MOSES 2.2 Technical Documentation

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Abstract

MOSES 2.2 is a new version of the Met Office Surface Exchange Scheme including a tiled representation of heterogeneous surfaces. The implementation of MOSES 2.2 in the radiation, boundary layer and hydrology sections of the Unified Model is described. Instructions are provided for running MOSES 2.2 as a modification to UM version 4.5, as an option in version 5.2 or in an off-line version.

1 Introduction

MOSES 2.2 introduces a tiled model of subgrid heterogeneity in the MOSES land-surface scheme. Whereas MOSES I (Cox *et al* (1999)) used effective parameters to calculate a single surface energy balance for each gridbox, MOSES 2.2 treats subgrid land-cover heterogeneity explicitly. Separate surface temperatures, shortwave and longwave radiative fluxes, sensible and latent heat fluxes, ground heat fluxes, canopy moisture contents, snow masses and snow melt rates are computed for each surface type in a gridbox. Nine surface types are recognized : broadleaf trees, needleleaf trees, C_3 (temperate) grass, C_4 (tropical) grass, shrubs, urban, inland water, bare soil and ice. Except for those classified as land-ice, a land gridbox can be made up from any mixture of the first 8 surface types. Fractions ν_j ($j = 1, \ldots, 9$) of surface types within each land-surface gridbox are read from an ancillary file or modelled by TRIFFID (Cox (2001)). Air temperature, humidity and windspeed on atmospheric model levels above the surface and soil temperatures and moisture contents below the surface are treated as homogeneous across a gridbox.

Other new features in MOSES 2.2 include :

- Vegetation-dependent surface parameters are calculated on-line from vegetation height and leaf area index rather than read from ancillaries.

- New AVHRR vegetation maps are available.

- An optional spectral albedo scheme calculates separate diffuse and direct beam albedos in visible and near-infrared bands for vegetation tiles, with snow aging parametrized using a prognostic grain size.

- The Penman-Monteith elimination of the surface temperature from the surface energy balance has been extended to include upward longwave radiation, and a diagnostic has been added to output the adjusted TOA outgoing longwave radiation between radiation timesteps.

- Canopy heat capacity and fractional coverage calculations in the optional canopy model have been reformulated.

- An implicit numerical scheme for updating temperatures and moisture contents of soil layers has been introduced.

- An exponential root-depth distribution has been introduced and the conductance for evaporation from bare soil and soil beneath sparse vegetation has been reformulated.

- The code has been restructured as suggested by Polcher *et al* (1998) to give a clearer separation between surface and boundary-layer routines. This also bring increments due to snow melt or limited moisture availability within the implicit calculation of surface heat and moisture fluxes.

The performance of MOSES 2.2 is discussed in climate simulations by Essery *et al* (2001) and in mesoscale forecasts by Best *et al* (2000).

2   Radiation

Rather than the net radiation used in the MOSES I surface energy budget, MOSES 2.2 requires net shortwave radiation on tiles and downward longwave radiation to be calculated by the radiation scheme. Surface albedos are specified either as single values for all bands with diagnosed snow albedos or, if selected by L_SNOW_ALBEDO=.TRUE. in namelist NLSTCATM, spectral values with prognostic snow albedos.

2.1   All-band albedos

Snow-free and cold deep snow albedos for unvegetated tiles are given in Table 1. Bare soil albedos vary geographically with soil colour, and are read from an ancillary file. For vegetation with leaf area index Λ, snow-free and cold deep snow albedos are

$$\alpha_o = (1 - f_r)\alpha_{\text{soil}} + f_r \alpha_o^{\infty}, \tag{1}$$

and

$$\alpha_{cds} = (1 - f_r)\alpha_s^o + f_r \alpha_s^{\infty}, \tag{2}$$

where the radiative fraction, f_r, is

$$f_r = 1 - e^{-\Lambda/2} \tag{3}$$

and α_{soil} is the albedo for snow-free soil underlying the vegetation. Values for the vegetation type dependent parameters α_o^{∞}, α_s^{∞} and α_s^o are given in Table 2.

Snow aging is represented by reducing the snow albedo when surface temperature T_* exceeds -2°C according to

$$\alpha_s = \begin{cases} \alpha_{cds} & T_* < T_m - 2 \\ \alpha_{cds} + 0.3(\alpha_o - \alpha_{cds})(T_* - T_m + 2) & T_m - 2 < T_* < T_m \end{cases}, \tag{4}$$

where T_m is the melting point. For a tile with snow mass S (kg m^{-2}), the albedo is a weighted average

$$\alpha = \alpha_0 + (\alpha_s - \alpha_0)(1 - e^{-0.2S}). \tag{5}$$

	α_o	α_{cds}
Urban	0.18	0.4
Inland water	0.06	0.8
Soil	0.11-0.35*	0.8
Ice	0.75	0.8

Table 1. Snow-free and cold deep snow albedos for unvegetated surface types from `NVEGPARM.cdk`.
* Snow-free soil albedos depend on soil colour.

	α_o^∞	α_s^∞	α_s^o
Broadleaf trees	0.1	0.15	0.3
Needleleaf trees	0.1	0.15	0.3
C_3 grass	0.2	0.6	0.8
C_4 grass	0.2	0.6	0.8
Shrubs	0.2	0.4	0.8

Table 2. Albedo parameters for vegetation types from `PFTPARM.cdk`

2.2 Spectral albedos

The Sellers (1985) two-stream canopy radiation model is used for vegetation albedos in the optional spectral albedo scheme. Separate direct-beam and diffuse albedos in visible and near-infrared wave bands are calculated for each vegetation type as

$$\alpha_{\text{dir}} = \frac{h_1}{\sigma} + h_2 + h_3 \tag{6}$$

and

$$\alpha_{\text{dif}} = h_7 + h_8 \tag{7}$$

where

$$h_1 = -dp_4 - cf, \tag{8}$$

$$h_2 = \frac{1}{D_1}\left[\left(d - \frac{p_3 h_1}{\sigma}\right)(u_1 - h)\frac{1}{S_1} - p_2 S_2\left(d - c - \frac{h_1}{\sigma}(u_1 + K)\right)\right], \tag{9}$$

$$h_3 = -\frac{1}{D_1}\left[\left(d - \frac{p_3 h_1}{\sigma}\right)(u_1 + h)S_1 - p_1 S_2\left(d - c - \frac{h_1}{\sigma}(u_1 + K)\right)\right], \tag{10}$$

$$h_7 = \frac{c}{D_1 S_1}(u_1 - h) \tag{11}$$

and

$$h_8 = -\frac{cS_1}{D_1}(u_1 + h) \tag{12}$$

with

$$\beta_0 = \frac{1 + K}{\omega K}a_s,$$

$$c = \frac{1}{3}(\alpha + \omega),$$

$$\beta = \frac{c}{\omega},$$

$$b = 1 - (1 - \beta)\omega, \quad d = \omega K \beta_0, \quad f = \omega K(1 - \beta_0),$$

$$h = (b^2 - c^2)^{1/2}, \quad \sigma = K^2 + c^2 - b^2,$$

$$u_1 = b - \frac{c}{\alpha_{\text{soil}}},$$

$$S_1 = e^{-h\Lambda}, \ \ S_2 = e^{-K\Lambda},$$

$$p_1 = b + h, \ \ p_2 = b - h, \ \ p_3 = b + K, \ \ p_4 = b - K$$

and

$$D_1 = \frac{p_1}{S_1}(u_1 - h) - p_2 S_1 (u_1 + h).$$

Assuming a spherical leaf-angle distribution, the single scattering albedo and the optical depth per unit leaf area are

$$a_s = \frac{\omega}{2}\left[1 - \mu \ln\left(\frac{\mu + 1}{\mu}\right)\right] \tag{13}$$

and

$$K = \frac{1}{2\mu} \tag{14}$$

for zenith angle cosine μ. Parameter values for leaf reflection coefficient α and leaf scattering coefficient ω, which depend on vegetation type and wave band, are given in Table 3.

	α_{vis}	α_{nir}	ω_{vis}	ω_{nir}
Broadleaf trees	0.1	0.45	0.15	0.7
Needleleaf trees	0.07	0.35	0.15	0.45
C_3 grass	0.1	0.58	0.15	0.83
C_4 grass	0.1	0.58	0.17	0.83
Shrubs	0.1	0.58	0.15	0.83

Table 3. Spectral albedo parameters from TRIF.cdk.

