Attachment: Appendix B from the 2nd Edition, COAMPS summary

Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS)

Date Information Provided: May 2012

Model Name: Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)

Coupled Ocean/Atmosphere Mesoscale Prediction System – Tropical Cyclone (COAMPS-TC)

Is the model still under active development? Yes

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1. Group: Marine Meteorology Division Naval Research Laboratory, Monterey, CA. The coupled model development with the ocean and wave models

performed in collaboration with Oceanography Division, Naval Research Laboratory, Stennis, MS.

COAMPS has been operational since 1998 with the primary operational customer being Fleet Numerical Meteorology and Oceanography Center (FNMOC). COAMPS is currently being used for real-time and research applications by many universities and academic partners, U.S. government agencies including DoD, and other international partners.

2. Equations used for [for clarity, please write them as they are used for at terrain]

(a) motion (or momentum) (Following Hodur 1997; Klemp and Wilhelmson 1978)

i. horizontal

$$\frac{\partial u}{\partial t} + C_p\theta_v\left(\frac{\partial \pi'}{\partial x} + G_x\frac{\partial \pi'}{\partial \sigma}\right) + K_D\left(\frac{\partial D_3}{\partial x} + G_x\frac{\partial D_3}{\partial \sigma}\right) = -u\left(\frac{\partial u}{\partial x}\right)_\sigma - v\left(\frac{\partial u}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial u}{\partial \sigma}\right) + fv + D_u + K_H\nabla^4 u$$

$$\frac{\partial v}{\partial t} + C_p\theta_v\left(\frac{\partial \pi'}{\partial y} + G_y\frac{\partial \pi'}{\partial \sigma}\right) + K_D\left(\frac{\partial D_3}{\partial y} + G_y\frac{\partial D_3}{\partial \sigma}\right) = -u\left(\frac{\partial v}{\partial x}\right)_\sigma - v\left(\frac{\partial v}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial v}{\partial \sigma}\right) - fu + D_v + K_H\nabla^4 v$$

ii. vertical

$$\frac{\partial w}{\partial t} + C_p\theta_v G_z\frac{\partial \pi'}{\partial \sigma} + K_D G_z\frac{\partial D_3}{\partial \sigma} = g\left(\frac{\theta'}{\overline{\theta}} + 0.608q_v' - q_c - q_r - q_s - q_i - q_g\right) - u\left(\frac{\partial w}{\partial x}\right)_\sigma - v\left(\frac{\partial w}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial w}{\partial \sigma}\right) + D_w + K_H\nabla^4 w$$

(b) heat

$$\frac{\partial \theta}{\partial t} = -u\left(\frac{\partial \theta}{\partial x}\right)_\sigma - v\left(\frac{\partial \theta}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial \theta}{\partial \sigma}\right) + \frac{Q_\theta}{\overline{\rho}} + D_\theta + K_H\nabla^4(\theta - \overline{\theta}),$$

(c) mass

(d) pressure

$$\frac{\partial \pi'}{\partial t} + \frac{\bar{c}^2}{C_p \bar{\rho} \bar{\theta}_v^2}(D_3) = -u\left(\frac{\partial \pi'}{\partial x}\right)_\sigma - v\left(\frac{\partial \pi'}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial \pi'}{\partial \sigma}\right) - \frac{R_d \bar{\pi}}{C_v}\nabla_3 \bullet \boldsymbol{V} + \frac{c^2}{C_p \theta_v^2}\frac{d\theta_v}{dt}$$

(e) moisture

i. ice

$$\frac{\partial q_i}{\partial t} = -u\left(\frac{\partial q_i}{\partial x}\right)_\sigma - v\left(\frac{\partial q_i}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial q_i}{\partial \sigma}\right) + D_{q_i} + K_H \nabla^4 q_i + \frac{S_i}{\rho}$$

$$\frac{\partial q_s}{\partial t} = -u\left(\frac{\partial q_s}{\partial x}\right)_\sigma - v\left(\frac{\partial q_s}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial q_s}{\partial \sigma}\right) + \frac{G_z}{\bar{\rho}}\frac{\partial}{\partial \sigma}(\bar{\rho} V_s q_s) + D_{q_s} + K_H \nabla^4 q_s + \frac{S_s}{\rho}$$

$$\frac{\partial q_g}{\partial t} = -u\left(\frac{\partial q_g}{\partial x}\right)_\sigma - v\left(\frac{\partial q_g}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial q_g}{\partial \sigma}\right) + D_{q_g} + K_H \nabla^4 q_g + \frac{S_g}{\rho}$$

