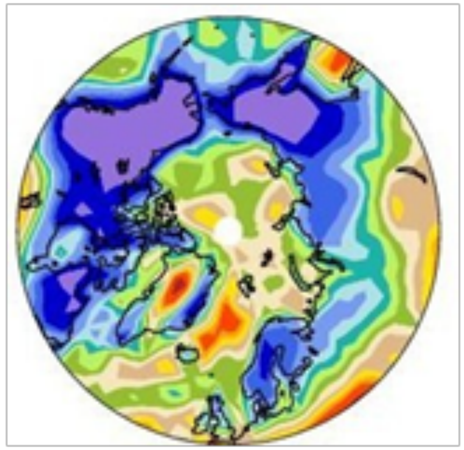
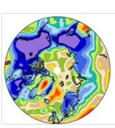


Simulating Atmospheric 'Physics'

Andrew Gettelman
National Center for Atmospheric Research



Outline

- Define the Problem of Physical Parameterization
- How it integrates into a GCM
- Drivers and time stepping
- Representing sub-grid processes
- Basic Requirements
- Some critical (or unappreciated) issues
- Examples

  Simple → Complex

General Circulation Modeling

Already covered:

- Basics of General Circulation Models
- Dynamics, Motion and Advection
- Now: lets talk about what we can’t resolve

Hydrostatic Primitive Equations

‘Hydrostatic’ = ‘larger’ scale (> 10km)

$$d\overline{\mathbf{V}}/dt + fk \times \overline{\mathbf{V}} + \nabla\overline{\phi} = \mathbf{F}, \qquad \textit{(horizontal momentum)}$$

$$d\overline{T}/dt - \kappa\overline{T}\omega/p = Q/c_p, \qquad \textit{(thermodynamic energy)}$$

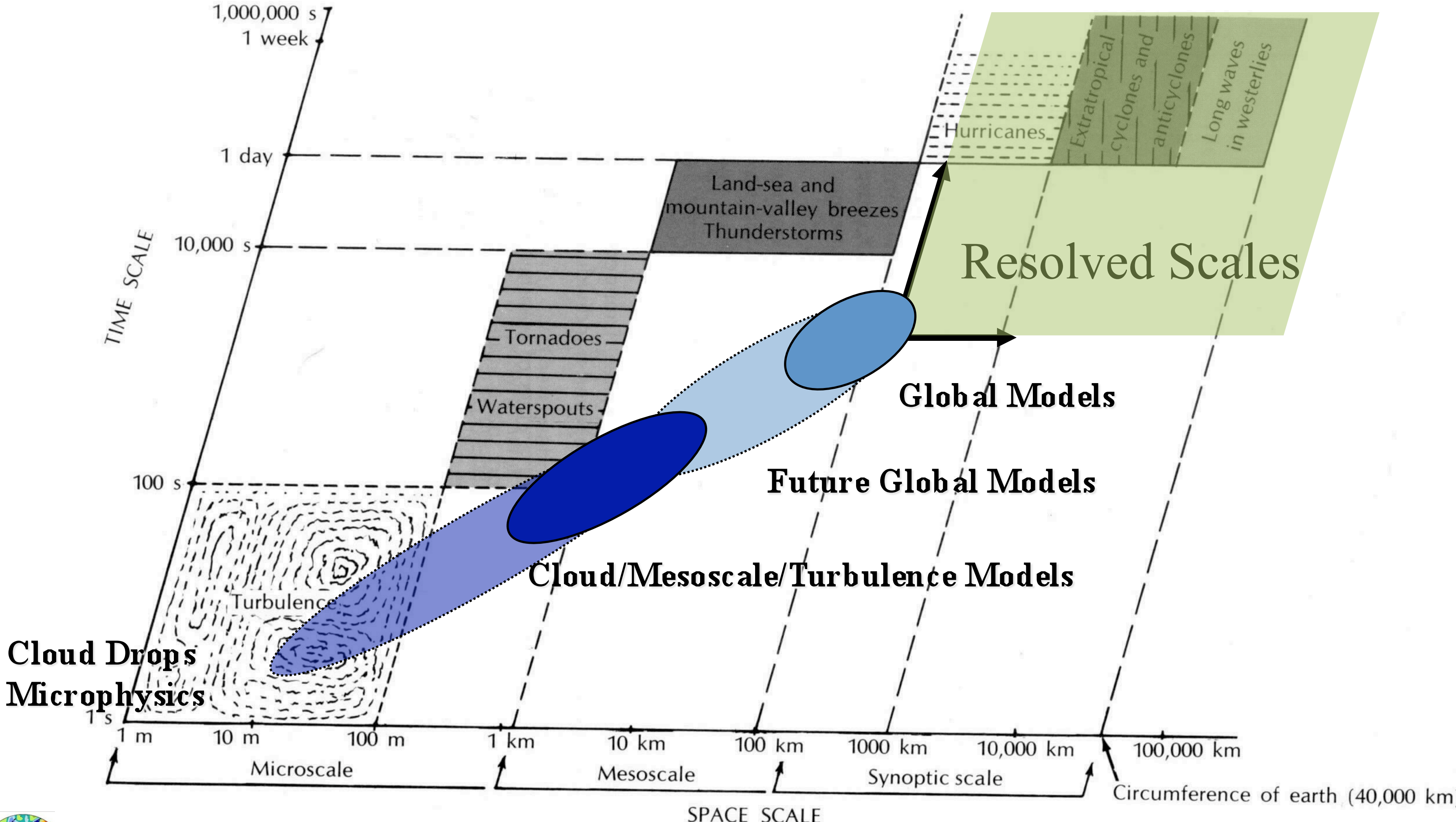
$$\nabla \cdot \overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0, \qquad \textit{(mass continuity)}$$

$$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0, \qquad \textit{(hydrostatic equilibrium)}$$

$$d\overline{q}/dt = S_q. \qquad \textit{(water vapor mass continuity)}$$

Harmless looking terms F, Q, and S_q $\Longrightarrow$ “physics”

Scales of Atmospheric Processes



Physical Parameterization

To close the forcing terms of the governing equations (F, S, Q), it is necessary to incorporate the effects of physical processes that occur on scales below the numerical truncation limit

- Physical parameterization
  - express unresolved physical processes in terms of resolved processes
  - "resolved processes" are the atmospheric state
  - generally includes empirical techniques (see below)

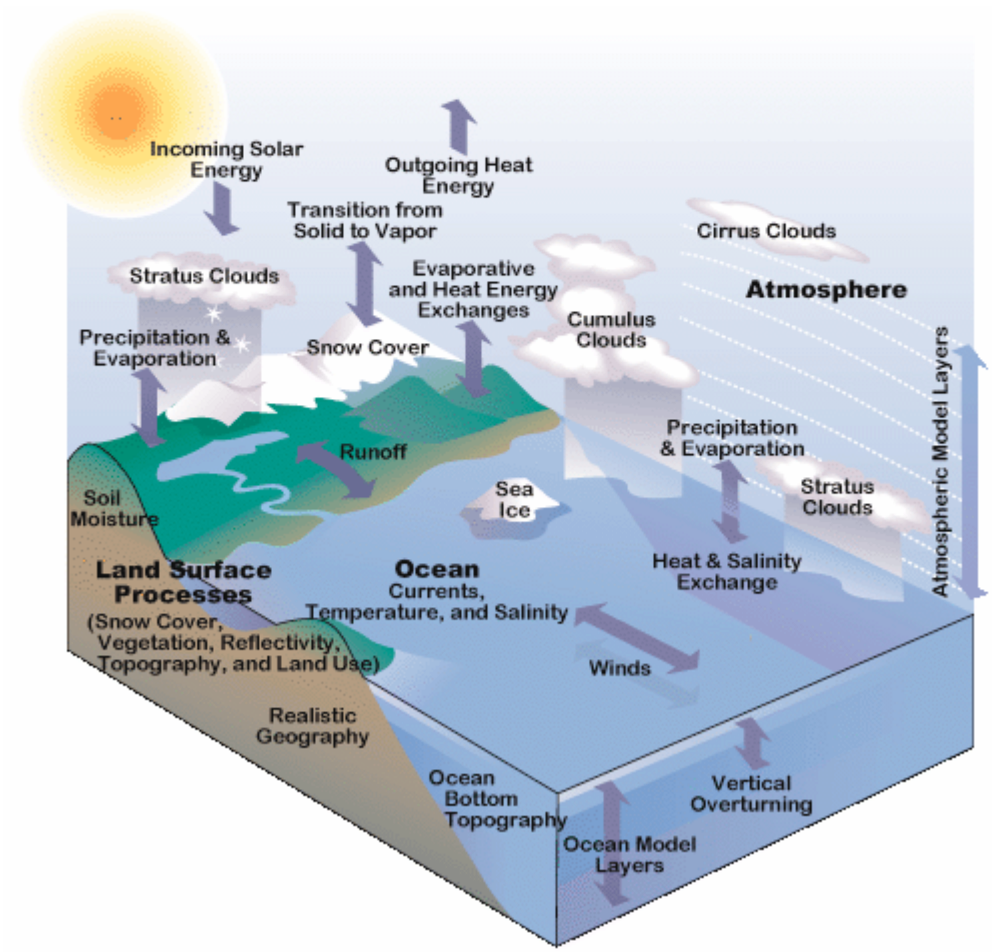
- Examples of parameterized physics
  - dry and moist convection
  - cloud amount/cloud optical properties
  - radiative transfer
  - planetary boundary layer transports
  - surface energy exchanges
  - horizontal and vertical dissipation processes
  - ...

