Description and Procedures for using the Pleim-Xiu LSM, ACM2 PBL and Pleim Surface Layer Scheme in WRF

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Contents:

Description of Physics Schemes (from WRF Technical Description)

ACM2
The ACM2 (Pleim, 2007) is a combination of the ACM, which is a simple transilient model that was originally a modification of the Blackadar convective model, and an eddy diffusion model. Thus, in convective conditions the ACM2 can simulate rapid upward transport in buoyant plumes and local shear induced turbulent diffusion. The partitioning between the local and nonlocal transport components is derived from the fraction of non-local heat flux according to the model of Holtslag and Boville (1993). The algorithm transitions smoothly from eddy diffusion in stable conditions to the combined local and non-local transport in unstable conditions. The ACM2 is particularly well suited for consistent PBL transport of any atmospheric quantity including both meteorological (u, v, θ, qv) and chemical trace species.

Pleim Surface Layer
The PX surface layer scheme (Pleim, 2006) was developed as part of the PX LSM but can be used with any LSM or PBL model. This scheme is based on similarity theory and includes parameterizations of a viscous sub-layer in the form of a quasi-laminar boundary layer resistance accounting for differences in the diffusivity of heat, water vapor, and trace chemical species. The surface layer similarity functions are estimated by analytical approximations from state variables.

Pleim-Xiu Land Surface Model

The PX LSM (Pleim and Xiu, 1995; Xiu and Pleim, 2001), originally based on the ISBA model Noilhan and Planton (1989), includes a 2-layer force-restore soil temperature and moisture model. The top layer is taken to be 1 cm thick, and the lower layer is 99 cm. The PX LSM features three pathways for moisture fluxes: evapotranspiration, soil evaporation, and evaporation from wet canopies. Evapotranspiration is controlled by bulk stomatal resistance that is dependent on root zone soil moisture, photosynthetically active radiation, air temperature, and the relative humidity at the leaf surface. Grid aggregate vegetation and soil parameters are derived from fractional coverages of land use categories and soil texture types. There are two indirect nudging schemes that correct biases in 2-m air temperature and RH by dynamic adjustment of soil moisture (Pleim and Xiu, 2003) and deep soil temperature (Pleim and Gilliam, 2009). Note that a small utility program (IPXWRF) can be used to propagate soil moisture and temperature between consecutive runs to create a continuous simulation of these quantities. The scheme also allows for sub-grid variability by averaging grid-cell properties from sub-grid fractions.

Suggested Applications

- The P-X LSM and ACM2 planetary boundary layer physics were originally developed in MM5 for use with air quality models, in particular, the Community Multi-Scale Air Quality (CMAQ) model. The ACM2 PBL scheme is also used for the mixing in the CMAQ model, so using this scheme in WRF alone or the WRF-CMAQ coupled model results in consistent mixing of the meteorology scalars like water vapor and pollutants.
- P-X LSM was designed for retrospective meteorological applications, not real-time forecasting because of the indirect soil nudging scheme. The indirect soil nudging requires accurate 2-m temperature and water vapor mixing ratio analyses (not available in real-time forecasting unless forecasted fields are used). These are computed by blending point surface observations and forecast model initial conditions using the Obsgrid pre-processor.
- ACM2 PBL and Pleim surface layer schemes have been successfully used with other land surface models such as Noah and RUC in a variety of applications from weather forecasting to wind energy. These will likely also work in climate applications, but not specifically tested by the developers.
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Important WRF Output Variables for CMAQ Applications

The P-X LSM has several variables that are essential for most CMAQ applications. It is critical that CMAQ users ensure their WRF outputs have these variables.

RS, RA, ZNT_PX, VEGF_PX, LAI_PX, LANDUSEF, WFC_PX, WSAT_PX, WWLT_PX, CSAND_PX, FMSAND_PX, CLAY_PX

Two simple methods can be used.