ii. liquid water

$$\frac{\partial q_c}{\partial t} = -u\left(\frac{\partial q_c}{\partial x}\right)_\sigma - v\left(\frac{\partial q_c}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial q_c}{\partial \sigma}\right) + D_{q_c} + K_H \nabla^4 q_c + \frac{S_c}{\rho}$$

$$\frac{\partial q_r}{\partial t} = -u\left(\frac{\partial q_r}{\partial x}\right)_\sigma - v\left(\frac{\partial q_r}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial q_r}{\partial \sigma}\right) + \frac{G_z}{\bar{\rho}}\frac{\partial}{\partial \sigma}(\bar{\rho} V_r q_r) + D_{q_r} + K_H \nabla^4 q_r + \frac{S_r}{\rho}$$

iii. water vapor

$$\frac{\partial q_v}{\partial t} = -u\left(\frac{\partial q_v}{\partial x}\right)_\sigma - v\left(\frac{\partial q_v}{\partial y}\right)_\sigma - \dot{\sigma}\left(\frac{\partial q_v}{\partial \sigma}\right) + D_{q_v} + K_H \nabla^4 (q_v - \bar{q}_v) + \frac{S_v}{\rho}$$

where

$$\dot{\sigma} = G_x u + G_y v + G_z w$$

$$G_x = \frac{\partial \sigma}{\partial x} = \left(\frac{\sigma - z_{\rm top}}{z_{\rm top} - z_{\rm sfc}}\right)\frac{\partial z_{\rm sfc}}{\partial x}$$

$$G_y = \frac{\partial \sigma}{\partial y} = \left(\frac{\sigma - z_{\rm top}}{z_{\rm top} - z_{\rm sfc}}\right)\frac{\partial z_{\rm sfc}}{\partial y}$$

$$G_z = \frac{\partial \sigma}{\partial z} = \frac{z_{\rm top}}{z_{\rm top} - z_{\rm sfc}}.$$

In the above equations, p is the pressure; ρ the density; R_d the gas constant for dry air; T the temperature; q_v, q_c, q_r, q_i, q_g, and q_s the mixing ratios of water vapor, cloud droplets, raindrops, ice crystals, graupel, and snowflakes, respectively; p_{00} a constant reference pressure; C_p the specific heat at constant pressure for the atmosphere and C_v the specific heat at constant volume; *u, v,* and *w* the wind components in the *x, y,* and *z* directions, respectively; *f* the Coriolis force; *g* the acceleration due to gravity; S_v, S_c, S_r, S_i, S_g, and S_s sources and sinks of q_v, q_c, q_r, q_i, q_g, and q_s, respectively; Q_θ sources and sinks of heat; V_r and V_s the terminal velocities of raindrops and snowflakes, respectively; $\theta_{\rm std}$ the standard atmospheric temperature; $q*_v$ the saturation mixing ratio corresponding to the standard atmospheric temperature; and D_3 the density and potential temperature–weighted three-dimensional divergence.

Additional prognostic equations associated with the Khairoutdinov and Kogan (2000) drizzle parameterization are:

$$\frac{\partial n}{\partial t} = -\frac{\partial u_i n}{\partial x_i} - \left(\frac{\partial N_c}{\partial t}\right)_{activ} + \left(\frac{\partial N_c}{\partial t}\right)_{evap} + \frac{\partial}{\partial x_i} K_h \frac{\partial n}{\partial x_i}$$

(1a)

$$\frac{\partial N_c}{\partial t} = -\frac{\partial u_i N_c}{\partial x_i} + \left(\frac{\partial N_c}{\partial t}\right)_{activ} - \left(\frac{\partial N_c}{\partial t}\right)_{evap} - \left(\frac{\partial N_c}{\partial t}\right)_{accr} - \left(\frac{\partial N_c}{\partial t}\right)_{auto} + \frac{\partial}{\partial x_i} K_h \frac{\partial N_c}{\partial x_i}$$

(1b)

$$\frac{\partial N_R}{\partial t} = -\frac{\partial u_i N_r}{\partial x_i} + \frac{\partial V_{N_R} N_R}{\partial z} - \left(\frac{\partial N_R}{\partial t}\right)_{evap} + \left(\frac{\partial N_R}{\partial t}\right)_{auto} + \frac{\partial}{\partial x_i} K_h \frac{\partial N_R}{\partial x_i}$$

