The role of microphysics in orographic precipitation

Greg Thompson, Roy Rasmussen, Trude Eidhammer, Paul Field, & Bill Hall

Funding by FAA Aviation Weather Research Program
Develop an efficient and observations-based bulk microphysical parameterization:

- improves quantitative precipitation forecasts when compared to similar, existing schemes
- improves forecasts of water phase everywhere aloft=aircraft icing; surface=FZDZ/RA/SN
- incorporates recent microphysical observations AIRS / IMPROVE / ICE-L / NASA-SLDRP
- is sufficiently optimized/fast real-time needs (WRF-Rapid Refresh)
- uses clean, well-documented code can be modified rapidly to increase complexity and perform sensitivity studies
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Additional Motivation
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Figure 35: The V82’s nominal output at 10.8 m/s is 1500 kW. Here it is producing less than one fifth of this due to iced-up blades.
Hydrometeor characteristics

Cloud water
- gamma distribution with shape factor dependent on droplet concentration
  \[ N(D) = N_0 D^\mu e^{-\lambda D} \]
- does not sediment
- "autoconverts" to rain using Berry & Reinhardt (1974) formulation with correct diameters

Cloud ice
- gamma distribution
- pristine (no riming) diameter < 200 µm
- initiation temperature-dependent (Cooper)
- predicted \( N_i \) (2-moment)
- slowly sediments (10–30 cm s\(^{-1}\))

Rain
- gamma distribution
- predicted \( N_r \) (2-moment) *new
- accurate fallspeed relation

Snow
- sum of 2 gamma distributions (Field et al, 2005)
- size distribution depends on ice content and temperature
- non-spherical geometry \( (m = aD^2) \)
- variable density \((1/D)\)

Graupel / Hail
- gamma distribution
- variable y-intercept parameter depends on mixing ratio (simulate both hail and snow-like graupel):
  - \( 1 \times 10^6 \text{ m}^{-4} \) (graupel)
  - \( 1 \times 10^4 \text{ m}^{-4} \) (hail)
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  - Graupel: \( 1 \times 10^6 \) m\(^{-4}\)
  - Hail: \( 1 \times 10^4 \) m\(^{-4}\)
- Variable density (1/D)

Maritime

- Fewer drops
- Larger mean size

Continental

- More drops
- Smaller mean size

Liquid water content = 0.25 g m\(^{-3}\)

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**New**
- Predicted \( N_c \) (2-moment)

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- Pristine (no riming) diameter < 200 µm
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- Slowly sediments (10–30 cm s\(^{-1}\))

**Rain**
- Gamma distribution
- Predicted \( N_r \) (2-moment) *new*
- Accurate fallspeed relation

**New**
- Explicit CCN from aerosols (sulfates + sea salts) predicted diameters

**Snow**
- Sum of 2 gamma distributions (Field et al, 2005)
- Size distribution depends on ice content and temperature
- Non-spherical geometry \((m = aD^2)\)
- Variable density \((1/D)\)

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  - \( 1 \times 10^6 \) m\(^{-4}\) (graupel)
  - \( 1 \times 10^4 \) m\(^{-4}\) (hail)

**New**
- Heterogeneous freezing on dust/mineral > 0.5 microns
- Homogeneous freezing of deliquesced aerosols following Koop et al (2000)
Snow density varies $1/D$

Temperature = $-10^\circ\text{C}$

Snow content = 0.2 g m$^{-3}$
Graupel (details)

Rimed Snow
converts to graupel more smoothly than other schemes

Mimics hail
variable y-intercept parameter allows terminal velocity 10+ m/s
Collection equation

\[
\frac{d(r_y)}{dt} = \frac{\pi}{4} \int_0^\infty \int_0^\infty E_{xy} m(D_x)(D_x + D_y)^2 \left[ v_x(D_x) - v_y(D_y) \right] N_x(D_x) N_y(D_y) \, dD_x \, dD_y
\]
Physical process and code improvements

- Snow is considered non-spherical and its density varies inversely with size as observed.
- Autoconversion uses correctly computed characteristics diameters.
- Cloud droplet size distribution utilizes variable shape parameter dependent on number concentration, therefore mean size varies following observations by Martin et al, 1994.
- Graupel y-intercept parameter (and terminal velocity) attempts to mimic hail in strong updrafts.
- Rimed snow to graupel conversion does not utilize thresholds but varies gradually depending on riming-to-deposition growth rates.
- Snow terminal velocity gets boosted by 10–50% when heavy riming; also melted snow/graupel fall faster not slower.
- Collisions between hydrometeors with similar fallspeed (rain & graupel) uses explicit bin method to compute collection.

