Physics and physics configurations

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OUTLINE

- Physics parameterizations and interactions between physics processes.
- Physics configurations.

PHYSICS PARAMETERIZATIONS

CONVECTION

MICROPHYSICS

PBL

Parameterizations describe the mean subgrid-scale effects of specific physics processes:

- diabatic processes (radiation, condensation,…).
- water phase transitions (convection, microphysics).

As spatial resolution increases:

- subgrid-scale processes become explicitly resolved by the dynamics.
- details of cloud physics processes are increasingly needed.

LW AND SW RADIATION

SURFACE

MPAS
Model for Prediction Across Scales

MAIN PHYSICS PARAMETERIZATIONS IN V-8.1.0

CONVECTION
nTIEDTKE,GF,KF

MICROPHYSICS
WSM6,THOMPSON

PBL
YSU,MYNN

LW/SW RADIATION
CAM,RRTMG

SURFACE
NOAH LSM,GWDO

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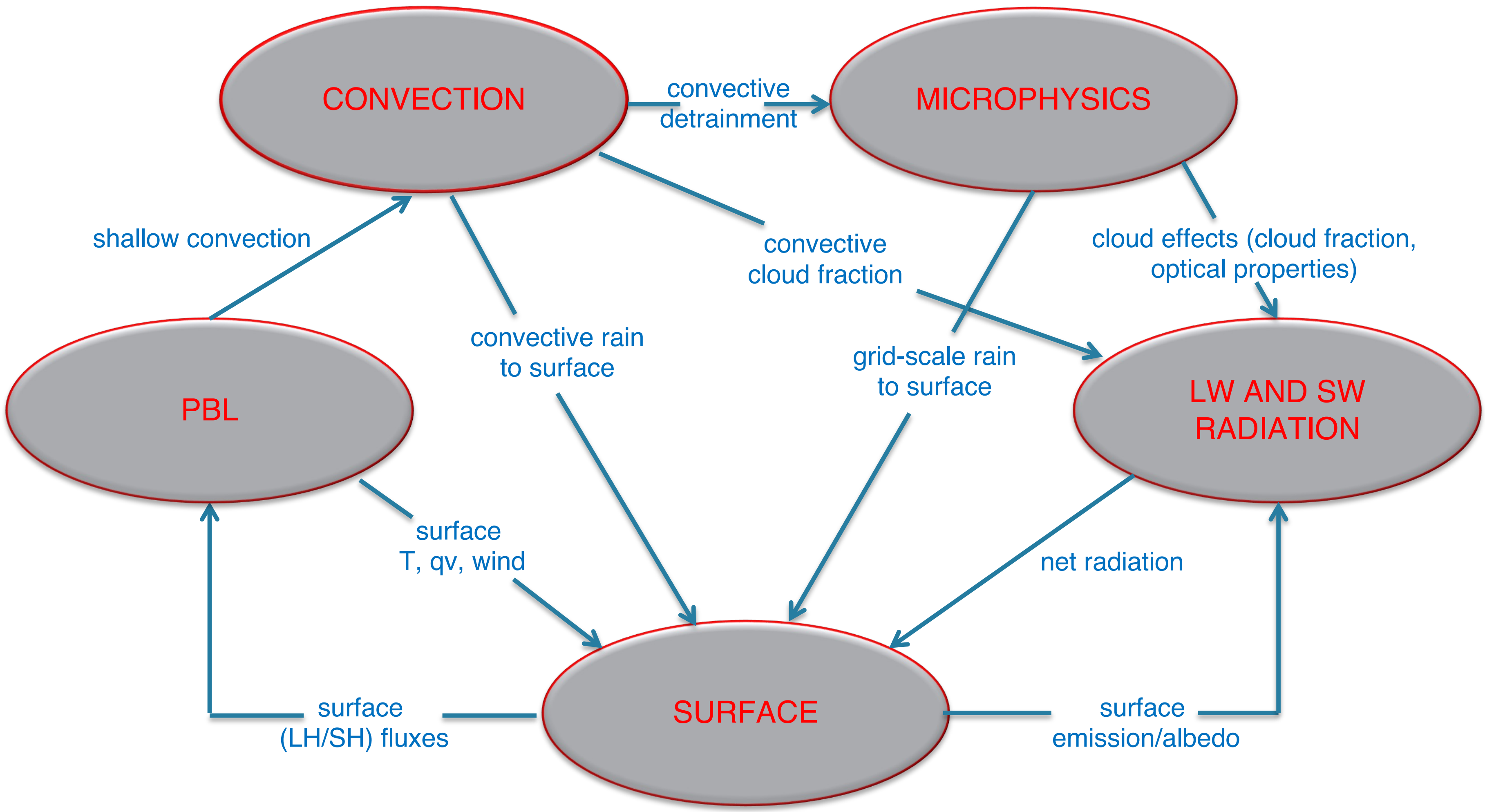
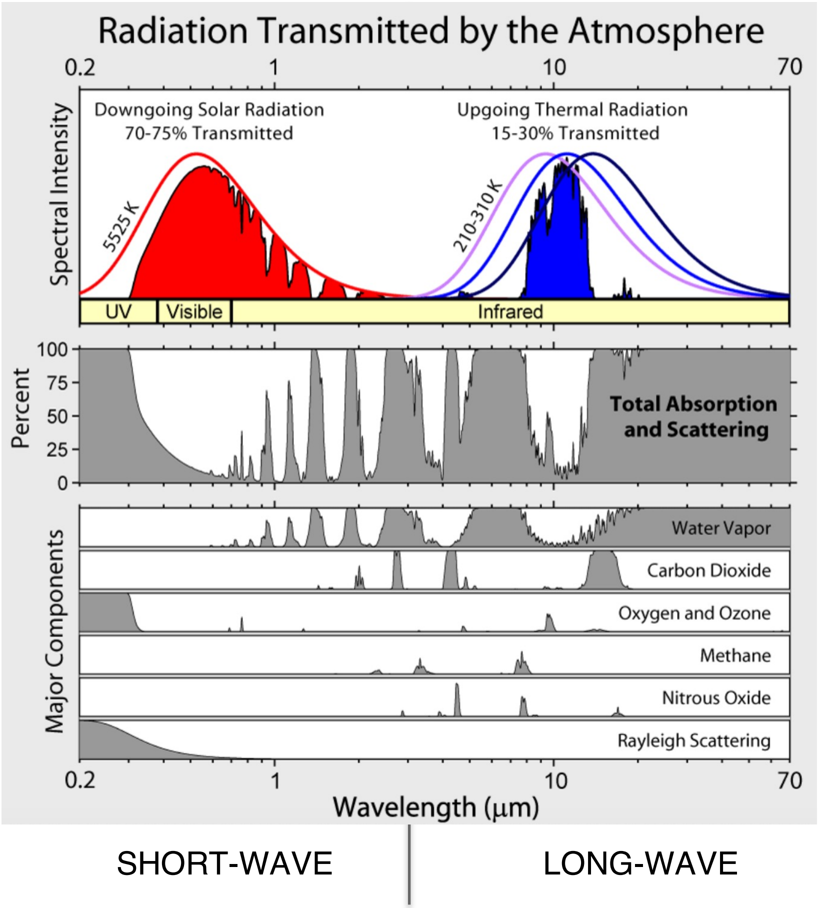
PHYSICS– INTERACTIONS BETWEEN PROCESSES



LONGWAVE AND SHORTWAVE RADIATION



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.

