GCM Overview: Lecture

Introduction

Welcome to the overview portion of the Mars Climate Modeling Center (MCMC) Legacy Mars Global Climate Model (GCM) tutorial. By the end of this section of the tutorial, you will have a basic understanding of the main components and structure of the GCM.

The GCM presented here is extensively documented in Haberle et al. (2019) for your reference.

Outline: GCM Overview

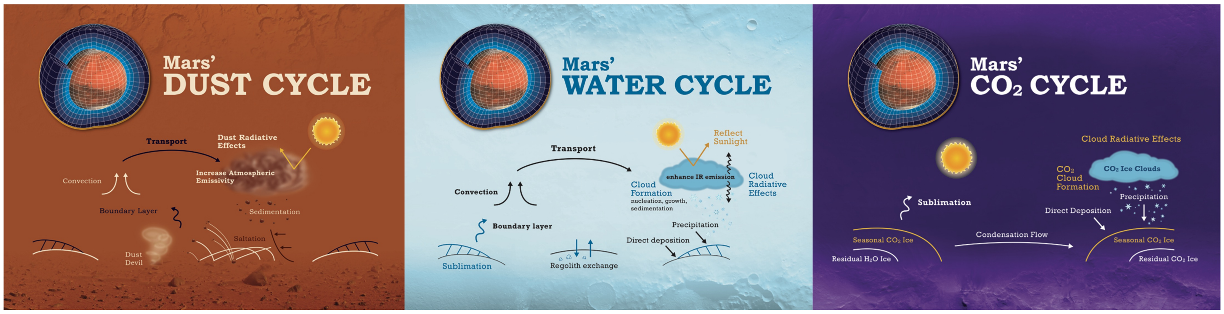
---

1. What is a GCM?

A GCM is a discretized numerical model of a planet's atmosphere that advances through time by solving a set of equations to conserve momentum, mass, and energy. GCMs can generally be divided into two parts based on a slightly rearranged version of Newton's second law:

$$\frac{f}{m} = a$$

- PART 1: The model **geophysical fluid dynamics**, which represent accelerations (a).
  - Adiabatic processes, computed in the dynamical core
- PART 2: The model **physics**, which provide the forcing functions for the circulation $\left(\frac{f}{m}\right)$.
  - Diabatic processes, computed in the physics routines
  - For Mars, it is critical to realistically represent the radiative effects of atmospheric dust and clouds



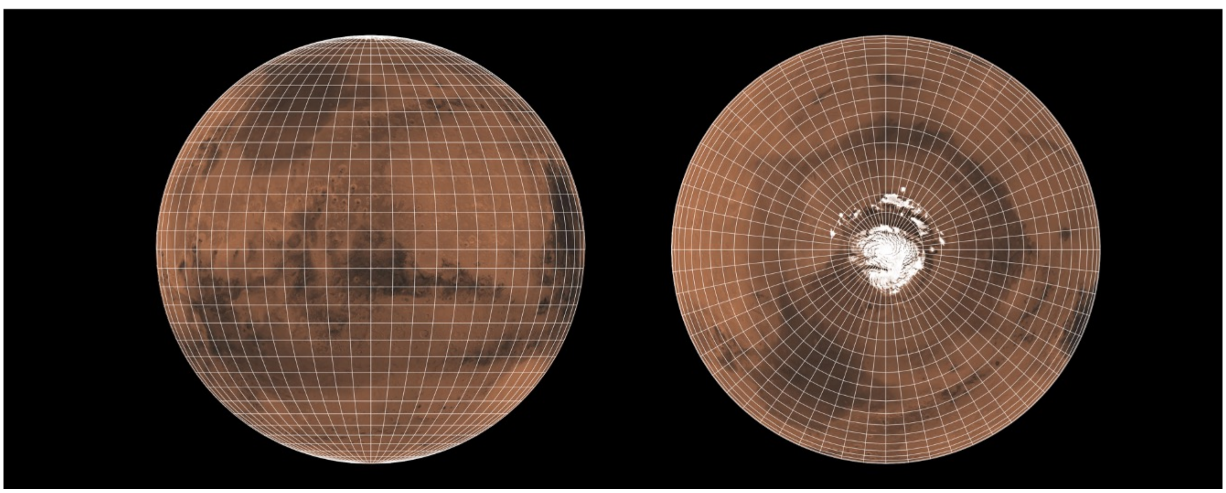
Model Physics: The Dust, Water, and CO_2 cycles on Mars.

---

2. Dynamical Core (DYCORE)

Overview:

- The Legacy GCM utilizes the NASA GSFC ARIES/GEOS dynamical core (Suarez and Takacs, 1995)
- Tracer transport is based on the Van Leer I scheme (Hourdin and Armengaud, 1998)



GCM Latitude-Longitude Horizontal Grid

Purpose:

- Computes pressure, wind, potential temperature, and tracer tendencies every dynamical timestep (~2 minutes).

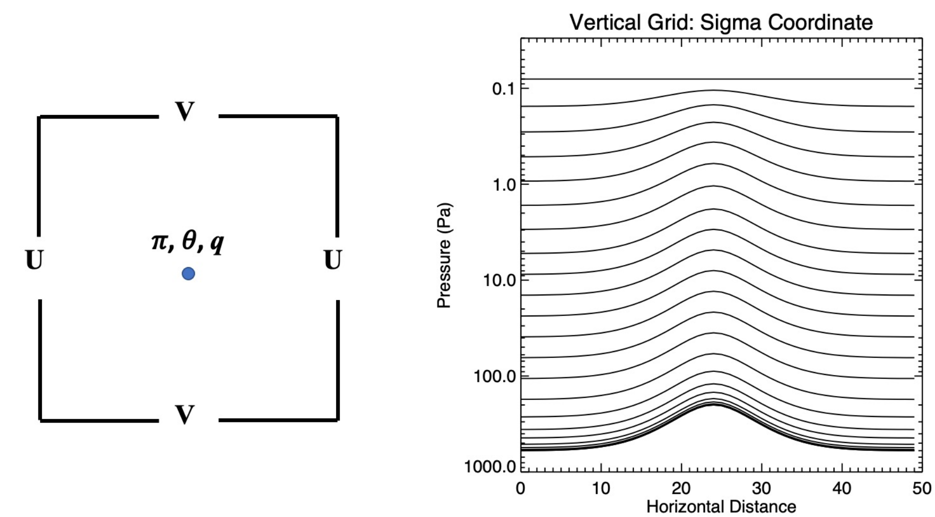
Methodology:

- Solves the **primitive equations of meteorology** in spherical coordinates using finite differences (Holton and Hakim, 2013):
  - Momentum equations in U and V
  - Continuity equation
  - Hydrostatic equation

- Thermodynamic energy equation

- **Tracer transport** is based on the flux form of the **continuity and advection equations**
  - Estimate distribution of tracer mixing ratio in each grid-box with a slope
  - Allows for transport across more than one grid in one timestep in the zonal direction only

- Grid Structure
  - Horizontal: **Arakawa C-Grid** (Staggered U and V winds)
    - Nominal Resolution: 5^{o} latitude by 6^{o} longitude
  - Vertical: **Sigma (terrain-following) coordinate**
    - Nominally 24 layers
    - Nominal model top at **~80 km**



Horizontal Arakawaka C-Grid (left) and Vertical Sigma Coordinate Grid (right)

Notes:

- Designed to **conserve energy and enstrophy**
- **Second-order accuracy** for all terms, except **fourth-order accuracy for vorticity advection**
- Dry dynamics only

References:

