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

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INTRODUCTION

The eastern part of South Africa is a summer rainfall region, and most of its rainfall is of convective origin. Convective rainfall is often associated with hail, lightning and tornadoes – all of which can damage property and cause casualties, especially within such a densely populated region. Improved forecasting of convective systems can lead to better early warming systems which will in turn reduce casualties and damage to movable properties.

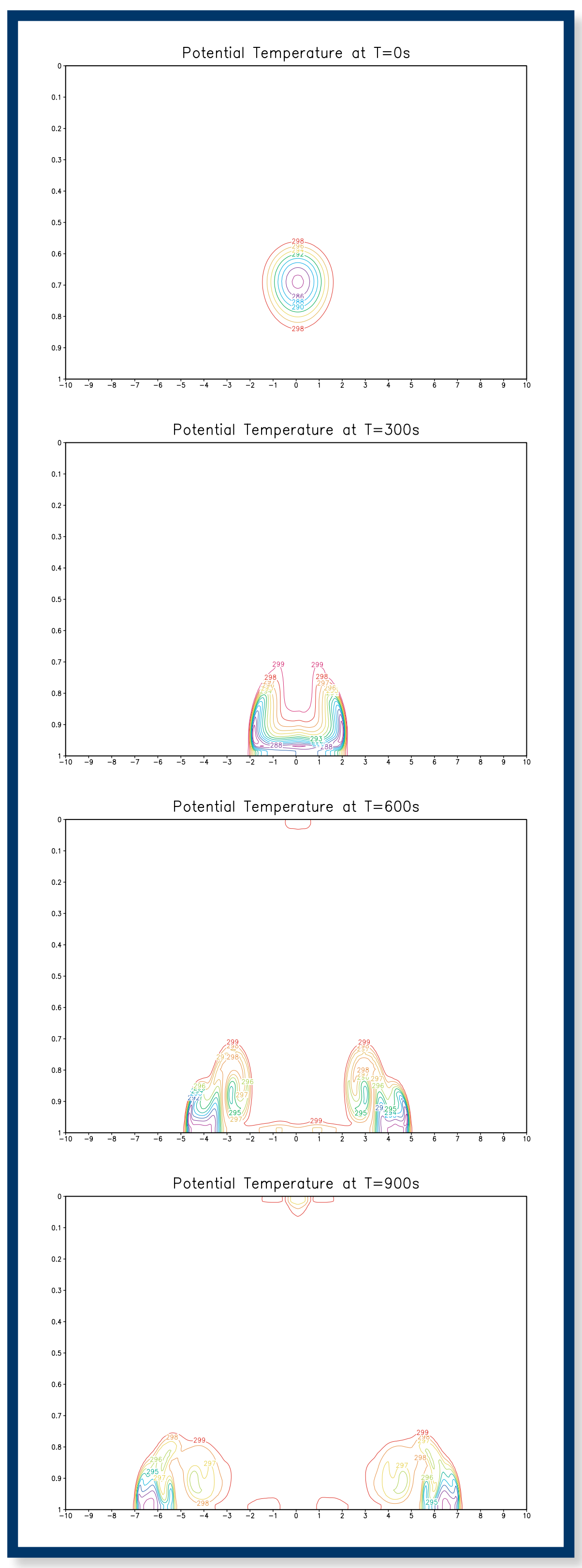

Figure 1: NSM cold bubble simulation

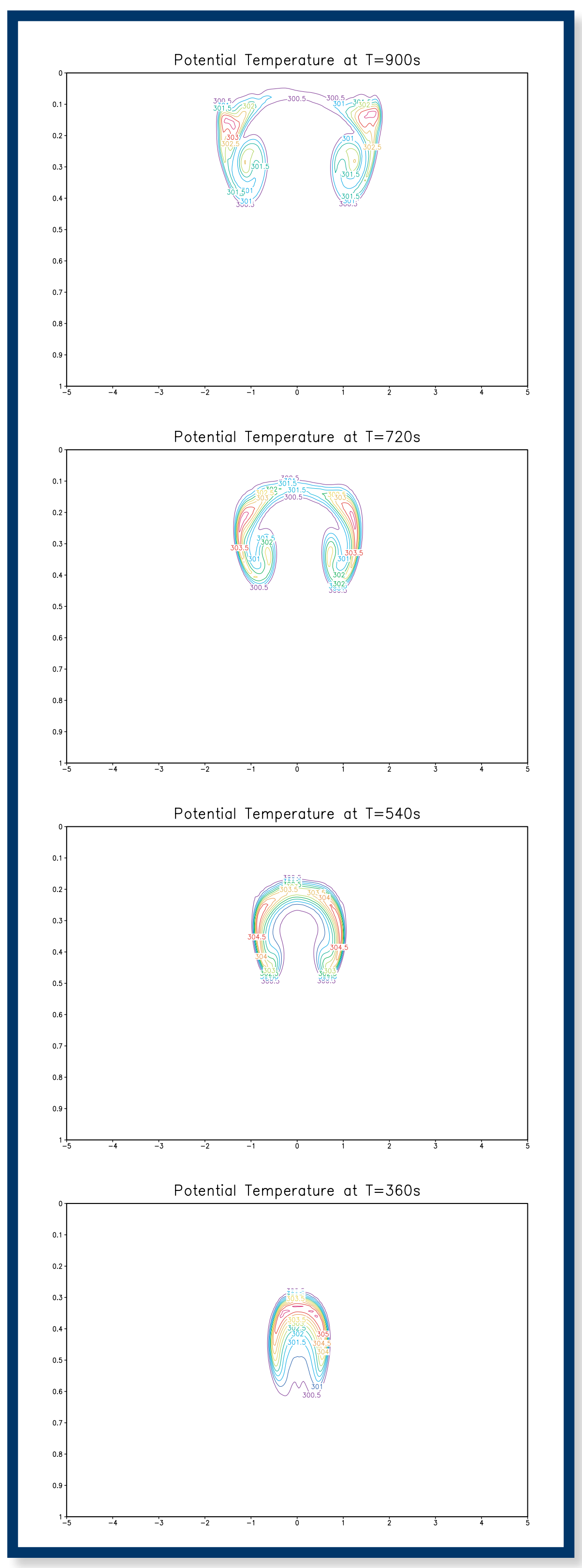

Figure 2: NSM warm bubble simulation

Atmospheric models that assume there is a balance of forces in the vertical direction in the atmosphere are called hydrostatic models, and have been used successfully to make operational forecasts since the 1950s at low resolutions. These models cannot explicitly simulate moist convection, but apply a procedure called *cumulus parameterisation* to statistically represent the effects of convection on the atmosphere. These parameterisation schemes are thought to be an important source of uncertainty in both numerical weather prediction and climate simulations.

The development of non-hydrostatic 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 co-ordinate model is currently being developed at the CSIR for purposes of simulating weather at spatial resolutions where the hydrostatic approximation is not valid (i.e. horisontal resolutions higher than about 10 km). Note that hydrostatic atmospheric models – applied at relatively low spatial resolutions where convection cannot be resolved – are likely to be applied for decades to come in the computationally expensive study field of climate simulation (and for numerical weather prediction over large regions). The cumulus parameterisation schemes, that statistically represent the effects of moist convection and convective rainfall on the larger environment, should therefore continue to be improved for use in hydrostatic models

