# Clouds and turbulent moist convection

## Lecture 3: Organization of deep convection at mesoscales

*Caroline Muller*

# Lectures Outline :

**Cloud fundamentals -** global distribution, types, visualization and link with large scale circulation

**Cloud Formation and Physics -** thermodynamics, cloud formation, instability, life cycle of an individual cloud

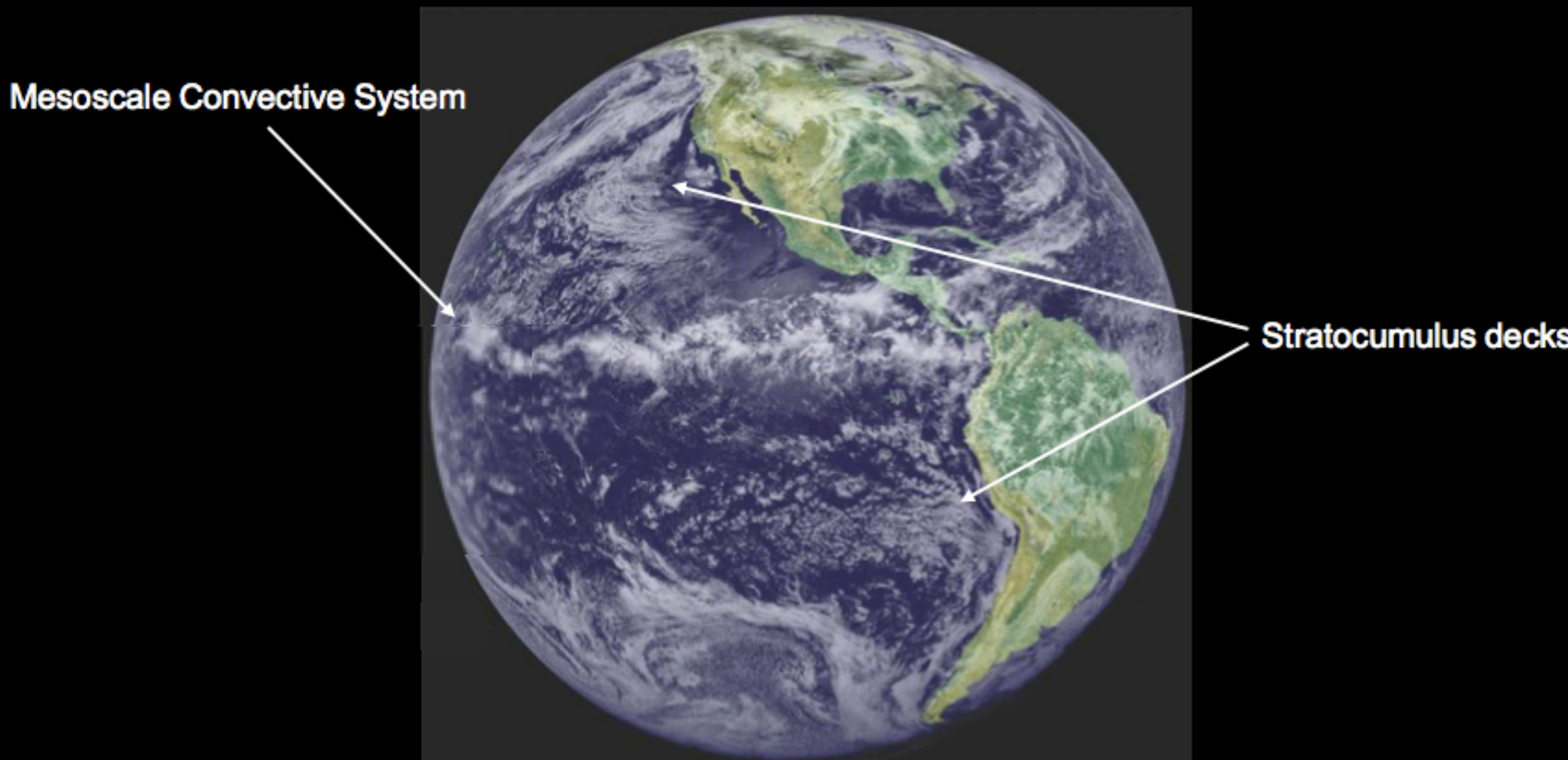
**Organization of deep convection at mesoscales -** MCSs, MCCs, Squall lines, Tropical cyclones, Processes, Self-aggregation

**Response of the hydrological cycle to climate change -** mean precip, precip extremes

**Clouds in a changing climate –** climate sensitivity, cloud effect, cloud feedback, FAT

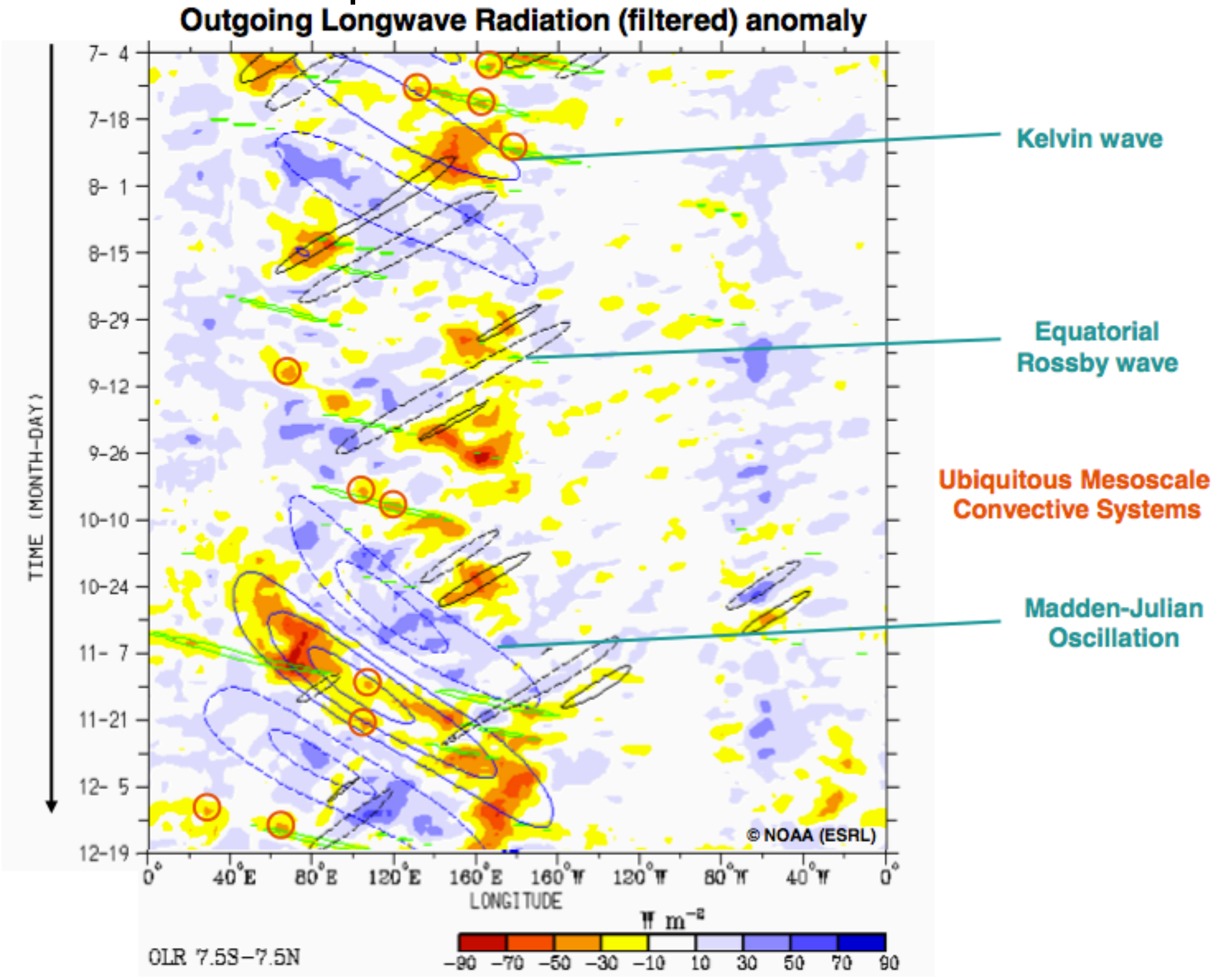
# Convective organization

**… often spatially organized, …**



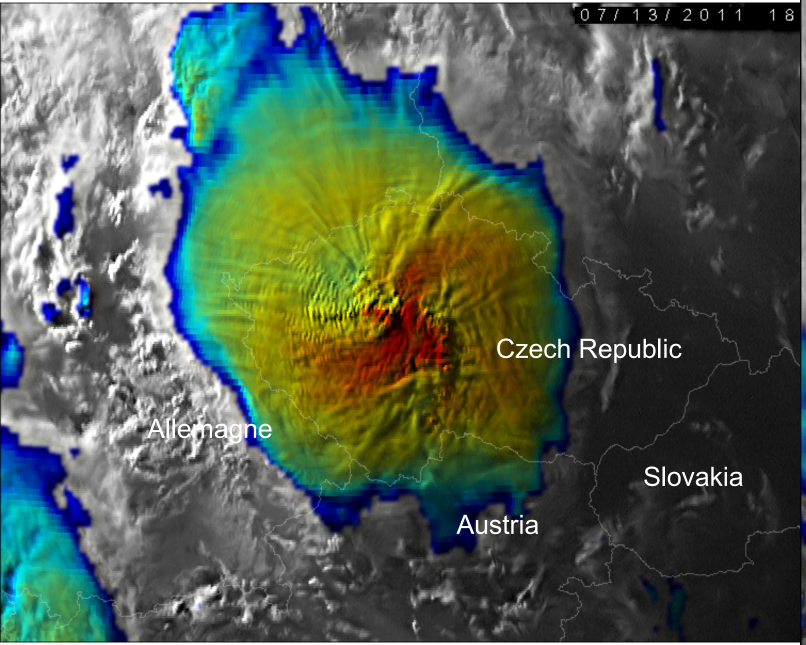
# Convective organization: recall

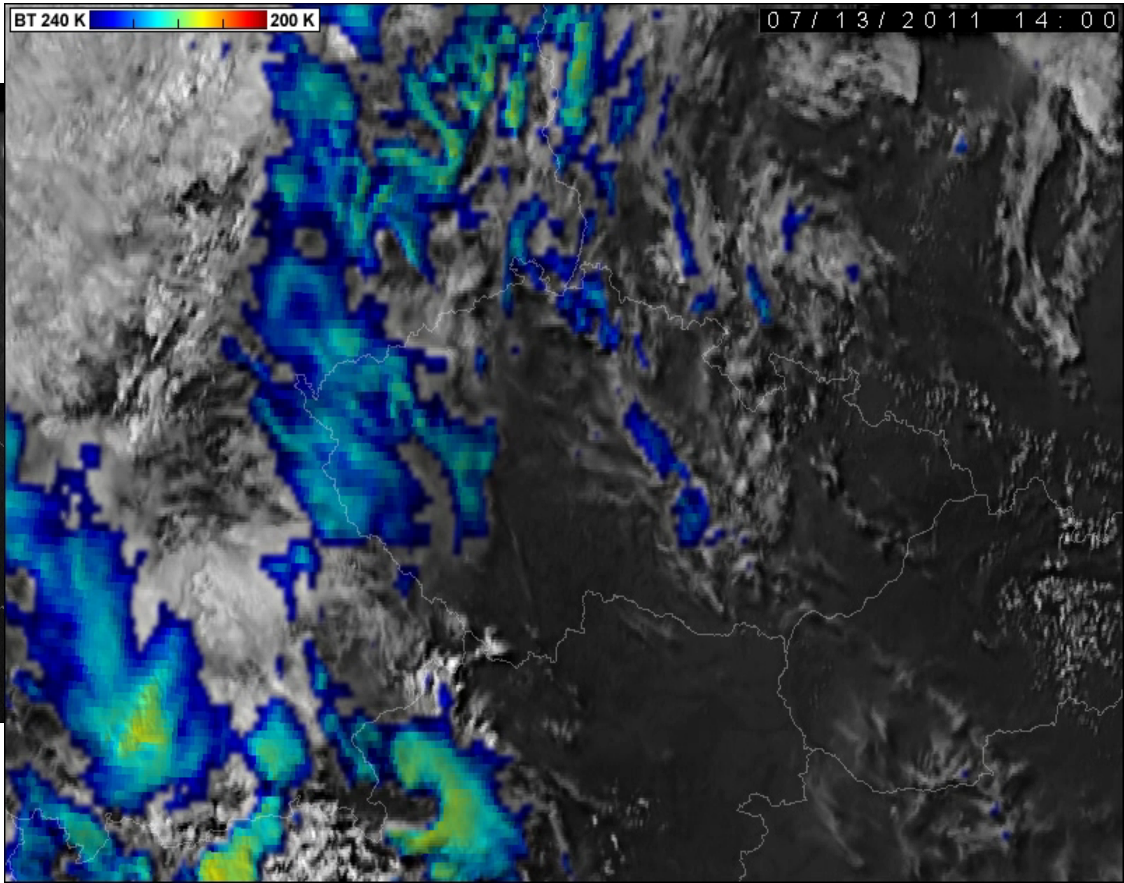
Recall OLR in the tropics :



