The governing equations for CM1

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1 Introduction

This document describes the governing equations for the CM1 numerical model, valid for release 20.3 (cm1r20.3; June 2021). This document is being provided because changes have occurred since the original release of the model (cm1r1, January 2003), which was first described by Bryan (2002) and Bryan and Fritsch (2002). Differences in the governing equations between cm1r1 and cm1r20 are relatively minor; however, this document is being provided for clarity and also to provide details that are not available in the two articles cited above.

Definitions of many symbols are provided in Table 1 (for variables that are arrays in the code) and Table 2 (for variables that are constants in the code).

2 Governing equations

CM1 (“Cloud Model 1”) integrates governing equations for u, v, w, π', θ', and q_χ, where $\pi \equiv (p/p_{00})^{R/c_p}$ is a nondimensional pressure, and q_χ ($\chi = v, l, i$) represents the mixing ratios of moisture variables: q_v is water vapor mixing ratio; q_l is the mixing ratio of liquid water; and q_i is the mixing ratio of solid water (ice). Herein, a superscript prime denotes the perturbation from a base-state value. A base-state variable, by definition, is invariant in time and is a function of z only, and is denoted herein by a subscript 0. Thus, a generic variable α may be defined as follows: $\alpha(x, y, z, t) = \alpha_0(z) + \alpha'(x, y, z, t)$. The base state is further assumed to be in hydrostatic balance,

$$\frac{d\pi_0}{dz} = -\frac{g}{c_p \theta_{\rho 0}}, \tag{1}$$

where θ_ρ is density potential temperature,

$$\theta_\rho = \theta \left(\frac{1 + q_v/\varepsilon}{1 + q_v + q_l + q_i} \right). \tag{2}$$

The equation of state is

$$p = \rho R T \left(1 + q_v/\varepsilon\right), \tag{3}$$

or, because $T = \theta\pi$, the equation of state may be equivalently stated as,

$$\pi = \left(\frac{\rho R \theta \left(1 + q_v/\varepsilon\right)}{p_{00}} \right)^{\frac{R}{c_v}}. \tag{4}$$

Note that base state variables must also obey the equation of state. Herein, ρ represents the density of dry air.

The governing equations for velocity are

$$\frac{\partial u}{\partial t} + c_p\theta_\rho \frac{\partial \pi'}{\partial x} = \mathrm{ADV}(u) + fv + P_u + T_u + D_u + N_u \tag{5a}$$
$$\frac{\partial v}{\partial t} + c_p\theta_\rho \frac{\partial \pi'}{\partial y} = \mathrm{ADV}(v) - fu + P_v + T_v + D_v + N_v \tag{5b}$$
$$\frac{\partial w}{\partial t} + c_p\theta_\rho \frac{\partial \pi'}{\partial z} = \mathrm{ADV}(w) + B + T_w + D_w + N_w \tag{5c}$$

where ADV is the advection operator, formulated in CM1 for a generic variable α as

$$\begin{aligned} \mathrm{ADV}(\alpha) = & -u\frac{\partial \alpha}{\partial x} - v\frac{\partial \alpha}{\partial y} - w\frac{\partial \alpha}{\partial z} \\ = & \frac{1}{\rho_0}\left[-\frac{\partial(\rho_0 u\alpha)}{\partial x} - \frac{\partial(\rho_0 v\alpha)}{\partial y} - \frac{\partial(\rho_0 w\alpha)}{\partial z} \right. & (6) \\ & \left. + \alpha\left(\frac{\partial(\rho_0 u)}{\partial x} + \frac{\partial(\rho_0 v)}{\partial y} + \frac{\partial(\rho_0 w)}{\partial z}\right)\right], & (7) \end{aligned}$$

B is buoyancy,

$$B = g\frac{\theta_\rho - \theta_{\rho 0}}{\theta_{\rho 0}} \cong g\left[\frac{\theta'}{\theta_0} + \left(\frac{1}{\varepsilon} - 1\right)(q_v - q_{v,0}) - q_l - q_i\right], \tag{8}$$

and where P terms in (5) represent specified large-scale pressure gradients (see Section 8), T terms represent tendencies from subgrid turbulence (see Section 4), the D terms represent optional tendencies from other diffusive processes (discussed at the end of this section), and N represents Newtonian relaxation (i.e., Rayleigh damping). An f-plane is assumed when Coriolis acceleration is included (`icor = 1`), and a beta plane is used when `icor = 1` and `betaplane = 1`.

The governing equations for the three moisture components are

$$\frac{\partial q_v}{\partial t} = \mathrm{ADV}(q_v) + T_{qv} + D_{qv} - \dot{q}_{\mathrm{cond}} - \dot{q}_{\mathrm{dep}} \, , \tag{9a}$$

$$\frac{\partial q_l}{\partial t} = \mathrm{ADV}(q_l) + T_{ql} + D_{ql} + \dot{q}_{\mathrm{cond}} - \dot{q}_{\mathrm{frz}} + \frac{1}{\rho}\frac{\partial \left(\rho V_l q_l\right)}{\partial z} \, , \tag{9b}$$

$$\frac{\partial q_i}{\partial t} = \mathrm{ADV}(q_i) + T_{qi} + D_{qi} + \dot{q}_{\mathrm{dep}} + \dot{q}_{\mathrm{frz}} + \frac{1}{\rho}\frac{\partial \left(\rho V_i q_i\right)}{\partial z} \, . \tag{9c}$$

The $\dot{q}$ terms represent phase changes between these three components, the T terms represent tendencies from subgrid turbulence (see Section 4), D represents other optional diffusive tendencies (see final paragraph of this section). The last term on the right sides of (9b) and (9c) represents hydrometeor fallout by a terminal fall velocity (V, which is assumed to be positive-definite).

