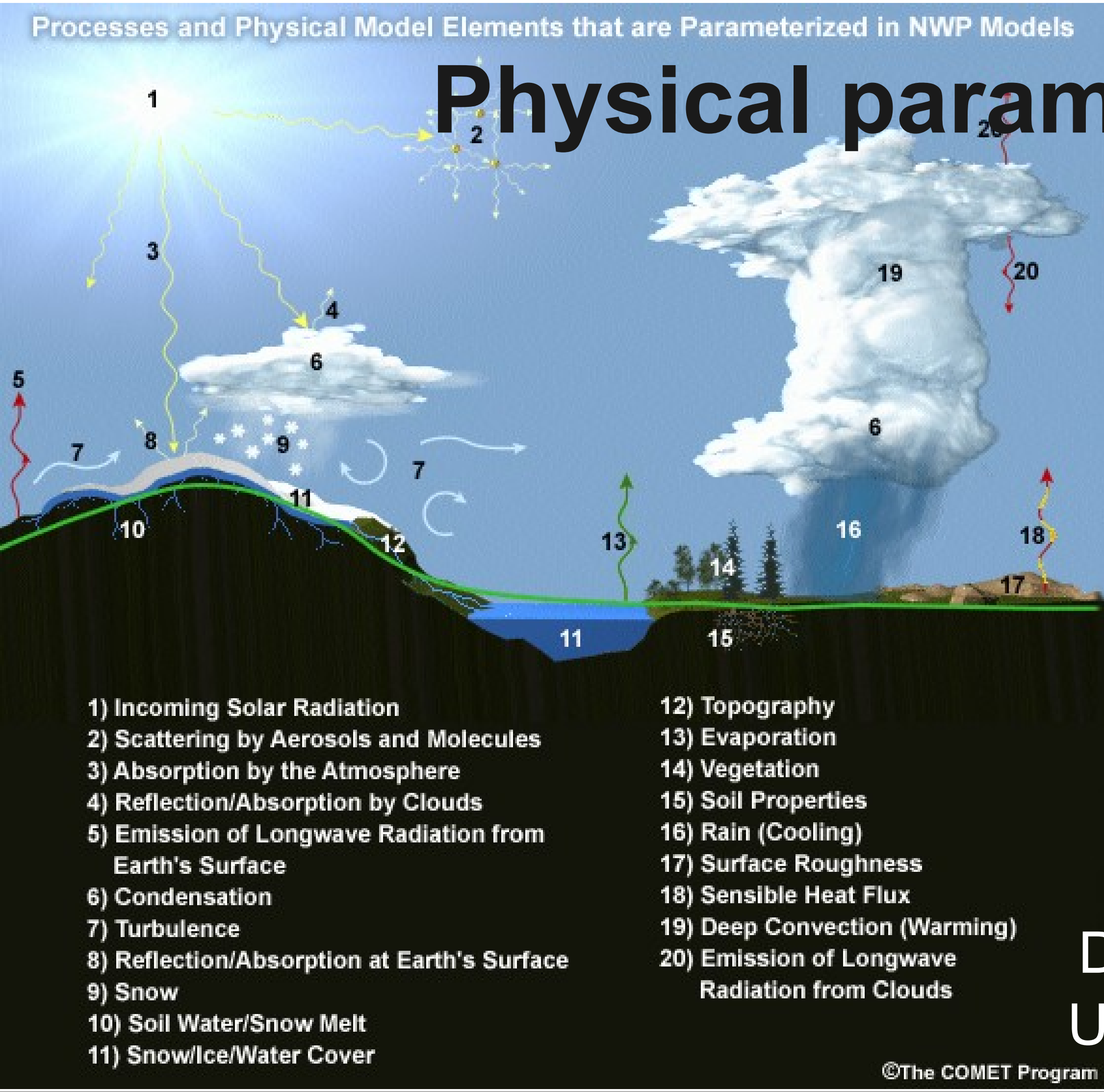
Physical parameterizations



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Physical parameterizations

Most of these slides are an excerpt of a presentation (consisting of more than 200 slides) by **Jimy Dudhia (NCAR)**, publicly available at

http://www.mmm.ucar.edu/wrf/users/tutorial/201207/Physics_full.pdf

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Numerical climate modelling

Atmospheric dynamics is driven by known physical laws:

Conservation of momentum, mass, energy and water vapor + state equation

$$
\begin{aligned}
\frac{d\boldsymbol{v}}{dt} &= -\alpha\boldsymbol{\nabla}p - \boldsymbol{\nabla}\phi + \boldsymbol{F} - 2\boldsymbol{\Omega}\times\boldsymbol{v} \\
\frac{\partial\rho}{\partial t} &= -\boldsymbol{\nabla}\cdot(\rho\,\boldsymbol{v}) \\
p\,\alpha &= R\,T \\
Q &= C_p\frac{dT}{dt} - \alpha\frac{dp}{dt} \\
\frac{\partial\rho\,q}{\partial t} &= -\boldsymbol{\nabla}\cdot(\rho\,\boldsymbol{v}\,q) + \rho\,(E-C)
\end{aligned}
$$

v = (u, v, w), T, p, $\rho=1/\alpha$ and q

These equations are valid at each point of a fluid continuum.

However, they can only be **solved** by numerical methods **over a discrete grid**.

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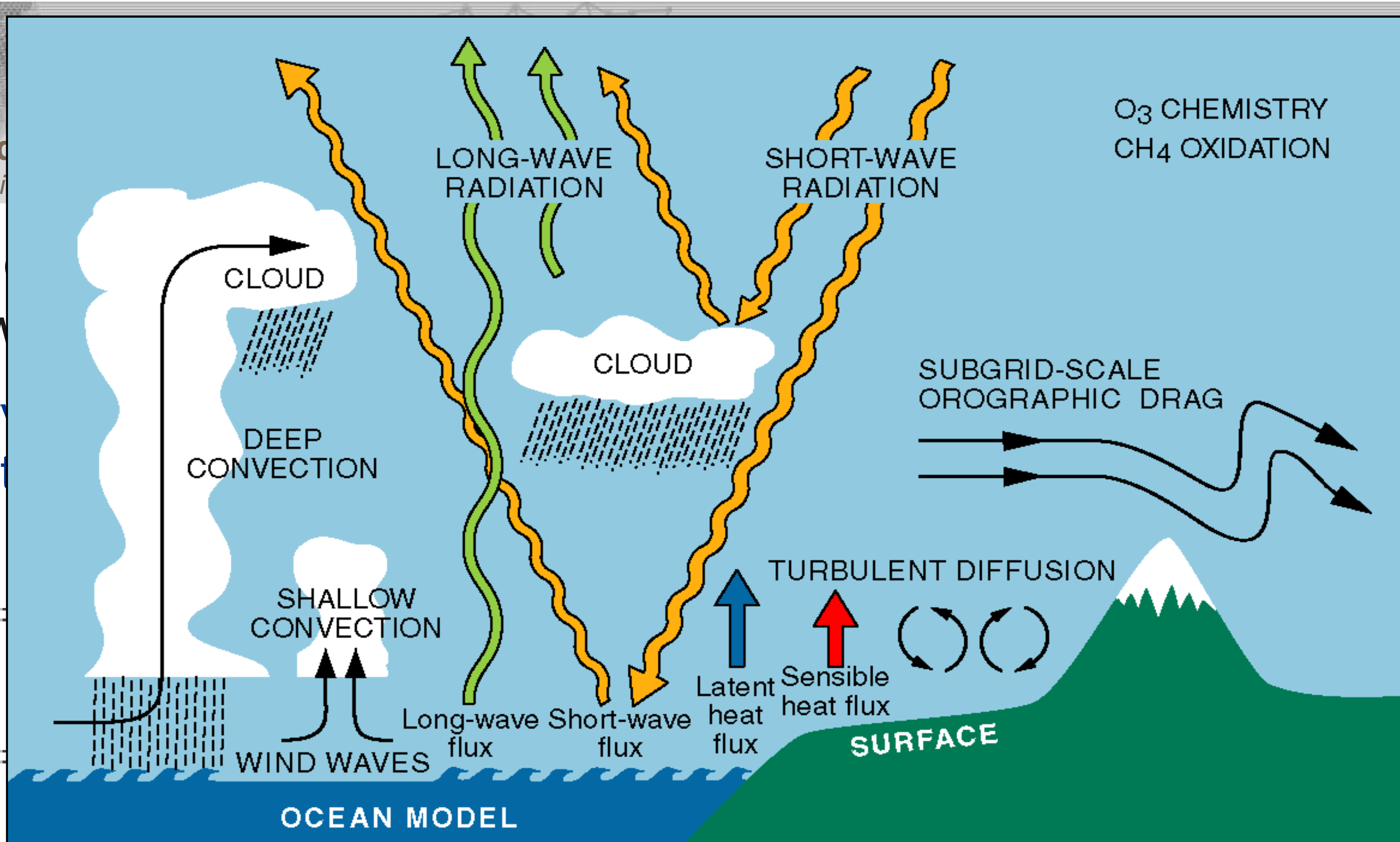


$$\frac{d\boldsymbol{v}}{dt} =$$

$$\frac{\partial \rho}{\partial t} =$$

$$p\,\alpha = RT$$

$$Q = C_p \frac{dT}{dt} - \alpha \frac{dp}{dt}$$

$$\frac{\partial \rho\, q}{\partial t} = -\boldsymbol{\nabla}\cdot(\rho\, \boldsymbol{v}\, q) + \rho\,(E - C)$$

v = (u, v, w), T, p, ρ=1/α and q

Some of these simple letters hide **complex processes** involving **small-scale** natural structures (EMR, molecules, droplets, leaves, trees, cumulus, ...)

However, they can only be **solved** by numerical methods **over a discrete grid**.

Parameterizations

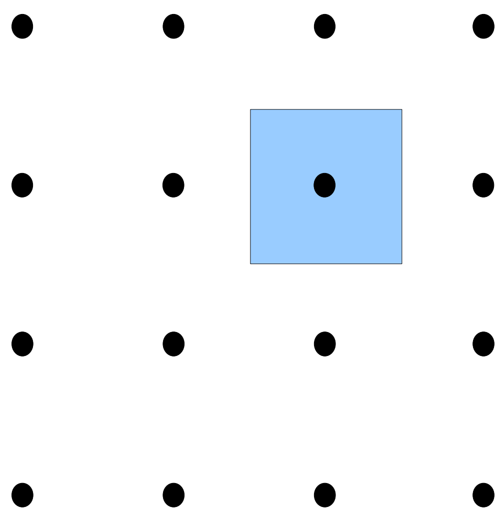
A parameterization is a **statistical** representation of the **effect** of processes occurring on **spatial scales smaller than the grid** spacing of a dynamical model (GCM, RCM, CRM, LES, …) **over mean variables** at each grid cell.

