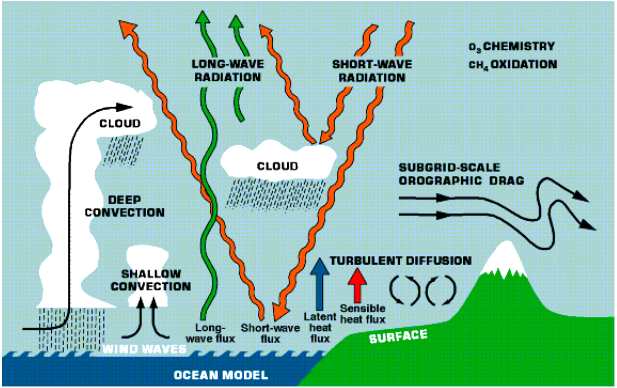
Numerical Weather Prediction: Model physics



Steven Cavallo

Model Physics

Recall that we can write a general form of the governing equations as:

$$\underbrace{\frac{d\phi}{dt}}_{\text{"Dynamics"}} = \underbrace{F_\phi}_{\text{"Physics"}} \tag{1}$$

where ϕ is any scalar. In meteorology, ϕ can be u, v, w, θ, and mass.

Methods used to solve the left-hand side of (1) are usually considered the model "dynamics" while solving the right-hand side of (1) is considered the model "physics."

Model Physics

Previously, we discussed how the dynamics can be broken into a time tendency and advection term, which can be reprsented on a grid by finite differencing. Using the Leapfrog method, for the 1-D advection case, we have:

$$\frac{\phi^{k+1} - \phi^{k-1}}{2\Delta t} = -u\left(\frac{\phi^k_{i+1} - \phi^k_{i-1}}{2\Delta x}\right) + F^k_\phi.$$

The above illustrates that ϕ can be integrated by combining *tendencies* into one term called $f(\phi^k)$:

$$\begin{aligned} \frac{\phi^{k+1} - \phi^{k-1}}{2\Delta t} &= f(\phi^k) \\ \Rightarrow \phi^{k+1} &= \phi^{k-1} + 2\Delta t\ f(\phi^k). \end{aligned} \tag{2}$$

Model Physics

Let's apply this to the thermodynamic equation. Letting $\phi = \theta$:

$$\theta^{k+1} = \theta^{k-1} + 2\Delta t \, f(\theta^k). \tag{3}$$

What is $f(\theta^k)$?

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What about the u and v momentum equations?

$$\begin{aligned} f(u^k) \quad = \quad & \text{Advection tendency} + \text{Pressure gradient tendency} + \\ & \text{Coriolis tendency} + \text{friction tendency}. \end{aligned} \tag{5}$$

Model Physics

Now let's step back and focus on the thermodynamic equation. This is the equation where most of the "model physics" is computed. In it's most general form:

$$\frac{d\theta}{dt} = F_\theta. \tag{6}$$

The right-hand side are the diabatic forcings, or external forcings that can create or destroy θ.
Recall that these are the **exact** forcings that can create or destroy **potential vorticity**.

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The physical forcings that we account for today are those due to radiative processes, phase changes (latent heating), convection, planetary boundary layer (pbl), and explicit mixing:

$$F_\theta = \theta_{t,radiation} + \theta_{t,latent\ heating} + \theta_{t,convection} + \theta_{t,pbl} + \theta_{t,mixing}. \tag{7}$$

Model Physics

In a numerical model, each of these forcings are predicted *independently* in a separate programming *subroutine* based on our current understanding of how the particular physical processes occur.
In the end, a single tendency is passed back into the main programming module. The final model integration step looks something like this:

$$\begin{aligned} f(\theta^k) &= \text{Advection tendency} + F_\theta \\ &= \theta_{t,advection} + \theta_{t,radiation} + \theta_{t,latent\ heating} + \theta_{t,convection} + \theta_{t,pbl} + \theta_{t,mixing} \end{aligned}$$

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and so the numerical integration step using a Leapfrog time scheme would look like

$$\begin{aligned} \theta^{k+1} &= \theta^{k-1} + 2\Delta t \left(f(\theta^k) \right) \\ &= \theta^{k-1} + 2\Delta t\, (\theta_{t,advection} + \theta_{t,radiation} + \theta_{t,latent\ heating} + \\ &\quad \theta_{t,convection} + \theta_{t,pbl} + \theta_{t,mixing}) \end{aligned} \tag{8}$$