# Convective organization: recall


Mesoscale convective systems

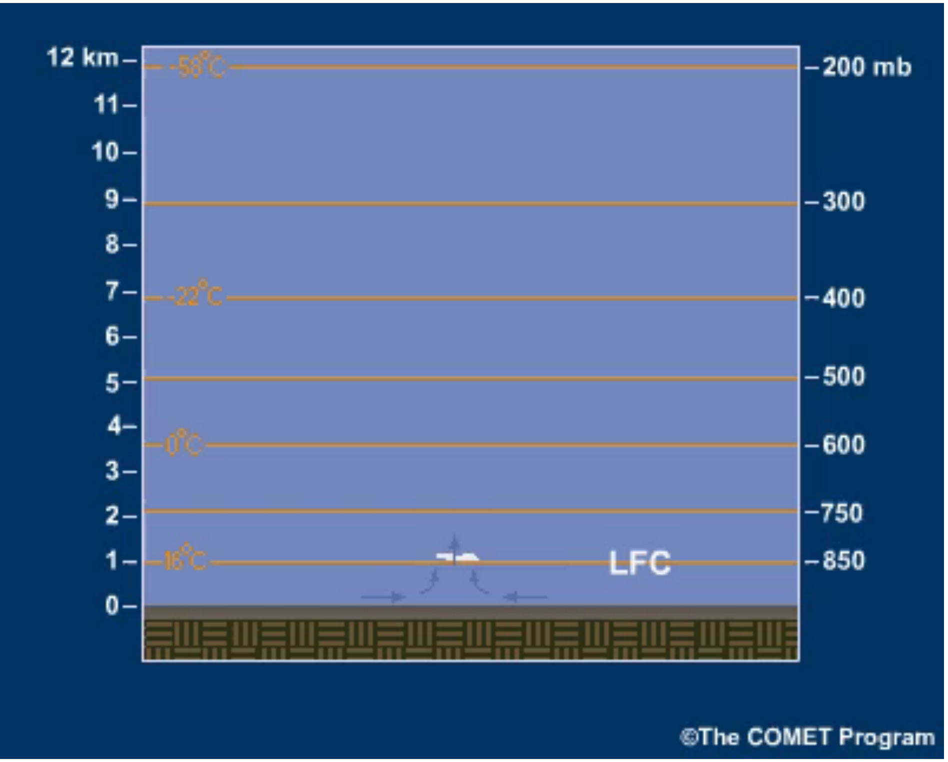


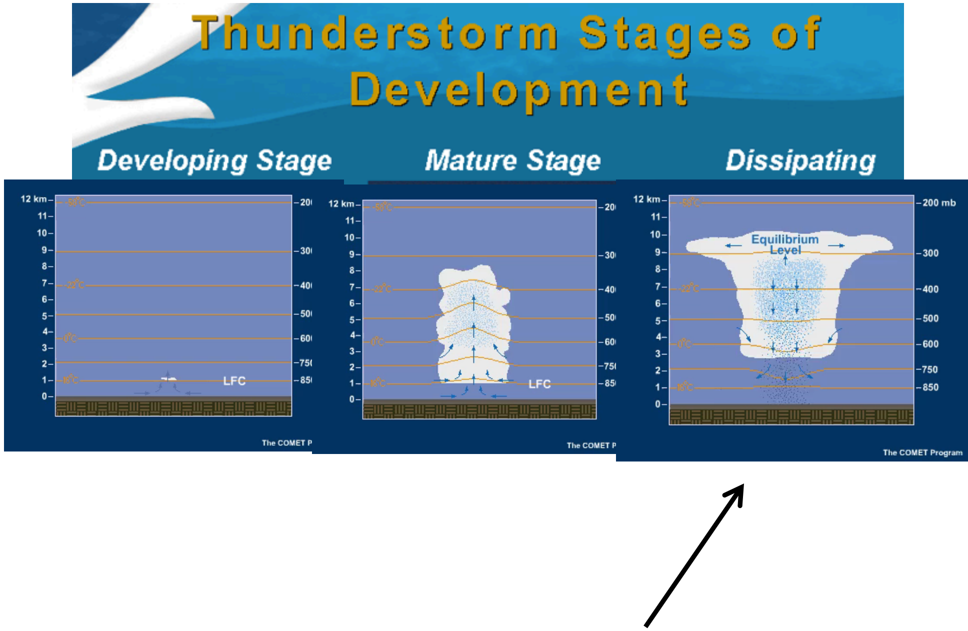




*More lecture 3 …*

## RECALL : LIFE CYCLE OF AN ORDINARY THUNDERSTORM

Strong updrafts develop in the cumulus cloud => mature, deep cumulonimbus cloud.
Associated with heavy rain, lightning and thunder.




Evaporative driven cold pools

# Convective organization: definition

**What is organized convection?**
*(adapted from AMS glossary and Todd Lane's lecture 2016 ARCCSS Winter School on Tropical Meteorology)*

- **Convection that is long-lived**
  Lasts longer than an individual convective cell

- **Convection that grows upscale**
  Covers an area larger than an individual convective cell

**Organization can arise from**

- **large-scale forcing**
  *e.g. SST gradient, presence of an island*

- **interaction with the large-scale flow**
  *e.g. interaction with vertical shear*

- **internal feedbacks that lead to upscale growth**
  *e.g. self-organization by moisture feedbacks ; by propagating gravity waves destabilizing the cloud environment and promoting new convection; by internal « self-aggregating » feedbacks… Still very much an area of research*

# Convective organization: definition

**What is organized convection?**

Adapted from the AMS Glossary:

**Mesoscale Convective System (MCS)** – A cloud system that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area on the order of 100 km or more in horizontal scale in at least one direction.

Sometimes also called **Cloud Cluster**

**Mesoscale Convective Complex (MCC)** – A subset of mesoscale convective systems that exhibit a large, circular (eccentricity > 0.7), long-lived (>6 hours), cold cloud shield. The cloud shield must:

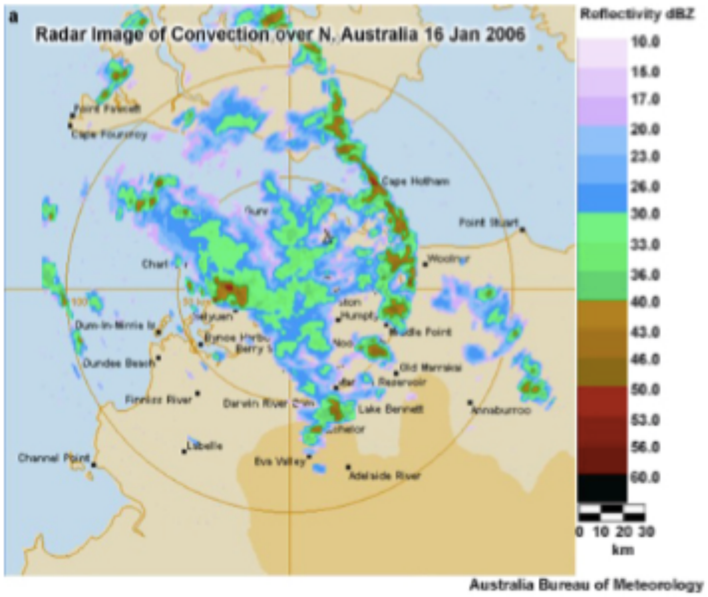
- Have an area >105 $km^2$ with IR temperature < -32$^oC$
- Interior cold cloud region with area > $5x10^4$ $km^2$ with IR temp < -52$^oC$ (This was originally defined by Maddox 1980, *BAMS*)

