PHYSICS AND PHYSICS CONFIGURATIONS

Laura D. Fowler

Mesoscale and Microscale Meteorological Laboratory
National Center for Atmospheric Research, Boulder, Colorado. USA.

MPAS TUTORIAL (1th-3rd May 2023).

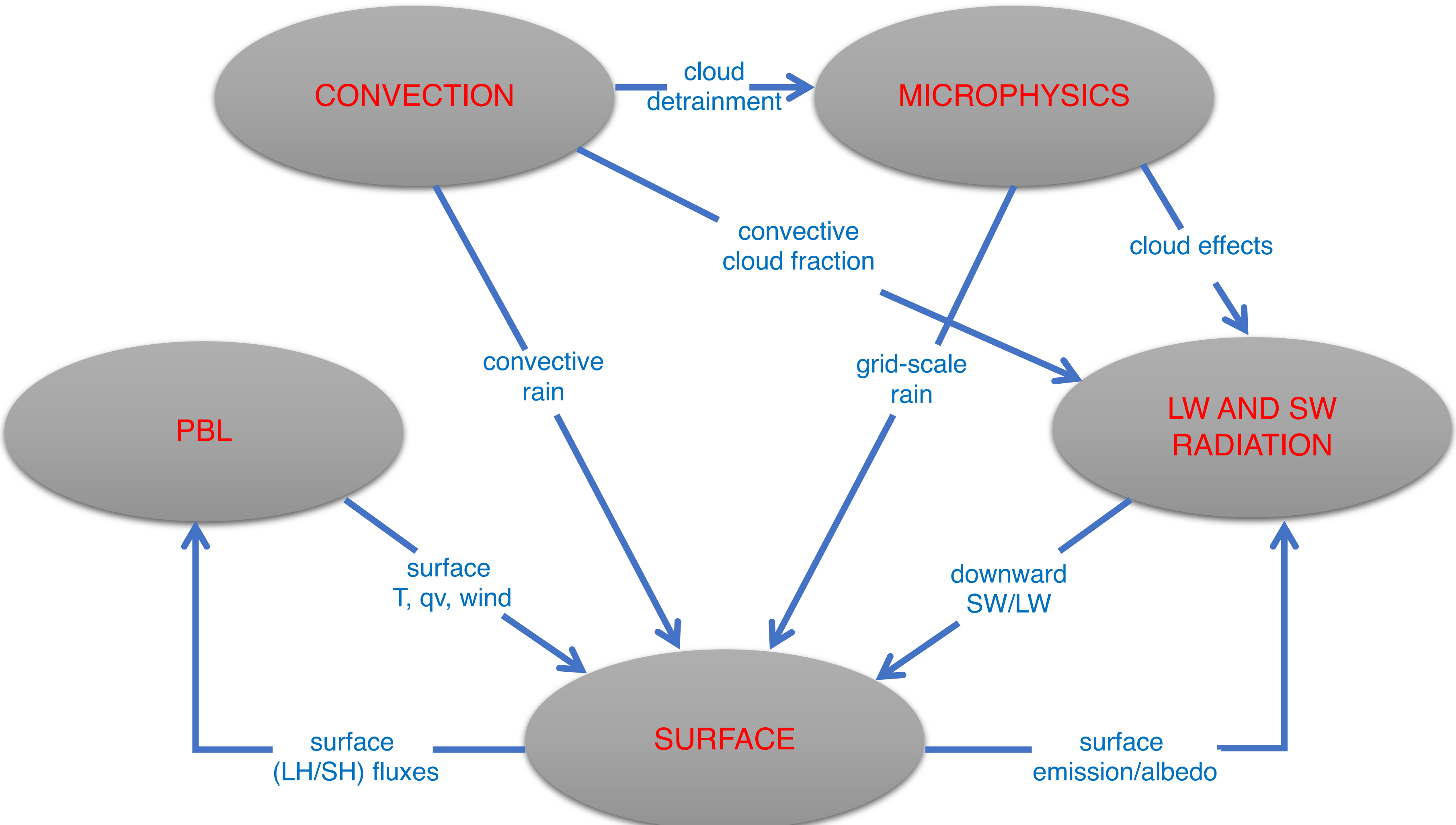
This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

OUTLINE

- Physics parameterizations and interactions between physics processes.
  - Radiation.
  - Convection.
  - Clouds and cloud microphysics.
  - Land surface and Planetary Boundary Layer (PBL) processes.
- Physics in MPAS.

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

PHYSICS - INTERACTIONS BETWEEN PHYSICS PROCESSES



LONG- AND SHORT-WAVE RADIATION PARAMETERIZATIONS

- Radiation is the ultimate driver of atmospheric circulations, because of its uneven global distribution at the Earth's surface and in the atmosphere (impact of solar insolation, land versus oceans).

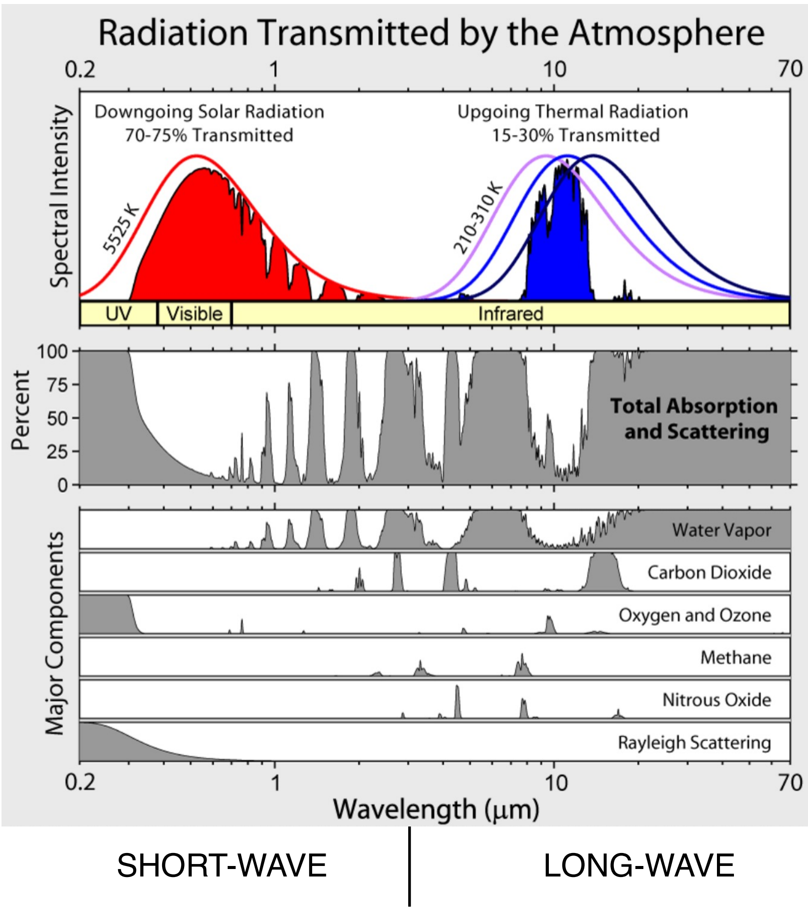
- Radiation parameterizations aim to provide a fast and accurate way to determine
  - the total radiative flux at the ground surface which is needed to compute the surface energy budget, and
  - the vertical radiative flux divergence which is used to compute the radiative heating and cooling rates in a given atmospheric column.

