**Description of Physical Parameterizations and Tunable Parameters in WRF-Solar2 based on WRF4.1.2.**

**1. Thompson aerosol aware (ThomA) microphysics scheme (Thompson et al. 2008):**

**1.1. Treatment of aerosol processes/properties**

When the namelist variable, '**use\_aero\_icbc**' is set to false, The ThomA scheme will assume all model horizontal grid points have the same vertical profile of water nucleating aerosols () and ice nucleating aerosols (). These parameters are controlled by the parameter settings at the top of '**phys/module\_mp\_thompson.F**'. The profile starts with naCCN0 (e.g., 300 per cubic centimeter, adjustable) near the surface and exponentially decays to naCCN1 (e.g., 50 per cubic centimeter, adjustable) which is the free tropospheric value of CCN. A set of similar variables are used for IN. These settings are done once at model initial time (inside subroutine thompson\_init) regardless of land versus ocean or other potential geographic information.

When the namelist variable, '**use\_aero\_icbc**' is set to true. ThomA scheme uses a monthly aerosol climatology placed into WRF through the WPS program. The aerosol climatology is derived from multi-year (2001-2007) global model simulations by the Goddard Chemistry Aerosol Radiation and Transport (GOCART) Model, and the aerosol number concertation is derived from the mass mixing ratio based on log-normal distribution. GOCART model simulates multiple aerosol species, while ThomA scheme simplifies aerosol treatment by accumulating dust mass larger than 0.5 micron into and combining all other species besides black carbon as an internally mixed cloud droplet–nucleating, hygroscopic, CCN mode .

During model integration, the and variables are advected and diffused exactly as other scalars (e.g., cloud ice number concentration), and a zero-gradient lateral boundary condition also follows the other scalars. A fake surface aerosol emissions/flux (constant through time) is computed as a 2D field (computed in subroutine thompson\_init and held in variable called nwfa2d) based on horizontal grid spacing and starting aerosol number concentration for the variable,

(1.1)

The 2D tendency field is added each time step to the first model vertical level value. Thus the aerosol number concentration remained very close to the climatological condition over most of the domain, No surface emission tendency is applied for .

**1.2. Cloud droplet nucleation**

Cloud droplet nucleation from water friendly aerosol () in ThomA scheme uses a lookup table of activated fraction based on the given temperature, vertical velocity, number of available aerosols, and pre-determined values of hygroscopicity parameter and aerosol mean radius. The lookup table was created using these five variables in a parcel model (Feingold and Heymsfield 1992). But the aerosol hygroscopicity and mean radius are fixed at 0.4 and 0.04 micron in ThomA scheme when creating the look up table for droplet activation. In addition, the aerosol sizes are assumed to follow lognormal distribution with a constant geometric standard deviation at 1.8. The activation of aerosols is considered at the cloud base and inside cloud where the lookup table is greater than the existing droplet concentration. After the activation, the participating aerosols are removed from the aerosol population, though they can be restored as regenerated aerosols via hydrometeor evaporation in which one aerosol is returned to for each cloud or rain drop evaporated.

It is not feasible to tune the table, but when the field of is not provided from the input data, one may specify a fixed value of in the code. In our case, time and spatial varying is provided from the input data, thus no need to tune .

**1.3. Liquid water content and saturation adjustment**

The diffusional growth of individual cloud droplets is not explicitly considered in ThomA scheme; instead, the changes in the overall cloud water mixing ratio is considered through a simplified liquid saturation adjustment strategy (Dudhia 1989),

(1.2)

where , and are the mixing ratios of cloud water, water vapor and saturation water vapor. The equation implies that the cloudy grid cells are always at 100% relative humidity. If the air is subsaturated or supersaturated, the cloud water is increased or removed until the saturation is reached within one time step.

Both cloud droplet activation and condensational growth are not feasible to be tuned within current set of codes.

**1.4. Collection-related processes**

**1.4.1. Autoconversion in ThomA**

The autoconversion parameterization follows Berry and Reinhardt (1974), except that the droplet spectrum follows the gamma distribution while Berry and Reinhardt used a slight different generalized Golovin distribution. The essence to compute characteristic diameters is the same. The autoconversion rate for rain water is

(1.3a)

where the characteristic diameters are,

(1.3b)

(1.3c)

(1.3d)

in which is the moist air density, is the water density, is the cloud water mixing ratio, is the cloud droplet number concentration, is the shape parameter of the cloud droplet spectrum of the gamma droplet size distribution,

and is the slope parameter of cloud droplet. For double moment scheme, assuming spherical water droplets, are related to and through the relationship,

with this relationship can be solved for with parameterized in ThomA scheme using the following equation:

and the shape parameter is determined by cloud droplet number concentration through an empirical relation,

Equation (1.7) indicates that a maximum of is assumed, which corresponds to a minimum relative dispersion of 0.25?. The conversion rate for cloud droplet number concentration is diagnosed from PL and the mean volume diameter ,

The rain self-collection used in the ThomA code is

(1.9)

which considers the breakup of the rain drops, therefore the overall rain drop increases. Although the comment in the code refer to Seifert 1994, no corresponding paper were found for the given author name and year. The formula used is more consistent to Seifert and Beheng (2001) without considering droplet breakup.

**1.4.2. Hydrometeor type, density and related parameterizations**

Hydrometeor are divided into 5 categories in ThomA scheme including cloud droplets (D>1), rain drops (D>50), ice crystals (mass>kg and derived size limit based on given density), snow (D>200) and graupel (D>250). Fixed densities are used in ThomA scheme. But for snow, graupel and cloud ice, their densities may vary. Different densities affect the mass power law and fall speed power law parameters, thus the collision and aggregation processes.

The mass-dimentional power law depends on hydrometer types and densities,

(1.10)

where m is mass, D is particle diameter. For cloud water, rain, cloud ice and graupel, hydrometer particles are assumed spherical and . The density, , for each species is fixed and tunable. For snow, .

Fall speed power law depends on hydrometer types and densities (Schoenberg Ferrier 1994)

(1.11)

where are fixed parameters for each hydrometeor species.

**1.4.3 Collision and coalescence (collection, where species y collects species x):**

The integration form of the collection equation used is

(1.12a)

where is the mass water content of species y and is collision efficiency. Assuming , substitute velocity power-law and do the integration of the equation, then we have

(1.12b)

where is the slope parameter of Gamma distribution and is derived based on the particle number and shape parameter. Besides the fall speed law parameters, the only parameter specified in the equation is and is tunable. For snow collect ice, rain collect snow, rain collect graupel and rain collect ice, fixed values are set, but no specific ranges are provided in the reference. As for the collection of cloud droplets, depends on the stokes number and is pre-calculated and provided as a lookup table in the code. Similarly, if we replace the mass to number concentration in Eqn 1.5a, we will have the changes in number concentration of the collected particle x,

(1.13)

In ThomA scheme all the collection processes between two hydrometeors are based on the collection equation (CE) in either original form (Eqn. 1.12a) or approximated form (Eqn. 1.12b) shown above including the accretion. Different definitions of accretion were used in the literature. Accretion is sometimes reserved for the capture of supercooled droplets by snow or graupel. However, since we are talking about accretion as warm rain process, a more general definition suites better that larger precipitation particle overtakes and captures a smaller one. Since Eqn 1.12b assumes , it is also referred as accretional equation (Verlinde et al. 1990).

There are 26 source/sink terms related to the collection between hydrometeors of different sizes. For raindrop collecting cloud droplet, cloud ice, Eqn 1.12b is used. For raindrop collecting snow and graupel, the explicit solution of CE is precalculated and stored in a lookup table. For snow and graupel collecting cloud water, similar equation as Eqn 1.12b is used, but different shape parameters of the size distributions from cloud droplet and rain drop result in slightly different form of accretional equation. The wet scavenging of aerosol particles and changes in number concentration due to other accretional processes use Eqn. 1.13. is either pre-calculated in the look up table for each process except for (snow collect ice), (rain collect ice), (rain collect snow), and (rain collect graupel), which are provided as fixed values, and all fixed collection efficiencies are listed as tunable parameter in the table below.