Snow albedos are calculated using a simplification of the Marshall (1989) parametrization of the Wiscombe and Warren (1980) spectral snow albedo model. The aging of snow is characterized by introducing a prognostic grain size, $r(t)$, set to $r_0 = 50$ μm for fresh snow and limited to a maximum value of 2000 μm. The change in $r(t)$ over a timestep Δt is given by

$$r(t + \Delta t) = \left[r(t)^2 + \frac{G_r}{\pi}\Delta t\right]^{1/2} - [r(t) - r_0]\frac{S_f \Delta t}{d_o}, \tag{15}$$

where S_f is the snowfall rate during the timestep and d_o, the mass of fresh snow required to refresh the albedo, is set to 2.5 kg m^{-2}. The empirical grain *area* growth rate is

$$G_r = \begin{cases} 0.6 \ \mu\text{m}^2 \ \text{s}^{-1} & T_* = T_m \ \text{(melting snow)} \\ 0.06 \ \mu\text{m}^2 \ \text{s}^{-1} & T_* < T_m, \ r < 150 \ \mu\text{m} \ \text{(cold fresh snow)} \\ A \exp(-E/RT_*) & T_* < T_m, \ r > 150 \ \mu\text{m} \ \text{(cold aged snow)} \end{cases} \tag{16}$$

where $A = 0.23 \times 10^6$ μm^2 s^{-1}, $E = 37000$ J mol^{-1} and $R = 8.13451$ J K^{-1} mol^{-1}. Snow albedos are calculated as

$$\alpha_{\text{vis}} = 0.98 - 0.002(r^{1/2} - r_0^{1/2}) \tag{17}$$

and

$$\alpha_{\text{nir}} = 0.7 - 0.09 \ln\left(\frac{r}{r_0}\right). \tag{18}$$

The zenith angle dependence is represented by using an effective grain size,

$$r_e = [1 + 0.77(\mu - 0.65)]^2 r, \tag{19}$$

in place of r in calculations of direct-beam albedos.

For a tile with snow-free albedo α_0, snowdepth d and roughness length z_0, the albedo in each band is

$$\alpha = f_{\text{snow}}\alpha_{\text{snow}} + (1 - f_{\text{snow}})\alpha_o \tag{20}$$

where

$$f_{\text{snow}} = \frac{d}{d + 10z_0}. \tag{21}$$

2.3 Radiation diagnostics

For a gridbox with tile fractions ν_j, the gridbox mean albedo

$$\alpha_i = \sum_j \nu_j \alpha_{ij} \tag{22}$$

for band i and the effective radiative surface temperature

$$T_{*R} = \left(\sum_j \nu_j T_{*j}^4\right)^{1/4} \tag{23}$$

are used in calculating downward shortwave and longwave radiation fluxes $LW_\downarrow$ and $SW_{\downarrow i}$. Surface energy flux calculations require the net all-band shortwave radiation on each tile

$$SW_{Nj} = \sum_i (1 - \alpha_{ij}) SW_{\downarrow i} \tag{24}$$

and

$$\Delta_{\text{OLR}} = OLR - \sigma T_{*R}^4, \tag{25}$$

which is used in diagnosing the adjustment in TOA outgoing longwave radiation OLR due to changes in surface temperature between radiation calls. SW_{Nj}, $LW_\downarrow$ and Δ_{OLR} are stored in the RADINCS array for use on timesteps between radiation calls.

3 Surface fluxes

3.1 Surface roughness and exchange coefficients

Momentum roughness length z_o is set to $h/20$ for trees of height h and $h/10$ for other vegetation types. Roughness lengths for unvegetated surface types are given in Table 4. The roughness length of a tile with snow mass S is reduced to $\max[z_o - 4 \times 10^{-4}S, 5 \times 10^{-4}]$.

A surface exchange coefficient for sensible and latent heat fluxes between the surface and the lowest atmospheric level at height z_1 over each tile is calculated as $C_H = f_h C_{Hn}$, where

$$C_{Hn} = k^2 \left[\ln\left(\frac{z_1 + z_o}{z_o}\right)\ln\left(\frac{z_1 + z_o}{z_{oh}}\right)\right]^{-1} \tag{26}$$

is the neutral exchange coefficient and

$$f_h = \begin{cases} (1 + 10\text{Ri}_\text{B}/\text{Pr})^{-1} & \text{Ri}_\text{B} \geq 0 \text{ (stable)} \\ 1 - 10\text{Ri}_\text{B}(1 + 10C_{Hn}\sqrt{-\text{Ri}_\text{B}}/f_z)^{-1} & \text{Ri}_\text{B} < 0 \text{ (unstable)} \end{cases} \tag{27}$$

with scalar roughness length $z_{oh} = z_o/10$,

$$f_z = \frac{1}{4}\left(\frac{z_o}{z_1 + z_o}\right)^{1/2} \tag{28}$$

and Prandtl number

$$\text{Pr} = \ln\left(\frac{z_1 + z_o}{z_o}\right)\left[\ln\left(\frac{z_1 + z_o}{z_{oh}}\right)\right]^{-1}. \tag{29}$$

The bulk Richardson number is

$$\text{Ri}_\text{B} = \frac{gz_1}{U_1^2}\left\{\frac{1}{T_1}\left[T_1 - T_* + \frac{g}{c_p}(z_1 + z_{om} - z_{oh})\right] + \psi\frac{q_1 - q_{\text{sat}}(T_*, p_*)}{q_1 + \epsilon/(1-\epsilon)}\right\}. \tag{30}$$

for level-1 temperature T_1, specific humidity q_1 and windspeed U_1. $q_{\text{sat}}(T_*, p_*)$ is the saturation humidity at the surface temperature and pressure, and the surface resistance factor ψ is defined in 3.3. Since ψ depends on C_H, routine SF_RESIST is first called to calculate ψ assuming neutral conditions, this is passed to routines SF_RIB and FCDCH for use in calculating Ri_B and C_H, and SF_RESIST is then called again to calculate a revised value for ψ.

The above discussion assumes no level-1 cloud and does not include orographic roughness; see Unified Model Documentation Paper 24 (Smith (1993)) for extensions. The alternative formulation of the stability functions used in the new boundary layer scheme is described by Smith and Williams (/home/hc0100/hadaw/public_html/docs/surf_exch.ps).

	z_o (m)
Urban	1.5
Water	3×10^{-4}
Soil	3×10^{-4}
Ice	1×10^{-4}

Table 4. Roughness lengths for unvegetated surface types from NVEGPARM.cdk.

3.2 Canopy heat capacity

A vegetation canopy model, which introduces a canopy heat capacity and radiative coupling between the canopy and underlying ground, can be selected by editing MOSES_OPT.cdk to set CAN_MODEL=3. TRIFFID (Cox (2001)) gives the masses of carbon in leaves and stems per unit area of canopy as $\sigma_l\Lambda_b$ and $a_{wl}\Lambda_b^{5/3}$, where the balanced-growth leaf area index for vegetation of height h is

$$\Lambda_b = \left(\frac{a_{ws}\eta_{sl}h}{a_{wl}}\right)^{3/2} \tag{31}$$

with parameters given in Table 5. An areal canopy heat capacity, C_c, is calculated assuming specific heat capacities (in kJ K^{-1} per kg of carbon) of 570 for leaves and 110 for wood, based on values given by Jones (1983) and Moore and Fisch (1986). For non-vegetated tiles, and vegetated tiles if the canopy model is not selected, C_c is set to zero.

	a_{wl}	a_{ws}	η_{sl}	σ_l
Broadleaf trees	0.65	10	0.01	0.0375
Needleleaf trees	0.65	10	0.01	0.1
C$_3$ grass	0.005	1	0.01	0.025
C$_4$ grass	0.005	1	0.01	0.05
Shrubs	0.1	10	0.01	0.05

Table 5. Vegetation parameters from TRIF.cdk.

3.3 Evaporation

Surface evaporation is drawn from soil, canopy and snow moisture stores. Evaporation from saturated parts of the surface (lakes, wet vegetation canopies and snow) is calculated at the potential rate (i.e. subject to an aerodynamic resistance only).