Model Physics

Let's look at an example: The Advanced Research Weather Research and Forecasting (WRF ARW) model:

- Grid point model; Equations are fully compressible, non-hydrostatic or hydrostatic, with scalar conservation.
- Terrain following hydrostatic pressure vertical coordinate system.
- Developed and maintained at the National Center for Atmospheric Research (NCAR) for research purposes.
- Free to download, free user support.
- User can define any domain, resolution, physics, time step, boundary conditions, initial conditions, etc.
- Time integration uses a Runge-Kutta scheme that is 3rd order accurate:

$$
\begin{aligned}
\phi^{*} &= \phi^{k} + \frac{\Delta t}{3} f(\phi^{k}) \\
\phi^{**} &= \phi^{k} + \frac{\Delta t}{2} f(\phi^{*}) \\
\phi^{k+1} &= \phi^{k} + \Delta t \, f(\phi^{**})
\end{aligned}
$$

Model Physics

WRF model computational flowchart:

Begin time step

Runge-Kutta loop (steps 1, 2, and 3)

(i) advection, p-grad, buoyancy using (ϕ^t, ϕ^*, ϕ^{**})

(ii) physics if step 1, save for steps 2 and 3

(iii) mixing, other non-RK dynamics, save…

(iv) assemble dynamics tendencies

Acoustic step loop

(i) advance U,V, then μ, Q, then w, ϕ

(ii) time-average U,V, W

End acoustic loop

Advance scalars using time-averaged U,V, W

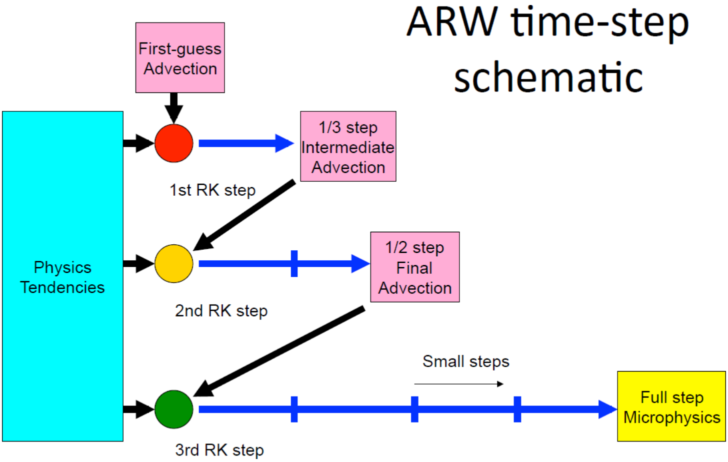
End Runge-Kutta loop

Adjustment physics (currently microphysics)

End time step

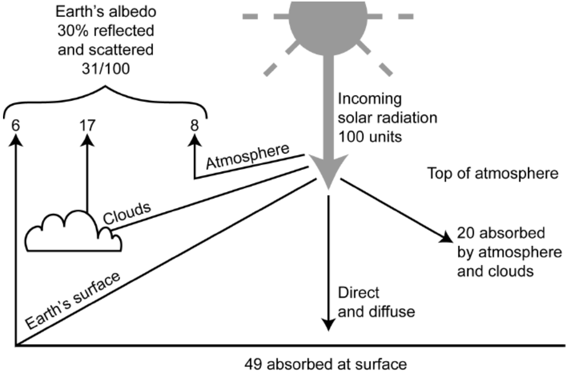
Model Physics

WRF model computational flowchart schematic:



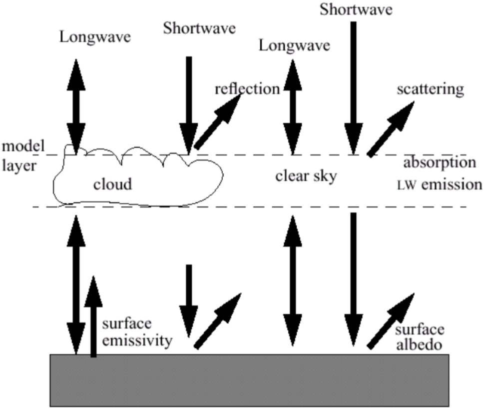
Model Physics

Shortwave radiation



Model Physics

Shortwave + longwave radiation



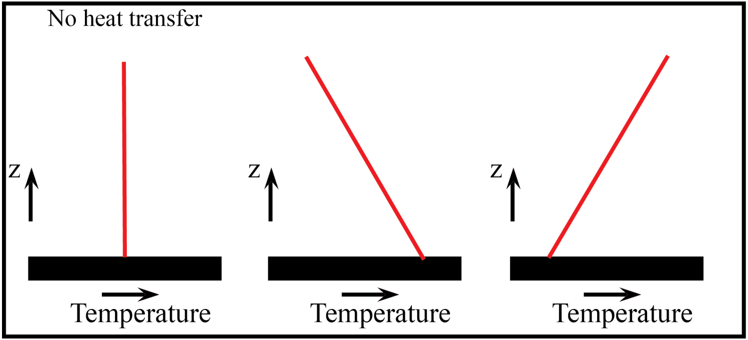
Model Physics

Shortwave and longwave radiation

Shortwave (SW)	**Longwave (LW)**
Generally warms atmosphere	Generally cools atmosphere
Depends on latitude, time of year, time of day	Depends on temperature (Stefan-Boltzmann $= \sigma T^4$)
Strongly absorbed by surface, weakly absorbed by atmosphere	Strongly emitted at surface, strong emittance by atmosphere
Function of albedo	No dependence on albedo
Strongly absorbed by ozone	Weakly emitted by ozone
Weakly absorbed by water vapor	Strongly emitted by water vapor
Depends on carbon dioxide	Depends on carbon dioxide

Model Physics

Surface heat fluxes



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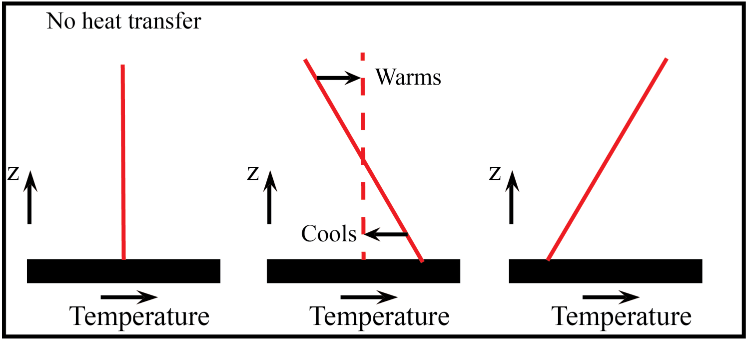

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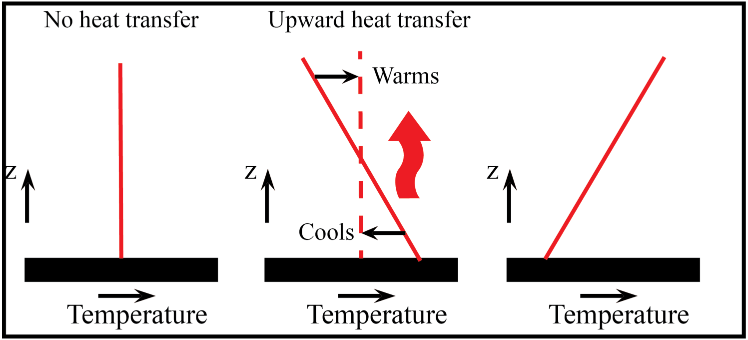

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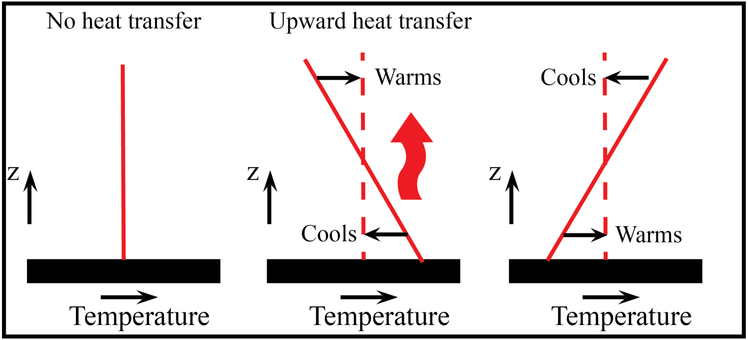