The governing equation for θ' is

$$\begin{aligned}\frac{\partial \theta'}{\partial t} = \mathrm{ADV}(\theta) - \Theta_1 \theta \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) + T_\theta + D_\theta + N_\theta \\ + \Theta_2 \left(L_v \dot{q}_{\mathrm{cond}} + L_s \dot{q}_{\mathrm{dep}} + L_f \dot{q}_{\mathrm{frz}} \right) + \Theta_3 \left(\dot{q}_{\mathrm{cond}} + \dot{q}_{\mathrm{dep}} \right) + \Theta_2 \epsilon + \dot{Q}_\theta + W_T\end{aligned} \tag{10}$$

where T_θ is the tendency from subgrid turbulence (see Section 4), D_θ represents optional diffusive tendencies (discussed at the end of this section), and term $\dot{Q}_\theta$ represents external tendencies to internal energy (primarily radiative heating/cooling). The N_θ term represents the tendency from Newtonian relaxation (i.e., Rayleigh damping), and the W_T term represents the cooling/warming effect from hydrometeors that fall relative to air (i.e., when $V_\chi \neq 0$); most numerical models neglect this effect but it is available in CM1 by setting `efall` = 1. The term with ϵ in (10) is associated with dissipative heating, which is the increase in internal energy that occurs when kinetic energy is dissipated; many numerical models neglect this effect but it is available in CM1 by setting `idiss` = 1.

The governing equations for π' is

$$\frac{\partial \pi'}{\partial t} = \mathrm{ADV}(\pi) - \Pi_1 \pi \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) + \Pi_2 \left(L_v \dot{q}_{\mathrm{cond}} + L_s \dot{q}_{\mathrm{dep}} + L_f \dot{q}_{\mathrm{frz}} \right)$$
$$+ \Pi_3 \left(\dot{q}_{\mathrm{cond}} + \dot{q}_{\mathrm{dep}} \right) + \Pi_4 \left(T_\theta + D_\theta + N_\theta + \Theta_2 \epsilon + \dot{Q}_\theta + W_T \right) + \Pi_5 \left(T_{qv} + D_{qv} \right). \quad (11)$$

In (10) and (11), the variables Θ and Π depend on the value chosen for `eqtset`, and determines whether the equation set mathematically conserves mass and energy in moist environments. For dry environments (`imoist`=0) and for `eqtset`=1:

$$\Theta_1 = 0, \qquad \Theta_2 = \frac{1}{c_p \pi}, \qquad \Theta_3 = 0, \quad (12)$$

$$\Pi_1 = \frac{R}{c_v}, \qquad \Pi_2 = \Pi_3 = \Pi_4 = \Pi_5 = 0. \quad (13)$$

This option yields the traditional (nonconservative) equation set that is used in many compressible nonhydrostatic models (such as ARPS, MM5, and the Klemp-Wilhelmson Model). The governing equation for θ under this option is equivalent to the one used in the Advanced Research WRF Model (ARW).

For `eqtset` = 2:

$$\Theta_1 = \left(\frac{R_m}{c_{vm}} - \frac{R c_{pm}}{c_p c_{vm}} \right), \qquad \Theta_2 = \frac{c_v}{c_{vm} c_p \pi}, \qquad \Theta_3 = -\theta \frac{R_v}{c_{vm}} \left(1 - \frac{R c_{pm}}{c_p R_m} \right), \quad (14)$$

$$\Pi_1 = \frac{R}{c_p} \frac{c_{pm}}{c_{vm}}, \qquad \Pi_2 = \frac{R}{c_p} \left(\frac{1}{c_{vm} \theta} \right), \qquad \Pi_3 = -\frac{R}{c_p} \left(\pi \frac{R_v c_{pm}}{R_m c_{vm}} \right),$$
$$\Pi_4 = \frac{R}{c_v} \frac{\pi}{\theta}, \qquad \Pi_5 = \frac{R}{c_v} \frac{\pi}{\epsilon + q_v}. \quad (15)$$

where

$$c_{pm} = c_p + c_{pv} q_v + c_l q_l + c_i q_i, \qquad c_{vm} = c_v + c_{vv} q_v + c_l q_l + c_i q_i, \qquad R_m = R + R_v q_v. \quad (16)$$

This option yields the mass- and energy-conserving equations of Bryan and Fritsch (2002). Note that (14) reduces to (12) and (15) reduces to (13) by setting $c_{pv} = c_{vv} = c_l = c_i = R_v = \Pi_2 = \Pi_3 = \Pi_4 = \Pi_5 = 0$.

The latent heats, L, are temperature-dependent according to Kirchoff's relations,

$$\frac{dL_v}{dT} = c_{pv} - c_l, \qquad \frac{dL_s}{dT} = c_{pv} - c_i, \qquad \frac{dL_f}{dT} = c_l - c_i. \tag{17}$$

Numerical values for L_v and L_s are obtained by integration of Kirchoff's relations using reference values $L_v(T_0)$ and $L_s(T_0)$ (see Table 2), and $L_f = L_s - L_v$.

The equations in this section are presented in the exact form that they are integrated in CM1 code. Users should be able to compare directly equations written herein with CM1 code. Note, however, that equations for the axisymmetric version of the model are slightly different; details can be found in Bryan and Rotunno (2009).

Finally, the optional diffusive tendencies represented by D terms above are excluded from most simulations. They can include sixth-order diffusion (`idiff`=1 with `difforder`=6) which is sometimes used to filter small-scale fluctuations smaller than ≈6 times the grid spacing (e.g., Bryan 2005; Knievel et al. 2007). For very idealized simulations, second-order diffusion can be applied on coordinate surfaces (`idiff`=1 with `difforder`=2).