(1c)

Where n, N_c, and N_R represent the number concentration of aerosol, cloud droplets, and rain drops, respectively; V_{NR} is the terminal velocity of the drizzle drops, the subscripts *activ, evap, accr*, and *auto* refer to droplet activation, evaporation, accretion, and autoconversion, respectively, and K_h is the eddy diffusivity. Currently no active sources are provide for aerosol number concentration (n) but recent work will lead to a more complete linkage with the NAAPS aerosol source functions both over land and the ocean once the generalized COAMPS scalar treatment is completed. A special feature of this near scalar treatment in COAMPS is that the user will be able to specify any number of scalar fields and will have complete control of the process-by-process execution of each field at run-time due to a unique grouping of scalar family properties that are assigned at run time. Loops executed for the scalar advection, for example, only act on those scalar fields which have their pointer assigned to the advection family loop indexing. Similar family pointer assignments control other dynamical and physical processes such as the form of the numerical diffusion, turbulent mixing, boundary updates, cloud-aerosol interactions, and so on. The great advantage of this infrastructure design is that it will facilitate with little additional work the complex interactions amongst the ever increasing sophistication of physics packages that now routinely involve any number of additional scalar fields.

(f) other chemical species

(g) Aerosols

A mineral-dust aerosol model is fully embedded in COAMPS as an in-line module of the prediction system, using COAMPS meteorological fields at each time step and each grid point. With the same grid structure as its dynamics model, it has multiple nested grids and interactions of grid nests. The mass conservation equation for a dust particle of radius *r* in generalized form is

$$\frac{\partial C_r}{\partial t} = -\frac{\partial u C_r}{\partial x} - \frac{\partial v C_r}{\partial y} - \frac{\partial (w + v_f) C_r}{\partial z} + D_x + D_y + D_z + C_{src} - C_{snk}$$

where u, v, w are the components of wind vector in x, y and z directions; v_f is particle settling velocity; D_x, D_y, and D_z are turbulent mixing in x, y and z; C_{src} is dust source term, i.e. dust mobilization from erodible dessert lands; C_{snk} is the dust sink term which includes dry deposition at surface and wet removal by precipitation. The dust emission is mainly a function of surface wind stress, in a formula which describes the vertical dust flux F being proportional to friction velocity (u_*) raised to the forth power or the square of wind stress:

$$F = A\ 1.42 \times 10^{-5} \times u_*^4 \qquad \text{when } u_* \geq u_{*t}$$

Coefficient A is the fraction of model grid box that is dust erodible, ranging from 0.0 to 1.0., and u_{*t} is the threshold friction velocity and land-type dependent. The fractional erodibility is derived using a 1-km-resolution land cover dataset developed by Naval Research Laboratory (Walker et al. 2010) for Southwest and East Asia, and a global land-use database by the U. S. Geological Survey.

Dust aerosol is modeled with a bimodal lognormal size distribution in mass. The mass median radius and geometric standard deviation in the size distribution are predicted by a sandblasting scheme at each time step, based on the particle's saltating kinetic energy in a dynamical environment. The number of size bins range from 5 to 50 depending on computational efficiency and modeling accuracy requirement.

Dust advection in both horizontal and vertical directions uses a 3rd, or 5th, or 7th order- accurate flux-form, positive-definite, mass-conserved scheme (Bott 1989). The sub-grid scale turbulent mixing is solved semi-implicitly with the eddy diffusivities for scalar by the TKE closure. The dust aerosol microphysics and aerosol optics can be found in Liu et al. (2003, 2007).

(h) Ocean circulation

The COAMPS system has the capability to operate in a fully coupled (two-way) air-sea interaction mode (Chen et al. 2010). The atmospheric module within COAMPS-TC is coupled to the NRL-developed Navy Coastal Ocean Model (NCOM) (Martin 2000; Martin et al. 2006) to represent air-sea interaction processes.

(i) Ocean wave models

The COAMPS system has two inter-changeable wave models Simulating WAves Nearshore (SWAN) and Wave Watch III (WWIII) to predict ocean surface waves. When operating in the fully coupled air-sea-wave coupled mode, forcings and feedbacks are exchanged between the wave and the atmosphere and ocean circulation models. COAMPS has also been coupled to the Wave Model (WAM) for extratropical and tropical cyclones (Doyle 2002; Doyle 1995).

