TECHNICAL MEMORANDUM

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A stochastic parameterization for deep convection using cellular automata

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Abstract

A cellular automaton (CA) is introduced to the deep convection parameterization of two NWP models; the global ECMWF IFS, and the high resolution limited area model ALARO. The self-organizational characteristics of the CA allows for lateral communication between adjacent NWP model grid-boxes, and adds additional memory to the deep convection scheme(s). The CA acts in two dimensions, with finer grid-spacing than that of the NWP model. It is randomly seeded in regions where CAPE, CIN or already active convection exceeds a threshold value. Both deterministic and probabilistic rules are explored to evolve the CA in time, and the resulting CA field can be advected with the mid-tropospheric wind on the sub-grid level. Case-studies indicate that the scheme has potential to organize cells along convective squall-lines, and enhance advective effects. An ensemble of forecasts using the present CA scheme demonstrated an ensemble spread in the resolved wind-field, in regions where deep convection is large. Such a spread represents the uncertainty due to sub-grid variability of deep convection, and could be an interesting addition to an ensemble prediction system.

1 Introduction

Due to the limited resolution of numerical weather prediction (NWP) models, deep convection is parameterized, and represented as gridbox means of an ensemble of subgrid updraughts. However, since one NWP model gridbox can contain a wide range of space and time-scales of convective updraughts, there is a sub-grid variability around the mean that gives rise to uncertainties.

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 such uncertainties arising from sub-grid variability (Buizza et al. 1999; Teixeira and Reynolds 2008; Lin and Neelin 2002). Such “stochastic physics” are both expected to improve the mean state as well as the spread around the mean in an Ensemble Prediction System, EPS. However, Bengtsson et al. (2008) found that even though stochastic parameterizations are 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. Examples of studies where such an avenue is explored include , where stochastic deep-convective parameterizations based on random perturbations to Convective Available Potential Energy (CAPE) is used together with “multiplicative noise” on the vertical heating profile. Also, Bright and Mullen (2002) introduced stochastic elements to the trigger function of the Kain and Fritsch (1993) scheme. Other studies include Plant and Craig (2008) , where random values are taken from a PDF based on the variability around an equilibrium state, and used to alter the cloud base mass-flux. Also, Maida and Khouider (2002) described a stochastic scheme for evaluating the fractional area of a grid box that supports deep convection using Convective Inhibition (CIN). Furthermore, Khouider et al. (2010) and Frenkel et al. (2011) used a stochastic parameterization based on several different cloud types using a Markov chain lattice model.

Following an idea by Palmer (2001) , Shutts (2005) implemented a stochastic physics scheme to the ECMWF EPS in which a stochastic term, added to the vorticity field, is generated using a cellular automaton (CA) as global pattern generator. Here the CA was used to generate patterns on the deep convective time and space scales in order to account for unresolved variability. 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. Furthermore, Bengtsson et al. (2011) studied, in an idealized setting, the interaction between near sub-grid scale motions, represented by a CA, and large-scale equatorial waves. It was shown that compared to a more conventional parameterization the CA scheme can organize sub-grid scale information across model grid-boxes and propagate this information against the mean flow, mimicking organization by gravity waves initiated from deep convection. It was demonstrated that for a single Kelvin mode, the CA used gave rise to an interaction between the simulated sub-grid scales and the large-scale flow, known from convectively coupled equatorial waves (Straub and Kiladis, 2002) . Thus, several studies have demonstrated success using CA to account for unresolved variability, and mimicking horizontal advective effects.

In this study, instead of using a CA as a global pattern-generator for stochastic parameterizations in an EPS, a CA is used within the convective closure assumptions of the deep convection parameterization of two state-of-the-art NWP models; the global ECMWF IFS, and the limited area model ALARO. The former utilizes a diagnostic deep convection parameterization (Bechtold et al. 2008), whereas in the latter deep convection is represented by prognostic equations for the convective updraught and the updraught mesh-fraction (Gerrard et al. 2009).

The impact of the proposed CA scheme can be viewed from a deterministic point of view, since increased lateral communication and memory adds an advective effect and helps organizing convective clusters. Mapes and Neale (2001) define convective organization as “nonrandomness in meteorological fields in convecting regions”, which can be seen as a missing functionality in conventional deep convective parameterizations (based on a steady-state plume model). A representation of convective organization using an additional prognostic two-dimensional field, that utilizes rain evaporation as a source and memory has been explored in Piriou et al. (2007) and Mapes and Neale 92011). The importance of convective memory has been further explored in Pana nd Randall (1998) , and Davies et al. (2009). A similar approach, to use a two-dimensional field in order to represent convective organization, is used in the present study, where the CA is acting on a higher resolution than the NWP model, and possess self-organizational properties.

Furthermore, the stochastic nature of the scheme also yields an opportunity to explore the impact in a probabilistic sense, by running an ensemble of forecasts, investigating the spread of large-scale variables. This is of particular interest as we go towards higher resolution, where forecasts become more detailed at scales with low predictability.

The Cellular Automata used in this study are discussed in the following section, with the coupling to the ALARO and ECMWF models described in sections 3, 4 respectively. The results are shown in section 5, and concluding remarks in 6.

2 The Cellular Automata

The impact of using CA within the deep convection parameterization is investigated in two numerical weather models, the global ECMWF model which uses a diagnostic scheme in order to represent deep convection, and the high resolution limited area model ALARO, where deep convection is prognostic. The CA used in both models, and the coupling to the two deep convection parameterizations is described below.

A cellular automaton 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, or probabilistic.

The CA used in the present study acts on a resolution higher than that of the numerical weather prediction

(NWP) model (4x4 times the model grid), and both deterministic rules of the CA following the automata "Conway's Game Of Life" (GOL) (i.e Chopard and Droz, 1998), and a probabilistic extension to such rules are explored. Advantages and disadvantages with both CAs are discussed below. From here on, we separate between *cells*, when speaking of sub-grid cells on the CA-grid, and *grid-boxes* when referring to the NWP-model grid. 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) . When appropriate, we also explore the option of advecting active sub-grid cells on the CA grid, allowing sub-grid information to propagate between sub-grid cells, something a conventional parametrisation scheme does not commonly do.