Parameterizations are based the **physics** of the processes, plus **simplifying (closure) assumptions** to relate unknown variables to prognostic (mean) model variables. Parameters are obtained from:

- Theory (e.g. known physical constants)
- Field campaigns
- Higher resolution models (CRM, LES)

Parametrization (turbulence)

A standard Reynolds decomposition: $A = \overline{A} + A'$ $(\overline{A'} = 0)$



$$A' = A - \overline{A} \qquad \overline{A'} = \overline{A - \overline{A}} = \overline{A} - \overline{A} = 0$$

Parametrization (turbulence)

A standard Reynolds decomposition: $A = \overline{A} + A' \qquad (\overline{A'} = 0)$

applied to, e.g., the water vapor continuity equation:

$$\frac{\partial q}{\partial t} + \nabla \vec{v}_h q + \frac{\partial \omega q}{\partial p} = e - c$$

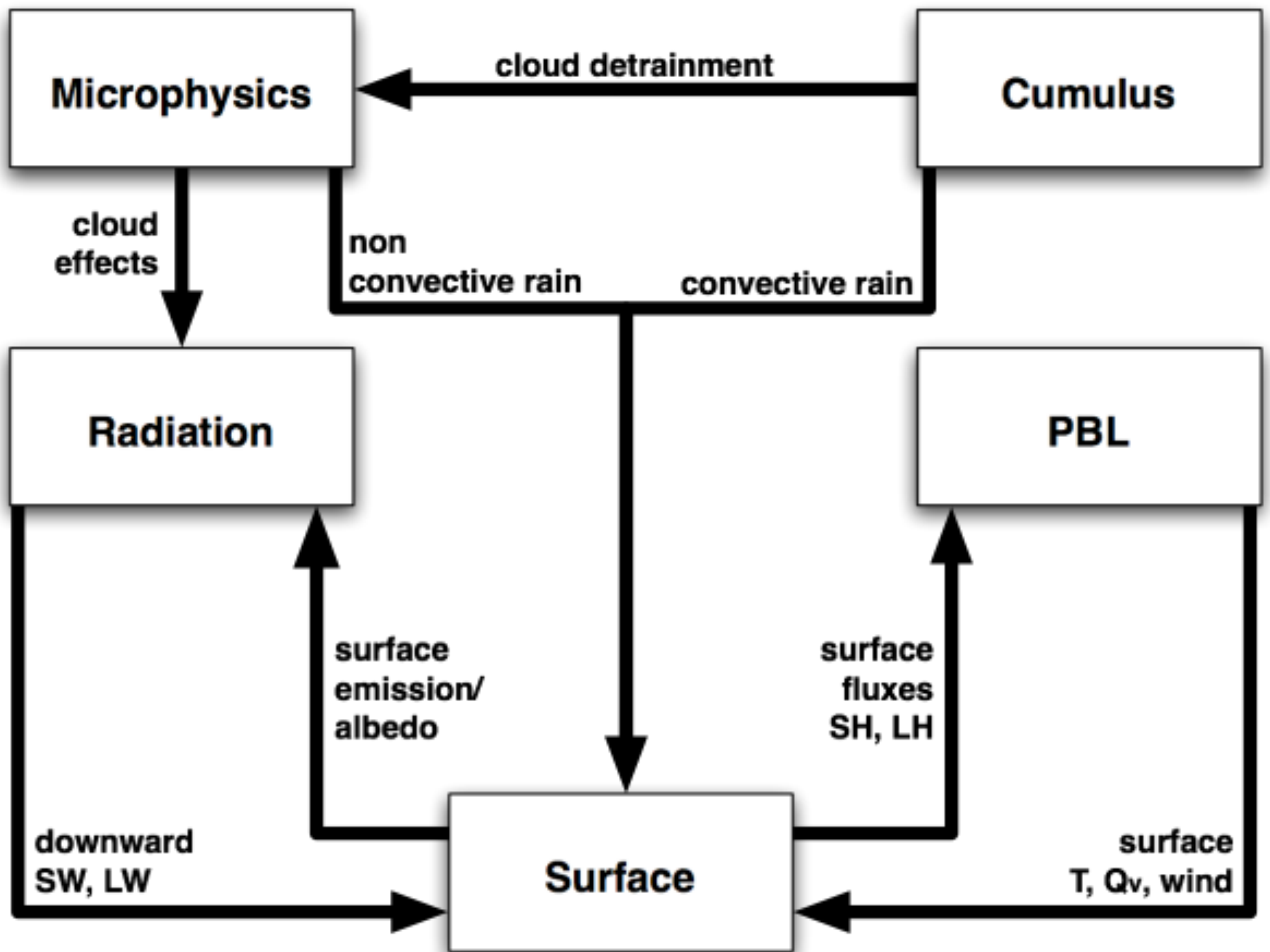
yields:

$$\frac{\partial \overline{q}}{\partial t} + \nabla \overline{\vec{v}_h} \overline{q} + \frac{\partial \overline{\omega}\, \overline{q}}{\partial p} = \overline{e} - \overline{c} - \frac{\partial \overline{\omega' q'}}{\partial p}$$

In this case, the parameterization requires expressing the eddy covariance terms as a function of mean grid-scale variables

$$f(\overline{\vec{v}_h}, \overline{w}, \overline{T}, \overline{q})$$

Direct Interactions of Parameterizations



J.Dudhia (NCAR)

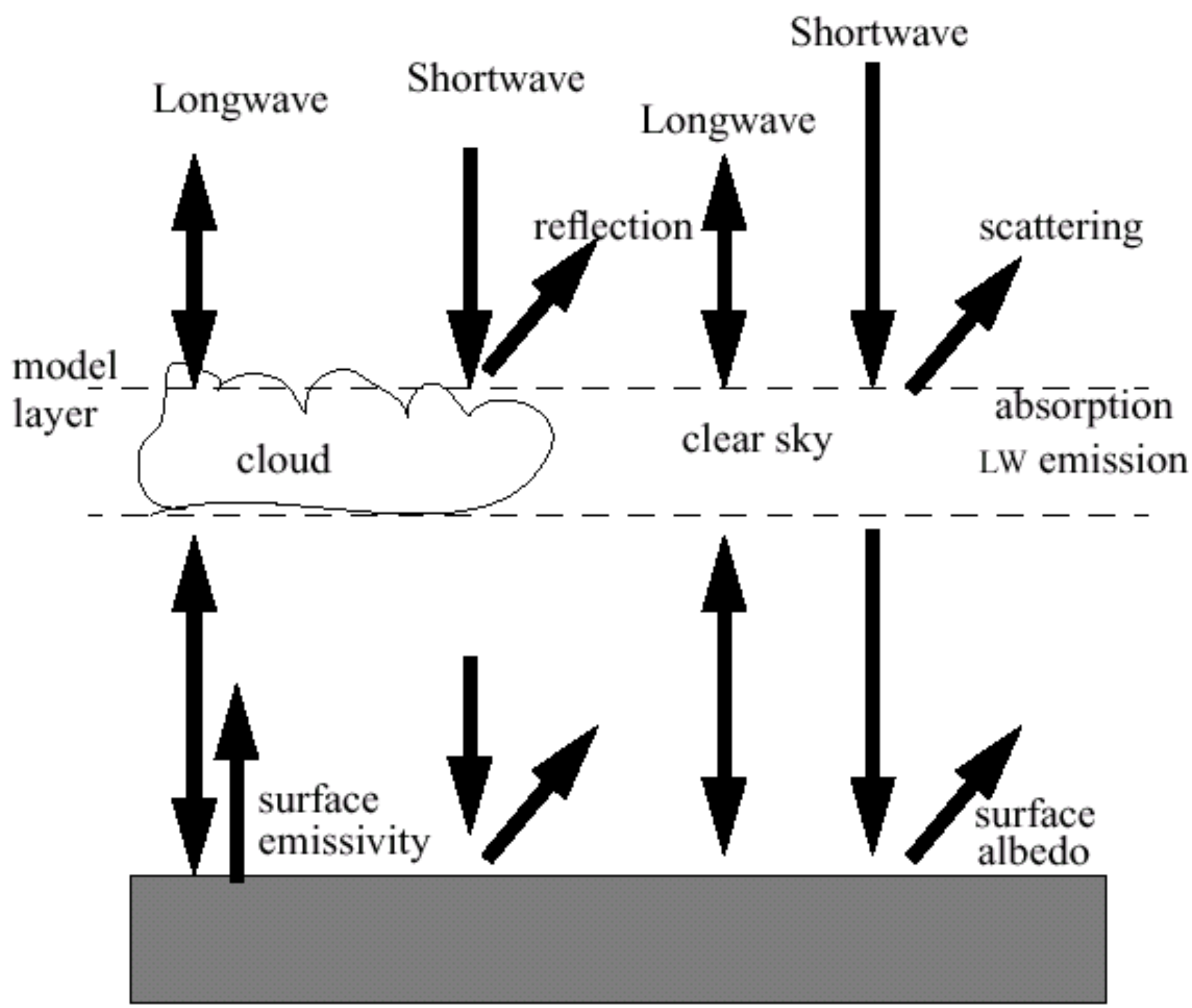
Radiation

Provides

Atmospheric temperature tendency profile

Surface radiative fluxes

Illustration of Free Atmosphere Radiation Processes



J.Dudhia (NCAR)

Radiation Schemes

- Longwave (thermal IR) and shortwave (visible, near IR) components
- Model columns handled independently (1d)
- Usually use spectral bands to handle major gases (H_2O, CO_2, O_3, CH_4, etc.)
- Clouds are "grey" and may be handled with cloud fraction and overlap assumptions
- Surface slope effects for direct shortwave component important for dx < ~5 km

