Improving the Kain-Fritsch convection scheme for simulating a squall line

Sensitivity to convective time scale

Ridick Roland Takong
African Institute for Mathematical Sciences
takong@aims.ac.za — +27 83 613 6216

Abstract

In order to explore the possibility of improving the Kain–Fritsch parameterization scheme for simulating a squall line, we performed idealized simulations with the Weather Research and Forecasting model using different convective time scale values and horizontal resolutions. Then, we examined the ability of the model to reproduce the main features of a well formed squall line at each resolution and time scale value considered with and without a Cumulus Parameterization Scheme. We found that the convective component of the total precipitation can be improved by reducing the convective time scale in the Kain–Fristch scheme.

Introduction

Convection takes place at scales of less than 1km. Global Climate Models (GCM) and Regional Climate Models (RCM) which are used for future weather and climate predictions have coarse grid resolutions of the order $100km \sim 600km$ and $5km \sim 50km$ respectively. Consequently, these models can not explicitly resolve subgrid processes like convection. This results in inaccurate predictions. To represent the subgrid scale effects of convection on grid scale variables, [6, 5, 7] proposed the idea of ***Convection or Cumulus Parameterization***. The Kain-Fritsch (KF) scheme [4], is one of several Convection Parameterization Schemes (CPS) that were developed for convection parameterization in Weather and Climate models. Its efficacy was confirmed by its ability to reproduce heating profiles which were consistent with those diagnosed for the GATE [GARP(Global Atmospheric Research Program) Atlantic Tropical Experiment] [4]. Moreover, Cohen (2002) [1] obtained the best forecast which was closer to observation with the Kain-Fritsch Scheme among some convection schemes which were being compared. Furthermore, its cloud model realistically represents the mixing of environmental and cloud air parcels. However, several complains were received from operational weather forecasters and numerical modellers concerning the performance of the scheme. In fact, the downdraft algorithm in the KF was not well formulated. It was formulated in terms of the vertical wind shear and the cloud base height. It produced widespread light precipitation in marginally unstable environments which resulted in under-predicted rain [8]. Furthermore, it used a minimum entrainment rate which caused strong dilution resulting in no parameterized convection occuring [3]. Although Kain-Fritsch (2004) [3] attempted to solve some of these problems, the KF still underestimates or overestimates precipitation thereby requiring improvements.

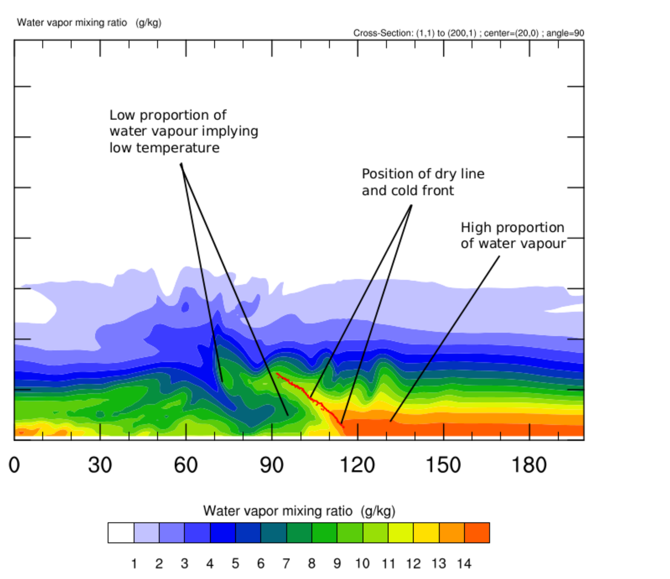

Figure 1: Cross-section of a squall line. The main features of a squall line are annotated. The dry line is the transition zone which separates dry and moist air. Cold front separates regions of low temperature (dry) and high temperature (moist).

Main Objectives

1. Explore the possibility of improving the KF CPS for weather and climate prediction.
2. Determine the convective time scale value t_c of the KF CPS for which a $5km$ resolution simulation of a squall line would resolve all the features of the squall line observed with a $0.25km$ simulation.

A squall is an atmospheric phenomenon which is characterised by winds of very high speeds. When it occurs along a fictious moving line it is called a squall line. The conspicuous features of a squall line are the gust front, the dry line, the cold front and the rainshaft (see Fig. 1 and Fig. 2). A squall line was chosen to evaluate the capacity of the scheme because it is a weather phenomenon whose development is strongly dependent on convection and it has conspicuous features which could be used to tell how well the scheme is performing. The convective time scale is the time interval during which convection takes place in a model.