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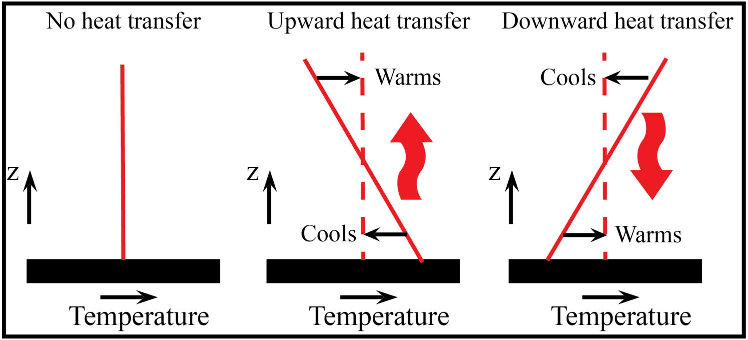


Model Physics

Between atmospheric layers, flow is controlled by the equations of motion. However, the surface is a boundary. That is, **we must *parameterize* the communication of energy between the atmosphere and surface**. Based on the previous diagram, formulas have been developed to estimate heat, and moisture exchange between the surface and atmosphere:

$$H_S = \rho c_p C_H U_1 \left(T_0 - T_1 \right) \quad (9)$$

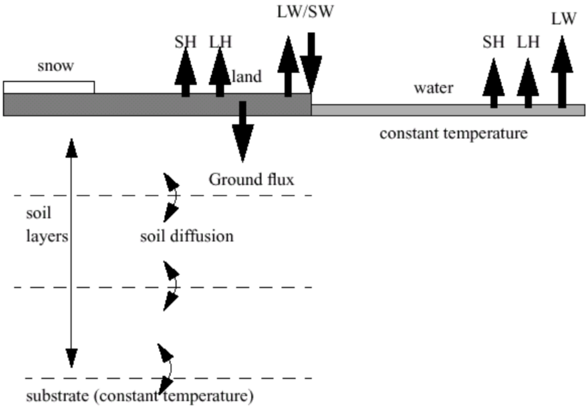
$$H_L = \rho L_v C_H U_1 \left(q_0 - q_1 \right). \quad (10)$$

H_S	:	Sensible heat flux
H_L	:	Latent heat flux
c_p, L_v	:	Specific heat of dry air const. p, latent heat of vaporization
C_H, ρ	:	Transfer coefficient, air density
U, T, q	:	Wind, temperature, mixing ratio
0,1 subscripts	:	2 meter and 10 meter model levels

