Overview of WRF Physics
Cumulus Parameterization

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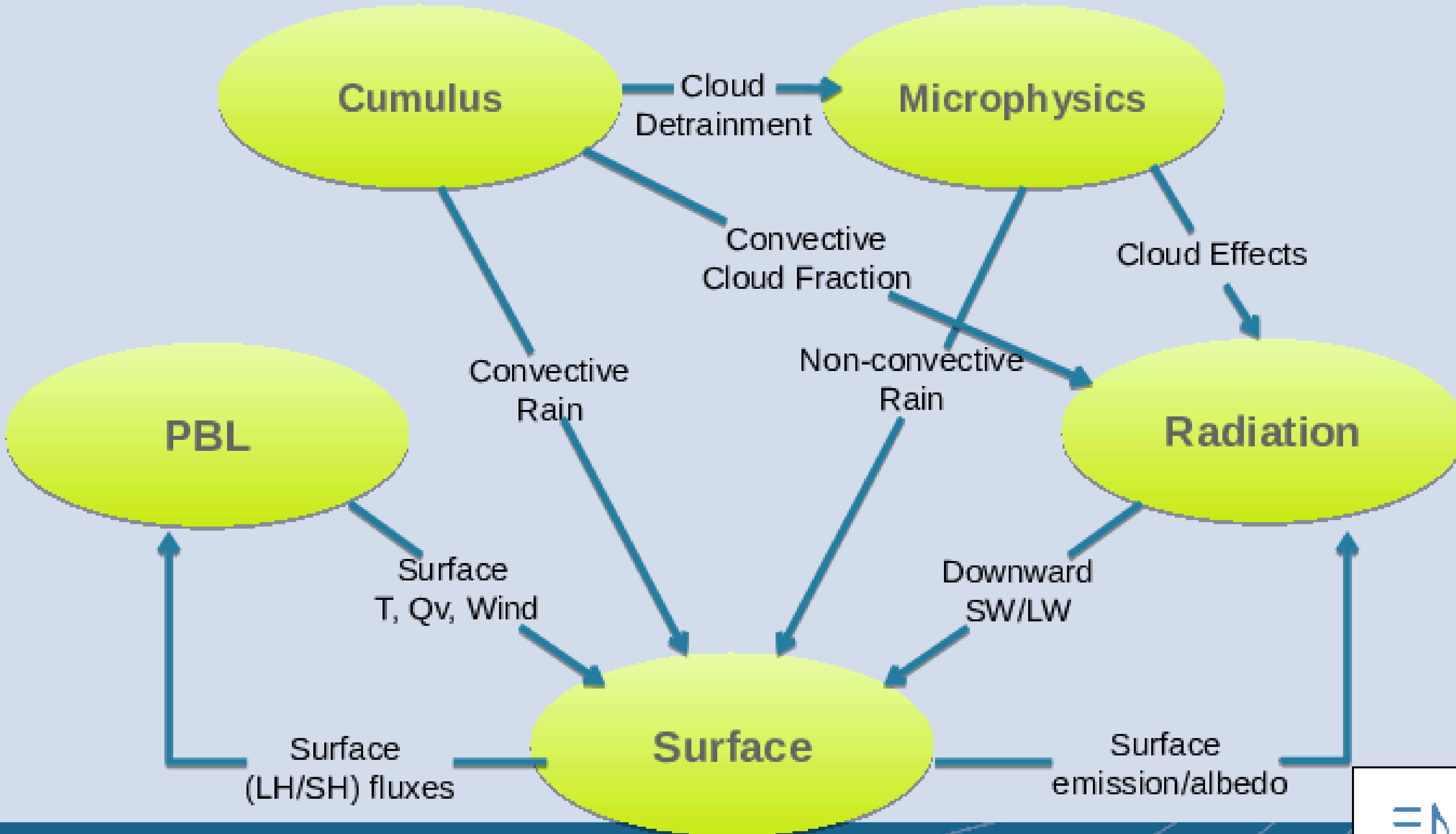
WRF Physics

- Radiation
  - Longwave (ra_lw_physics)
  - Shortwave (ra_sw_physics)
- Surface
  - Surface layer (sf_sfclay_physics)
  - Land/water surface (sf_surface_physics)
- PBL (bl_pbl_physics)
- Turbulence/Diffusion (diff_opt, km_opt)
- **Cumulus parameterization (cu_physics)**
- Microphysics (mp_physics)