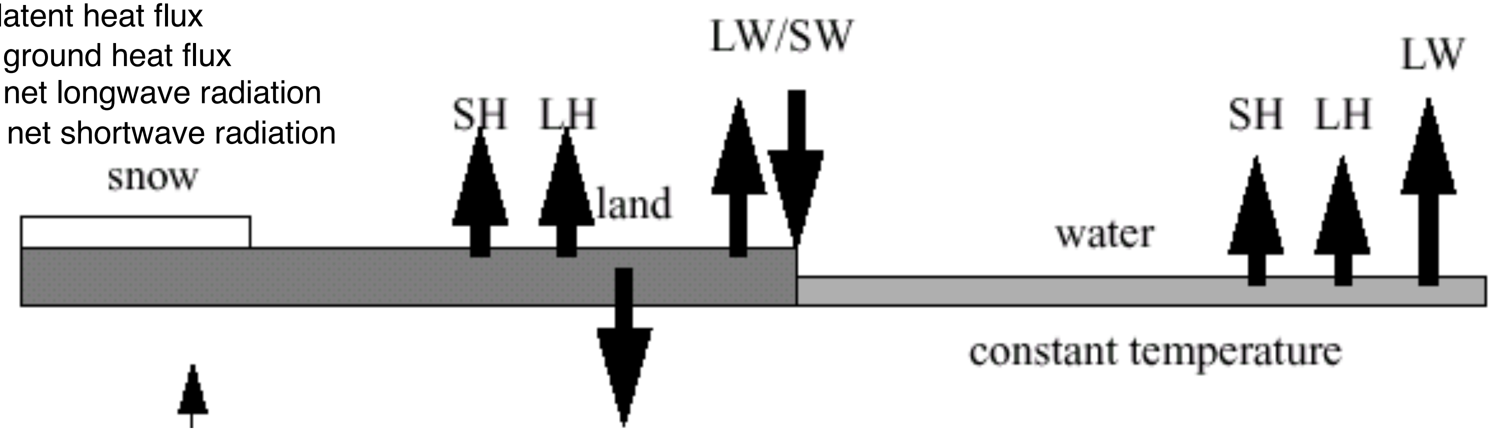
METHODS

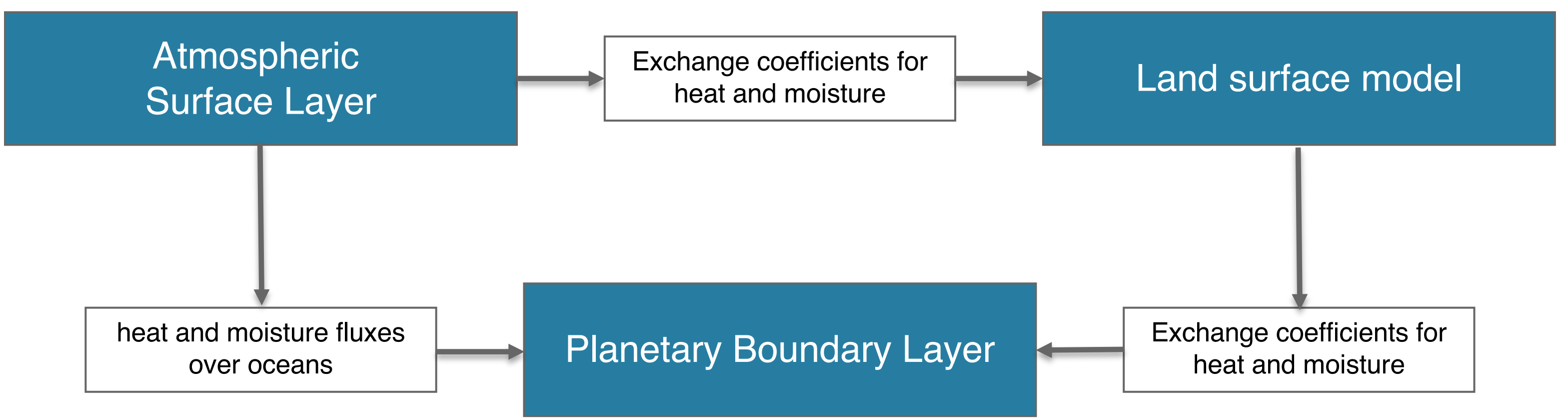
- Long- and short-wave radiation fluxes are computed in two steps: 1) for clear-sky fluxes; and 2) for all-sky fluxes to account for aerosols and clouds.
- Clouds and aerosols impact long- and short-wave radiation fluxes (cooling at cloud-tops, warming at cloud-base, aerosol scattering).

LAND SURFACE AND PBL PROCESSES

SURFACE ENERGY BUDGET

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





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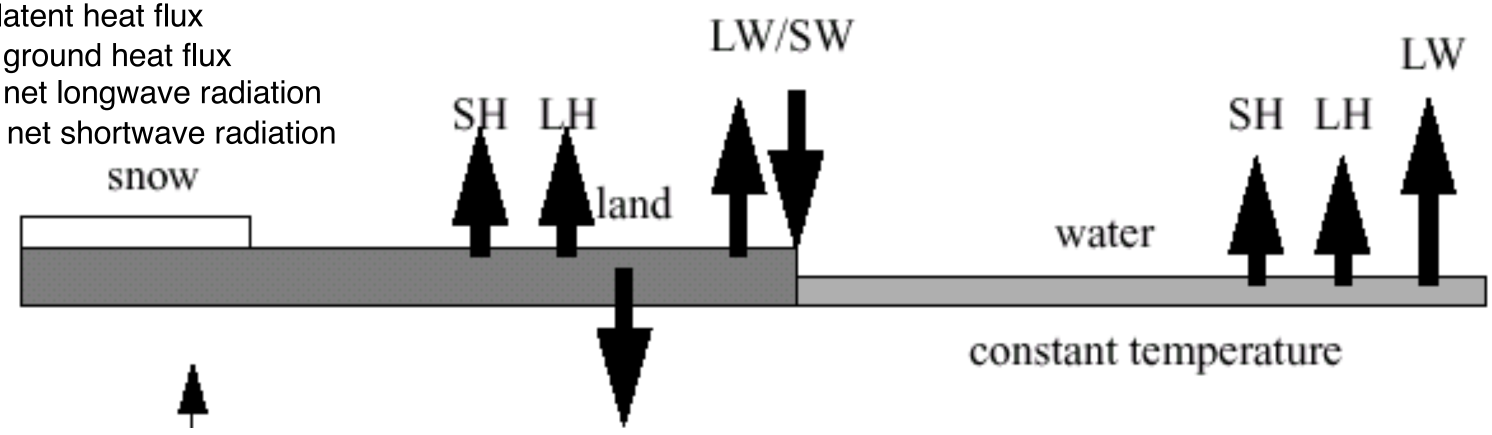


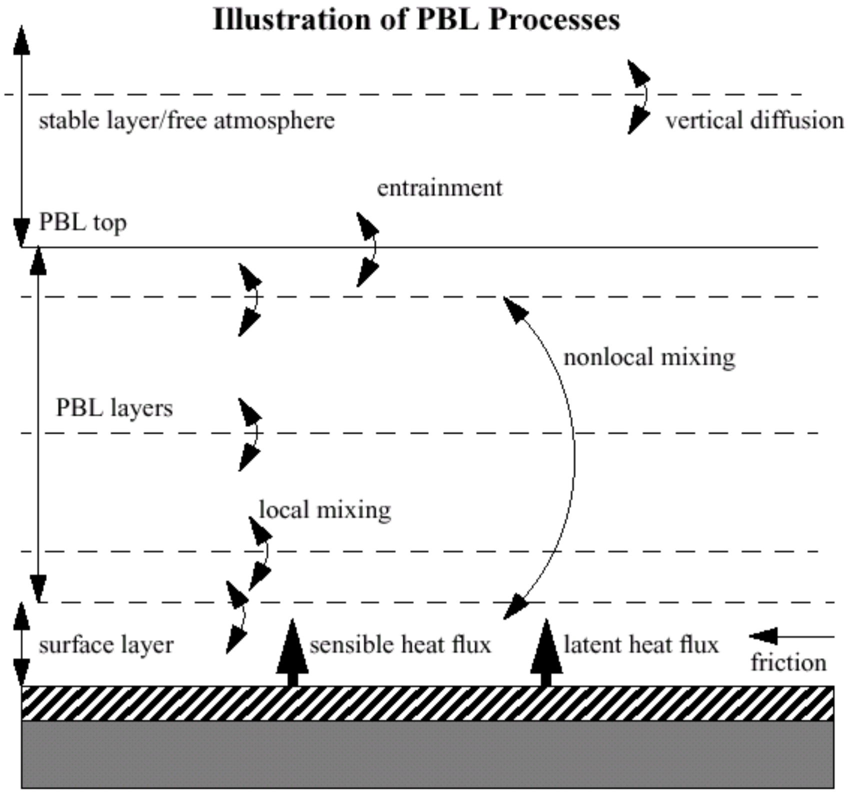
From similarity theory (Monin-Obukhov 1954)