$$\boxed{\frac{\partial T}{\partial t} = \frac{1}{\rho C_p}\frac{\partial}{\partial z}(F_D - F_U)}$$

F_D: downward radiation flux

F_U: upward radiation flux

LONG- AND SHORT-WAVE RADIATION PARAMETERIZATIONS



SIMPLIFICATIONS

- The long- and short-wave portions of the radiation spectrum are distinct and can therefore be treated separately.
- Many of the gases (H2O, CO2, O2, O3) are active in specific wavelength bands, allowing to compute their absorption, emission, scattering separately.

METHODS

- Long- and short-wave radiation fluxes are computed in two steps: 1) for clear-sky fluxes; and 2) for all-sky fluxes to account for aerosols and clouds.
- Clouds and aerosols impact long- and short-wave radiation fluxes (cooling at cloud-tops, warming at cloud-base, aerosol scattering).

MOIST CONVECTION AND CONVECTION PROCESSES

- Moist convection is a difficult process to parameterize because it occurs in many shapes and sizes: for convenience, moist convection is often categorized as *deep* or *shallow* convection.

The chaotic complexity of convection is evident in this picture taken during field observations in the western tropical Pacific. Credit: Dave Raymond

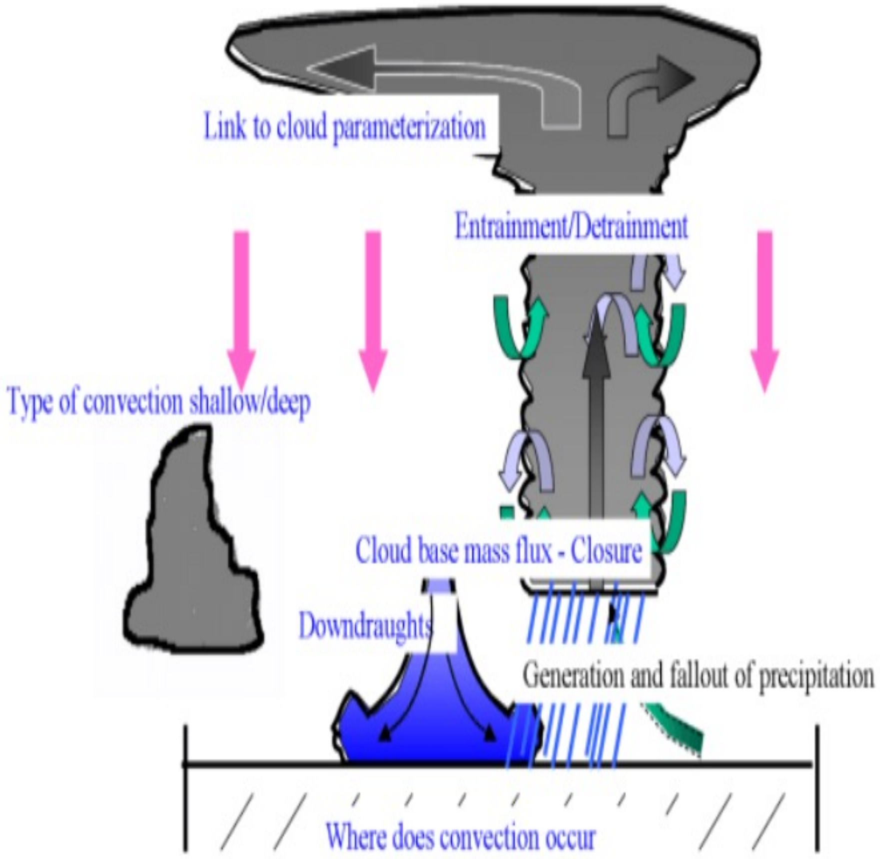
DEEP CONVECTION

- Characterized by strong precipitating updrafts that can span much of the troposphere.
- Characterized by extended anvils developing at the top of the narrow updrafts.
- Acts to warm and dry the environment through latent heat release.

SHALLOW CONVECTION

- Characterized by weak non-precipitating updrafts that can span a small portion of the troposphere.
- Detrainment and evaporation of cloud water at the top of the updrafts. Condensation at cloud base.
- Has a strong impact on surface radiation budget.

