A stochastic parameterization of deep convection organization using cellular automata

Lisa Bengtsson

SMHI, Folkborgsvgen 1, 60176 Norrkping

1 Introduction

Stochastic representations of atmospheric processes are becoming more and more frequent in order to address model errors associated with parameterization schemes and sub-grid scale variability, e.g. Lin and Neelin (2002), Shutts (2005), Teixeira and Reynolds (2008), Plant and Craig (2008), Berner et al. (2008). A typical example of sub-grid variability arises from organized deep convection in the atmosphere, which in turn is inherently associated with small-scale motions. Such processes are not well represented by grid-box means in NWP models Lin and Neelin (2002), Palmer (2001).

In the context of ensemble prediction, stochastic perturbations in form of "multiplicative noise" of the physical tendencies have been applied in order to account for uncertainties arising from such sub-grid variability Buizza et al. (1999). Such a "stochastic physics" is both expected to improve the mean state as well as the spread around the mean in an EPS. However, Bengtsson et al. (2008) found that even though stochastic physics is included in the ECMWF EPS, the ensemble forecast was under-dispersive in comparison with the characteristic variability of the atmosphere. Thus, it is crucial for the skill of the EPS to have a model with a sufficient level of inherent variance. It is therefore desired to address uncertainties which arise from sub-grid variability, such as deep convection, both within the deterministic forecast model, and within its accompanying EPS. One way of doing so is to introduce stochastic elements to the deep convection parameterization of the deterministic NWP model.

Following an idea by Palmer (2001), Shutts (2005) implemented a stochastic physics scheme to the ECMWF EPS in which stochastic noise is generated using a cellular automaton (CA) in order to introduce "multiplicative noise" on the deep convective time and space scales. Berner et al. (2008) extended the use of a CA stochastic scheme to the seasonal time scales, and found that the scheme resulted in a reduction of systematic model errors. Bengtsson et al. (2011) studied in an idealized setting, whether a CA can be used in order to enhance sub-grid scale organization and form clusters representative of the convective scales. It was shown that compared to a more conventional parameterization the CA scheme can organize sub-grid information across model grid-boxes and propagate this information against the mean flow, mimicking organization by gravity waves initiated from deep convection. It has the option of advecting sub-grid scale information with the resolved flow, which is not implemented in a conventional parameterization. Furthermore, the scheme is inherently stochastic, which generates an ensemble spread in the large-scale.

In this study, instead of using a CA as a pattern generator for "multiplicative noise" a CA is used within the deep convection parameterization of a state-of-the-art NWP limited area model; ALARO. Here the CA acts on a higher resolution than that of the model grid, and is allowed to be active in regions of intense large scale moisture convergence and CAPE. The organization of precipitation of a squall-line is studied. The study will be extended to look at the inherent stochastisity of the scheme.

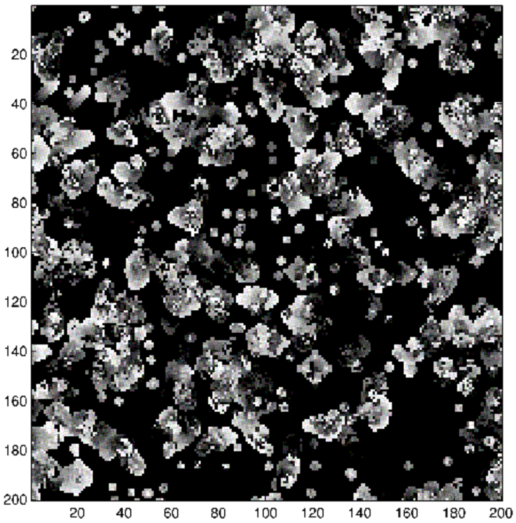


Figure 1: Example of a Cellular Automaton following the rules of Conway's game of life

2 Method

A cellular automata describes the evolution of discrete states on a grid according to a set of rules applied on the states of neighbouring cells at the previous time step. The given rule can generate self-organization of cells, and complex patterns emerge from the implementation of very simple rules. The rules can be deterministic (i.e, the automata is reversible), or probabilistic. The CA used in the present study acts on a resolution higher than that of the numerical weather prediction (NWP) model, and follows rules of the CA "Conway's game of life" (GOL). If active cells form on the finer CA grid, these cells can act to spread information across model grid-boxes, as a way of representing communication between grid-boxes, analogous to communication via gravity waves that propagate radially outward from a convective cell Huang (1988). Deterministic rules based on the GOL describes the evolution of a given initial condition, governing a self-organizing system Chopard and Droz (1998). With proper parameter selection these rules are able to generate continuous patterns which appear close to the spatial scales of organized deep convection, and can serve as a crude representation of convective organization. The CA yields a statistical representation of the sub-grid scale variability, with the possibility of organizing clusters larger than the truncation scales of the SW-model Bengtsson et al. (2011).