**1.5. Diffusional growth of ice crystals**

The basic diffusional growth equation for a single ice particle is

(1.14)

where C is the electrical capacitance varying with crystal shapes (sphere v.s. plates/aggregates). Since different species are assumed with different shapes, different values of C correspond with different hydrometeor types. Following the derivation by Srivastava and Coen (1992), the complete set of diffusional growth equations is as following

where D is the diameter of particle, F is the ventilation coefficient, is the diffusivity of water vapor in air, is the saturation mixing ratio over ice, is the saturation with respect to ice, and the parameters and are

where is latent heat of sublimation, is thermal conductivity of air, is gas constant for water vapor, and T is temperature in Kelvin. Then integrating for all particles with different diameters leads to

where

is the part independent to particle diameter, and C is different for ice and snow due to different shapes. Two basic values of electrical capacitance are provided in ThomA scheme, for spherical particles and for plates/aggregates. Ice particles are assumed to be spherical while snow has variable electrical capacitance decreasing from 0.5 (spherical) to 0.3 as temperature increasing from to via the following equation,

in which and are tunable.

**1.6. Calculation of effective radius in ThomA**

ThomA scheme calculates effective radius, , for cloud droplets, rain?, cloud ice, and snow by definition, e.g. the 3rd moment divided by the 2nd moment. For the gamma distribution it is . Since the shape parameter and slope parameter are calculated based on Nc and qc the relative dispersion is not fixed when calculating effective radius in the ThomA scheme.

The ThomA scheme does not make use of relative dispersion directly; but it is equivalent to considering the relative dispersion via the relationship between m and dispersion for the Gamma function such that

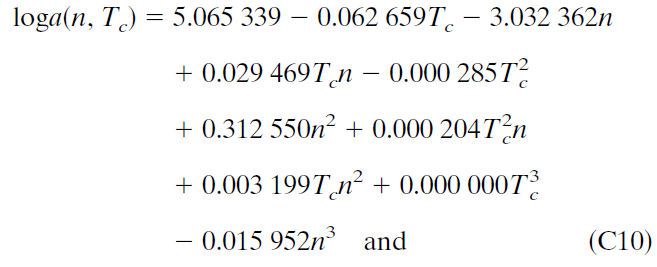
Where rv is the mean volume radius and is a dimensionless parameter related to the relative dispersion as

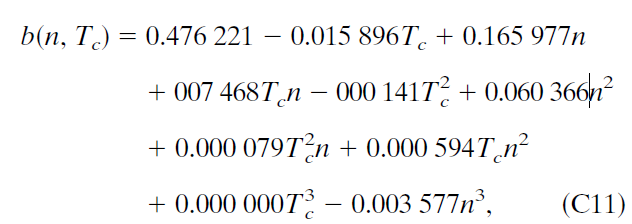
where is relative disperion, For gamma distribution, the relation between and is

Or

In calculation of for snow, the ThomA scheme makes use of the second moment to calculate all other moments following a scaling method by Field et al. (2005),

where a and b are two constants determined by the moment order n and temperature ,





**2. BNL microphysics schemes**

**2.1. Introduction**

At this point, only cloud-to-rain autoconversion processes and effective radius in liquid water clouds in ThomA are replaced with the BNL parameterizations. . Briefly, The autoconversion rate of the mass, , and the number, of cloud water are expressed by

where is the normalized critical mass defined as

and is the critical radius given by

Note that the current scheme lumps all unknown effects (likely from turbulence-related processes) into the empirical condensation rate constant, , that can be tuned for optimal turbulence effect.

When the BNL parameterizations are used, e.g. dispers is greater than 0, a parameterized effective radius for cloud droplets, , is used based on eqns 1.18 and 1.19. Note that no lower limit is provided for using BNL parameterization. The lower limits for and in ThomA scheme are 2.5 and 5 micron respectively. These lower limits of effective radii from ThomA scheme are smaller than the default lower limits in RRTMG scheme, which make some of the limits in RRTMG tunable.

In BNL scheme 1, we treat relative dispersion and condensation rate constant, as tunable parameters with the ranges given in Table 1.

BNL scheme 2 will diagnose relative dispersion from the empirical relationships between relative dispersion and droplet concentration, , with tunable parameter(s) to quantify the specific dependence of relative dispersion on aerosols. This will eventually be replaced BNL scheme 3 that prognoses relative dispersion.

Set the dispersion option to 1 to use fixed value before tuning (BNLscheme 1), or chose other options (2-5) for parameterized based on droplet number concentration (BNL scheme 2, See the table below). Code has been modified to specify the dispersion options directly in the code (might be easier for tuning) instead of passing the parameters to namelist.input (better for operational runs).

**2.2 Entrainment Mixing Parameterization (available only in the latest version)**

In the later versions of BNL scheme, we also included an entrainment mixing parameterization (Lu et al. 2013, 2014). It considers the evaporation of the cloud water due to entrainment mixing through the following relation,

where and are the number concentration of cloud droplets and mixing ratio after the evaporation process, while and are corresponding properties before evaporation. In the above relation, the properties after evaporation is related to the pre-evaporation conditions through representing the homogeneous mixing degree with a value between 0 to 1. In this parameterization, we use a different homogeneous mixing degree, (Lu et al. 2013). is further related to the transition scale number, , through the empirical power law relation,

in which and are related

A typical value of a = 52 is used as a default value but a can be treated as a tunable parameter varyin between 10-100.

is a dynamical measure of homogeneous mixing degree that can be diagnosed as follows (Lu et al. 2011),

where is the transition scale length proposed by Lehmann et al. (2009) to simplify the the representation of entrainment-mixing processes by removing the need to consider the size of entrained turbulent eddy, and is a function of the TKE dissipation rate, , and evaporation time, ,

and the Kolmogorov microscale is calculated by

where is the kinematic viscosity determined by the temperature. The TKE dissipation rate is estimated using the characteristic velocity, and the corresponding length scale, (Andrejczuk et al. 2009),

The is taken as the scale of cloud filaments in the application and assumed to be the Taylor microscale for the cloud water field. Using the internal ranges scaling, , with L being model grid size and the corresponding velocity , the dissipation rate can be estimated by,

As for , the calculation is based on the diffusional growth equation,

where r is the droplet radius, is the super/sub-saturation of the dry air, e.g. , and

in which is the latent heat of evaporation, is the specific gas constant for water vapor, is the density of liquid water, is the coefficient of thermal conductivity of air, is the coefficient of diffusion of water vapor in air, and is the saturation vapor pressure over a plane water surface at temperature T. Then can be obtained by integrating the diffusional equation from r to r=0, e.g.,

Note that the relative humidity of dry air, is needed to calculate in the diffusional growth equation. Since the model does not provide directly in the microphysics scheme, we estimate the using the cloud fraction, CF, and the averaged RH in the model grid as follows. First,. assuming that the cloudy part of the grid box is saturated (RHc =1) and has the same temperature as the cloud-free part, we have

An alternative way is to approximate as the “critical relative humidity” , that is used in cloud fraction parameterization and normally reflect the strength of subgrid cloud variability (Quaas 2012),

The two ways of calculation result in different values with normally lower than the depending on the cloud fraction CF and grid RH and the real lies likely between the two values. Thus, we propose a simple equation to combine the two methods and find a intermediate value,

where c is related likely to sub-grid cloud variability meriting further investigation, but can be treated as a tunable parameter before a general expression is obtained. For the current version of entrainment mixing parameterization, is implemented in the model and we are implementing which will be available in the future version model.

Microphysics scheme does not provide CF needed to calculate either. Thus we use the CF parameterization following Xu and Randall (1996) with different fitting parameters optimized to a shallow cumulus case which will be discussed in Section 3.2. Note that the parameterized CF in the entrainment mixing process is locally available in the BNL microphysics scheme, a separate calculation of CF in the radiation driver using the original Xu and Randall’s formula is the default input of CF to radiative scheme in WRF model.

**2.3. List of potential parameters in “BNL” microphysics**

A list of tunable parameters in the microphysics scheme is provided below. Note that if no reference is found for the range, a percentage of +/-15% is recommended for start. “-” indicates that a parameter is not preferred to be tuned in combination of other tuning parameters. The parameters related to entrainment mixing in blue color are only available in the latest version of microphysics. Yellow colored parameters will be implemented in the up coming versions of the code.