Sign convention: Positive (negative) $\Rightarrow$ upward (downward) flux

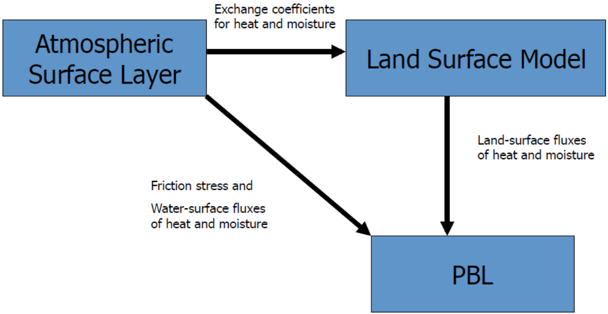
Model Physics

Surface physics



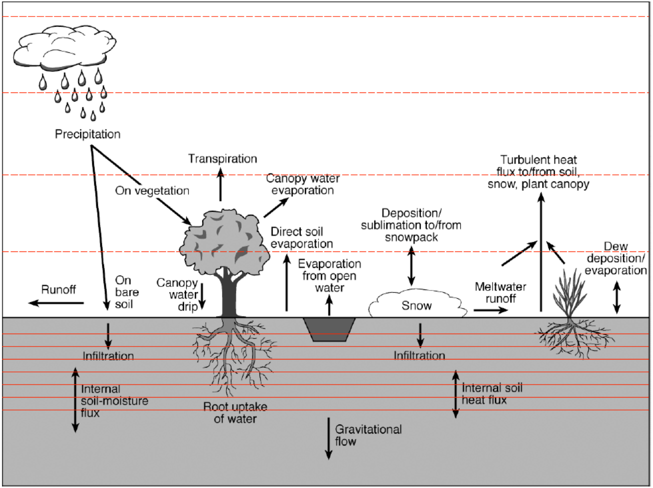
Model Physics

How surface physics gets into atmosphere



Model Physics

Processes accounted for in Land Surface Models



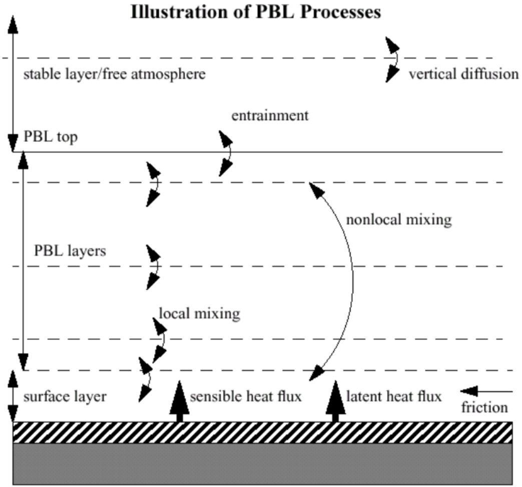
Model Physics

Processes in Land Surface Models:

- Evapotranspiration, root zone, leaf effects
- Seasonally varying vegetation fraction
- Vegetation categories (e.g. cropland, forest types, etc.), soil categories (e.g. sandy, clay, etc.)
- Fractional snow and ice cover, frozen soil water, melting, runoff
- Sea surface temperature, sea ice, vegetation fraction can be updated during simulation (boundary conditions)
- Urban effects can be included (e.g. buildings, heating and A/C effects, etc.)

Model Physics

Planetary boundary layer (PBL)



Model Physics

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- Schemes can be used for most model grids wherever there are surface fluxes.
- Schemes assume that PBL eddies are not resolved.
  - ➔ Assumptions break down if $\Delta x \ll 1$ km.
  - ➔ When $\Delta x \ll 1$ km, model diffusion does the job since the processes are resolved.

Model Physics

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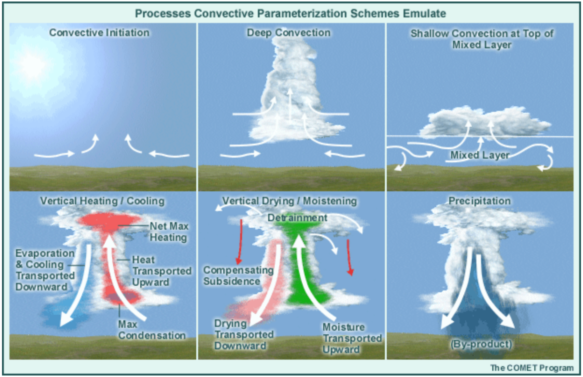
- When triggered, scheme will:
  - ➔ Activate the grid point as a convective column
  - ➔ Compute and pass a heating tendency and a moisture tendency to the right-hand sides of the thermodynamic and water vapor equations.

Model Physics

Model physics: Convection



Model Physics

Convection

- There are 2 classes of cumulus schemes:
  - ➔ Adjustment type—Also called a static scheme. Determines what the atmospheric state needs to be after convection and moves toward that state over some time period.
  - ➔ Mass-flux type—Also called a dynamic scheme. Evaluates mass flux based on updrafts and downdrafts.

