Coupled WRF/Unified Noah/Urban-Canopy Modeling System

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This document provides information about running the Urban Canopy Model (UCM) coupled with WRF-Noah land surface model along with WRF routines that need to be modified to accommodate the coupled unified Noah/Urban model (most useful for users wanting to modify LSM routines)

1 What is an Urban Canopy Model (UCM)

In order to better represent the physical processes involved in the exchange of heat, momentum, and water vapor in urban environment in mesoscale model, an UCM is coupled to the WRF model. The main purpose of the coupled model is to improve the description of lower boundary conditions and to provide more accurate forecasts for urban regions. The UCM is a single layer model which has a simplified urban geometry. Some of the features of the UCM include, shadowing from buildings, reflection of short and longwave radiation, wind profile in the canopy layer and multi-layer heat transfer equation for roof, wall and road surfaces (Kusaka and Kimura, JAM, 2004).

1.1 Schematic of Urban-Canopy model

Fig 1 shows a schematic of the single layer urban canopy model which consists of 2-dimensional, symmetrical street canyons with infinite length, meaning, it has a simplified geometry of the buildings. The radiation treatment is 3-dimensional because it includes the canyon orientation and the diurnal variation of azimuth angle. The model estimates the surface temperature of roof, wall and road surfaces as well as the fluxes from these surfaces. Fig 2 shows the radiation trapping between the walls of the buildings. The solar radiation is positive when it is directed towards the surface.

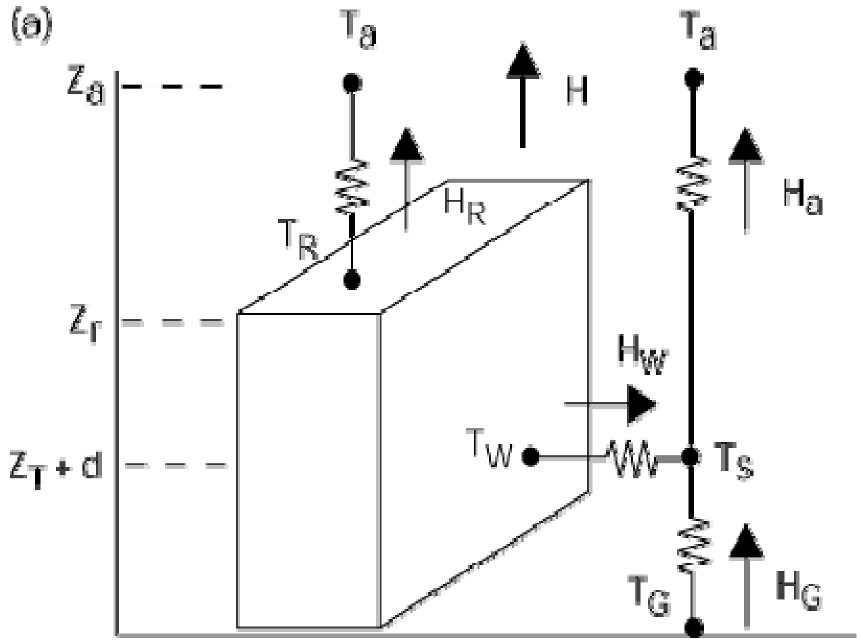

FIG. 1. Schematic of the single-layer urban canopy model: Ta is the air temperature at reference height za, TR is the building roof temperature, TW is the building wall temperature, TG is the road temperature, TS is the temperature defined at zT + d, H is the sensible heat exchange at the reference height, Ha is the sensible heat flux from the canyon space to the atmosphere, HW is that from wall to the canyon space, HG is that from road to the canyon space, and HR is that from roof to the atmosphere (From Kusaka and Kimura 2004).