Registry Update (Method 1)
Before compiling WRF, the following registry file should be checked and modified so all variables listed have the "h" (for history or the WRF output file) in the <IO> column. An example is provided for RA (aerodynamic resistance). Search for all variables and add h where needed. Some of the listed variables have h by default in the WRF release, but wise to double check all of the listed variables.
Registry file & example entry: *WRFDIR/Registry/Registry.EM_COMMON*
state real RA ij misc 1 - r**h** "RA" "AERODYNAMIC RESISTANCE" "s m-1"

Run-time (Method 2)
Second method is dynamic and does not require recompiling WRF codes. This will work for any WRF executable and simple. This method is a text file in the WRF run directory and namelist.input file setting to identify this file. For CMAQ the following line should be used. The plus (+) indicates add these to the history (h) or WRF output file. The file name is user defined and does not matter, but output.var.txt is used in the example below. The WRF namelist.input file specification *iofields_filename* is below and placed in the *&time_control* section of the namelist.input file.

+:h:0:,RS,RA,ZNT_PX,VEGF_PX,LAI_PX,LANDUSEF,WFC_PX,WSAT_PX,WWLT_PX,CSAND_PX,FMSAND_PX,CLAY_PX

iofields_filename = "output.var.txt"

Pros and Cons

- PRO: The central benefit of the P-X LSM lies in the indirect soil temperature and moisture nudging algorithm that significantly improves error and bias of near-surface meteorology if more precise 2-m temperature and moisture analyses are provided as input.
- PRO: Since the P-X LSM was designed for retrospective applications, snow cover is not a simulated quantity. Snow cover is an input from forecast initial condition analyses every 3 to 6 hours, or, from a high resolution 1 km snow analysis like the SNOw Data Assimilation System (SNODAS). This ensures very accurate snow cover, although it can introduce an inconsistency in some cases, namely, if the model atmosphere is producing snow when the analysis has none, or vice-versa. In more recent years, datasets like the High Resolution Rapid Refresh can provide detailed snow information at ~3 km grid scales and temporal scales as small as hourly.
- PRO: Land use properties are computed using land use fractional weighting, which provides more realistic values, especially at grid scales much greater than the land use dataset resolution (~250 m for NLCD and ~1 km for MODIS and USGS).

- PRO: New datasets like the ~250 m resolution NLCD land use, impervious surface and canopy fraction have been created for the P-X LSM. These provide more detailed land use fractional data at typical model grid scales and the impervious and canopy fraction are used for better urban modeling. This NLCD40 dataset is distributed with WRF and valid for 2011 satellite NLCD and MODIS. A 2019 dataset is also available, but requires users to process using a version of spatial allocator for their domain (need to contact US EPA CMAQ modeling group).
- PRO: Snow albedo was updated (WRFV3.7) to use fractional land use data and land use specific snow albedo to compute a weighted snow albedo for each grid cell. Many LSM's use the dominate land use class or coarse satellite data to specify snow albedo. This provides a more realistic snow albedo that adapts to varying model resolutions.
- CON: Snow cover surface physics are quite simple. Fractional snow cover is determined by land use-based snow depth thresholds similar to the Noah LSM (SNUP variable in WRF LANDUSE tables), above which, the surface is considered 100% covered. Surface specific heat capacity is weighted by the percent covered by snow and no snow. This is much simpler than the multi-layer Noah or RUC snow scheme that accumulates, melts, sublimates and packs snow with age. This limits the usage to retrospective simulations where snow cover is known, and does not allow for uses such as snow forecasting or future climate scenarios.
- CON: Snow albedo and density are constant. Snow density impacts the specific heat capacity and aged snow has lower albedo than fresh. Researchers do have plans to track snow age so the snow albedo and density are dynamic, not static.
- CON: The 40 class NLCD dataset prepared specifically for the P-X LSM only covers North America, covering the area of NCEP's NAM-12 km analysis. Users with larger domains or domains in other parts of the world should use the 20 class MODIS land use, or USGS, which are also compatible with the P-X LSM. Similarly, the impervious surface and canopy fraction data only cover the CONUS.