Evaporation from transpiring vegetation is controlled by a canopy conductance, g_c, calculated by a photosynthesis model depending on temperature, humidity deficit, incident radiation, soil moisture availability and vegetation type (Cox *et al* (1998), Cox (2001)). The ability of vegetation to access moisture at each level in the soil is determined by root density, assumed to follow an exponential distribution with depth. The fraction of roots in soil layer k extending from depth z_{k-1} to z_k is

$$r_k = \frac{e^{-2z_{k-1}/d_r} - e^{-2z_k/d_r}}{1 - e^{-2z_t/d_r}}, \tag{32}$$

where d_r is the rootdepth for the vegetation type (Table 6) and z_t is the total depth of the soil model. For transpiration E_t, the flux extracted from soil layer k is $e_k^0 E_t$, where

$$e_k^0 = \frac{r_k \beta_k}{\sum_k r_k \beta_k} \tag{33}$$

and

$$\beta_k = \begin{cases} 1 & \theta_k \geq \theta_c \\ (\theta_k - \theta_w)/(\theta_c - \theta_w) & \theta_w < \theta_k < \theta_c, \\ 0 & \theta_k \leq \theta_w \end{cases} \tag{34}$$

is a soil moisture availability factor for a soil layer with unfrozen volumetric soil moisture concentration θ_k, critical point θ_c and wilting point θ_w.

Bare-soil evaporation is calculated using a conductivity

$$g_{\mathrm{soil}} = \frac{1}{100} \left(\frac{\theta_1}{\theta_c} \right)^2 \tag{35}$$

and is extracted from the surface soil layer for both bare-soil tiles and fraction $1 - f_r$ of vegetated tiles (Equation 3). Adding the soil and canopy conductances in parallel to give a total surface conductance $g_s = g_c + (1 - f_r)g_{\mathrm{soil}}$, the fraction of the evapotranspiration extracted from each soil layer is

$$e_1 = \frac{g_c e_1^o + (1 - f_r)g_{\mathrm{soil}}}{g_s} \tag{36}$$

for the surface layer and

$$e_k = \frac{g_c e_k^o}{g_s} \tag{37}$$

for lower layers.

The total evaporation from a tile is $E = \psi E_0$, where E_0 is the potential evaporation,

$$\psi = f_a + (1 - f_a)\frac{g_s}{g_s + C_H U_1} \tag{38}$$

and f_a is the fraction of the tile which is saturated and hence has aerodynamic resistance only; $f_a = 1$ for lake, ice or snow-covered tiles, and $f_a = C/C_m$ for a vegetated tile with canopy moisture content C (kg m^{-2}) and canopy capacity $C_m = 0.5 + 0.05\Lambda$. The urban tile is also given a small surface capacity of 0.5 kg m^{-2}.

	d_r (m)
Broadleaf trees	3
Needleleaf trees	1
C_3 grass	0.5
C_4 grass	0.5
Shrubs	0.5

Table 6. Rootdepths from `PFTPARM.cdk`.

3.4 Surface energy balance

Surface temperature T_* is interpreted as a surface skin temperature unless the canopy model is selected, in which case it is a canopy layer temperature for vegetated tiles. In the absence of snowmelt, the surface energy balance for each tile is

$$C_c \frac{dT_*}{dt} = R_N - H - LE - G_0, \tag{39}$$

where the surface net radiation is

$$R_N = SW_N + LW_\downarrow - \sigma T_*^4, \tag{40}$$

H and E are fluxes of sensible heat and moisture, and L is the latent heat of vaporization for snow-free tiles or sublimation for snow-covered or ice tiles. The heat flux into the ground, combining radiative fluxes below vegetation canopies and conductive fluxes for the unvegetated fraction, is parametrized as

$$G_0 = f_r(\sigma T_*^4 - \sigma T_s^4) + (1 - f_r)\frac{2\lambda}{\Delta z_s}(T_* - T_s) \tag{41}$$

where Δz_s and T_s are the thickness and temperature of the surface soil layer. Radiative canopy fraction f_r is given by Equation (3) if the canopy model is selected but is set to zero otherwise. The thermal conductivity, λ, is equal to the soil conductivity $\lambda_{\rm soil}$ for snow-free tiles, but is adjusted for insulation by snow of depth d according to

$$\lambda = \begin{cases} \lambda_{\rm soil}\left[1 + \frac{2d}{\Delta z_s}\left(\frac{\lambda_{\rm soil}}{\lambda_{\rm snow}} - 1\right)\right]^{-1} & d < \Delta z_s/2 \\ \lambda_{\rm snow} & d \geq \Delta z_s/2, \end{cases} \tag{42}$$

with $\lambda_{\rm snow} = 0.265$ W m^{-1} K^{-1}.

Expressions for surface fluxes of sensible heat and moisture over each tile are derived from the bulk aerodynamic formulae

$$H = c_p RK_H(1)\left[T_* - T_1 - \frac{g}{c_p}(z_1 + z_o - z_{oh})\right] \tag{43}$$

and

$$E = \psi RK_H(1)\left[q_{\rm sat}(T_*, p_*) - q_1\right], \tag{44}$$

where $RK_H(1) = \rho C_H U_1$; ρ and c_p are the density and heat capacity of air. $q_{\rm sat}$ can be linearized about T_1 to give

$$q_{\rm sat}(T_*, p_*) \approx q_{\rm sat}(T_1, p_*) + D(T_* - T_1), \tag{45}$$

where

$$D = \frac{q_{\rm sat}(T_*^{(n)}, p_*) - q_{\rm sat}(T_1^{(n)}, p_*)}{T_*^{(n)} - T_1^{(n)}}. \tag{46}$$

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Discretizing the time derivative of T_* between timesteps n and $n + 1$ as

$$\frac{dT_*}{dt} \approx \frac{T_*^{(n+1)} - T_*^{(n)}}{\Delta t}, \tag{47}$$

linearizing G_0 as

$$G_0 \approx \left[4 f_r \sigma T_s^3 + (1 - f_r) \frac{2\lambda}{\Delta z_s} \right] (T_* - T_s), \tag{48}$$

linearizing R_N as

$$R_N \approx R_s + 4\sigma T_s^3 (T_s - T_*), \tag{49}$$

where $R_s = SW_N + LW_\downarrow - \sigma T_s^4$, and using Equation (39) to eliminate T_* from Equations (43) and (44), the heat and moisture fluxes are given by

$$H = c_p R K_{PM} [\tilde{R} - L\psi R K_H(1) \Delta q_1] \tag{50}$$

and

$$E = \psi R K_{PM} [D\tilde{R} + (c_p R K_H(1) + A_*) \Delta q_1] \tag{51}$$

where

$$A_* = (1 - f_r) \frac{2\lambda}{\Delta z_s} + \frac{C_c}{\Delta t} + 4(1 + f_r) \sigma T_s^3, \tag{52}$$

$$\Delta q_1 = q_{\text{sat}}(T_1, p_*) - q_1 + D\frac{g}{c_p}(z_1 + z_o - z_{oh}), \tag{53}$$

$$\tilde{R} = R_s - A_* \left[T_1 - T_s + \frac{g}{c_p}(z_1 + z_o - z_{oh}) \right] + \frac{C_c}{\Delta t}(T_*^{(n)} - T_s) \tag{54}$$

and

$$RK_{PM} = \frac{RK_H(1)}{(c_p + LD\psi)RK_H(1) + A_*}. \tag{55}$$

3.5   Implicit boundary layer fluxes (1)

Increments in temperatures on boundary-layer levels $k = 1, \ldots, N$ are calculated as

$$\delta T_k = \frac{g\Delta t}{\Delta p_k} [F_T(k + 1) - F_T(k)], \tag{56}$$

where the fluxes are

$$F_T(k) = -RK_H(k) \left[\frac{T_k - T_{k-1}}{\Delta z_{k-1/2}} + \frac{g}{c_p} \right] \tag{57}$$

for $1 < k \le N$ with boundary conditions $F_T(N + 1) = 0$ and $F_T(1) = \overline{H}/c_p$ for gridbox-mean surface sensible heat flux

$$\overline{H} = \sum_j \nu_j H_j. \tag{58}$$

Implicit fluxes during timestep n are calculated using

$$\begin{aligned} T_k &= (1 - \gamma_k)T_k^{(n)} + \gamma_k T_k^{(n+1)} & (59) \\ &= T_k^{(n)} + \gamma_k \delta T_k & (60) \end{aligned}$$