# Convective organization: definition

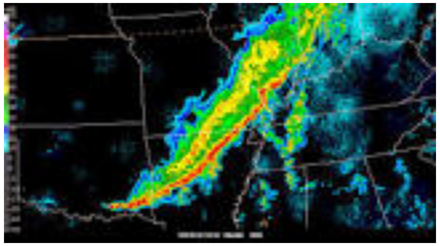
**What is organized convection?**

**Mesoscale Convective System (MCS) Include :**

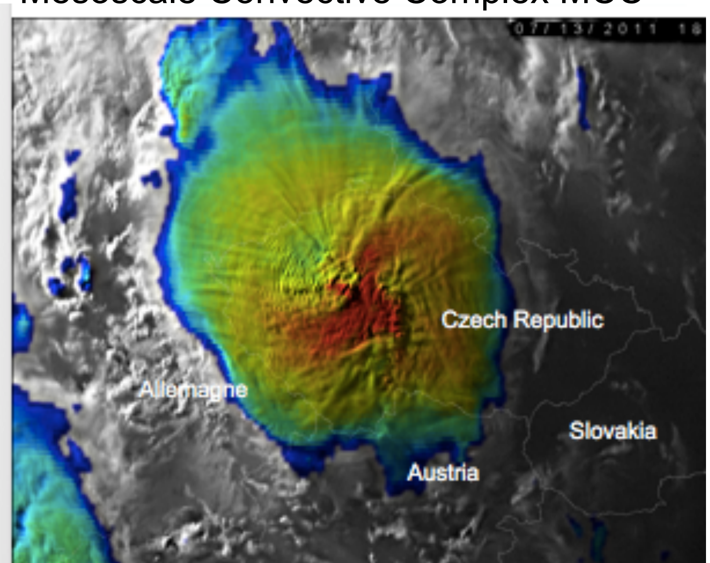
MCS



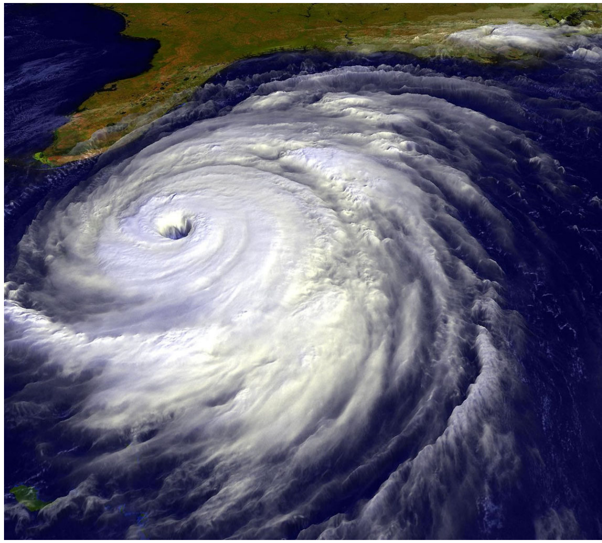

Squall line



Mesoscale Convective Complex MCC

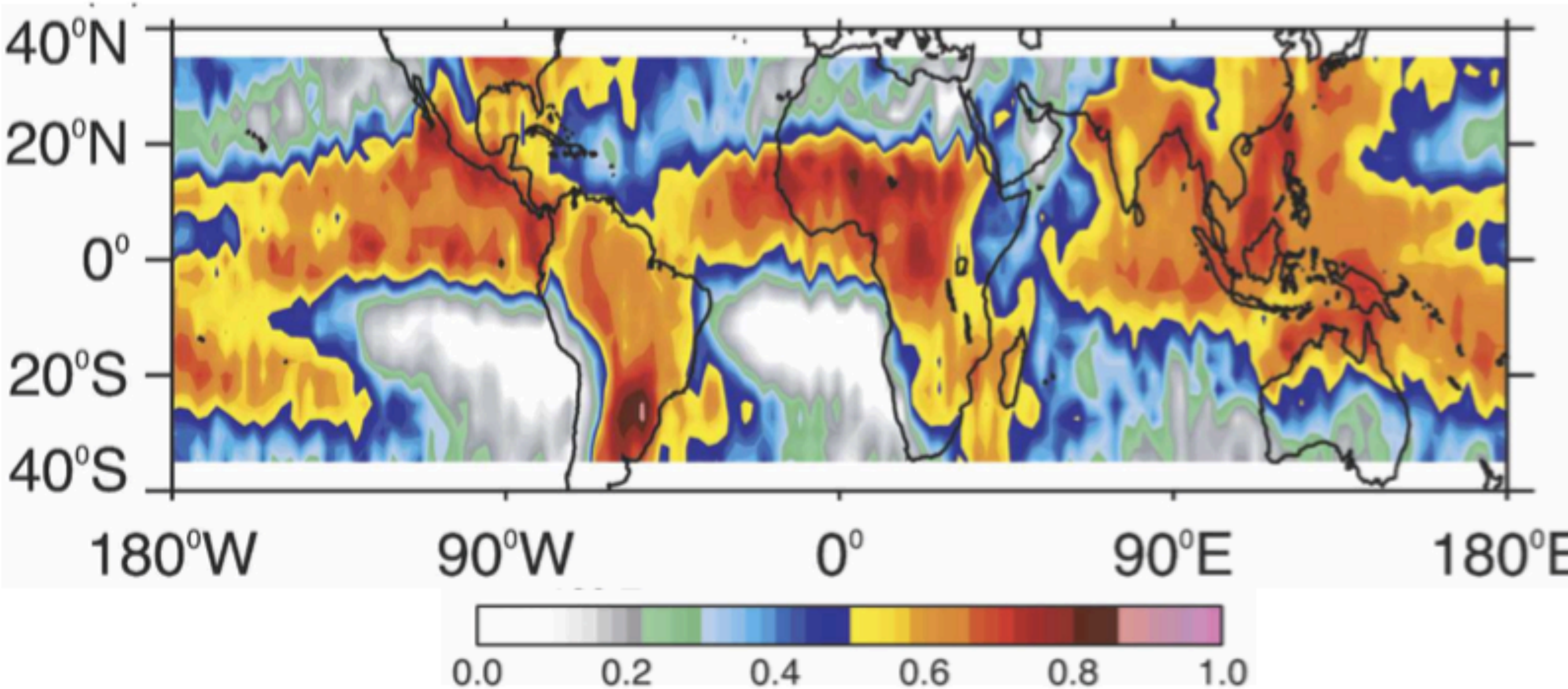



**Hurricane** approaching Florida



# Convective organization: definition

Fraction of rainfall from Mesoscale Convective Systems MCSs




Nesbitt et al. (2006, *MWR*)

# Convective organization: processes

Processes which can lead to convective organization :

Vertical shear

Waves

Surface Fluxes WISHE (Wind-induced surface-heat exchange) effects

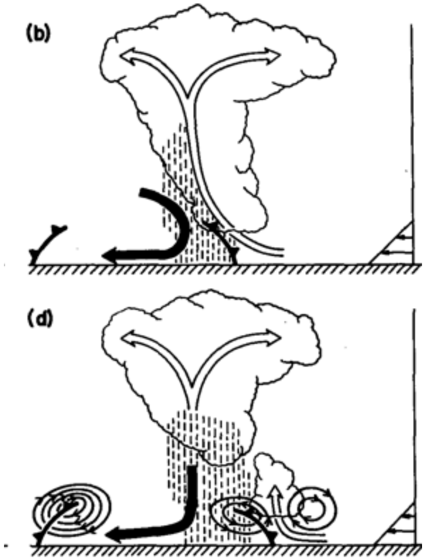
Self-aggregation feedbacks

# Convective organization: processes - shear

**Interaction with vertical shear : A theory of long-lived convective systems and squall lines**

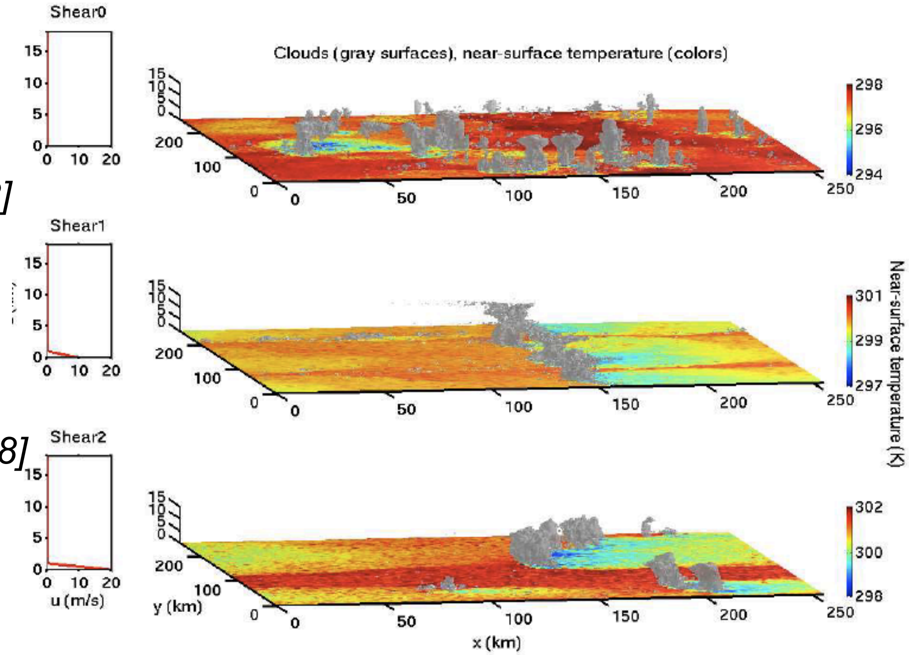
**Squall lines**


Role of vertical shear & cold pools




*[Thorpe et al 1982]*

*[Rotunno et al 1988]*




*[Rotunno et al. 1988; Fovell and Ogura 1988; Garner and Thorpe 1992; Weisman and Rotunno 2004; Houze 2004; Moncrieff 2010]*

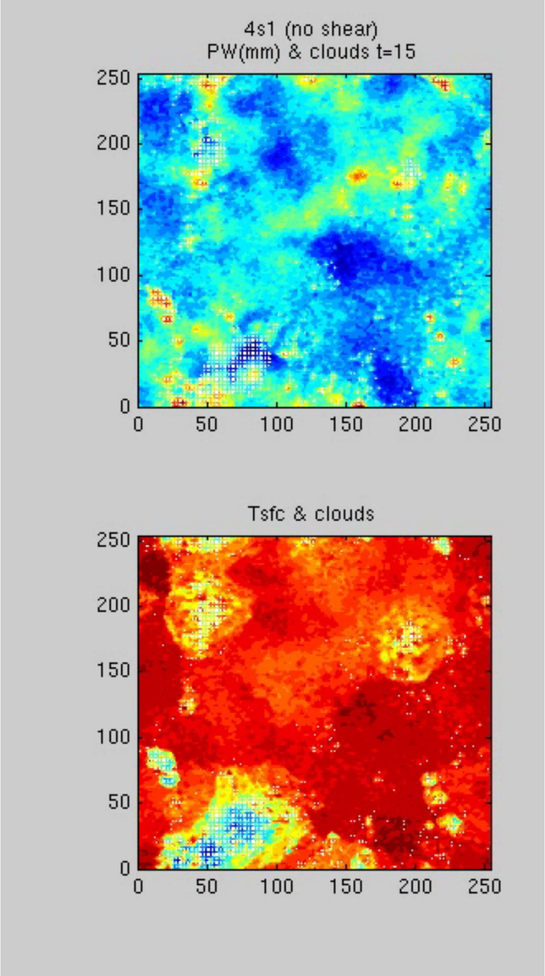
# Convective organization: processes - shear