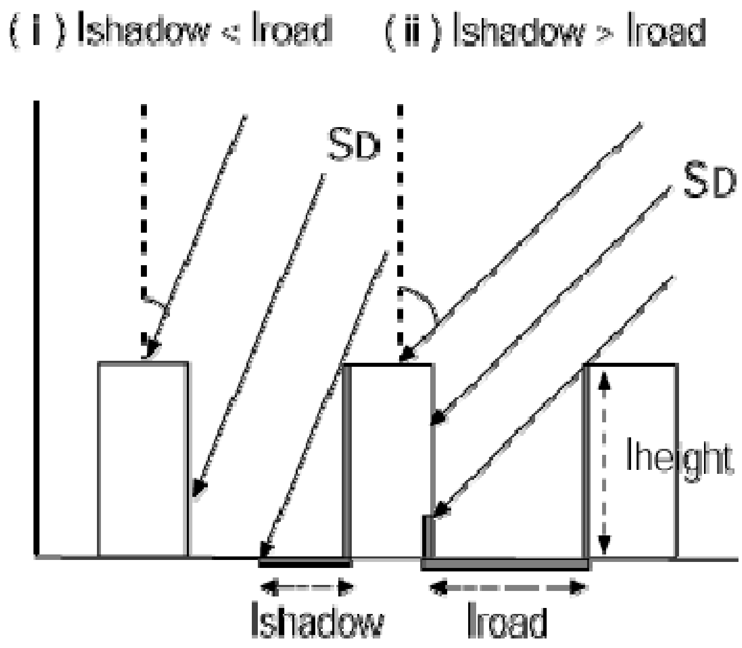

FIG. 2. Radiation of the single-layer urban canopy model; SD is the direct solar radiation incident on a horizontal surface, lroad is the normalized road width, hc is the normalized building height (lroof + lroad = 1), and lshadow is the normalized shadow length on the road (From Kusaka and Kimura 2004).

2 How to Use UCM

2.1 What is needed to run the UCM

(i) If the user doesn't have the detailed urban map of the region of their interest, they can still use the UCM with the default USGS (1993) landuse map, which has only one urban category.

(ii) The UCM is coupled with the Noah Land Surface Model (option 2 in the sf_surface_physics option of the namelist.input file) and is available to run with the ARW core only for now.

(iii) The user needs to add 'h' (meaning a history variable in the 8^{th} column) in the Registry.EM file in Registry/ in order to output the variables they need to see in the wrfout* files, e.g if they need to see the winds in the urban canopy, they need to add an "h" in the 8^{th} column of the state variable "UC_URB2D".

(iv) The user needs to set UCMCALL for every domain in the namelist.input file (0 off, 1 on) and num_land_cat=33, if he/she has the detailed landuse map with 33 landuse categories.

(v) It is preferable to use Urban land-use maps of the region of interest with the following three urban categories:

31: ***Low Intensity residential:*** Includes areas with a mixture of constructed materials and vegetation. Constructed materials account for 30-80 percent of the cover. Vegetation may account for 20 to 70 percent of the cover. These areas most commonly include single-family housing units. Population densities will be lower than in high intensity residential areas.

32: ***High Intensity residential:*** Includes highly developed areas where people reside in high numbers. Examples include apartment complexes and row houses. Vegetation accounts for less than 20 percent of the cover. Constructed materials account for 80 to100 percent of the cover.

33**:** ***Commercial/Industrial/Transportation*** - Includes infrastructure (e.g. roads, railroads, etc.) and all highly developed areas not classified as High Intensity Residential.

In order to use the NLCD (2001) which has following 4 urban categories instead of 3 as is the case with 1992 data,

21. Developed, Open Space - Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes

22. Developed, Low Intensity - Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20-49 percent of total cover. These areas most commonly include single-family housing units.

23. Developed, Medium Intensity - Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50-79 percent of the total cover. These areas most commonly include single-family housing units.

24. Developed, High Intensity - Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to100 percent of the total cover.

The following remapping procedure should be adopted,

The land use categories 21 and 22 should be mapped to land use category 31,
The land use category 23 should be mapped to 32, and
The land use category 24 should be mapped to 33.

The procedure to download the data and the source code to change the data to the compatible WPS format is described at
http://www.mmm.ucar.edu/people/duda/files/how_to_hires.html

There are 2 sample programs available at this site to process the NLCD (1992) data and the NLCD (2001) data.

The following is recommended for users who had prior experience working with the urban models:

(i) The users may want to modify the procedures to initialize the temperature profiles within roof (TR_URB2D, TRL_URB3D), wall (TB_URB2D, TBL_URB3D), and road (TG_URB2D, TGL_URB3D) in SUBROUTINE urban_var_init of the module_sf_urban.F.

(ii) The user may want to adjust urban parameters in the urban_param.tbl (in run/) which are described later in this document.

3 How to run UCM

(i) ***Set namelist option:*** The user should set UCMCALL for every domain in the namelist option (0 off, 1 on) as 1 in order to run the coupled WRF-Noah-UCM.

(ii) ***Bring urban map:*** If the user wants to bring in the urban area map of their study at the desired resolution he needs to follow format description of the WPS (WRF preprocessing system). It is recommended to refer the Input data format section of the WPS document (http://www.mmm.ucar.edu/people/duda/files/wps_files/users_guide_chap3.pdf) for a more detailed description about the input format of the urban data. The urban landuse data goes to the geogrid program of WPS in a binary format. Provided with this package is the Landuse map for the Houston region which is on a regular lat/lon grid. This file has the information about the urban types. Remap the urban information about the landuse types e.g. 21 (Low Intensity residential), 22 (High Intensity residential), 23 (Commerical/ Industrial/ Transportation) which is a function of lat/lon, 31, 32, 33 respectively and process it through the WPS. The Houston map already has the categories 31, 32 and 33.