The deterministic rules are based on the CA ruleset described by Shutts (2004B) , which has been previously used for generating stochastic patterns in the ECMWF model (Shutts 2004A,B; Berner et al. 2005) . It is an extension to the CA family known as 'Generations', which in turn is based on the 'Game of Life' but adds cell history to the ruleset (Shutts 2004A) . The rules describe 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 forecast 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 CA 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 CA 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.

An example of a CA following the rules of GOL, with cell history, can be seen in Figure 1. An advantage with this CA is that, if initialized with a large enough sample, the rules according to GOL yield a CA which is continuous in time, i.e. the CA never dies. Thus, independently of seeding with new cells based on the information from the numerical weather model, the CA yields a continuous self-organization on the sub-grid, thus making it an interesting candidate to describe deep convective organization. The stochastisity of the CA using deterministic rules comes from the random initial condition, and random seeding each time-step of new cells to the CA. The deterministic CA described above is explored within the deep convection parameterization of the ALARO model.

Inspired by probabilistic CAs used in other fields, e.g. forest fire simulations Sullivan and Knight (2008), the CA described above has been extended to be probabilistic, and the resulting CA is explored within the ECMWF model. Instead of discrete rules based on the number of neighbours with the state 1, the birth and survival of cells is based on probabilities given by the number of neighbours with the state 1. The above ruleset can be reproduced by the probabilistic CA by specifying probabilities of 100 % that 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. Similarly, probabilities of 100 % are specified if the current state is 0 and it is surrounded by exactly three neighbours with the CA cell state of 1, it will take

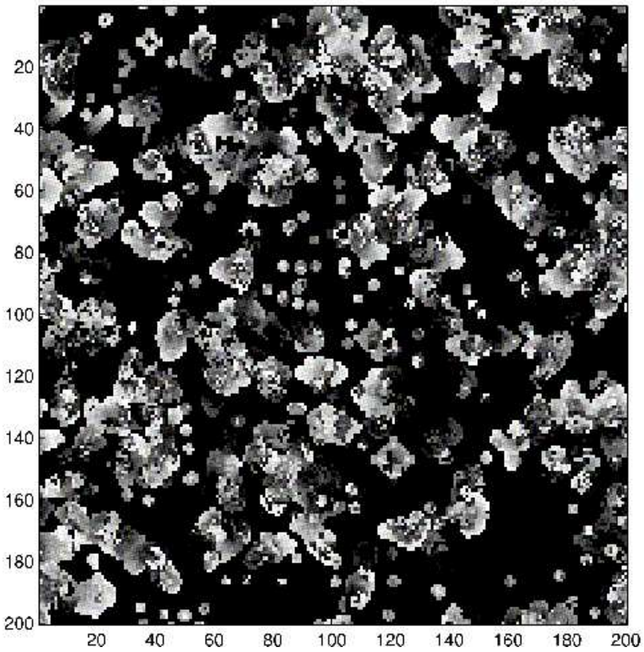

Figure 1: Example of a Cellular Automaton following the rules of Conway's game of life

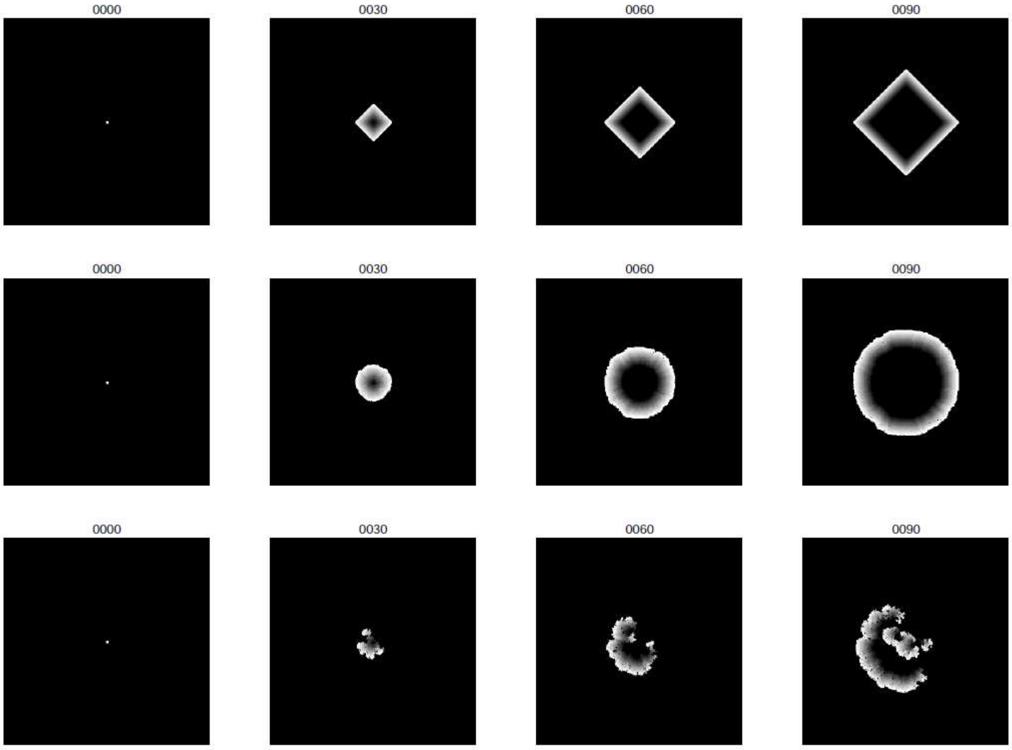

Figure 2: CA patterns at steps 0, 30, 60 and 90. Starting from a single 4x4 block of living cells. Top row for discrete CA, middle row for probabilistic CA with fixed probabilities, bottom row for probabilistic CA with wind dependent probabilities.

on the value 1 at the next time step, otherwise the probabilities are set to zero.

