Lecture 7

Representation of cloud processes in models

1. Major cloud processes
2. Example of cloud parameterizations in WRF

Required reading:

Randall, D., M. Khairoutdinov, A. Arakawa, and W. Grabowski, Breaking the cloud parameterization deadlock. BAMS, 1547-1564, 2003.

Additional reading:

Cantrell, W., and A. Heymsfield, Production of ice in tropospheric clouds: A review. BAMS,795-807, 2005.

Akio Arakawa. (2004) The Cumulus Parameterization Problem: Past, Present, and Future. *Journal of Climate* **17**:13, 2493-2525

An idealized cloud:

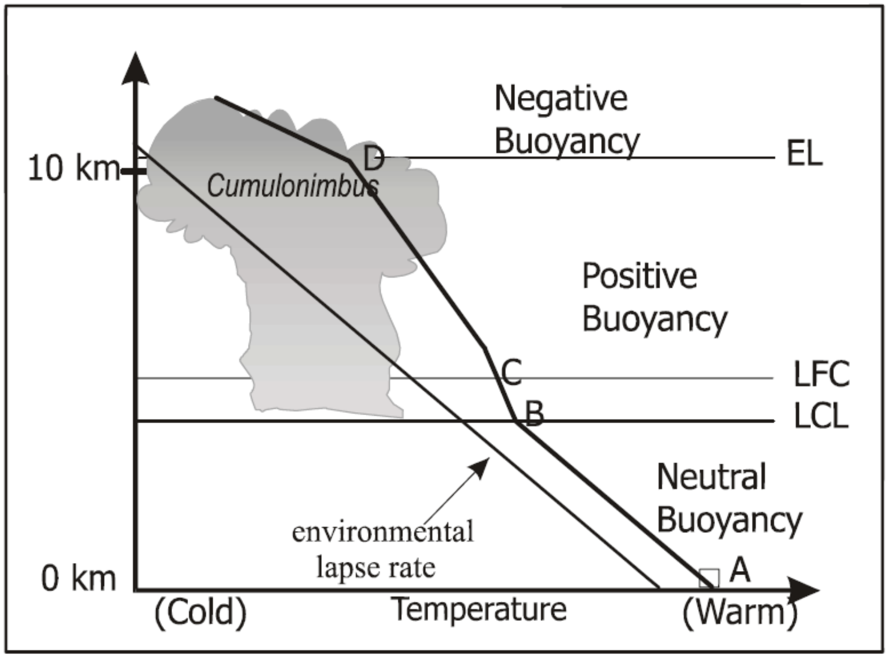


Figure 7.1 Temperature profile of idealized cloud.

- Between points A and B, the parcel cools at the dry adiabatic lapse rate (-9.8^{o}C km^{-1}).
- At B the parcel becomes saturated and condensation initiates (called Lifting Condensation Level (LCL), and varies in height according to the initial temperature and moisture content of the parcel).
- Once water droplets or ice crystals form, latent heat (energy released/required in phase changes) is released into the parcel, increasing its temperature. Further cooling due to lifting occurs at the moist adiabatic lapse rate which varies between 4^{o}C km^{-1} in the lower troposphere to 7^{o}C km^{-1} in the middle and upper troposphere.
- If the lifting continues past the LCL, it is possible that the cloud reaches a elevation where it becomes positively buoyant (point C) (called the Level of Free Convection (LFC).
- Once the top of a cloud passes the LFC, it continues to rise until it either runs out of moisture or when it encounters a stable layer of warm air. The height at which the parcel is no longer positively buoyant is called the equilibrium height (point D). The height of the LFC is a function of environmental lapse rate. Cool or cold air in the mid-troposphere usually has a high environmental lapse rate (>7^{o}C km^{-1}), which is very conducive to cumulus development. The closer the LFC is to the LCL, the easier it is for cumulus clouds to develop.
- *In the simplest of terms, clouds that are contained between the LCL and LFC are stratiform while those that continue to grow above the LFC are cumuliform.*

Major cloud processes.