MOIST CONVECTION AND CONVECTION PROCESSES



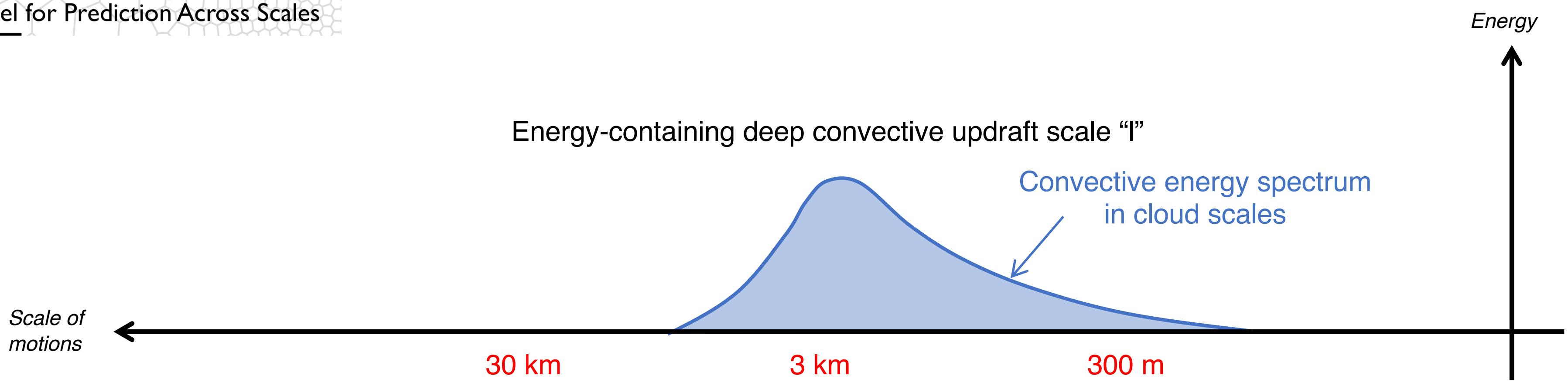
Schematic of a bulk convection scheme with a shallow and deep entraining/detraining cloudy ascending plume, and downdraught region. Further represented features are trigger of convection, environmental subsidence, microphysics and precipitation, and detrainment of cloud mass in anvils (Bechtold, 2017).

CONVECTIVE PARAMETERIZATIONS
MASS FLUX SCHEMES

- Triggering function that determines which atmospheric column is convectively unstable.
- Cloud model that describes moist processes in the updrafts (condensation and precipitation) and downdrafts (evaporation).
- Closure that determines the cloud base mass flux.
- Large-scale feedbacks.

MPAS
Model for Prediction Across Scales

MOIST CONVECTION AND CONVECTION PROCESSES



Convective Grey Zone

Δ >> l

Δ < l

For coarse grid spacing

- Cumulus parameterization schemes have been designed for Δ >> l
- All updrafts and downdrafts are sub-grid scales.
- 1d cloud model handles sub-grid vertical fluxes and precipitation.

For fine grid spacing

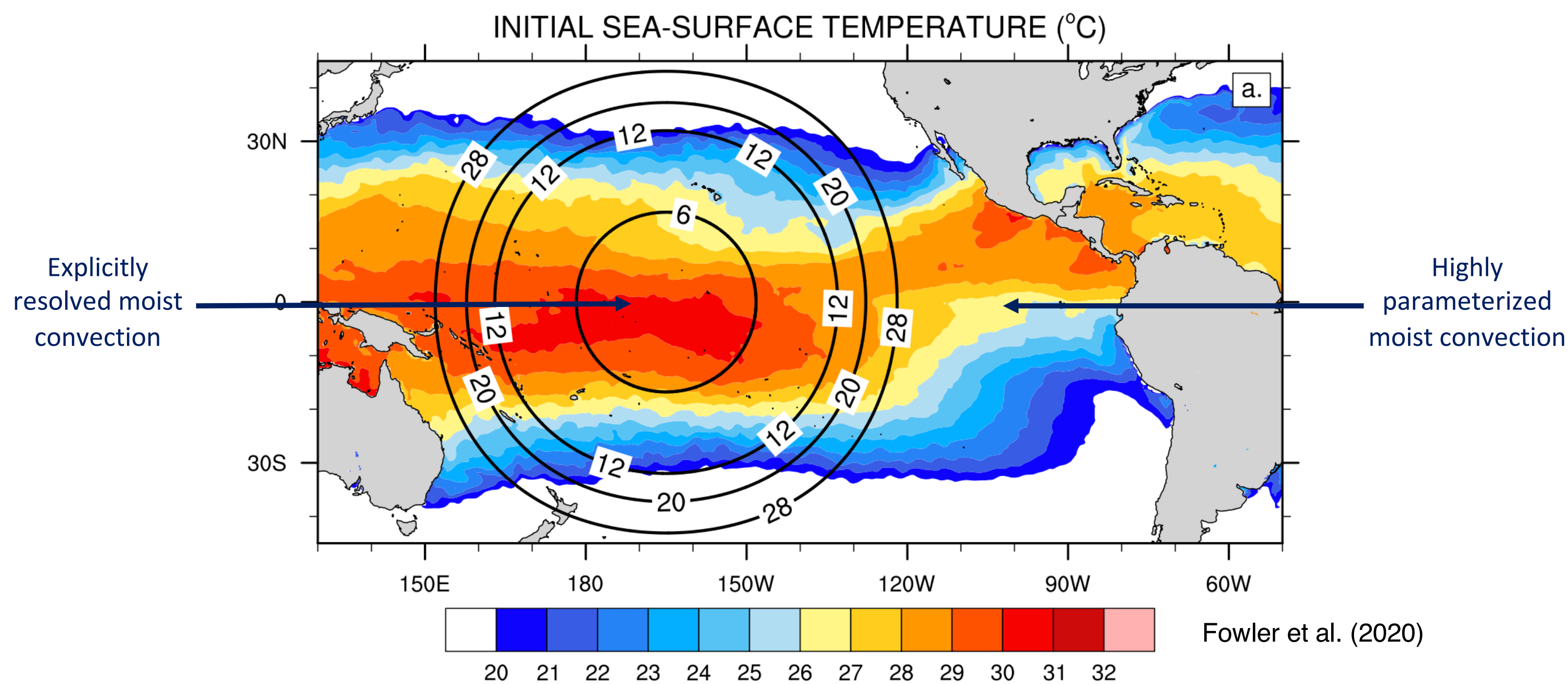
- Resolved dynamics and microphysics work for Δ << *l*
- *Updrafts and downdrafts are resolved*

Scale-aware parameterizations

MOIST CONVECTION AND CONVECTION PROCESSES

- Recent years have seen the development of *faster* supercomputers, and global NWP models to run on increasingly higher (convection-permitting) horizontal resolutions.
- MPAS variable-resolution meshes present a challenge for convective parameterizations tasked to represent the effects of subgrid-scale convective processes on the mesh, and developed for low-resolution horizontal meshes.