Direct Interactions of Parameterizations



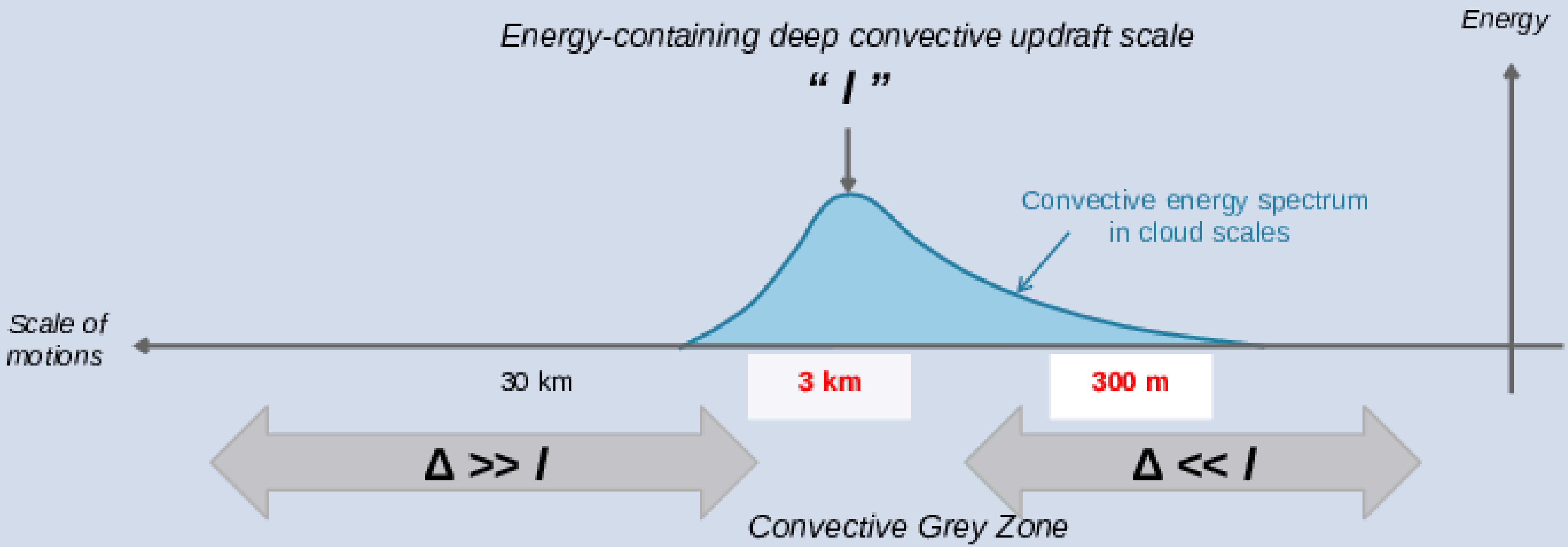
Cumulus Parameterization

Provides

Atmospheric heat and moisture/cloud and possibly momentum tendency profiles

Surface (sub-grid) convective rainfall

Cumulus Parameterization and Cloud-Resolving



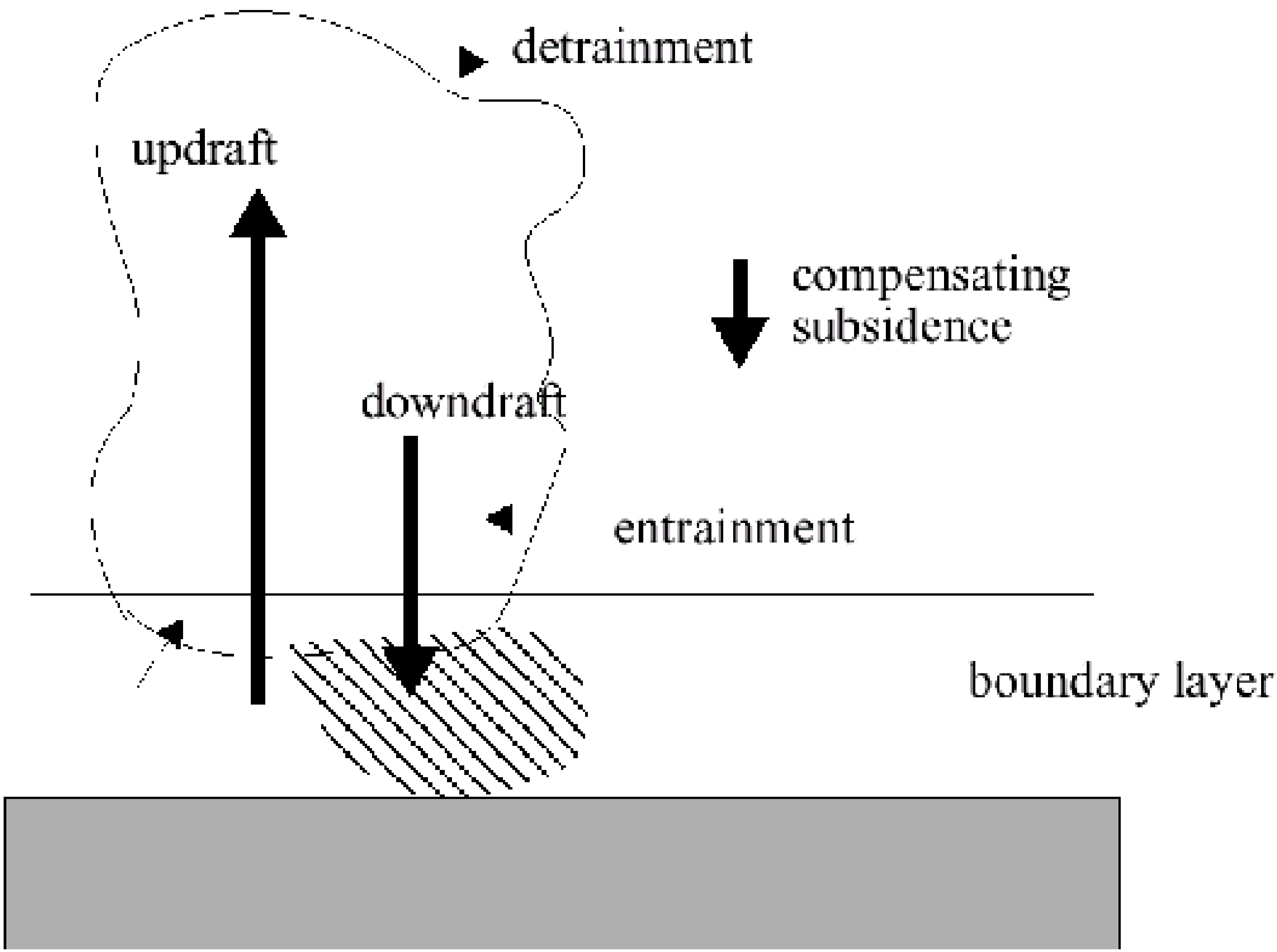
For coarse grid spacing

- ✓ Cumulus parameterization schemes have been designed for Δ >> *l*
- ✓ *All updrafts and downdrafts are sub-grid*
- ✓ *1d column schemes handle sub-grid vertical fluxes*

For fine grid spacing

- ✓ Resolved dynamics and microphysics work for Δ << *l*
- ✓ *Updrafts and downdrafts are resolved*