Materials and Methods

- Idealized 48–hours simulations were performed with version 3.5 of the Weather Research and Forecasting (WRF) model.
- The squall test case "em_squall2d_x" which comes packaged with the WRF was employed with and without the Kain–Fritsch [3] Cumulus Parameterization Scheme (CPS) at different model grid resolutions.

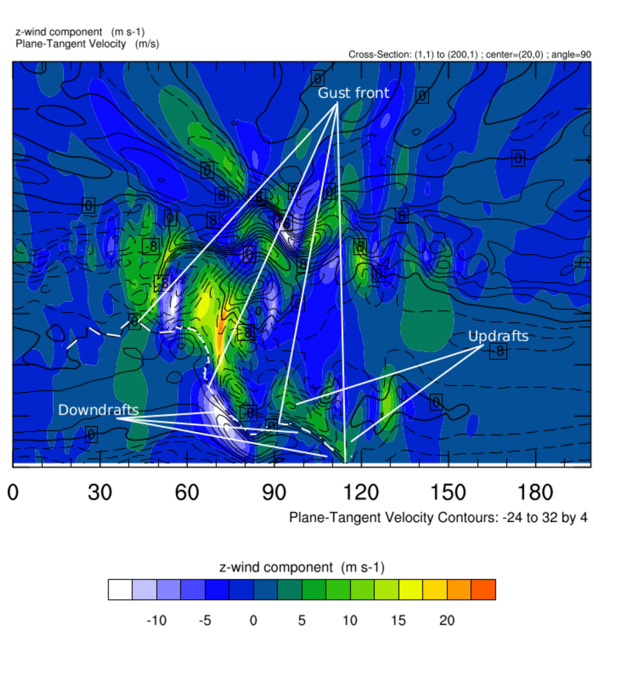

Figure 2: A gust front is the zone which separates cold downdrafts from warm updrafts. Negative velocity values correspond to downdrafts in contrast to positive values which represent updrafts.

- The purpose was to study the capacity of the scheme to simulate the main features of a squall line at different model horizontal resolution and convective time scale (t_c).
- t_c in the Kain–Fritsch (KF) scheme is defined as $t_c = \frac{\Delta X}{V_{clayer}}$. ΔX is the horizontal resolution of the model which is constant through out a given simulation. V_{clayer} is the mean cloud layer speed which is usually variable during a simulation as substantiated by the histogram on Fig. 3 but we made it constant.
- t_c was varied between $1800s$ and $5s$ but only the results of the simulations for t_c equals $30s$, $200s$, and $500s$ at $5km$ resolution are reported here. They are hereafter referred to as **KF30**, **KF200** and **KF500** respectively. Simulations were also performed at a cloud resolving resolution of $0.25km$ without a CPS. This was considered as the **reference case** to which the other simulations were compared. Another simulation was performed at $5km$ resolution with the default model t_c value and was known as the **5km with CPS** whereas another was performed at $5km$ without CPS and was referred to as the **5km No CPS**. The simulations were compared with the reference simulation by using the eyeball verification method and by computing the bias skill score. The choice of the 0.25km grid resolution as the reference simulation for comparing our simulations is corroborated by a study performed by Gilland et al.[2]. In fact, they found that, the WRF model can explicitly resolve convection at resolutions of about 4km. The NCAR Command Language was used for graphics and visualization.

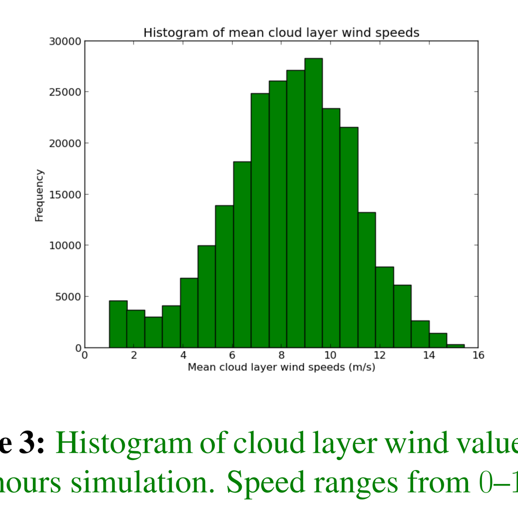

Figure 3: Histogram of cloud layer wind values during a 24–hours simulation. Speed ranges from 0–$15ms^{-1}$

Results

Analysing the temporal evolution of hourly precipitation in Fig. 4, it was found that, decreasing t_c improves the convective component of total precipitation simulated with KF CPS. In addition, KF30 with the shortest t_c value produces the largest amount of convective precipitation as illustrated in Fig. 4c and Fig. 4d. KF30 is followed by KF200. The KF500 case appears to be identical to the 5km case with NO CPS.