- Code:
  - clean, well-documented
  - generalized gamma distributions and simple mass/velocity–diameter relations
  - look-up tables for most costly calculations (collection)
Clean, well-documented code

!..Densities of rain, snow, graupel, and cloud ice.
   REAL, PARAMETER, PRIVATE:: rho_w = 1000.0
   REAL, PARAMETER, PRIVATE:: rho_s = 100.0
   REAL, PARAMETER, PRIVATE:: rho_g = 650.0
   REAL, PARAMETER, PRIVATE:: rho_i = 890.0

!..Prescribed number of cloud droplets. Set according to known data or
!.. roughly 100 per cc (100.E6 m^-3) for Maritime cases and
!.. 300 per cc (300.E6 m^-3) for Continental. Gamma shape parameter,
!.. N_0_c, calculated based on N_t_c is important in autoconversion
!.. scheme.
   REAL, PARAMETER, PRIVATE:: N_0_c = 250.E6

!..Generalized gamma distributions for rain, graupel and cloud ice.
!.. N(D) = N_0 * D**mu * exp(-lambda0*D); mu=0 is exponential.
   REAL, PARAMETER, PRIVATE:: mu_r = 0.0
   REAL, PARAMETER, PRIVATE:: mu_s = 0.0
   REAL, PARAMETER, PRIVATE:: mu_i = 0.0
   REAL, PRIVATE:: mu_c

!..Sum of two gamma distrib for snow (Field et al. 2005).
!.. N(D) = M2**4/M3**3 * [Kap0*exp(-M2*Lam0*D/M3)
!.. + Kap1*(M2/M3)**mu_s * D**mu_s * exp(-M2*Lam1*D/M3)]
!.. M2 and M3 are the (bm_s)th and (bm_s+1)th moments respectively
!.. calculated as function of ice water content and temperature.
   REAL, PARAMETER, PRIVATE:: mu_s = 0.6357
   REAL, PARAMETER, PRIVATE:: Kap0 = 490.6
   REAL, PARAMETER, PRIVATE:: Kap1 = 17.46
   REAL, PARAMETER, PRIVATE:: Lam0 = 20.78
   REAL, PARAMETER, PRIVATE:: Lam1 = 3.29

!..Y-intercept parameter for graupel is not constant and depends on
!.. mixing ratio. Also, when mu_g is non-zero, these become equiv
!.. Y-intercept for an exponential distrib and proper values are
!.. computed based on same mixing ratio and total number concentration.
   REAL, PARAMETER, PRIVATE:: gosv_min = 3.64
   REAL, PARAMETER, PRIVATE:: gosv_max = 3.66

!..Mass power law relations: mass = am*D**bm
!.. Snow from Field et al. (2005), others assume spherical form.
   REAL, PARAMETER, PRIVATE:: am_r = PI*rho_w/6.0
   REAL, PARAMETER, PRIVATE:: bm_r = 3.0
   REAL, PARAMETER, PRIVATE:: am_s = 0.869
   REAL, PARAMETER, PRIVATE:: bm_s = 2.0
   REAL, PARAMETER, PRIVATE:: am_g = PI*rho_g/6.0
   REAL, PARAMETER, PRIVATE:: bm_g = 3.0
   REAL, PARAMETER, PRIVATE:: am_i = PI*rho_i/6.0
   REAL, PARAMETER, PRIVATE:: bm_i = 3.0

!..Fallspeed power laws relations: \( v = (av*D**bv)*exp(-fv*D) \)
!.. Rain from Ferrier (1994), ice, snow, and graupel from
   REAL, PARAMETER, PRIVATE:: av_r = 485.4
   REAL, PARAMETER, PRIVATE:: bv_r = 1.0
   REAL, PARAMETER, PRIVATE:: fv_r = 195.0
   REAL, PARAMETER, PRIVATE:: av_s = 40.0
   REAL, PARAMETER, PRIVATE:: bv_s = 0.85
   REAL, PARAMETER, PRIVATE:: fv_s = 75.0
   REAL, PARAMETER, PRIVATE:: av_i = 442.0
   REAL, PARAMETER, PRIVATE:: bv_i = 0.89
   REAL, PARAMETER, PRIVATE:: fv_i = 1847.5
   REAL, PARAMETER, PRIVATE:: bv_i = 1.0
## Summary: Improvements over “legacy” schemes