- Suarez and Takacs, 1995
- Hourdin and Armengaud, 1998

3. Physics: Summary of Processes

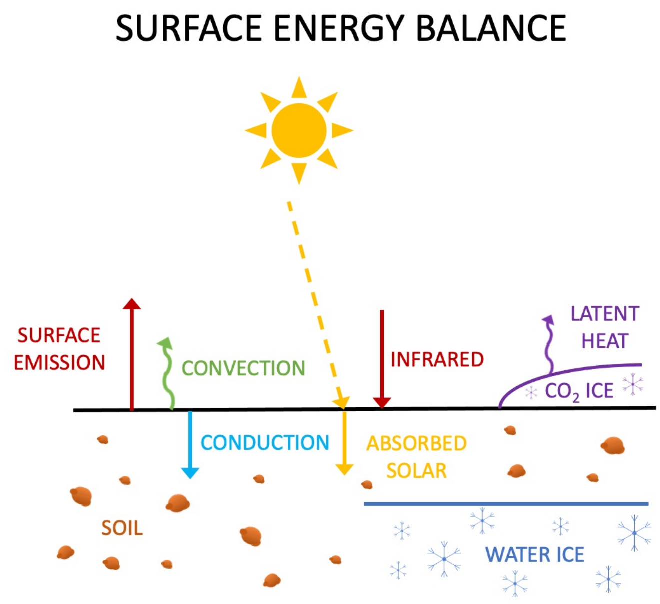
No	Process	Primary Subroutine(s)	Timestep
1	Surface CO_2, Surface and Sub-Surface Temperatures	TEMPGR	Dynamical (~2 min)
2	Radiative Heating and Cooling	OPTCV, OPTCI, SFLUXV, SFLUXI	Physical (~16 min)
3	Atmospheric CO_2 Condensation	COLDAIR	Physical (~16 min)
4	Planetary Boundary Layer	NEWPBL	Physical (~16 min)
5	Convective Adjustment to Ensure Stability	CONVECT	Physical (~16 min)
6	Atmospheric Dust Distribution	FILLTAUCUM, MICROPHYS	Physical (~16 min)
7	Dust and Cloud Microphysics	MICROPHYS	Physical (~16 min)
8	Rayleigh Friction	computed in COMP3	Physical (~16 min)

- Subroutines are called from COMP3

3.1 Physics: TEMPGR

Purpose:

- Solve surface energy balance equation to calculate surface temperature
- Compute rate of CO_2 condensation at the surface
- Compute subsurface temperatures



Surface Temperature (Energy Balance):

$$\epsilon_G \sigma T_G^4 - F_{IR}^{\downarrow} - (1 - A)\, F_s + F_{conv} + F_{cond} = 0.$$

- Where:

Parameter	Meaning	Units
T_G	Ground Temperature	K
ϵ_G	Surface Emissivity	None
$F_{IR}^{\downarrow}$	Downward IR Flux at the Surface	W m^{-2}
$(1 - A)\, F_s$	Absorbed Solar Flux at the Surface	W m^{-2}
F_{conv}	Upward Heat Exchange with the Atmosphere	W m^{-2}
F_{cond}	Downard Conduction into the Surface	W m^{-2}

- Solve for ground temperature (T_G) using the Newton-Raphson method

Surface CO_2 Condensation:

- Compute CO_2 condensation temperature, $T_{\mathrm{CO_2}}$:

$$T_{CO_2} = \frac{3192.48}{23.349 - \ln(p_s)}$$

- Hold T_G at T_{CO_2}, and use surface energy balance and latent heat of condensation of CO_2, L, to compute rate of CO_2 condensation/sublimation, $\frac{\partial M_{CO_2}}{\partial t}$:

$$\frac{\partial M_{CO_2}}{\partial t} = \frac{\epsilon_G \sigma T_{CO_2}^4 - F_{IR}^{\downarrow} - (1-A) F_s + F_{conv} + F_{cond}}{L}$$

- Where:

Parameter	Meaning	Units
L	CO_2 Latent Heat of Condensation	J kg^{-1}

Subsurface Temperatures (Diffusion Equation):

$$\frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z}\left(\frac{J}{\rho_s c_s}\right) = \frac{\partial^2}{\partial z^2}\left(\frac{T\lambda_s}{\rho_s c_s}\right)$$

- Where:

Parameter	Meaning	Units
T_s	Soil Temperature	K
J	Conductive Heat Flux	W m^{-2}
ρ_s	Soil/Ice Density	kg m^{-3}
c_s	Soil/Ice Specific Heat	J kg^{-1} K^{-1}
λ_s	Soil Conductivity	W m^{-1} K^{-1}

- Simple one- or two-component soil model
    - Water ice under soil at high latitudes
- 40 subsurface layers; extends down to ~100 meters
- Solved explicitly with a zero flux bottom boundary condition

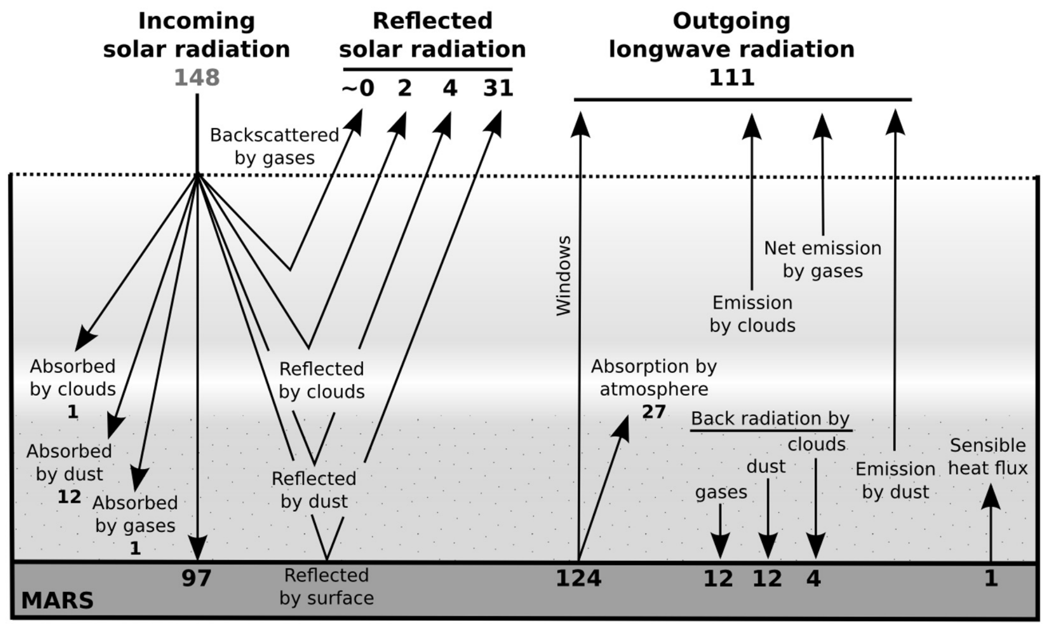
References

- Haberle and Jakosky, 1991
- Haberle et al. 1999

3.2 Physics: Radiation Code

Purpose:

- Compute solar and infrared heating rates (K s^{-1})



From Wolff et al. 2017

Method:

- Compute heating rates from flux divergences
- Compute fluxes from 2-stream code (needs opacities and scattering properties)

Radiatively active species: CO_2, H_2O, aerosols (dust and ice)

Opacities:

- Correlated k's for gases (CO_2/H_2O)
- Extinction efficiencies for dust and ice

Scattering properties:

- Rayleigh scattering for CO_2
- Aerosol scattering properties are functions of size and amount of ice.
  - We use a core/mantle Mie code to generate a lookup table.
  - Refractive indices from Wolff (2009) for dust and Warren (1984) for ice.