Microphysics of warm clouds:

- ✓ *Nucleation of drops*

  Homogeneous nucleation is not efficient, requires supersaturation of 300-400%.

  Heterogeneous nucleation requires cloud condensation nuclei (CCN).
- ✓ *Condensation and evaporation*

  Once formed, water drops may continue to grow as vapor diffuses toward them (this process is called condensation). The reverse process, drops decreasing in size as vapor diffuses away from them, is called evaporation.
- ✓ *Fallout of drops*

  Depends on drop size. Terminal fall speed is when gravitational force is balanced by friction.

- ✓ *Coalescence*

  Continuous collection: cloud drop growth by coalescence with other drops as a drop falling through a cloud;

  Stochastic collection: cloud drop growth in a discrete, stepwise, probabilistic manner.
- ✓ *Breakup of drops*

  When raindrops achieve a certain size, they become unstable and break up into smaller drops.

Microphysics of cold clouds:

- ✓ *Homogeneous nucleation of ice particles*

  Nucleation of ice particles from either liquid or water vapor phase. Occurs at lower than about -35 to -40^{0}C (unfrozen water is called supercooled but freezes spontaneously below -40^{0}C)
- ✓ *Heterogeneous nucleation of ice particles*

  Several modes: condensational nucleation, immersion freezing, deposition nucleation, and contact nucleation. Occurs at temperature from 0C to -40^{0}C.
- ✓ *Deposition and sublimation*

  Growth of in ice particle by diffusion of ambient vapor toward the particle is called deposition. The lost of mass of an ice particle by diffusion of vapor from the ice-phase into the air is called sublimation.
- ✓ *Aggregation and riming*

  If ice particle collect other ice particles, the process is called aggregation. If ice particles collect liquid drops, which freeze on contact, the process is called riming.

  Extreme riming produces hail (~ 1 cm, can be as large as 10-15 cm).
- ✓ *Ice enhancement*

  Far more ice particles than ice nuclei. Hypotheses: 1) fragmentation of ice crystals; 2) ice splinter production in riming
- ✓ *Fallout of ice particles*
- ✓ *Melting*

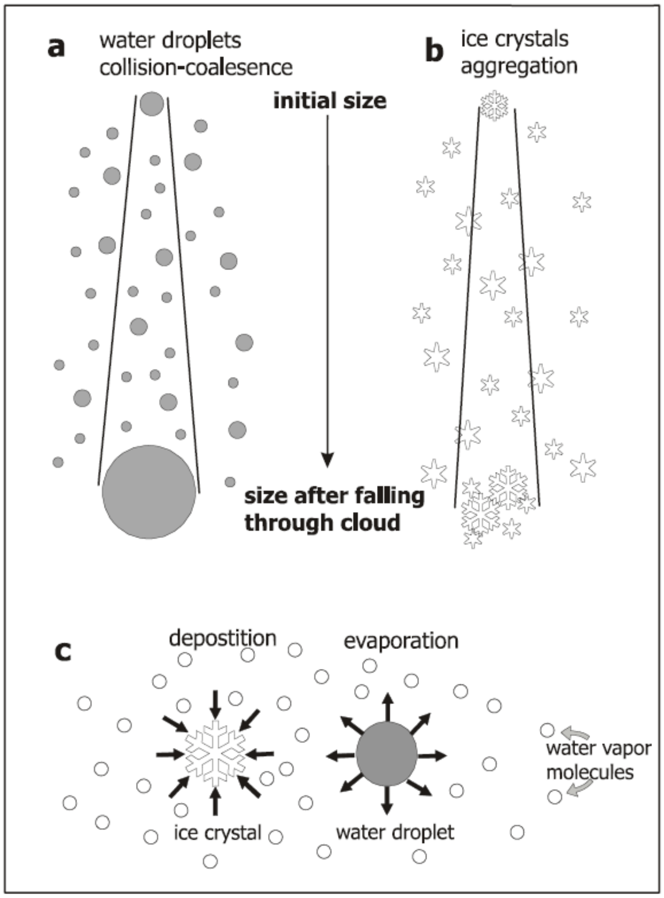


Figure 7.2 Growth of precipitation.