(j) Coupling method

COAMPS makes use of the Earth System Model Framework (ESMF) to facilitate the air-sea-wave coupling. This is done through a generalized coupler routing information between component models that allow each model to operate using independent resolutions and projections. The atmospheric component provides a total of six ocean surface boundary forcing fields to the ocean component while the ocean model returns a new sea surface temperature to the atmosphere that influences the next time step prediction of the atmospheric surface fluxes and wind stress. The ocean component provides the current and sea surface height to the wave component while the atmospheric component impacts the waves through the wind driven momentum drag. The feedback of wave component to the ocean consists of ten forcing terms including the Stokes drift current, wave radiation stress gradients, wave-bottom current, and wave-bottom current radian frequency. The wave component feedback to the atmosphere consists of a non-dimensional roughness length (Charnock number) which is related to the atmospheric momentum drag.

(k) Coupled interface

COAMPS makes use of the Earth System Model Framework (ESMF) to facilitate the air-sea-wave coupling. This is done through a generalized exchange of information between models that allow each model to operate using independent resolutions and projections, with the feedbacks through the various components taking place on an exchange grid.

(l) Tropical Cyclone (TC) capability, COAMPS-TC

The COAMPS-TC is comprised of data quality control, analysis, initialization, and forecast model sub-components (Doyle et al. 2012). The NRL Atmospheric Variational Data Assimilation System (NAVDAS) is used to blend conventional and remote sensing observations. Synthetic observations following (Liou and Sashegyi 2011) are used to specify the tropical cyclone structure and a relocation procedure is used to initialize the position. The sea-surface temperature is analyzed directly on the model computational grid using the Navy Coupled Ocean Data Assimilation (NCODA) system, which makes use of all available satellite, ship, float, and buoy observations. Both the NCODA and NAVDAS systems are applied using a data assimilation cycle in which the first guess for the analysis is derived from the previous short-term forecast. The COAMPS-TC features the COAMPS nonhydrostatic dynamical core. The suite of physical parameterizations include representations of the cloud microphysics, boundary layer, surface fluxes, radiation, and deep and shallow convection processes, all of which were modified to better represent the tropical cyclone environment.

(m) Large Eddy Simulation (LES) application

COAMPS options have been formulated to allow for high-resolution applications within the atmospheric boundary layer. Several new closures were developed along with an anelastic dynamical core for efficiency purposes (Golaz et al. 2009; Doyle et al. 2009).

3. Horizontal domain sizes used

Horizontal domain sizes varying both operationally and in a research mode. Typical domain sizes for a 45 km resolution coarse mesh might be 9000 km x 6750 km, with a fine mesh of 5 km covering an area of 1000 km x 1000 km.

4. Horizontal grid increment(s)

Grid increments vary from 54 km to a 10 m used in large-eddy simulation mode.

5. Vertical domain sizes used

The vertical domain depth is typically 30 km, with recent advancements that allow the model top up to 60 km. Idealized applications have used shallow to very deep model domains.

6. Vertical grid increment(s)

For real data cases, vertically stretched from 10 m at the lowest model level. Idealized applications have used uniform and stretched vertical grid increments.

7. Initialization procedure

NAVDAS (Daley and Barker 2000) is used to blend observations of winds, temperature, moisture, and pressure from a plethora of sources such as radiosondes, pilot balloons, satellites, surface measurements, ships, buoys, and aircraft. The sea-surface temperature is analyzed directly on the model computational grid using the Navy Coupled Ocean Data Assimilation (NCODA) system, which makes use of all available satellite, ship, float, and buoy observations. Both the NCODA and NAVDAS systems are applied using a data assimilation cycle in which the first guess for the analysis is derived from the previous short-term forecast.

8. Solution techniques for dynamic core equations:

(a) advection

(b) vertical flux divergence

(c) horizontal pressure gradient force

(d) Coriolis term

The model equations are solved time-splitting method, which allows for large time steps to be taken for the slow modes and shorter time steps for the faster sound modes (Klemp and Wilhelmson 1978; Skamarock and Klemp 1992).