Path: /WRF/phys/module\_mp\_thompson.F

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameters | Description | Default Value | Range | Code |
|  | Density of snow | 100, kg/m^3 | 50-200, kg/m^3 | rho\_s, Line 88 |
|  | Density of graupel | 500, kg/m^3 | 450-700, kg/m^3 | rho\_g, Line 89 |
|  | Density of ice | 890, kg/m^3 | 700-900, kg/m^3 | rho\_i, Line 90 |
|  | Mass power-law constant | Snow: 0.069 | 0.0185-0.176(Cotton et al. 2013) | am\_s, Line 139 |
|  | Mass power-law constant | Snow: 2 | 1.9-2.2 | bm\_s, Line 140 |
|  | Fall speed power-law constant | Rain: 4854  Ice: 1847.5  Snow: 40  Graupel: 442 | Rain: 15 %  Ice: 336-1847.5  Snow: 129.6-40  Graupel: 351.2-442 | R: av\_r, L149  I: av\_i, L157  S: av\_s, L152  G: av\_g, L155 |
|  | Fall speed power-law constant | Rain: 1  Ice: 1  Snow: 0.55  Graupel: 0.89 | Rain: -  Ice: 0.6635-1  Snow:0.42- 0.55  Graupel: 0.37-0.89 | R:  I: bv\_i, L158  S: bv\_s, L153  G: bv\_g, L156 |
|  | Fall speed power-law constant | Rain: 195  Ice: 0  Snow: 125  Graupel: 0 | Rain: -  Ice: -  Snow: 100-125  Graupel: - | R:  I:  S: fv\_s, L154  G: |
|  | Capacitance of hydrometeors | Sphere: 0.5  Plates/aggregates: 0.15 | Sphere: 15%  Plates/aggregates: 15% | S: C\_cube, L163  P: C\_sqrd, L164 |
|  | Collection efficiencies, y collects x | si: 0.05  rs: 0.95  rg:0.75  ri: 0.95 | si: 15 % within 0-1  rs: 15 % within 0-1  rg: 15 % within 0-1  ri: 15 % within 0-1 | si: Ef\_si, L170  rs: Ef\_rs, L171  rg: Ef\_rg, L172  ri: Ef\_ri, L173 |
|  | Condensation rate constant. Set turbopt (L77) to 1 to use tunable | 1.15E23, s^-1 | 1.02E20 – 1.67e24 (Liu et al. 2004) | beta\_con, L78 |
|  | Options for relative dispersion. Use option 1 for tunable values. Other options are for specific relations currently not to be tuned. | 1 | 1,2,3,4,5 | dispers, L68 |
|  | Relative dispersion of cloud droplet spectrum, set dispers to 1 before tuning | 0.1 | 0.01 to 1.4 | vdis, L69 |
|  | Lower limit of hydrometeor diameters | Cloud:1e-6, m  Rain: 50e-6, m  Snow: 200e-6, m  Graupel: 250e-6, m | C: [0.5e-6, 2e-6]  R: [50e-6, 100e-6]  S: [150e-6, 250e-6]  G: [200e-6,300e-6] | C: D0c, L220  R: D0r, L221  S: D0s, L222  G: D0g, L223 |
| *entrmix\_opt* | Option of entrainment mixing | 0, no entrainment mixing turned on | 0, 1, 2, 3  0: no entrainment mixing  1: entrainment mixing for cumulus case  2: entrainment mixing for stratocumulus case  3: entrainment mixing considering  , and | Modify in the namelist.input physics section |
| *entrcf\_opt* | Option of cloud fraction parameterization used in entrainment mixing process | 0, Xu and Randall’s 2 parameter formula with Xiaoqi’s fitting | 0, 1, 2  0: two-parameter formula + Xiaoqi’s fitting  1: three-parameter formula + Xiaoqi’s fitting  2: original three-parameter formula | Modify in the namelist.input physics section |
| *entrmix\_a* | The intercept parameter in the power law relation between homogenous mixing degree and transition number . It only works when *entrcf\_opt*=3 | 52 | 10 - 100 | Modify in the namelist.input physics section |
| *entrRHd\_c* | Adjustment parameter in the RHd calculation | 1, using the RHd1 calculation | 0 - 1 | Modify in the namelist.input physics section |

ThomA uses variable rain intercept parameter within a specific range, but the code implements a table of intercept parameter limits which seems not consistent with the description in Thompson et al. 2008. It is possible that the tabled value is pre-calculated, thus tuning the limits of intercept parameter is not feasible. The lower limits of the particle sizes are specified and may be tunable.

**3. The RRTMG radiation scheme and radiation related parameterizations:**

**3.1. Lower limits of effective radius used in RRTMG**

Effective radius in RRTMG are treated in two ways now: 1) using default values for each hydrometeor types; 2) take as inputs from the cloud microphysics schemes such as ThomA.

**3.1.1. lower limit of input effective radius to RRTMG**

When ThomA scheme is used and the calculated effective radius is passed as inputs to RRTMG, the incoming effective radii in RRTMG scheme for each hydrometeor type is regulated to specific ranges before any calculations. When selected microphysics scheme does not calculate effective radius, two options of default re parameterization are available within RRTMG by setting the flags inflagsw and iceflagsw (inflaglw and iceflaglw for LW scheme). When inflagsw ≥ 3, and iceflagsw ≥ 4. The default re\_cloud, re\_ice, and re\_snow are fixed at 5, 10, and 10 micron respectively.

For inflagsw < 3, and iceflagsw < 4, re\_liq and re\_ice are parameterized while a fixed value of re\_snow=10 micron is used. Specifically, for re\_cloud parameterization, the default sizes over land, ocean and sea ice are 8, 14, and 14 micron at 273.16K. Then re\_liq is scaled between 8 – 14 micron depending on the given temperature, snow depth, land fraction and sea ice fraction, e.g.,

1) temperature-dependent scaling

2) snow-depth-dependent scaling, snow depth used is water equivalent in meters

3) land-fraction-dependent scaling

4) sea-ice-fraction-dependent scaling

As for the re\_ice, parameterized values are tabulated in RRTMG assuming hexagonal columns and a dependence on temperature from 180K to 274K, but the reference the author provided does not match the code.

Note that the lower limit of snow size in ThomA scheme is much larger (D=200 micron) than the lower limit of the corresponding effective radius in RRTMG (10 micron), therefore adjusting the lower limit of effective radius of snow in RRTMG may have little effect when using ThomA scheme calculated effective radius.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| Lower limit of the RRTMG input effective radius | SW: 2.5 micron  LW: 2.5 micron | SW: 5 micron  LW: 5 micron | SW: 10 micron  LW: 10 micron |

By the way, if selected microphysical scheme does not calculate re, the default value of re ice and re snow in RRTMG are switched in SW and LW code. Is this a mistake? Or different values of re should be used in SW an LW code? Suppose re snow should be larger than re ice, thus the LW code is wrong. The coding error only affect the results when setting inflagsw/inflaglw < 3 and iceflagsw/iceflagsw < 4, but these are not popular choices. In our case, ThomA scheme calculates re and passes the value to RRTMG scheme, thus the coding error does not affect our simulations.

**3.1.2. Lower limit of effective radius used to calculate cloud optical depth**

Later in the RRTMG scheme, the cloud optical depth for SW and LW are calculated based on the following formulas,

where and are the extinction coefficient for SW and absorption coefficient for LW, the subscript , and represent cloud water, ice, and snow respectively; LWP, IWP, and SWP are the accumulated water path for cloud water, ice, and snow respectively. Specifically, the water path of a hydrometeor type is calculated for each model level in RRTMG as following,

where x represents the hydrometeor species, dp is the thickness of the layer in pressure, g is the gravitational acceleration. Then the in-cloud water path, , is calculated by dividing the cloud fraction.

which is used to represent the cloud fraction of sub-grid-columns during the Monte-Carlo Independent Column Approximation in Section 3.3. With different overlap assumption and sampling of sub-columns, the average of in-cloud water path among all sub-columns is made equal to the grid scale value .

The extinction and absorption coefficients for each hydrometeor category are tabulated for different values of effective radius with an interval of 1 micron for re\_cloud and 3 micron for re\_ice and re\_snow. Note the lower limits of effective radii in the table are prescribed and different from the limit on input effective radius for some species. Therefore, the lower limit of input re in section 3.1.1 is tunable.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| Lower limit of the table | SW: 1.5 micron  LW: 2.5 micron | SW: 5 micron  LW: 5 micron | SW: 5 micron  LW: 5 micron |

**3.2. Cloud fraction parameterization**

Cloud fraction is used in the radiative calculation and have very important role in radiative transfer. Cloud fraction is calculated in the radiation driver, which collects all the cloud water generated from individual schemes including microphysics, convection and PBL schemes, then passes the calculated cloud fraction to radiation scheme. WRF has limited options to calculate cloud fraction and the Xu-Randall parameterization is a popular one and used in our study **(Xu and Randall 1996):**

where RH is the grid relative humidity, ….; are three empirical parameters based on the GATE simulation. Note that the parameters are optimized to least underestimate middle troposphere (p) with a best match of maximum cloud fraction at lower and upper troposphere ().Note that the GATE simulation underestimates low level clouds, thus the parameterization may be sensitive to the underestimate of simulated low-level clouds. The decrease of with an increase of from default values gives an overestimate of the maximum in the lower troposphere.