In the CA according to GOL each grid cell can take on the state of either 0 or 1 and the evolution is according to the following rules:

-If the current state of the CA cell is 1, and it has exactly two or three neighbouring cells with the state 1, it will remain at the state 1 at the next time step.
-If the current state of the BF cell is 1, but it has less than two neighbouring cells with the state 1, it will become 0 at the next time step.
-If the current BF cell state is 1 and is surrounded by more than three neighbours with state 1 it will become 0 at the next time step.
-If the current state is 0 and it is surrounded by exactly three neighbours with the CA cell state of 1, it will take on the value 1 at the next time step, otherwise, it will remain at 0.

These rules alone yield a stochastic representation of the sub-grid variability, as the CA is initialized randomly. An example of a CA following the rules of GOL can be seen in Figure 1. The CA yields self-organization on the sub-grid, and is continuous in time, thus making it an interesting candidate to describe deep convective organization.

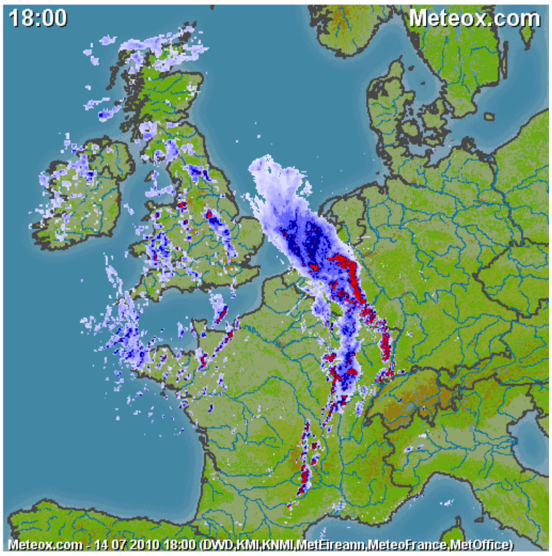


Figure 2: Radar image valid 16 UTC on 2010 07 14. Red colours indicate hourly precipitation exceeding 10 mm

The resolved model fields coupled to the CA scheme in step (2) above are convective available potential energy, CAPE, and large scale moisture convergence. When a weighted value between these parameters exceeds a threshold, sub-grid cells generated in step (1) are allowed to be active, and are assigned a lifetime. These active sub-grid cells are in turn coupled back to the NWP model through the closure assumption in the deep convection parameterization according to step (4).

The sub-grid convection scheme in ALARO Gerard et al. (2009), uses prognostic equations of relative updraught vertical velocity, updraught mesh-fraction σ_u in order to describe the updraught mass flux. The mesh-fraction goes to 1 as the horizontal resolution increases:

$$\partial\sigma_u\partial t\int\left(h_u-\overline{h}\right)dpg = L\int\sigma_u\omega_u^*\delta q_c g + L\int CVGQdpg + \frac{\sigma_{CA}-\sigma_u}{\tau} * (\int\left(h_u-\overline{h}\right)dpg) \qquad (1)$$

The left hand side of eq. 1 represents the storage of moist static energy, h, through the increase of the updraught fraction. The source to the updraught mesh fraction is moisture convergence, whereas the sink is condensation in the updraught air. σ_u is the updraught vertical velocity, q_c is the cloud condensation along the ascent, and $CVGQ$ stands for resolved moisture convergence. In the present study the third term on the right hand side in equation 1 describes organization using the CA field. As σ_u is integrated over all vertical levels it is a suitable prognostic variable to apply the CA on, since the CA is acting in only 2 dimensions.

3 Result

A couple cases of organized deep convection, squall-lines or meso-scale convective systems, at mid-latitudes have been investigated using the CA-scheme implemented into ALARO. Presented here is an organized squall-line over central Europe on July 14, 2010.

The radar image (Figure 2) shows the squall-line at 16 UTC. Red colours indicate one hour accumulated precipitation exceeding 10 mm.

