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A Machine Learning Assisted Development of a Model for the Population Dynamics of Clouds

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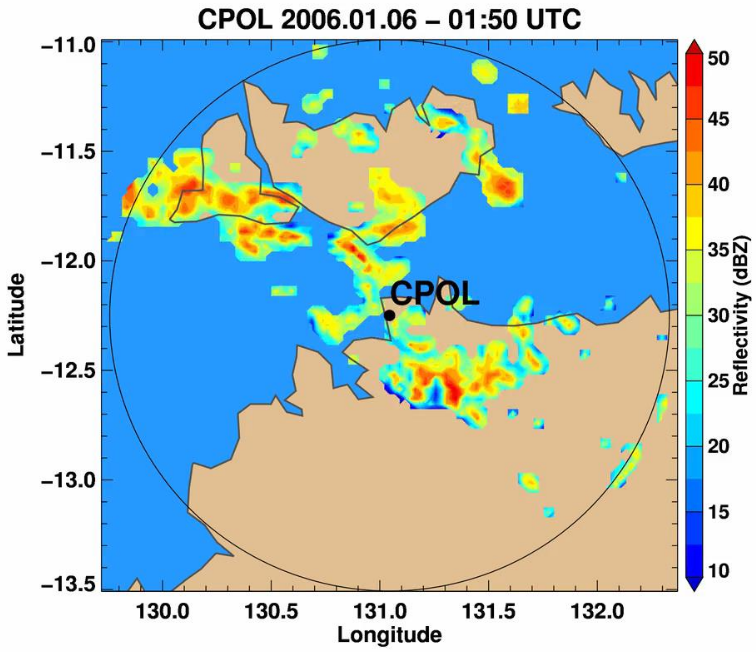
U.S. DEPARTMENT OF ENERGY

Introduction



Science Questions:

1. What are the processes the govern the evolution of the population of convective cells?
2. How can these processes be modelled and represented in global models?

Objectives

To develop a **model of non-equilibrium dynamics of cloud populations for**:

- Testing hypotheses regarding the roles of various physical processes and
- Parameterizing the spectrum of convective clouds (from isolated to MCSs) in a unified framework.

Background

A brief history of the problem

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General energy cycle

(Arakawa and Schubert 1974)

$$\frac{dA_i}{dt} = -\sum_{j=1}^{N} \gamma_i M_{Bj} + F_i$$

Mass flux   Forcing

Paths followed since

- Quasi-equilibrium assumption

$$-\sum_{j=1}^{N} \gamma_i M_{Bj} + F_i = 0$$

1970

- Bulk and spectral finite deviation from quasi-equilibrium

  (Pan and Randall 1998, Yano and Plant 2010)

1990

- Stochastic variations about quasi-equilibrium

  (Craig and Plant 2008, Wagner and Graf 2010)

2000

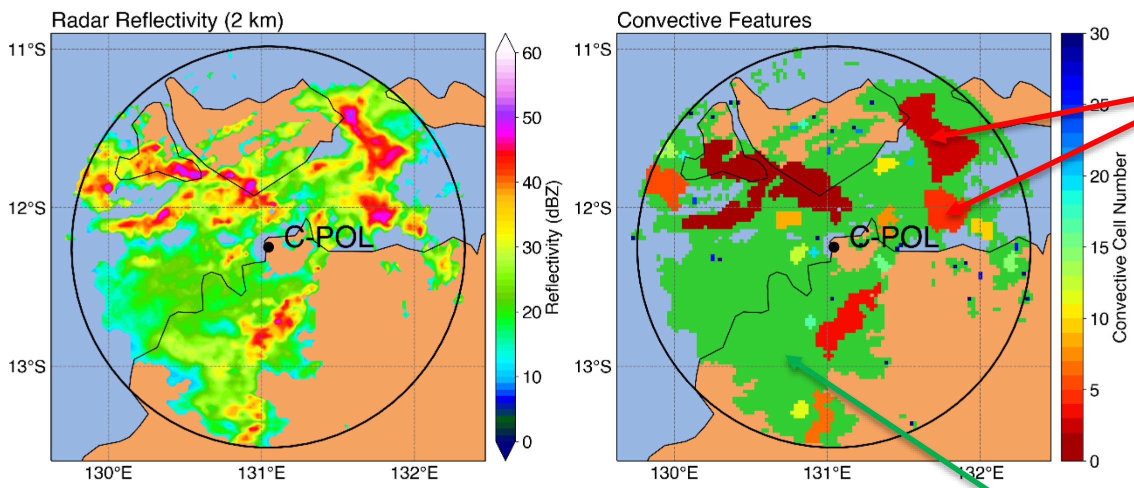
- Prognostic, stochastic cloud population models

  (Plant 2012, Hagos et al. 2018)

2010

Observational data and definitions

12 winters of C-Pol Radar reflectivity data at Darwin



Convective cells

$$\boldsymbol{c}(t) = [c_1, c_2, \ldots c_n]$$

Total convective area

$$A_c(t) = \sum_{i=0}^{n} \boldsymbol{c}_i(t)$$

Stratiform area

$$s(t)$$

C-Pol observation at Darwin

- Stainer et al. (2005) algorithm is used to identify convective cells and stratiform areas.