Best Practices

- Unless testing proves otherwise, user are encouraged to choose the ACM2 and Pleim surface layer schemes with the P-X LSM. The P-X LSM does operate with the YSU PBL and base M-O surface layer, but has not been extensively tested by developers while the former combination has been extensively tested for years.
- Always use the P-X LSM indirect soil nudging option in the &fdda section of the WRF namelist.input (*pxlsm_soil_nudge =1*), unless one wants to do a sensitivity as to the effectiveness of the soil nudging.
- Allow for a soil spin-up period of 5, to preferably 10 days before the start of the study period. At the start of the spin-up use the namelist.input (see namelist suggestions below) option *pxlsm_smois_init = 1* to initialize the deep soil moisture. After the spin-up period, make sure *pxlsm_smois_init =0*. This allows the soil moisture to stabilize before the main period of interest.

- For the spin-up period, initialize the deep soil temperature as the average 2-m air temperature for 5, to preferably 10 days. This can be accomplished using the *IPXWRF* utility distributed by NCAR. This utility also allow the user to update a *wrfinput_d0** files soil temperature and moisture with a *wrfout_d01** file.
- Use *Obsgrid* objective analysis tool to blend surface observations from the MADIS observations system with WPS metgrid files (*met_em**) to produce 2-m temperature and moisture re-analyses on the users WRF domain. *Obsgrid* produces the file named *wrfsfdda_d0**. See namelist section below for more details on settings including QC levels and radius of influence for various grid scales
- Using mesonet surface observations available in the MADIS system along with the standard National Weather Service observations can improve the soil nudging by providing a significant number of additional data points (well over 8000 extra across the United States) and an improved surface meteorological analysis.
- For fine-scale simulations, if the model analyses used to derive the *wrfsfdda_d0** file(s) have much coarser resolution than the WRF grid, the P-X soil nudging may suffer. This was originally discovered when 12 km analyses were used in 1 km WRF simulations. The background analysis, even when blended with observations, does not have the fine-scale geographically induced details needed for quality soil nudging. This is most apparent in areas with dramatic variability in topography or complex coastlines. In more recent years an alternative dataset has emerged (High Resolution Rapid Refresh) and freely available via NOAA sponsored archives. The surface analysis is highly accurate as it uses NOAA data assimilation including a wealth of observations to produce not only precise 2-m temperature and moisture fields, but also precision snow and sea surface temperature. Contact developers for help including a script that acquire the data and WPS pre-preprocessing steps.

Namelist(s) Options

namelist.input (WRF)

```
&physics
bl_pbl_physics        = 7,              ACM2 PBL
sf_sfclay_physics     = 7,              Pleim Sfc. Layer
sf_surface_physics    = 7,              Pleim-Xiu LSM
num_soil_layers       = 2,              P-X two soil layer configuration
pxlsm_smois_init      = 0,              Use 1 for initialization and 0 after 10-day soil spin-up


&fdda
pxlsm_soil_nudge      = 1,              P-X soil nudging (1) or no soil nudging (0)
grid_sfdda            = 1,              Tell WRF to open wrfsfdda_d0* file for P-X nudging
sgfdda_inname         = "wrfsfdda_d01",   P-X soil and surface layer nudging file (Obsgrid)
```

sgfdda_end_h	= 99999999,	End hour of nudging (large here to always nudge)
sgfdda_interval_m	= 180,	Interval of nudging fields (min) typically 180 or 360
guv_sfc	= 0.0000,	Set to zero to enable P-X soil nudging, but disable
gt_sfc	= 0.0000,	Surface layer nudging of wind, temp and moisture.
gq_sfc	= 0.0000,	Recommended for most applications.

namelist.oa (Obsgrid)