3 Terrain

CM1 uses terrain-following coordinates, following Gal-Chen and Somerville (1975). The nominal heights of the coordinate surfaces are given by

$$\sigma = \frac{z_t \left(z - z_s \right)}{z_t - z_s} \tag{18}$$

where $z_s(x, y)$ is the terrain elevation, and z_t is the constant height of the model top. The following metric terms are used in CM1 to account for the coordinate transformation:

$$
\begin{aligned}
G_x &= \frac{\partial \sigma}{\partial x} = \frac{\sigma - z_t}{z_t - z_s} \frac{\partial z_s}{\partial x} \\
G_y &= \frac{\partial \sigma}{\partial y} = \frac{\sigma - z_t}{z_t - z_s} \frac{\partial z_s}{\partial y} \\
G_z &= \frac{\partial \sigma}{\partial z} = \frac{z_t}{z_t - z_s}.
\end{aligned} \tag{19}
$$

Horizontal gradients in Cartesian space (e.g., $\partial/\partial x|_z$) can be calculated from gradients along the terrain-following computational coordinates ($\partial/\partial x|_\sigma$) plus "correction terms" as follows:

$$
\begin{aligned}
\left.\frac{\partial \alpha}{\partial x}\right|_z &= G_z \frac{\partial}{\partial x} \left.\left(\frac{\alpha}{G_z}\right)\right|_\sigma + \frac{\partial}{\partial \sigma} \left(G_x \alpha\right) \\
\left.\frac{\partial \alpha}{\partial y}\right|_z &= G_z \frac{\partial}{\partial y} \left.\left(\frac{\alpha}{G_z}\right)\right|_\sigma + \frac{\partial}{\partial \sigma} \left(G_y \alpha\right).
\end{aligned} \tag{20}
$$

Vertical gradients are calculated simply by

$$
\frac{\partial \alpha}{\partial z} = G_z \frac{\partial \alpha}{\partial \sigma}. \tag{21}
$$

For the normal component of velocity to vanish at the surface, the following must hold:

$$
w = u \frac{\partial z_s}{\partial x} + v \frac{\partial z_s}{\partial y} \qquad \text{at} \qquad \sigma = 0. \tag{22}
$$

From (19) and (22) it follows that

$$
\dot{\sigma} \equiv u G_x / G_z + v G_y / G_z + w = 0 \qquad \text{at} \qquad \sigma = 0. \tag{23}
$$

Further, it is convenient to formulate the advection operator (6) for simulations with terrain as follows:

$$\mathrm{ADV}(\alpha) = \frac{G_z}{\rho_0}\left[- \left.\frac{\partial\left(\alpha\rho_0 u/G_z\right)}{\partial x}\right|_\sigma - \left.\frac{\partial\left(\alpha\rho_0 v/G_z\right)}{\partial y}\right|_\sigma - \frac{\partial\left(\alpha\rho_0\dot{\sigma}\right)}{\partial\sigma} \right.$$
$$\left. + \alpha\left(\left.\frac{\partial\left(\rho_0 u/G_z\right)}{\partial x}\right|_\sigma + \left.\frac{\partial\left(\rho_0 v/G_z\right)}{\partial y}\right|_\sigma + \frac{\partial\left(\rho_0\dot{\sigma}\right)}{\partial\sigma}\right)\right]. \quad (24)$$

4 Turbulence

If `cm1setup` ≥ 1 then tendencies due to small-scale turbulence and/or molecular-scale diffusion (represented generically by the T terms in Section 2) are formulated as follows:

$$T_u = \frac{1}{\rho}\left[\frac{\partial\tau_{11}}{\partial x} + \frac{\partial\tau_{12}}{\partial y} + \frac{\partial\tau_{13}}{\partial z}\right] \quad (25)$$

$$T_v = \frac{1}{\rho}\left[\frac{\partial\tau_{12}}{\partial x} + \frac{\partial\tau_{22}}{\partial y} + \frac{\partial\tau_{23}}{\partial z}\right] \quad (26)$$

$$T_w = \frac{1}{\rho}\left[\frac{\partial\tau_{13}}{\partial x} + \frac{\partial\tau_{23}}{\partial y} + \frac{\partial\tau_{33}}{\partial z}\right] \quad (27)$$

$$T_s = -\frac{1}{\rho}\left[\frac{\partial\tau_1^s}{\partial x} + \frac{\partial\tau_2^s}{\partial y} + \frac{\partial\tau_3^s}{\partial z}\right] \quad (28)$$

where s represents one of the model scalars (θ, q_v, q_l, or q_i). The subgrid stress terms (τ_{ij}) are typically formulated as follows:

$$\tau_{ij} \equiv \rho\overline{u_i' u_j'} = 2\rho K_m S_{ij}, \quad (29)$$

where K_m is viscosity (explained below) and S_{ij} is the strain tensor,

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right). \quad (30)$$

Exceptions to (29) are described below (i.e., for `sgsmodel` ≥ 3). The turbulent fluxes for scalars are

$$\tau_i^{\theta} \equiv \overline{\rho u_i'\theta'} = -K_h\rho\frac{\partial\theta}{\partial x_i}, \tag{31}$$

$$\tau_i^{q_v} \equiv \overline{\rho u_i'q_v'} = -K_h\rho\frac{\partial q_v}{\partial x_i}, \tag{32}$$

$$\tau_i^{q_l} \equiv \overline{\rho u_i'q_l'} = -K_h\rho\frac{\partial q_l}{\partial x_i}, \tag{33}$$

$$\tau_i^{q_i} \equiv \overline{\rho u_i'q_i'} = -K_h\rho\frac{\partial q_i}{\partial x_i}, \tag{34}$$

where K_h is diffusivity (see below). The relations (29) and (31)–(34) apply to the interior of a model domain; different formulations are applied on boundaries to account for surface stress (i.e., drag) and fluxes of temperature and moisture.

The method to determine K_m and K_h depends on the setup of CM1. For `cm1setup=0`, $K_m = K_h = 0$, so all T terms in Section 2 are set to zero. The methods for `cm1setup` ≥ 1 are described below.

4.1 Large-Eddy Simulation (LES) (`cm1setup=1`)

For `cm1setup = 1` a large-eddy simulation (LES) closure is used. Several different approaches are currently available in CM1, depending on the setting for the subgrid-scale model (`sgsmodel`).