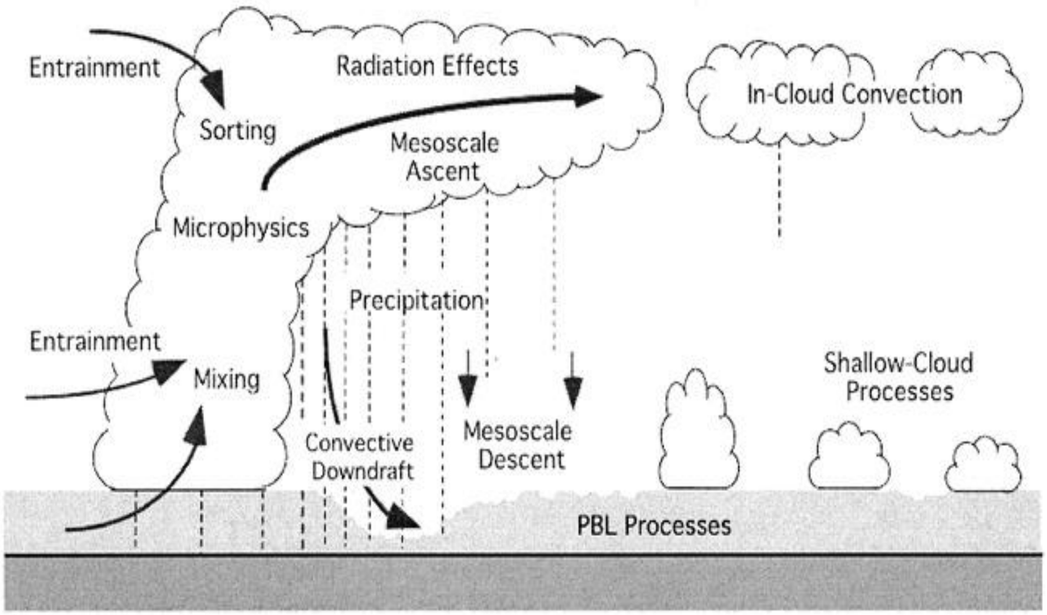
<u>Growth in warm (liquid) clouds:</u>

- ✓ Small droplets evaporate, producing extra water vapor which is in turn made available to the larger droplets. Once this process is initiated, a select few droplets grow quite rapidly. When droplets reach a size of about d= 0.1 mm, they start to fall through the cloud.
- ✓ Falling large collide and coalesce (merge) with the smaller droplets in a process called collision-coalescence (Figure 7.2a). Large droplets exit the base of the cloud as soon as their fall velocities exceed the speed of any updrafts.

<u>Growth in mixed phase (liquid-ice) clouds:</u>

- ➢ Ice crystals can grow at the expense of water droplets. When this occurs some of the ice crystals grow large enough to fall through the cloud, colliding and merging with other ice crystals, in a process called aggregation (Figure 7.2b)

Convective clouds



UNCERTAINTIES IN FORMULATING CLOUD AND ASSOCIATED POCESSES

There is no a sufficiently general framework, such as a unified cloud system model, for implementing detailed formulations of these processes for the purpose of parameterization (Arakawa, 2004)

Purpose of a convective parameterization

- Determine when and if convection occurs:

Trigger function

- Determine vertical distribution of heating, moiste and momentum changes:

Cloud model

- Determine overall amount of energy conversion, change in wind fields, convective precipitation, latent heat release:

Closure

<u>Representation of cloud microphysics in models:</u>

<u>Single moment microphysics scheme:</u>

- ✓ Predicts only mixing ratios of species.
- ✓ Diagnoses the number of concentrations from specified size distribution parameter and predicted mixing ratio

<u>Double moment microphysics scheme:</u>

- ✓ Predicts mixing ratios and number concentration of species. (improves representation of particle size distribution)