&record4	Suggested settings for QC checks
qc_test_error_max	= .TRUE.
qc_test_buddy	= .TRUE.
qc_test_vert_consistency	= .TRUE.
qc_test_convective_adj	= .FALSE.
max_error_t	= 8
max_error_uv	= 4
max_error_z	= 4
max_error_rh	= 20
max_error_p	= 600
max_buddy_t	= 6
max_buddy_uv	= 4
max_buddy_z	= 4
max_buddy_rh	= 20
max_buddy_p	= 800
buddy_weight	= 0.75
max_p_extend_t	= 1300
max_p_extend_w	= 1300

&record7

use_first_guess	= .TRUE.	Use supplied model analysis as first guess
f4d	= .TRUE.	Produce *wrfsdda_d01* file for P-X LSM nudging
intf4d	= 10800	Time interval of surface analysis (sec)

&record9

oa_type	= 'Cressman'	Cressman objective analysis method of blending
radius_influence	= 20,15,10,5	12 km domain suggestion
radius_influence	= 40,30,20,10	4 km domain suggestion
radius_influence	= 60,45,30,15	1 km domain suggestion

namelist.ipxwrf (IPXWRF)

```
&FILENAMES
file_wrfout_last       = 'wrfout_d01'     wrfout used to replace soil temp./moist. of wrfinput_d01
file_wrfin_next        = 'wrfinput_d01'   wrfinput to alter
file_wrffdda_next      = 'wrfsfdda_d01'   wrfsfdda used to calculate avg. 2-m air temperature for
                                          deep soil temperature initialization
do_msoil               = .FALSE.          Replace wrfinput SMOIS with that of wrfout above
do_tsoil               =  .FALSE.         Replace wrfinput TSLB with that of wrfout above
do_tsoildeep_from2m    = .TRUE.           Replace TSLB layer 2 with avg. air temperature
avg_period_2m          = 10               Number of days to average air temperature
&END
```

Updates in WRFV3.7 (2015)

Wetlands Treatment:

In WRFV3.7 the treatment of wetland areas was changed. It was not a full-fledged wetlands soil model, but rather, a simple lower bound limit on layer two soil moisture. If a grid cell is 100% wetlands, the soil moisture is not allowed to drop below 100% of soil saturation. If a grid cell is 25% wetlands, the soil moisture is not allowed to fall below 25% of soil saturation for that grid cell. This approximates the impact of the fractional wetland of a grid cell on soil behavior.

Snow Albedo:

Rather than existing WRF methods for snow albedo (satellite or dominant land use values), the P-X LSM was updated to leverage fractional land use to calculate a weighted snow albedo. Each land use class has a maximum snow albedo defined in the module_sf_pxlsm_data.F file. The fractional land use weights the albedo for a grid cell value. This provides a much more detailed/textured albedo of snow surfaces. Since the land use data is resolved down to ~250 m, this fractional weighting method works well at most grid scales, especially compared to the default coarse satellite data method.

High-Resolution NLCD Dataset:

Several new datasets were prepared for the PX-LSM and other land-surface models, although testing of other LSM's has been limited to a simple run test using the Noah LSM. The first is a 9 arcsecond, ~250 m National Land Cover Dataset valid for 2011. This dataset is an update to the NLCD40 (40 class) data (valid 2006) made available to the community in WRFV3.4. The old 2006 dataset was aggregated to 30 sec (~900 m), so the new 2011 NLCD40 provides much more detail for fine scale modeling, especially LSMs that leverage fractional land use like the PX LSM and Noah-MP. We've also provided a 2006 version of this dataset at the 9 arcsecond resolution. Since the NLCD is only available for the CONUS, areas of Canada and Mexico are defined using the 20 class MODIS scheme. The dataset is not global; it covers NCEP's North American Model (NAM) 12 km area, so it is only applicable to regional modeling centered on the CONUS or more local fine-scale US modeling. See LANDUSE.TBL or VEGPARM.TBL for details on the land use classes. The data can be used by geogrid with specification: *geog_data_res = 'nlcd2006_9s+9s'* or *geog_data_res = 'nlcd2011_9s+9s'*.