4.1.1 No subgrid model for interior flow (`sgsmodel=0`)

With `sgsmodel=0` the stress terms (τ_{ij}) and flux terms (e.g., τ_i^{θ}, $\tau_i^{q_v}$, etc.) are set to zero *except* at the lower and upper boundaries. Thus, no subgrid-scheme model is used in the interior of the model domain, but boundary conditions are set consistently with LES methods. The turbulence tendency terms (T) are generally zero except near the upper and lower boundaries. Small-scale diffusion can still be included in these types of simulations through implicit diffusion in the advection scheme; this approach is sometimes called "implicit large eddy simulation" (ILES).

4.1.2 TKE scheme (`sgsmodel=1`)

With `sgsmodel=1` a subgrid turbulence kinetic energy (TKE) is predicted and used to determine K_m and K_h. The scheme in CM1 is similar to that described by Deardorff (1980). The eddy viscosity K_m is determined from the relation

$$K_m = c_m l e^{1/2}. \tag{35}$$

and the eddy diffusivity K_h is determined from the relation

$$K_h = c_h l e^{1/2}, \tag{36}$$

where $e = \frac{1}{2}\overline{u_i' u_i'}$ is the subgrid TKE. The predictive equation for e is

$$\frac{\partial e}{\partial t} = \mathrm{ADV}(e) + \tau_{ij} S_{ij} - K_h N_m^2 + \frac{1}{\rho}\frac{\partial}{\partial x_i}\left(2\rho K_m \frac{\partial e}{\partial x_i}\right) - \epsilon \tag{37}$$

where ϵ is dissipation, which is parameterized as

$$\epsilon = c_\epsilon e^{3/2}/l, \tag{38}$$

N_m^2 is the squared Brunt-Väisälä frequency, which for subsaturated air is given by

$$N_m^2 = \frac{g}{\theta_\rho}\frac{\partial \theta_\rho}{\partial z}, \tag{39}$$

and for saturated air is given by Shi et al. (2019).

The parameters c_m, c_h, c_ϵ, and l must be specified to close these equations. In CM1, the default value for c_m is 0.1. The parameters c_h, c_ϵ, and l have a stability dependence that is designed to reduce subgrid-scale mixing in statically stable conditions (i.e., for $N_m^2 > 0$). The default formulation in CM1 is as follows:

$$c_h = 1 + 2\frac{l}{\Delta} \quad , \quad c_\epsilon = c_{\epsilon,1} + c_{\epsilon,2}\frac{l}{\Delta} \quad , \quad l = \left(c_l \frac{e}{N_m^2} \right)^{1/2} , \tag{40}$$

where Δ is a measure of the grid size, e.g.,

$$\Delta = (\Delta x \, \Delta y \, \Delta z)^{1/3} , \tag{41}$$

$c_l = 2/3$, $c_{\epsilon,1} + c_{\epsilon,2} = \pi^2 c_m$, and $c_{\epsilon,1} = c_m {c_l}^2 \, (\mathrm{Ri_c} - 1)$ (Stevens et al. 1999). Note that $l = \Delta$ when $N_m^2 \leq 0$. The settings for c_m, c_ϵ, and l in CM1 ensure that turbulence is inactive (i.e., $K_m = K_h = 0$) when $\mathrm{Ri} > \mathrm{Ri_c}$, where Ri is the Richardson number,

$$\mathrm{Ri} = \frac{N_m^2}{S^2} \tag{42}$$

S^2 is deformation,

$$S^2 = 2 S_{ij} S_{ij}, \tag{43}$$

and $\mathrm{Ri_c} = 0.25$ is a 'critical' value for subgrid turbulence.

4.1.3 Smagorinsky scheme (`sgsmodel=2`)

For `sgsmodel = 2` a simpler approach is used. By assuming steady and homogeneous subgrid turbulence, and by neglecting the stability dependence of the parameters discussed in the previous subsection, then the following relation can be derived:

$$K_m = (C_s \Delta)^2 \left[S^2 \left(1 - \frac{\mathrm{Ri}}{\mathrm{Pr}} \right) \right]^{1/2} , \tag{44}$$

where $C_s = (c_m/\pi)^{1/2} = 0.18$ is the Smagorinsky constant [after Smagorinsky (1963)] and $\mathrm{Pr} \approx 1/3$ is the Prandtl number. The eddy diffusivity is given by

$$K_h = K_m/\mathrm{Pr}. \tag{45}$$

If $\mathrm{Ri} > \mathrm{Pr}$ in (44) then K_m is set to zero; hence, subgrid turbulence is active (i.e., $K_m > 0$) only when $\mathrm{Ri} < \mathrm{Pr}$.

Compared to the TKE scheme, the Smagorinsky scheme has three primary disadvantages: 1) Subgrid turbulence for the Smagorinsky scheme is active (i.e., $K_m > 0$) only when $S^2 > 0$ (i.e., in locally sheared conditions). 2) The assumption of steady and homogeneous turbulence inherent in the Smagorinsky scheme is a major disadvantage in some situations, particularly when resolution is poor. 3) As formulated, there is no stability dependence to the inherent length scales in this Smagorinsky scheme, which makes it too diffusive in stable conditions ($N_m^2 > 0$). This last deficiency can be alleviated (see, e.g., Stevens et al. 1999), and might be addressed in a future version of CM1.

4.1.4 Two-part models (`sgsmodel`=3 and 4)

A well-documented shortcoming of the LES subgrid models described above is the typically poor match to the surface-layer parameterization near the surface (e.g., Brasseur and Wei 2010). For neutral conditions, this means the near-surface wind profiles is not logarithmic. To address this shortcoming, Sullivan et al. (1994) developed a "two-part" model for subgrid stress that includes the standard model listed above, (29), plus a term designed to ensure that the mean profile matches similarity theory. In CM1, this approach is implemented as follows:

$$\tau_{13} = 2\rho K_m S_{13} + \rho K_w \frac{\partial \langle u \rangle}{\partial z} \quad , \quad \tau_{23} = 2\rho K_m S_{23} + \rho K_w \frac{\partial \langle v \rangle}{\partial z} \quad , \tag{46}$$

where K_w is a 'near-wall' eddy viscosity and the brackets denote average values (either domain-average or time-average). For `sgsmodel=3`, the method for determining K_w is based on zero stress gradient at the lowest model level, as described in Sullivan et al. (1994). For `sgsmodel=4`, the method for determining K_w is determined from the equation for mean wind speed assuming the local time-tendency is small compared to the subgrid terms (manuscript in preparation).