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where γ_k is the forward timestep weighting factor for level k. This gives a tridiagonal system of equations

$$
\begin{array}{rcll}
B_{TN}\delta T_N + C_{TN}\delta T_{N-1} & = & (\delta T_N)_{\mathrm{ex}} & \\
A_{Tk}\delta T_{k+1} + B_{Tk}\delta T_k + C_{Tk}\delta T_{k-1} & = & (\delta T_k)_{\mathrm{ex}} & k = 2,\ldots,N-1 \\
A_{T1}\delta T_2 + B_{T1}\delta T_1 & = & (\delta T_1)_{\mathrm{ex}} - (g\Delta t/\Delta p_1)F_T(1) &
\end{array}
\tag{61}
$$

with matrix elements

$$
A_{Tk} = \gamma_{k+1}\frac{g\Delta t}{\Delta p_k}\frac{RK_H(k+1)}{\Delta z_{k+1/2}} \qquad k = 1,\ldots,N-1
\tag{62}
$$

$$
B_{Tk} = \begin{cases}
1 - C_{TN} & k = N \\
1 - A_{Tk} - C_{Tk} & k = 2,\ldots,N-1 \\
1 - A_{T1} & k = 1
\end{cases}
\tag{63}
$$

and

$$
C_{Tk} = \gamma_k\frac{g\Delta t}{\Delta p_k}\frac{RK_H(k)}{\Delta z_{k-1/2}} \qquad k = 2,\ldots,N.
\tag{64}
$$

The explicit increments on the rhs of Equation (61) are

$$
(\delta T_k)_{\mathrm{ex}} = \begin{cases}
-(g\Delta t/\Delta p_N)F_T^{(n)}(N) & k = N \\[2mm]
(g\Delta t/\Delta p_N)[F_T^{(n)}(k+1) - F_T^{(n)}(k)] & k = 2,\ldots,N-1 \\[2mm]
(g\Delta t/\Delta p_1)F_T^{(n)}(2) & k = 1
\end{cases}
\tag{65}
$$

where the explicit fluxes are given by Equation (57) with temperatures at the beginning of the timestep. A downward sweep to eliminate the below-diagonal elements in (61) gives

$$
\begin{array}{rcll}
\delta T_k + C'_{Tk}\delta T_{k-1} & = & \delta T'_k & k = 2,\ldots,N \\
\delta T_1 & = & \delta T'_1 - \beta F_T(1) &
\end{array}
\tag{66}
$$

where $C'_{Tk} = C_{Tk}/B'_{Tk}$ with

$$
B'_{Tk} = \begin{cases}
1 - C_{TN} & k = N \\[2mm]
1 - A_{Tk}(1 + C'_{Tk+1}) - C_{Tk} & k = 2,\ldots,N-1 \\[2mm]
1 - A_{T1}(1 + C'_{T2}) & k = 1
\end{cases}
\tag{67}
$$

$$
\beta = \frac{g\Delta t}{\Delta p_k}\frac{1}{B'_{Tk}}
\tag{68}
$$

and

$$
\delta T'_k = \begin{cases}
(\delta T_N)_{\mathrm{ex}}/B'_{TN} & k = N \\[2mm]
[(\delta T_k)_{\mathrm{ex}} - A_{Tk}\delta T'_{k+1}]/B'_{TN} & k = 1,\ldots,N-1
\end{cases}
\tag{69}
$$

An analogous set of equations links the humidity increments and the gridbox-mean surface evaporation.

3.6 Implicit surface fluxes

Writing the level-1 temperature and humidity as

$$T_1 = T_1^{(n)} + \gamma_1 \delta T_1 \tag{70}$$

and

$$Q_1 = Q_1^{(n)} + \gamma_1 \delta Q_1 \tag{71}$$

in Equations (43) and (44), taking gridbox means gives

$$\frac{\overline{H}}{c_p} = \sum_j \nu_j \frac{H_j^{(n)}}{c_p} + A_1 \delta T_1 + A_2 \delta Q_1 \tag{72}$$

and

$$\overline{E} = \sum_j \nu_j E_j^{(n)} + B_1 \delta T_1 + B_2 \delta Q_1, \tag{73}$$

where

$$A_1 = -\gamma_1 \sum_j \nu_j RK_{PMj}[LD_j \psi_j RK_H(1)_j + A_{*j}], \tag{74}$$

$$A_2 = \gamma_1 \sum_j \nu_j RK_{PMj} L\psi_j RK_H(1)_j, \tag{75}$$

$$B_1 = \gamma_1 c_p \sum_j \nu_j RK_{PMj} D_j \psi_j RK_H(1)_j \tag{76}$$

and

$$B_2 = -\gamma_1 \sum_j \nu_j RK_{PMj} \psi_j [c_p RK_H(1)_j + A_{*j}]. \tag{77}$$

Substituting Equation (66) for δT_1 and the analogous equation for δQ_1 in Equations (72) and (73), solving for the gridbox-mean fluxes gives

$$\frac{\overline{H}}{c_p} = \frac{(1 + \beta B_2)[F_T(1)^{(n)} + A_1 \delta T_1' + A_2 \delta Q_1'] - \beta A_2[F_Q(1)^{(n)} + B_1 \delta T_1' + B_2 \delta Q_1']}{(1 + \beta A_1)(1 + \beta B_2) - \beta^2 A_2 B_1} \tag{78}$$

and

$$\overline{E} = \frac{(1 + \beta A_1)[F_Q(1)^{(n)} + B_1 \delta T_1' + B_2 \delta Q_1'] - \beta B_1[F_T(1)^{(n)} + A_1 \delta T_1' + A_2 \delta Q_1']}{(1 + \beta A_1)(1 + \beta B_2) - \beta^2 A_2 B_1}. \tag{79}$$

Tile fluxes are recovered as

$$\frac{H_j}{c_p} = \frac{H_j^{(n)}}{c_p} \quad - \quad \gamma_1 RK_{PMj}[LD_j \psi_j RK_H(1)_j + A_{*j}][\delta T_1' - \beta \overline{H}/c_p] \tag{80}$$

$$+ \quad \gamma_1 RK_{PMj} L\psi_j RK_H(1)_j[\delta Q_1' - \beta \overline{E}] \tag{81}$$

and

$$E_j = E_j^{(n)} \quad + \quad \gamma_1 RK_{PMj} D_j \psi_j RK_H(1)_j[c_p \delta T_1' - \beta \overline{H}] \tag{82}$$

$$- \quad \gamma_1 RK_{PMj} \psi_j[c_p RK_H(1)_j + A_{*j}][\delta Q_1' - \beta \overline{E}]. \tag{83}$$

A first estimate of the surface temperature for each tile is diagnosed as

$$T_* = T_s + \frac{1}{A_*}\left[R_s - H - LE + \frac{C_c}{\Delta t}\left(T_*^{(n)} - T_s\right)\right]. \tag{84}$$

This has to be adjusted if evaporation exhausts any of the moisture stores during the timestep or if the tile has a melting snowcover.

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3.6.1 Limited evaporation

Downward surface moisture fluxes are added to canopy moisture or, if the surface temperature is below freezing, snowcover.

For an upward total moisture flux E, the rates of evaporation from the canopy and soil moisture stores are

$$E_c = f_a \frac{E}{\psi} \tag{85}$$

and

$$E_s = (1 - f_a)\psi_s \frac{E}{\psi} \tag{86}$$

where

$$\psi_s = \frac{g_s}{g_s + C_H U_1}. \tag{87}$$

If the predicted canopy evaporation would exhaust the canopy moisture store C during a timestep, the soil evaporation is recalculated as

$$E_s = \psi_s \left(1 - \frac{f_a C}{E_c \Delta t}\right) \frac{E}{\psi} \tag{88}$$

and E_c is reset to $C/\Delta t$ (see Smith (1993)). If E_s would then exhaust the available soil moisture m, it is limited to $m/\Delta t$.

For an adjustment $\Delta(LE)$ in the latent heat flux, repartitioning the surface energy balance gives adjustments

$$\Delta H = -\left[1 + \frac{A_*}{c_p R K_H(1)}\right]^{-1} \Delta(LE) \tag{89}$$

and

$$\Delta T_* = -\frac{\Delta H + \Delta(LE)}{A_*} \tag{90}$$

in the surface sensible heat flux and temperature.