The Xu-Randall expression is based on simulations (provide domain, resolution and cloud type here). In Xiaoqi’s work, a different set of empirical values based on a WRF-Solar-LES simulations of a shallow cumulus case such that . It seems to me that Xiaoqi’s fitting is optimized towards the shallow clouds, while XR1996 is optimized towards a vertical profile of clouds with two maxima at lower and upper troposphere. Decreasing and increasing is the right direction to enhance low level clouds. Xiaoqi’s fitting is an extreme case towards the shallow clouds. Based on these studies, we estimate the range of variations for the three parameters in Table 2. Since the two fittings are based on different models at different resolutions and for different clouds, we can tune the three parameters in general for now.

**3.2. Cloud overlap assumption**

To represent the cloud variability in the sub-grid scale, the Monte-Carlo Independent Column Approximation (McICA) is used to generate the stochastic sub-columns of clouds. Given a profile of cloud fraction, cloud water and cloud ice, McICA produces a set of sub-columns. Each layer within each sub-column is homogeneous, with cloud fraction equal to zero or one with uniform cloud liquid and cloud ice concentration. The ensemble as a whole reproduces the probability function of cloud liquid and ice within each layer and obeys an overlap assumption in the vertical.

Four overlap assumptions are available in current version of RRTMG (the exponential random option is still underdevelopment). They are,

1 – random: pick random value at every level

2 – maximum-random: pick a random value for top layer then walk down the column. If the layer above is cloudy, then the same random umber is used; if the layer above is clear, then we use a new random number.

3 - maximum: pick the same random number at every level

4 – exponential: weighting between maximum and random overlap increases with the distance

The default is option 2, maximum-random overlap.

**3.4 Diffusivity angle / diffusivity factor (Liou 2002)**

Diffusivity angle, , converts spectral transmittance, to diffuse transmittance at a given ? and the latter is required in the flux calculation.

(3.8)

where and are optical depth and specified wavenumber. For IR radiative transfer, a good approximation for ranges from 1.66 to 2. RRTMG use variable diffusivity angle for some bands, but a fixed value of 1.66 for the rest bands which is tunable.

Path of the code:

/WRF/phys/module\_ra\_rrtmg\_sw.F (SW in the table)

/WRF/phys/module\_ra\_rrtmg\_lw.F (LW in the table)

/WRF/phys/module\_radiation\_driver.F (DR in the table)

/WRF/runwrf/namelist.input

Table 2. Empirical parameters in RRTMG

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Description | Default Value | Range | Code |
|  | Effective radius of cloud droplets | 5.0 micron | 2.5 - 10 | SW: recloud1D, L10561  LW: recloud1D, L12115 |
|  | Lower limit of input | 2.5 micron | 1.5 – 2.5  (See SW: L2302 for the bounds) | Hard coded in  SW: L10549, 10550, 10553  LW: L12104, 12105, 12108 but prefer not to be tuned based on the table limit LW absorption coeffcient |
|  | Effective radius of cloud ice | 10 micron | 5 - 15 | SW: reice1D, L10584  LW: reice1D, L12136 |
|  | Effective radius of snow | 10 micron | 10 - 25 | SW: resnow1D, L10584  LW: renow1D, L12136 |
|  | Lower limit of input | 10 micron | 5 - 10  (See SW: L2234, and LW: L2890 for the bounds) | Hard coded in  SW: L10592  LW: L12162 |
|  | Cloud overlap option in RRTMG | 2 – maximum randum | 1, 2, 3, 4 | Two ways to set the parameter:  1) set cldovrlp=2 in the physics section of namelist.input  2) SW: cldovrlp, L10532  LW: cldovrlp, L12086 |
|  | Diffusivity angle | 1.66 | 1.50 - 2 | LW: secdiff, L3168 |
|  | Cloud fraction scheme constant | 0.25 | 0.25 - 15 | DR: PEXP, L3480 |
|  | Cloud fraction scheme constant | 0.49 | 0.01-0.49 | DR: GAMMA, L3479 |
|  | Cloud fraction scheme constant | 100 | 100-3e6 | DR: ALPHA0, L3479 |

**4. The GF cumulus scheme:**

The GF cumulus scheme **(Grell and Freitas 2014)** is developled for both deep and shallow convections, and the shallow convection parameterization can be turned off independently from the deep convection parameterization through the namelist.input parameter “**ishallow**”. In our case, an alternative shallow convection parameterization is used instead of GF shallow convection parameterization. Specifically, the shallow convection is considered in the MYNN-EDMF that unifies the treatments of shallow convection, PBL physics and turbulence. Several tuning parameters are already set in the code of GF scheme which are not found in the reference. The code is very difficult to read with limited comments and peculiar variable names. In this case, the formula used in the code is provided in comparison with the process described in the paper.

Note that cumulus scheme only output cloud water, the cloud fraction is calculated in the radiation driver which prepare the cloud properties for radiation schemes.

**4.1 Tuning constant for cloudwater/ice detrainment, c1 or c1d,**

Formula in the code,

dellaqc = zuo \* c1d \* qrc \* dz / dp \* g

where dellaqc is the change of qc per unit mass flux of cloud ensemble; zuo is nomalized updraft mass flux; qrc is the liquid water content in cloud after rainout. Note that the tuning parameter is not explicitly presented in (Grell and Freitas 2014) considering the process. The original formula is

where and are the ensemble averaged fluxes for water vapor and cloud liquid water. is the ensemble averaged convective precipitation. And the fluxes can be calculated as follow,

where mu and md are mass fluxes within the updraft and downdraft, and l is the mixing ratio of liquid water. And the mass fluxes are then normalized by the mass flux at cloud base,

where is the entrainment rate.

The entrainment rate is calculated using the formula

where and are entrainment and detrainment rate, and is the normalized mass flux. In the code, a normalized mass flux profile from updraft origination level to the cloud top is calculated. Then a prescribed close-zero constant detrainment rate (1.0e-9) for these levels are used to calculate the entrainment rate from the originating level to the level with maximum mass flux, then the detrainment rate is updated from the level with maximum mass flux to the cloud top.

**4.2. Calculation of moisture properties in the code**

Moisture properties in the calculation, notations following the code:

qc – total mixing ratio of water substance

qrc – liquid water in cloud after rainout

pw – precipitation

qv – water vapor mixing ratio

qvs – saturation water vapor mixing ratio

The scheme does consider the entrainment in the calculation. The calculations of the above moisture properties are as following

where k represent the values on the k-th level. When qc > qvs then update the cloud water,

where is autoconversion rate fixed at 0.004 for warm conditions and 0.002 when temperature is smaller than 270 K, and the value is tunable in the code. The corresponding precipitation is

After the calculation of , on the k-th level is updated

**4.3. Tuning for shallow and mid convection, flux\_tun**

Formula in the code,

zws = max(0., flux\_tun \* 0.41\* buo\_flux \* zo \*g / T)

ztexec = max(flux\_tun \* hfx / (rho \* zws \* cp), 0.0)

zqexec = max(flux\_tun \* qfx / xlv / (rho \* zws), 0.)

where zws is the convective-scale velocity derived from similarity theory; ztexec and zqexec are temperature and moisture excess.

To optionally increase diurnal forcing, an excess temperature and moisture perturbation is added when calculating the forcing and checking for trigger functions. And the perturbations are proportional to surface fluxes,

where H and LE are sensible and latent heat fluxes coming from land surface model, L is the latent heat of evaporation, and is the convective-scale velocity (with no formula provided in the paper, see below and take from the same surface-layer scheme?)