Figure 3 shows the field of active sub-grid cells from the CA, averaged out onto the numerical model grid. The prescribed maximum lifetime was 30 lives (corresponding to 3600 s for a simulation using a

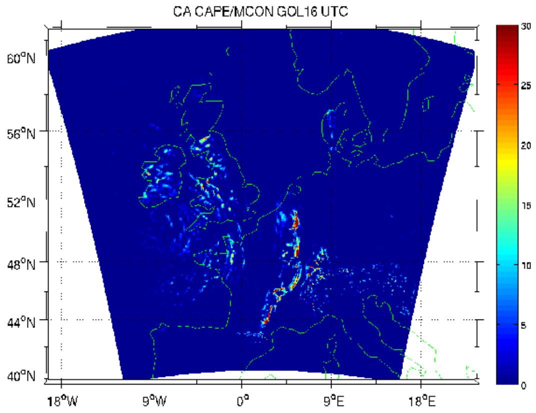


Figure 3: The field of active sub-grid cells from the CA, averaged out onto the model grid, valid at 16 UTC on 2010 07 14. The active sub-grid cells has a maximum lifetime of 30 lives.

numerical model time-step of 120 s). It can be seen that this field is only active in regions of large scale moisture convergence and CAPE.

Looking at the vertical integrated updraught mesh-fraction (eq. 1) comparing the reference ALARO cy36t1 (2011) with the CA implementation (Figures 3 and 3) it can be seen that σ_u appears more organized along the line of the observed squall line.

Furthermore, the 1 hour accumulated precipitation (Figures 3 and 3) shows that the precipitation is increased along the squall-line, red colours represent one hour accumulated precipitation exceeding 10 mm, and appears more organized. Note that the precipitation has not increased significantly elsewhere, only along the convergence zone of the squall-line.

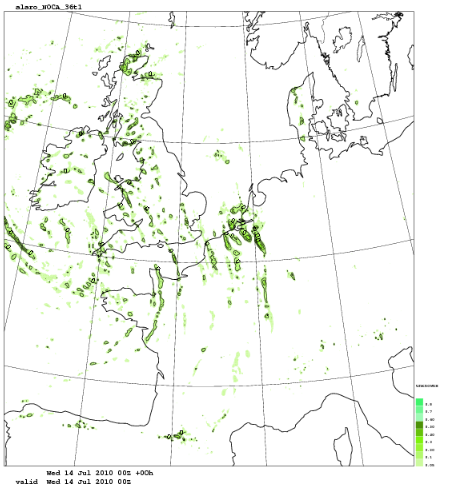
Finally Figure 6 shows the resolved, sub-grid and total precipitation as a function of time, here it can be seen that the total precipitation is increased as a result of increased sub-grid precipitation.

4 Conclusion, discussion and future outlook

A cellular automata (CA) has been coupled to the closure assumptions of the deep convection parameterization scheme in the ALARO model. The CA acts on a higher resolution than that of the NWP model, and is updated with information from the NWP model resolved scale moisture convergence and CAPE. As the CA acts on the sub-grid, organization due to the neighbourhood rules of the CA can take place across the NWP model grid-boxes. Early results of case studies of squall-lines and meso-scale convective systems at mid-latitudes indicate that the proposed scheme is successful in triggering convection in an organized fashion.

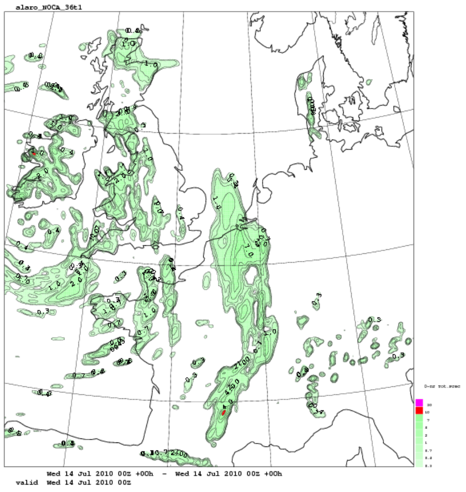
Stochastic elements to the CA sub-grid parameterization can enter in one of two ways; either from a random initial seeding of the CA, or by probabilistically updating the CA at the next time-step with a stochastic probability of the choice of the rules. In this study the former is chosen in order to ensure that the self-organizational properties of the CA following the deterministic rules of the game of life is maintained. The rules according to GOL can yield clusters on the scales of deep convection in the atmosphere, and is continuous in time. Probabilistic rules does not maintain a continuous self-organization, although the approach is intriguing as the rules of the CA can be chosen on a physical basis.