Global Climate Model Physics

Assume *F, Q,* and S_q represent physical processes

- Equations of motion, *F*
  - turbulent transport, generation, and dissipation of momentum
- Thermodynamic energy equation, *Q*
  - convective-scale transport of heat
  - convective-scale sources/sinks of heat (phase change)
  - radiative sources/sinks of heat
- Water vapor mass continuity equation, S_q
  - cloud-scale transport of water substance
  - cloud-scale water sources/sinks (phase change)
- Other continuity equations for other tracers S_χ
  - Includes chemistry and aerosols
  - Wet deposition, scavenging, etc

Earth's Climate System



Model Physical Parameterizations

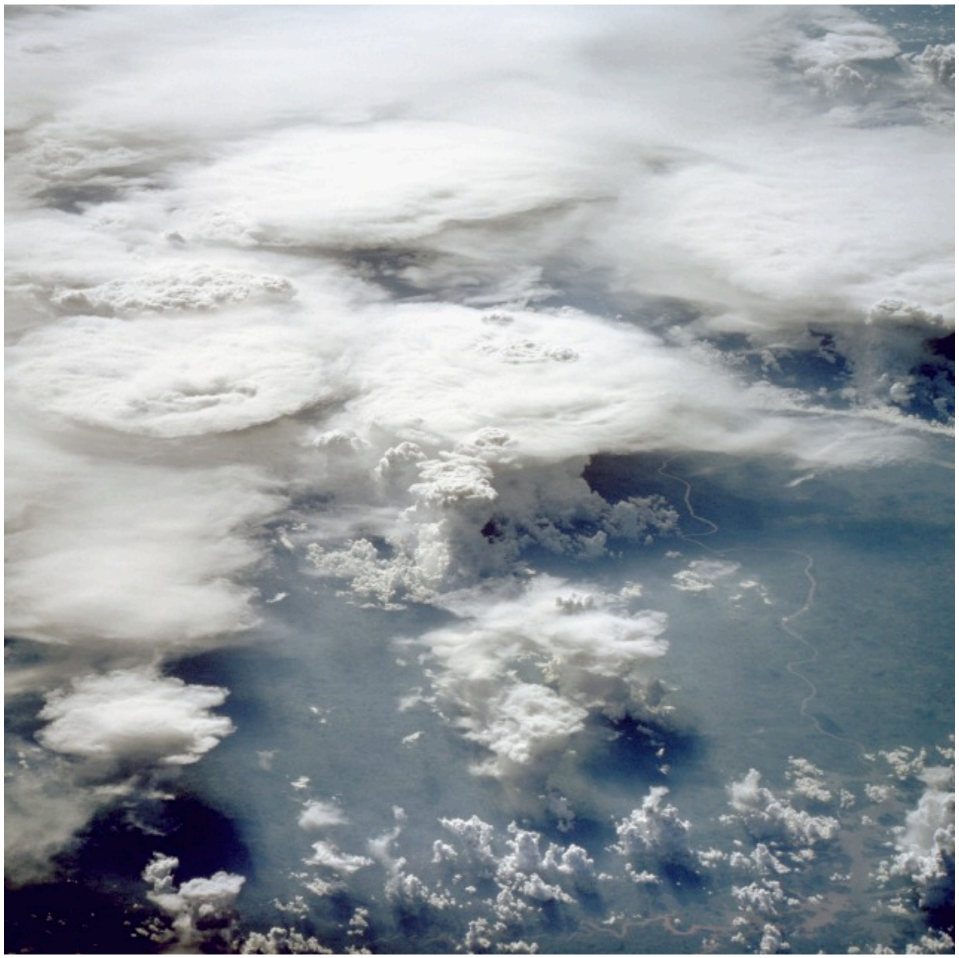
Physical processes breakdown:

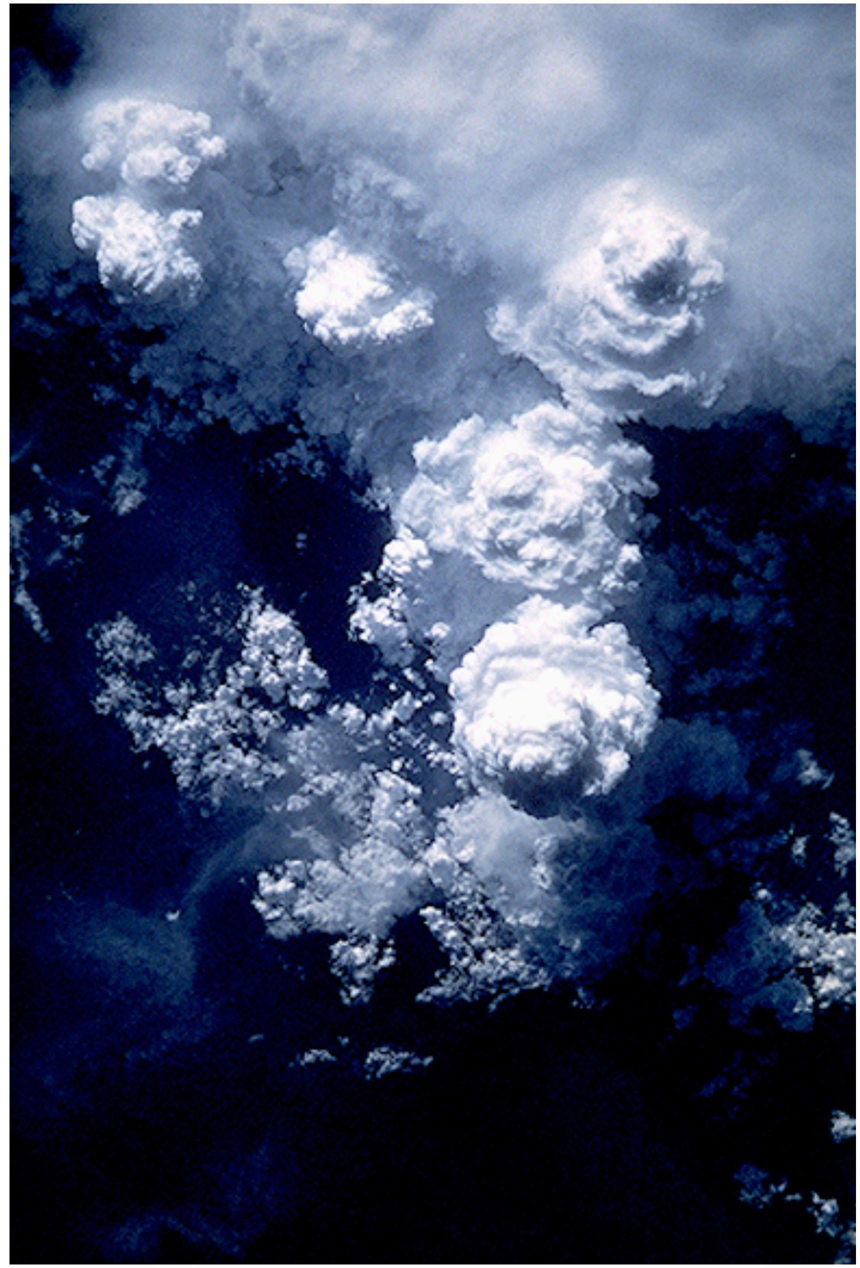
- Moist Processes
  - Moist convection, shallow convection, large scale condensation
- Radiation and Clouds
  - Cloud microphysics, precipitation processes, radiation
- Surface Fluxes
  - Fluxes from land, ocean and sea ice (from data or models)
- Turbulent mixing
  - Planetary boundary layer parameterization, vertical diffusion, gravity wave drag (several for different waves)