Evaporation from a lake tile (or the lake fraction of an aggregated surface) is not limited and does not draw on the conserved moisture stores.

3.6.2 Snowmelt

Equation (39) neglects snowmelt heat fluxes in the surface energy balance. If $T_* > T_m$ for a snow-covered tile and sufficient snow is available, T_* is reset to T_m by adding an increment

$$\Delta T_* = T_m - T_*, \tag{91}$$

corresponding to a snowmelt heat flux

$$S_m = -[(c_p + L_s D)R K_H(1) + A_*]\frac{\Delta T_*}{L_f}. \tag{92}$$

The maximum melt rate that can be sustained over a timestep Δt, however, is $S/\Delta t - E$, giving

$$\Delta T_* = \frac{L_f(S/\Delta t - E)}{(c_p + L_c D)R K_H(1) + A_*}. \tag{93}$$

ΔT_* is set to the smaller of the values given by Equations (92) and (93), and the surface energy balance is repartioned by adding increments

$$\Delta H = c_p R K_H(1) \Delta T_* \tag{94}$$

and

$$\Delta E = D R K_H(1) \Delta T_* \tag{95}$$

to the tile heat and moisture fluxes.

3.7   Implicit boundary layer fluxes (2)

After adjustment of the surface fluxes, an upward sweep through the matrix equation gives temperature increments

$$\begin{aligned}
\delta T_1 &= \delta T_1' - \beta \overline{H}/c_p, \tag{96}\\
\delta T_k &= \delta T_k' - C'_{Tk} \delta T_{k-1} \quad k = 2, \dots, N \tag{97}
\end{aligned}$$

and humidity increments

$$\begin{aligned}
\delta Q_1 &= \delta Q_1' - \beta \overline{E}, \tag{98}\\
\delta Q_k &= \delta Q_k' - C'_{Tk} \delta Q_{k-1} \quad k = 2, \dots, N. \tag{99}
\end{aligned}$$

3.8   Screen level diagnostics

Screen level exchange coefficients are calculated for each tile by the same interpolation method as currently used by the boundary-layer scheme in routine SFL_INT. Air temperatures and humidities over tiles are calculated by SCREEN_TQ and averaged to give gridbox-mean values, which are converted from cloud-conserved forms to actual temperatures and humidities by BL_CTL. This conversion is required if level-1 cloud is present, but has not been applied to the individual tile diagnostics.

4   Hydrology

4.1   Surface hydrology

The partitioning of precipitation into interception, throughfall, runoff and infiltration is the same as described in UM Documentation Paper 25 (Gregory and Smith (1990)) but is applied separately on each tile. For rainfall rate R covering fraction ϵ of a gridbox (1 for large-scale rain or condensation and 0.3 for convective rain), the throughfall from the canopy on a vegetated tile is calculated as

$$T_F = R \left(1 - \frac{C}{C_m} \right) \exp \left(-\frac{\epsilon C_m}{R \Delta t} \right) + R \frac{C}{C_m} \tag{100}$$

and the tile canopy water content is updated by

$$C^{(n+1)} = C^{(n)} + (R - T_F)\Delta t. \tag{101}$$

Surface runoff is calculated as

$$Y = \begin{cases} R\frac{C}{C_m} \exp\left(-\frac{\epsilon K C_m}{RC}\right) + R\left(1 - \frac{C}{C_m}\right) \exp\left(-\frac{\epsilon C_m}{R\Delta t}\right) & K\Delta t \leq C \\ R \exp\left[-\frac{\epsilon(K\Delta t + C_m - C)}{R\Delta t}\right] & K\Delta t > C \end{cases} \tag{102}$$

where the surface infiltration rate K is equal to βK_s; K_s is the soil saturated hydrological conductivity and β is an enhancement factor, values of which are given in Table 7. Runoff of melt water is calculated using snowmelt rate S_m in place of R and $\epsilon = 1$. The flux of water into the soil is given by the gridbox average

$$W_0 = \sum_j \nu_j (T_{Fj} + S_{mj} - Y_j). \tag{103}$$

	β		β
Broadleaf trees	4	Urban	0.1
Needleleaf trees	4	Water	0
C_3 grass	2	Soil	0.5
C_4 grass	2	Ice	0
Shrubs	2		

Table 7. Infiltration enhancement factors from `PFTPARM.cdk` and `NVEGPARM.cdk`.

4.2   Soil Thermodynamics

As in MOSES I, subsurface temperatures are updated using a discretized form of the heat diffusion equation, which is coupled to the soil hydrology module through:

- soil water phase changes and the associated latent heat

- soil thermal characteristics which are dependent on soil moisture content (liquid water and ice).

The temperature of the nth soil layer, of thickness Δz_n, is incremented by the diffusive heat fluxes into and out of the layer, G_{n-1} and G_n respectively, and the net heat flux, J_n, advected from the layer by the moisture flux:

$$C_A \, \Delta z_n \frac{dT_n}{dt} = G_{n-1} - G_n - J_n \, \Delta z_n \tag{104}$$

The diffusive and advective fluxes are given by:

$$G = \lambda \frac{\partial T}{\partial z} \tag{105}$$

$$J = c_w \, W \frac{\partial T}{\partial z} \tag{106}$$

where z is the vertical coordinate, W is the vertical flux of soil moisture (calculated within the soil hydrology module), c_w is the specific heat capacity of water, and λ is the local soil thermal conductivity (Cox *et al* (1999)), modified in the presence of lying snow (see 3.4). The "apparent" volumetric heat capacity of the layer, C_A, is given by:

$$C_A = C_s + \rho_w c_w \Theta_u + \rho_i c_i \Theta_f + \rho_w \left\{ (c_w - c_i)T + L_f \right\} \frac{\partial \Theta_u}{\partial T} \tag{107}$$

where Θ_u and Θ_f are the volumetric concentrations of frozen and unfrozen soil moisture, and ρ_i and c_i are the density and specific heat capacity of ice. The first three terms on the right hand side of Equation (107) represent contributions from dry soil, liquid water and ice, and the final term is the apparent heat capacity associated with phase changes. The relationship between unfrozen water concentration, Θ_u, and temperature, T, can be derived by minimizing the Gibbs free energy

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of the soil-water-ice system (Williams and Smith (1989)). This results in an equation relating the water suction, Ψ (m), to the temperature, T (K), when ice is present (Miller (1965), Black and Tice (1988)):

$$\Psi = -k \left\{ \frac{\rho_i}{\rho_w} \frac{L_f}{T_m g} \right\} (T - T_m) \tag{108}$$

where T_m (K) is the freezing point of pure water, g is the acceleration due to gravity and k is a dimensionless constant which depends on the nature of the soil. A value of $k = 1.0$ is assumed, which is consistent with a clay-rich soil for which absorption forces dominate over capillary forces. ($k = 2.2$ would be more appropriate for granular soils (Black and Tice (1988))). Combining Equation (108) with the Clapp and Hornberger (1978) form (Equation 121) for the suction as a function of liquid water yields:

$$\frac{\Theta_u^{max}}{\Theta_s} = \left\{ -\frac{\kappa(T - T_m)}{\Psi_s} \right\}^{-1/b} \tag{109}$$

where Θ_u^{max} is the maximum unfrozen water that can exist at temperature T, Θ_s is the saturation soil moisture concentration, Ψ_s and b are other soil specific parameters and κ is a constant defined by:

$$\kappa = k \frac{\rho_i}{\rho_w} \frac{L_f}{g T_m} \approx 114.3 \quad \text{m K}^{-1} \tag{110}$$

The actual value of Θ_u is limited by the total water content of the soil:

$$\Theta_u = \min \left\{ \Theta_u^{max}, \Theta \right\} \tag{111}$$

where Θ is the "liquid" total volumetric concentration, i.e. that which would arise if all the moisture was in liquid form:

$$\Theta = \Theta_u + \frac{\rho_i}{\rho_w} \Theta_f \tag{112}$$

The temperature above which all soil moisture is unfrozen, T_{max}, can be derived by equating Θ to Θ_u^{max} in Equation (109):

$$T_{max} = T_m - \frac{\Psi_s}{\kappa} \left\{ \frac{\Theta_s}{\Theta} \right\}^b \tag{113}$$

The second term on the right hand side represents the suppression of the initial freezing point. It is useful to rewrite Equation (111) in terms of two distinct temperature regimes:

$$\Theta_u = \begin{cases} \Theta_u^{max} & \text{if } T < T_{max} \\ \Theta & \text{if } T \geq T_{max} \end{cases} \tag{114}$$

then differentiation with respect to temperature yields:

$$\frac{\partial \Theta_u}{\partial T} = \begin{cases} \frac{\kappa \Theta_s}{b \Psi_s} \left\{ -\frac{\kappa(T - T_m)}{\Psi_s} \right\}^{(-1/b-1)} & \text{if } T < T_{max} \\ 0 & \text{if } T > T_{max} \end{cases} \tag{115}$$

which is used in Equation (107). The surface soil heat flux, G_0, is calculated in boundary layer routine SF_IMPL as a residual in Equation (39). Heat advection by surface infiltration is currently neglected. The lower boundary condition corresponds to zero vertical gradient in soil temperature.