One advantage with probabilistic rules compared with its discrete counterpart is shown in Figure 2. The CAs are starting from a single block of 4x4 initial cells. The probabilistic CA, middle row, shows a more realistic looking evolution in form of a circle, while the discrete CA, top row, show an artificial looking diamond shape. When coupling the CA to deep convection, with the intention that the CA should couple neighbouring NWP grid-cells, it seems beneficial to have a homogeneous propagation in space.

Furthermore, even though the space and time scales achieved by the deterministic CA can arguably be linked to deep convection Bengtsson et al. (2011) , the rules used to evolve the CA based on GOL lack physical relevance. When using probabilistic rules, the probabilities can be adjusted according to physical model fields. It was tested to couple the CA to the model wind (mean of 500 and 850 hPa winds) to favour downwind propagation. To achieve that, the neighbours are distinguished between those lying upwind and downwind of the considered cell. The evolution of the wind dependent CA is shown at the bottom row of Fig. 2. However, the impact of this coupling on the final results was much smaller than from CA advection and hence the coupling to the wind is not explored further in this study.

Another advantage with the probabilistic rules can be found when applying the CA on global model simulations, using the reduced Gaussian grid in the ECMWF IFS. On this grid the number of grid points is reduced towards the poles, that means that CA cells on neighbouring latitudes with different numbers of grid-points do not have a constant number of neighbours. This introduces artifacts in the CA pattern when using deterministic rules, while it does not effect the pattern of the probabilistic CA.

The following steps are taken in order to couple the CA to the NWP models: (1) The CA is initialized randomly, and is seeded with new cells every time-step, in cells where the NWP grid box exceeds a threshold value of convective activity based on either CAPE, CIN, or already active convection. (2) The CA is evolved in time according to deterministic or probabilistic rules, and cells are assigned a prescribed lifetime, L_{pre}. The actual lifetime is denoted L. (3) In case of advection, the CA pattern is advected with the tropospheric wind using a quasi-Lagrangian scheme at the sub-grid level. For every cell a departure cell is found using the departure point calculated in the model's semi-Lagrangian advection scheme for the particular grid-box the cell belongs to. The departure value is considered to be the value of the cell without any interpolation. The arrival cell value is then set to the departure value. (4) Finally, the active sub-grid cells are averaged out onto the model grid and coupled to the deep convection parametrization scheme of the NWP model, the coupling is explained in detail below.

3 Prognostic deep convection in ALARO

In a convective parameterization, the closure regulates the amount of convection by the grid-scale variables. Examples of deep convective closures include quasi-equilibrium closures, closures based on CAPE or closures based on moisture convergence. When utilizing the CA scheme in the high resolution (5.5 km horizontal resolution) NWP model ALARO (Bénard et al. 2010; Váňa et al. 2008; Gerrard et al. 2009), the resolved model fields coupled to the CA scheme in step (1) above is convective available potential energy, CAPE. Since CAPE is not part of the convective closure in the deep convection scheme of ALARO, it also provides an independent source of information on potential convective activity, in addition to the large-scale moisture convergence. When CAPE exceeds a threshold value, sub-grid cells are seeded and assigned a lifetime, L_{pre}. These active sub-grid cells are in turn coupled back to the NWP model through the closure assumption in the deep convection parameterization.

The sub-grid convection scheme in ALARO (Gerard et al. 2009) uses prognostic closure equations of relative updraught vertical velocity, ω_u^*, and updraught mesh-fraction σ_u in order to describe the updraught mass flux, M_u:

$$M_u = -\sigma_u \frac{\omega_u^*}{g} \tag{1}$$

where $\omega_u^* = \omega_u - \omega_e$, the updraught vertical velocity relative to its environment. $\omega = \frac{dp}{dt}$, and the updraught-environment velocity $\omega_e = \omega - \sigma_u \omega_u$

The updraught mesh-fraction is defined by:

$$\frac{\partial \sigma_u}{\partial t} \int (h_u - \overline{h}) \frac{dp}{g} = L \int \sigma_u \omega_u^* \frac{\delta q_c}{g} + L \int CVGQ \frac{dp}{g} + \frac{\sigma_{CA} - \sigma_u}{\tau} (\int (h_u - \overline{h}) \frac{dp}{g}) \tag{2}$$

The left hand side of eq. 2 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. 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 2 describes organization using the CA fields, where τ is the relaxation time-scale. Here, σ_{CA} is a fraction between 0 and 1 given by L/L_{pre}. Since σ_u is a scaling parameter for the updraught mass-flux, it is a convenient approximation to consider it a horizontal extension of the vertical updraught (Gerard et al. 2009).

Because σ_u is a prognostic variable which is advected with the windfield, the CA is in this formulation not advected prior to updating σ_u. Nevertheless, since the CA is acting on a higher resolution than that of the NWP model, information is spreading across adjecent grid-boxes due to the self-organization of the deterministic CA.

The impact on σ_u by the CA-term in eq. 2 depends on the relaxation time-scale τ, the threshold criterion for CAPE, the prescribed lifetime, L_{pre} and the neighbourhood rules of the CA. τ is a tuning parameter of the implementation, and the choice of τ depends on the numerical procedure that is used to solve eq. 2. In the present study, eq. 2 is solved explicitly, and $\tau = 1000s$. $L_{pre} = 30$, and the threshold criterion for seeding of new CA cells is $CAPE > 100J/kg$. A prescribed lifetime, L_{pre} of 30 yields a time-scale of 3600s when using a model time-step of 120s.