(iii) ***Other urban regions of interest:*** If the user wants to study any other urban region, he needs to bring in his own urban data, follow the steps of the input data format and process it through the WPS in order to run the UCM with the new urban map.

(iv) ***Fine tune parameters of urban table:*** The urban_param.tbl should be present in the run/ directory along with other tables such as LANDUSE.TBL etc.

The user should carefully go through the description of the parameters in the urban_param.tbl and fine tune it according to the available information for the urban region of their study.

4 Urban Canopy Model

4.1 Urban State Variables

TR_URB2D "URBAN ROOF SKIN TEMPERATURE" "K"
TB_URB2D "URBAN WALL SKIN TEMPERATURE" "K"
TG_URB2D "URBAN ROAD SKIN TEMPERATURE" "K"
TC_URB2D "URBAN CANOPY TEMPERATURE" "K"
UC_URB2D "URBAN CANOPY WIND SPEED" "K"
QC_URB2D "URBAN CANOPY HUMIDITY" "kg kg{-1}"
XXXR_URB2D "M-O LENGTH ABOVE URBAN ROOF" "dimensionless"
XXXB_URB2D "M-O LENGTH ABOVE URBAN WALL" "dimensionless"
XXXG_URB2D "M-O LENGTH ABOVE URBAN ROAD" "dimensionless"
XXXC_URB2D "M-O LENGTH ABOVE URBAN CANOPY" "dimensionless"
TRL_URB3D "ROOF LAYER TEMPERATURE" "K"
TBL_URB3D "WALL LAYER TEMPERATURE" "K"
TGL_URB3D "ROAD LAYER TEMPERATURE" "K"
SH_URB2D "SENSIBLE HEAT FLUX FROM URBAN SFC" "W m{-2}"
LH_URB2D "LATENT HEAT FLUX FROM URBAN SFC" "W m{-2}"
G_URB2D "GROUND HEAT FLUX INTO URBAN" "W m{-2}"
RN_URB2D "NET RADIATION ON URBAN SFC" "W m{-2}"
COSZ_URB2D "COS of SOLAR ZENITH ANGLE" "dimensionless"
OMG_URB2D "SOLAR HOUR ANGLE" "dimensionless"
DECLIN_URB "SOLAR DECLINATION" "dimensionless"

4.2 Table 1: Primary and Secondary UCM Variables

Primary UCM Variables			
Symbol	**Name**	**Unit**	**Function**
ZR	Building Height	m	Urban Type
Z0C	Roughness length above canyon for momentum	m	Urban Type
Z0HC	Roughness length above canyon for heat	m	Urban Type
ZDC	Zero plane displacement height	m	Urban Type
R	Building coverage ratio	-	Urban Type
HGT	Normalized building height	-	Urban Type
CDS	Drag coefficient by buildings	-	Urban Type
AS	Building volumetric parameter	1/m	Urban Type
AH	Anthropogenic heat	W/m/m	Urban Type
BETR	Moisture availability on roof	-	Urban Type
BETB	Moisture availability on building wall	-	Urban Type
BETG	Moisture availability on road	-	Urban Type
FRC_URB	Urban Fraction	-	Urban Type
CAPR	Heat capacity of roof	Cal/cm/cm/cm/degC	
CAPB	Heat capacity of building wall	Cal/cm/cm/cm/degC	
CAPG	Heat capacity of road	Cal/cm/cm/cm/degC	
AKSR	Thermal conductivity of roof	Cal/cm/sec/degC	
AKSB	Thermal conductivity of building wall	Cal/cm/sec/degC	
AKSG	Thermal conductivity of road	Cal/cm/sec/degC	

Primary UCM Variables			
Symbol	**Name**	**Unit**	**Function**
ALBR	Surface albedo of roof	-	
ALBB	Surface albedo of building wall	-	
ALBG	Surface albedo of ground	-	
EPSR	Surface emissivity of roof	-	
EPSB	Surface emissivity of building wall	-	
EPSG	Surface emissivity of ground	-	
Z0R	Roughness length for momentum of roof	m	
Z0B	Roughness length for momentum of building wall	m	
Z0G	Roughness length for momentum of ground	m	
Z0HR	Roughness length for heat of roof	m	
Z0HB	Roughness length for heat of building wall	m	
Z0HG	Roughness length for heat of ground	m	
Num_Roof_Layers	Number of roof layers	-	
Num_Wall_Layers	Number of wall layers	-	
Num_Road_Layers	Number of road layers	-	
DZR	Thickness of each roof layer	cm	
DZB	Thickness of each building wall layer	cm	
DZG	Thickness of each ground layer	cm	