What is a ‘Parameterization’?

- A representation of a physical process
- Usually based on
  - Basic physics (laws of thermodynamics)
  - Empirical formulations from observations
- In many cases: no explicit formulation based on first principles is possible at the level of detail desired. Why
  - Non-linearities & interactions at ‘sub-grid’ scale
  - Often coupled with observational uncertainty

Example: Clouds

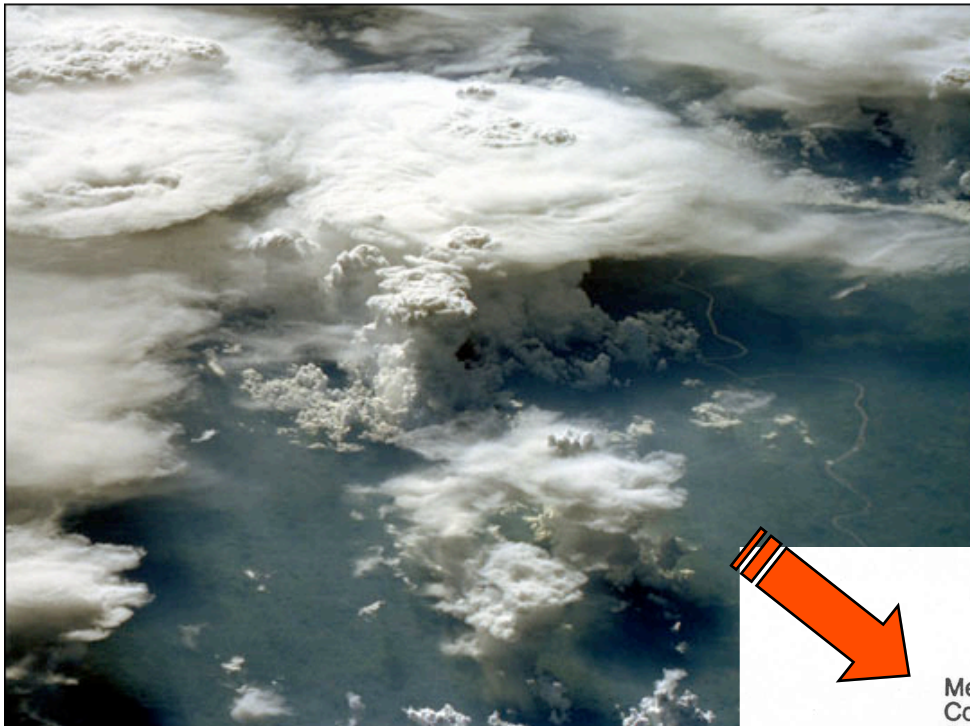




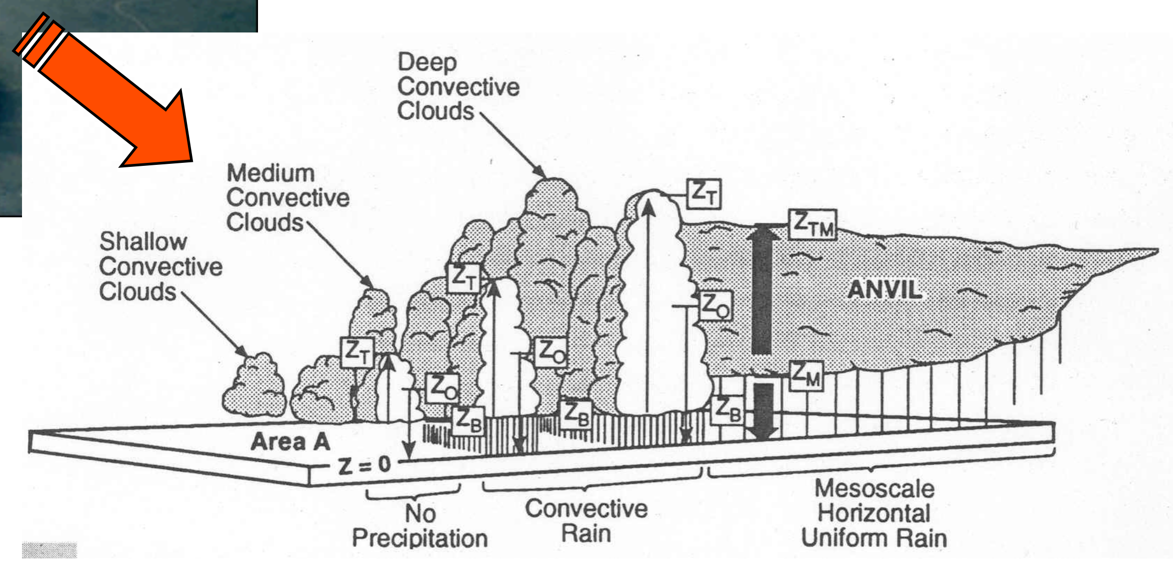
Cloud Parameterization

- Let's build a simple parameterization
- Need some basic theories
  - For example: water vapor cannot be supersaturated
- Add some rules to define it ('closure')
  - $q(x,y,z,t) < q_{sat}(x,y,z,t)$ where $q_{sat} = f(T,p)$ (t=time, T=temp)
  - if $q > q_{sat}$ then A (cloud flag) = 1, else $A = 0$
  - q_c (cloud water) = $q - q_{sat}$
- Done. Now you have a cloud parameterization

Process Models and Parameterization



- Boundary Layer
- Clouds
  - Stratiform
  - Convective
- Microphysics

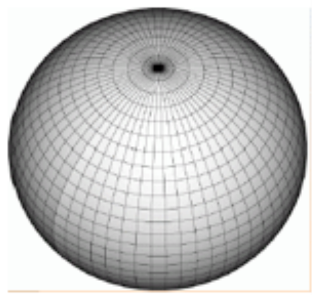


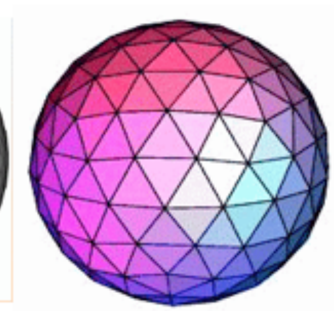
Implementation: Grid Discretization

- General Grids: discretization on a sphere
  - Horizontal, Vertical
- Terms *S, F, Q* are usually solved at each grid point: ‘Column’ Physics
  - Physics are usually independent of other columns
  - This assumption is dependent on time/space scales
  - Examples relevant for advection: CFL condition
  - For physics the timescale < interactions
    - e.g.: short enough that the heat of condensation can be added to dynamics in the next time step.
- Sometimes a ‘stencil’ or neighboring points are necessary
- Or sub-steps can be run in a column (precipitation)
- Boundary conditions necessary at the top and bottom

