Cloud-Aerosol-Climate Interactions in the Southeastern Pacific: What did we learn from VOCALS?

Robert Wood
*University of Washington*
and the VOCALS Science Team

Photograph: Tony Clarke, VOCALS REx flight RF07

Image: Pablo Saide, University of Iowa
Participants
R. Wood (U. Wash., REx-PI), C. R. Mechoso (UCLA, Chair), C. Bretherton (U. Wash.), R. Weller (WHOI), C. Fairall (NOAA), H. Coe (Manchester U., UK), F. Straneo (WHOI), C. Grados (IMARPE, Peru), R. Garreaud (U. Chile), G. Feingold (NOAA), B. Huebert (U. Hawaii), J. L. Brenguier (M. France), S. de Szoeke (NOAA), T. Toniazzo (U. Reading, UK), M. Kohler (ECMWF), and many others…

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Reading, UK
Washington
Wyoming
Climate models poorly represent several of these key processes.
Radiative impact of cloud droplet concentration variations

Pockets of open cells (POCs)
Motivating goal: Improved understanding and regional/global model representation of aerosol indirect effects over the Southeast Pacific.

AEROSOL-CLOUD-DRIZZLE HYPOTHESES

• Variability in the physicochemical properties of aerosols has a measurable impact upon the formation of drizzle in stratocumulus clouds over the SEP.

• Precipitation is a necessary condition for the formation and maintenance of pockets of open cells (POCs) within stratocumulus clouds.

• The small effective radii measured from space in the coastal region of 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).

• Depletion of aerosols by coalescence scavenging is necessary for the maintenance of POCs.
20°S Cross Section (sampled with ships, planes, buoy, satellites)

Offshore

Coast
C-130 WCR radar strips show near ubiquity of drizzle offshore

Little drizzle near coast: thin clouds/polluted clouds

85°W  1500 km  70°W
NOAA VOCALS Cruises

• 2000-2008 during Sept-Dec
• repeated sampling of Sc deck

thicker clouds; deeper, more decoupled MBL

d de Szoek e et al. (2011)
Aerosol-cloud interactions

Strong variability in cloud droplet concentration observed during VOCALS-REx. Aerosol transport events observed extending out to beyond 80°W
Bretherton et al., ACP, 2010

Sulfate aerosol mass loading

Most of the submicron aerosol is sulfate. Both anthropogenic and natural sources, but dominated by the former close to the coast, Allen et al. ACP, 2010
Conceptual diagram of cloud, PBL structure and aerosols along 20°S

 Mechoso et al. (BAMS, 2014)
Precipitation and pockets of open cells

Strikingly different precipitation structure in POCs compared with overcast stratocumulus
Sandra Yuter, NCSU

Precipitation generates cold outflows and local convergence that maintains open cell structure
Feingold et al., Nature, 2010

New conceptual models of macrophysical-microphysical interaction across POC boundary
Wood et al. ACP, 2010
Extreme coupling between drizzle and CCN

- Aerosols and cloud macrophysical properties are strongly coupled in Pockets of Open Cells (POCs):

- Drizzle strongly depletes aerosols and causes cloud morphological transitions in LES (Wang et al. 2011, Berner et al. 2011, 2014):

LES modeling based on VOCALS RF06 case: Berner et al., *Atmos. Chem. Phys.* (2014)
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LES phase plane analysis

Slow (20 day) limit cycle (left, weaker subsidence)
Stable equilibrium with well mixed closed cells (right, strong subsidence)
.....but why do open celled PBLs not usually collapse in nature?
LES modeling of open-closed cell boundary

$N_d = 60 \text{ cm}^{-3}$  $N_d = 10 \text{ cm}^{-3}$

secondary circulation above MBL
inversion rises at same rate in both regions

Berner and Bretherton (2011, ACPD), and Bretherton et al. (2010, JAMES)
Wang and Feingold (2009), Wang et al. (2010)
Ultra-clean layers in POCs

- Ubiquitous layer near top of POC MBL almost completely devoid of CCN
- Driven by coalescence scavenging by efficient precipitation production

See Wood et al. (2011, ACP) also Petters et al. (2006)
New particle formation in ultraclean layers

- WRF-Chem run in LES mode
- New particle formation rate comparable with sources from FT and sea-salt
- Not yet understood how important regionally

Kazil et al. (2011)
Gravity waves: a trigger for POC formation?