## No shear

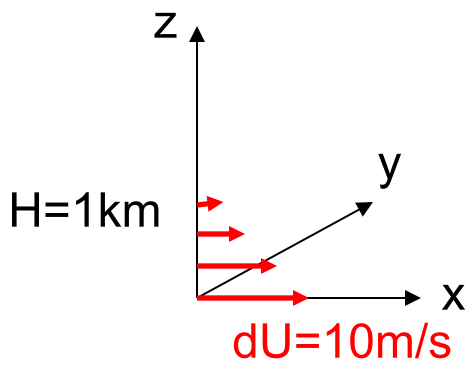
Top view

Color: PW

Color: Tsfc



# Convective organization: processes - shear

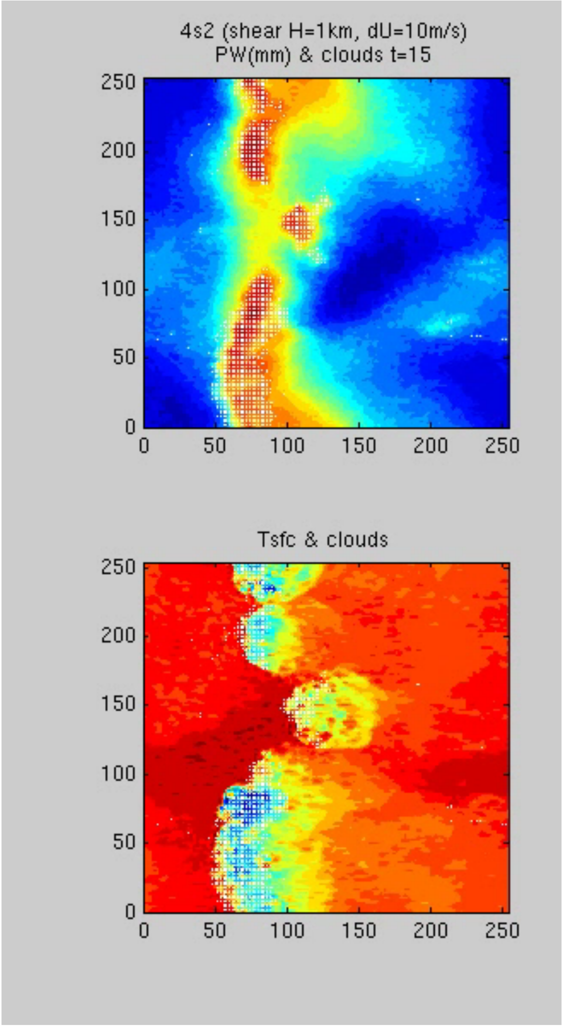



## Critical shear

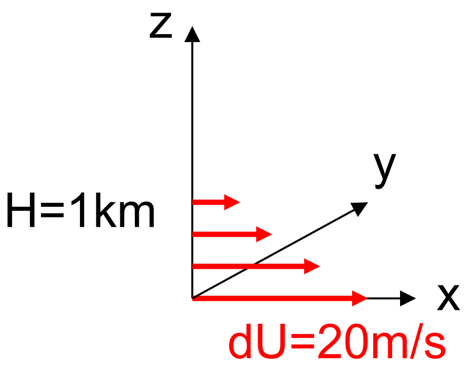
### Top view

Color: PW

Color: Tsfc



# Convective organization: processes - shear

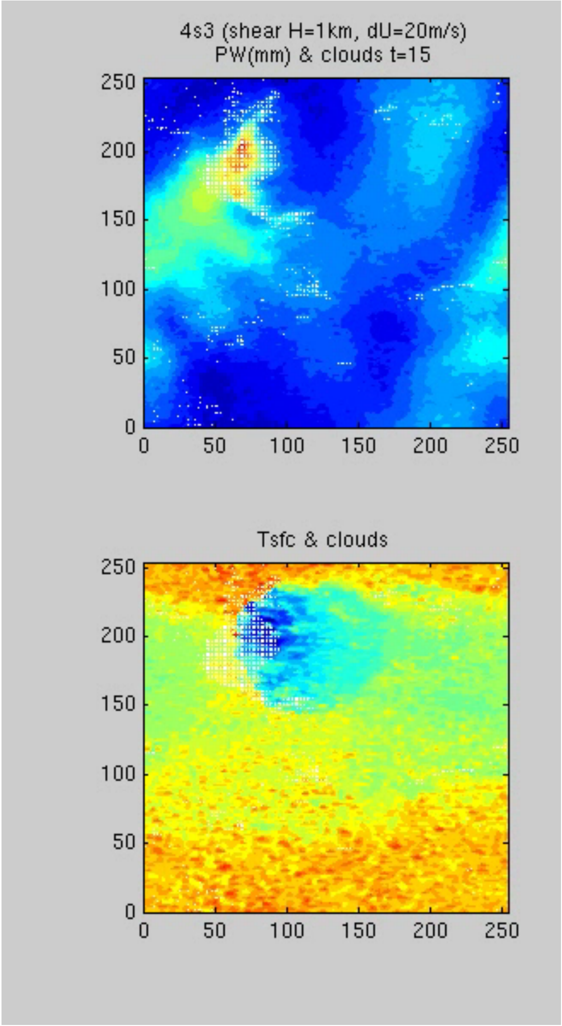



## Super critical shear

Top view

Color: PW

Color: Tsfc

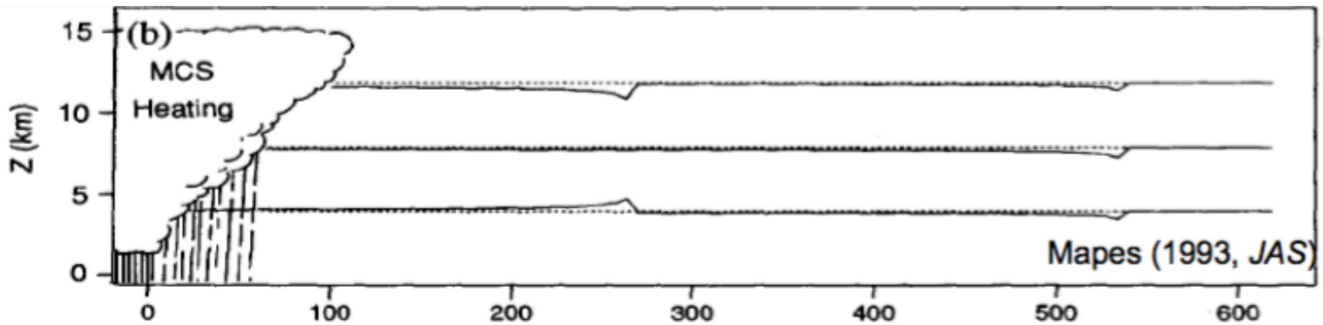



*[Robe & Emanuel 1996; Muller 2013]*

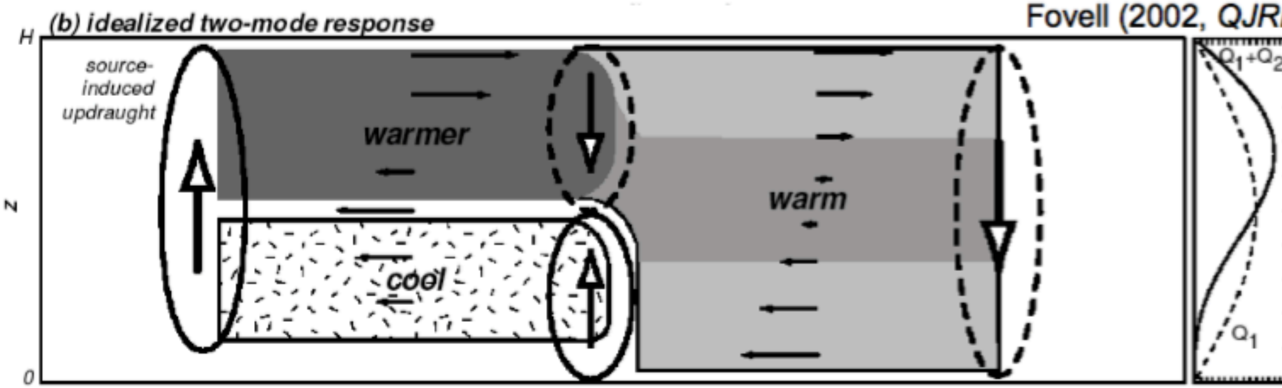
# Convective organization: processes - waves

Shear alone cannot explain organization of all convective systems in tropics :
- wind shear is often too weak
- upscale growth is ubiquitous and sometimes rapid, occurring beyond the extent of cold pools
- convective inhibition is small => small perturbations can easily initiate new convection

=> Mapes (1993, *JAS*) described tropical convection as ‘gregarious’, prone to form in clusters, as a result of horizontally propagating gravity waves destabilizing the cloud environment and promoting new convection.



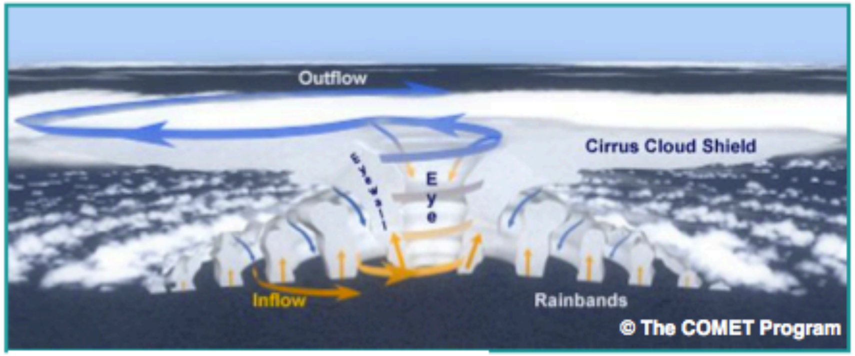

Fovell (2002, *QJRMS*)

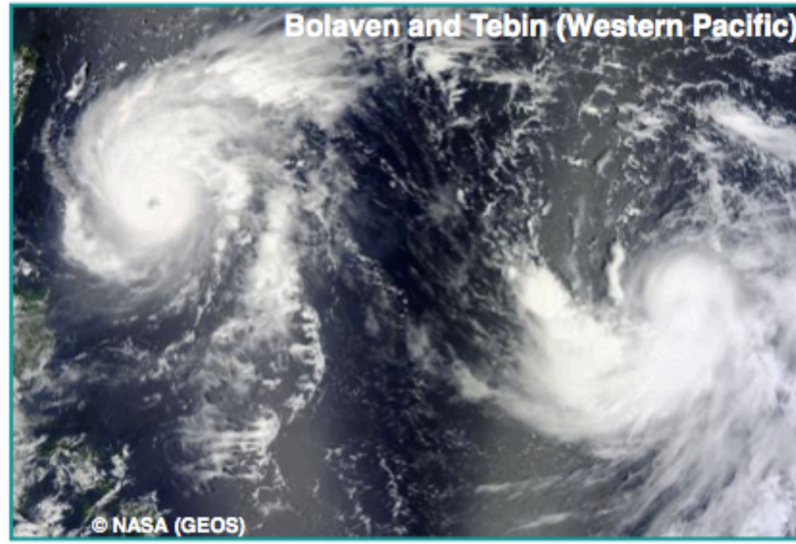


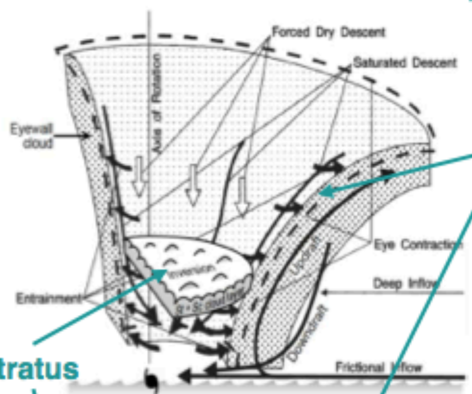

Horizontally propagating gravity waves communicate diabatic heating/cooling to environment:
- Deep heating generates deep waves that propagate fastest and warm (stabilize) the troposphere;
- Shallow (evaporative) cooling generates shorter waves that cool (destabilize) the low levels, destabilizing the environment and promoting new convection nearby

# Convective organization: processes - WISHE

## Hurricanes



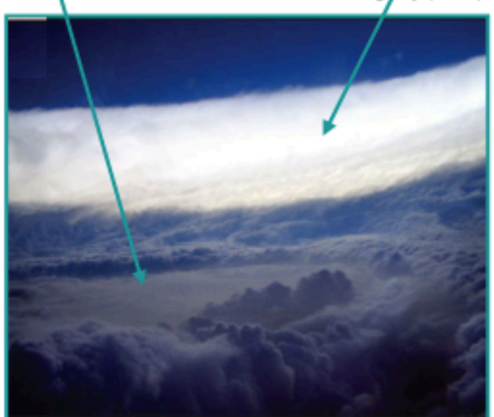



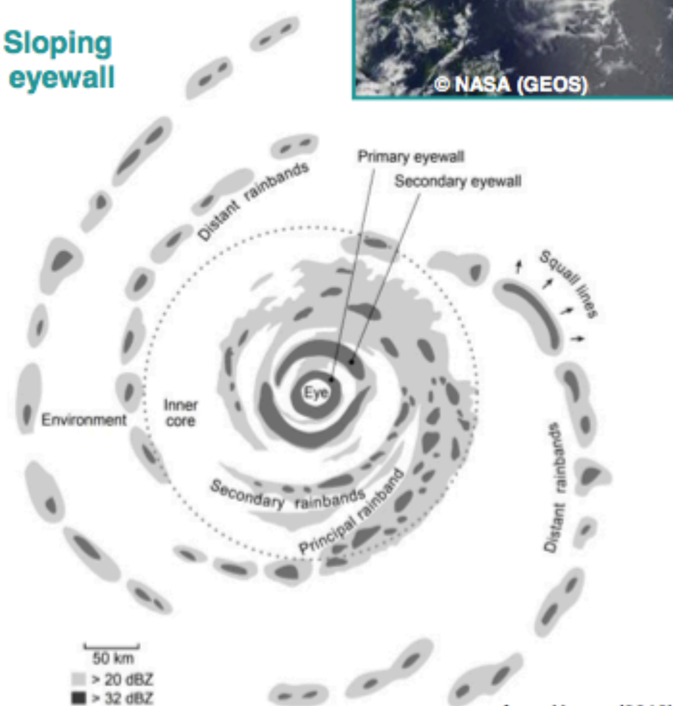




from Willoughby (1998)

Sloping eyewall

Stratus






from Houze (2010)

# Convective organization: processes - WISHE

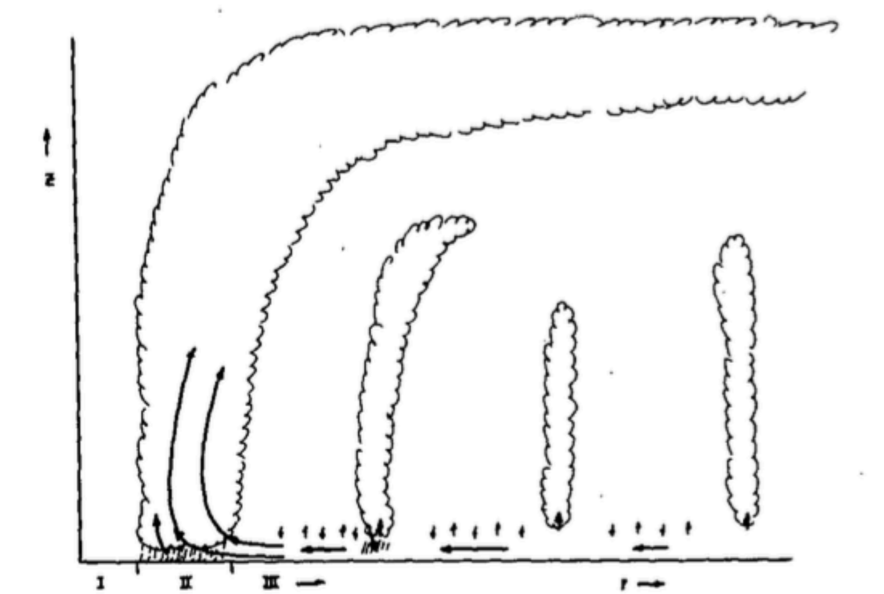



FIG. 5. Subdivision of the tropical cyclone boundary layer. Region I: the eye; Region II: the eyewall; Region III: the outer region. Considerable mixing of $\theta_e$ across the boundary layer top is assumed to occur in Region III. (See text.)