Secondary UCM Variables

Symbol	Name	Unit	Function
SVF	Sky View Factor	-	Building height, Building coverage

4.3 Urban_param.tbl

Below is a sample of the table for urban parameters. The UCM is sensitive to these parameters. For best performance of the UCM, the user should set these parameters based on the observations/or from some authentic resources.

```
Urban Parameters depending on Urban type
USGS
3, 'ZR[m] Z0C[m] Z0HC[m] ZDC[m] SVF    R      RW    HGT    CDS   AS    AH    BETR  BETB  BETG
FRC_URB  UrbanType'
1,  10.,  1.0,   1.0,    2.0,   0.48,  0.50,  0.50,  0.50,  0.1,  0.4,  90.0,  0.0,  0.0,  0.0   0.95    'Commercial'
2,  7.5,  0.75,  0.75,  1.5,   0.56,  0.50,  0.50,  0.40,  0.1,  0.3, 50.0,  0.0,  0.0,  0.0   0.9     'High Intensity Res'
3,  5.,    0.5,   0.5,    1.0,   0.62,  0.50,  0.50,  0.30,  0.1,  0.2,  20.0,  0.0,  0.0,  0.0   0.5     'Low Intensity Res'
CAPR [cal/cm/cm/cm/degC]
0.50
CAPB [cal/cm/cm/cm/degC]
0.50
CAPG [cal/cm/cm/cm/degC]
0.50
AKSR [cal/cm/sec/degC]
0.004
AKSB [cal/cm/sec/degC]
0.004
AKSG [cal/cm/sec/degC]
0.004
ALBR [-]
0.10
ALBB [-]
0.10
ALBG [-]
0.10
EPSR [-]
0.97
EPSB [-]
0.97
EPSG [-]
0.97
Z0R [m]
0.1
Z0B [m]
0.1
Z0G [m]
0.1
Z0HR [m]
```

0.1
Z0HB [m]
0.1
Z0HG [m]
0.1
Num_Roof_Layers [-]
4
Num_Wall_Layers [-]
4
Num_Road_Layers [-]
4
DDZR(1) [cm]
5.
DDZR(2) [cm]
5.
DDZR(3) [cm]
5.
DDZR(4) [cm]
5.
DDZB(1) [cm]
5.
DDZB(2) [cm]
5.
DDZB(3) [cm]
5.
DDZB(4) [cm]
5.
DDZG(1) [cm]
5.
DDZG(2) [cm]
25.
DDZG(3) [cm]
50.
DDZG(4) [cm]
75.
Lower Boundary Condition for Roof Layer Temp [1: Zero-Flux, 2: T = Constant]
1
Lower Boundary Condition for Wall Layer Temp [1: Zero-Flux, 2: T = Constant]
1
Lower Boundary Condition for Road Layer Temp [1: Zero-Flux, 2: T = Constant]
1
TRLEND [K]
300.15
TBLEND [K]
300.15
TGLEND [K]
300.15
Ch of Wall and Road [1: M-O Similarity Theory, 2: Empirical Form (recommend)]
2
Surface and Layer Temperatures [1: 4-layer model, 2: Force-Restore method]
1
ahoption [0: no ah, 1: add ah to FLXTH]
1
AH Diurnal profile (tloc from 1~12 and 13~24) :
0.16 0.13 0.08 0.07 0.08 0.26 0.67 0.99 0.89 0.79 0.74 0.73
0.75 0.76 0.82 0.90 1.00 0.95 0.68 0.61 0.53 0.35 0.21 0.18

