A remote-sensing and modeling perspective of ice crystals in deep convective clouds

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(GISS lunch seminar)

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Deep convective clouds
Deep convective clouds

Adapted from Houze et al. (1980)
Net Forcing

- Shortwave/longwave cloud forcing depends on
  - Cloud top temperature
  - Optical thickness
  - Ice crystal sizes
  - Ice crystal shapes ('Habits')
  - Glaciation temperatures
  - .....

![Net Cloud Forcing](image1)

![Seasonal Variation of Net CRF in the Asian Monsoon Region](image2)
Ice formation in deep convective clouds

- Homogeneous ice formation
  - Direct freezing of droplets
  - $T < -38 \, ^\circ\text{C}$

- Heterogeneous ice formation
  - Ice formation induced by ice nuclei (IN)
  - $0 \, ^\circ\text{C} > T > -38 \, ^\circ\text{C}$
Ice crystals in Tropical deep convection

- CPI images
  - Many irregular shapes
  - Some more ‘pristine’ rosettes in aged anvil

From Baran, review, JQSRT 2009
Objectives

- Ice formation not well understood
- Use cloud-resolving modeling studies to investigate
  - Ice formation processes
  - Sensitivity to IN and CCN concentrations
- Provide observational constraints on
  - Glaciation temperatures
  - Ice crystal sizes
  - Ice crystal shapes ('Habits')
ARM’s TWP-ICE campaign

- The Tropical Warm Pool—International Cloud Experiment
- Near Darwin, Australia
- From January 20 through February 13, 2006
  - Active monsoon 20-24 Jan.
  - Monsoon break >3 Feb.
- Over ocean, weak daily cycle
Geostationary MTSAT IR measurements

- Active monsoon 16-24 Jan.
- Monsoon break >3 Feb.
MODIS brightness temperature and optical thickness

- Within 5° from Darwin
- Over sea
- Active Monsoon
Cloud phase information from POLDER-PARASOL

- Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar
- Was in A-train (2004-2009 ran out of fuel)
- 10 x 10 km² resolution
- Provides reflectivity at 9 wavelengths at 13-15 viewing angles
- Polarized reflection at 490, 670 & 865 nm
Polarized reflectance

- Polder measures Stokes parameters I, Q & U
- Polarized reflectance

\[
P_r(\mu) = \frac{\pi \sqrt{Q(\mu)^2 + U(\mu)^2}}{\mu_0 F_0},
\]

(F_0 is incoming Solar, \(\mu_0\) is cosine of solar zenith angle)

- Dominated by low order scattering
- Saturated for cloud optical thickness > \(\sim 2\)
- Probes cloud top
Cloud phase information from POLDER-PARASOL

- Directional polarized reflectance ($R_p$)
- Phase retrieval
  - Droplets show rainbow feature in $R_p$ at 140 degrees
  - No/weak structure in $R_p$ due to ice

![Graph showing global POLDER measurements](image-url)
POLDER Liquid index

- Fit straight line through $120^\circ$-$160^\circ$ measurements
- Ice index = Mean($|\text{fit-measurement}|$)
- Straight-forward to simulate from model
Physical interpretation of liquid index

- **Liquid index**
  - Indicates to what degree liquid is *obscured* by ice above
  - ~3 for pure water clouds
  - ~0 for pure ice clouds or ice topped clouds
Liquid index for TWP-ICE active monsoon

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Ice shape information from POLDER-PARASOL

- Polarized reflectance depends on ice shape
- Most important parameters are:
  - Aspect ratio of ice crystal (components)
  - Small-scale roughness
Polarized phase function

- Structures decrease with increasing roughness
- Scattering $<120^\circ$ increases with increasingly extreme aspect ratio

![Graphs showing polarization phase functions for different aspect ratios and roughness levels.](image)
Ice shape information from POLDER-PARASOL

- Severely roughened ice
- Compact AR~0.7 crystals in cold clouds (homogeneous ice formation?)
- More extreme AR in warmer clouds (heterogeneous ice formation?)

Light grey: Interquartile range of measurements
MODIS Aqua ice crystal effective radius and cloud optical thickness

\[ R_{\text{eff}} = \frac{3}{4} \frac{\int_0^\infty V(D)N(D) \, dD}{\int_0^\infty A_p(D)N(D) \, dD}. \]

- Ice crystal effective radius
- Cloud optical thickness

\text{from } 0.87 \, \mu \text{m (non-absorbing)} \text{ and } 2.13 \, \mu \text{m (absorbing)}

\text{Zhang et al. 2010}
MODIS ice effective radius and 2.13 um reflectance

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DHARMA CRM Simulations
(Ackerman et al., Nature 2004; Fridlind et al, JGR 2007)

