Warm rain and climate:
VOCALS, CloudSat, Models

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Warm rain – a missing climatology

- Shipboard remote-sensing shows frequent precipitation from shallow clouds
- Many echoes below detection limit of current satellite sensors (passive or active)
Warm rain – macrophysical vs microphysical control

- In shallow stratocumulus-topped MBLs ($z_i < 1500$ m) recent studies indicate a dependence of drizzle rate upon cloud droplet concentration (see right).

- In deeper trade wind boundary layers no definitive relationship between precipitation rate and microphysics has been observed (e.g. Nuijens et al. 2009).

Warm rain – why do we care?

- GCMs estimate that:
  
  1\textsuperscript{st} AIE: -0.5 to -1.9 W m\textsuperscript{-2}
  
  2\textsuperscript{nd} AIE: -0.3 to -1.4 W m\textsuperscript{-2}

Change in LWP [g m\textsuperscript{-2}] estimated using the GFDL AM2: Ming et al. (2008)

Warm rain rate and its sensitivity to aerosols/microphysics is important and unknown
CloudSat now observes drizzle

MODIS Visible Imagery

Radar reflectivity [Cloudsat]

CloudSat ground track

DRIZZLE CELLS

Pocket of Open Cells

Non-drizzling stratocumulus

SE Pacific
Data/Methods

- Collocated CloudSat and Aqua-MODIS data:
  - Daytime data only (~13:30 local)
  - Warm clouds
- MODIS used to estimate $LWP$ and $N_d$:
  - $N_d$ using method of Bennartz (2007), assuming adiabatic vertical cloud profile
- CloudSat used to determine maximum $Z$ in column. Classify $> -15$ dBZ as precipitating.
Fraction of clouds that are drizzling
(> -15 dBZ)

qualitatively consistent with Byers and Hall (1955)
Effective radius **not** unique determinant of precipitation

![Graph showing fraction of drizzling warm clouds vs. median radius (µm)]
Heuristic model

• Goals:
  – Attempt to reproduce salient features of A-Train data
  – Minimal physics necessary

• Continuous collection model:
  – Given realistic assumed macro/micro-microphysical cloud structure, allow small fraction of largest cloud droplets at cloud top to fall through cloud collecting droplets (10 liter⁻¹ leads to Z-R consistent with obs.)
  – Essential inputs are cloud liquid water path (LWP) and cloud droplet concentration (N_d)
  – Other free parameters constrained by observations
Model cloud structure

• Subadiabatic to represent entrainment effects in precipitating trade-cumulus

• Adiabaticity parameter $f_{ad}$ decreases with height $z$ above cloud base

$$f_{ad} = \frac{z_0}{z_0 + z}$$

• Adiabaticity height scale $z_0=500$ m (estimated from RICO observations)

• Gives liquid water content as a function of height
Precipitation embryos

Assumed size distribution (Gamma)

Tail of distribution (10 liter\(^{-1}\)) constitutes embryonic precipitation drops

Gamma distribution of cloud drops determined from LWC at cloud top and cloud droplet concentration
Microphysics vs macrophysics

Increasing relative importance of LWP over $N_d$
Rain rate-to-reflectivity (94 GHz)

• Several steps need to be taken to compare model with CloudSat:

  (1) Use model assumed precipitation DSD to determine radar reflectivity in Rayleigh limit
  (2) Mie correction for 94 GHz reflectivity (Bohren-Huffman)
  (3) Attenuate model 94 GHz reflectivity using two-way attenuation correction of 8.3 dBZ mm\(^{-1}\) of cloud liquid water (Lhermitte 1990)
Reflectivity in $[LWP, N_d]$ space

Increasing relative importance of $LWP$ over $N_d$ at high rainrates

CloudSat: colors
Model: lines

see also Suzuki and Stephens (2008)
Warm rain, cloud structure and dynamics
Drizzle affects MBL dynamics
Shiptrack surprises!

- Liquid water content in shiptracks is typically reduced compared with surrounding cloud.
- Clear refutation of Albrecht’s hypothesis.

courtesy Jim Coakley, see Coakley and Walsh (2002)
LES results

- Impact of aerosols simulated by varying $N_d$
  - Increased $N_d \Rightarrow$ Reduced precipitation $\Rightarrow$ increased TKE $\Rightarrow$ increased entrainment $w_e$
  - Changes in $w_e$ can sometimes result in cloud thinning (reduced LWP)
  - Also noted by Jiang et al. (2002)

![Graphs showing LES results](attachment://graphs.png)
Drizzle and mesoscale cellularity

courtesy Dave Leon, U of Wyoming
Drizzle and cellularity

2D Reflectivity map 2310 UTC

(b) Reflectivity (dBZ)

(c) VR' (m s⁻¹)

(d)

Comstock et al. (2007, Mon Wea Rev)
POCKETS of OPEN CELLS (POCs)