Horizontal Grids

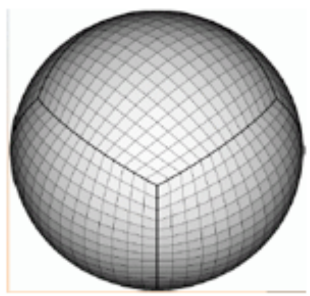
Lat-Lon
(Gaussian)

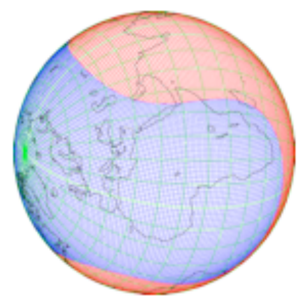




Spherical
icosahedral

Cubed-
Sphere





Yin-Yang

CAM Grid Structure

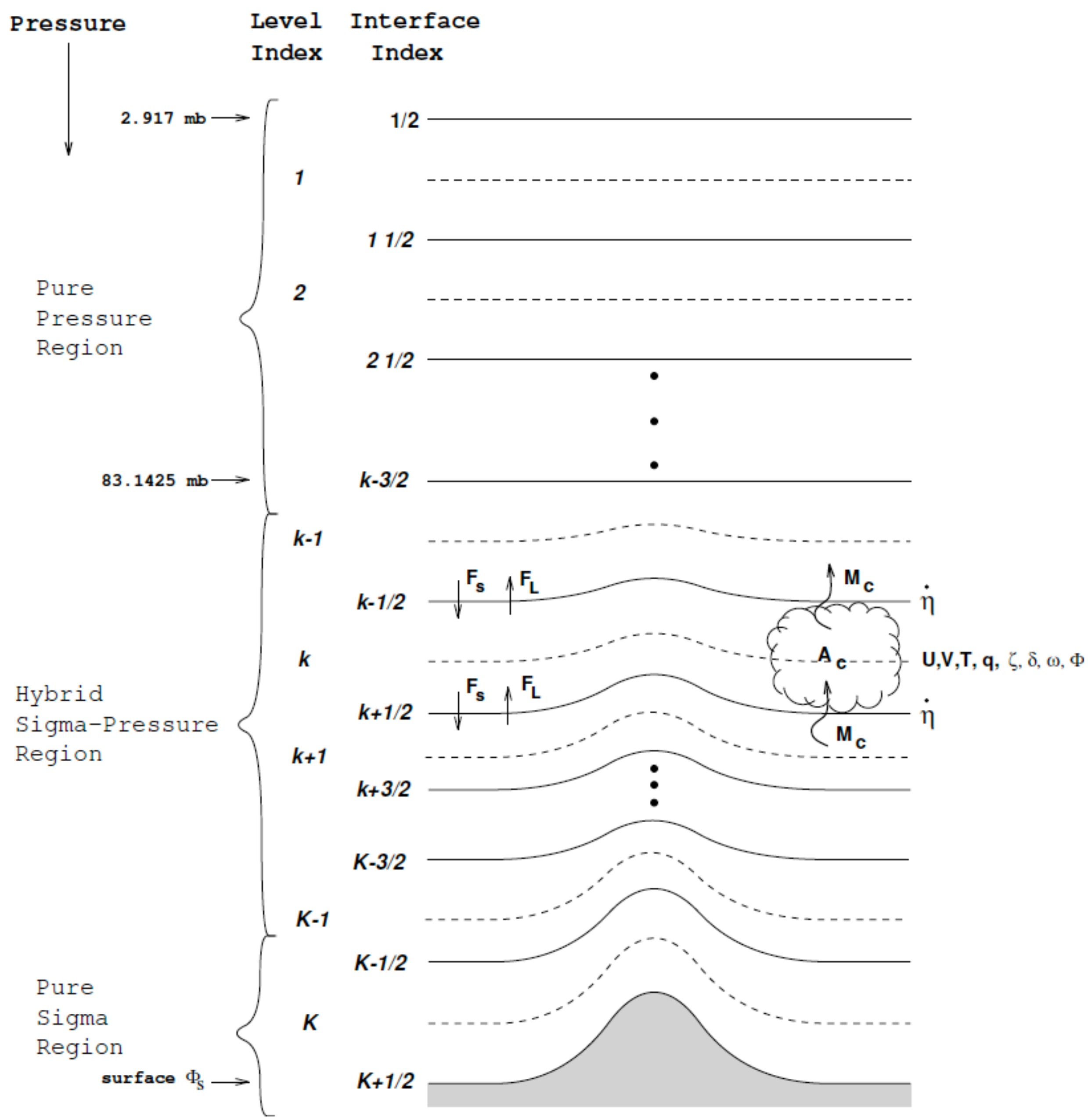
- In general, a physics parameterization does not know where it is on the earth.
- Code is broken into ‘chunks’ of columns and each ‘chunk’ is distributed to different a different processor on a machine
- This requires physics processes to be general (applicable for all possible atmospheric states)

Horizontal Resolution

- Code generally does not know or assume a horizontal or vertical resolution
- However: most physics packages (or the combination of them) are resolution dependent (answers change with resolution)
- Often parameters are set differently at different resolutions
  - This is in addition to dynamics changes (time-step)

Vertical Grid

- Fixed pressure
  - not suited to following terrain
- Sigma $\sigma = P / P_s$
  - $0 < \sigma < 1$, $\sigma = 1$ at surface
- Hybrid
  - combines both at an interface (83hPa in CAM)
- CAM Usually 26 levels,
  - 3→1000 hPa
- CAM defines layer by
  - Midpoints: State variables
  - Interfaces: Fluxes
- CAM Codes are also dependent on vertical resolution



Basic Logic in the Time-step Loop

For a grid of atmospheric columns:

1. ‘Dynamics’: Iterate Basic Equations
   Horizontal momentum, Thermodynamic energy,
   Mass conservation, Hydrostatic equilibrium,
   Water vapor mass conservation
2. Transport ‘constituents’ (water vapor, aerosols, etc)
3. Calculate forcing terms (“Physics”) for each column
   Clouds & Precipitation, Radiation, etc
4. Update dynamics fields with physics forcings
5. Gravity Waves, Diffusion (fastest last)
6. Next time step (repeat)

Basic Concepts: Time Iterations

- Multiple parameterization models are run in a time step. Can they run all at the same time? How do they interact?

Two methods:

- Process split: Processes act at the same time (i.e. on the same state)
- Time Split: Processes act sequentially (one after each other, on updated states)

Time Iteration

In general: Physics processes are time-split

Time-scale of process < than model time-step

Coupling to Dynamics can be process split:

- Process Splitting used for Spectral Core
  - Extra dynamical terms arise from time-splitting
- Time Splitting used for Finite Volume core
  - Dynamics sub steps (vertical remapping) make process splitting difficult (multiple interpolation)