Spectral resolution: 7 bands in visible (0.4-4.5 μm), 5 bands in IR (4.5-1000 μm)

No	GCM Band	Wavelength Interval (μm)	Wavenumber Interval (cm^{-1})

No	GCM Band	Wavelength Interval (μm)	Wavenumber Interval (cm^{-1})
1	Vis-7	0.24-0.40	41666.7 - 25000.0
2	Vis-6	0.40-0.80	25000.0 - 12500.0
3	Vis-5	0.80-1.31	12500.0 - 7633.59
4	Vis-4	1.31-1.86	7633.59 - 5376.34
5	Vis-3	1.86-2.48	5376.34 - 4032.26
6	Vis-2	2.48-3.24	4032.26 - 3086.42
7	Vis-1	3.24-4.50	3086.42 - 2222.22
8	IR-5	4.50-8.00	2222.22 - 1250.00
9	IR-4	8.00-12.0	1250.00 - 833.33
10	IR-3	12.0-24.0	833.33 - 416.67
11	IR-2	24.0-60.0	416.67 - 166.67
12	IR-1	60.0-1000	166.67 - 10.0

Main Routines Involved:

- OPTCV(I): sets optical properties
- SFLUXV(I): sums fluxes over spectral intervals
- GFLUXV(I): gets fluxes by solving a tri-diagonal matrix

Other routines involved:

- FILLPT: readies p,T fields for radiation routines
- OPT_DST & OPT_CLD: integrate over size bins to get the scattering properties

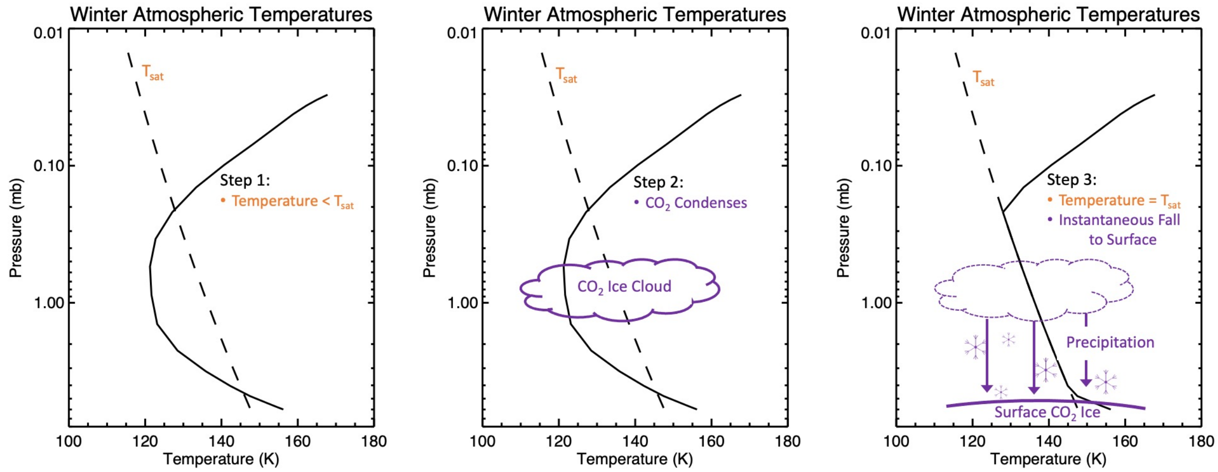
References

- Toon et al. 1989
- Haberle et al. 2019

3.3 Physics: COLDAIR

Purpose:

- Compute atmospheric CO_2 condensation



Methodology:

- Diagnose layers that have temperatures less than CO_2 condensation temperature:

$$T_{\mathrm{CO_2}} = \frac{3192.48}{23.349 - \ln{(p_l)}}$$

- In these layers, compute amount of CO_2, $\delta \mathrm{M}_{\mathrm{CO_2}}$, that needs to condense to maintain $T_{\mathrm{CO_2}}$:

$$\delta M_{\mathrm{CO_2},l} = \frac{100 * C_p \left(T_{\mathrm{CO_2}} - T_l\right) \delta \sigma_l \pi}{gL}$$

- Where:

Parameter	Meaning	Units
p_l	Pressure of Layer l	mbars
C_p	Specific Heat of Air	J kg^{-1} K^{-1}
T_l	Temperature of Layer l	K
$\delta \sigma_l$	Thickness of Layer l in σ coordinates	None
π	$= p_s - p_{trop}$	mbars

Parameter	Meaning	Units
p_s	Surface Pressure	mbars
p_{trop}	Pressure at the Top of the Dynamical Domain (Tropopause Pressure)	mbars
g	Gravity	m s^{-2}
L	CO_2 Latent Heat of Condensation	J kg^{-1}

- Sum $\delta M_{\mathrm{CO_2}}$ through the column and add to the surface CO_2 budget
- If $T_g > T_{\mathrm{CO_2}}$, calculate the amount of CO_2 that will remain on surface as T_g cools to $T_{\mathrm{CO_2}}$

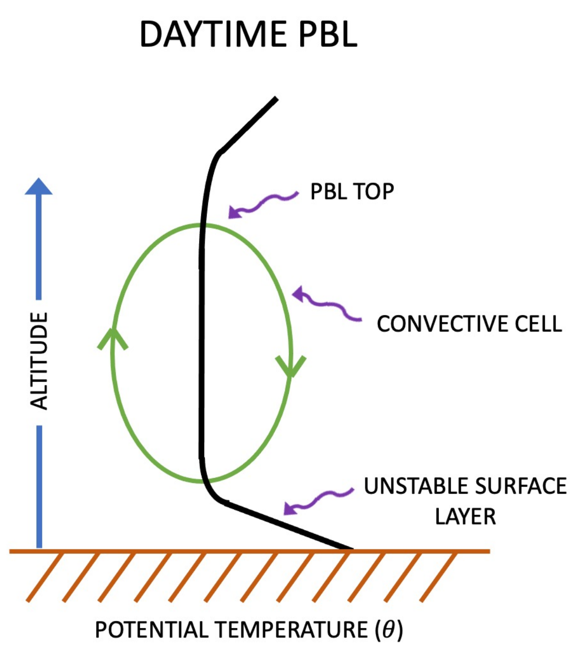
Reference

- Pollack et al. 1990

3.4 Physics: NEWPBL

Purpose:

- Compute the upward surface turbulent fluxes of heat, momentum, and mass (tracers)
- Vertically mix these in the atmosphere



Basic Physics:

- Surface fluxes calculated from Monin-Obukhov theory (drag laws)
- For example, the heat flux (F_{conv}) is:

$$F_{conv} = -\rho c_p c_h u_* \left(T_a - T_g\right)$$

- Where:

Parameter	Meaning	Units
F_{conv}	Heat Flux	W m^{-2}
ρ	Near-Surface Air Density	kg m^{-3}
c_p	Air Specific Heat	J kg^{-1} K^{-1}
c_h	Heat Drag Coefficient	None
u_*	Frictional Wind Speed	m s^{-1}
T_a	Near-Surface Air Temperature	K
T_g	Ground Temperature	K

- Mixing coefficients are functions of the local Richardson number and are based the Mellor and Yamada (1982) Level 2 scheme
- The Richardson number, R_i is given by:

$$R_i = \frac{\frac{g}{\theta}\frac{\partial \theta}{\partial z}}{\left(\frac{\partial V}{\partial z}\right)^2}$$

- Where:

Parameter	Meaning	Units
g	Gravity	m s^{-2}
θ	Potential Temperature	K
V	Wind Speed	m s^{-1}
z	Altitude	m

Methodology:

- Solves a diffusion equation with an arbitrary vertical co-ordinate
- Scheme can be implicit or explicit (we always run with the implicit option)

Notes:

- Does not completely eliminate instabilities (i.e., it is not a convective adjustment scheme)
- Mixing effectively shuts off when $R_i > 0.25$
- Water vapor tracer is mixed in NEWPBL with the heat coefficients; other tracers are mixed in the sedimentation routine.