Regional Climate Issues Related to Radiation

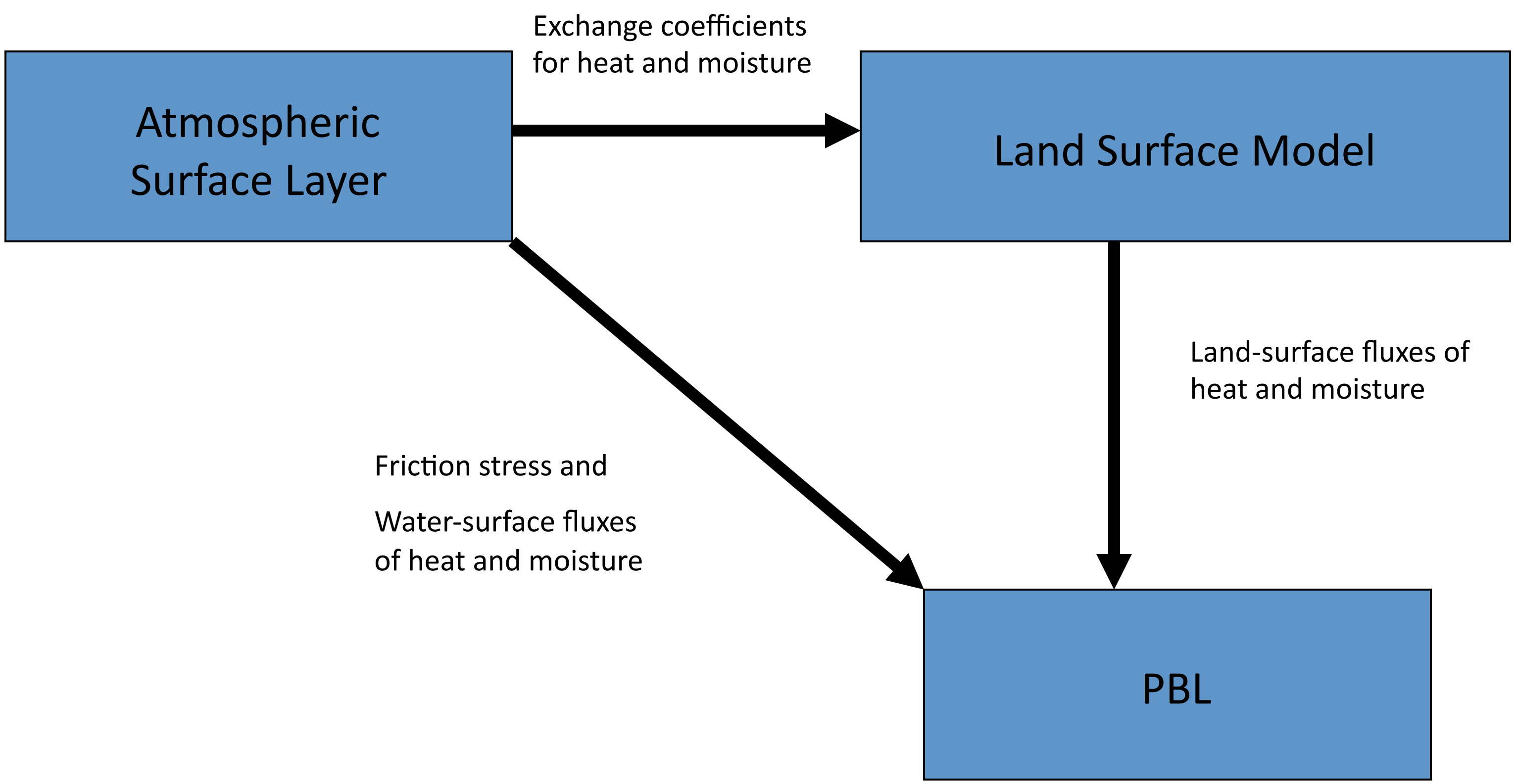
- Most radiation schemes have very simple aerosol assumptions
  - May lead to biases in surface shortwave effect
- Cloudiness that may come from other problems affects surface radiation
- Surface albedo and snow cover biases affect net shortwave at the surface
- CO_2 and trace gas changes important for long simulations

Surface schemes

Surface layer of atmosphere diagnostics (exchange/transfer coeffs)

Land Surface: Soil temperature /moisture / snow prediction /sea-ice temperature

Surface Physics Components



J.Dudhia (NCAR)

Surface Fluxes

- Heat, moisture and momentum

$$H = \rho c_p u_* \theta_* \qquad E = \rho u_* q_* \qquad \tau = \rho u_* u_*$$

$$u_* = \frac{kV_r}{\ln(z_r / z_0) - \psi_m} \qquad \theta_* = \frac{k\Delta\theta}{\ln(z_r / z_{0h}) - \psi_h} \qquad q_* = \frac{k\Delta q}{\ln(z_r / z_{0q}) - \psi_h}$$

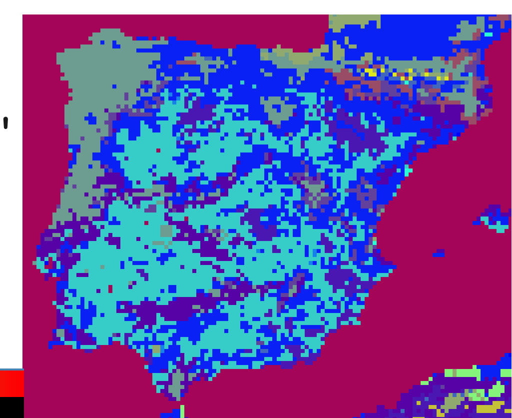
Subscript *r* is reference level (lowest model level, or 2 m or 10 m)
Δ refers to difference between surface and reference level value
z_0 are the roughness lengths
k is the von Karman constant (0.4)

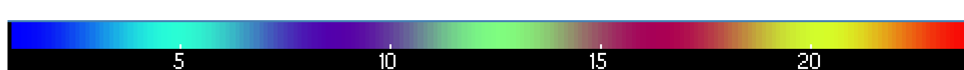
Roughness Lengths

- Roughness lengths are a measure of the “initial” length scale of surface eddies, and generally differ for velocity and scalars
- Roughness length depends on land-use type
- Some schemes use smaller roughness length for heat than for momentum
- For water points roughness length is a function of surface wind speed

WRF → VEGPARM.TBL

```
Vegetation Parameters
USGS
27,1, 'ALBEDO    Z0   SHDFAC NROOT   RS    [...]'
1,      .15,    1.00,   .10,   1,     200.,   ...    'Urban and Built-Up Land'
2,      .19,     .07,   .80,   3,      40.,   ...    'Dryland Cropland and Pasture'
3,      .15,     .07,   .80,   3,      40.,   ...    'Irrigated Cropland and Pasture'
4,      .17,     .07,   .80,   3,      40.,   ...    'Mixed Dryland/Irrigated Cropland and Past
5,      .19,     .07,   .80,   3,      40.,   ...    'Cropland/Grassland Mosaic'
6,      .19,     .15,   .80,   3,      70.,   ...    'Cropland/Woodland Mosaic'
7,      .19,     .08,   .80,   3,      40.,   ...    'Grassland'
8,      .25,     .03,   .70,   3,     300.,   ...    'Shrubland'
9,      .23,     .05,   .70,   3,     170.,   ...    'Mixed Shrubland/Grassland'
10,     .20,     .86,   .50,   3,      70.,   ...    'Savanna'
11,     .12,     .80,   .80,   4,     100.,   ...    'Deciduous Broadleaf Forest'
12,     .11,     .85,   .70,   4,     150.,   ...    'Deciduous Needleleaf Forest'
13,     .11,    2.65,   .95,   4,     150.,   ...    'Evergreen Broadleaf Forest'
14,     .10,    1.09,   .70,   4,     125.,   ...    'Evergreen Needleleaf Forest'
15,     .12,     .80,   .80,   4,     125.,   ...    'Mixed Forest'
16,     .19,    .001,   .00,   0,     100.,   ...    'Water Bodies'
[...]
23,     .17,     .03,   .30,   2,     200.,   ...    'Bare Ground Tundra'
24,     .70,    .001,   .00,   1,     999.,   ...    'Snow or Ice'
25,     .30,     .01,   .50,   1,      40.,   ...    'Playa'
26,     .16,     .15,   .00,   0,     999.,   ...    'Lava'
27,     .60,     .01,   .00,   0,     999.,   ...    'White Sand'
```





Exchange Coefficient

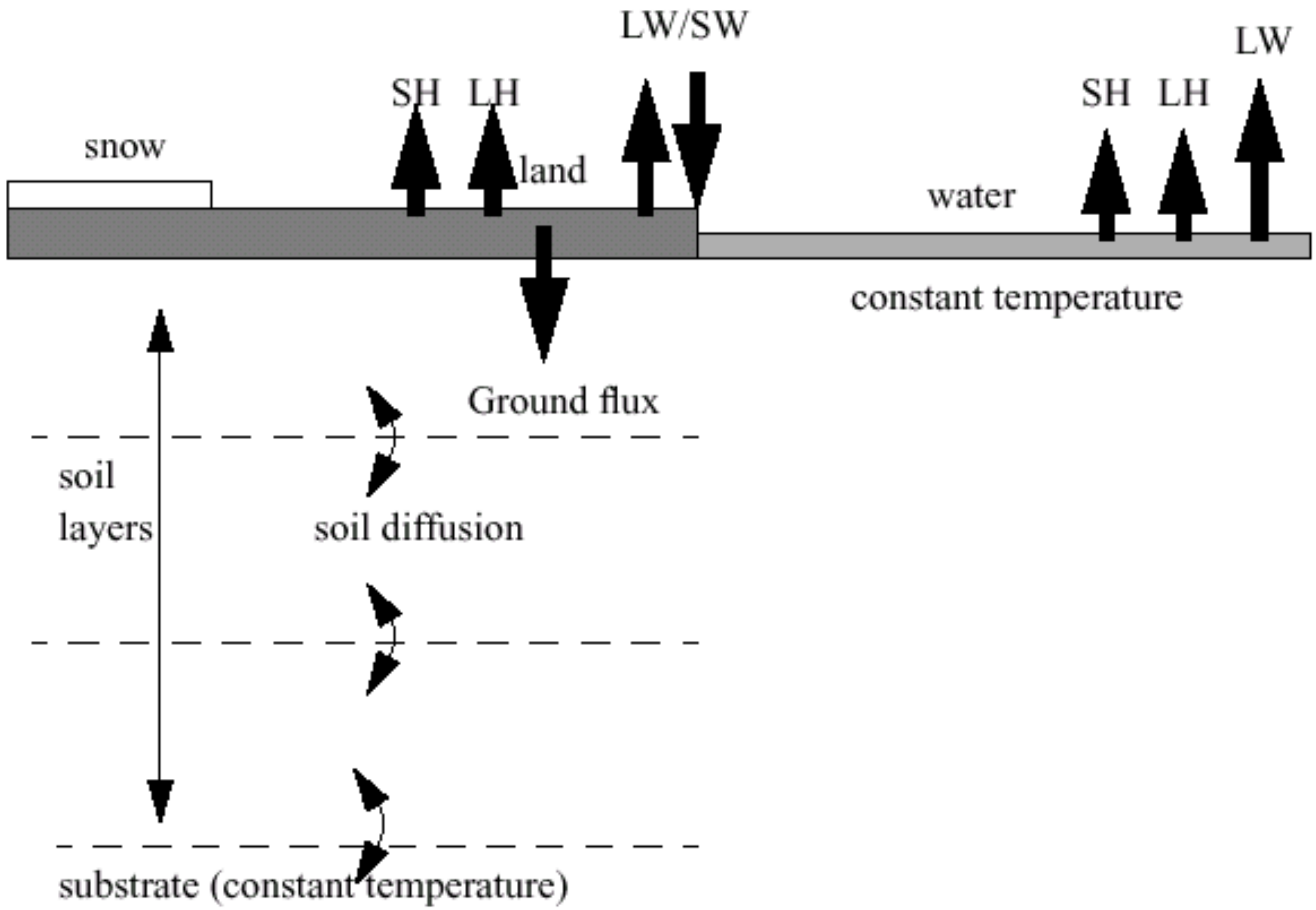
- C_{hs} is the exchange coefficient for heat, defined such that