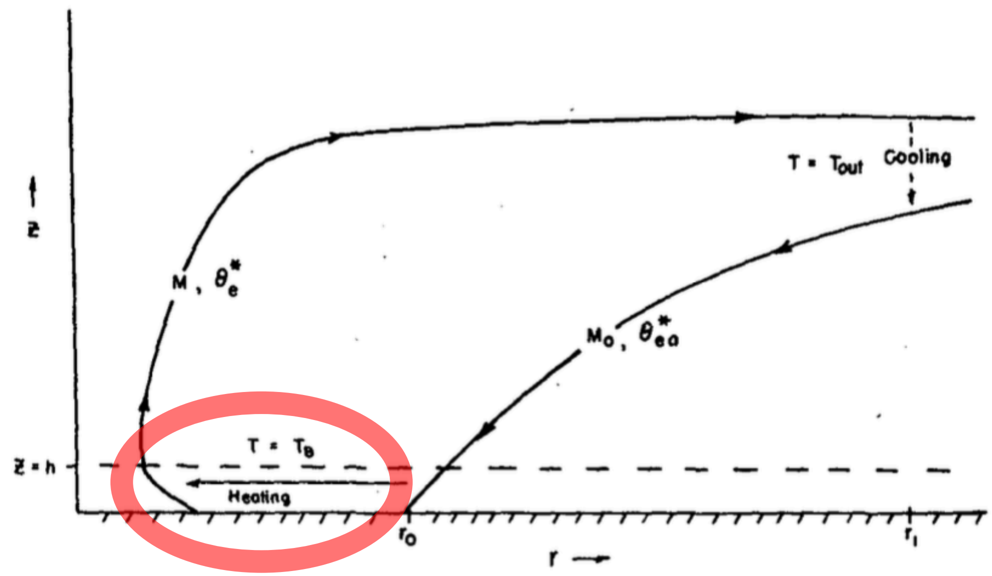


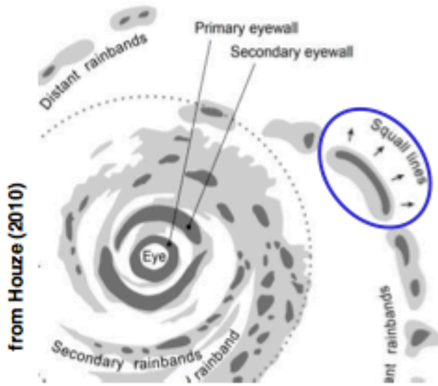

FIG. 13. The tropical cyclone as a Carnot heat engine. See text for explanation.

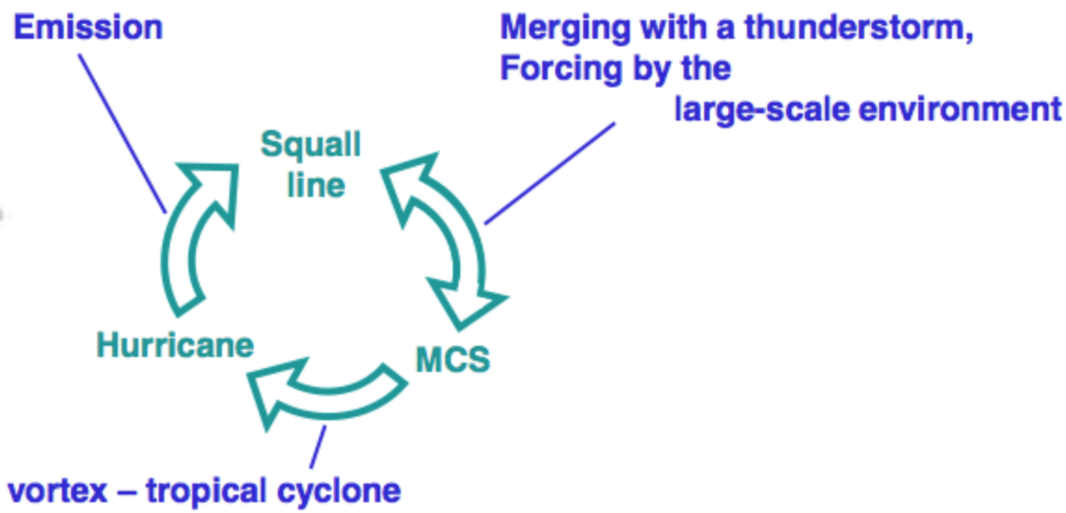
« Wind-induced surface-heat exchange » (WISHE):
Surface fluxes are enhanced in the moist eyewall region
⇒ energy (MSE) increases in the high-energy region
⇒ positive feedback on convective organization

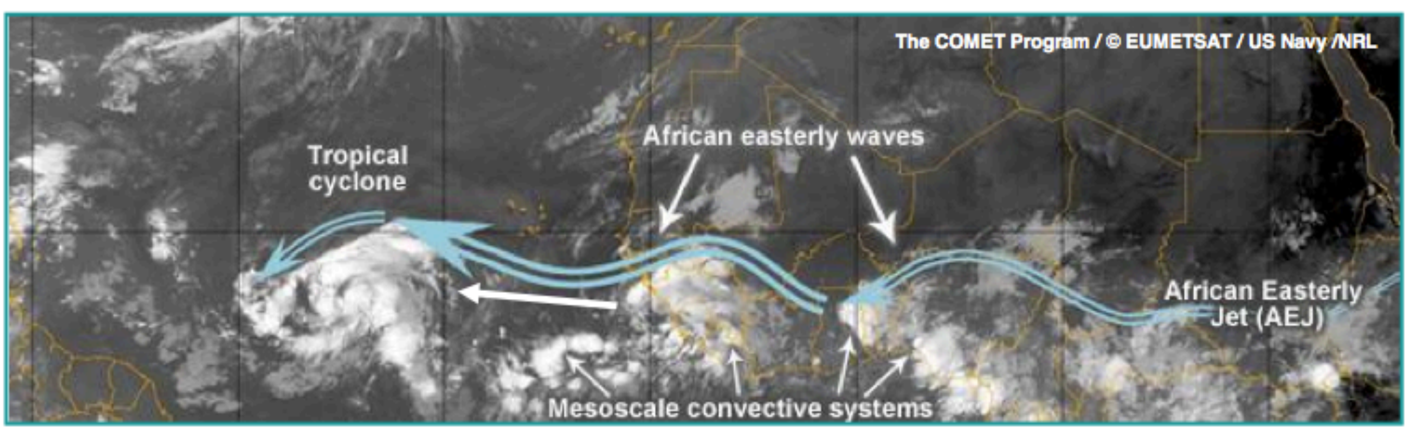
*Emanuel 86*

# Convective organization

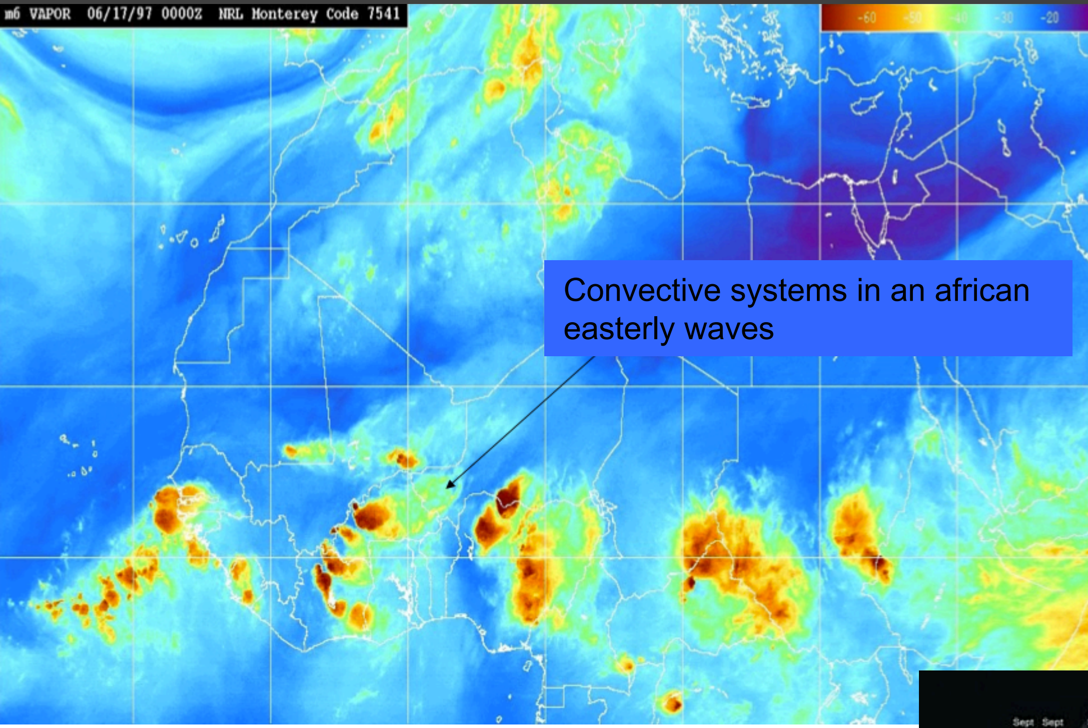
## Transitions between organized structures