Path of the code:

/WRF/phys/module\_cu\_gf\_deep.F (DP in the table)

/WRF/phys/module\_cu\_gf\_sh.F (SH in the table)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Description | Default Value | Range | Code |
|  | Tuning constant for cloudwater/ice detrainment | 0.001 | 0.0005 – 0.0015 | DP: c1, L8 |
|  | Fixed autoconversion rate for deep convection | 0.004 | 0.002-0.005 | DP: c0, L3423, L3450 |
|  | Fixed autoconversion rate for shallow convection | 0.001 | 0.0005 – 0.0015 | SH: c0\_shal, L48 |
|  | Tuning parameter for shallow and mid convection | 1.5 | 1 - 2 | DP: fluxtune, L19  SH: fluxtune, L49 |

### **5. MYNN PBL scheme**

The MYNN PBL parametrization scheme (Nakanishi, 2001; Nakanishi and Niino, 2006; 2009) was developed based on the Mellor–Yamada (MY) turbulence closure model (Mellor and Yamada, 1974; 1982) but with a new relation for the turbulent length scale and re-estimated constants (Nakanishi, 2001). Nakanishi and Niino (2004) further updated the model by introducing a more efficient algorithm for the MY level-3 model. Here the level-2.5 MYNN scheme is used, and the basic formulae relevant to the present study are briefly introduced. Following Nakanishi (2001), and Nakanishi and Niino (2006; 2009), capital and small letters denote ensemble-mean and turbulent variables, respectively, an angle bracket indicates an ensemble average, and a subscript 0 refers to a reference state.

In the level-2.5 model, the TKE, , (define q) is predicted while the other covariances such as and (where is the liquid water potential temperature) are computed diagnostically. The dissipation rates, pressure covariance, and third-order turbulent fluxes are parameterized. In the MYNN model, the dissipation rates of TKE and temperature variance are given as

, (5.1)

, (5.2)

where *L* is the turbulent length scale (see Eqs. 5.9-5.12), and and are closure constants.

The pressure covariance is parametrized as

, (5.3)

, (5.4)

where are the velocity components, *p* is the pressure, is the air density, is the virtual potential temperature, and is the Kronecker delta. , , and are closure constants, and the terms with and ( and ) represent the effects induced by shear (buoyancy). The term is eliminated based on Nakanishi and Niino (2009). Some closure constants are interconnected, including

, (5.5)

, (5.6)

, (5.7)

where *Pr* is the turbulent Prandtl number. Note that the term is fixed with the default value of in the WRF model code to make the model more stable (Joseph Olson, personal communication, 2015).

By using the parametrizations, including those in Eqs. 5.1–5.4, the prognostic and diagnostic equations of turbulent variables can be solved and the second-order turbulent fluxes are derived in the form of

, (5.8)

where is the stability function for momentum, and analogous forms are applied for , , and .

Based on a large-eddy simulation database, the MYNN model introduced a new diagnostic equation for the turbulent length scale *L*

, (5.9)

, (5.10)

, (5.11)

, (5.12)

where *k* is the von Kármán constant, is the dimensionless height, is the Obukhov length, *N* is the Brunt-Väisälä frequency, and  is analogous to the Deardorff convective velocity scale but with the mixed-layer depth replaced with . The value of *L* (Eq. 5.9) is mainly controlled by the smallest length scale among , and , where is the length scale in the surface layer and less important at higher altitude, is the length scale that depends on the planetary boundary layer height (PBLH), and is related to the buoyancy length scale . The constants and need to be determined.

We blended the two definitions such that PBLH defined with theta (i.e., *ziθ*) will dominate for neutral and unstable conditions (when *ziθ* > 200 m), while PBLH defined with TKE (i.e., *ziTKE*) will dominate for stable conditions (*ziθ* < 200 m), where *ziθ* is used as an indicator of stability. We used a hyperbolic tangent for blending the two definitions:

, (5.13)

, (5.14)

where we set blending height determined by the denominator in the hyperbolic tangent argument (*zd*) to 400 m. This hybrid algorithm has been shown to accurately diagnose the PBLH throughout a diurnal cycle (Fitch et al., 2013). We took a virtual liquid water and ice potential temperature-based version of the boundary layer height definition (ziθ) of Nielsen-Gammon et al. (2008). This algorithm first searches the lowest 200 m of the atmosphere to find the height of the minimum virtual liquid and ice potential temperature *θvli=θvli\_min+Δθvli*. This helps to reduce the impact of surface-based superadiabatic layers on the diagnosis of ziθ. Then ziθ is determined to be the height at which *θvli=θvli\_min+Δθvli*, where *Δθvli* is set to 0.75 K over water and 1.25 K over land. We took the TKE-based definition of boundary-layer height (ziTKE) to be the height at which the TKE at the surface, TKEsfc, decreases to below a threshold value, TKEmin. We chose the quantity TKEmin to be 2.5% of the TKEsfc a criterion chosen independently by Kosovic and Curry (2000) as well as used in Cuxart et al. (2005). TKEmin is also bound to be greater than 0.02 m2 s-2 in the case of stagnant cold pools, where the lack of a lower limit can result in an excessively large estimate of ziTKE.

**6. Revised MM5 Surface-Layer Scheme**

The revised MM5 (Grell et al., 1994) surface-layer parametrization (Jiménez et al., 2012) is also used. The similarity functions in the original MM5 surface-layer scheme were estimated based on the Kansas field program (Izumi 1971) that applies to a limited range of atmospheric stabilities. Jiménez et al. (2012) updated the similarity functions with those proposed by Fairall et al. (1996) and Cheng and Brutsaert (2005), so as to make the scheme more suitable for the full range of atmospheric stabilities, including highly stable and unstable conditions.

The surface layer is assumed to be the first vertical layer and the surface fluxes are parameterized as follows:

, (6.1)

, (6.2)

, (6.3)

where τ, H, and LH are the fluxes of momentum, sensible heat, and latent heat, respectively; u\* and q\* are the temperature and moisture scales, respectively; ρ is the air density in the surface layer; cp is the specific heat capacity at constant pressure; and U is the wind speed in the lower layer enhanced by a convective velocity following Beljaars (1995) and a subgrid velocity following Mahrt and Sun (1995). This last correction only applies for horizontal grid resolutions higher than 5 km. Here Le is the latent heat of vaporization; M is the soil moisture availability; ua and ug are the air and ground surface potential temperature, respectively; qg is the saturated specific humidity at the ground; qa is the specific humidity in the surface layer; and Cd, Ch, and Cq are the dimensionless bulk transfer coefficients (Stull 1988) for momentum, heat, and moisture, respectively.

The Monin–Obukhov similarity theory is used to calculate the transfer coefficients. The dimensionless wind shear and potential temperature gradient are usually expressed as (e.g., Arya 1988)

(6.4)

, (6.5)

where k=0.4 is the von Karman constant, ua is the wind speed at level *z*, and *LM* is the Obukhov length (Obukhov 1946) mentioned above. Integrating the equations with respect to height *z*, leads to

, (6.6)

, (6.7)

where *z0* is the roughness length [set as 0.01 meter for the land surface, and *z0* over water surface parameterized based on Edson et al. (2013) and shown at the end of this section] and are the integrated similarity functions for momentum and heat that are defined as follows [e.g., Panofsky (1963)]:

, (6.8)

Combining Eq. (6.1) and Eq. (6.4) and neglecting the contribution of allows one to obtain the bulk transfer coefficient for momentum:

. (6.9)

Analogously, combining Eq. (6.2) with Eqs. (6.4) and (6.5), and neglecting the contribution of allows one to obtain the bulk transfer coefficient for heat:

, (6.10)

where it has been assumed that *ua=U*.

For the case of moisture the surface layer formulation follows Carlson and Boland (1978). The existence is assumed of a viscous sublayer from the ground to a height z0 (z0 = 0.01 m over land and z0 over water), and a turbulent layer wherein Monin–Obukhov theory is applicable from z0 to z. A similar derivation to the one used to obtain the transfer coefficients for momentum and heat leads to obtain the value of the bulk transfer coefficient form moisture (Carlson and Boland, 1978; Grell et al., 1994):

, (6.11)

where cs is the effective heat transfer coefficient for nonturbulent processes.

For stable conditions, the integrated similarity functions for momentum, and heat, , adopted from Cheng and Brutsaert (2005) are used

, (6.12)

. (6.13)

For unstable conditions, the Kansas-type functions and the Monin-Obukhov functions at the free convective limit are combined to generate the new similarity functions (Fairall et al., 1996),

, (6.14)

which are weighted by the Kansas-type functions, , at near-neutral conditions and by the convective part in strongly as unstable conditions. The Kansas-type functions are formulated as

, (6.15)

, (6.16)

where

, (6.17)

. (6.18)

The integrated similarity functions at the free convective limit are

, (6.19)

where

, (6.20)

. (6.21)

In Eqs. 6.12-6.21, and are estimated coefficients and their default values in the WRF model are given in Table 2 in the main text.