The model

$$\frac{dA_c}{dt} = \frac{1}{m_{b1}}\left(-\frac{1}{\tau_c}M_b + F\right)$$

$$\mathbf{c}_{(t+dt)} = f_c([s(t), \mathbf{c}_{(t)}], dA_c(t))$$

$$M_b = \mathbf{c} \cdot \mathbf{m}_b$$

$$\frac{ds(t)}{dt} = -\frac{s(t)}{\tau_s} + f_s(\mathbf{c})$$

- After Arakawa and Schubert (1974)
- The next state is **some function** of the current state and the change in convective area fraction.
- Convective mass flux per cell depends on cell size.
- The growth rate of stratiform area is **some function** of convective cells and decays exponentially in the absence of active convection.

1. Machine learning algorithm for deteriming f_c and f_s

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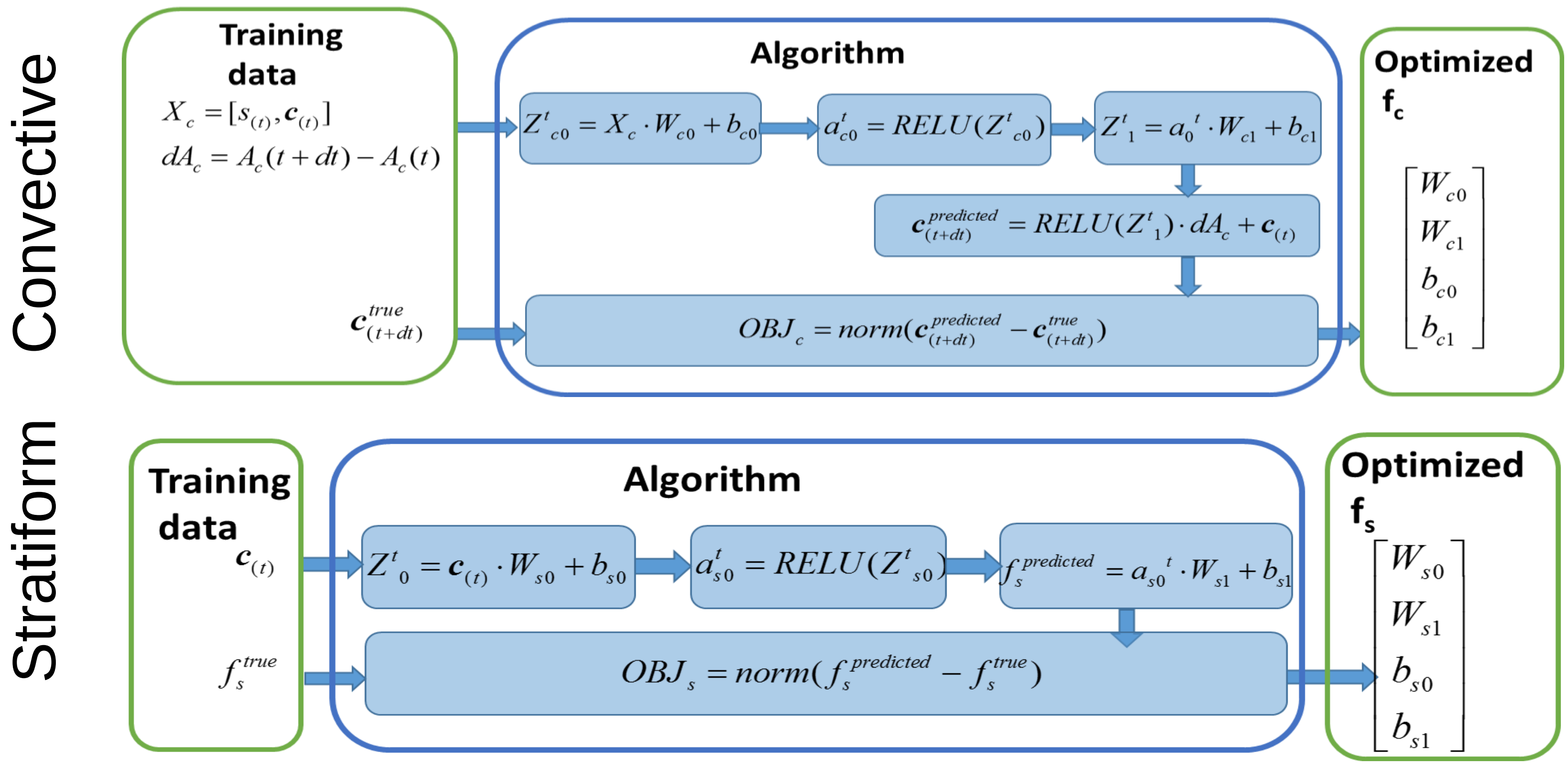
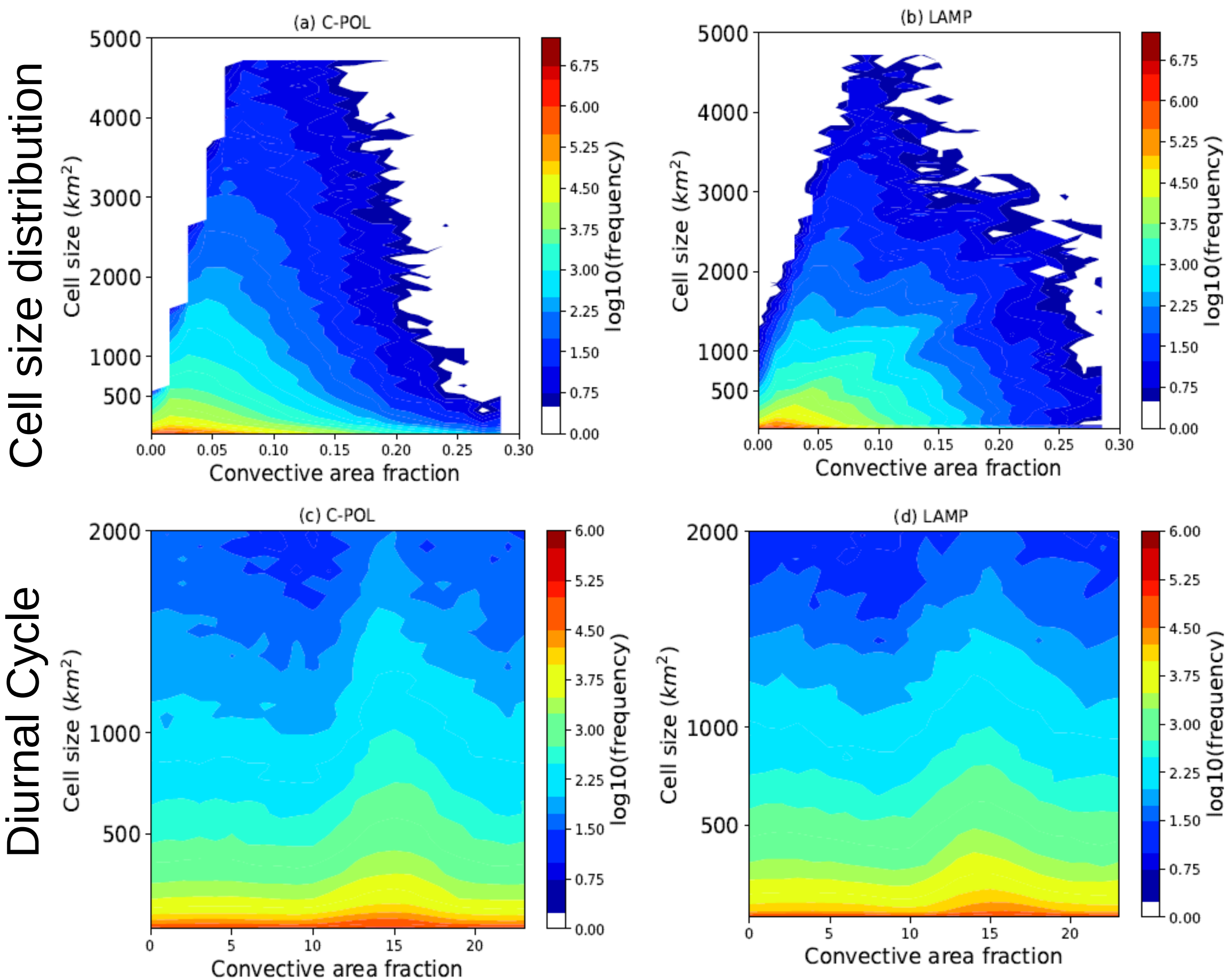