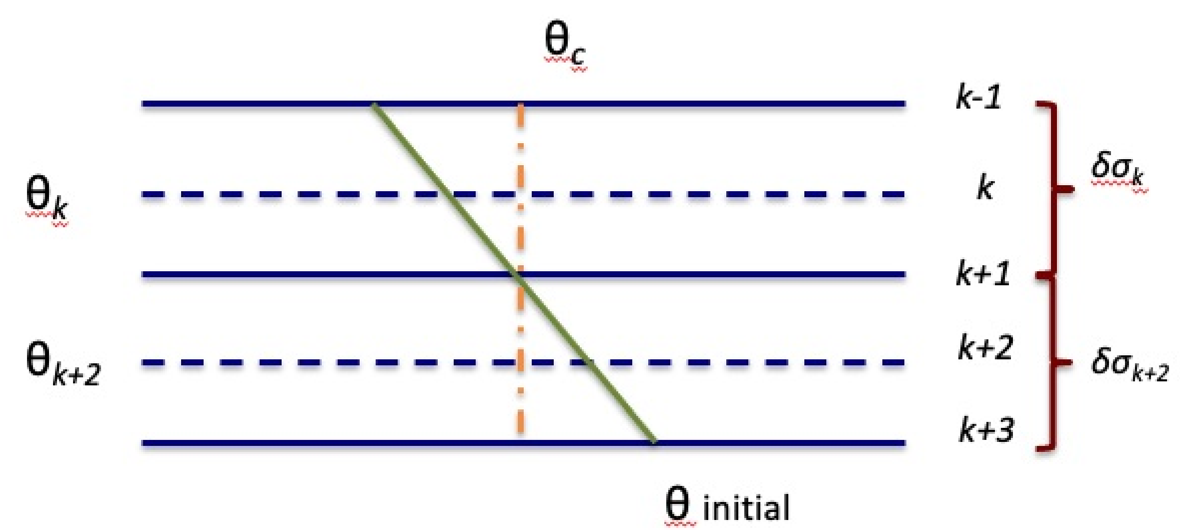
References:

- Haberle et al. 1993
- Haberle et al. 1999

3.5 Physics: CONVECT

Purpose:

- Remove any remaining superadiabatic atmospheric layers after NEWPBL.
- Determine the potential temperature within the convective layer (θ_c).
- Determine the pressure of the top of the convective layer that exists above the surface (i.e., pressure at the top of the boundary layer, p_c).



Method:

- Stabilize regions where potential temperature decreases with height by conserving the total heat energy.

$$\theta_c = \frac{(p_k)^{\kappa}\delta\sigma_k\theta_k + (p_{k+2})^{\kappa}\delta\sigma_{k+2}\theta_{k+2}}{(p_k)^{\kappa}\delta\sigma_k + (p_{k+2})^{\kappa}\delta\sigma_{k+2}}$$

- Where:

Parameter	Meaning	Units
p	Pressure	mbars

Parameter	Meaning	Units
$\delta\sigma$	Layer Thickness in σ Coordinates	None
θ	Potential Temperature	K
κ	$\frac{R_{gas}}{c_p}$	None
R_{gas}	Gas Constant for CO_2	J kg^{-1} K^{-1}
c_p	Specific Heat	J kg^{-1} K^{-1}

- Instantaneously mix all tracers in unstable regions.

References:

- Pollack et al. 1990
- Pollack et al. 1981

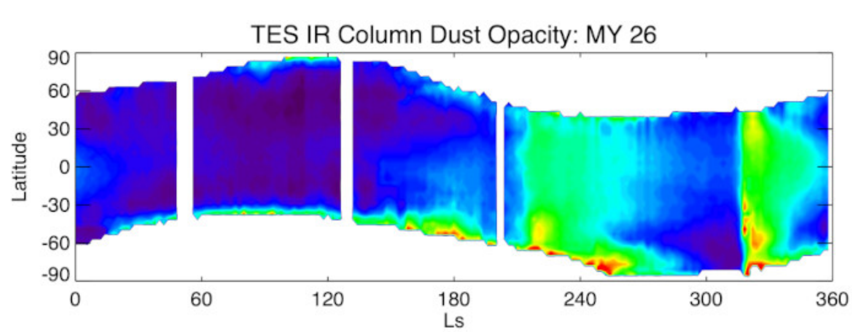
3.6 Physics: Atmospheric Dust Distribution

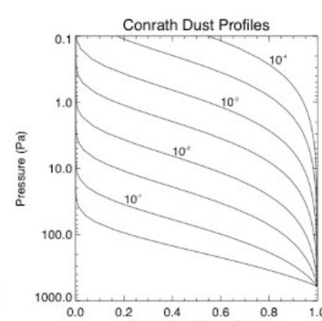
Purpose:

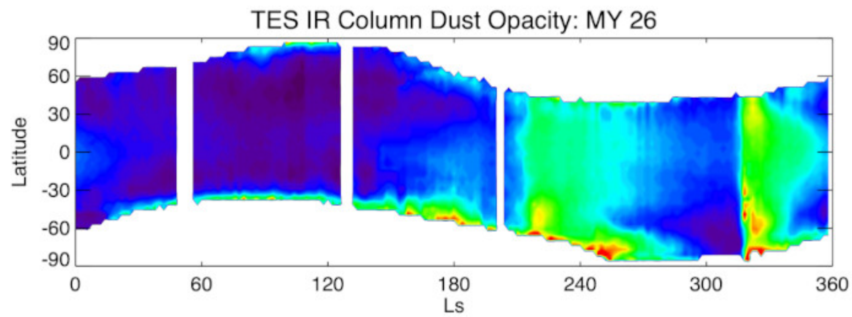
- Provide multiple options for determining the atmospheric dust distribution
- Hierarchy of dust treatment options, from simple to complex
- Important for including the radiative forcing from dust

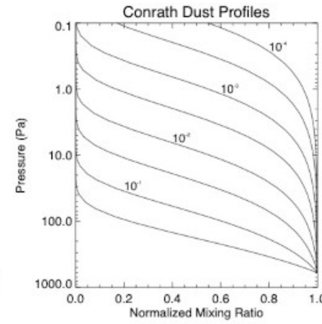
Methods

- **Option 1: Fully Prescribed**
  - Horizontal: Globally constant or based on an observation-based dust opacity map
  - Vertical: Prescribed using Conrath profiles or similar (Conrath, 1975)
  - Lifting: NONE