Illustration of Cumulus Processes



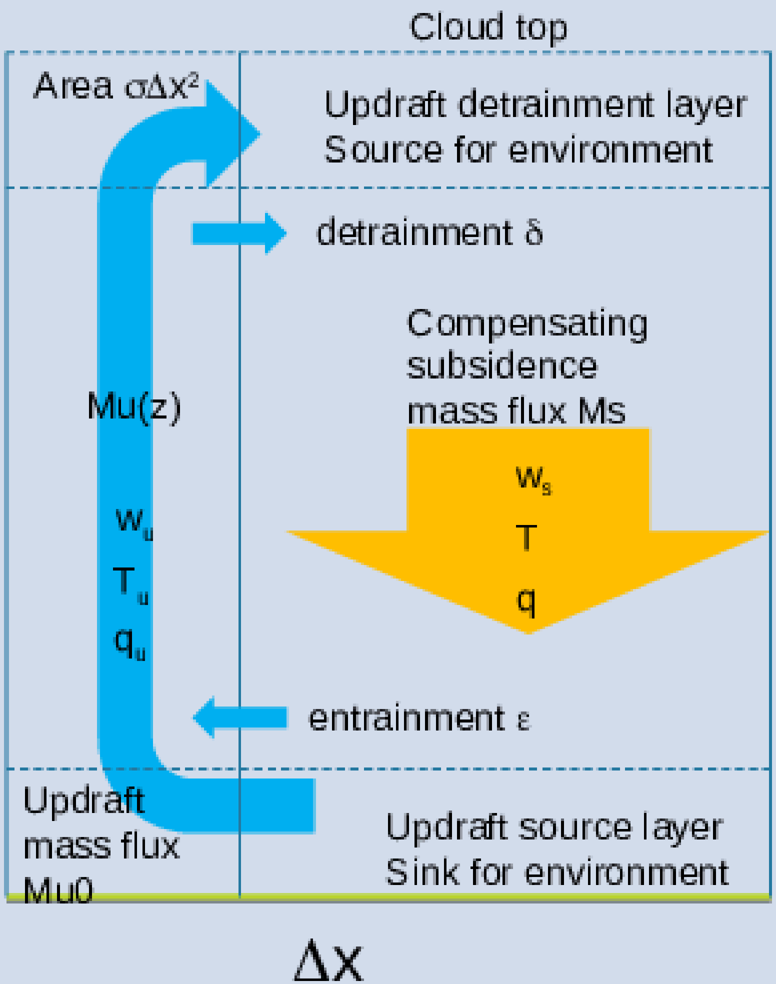
Cumulus Schemes

- Use for grid columns that completely contain convective clouds (typically dx > 10 km)
- Re-distribute air in column to account for vertical convective fluxes
  - Updrafts take boundary layer air upwards
  - Downdrafts take mid-level air downwards
- Schemes have to determine
  - When to trigger a convective column
  - How fast to make the convection act

Deep Convection

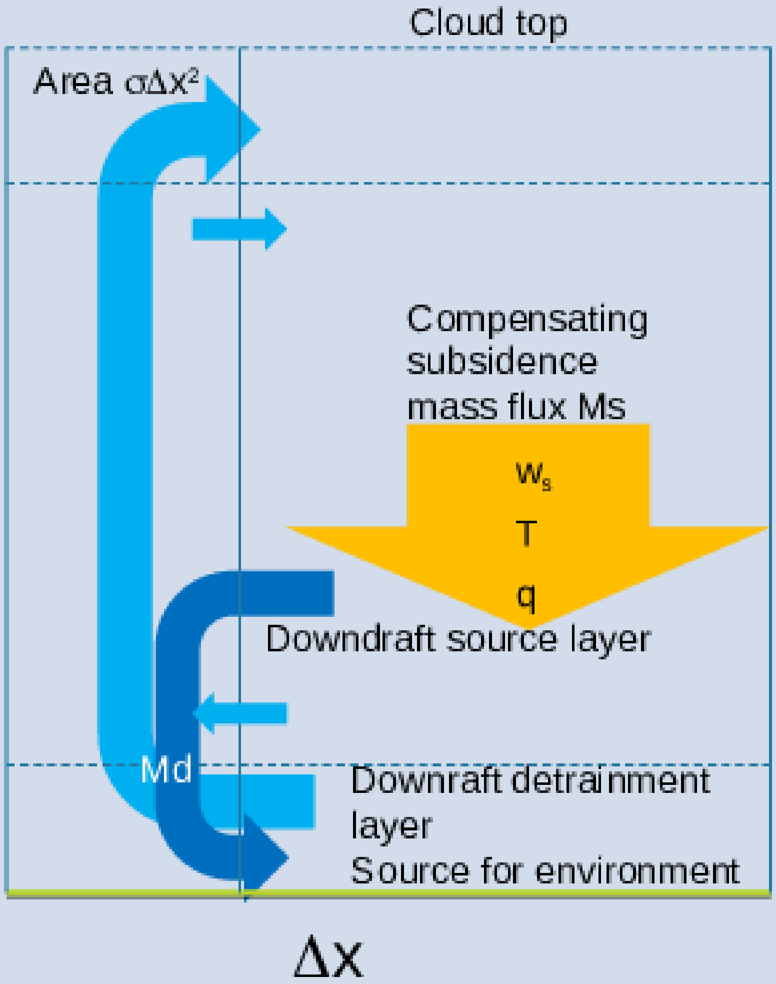
- Schemes work in individual columns that are considered convectively unstable
- Mass-flux schemes transport surface air to top of cloud and include environmental subsidence around clouds
  - Note: schemes have no net mass flux – subsidence compensates cloud mass fluxes exactly
  - Environmental subsidence around cloud warms and dries troposphere removing instability over time
    - Dynamics may produce mean vertical motion in grid cell in response to scheme's heating profile
- Additionally downdrafts may cool PBL