A future outlook of this work includes looking at the model spread generated by the parameterization



[a] [b]

Figure 4: Updraught mesh-fraction from reference ALARO cy36t1 run a, and from experiment using the CA implementation b, valid at 16 UTC on 2010 07 14



[a] [b]

Figure 5: One hour accumulated precipitation from reference ALARO cy36t1 run, a, and the CA experiment, b, valid at 16 UTC on 2010 07 14, red colours indicate hourly precipitation exceeding 10 mm

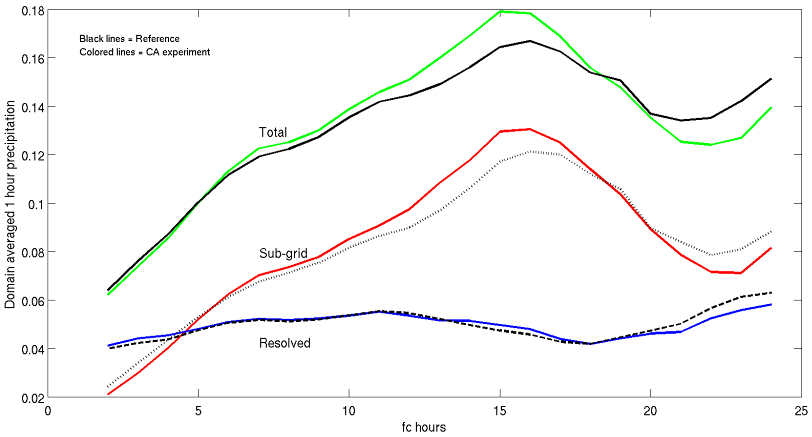


Figure 6: Time evolution of total, resolved and sub-grid precipitation from the reference experiment (black lines), and the CA experiment (green, blue and red lines respectively).

in order to investigate the stochastisity of the scheme. Future simulations of atmospheric phenomena in which convective organization play an important roll will be carried out, where MJO simulations is of particular interest.

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References

Bengtsson, L., L. Magnusson, and E. Klln (2008). Independent Estimations of the Asymptotic Variability in an Ensemble Forecast System. *Mon. Wea. Rev. 136*, 4105–4112.

Bengtsson-Sedlar, L., H. Krnich, E. Klln, and G. Svensson (2011). Large-scale dynamical response to sub-grid scale organization provided by cellular automata. *Journal of Atmospheric Science, accepted July 2011.*

Berner, J., F. Doblas-Reyes, T. Palmer, G. Shutts, and A. Weisheimer (2008). Impact of a quasi-stochastic cellular automaton backscatter scheme on the systematic error and seasonal prediction skill of a global climate model. *Phil. Trans. R. Soc. 366*, 2561–2579.

Buizza, R., M. Miller, and T. Palmer (1999). Stochastic representation of model uncertainties in the ECMWF Ensemble Prediction System. *Q. J. R. Met. Soc. 125*, 2887–2908.

Chopard, B. and M. Droz (1998). *Cellular Automata Modeling of Physical Systems*. Cambridge University Press.

Gerard, L., J.-M. Piriou, R. Brožková, J.-F. Geleyn, and D. Banciu (2009). Cloud and precipitation parameterization in a meso-gamma scale operational weather rediction model. *Mon. Wea. Rev. 137*, 3960–3977.

Huang, X.-Y. (1988). The organization of moist convection by internal gravity waves. *Tellus A 42*, 270–285.

Lin, J. and J. Neelin (2002). Considerations for stochastic convective parameterization. *J.Atmos.Sci 59*, 959–975.

Palmer, T. N. (2001). A non-linear dynamical perspective on model error: a proposal for non-local stochastic-dynamic parameterization in weather and climate prediction. *Q.J.R. Meteor. Soc. 127*, 279–304.

Plant, R. and G. Craig (2008). A stochastic parameterization for deep convection based on equilibrium statistics. *J. Atmos. Sci. 65*, 87–105.

Shutts, G. (2005). A kinetic energy backscatter algorithm for use in ensemble prediction systems. *Q. J. R. Met. Soc. 131*, 3079–3102.

Teixeira, J. and C. Reynolds (2008). The stochastic nature of physical parameterizations in ensemble prediction: a stochastic convection approach system. *Mon.Wea.Rev 136*, 483–496.