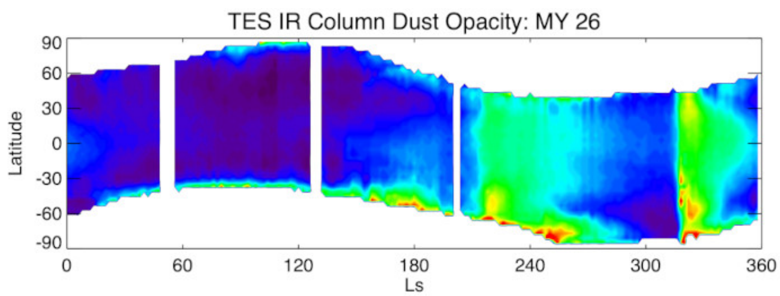


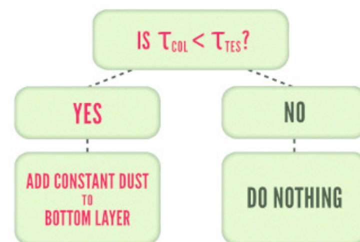




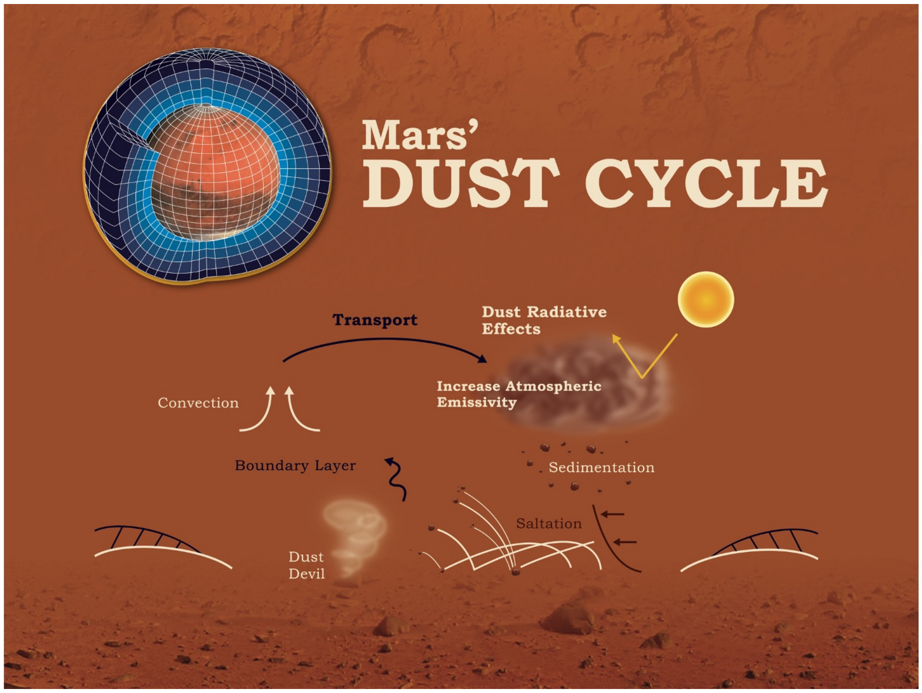


- **Option 2: Semi-Prescribed (Tracking)**
  - Horizontal: Based on a observation-based dust opacity map
  - Vertical: Self-consistenly determined from transported dust tracers
  - Lifting: As needed to track desired horizontal distribution (usually a map)





- **Option 3: Fully Interactive**
  - Horizontal: Self-consistently determined by predicted lifting and transport
  - Vertical: Self-consistenly determined from transported dust tracers
  - Lifting: Based on physical dust lifting parameterizations (usually wind stress and dust devils)



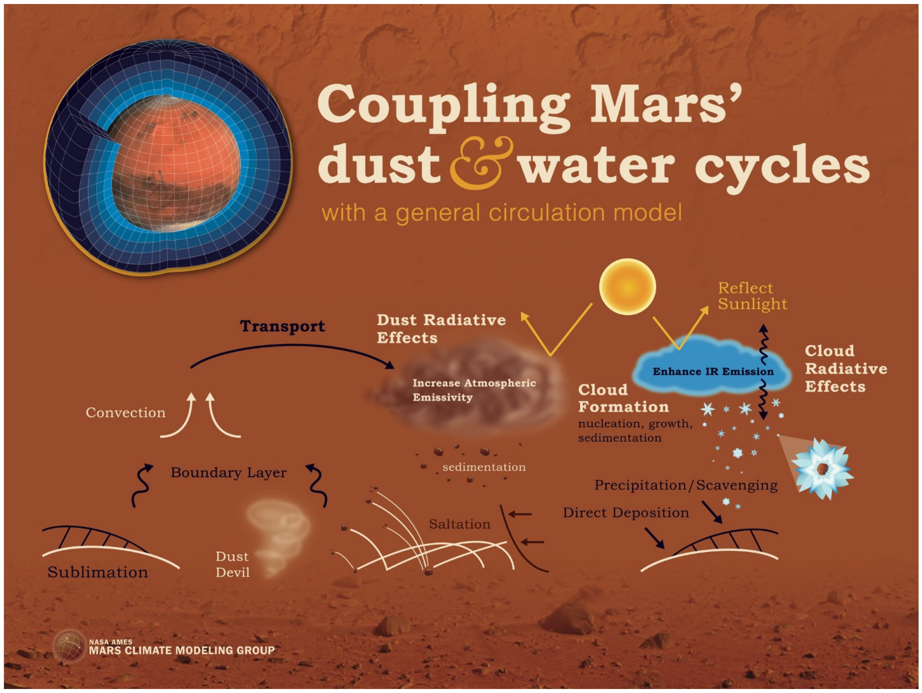
References:

- Haberle et al. 2019
- Kahre et al. 2015

3.7 Physics: MICROPHYS

Purpose:

- Compute dust injection, aerosol sedimentation, and cloud nucleation and growth



Basic Physics:

- Multiple dust injection methods, including dust tracking, dust devil lifting and wind stress lifting
- Cunningham-Stokes gravitational sedimentation
- Cloud nucleation and growth as described in Haberle et al. (2019) and Montmessin et al. (2002/2004)
- Transported dust and clouds are optionally radiatively active

Methodology:

Moment Method

- Assume particle size distribution is log-normal

$$n\left(r\right) = \frac{N_o}{r\sigma_o\sqrt{2\pi}} \exp\left[\frac{1}{2}\left(\frac{\ln(r/r_o)^2}{\sigma_o}\right)\right]$$

- Where:

Parameter	Meaning	Units
$n\left(r\right)$	Number of Particles of Radius r	# per unit volume per unit radius
N_o	Total Number of Particles	# per unit volume
r_o	Median Radius	m

Parameter	Meaning	Units
σ_o	Standard Deviation	none

- It follows that the total number of particles between $r_{\min}$ and $r_{\max}$ is:

$$N = \int_{r_{min}}^{r_{max}} n\left(r\right)dr = \frac{N_o}{2}\left[\mathrm{erf}\left(\frac{\ln\left(r_{max}/r_o\right)}{\sqrt{2\pi\sigma_o}}\right) - \mathrm{erf}\left(\frac{\ln\left(r_{min}/r_o\right)}{\sqrt{2\pi\sigma_o}}\right)\right]$$

- Separately, the total mass of the distribution (M_o) can be calculated from r_o:

$$M_o = \frac{4}{3}\pi\rho\int r^3 n\left(r\right) = \frac{4}{3}\pi\rho N_o r_o^3 \exp\left(\frac{9}{2}\sigma_o^2\right)$$

- Solving for r_o:

$$r_o = \left[\frac{3M_o}{4\pi\rho N_o}\right]^{1/3}\exp\left(-\frac{3}{2}\sigma_o^2\right)$$

- Thus, the distribution can be fully represented by M_o, N_o, and σ_o
- We assume σ_o is a constant, so only M_o and N_o are carried as tracers.
- Taking further advantage of the properties of log-normal distributions, many representative particle radii can be calculated

Process	Symbol	Formula
Nucleation	r_o	$\left(\frac{3M_o}{4\pi\rho N_o}\right)^{1/3}\exp\left(-1.5\sigma_o^2\right)$
Growth	r_v	$r_o\exp\left(1.5\sigma_o^2\right)$
Mass Sedimentation	$r_{sed,m}$	$r_o\exp\left(4.5\sigma_o^2\right)$
Number Sedimentation	$r_{sed,n}$	$r_o\exp\left(1.5\sigma_o^2\right)$
Opacity (total cross-section)	r_s	$r_o\exp\left(\sigma_o^2\right)$
Scattering properties	r_{eff}	$r_o\exp\left(2.5\sigma_o^2\right)$

- We use the most appropriate representative radius for each physical process

Tracers

- The GCM carries an array (`QTRACE`) with 6 atmospheric tracers:

Tracer	Units	Array Index	Index Name
Dust Mass	kg kg^{-1}	1	ima_dt
Dust Number	# kg^{-1}	2	inb_dt
Water Cloud Mass	kg kg^{-1}	3	ima_cld
Water Cloud Number	# kg^{-1}	4	inb_cld
Dust Core Mass	kg kg^{-1}	5	ima_cor
Water Vapor Mass	kg kg^{-1}	6	ima_vap