Mass Flux Schemes



- Updraft mass changes with z
  - $d\,Mu / dz = Mu\,(\varepsilon - \delta)$
- Compensating subsidence balances
  - $Ms = -\,Mu \;:\; w_s = -\,\sigma\,w_u$
- Updraft transport of conserved moist static energy, h_u (J/kg)
  - $h_u = c_p\,T_u + L_v\,q_u + g\,z$
  - $\rho\;w_u\,h_u\,\sigma = Mu\,h_u$
  - $h_u(z)$ dilutes due to entrainment
- Subsidence
  - $d/dt(\rho\;\theta) = -\,d/dz(Ms\;\theta)$:warming
  - $d/dt(\rho\;q) = -\,d/dz(Ms$ $q)$:drying

Mass Flux Schemes



- **Updrafts**
  - Driven by buoyancy
  - Moist air to upper troposphere
  - Condensation to convective rainfall
- **Downdrafts**
  - Driven by convective rain evaporation
  - Evaporatively cooled air to boundary layer
- **Subsidence**
  - Warms and dries troposphere
  - Main warming effect in column

WRF Cumulus Parameterization Options

- Cumulus schemes fall into two main classes
  - Adjustment type (Betts-Miller-Janjic)
    - Relaxes towards a post-convective (mixed) sounding
  - Mass-flux type (all others in WRF)
    - Determines updraft (and often downdraft) mass flux and other fluxes (sometimes including momentum transport)

Cumulus schemes

cu_physics	Scheme	Reference	Added
1	Kain-Fritsch	Kain (2004, JAM)	2000
2	Betts-Miller-Janjic	Janjic (1994, MWR; 2000, JAS)	2002
3	Grell-Freitas	Grell and Freitas (2013, to be published)	2013
4	Old Simplified Arakawa-Schubert	Pan and Wu (1995, NCEP Office Note)	2002/ 2011
5	Grell-3	Grell and Devenyi (2002, GRL)	2008
6,16	Tiedtke	Tiedtke (1989, MWR), Zhang, Wang and Hamilton (2011, MWR)	2011, 2015
7	Zhang-McFarlane	Zhang and McFarlane (1995, AO)	2011
10	KF CuP	Berg and Stull (2004, 2005, JAS)	2016
11	Multi-Scale KF	Alapaty and Herwehe	2015
14	KSAS	Kwon and Hong (2017, MWR)	2017
84	New SAS (HWRF)	Han and Pan (2010,...)	2012
93	Grell-Devenyi	Grell and Devenyi (2002, GRL)	2002
99	Old Kain-Fritsch	Kain and Fritsch (1990, JAS; 1993 Meteo. Monogr.)	2000

Triggers

- Clouds only activate in columns that meet certain criteria
  - Presence of some convective available potential energy (CAPE) in sounding
  - Not too much convective inhibition (CIN) in sounding (cap strength)
  - Minimum cloud depth from parcel ascent

Cloud Model

- The base of these schemes is a 1d cloud model that calculates vertical variation of updraft properties based on
  - Initial properties at base
  - Entrainment dilution from environment
  - Condensation to cloud particles
  - Conversion of cloud to rain that falls out of the updraft
  - Buoyancy that determines cloud top and detrainment level

Closures

- Closure determines cloud strength (mass-flux) based on various methods
  - Clouds remove CAPE over time
    - Specified CAPE-removal time scale (KF, ZM, Tiedtke, BMJ)
      - E.g. H/w_u cloud height over updraft speed
    - Quasi-equilibrium (Arakawa-Schubert) with large-scale destabilization d(CAPE)/dt (SAS, NSAS)
    - Moisture convergence
    - Low-level large-scale ascent (mass convergence)
- Scale-awareness is introduced by reducing deep convection mass flux based on criteria such as grid size (GF scheme, MSKF)