$$H = \rho c_p C_{hs} \Delta\theta$$

It is related to the roughness length, stability function and u* by

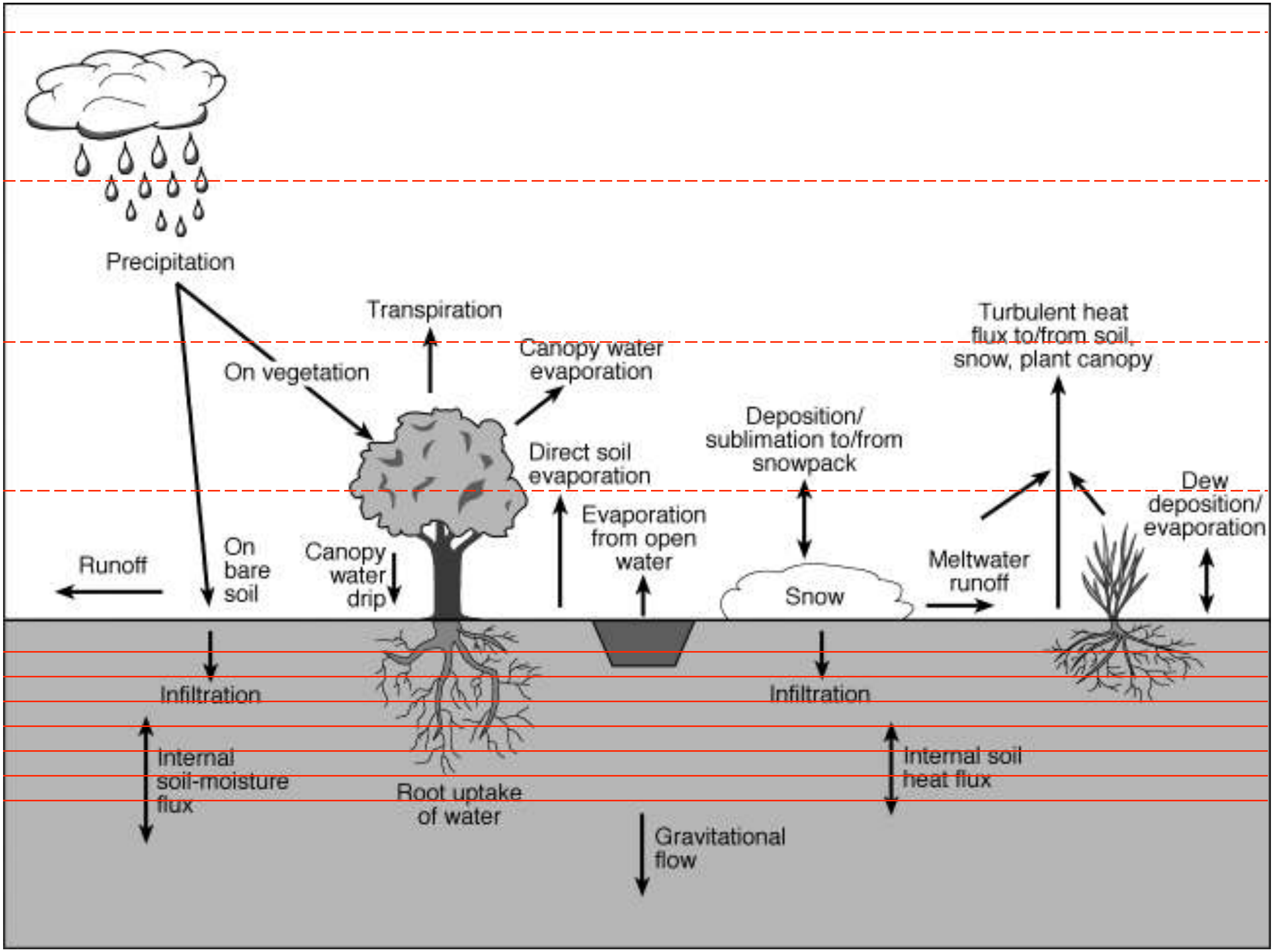
$$C_{hs} = \frac{k u_*}{\ln\left(\frac{z}{z_0}\right) - \psi_h}$$

Illustration of Surface Processes



J.Dudhia (NCAR)

Land-Surface Model Processes



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Land-Surface Model

- Predicts soil temperature and soil moisture in layers and a skin temperature
- Predicts snow water equivalent on ground and may include multi-layer snow model
- Includes vegetation root and canopy effects
- Includes soil texture and diffusion properties
- Some also include urban canopy models

Regional Climate Issues Related to Surface Physics

- Land surface has a long memory due to soil moisture and this can be self-sustaining when over large areas
  - In some regions precipitation biases may persist
  - In others droughts may persist
- Treatment of snow cover also affects climate if it melts too quickly or slowly
- Other parameters related to vegetation and soil impact evapotranspiration and soil drainage of water

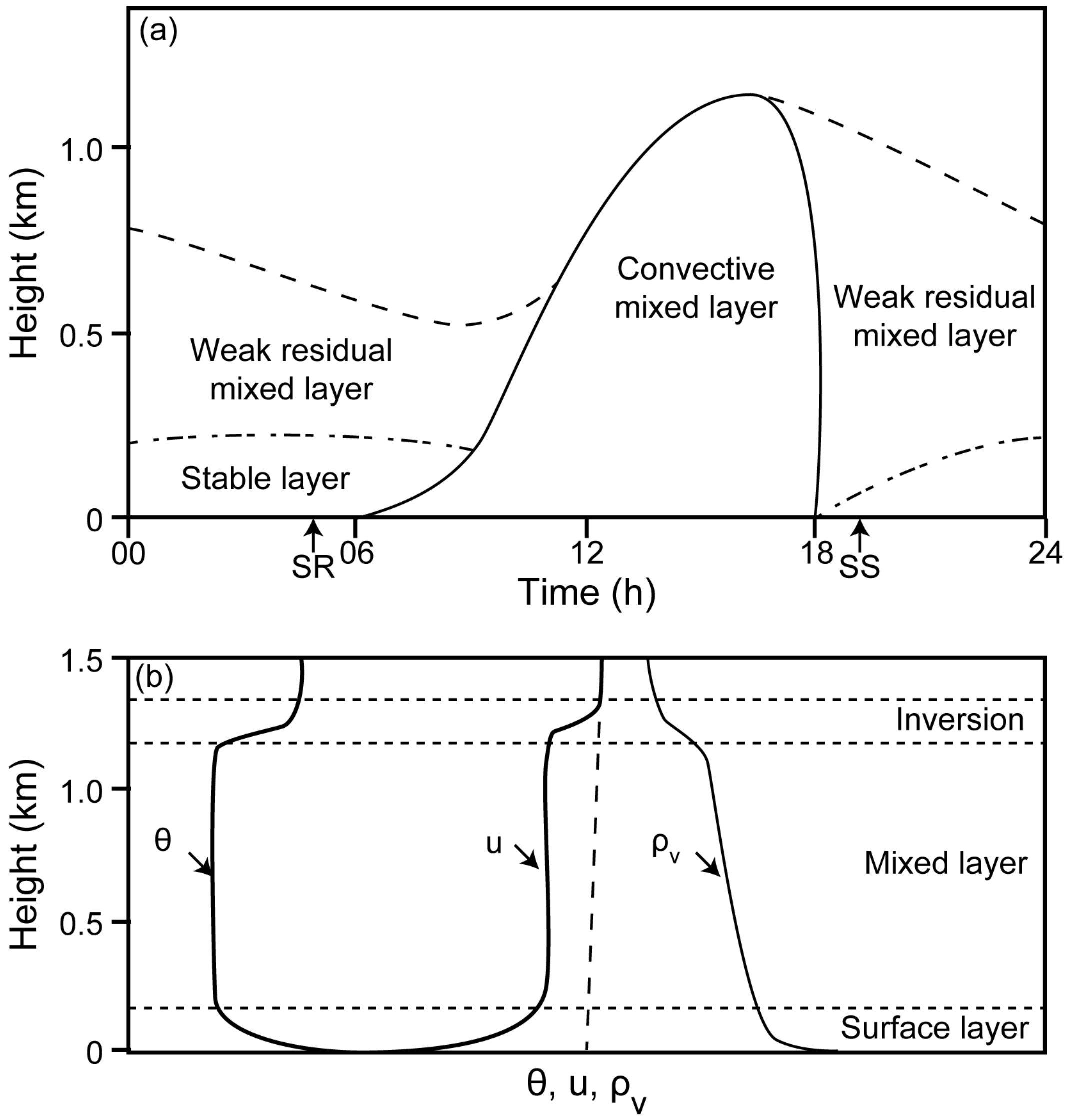
Planetary Boundary Layer

Provides

Boundary layer fluxes (heat, moisture, momentum)