9. Coordinate system used [provide equation relating z to the system used]

COAMPS makes use of a terrain following coordinate (Gal-Chen and Sommerville 1975).

$$\dot{\sigma} = G_x u + G_y v + G_z w$$

$$G_x = \frac{\partial \sigma}{\partial x} = \left(\frac{\sigma - z_{top}}{z_{top} - z_{sfc}} \right) \frac{\partial z_{sfc}}{\partial x}$$

$$G_y = \frac{\partial \sigma}{\partial y} = \left(\frac{\sigma - z_{top}}{z_{top} - z_{sfc}} \right) \frac{\partial z_{sfc}}{\partial y}$$

$$G_z = \frac{\partial \sigma}{\partial z} = \frac{z_{top}}{z_{top} - z_{sfc}}.$$

10. Nested domains [how many and how implemented]

Generalized nested domains, with the model supporting an arbitrary number of grid meshes. The COAMPS-TC option makes use of moving nested grids that automatically follow the tropical cyclone center.

11. Lateral boundary condition for outer most grid [source of this data also]

Lateral boundaries for real data applications follow Davies (1976). Global model boundary conditions are typically derived from NOGAPS, NAVGEM, GFS. Other options are available as well. Idealized application options include i) wall, ii) periodic, and iii) open (or radiation).

12. Top boundary condition

Rigid lid, sponge (explicit and implicit Rayleigh damping), and radiation (linear gravity wave condition) options are available.

13. Surface boundary treatment

The surface fluxes are represented by a hybrid scheme as described in Wang et al. (2002). The scheme uses Richardson number as a stability parameter as in Louis (1982); it is further tuned to match the stability functional dependence as described in Fairall et al. (1996). The surface momentum roughness length over water follows the Charnock parameterization for wind speed less than 35 m s^{-1}, above which the roughness is specified as discussed in Donelan et al. (2004). The temperature and moisture roughness lengths are set to be one tenth of the momentum roughness over land. They are functions of both the momentum roughness and the roughness Reynolds number as described in Fairall (2003) over water conditions.

The single layer vegetation canopy approach from the WRF NOAH land surface model (LSM) based on Chen and Dudhia (2001) and Ek et al. (2003) is used to compute latent and sensible heat fluxes over land. Volumetric soil moisture and temperature is predicted at four soil layers. Urban effects on surface fluxes can also be activated using the WRF single –layer urban canopy model (Kusaka et al. 2001) or a multi-layer urban model (Holt and Pullen 2007).

14. Parameterization of subgrid-scale flux divergence for

(a) motion (or momentum)

(b) heat

(c) moisture in its three phases, and

(d) other chemical species

For each, separate those for turbulence and for other subgrid-scale processes.

For turbulence parameterization, the Mellor-Yamada's 1.5 order turbulence closure model that predicts turbulence kinetic energy and determines the turbulent fluxes in terms of the down-gradient transport approach (Mellor and Yamada, 1982). To account for latent heat effect of clouds on the buoyancy in turbulence mixing, the subgrid-scale cloud fraction is calculated using a Gaussian distribution of turbulent fluctuations of conserved variables (Sommeria and Deardorff, 1977). For subgrid-scale parameterization in the LES version (Golaz et al., 2005), both the TKE model (Deardorff, 1980) and the local equilibrium model (Stevens et al., 1999) are included.

15. Flux divergence from cumulus cloud parameterization

(a) motion (or momentum)

(b) heat

(c) moisture in its three phases

The Kain-Fritsch convective parameterization scheme (Kain and Fritsch 1990) is used for most mid-latitude convective forecasts in COAMPS. By default it becomes active on grids with horizontal spacing greater than or equal to 10 km. The KF scheme removes convective available potential energy (CAPE) at each grid element over an advective time scale of about one hour. CAPE is calculated for a series of 50 hPa thick parcels starting near the surface and extending to 300 hPa. Resolved vertical motion is used as an additional buoyant term to initiate convection. If convection is initiated, fluxes of heat and moisture for both updrafts and downdrafts are calculated with the aid of an entraining/detraining plume model. The entrainment rate is determined by the parcel buoyancy as well as predetermined updraft radius, generally on the order of 1.5 km. Moisture is detrained in the form of vapor, cloud water, cloud ice, rain, and snow. Detraining moisture is partitioned by assuming a linear transition of liquid to ice from θ_e = 268 K to θ_e = 248 K. Detrained precipitation is distributed between rain and snow while cloud material is distributed between cloud ice and cloud water. Convectively generated rain that is not detrained from the updraft is considered separately as convective rainfall. This liquid is not currently passed back to the explicit microphysics scheme in COAMPS, though the KF scheme does allow for this option. Tests of both options indicated little difference in model performance. Convective heating is considered within the updraft due to condensation and freezing of water. Detrainment of updraft temperature is calculated directly by the parcel model. Subsidence heating outside the updraft is assumed to occur entirely within the gridbox. Convective momentum transfer is not directly considered in the KF scheme. The convective heating indirectly affects the momentum distribution through the explicit physics, but the impacts are likely underestimated.