4 Diagnostic deep convection in the ECMWF IFS

The global ECMWF Integrated Forecasting System (IFS) uses a diagnostic bulk mass-flux scheme. The deep convective activity, or equivalently the cloud base mass-flux, is controlled by a CAPE closure with variable adjustment time scale (Bechtold et al. 2008). It has been shown in that study that the current deep convection scheme in the ECMWF IFS is able to realistically simulate tropical and mid-latitude convective activity and related large-scale dynamical variability. However, drawbacks of a diagnostic convection scheme, which become particularly relevant at higher horizontal resolution, are the lack of communication with neighbouring grid columns and the lack of advective effects.

In order to mimic these effects the cloud base mass flux is modulated by the CA. Three different criteria for seeding with new sub-grid cells have been explored; seeding is allowed in regions where $CAPE > 1J/kg$, seeding is allowed in regions where the convective inhibition $CIN < 400J/kg$, or seeding is allowed in regions with convective precipitation. Only the latter criteria links the CA seeding directly to the outcome of the convection parametrization. In this configuration the CA includes a quasi semi-Lagrangian advection of the cells, with the mid-tropospheric wind, and the prescribed lifetime, $L_{pre} = 10$ (the time-step of the current ECMWF IFS is 600 s). The neighbourhood rules utilised are probabilistic.

Finally, the cloud base mass flux is modulated by the CA through a factor α as

$$M_{\mathrm{u}} = \alpha M_{\mathrm{u}} \qquad \alpha = \beta \frac{L}{L_{pre}} \tag{3}$$

where the factor $\beta = 2.7$ has been chosen such that the median of the global distribution of α is close to one. Furthermore, α has been limited to values of $0.3 \leq \alpha \leq 1.7$ in order to allow only moderate mass flux perturbations and keep the model convection close to its deterministic balance.

5 Results

Firstly, we investigate the potential of the proposed CA scheme to yield enhanced convective organization and advective effects, due to the lateral communication between adjacent model grid-boxes and additional memory. The first two cases are explored using the ALARO model with prognostic convection, where the organization along summertime squall-lines are studied with the CA scheme implemented as described above. The third case studied uses the ECMWF IFS with its proposed CA scheme, where the inland penetration of coastal convective winter showers is investigated.

Secondly we investigate the stochastisity of the scheme, and its impact on the spread of large-scale variables around an ensemble mean. Both deterministic and probabilistic rules in the CA scheme have a stochastic component that comes from randomly seeded cells at each time-step. In case of rules based on probabilities that have been adjusted according to the model wind field, additional impact on the ensemble spread could be expected, since the large-scale wind field is modified by the CA implementation in the deep convection scheme.

5.1 Mid-lattidue convective organization, studied with the ALARO model

The first case is a squall-line over France. In this case an upper air trough is located west of the British Islands bringing warm and moist air in a south-westerly flow over France. Figure 3a shows the observed 1 hour accumulated precipitation by the European OPERA radar product. The radar uses a horizontal resolution of 0.25 degrees. It can be seen that the convection is organized within the squall-line covering most of France at 15 UTC.

The 1 hour accumulated precipitation field at 15 UTC from the reference ALARO (cy36h1.1, 2011) is shown in Figure 3b. The model underestimates the intense precipitation cells that are organized along the squall-line. In contrast, as shown in Figure 3c, with the CA implementation the precipitation intensity and the convective organization is in better agreement with the radar observation. The corresponding CA pattern (number of lives averaged onto the model grid) is illustrated in Figure 3d. The leading edge of the squall-line shows the largest values of the CA life-time, with lower life-time values trailing behind as the squall-line is propagating eastward. This illustrates that there is a memory component of the scheme, which is important for convective organization. It can also be seen that in some places the CA cells propagate against the mean flow, as a consequence of the neighbourhood rules of the CA. This is a unique feature of the CA scheme, and such propagation is not seen in conventional deep convection parameterizations.