4.3 Soil Hydrology

The soil hydrology component of MOSES 2.2 is based on a finite difference approximation to the Richards' equation (Richards (1931)), with the same vertical discretization as the soil thermodynamics module. The prognostic variables of the model are the total soil moisture content within each layer:

$$M = \rho_w \, \Delta z \, \Theta_s \, \{S_u + S_f\} \tag{116}$$

where Δz is the thickness of the layer, and S_u and S_f are the mass of unfrozen and frozen water within the layer as a fraction of that of liquid water at saturation:

$$S_u = \frac{\Theta_u}{\Theta_s} \tag{117}$$

$$S_f = \frac{\rho_i}{\rho_w} \frac{\Theta_f}{\Theta_s} \tag{118}$$

The total soil moisture content within the nth soil layer is incremented by the diffusive water flux flowing in from the layer above, W_{n-1}, the diffusive flux flowing out to the layer below, W_n, and the evapotranspiration extracted directly from the layer by plant roots and soil evaporation, E_n:

$$\frac{dM_n}{dt} = W_{n-1} - W_n - E_n \tag{119}$$

E_n is calculated from the total evapotranspiration, E_t, based on the profiles of soil moisture and root density, $E_n = e_n \, E_t$. The e_n weighting factors are described in section 3.3. The water fluxes are given by the Darcy equation:

$$W = K \left\{ \frac{\partial \Psi}{\partial z} + 1 \right\} \tag{120}$$

where K is the hydraulic conductivity and Ψ is the soil water suction. To close the model it is necessary to assume forms for the hydraulic conductivity and the soil water suction as a function of the soil moisture concentration. The dependencies suggested by Clapp and Hornberger (1978) are most often used in GCM land-surface schemes, primarily because of their relative simplicity. In addition the work of Cosby *et al* (1984) offers a means of linking the parameters which define these curves to soil particle size distribution. More sophisticated dependencies, such as those derived by van Genuchten *et al* (1991), can be included with fairly minor code modification. However,the Clapp and Hornberger relations are currently used by default in MOSES 2:

$$\Psi = \Psi_s \, S_u^{-b} \tag{121}$$

$$K = K_s \, S_u^{2b+3} \tag{122}$$

where K_s, Ψ_s and b are empirical soil dependent constants. The interpretation of the Clapp-Hornberger relations in terms of unfrozen rather than total soil moisture is consistent with the observation that the freezing of soil moisture reduces hydraulic conductivity and produces a large suction by reducing the unfrozen water content (Williams and Smith (1989)).

The top boundary condition for the soil hydrology module is given by Equation (103). The default lower boundary condition corresponds to "free drainage":

$$W_N = K_N \tag{123}$$

where W_N is the drainage from the lowest deepest soil layer and K_N is the hydraulic conductivity of this layer.

4.4   Soil numerics

A key difference between the MOSES I soil scheme and that used in MOSES 2.2 concerns the numerical scheme used to update soil moisture and soil temperatures through Equations (104) and (119). MOSES I used a simple explicit scheme, in which the fluxes on the righthandside of these equations are calculated from the beginning of timestep values of T and M. By contrast, MOSES 2.2 includes an implicit scheme which remains numerically stable and accurate at much longer timesteps and higher vertical resolution. Although this scheme has a relatively small impact on the model performance at the standard soil model resolution (4 soil layers with thicknesses from the top of 0.1, 0.25, 0.65, 2.0 metres), it does make it feasible for users to choose many more soil layers without incurring massive computational costs (see for example Hall *et al* (2001)).

The prognostic equations for the soil (Equations 104 and 119) take the form:

$$\frac{dY_n}{dt} = F_{n-1} - F_n - s_n \tag{124}$$

where $Y_n = \{T_n, M_n\}$, $F_n = \{G_n/C_A, W_n\}$ and $s_n = \{J_n/C_A, E_n\}$. The fluxes F_n are a function of the prognostic variables Y_n. In the explicit MOSES I scheme the F_n were calculated using the values of Y_n at the beginning of timestep t, denoted Y_n^t. In MOSES 2.2 these same fluxes are calculated using a forward timestep weighting, γ, such that:

$$F_n = F_n^t + \gamma \frac{\partial F_n}{\partial Y_n} \Delta Y_n + \gamma \frac{\partial F_n}{\partial Y_{n+1}} \Delta Y_{n+1} \tag{125}$$

where ΔY_n is the increment to Y_n during the timestep t to $t + \Delta t$. The derivatives of the fluxes with respect to the prognostic variables are calculated in subroutines DARCY, HYD_CON and SOIL_HTC. Equation (125) can be substituted into Equation (124) to yield a series of n simultaneous equations for the n prognostic variables:

$$a_n \Delta Y_{n-1} + b_n \Delta Y_n + c_n \Delta Y_{n+1} = d_n \tag{126}$$

where:

$$
\begin{aligned}
a_n &= -\gamma \Delta t \frac{\partial F_{n-1}}{\partial Y_{n-1}} \\
b_n &= \Delta z - \gamma \Delta t \left[\frac{\partial F_{n-1}}{\partial Y_n} - \frac{\partial F_n}{\partial Y_n} \right] \\
c_n &= -\gamma \Delta t \frac{\partial F_n}{\partial Y_{n+1}} \\
d_n &= \Delta t \left\{ F_{n-1}^t - F_n^t - s_n^t \right\}
\end{aligned}
\tag{127}
$$

The lefthandside of this equation represents the explicit update to the variable Y_n as in MOSES I. Note that no implicit correction is made to the sink term, s_n, since this would require an unwieldy implicit update to the entire coupled soil hydrology, soil thermodynamics and boundary layer system. By treating this term explicitly we decouple the updates to the soil temperatures and soil moistures, such that these variables can be incremented independently on each timestep. The equations represented by (126) are a tridiagonal set which can be solved routinely by Gaussian elimination (see appendix A for details).

The other major numerical difference between MOSES I and MOSES 2.2 involves the treatment of supersaturation in a soil layer. This can occur by two separate means. The first is a numerical artifact arising from the use of a finite timestep during which a very large quantity of incident water (for

example from a very intense rainstorm) can overfill the top soil layer. This occurred very infrequently in MOSES I (owing to the relatively thick top soil layer) and should be even less common within the implicit soil scheme of MOSES 2.2. Nevertheless, supersaturation can still occur when drainage from the base of a soil layer is impeded (either by frozen soil water or an assumed reduction of K_s with depth). Under these circumstances it may be necessary to return the soil water content in a layer to the saturation value. In MOSES I the excess water in a layer was arbitrarily routed downwards. The justification for this was weak, but based on the idea that such excess moisture might flow overland for some fraction of a large GCM gridbox, but would eventually move down through the soil profile at subgrid locations in which drainage is less impeded (e.g. where there is fractured permafrost or less compacted-faster draining soil types). However, this assumption was found to lead to poor runoff simulation and excessive soil moisture in the PILPS2d tests of MOSES I (Schlosser *et al* (2000)). In MOSES 2.2 excess moisture in a soil layer is instead removed by lateral flow which contributes to a larger fast runoff component. This alternative assumption is more consistent with the improved soil numerics (which should not lead to supersaturation as a numeric artifact), and results in much better water budgets for permafrost regions, such as the PILPS2d Valdai site.