4.1.5 Nonlinear backscatter and anisotropy model (`sgsmodel`=5 and 6)

The nonlinear backscatter and anisotropy (NBA) subgrid model is based on the approach by Kosović (1997), which includes terms that allow for backscatter (i.e., non-dissipative stress) and non-isotropic mixing. One version (`sgsmodel`=5) is based upon a subgrid TKE equation as in `sgsmodel`=1, and the other version (`sgsmodel`=6) uses a Smagorinsky-type local equation for eddy viscosity as in `sgsmodel`=2. Further details are documented in Mirocha et al. (2010).

4.2 Mesoscale modeling / Planetary Boundary Layer (PBL) parameterization (`cm1setup`=2)

For `cm1setup` = 2, it is assumed that no turbulent eddies are resolved on the grid, and hence their effects must be accounted completely via the T terms in section 2. The schemes in CM1 use slightly different forms of (29) and (31)–(34):

$$\tau_{11} = 2\rho K_{m,h}\frac{\partial u}{\partial x}, \quad \tau_{22} = 2\rho K_{m,h}\frac{\partial v}{\partial y}, \quad \tau_{33} = 2\rho K_{m,h}\frac{\partial w}{\partial z},$$

$$\tau_{12} = \rho K_{m,h}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right), \quad \tau_{13} = \rho K_{m,v}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right), \quad \tau_{23} = \rho K_{m,v}\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right), \quad (47)$$

$$\tau_1^s = -\rho K_{h,h}\frac{\partial s}{\partial x}, \quad \tau_2^s = -\rho K_{h,h}\frac{\partial s}{\partial y}, \quad \tau_3^s = -\rho K_{h,v}\frac{\partial s}{\partial z}.$$

4.2.1 Horizontal turbulence scheme (`horizturb` = 1)

For `horizturb` = 1, a simple scheme is used. This scheme is often called a "horizontal Smagorinsky scheme" in the literature. Here, a horizontal eddy viscosity is calculated,

$$K_{m,h} = l_h^2 S_h \tag{48}$$

where the horizontal deformation is:

$${S_h}^2 = 2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{\partial w}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 . \tag{49}$$

The variable l_h is a horizontal length scale associated with turbulence, and must be set by the user (see variables `l_h`, `lhref1`, and `lhref2` in README.namelist). The turbulence diffusivity is the same as viscosity, i.e., $K_{h,h} = K_{m,h}$.

4.2.2 Vertical turbulence / PBL schemes (`ipbl` $\geq$ 1)

When `cm1setup` = 2, a Planetary Boundary Layer (PBL) parameterization may be used. For `ipbl` =1, the Yonsei University (YSU) PBL scheme is used. This scheme is described in Hong et al. (2006). The YSU scheme is based on a K-Profile Parameterization (KPP) approach for the near-surface boundary layer, but includes an explicit treatment of entrainment at the top of the PBL (Hong et al. 2006).

When `ipbl` = 2, a Smagorinsky-type scheme is used in the vertical direction, where

$$K_{m,v} = l_v^2 S_v \left(1 - \frac{\mathrm{Ri}}{\mathrm{Pr}}\right)^{1/2} \tag{50}$$

where

$${S_v}^2 = \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 . \tag{51}$$

Since cm1r17, l_v is determined from the relation $l_v^{-2} = (\kappa z)^{-2} + l_\infty^{-2}$ where l_∞ is a specified asympototic length scale far from the surface (see l_inf in README.namelist). The value for the Prandtl number Pr must is set to 1 by default.

Other PBL models have been added to CM1 in recent years, including the GFS-EDMF scheme (ipbl = 3), the Mellor-Yamada-Nakanishi-Niino scheme (ipbl = 4 and 5), and the Mellor-Yamada-Janjic scheme (ipbl = 6).

4.3 Direct Numerical Simulation (cm1setup=3)

For cm1setup=3, the viscosity and diffusivity in (29) and (31)–(34) are set to constant values (K_m = viscosity; K_h = viscosity / pr_num).

5 Anelastic/incompressible equations

The equations in section 2 are used in CM1 when one of the compressible solvers are chosen (psolver = 1,2,3). CM1 also has the ability to use the anelastic equations (psolver = 4) and the incompressible equations (psolver = 5).

For the anelastic equations, the velocity equations can be written as:

$$\frac{\partial u}{\partial t} + \frac{\partial \phi}{\partial x} = F_u \tag{52a}$$

$$\frac{\partial v}{\partial t} + \frac{\partial \phi}{\partial y} = F_v \tag{52b}$$

$$\frac{\partial w}{\partial t} + \frac{\partial \phi}{\partial z} = F_w. \tag{52c}$$

where F_u, F_v, and F_w represent all terms on the right side of (5a), (5b), and (5c), respectively. Notice that the pressure-gradient terms are written in terms of $\phi \equiv p'/\rho_0$. There is no predictive equation for pressure in this system of equations. Hence, (11) is not integrated in the anelastic system. Instead, a diagnostic equation for ϕ is developed by using the anelastic mass-continuity equation,

$$\frac{\partial}{\partial x_i}\left(\rho_0 u_i\right) = 0. \tag{53}$$

Using (52) and (53), the diagnostic equation for ϕ is simply

$$\frac{\partial}{\partial x_i}\left(\rho_0 \frac{\partial \phi}{\partial x_i}\right) = \frac{\partial\left(\rho_0 F_u\right)}{\partial x} + \frac{\partial\left(\rho_0 F_v\right)}{\partial y} + \frac{\partial\left(\rho_0 F_w\right)}{\partial z}. \tag{54}$$

CM1 solves (54) using a direct method based on fast Fourier transforms. Because the anelastic equations do not permit acoustic waves, there is no need for 'small' time steps (i.e., time-splitting is not used).