Example of a variable-resolution (50-3 km) mesh centered over the western Pacific Ocean
decreasing contribution of CP as horizontal resolution increases

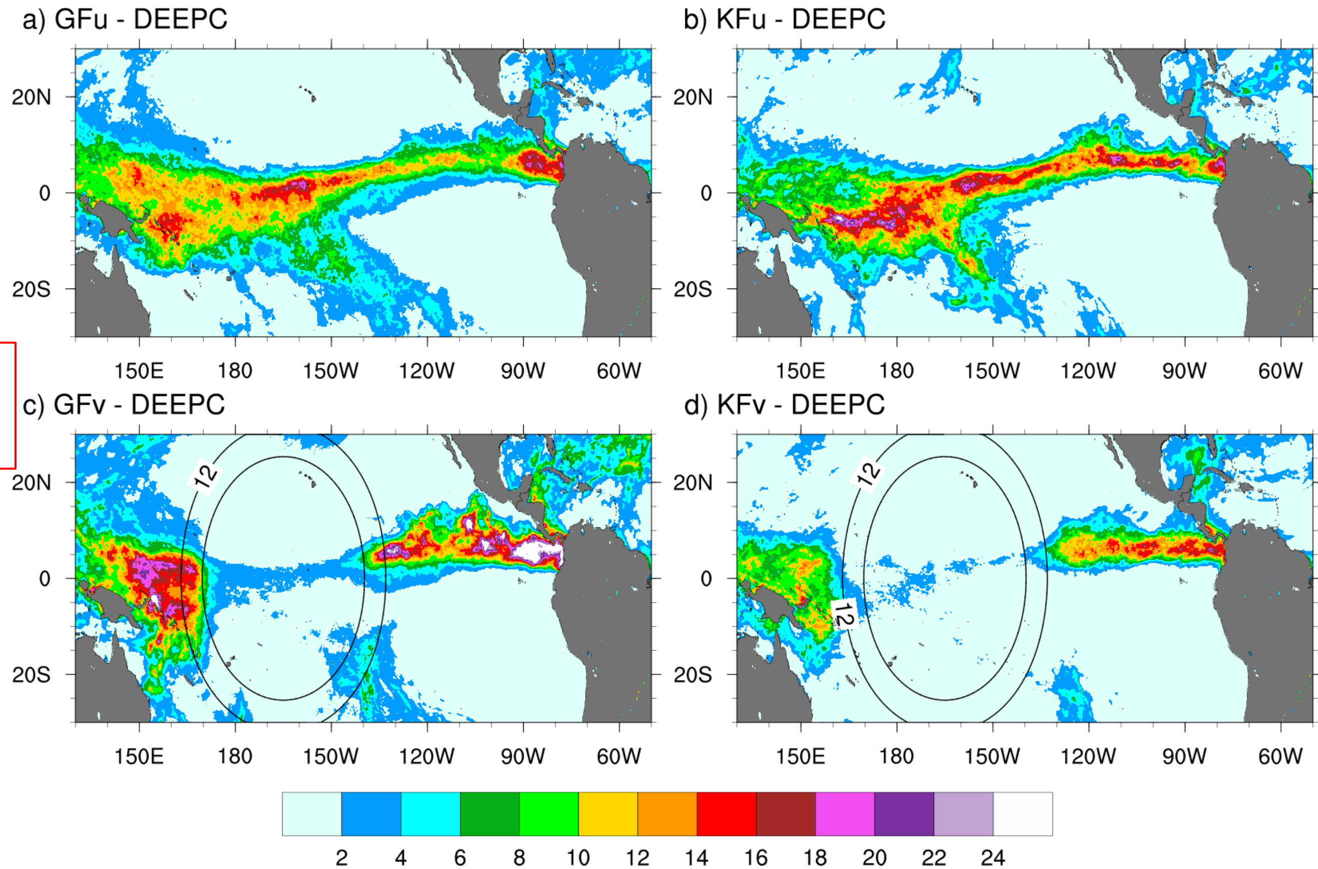


MPAS
Model for Prediction Across Scales

MOIST CONVECTION AND CONVECTION PROCESSES
Scale-aware convective parameterizations

CONVECTIVE PRECIPITATION RATE (mm day^{-1})

Grell-Freitas: Scaling of the cloud-base mass flux



Muti-scale KF: Scaling of the adjustment timescale

As horizontal resolution increases, the contribution of convective precipitation to the total precipitation decreases.

CLOUD MICROPHYSICS PARAMETERIZATIONS

- Cloud microphysics parameterizations are intended to simulate cloud processes describing the formation and lifecycle of a non-convective stratiform (grid-scale) cloud. Once the relative humidity exceed 100%, then cloud droplets (ice crystals) can form producing clouds.

- Cloud microphysics processes modify the atmosphere energy budget and hydrological cycle through:
  - latent heat release associated with condensation, evaporation, deposition, sublimation, freezing, and melting;
  - grid-scale precipitation;
  - cloud optical properties, and;
  - mass loading of the different hydrometeors in the dynamics.

- Microphysics parameterizations are typically grouped into “bulk” and “bin” approaches.
  - bulk schemes use a specified functional form for the particle size distributions of hydrometeors; include single-moment and double-moment schemes.
  - bin schemes divide the particle size distribution into a number of finite size or mass categories (more expensive to run).

WRF Single-Moment 6-class Microphysics scheme (WSM6; Hong and Lim, 2006)

Single-Moment: predict only mass mixing ratios.