Vertical diffusion in whole column

Planetary Boundary Layer



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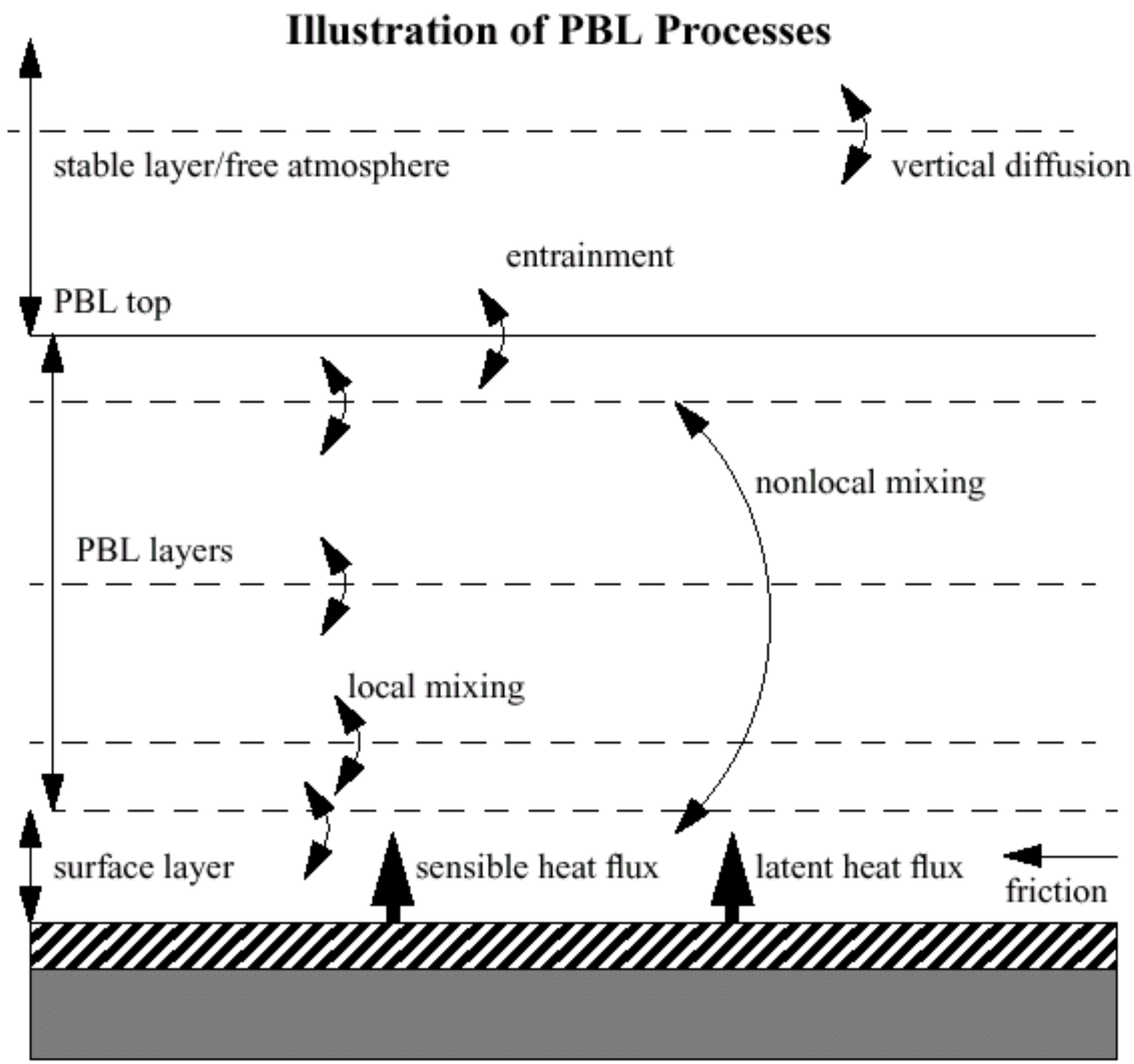

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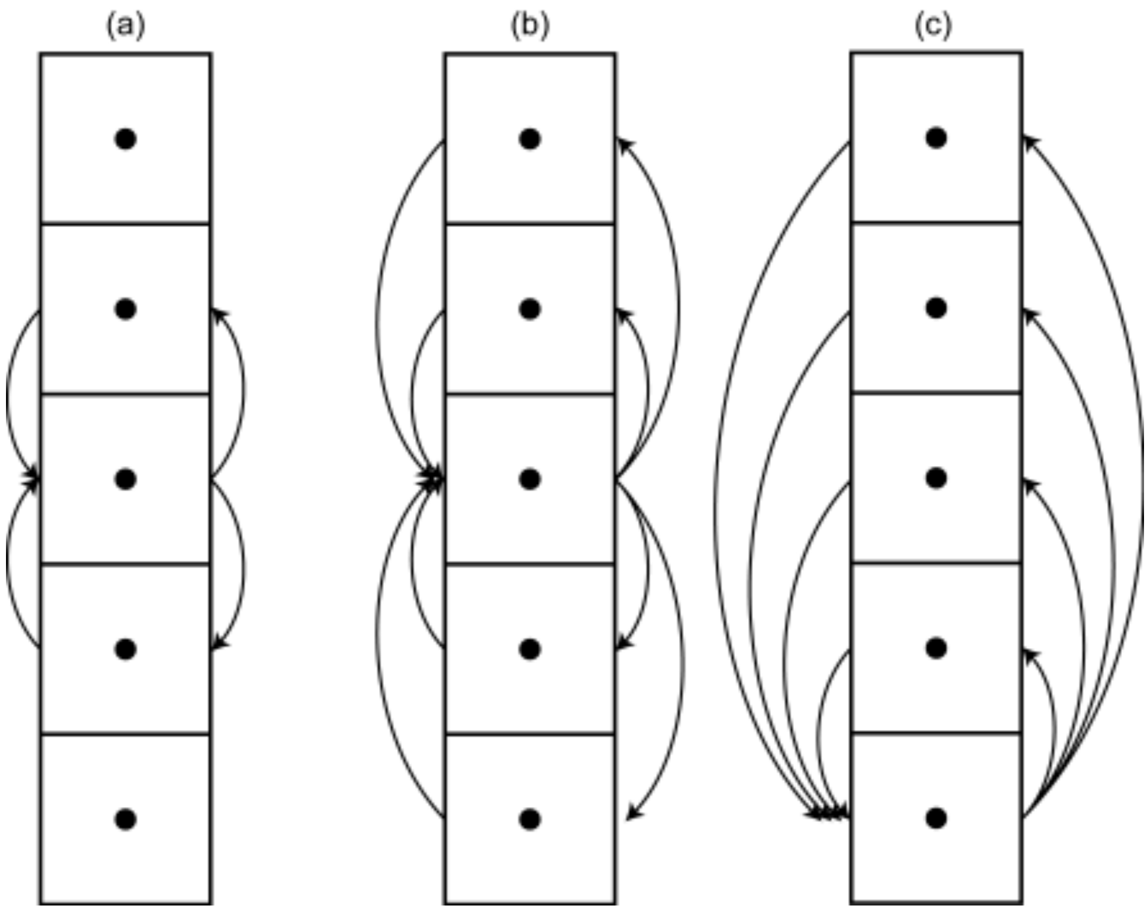
Different approaches



Local closure

Non-local closures

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PBL Schemes

- Main purpose is to receive surface fluxes from surface scheme (land or water) and distribute vertically to represent PBL growth (1d)
- Nocturnal PBL is also a challenge because mixing can occur with sufficient wind
- These schemes often also handle vertical diffusion through atmosphere (e.g. elevated turbulent layers)
- Several classes exist to handle unstable PBL

TKE schemes

- Solve for TKE in each column
  - Buoyancy and shear production
  - Dissipation
  - Vertical mixing $\frac{\partial}{\partial z} K_v \frac{\partial}{\partial z} \theta$
- TKE (*e*) and length-scale (*l*) are used to determine the diffusion coefficient (K_v) for local vertical mixing $K_v = le^{1/2}$
- Schemes differ most in diagnostic length-scale computations

Nonlocal Schemes

- Diagnose a PBL top (either stability profile or Richardson number)
- Specify a *K* profile
- Some include a non-gradient term (Γ)
- Others include a mass-flux profile, *M*, which is an additional sub-grid thermal flux

$$\frac{\partial}{\partial z} K_v \left(\frac{\partial}{\partial z} \theta + \Gamma \right)$$

$$\frac{\partial}{\partial z} \left(K_v \frac{\partial}{\partial z} \theta + M(\theta_u - \theta) \right)$$

Regional Climate Issues Related to the Boundary Layer

- Boundary-layer mixing impacts diurnal cycle
  - Daytime PBL growth rate determines surface temperature, moisture and wind
    - Underestimated mixing makes PBL too cool and moist, and less windy. Overestimation is opposite.
    - Can impact timing of convection
  - Night-time stable layers can be problematic
    - Often too thin for model to resolve surface cooling well
    - Effects of local drainage flows due to sub-grid complex terrain are not represented (sub-grid heterogeneity)