The incompressible equations are the same as the anelastic equations except it is assumed that ρ_0 = constant. This system of equations is only appropriate for simulations with a shallow domain (of order 1 km or less).

6 Compressible-Boussinesq equations

Since cm1r18, there is an option to use the "compressible Boussinesq" equations (`psolver = 6`). In this equation set, the Boussinesq approximation has been made, in which density variations are neglected in the velocity equations (except where multiplied by gravity). Further, a prognostic "pressure" equation is used, and thus acoustic waves are permitted. The equations are as follows:

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - \frac{\partial \phi}{\partial x} + fv + T_u + D_u + N_u \tag{55}$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - \frac{\partial \phi}{\partial y} - fu + T_v + D_v + N_v \tag{56}$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - \frac{\partial \phi}{\partial z} + g\frac{\theta'}{\theta_0} + T_w + D_w + N_w \tag{57}$$

$$\frac{\partial \phi}{\partial t} = -c_s^2\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right). \tag{58}$$

In (58), c_s is a constant speed of sound that can be specified by the user; the default value is 300 m s^{-1}. A value of at least 10 times the maximum wind speed is advised. These equations are most applicable to shallow flows (of order 1 km) and should only be used in similar situations as the incompressible equations. These equations are solved using the Klemp-Wilhelmson time-splitting scheme with explicit calculations in both horizontal and vertical directions (the same as `psolver = 2`).

7 Modified-compressible equations

This option (`psolver = 7`) is similar to the compressible-Boussinesq option in CM1 in the sense that the speed of sound can be modified by the model user. In this case, however, density is not assumed to be constant, but rather is a function of height as in the anelastic equation set in CM1. The governing equations in this case are:

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - c_p\theta_{\rho 0}\frac{\partial \phi}{\partial x} + fv + T_u + D_u + N_u \tag{59}$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - c_p\theta_{\rho 0}\frac{\partial \phi}{\partial y} - fu + T_v + D_v + N_v \tag{60}$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - c_p\theta_{\rho 0}\frac{\partial \phi}{\partial z} + g\frac{\theta'}{\theta_0} + T_w + D_w + N_w \tag{61}$$

$$\frac{\partial \phi}{\partial t} = -\frac{c_s^2}{c_p\rho_0{\theta_{\rho 0}}^2}\frac{\partial}{\partial x_i}\left(\rho_0\theta_{\rho 0}u_i\right) \tag{62}$$

(Klemp and Wilhelmson 1978; Durran and Klemp 1983). These equations are applicable to deep flows (of order 10 km) and can be used in similar situations as the anelastic equations. These equations are solved in CM1 using the Klemp-Wilhelmson time-splitting scheme with explicit calculations in both horizontal and vertical directions (the same as `psolver = 2`). Because the speed of sound can be modified, this equation set can be advantageous for weak flows in which the velocity is much smaller than the actual speed in sound. In particular, for the traditional time-split solver (`psolver = 2,3`), when the number of time-split 'small' steps per 'large' time step is greater than 100, it can be computationally costly to calculate pressure-gradient and divergence terms so many times; for `psolver = 7`, c_s can be reduced such that the number of small steps per large step is of-order 10, thus saving considerable computation resources. Based on tests of this equation set, a value of c_s that is (at least) 10 times greater than the maximum wind speed is recommended.

8 Large-scale pressure gradient

For simulations with Coriolis acceleration (`icor = 1`) a large-scale pressure gradient term may be needed to counteract (or "balance") the tendency of the wind profiles to rotate over time. Beginining with cm1r19 this term is explicitly added to the horizontal velocity equations, i.e.,

$$\frac{\partial u}{\partial t} = \ldots + P_u \,, \tag{63a}$$

$$\frac{\partial v}{\partial t} = \ldots + P_v \,. \tag{63b}$$

The large-scale pressure gradient terms P_u and P_v can be specified arbitrarily (`lspgrad` $= 4$), which is useful from some highly idealized simulations. However, in practice, the P terms are determined via balance relations applicable to assumed large-scale conditions. Specifically, in CM1 with `lspgrad = 1,2` a geostrophic balance equation is invoked

$$P_u \equiv \left\langle -c_p \theta_v \frac{\partial \pi}{\partial x} \right\rangle = - \, f v_g \,, \tag{64a}$$

$$P_v \equiv \left\langle -c_p \theta_v \frac{\partial \pi}{\partial y} \right\rangle = + \, f u_g \,, \tag{64b}$$

where $u_g(z,t)$ and $v_g(z,t)$ represent the geostrophic wind components, and the angled brackets denote averaging over a large area (i.e., the entire extent of a CM1 domain). For `lspgrad = 1`, the u_g and v_g profiles are set equal to the base-state wind profiles; for `lspgrad = 2`, u_g and v_g are specified by the model user and are typically similar (but not necessarily equal) to the base state.

To put the `lspgrad=1,2` formulations into context with previous studies, note that the sum of the Coriolis and large-scale pressure-gradient terms can be written,

$$\frac{\partial u}{\partial t} = \ldots + fv + P_u = \ldots + f\left(v - v_g\right) , \tag{65a}$$
$$\frac{\partial v}{\partial t} = \ldots - fu + P_v = \ldots - f\left(u - u_g\right) . \tag{65b}$$

The form of (65) suggests that the perturbation winds (relative to u_g and v_g) are used to calculate the Coriolis acceleration terms, and so this methodology is sometimes called a "perturbation Coriolis" technique (e.g. in the WRF model, and earlier versions of CM1). This terminology is no longer used in CM1 so that the fundamental methodology can be highlighted, i.e., a large-scale pressure-gradient term is applied to the horizontal velocity equations. Also, beginning with cm1r19, other balance relations besides geostrophic balance can be applied, as described below.