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

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

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

LAND SURFACE AND PBL PROCESSES

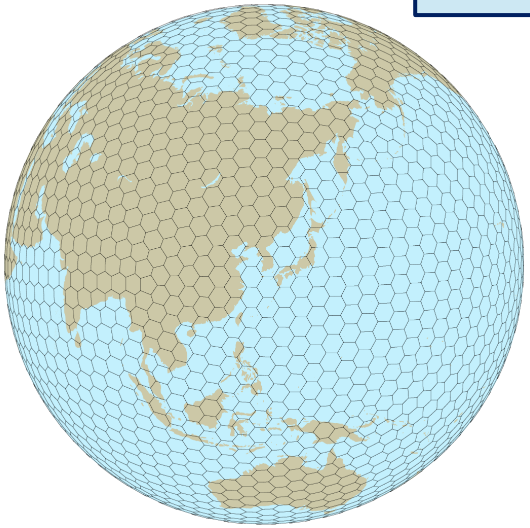


- The PBL includes atmospheric layers that are directly influenced by surface heat, moisture, and momentum fluxes.
- The PBL height is strongly influenced by the diurnal cycle, varying between a few tens of meters and several kms.
- Turbulence is the chief mechanism by which surface forcing is transmitted through the PBL. It acts to uniformly mix the boundary layer, especially the potential temperature.
- Turbulent flows occurs at very small scales: Reynolds averaging allows to parameterize turbulent flows at NWP scales.
- PBL schemes include “non-local” closure schemes (YSU) and ”local” closure schemes (MYNN).
- Basic turbulence diffusion equation (u,v,T,q):

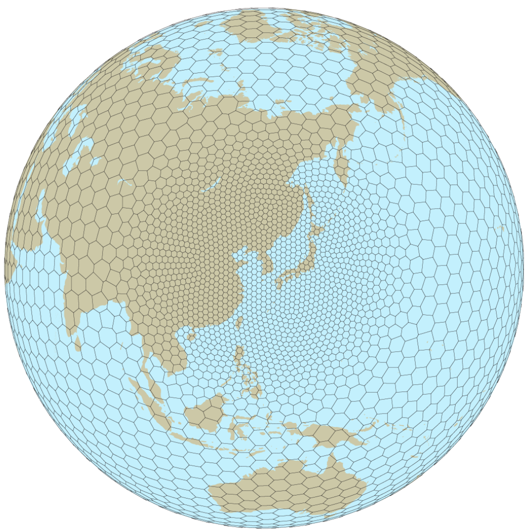
$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[K_c\left(\frac{\partial C}{\partial z} - \gamma_c\right)\right]$$

K_c: diffusivity coefficient.
γ_c : counter gradient

SCALE-AWARE PHYSICS WITH MESH REFINEMENT MOIST PROCESSES AND CLOUDS



Global uniform-resolution mesh



Global variable-resolution mesh

ADVANTAGES OF USING MESH REFINEMENT

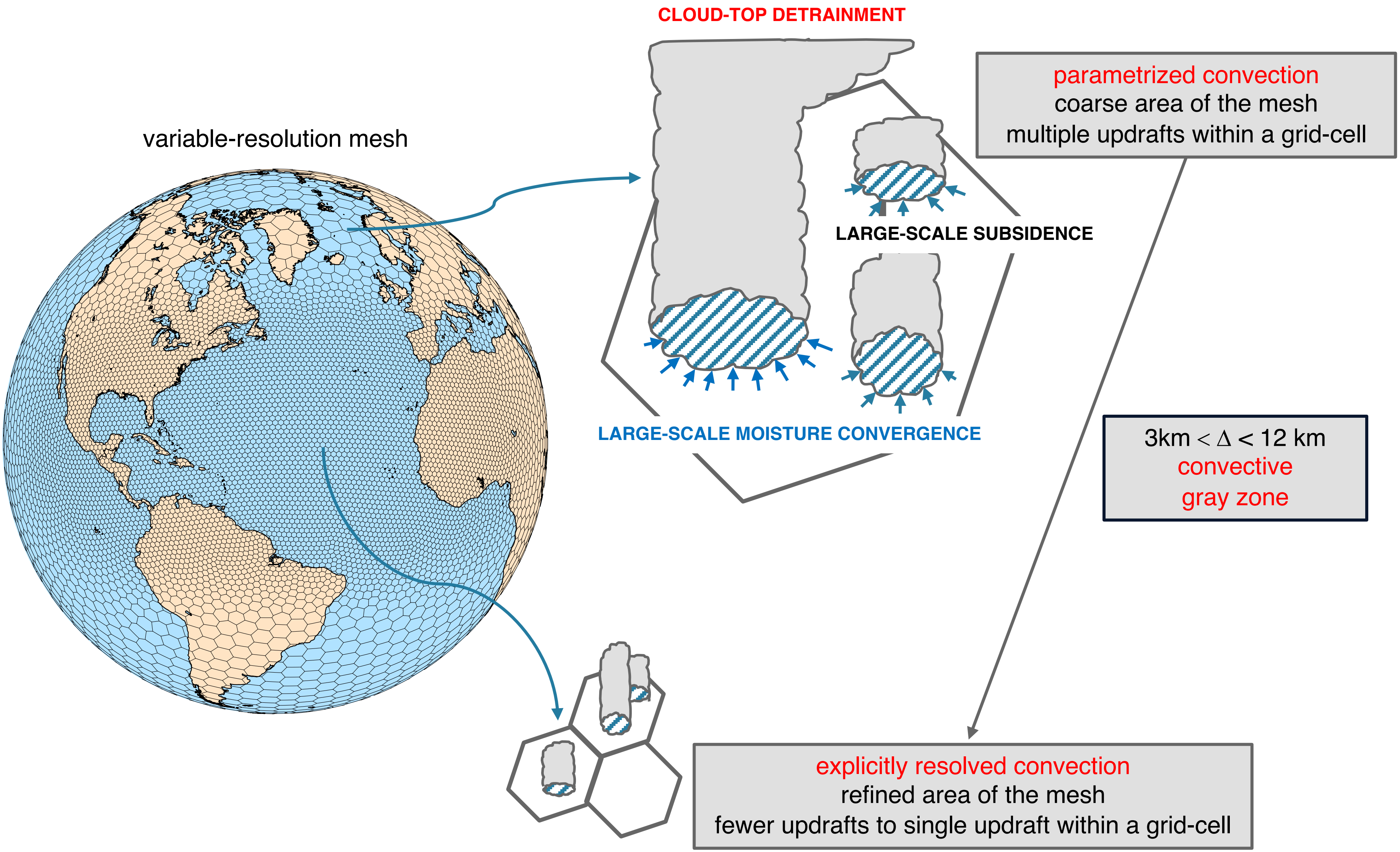
- We avoid issues related to updating the lateral boundaries of the regional domain, or issues related to nesting and nudging.
- We have two-way feedbacks between the coarser and refined regions.