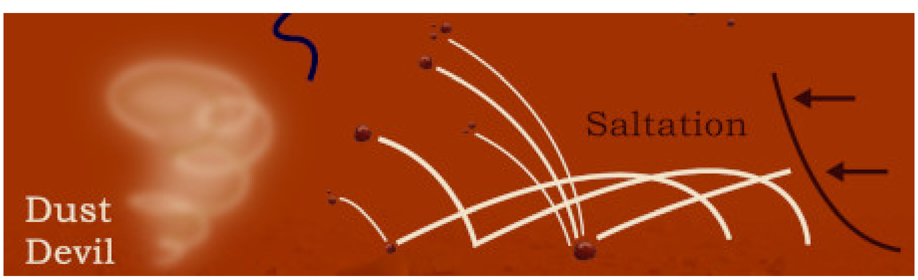
- An array of 6 surface tracers (`QCOND`) is also carried, but some indices are empty:

Tracer	Units	Array Index	Index Name
Dust Mass Deposited	kg m^{-2}	1	ima_dt
EMPTY	N/A	2	N/A
Water Cloud Mass Deposited	kg m^{-2}	3	ima_cld
EMPTY	N/A	4	N/A
Dust Core Mass Deposited	kg m^{-2}	5	ima_cor
Water Mass Reservoir	kg m^{-2}	6	ima_vap

Processes

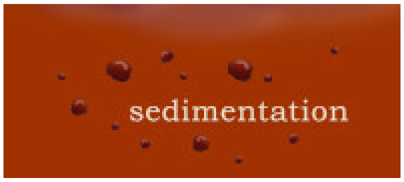
Dust Injection: **DUST_UPDATE**

- Computes flux of dust from the surface to the atmosphere
- Assumes a log-normal distribution with r_{eff} = 2.0 μm
- Adds to mass and number moments for dust



Sedimentation: **SEDIM**

- Uses mass and number weighted mean radii of dust and cloud particles
- Computes fall velocities for each type of particle
- Update column tracer arrays for all tracers (except H_2O vapor)



Cloud Nucleation and Growth: **NUCLEACOND**

- Nucleation:
    - Expands dust mass and number moments into bin
    - Computes nucleation rate for each bin
    - Sums over bins to compute total mass and number of nucleated dust particles
- Growth:
    - Compute volume mean radius for cloud particles
    - Computes growth rate and converts to cloud mass exchange
    - Updates cloud mass (and cloud number if cloud particles sublimate completely)

References:

- Haberle et al. 2019
- Montmessin et al. 2004
- Montmessin et al. 2002

3.8 Physics: Rayleigh Friction

Purpose:

- To damp waves as they approach the model top to minimize reflections from the top boundary

Method:

- Damp zonal (U) and meridional (V) winds with a rate of change that is proportional to their magnitude:

$$\frac{\partial U}{\partial t} = -\frac{U}{\tau} \tag{1}$$

$$\frac{\partial V}{\partial t} = -\frac{V}{\tau} \tag{2}$$

- where τ is a damping timescale (~1 day)
- Convert lost kinetic energy into heat and update potential temperature of affected layers
- Applied to the top 3 model layers
- Negligible effect on the lower atmosphere

Reference:

- Pollack et al. 1990

^

---

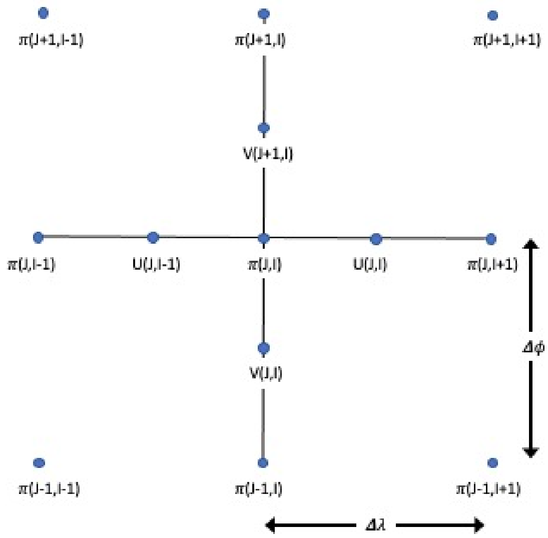
4. Horizontal Grid Structure

Horizontal: Latitude-Longitude Grid

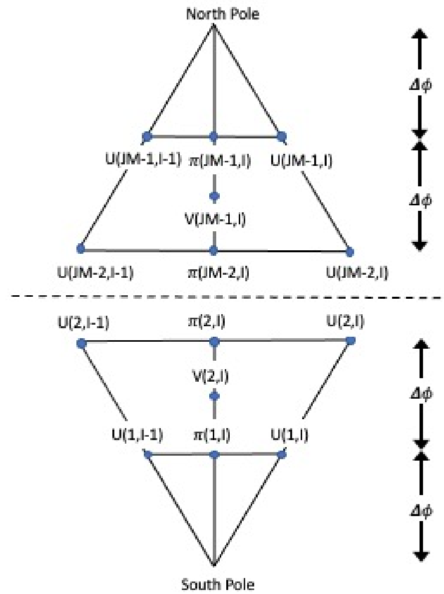
- Arakawa C-Grid Staggered Grid Structure
- Nominal horizontal resolution is 5^{o} latitude by 6^{o} longitude

> While it is possible to change the horizontal resolution, it is not straightforward. Please ask us about it before you try it!

- Modified pressure ($\pi = p - p_{trop}$, where p_{trop} is the tropopause pressure), potential temperature (θ), tracers (q) carried at grid mid-points
- Winds are carried at grid boundaries
  - Zonal winds (U) staggered E/W
  - Meridional winds (V) staggered N/S



