \, dr = -\frac{3}{4\rho_w} E_0 NP \]

Steady state (equilibrium) CCN concentration

\[ N_{eq} = \frac{\left( N_{FT} + \frac{\beta U_{10}^{3.41}}{Dz_i} \right)}{\left( 1 + \frac{hkP_{CB}}{Dz_i} \right)} \]

\[ \frac{w_e}{z_i} = D = \text{surface divergence} \]
### Observable constraints from VOCALS and A-Train

\[ N_{eq} = \left( \frac{N_{FT} + \beta U_{10}^{3.41}}{Dz_i} \right) \left( \frac{hkP_{CB}}{Dz_i} \right) \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Source</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_{FT})</td>
<td>Weber and McMurry (1996) &amp; VOCALS in-situ observations (next slide)</td>
<td>150-200 cm(^{-3}) active at 0.4% SS in remote FT</td>
</tr>
<tr>
<td>(D)</td>
<td>ERA-40 Reanalysis</td>
<td>divergent regions in monthly mean</td>
</tr>
<tr>
<td>(U_{10})</td>
<td>Quikscat/Reanalysis</td>
<td>-</td>
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<tr>
<td>(P_{CB})</td>
<td>CloudSat VOCALS (WCR and in-situ)</td>
<td>PRECIP-2C-COLUMN, Haynes et al. (2009) &amp; Z-based retrieval</td>
</tr>
<tr>
<td>(h)</td>
<td>MODIS</td>
<td>LWP, adiabatic assumption</td>
</tr>
<tr>
<td>(z_i)</td>
<td>CALIPSO or MODIS or COSMIC</td>
<td>MODIS (T_{top}), CALIPSO (z_{top}), COSMIC hydrolapse</td>
</tr>
</tbody>
</table>
Free tropospheric CCN source

Data from VOCALS (Jeff Snider)

Weber and McMurry (FT, Hawaii)

Remote “background” FT

Continentally-influenced FT

CCN concentration [cm⁻³]

S = 0.9%

S = 0.25%

S = 0.1
Self-preserving aerosol size distributions

- after Friedlander, explored by Raes:

Fixed supersaturation: 0.8% 0.4% 0.2%
Variable supersat. 0.3 ± 0.2%

Kaufman and Tanre (Nature 1994)

Precipitation over the VOCALS region

- **CloudSat**
  Attenuation and Z-R methods

- **VOCALS**
  Wyoming Cloud Radar and in-situ cloud probes

Very little drizzle near coast

Significant drizzle at 85°W

WCR data courtesy Dave Leon
Predicted and observed $N_d$, VOCALS

- Model increase in $N_d$ toward coast is related to **reduced drizzle** and explains the majority of the observed increase.

- Very close to the coast (<5°) an **additional CCN source** is required.

- Even at the heart of the Sc sheet (80°W) coalescence scavenging halves the $N_d$.

- Results insensitive to sea-salt flux parameterization.
Mean precipitation rate (CloudSat, 2C-PRECIP-COLUMN, Stratocumulus regions)
Predicted and observed $N_d$


- Derive mean for locations where there are >3 months for which there is:
  1. positive large scale div.
  2. mean cloud top height <4 km
  3. MODIS liquid cloud fraction > 0.4

- Use 2C-PRECIP-COLUMN and Z-R where 2C-PRECIP-COLUMN missing
Reduction of $N_d$ from precipitation sink

- Precipitation from midlatitude low clouds reduces $N_d$ by a factor of 5
- In coastal subtropical Sc regions, precip sink is weak
But what controls precipitation?

- Precipitation rates $P_{CB}$ scale approximately with $LWP^{1.5}$ and $N_d^{-1}$ (e.g. Pawlowska and Brenguier 2003, Comstock et al. 2004, VanZanten et al. 2005)
- $LWP^{1.5}$ *increases* by a factor of $\sim 2.2$ from 72.5°W to 82.5°W, while $N_d$ *decreases* by a factor of 2.5 (Bretherton et al. 2010)
  $\Rightarrow LWP$ and $N_d$ influence the zonal gradient in precipitation rate along 20°S in approximately equal measure
  $\Rightarrow$ significant positive feedback on $N_d$ through aerosol-driven precipitation suppression; $N_d \uparrow \Rightarrow P_{CB} \downarrow \Rightarrow N_d \uparrow$

- But see Chris Terai’s poster on precipitation susceptibility
Conclusions

• Simple CCN budget model, constrained with VOCALS observations predicts observed gradients in cloud droplet concentrations with some skill. **FT aerosol significant possible source west of 75°W.**

• Significant fraction of the variability in $N_d$ across regions of extensive low clouds (from remote to coastal regions) is likely related to precipitation sinks rather than source variability. **Implications for VOCALS Hypothesis H1c:**
  – The small effective radii measured from space over the SEP are primarily controlled by anthropogenic, rather than natural, aerosol production, and entrainment of polluted air from the lower free-troposphere is an important source of cloud condensation nuclei (CCN)