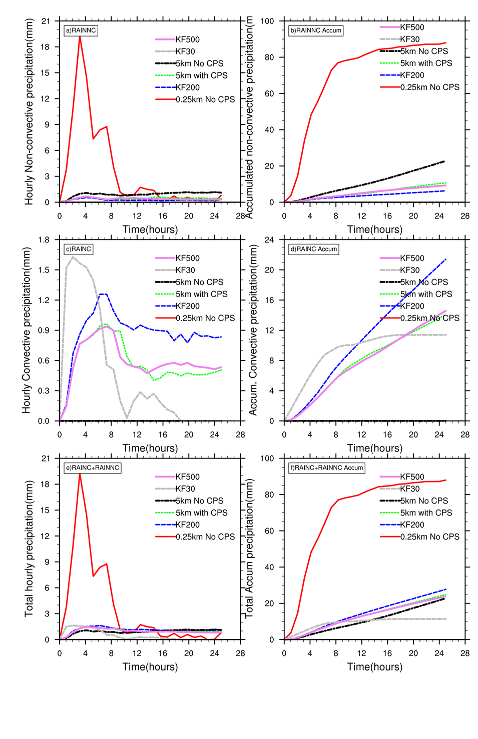

Figure 4: 24–hours simulation with and without CPS. Left panels illustrate the hourly precipitation whereas the right panels depict the accumulated precipitation. The top panels $a)$ Hourly non-convective precipitation, $b)$ Temporal evolution of accumulated non-convective precipitation, $c)$ Hourly convective precipitation, $d)$ Temporal evolution of accumulated convective precipitation, and the bottom panels $e)$ and $f)$, illustrate the total precipitation which is a sum of convective and non convective precipitation.

The hovmueller plots in Fig. 5 illustrate the propagation of the squall line. All the cases agree that the squall line is formed around 90°E and is characterised by intense precipitation. The reference case predicts that the precipitation spreads both to the West and to the East whereas all the other cases except the KF30 predict that it spreads only to the East.

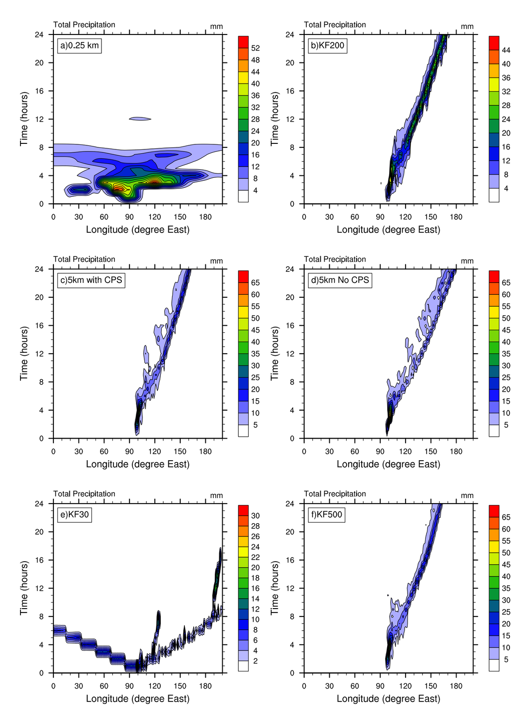

Figure 5: Hovmueller plots for the precipitation produced by the squall line. The vertical axis represents time in hours while the horizontal axis represents longitudes in degree east.

Fig. 5a shows that the reference case appears to travel faster than the other cases. Within the first 4hours it reaches 180 °E. The $5km$ case with CPS travels faster than the other cases with CPS except the KF30. The KF30 appears to have a beviour closer to the reference case as illustrated in Fig. 5e. This behaviour is deceptive because when we analyse the features of the squall line formed in Fig. 6e and Fig. 6f, we notice that non of the features of the squall line are formed by the KF30 case two hours after start of simulation and beyond. The features of the squall line become visible only after 4 hours for the KF200 case which is late compared to the rest of the cases which become conspicuous after 2hours.