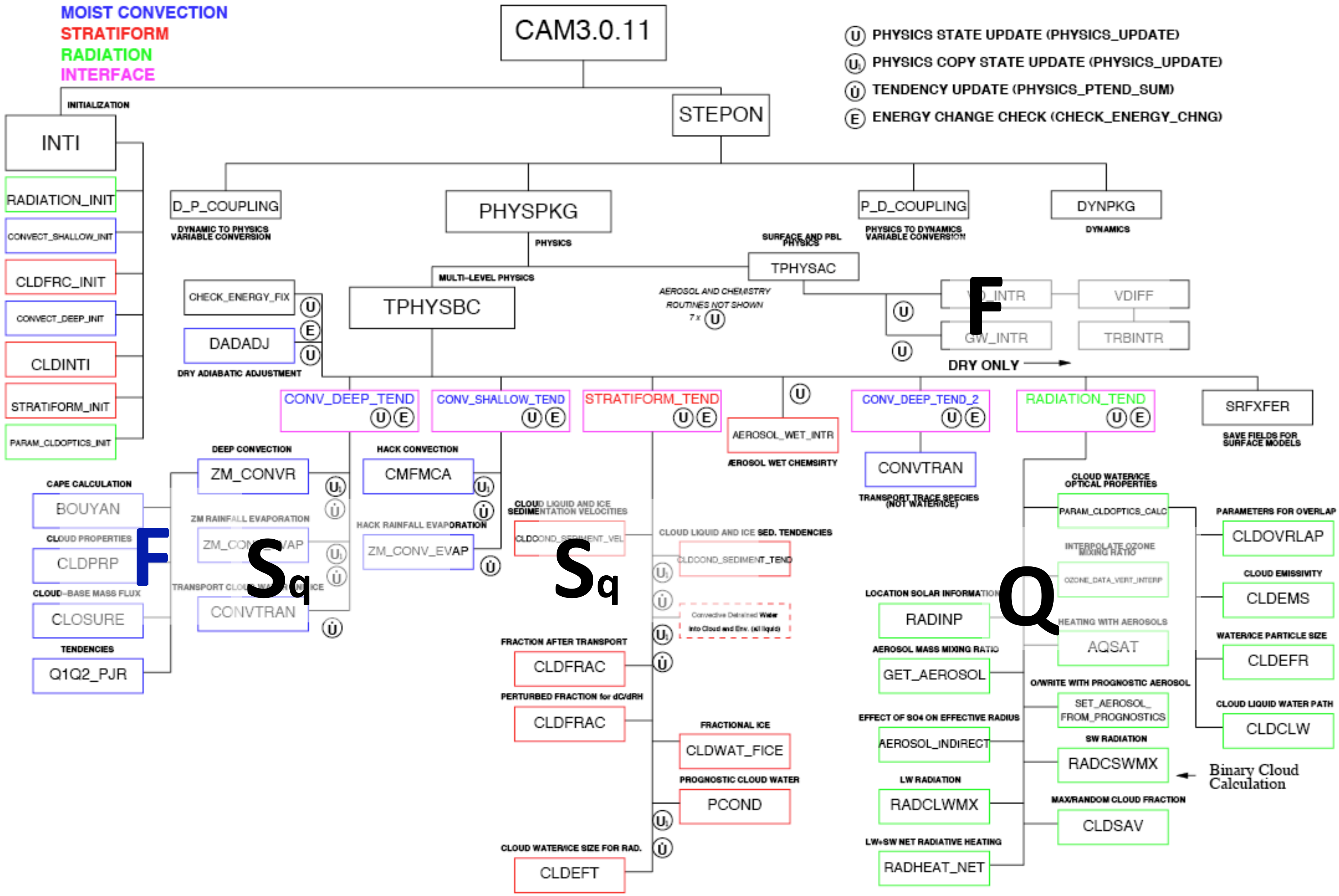
Ordering of Processes

- In theory the ordering of processes is arbitrary and should not matter (time stepping is a loop)
- In practice, fastest processes “last” (before next dynamics update, or after coupling): waves
- Moist processes (clouds) run before radiation to ensure radiation sees a consistent state

More on Time Splitting

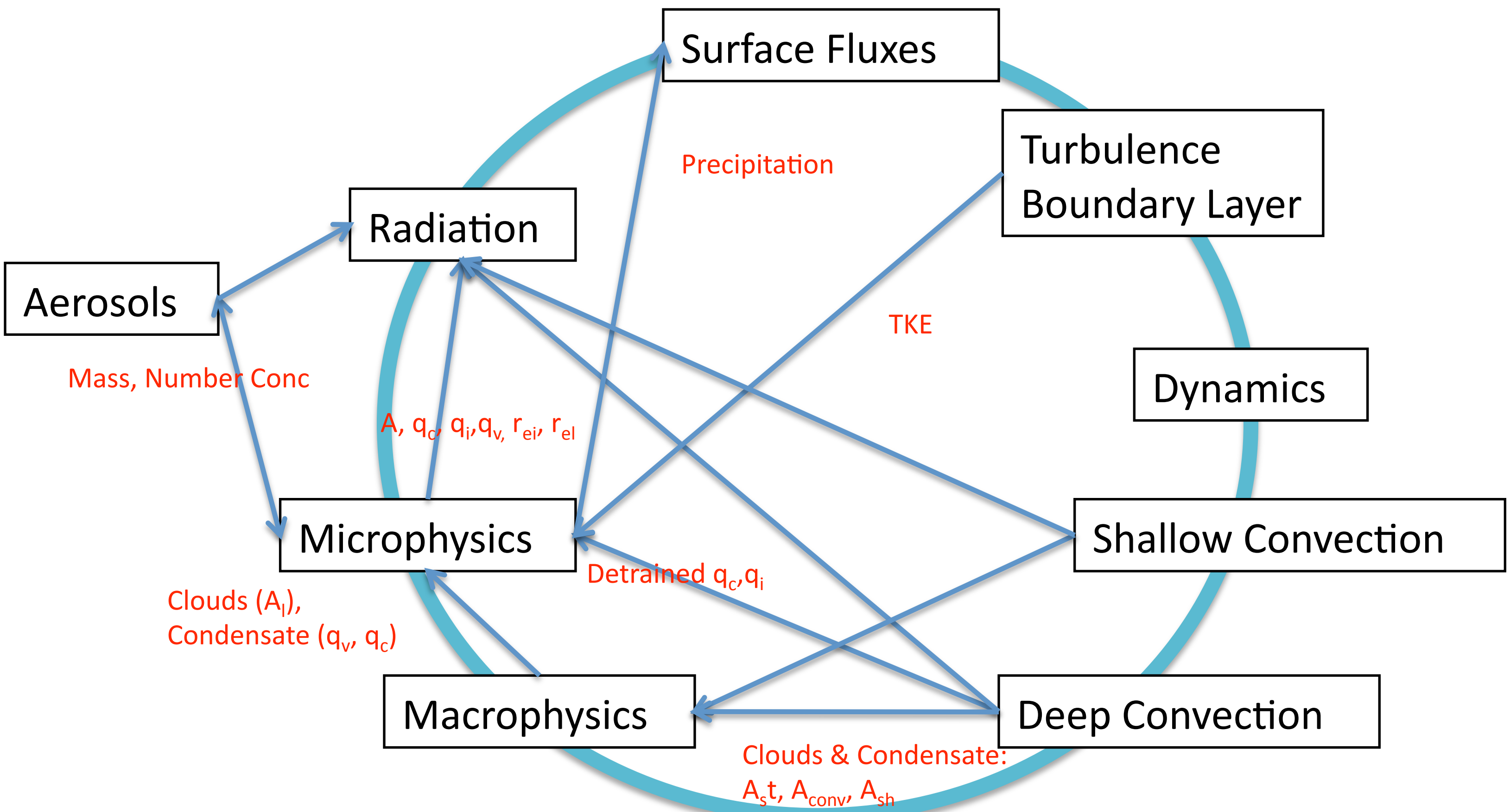
- Lenderink, G., and A.A.M. Holtslag, 2000: Evaluation of the Kinetic Energy Approach for Modeling Turbulent Fluxesin Stratocumulus. *Mon. Wea. Rev.*, **128**, 244–258.