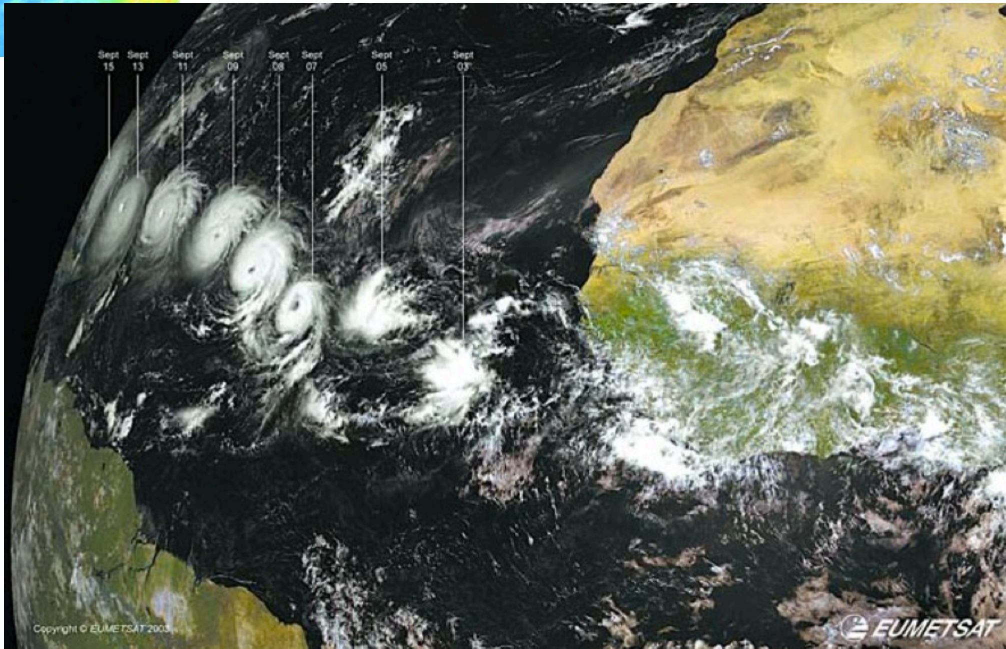



# Convective organization




Hurricane Isabel off the coast of Africa



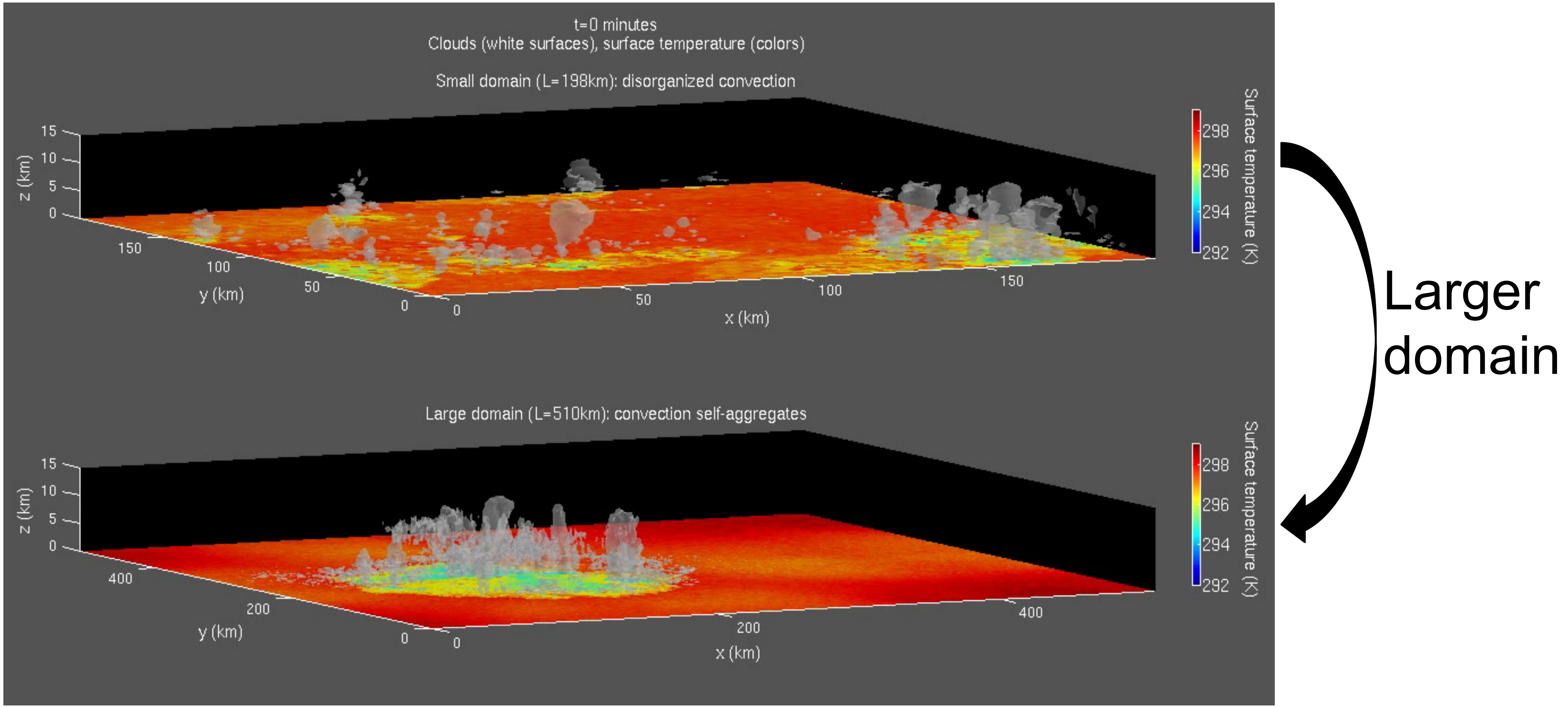
# Convective organization: Self-aggregation?

In recent years, high resolution (~km resolution) simulations on large mesoscale domains (~100s km domain)

⇒ allowed the use of convection-resolving simulations to study the mesoscale organization of convection

⇒ Led to the discovery of « self-aggregation », spectacular ability of deep convection to spontaneously organize in space under certain conditions

*Clouds over near-surface temperature*



# A recently discovered phenomenon : Self-aggregation of tropical convection

First discovered in idealized cloud-resolving models (CRM)

Idealized state of tropical convection :
- Radiative Convective Equilibrium (neglects export of energy=MSE to higher latitudes)
- Non-rotating (i.e. Coriolis parameter $f = 0\ s^{-1}$)

Since then found to be robust in other models and settings …

# Radiative Convective Equilibrium

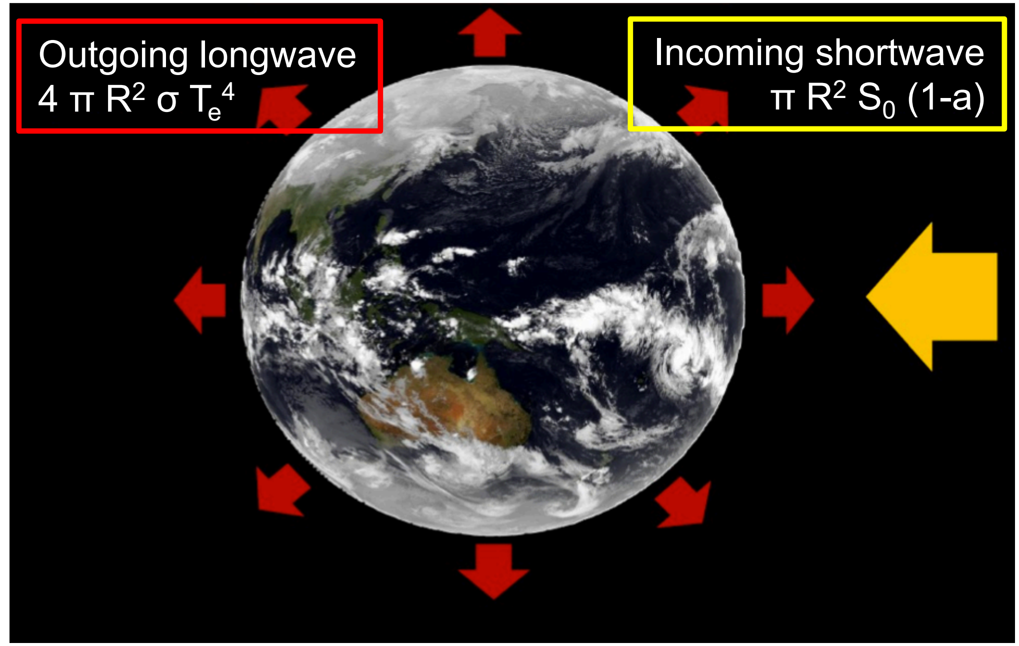
**Radiative Equilibrium:**

Equilibrium state of atmosphere and surface in the absence of non-radiative fluxes

Radiative heating&cooling drives atmosphere toward state of radiative equilibrium

# Radiative Convective Equilibrium

**Radiative Equilibrium:**

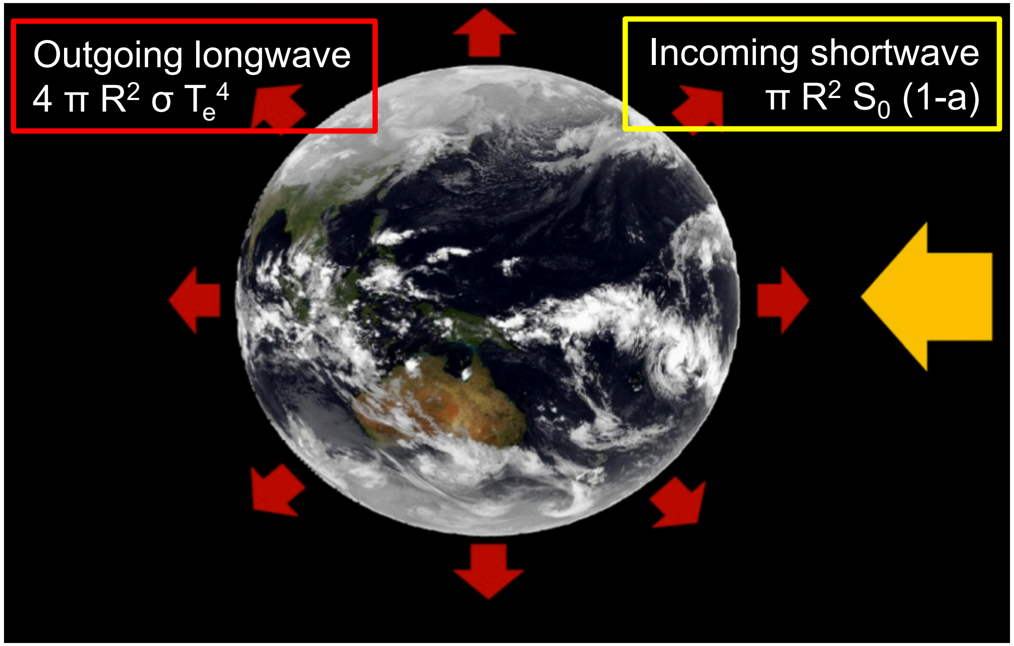


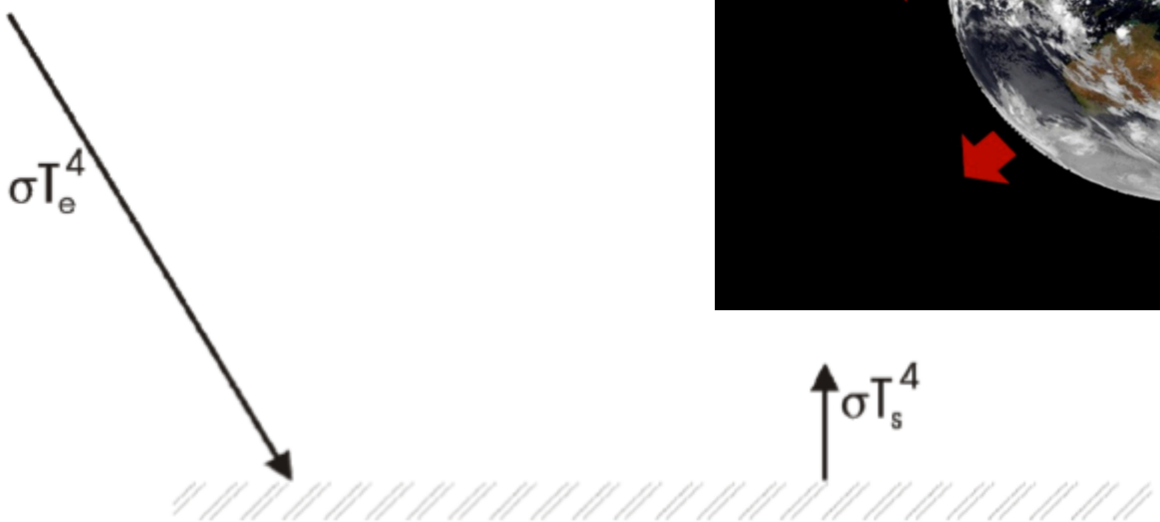


TOA: $\sigma T_e^4 = S_0 (1\text{-}a) / 4$

# Radiative Convective Equilibrium

**Radiative Equilibrium:**




TOA: $\sigma\, T_e^4 = S_0\,(1\text{-}a)\,/\,4$

Earth => $T_e = T_s$ = 255K = −18° C !!

