Development of a moisture scheme for the explicit numerical simulation of moist convection

Mary-Jane Bopape, Francois Engelbrecht, David Randall and Willem Landman

Natural Resources and Environment,Council for Sceintific and Industrial Reseach, mbopape@csir.co.za

Abstract

The Council for Scientific and Industrial Research is developing a nonhydrostatic sigma coordinate model (NSM). This model will be used to simulate nonhydrostatic processes to help meteorologists better understand and forecast convective processes. The aim of this study is to add a moisture scheme to the NSM. As a first step a simple model that is equivalent to the first pressure-coordinate nonhydrostatic model used to simulate cumulonimbus clouds in 1974 is developed. The equation set that includes 3 water particles, cloud water, water vapour and rain water has been derived.The equation set will be coded and tested using theoretical studies. The model will be extended to represent the real atmosphere and will include 8 different types of water particles usually used in bulk models and tested using theoretical studies and later the real atmosphere.

Introduction

The development of nonhydrostatic atmospheric models that can explicitly simulate the dynamics of atmospheric convection, has been ongoing since the 1960s. These models have been utilised largely for research purposes, as their application to operational weather forecasting and climate simulation was hindered by computational restrictions.

However, with the advent of ever faster computers, the operational numerical integration of weather prediction models at spatial resolutions beyond the hydrostatic limit, has become a reality. This has led to a renewed and worldwide effort to develop nonhydrostatic models. A nonhydrostatic sigma coordinate model is currently being developed at the Council for Scientific and Industrial Research (CSIR) for purposes of simulating weather at spatial resolutions where the hydrostatic approximation is not valid.

Development of a nonhydrostatic sigma coordinate model

Geometric height can be used as the vertical coordinate in atmospheric models. However, pressure-based coordinates are currently used in most atmospheric models. The use of pressure as a vertical coordinate is prompted by the availability of observational data at pressure levels and the neatness of handling the air density in the momentum and continuity equations. Miller (1974) developed the first nonhydrostatic model in pressure coordinates and Miller and Pearce (1974) used that model to simulate cumulonimbus clouds. This model assumes that departures from a reference state only occur because of convective processes and can therefore not be applied globally.

White (1989) developed a pressure coordinate model that did not make use of the reference profile, and therefore has the potential to be applied globally. Coordinates that do not follow the terrain are difficult to deal with when the surface is not flat. Engelbrecht (2007) developed a nonhydrostatic model equivalent to that of White (1989) based on sigma vertical coordinates as sigma coordinates follow the terrain – the nonhydrostatic sigma coordinate model (NSM). The NSM is based on pressure and is defined as $\sigma = \frac{p - p_T}{p_{surf} - p_T}$ where p is pressure, p_T is pressure at the top and p_{surf} is pressure at the surface of the model.

The CSIR NRE is developing a new nonhydrostatic sigma coordinate model, that incorporates moisture effects, so that it can simulate convective clouds and precipitation. Moisture terms equivalent to those of the Miller and Pearce (1974) model are incorporated in the equation set used:

$$\frac{Du}{Dt}+\frac{\partial\varphi}{\partial x}-\sigma\frac{\partial\varphi}{\partial\sigma}\frac{\partial\ln p_s}{\partial x}=0 \quad (1);$$

$$\frac{R}{g}\frac{D}{Dt}\left(\frac{\omega T}{p}\right)+g+\frac{p}{p_s}\frac{(1+q)g}{RT}\frac{\partial\varphi}{\partial\sigma}=0 \quad (2);$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial\dot\sigma}{\partial\sigma}+\frac{D\ln p_s}{Dt}=0 \quad (3);$$

$$\frac{DT}{Dt}-\kappa\frac{\omega T}{p}=\frac{LQ}{c_p} \quad (4);$$

$$\frac{D}{Dt}(q_v+q_c)=-PROD \quad (5);$$

$$\frac{D}{Dt}(q_r)=PROD-\frac{g}{p_s}\frac{\partial}{\partial\sigma}(\rho q_r V_r) \quad (6);$$

$$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial}{\partial\sigma}\left[s^2(1+q)^2\frac{\partial\varphi}{\partial\sigma}\right]$$
$$-2\sigma\left[\frac{\partial\ln p_s}{\partial x}\left(\frac{\partial^2\varphi}{\partial x\partial\sigma}\right)\right]$$
$$+\frac{\partial}{\partial\sigma}\left(\sigma^2\frac{\partial\varphi}{\partial\sigma}\right)\left[\left(\frac{\partial\ln p_s}{\partial x}\right)^2\right]$$
$$-\frac{\sigma}{p_s}\frac{\partial\varphi}{\partial\sigma}\left(\frac{\partial^2 p_s}{\partial x^2}\right)=2\left(\frac{\partial u}{\partial x}\right)\frac{\partial}{\partial\sigma}\left(\frac{\Omega p}{p_s}\right)$$
$$-\frac{2}{p_s}\left[\frac{\partial u}{\partial\sigma}\frac{\partial}{\partial x}(p\Omega)\right]$$
$$-\frac{\partial}{\partial\sigma}\left(sg-\frac{p}{p_s}\Omega^2\frac{1}{\gamma}+\frac{LQp\,\Omega}{p_sTc_p}\right) \quad (7)$$

Equations 1 to 7 include moisture terms and are to be solved within the new nonhydrostatic model. Equation 1 is the horizontal momentum equation while equation 2 is the vertical momentum equation. The latter differs from the associated equation for a dry atmosphere, with the inclusion of the mixing ratio (q) that appears in the expression: $g=(1+q)g$. Equation 3 is the continuity equation, which describes conservation of mass. Equation 4 is the thermodynamic energy equation, and its right hand side describes the change in the system that occurs due to latent heat release (absorption) during condensation (evaporation). The right hand side of this equation is zero for a dry system because, if there are no water particles, there will not be latent heat release or absorption. Equations 5 (cloud water and water vapour) and 6 (rainwater) are the water continuity equations and they describe changes in water particles due to microphysical processes and fallout of rain. Equation 7 is the elliptic equation used to forecast the geopotential height and has an important effect of balancing the atmopsheric fields.

Conclusion

The developed code will be extended so that the water continuity equations are included for eight main water particles, namely water vapour, cloud liquid water, drizzle, rainwater, cloud ice, snow, graupel (soft hail) and hail. It is expected that the new nonhydrostatic model will eventually be applied to the real-atmosphere for the simulation of convective storms, and that it will assist South African atmospheric scientists to better understand the attributes of moist convection.

References

Engelbrecht FA, JL McGregor and CJdeW Rautenbach, 2007: On the development of a new nonhydrostatic atmospheric model in South Africa. South African Journal of Science, 103, 127-134.

Miller MJ, 1974: On the use of pressure as vertical co-ordinate in modelling convection. Quarterly Journal of Royal Meteorological Society, 100, 155-162.

Miller MJ and RP Pearce, 1974: A three dimensional primitive equation model of cumulonimbus convection. Quarterly Journal of the royal meteorological society, 100, 133-154.

Whyte AA, 1989: An extended version of a nonhydrostatic, pressure coordinate model. Quarterly Journal of Royal Meteorological Society, 115, 1243-1251.