Cumulus Parameterization

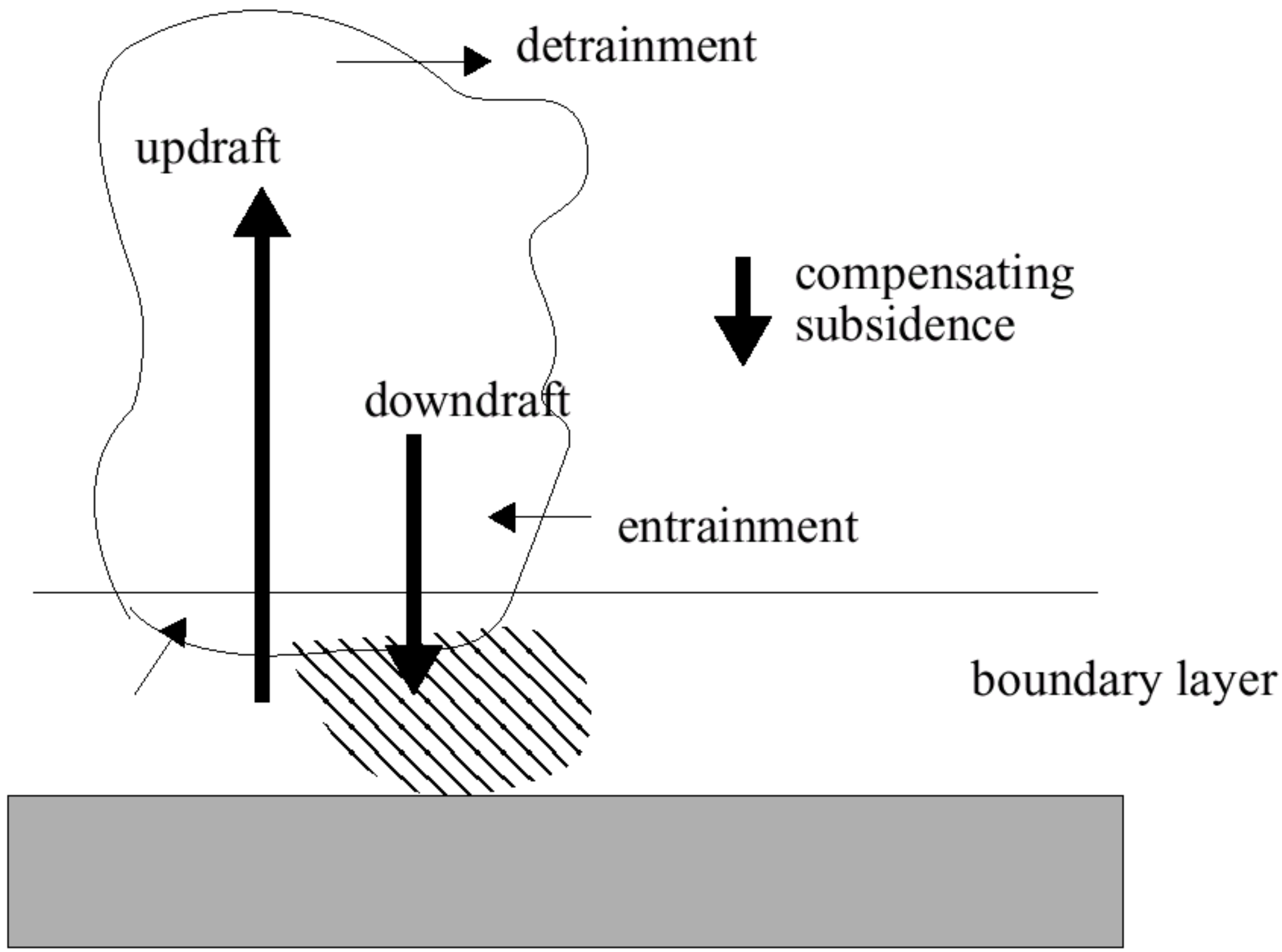
Provides

Atmospheric heat and moisture/cloud tendency profiles

Surface sub-grid-scale (convective) rainfall

J.Dudhia (NCAR)

Illustration of Cumulus Processes



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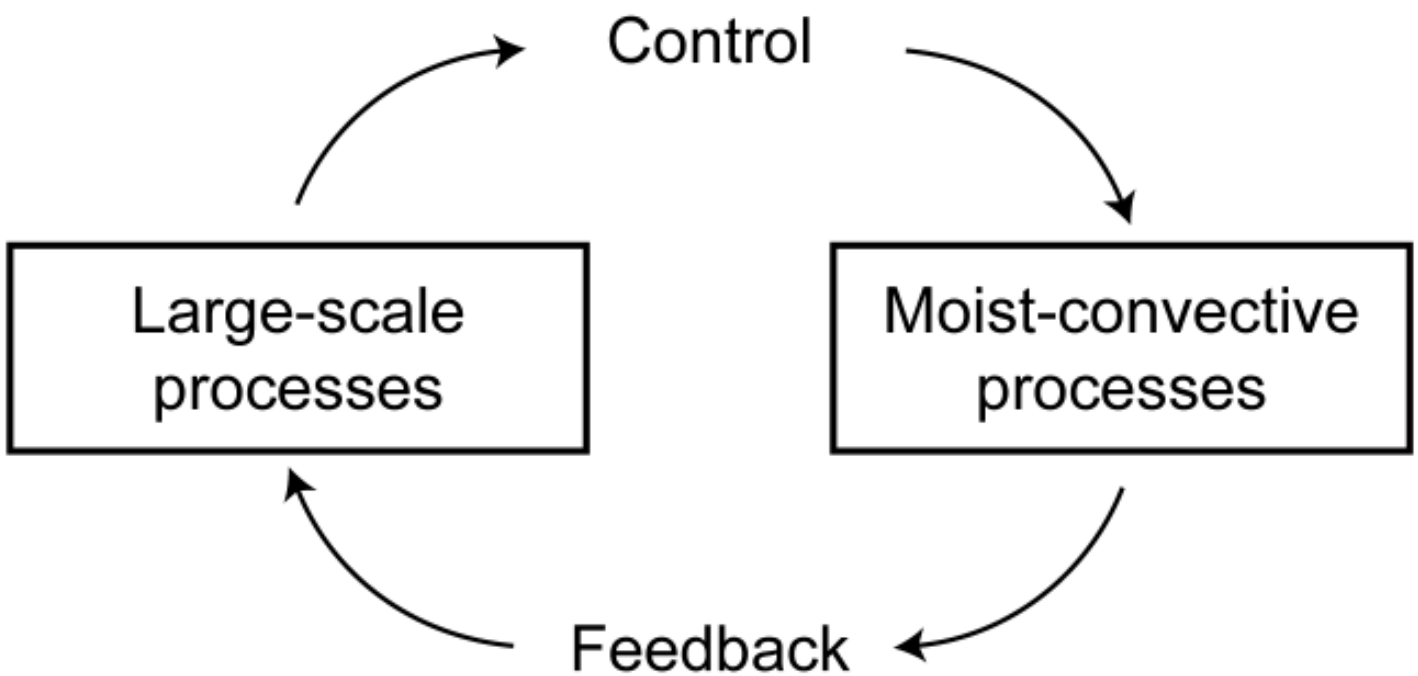
Cumulus Schemes

- Used for grid columns that completely contain convective clouds (1d)
- 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 once triggered

Deep Convection

- Schemes work in individual columns that are considered convectively unstable
- Mass-flux schemes transport surface air to top of cloud and include subsidence
  - Subsidence around cloud warms and dries troposphere removing instability over time
  - Additionally downdrafts may cool PBL
- Adjustment schemes (e.g. Betts-Miller) adjust towards mixed post-convective state

Parameterizations of cumulus convection



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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 thickness from parcel ascent
    - Some may activate non-precipitating shallow convection for lower tops

Closures

- Closure determine cloud strength (mass-flux) based on various methods
  - Clouds remove CAPE over time
    - Specified CAPE-removal time scale (KF, Tiedtke, ZM, BMJ)
    - Quasi-equilibrium (Arakawa-Schubert) with large-scale destabilization d(CAPE)/dt (SAS, NSAS)
  - Column moisture convergence (Kuo-type)
  - Low-level large-scale ascent (mass convergence)

Cloud Detrainment

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

Regional Climate Issues Related to Cumulus Schemes

- Long regional climate runs need cumulus schemes for dx > 10 km
- Over land these may have problems related to
  - Triggering too much – light rain area bias
  - Triggering to easily - diurnal cycle error
- Over oceans (especially tropical) deep convection controls large-scale dynamics
  - Biases lead to tropical circulation biases
  - Important to get heating and moistening profile correct (shallow convection also important)

Microphysics

Provides

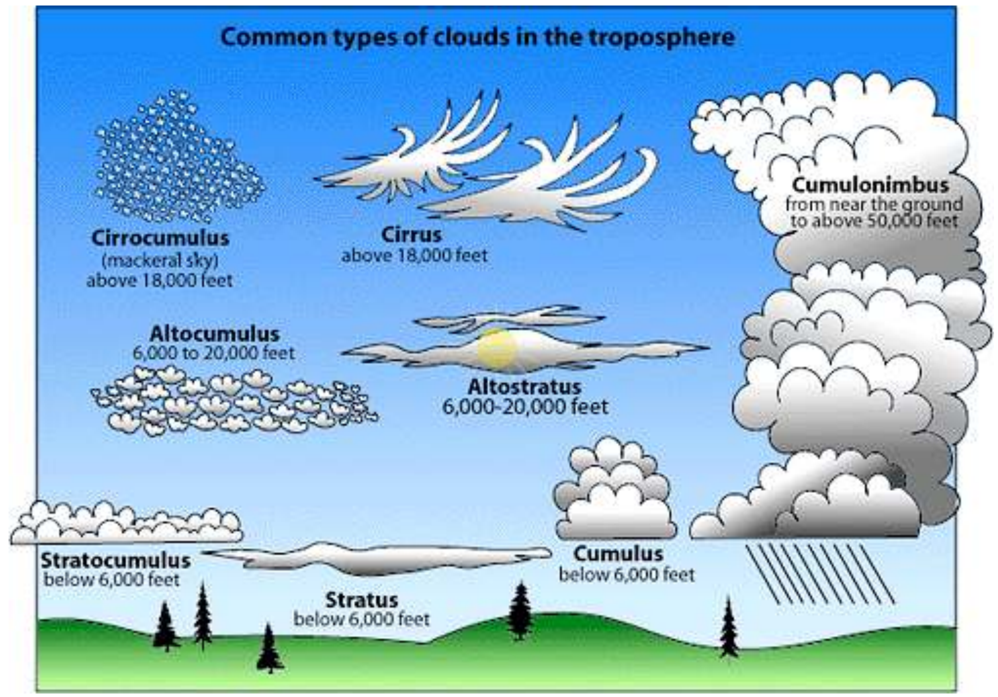
Atmospheric heat and moisture tendencies

Microphysical rates

Surface resolved-scale rainfall

Resolved clouds

- Formed by radiative, dynamical or convective processes
- Model only considers grid-scale average so will not resolve fine-scale structures