- Williamson, D.L., 2002: Time-Split versus Process-Split Coupling of Parameterizations and Dynamical Core. *Mon. Wea. Rev.*, **130**, 2024–2041. (also in CAM3 Description)



MOIST CONVECTION
STRATIFORM
RADIATION
INTERFACE
CAM3.0.11
U PHYSICS STATE UPDATE (PHYSICS_UPDATE)
U PHYSICS COPY STATE UPDATE (PHYSICS_UPDATE)
U TENDENCY UPDATE (PHYSICS_PTEND_SUM)
E ENERGY CHANGE CHECK (CHECK_ENERGY_CHNG)
INITIALIZATION
INTI
RADIATION_INIT
CONVECT_SHALLOW_INIT
CLDFRC_INIT
CONVECT_DEEP_INIT
CLDINTI
STRATIFORM_INIT
PARAM_CLDOPTICS_INIT
STEPON
D_P_COUPLING
DYNAMIC TO PHYSICS VARIABLE CONVERSION
PHYSPKG
PHYSICS
P_D_COUPLING
PHYSICS TO DYNAMICS VARIABLE CONVERSION
DYNPKG
DYNAMICS
SURFACE AND PBL PHYSICS
TPHYSAC
MULTI-LEVEL PHYSICS
TPHYSBC
CHECK_ENERGY_FIX
DADADJ
DRY ADIABATIC ADJUSTMENT
AEROSOL AND CHEMISTRY ROUTINES NOT SHOWN
7 x U
VD_INTR
VDIFF
GW_INTR
TRBINTR
F
DRY ONLY
CONV_DEEP_TEND
CONV_SHALLOW_TEND
STRATIFORM_TEND
AEROSOL_WET_INTR
AEROSOL WET CHEMSIRTY
CONV_DEEP_TEND_2
CONVTRAN
TRANSPORT TRACE SPECIES (NOT WATER/ICE)
RADIATION_TEND
SRFXFER
SAVE FIELDS FOR SURFACE MODELS
DEEP CONVECTION
ZM_CONVR
HACK CONVECTION
CMFMCA
CAPE CALCULATION
BOUYAN
CLOUD PROPERTIES
CLDPRP
CLOUD-BASE MASS FLUX
CLOSURE
TENDENCIES
Q1Q2_PJR
F
ZM RAINFALL EVAPORATION
ZM_CONV_EVAP
TRANSPORT CLOUD WATER AND ICE
CONVTRAN
HACK RAINFALL EVAPORATION
ZM_CONV_EVAP
Sq
CLOUD LIQUID AND ICE SEDIMENTATION VELOCITIES
CLDCOND_SEDIMENT_VEL
CLOUD LIQUID AND ICE SED. TENDENCIES
CLDCOND_SEDIMENT_TEND
Sq
Convective Detrained Water into Cloud and Env. (all liquid)
FRACTION AFTER TRANSPORT
CLDFRAC
PERTURBED FRACTION for dC/dRH
CLDFRAC
FRACTIONAL ICE
CLDWAT_FICE
PROGNOSTIC CLOUD WATER
PCOND
CLOUD WATER/ICE SIZE FOR RAD.
CLDEFT
CLOUD WATER/ICE OPTICAL PROPERTIES
PARAM_CLDOPTICS_CALC
INTERPOLATE OZONE MIXING RATIO
OZONE_DATA_VERT_INTERP
LOCATION SOLAR INFORMATION
RADINP
Q
HEATING WITH AEROSOLS
AQSAT
AEROSOL MASS MIXING RATIO
GET_AEROSOL
O/WRITE WITH PROGNOSTIC AEROSOL
SET_AEROSOL_FROM_PROGNOSTICS
EFFECT OF SO4 ON EFFECTIVE RADIUS
AEROSOL_INDIRECT
SW RADIATION
RADCSWMX
Binary Cloud Calculation
LW RADIATION
RADCLWMX
MAX/RANDOM CLOUD FRACTION
CLDSAV
LW+SW NET RADIATIVE HEATING
RADHEAT_NET
PARAMETERS FOR OVERLAP
CLDOVRLAP
CLOUD EMISSIVITY
CLDEMS
WATER/ICE PARTICLE SIZE
CLDEFR
CLOUD LIQUID WATER PATH
CLDCLW

CAM4 GCM physical processes



Key Interactions

- Cloud Processes & Radiation
  - Feedbacks
- Precipitation & Scavenging
  - Chemical (gas phase) constituents
  - Aerosols (condensed phase constituents)
- Microphysics and Aerosols
- Boundary Layer / Cumulus & Dynamics
- Resolved scales and unresolved scales

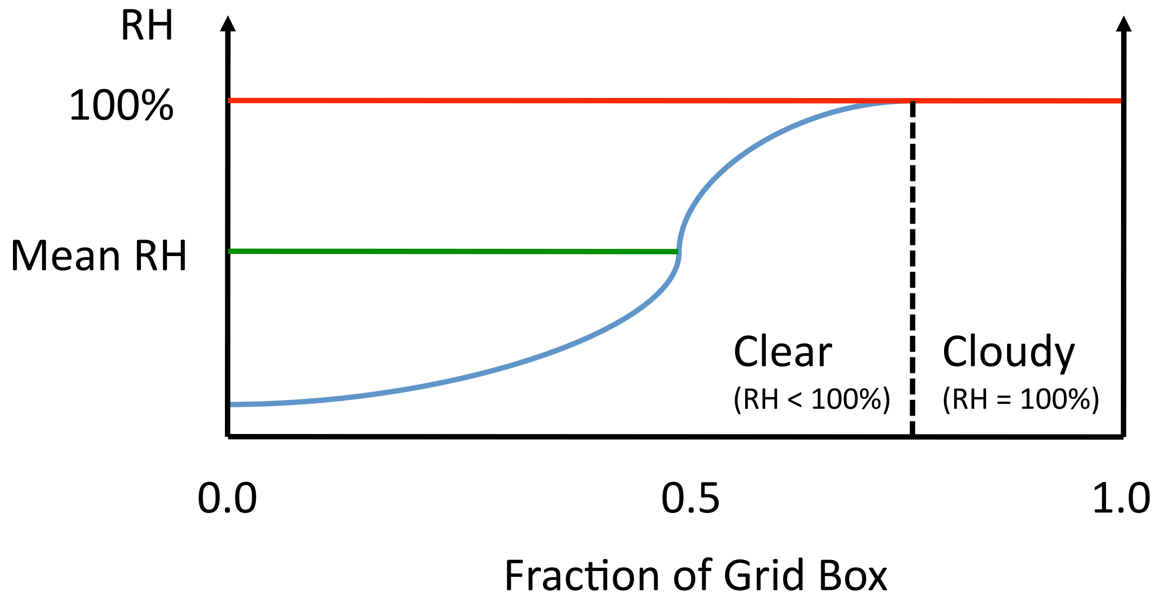
‘Sub-Grid’ Processes

- Not all processes assume uniform state for each grid cell.
- Generalized way to deal with small scales
- Some processes are highly non-linear, so ‘sub-grid’ variability is assumed
- Simple example: ‘fractional cloudiness’
  - Also called ‘cloud macrophysics’
  - Used by microphysics and radiation
  - This will take our simple cloud parameterization one step further

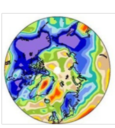
Sub-Grid Humidity and Clouds

Liquid clouds form when RH = 100% ($q = q_{sat}$)

But if there is variation in RH in space, some clouds will form before *mean* RH = 100%



Assumed Cumulative Distribution function of Humidity in a grid box with sub-grid variation