• It may be difficult to separate the chicken from the egg in correlative studies suggesting inverse dependence of precipitation rate on cloud droplet concentration. **Implications for Hypothesis H1a:**
  – Variability in the physicochemical properties of aerosols has a measurable impact upon the formation of drizzle in stratocumulus clouds over the SEP.
Sea-salt source strength compared with entrainment from FT
Precipitation closure

- Precipitation rate dependent upon:
  - cloud macrophysical properties (e.g. thickness, LWP);
  - microphysical properties (e.g. droplet conc., CCN)

from Brenguier and Wood (2009)
A proposal

• A limited area perturbation experiment to critically test hypotheses related to aerosol indirect effects

• Cost ~$30M
Precipitation susceptibility

- Construct from Feingold and Siebert (2009) can be used to examine aerosol influences on precipitation in both models and observations

\[ S = -(\frac{d\ln R_{CB}}{d\ln N_a})_{LWP,h} \]

- \( S \) decreases strongly with cloud thickness
- Consistent with increasing importance of accretion in thicker clouds
- Consistent with results from A-Train (Kubar et al. 2009, Wood et al. 2009)

Data from stratocumulus over the SE Pacific, Terai and Wood (Geophys. Res. Lett., 2011)
Effect of variable supersaturation

- Kaufman and Tanre 1994

**Graphs:**
- **Constant $\sigma$:**
  - $S_c = 0.3 \pm 0.0$
  - $n/dr$ (particles cm$^{-3}$ $\mu$m$^{-1}$)
- **Variable $\sigma$:**
  - $S_c = 0.3 \pm 0.2$
  - $n/dr$ (particles cm$^{-3}$ $\mu$m$^{-1}$)
• Range of observed and modeled CCN/droplet concentration in Baker and Charlson “drizzlepause” region where loss rates from drizzle are maximal

• Baker and Charlson source rates

• Timescales to relax for N

Entrainment:

Surface: $\tau_{\text{sfc}} \sim \frac{N z_i}{\beta U_{10}^{3.4}}$

Precip: $\frac{z_i}{(hKP_{CB})} = \frac{8 \times 10^5}{(3 \times 2.25)} = 1 \text{ day for } P_{CB}=1 \text{ mm day}^{-1}$

$\tau_{\text{dep}} \sim \frac{z_i}{w_{\text{dep}}} \text{ - typically 30 days}$
Can dry deposition compete with coalescence scavenging?

\[
\frac{[\dot{N}]}{[\dot{N}]_{\text{coal}}} = \frac{K P_{\text{CB}} h}{w_{\text{dep}}} \]

\[w_{\text{dep}} = 0.002 \text{ to } 0.03 \text{ cm s}^{-1} \text{ (Georgi 1988)}\]
\[K = 2.25 \text{ m}^2 \text{ kg}^{-1} \text{ (Wood 2006)}\]

For \(P_{\text{CB}} > 0.1 \text{ mm day}^{-1}\) and \(h = 300 \text{ m}\)

\[
\frac{[\dot{N}]}{[\dot{N}]_{\text{coal}}} = 3 \text{ to } 30
\]

For precip rates > 0.1 mm day\(^{-1}\), coalescence scavenging dominates
• Examine MODIS Nd imagery – fingerprinting of entrainment sources vs MBL sources.
Cloud droplet concentrations in marine stratiform low cloud over ocean

The view from MODIS

....how can we explain this distribution?

Baker and Charlson model

- CCN/cloud droplet concentration budget with sources (specified) and sinks due to drizzle (for weak source, i.e. low CCN conc.) and aerosol coagulation (strong source, i.e. high CCN conc.)
- Stable regimes generated at point A (drizzle) and B (coagulation)
- Observed marine CCN/$N_d$ values actually fall in unstable regime!

Baker and Charlson model

- Stable region A exists because CCN loss rates due to drizzle increase strongly with CCN concentration.
  - In the real world this is probably not the case, and loss rates are \(~\) constant with CCN conc.

- However, the idea of a **simple** CCN budget model is alluring.

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Mean precipitation rate (2C-PRECIP-COLUMN)
Sea-spray flux parameterizations

\[ u_{10} = 8 \text{ m s}^{-1} \]

Courtesy of Ernie Lewis, Brookhaven National Laboratory
MODIS-estimated cloud droplet concentration $N_d$, VOCALS Regional Experiment

- Data from Oct-Nov 2008
- Sampling along 20°S across strong microphysical gradient
Conceptual model of background FT aerosol

Clarke et al. (J. Geophys. Res. 1998)
Observed MBL aerosol dry size distributions (SE Pacific)

Predicted and observed $N_d$ - histograms

Minimum values imposed in GCMs
Loss terms in CCN budget: (2) Dry deposition

\[
\left[ \frac{\dot{N}}{\dot{N}} \right]_{dry \ dep.} = -N \frac{W_{dep}}{Z_i}
\]

Deposition velocity

\[
\frac{[\dot{N}]_{coal}}{[\dot{N}]_{dry \ dep.}} = \frac{KP_{CB}h}{W_{dep}}
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![Graph showing mean precipitation rate vs longitude for the VOCALS region, with significant drizzle at 85°W and very little drizzle near the coast.]

WCR data courtesy Dave Leon