5 Implementation of UCM in WRF

5.1 General information about the Urban-Canopy model (UCM)

Flowchart of Urban model: subroutine urban

(1) Get atmospheric variables of the WRF and state variables of the urban canopy model wind speed, air temperature, humidity, downward short wave radiation, downward long wave radiation, air density, cosine of solar zenith angle, solar declination, height of the first atmospheric level, roof surface temperature, wall surface temperature, road surface temperature, roof layer temperature, wall layer temperature, road layer temperature, Monin-Obkhov stability length above roof, wall, and road.
(2) Get urban parameters
(3) Convert unit
(4) Calculate wind profile within the urban canopy layer
(5) Calculate net short wave radiation on the roof, wall, and road
(6) Calculate Monnin-Obkhov stability length above the roof by the Newton-Rapson method: Solving non-liner equation. First guess is the same as the stability length at the previous step.
(7) Calculate C_H, C_D and moisture availability of the roof
(8) Calculate Rn, H, lE, and G from the roof surface
(9) Calculate roof surface temperature
(10) Iteration of (7) and (8) by the Newton-Rapson method: Solving non-liner equation
(11) New roof surface temperature
(12) New Rn, H, lE, and G using new roof surface temperature
(13) New roof layer temperature using new roof surface temperature: Solving 4-layers heat equation model
(14) Calculate C_H of the wall and road by the Jurges formula and moisture availability
(15) Calculate Rn, H, lE, and G from the wall and road surfaces
(16) Calculate wall and road surface temperature
(17) Iteration of (15) and (16) by the Newton-Rapson method: Solving non-linear simultaneous two equations
(18) New wall and road surface temperatures
(19) New Rn, H, lE, and G using new wall and road surface temperature
(20) New wall and road layer temperatures using new wall and road surface temperatures: Solving 4-layers heat equation model
(21) Calculate Monnin-Obkhov stability length above the urban canopy by the Newton-Rapson method: Solving non-liner equation. First guess is the same as the stability length at the previous step.
(22) Calculate C_H, C_D of the urban canopy
(23) Calculate Rn, H, lE, and G from the urban canopy
(24) Calculate new canopy air temperature and humidity using heat fluxes from canopy, wall, and road

(25) Calculate new total heat and momentum fluxes from the urban canopy layer including the roof
(26) Convert unit

Calling structure of the subroutine urban

- Call read param: to read urban parameters
- Call mos: to calculate Monin-Obkhov stability length above the roof
- Call mos: to calculate new Monin-Obkhov stability length above the roof
- Call multi-layer: to solve the 4-layers heat equation model for the roof
- Call multi-layer: to solve the 4-layers heat equation model for the wall and road
- Call mos: to calculate new Monin-Obkhov stability length above the urban canopy

Parameter tables

Urban type,

- building height, ZR
- roughness for momentum above the urban canopy layer, Z0C
- roughness for heat above the urban canopy layer Z0HC
- zero-displacement height above the urban canopy layer, ZDC
- percentage of urban canopy, PUC
- sky view factor, SVF
- building coverage ratio (roof area ratio), R
- normalized building height, HGT
- drag coefficient by buildings, CDS
- buildings volumetric parameter, AS
- anthropogenic heat, AH
- heat capacity of the roof, wall, and road
- heat conductivity of the roof, wall, and road
- albedo of the roof, wall, and road
- emissivity of the roof, wall, and road
- roughness length for momentum of the roof, wall, and road
- roughness length for heat of the roof, wall, and road
- number of roof layers (= number of soil layers)
- number of wall layers (= number of soil layers)
- number of road layers (= number of soil layers)
- layer thickness of the roof
- layer thickness of the wall
- layer thickness of the road
- option to surface layer scheme (Louis or M-O theory iteration)
- option to lower boundary condition for roof (zero-flux or constant temperature)
- option to lower boundary condition for wall (zero-flux or constant temperature)
- option to lower boundary condition for road (zero-flux or constant temperature)

5.2 WRF physics calling order

5.2.1 SOLVER

1. Set up

   Set leapfrog or runge-kutta solver (2nd or 3rd order)
      CALL get_ijk_from_grid
   Compute these starting and stopping locations for each tile and number of tiles
      CALL set_tile

2. Physics
      CALL radiation_driver (calculate T tendency)
      CALL surface_driver (call surface layer and LSM to calculate surface fluxes and skin temperature, update soil moisture, temperature, snow, LSM calls sflx and urban)
      CALL pbl_driver (calculate T,q tendency)
      CALL cumulus_driver (calculate T,q tendency)
      CALL calculate_phy_ten (sum up all tendencies)

3. Dynamics
      Updates dry dynamic variables (u,v,theta,geopot. height, W)
      Update scalers (qv, qc, TKE)
      Advection, working on updated variables, to update everything

      CALL update_phy_ten
      CALL vertical_diffusion
      CALL horizontal_diffusion
      CALL rk_tendenc

4. Microphysics
      CALL microphysics_driver

5.3 Modified Routines for Noah/Urban LSM

5.3.1 Physics routines

/main:

wrf.F (no LSM/Urban related change)
   USE module_wrf_top

/**share:**
USE module_integrate ((no LSM/Urban related change)

/frame:

module_integrate.F (no LSM/Urban related change)

Call solve_interface

/share:

solve_interface.F (no LSM/Urban related change)

CALL solve_em

CALL solve_nmm

/dyn_em:

solve_em.F

```
          CALL radiation_driver (add
&      ,DECLIN_URB=declin_urb      ,COSZ_URB2D=cosz_urb2d      &  !urban
&      ,OMG_URB2D=omg_urb2d
                                  )
```