5   Parameter aggregation

A single tile version of MOSES 2.2 can be selected by setting NTILES=1 in namelists RECON and NLSIZES. Separate surface parameters are still calculated for each surface type within a gridbox, but they are aggregated by routines SPARM, TILE_ALBEDO and PHYSIOL before use. Albedos (α_i), maximum infiltration rate (βK_s), canopy heat capacity (C_c), canopy coverage (f_r) and soil moisture extraction fractions (e_k) are simply area-averaged. Canopy water capacity (C_m) and surface conductance (g_s) are averaged over the non-lake fractions of gridboxes. Roughness lengths are aggregated at a blending height l_b (set to 20 m in BLEND_H.cdk) using the method of Mason (1988) to give

$$z_o = l_b \exp \left\{ - \left[\sum_j \frac{\nu_j}{\ln^2(l_b/z_{oj})} \right]^{-1/2} \right\}. \tag{128}$$

6   Running MOSES 2.2

6.1   UM vn 4.5

Running MOSES 2.2 in the version 4.5 Unified Model requires modsets

~t20re/MOSESII/arerf406

for the reconfiguration and

~t20re/MOSESII/amv1f406
~t20re/MOSESII/apa1f406
~t20re/MOSESII/are1f406
~t20re/MOSESII/are2f406
~t20re/MOSESII/are3f406
~t20re/MOSESII/newdecks

for the model. The radiative canopy model is selected by including modset

~t20re/MOSESII/amv2f406

A hand-edit is required to set NTILES in namelists RECON and NLSIZES. This can be achieved with
the script

```
sed -e '/LAND_FIELD/a\
 NTILES=9,'\
 $HOME/umui_jobs/$1/SIZES > het.$$
 mv het.$$ $HOME/umui_jobs/$1/SIZES
sed -e '/LAND_POINTS/a\
 NTILES=9,'\
 $HOME/umui_jobs/$1/RECONA > het.$$
 mv het.$$ $HOME/umui_jobs/$1/RECONA
```

where $1 is the job name. For agreggated tiles, set NTILES=1.
The following scientific section options should be selected :

```
SW radiation 3A
LW radiation 3A
Boundary layer 7A or 8A
Hydrology 7A
Vegetation 1A or 2A
```

Select 'Including prognostic snow albedo' in UMUI window atmos_Science_Section_SWGen2 to
use spectral albedos.
'Vegetation Distribution : Area and structure' ancillaries are obtained from files qrfrac.type
(fractions of surface types) and qrparm.pft (LAI and height of plant functional types). Alternative
vegetation maps are provided in the directories :

```
~t20bx/TRIFFID/vn4.4/ancil/cl_9673          Wilson and Henderson-Sellers
~t20my/TRIFFID/vn4.4/ancil/cl_9673/test     IGBP
~t20my/TRIFFID/vn4.4/ancil/cl_9673/test2    University of Maryland
```

The user stash master file should be copied from ~t20re/MOSESII/ustash. This introduces 5 new
prognostics, which should be initialized as follows in window atmos_STASH_UserProgs :

Item	Name	Option
231	SNOW GRAIN SIZE ON TILES	1
233	SURFACE TEMP ON TILES	1
234	ROUGHNESS LENGTH ON TILES	1
235	SNOW AMOUNT ON TILES	1
236	TILE MODIFIED INFILTRATION RATE	3

A domain profile with 9 pseudo levels on a single level has to be created for tiled diagnostics.

6.2   UM vn 5.2

MOSES 2.2 can be selected from the UMUI at version 5.2. In window atmos_Science_BLay, select version 8A. Buttons are provided in the same window to select the number of tiles and the version of the canopy model.
Two fix modsets are required :

/u/um1/vn5.3/mods/source/amv0503/amv0n503.mf90

for the reconfiguration and

/u/um1/vn5.3/mods/source/amv1503/amv1f503.mf77

for the model.
Diagnostics on surface tiles are not available from stash at version 5.2. These are to be reintroduced at 5.3.

7 Stand-Alone MOSES 2.2 (SAM)

MOSES 2.2 and TRIFFID can be driven in stand-alone mode using meteorological data. Copy files updefs, deklst, nlsts and makesam from HP directory /home/hc0200/surfbl/sam4.6. 7A or 8A surface exchange coefficients are selected by including A03_7A or A03_8A in updefs. Execute makesam to process and compile program sam.f from decks in source. Alternatively, a portable version, not requiring nupdate, is available in psource; copy all the files from this directory and compile either MOSES7A.f or MOSES8A.f.

Runs are controlled by namelists in nlsts described below.

Namelist OPTS : run options

L_TRIFFID	Switch for interactive vegetation
L_TRIF_EQ	Switch for vegetation equilibrium
L_PHENOL	Switch for interactive leaf phenology
L_Z0_OROG	Switch for orographic roughness
L_SPEC_ALBEDO	Switch for spectral albedos
DUMP_TS	Switch for timestep diagnostics
DUMP_MN	Switch for time-mean diagnostics

Namelist PARAM : parameters

ALBSOIL	Soil albedo
CANHT_FT	Vegetation canopy height (m)
CO2	Atmospheric CO_2 concentration (kg CO_2 / kg air)
FRAC_DISTURB[1]	Fraction of gridbox in which vegetation is disturbed
HO2R2_OROG[2]	Standard deviation of unresolved orography (m)
SIL_OROG[2]	Silhouette area of unresolved orography
TIMESTEP	Timestep (s)
ZREF	Atmospheric reference height (m)
NSTEPS[3]	Number of timesteps in run
NTSMEAN	Number of timesteps in meaning period
NTILES[4]	Number of surface tiles
SOIL_TYPE	Soil type
PHENOL_PERIOD[5]	Phenology calling period (days)
TRIFFID_PERIOD[1]	TRIFFID calling period (days)
MET_FILE	Path and name of file containing met. data
DUMP_FILE	Path and name of file for prognostic dump at end of run
RUNID[6]	Run identifier

[1] Only required if TRIFFID selected.

[2] Only required if orographic roughness selected.

[3] Number of records in met. data must be at least one greater than NSTEPS.

[4] NTILES = 1 (aggregate tiles) or 9 (surface types) only.

[5] Only required if phenology selected.

[6] 6 character string. For RUNID='aaaa01', timestep and mean diagnostics are written to files aaaa01_ts and aaaa01_mn.

Namelist `INIT` : initialization of prognostic variables

CS	Soil carbon (kg m^{-2})
GS	Surface conductance (m s^{-1})
CAN_TILE[7]	Surface / canopy water (kg m^{-2})
FRAC[8]	Fractional coverage of surface types
RGRAIN[7]	Snow grain size for spectral albedo (μm)
SNOW_TILE[7]	Snow mass (kg m^{-2})
TSTAR_TILE[7]	Surface temperature (K)
T_SOIL[9]	Soil layer temperatures (K)
STHETA[9]	Soil moisture contents as fractions of saturation

[7] NTILES-element arrays for surface tiles.
[8] 9-element array for surface types. Elements should add up to 1.
[9] Four-element arrays for soil layers.

Namelist `DIAGS` : diagnostic output

incg(1) =0	nameg(1) ='ALBEDO'	Gridbox-mean diagnostics
$\vdots$	$\vdots$	
incg(31)=0	nameg(31)='U10M'	
incs(1) =0	names(1) ='EXT'	Diagnostics on soil layers
$\vdots$	$\vdots$	
incs(5) =0	names(5) ='T_SOIL'	
inct(1) =0	namet(1) ='ALB_TILE'	Diagnostics on surface tiles
$\vdots$	$\vdots$	
inct(19)=0	namet(19)='Z0_TILE'	
incv(1) =0	namev(1) ='C_VEG'	Diagnostics on vegetation types
$\vdots$	$\vdots$	
incv(14)=0	namev(14)='RESP_W_DR_OUT'	

Diagnostic names in `name*` arrays are same as variable names in deck `SAM_CTL` - see comments for details. Set corresponding element in `inc*` array to 1 to select a diagnostic for output. Output files have a header listing the requested diagnostics and timestamps for each timestep or meaning period.
The required input data and format are

```
       READ(8,100) SW,LW,RAIN,SNOW,TA,U,V,PSTAR,QA
100    FORMAT(2F7.1,2E14.3,3F10.3,F10.1,E12.3)
```