Ensemble methods

- GF, G3 and GD use ensemble of triggers and closures possibly with varying parameters (up to 144 members)
- Take mean of ensemble to feed back to model
- In principle, can be tuned to emphasize various members under different conditions

Shallow Convection

- Non-precipitating shallow mixing dries PBL, moistens and cools above
- This can be done by an enhanced mixing approach (SAS, GRIMS) or mass-flux approach (KF, NSAS, Tiedtke, G3, GF, Deng)
- May be useful at grid sizes that do not resolve shallow cumulus clouds (> 1 km)

Shallow Convection

- Cumulus schemes may include shallow convection (KF, SAS schemes, G3, GF, BMJ, Tiedtke)
- Standalone shallow schemes
  - UW Park-Bretherton (shcu_physics=2)
  - GRIMS shallow scheme (shcu_physics=3)
  - NSAS shallow convection (shcu_physics=4) – to use with KSAS deep scheme
  - Deng shallow scheme (shcu_physics=5) – new in V4.1
- Part of PBL schemes with mass-flux method
  - TEMF PBL option (bl_bl_physics=10)
  - GBM PBL option (bl_bl_physics=12)
  - QNSE-EDMF PBL (bl_bl_physics=4)
  - MYNN (EDMF option) (bl_pbl_physics =5)

Momentum Transport

- Some cumulus parameterizations also have momentum transport (SAS, NSAS, Tiedtke, ZM, GF)
- Most schemes transport momentum as a passive scalar but ZM and NSAS include a convective pressure gradient term

Cloud Detrainment

- Most schemes detrain cloud and ice at cloud top (except BMJ)
- KF schemes also detrain snow and rain
- These are then used by the microphysics

Radiation Interaction

- The Grell schemes, KF and MSKF interact using cu_rad_feedback=1 which allows them to provide a cloud fraction and amount in active grid columns
- Zhang-McFarlane is part of the CESM suite that also provides a part of the cloud fraction (used with CESM (or MG) microphysics and UW shallow scheme)
- If using the GFDL radiation scheme there is a Slingo method of cloud fraction from many schemes using precip rate, top and bottom, to compute a cloud fraction

Call Frequency (cudt)

- Time between cumulus scheme calls
- Typical value is 5 minutes
  - Note: for KF scheme this is also used for averaging time for vertical velocity trigger
  - Not used by G3 or GD schemes

Cumulus schemes

cu_physics	Scheme	Cores	Moisture Tendencies	Momentum Tendencies	Shallow Convection	Radiation Interaction
1	Kain-Fritsch Eta	ARW NMM	Qc Qr Qi Qs	no	yes	yes
2	Betts-Miller-Janjic	ARW NMM	-	no	yes	GFDL
3	Grell-Freitas	ARW	Qc Qi	no	yes	yes
4	Old Simplified Arakawa-Schubert	ARW NMM	Qc Qi	yes (NMM)	yes (ARW)	GFDL
5	Grell-3	ARW	Qc Qi	no	yes	yes
6,16	Tiedtke	ARW	Qc Qi	yes	yes	no
7	Zhang-McFarlane	ARW	Qc Qi	yes	no	RRTMG
10	KF CuP	ARW	Qc Qi	no	yes	yes
14, 96	KSAS, NSAS	ARW	Qc Qi	yes	no/yes	GFDL
84	New SAS (HWRF)	ARW NMM	Qc Qi	yes (NMM)	yes	GFDL
93	Grell-Devenyi	ARW	Qc Qi	no	no	
99	Old Kain-Fritsch	ARW	Qc Qr Qi Qs	no	no	

yes=RRTM… …DL

Cumulus scheme: Recommendations

- dx ≥ 10 km:
  - Probably need cumulus scheme
  - These release instability gradually (prevent grid-point storms)
- dx ≤ 3 km:
  - Probably do not need scheme (resolved/permitted by dynamics)
  - However, there are cases where the earlier triggering of convection by cumulus schemes help
- dx=3-10 km:
  - Scale separation is a question
  - Few schemes are specifically designed with this range of scales in mind
  - G3 has an option to spread subsidence in neighboring columns
  - GF, MSKF, KSAS automatically phase out deep convection at fine grid size

- Issues with 2-way nesting when physics differs across nest boundaries (seen in precip field on parent domain)
  - Best to use same physics in both domains or 1-way nesting or make nested domain large enough to keep parent effects away from interior