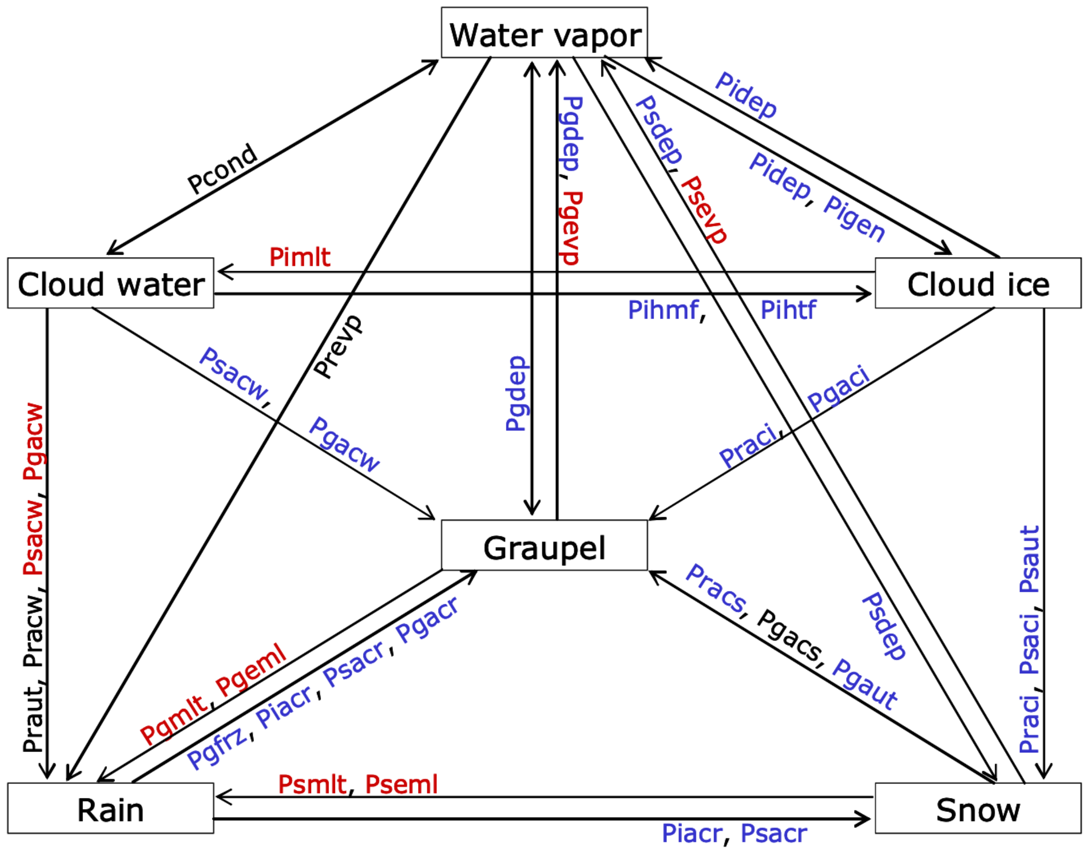


Fig. 1. Flowchart of the microphysics processes in the WSM6 scheme. The terms with red (blue) colors are activated when the temperature is above (below) 0 °C, whereas the terms with black color are in the entire regime of temperature.

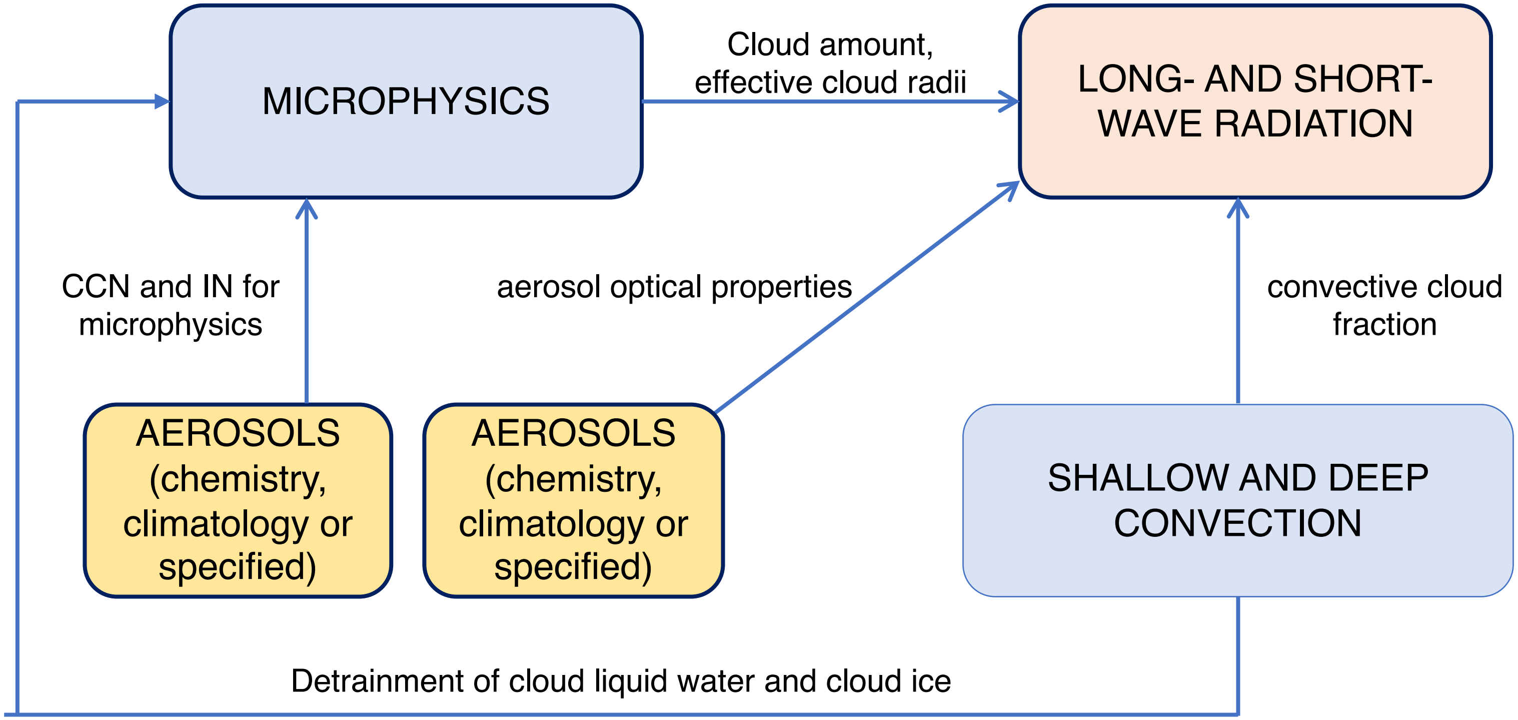
CLOUD MICROPHYSICS PARAMETERIZATIONS

WRF Double-Moment 6-class Microphysics scheme (Thompson; Thompson et al. 2004)
Double-Moment: predict mass mixing ratios plus number concentrations of cloud species.