Microphysics Parameterization

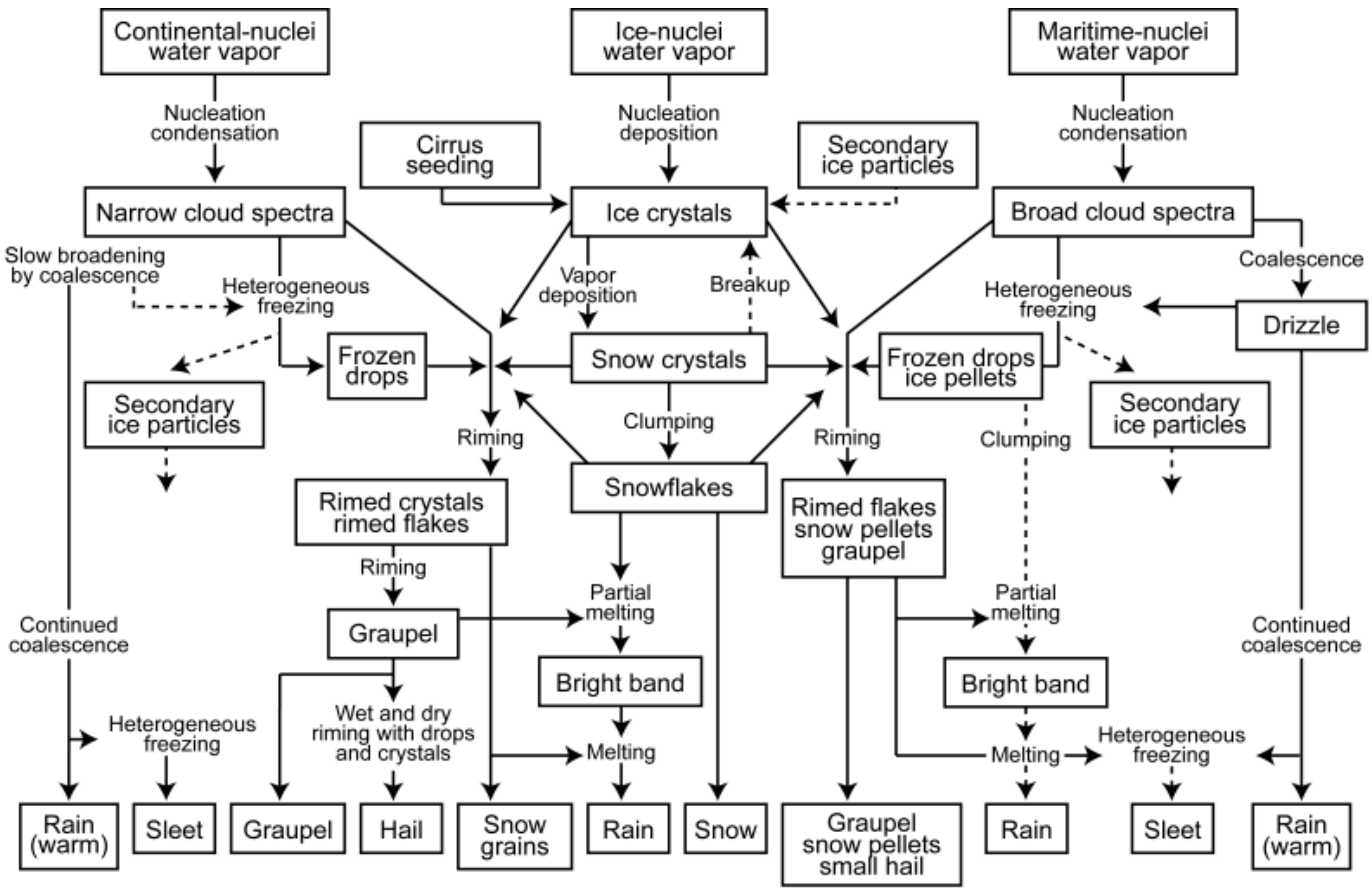


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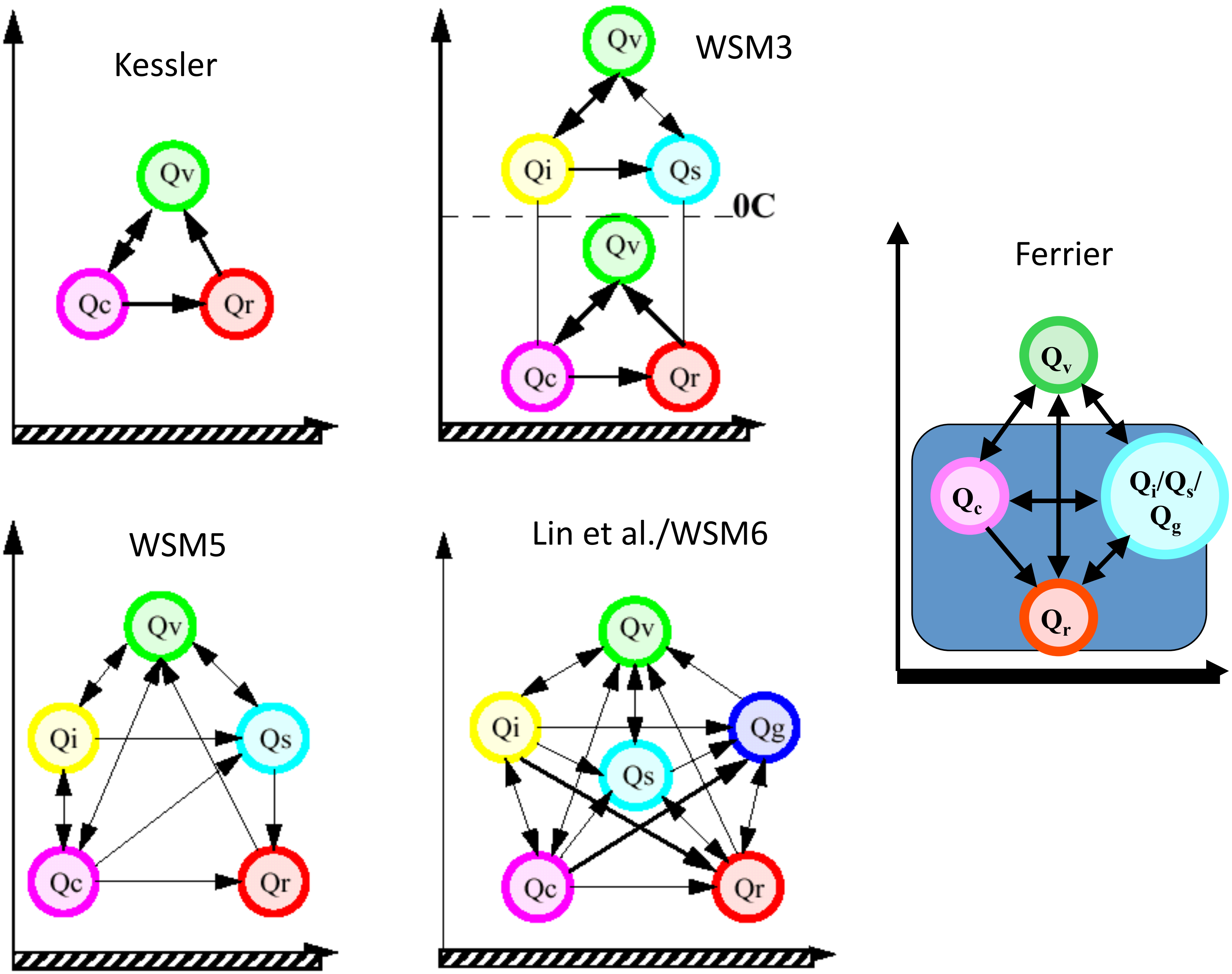
Illustration of Microphysics Processes



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Microphysics

- Latent heat release from
  – Condensation, evaporation, deposition, sublimation, freezing, melting
- Particle types
  – Cloud water, rain drops, ice crystals, snow, graupel (also hail in some)
    - Total mass contributes to liquid loading in dynamics
- Processes
  – Aggregation, accretion, nucleation, growth, fall-out

Microphysics: Single and Double Moment Schemes

- Single-moment schemes have one prediction equation for mass (kg/kg) per species (Qr, Qs, etc.) with particle size distribution being derived from fixed parameters
- Double-moment (DM) schemes add a prediction equation for number concentration (#/kg) per DM species (Nr, Ns, etc.)
- DM schemes may only be double-moment for a few species
- DM schemes allow for additional processes such as size-sorting during fall-out and sometimes aerosol (CCN) effects

Rainfall Output

- Cumulus and microphysics can be run at the same time
- These each generate surface rainfall referred to as
  - Convective or implicit
  - Nonconvective or explicit or large-scale

Physics Interactions

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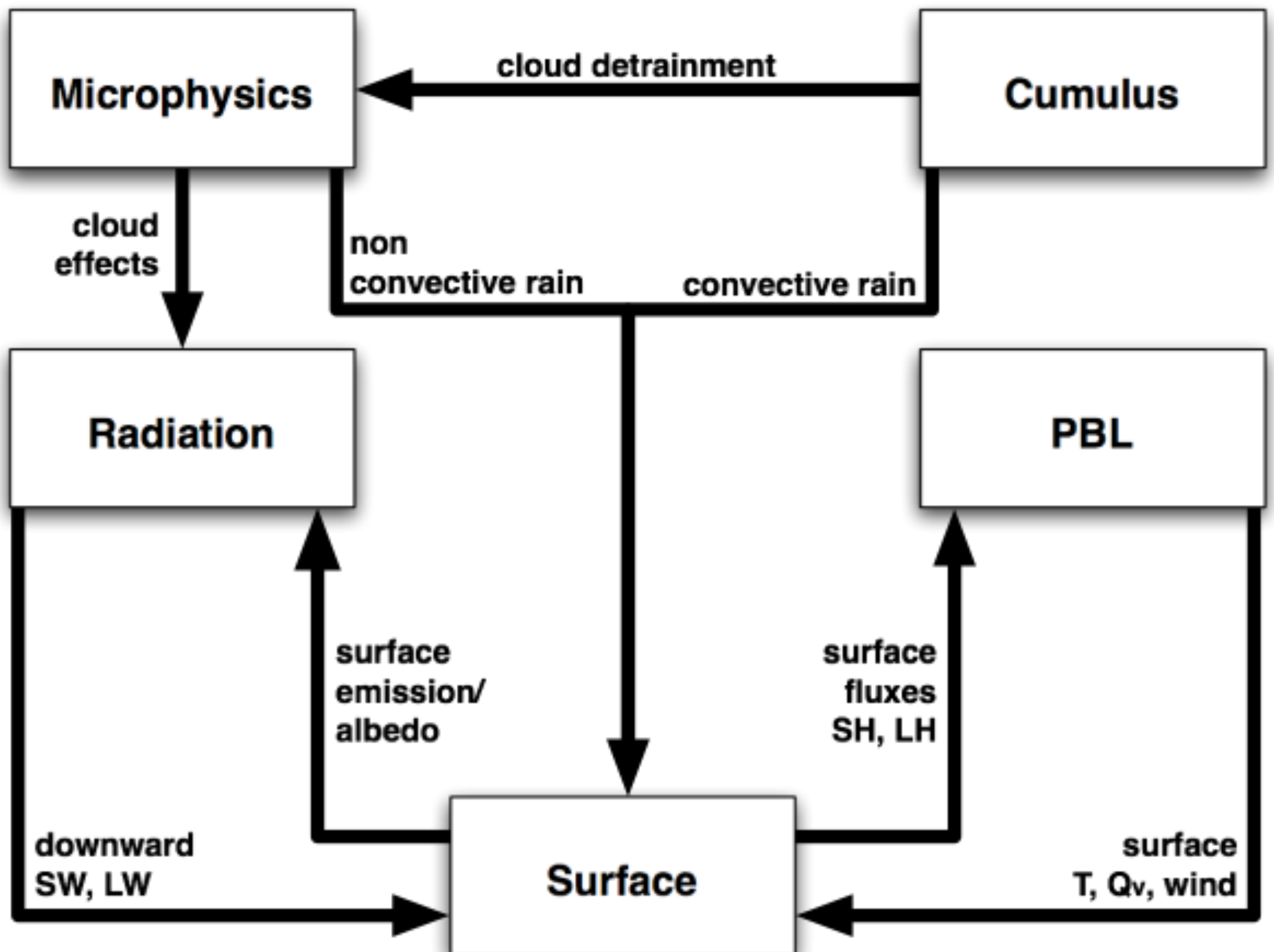
Direct Interactions of Parameterizations