For `lspgrad = 3` a gradient-wind balance equation is invoked,

$$P_u \equiv \left\langle -c_p \theta_v \frac{\partial \pi}{\partial x} \right\rangle = -f v_{gr} - \frac{{v_{gr}}^2}{R} , \tag{66}$$

where $v_{gr}(z,t)$ represents a gradient wind speed and R is a specified radius from the center of a vortex (see Bryan et al. 2017). Currently, v_{gr} is set equal to the base-state v profile, although the CM1 code could be modified to incorporate arbitrary or analytic profiles.

By default, the variables u_g, v_g, and v_{gr} are held fixed in time. A new option (described in the next section) has been developed that allows these variables to vary in time.

9 Large-scale wind nudging

By default, the large-scale wind profile remains nearly the same throughout a CM1 simulation (except, of course, for modifications that are caused by the simulation itself, e.g., by topography, boundary-layer evolution, convective systems, etc). But there are instances were the large-scale conditions may need to be changed throughout a simulation, e.g., to include the effects of storm moving into a different environment, or for strictly theoretical reasons. Thus, a method to modify the large-scale wind profile has been implemented into CM1.

The method roughly follows the technique introduced by Onderlinde and Nolan (2017), which nudges the simulated winds towards a specified profile using Newtonian relaxation. In CM1, this nudging is accomplished using a simple term added to the horizontal velocity equations,

$$\frac{\partial u}{\partial t} = \ldots - \frac{\langle u \rangle - u_{ref}}{\tau_n}, \tag{67a}$$

$$\frac{\partial v}{\partial t} = \ldots - \frac{\langle v \rangle - v_{ref}}{\tau_n}, \tag{67b}$$

where brackets represents a horizontal average over the entire domain (on constant height levels), $u_{ref}(z,t)$ and $v_{ref}(z,t)$ are the "reference" profiles that the large-scale flow is nudged towards, and τ_n is a relaxation timescale. The goal of this formulation is to nudge the *domain-average* wind profiles to a specified profile, which is important because it ensures that vertical vorticity is not added to a simulation via the nudging term, i.e.,

$$\begin{aligned}
\frac{\partial \zeta}{\partial t} &\equiv \frac{\partial}{\partial t}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) \\
&= \frac{\partial}{\partial x}\left(\frac{\partial v}{\partial t}\right) - \frac{\partial}{\partial y}\left(\frac{\partial u}{\partial t}\right) \\
&= \ldots + 0
\end{aligned}$$

where (67) is used for the last step, recognizing that none of the terms on the right side of (67) are functions of x or y.

When using this technique in CM1, the large-scale pressure gradient terms, (63), may need to be modified consistently, particularly if Coriolis acceleration is included in a simulation. Therefore, when the large-scale wind nudging scheme is in use, the appropriate "balance" wind profiles are also updated throughout the simulation, e.g., when lspgrad = 1 or 2:

$$\frac{\partial u_g}{\partial t} = -\frac{u_g - u_{ref}}{\tau_n}\,, \tag{68a}$$

$$\frac{\partial v_g}{\partial t} = -\frac{v_g - v_{ref}}{\tau_n}\,. \tag{68b}$$

Further details are provided in Alland et al. (2021).

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Table 1: Variables and arrays in CM1.

Symbol	Description	Name in code
Predicted variables:		
q	Mixing ratio of moisture	`qa` (at t)
		`q3d` (at $t + \Delta t$)
u	Velocity in x	`ua` (at t)
		`u3d` (at $t + \Delta t$)
v	Velocity in y	`va` (at t)
		`v3d` (at $t + \Delta t$)
w	Velocity in z	`wa` (at t)
		`w3d` (at $t + \Delta t$)
θ_0	Base-state θ	`th0`
θ'	Perturbation θ	`tha` (at t)
		`th3d` (at $t + \Delta t$)
π_0	Base-state π	`pi0`
π'	Perturbation π	`ppi` (at t)
		`pp3d` (at $t + \Delta t$)
Derived variables:		
p	Pressure	`prs`
T	Temperature ($T = \theta\pi$)	varies
θ	Potential temperature ($\theta = \theta_0 + \theta'$)	varies
π	Nondimensional pressure ($\pi = \pi_0 + \pi'$)	varies
ρ	Density of dry air	`rho`
$\rho_0 u$	u multiplied by ρ_0	`rru` (if no terrain)
$\rho_0 v$	v multiplied by ρ_0	`rrv` (if no terrain)
$\rho_0 w$	w multiplied by ρ_0	`rrw` (if no terrain)
$\rho_0 u/G_z$	$\rho_0 u/G_z$	`rru` (if terrain)
$\rho_0 v/G_z$	$\rho_0 v/G_z$	`rrv` (if terrain)
$\rho_0 \dot{\sigma}$	$\rho_0 \dot{\sigma} = \rho_0 \left(uG_x/G_z + vG_y/G_z + w \right)$	`rrw` (if terrain)
Variables for terrain only:		
G_x	$\frac{\sigma - z_t}{z_t - z_s} \frac{\partial z_s}{\partial x}$	`gx`
G_y	$\frac{\sigma - z_t}{z_t - z_s} \frac{\partial z_s}{\partial y}$	`gy`
G_z	$\frac{z_t}{z_t - z_s}$	`gz`
z_s	Terrain height	`zs`
z_t	Height at top of domain	`zt`
σ	Nominal height of model levels, $\sigma = \frac{z_t(z - z_s)}{z_t - z_s}$	`sigma`

Table 2: Constants in CM1. See `constants.F` for values.

Symbol	Description	Name in code
c_i	Specific heat of ice	`cpi`
c_l	Specific heat of liquid water	`cpl`
c_p	Specific heat of dry air at constant pressure	`cp`
c_{pv}	Specific heat of water vapor at constant pressure	`cpv`
c_v	Specific heat of dry air at constant volume	`cv`
c_{vv}	Specific heat of water vapor at constant volume	`cvv`
f	Coriolis parameter	`fcor`
g	Gravitational acceleration	`g`
$L_v(T_0)$	Reference value of L_v at $T = T_0$	`xlv`
$L_s(T_0)$	Reference value of L_s at $T = T_0$	`xls`
p_{00}	Reference pressure	`p00`
R	Gas constant for dry air	`rd`
R_v	Gas constant for water vapor	`rv`
T_0	Reference temperature	`to`
ε	Ratio of gas constants: R/R_v	`eps`
κ	von Karman constant	`karman`

Table 3: Description of potential temperature (θ) "budget" variables in CM1 output.

