Extracting Horizontal Momentum Tendency Terms from WRF 3.4.1

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This document is intended to summarize the steps for extracting individual tendency terms of the horizontal momentum equations from the WRF model for real case simulations. For full description of the model dynamics please refer to the WRF Technical Manual (*Skamarock et al.*, 2008). For a detailed description of a similar procedure for an idealized LES simulation in WRF see Lehner (2012).

This work was completed as part of a masters thesis project, available at https://circle.ubc.ca/handle/2429/46069 (*Moisseeva*, 2014).

Please note that modified WRF code files are included as embedded content in this PDF document. Instructions on using the modified modules are provided at the end of the summary.

Modifications of the Dynamical Solver

The horizontal momentum equations in WRF are formulated using terrain-following dry-hydrostatic pressure as a vertical coordinate η, defined as:

$$\eta = (p_h - p_{ht})/\mu \tag{1}$$

where $\mu = p_{hs} - p_{ht}$, and p_h, p_{ht}, p_{hs} correspond to hydrostatic component of pressure, pressure at the top and surface boundaries for a dry atmosphere, respectively. Since μ represents the mass of a dry air column per unit area, flux-form velocity can be written as

$$\mathbf{V} = \mu\mathbf{v} = (U, V, \Omega), \tag{2}$$

where $\mathbf{v} = (u, v, \omega)$ are the covariant velocities in horizontal and vertical directions and $\Omega = \mu\dot{\eta}$, with $\dot{\eta} = \frac{\partial \eta}{\partial t}$. Using the above definition, flux-form horizontal momentum equations can be written as follows:

$$\partial_t U + (\nabla \cdot \mathbf{V}u) + \mu\alpha\partial_x p + \frac{\alpha}{\alpha_d}\partial_\eta p\partial_x\phi = F_U \tag{3}$$

$$\partial_t V + (\nabla \cdot \mathbf{V} v) + \mu \alpha \partial_y p + \frac{\alpha}{\alpha_d} \partial_\eta p \partial_y \phi = F_V \qquad (4)$$

where subscripts t, x and y correspond to derivatives with respect to time and horizontal coordinates, p denotes pressure, $\phi = gz$ is the geopotential and α and α_d are the specific volume of moist air and specific volume of dry air, respectively. The right hand side terms F_U and F_V represent the sum of the forcing terms arising from map projections, earth rotation, advection, physics, turbulent mixing, and boundary layer parameterizations.

Standard WRF configuration allows a user to easily output the *total* mass-coupled horizontal momentum tendencies **ru_tend** and **rv_tend** (first terms in Equations (3) and (4)), which are accumulated over each user-defined large time-step. However, additional variables must be introduced within the dynamical solver to output individual forcing terms, making up the RHS of Equations (3) and (4). These variables must be appropriately staggered, mass-coupled and passed on to the **%grid** structure, which in turn makes them available for history output.

Advection and pressure gradient tendencies are expressed explicitly on the LHS of Equations (3) and (4) (terms 2, 3 and 4). These can be extracted from the **rk_tendency** subroutine in **module_em.F** module by tracking the change in total accumulated momentum tendency prior to and after the terms are re-calculated. Curvature forcing, arising from map projections, Coriolis, turbulent mixing and physics parameterizations are contained in the RHS of the equations. Similarly to advection and pressure gradient, these are extracted by introducing additional variables in **rk_tendency** prior to and after the calls to the respective routines.

WRF offers a number of formulations for spatial dissipation including diffusion along coordinate surfaces, diffusion in physical space and sixth-order diffusion applied on horizontal coordinate surfaces, as well as several options for calculating eddy viscosities. Similarly to the forcings described above, horizontal diffusion tendencies are calculated on a staggered grid as part of **rk_tendency** subroutine, and can be deduced by tracking the change in the accumulated horizontal tendency terms. If a PBL parameterization scheme is enabled vertical diffusion is handled independently and stored as a physics tendency term. Coupled PBL momentum tendency terms from PBL scheme are already available in the **Registry.EM_COMMON**, however, as the physics in the model are calculated on mass points (unstaggered Arakawa-A grid), these would subsequently need to be interpolated to produce balanced equations with the rest of non-physics tendencies. As there are no other interactions with momentum tendencies in the physics driver it is more efficient to extract these tendencies as total momentum forcing due to physics **ru_tendf** and **rv_tendf**. These are present in the **Registry** as **i1** variables and hence cannot be output directly. Once again, new variables can be introduced in the main solver to extract them prior to the call to **rk_addtend_dry** in **solve_em.F**, which sums physics and dynamics tendencies.

WRF advances the horizontal momentum Equations (3) and (4) on a user-

defined time step Δt using a third-order RK integration scheme in three sub-steps. Within each substep acoustic modes are integrated using time-split integration with a smaller time step $\Delta\tau$, which varies among the three RK substeps. A correction term is then introduced to adjust the pressure-gradient tendency. This code adaptation was tested for a mesoscale simulation, where the acoustic correction was found to be insignificant and remained less 1 % of the total pressure-gradient term throughout the domain, except near mountain peaks and hence was not extracted from the model. However, the procedure is summarized in detail by Lehner (2012) for an idealized Large Eddy Simulation (LES).

Instructions for Using Modified Code

- save the files attached to this PDF document into a temporary location (ensure your viewer can display embedded content, e.g. Adobe Reader)
  $\left[\texttt{Registry.EM\_COMMON},\ \texttt{module\_em.F},\ \texttt{solve\_em.F}\right]$

- switch to your WRF directory and clean your previous build using
  `./clean -a`

- locate and backup the original versions of the following files:
  `./dyn_em/module_em.F`
  `./dyn_em/solve_em.F`
  `./Registry/Registry.EM_COMMON`

- copy the enclosed modified versions of the files to their corresponding locations

- edit the `Registry.EM_COMMON` to suit the needs of your simulation (the enclosed version only makes dynamical and velocity terms available for output)

- run `./configure` and `./compile em_real`

Successful build should produce `real.exe` and `wrf.exe` in the `./main` directory. **After completion of each model run, ensure that the momentum equations are balanced within the desired accuracy:**

`ru_tend` $\approx$ `ru_tend_adv + ru_tend_pgf +`
`ru_tend_cor + ru_tend_curv + ru_tend_hdiff + ru_tend_phys`

`rv_tend` $\approx$ `rv_tend_adv + rv_tend_pgf +`
`rv_tend_cor + rv_tend_curv + rv_tend_hdiff + rv_tend_phys`

Unsatisfactory balance likely indicates that the acoustic correction is required.

References

Lehner, M. (2012), Observations and large-eddy simulations of the thermally driven cross-basin circulation in a small, closed basin, Ph.D. thesis, University of Utah.

Moisseeva, M. (2014), Dynamical analysis of sea breeze hodograph rotation in sardinia, Master's thesis, University of British Columbia, `https://circle.ubc.ca/handle/2429/46069`.

Skamarock, W., J. Klemp, J. Dudhia, D. Gill, D. Barker, W. Wang, and J. Powers (2008), A description of the advanced research WRF version 3, *Tech. rep.*