- The machine learning code is written in TensorFlow™
- The algorithm is trained by half of the 150,000 cases of observed transitions.

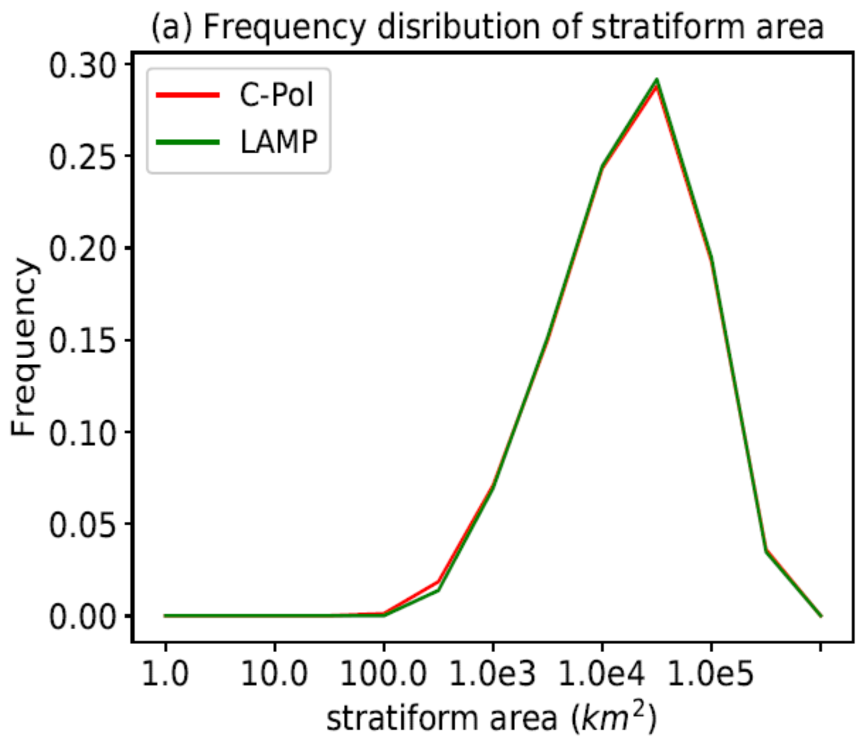
1. Machine learning
Validation of f_c: Convective clouds