In WRF–ARW, the MYNN surface-layer scheme (not described in this document) is called prior to the call to the Land-Surface Model (LSM), which is called prior to the PBL schemes. The MYNN surface-layer scheme computes the surface stability parameter *z/LM*, transfer coefficients, and the momentum and scalar fluxes (*u*\*, HFX, and QFX) over land, water, and snow grid points; however, the LSM will recalculate the scalar fluxes over land and snow grid points by weighting the fractions of land surface coverage and snow coverage. The MYNN-EDMF uses the following as input: *u*\*, HFX, QFX, and *z/LM*. The first three variables are used for a variety of calculations, such as lower-boundary conditions for the solver or initializing the parcels for the mass-flux scheme. The surface stability parameter *z/LM* is used for computing the surface-layer length scale.

The COARE algorithm is used in the revised MM5 surface scheme to estimate the total roughness over water surface

, (A1)

used in Eq. (6.6) and Eq. (6.7), where γ=0.11, and . Additionally, (Zhang and Anthes, 1982) parameterize u\* as

, (A2)

where k is Karman constant (see Table 3), is 50% of lowest layer height, Va is wind speed at lowest layer, is roughness length and is from Eq. 6.12. Note that the calculation of needs a known and calculation of needs a known , which is a dilemma. Therefore, a time-split approach is used, where the is calculated based on and is calculated based on . The initialization of is from initial condition file. Again, all derivation of is for water surface, whereas for the land surface is set as 0.01.

**7. EDMF scheme**

The total turbulent fluxes (mixing and transport) of any arbitrary variable can be represented as two terms as follow:

, (7.1)

where i represents an individual plume and n is the total number of plumes. The vertical integration of each plume is performed with an entraining bulk plume model for the variables *φ* = (*θli, qt, u, v,* and TKE). As in Teixeira and Siebesma (2000) and most other mass-flux schemes, we used a simple entraining rising parcel:

, (7.2)

Where *εi* is the fractional entrainment rate, defined above, which regulates the lateral mixing of the updraft properties, , with the surrounding air, *ϕ*. Additionally, the entrainment rate e*i* is given by Tian and Kuang (2016):

, (7.3)

where *wi* is the vertical velocity and *di* is the diameter of each plume *i*. The constant *ε* is set to 0.35. The vertical velocity equation using a modified version of that from Simpson and Wiggert (1969), with the buoyancy as a source term:

, (7.4)

The coefficients *a* and *b* are discussed in several papers [e.g. de Roode et al. (2012) and Siebesma et al., (2003)]. They represent the effect of pressure perturbations and subplume turbulence terms. The precise value of these coefficients is still a subject of research and diagnosed values from LES studies give different results in the cloud layer and in the subcloud layer. Here *a* = 2.0. The impact of buoyancy is governed by *b*, which takes the value 0.15 when the buoyancy *B* is positive and 0.2 when *B* is negative. Some limits are in place to prevent unreasonably large values of *w* from developing, such as a maximum layer depth of *z* = 250 m and a maximum updraft vertical velocity of *wui* = 3 m s-1.

The activation criteria of the mass-flux scheme in the MYNN-EDMF is threefold, where all three conditions must be met. (1) The conditions above that determine the maximum number (or largest size) of plumes to be activated must specify at least one plume is to be used [namely the total cloud fraction should be larger than 100\*100/(Δx)2]; (2) there must be a positive surface buoyancy flux; (3) the model surface layer must be superadiabatic in the lowest 50 m. If any one of these conditions fail, then the mass-flux scheme will be inactive and the MYNN-EDMF is run in eddy-diffusivity configuration only for that model grid column at that specific time step.

**8. Subgrid-scale cloud parameterization in MYNN-EDMF**

**8.1 Cloud PDF Options**

The representation of subgrid-scale (SGS) clouds and their connection to SGS turbulence is an important aspect in both general circulation and limited-area mesoscale models. This is typically accomplished by use of joint probability distribution functions, known as cloud probability distribution functions (cloud PDFs, also known as partial-condensation schemes), which can either make use of the higher-order moments or vertical gradients of the resolved-scale fields to determine the SGS cloud mixing ratio, cloud fraction, and the buoyancy flux. The more sophisticated forms [i.e., Golaz et al. (2002)], which rely on additional prognostic equations, allow for a more direct physically consistent interaction between the higher-order turbulent quantities and the clouds, but come with a computational cost. The simpler forms, such as Sommeria and Deardorff (1977), Mellor (1973), Chaboureau and Bechtold (2005) and Jean-Christophe and Bechtold (2002), are generally capable of representing first-order macrophysical aspects of subgrid clouds and are effective at reducing time step variability in TKE-based schemes associated with grid-scale condensation. This is because the statistical representation of the SGS cloud properties evolve more continuously and consistently as the background moisture changes in the model grid cell (Sommeria and Deardorff, 1977).

The original MYNN was designed with the representation of SGS clouds according to the cloud PDF from Sommeria and Deardorff (1977). In early versions of WRF–ARW (pre-v3.8), the macrophysical properties (SGS cloud fraction and SGS liquid water content) from this cloud PDF were only used to parameterize the SGS buoyancy flux; coupling to the radiation scheme was not yet performed. Since v3.8, more cloud PDFs have been integrated into the MYNN with full coupling to the radiation. Namelist parameters were added to WRF–ARW to switch between different cloud PDFs (i.e., *bl\_mynn\_cloudpdf*) and to active the coupling to the radiation scheme (i.e., *icloud\_bl*) (refer to Appendix). We describe a description of each option for the namelist parameter *bl\_mynn\_cloudpdf* below.

i. Original (Gaussian) form: *bl\_mynn\_cloudpdf* = 0

The original cloud PDF described in Nakanishi and Niino (2004) is based on the joint-Gaussian probability distribution functions for the liquid potential temperature *θl* and total water content *qt* proposed by Sommeria and Deardorff (1977) and Mellor (1973). We essentially repeat the description here for comparison to alternative approaches later. In this approach, the standard deviation is estimated using the second-order moments in the MYNN. The cloud water content *ql* can be written as

(8.1)

and the areal cloud fraction *Acf* is:

(8.2)

The normalized saturation deficit is:

(8.3)

and the variance of the saturation deficit,

(8.4)

and *a* and *b* are thermodynamic functions arising from the linearization of the functions for the water vapor saturation mixing ratio:

, (8.5)

. (8.6)

and are determined from the Tetens formula and the Clausius-Clapeyron equation, respectively, where *Qs* is the saturation-specific humidity and *,* and *Lv* is the specific latent heat of vaporization.

The form of the buoyancy flux, , in the MYNN TKE equation is:

(8.7)

where the buoyancy functions are:

(8.8)

(8.9)

and

(8.10)

(8.11)

ii. First-order form: *bl\_mynn\_cloudpdf* = 1, -1

When using the level 2.5 configuration of the MYNN, the higher order moments (with the exception of the TKE) are diagnostically calculated. Therefore, the higher-order moments may be less accurate, limiting their usefulness in the original cloud PDF. We then integrated into the MYNN an alternative form, which avoids the use of the higher-order moments. This form is based on Nakanishi and Niino (2004), and Kitamura (2010). It uses a different expression for s based on gradients of the first-order fields (*θl* and *qt*),

, (8.12)

but is also dependent upon on the mixing lengths, L, a closure constant B2, the stability function for heat St, and thermodynamic variables a and b (defined above). Kitamura (2010) added a lower limit on SH= 0.03, arguing that a minimum is necessary for coarse vertical resolution model configurations to compensate for under-resolved strength and variation of inversions. Therefore, this form is likely preferable to the original form for course-resolution modeling and possibly when run at level 2.5. The calculation of the buoyancy is the same as outlined above for *bl\_mynn\_cloudpdf* = 0.