- Prognostic water vapor, cloud water, cloud ice, rain, snow, and graupel mass mixing ratios.
- Prognostic cloud ice and rain number concentrations.
- a two-moment scheme allows cloud-aerosols-radiation interactions through nucleation of aerosols to CCN and activation of aerosols to IN.

CLOUD MICROPHYSICS PARAMETERIZATIONS

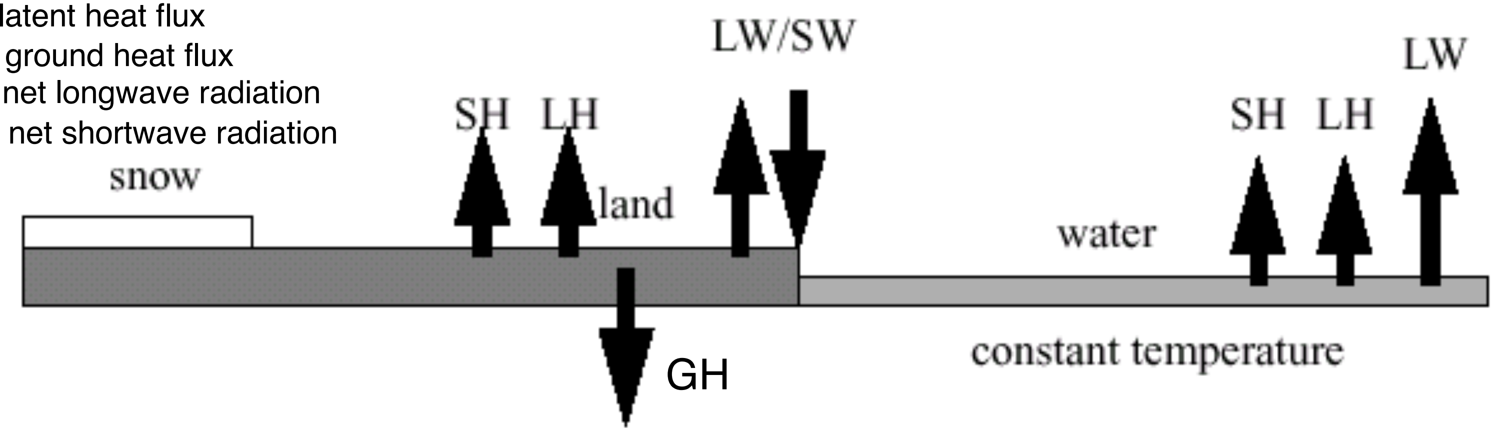
Aerosols-Cloud-Radiation interactions



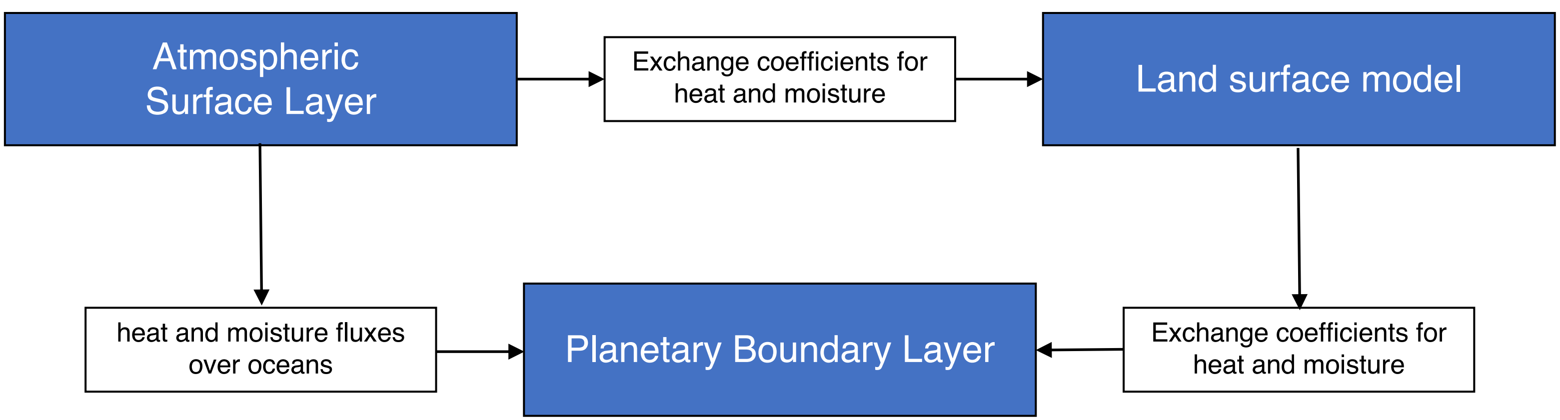
MPAS
Model for Prediction Across Scales

SURFACE, PBL, AND LAND MODEL PROCESSES

SH: sensible heat flux
LH: latent heat flux
GH: ground heat flux
LW: net longwave radiation
SW: net shortwave radiation