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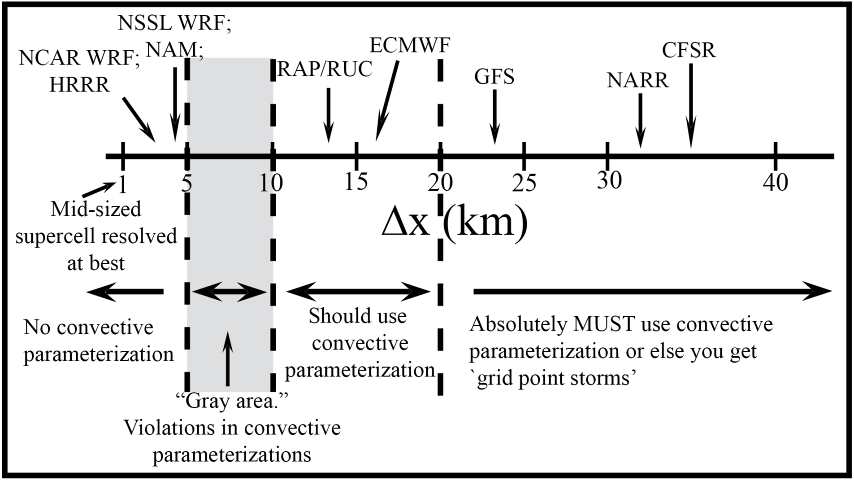
  - ➔ Mass-flux type—Also called a dynamic scheme. Evaluates mass flux based on updrafts and downdrafts.
- ALL cumulus schemes have a “trigger” function that determines when to initiate convection at a grid point. Criteria are:
  - ➔ Presence of CAPE
  - ➔ Not too much convective inhibition (CIN) (cap strength)
  - ➔ Minimum cloud depth from parcel ascent

Model Physics

Convection



Model Physics

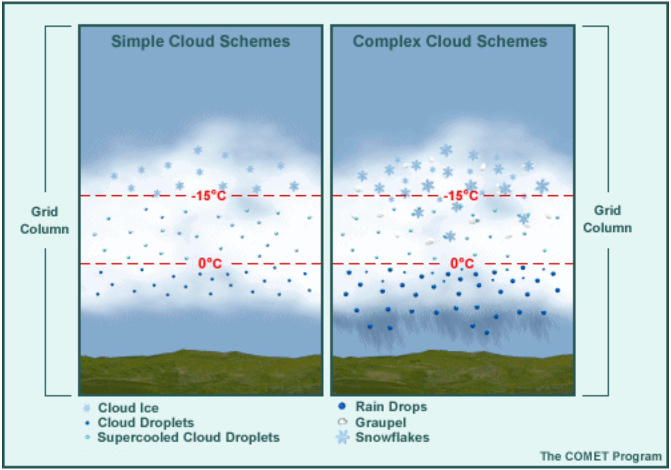
Latent heating (microphysics)

- When model grid spacing is small enough to resolve clouds, then it is handled by a microphysics scheme.
- Water substance in a sample of air may be represented by eight mixing ratios:

q_v	:	Water vapor
q_c	:	Cloud liquid water
q_d	:	Drizzle
q_r	:	Rainwater
q_I	:	Cloud ice
q_s	:	Snow
q_g	:	Graupel
q_h	:	Hail

Model Physics

Latent heating (microphysics)



Model Physics

Many microphysics scheme predict based on the bulk continuity model, meaning water substance is conserved.

The most simple model is a warm cloud ($T > 0$°C), where there is only condensation ($C > 0$) and evaporation ($C < 0$):

$$\frac{dq_v}{dt} = -C$$
$$\frac{dq_c}{dt} = C$$

Model Physics

For a warm, precipitating cloud, the following can occur:

C_c	:	Condensation of cloud water
E_c	:	Evaporation of cloud water
E_r	:	Evaporation of rain water
A_c	:	Autoconversion[1] of cloud water
K_c	:	Collection of cloud water
F_r	:	Sedimentation of raindrops

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Then the model becomes:

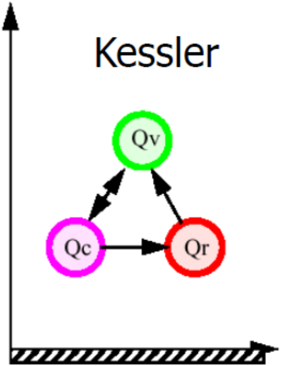
$$\frac{dq_v}{dt} = -C_c + E_c + E_r$$

$$\frac{dq_c}{dt} = +C_c - E_c - A_c - K_c$$

$$\frac{dq_r}{dt} = -E_r + A_c + K_c + F_r$$

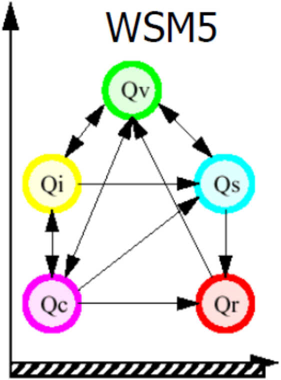
Model Physics

Since there were 3 “classes” for which water substance could be classified, the above example would be considered a **3-class** microphysics scheme.