<table>
<thead>
<tr>
<th>Property</th>
<th>Deficiency</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud water</td>
<td>Monodisperse or exponential distrib</td>
<td>Generalized gamma, variable shape param</td>
</tr>
<tr>
<td>Rain</td>
<td>Constant intercept parameter</td>
<td>Double-moment; proper size-sorting sedimentation</td>
</tr>
<tr>
<td>Snow</td>
<td>Constant density, spherical snow, constant intercept param</td>
<td>Variable density, non-spherical, size distrib based on 9000 obs</td>
</tr>
<tr>
<td>Graupel/Hail</td>
<td>Constant intercept param</td>
<td>Variable y-intercept attempts to mimic graupel and hail</td>
</tr>
<tr>
<td>Autoconversion</td>
<td>Often a simple threshold</td>
<td>Follows results of bin model; proper characteristic diameters</td>
</tr>
<tr>
<td>Collision/collection</td>
<td>Oversimplified, E=1.0 and improper Vx-Vy</td>
<td>Explicit size-dependent collection efficiencies, full double-integral</td>
</tr>
<tr>
<td>Graupel production</td>
<td>Cloud water &amp; snow threshold to create all graupel</td>
<td>Rimed snow forming graupel is continuous, not abrupt</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>Not physically correct</td>
<td>Melting snow/graupel fall faster, not slower</td>
</tr>
</tbody>
</table>

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Model Testing

**Idealized tests:**
1. 2-d bell-shaped hill
2. 2-d complex terrain profile with melting
3. 2-d & 3-d squall line (warm bubble & cold pool initiated)
4. 3-d supercell hodograph
5. “cloud-seeding” tests

**Case studies:**
1. Aircraft icing & winter storm cases
2. CO upslope cases
3. IMPROVE-2 cases
4. Convective cases: IHOP, BAMEX, VORTEX
5. CO Headwaters

**Real-time applications:**
1. NCAR-MMM
2. OU-CAPS spring experiment
3. NOAA/ESRL: Rapid Refresh
4. NCEP/EMC - RAP (20 March 2012)
5. many universities and international WRF-based model efforts

Also, periodic intercomparisons with explicit/bin microphysics scheme from Istvan Geresdi and against other bulk schemes such as Morrison, Milbrandt, Seifert, WSM6, WDM6, Goddard, and Lin
Comparisons to explicit/bin model

Maritime (25 cm$^{-3}$)

Continental (300 cm$^{-3}$)
Bin vs. bulk rain fallspeeds

with Eric Aligo, Bill Gallus, Brad Ferrier
Bin vs. bulk snow fallspeeds
Bin vs. bulk graupel fall speeds

The diagrams illustrate the fall speed distribution and pressure fields for different models. The fall speed distribution shows the frequency (%) of graupel at various fall speeds. The models compared include Thompson, WSM6, Lin, and Geresdi. The pressure fields (a, b, c, d) depict the distribution of pressure (hPa) and wind speed (m s⁻¹) at different altitudes.
Formation and Spread of Aircraft-Induced Holes in Clouds

Andrew J. Heymsfield,1* Gregory Thompson,1 Hugh Morrison,1 Aaron Bansemer,1 Roy M. Rasmussen,1 Patrick Minnis,2 Zhien Wang,3 Damao Zhang3

Hole-punch and canal clouds have been observed for more than 50 years, but the mechanisms of formation, development, duration, and thus the extent of their effect have largely been ignored. The holes have been associated with inadvertent seeding of clouds with ice particles generated by aircraft, produced through spontaneous freezing of cloud droplets in air cooled as it flows around aircraft propeller tips or over jet aircraft wings. Model simulations indicate that the growth of the ice particles can induce vertical motions with a duration of 1 hour or more, a process that expands the holes and canals in clouds. Global effects are minimal, but regionally near major airports, additional precipitation can be induced.

The passage of aircraft through subfreezing, supercooled liquid water clouds can produce circular and linear voids called hole-punch and canal clouds on the basis of their distinctive appearance (Fig. 1A). Ice streamers embedded within or descending from circular holes or elongated channels carved out of mid-level, subfreezing cloud layers were first reported in the meteorological literature in the 1940s (1). In correspondence titled “Man-Made Cirrus?” in Weather (2), a large horizontal loop sketched in a midlevel cloud was the first of...
of