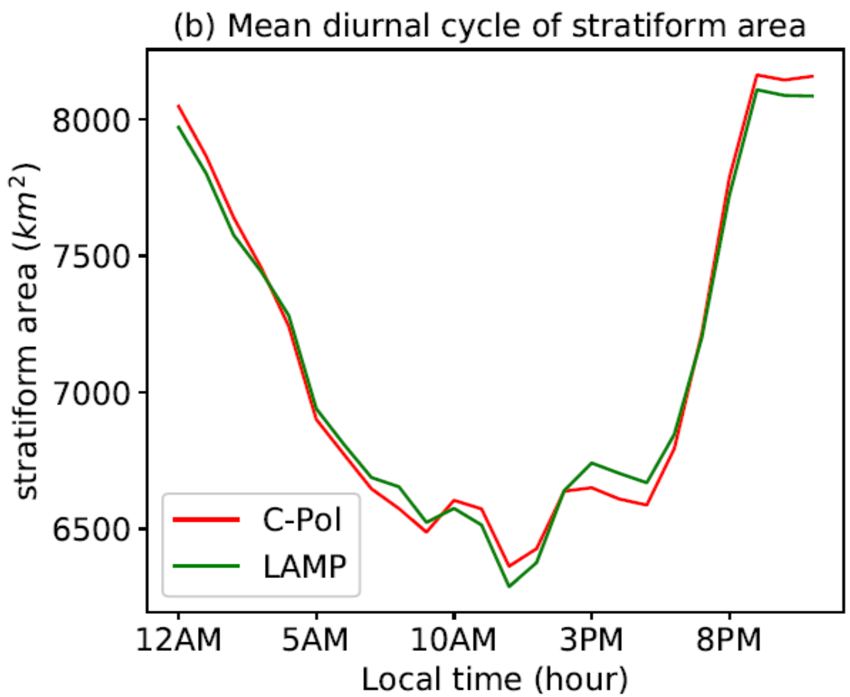
- Hereafter the model will be referred to as “machine **Learning Assisted Model for Population** of clouds **(LAMP)**”.



- The algorithm predicts the convective cell size distribution and its diurnal cycle reasonably well.

1. Machine learning
Validation of f_s (Stratiform area)





- Given convective cell sizes the algorithm represents stratiform area distribution and it diurnal cycle well.

1. Machine learning Interpretation: Convective clouds

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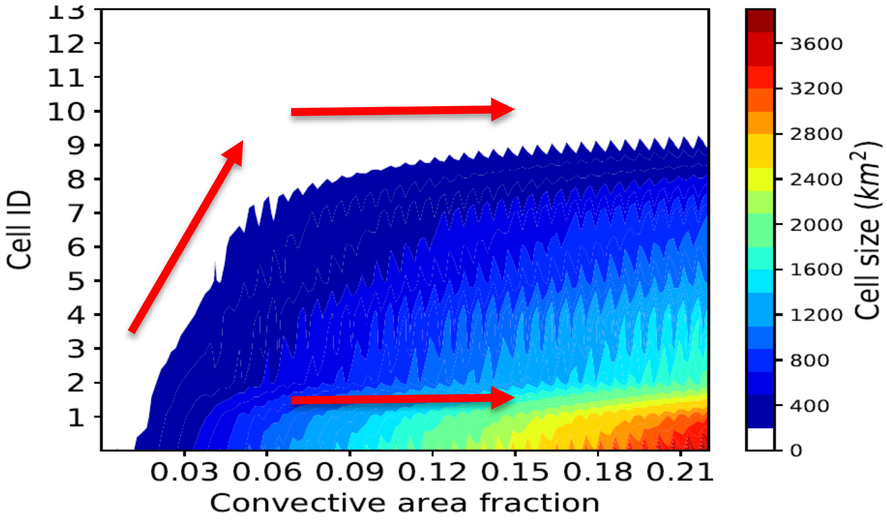
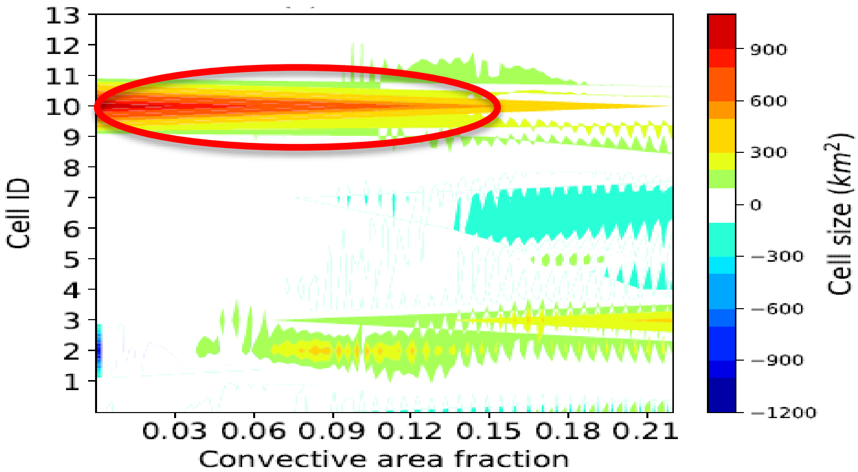
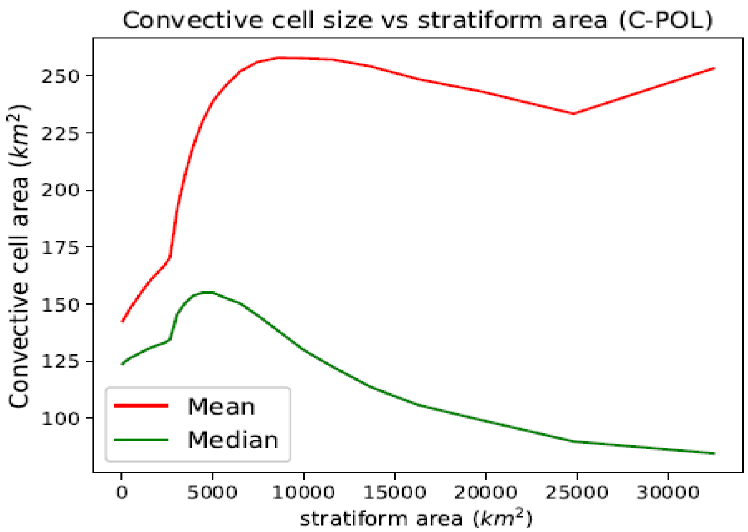
Convictive cells vs convective area fraction (stratiform feedback off)