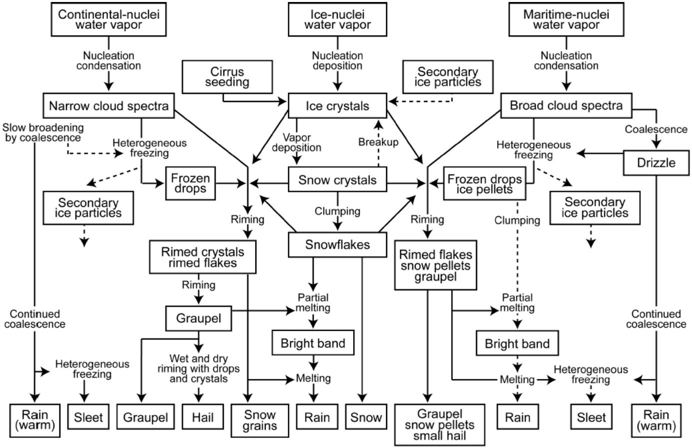
Model Physics

When including cold clouds ($T < 0°C$), an equation for cloud ice and snow must be added, making it a **5-class** microphysics scheme.



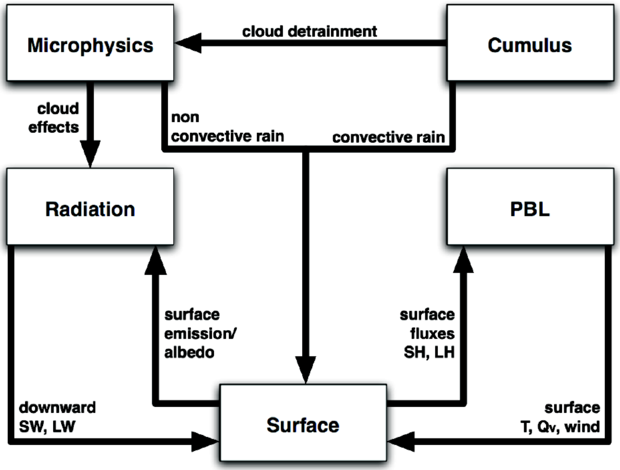
Model Physics

Of course, you don't *really* want to know everything that is considered in a microphysics scheme:



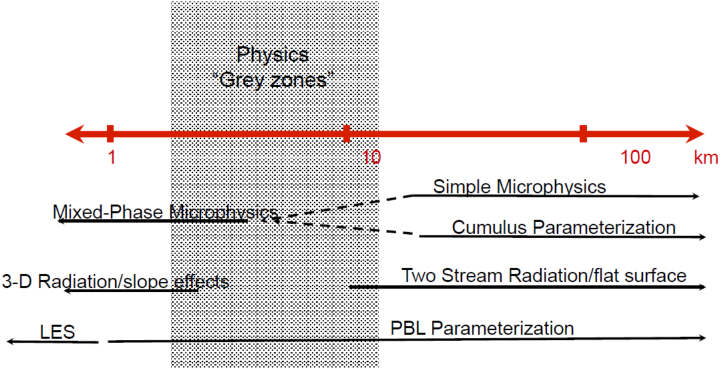
Model Physics

Combined, the physics schemes interact, which can be summarized like below:



Model Physics

When using, running, or creating a new model, ALWAYS keep in mind the scales that a physics parameterization is designed for:



Important points and questions for review

- What are 4 different physical processes that are parameterized in a numerical model?
- Suppose you are a forecaster, trying to forecast what the high temperature will be in your forecast area. You have two numerical models to use for forecast guidance. Both models show that it will remain sunny and clear, and that there will be no temperature advection. However, one model shows that a deep layer of higher relative humidities will move over the forecast area while the other does not. How will the forecast high temperatures differ between the 2 models and why?
- Hudson Bay, located in northern Canada, is unfrozen in November but completely freezes over by January. How would a model's surface heat and moisture fluxes vary between November and January over Hudson Bay?
- What horizontal grid spacing does your model need to have in order to **NOT** use a cumulus parameterization? Where are convective processes handled in a model when you do not use a cumulus parameterization?
- Name 8 different classes of water substance that may be represented in a microphysical parameterization.