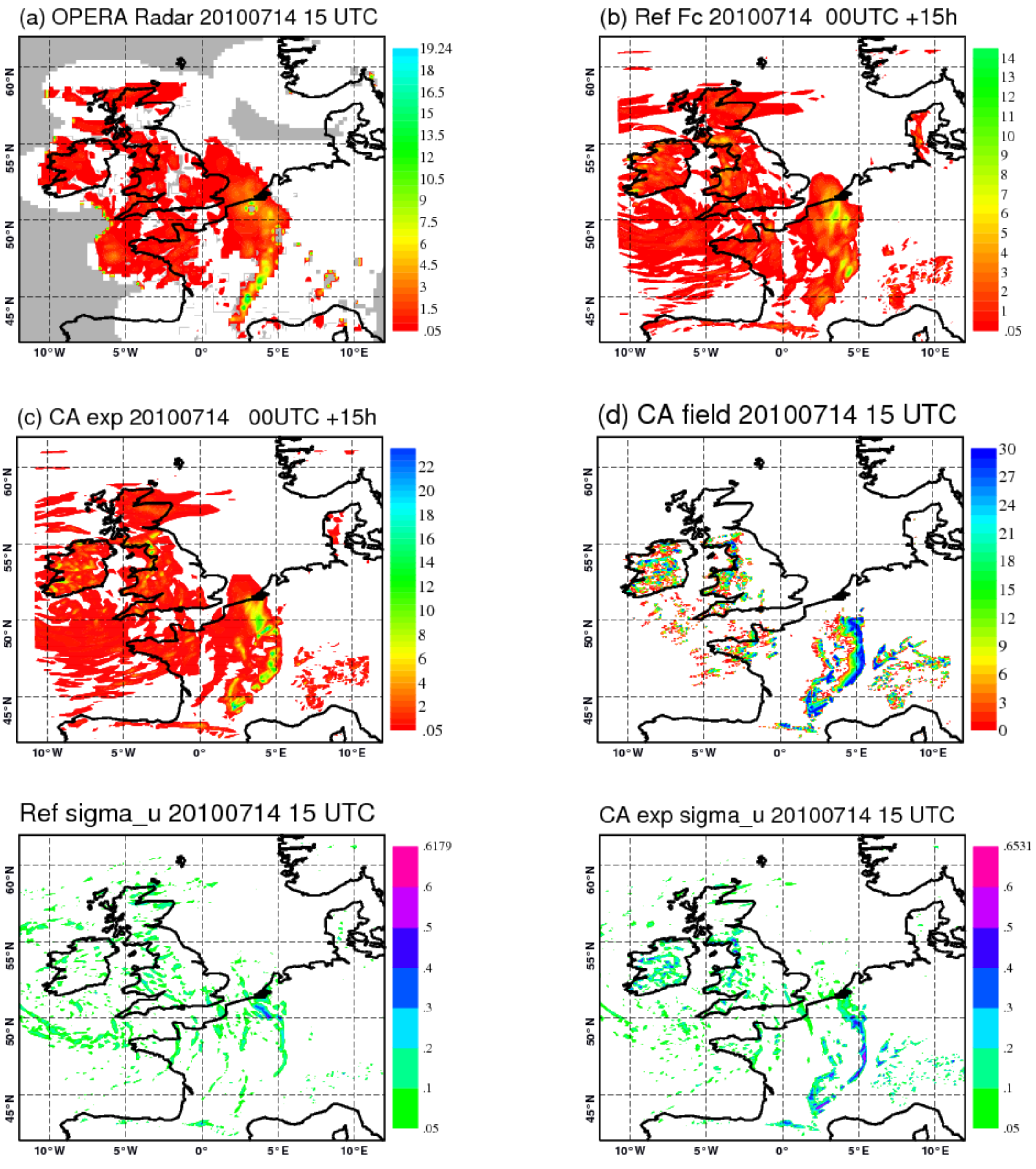

Figure 3: 1 hour accumulated precipitation (mm) on 14 August 2010, 15 UTC as observed by the OPERA radar network at 0.25 degree resolution (a), the ALARO reference 1 hour accumulated forecast at 5.5 km horizontal resolution (b), 1 hour accumulated precipitation of CA experiment at 5.5 km horizontal resolution (c), CA (number of lives) with CAPE seeding (d), and vertically averaged updraught mesh-fraction, σ_u, raging from 0-1 for the reference (e) and the CA experiment (f).

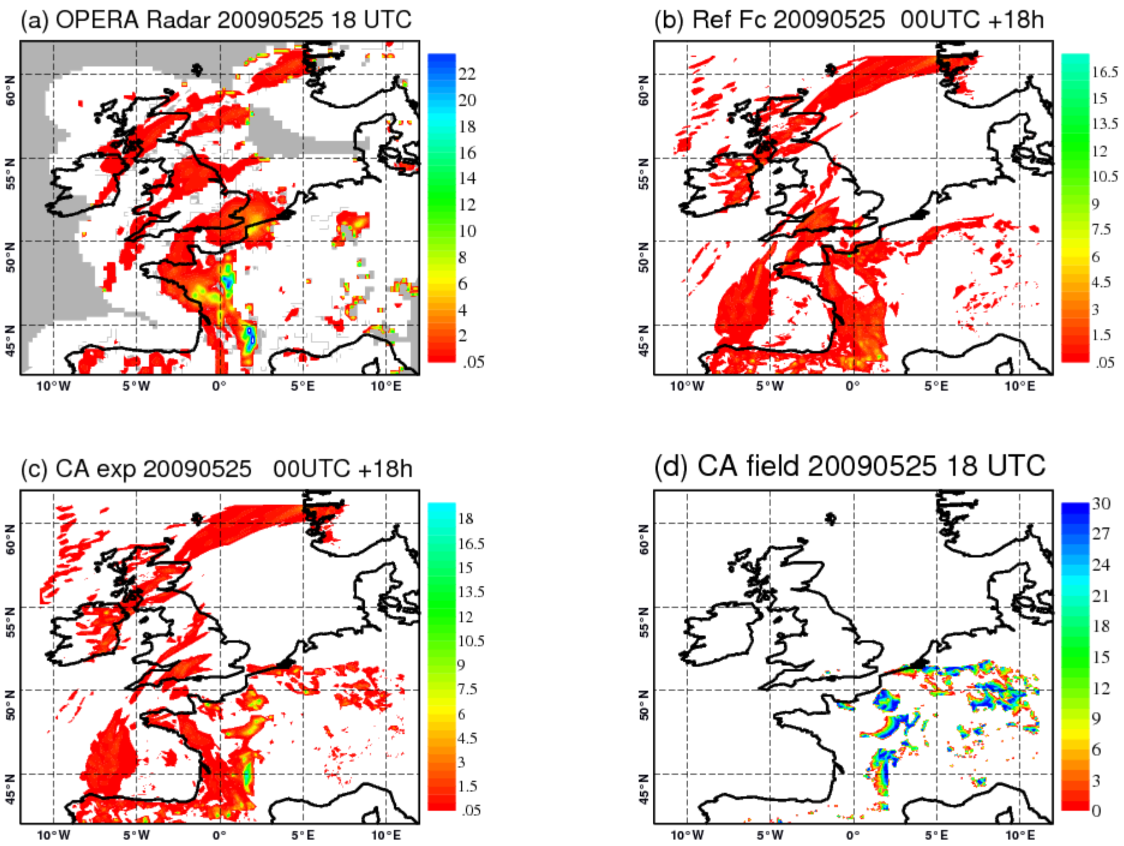

Figure 4: 1 hour accumulated precipitation (mm) on 25 May 2009, 18 UTC as observed by the OPERA radar network at 0.25 degree resolution (a), the ALARO reference 1 hour accumulated forecast at 5.5 km horizontal resolution (b), 1 hour accumulated precipitation of CA experiment at 5.5 km horizontal resolution (c), and CA (number of lives) with CAPE seeding (d).

The corresponding vertically averaged updraught mesh-fraction σ_u (eq. 2) is shown in Figure 3e-f, comparing the reference ALARO with the experiment using the proposed CA-scheme. The mesh-fraction is clearly enhanced in the region of the squall-line as a consequence of the new CA implementation.