CALL surface_driver (lots of changes to accommodate prognostic variables for the urban-canopy model)

/phys:

module_radiation_driver.F

```
          SUBROUTINE radiation_driver  (add
         ,declin_urb,COSZ_URB2D, omg_urb2d              & !urban
                                            )
```

module_surface_driver.F

```
          SUBROUTINE surface_driver (add
&      ,declin_urb,cosz_urb2d,omg_urb2d,xlat_urb2d         & !I urban
&      ,num_roof_layers, num_wall_layers                   & !I urban
&      ,num_road_layers, dzr, dzb, dzg                     & !I urban
&      ,tr_urb2d,tb_urb2d,tg_urb2d,tc_urb2d,qc_urb2d       & !H urban
&      , uc_urb2d                                          & !H urban
&      ,xxxr_urb2d,xxxb_urb2d,xxxg_urb2d,xxxc_urb2d        & !H urban
&      ,trl_urb3d,tbl_urb3d,tgl_urb3d                      & !H urban
```

&   ,sh_urb2d,lh_urb2d,g_urb2d,rn_urb2d,ucmcall   & !H urban
)

CALL lsm (add

ucmcall   &
!Optional urban
,tr_urb2d,tb_urb2d,tg_urb2d,tc_urb2d,qc_urb2d, & !H urban
uc_urb2d,   & !H urban
xxxr_urb2d,xxxb_urb2d,xxxg_urb2d,xxxc_urb2d,   & !H urban
trl_urb3d,tbl_urb3d,tgl_urb3d,   & !H urban
sh_urb2d,lh_urb2d,g_urb2d,rn_urb2d,ts_urb2d,   & !H urban
psim_urb2d,psih_urb2d,u10_urb2d,v10_urb2d,   & !O urban
GZ1OZ0_urb2d, AKMS_URB2D,   & !O urban
th2_urb2d,q2_urb2d,ust_urb2d,   & !O urban
declin_urb,cosz_urb2d,omg_urb2d,   & !I urban
xlat_urb2d,   & !I urban
num_roof_layers, num_wall_layers,   & !I urban
num_road_layers, DZR, DZB, DZG,   & !I urban
FRC_URB2D, UTYPE_URB2D   & ! urban
..)

/phys:

module_physics_init.F

SUBROUTINE phy_init (add
DZR, DZB, DZG,   & !Optional urban
TR_URB2D,TB_URB2D,TG_URB2D,TC_URB2D,   & !Optional
urban
QC_URB2D, XXXR_URB2D,XXXB_URB2D,   & !Optional urban
XXXG_URB2D, XXXC_URB2D,   & !Optional urban
TRL_URB3D, TBL_URB3D, TGL_URB3D,   & !Optional urban
SH_URB2D, LH_URB2D, G_URB2D, RN_URB2D, & !Optional
urban

)

CALL bl_init (add
DZR, DZB, DZG,   & !Optional urban
TR_URB2D,TB_URB2D,TG_URB2D,TC_URB2D,QC_URB2D,
& !Optional urban
XXXR_URB2D,XXXB_URB2D,XXXG_URB2D,XXXC_URB2D,
& !Optional urban
TRL_URB3D, TBL_URB3D, TGL_URB3D,   & !Optional urban

```
            SH_URB2D, LH_URB2D, G_URB2D, RN_URB2D,        & !Optional urban
            TS_URB2D, FRC_URB2D, UTYPE_URB2D, UCMCALL,     & !Optional
urban
                                    )


         SUBROUTINE bl_init (add
           DZR, DZB, DZG,                            & !Optional urban
            TR_URB2D,TB_URB2D,TG_URB2D,TC_URB2D,QC_URB2D,
& !Optional urban
            XXXR_URB2D,XXXB_URB2D,XXXG_URB2D,XXXC_URB2D,
& !Optional urban
            TRL_URB3D, TBL_URB3D, TGL_URB3D,            & !Optional urban
            SH_URB2D,LH_URB2D,G_URB2D,RN_URB2D,          & !Optional urban
            TS_URB2D, FRC_URB2D, UTYPE_URB2D,UCMCALL,     & !Optional
urban

                                     )
```