- Numerous hypotheses for triggering of POCs
  - Drizzle (Stevens et al. 1998)
  - Aerosol (Berner et al. 2011, Wang et al. 2011)
  - PBL moisture, temperature, LWP perturbations (Wang et al. 2011)
  - Gravity waves (Allen et al. 2012, Connolly et al. 2013)
Constraining and improving models
Pre-VOCA and VOCA

- PreVOCA/VOCA compared 15 regional, weather forecast, and climate models (in forecast mode) for Oct (2006, 2008) in the VOCALS region.
- Many models had large errors in distribution of low cloud cover, though ECMWF and UKMO performed well.
- Most models produced a marine BL too shallow near the coast at 20S.
- Most models qualitatively captured diurnal and day-to-day variability of the cloud and BL despite mean biases.
- Global models outperformed most regional models.
VOCA (post field phase)

- Obs. from VOCALS-REx
- Concentration on cloud-relevant aerosol properties and cloud microphysics
- Regional chemistry climate models (WRF-Chem) perform better than global models
- Large spread in representation of aerosols and cloud drop conc. (right)
- All models underestimate FT CCN

Wyant et al. (2014)
Precipitation susceptibility

- Construct from Feingold and Siebert (2009) used to examine aerosol influences on precipitation VOCALS-REx data

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

- \( S \) 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)
Constraining microphysical process rates

- Accretion/autoconversion ratio severely overestimated in CAM5
- Warm rain production incorrectly dominated by autoconversion
- Expected to cause overestimation of precipitation susceptibility to aerosols

Gettelman et al. (2013)
Marine Sc grey zone

- Unified model at 1 km resolution simulates mesoscale cellular nature of the Sc field

Boutle and Abel (2012)
Seamless partitioning of the vertical wind variance

- Aircraft, LEM and 1km UM used to derive height-dependent prediction of unresolved variance in updraft speed
- Predicted as a function of mixed layer depth $z_{ml}$ and model grid spacing $\Delta x$ to cross the “grey zone” (few km for marine low clouds)

Malavelle et al. (2014)
What controls cloud droplet concentration?

- **Simple** budget model (Baker and Charlson 1990) for CCN/\(N_d\) in the MBL:

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

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

- Assume aerosol sources constant (here represented by FT concentration “buffer”)
- Model \(N\) variation mostly explained by precipitation sinks
- Can reproduce significant amount of variance in \(N_d\) over oceans \(\Rightarrow\) implications for significance of AOD vs \(r_e\) relation ships

Wood et al. (2012)
Precipitation and FT CCN along 20°S

(a) MODEL INPUTS

Precipitation

Mean precipitation rate [mm d⁻¹]

Aerosol concentration [cm⁻³]

CloudSat radar
VOCALS, C-130 radar
VOCALS, in-situ (2D-C)

Oct-Nov 06-09
Oct-Nov 08

03-09 am local
1:30pm local
1:30am local

daily mean

CCN (S=0.2-0.5%)
Non-volatile CN

Free-tropospheric aerosols

Mauna Loa

90°W 80°W 70°W
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 relatively insensitive to sea-salt flux parameterization.
Sensitivity to sea-salt parameterization
Predicted and observed $N_d$

- Monthly climatological means
- Simple model predicts MODIS-observed $N_d$ with skill.
- Aerosols from FT and sea-spray are both important in supplying CCN to MBL
- Much of the variability in $N_d$ in marine Sc is due to drizzle sinks rather than source variability

Wood et al. (2012)
VOCALS Regional Experiment Impact

• Comprehensive, organized, and accessible field datasets from 5 aircraft and 2 ships for the Southeastern Pacific
  – unprecedented data on clouds, aerosols, and marine boundary layer structure; unique sampling strategies (20ºS)
• Strong synergies between field observations and process/large scale modeling studies
• Precipitation more prevalent and important than previously thought
  – POC formation/maintenance
  – Major driver of CCN variability (rival to sources)
• Aerosols now seen to be far more ‘interactive’ with stratocumulus than previously imagined
  – Precipitation susceptible to aerosol variability
  – Macrophysical cloud variability strongly coupled with aerosol variability