CHALLENGES

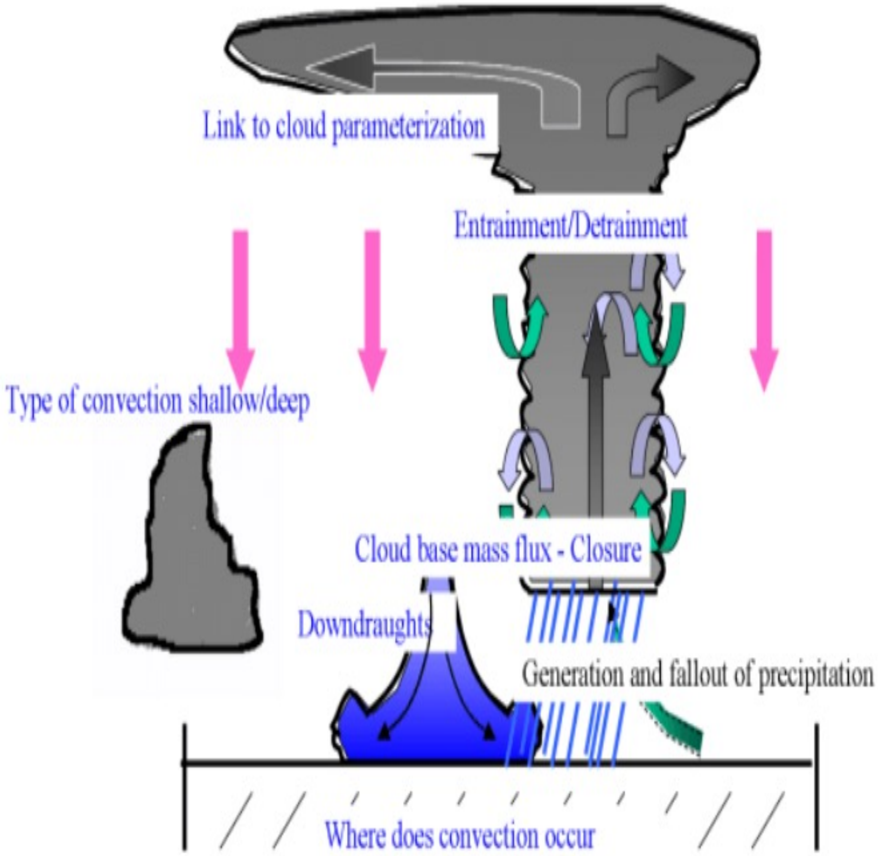
- **COST**: The time-step is the same in the coarse and refined regions, and is the one needed over the refined area of the global mesh.
- We need to *have scale-aware* physics schemes, or physics that can be used from hydrostatic down to nonhydrostatic scales, particularly **deep convection** and cloud microphysics.

MPAS
Model for Prediction Across Scales

SCALE-AWARE PHYSICS WITH MESH REFINEMENT DEEP CONVECTION



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

SCALE-AWARE PHYSICS WITH MESH REFINEMENT
TWO APPROACHES TO MODIFY NON SCALE-AWARE TO SCALE-AWARE

GRELL FREITAS (GF)

Grell and Freitas 2014; Fowler et al. 2016; Freitas et al. 2018

- Follows Arakawa and Wu (2013) to scale the cloud base mass flux as a function of the area of the convective updraft (σ).

$$M_{Bsca}=(1-\sigma)^2\, M_B$$

M_{Bsca}: Scaled mass flux.

M_B: Original mass flux.

- σ is simply parameterized as:

$$\sigma = \frac{\pi R^2}{A} \text{ and } R = \frac{0.2}{\varepsilon}$$

Simpson and Wiggert (1969)

A: Area of updraft.

R: Half-width radius.

ε: entrainment rate.

MULTI-SCALE TIEDTKE (nTIEDTKE)

Wang 2022

- Unlike GF, and as MSKF, nTIEDTKE does not compute σ. Instead, nTIEDTKE choose to modify convection parameters used in the original Tiedtke (1989) CP.
- nTIEDTKE scales the convective time-scale.
- nTIEDTKE scales the entrainment rate.

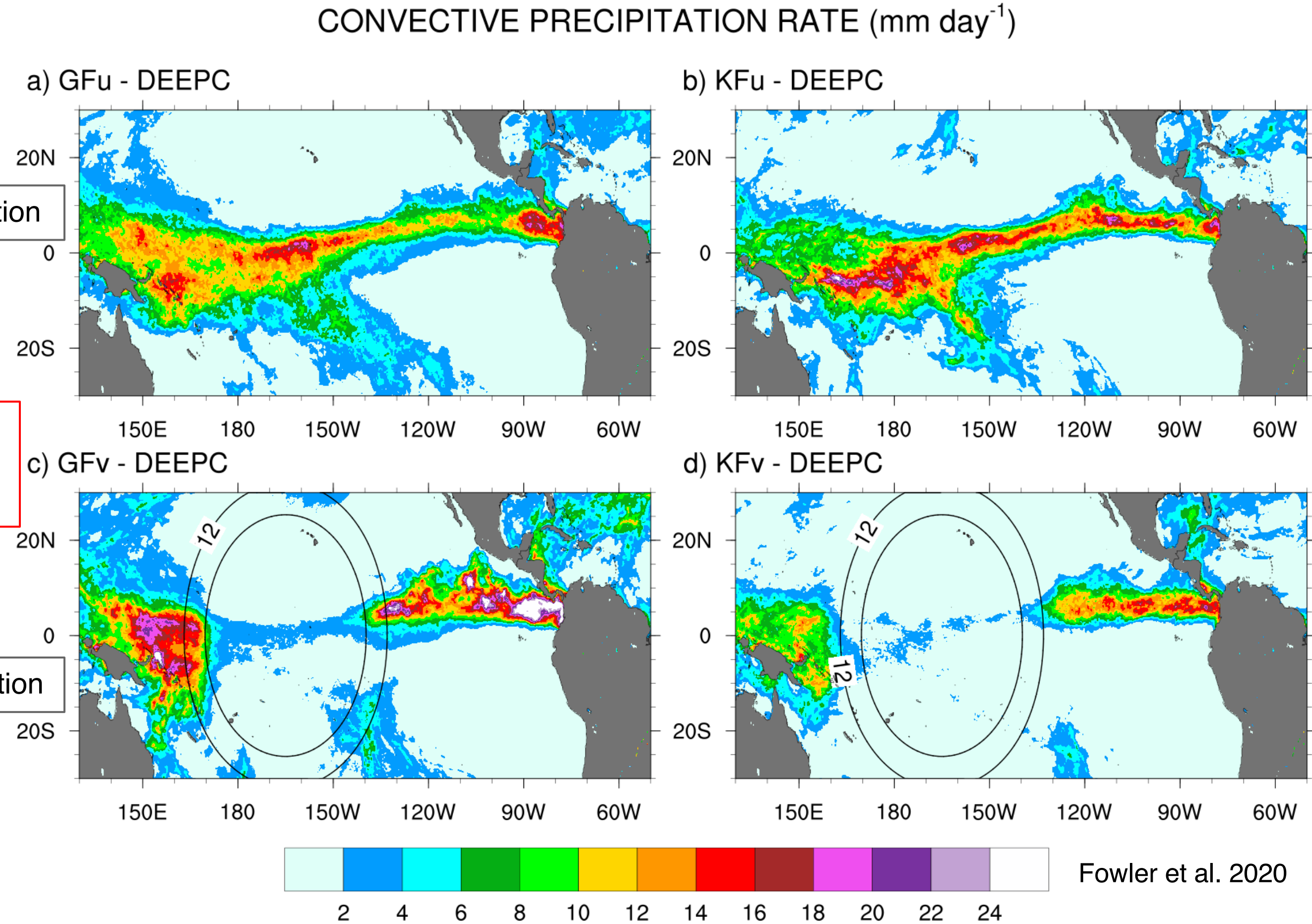
MULTI-SCALE KAIN-FRITSCH (MSKF)

Zheng et al. 2016; Glotfelty et al. 2019

- Unlike GF, MSKF does not compute σ. Instead, MSKF choose to modify convection parameters used in the original Kain-Fritsch (Kain, 2004) CP.
- MSKF scales the convective time-scale.
- MSKF scales the stabilization capacity (i.e. CAPE).