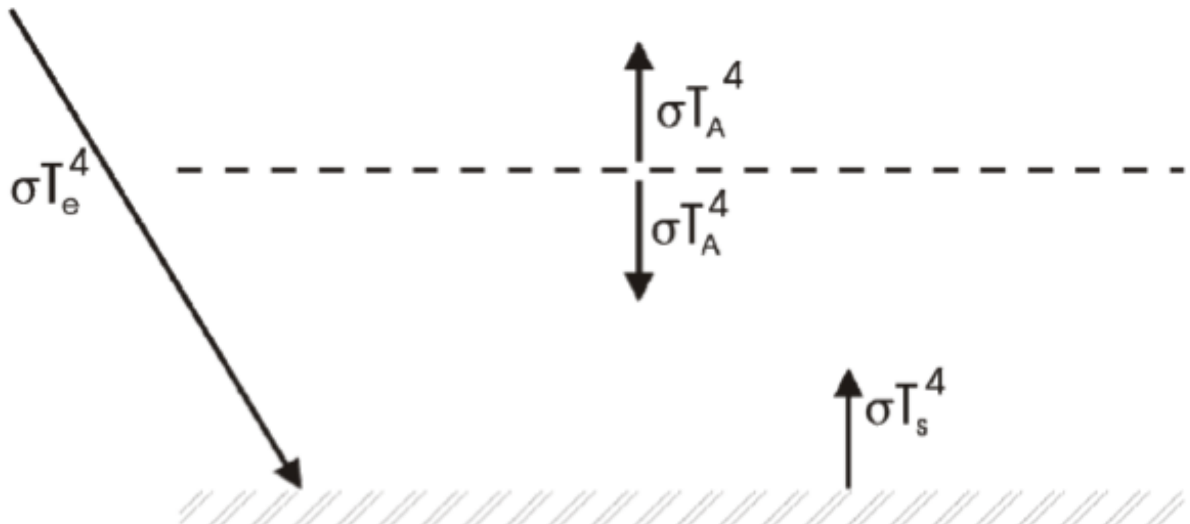
Observed average surface temperature = 288K = 15° C…

# Radiative Convective Equilibrium

**Radiative Equilibrium:**

**One-Layer Model**

Transparent to solar radiation
Opaque to infrared radiation
Blackbody emission from surface and each layer




*Courtesy Kerry Emanuel*

TOA: $\sigma T_e^4 = S_0 (1\text{-}a) / 4$

# Radiative Convective Equilibrium

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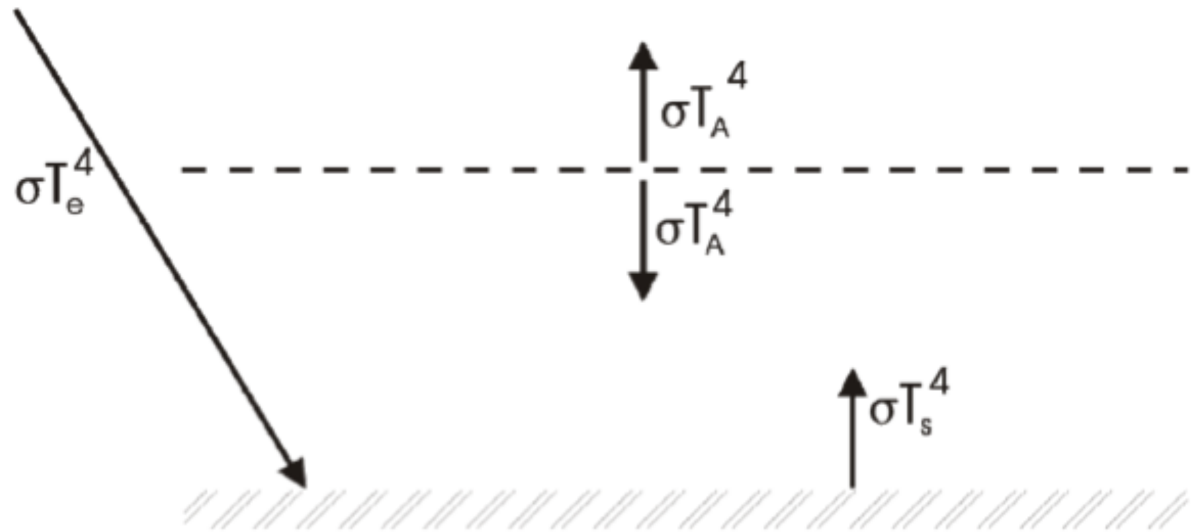



*Courtesy Kerry Emanuel*

TOA: $\sigma T_e^4 = S_0 (1\text{-}a) / 4$

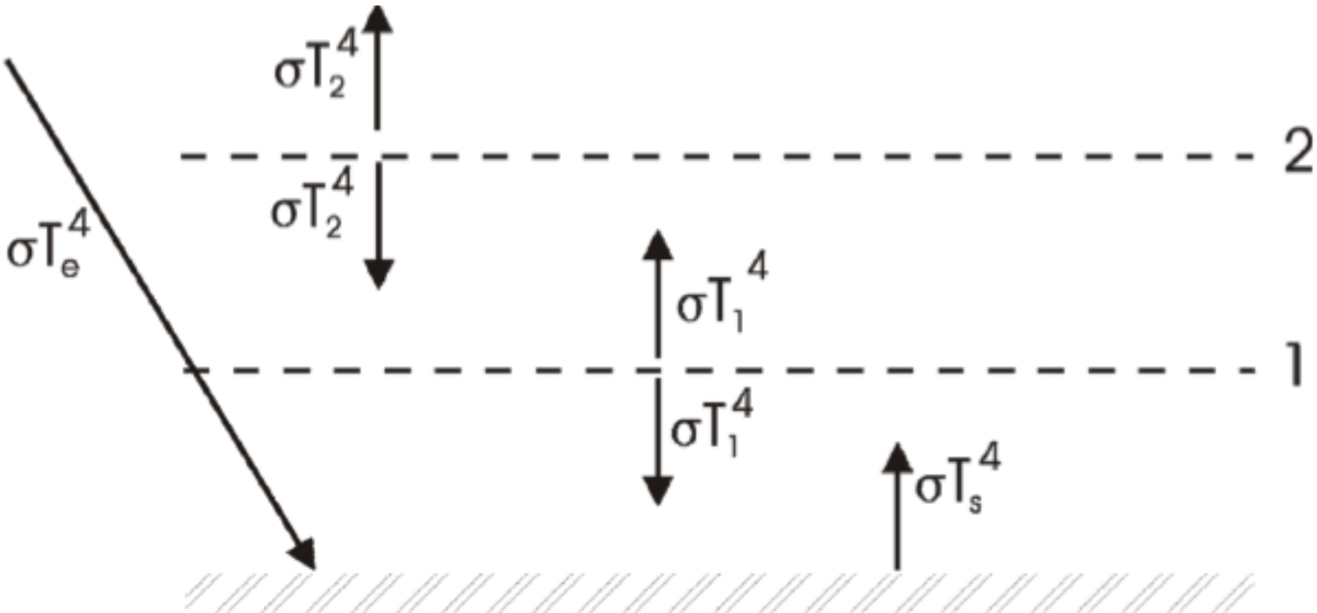
Level 1: $2 \sigma T_A^4 = \sigma T_s^4$

Surface: $\sigma T_s^4 = \sigma T_e^4 + \sigma T_A^4$

$\Rightarrow T_A^4 = T_e^4$ and $T_s^4 = 2 T_e^4 \Rightarrow T_s = 2^{1/4} T_e = 303$ K

# Radiative Convective Equilibrium

**Radiative Equilibrium:**
**Two-Layer Model**




TOA: $\sigma T_e^4 = S_0 (1\text{-}a) / 4$

*Courtesy Kerry Emanuel*

Level 2: $2 \sigma T_2^4 = \sigma T_1^4$

Level 1: $2 \sigma T_1^4 = \sigma T_s^4 + \sigma T_2^4$

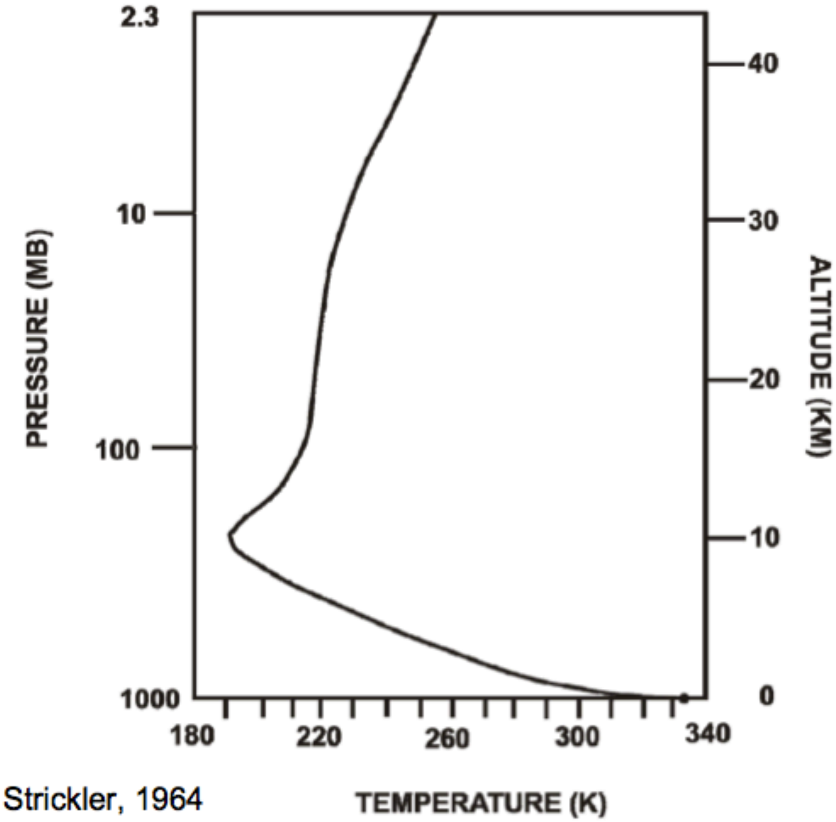
Surface: $\sigma T_s^4 = \sigma T_e^4 + \sigma T_1^4$

$\Rightarrow T_s = 3^{1/4} T_e$

# Radiative Convective Equilibrium

**Radiative Equilibrium:**

**Full calculation of Radiative Equilibrium**




After Manabe and Strickler, 1964

# Radiative Convective Equilibrium

**Radiative Equilibrium:**

**Problems with radiative equilibrium solution:**

- Too hot at and near surface
- Too cold at a near tropopause
- Lapse rate of temperature too large in the troposphere
- (But stratosphere temperature close to observed)

=> Troposphere is unstable to moist convection

# Radiative Convective Equilibrium

**Radiative Convective Equilibrium:**

Radiative relaxation time scales ~ 40 days

Convective adjustment time scales: minutes (dry) to hours (moist)

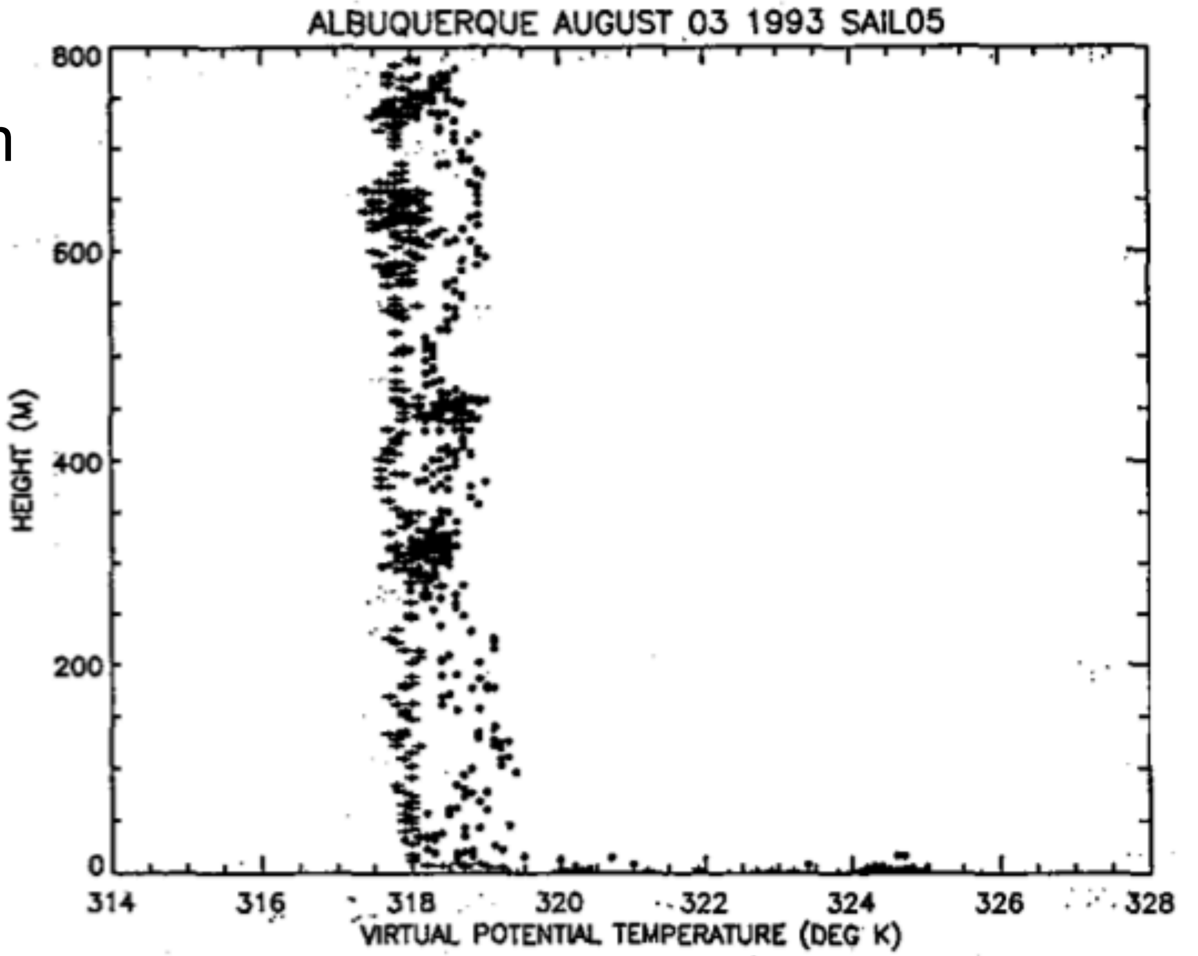
In competition between radiation and convection, convection “wins” and the observed state is much closer to convective neutrality than to radiative equilibrium

