CRITICALITY: A THEORY FOR UNDERSTANDING AND FORECASTING DEEP CONVECTIVE INITIATION

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I. INTRODUCTION

The conventional approach to forecasting deep convective initiation (DCI) is to use proximity soundings of temperature and moisture to quantify the convective inhibition (CIN) based on parcel theory and then to apply an approximate lifting depth to determine if the level of free convection (LFC) of an idealized parcel would be attained. But as Ziegler and Rasmussen (1998) have demonstrated, DCI is not assured even in the presence of a trigger and zero CIN. Based on the conventional approach, lifting and zero CIN should guarantee that parcels will attain their LFC and yield DCI. However, assuming parcel theory requires neglecting the effects of entrainment, detrainment, and mixing which dilute a parcel with environmental air. Ziegler and Rasmussen argue that predicting DCI requires determining whether or not the LFC of individual diluted parcels can be attained. Since tracking individual parcels and quantifying their dilution requires detailed knowledge of the paths parcels take through the atmosphere, accounting for dilution is a daunting challenge to be sure. Nevertheless, the importance of relaxing parcel theory and considering dilution is clear.

In an attempt to simplify the conceptual paradigm of DCI, Houston and Niyogi (2007; hereafter HN07) proposed the concept of criticality. Criticality captures the non-linear relationship between buoyancy and dilution (Neggers et al. 2002). This non-linear relationship can be understood by considering two parcels with identical initial conditions ascending through a layer. Assuming that the environmental lapse rate that each parcel encounters through this layer is different we would expect that the vertical velocity would increase more rapidly for the parcel in the large lapse rate environment. As a result, this parcel would spend less time entraining environmental air within the layer. In contrast, the second parcel would ascend more slowly through the layer and the amount of entrainment would be larger. Entrainment will reduce parcel buoyancy below the adiabatic maximum for both parcels. However, because the amount of entrainment is larger for the second parcel, the reduction in buoyancy would be larger. The parcel would ascend more slowly further increasing the amount of entrainment. Thus a feedback exists between buoyancy and dilution.

Criticality uses this non-linear relationship between buoyancy and dilution to define two convective regimes: a supercritical regime in which the rate of increase in the buoyancy of a parcel as it ascends exceeds the reduction in buoyancy due to dilution – DCI is likely in this regime; and a subcritical regime in which the rate of increase in the buoyancy of a parcel as it ascends is outpaced by the rate of reduction in buoyancy from dilution – DCI is unlikely in this regime. *Thus, ultimately, the probability of DCI is seen to depend not on the likelihood that parcels will become unstable but on the likelihood that parcels will become supercritical.*

II. DEVELOPMENT AND TESTING OF CRITICALITY

HN07 developed the concept of criticality through a set of numerical experiments conducted using a 2D cloud-resolving numerical model, the Illinois Collaborative Model for Multiscale Atmospheric Simulations (ICOMMAS; Houston 2004). These experiments tested the sensitivity of DCI to differences in the lapse rate of the active cloud-bearing layer (ACBL; the layer above the LFC where a shallow convective cloud would reside). They found that the likelihood of DCI increases with increasing lapse rate of the ACBL. They also found that parcels ascending through shallow convective clouds that failed to become deep ascended slower and therefore became more diluted through entrainment. Thus, the relationship between buoyancy and dilution that underpins criticality emerged.

HN07 formalized the existence of criticality with a heuristic 1D (column) Lagrangian model that accounted for the non-linear relationship between dilution and buoyancy. This model illustrated that parcels in the subcritical regime fail to ascend through a significant depth of the troposphere, whereas parcels in the supercritical regime do.

While this heuristic Lagrangian model is capable of exposing the concept of criticality by isolating it from the complex dynamics and microphysics operating within a convective cloud, it involves a rather simplistic treatment of entrainment/dilution. A more robust method for formalizing the concept of criticality is necessary. Such a method could then be used to quantify criticality for both research and operational applications.

The new method used here involves a laterally entraining plume (LEP) model. LEP models are single column cloud models that originated with Stommel (1947) and have been implemented in the convective parameterizations of Kuo (1965), Arakawa and Schubert (1974), Jakob and Siebesma (2003), and others. Accurately imposing the entrainment rate for LEP models is difficult because suitable observations of entrainment rates are limited (Bretherton 1997; Neggers et al. 2002). Neggers et al. (2002; hereafter NSJ02) implemented an approach in which the entrainment is not explicitly imposed but is calculated based on the properties of the cloud. Specifically, they assume that the entrainment rate is inversely proportional to the vertical velocity. Because the vertical velocity depends on the buoyancy, the approach of NSJ02 couples the entrainment rate to the thermodynamics of the cloud. This approach differs from the traditional forms of the entrainment rate which assume it to be a function of cloud radius (Kain and Fritch 1990; and others) or height (Kuang and Bretherton 2006; and others).