On the 25th and 26th of May, 2009, unusually intense thunderstorms occurred over parts of France, Belgium and the Netherlands, were hailstones up to 10 cm were reported in Belgium on the 26th. In this case a strong upper air trough was located just west of France moving eastward, advecting cold air to a region which was dominated by a upper air ridge. At 850 hPa a plume of very warm air from the Mediterranean Sea penetrated main-land Europe towards Germany, causing instability.

Figure 4a shows the observed 1 hour accumulated precipitation by the European OPERA radar product at 18 UTC on the 25th of May, 2009. At this time convection had started to organize with intense precipitation amounts in a line covering central France. Figure 4b and c show the 1 hour accumulated precipitation at 18 UTC from the reference ALARO (cy36h1.1, 2011), and the model experiment using the CA scheme respectively. The reference model run captures the main precipitation line over France, but fails to capture the intense convective cells along the leading edge of the band. With the CA organized intense convective systems are generated in better agreement with the radar observations.

Figure 4d shows the number of lives from the CA scheme on the model grid. It can be seen that cells are seeded in regions of high values of CAPE, and that the pattern closely correlates with the modified precipitation field in Figure 4c. The region (or number of grid-boxes) in which the CA is active depends on the threshold value for CAPE, the neighbourhood rules, and the prescribed lifetime L_{pre}. The impact on σ_u by the CA-term in eq. 2 depends on the relaxation time-scale τ.

Figures 3c and 4c show that based on the current threshold criteria chosen for seeding of new cells $(CAPE > 100J/kg)$, there is now too much convective activity over Ireland and the west coast of England on the case of August 14th, 2010, and too much scattered convection over Germany on the case of May 25th, 2009. In future developments of the scheme, it could be interesting to explore the use of a dynamic threshold set as a percentage of the maximum amount of CAPE in the domain, for each time-step.

5.2 Winter showers and diagnostic convection using ECMWF IFS

The formation and inland penetration of coastal convective showers is a complex problem. Some of the physical processes involved are described e.g. in Bennett et al. (2006). Representing these processes with a diagnostic convection scheme is challenging since the convection itself can not propagate. It is only the temperature, moisture and wind anomalies that are associated with the large-scale (convective) forcing or are induced by the convection, that can propagate using a diagnostic convection scheme.

A typical example of winter showers is shown in Figure 5a. It occurred on 17 December 2010, producing 24 hour snowfall accumulations between 0 and 20 cm as observed by the European OPERA radar product. Snowfall accumulations in excess of 10 cm are recorded along the Irish and Scottish Coast, Wales, the Brittany region in France, and parts of Netherlands leading to the closure of the main Schiphol airport. The operational forecast for that day (Figure 5b) reasonably reproduced the overall precipitation pattern (the precipitation was nearly exclusively of the convective type), but underestimated the inland penetration of the snow showers and instead produced too much precipitation just off the coastlines, a well known problem using a parametrized representation of convection. However, it can be shown that it is possible to reduce these biases to a large extent by reducing the convective activity near the coast, i.e by modulating the the cloud base convective mass flux. Less convective stabilisation allows the moist and convectively unstable air masses to be transported further inland.

As a flexible and dynamical method for modulating the convective activity via eq. (3) we employ the CA. In Figure 5c the results are displayed as the difference between the operational forecast and the experiment using the CA when a CAPE seeding is utilized; the corresponding CA pattern (number of lives) is illustrated in Figure 5d. Also, Figure 5c shows the 850-500 hPa mean wind that is used to advect the CA pattern. The CA pattern seems to reasonably follow the observed precipitation pattern, and the model now produces increased precipitation in particular over Wales, but also for the near coastal regions of Ireland, the Netherlands and Britanny, with a corresponding reduction in precipitation over sea. In Figure 5e the results when using CIN as a critera for CA seeding is shown, which is more restrictive and therefore reduces the area of active CA cells Figure 5f. The effect on the precipitation field is then more pronounced in model gridpoints where the CA is inactive or the average number of lives is small, since the convective activity is strongly reduced through eq.(3). Finally, the results using a seeding based on previous deep convective activity (rainfall) are similar to those obtained with CAPE seeding and are therefore not shown.

Overall the CA appears to be a useful dynamical tool to modulate convective activity. In the present configuration the CAPE seeding is prefered to the CIN seeding which is too restrictive. However, whereas it is easy to modulate existing convective activity with the CA, it is not obvious how to generate model