SCALE-AWARE PHYSICS WITH MESH REFINEMENT

MPAS
Model for Prediction Across Scales



uniform resolution

uniform resolution

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

Muti-scale KF: Scaling of the adjustment timescale

variable resolution

variable resolution

Fowler et al. 2020

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

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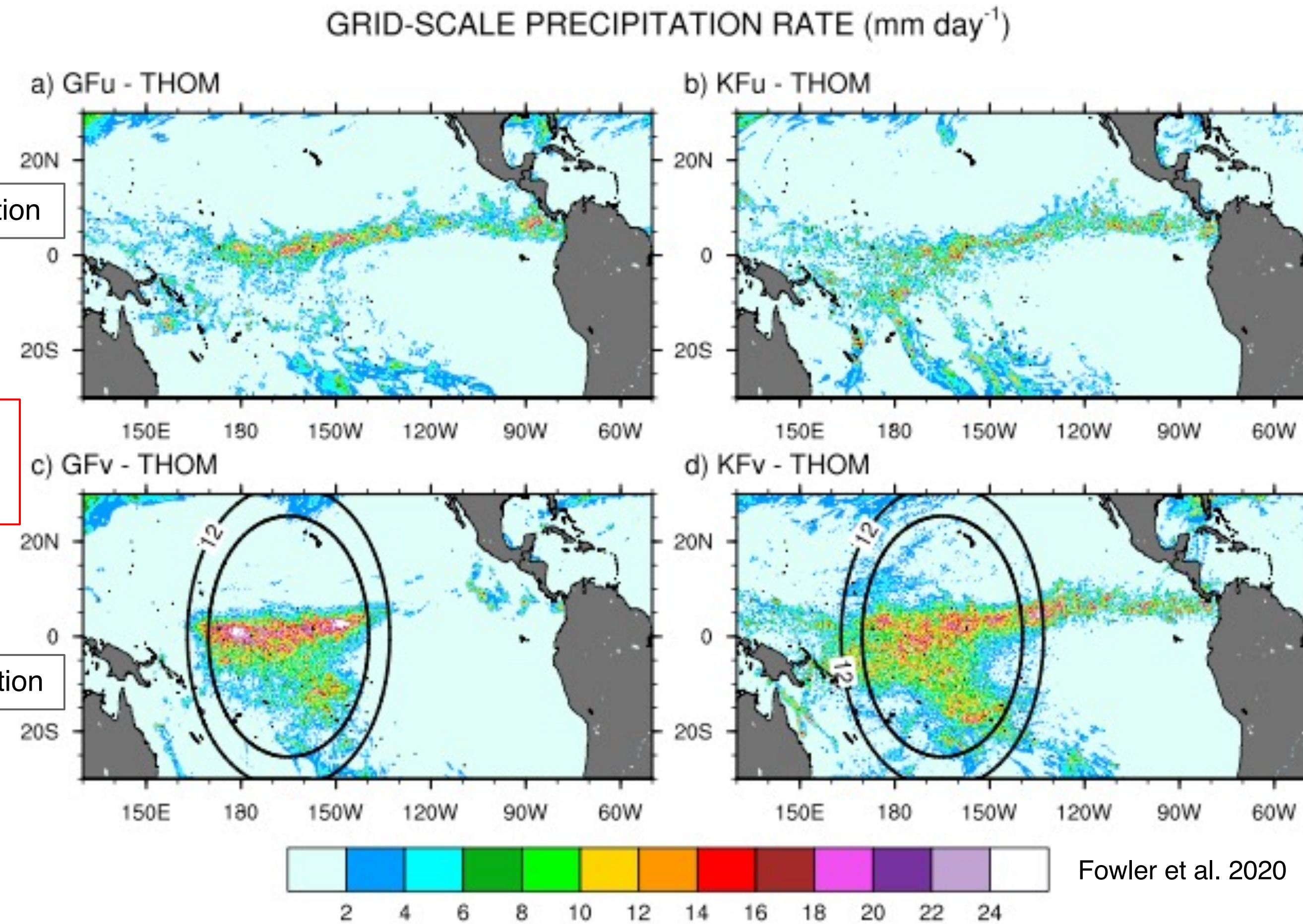
Model for Prediction Across Scales

SCALE-AWARE PHYSICS WITH MESH REFINEMENT



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

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variable resolution

variable resolution

Fowler et al. 2020

As horizontal resolution increases, the contribution of grid-scale precipitation to the total precipitation increases. Details of cloud microphysics processes are increasingly needed.

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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.

- 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 fraction, 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 (triple-moment) schemes.
    - bin schemes divide the particle size distribution into a number of finite size or mass categories (more expensive to run).

CLOUD MICROPHYSICS PARAMETERIZATIONS

WRF Single-Moment 6-class MP
(WSM6; *Hong and Lim, 2006*)
Single-Moment: predict only mass mixing ratios.