MODIS image courtesy of NASA
Drizzle and POCs

- Drizzle can exert important forcing on the MBL

Savic-Jovcic and Stevens (2007)
POCs prefer to form at night
October-November 2008
SE Pacific
VOCALS Regional Experiment (REx)

VOCALS-Rex will collect datasets required to address a set of issues that are organized into two broad themes:

- **Aerosol-cloud-drizzle interactions** in the marine boundary layer (MBL) and the physicochemical and spatiotemporal properties of aerosols
- **Chemical and physical couplings** between the upper ocean, the land, and the atmosphere.
Aerosols and clouds

Chuquicamata, Chile

Cloud droplet concentration

SON 2001-2004
Visible imagery

100 km
October 27/28th 2008
POC Lagrangian - BAe-146 & NSF C-130

MODIS Terra, 250 m visible image  
Photo from BAe-146, Hugh Coe
OPEN CELL MORPHOLOGY

Optically thin cell centers

Optically thick cell walls

10 km
Boundary cells

C-band images
Matt Miller, NCSU
Conceptual model of POC edge

Decoupled MBL
- Extremely clean
  - [CN = 20-50 cm⁻³, CCN = 5-20 cm⁻³]

Relatively well-mixed MBL
- Moderately polluted
  - [CN = 500-1000 cm⁻³, CCN = 100 cm⁻³]
Coalescence and CCN depletion

- Loss rate of CCN number concentration through coalescence
  \[ \propto LWP^2 \]
Steady-state cloud condensation nucleus (CCN) model

Assumptions:

1. Wind-driven sea-salt production and entrainment of 100 cm$^{-3}$ from free-troposphere are only aerosol sources.

2. Coalescence scavenging is the only loss term

3. Examine steady state solution for CCN concentration

![Graph showing LWP as a function of wind speed with no steady state solutions and steady state solutions indicated.]
Take-home messages

• Precipitation common in, and energetically important for, shallow marine boundary layers

• Precipitation rate is macrophysically-determined but can be influenced microphysically

• Precipitation important for organization of mesoscale structure in the stratocumulus-topped boundary layer

• Precipitation important for controlling aerosol population within the marine boundary layer
Data/Methods

• Collocated CloudSat (GEOPROF) and Aqua-MODIS (MOD06) data:
  – Daytime data only (~13:30 local)
  – CloudSat cloud top height below freezing level
  – MODIS cloud top temperature > 0°C
  – MODIS cloud optical depth $\tau > 3$

• MODIS used to estimate $LWP$ and $N_d$:
  – $LWP$ from standard MODIS cloud product
  – $N_d$ using method of Bennartz (2007), assuming adiabatic vertical cloud profile

• CloudSat used to determine maximum Z in column. Classify $> -15$ dBZ as precipitating.
Regions Studied

Asian Coast

NE Pac

Far NE Pac

Gulf of Mexico

ITCZ

Eqt. Cold Tongue

SPCZ

SE Pac

Far SE Pac
Cloud properties associated with different amounts of precipitation

SE Pacific

As clouds move from non-precipitating to precipitating:

1. LWP and cloud top height show steady increases

2. Microphysical parameters “saturate”
Fraction of clouds that are drizzling (> -15 dBZ)

qualitatively consistent with Byers and Hall (1955)
Effective radius **not** unique determinant of precipitation

decreasing LWP
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see also Suzuki and Stephens (2008)

CloudSat: colors
Model: lines
Given $[LWP, N_d]$ joint pdf, model can determine the drizzling fraction and intensity of drizzle in each region.
Understanding the model behavior

• Precipitation drop embryo formation
  – depends very strongly upon microphysics ($N_d$)

• Accretion
  – primarily limited by availability of cloud liquid water (not microphysics)

• Clouds in which accretion dominates (thicker clouds, higher $LWP$) show reduced sensitivity to $N_d$
Conclusions

• Observations and simple heuristic model show decreasing relative importance of microphysics as precipitation rate in warm clouds increases

• Broadly consistent with field observations (DYCOMS, ACE-2, EPIC, RICO)

• Implications for aerosol-cloud-precipitation interactions
October-November 2008

SE Pacific
VOCALS-CloudSat

• VOCALS will yield a unique dataset detailing the properties of clouds, aerosols, and precipitation in the largest stratocumulus sheet on Earth

• Development/testing of CloudSat/CALIPSO/A-Train retrievals of light precipitation and MBL microphysical and macrophysical structure

• Near-surface issues
  – technical: surface clutter
  – physical: evaporation of drizzle
Cloud properties associated with different amounts of precipitation

Asian Coast
Drizzle suppression in shiptracks

- Drizzle is frequently found to be suppressed in shiptracks
- So what’s wrong with Albrecht’s hypothesis?

Ferek et al. 2000