INTERIOR



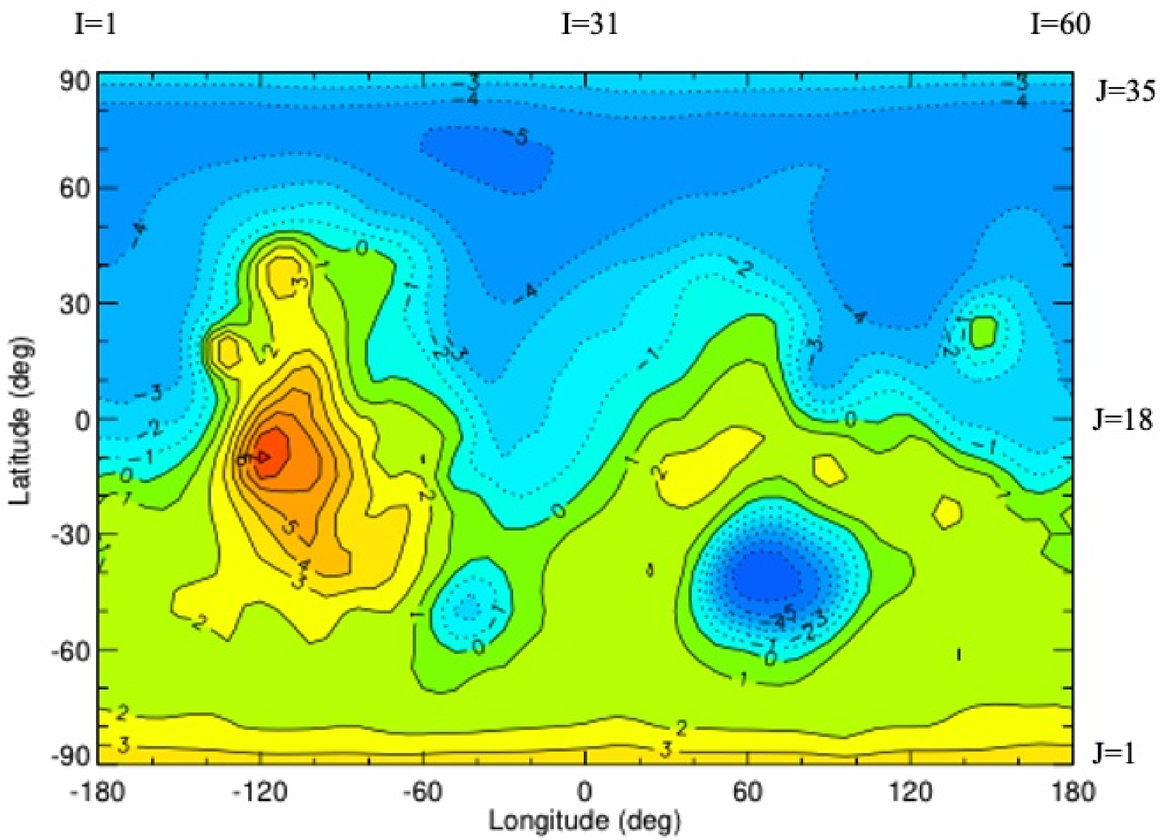
POLES

Latitude (ϕ_j): $\Delta\phi = \frac{180.0}{JM}$, where JM is the number of latitude grid points (nominally 36).

Equation	Range
$\phi_j(\pi, T) = -90.0 + \Delta\phi \cdot J$	$J = 1, JM - 1$
$\phi_j(U) = -90.0 + \Delta\phi \cdot J$	$J = 1, JM - 1$
$\phi_j(V) = (-90.0 + 1.5 \cdot \Delta\phi) + \Delta\phi \cdot (J - 2)$	$J = 2, JM - 1$

Longitude (λ_i): $\Delta\lambda = \frac{360.0}{IM}$, where IM is the number of longitude grid points (nominally 60).

Equation	Range
$\lambda_i(\pi, T) = -180.0 + \Delta\lambda \cdot (I - 1)$	$I = 1, IM$
$\lambda_i(U) = (-180.0 + 0.5 \cdot \Delta\lambda) + \Delta\lambda \cdot (I - 1)$	$I = 1, IM$
$\lambda_i(V) = -180.0 + \Delta\lambda \cdot (I - 1)$	$I = 1, IM$



5. Vertical Grid Structure

Sigma Coordinate (Terrain Following)

- Simplifies the handling of the lower boundary in the presence of topography.
- σ is defined by:

$$\sigma = \frac{(p - p_{trop})}{(p_s - p_{trop})}$$

- Where:

Parameter	Meaning	Units
p	Pressure	mbars
p_{trop}	Tropopause Pressure (Top of the Dynamical Domain; CONSTANT)	mbars
p_s	Surface Pressure	mbars

- The σ surfaces are fixed in a GCM simulation. Thus, the pressure at a given layer (l) at any time can be calculated: by:

$$p_l = (p_s - p_{trop}) \cdot \sigma_l + p_{trop}$$

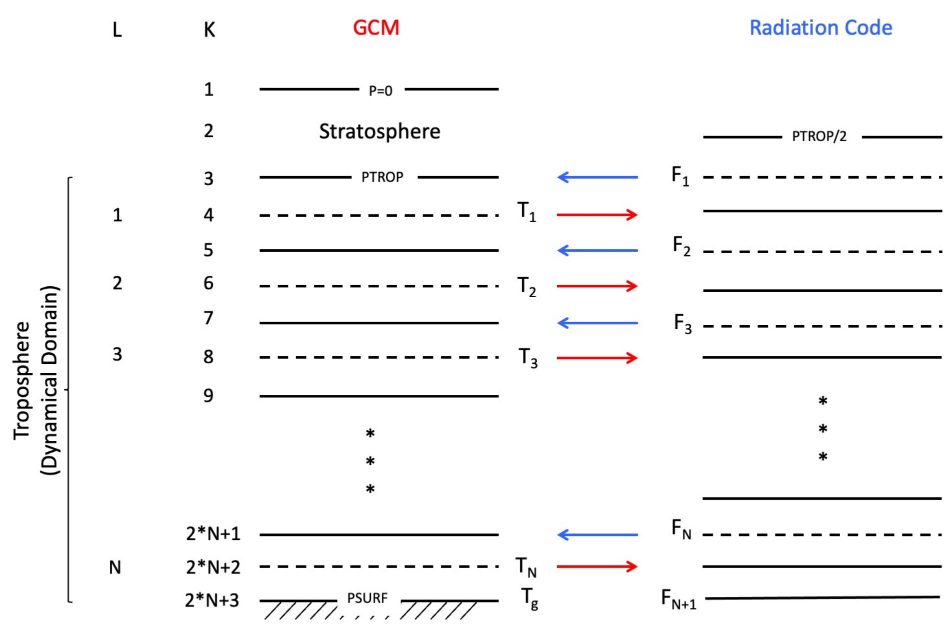
GCM Layering:

- N layers (nominally 24) in the vertical, with both midpoints and boundaries available for calculations
  - Vertical resolution ranging from: ~10 meters near the surface to ~10 kilometers aloft

  > While it is possible to change the vertical resolution, it is not straightforward. Please ask us about it before you try it!

Radiation Code Layering:

- N+1 layers
  - Layer midpoints line up with GCM layer boundaries
  - N+1 layer is a half-layer just above the surface, to simplify including the bottom temperature boundary condition.



---

6. Time Stepping (NEWSTEP)

Called every dynamical timestep (~2 min).

Purpose:

- Update all atmospheric fields (π, θ, U, V, QTRACE)
- Update surface tracer field (QCOND)
- Apply Robert time filter and Shapiro spatial filters (but not on QTRACE)

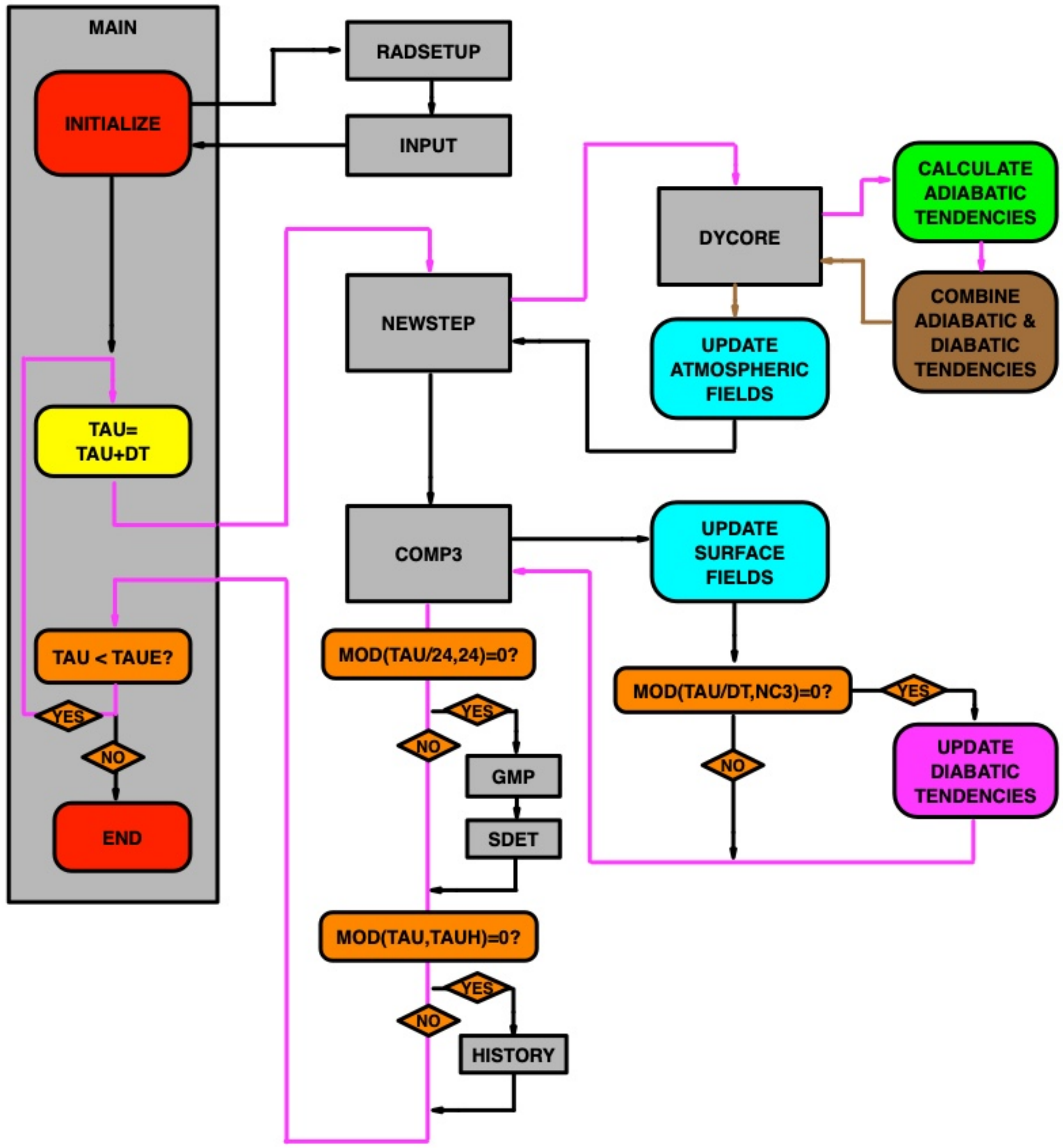
Method:

- Use leap frog scheme in combination with a Robert time filter (α = 0.05) to suppress computational mode.
- Note that potential temperature (θ) and tracers (q) are pressure-weighted, while the other fields are not.

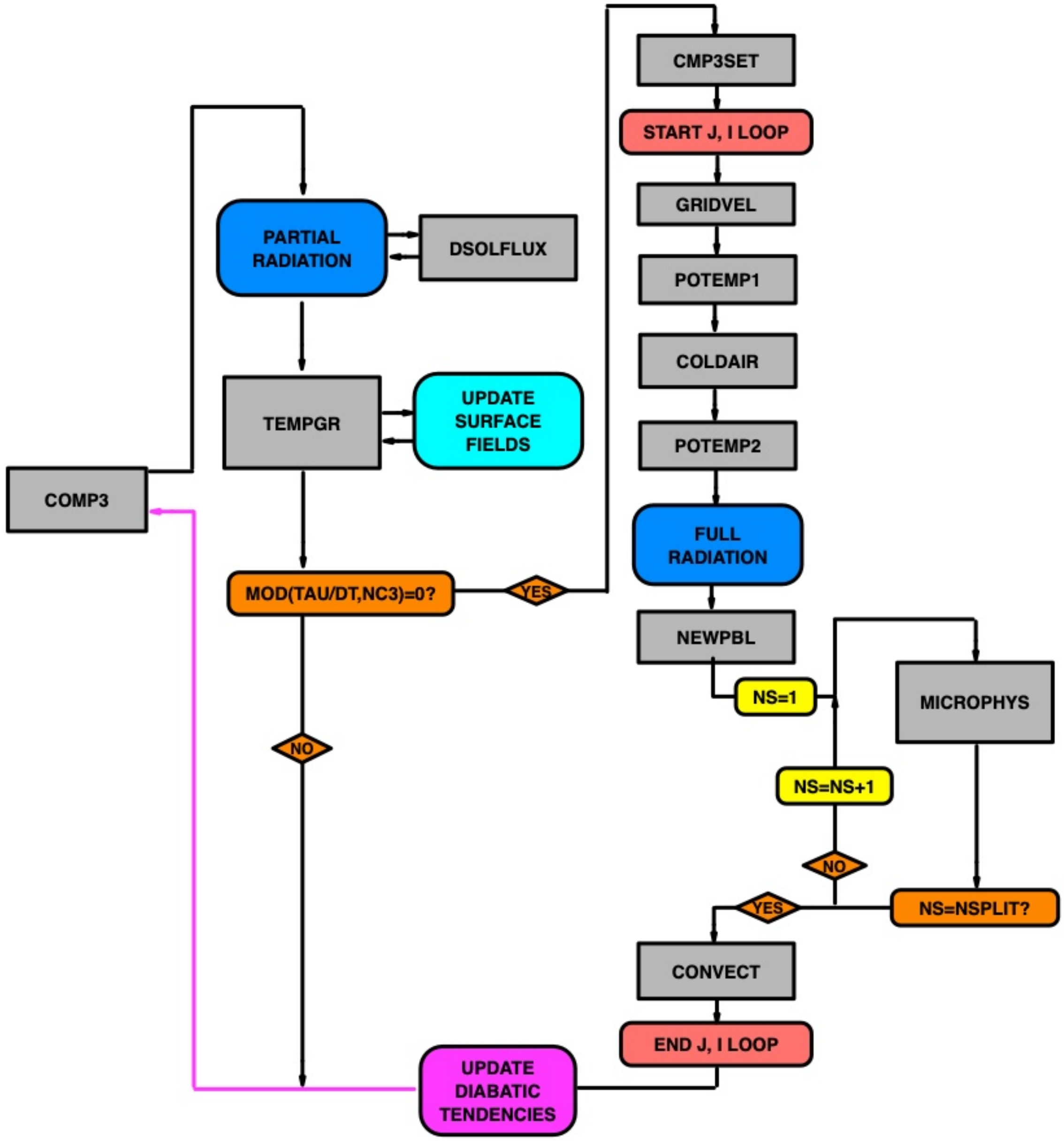
Field	Advance Fields to Future Timestep (t+1)	Filter Current Timestep (t)
Pressure	$\pi_{t-1} + \frac{\partial \pi}{\partial t} 2\mathrm{dt}$	$\alpha \frac{\pi_{t-1} + \pi_{t+1}}{2} + (1-\alpha)\,\pi_t$
Potential Temperature	$\frac{1}{\pi_{t+1}} \left[\pi_{t-1}\theta_{t-1} + \frac{\partial \pi\theta}{\partial t} 2\mathrm{dt} \right]$	$\frac{1}{\pi_t} \left[\alpha \frac{(\pi_{t-1}\theta_{t-1} + \pi_{t+1}\theta_{t+1})}{2} + (1-\alpha)\,\pi_t\theta_t \right]$
Zonal Wind	$u_{t-1} + \frac{\partial u}{\partial t} 2\mathrm{dt}$	$\alpha \frac{(u_{t-1} + u_{t+1})}{2} + (1-\alpha)\,u_t$
Meridional Wind	$v_{t-1} + \frac{\partial v}{\partial t} 2\mathrm{dt}$	$\alpha \frac{(v_{t-1} + v_{t+1})}{2} + (1-\alpha)\,v_t$
Tracers	$\frac{1}{\pi_{t+1}} \left[\pi_{t-1}q_{t-1} + \frac{\partial \pi q}{\partial t} 2\mathrm{dt} \right]$	$\frac{1}{\pi_t} \left[\alpha \frac{(\pi_{t-1}q_{t-1} + \pi_{t+1}q_{t+1})}{2} + (1-\alpha)\,\pi_t q_t \right]$
Surface Tracers	$qc_{t-1} + \frac{\partial qc}{\partial t} 2\mathrm{dt}$	$\alpha \frac{(qc_{t-1} + qc_{t+1})}{2} + (1-\alpha)\,qc_t$

7. Code Architecture

Full Code Architecture



Physics Code Architecture



This concludes the GCM Overview. Next we will cover more practical aspects of running the GCM!

```
In [ ]:
```