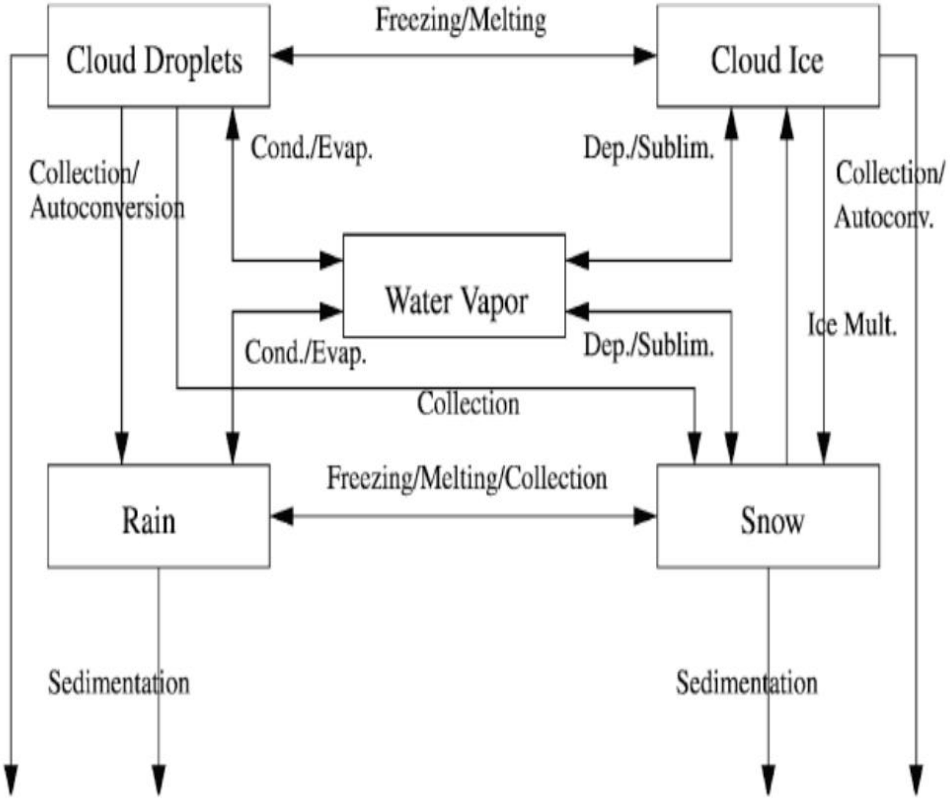


Figure 7.3 Microphysical processes included in the Morrison et al.(2005) double-moment scheme.

Cloud microphysics parameterizations in WRF-Chem.

Summary of Microphysics Options (WRF v3.2)

mp_physics	Scheme	Reference	Added
1	Kessler	Kessler (1969)	2000
2	Lin (Purdue)	Lin, Farley and Orville (1983, JCAM)	2000
3	WSM3	Hong, Dudhia and Chen (2004, MWR)	2004
4	WSM5	Hong, Dudhia and Chen (2004, MWR)	2004
5	Eta (Ferrier)	Rogers, Black, Ferrier, Lin, Parrish and DiMego (2001, web doc)	2000
6	WSM6	Hong and Lim (2006, JKMS)	2004
7	Goddard	Tao, Simpson and McCumber (1989, MWR)	2008
8 (+98)	Thompson (+old)	Thompson, Field, Rasmussen and Hall (2008, MWR)	2009
9	Milbrandt 2-mom	Milbrandt and Yau (2005, JAS)	2010
10	Morrison 2-mom	Morrison, Thompson and Tatarskii (2009, MWR)	2008
14	WDM5	Lim and Hong (2010)	2009
16	WDM6	Lim and Hong (2010)	2009

mp_physics	Scheme	Cores	Mass Variables	Number Variables
1	Kessler	ARW	Qc Qr	
2	Lin (Purdue)	ARW	Qc Qr Qi Qs Qg	
3	WSM3	ARW	Qc Qr	
4	WSM5	ARW/NMM	Qc Qr Qi Qs	
5	Eta (Ferrier)	ARW/NMM	Qc Qr Qs (Qt*)	
6	WSM6	ARW/NMM	Qc Qr Qi Qs Qg	
7	Goddard	ARW	Qc Qr Qi Qs Qg	

