Coupled atmosphere-hydrology system for routine prediction of overland water flow

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The atmosphere-soil physical system interacts by exchanging the moisture and heat at their interface. In numerical weather prediction systems, soil parameterization modules provide information on the soil state as a lower boundary condition for atmospheric models. Parameterization of the soil processes includes, among others, columnar water infiltration process. Although the rainfall overland and underground runoff is usual output of the soil parameterization, it is rarely used as a driving parameter for hydrology models. In this study, we describe a system that couples the atmospheric WRF-NCEP/NMM model (Janjic et al., 2001; Janjic, 2002) with a newly developed dynamic hydrology model using the rainfall runoff as a coupling variable.

The NMM model is an advanced nonhydrostatic model developed in the National Centres for Environmental Predictions (NCEP), Washington. The model is introduced in 2006 as the operational regional model, replacing so the hydrostatic Eta model at NCEP. NMM introduces an alternative approach to the design of nonhydrostatic weather prediction models. Instead of extending meso–scale nonhydrostatic modelling concepts to the synoptic scales and beyond, NMM uses a mass based vertical coordinate which has been extended to include the nonhydrostatic motions, preserving so favourable features of the hydrostatic formulation. In order to do so, the system of nonhydrostatic equations was split into two parts: the *first* part that corresponds to the hydrostatic dynamics, and the *second* part that allows computation of corrections due to the nonhydrostatic vertical acceleration. The NMM model 'physics' package is generally the same as used in the Eta model (Janjic 1990, 1994); it includes the Ferrier cloud microphysics, Mellor-Yamada-Janjic turbulence scheme, Betts-Miller-Janjic convection scheme and the GFDL radiation model.

In the NMM model, the NOAH land surface 1-d column model (Chen et al, 1996; Koren et al., 1999; Ek et al., 2003) is applied for the soil processes. NOAH considers both warm-surface and snow-pack/frozen-surface processes. The forcing variables for NOAH are predicted temperature, humidity, wind and surface pressure from NMM. Parameters describing the state of the soil surface are the land cover, soil texture and green vegetation fraction. Four layers (10, 30, 60 and 100 cm thick) are used to describe soil processes. NOAH solves the heat and moisture balance equations at the air-soil interface through direct and canopy water evaporation, water soil infiltration and internal moisture and heat flux processes. In the soil water balance equation, the Richard's equation is applied to simulate the soil water movement. Depending on the soil state, precipitation, evaporation and infiltration, the overland and underground rainfall runoffs are predicted simultaneously with the other atmospheric model variables. Since parameterization of the soil processes includes columnar water infiltration, soil models such as NOAH have a columnar component of the soil hydrology.

This study extends the columnar hydrology process to two other dimensions. For that purpose, we have developed a numerical hydrology prediction model (NHPM) that is designed to use the predicted rainfall runoff from the atmospheric model as a forcing hydrology NHPM solves a full set of shallow-water dynamic equations using a grid point approach. Unlike most of operational hydrology models that simplify the momentum equations to the kinematic (*diagnostic*) form, the NHPM solves all three governing equations (two for velocity components and one for the water height) in the *prognostic* mode. High-resolution data sets for real topography, river routing and land-cover are used to describe the surface physical features. The NHPM '*dynamics'* includes advection, diffusion and water gradient force, while the model '*physics'* (e.g. the friction slope terms) is parameterized, i.e. expressed in terms of the model grid-point variables. NHPM also includes a river-routing sub-model that drives the water excess due to precipitation.

NHPM, being restricted to the surface water dynamics, includes the following major processes: the water movement downhill due to the topography influence; the water movement away from precipitation sources due to the local water surplus and the horizontal water gradients; other components of the water dynamics such as the surface friction, advection and diffusion.

The governing equations are:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\left[\frac{\partial h}{\partial x}+S_{fx}-S_{0x}\right]=0, \quad \frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\left[\frac{\partial h}{\partial y}+S_{fy}-S_{0y}\right]=0, \quad \frac{\partial h}{\partial t}+\frac{\partial(hu)}{\partial x}+\frac{\partial(hv)}{\partial y}+\dot{H}=0.$$

Here, $\dot{H}$ is the height source/sink term; $S_{fx}=\frac{n^2\sqrt{u^2+v^2}}{h^{4/3}}u$, $S_{fy}=\frac{n^2\sqrt{u^2+v^2}}{h^{4/3}}v$ are the friction velocity terms; $S_{0x}=-\frac{\partial h_0}{\partial x}$, $S_{0y}=-\frac{\partial h_0}{\partial x}$ are the topography gradient terms; h_0 is the topography height; g is the gravity acceleration; n is the Manning coefficient.

We have developed/applied several numerical methods for the horizontal rectangular semi-staggered grid used in the model (Figure 1). The horizontal advection is represented by a mass conservative, positive definite numerical scheme free of generating new extremes (Janjic, 1997). An explicit forward-backward time differencing scheme for the gravity wave terms (Janjic, 1979) is implemented to provide efficient time integrations of the model.

A new method for mass redistribution at sources/sinks $\dot{H}$ is developed to suppress a computational grid decoupling of gravity waves typical for the semi-staggered grid. The proposed scheme is applied to the continuity equation as:

$$\frac{\partial h}{\partial t} + (\delta_x hu + \delta_y hv) + \frac{1}{2}\left(\dot{H} + \overline{\dot{H}}^{xy} \right) = 0$$

Here, δ_x and δ_y are second-order finite-differencing operators; $\overline{(\ )}^{xy}$ is the averaging operator applied along x and y directions.

Furthermore, a numerical scheme for the friction slope terms based on physical principles is developed. The scheme successfully avoids a singular instability that may occur when vanishing water heights in the denominator of the friction terms generates their uncontrolled growth. The proposed scheme using an implicit time differencing is written in the following form:

$\frac{u^{n+1} - u^n}{\Delta t} + B^n u^{n+1} + g\frac{\partial h_0}{\partial x} = 0$,. Here, $B \equiv \frac{gn^2\sqrt{u^2 + v^2}}{\left(\overline{h}^{xy}\right)^{4/3}}$. The corresponding solution of the scheme is $u^{n+1} = \left[\left(u - g\frac{\partial h_0}{\partial x}\Delta t\right) / (1 + B\Delta t)\right]^n$. Analogous equations are applied to the v velocity component. When the time step Δt vanishes, the velocities at the time level $n+1$ converge to values at the level n, which confirms the numerical consistency of the scheme. Furthermore, when the water depth vanishes, the velocity converges to zero; the stability of the scheme is therefore secured.

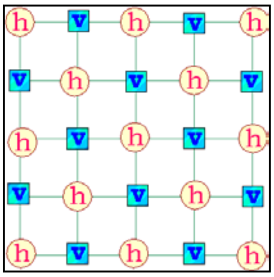

Figure 1. Grid spacing of height and velocity points

NHPM could be easily applied over different geographic domains and be efficiently run on conventional personal computer platforms. Preliminary real-time experiments set up over two smaller watersheds in the Balkan Peninsula have demonstrated that NHPM is capable to successfully simulate major features of the water flood dynamics (Pejanovic, personal communication).

ACKNOWLEDGEMET

Major part of the NHPM developments was performed within the 4th Italo-Maltese Protocol (1995-2000).

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