add:

```
!URBAN
       IF(UCMCALL.eq.1) THEN

         IF ( PRESENT( FRC_URB2D ) .AND. PRESENT( UTYPE_URB2D )) THEN

           CALL urban_param_init(DZR,DZB,DZG,num_soil_layers
& !urban
                       )
!                       num_roof_layers,num_wall_layers,road_soil_layers)   !urban
           CALL urban_var_init(TSK,TSLB,TMN,IVGTYP,                       & !urban
                     ims,ime,jms,jme,num_soil_layers,            & !urban
!                     num_roof_layers,num_wall_layers,num_road_layers, & !urban
                     XXXR_URB2D,XXXB_URB2D,XXXG_URB2D,XXXC_URB2D,
& !urban
                     TR_URB2D,TB_URB2D,TG_URB2D,TC_URB2D,QC_URB2D,
& !urban
                     TRL_URB3D,TBL_URB3D,TGL_URB3D,              & !urban
                     SH_URB2D,LH_URB2D,G_URB2D,RN_URB2D, TS_URB2D,
& ! urban
                     FRC_URB2D, UTYPE_URB2D)                     !urban
         ELSE
           CALL wrf_error_fatal ( 'arguments not present for calling urban model' )
         ENDIF
       ENDIF
```

/phys:

module_ra_gfdleta.F

```
            SUBROUTINE ETARA (add

  &         COSZ_URB2D,OMG_URB2D                    & !urban
                                 )

            CALL RADTN (add
  &       COSZ_URB2D,OMG_URB2D,                     & !urban
                             )

            SUBROUTINE RADTN  (add

  &         COSZ_URB2D,OMG_URB2D,                   & !urban
                                 )
```

/phys:

module_ra_gsfcsw.F

```
            SUBROUTINE GSFCSWRAD  (add
          ,cosz_urb2d,omg_urb2d                 & !urban
                                          )
```

/phys:

module_ra_sw.F

```
            SUBROUTINE SWRAD (add
              cosz_urb2d,omg_urb2d,             & !urban
                                 COSZ2D)

            CALL SWPARA (add
                   COSZ, OMG,                   & !urban
                              )

            SUBROUTINE SWPARA (add
                         COSZ, OMG,             & !urban
                                   )
```

/phys:

module_sf_noahlsm.F

Add: USE module_sf_urban

```
CALL  urban(LSOLAR_URB, num_roof_layers,
num_wall_layers, num_road_layers, DZR,  DZB,  DZG,
UTYPE_URB,  TA_URB,  QA_URB,  UA_URB, SSG_URB,
SSGD_URB, SSGQ_URB, LLG_URB, RAIN_URB,
RHOO_URB, ZA,DECLIN_URB, COSZ_URB,
XLAT_URB, DELT_URB, TR_URB, TB_URB, TG_URB,
TC_URB, QC_URB, UC_URB,
TRL_URB,TBL_URB,TGL_URB,
XXXR_URB, XXXB_URB, XXXG_URB, XXXC_URB,
TS_URB,SH_URB,LH_URB,LH_KINEMATIC_URB,
TAU_URB, SW_URB, ALB_URB,LW_URB,G_URB)
```

```
      SUBROUTINE lsm (add
    ucmcall,                         &
!Optional Urban
    TR_URB2D,TB_URB2D,TG_URB2D,TC_URB2D,QC_URB2D, & !H
urban
    UC_URB2D,                        & !H urban
    XXXR_URB2D,XXXB_URB2D,XXXG_URB2D,XXXC_URB2D,  & !H
urban
    TRL_URB3D,TBL_URB3D,TGL_URB3D,             & !H urban
    SH_URB2D,LH_URB2D,G_URB2D,RN_URB2D,TS_URB2D,  & !H urban
    PSIM_URB2D,PSIH_URB2D,U10_URB2D,V10_URB2D,    & !O urban
    GZ1OZ0_URB2D,  AKMS_URB2D,                 & !O urban
    TH2_URB2D,Q2_URB2D, UST_URB2D,             & !O urban
    DECLIN_URB,COSZ_URB2D,OMG_URB2D,           & !I urban
    XLAT_URB2D,                      & !I urban
    num_roof_layers, num_wall_layers,          & !I urban
    num_road_layers, DZR, DZB, DZG,            & !I urban

                            )
```

/phys:

new **module_sf_urban.F**

5.3.2 Initialization routines

/dyn_em:

start_em.F

```
CALL phy_init   (add
grid%DZR, grid%DZB, grid%DZG,                        & !Optional urban

grid%TR_URB2D,grid%TB_URB2D,grid%TG_URB2D,grid%TC_URB2D,
& !Optional urban
grid%QC_URB2D, grid%XXXR_URB2D,grid%XXXB_URB2D,
& !Optional urban
grid%XXXG_URB2D, grid%XXXC_URB2D,                & !Optional
urban
grid%TRL_URB3D, grid%TBL_URB3D, grid%TGL_URB3D,
& !Optional urban
grid%SH_URB2D, grid%LH_URB2D, grid%G_URB2D,
grid%RN_URB2D,  & !Optional urban
grid%TS_URB2D, grid%FRC_URB2D, grid%UTYPE_URB2D,
& !Optional urban
)
```