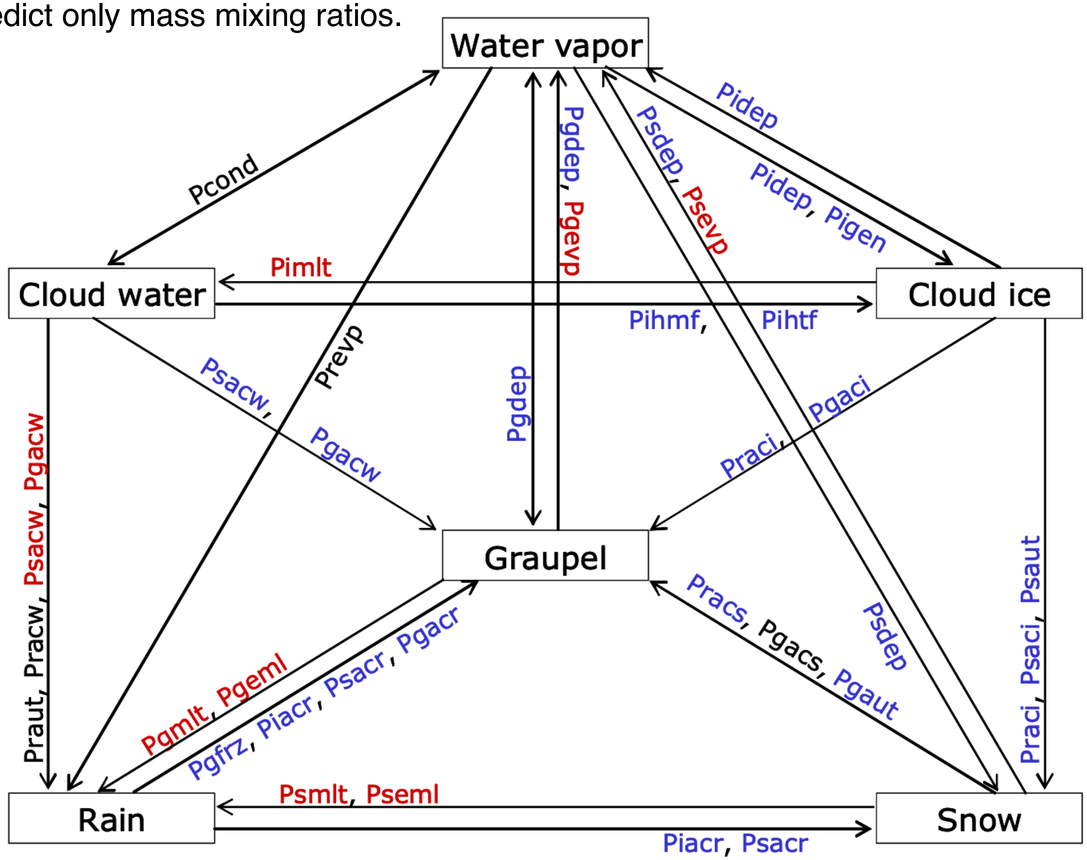

Fig. 1. Flowchart of the microphysics processes in the WSM6 scheme. The terms with red (blue) colors are activated when the temperature is above (below) 0 °C, whereas the terms with black color are in the entire regime of temperature.

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WRF Double-Moment 6-class MP
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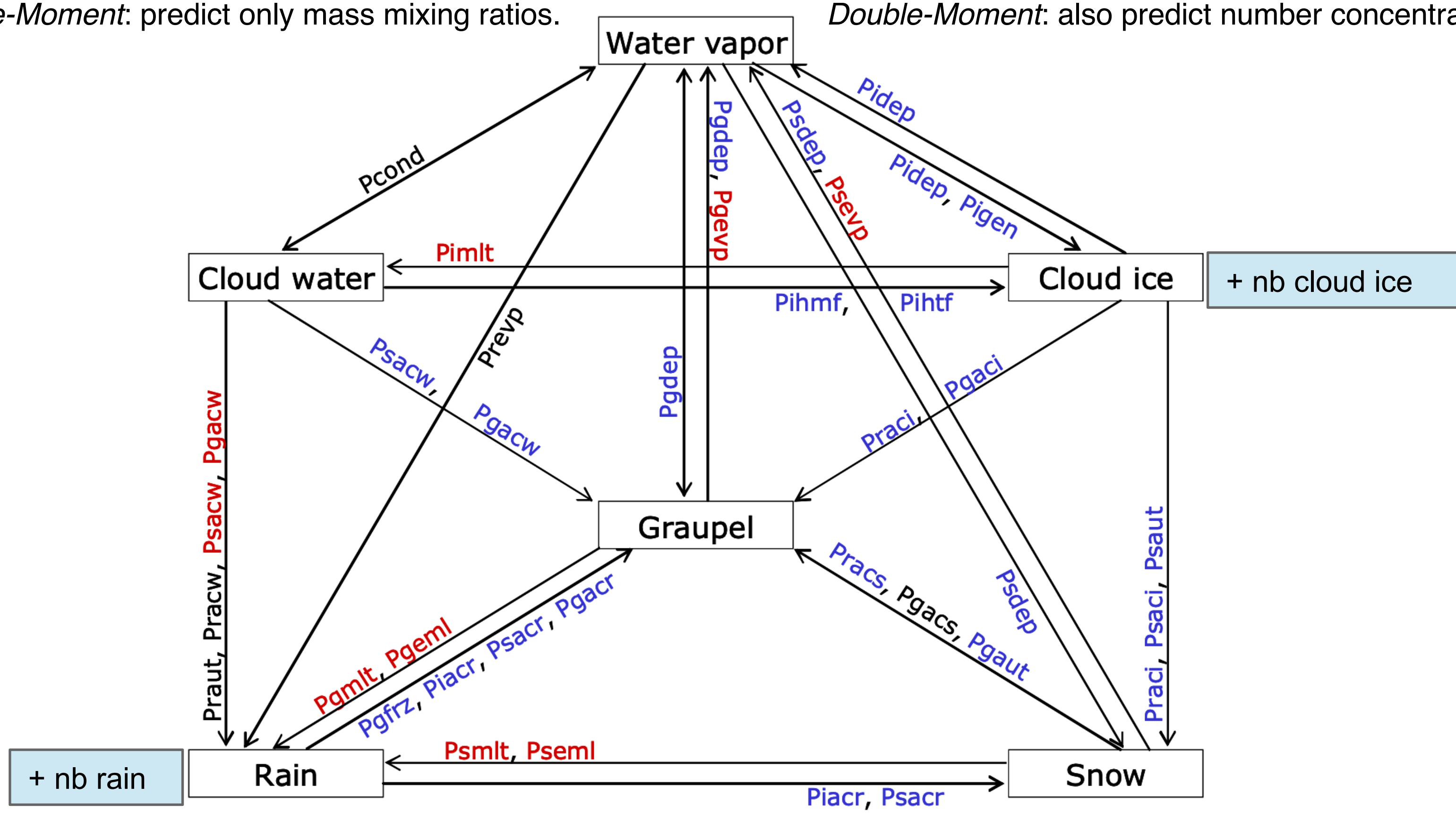
Double-Moment: also predict number concentrations.



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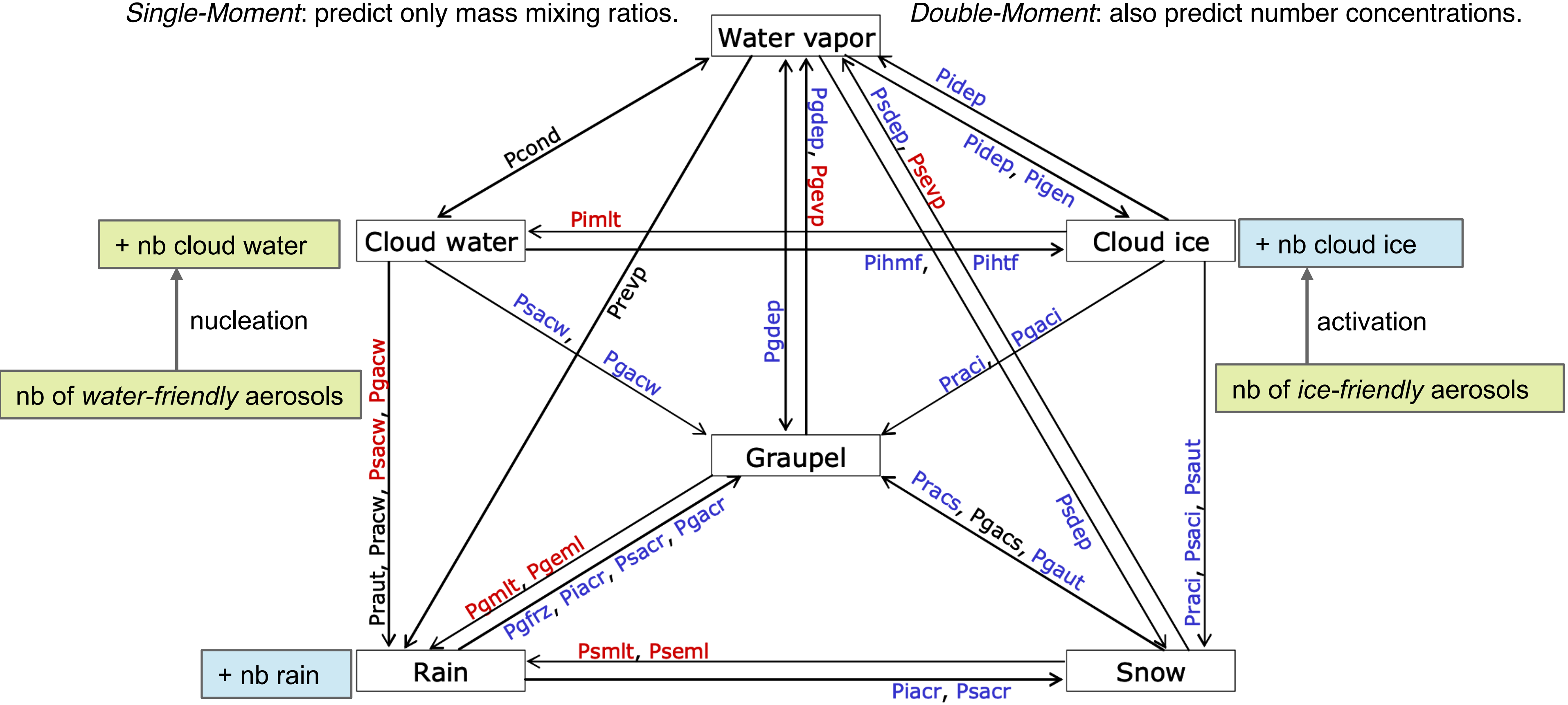