An updated version of the KF scheme (Kain 2004) is also available as a separate option. This version is similar to the original scheme with a few notable exceptions. A minimum entrainment rate is specified to prevent undiluted ascent in weak updrafts. Entrainment is considered in the CAPE calculation to more realistically estimate updraft intensity. Shallow, non-precipitating convection is added to account for the effects of towering cumulus. Also, the updraft radius is considered to be a function of the resolved vertical motion. The updated scheme performs better in the mid latitudes due to the reduction of light precipitation in unstable but dry environments. However, performance in the tropics is slightly degraded as determined by TC track and intensity metrics.

Options also include a simplified Arakawa Schubert cumulus parameterization (Arakawa and Schubert 1974) parameterization of shallow cumulus convection (Tiedtke et al. 1988).

16. Radiational flux divergence

(a) longwave flux divergence

(b) shortwave flux divergence

COAMPS has two radiative transfer (RT) models being implemented: one is Fu-Liou's four-stream scattering-absorption algorithm (with a two-stream option), integrating over six shortwave bands and 12 longwave bands; the other is Harshvardhan's fast-speed two-stream algorithm of three short wave bands and six longwave bands.

Fu-Liou (1992 and 1993) contains both scattering and absorption in the solar and thermal inferred radiation with a delta-function to correct strong forward scattering from large cloud and aerosol particles. It calculates spectral and species-dependent optical properties to obtain high-order accurate radiative fluxes in clear, cloudy, and aerosol-laden atmospheres. Cloud effective radii of liquid and ice are parameterized with the explicit cloud mass for cloud optics, so are the cloud and radiation interactions effectively achieved. This RT model is being used in COAMPS hurricane track daily forecast.

The Harshvardhan RT model (1987) has been used since the beginning of COAMPS operations. In this model, cloud optical depth is calculated with modeled mean state variables, pressure and temperature, along with constant cloud single scattering albedo and asymmetry factor. Meanwhile it neglects the cloud scattering in the longwave radiation. These simplifications and the coarse spectral resolution make the radiative transfer highly efficient in numerical weather forecasts and climate predictions.

17. Stable clouds and precipitation

T The primary purpose of the COAMPS moist physics schemes are to provide realistic and computationally efficient parameterizations that provide estimates of source/sink terms for the scalar equations involving potential temperature, water vapor, the number concentration of aerosol, cloud droplets and rain droplets, and each of the five condensate species (q_c, q_r, q_i, q_s, and q_g) currently carried by the model. Numerical treatment of the advective terms is performed with either a standard leapfrog approach or an optional hybrid time-differencing scheme that allows for integration of the scalar fields on a forward time step. The choice of advection schemes currently includes the 3rd and 5th order positive-definite and monotonic schemes of Bott (1989, 1992) or the selective advection method described by Blossey and Durran (2008). The choice of Bott schemes are the same as currently used within the stand-alone COAMPS aerosol module described by Liu and Westphal (2001). The numerical diffusion term is treated as described for the other model variables. An optional 6th order monotonic diffusion scheme described by Xue (2000) is also currently being tested particularly for use in higher resolution research runs involving cloud-aerosol interactions where it is desired to prevent numerical over-shooting of the scalar fields resulting from both the advection and 4th order diffusion schemes. The sedimentation scheme is treated with a forward upstream technique using time splitting to ensure numerical stability. The standard scheme currently used in COAMPS is quite diffusive and therefore optional schemes based on the Bott (1989, 1992) schemes are now available to improve accuracy. The vertical mixing terms are computed implicitly and based off the closure scheme described by Klemp and Wilhelmson (1978) and Mellor and Yamada (1974).