Sub-Grid Processes

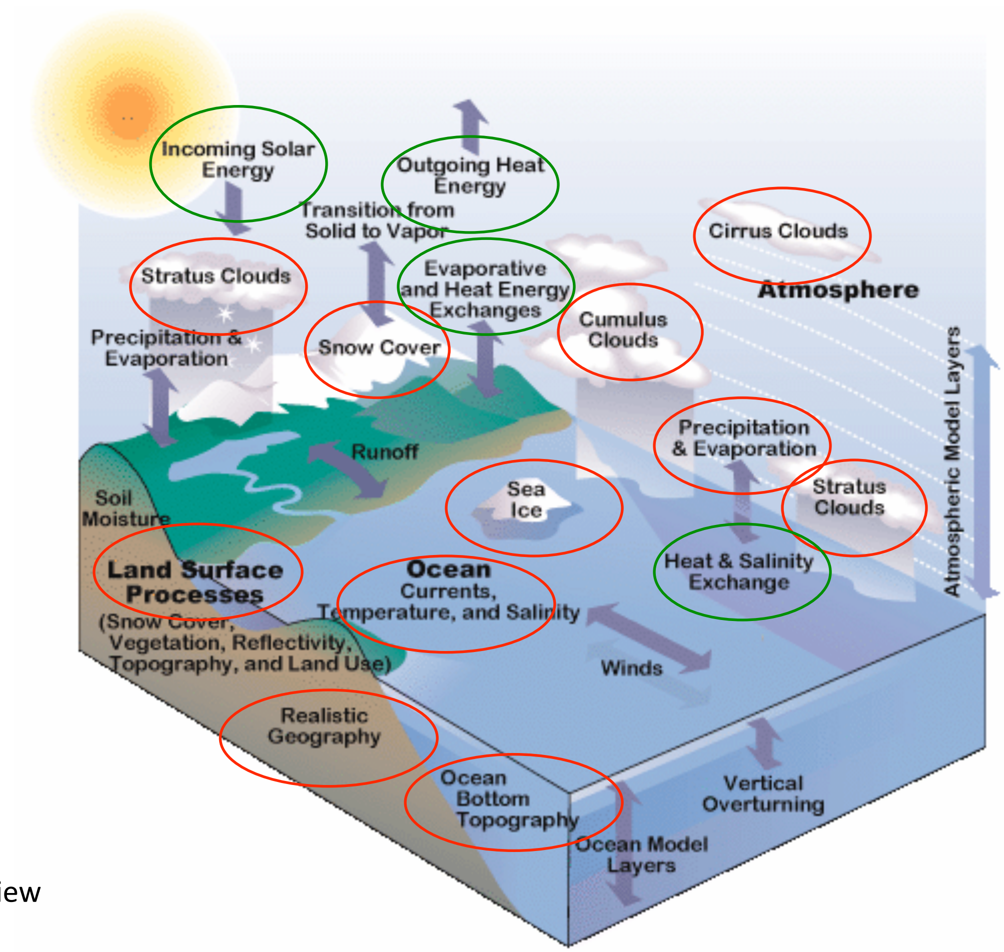
- Fractional cloudiness used by many processes
- Also implications for radiation
  - This will be discussed later
- Also Sub-grid distributions of vertical velocity (w)
  - upward & downward motion even if mean w=0
- More complex treatments:
  - Single & multi-variate PDFs
  - Starting to be used now in CAM
- Similar interactions with surface models
  - Fractional sea ice, fractional forest cover, etc

Key ‘sub-grid’ parts of the system

Nearly Everything!

Sub-Grid Process

Affected by Sub-Grid Process



Commandments

Thou shalt not
create or destroy mass

Requirements or ‘Commandments’

1. Mass and Energy (Moist Static Energy) must be conserved.
2. Reproducability: the same configuration should produce the same answer

Notes:

-Still can have stochastic elements

(same seeds for random number generators)

-Be careful of machine precision (1 + 1 ≠ 2)

Fundamental Issues

- In many cases, no clean physical equations define a problem
- Many empirical formulations exist (e.g.: define a parameter based on model physical state and an empirical formulation of the same from observations)
  - Dangers: state ends up outside valid range!

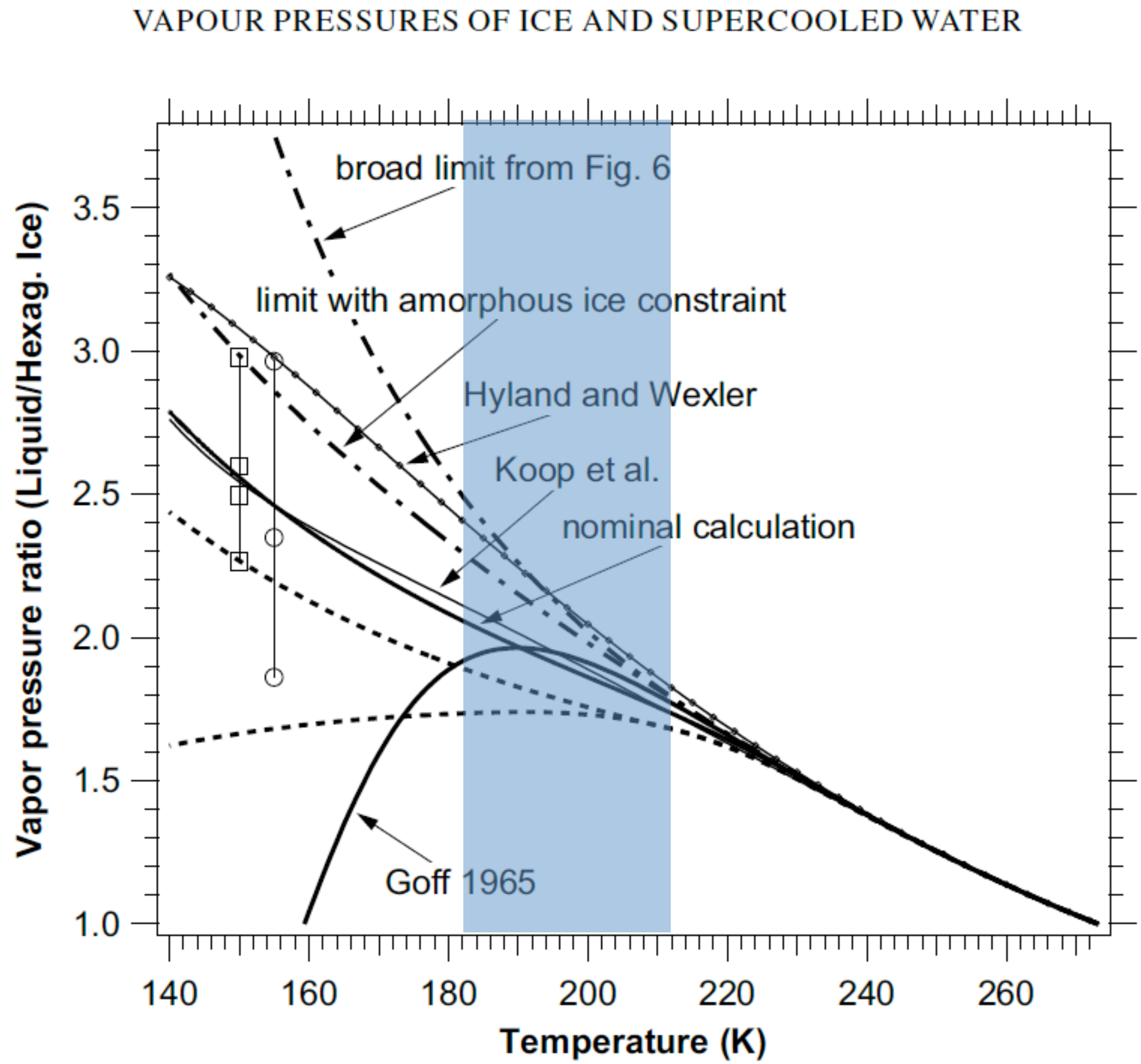
Hidden Dangers

- Even the simplest things are often empirical or have hidden assumptions
- Remember our simple cloud model:
  - *A=f(RH)* so that A=1 if $q > q_{sat}$
  - What is q_{sat}?
  - For cold temperatures, q_{sat} for liquid, which is still important for driving condensation, is an empirical fit to laboratory observations!
  - Few experiments exist below -20C!
  - q_{sat} itself may be uncertain!

Vapor Pressure Differences

q_{sat} is highly uncertain at low T.

Also note: Goff 1965 is extrapolated!