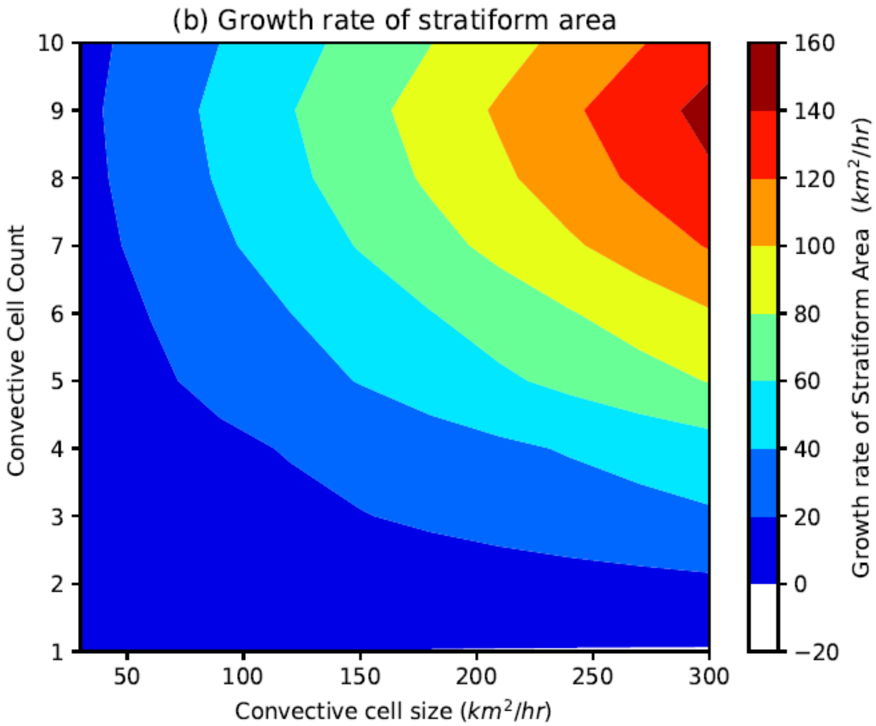
The effect of stratiform feedback



- At low cloud fraction the **number of cells** grows rapidly.
- At larger area fraction the **size of cells** grows rapidly.
- Stratiform area favors formation of new smaller cells



1. Machine learning Interpretation: Stratiform area

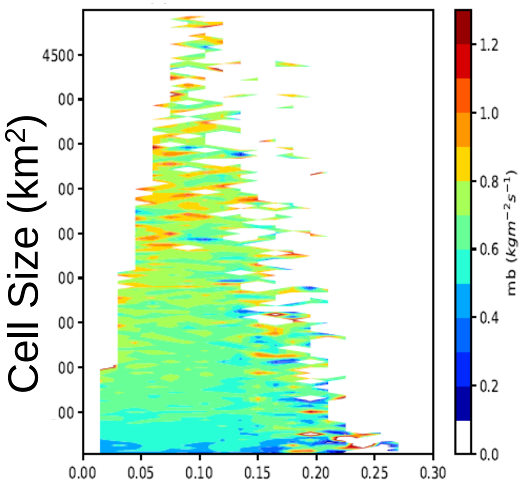


- The growth rate of stratiform area is approximately linearly related to convective area.
- it is relatively insensitive to the size distribution.

2. Mass Flux
Relationship with Convective Cell Sizes

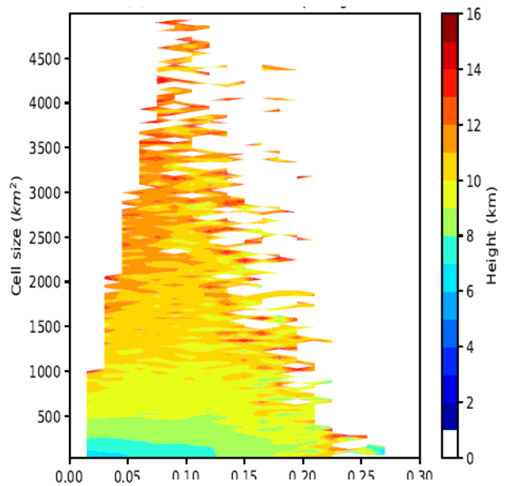
Why do we care about cell size distribution anyway?