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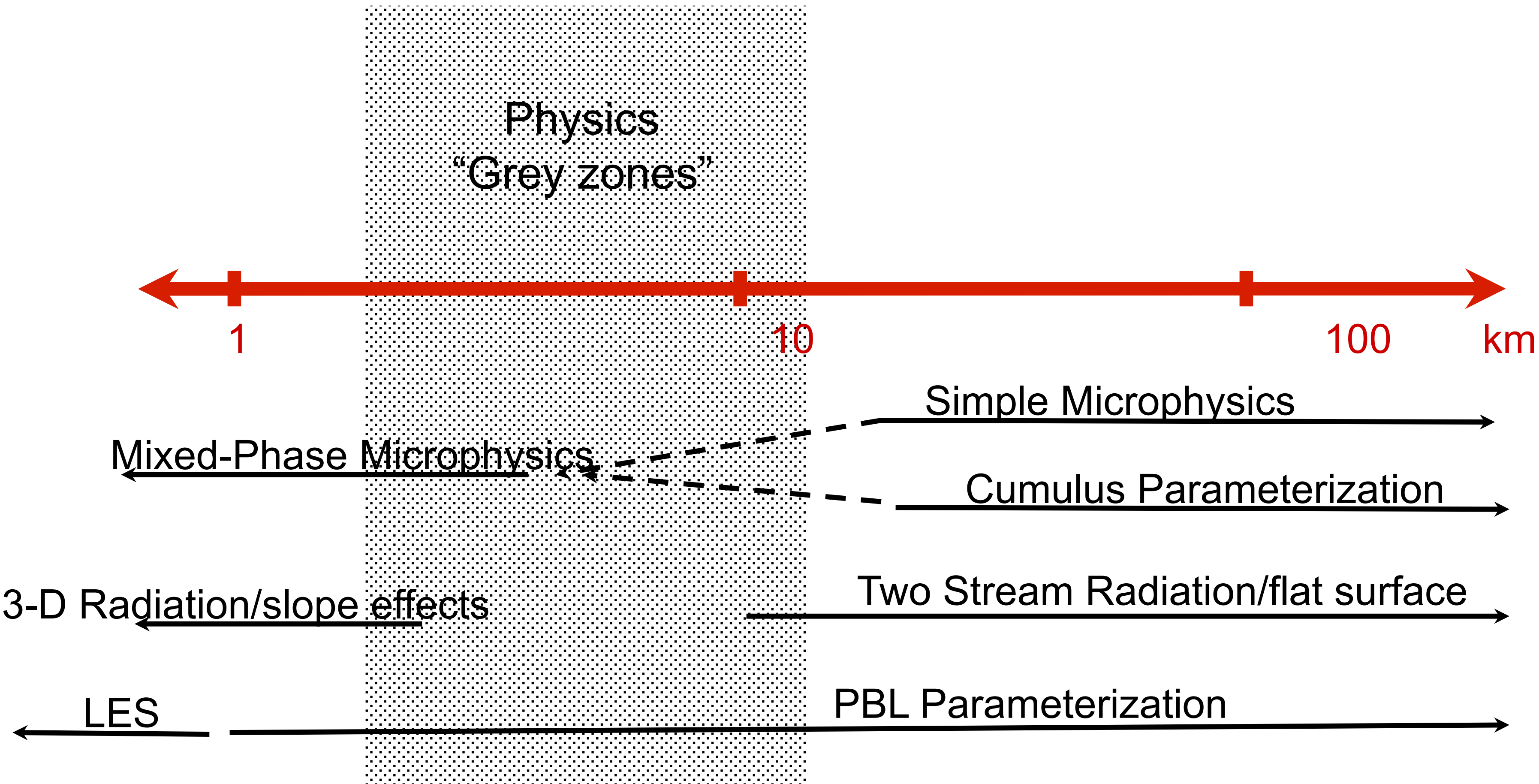
Physics in Multiscale NWP Model



WRF: A multi-physics model

- The Weather Research and Forecasting (WRF) model is a public-domain state-of-the-art model
- Parameterizations are initially tested as off-line 1D models, but in the end they need to be tested within a full 3D model.
- Many researchers choose WRF to test their new or improved parameterization schemes
- WRF has a huge amount of physics options

Longwave Radiation in V3.4

3.4 new

ra_lw_physics	Scheme	Cores+Chem	Microphysics Interaction	Cloud Fraction	CO2*
1	RRTM	ARW NMM	Qc Qr Qi Qs Qg	1/0	330
3	CAM	ARW	Qc Qi Qs	Max-rand overlap	yearly
4	RRTMG	ARW +Chem(τ)	Qc Qr Qi Qs	Max-rand overlap	379
5	New Goddard	ARW	Qc Qr Qi Qs Qg	1/0	337
7	FLG (UCLA)	ARW	Qc Qr Qi Qs Qg	1/0	345
31	Held-Suarez	ARW	none	none	none
99	GFDL	ARW NMM	Qc Qr Qi Qs	Max-rand overlap	fixed

* 2012 value = 392

Shortwave Radiation in V3.4

3.4 new

ra_lw_ physics	Scheme	Cores+Chem	Microphysics Interaction	Cloud Fraction	Ozone
1	Dudhia	ARW NMM + Chem(PM2.5)	Qc Qr Qi Qs Qg	1/0	none
2	GSFC	ARW +Chem(τ)	Qc Qi	1/0	5 profiles
3	CAM	ARW	Qc Qi Qs	Max-rand overlap	Lat/ month
4	RRTMG	ARW +Chem(τ)	Qc Qr Qi Qs	Max-rand overlap	1 profile
5	New Goddard	ARW	Qc Qr Qi Qs Qg	1/0	5 profiles
7	FLG (UCLA)	ARW	Qc Qr Qi Qs Qg	1/0	5 profiles
99	GFDL	ARW NMM	Qc Qr Qi Qs	Max-rand overlap	Lat/date

PBL schemes in V3.4

3.4 changes

bl_pbl_ physics	Scheme	Cores	sf_sfclay_ physics	Prognostic variables	Diagnostic variables	Cloud mixing
1	YSU	ARW NMM	1,11		exch_h	QC,QI
2	MYJ	ARW NMM	2	TKE_PBL	EL_PBL, exch_h	QC,QI
3	GFS(hwrf)	NMM	3			QC,QI
4	QNSE-EDMF	ARW NMM	4	TKE_PBL	EL_PBL, exch_h, exch_m	QC,QI
5	MYNN2	ARW	1,2,5	QKE	Tsq, Qsq, Cov, exch_h, exch_m	QC
6	MYNN3	ARW	1,2,5	QKE, Tsq, Qsq, Cov	exch_h, exch_m	QC
7	ACM2	ARW	1,7			QC,QI
8	BouLac	ARW	1,2	TKE_PBL	EL_PBL, exch_h, exch_m	QC
9	UW	ARW	1,2	TKE_PBL	exch_h, exch_m	QC
10	TEMF	ARW	10	TE_TEMF	*_temf	QC, QI
94	QNSE	ARW	4	TKE_PBL	EL_PBL, exch_h, exch_m	QC,QI
99	MRF	ARW NMM	1			QC,QI

Cumulus schemes in V3.4

3.4 new

cu_physics	Scheme	Cores	Moisture Tendencies	Momentum Tendencies	Shallow Convection
1	Kain-Fritsch Eta	ARW NMM	Qc Qr Qi Qs	no	yes
2	Betts-Miller-Janjic	ARW NMM	-	no	yes
3	Grell-Devenyi	ARW	Qc Qi	no	no
4	Old Simplified Arakawa-Schubert	ARW NMM	Qc Qi	yes (NMM)	yes (ARW)
5	Grell-3	ARW	Qc Qi	no	yes
6	Tiedtke	ARW	Qc Qi	yes	yes
7	Zhang-McFarlane	ARW	Qc Qi	yes	no
14	New SAS	ARW	Qc Qi	yes	yes
84	New SAS (HWRF)	ARW NMM	Qc Qi	yes (NMM)	yes (ARW)
99	Old Kain-Fritsch	ARW	Qc Qr Qi Qs	no	no

Microphysics schemes in V3.4

* Advects only total condensate Nn= CCN number

mp_physics	Scheme	Cores	Mass Variables	Number Variables
1	Kessler	ARW	Qc Qr	
2	Lin (Purdue)	ARW (Chem)	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	Thompson	ARW NMM	Qc Qr Qi Qs Qg	Ni Nr
9	Milbrandt 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
10	Morrison 2-mom	ARW (Chem)	Qc Qr Qi Qs Qg	Nr Ni Ns Ng
13	SBU-YLin	ARW	Qc Qr Qi Qs	
14	WDM5	ARW	Qc Qr Qi Qs	Nn Nc Nr
16	WDM6	ARW	Qc Qr Qi Qs Qg	Nn Nc Nr
17	NSSL 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
18	NSSL 2-mom+ccn	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh Nn

Thanks!

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