Murphy & Koop , 2005

Computational Issues

- Model code should be reproduceable
- Easy for it not to be for numerical reasons

  "x=2." can be stored as 2. + whatever else is in the other byte of memory (e.g. 2.0000567)

  Or: variables defined but not =0. (need to clear memory)
- Careful coding and checking is key
  - We test for this (or try to)
- Column physics code is 'stupidly parallel'
  - Ideally does not care what next neighbor is doing
  - Run on lots of processors
  - Sometimes memory is an issue (large – look up tables)

Software Interface Standards

- Goal is to allow the process parameterizations to be model independent through a ‘physics interface’
- Ideally you can just ‘plug-in’ any process model.
  - Practically there are requirements and standards
  - Will cover this in more detail in practical session 4

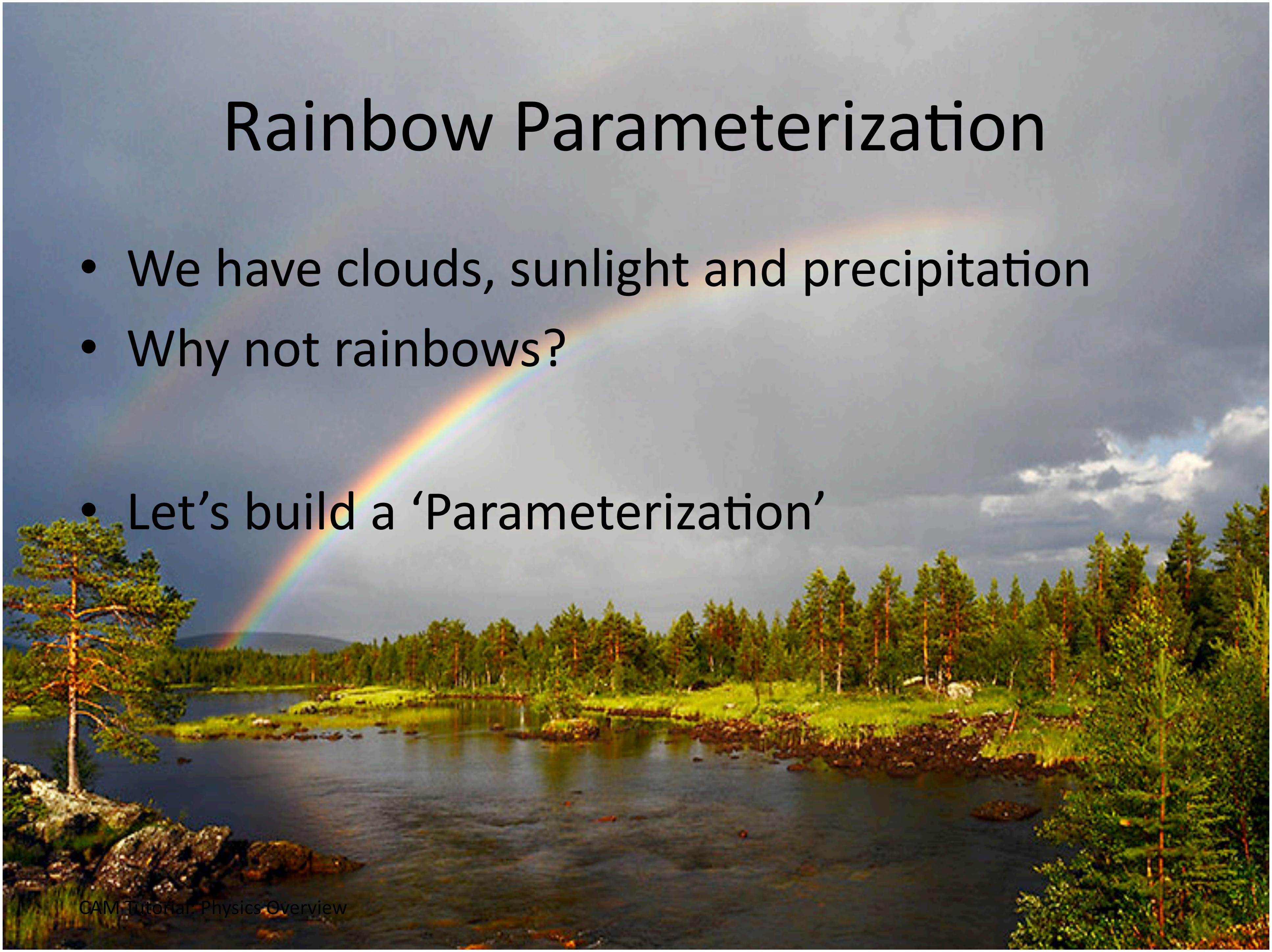
Summary

- ‘Physics’ provides forcing terms for the basic equations
- It is usually discretized into independent columns
- ‘Parameterization’ is the art of representing complex processes below the grid scale from the model state: building a process model
- The time discretization of the process models may be important
- Representing un-resolved scales is critical
- Significant assumptions are embedded in almost anything!
- Computational issues can also play a role: minimize them!
- Let’s see how we can put this together...

Rainbow Parameterization

- We have clouds, sunlight and precipitation
- Why not rainbows?

- Let's build a 'Parameterization'



Rainbows? Frivolous?

- Maybe a good indicator of:
  - relationships between clouds and precip
  - diurnal cycle of precipitation
  - Maybe an indicator of climate change?
- Other examples that are similar:
  - Contrails
  - Heat or drought index
  - Polar Mesospheric Clouds

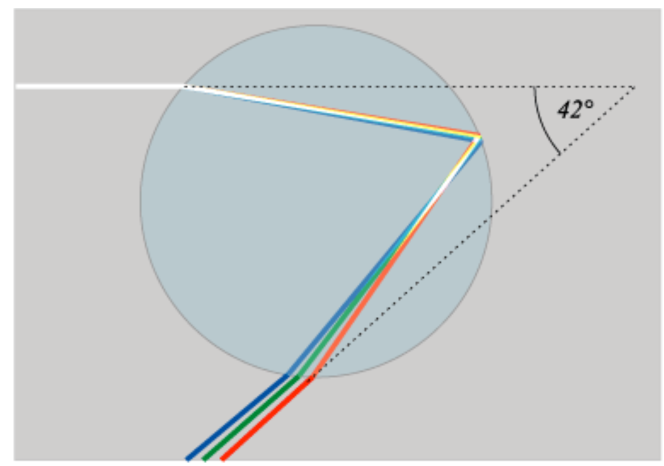
Goal

- Suppose we want to know the fractional occurrence of rainbows
  - Test cloud & precip occurrence and diurnal cycle
- Definitely sub-grid
- Purely diagnostic
  - does not affect solution
  - diagnosed each time-step independently

Rainbow Physics

- Rainbows require light from the sun to hit a raindrop and be refracted back to the observer
- Need some fraction clear sky
- Some precipitation fraction
- The refraction angle is ~42^o
- So the solar zenith angle ϕ > 48^o
- Lower sun = larger rainbow

  (coverage)



Now build some logic

- If $\phi > 48^{o}$
- and cloud fraction A <0.5 (need some sun)
- and rain fraction $F_p > 0.5$ (need some rain)
- Then rainbow frequency $F_{RB} = sin\ (\phi - 48)$
  - This yields a rainbow frequency from 0→0.67 as f goes from 48°→90°.
  - Maybe we want to add the rain fraction in it (because more rain increases the odds, and rainbows really aren't that common):

$$F_{RB} = F_p * \sin(\phi - 48)$$

Evaluate and Adjust

- Look at different cases: In-situ observations
  - Need data on rainbows, precipitation, sun, clouds
  - Evening Rainbows: Boulder
  - Morning rainbows: Field project in Hawaii
- Empirical factor to adjust the parameterization?

  $F_{RB} = U_{RB} * F_p * \sin(\phi - 48)$

  Where U_{RB} is the 'rainbow factor'
- Or we could fit $U_{RB} = f(A, F_p)$
  - Most likely, want to look at convective clouds
- Maybe sine is not the right functional form?
  - perhaps there is something better from optics

‘Parameterization’

- This is tongue in cheek, but the concept is to add a process model based on
  - Known physics
  - Known model state parameters
  - Empirical relations (last resort)

- It is trivial to then add:
  - Sun Dogs (ice phase, specified habits, etc)
  - A pot of gold: Just find the end of the rainbow

Different parameterizations

- Planetary Boundary Layer [F,S]
- Cloud Macrophysics (large scale condensation) [S]
- Cloud Microphysics (stratiform clouds) and Aerosols [S]
- Radiative Transfer [Q]
- Cumulus Parameterization [F,S]
- Momentum Transport and Gravity Waves [F]