Note that the negative option (*bl\_mynn\_cloudpdf* = - 1) is for testing only. This option disables the “nonconvective” portion of the SGS clouds so simulations can be done with the convective SGS clouds from the mass-flux scheme only. This allows for a convenient way to test changes in the mass-flux scheme without the ambiguity of other sources of SGS clouds.

iii. Non-gaussian form: *bl\_mynn\_cloudpdf* = 2, - 2 (default and used)

CB02 introduced a statistical SGS cloud scheme for representing nonconvective, or stratus, clouds. As in Sommeria and Deardorff (1977), the cloud fraction and diagnosed cloud water are functionally dependent on a single variable, the normalized grid box saturation deficit *Q1*, but CB02 also uses a form for based off of gradients of the first-order fields. The subgrid variability of the saturation deficit, , is expressed as:

(8.13)

where *hl* is the grid box mean moist static energy and *L* is the mixing length from the turbulence scheme (described in section 2.2). In this manner, the diagnosed cloud fraction and cloud water amounts are directly linked to the amount of simulated turbulence. However, CB02 set *L* to a constant value of 900 m and was later revised in CB05 to *L* = 620 m. The parameter *cσ* is a tuning constant, originally set to 0.2, and *a* and *b* are thermodynamic functions (defined above). The *cpm* is the heat capacity of moist air (*= cpd + qtcpυ*). In a nonconvective boundary layer, this estimate of the subgrid scale variation of saturation state appears sufficient to accurately simulate the evolution of nonconvective SGS clouds, but to account for convective clouds, we extended this scheme by CB05.

The standard deviation of the subgrid saturation deficit is proportional to the mass flux *M*:

(8.14)

where *αconv* is a constant of proportionality (≈5x10-3) and a-1 is used as a vertical scaling function (*a* is defined above). With both the stratus and convective component of σs defined, CB05 then redefined s-conv to be:

. (8.15)

The new s-conv is then used to calculate the normalized saturation deficit using (32), which is then used to calculate the SGS areal cloud fraction:

. (8.16)

Note that we use this same equation for *Acf* for the SGS stratus component, but only *σs-strat* is used to calculate *Q1* using (8.3).

We included the following modifications to CB02 and CB05: 1) a factor of m [= 1 + MAX(*RH*-*RHc*, 0)/(*RHss*-*RHc*), where *RH* is the relative humidity, *RHc* = 0.83 and *RHss* = 1.01] multiplied by *Acf* for nonconvective cloud component only, allowing *Acf* to exceed 50% in high relative humidity (stratus) conditions, 2) the tuning constant *cσ* was increased to 0.225, 3) the mixing length *L* in the boundary layer was amplified in convective conditions with strong surface heat fluxes, such that *L* can be increased up to 600 m, but is otherwise relaxed to 300 m in nonconvective conditions and above the boundary layer, and 4) the tunable constant *αconv* in the mass-flux portion of *σs*, *σs­conv*, is set to *αconv* = 0.009. With the exception of 3), these modifications slightly increase the cloud fractions relative to CB02 and CB05.

As noted above, we use the negative option (*bl\_mynn\_cloudpdf* = -2) for testing purposes only. This option disables the “nonconvective” portion of the SGS clouds so simulations can be performed with the convective SGS clouds (from the mass-flux scheme) only. This allows for a convenient way to isolate testing to the mass-flux clouds without the ambiguity of other sources of SGS clouds.

**8.2 Temporal Dissipation of Sub-grid Cloud Fraction**

The SGS shallow-cumulus clouds produced by the MYNN-EDMF will vary from time step to time step as the ambient environment and its forcing change. However, in nature, forced shallow-cumuli can persist in a passive phase well after genesis. To retain some SGS cloud fraction information at subsequent time steps, we implemented a temporal dissipation as:

. (8.17)

Thus, the cloud fraction is only allowed to dissipate by *AM*(Δ*t/*Δ*tdiss*) in one time step. If the current predicted cloud fraction at time *t*+Δ*t*, is greater than the dissipated cloud fraction from the previous time step, , then we use the current predicted cloud fraction. The factor AM= 0.25 corresponds to typical shallow-cumulus cloud fraction, and we set Δ*tdiss* equal to the eddy turnover time scale, Δ*teddy* = 1800 s. This time scale is adequate for low to moderate wind speed regimes or at coarse model grid spacing, but a higher rate of dissipation is needed at high horizontal resolution with moderate-high background wind speeds. In these conditions, the SGS clouds may inappropriately linger within a grid cell for a longer time than it would take to advect a parcel through the grid cell. Therefore, the timescale of dissipation is further restricted by the advective time scale, Δ*tadv*=3Δ*x*/*U*, where Δ*x* is the model horizontal grid spacing and *U* is the resolved mean horizontal wind speed in the model grid cell. We set Δ*tdiss* to the minimum of Δ*teddy* and Δ*tadv*. This feature has a relatively small impact, but overall, acts to slightly smooth out the SGS cloud field.

**8.3 Coupling between SGS cloud and radiation scheme (RRTMG)**

The SGS clouds produced by the MYNN-EDMF (section 3) are coupled to the longwave and shortwave radiation schemes if the namelist parameter *icloud\_bl* is set to 1. In this case, the SGS cloud fraction, *CLDFRA\_BL*, and the SGS cloud-mixing ratio, *QC\_BL*, are added to the microphysics arrays within the radiation driver. The following two steps are performed: (1) the cloud fraction of the resolved-scale clouds are computed using Xu and Randall (1996); (2) if the resolved-scale cloud liquid and ice, *qc* and *qi*, is less than 10-6 kg kg-1 and 10-8 kg kg−1,respectively, and there exists a nonzero SGS cloud fraction, then the SGS components are added to their respective resolved-scale components by a temperature weighting, according to a linear approximation of Hobbs (1974):

; (8.18)

(8.19)

Then we sort the SGS cloud water and liquid as:

(8.20)

. (8.21)

This allows us to only use one 3-D array for both SGS cloud water and ice. The updated *q*c, *qi*, and *CLDFRA* are then used as input into the radiation schemes. After exiting the radiation schemes, the original values of *q*c, *qi*, and *CLDFRA* are restored, so the SGS clouds do not impact the resolved-scale moisture budget.

**Table 1** Investigated parameters in the MYNN PBL scheme

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Description | Default value | Estimated range |
| *B1* | Constant for dissipation rate of TKE | 24 | [12, 36] |
| *Df (sqfac)* | TKE diffusion factor | 2 | [1.5, 4.5] |
| *Pr* | Turbulent Prandtl number | 0.74 | [0.5, 2] |
| *C3* | Closure constant | 0.34 | [0.33, 0.50] |
| *C5* | Closure constant | 0.2 | [0.1, 0.3] |
| *γ1*(*g1*) | Closure constant | 0.229 | [0.18, 0.24] |
| *α1* | Constant for calculation of the turbulent length scale (*LT*) | 0.23 | [0.115, 0.345] |
| *α2* | Constant for calculation of the turbulent length scale (*LB*) | 0.65 | [0.5, 1.0] |
| *α3* | Constant for calculation of (*LB*) | 3 | [2.5, 7.5] |
| *α4* | Constant for calculation of the turbulent length scale (*LS*) | 20 | [20, 100] |
| *α5* | Constant for calculation *LT* | 2.1 | [1.35, 4.05] |
| *β* | Exponent on equation of *LS* | 0.2 | [0.1, 0.3] |

WRF-4.1.2/phys/module\_bl\_mynn.F

Line: 957-961 (alpha1-alpha5)

Note: alp2 to alp5 have been outside the estimated range by Yang et al. (2016). Therefore, we can assume the alpx (i.e., alp2 to alp5) range from 0.5\*alpx to 2\* alpx.

Line: 171 *Pr*

Line: 173 *b1*

Note: The *b1* is the most important parameter introducing significant surface wind speed variance.