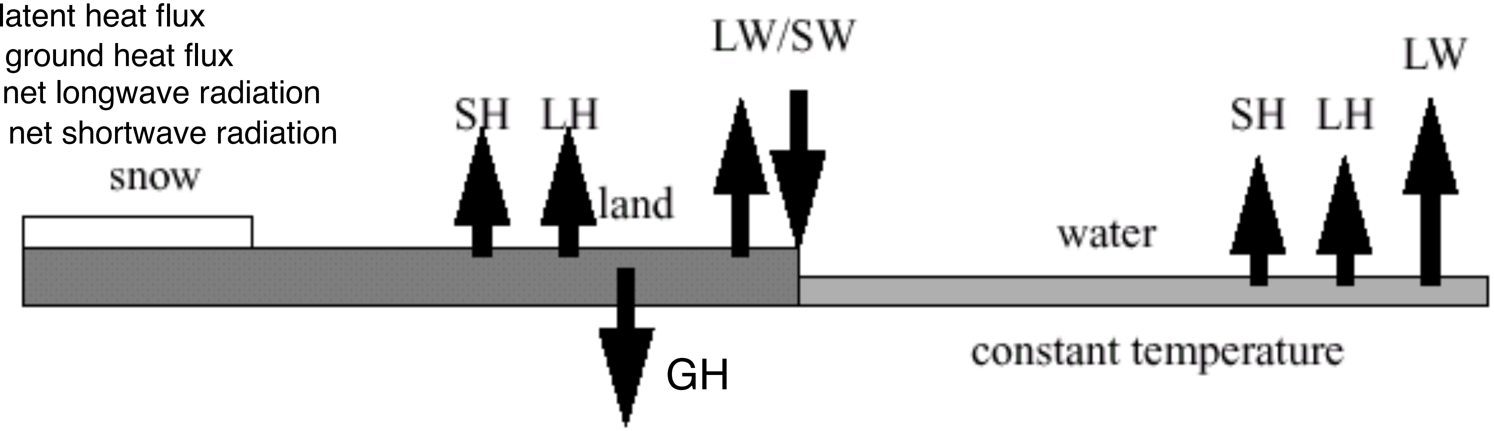


SURFACE ENERGY BUDGET



LAND SURFACE, PBL, AND LAND MODEL PROCESSES

SH: sensible heat flux
LH: latent heat flux
GH: ground heat flux
LW: net longwave radiation
SW: net shortwave radiation



SURFACE ENERGY BUDGET

$$H = \rho c_p u_* \theta_* \qquad \theta_* = \frac{k\Delta\theta}{\ln(z_r / z_{0h}) - \psi_h}$$

From similarity theory

$$E = \rho u_* q_* \qquad q_* = \frac{k\Delta q}{\ln(z_r / z_{0q}) - \psi_h}$$

$$\tau = \rho u_* u_* \qquad u_* = \frac{kV_r}{\ln(z_r / z_0) - \psi_m}$$

LAND SURFACE, PBL, AND LAND MODEL PROCESSES

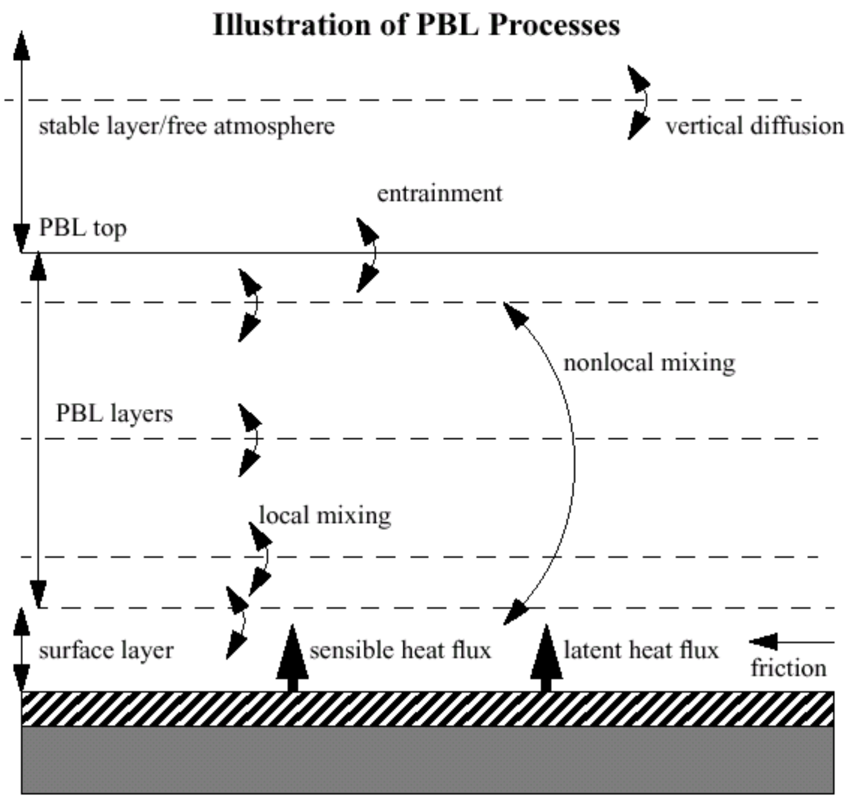
LAND SURFACE MODELS

Interactions between the atmosphere and vegetation

- Impact of vegetation (evapotranspiration and photosynthesis by plants, plant roots in deep soil layers, ...)
- Momentum transfer (vegetation canopies are rough surfaces with large roughness lengths that produce larger surface forces and surface drag).
- Soil moisture availability (LSMs predict soil temperature and soil moisture) as a function of soil type (bare soil versus canopy).
- Impact of snow on ground (LSMs predict the snow water equivalent).
- Radiation (multiple reflections from leaves, absorption of radiation by chlorophyll,…)
- Insulation (type and density of vegetation).

MPAS
Model for Prediction Across Scales

LAND SURFACE, PBL, AND LAND MODEL PROCESSES



- The PBL includes atmospheric layers that are directly influenced by surface heat, moisture, and momentum fluxes.
- The PBL height is strongly influenced by the diurnal cycle, varying between a few tens of meters and several kms.
- Turbulence is the chief mechanism by which surface forcing is transmitted through the PBL.
- PBL schemes include “non-local” closure schemes (YSU) and ”local” closure schemes (MYNN).
- Basic turbulence diffusion equation (u,v,T,q):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[K_c\left(\frac{\partial C}{\partial z} - \gamma_c\right)\right]$$

K_c: diffusivity coefficient.
γ_c: counter gradient

MPAS TIMESTEP

0. CALL TO PHYSICS INITIALIZATION

read input tables for land surface scheme, ozone, and LW and SW radiation

1. CALL TO PHYSICS DRIVER

compute physics tendencies and surface fluxes.

- Clouds, longwave and shortwave radiation schemes.
- Surface layer scheme.
- Land-surface scheme.
- Planetary Boundary Layer (PBL) schemes.
- Gravity wave drag over orography.
- Deep and shallow convection.

2. ADD PHYSICS TENDENCIES IN DYNAMICAL CORE

multiply the tendencies by mass, and add tendencies to state variables

3. CLOUD MICROPHYSICS

directly update state variables and restore RH to 100%.
back to 1.