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 sigma coordinate model used by Engelbrecht (2007) 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 of the model and p_{surf} is pressure at the surface of the model. Sigma is therefore 1 at the model surface and 0 at the top of the model atmosphere.

As an essential part of model development, theoretical experiments such as the simulation of warm and cold moist convective bubbles (thermals) are made to investigate the stability, accuracy and efficiency of the numerical integration scheme. A cold bubble is expected to induce a density current and to sink, forming a gust front at the surface (see **Figure 1** for NSM cold bubble simulation). A warm thermal is expected to rise for as long as it maintains its buoyancy (see **Figure 2** for NSM warm bubble simulation).

The CSIR 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:

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

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

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

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

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

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

Equations 1 to 6 include moisture terms and are to be solved within the new nonhydrostatic model. **Equation 1** is the horisontal 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.

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. This is of great importance in South Africa, where most of the rainfall occurring over the summer rainfall region is of convective origin. It is envisaged that the insights gained from simulating moist convection at ultra-high resolution with this model may additionally be used to improve the cumulus parameterisation schemes used in hydrostatic models – and in particular, the new coupled climate model under development at the CSIR. Improved convection schemes applied within hydrostatic atmospheric models may significantly reduce the uncertainty range associated with both numerical weather prediction and climate change projection – which will have positive implications for real-time operational decision-making and long-term policy making in South Africa.