Clouds

Harrison,1 Aaron Bansemer,1
Guomao Zhang3

than 50 years, but the mechanisms for their effect have largely been ignored. The
clouds with ice particles generated by aircraft,
are cooled as it flows around aircraft propeller
but the growth of the ice particles can induce
holes that expands the holes and canals in clouds.
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clouds and canal clouds on the basis of their
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the clouds, rounded holes or elongated channels carved
in the mid-level, subfreezing cloud layers were
reported in the meteorological literature in
the 1940s (1). In correspondence titled “Man-
Cirrus?” in Weather (2), a large horizontal
clouds etched in a midlevel cloud was the first of
embryo in Clouds

and Aaron Bansemer, 
Yuming Zhang

than 50 years, but the mechanisms and their effects have largely been ignored. The clouds with ice particles generated by aircraft, as they cooled as it flows around aircraft propellers and the growth of the ice particles can induce changes in the clouds that expands the holes and canals in clouds. Thus, additional precipitation can be induced.

Clouds burst and canals clouds on the basis of their convective appearance (Fig. 1A).

Streamers embedded within or descending into cirrus holes or elongated channels carved into mid-level, subfreezing cloud layers were reported in the meteorological literature in the 1940s (1). In correspondence titled “Man-made Cirrus?” in Weather (2), a large horizontal

etching in a midlevel cloud was the first of

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Science magazine, July 2011

- WRF v3.1.1
- 600 x 300 grid points, 50-meter spacing
- 135 levels, 150-m decreasing to 50-m increasing to 250-m spacing
- Thompson et al (2008) bulk microphysics
  - adiabatic liquid water cloud 150 meters deep at 7 km, T=–30°C
  - no ice allowed to initiate for first 30 minutes
  - 100 ice crystals per liter for 60 seconds in 4x4 square of grid boxes
- Experiment NO-LH turned off latent heating due to vapor deposition onto snow/ice; latent cooling by evaporation of droplets remains
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Experiment: Control
- t = 40 min
- 2.7 km
- 2.1 km

No Latent Heat
- t = 40 min
- Vertical velocity

- t = 60 min
- t = 80 min
- t = 100 min
- Vertical velocity

Experiment NO-LH turned off latent heating due to vapor deposition onto snow/ice; latent cooling by evaporation of droplets remains.
2-d tests IMPROVE-2 case
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Precipitation intercomparison

- Istvan Geresdi bin microphys
- Bill Hall R-T; 2-moment snow; S&B autoconv.
- Jean-Pierre Chaboureau 2-moment MesoNH
- Axel Seifert 2-moment WRF
- Winfried Straub 2-moment Seifert in KAMM2
WRF forecasts for ICE–L project

NCAR C–130 wave cloud flight near Wheatland, WY 2035–2125 UTC 16 Nov 2007
WRF forecasts for ICE–L project
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WRF forecasts for ICE–L project

NCAR C–130 wave cloud flight near Wheatland, WY 2035–2125 UTC 16 Nov 2007
WRF forecast of ICE-L wave cloud

Grid 1: 425x319 \( \Delta x = 12 \text{km} \)
Grid 2: 271x271 \( \Delta x = 4 \text{km} \)
Grid 3: 295x280 \( \Delta x = 1.33 \text{km} \)
WRF forecast of ICE-L wave cloud
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Colorado Headwaters project

• Predict Colorado mountain snowfall and resulting stream runoff

• High-resolution, 2 km grid spacing, excellent terrain representation, NARR forcing

• Three seasons, 6-month duration:
  ‣ 01 Nov 2007 – 30 Apr 2008 (above average)
  ‣ 2005 – 2006 (average year)
  ‣ 2001 – 2002 (below average)

• Verified against SNOTEL observations

• Sensitivity experiments:
  ‣ CCSM year 2050
  ‣ microphysics: Thompson et al, 2008 vs. WSM6
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Figure 1: Retrospective model domain and location of SNOTEL sites (black dots). (a) full model domain (b) sub-domain focused over the Colorado Headwaters region.

WRF simulations by Changhui Liu
preliminary analysis by Kyoko Ikeda
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Figure 1: Retrospective model domain and location of SNOTEL sites sub-domain focused over the Colorado Headwaters region.