Impervious Surface and Canopy Fraction:

Two other datasets derived from NLCD 2011 are impervious surface and tree canopy fraction. Both of these WPS-read datasets are also provided at 9 arcsecond/~250 m resolution. Impervious surfaces are manmade structures, primarily features such as parking lots, roads and roofs and can be leveraged by land surface models for urban adjustments. Canopy fraction is straightforward, the fraction of tree cover in any particular grid cell. WPS Geogrid table file has been updated so these data can easily be gridded to WRF domains within the WPS structure. The Pleim-Xiu LSM (others may follow) in WRFV3.7+ is capable of leveraging these data for improved urban modeling.

Impervious data is used to adjust the surface heat capacity with the assumption that most of these structures are concrete and pavement with high heat capacity. The fractional impervious area and vegetation area are used via weighting for a grid cell average heat capacity. Civil engineering data were used to derive an estimate of the heat capacity for impervious surfaces with the major assumption being the surface is concrete of a certain thickness. This number is documented in the main PX LSM physics module (*module_sf_pxlsm.F*). The highly accurate canopy fraction is used to adjust the grid cell vegetation fraction and leaf area index, which were originally based on distinct minimum and maximum annual values for each land use class. The canopy fraction essentially adds more detail to those parameters. If these data are not supplied through a user's geogrid file, when the WRFV3.7 real.exe is completed, the wrfinput_d0* file(s) will produce the arrays with zero values and have no impact on any PX LSM simulations. Users should check *wrfinput_d** files in case a particular compiler initializes with no-zero values.

Updates in WRFV4.0 (https://github.com/wrf-model/WRF/pull/733)

- Added vegetation and leaf-area index option for Pleim-Xiu land-surface runs. Until this version, the PX LSM uses VEGFRA and LAI computed from the module_sf_pxlsm_data.F PX data table. This uses fractional land use and these lookup values to compute the LAI and VEGFRA for each grid cell. The new option (pxlsm_modis_veg = 1) is activated using this option in the physics section of the namelist.input file. It uses the time-varying VEGFRA and LAI from the wrflowinp_d01 file instead of the look-up values in the PX data table. This allows use of more accurate high resolution MODIS that is now available in WPS in WRFv4+. Alternatively, users can process their own MODIS data for specific years and put in this same input file.
- Also, the soil calculations in the PX LSM were modified to use analytical functions from Noilhan and Mahfouf (1996) for field capacity, saturation and wilting point based on fractional soil data. Also, variables for fractional clay, fine and coarse sand were added in PX for output to the CMAQ air quality model. This is an important update because these data are used for dust emissions in the air quality model along with the new soil

properties (wilting, saturation and field capacity). SOILTYP was also updated in the PX LSM so soil classes are consistent with the standard 16 soil types in the WRF system. Prior, PX only had 12 classes and classes 4-12 were not the same as those classes used by other LSMs.

Updates in WRFV4.3 (https://github.com/wrf-model/WRF/pull/1433)

- Modified the ACM2 PBL height algorithm for stable conditions so that the Richardson number is computed using windspeed in layer k rather than wind speed difference between layer k and ksrc.
- Added new pathway for evaporation from the ground in the vegetated fraction of the grid cell in PX LSM module.
- Cleaned old commented out calculations and notes from tracking code pre-GitHub. Fixed several instances where code was not aligned consistently. This was done for all U.S. EPA contributed code here including the module_sf_pxsfclay.F that was not modified otherwise.
- Consolidated the WRF PX LSM code with the MPAS version. The PX LSM code in WRFV4.4 is essentially the same code as that for MPASv7.3+.

Updates in WRFV4.6 (https://github.com/wrf-model/WRF/pull/2023)

- P-X LSM now compatible with 61 class MODIS Local Climate Zone (LCZ) landuse option
- P-X LSM added the latent heat effect on ground temperature from the vegetated fraction of the grid cell and from wet canopy was added to P-X LSM.
- P-X LSM NaN fix from a divide by zero because of a zero-value soil parameter when a water cell turns to sea ice.

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