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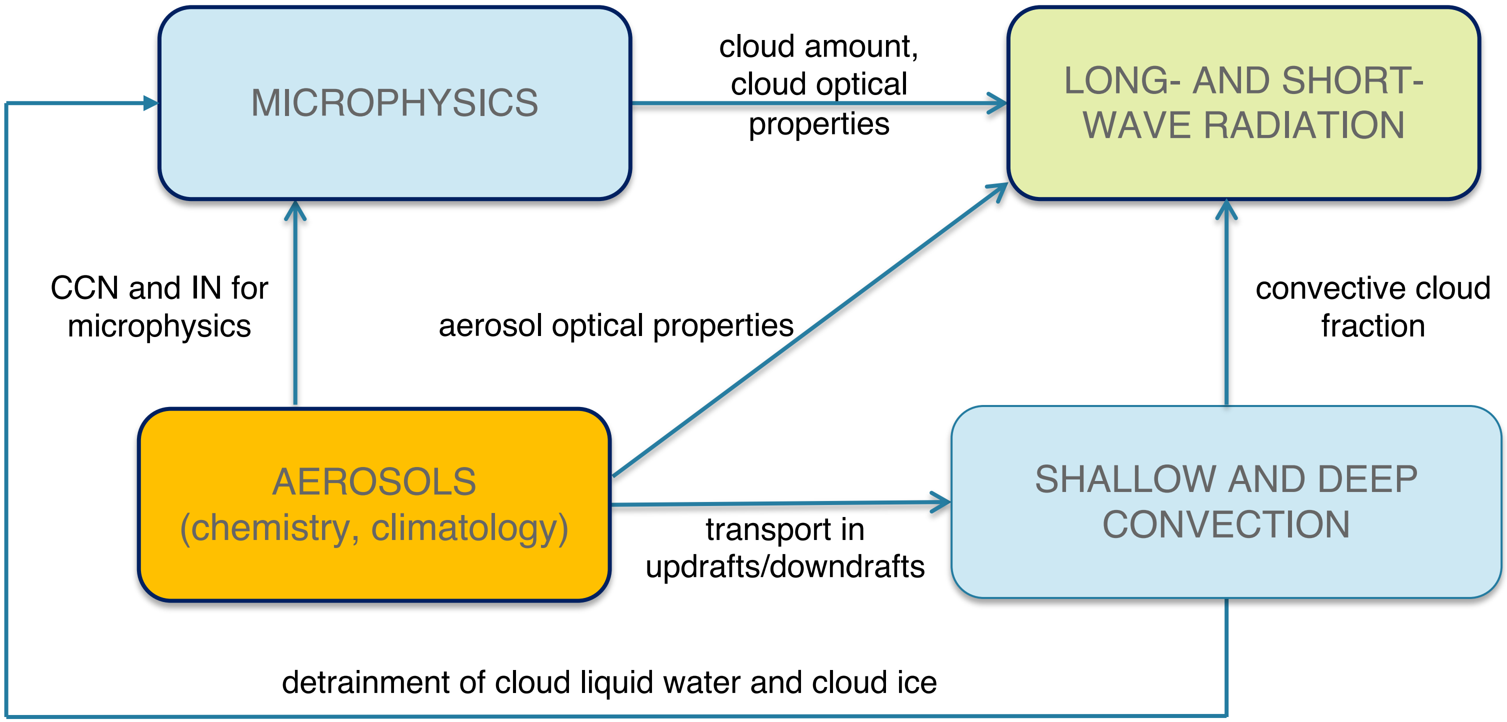
AEROSOLS-CLOUD-RADIATION INTERACTIONS



PHYSICS CONFIGURATION

/MPAS-Model/src/core_atmosphere:

```
build_options.mk  inc               mpas_atm_core_interface.F  physics
diagnostics       Makefile          mpas_atm_dimensions.F      Registry.xml
dynamics          mpas_atm_core.F   mpas_atm_threading.F       utils
```

PHYSICS CONFIGURATION

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diagnostics       Makefile        mpas_atm_dimensions.F      Registry.xml
dynamics          mpas_atm_core.F mpas_atm_threading.F       utils
```

/MPAS-Model/src/core_atmosphere/Makefile:

```
#
# To build a dycore-only MPAS-Atmosphere model, comment-out or delete
# the definition of PHYSICS, below
#
#PHYSICS=-DDO_PHYSICS
PHYSICS =


ifdef PHYSICS
    PHYSCORE = physcore
    PHYS_OBJS = libphys/*.o
endif
```

This “PHYSICS” option allows to add a physics package, completely separate from the currently available physics parameterizations.

PHYSICS CONFIGURATION

/MPAS-Model/src/core_atmosphere/physics

access to data files

initialization of separate physics process

```
ccpp_kinds.F
checkout_data_files.sh
Makefile
mpas_atmphys_camrad_init.F
mpas_atmphys_constants.F
mpas_atmphys_control.F
mpas_atmphys_date_time.F
mpas_atmphys_driver_cloudiness.F
mpas_atmphys_driver_convection.F
mpas_atmphys_driver.F
mpas_atmphys_driver_gwdo.F
mpas_atmphys_driver_lsm.F
mpas_atmphys_driver_lsm_shared.F
mpas_atmphys_driver_microphysics.F
mpas_atmphys_driver_oml.F
mpas_atmphys_driver_pbl.F
mpas_atmphys_driver_radiation_lw.F
mpas_atmphys_driver_radiation_sw.F
mpas_atmphys_driver_sfclayer.F
mpas_atmphys_finalize.F
```

```
mpas_atmphys_functions.F
mpas_atmphys_init.F
mpas_atmphys_initialize_real.F
mpas_atmphys_init_microphysics.F
mpas_atmphys_interface.F
mpas_atmphys_landuse.F
mpas_atmphys_lsm_noahinit.F
mpas_atmphys_manager.F
mpas_atmphys_o3climatology.F
mpas_atmphys_packages.F
mpas_atmphys_rrtmg_lwinit.F
mpas_atmphys_rrtmg_swinit.F
mpas_atmphys_todynamics.F
mpas_atmphys_update.F
mpas_atmphys_update_surface.F
mpas_atmphys_utilities.F
mpas_atmphys_vars.F
physics_mmm
physics_wrf
```

parameterizations

drivers for separate physics process

PHYSICS CONFIGURATION

/MPAS-Model/src/core_atmosphere/physics/physics_wrf