WRF simulations by Changhai Liu
preliminary analysis by Kyoko Ikeda
Comparison of 4 winter seasons

Figure 5: Comparison of 2 km WRF to SNOTEL site average accumulative precipitation (mm) for a 6-month simulation period during (a) 2001/2002 (dry year), (b) 2003/2004 (average year), (c) 2005/2006 (average year), and (d) 2007/2008 (wet year) water years.
3-month comparison of 7 MP schemes
3-month comparison of 7 MP schemes

FIG. 9. Spatially and temporally averaged profiles of cloud water, rain water, ice, snow, and graupel mixing ratio over the sub-domain for simulations (a) CTRL, (b) MPM2M, (c) MPWSM5, (d) MPWSM6, (e) MPWDM6, (f) MPGCE, and (g) MPLIN.
New developments - aerosols
Aerosol activation as CCN

**Activation depends on:**
1. aerosol concentration
2. updraft velocity
3. temperature
4. hygroscopicity (kappa)
5. aerosol mean radius

**Implementation details:**
1. nearest neighbor $T$, $k=0.4$, $r=0.02$
2. interpolated $Na$, $w$
3. grid-scale vertical velocity only
4. negative $w$ uses $+1 \text{ cm s}^{-1}$
5. added 2 components to WRF scalar array $(N_c, N_a)$
6. never fewer than 10 aerosols per cc

**Potential improvements:**
1. vertical velocity variance
2. variable kappa and mean size depend on ocean vs. land
3. connect to ice initiation
4. connect to radiation
5. separate sulfates, sea salts, other aerosol species
6. couple with WRF-Chem

Look-up table of fraction of activated aerosols created using parcel model of Feingold and Heymsfield (1992) with additions by T. Eidhammer & S. Kreidenweis

<table>
<thead>
<tr>
<th>$Na$</th>
<th>$w$</th>
<th>$T$</th>
<th>$k$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.90678394</td>
<td>0.01</td>
<td>4.79E-02</td>
<td>243.15</td>
</tr>
<tr>
<td>31.6</td>
<td>0.80150497</td>
<td>0.016</td>
<td>1.3115799</td>
<td>253.15</td>
</tr>
<tr>
<td>100</td>
<td>0.670093</td>
<td>0.1</td>
<td>0.30511799</td>
<td>263.15</td>
</tr>
<tr>
<td>316</td>
<td>0.54022598</td>
<td>0.316</td>
<td>0.54022598</td>
<td>273.15</td>
</tr>
<tr>
<td>1000</td>
<td>0.354206</td>
<td>1</td>
<td>0.76158798</td>
<td>283.15</td>
</tr>
<tr>
<td>3160</td>
<td>0.16229999</td>
<td>3.16</td>
<td>0.91756499</td>
<td>293.15</td>
</tr>
<tr>
<td>10000</td>
<td>0.18E-02</td>
<td>10</td>
<td>0.98596396</td>
<td>303.15</td>
</tr>
</tbody>
</table>

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Input aerosols (CCN)

GOCART 2.5° (lon) x 2.0° (lat) global monthly avg data, 20 sigma levels

6 sulfate bins,
4 sea salt bins
7 dust bins
mass converted to number conc.
Mineral/dust as ice nuclei
Mineral/dust as ice nuclei
Mineral/dust as ice nuclei

Georgii and Kleinjung (1967)

Aerosol conc. > 0.5 μm (cm⁻³ STP)
Mineral/dust as ice nuclei

Homogeneous freezing of deliquesced aerosols (can be > 1000 L⁻¹)

Typical aerosol background values

DeMott et al (2010)
Vertical profiles: sea, land, urban
WRF simulation 2001Dec13 (IMPROVE-2)

**Model Setup**

**WRF version 3.2.1 using:**
- 3 grids: 9, 3, 1-km spacing
- 71 vertical levels
- FNL model used for initial/boundary conditions
- RRTM (longwave) & Dudhia (shortwave) radiation
- YSU PBL scheme
- NO cumulus parameterization
- Simulation started 0000 UTC 2001Dec13 and run for 36 hours
Results
Droplets from control vs. polluted aerosols

18-h forecast valid 1800 UTC Thu 13 Dec 2001
Control experiment, k=18
Cloud droplet concentration

18-h forecast valid 1800 UTC Thu 13 Dec 2001
Polluted experiment, k=18
Cloud droplet concentration
Droplets from control vs. polluted aerosols
Droplets from control vs. polluted aerosols

Control Jumpoff Joe aerosols/droplets

Polluted Jumpoff Joe aerosols/droplets

- Height (km)
- Number concentration (per cc)
Constant droplet number versus variable
New proposal - ConUS 3-km simulations

Terrain height (m)
Summary

• Numerous updates/improvements from “legacy” Lin, Farley, Orville (1983) scheme(s) that keep getting duplicated

• Well-tested, flexible, documented code

• Many applications: QPF, icing, winter weather, summer convection

• First steps of aerosol-cloud-precipitation feedbacks
  ♦ initial indications are successful - primary effects working
  ♦ need to connect with radiation