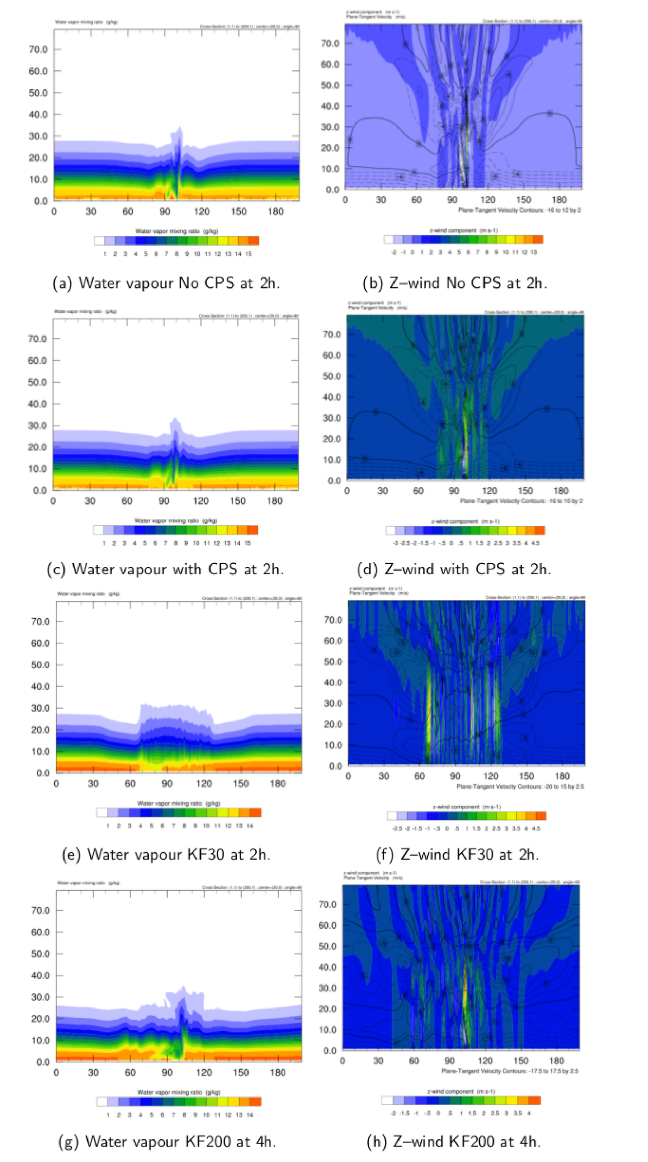

Figure 6: Gust fronts, dry line and cold front of simulated squall line 2–hours after start of simulation. Vertical axis represents the model levels in the Z–direction whereas the horizontal axis represent the longitudes counted in degree East. Negative velocity values correspond to downdrafts in contrast to positive values which represent updrafts.

Conclusions

- Beyond model resolutions of 0.25km, a CPS is needed to account for subgrid scale effects.
- Using a CPS improves the forecast.
- Reducing the convection time scale increases (improves) the sub-grid scale convective precipitation when employing the KF CPS scheme [3].
- There exist a threshold value below which the squall line features become indistinguishable. The value we found in this study is 200s.
- Employing a CPS makes the squall line appear to be propagating with a low speed.
- As model horizontal resolution becomes coarser, the squall line appears to move slowly.
- At coarser grid resolutions and small convective time scale value, the scheme underestimates downdraft and updraft speeds.

Forthcoming Research

We look forward to test the TIMEC value we obtained on a real case to see the performance of the scheme. Since the value we obtained did not significantly change the total precipitation though it significantly improved the convective component, we plan to determine which other set of parameters significantly influence the squall line forecast. Finally, for future climate models, the state of the problem must be drastically expanded from cumulus parameterization to Super–parameterization.

References

[1] Charles Cohen. A comparison of cumulus parameterizations in idealized sea-breeze simulations. *Monthly weather review*, 130(11), 2002.

[2] Erin Gilland and Clinton M. Rowe. A comparison of cumulus parameterization schemes in the wrf model. Department of Geosciences, Univ. of Nebraska, Lincoln, 2005.

[3] John S. Kain. The Kain-Fritsch Convective Parameterization : An update. *Journal of Applied Meteorology*, 43:170 –181, 2004.

[4] John S Kain and J Michael Fritsch. A one-dimensional entraining/detraining plume model and its application in convective parameterization. *Journal of the Atmospheric Sciences*, 47(23):2784–2802, 1990.

[5] Hsiano-Lan Kuo. On formation and intensification of tropical cyclones through latent heat release by cumulus convection. *Journal of the Atmospheric Sciences*, 22(1):40–63, 1965.

[6] Syukuro Manabe and Robert F Strickler. Thermal equilibrium of the atmosphere with a convective adjustment. *Journal of the Atmospheric Sciences*, 21(4):361–385, 1964.

[7] Katsuyuki Ooyama. A Theory on Parameterization of Cumulus Convection. *Journal of the Meteorological Society of Japan*, 49:744–756, 1971.

[8] Thomas T Warner and Hsiao-Ming Hsu. Nested-model simulation of moist convection: The impact of coarse-grid parameterized convection on fine-grid resolved convection. *Monthly weather review*, 128(7), 2000.

Acknowledgements

This poster is an excerpt of my master's project at AIMS South Africa which was supervised by Prof. Steyn DOUW (*University of British Columbia, Canada*) and Dr. Joseph Abiodun BABATUNDE (*University of Cape Town, South Africa*).