The treatment of the microphysical source terms for the operational bulk cloud microphysics scheme is a Lin et al. (1983) variant described by Rutledge and Hobbs (1983, 1984). The original Rutledge and Hobbs (1983, 1984) scheme has been extensively modified to allow for an improved representation of the multi-species interactions as well as through the inclusion of an implicit Soong and Ogura (1973) type saturation adjustment scheme that prevents undesired cycling from unsaturated to saturated conditions both between and during the time step. The sequential process-by-process adjustment has also been replaced by grouping the main adjustment into four groups tied to all fusion/melting terms (computed first), vapor transfer to liquid and ice (second and third stages, respectively), and finally all conversions in which neither temperature or vapor changes are involved (collection terms not involving phase change). The adjustment to saturated conditions only occurs if the physics dictate that the entire vapor excess is to be consumed during a time step. Thus, regions of low crystal concentration that arise at warmer temperatures near the melting level may remain supersaturated with respect to ice. Validation of the scheme is conducted using standard comparison with rawinsonde soundings, precipitation analyses, and direct comparison with satellite and radar data sets (cf. Nachamkin et al. 2009)

Additional physics have been added to account for homogeneous nucleation, all temperature and pressure dependencies in the thermodynamic coefficients (Pruppacher and Klett 1978), a variety of autoconversion formulizations [such as variants of the Khairoutdinov and Kogan (2000) scheme based on specified 3-D aerosol distributions; Manton and Cotton (1977), and Kessler (1969) as well as a number of primary and secondary ice nucleation options (Fletcher 1962, Cooper 1986, Meyers et al. 1992, Cotton et al. 198, mixed Cooper/Fletcher (used operationally), Hallet and Mossop (1974) as well as other variants described by

DeMott (1994) which attempt to account for density variability. The two-moment drizzle parameterization of the Khairoutdinov and Kogan (2000) is used as a basis for conducting cloud/aerosol interactions. Options exist to initialize the aerosol either in an idealized 3-D distribution or using input and lateral boundary conditions from the NRL Navy Aerosol and Analysis Prediction System (NAAPS) which is modeled after the system developed by Christensen (1997). Numerical efficiency is improved with the use of a gather-scatter algorithm on the active grid points only. The cloud microphysics scheme is called as an adjustment to the prognostic fields after an update to the model dynamics and turbulence mixing is performed.

The research version of the microphysics available with COAMPS stem from two primary sources. First, a concerted effort was made to alter the COAMPS infrastructure to readily allow the incorporation of community based schemes such as those developed for WRF. Using the modular format, all available microphysics schemes are readily available for testing purposes within COAMPS. Second, an independent research scheme was developed at NRL and modeled after the generalized scheme of Flatau et al. (1989). As in that scheme, the user has the choice of setting the size distributions at run-time. For the applications in COAMPS, the two primary size distributions are the Marshall and Palmer (1948) or the Gamma distribution such as outlined by Willis and Tattleman (1989). This provides considerable flexibility in examining the impact of the various size distributions of the development of the modeled cloud field. The generalized collection and vapor transfer equations have been further modified to allow easy adaptation with ensemble-based systems by allowing the shape parameter and fall-speed coefficients to vary for each ensemble member in the following manner:

$$v_{a,k} = a_{v_a,k} D^{b_{v_a},k} \qquad (1)$$

$$m_a = a_{m_a,k} D^{b_{m_a},k} \qquad (2)$$

$$P(a,b) = \int_0^\infty \int_0^\infty e_{ab,k} \pi \frac{(D_a + D_b)^2}{4} \left| V_{a,k} - V_{b,k} \right| \frac{N_{t_a,k}}{\Gamma(v_{a,k})} \left(\frac{\beta_{a,k}}{D_{n_a,k}} \right) D_a^{v_{a,k}-1} e^{\frac{\beta_{a,k} D_a}{D_{n,k}}} a_{m_b,k} D^{b_{m,k}} \frac{N_{t_b,k}}{\Gamma(v_{b,k})} \left(\frac{\beta_{b,k}}{D_{n_b,k}} \right) D_b^{v_{a,k}-1} e^{\frac{\beta_{b,k} D_b}{D_{b,k}}} dD_a dD_b \qquad (3)$$

$$\frac{dM_a}{dt} = \int_0^\infty F_k(T,P)(\alpha - \alpha_0)\frac{N_{t_a,k}}{\Gamma(v_{a,k})}\left(\frac{\beta_{a,k}}{D_{n_a,k}}\right) D_a^{v_{a,k}-1} e^{\frac{\beta_{a,k}D_a}{D_{n,k}}} dD_a \quad (4)$$

Where e_{ab} is the variable collection efficiency, D represents the particle diameter, V represents the terminal velocity, N the total particle concentration, m is the mass of the collected particle, β is a parameter associated with the slope of the distribution, D_n represents the mean diameter, v is the distribution shape parameter (in 3), a_v and a_m are coefficients determining the mass-diameter and velocity diameter relationships (in 1 and 2), F_k contains all the temperature and pressure dependencies impacting all fusion and vapor transfer calculations, α-α_0 represents a given scalar field gradient for temperature or vapor, and Γ is the gamma function. The subscripts *a* and *b* refer to the collector and collected species, respectively. The subscript, *k*, refers to the value of each parameter for a given ensemble member.