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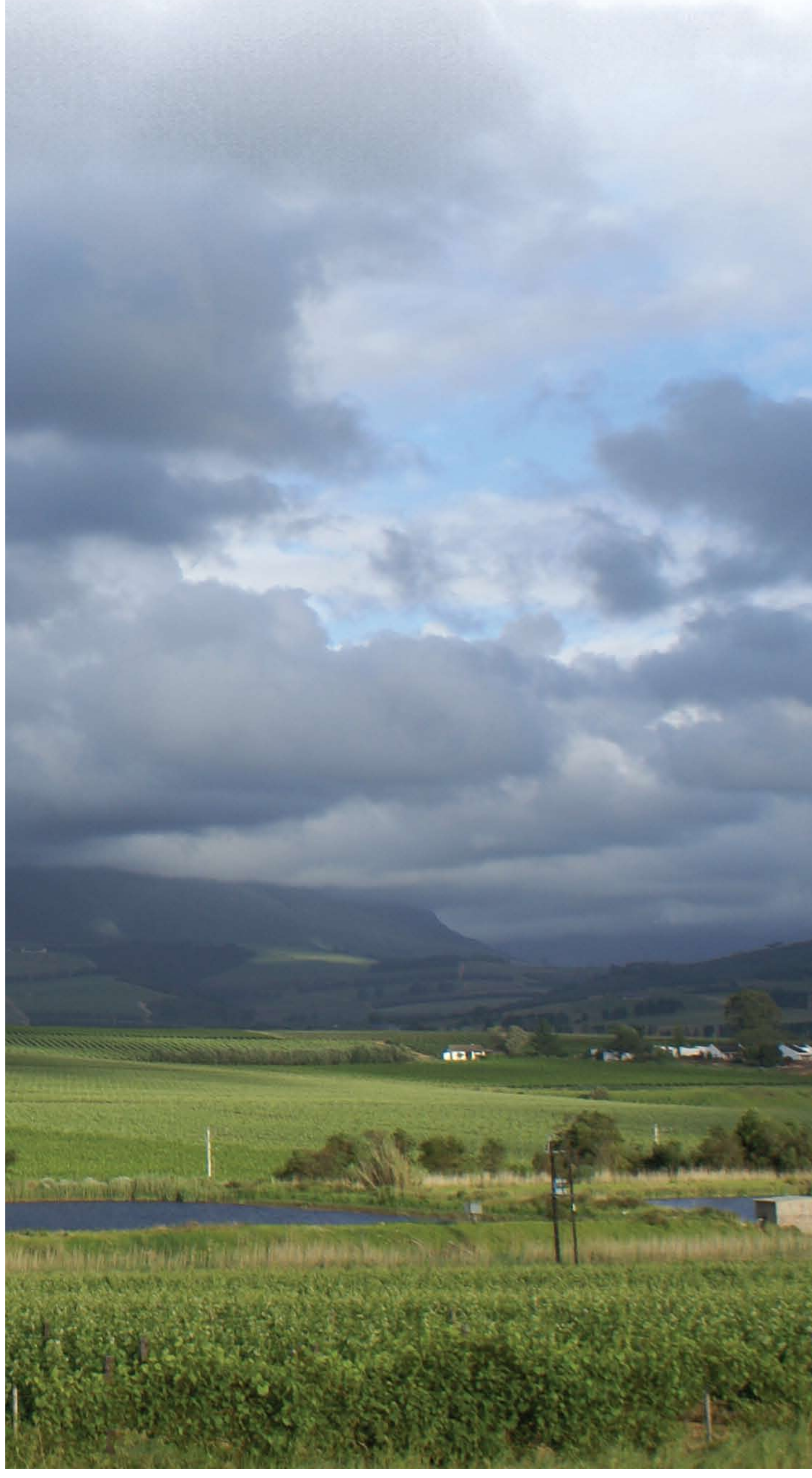
A new convection scheme for atmospheric models may significantly reduce the uncertainty range associated with numerical weather prediction and climate change projection – with positive implications for real-time operational decision-making and long-term policy making in South Africa.



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