It is the relationship between entrainment rate and cloud properties in the NSJ02 LEP model that allows this model to capture the non-linear relationship between buoyancy and dilution essential to criticality. Because the entrainment rate is inversely proportional to the vertical velocity, parcels with shorter residence times in a given layer will dilute less and remain more buoyant than their slower ascending counterparts.

Application of the heuristic Lagrangian model to modelled environments with different ACBL lapse rates clearly illustrated the two regimes of criticality (HN07). Application of the NSJ02 LEP model (now simply referred to as the 1D criticality model) to these same environments reveals it too can capture the different criticality regimes. The heights of the clouds simulated by the 1D criticality model are illustrated in Fig. 1. The near discontinuity in simulated cloud heights at a lapse rate of approximately 7.5 K km^{-1} indicates that the 1D criticality model can capture criticality: the feedback between buoyancy and dilution yields a sharp delineation between environments that can support deep convection from those that cannot. Figure 1 also illustrates that the 1D criticality model is able to capture the distinction between environments that are capable of supporting shallow convective clouds (simulated environments with lapse rates greater than ~6.3 K km^{-1} but less than 7.5 K km^{-1}) from those that are unable to support any convective clouds (lapse rates less than ~6.3 K km^{-1}).

These results are remarkably consistent with the results from the 2D cloud-resolving simulations of HN07. In the experiments of HN07, ACBL lapse rates of 9.8, 8.8, and 7.9 K km^{-1} yield DCI while environments with ACBL lapse rates of 6.9, 6.0, and 5.1 K km^{-1} do not. Moreover, the 6.9 K km^{-1} lapse rate environment yields thermal instability release but the convection remains shallow.

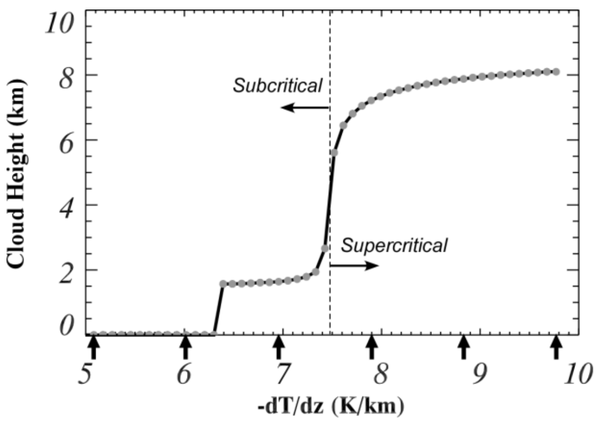

FIG. 1: Criticality regimes simulated through application of the 1D criticality model to environments with different ACBL lapse rates. The 6 values of lapse rate used in the cloud-resolving simulations of HN07 are indicated with thick arrows along the abscissa.

III. FUTURE WORK

One of the objectives of future work is to solidfiy the theory of criticality through additional numerical experiments similar to those conducted by HN07. However, in an attempt to introduce more realism into the experimental design adopted by HN07, the proposed simulations will be 3D instead 2D. Since criticality is a function of both buoyancy and dilution, specific numerical experiments will focus on evaluating how DCI responds to changes in these two quantities. Furthermore, because of the importance of vertical shear in DCI, the parameter space for the proposed experiments will also include different values of vertical shear.

Solidfying the theory of criticality will also involve application of the 1D criticality model to the 3D cloud-resolving simulations. However, unlike the application illustrated above, the proposed application will not apply the 1D criticality model to a single cloud column but will instead apply it to an ensemble of cloud columns. This will be achieved by initializing multiple cloud columns with slightly different initial conditions. The criticality metrics that evolve from this application of the 1D criticality model will be statistics of the ensemble.

With criticality metrics derived from the work described above, the feasibility of using criticality in general and criticality metrics in particular for forecasting DCI can be assessed. This assessment will involve real data cases chosen in an effort to sample the variety of environments within which DCI can occur.

IV. AKNOWLEDGMENTS

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