CPM Cloud-base Mass-flux



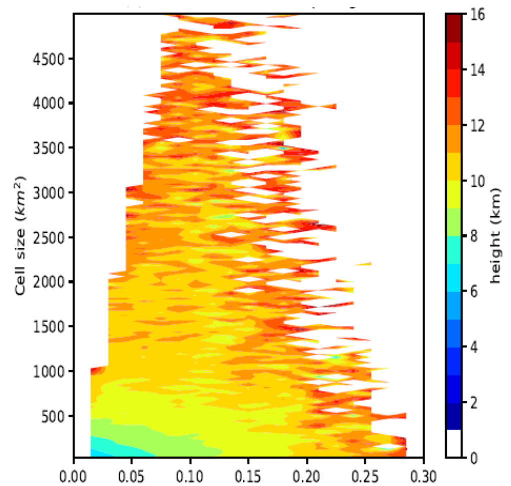
Cell Area Fraction

CPM 10dBZ Echo-Top Height

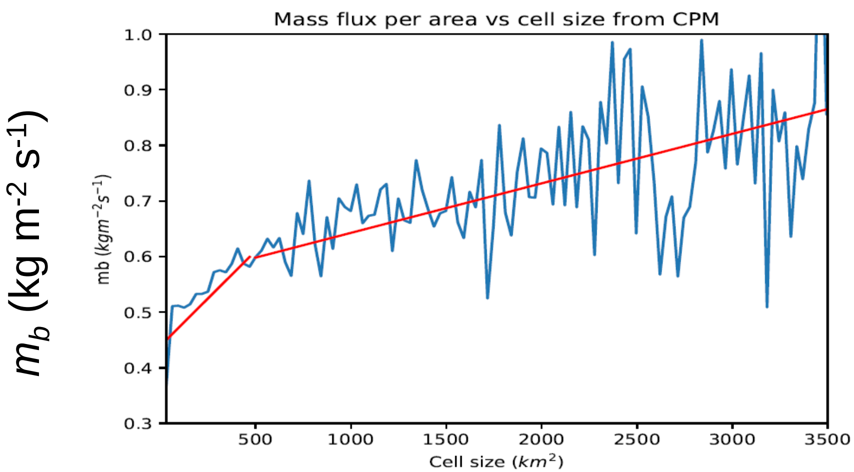


Cell Area Fraction

C-Pol 10dBZ Echo-top Height



Cell Area Fraction



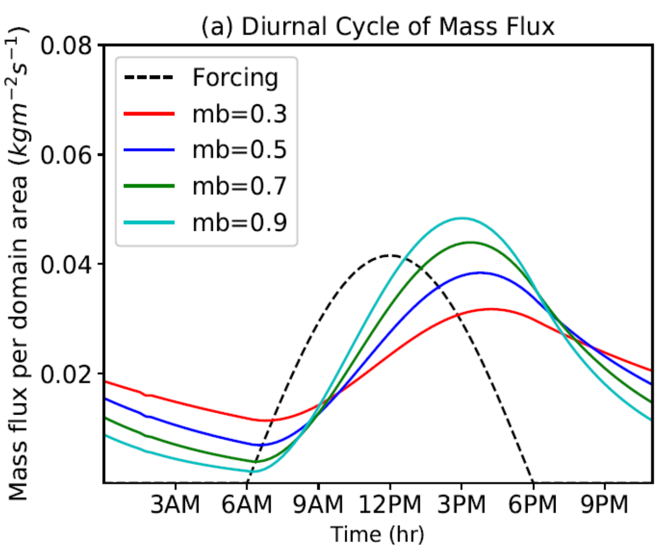
- Because larger cells carry more than their share of **mass flux**.

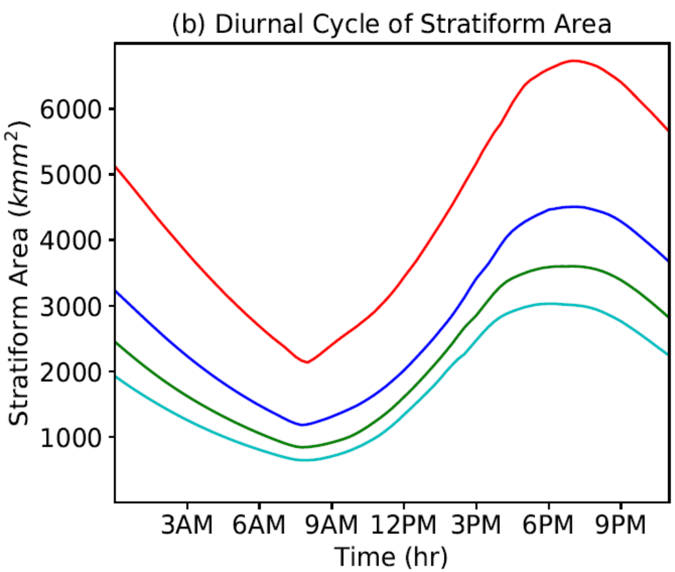
$$M_b = \boldsymbol{c} \cdot \boldsymbol{m}_b$$

From Hagos et al. 2018 (JAMES)

3. The Model
(a) Linear

$$M_b = \boldsymbol{c} \cdot \boldsymbol{m}_b \qquad m_b \text{ independent of cell size } \boldsymbol{c} \text{ (constant)}$$