Name in CM1 output	Budget term	Description
`ptb_hadv`	$-u\dfrac{\partial\theta}{\partial x} - v\dfrac{\partial\theta}{\partial y}$	horizontal advection
`ptb_vadv`	$-w\dfrac{\partial\theta}{\partial z}$	vertical advection
`ptb_hturb`	$-\dfrac{1}{\rho}\left[\dfrac{\partial\tau_1^\theta}{\partial x} + \dfrac{\partial\tau_2^\theta}{\partial y}\right]$ (part of T_θ)	horizontal turbulence tendency
`ptb_vturb`	$-\dfrac{1}{\rho}\left[\dfrac{\partial\tau_3^\theta}{\partial z}\right]$ (part of T_θ)	vertical turbulence tendency
`ptb_mp`	(see terms with $\dot{q}$)	tendency from microphysical scheme
`ptb_rdamp`	N_θ	tendency from Rayleigh damping
`ptb_rad`	$\dot{Q}_\theta$	tendency from radiation scheme
`ptb_div`	$-\Theta_1\theta\left(\dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} + \dfrac{\partial w}{\partial z}\right)$	moist divergence term
`ptb_diss`	$\Theta_2\epsilon$	dissipative heating
`ptb_pbl`	(part of T_θ)	tendency from PBL scheme

Table 4: Description of water vapor mixing ratio (q_v) "budget" variables in CM1 output.

Name in CM1 output	Budget term	Description
`qvb_hadv`	$-u\dfrac{\partial q_v}{\partial x} - v\dfrac{\partial q_v}{\partial y}$	horizontal advection
`qvb_vadv`	$-w\dfrac{\partial q_v}{\partial z}$	vertical advection
`qvb_hturb`	$-\dfrac{1}{\rho}\left[\dfrac{\partial \tau_1^{q_v}}{\partial x} + \dfrac{\partial \tau_2^{q_v}}{\partial y}\right]$ (part of T_{q_v})	horizontal turbulence tendency
`qvb_vturb`	$-\dfrac{1}{\rho}\left[\dfrac{\partial \tau_3^{q_v}}{\partial z}\right]$ (part of T_{q_v})	vertical turbulence tendency
`qvb_mp`	(see terms with $\dot{q}$)	tendency from microphysical scheme
`qvb_pbl`	(part of T_{q_v})	tendency from PBL scheme

Table 5: Description of horizontal velovity (u) "budget" variables in CM1 output.

Name in CM1 output	Budget term	Description
`ub_hadv`	$-u\dfrac{\partial u}{\partial x} - v\dfrac{\partial u}{\partial y}$	horizontal advection
`ub_vadv`	$-w\dfrac{\partial u}{\partial z}$	vertical advection
`ub_hturb`	$+\dfrac{1}{\rho}\left[\dfrac{\partial \tau_{11}}{\partial x} + \dfrac{\partial \tau_{12}}{\partial y}\right]$ (part of T_u)	horizontal turbulence tendency
`ub_vturb`	$+\dfrac{1}{\rho}\left[\dfrac{\partial \tau_{13}}{\partial z}\right]$ (part of T_u)	vertical turbulence tendency
`ub_pgrad`	$-c_p\theta_\rho\dfrac{\partial \pi'}{\partial x}$	pressure gradient acceleration
`ub_rdamp`	N_u	tendency from Rayleigh damping
`ub_cor`	fv	Coriolis acceleration
`ub_cent`	$\dfrac{vv}{r}$	centrifugal acceleration (for `axisymm` = 1)
`ub_pbl`	(part of T_u)	tendency from PBL scheme

Table 6: Description of horizontal velovity (v) "budget" variables in CM1 output.

Name in CM1 output	Budget term	Description
`vb_hadv`	$-u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y}$	horizontal advection
`vb_vadv`	$-w\frac{\partial v}{\partial z}$	vertical advection
`vb_hturb`	$+\frac{1}{\rho}\left[\frac{\partial \tau_{12}}{\partial x} + \frac{\partial \tau_{22}}{\partial y}\right]$ (part of T_v)	horizontal turbulence tendency
`vb_vturb`	$+\frac{1}{\rho}\left[\frac{\partial \tau_{23}}{\partial z}\right]$ (part of T_v)	vertical turbulence tendency
`vb_pgrad`	$-c_p\theta_\rho\frac{\partial \pi'}{\partial y}$	pressure gradient acceleration
`vb_rdamp`	N_v	tendency from Rayleigh damping
`vb_cor`	$-fu$	Coriolis acceleration
`vb_cent`	$-\frac{uv}{r}$	centrifugal acceleration (for `axisymm` = 1)
`vb_pbl`	(part of T_v)	tendency from PBL scheme

Table 7: Description of horizontal velovity (w) "budget" variables in CM1 output.

Name in CM1 output	Budget term	Description
`wb_hadv`	$-u\dfrac{\partial w}{\partial x} - v\dfrac{\partial w}{\partial y}$	horizontal advection
`wb_vadv`	$-w\dfrac{\partial w}{\partial z}$	vertical advection
`wb_hturb`	$+\dfrac{1}{\rho}\left[\dfrac{\partial \tau_{13}}{\partial x} + \dfrac{\partial \tau_{23}}{\partial y}\right]$ (part of T_w)	horizontal turbulence tendency
`wb_vturb`	$+\dfrac{1}{\rho}\left[\dfrac{\partial \tau_{33}}{\partial z}\right]$ (part of T_w)	vertical turbulence tendency
`wb_pgrad`	$-c_p\theta_\rho\dfrac{\partial \pi'}{\partial z}$	pressure gradient acceleration
`wb_rdamp`	N_w	tendency from Rayleigh damping
`wb_buoy`	B	buoyancy