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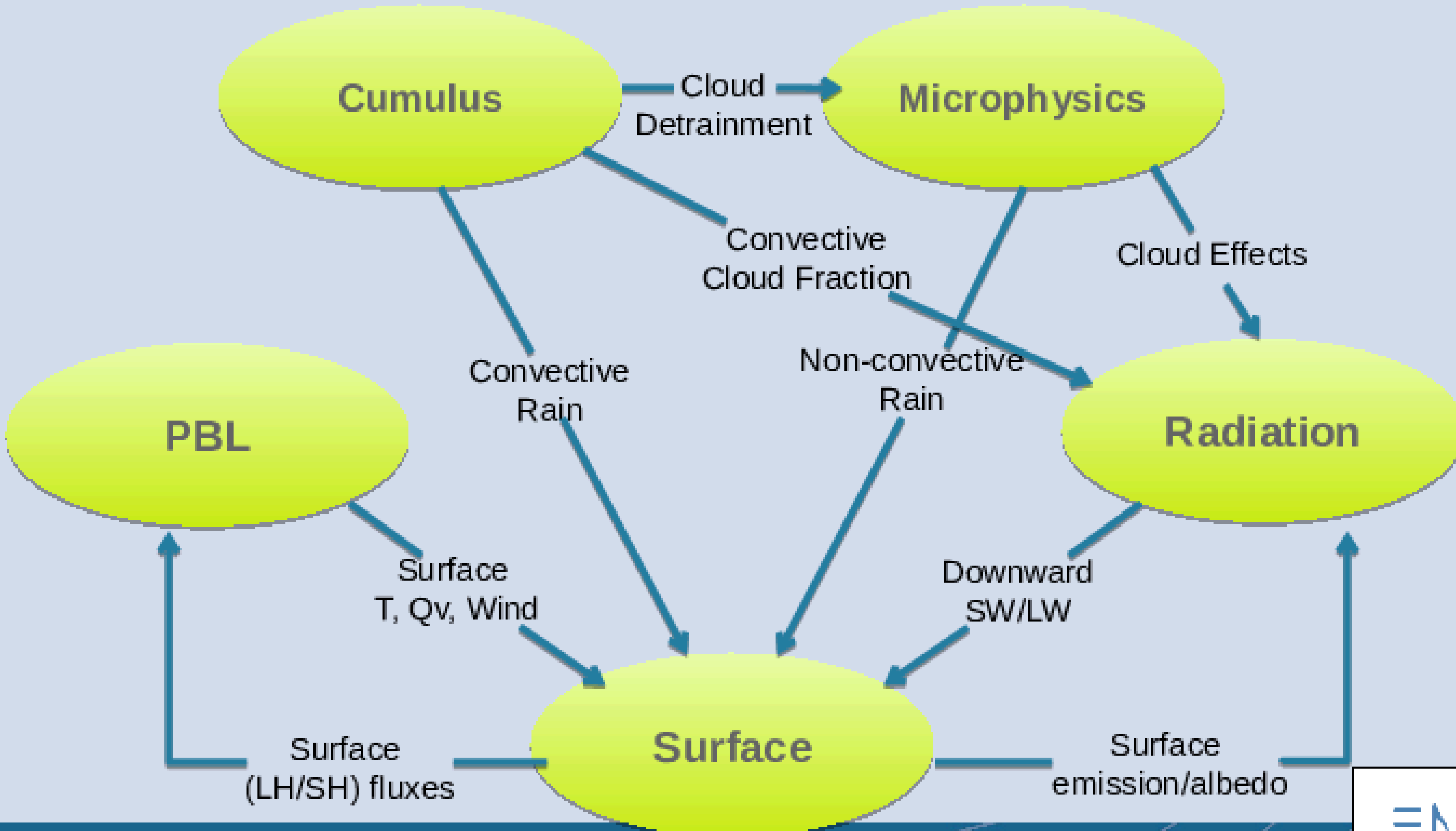
Direct Interactions of Parameterizations



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Convection Summary

- Cumulus Parameterization and Cloud Resolving
- Cumulus Schemes
  - Deep convection, mass flux schemes, triggers, 1d cloud model, closures, ensemble methods, shallow convection, momentum transport, cloud detrainment, radiation interaction
- Recommendations
  - Grid size