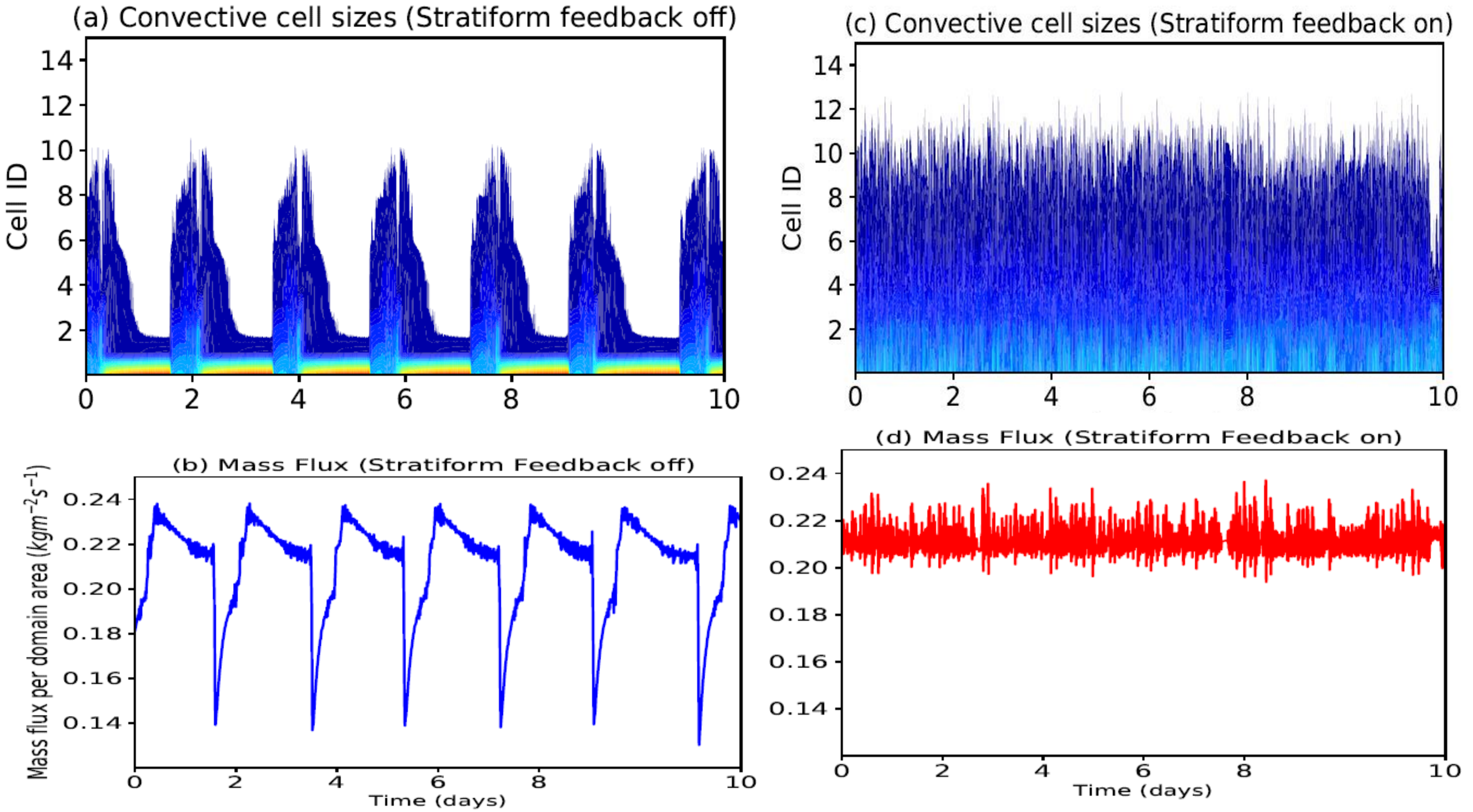




- Smaller mass flux per-cell delays the diurnal cycle of total mass flux because larger cells are required.
- Larger cells then lead to larger stratiform area.

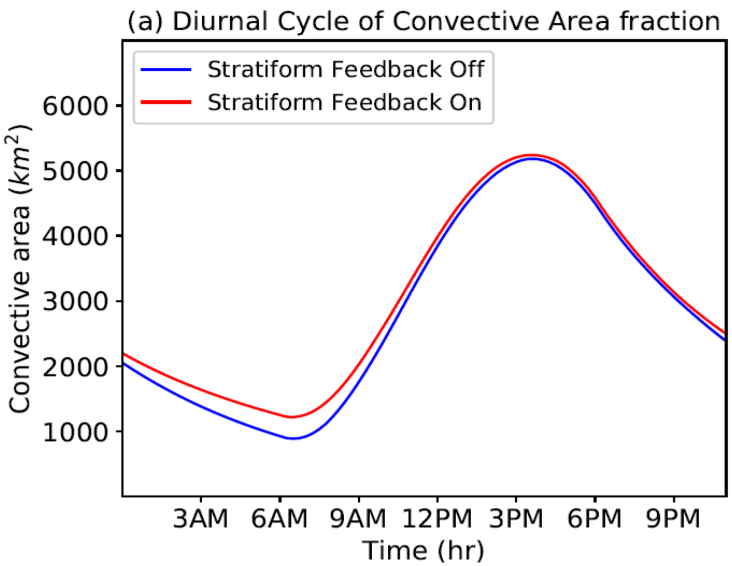
3. The Model: Non-linear
(b) Response to constant forcing