```
./
../
LICENSE
Makefile
bl_mynn_post.F
bl_mynn_pre.F
libmassv.F
module_bep_bem_helper.F
module_bl_gwdo.F
module_bl_mynn.F
module_bl_ysu.F
module_cam_error_function.F
module_cam_shr_kind_mod.F
module_cam_support.F
module_cu_gf.mpas.F
module_cu_kfeta.F
module_cu_ntiedtke.F
module_cu_tiedtke.F
module_mp_kessler.F
module_mp_radar.F
module_mp_thompson.F
module_mp_thompson_cldfra3.F
module_mp_wsm6.F
module_ra_cam.F
module_ra_cam_support.F
module_ra_rrtmg_lw.F
module_ra_rrtmg_sw.F
module_ra_rrtmg_vinterp.F
module_sf_bem.F
module_sf_bep.F
module_sf_bep_bem.F
module_sf_mynn.F
module_sf_noah_seaice.F
module_sf_noah_seaice_drv.F
module_sf_noahdrv.F
module_sf_noahlsm.F
module_sf_noahlsm_glacial_only.F
module_sf_oml.F
module_sf_sfcdiags.F
module_sf_sfclay.F
module_sf_sfclayrev.F
module_sf_urban.F
sf_mynn_pre.F
```

- most files are similar to the ones developed for WRF.

MPAS
Model for Prediction Across Scales

PHYSICS CONFIGURATION

/MPAS-Model/src/core_atmosphere/physics/physics_mmm

```
./            bl_gwdo.F                bl_ysu.F              mp_radar.F              mynn_shared.F
../           bl_mynn.F                cu_ntiedtke.F         mp_wsm6.F               sf_mynn.F
Makefile      bl_mynn_subroutines.F    module_libmassv.F     mp_wsm6_effectRad.F     sf_sfclayrev.F
```

- initial set of parameterizations that are void of WRF centric sourcecode starting in MPAS-v8.0.0.
- shared by MPAS, WRF, and CM1.
- will later be downloaded from a github shared-physics repository maintained by MMM.
- parameterizations in ./../physics_wrf are being moved to ./physics_mmm.
- corresponding modules in ./../physics_wrf are simplified and updated.
- see “Physics updates in MPAS”, WRF&MPAS workshop 2024”.

PHYSICS CONFIGURATION
structure of a physics driver

/MPAS-Model/src/core_atmosphere/physics/physics/mpas_atmphys_driver_convection.F:

```
!=============================================================================================
 subroutine driver_convection(itimestep,configs,mesh,sfc_input,diag_physics,tend_physics,its,ite)
!=============================================================================================
!input arguments:
 type(mpas_pool_type),intent(in):: configs
 type(mpas_pool_type),intent(in):: mesh
 type(mpas_pool_type),intent(in):: sfc_input
 integer,intent(in):: its,ite
 integer,intent(in):: itimestep

!inout arguments:
 type(mpas_pool_type),intent(inout):: diag_physics
 type(mpas_pool_type),intent(inout):: tend_physics
 ...
!---------------------------------------------------------------------------------------------

 call convection_from_MPAS(...)

!--- CALLS TO PARAMETERIZATIONS:
 convection_select: select case(convection_scheme)
    case ("cu_grell_freitas")
       call cu_grell_freitas  ( &
                              )
    case ("cu_kain_fritsch")
       call  kf_eta_cps       ( &
                              )
    case("cu_tiedtke")
       call cu_tiedtke        ( &
                              )
    case("cu_ntiedtke")
       call cu_ntiedtke_driver( &
                              )
    case default
 end select convection_select

 call convection_to_MPAS(...)

 end subroutine driver_convection
!=============================================================================================
```

interface between global arrays defined in Registry and arrays local to parameterizations for

- initialization before call to parameterization (…_from_MPAS); expands individual pools into local arrays.
- update after call to parameterization (…_to_MPAS); puts updated arrays back into respective pools.

PHYSICS CONFIGURATION: timestep

0. Physics Initialization
reads input data and initializes variables once at the beginning of a forecast.

- read the gridded lat-lon monthly-mean ozone climatology and interpolate the data to the MPAS mesh.
- read input properties of individual land use category.
- read input tables needed for the land surface scheme.
- read input tables needed for the long-wave and short-wave radiation schemes.
- read input tables for the cloud microphysics schemes.
- other initializations.

call physics_init (…)

./src/core_atmosphere/physics/physics_wrf/files

PHYSICS CONFIGURATION: timestep

1. call to physics_driver

compute physics tendencies, top-of-the-atmosphere and surface fluxes, and diagnostics. MPAS uses a *process-split* approximation that parameterizations have the same input state.

- 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.

call physics_driver (…)

1) call driver_cloudiness (…)
2) call driver_radiation_sw (…)
3) call driver_radiation_lw (…)
4) call driver_sfclayer (…)
5) call driver_lsm (…)
6) call driver_pbl (…)
7) call driver_gwdo (…)
8) call driver_convection (…)

PHYSICS CONFIGURATION: timestep

2. add physics tendencies in dynamical core,
multiply tendencies by mass, and add tendencies to state variables

$$F_{\Theta_m} = \left(\frac{\partial \Theta_m}{\partial t}\right)_{cu} + \left(\frac{\partial \Theta_m}{\partial t}\right)_{bl} + \left(\frac{\partial \Theta_m}{\partial t}\right)_{lw} + \left(\frac{\partial \Theta_m}{\partial t}\right)_{sw}$$

$$F_{Q_j} = \left(\frac{\partial Q_j}{\partial t}\right)_{cu} + \left(\frac{\partial Q_j}{\partial t}\right)_{bl}$$

see slide 2 on Description of Atmospheric Solver

call physics_get_tend(…)

call to dynamical core

3. cloud microphysics

call driver_microphysics(…)
Relative humidity is 100%
back to step 1

PHYSICS CONFIGURATIONS

- In MPAS-v8.1.0, 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 organized in physics suites (by design; some additional parameterizations are not in suites).

./src/core_atmosphere/physics/

- *physics_wrf*: copied directly from WRF as in earlier versions of MPAS.
- *physics_mmm*: cleaned from WRF centric sourcecode starting in MPAS-v8.0.0. see “Physics updates in MPAS, WRF&MPAS workshop 2024”.

PHYSICS CONFIGURATIONS

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

```
<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*.
    - A few parameterizations are not part of a physics suite, but can be used in a suite.

PHYSICS CONFIGURATIONS
config_physics_suite = “…”

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

- 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 FRACTION.

PHYSICS OPTIONS: 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'
```

in mpas_atmphys_control.F

- As the Grell-Freitas scheme, the nTIEDTKE deep convection scheme is sensitive 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 OPTIONS: 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'
```

in mpas_atmphys_control.F

- 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.

HOW TO MODIFY PHYSICS NAMELIST OPTIONS IN NAMELIST.ATMOSPHERE

- the default physics suite is the *mesoscale-reference* suite.

```
&physics
    config_physics_suite            = 'convection_permitting'
/
```

- do as shown below to not run the long-wave and short-wave radiation codes, and clouds.

```
&physics
    config_physics_suite            = 'convection_permitting'
    config_radt_lw_scheme           = 'off'
    config_radt_sw_scheme           = 'off'
    config_radt_cld_scheme          = 'off'
/
```

- do as shown below to not substitute a parameterization with another. All the other parameterizations in the suite would remain as in the default suite.

```
&physics
    config_physics_suite            = 'convection_permitting'
    config_convection_scheme        = 'cu_ntiedtke'
    config_microp_scheme            = 'mp_wsm6'
/
```

ADDITIONAL 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.
- Several addition of parameterizations are running and making their way to the next MPAS releases (Noahmp land surface scheme, aerosol-aware Thompson microphysics, EPA physics suite, development of the GOCART chemistry).
- Contributions from developers and scientists interested in contributing to the MPAS physics using the existing framework.