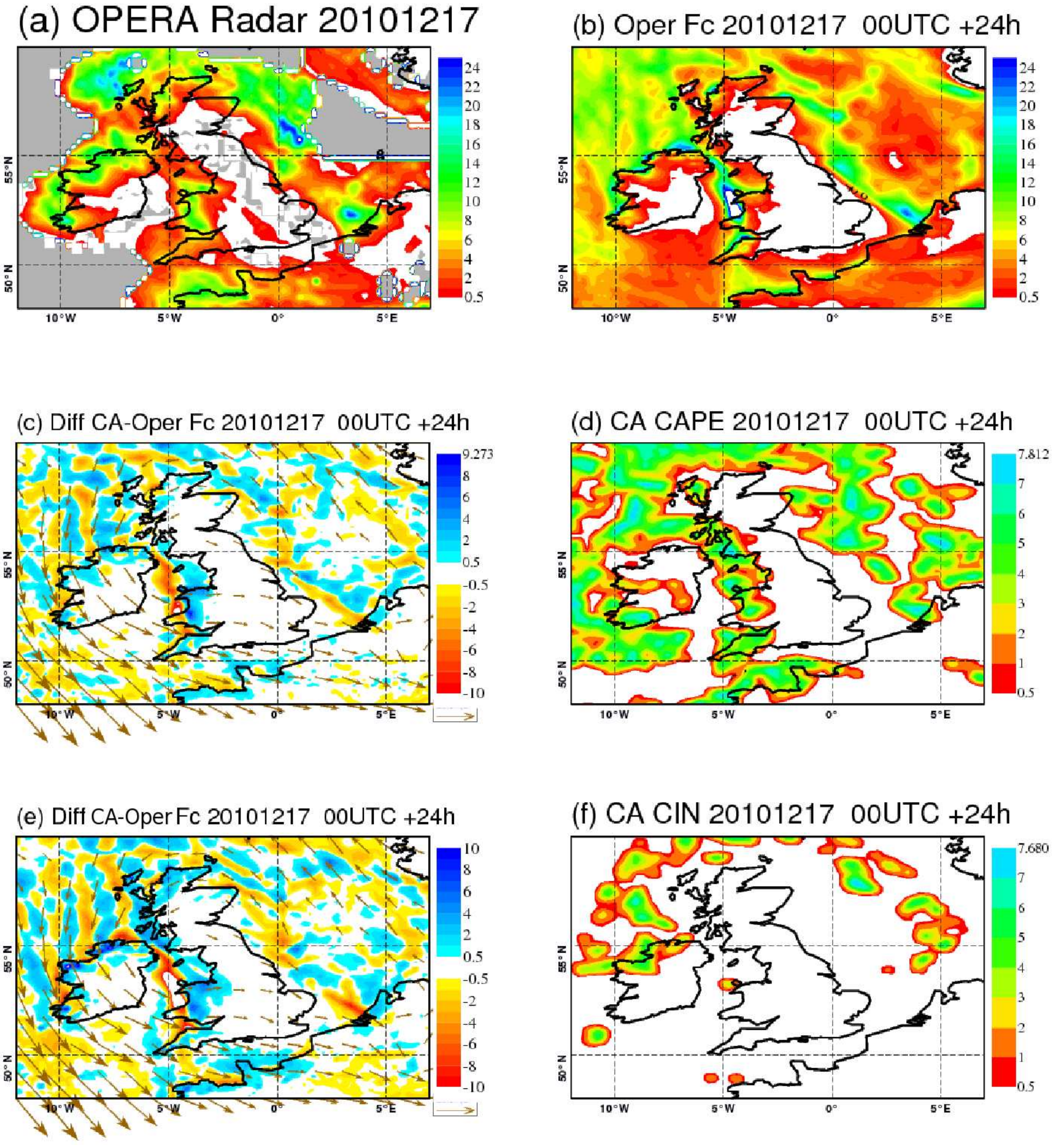

Figure 5: 24 hour accumulated precipitation (mm) on 17 December 2010 over the British Isles and Western Europe as observed by the OPERA radar network (a), the operational 24 hour deterministic IFS forecast at spectral resolution T1279=16 km (b), difference (mm) between the operational forecast and forecast using CA with CAPE seeding (c), the corresponding CA pattern for CAPE seeding (number of lives) (d), difference (mm) between the operational forecast and forecast using CA with CIN seeding (e), and corresponding CA pattern for CIN seeding (number of lives) (f)

convective activity. One way would be to use the CA to modulate parameters in the convection scheme, or alternatively perturb the input temperature and moisture profiles to the convection. We have experimented with the latter possibility perturbing the input temperature and moisture profiles by sine functions (conserving mass and energy). However, small normalised amplitudes of O(0.2 K) only had small effects while larger amplitudes led to model biases.

5.3 Stochastisity

The stochastisity of the proposed CA scheme as implemented in the ALARO model has been studied by looking at the short-range (up to 24 hours) ensemble spread in large-scale variables. A 20 member ensemble of the deterministic CA coupled to ALARO presented above was used.

Figure 6 illustrates the ensemble spread of the wind-speed at 850 hPa, on May 25th, 2009 (case number 2 described above). Figure 6a-c show the spread for 12, 18 and 24 hour forecasts respectively. A spread in the wind-field can be found in regions where deep convection is present. The maximum magnitude of the spread around the ensemble mean of the wind-speed at 850 hPa is comparable to the maximum magnitude found in the operational ECMWF EPS (January, 2012) at 12 and 18 hours (Figure 6g-h) at the same height. After 24 hours the maximum magnitude of the spread in the ECMWF EPS have grown larger. The geographical distribution of the spread differs between the CA-experiment and the ECMWF EPS, which may be due to the initial perturbations of the ECMWF EPS, or the stochastic physics present. It should be noted that in the current ECMWF EPS (January, 2012), the initial perturbations uses Ensemble Data Assimilation (EDA) based perturbations to represent uncertainties that have been growing during the data assimilation cycles, together with singular vectors optimally growing during the first 48 hours of the forecast (Buizza et al. 2008,2010). Thus a 12-24 hour forecast is very short-range.

The ensemble spread generated by the CA scheme can be viewed as the uncertainty due to sub-grid variablity of deep convection. It could be an interesting complement to an ensemble prediction system with initial perturbations aimed for the synoptic scale, and serve as ”stochastic physics“ that is part of the parameterization in the deterministic model.

6 Conclusions and discussion

A stochastic deep convection parameterization with memory has been implemented in two NWP models; the global ECMWF IFS, and the limited area, high resolution, ALARO model. The parameterization uses a Cellular Automaton as a two-dimensional field with a finer grid-spacing than the NWP model. The self-organizational characteristics of the CA allows for lateral communication between adjacent NWP model grid-boxes, and adds additional memory to the deep convection scheme(s). The CA is updated according to deterministic or probabilistic rules, and can be advected with the mid-tropospheric wind on the sub-grid level. It is randomly seeded with new cells each time-step in regions where either CAPE, CIN, or already active convection exceeds a threshold value.

Case-studies of convective precipitation along summertime squall-lines within the ALARO model indicate that the CA scheme in the present study has potential to organize convection at the leading edge of the squall-line, and enhance precipitation in regions where there is sufficient amount of CAPE.