SW	Surface downward shortwave radiation (Wm^{-2})
LW	Surface downward longwave radiation (Wm^{-2})
RAIN	Rainfall rate (kg m^{-2}s^{-1})
SNOW	Snowfall rate (kg m^{-2}s^{-1})
TA	Air temperature (K)
U	Westerly wind component (ms^{-1})
V	Southerly wind component (ms^{-1})
PSTAR	Surface pressure (Pa)
QA	Specific humidity (kg kg^{-1})

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A   Gaussian Elimination

The set of equations represented by (126) is solved by a two-sweep algorithm (subroutine GAUSS). Firstly, in an upward sweep, the ΔY_{n+1} terms are eliminated by transforming the nth equation, $Eq(n)$, thus:

$$Eq(n) \longrightarrow Eq(n)' = b'_{j+1}\, Eq(n) - c_n\, Eq(n+1)' \tag{129}$$

where $'$ denotes a transformed equation or variable. Under this transformation the nth equation becomes:

$$a'_n\, \Delta Y_{n-1} + b'_n\, \Delta Y_n = d'_n \tag{130}$$

where:

$$
\begin{aligned}
a'_n &= b'_{n+1}\, a_n \\
b'_n &= b'_{n+1}\, b_n - a'_{n+1}\, c_n \\
d'_n &= b'_{n+1}\, d_n - d'_{n+1}\, c_n
\end{aligned}
\tag{131}
$$

In the upward sweep a'_n, b'_n and d'_n are evaluated iteratively beginning at the lowest soil layer, (N), where the lower boundary conditions of the soil model imply $c_N = 0$ such that $a'_N = a_N$, $b'_N = b_N$ and $d'_N = d_N$. In the downward sweep the increments to the prognostics variables, ΔY_n are derived iteratively from the top downwards using Equation (130):

$$\Delta Y_n = \frac{d'_n - a'_n\, \Delta Y_{n-1}}{b'_n} \tag{132}$$

The top boundary conditions of the soil model imply $a_1 = 0$ such that $\Delta Y_1 = d'_1/b'_1$.

B   Array indexing

Routine TILEPTS sets array elements TILE_PTS(J) to the number of gridboxes including surface type j and TILE_INDEX(I,J) to the land array index of the ith gridbox containing surface type j. Calculations for a specific surface type are only performed in gridboxes where that surface type is present. In UM version 4.5, loops of surface types and gridboxes take the form

```
    DO N=1,NTILES
      DO J=1,TILE_PTS(N)
        L = TILE_INDEX(J,N)   ! Land field index
        I = LAND_INDEX(L)     ! Full field index
        .
        .
        .
      ENDDO
    ENDDO
```

In version 5.2, two-dimensional indices are used for full field arrays :

```
    DO N=1,NTILES
      DO K=1,TILE_PTS(N)
        L = TILE_INDEX(K,N)
        J = (LAND_INDEX(L)-1)/ROW_LENGTH + 1
        I = LAND_INDEX(L) - (J-1)*ROW_LENGTH
```

```
             .
             .
             .
           ENDDO
         ENDDO
```

For use in NI_rad_ctl, the I and J indices are stored in arrays land_index_i and land_index_j.

C Code structure

C.1 Surface and 7A boundary layer

Routines named in lower case are new for MOSES 2.2.

```
BL_INTCT ---|
            |-- TILEPTS
            |
            |-- VSHR_Z1
            |
            |-- PHYSIOL ---|
            |              |-- ROOT_FRAC
            |              |-- SMC_EXT
            |              |-- RAERO
            |              |-- SF_STOM -----|
            |              |-- soil_evap    |-- QSAT
            |              |-- LEAF_LIT      |-- CANOPY ---|
            |              |-- cancap                      |-- LEAF_C3
            |              |-- MICROBE                      |-- LEAF_C4
            |
            |-- sf_expl ---|
            |              |-- Z
            |              |-- HEAT_CON
            |              |-- BOUY_TQ
            |              |-- SF_EXCH -----|
            |                               |-- QSAT
            |                               |-- SF_OROG
            |                               |-- SF_RESIST
            |                               |-- SF_RIB_(LAND/SEA)
            |                               |-- SF_OROG
            |                               |-- FCDCH_(LAND/SEA)
            |                               |-- SF_RESIST
            |                               |-- SF_FLUX_(LAND/SEA)
            |-- bdy_expl --|               |-- STDEV1_(LAND/SEA)
            |              |-- Z            |-- SF_OROG_GB
            |              |-- BOUY_TQ      |-- SFL_INT_(LAND/SEA)
            |              |-- BTQ_INT
            |              |-- KMKH ---------- EX_COEF
            |              |-- EX_FLUX_TQ
            |              |-- EX_FLUX_UV
            |              |-- im_bl_pt1
            |
            |-- sf_impl ---|
            |              |-- im_sf_pt
            |              |-- SF_EVAP
            |              |-- SF_MELT
            |              |-- SCREEN_TQ
            |              |-- SICE_HTF
            |
            |-- bdy_impl --|
                           |-- im_bl_pt2
```

C.2 Hydrology

```
HYDROL ----|
           |-- SFSNOW
           |
           |-- SURF_HYD --|
           |              |-- FRUNOFF
           |              |-- SIEVE
           |
           |
           |-- SOIL_HYD --|
           |              |-- HYD_CON
           |              |-- DARCY
           |              |-- gauss
           |
           |
           |-- SOIL_HTC --|
           |              |-- HEAT_CON
           |              |-- gauss
           |
           |
           |-- ICE_HTC
           |
           |-- SOILMC
```

C.3 Radiation

```
RAD_CTL ----|
            .
            .
            .
            |-- TILEPTS
            .
            .
            .
            |-- FTSA
            |
            |-- tile_albedo --|
            |                 |-- alb_pft
            |                 |-- albsnow
            |
            |
            |-- R2_SWRAD --|
            |              .
            .              .
            .              .
            .
```

C.4   Stand-Alone MOSES

```
sammain --|
          |-- FREEZE_SOIL
          |-- diaglist
          |-- sam_ctl --|
                        |-- TILEPTS
                        |-- SPARM --- PFT_SPARM
                        |
                        |-- tile_albedo--------------|
                        |                            |-- albpft
                        |-- PHYSIOL --|              |-- albsnow
                        |             |-- ROOT_FRAC
                        |             |-- SMC_EXT
                        |             |-- RAERO
                        |             |-- SF_STOM ----|
                        |             |-- soil_evap   |-- QSAT
                        |             |-- LEAF_LIT    |-- CANOPY --|
                        |             |-- cancap                  |-- LEAF_C3
                        |             |-- MICROBE                 |-- LEAF_C4
                        |
                        |-- bdy_sam --|
                        |             |-- HEAT_CON
                        |             |-- SF_EXCH ----------------|
                        |             |                          |-- QSAT
                        |             |-- sf_impl --|             |-- SF_RESIST
                        |                           |-- im_sf_pt  |-- SF_OROG
                        |                           |-- SF_EVAP   |-- SF_RIB_LAND
                        |                           |-- SF_MELT   |-- SF_OROG
                        |                           |-- SCREEN_TQ |-- FCDCH_LAND
                        |                           |-- SICE_HTF  |-- SF_RESIST
                        |                                         |-- SF_FLUX_LAND
                        |                                         |-- STDEV1_LAND
                        |-- HYDROL ---|                           |-- SF_OROG_GB
                        |             |-- SFSNOW                  |-- SFL_INT_LAND
                        |             |-- SURF_HYD ---|
                        |             |               |-- FRUNOFF
                        |             |               |-- SIEVE
                        |             |
                        |             |-- SOIL_HYD ---|
                        |             |               |-- HYD_CON
                        |             |               |-- DARCY
                        |             |               |-- gauss
                        |             |
                        |             |-- SOIL_HTC ---|
                        |             |-- ICE_HTC    |-- HEAT_CON
                        |             |-- SOILMC     |-- gauss
                        .
                        .
                        .
```

```
.
.
.
|
|-- VEG ------|
|             |-- TILEPTS
|             |-- PHENOL
|             |-- TRIFFID ----|
|             |               |-- VEGCARB --- GROWTH
|             |               |-- LOTKA ----- COMPETE
|             |               |-- SOILCARB -- DECAY
|             |
|             |-- TILEPTS
|-- diag      |-- SPARM --- PFT_SPARM
```