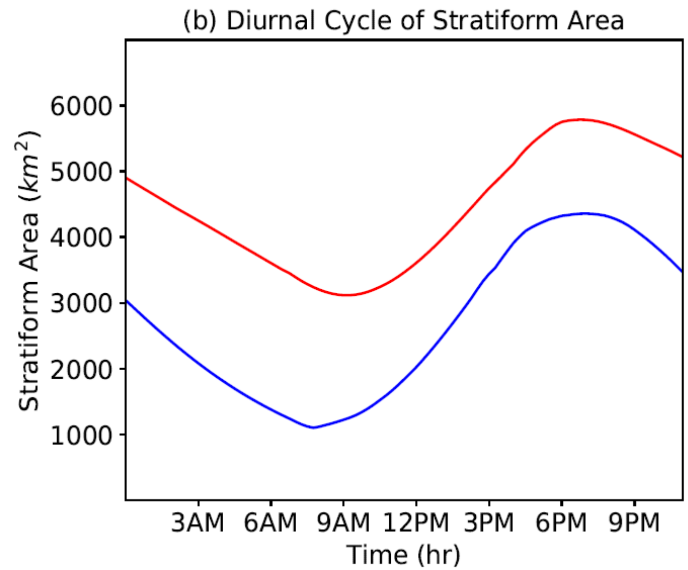
$M_b = \boldsymbol{c} \cdot \boldsymbol{m}_b$ m_b dependent of cell size $\boldsymbol{c}$

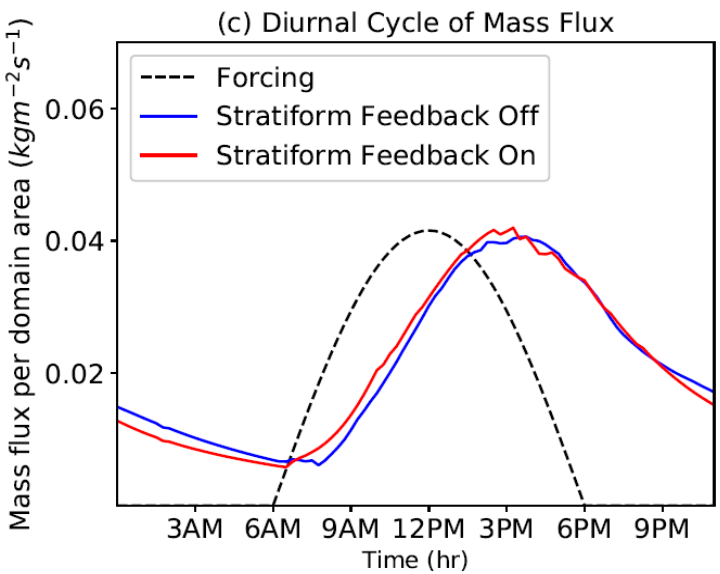


- Non-linearity leads to oscillation in mass flux.
- Stratiform feedback damps the oscillation by favoring smaller convective cells.

3. The Model: Non-linear
(b) Response to diurnally varying forcing







- ▶Stratiform feedback leads to smaller cells
- ▶The mass flux then requires larger total convective area.
- ▶ Resulting larger stratiform area.

Summary

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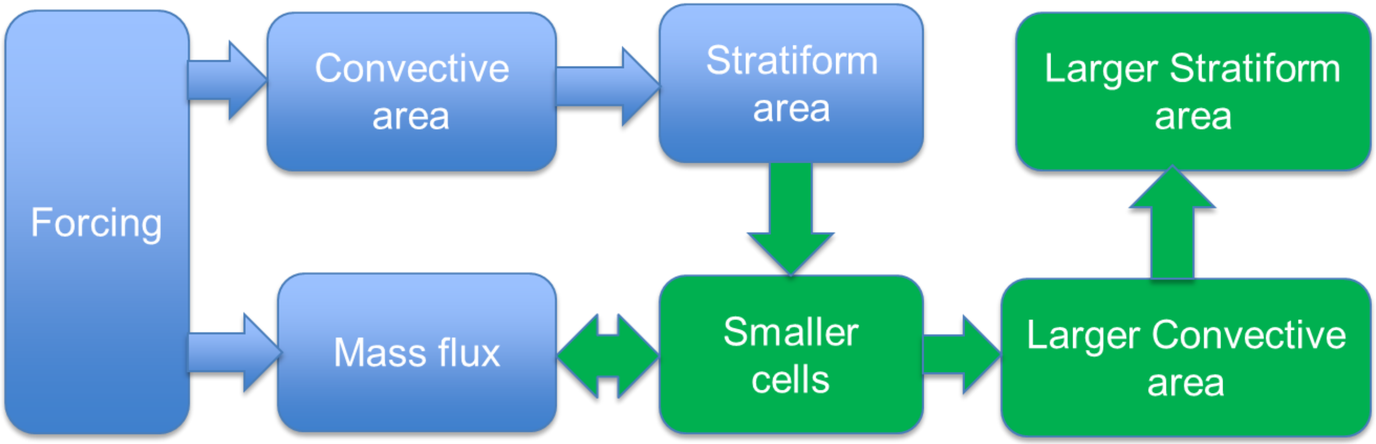
- Formation of large stratiform areas (i.e MCS like feature)



- Furthermore
  - The diurnal cycle of convection in a non-equilibrium framework is sensitive to mass flux per unit convective cell area.
  - low-frequency variability of large-scale forcing favors larger stratiform area.
- Future work: A parameterization based on this framework will be tested in a climate model after the similar analyses are performed over other regions.