8 (/98)	Thompson(/old)	ARW/NMM	Qc Qr Qi Qs Qg	Ni Nr (/Ni)
9	Milbrandt 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
10	Morrison 2-mom	ARW	Qc Qr Qi Qs Qg	Nr Ni Ns Ng
14	WDM5	ARW	Qc Qr Qi Qs	Nn** Nc Nr
16	WDM6	ARW	Qc Qr Qi Qs Qg	Nn** Nc Nr

*Advects only total condensates   ** Nn = CCN number

Qc - cloud water mixing ratio (kg/kg)
Qr - rain mixing ratio (kg/kg)
Qi - ice mixing ratio (kg/kg)
Qs - snow mixing ratio (kg/kg)
Qg - graupel mixing ratio (kg/kg)
Qh - hail mixing ratio (kg/kg)

Microphysics (mp_physics)

a. Kessler scheme: A warm-rain (i.e. no ice) scheme used commonly in idealized cloud modeling studies (*mp_physics* = 1).

b. Lin et al. scheme: A sophisticated scheme that has ice, snow and graupel processes, suitable for real-data high-resolution simulations (2).

c. WRF Single-Moment 3-class scheme: A simple efficient scheme with ice and snow processes suitable for mesoscale grid sizes (3).

d. WRF Single-Moment 5-class scheme: A slightly more sophisticated version of (c) that allows for mixed-phase processes and super-cooled water (4).

e. Eta microphysics: The operational microphysics in NCEP models. A simple efficient scheme with diagnostic mixed-phase processes (5).

f. WRF Single-Moment 6-class scheme: A scheme with ice, snow and graupel processes suitable for high-resolution simulations (6).

g. Goddard microphysics scheme. A scheme with ice, snow and graupel processes suitable for high-resolution simulations (7). New in Version 3.0.

h. New Thompson et al. scheme: A new scheme with ice, snow and graupel processes suitable for high-resolution simulations (8). This adds rain number concentration and updates the scheme from the one in Version 3.0. New in Version 3.1.

i. Milbrandt-Yau Double-Moment 7-class scheme (9). This scheme includes separate categories for hail and graupel with double-moment cloud, rain, ice, snow, graupel and hail. New in Version 3.2.

j. Morrison double-moment scheme (10). Double-moment ice, snow, rain and graupel for cloud-resolving simulations. New in Version 3.0.

k. WRF Double-Moment 5-class scheme (14). This scheme has double-moment rain. Cloud and CCN for warm processes, but is otherwise like WSM5. New in Version 3.1.

l. WRF Double-Moment 6-class scheme (16). This scheme has double-moment rain. Cloud and CCN for warm processes, but is otherwise like WSM6. New in Version 3.1.

m. Thompson et al. (2007) scheme (98). This is the older Version 3.0 Thompson scheme that used to be option 8.

Cumulus Parameterization (cu_physics)

a. Kain-Fritsch scheme: Deep and shallow convection sub-grid scheme using a mass flux approach with downdrafts and CAPE removal time scale (*cu_physics* = 1).

b. Betts-Miller-Janjic scheme. Operational Eta scheme. Column moist adjustment scheme relaxing towards a well-mixed profile (2).

c. Grell-Devenyi ensemble scheme: Multi-closure, multi-parameter, ensemble method with typically 144 sub-grid members (3).

d. Grell 3d ensemble cumulus scheme. Scheme for higher resolution domains allowing for subsidence in neighboring columns (5). New in Version 3.0.

e. Old Kain-Fritsch scheme: Deep convection scheme using a mass flux approach with downdrafts and CAPE removal time scale (99).

f. *ishallow*: shallow convection option. = 1, option on. Works together with Grell 3D scheme (*cu_physics* = 5)