Line: 172 *γ1*(*g1*)

Line: 176 *c3*

Line: 178 *c5*

Line: 196 (*Df*)sqfac

**Table 2** Investigated special parameters in the PBLH calculation in MYNN PBL scheme

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Description | Default value | Estimated range |
| Dtheta | Theta decrease to identify PBLH  (separately for water and land) | 0.75 and 1.25 | - |
| TKEmin | Lower bound of TKE for PBLH | 0.02 | - |
| FracTKE | Decreased TKE fraction for PBLH | 2.5% | - |
| zd | Transition length for blending | 400 | - |
|  | Upper limit height of stable PBL | 200 | - |

WRF-4.1.2/phys/module\_bl\_mynn.F

Line: 4819

Line: 4820 zd

Line: 4847 and 4850 Dtheta

Line: 4879 TKEmin

Line: 4848 FracTKE

**Table 3** Investigated parameters in the revised MM5 surface-layer scheme. Note that *ψm* and *ψh* are the integrated similarity functions for momentum and heat

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Description | Default value | Estimated range |
| *a1* | Constant associated with *ψm* at stable condition | 6.1 | [4.8, 9.4] |
| *b1* | Exponent on equation of *ψm* at stable condition | 2.5 | [1.1, 2.5] |
| *a2* | Constant associated with *ψh* at stable condition | 5.3 | [4.5, 9.0] |
| *b2* | Exponent on equation of *ψh* at stable condition | 1.1 | [1.1, 2.5] |
| *a3* | Constant associated with Kansas-type *ψm* at stable condition | 16 | [14, 18] |
| *b3* | Exponent on equation of Kansas-type *ψm* at stable condition | 4 | [3.5, 4.5] |
| *a4* | Constant associated with Kansas-type *ψh* at stable condition | 16 | [14, 18] |
| *b4* | Exponent on equation of Kansas-type *ψh* at stable condition | 2 | [1.5, 2.5] |
| *a5* | Constant associated with *ψm* at convective limit | 10 | [9.7, 11.6] |
| *b5* | Exponent on equation of *ψm* at convective limit | 3 | [2.5, 3.5] |
| *a6* | Constant associated with *ψh* at convective limit | 34 | [26, 42] |
| *b6* | Exponent on equation of *ψh* at convective limit | 3 | [3.0, 3.5] |
| *zf* | Scaling factor for surface roughness | 1 | [1.0, 2.0] |
| *k* | von Kármán constant | 0.4 | [0.35, 0.40] |

WRF-4.1.2/phys/module\_sf\_sfclayrev.F

Line 1164: *a1* and *b1*

Line 1169: *a2* and *b2*

Line 1174: *a3* and *b3*

Line 1186: *a4* and *b4*

Line 1177: *a5* and *b5*

Line 1189: *a6* and *b6*

Note: there is no variables named as a1 to a6 and b1 to b6. Instead, they are set as constants directly.

**Table 4** Investigated special parameters in the mass flux parameterization in MYNN PBL scheme

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Description | Default value | Estimated range |
| *ε* | Constant in entrainment rate | 0.35 |  |
| a | Kinetic weighting in w equation | 2 |  |
| b | Buoyancy weighting in w equation | 0.15 or 0.2 |  |
| wu,max | Maximal w | 3 |  |

WRF-4.1.2/phys/module\_sf\_sfclayrev.F

Line 5365: *ε*

Line 5439: a

Line 5425 and 5427: b

Line 5452: wu,max

**Table 5** Investigated special parameters in the roughness length parameterization in Revised MM5 surface scheme

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Description | Default value | Estimated range |
| γ | Tuning parameter of kinematic viscosity term in roughness | 0.11 |  |
| ν | Kinematic viscosity constant | 1.5x10-5 |  |
| α | Constant parameter in Charnock’s (1955) expression of z0 | 0.0185 | (0.011,0.0185) |

WRF-4.1.2/phys/module\_sf\_sfclayrev.F

Line 975: γ

Line 975: ν

Line 6: α

**Appendix A Calling Order of Schemes in WRF-Solar**

This document lists the major modules called in one time-step of WRF integration following the calling sequence. Green colored parts are comments, **Bold characters are modules related to physics**.

; --- integration of domain 01 for 1 time step

module\_integrate: calling solve interface

call rk\_step\_prep (preparation for the rk method)

call rk\_phys\_bc\_dry\_1 (prepare the boundary condition)

call init\_zero\_tendency (clean the tendencies from previous timestep)

**call phy\_prep**

**call radiation\_driver** (prepare the related properties and chose radiative scheme)

**Top of Radiation Driver**

**CALL cldfra1** (calculate cloud fraction to be used in radiative scheme)

**CALL rrtmg\_lw** (call longwave radiative transfer)

**call calc\_aerosol\_rrtmg\_sw** (prepare the aerosol optical properties e.g. AOD@550nm, single scattering albedo, Angstrom exponent and asymmetry parameter )

**CALL rrtmg\_sw** (call shortwave radiative transfer)

**SW surface irradiance calculated with FARMS** (interpolation of short wave radiation if FARMS is used)

**call surface\_driver**

**call MYNNSFC** (surface layer parameterization called first)

**call RUC LSM** (LSM is called after the surface layer parameterization)

**call pbl\_driver**

**call MYNNPBL** (chose and call MYNN PBL scheme)

**call cumulus\_driver** (chose and call cumulus parameterization)

**call shallow\_cumulus\_driver** (chose and call shallow cumulus parameterization when the option is enabled)

call fddagd\_driver (FDDA analysis nudging)

call calculate\_phy\_tend

call compute\_diff\_metrics

call bc for diffusion\_metrics

call cal\_deform\_and\_div

call calculate\_km\_kh

call phy\_bc

call update\_phy\_ten

call horizontal\_diffusion\_2

call rk\_tendency

call small\_step\_prep (inplement rk method iteratively)

call rk\_small\_finish

call rk\_scalar\_tend

call rk\_update\_scalar

…

call rk\_phys\_bc\_dry\_2

call rk\_step\_prep

call rk\_phys\_bc\_dry\_1

call rk\_tendency

call small\_step\_prep

call rk\_small\_finish

call rk\_scalar\_tend

call rk\_update\_scalar

…

call rk\_phys\_bc\_dry\_2

call rk\_step\_prep

call rk\_phys\_bc\_dry\_1

call rk\_tendency

call small\_step\_prep

call rk\_small\_finish

call rk\_update\_scalar\_pd

call rk\_scalar\_tend

call rk\_update\_scalar

…

call advance\_ppt

**call moist\_physics\_prep** (start the moist physics)

**call microphysics\_driver** (chose and call microphysics scheme)

**microphysics\_driver: calling thompson**

**call moist\_physics\_finish**

call chem polar filter

call set\_phys\_bc\_dry\_2

call spec\_bdy\_final

call set\_w\_surface

--> TOP OF AFTER ALL RK STEPS

--> CALLING DIAGNOSTICS DRIVER

--> TOP OF DIAGNOSTICS PACKAGE

--> CALL DIAGNOSTICS PACKAGE: NWP DIAGNOSTICS

call end of solve\_em

module\_integrate: back from solve interface

; --- domain 01 is finished for the time step. Enter the solve interface for nested domains, and call the modules in the sequence pretty much the same as domain 01 and iterate the whole process 3 times due to smaller time step for the nested domain (with a time step ratio of 1:3)

module\_integrate: calling med\_nest\_force

module\_integrate: calling solve interface

call rk\_step\_prep

call rk\_phys\_bc\_dry\_1

call init\_zero\_tendency

call phy\_prep

call radiation\_driver

Top of Radiation Driver

CALL cldfra1

CALL rrtmg\_lw

call calc\_aerosol\_rrtmg\_sw

CALL rrtmg\_sw

SW surface irradiance calculated with FARMS

call surface\_driver

in MYNNSFC

in RUC LSM

call pbl\_driver

in MYNNPBL

call cumulus\_driver

call shallow\_cumulus\_driver

call fddagd\_driver

call calculate\_phy\_tend

call bc for diffusion\_metrics

call cal\_deform\_and\_div

call calculate\_km\_kh

call update\_phy\_ten

call horizontal\_diffusion\_2

call rk\_tendency

call small\_step\_prep

call rk\_small\_finish

call rk\_scalar\_tend

call rk\_update\_scalar

…

call rk\_phys\_bc\_dry\_2

call rk\_step\_prep

call rk\_phys\_bc\_dry\_1

call rk\_tendency

call small\_step\_prep

call rk\_small\_finish

call rk\_scalar\_tend

call rk\_update\_scalar

…

call rk\_phys\_bc\_dry\_2

call rk\_step\_prep

call rk\_phys\_bc\_dry\_1

call rk\_tendency

call small\_step\_prep

call rk\_small\_finish

call rk\_update\_scalar\_pd

…

call rk\_scalar\_tend

call rk\_update\_scalar

…

call advance\_ppt

call phy\_prep\_part2

call moist\_physics\_prep

call microphysics\_driver

microphysics\_driver: calling thompson

call moist\_physics\_finish

call chem polar filter

call set\_phys\_bc\_dry\_2

call spec\_bdy\_final

call set\_w\_surface

--> TOP OF AFTER ALL RK STEPS

--> CALLING DIAGNOSTICS DRIVER

--> TOP OF DIAGNOSTICS PACKAGE

--> CALL DIAGNOSTICS PACKAGE: NWP DIAGNOSTICS

call end of solve\_em

module\_integrate: back from solve interface

module\_integrate: back from recursive call to integrate

; --- After 3 times of iteration, feedback to the outer domain when two-way nesting is enabled.

module\_integrate: calling med\_nest\_feedback

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