- Grid
  - $176 \times 176 \times 20$ km$^3$ domain
  - $192 \times 192 \times 96$ grid points (for now)
- Microphysics
  - Size resolved microphysics in 36 bins
  - Fluffy aggregates and dense graupel ice types
- Ice properties modeled using
  - Mass-Diameter relationships (Böhm et al., Atm. Res. 1992)
  - Area-Diameter relationships (Mitchell, JAS, 1996)
  - Aspect ratios (Korolev & Isaac, JAS, 2003)
Simulations

- Simulations with different ice formation
  1. Diagnostic ice nuclei: $N_{\text{ice}} + N_{\text{IN}} = 30 \text{ L}^{-1}$
  2. Prognostic: ice nuclei consumed (nudged at 6 h time scale)
- Moderately strong monsoon event (19-20 Jan.)
- 20-hour simulations (after 36-hour spinup with bulk microphysics)
- Sampled every hour
Model simulations

- Prognostic IN
Domain averages vs time

- Liquid mixing ratio
- Ice mixing ratio

Prognostic IN

Diagnostic IN

Brightness temperature

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Brightness temperatures and optical thickness
Liquid index for TWP-ICE active monsoon

Measurements

Active Monsoon

MODIS COT
- O 5.– 10.
- △ 10.– 30.
- ▽ 30.– 90.
- ◇ 90.–999.

MODIS 11 μm BT [°C]
- -80
- -60
- -40
- -20
- 0
- 20

POLDER Liquid index
- 0
- 1
- 2
- 3

Liquid/mixed/ice

Liquid

Ice
Simulated Liquid index

- Liquid indices simulated from model
- Using forward calculations of 0.86 μm polarized reflectances
- Too much ice at T > -20 C (spinup problems?)
- Super-cooled liquid at T~ -30 C
MODIS ice effective radius and 2.13 μm reflectance

Measurements

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Evaluating modeled effective radius

- Definitions of ice effective radius vary
- Most models predict total ice mass, not effective radius
- Retrieval represents $R_{\text{eff}}$ somewhere in cloud top, but where?
- Retrieval of effective radius depends on ice habit assumed
- $R_{\text{eff}}$ of equal volume sphere $>> R_{\text{eff}}$ real ice!

\[ R_{\text{eff}} = \frac{3}{4} \int_0^\infty \frac{V(D)N(D)\,dD}{A_p(D)N(D)\,dD} \]
Calculation of effective radius from model

- DHARMA model uses 36 bins with specified
  - Maximum diameter
  - Mass
  - Area
- Same assumptions used for micro-physics and optical properties

\[ D_{eff} = \frac{3}{2} \frac{V}{A} \]
Calculation of effective radius from model

- Retrieval of ice $R_{\text{eff}}$ represent the effective radii somewhere in the top of the cloud, but where?
- Past studies show retrieval is mostly sensitive to first 2 optical depths
Retrieval of effective radius depends on ice habit assumed.

\[ R_{eff} = \frac{3}{4} \frac{\int_0^\infty V(D)N(D) \, dD}{\int_0^\infty A_p(D)N(D) \, dD} \]

- Overcome problems by forward simulating 2.13 µm reflectance with known ice habit.

- Graphs showing 2.13 µm reflectance vs. 0.86 µm reflectance for:
  a) Pristine ice crystals
  b) Roughened ice crystals
  c) MODIS C5 aspect ratios
  d) Aspect ratio = 0.7
Evaluation of model $R_{eff}$

- $R_{eff}$ integrated over first 2 optical depths
- Simulated 2.13 $\mu$m reflectances
  - AR = 0.7
  - Roughness = 0.6
- Sizes not sensitive to IN treatment (homogeneous nucleation dominates?)
2.13 sensitivity to ice aspect ratio

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Conclusions measurements

- **Glaciation**
  - Liquid at $T > -20 \, \text{C}$
  - Liquid/Mixed/Ice at $-20 \, \text{C} > T > -35 \, \text{C}$
  - Ice at $T < -40 \, \text{C}$

- **Ice shapes**
  - Compact rough crystals at $T < -40 \, \text{C}$
  - More extreme aspect ratios at $T > -40 \, \text{C}$

- **Ice sizes**
  - $18-28 \, \mu\text{m}$ at $T < -40 \, \text{C}$
  - $24-35 \, \mu\text{m}$ at $T > -40 \, \text{C}$
Conclusions model

- Model evaluated using forward calculations of
  - Brightness temperatures
  - 0.86 μm polarized reflectances
  - 2.13 μm reflectances

- Glaciation
  - Super-cooled liquid up to T~ -30 C (similar to measurements)
  - Too much ice 0 C > T > -20 C (depending on IN treatment; spinup?)

- Ice sizes
  - $R_{eff}$ 5-10 um too small
  - Sizes in cold tops not sensitive to IN treatment
  - Some too large ice in warm tops (Spinup?)

- Calculated $R_{eff}$ and simulated 2.13 μm reflectances give similar results