Within the ECMWF IFS, the CA was also found useful in modulating convective activity. A case study with convective winter showers showed that the CA is able to improve inland penetration of convective showers, due to its enhanced advective effect and the targeted modulation of convective adjustment. An

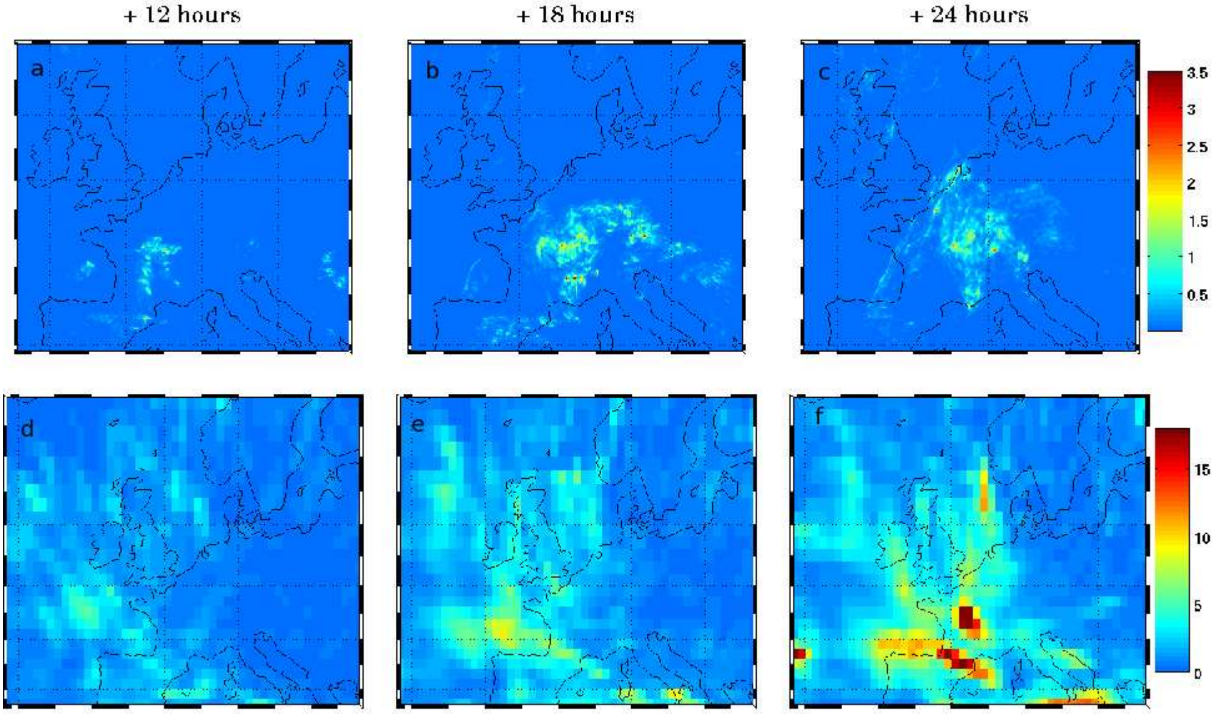

Figure 6: 12, 18 and 24 hour ensemble spread of 850 hPa wind-speed for a-c) CA as implemented in ALARO, using 20 members, and d-f) the operational ECMWF EPS (January, 2012). The forecast is based on 25 May, 2009 at 00 UTC.

extended evaluation of the CA in the IFS for a summer season revealed an overall neutral impact for northern hemisphere precipitation scores with respect to the reference model without the CA.

It was demonstrated that an ensemble of forecasts with the CA scheme in the ALARO model gave a spread in the resolved wind field at 850 hPa, in regions where the convective activity was large. Such convective-scale spread is not well represented in, for instance, the ECMWF EPS. Thus the scheme has potential to give an additional contribution to the spread of an EPS, representing the uncertainty due to sub-grid variability of deep convection.

Several components of the scheme, such as neighbourhood rules and prescribed lifetime of the CA, influences the impact that the scheme has on modulating convective activity. However, the most important factor seems to be the source to the CA from the NWP model. Experimentation has been done with CAPE, CIN, large-scale moisture convergence, and already activated convection, and thus far experiments using CAPE only has been the most successful.

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Appendix

The definition of CAPE is:

$$\mathrm{CAPE} = \int_{z_{\mathrm{LFC}}}^{z_{\mathrm{LNB}}} g \left(\frac{T_{\mathrm{uv}} - \overline{T_v}}{T_v} \right) \mathrm{dz}; \qquad T_{\mathrm{uv}} - \overline{T_v} > 0 \tag{4}$$

where $\overline{T_v}$ and T_{uv} are the environmental and updraught virtual temperatures, LFC is the Level of Free Convection, and LNB is the Level of Neutral Buoyancy. In the ECMWF IFS, CAPE is approximated as:

$$\mathrm{CAPE} = \int_{z_{\mathrm{LFC}}}^{z_{\mathrm{LNB}}} g \left(\frac{\theta_{\mathrm{e,u}} - \overline{\theta}_{\mathrm{esat}}}{\overline{\theta}_{\mathrm{esat}}} \right) \mathrm{dz}; \qquad \theta_{\mathrm{e,u}} - \overline{\theta}_{\mathrm{esat}} > 0 \tag{5}$$

where $\theta_{\mathrm{e,u}}$ and $\overline{\theta}_{\mathrm{esat}}$ are the updraught equivalent potential temperature, and the saturated equivalent temperature of the environment, respectively. LFC is the Level of Free Convection.

Convective Inhibition, CIN is in the ECMWF IFS approximated accordingly:

$$\mathrm{CIN} = -\int_{z_{\mathrm{dep}}}^{z_{\mathrm{LFC}}} g \left(\frac{\theta_{\mathrm{e,u}} - \overline{\theta}_{\mathrm{esat}}}{\overline{\theta}_{\mathrm{esat}}} \right) \mathrm{dz}; \qquad \theta_{\mathrm{e,u}} - \overline{\theta}_{\mathrm{esat}} < 0 \tag{6}$$

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