The value of P (a,b) is computed analytically during run-time using constant coefficients for e_{ab} and the Wisner (1972) approximation or through the use of numerically generated look-up tables. With the look-up table option, the variable collection efficiencies are derived from Khain et al. (2001) [graupel/drop], Pinsky et al. (2001) [drop/drop], and Wang and Ji (2001) [ice/drop], and Cotton et al. (1986) [ice/ice]. To reduce the large temporal truncation errors associated with the discretized solution of Eq. 3, the numerical bounding technique of Gaudet and Schmidt (2007) is employed. This scheme has been found to significantly reduce the over-collection problem that commonly arises in bulk cloud microphysical schemes for time-steps typically employed in mesoscale model simulations. To improve efficiency, the look-up tables can be computed from a stand-alone module which is executed prior to run-time. The tables are output as 2-D arrays and then read back in and stored for subsequent use as needed within the cloud microphysics scheme.

Another microphysical scheme implemented in COAMPS is the Thompson scheme (Thompson et al. 2008). This scheme (released in WRF 3.3 and further updated in July 2011), is also a bulk microphysical parameterization, predicting explicitly mixing ratios of five hydrometeor species: cloud water, rain, cloud ice, snow and graupel. Additionally, the number concentration of cloud ice and rain are predicted. As such, this scheme is a single-moment for cloud water, snow and graupel, but a double-moment scheme for cloud ice and rain. Look-up tables are created wherever possible by the scheme to employ techniques consistent with those in spectral/bin microphysical schemes. Incorporating observations from recent field experiments, this scheme allows the snow to assume non-spherical shape with varied bulk density, in contrast to the spherical snow of constant density assumed by other bulk schemes. COAMPS simulations were performed and evaluated with this scheme for both continental convections and tropical cyclone cases.

18. Other parameterizations

A physically consistent method is developed in COAMPS to include dissipative heating based on turbulent kinetic energy (TKE) dissipation to ensure energy conservation (Jin et al. 2007). The dissipative heating rate is considered at all levels of the model, including both the surface layer and the layers above, in contrast to other studies where dissipative heating is considered at the surface only due to lack of TKE representation in the models. Furthermore, the TKE dissipation in this method is computed semi-implicitly to maintain computational stability. Additionally, for tropical cyclones, a sea spray parameterization option is available. (Fairall et al. 2009)

19. Summary of how these physical processes are modeled each time step at individual grid points.

(a) the total diabatic heating per time step

i. from resolvable scales

ii. from subgrid scales

(b) the total moistening/drying per time step

i. from resolvable scales

ii. from subgrid scales

(c) the total acceleration/deceleration per time step

i. from resolvable scales

ii. from subgrid scales

20. Phenomena studied

(a) for operational weather forecasting

Over 70 areas are being run at FNMOC at least twice daily around the world for many different applications. A GUI based system, the COAMPS-On Demand System (COAMPS-OS) is used in operations (and in research applications) to the tailor domain set up, model options, graphics, and linked models and products based on the application and requirements.

(b) for research applications

COAMPS is being run in real-time for all hurricanes in the western Atlantic and the eastern and central Pacific in support of the Hurricane Forecast Improvement Project (HFIP); and for all tropical cyclones in the western Pacific, Indian Ocean, and southern Hemisphere for evaluation by the Joint Typhoon Warning Center (JTWC).

Research has focused on a variety of mesoscale and synoptic-scale topics from the tropics to the Arctic, and from the ocean bottom to the middle atmosphere. In the past, COAMPS has been used in support of many research and field programs including ITOP, LABSEA, Sierra Rotor Experiment, AOSN, AOSN-II, AESOP, Indonesian Straits, T-REX, CBLAST, MAP, America's Cup, ACE, VOCALS, CALJET, PACJET, COAST, COMPARE, FASTEX, GUFMEX, LEADEX, SHAREM, SWADE, PHILEX, and VOCAR.

21. Computer(s) used; examples of time of integration for specific model runs

Cray-XT5: 75 minutes wall time for a 120-hour forecast on a triply-nested (45/15/5 km; 281x151, 121x121, 181x181 grid; 40 levels) using 160 processors.

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