MPAS TIMESTEP

0. CALL TO PHYSICS INITIALIZATION

call physics_init (…)

1. CALL TO PHYSICS DRIVER

call physics_driver

- call driver_cloudiness (…)
- call driver_radiation_sw / call driver_radiation_lw (…)
- call driver_sfclayer (…) / call driver_lsm (…)
- call driver_pbl (…)
- call driver_gwdo (…)
- call driver_convection (…)

2. ADD PHYSICS TENDENCIES IN DYNAMICAL CORE

call physics_get_tend

3. CLOUD MICROPHYSICS

call driver_microphysics

back to 1.

MPAS
Model for Prediction Across Scales

PHYSICS PARAMETERIZATIONS

- At present, all the physics parameterizations available in the MPAS public release come from the *WRF phys* directory.

- MPAS includes only a small subset of the WRF physics.

- Physics parameterizations are not as *updated* as the WRF physics.

PHYSICS CONFIGURATIONS

- All the physics options are available in *./src/core_atmosphere/Registry.xml* in the namelist record "physics".

  <nml_record name="physics" in_defaults="true">

- In *Registry.xml*, each physics option has a default value set for generic global-scale forecasts. For instance:

  <nml_option name="config_sfc_albedo" type="logical" default_value="true" in_defaults="false"
  units="-" description="logical for configuration of surface albedo"
  possible_values=".true. for climatologically varying surface albedo; .false. for fixed input data"/>

- Physics options are modified and added in namelist.atmosphere in the "&physics" namelist record:
  - note that *atmosphere_model* will run if you do not specify any physics options. It will simply use the default options set in Registry.xml.
  - in terms of physics parameterizations, MPAS uses the concept of *physics suite*.

PHYSICS CONFIGURATIONS
config_physics_suite = "…"

- A physics suite comprises a set of parameterizations, each parameterization describing an individual physics process (radiation, PBL, convection, …)

- Each physics suite *targets* a certain application, driven by the complexity of the schemes it includes.

- In MPAS, there are two separate suites:
    - the *mesoscale_reference* suite, better suited for mesoscale horizontal resolution (> 20 km), long-term simulations.
    - the *convection_permitting* suite, better suited for high spatial resolution where convective motions are explicitly resolved, at least in a portion of the mesh.
    - the suites use different parameterizations of PBL processes, different parameterizations of deep convection, and different parameterizations of cloud microphysics.
    - the suites share the same parameterizations of land surface processes, radiation, and gravity wave drag over orography.
    - in each suite, a parameterization can be easily substituted by another, if needed.

PHYSICS OPTIONS

- shared
- mesoscale_reference
- convection_permitting

- LAND SURFACE SCHEME: → NOAH.
- SURFACE LAYER SCHEMES: → MONIN-OBUKHOV, MYNN.
- PBL SCHEMES: → YSU, MYNN.
- GRAVITY WAVE DRAG OVER OROGRAPHY: → GWDO.
- CONVECTION SCHEMES (SHALLOW PLUS DEEP): → KAIN-FRITSCH, TIEDTKE, NTIEDTKE, GRELL-FREITAS.
- MICROPHYSICS SCHEMES: → KESSLER, WSM6,THOMPSON.
- LW AND SW RADIATION SCHEMES: → RRTMG, CAM.
- CLOUD SCHEMES: → INCIDENCE, FRACTION, THOMPSON.

PHYSICS SUITES: THE MESOSCALE_REFERENCE SUITE

config_physics_suite = “mesoscale_reference”

```
config_microp_scheme      = 'mp_wsm6'
config_convection_scheme  = 'cu_ntiedtke'
config_pbl_scheme         = 'bl_ysu'
config_gwdo_scheme        = 'bl_ysu_gwdo'
config_radt_lw_scheme     = 'rrtmg_lw'
config_radt_sw_scheme     = 'rrtmg_sw'
config_radt_cld_scheme    = 'cld_fraction'
config_sfclayer_scheme    = 'sf_monin_obukhov'
config_lsm_scheme         = 'sf_noah'
```

- The nTIEDTKE deep convection scheme is insensitive to the horizontal grid-spacing.
- The WSM6 cloud microphysics scheme is a one-moment scheme, and assumes an infinite number concentrations for the 5 hydrometeor species.

PHYSICS SUITES: THE CONVECTION_PERMITTING SUITE

config_physics_suite = “convection_permitting”

```
config_microp_scheme      = 'mp_thompson'
config_convection_scheme = 'cu_grell_freitas'
config_pbl_scheme         = 'bl_mynn'
config_gwdo_scheme        = 'bl_ysu_gwdo'
config_radt_lw_scheme     = 'rrtmg_lw'
config_radt_sw_scheme     = 'rrtmg_sw'
config_radt_cld_scheme    = 'cld_fraction'
config_sfclayer_scheme    = 'sf_mynn'
config_lsm_scheme         = 'sf_noah'
```

- The GRELL-FREITAS (and the scale-aware nTIEDTKE) deep convection scheme takes into account variations in the horizontal grid-spacing.
- The THOMPSON cloud microphysics scheme is a two-moment scheme, and includes prognostic equations for cloud ice and rain.

PHYSICS OPTIONS

- Once a physics suite is chosen, additional physics options can be added in the namelist record “physics”:

```
<nml_option name="config_radtlw_interval" type="character" default_value="00:30:00"
  units="-"
  description="time interval between calls to parameterization of long-wave radiation"
  possible_values="`DD_HH:MM:SS' or `none'"/>

<nml_option name="config_radtsw_interval" type="character" default_value="00:30:00"
  units="-"
  description="time interval between calls to parameterization of short-wave radiation"
  possible_values="`DD_HH:MM:SS' or `none’”/>
.
.
<nml_option name="config_microp_re" type="logical" default_value="false”
  units="-"
  description="logical for calculation of the effective radii for cloud water, cloud ice, and snow"
  possible_values=".true. for calculating effective radii; .false. for using defaults in RRTMG
  radiation"/>
```

CONCLUSIONS

- MPAS physics includes the fundamental parameterizations to produce realistic forecasts.

- MPAS variable-resolution meshes offer the opportunity to investigate scale-aware parameterizations; in particular, deep convection.

- Despite the fact that high-resolution global forecasts have been successfully produced, the need for added and improved parameterizations remains:

  - improved parameterization of the cloud fraction.

  - formal parameterizations of aerosols and their interactions with clouds and radiation.

- Contributions from developers and scientists interested in contributing to the MPAS physics.

NCAR

NSF

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.