5.3.3 Registry

/Registry:

Registry.EM

Add:

```
# urban model variables
state   real   DZR       l     em    -       Z    ir     "DZR"
                          "THICKNESSES OF ROOF LAYERS"           "m"
state   real   DZB       l     em    -       Z    ir     "DZB"
                          "THICKNESSES OF WALL LAYERS"           "m"
state   real   DZG       l     em    -       Z    ir     "DZG"
                          "THICKNESSES OF ROAD LAYERS"           "m"

# urban state variables

state   real   TR_URB2D      ij    misc      1      -
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm)     "TR_URB"
"URBAN ROOF SKIN TEMPERATURE"       "K"
state   real   TB_URB2D      ij    misc      1      -
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm)     "TB_URB"
"URBAN WALL SKIN TEMPERATURE"       "K"
```

state real TG_URB2D ij misc 1 -
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "TG_URB"
"URBAN ROAD SKIN TEMPERATURE" "K"
state real TC_URB2D ij misc 1 -
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "TC_URB"
"URBAN CANOPY TEMPERATURE" "K"
state real UC_URB2D ij misc 1 -
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "UC_URB"
"URBAN CANOPY WIND" "m s{-1}"
state real QC_URB2D ij misc 1 -
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "QC_URB"
"URBAN CANOPY HUMIDITY" "kg kg{-1}"
state real XXXR_URB2D ij misc 1 -
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "XXXR_URB" "M-O
LENGTH ABOVE URBAN ROOF" "dimensionless"
state real XXXB_URB2D ij misc 1 -
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "XXXB_URB" "M-O
LENGTH ABOVE URBAN WALL" "dimensionless"
state real XXXG_URB2D ij misc 1 -
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "XXXG_URB" "M-O
LENGTH ABOVE URBAN ROAD" "dimensionless"
state real XXXC_URB2D ij misc 1 -
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "XXXC_URB" "M-O
LENGTH ABOVE URBAN CANOPY" "dimensionless"
state real TRL_URB3D ilj misc 1 Z
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "TRL_URB" "ROOF LAYER
TEMPERATURE" "K"
state real TBL_URB3D ilj misc 1 Z
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "TBL_URB" "WALL LAYER
TEMPERATURE" "K"
state real TGL_URB3D ilj misc 1 Z
rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm) "TGL_URB" "ROAD LAYER
TEMPERATURE" "K"
state real SH_URB2D ij misc 1 - rh "SH_URB" "SENSIBLE
HEAT FLUX FROM URBAN SFC" "W m{-2}"
state real LH_URB2D ij misc 1 - rh "LH_URB" "LATENT
HEAT FLUX FROM URBAN SFC" "W m{-2}"
state real G_URB2D ij misc 1 - rh "G_URB" "GROUND
HEAT FLUX INTO URBAN" "W m{-2}"
state real RN_URB2D ij misc 1 - rh "RN_URB" "NET
RADIATION ON URBAN SFC" "W m{-2}"

urban variables from radiation scheme
state real COSZ_URB2D ij misc 1 - r "COSZ_URB" "COS of
SOLAR ZENITH ANGLE" "dimensionless"

state real OMG_URB2D ij misc 1 - r "OMG_URB" "SOLAR HOUR ANGLE" "dimensionless"
state real DECLIN_URB - misc 1 - r "DECLIN_URB" "SOLAR DECLINATION" "dimensionless"

rconfig integer ucmcall namelist,physics max_domains 1 h "ucmcall" "activate urban model 0=no, 1=yes" ""

5.3.4 Namelist

/test/em_real

namelist.input

UCMCALL	= 0, 0, 0, (off)
	0, 0, 1, (on)
num_land_cat	=33

5.3.5 Tables

/run:

Add:

urban_param.tbl

5.3.6 Makefile

/phys:

Makefile

References

Chen, F., Y. Liu, H. Kusaka, M. Tewari, J-W Bao, C-F Lo, and K-H Lau, 2004: Challenge of Forecasting Urban Weather with NWP Models. *5th MM5 and WRF Users Workshop*, 21-25 June, Boulder, Colorado.

Kusaka, H., H. Kondo, Y. Kikegawa, and F. Kimura, 2001: A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. *Bound.-Layer Meteorol.*, 101, 329-358.

Kusaka, H. and F. Kimura, 2004: Coupling a single-layer urban canopy model with a simple atmospheric model: Impact on urban heat island simulation for an idealized case. *Journal of the Meteorological Society of Japan*, 82, 67-80.