Vertical T profile neutral to dry convection below condensation level (Dry adiabat)
&
Vertical T profile neutral to moist convection above LFC (Moist adiabat)

# Radiative Convective Equilibrium

Dry convective boundary layer over daytime desert *[Renno and Williams, 1995]*

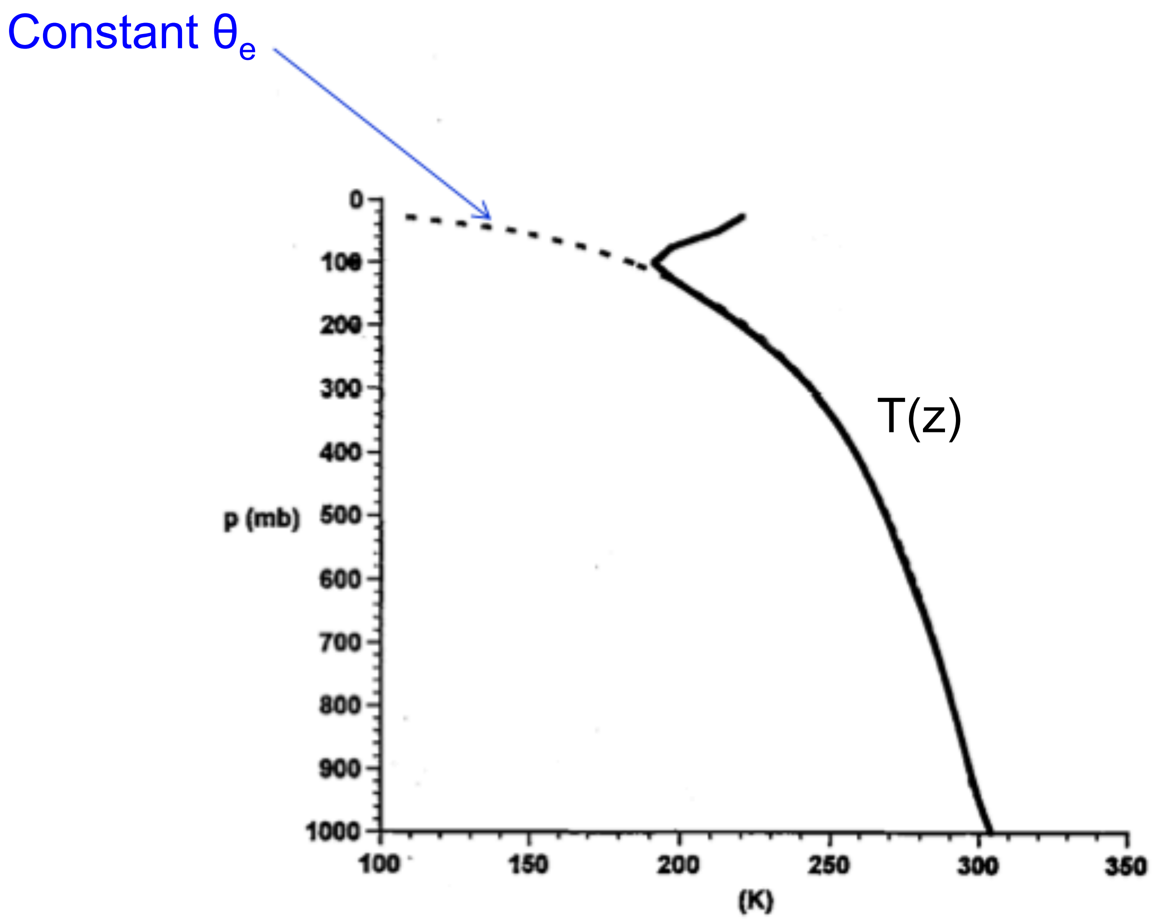
800m




But above a thin boundary layer, most atmospheric convection involves phase change of water: Moist Convection

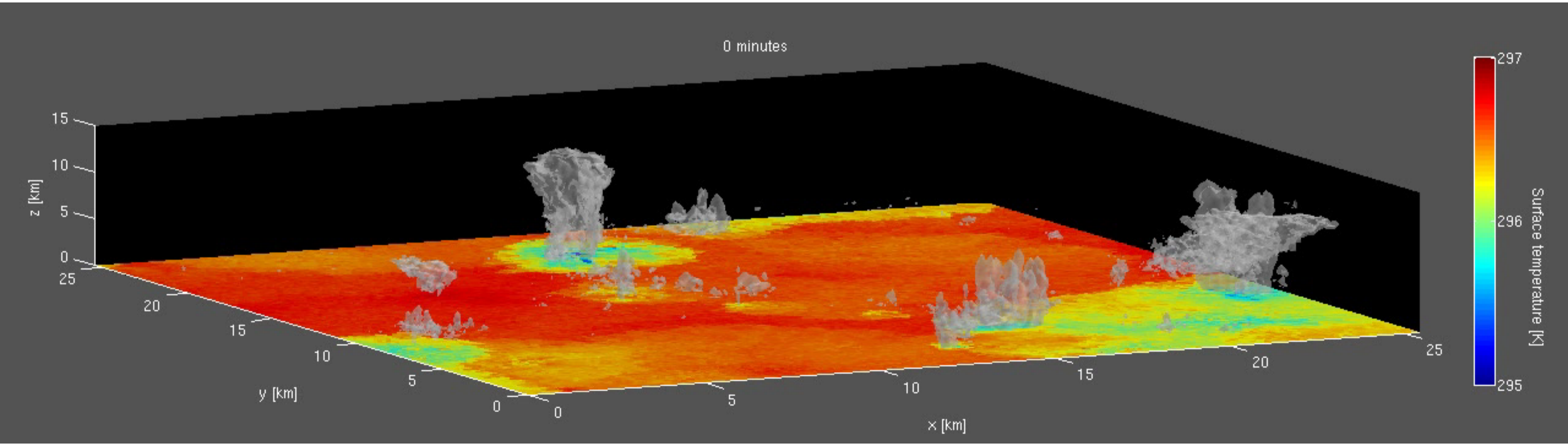
# Radiative Convective Equilibrium

Tropical sounding => moist adiabatic



# Radiative Convective Equilibrium

*Clouds over near-surface temperature*




Radiative cooling in the interior of the atmosphere => destabilizes

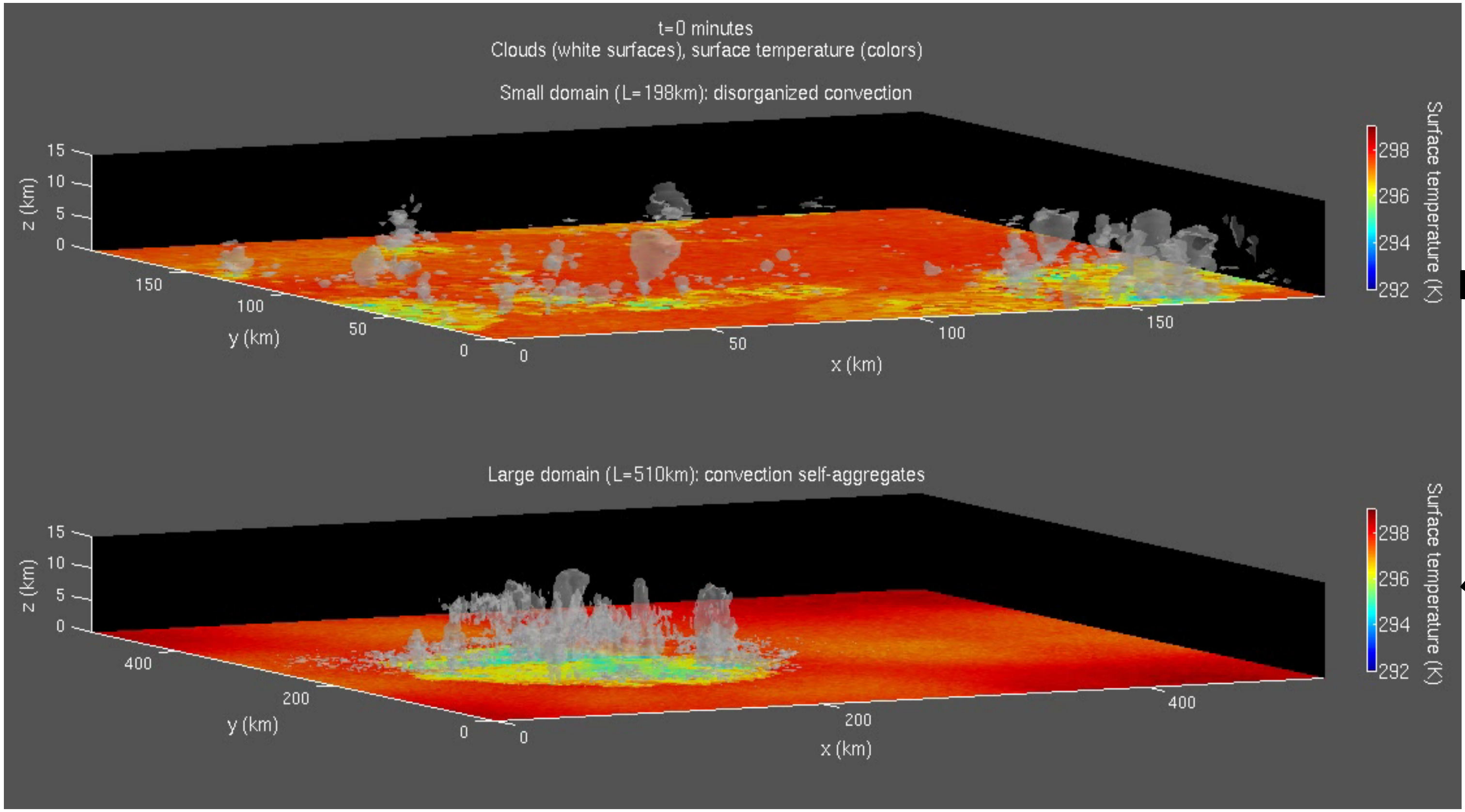
Convective updrafts bring moist, high energy air from surface to interior of the atmosphere => stabilizes

Convective downdrafts bring cold&dry, low energy air from interior to surface => stabilizes

# What is self-aggregation ?

Self-aggregation = instability of disorganized RCE “pop corn” state

*Clouds over near-surface temperature*



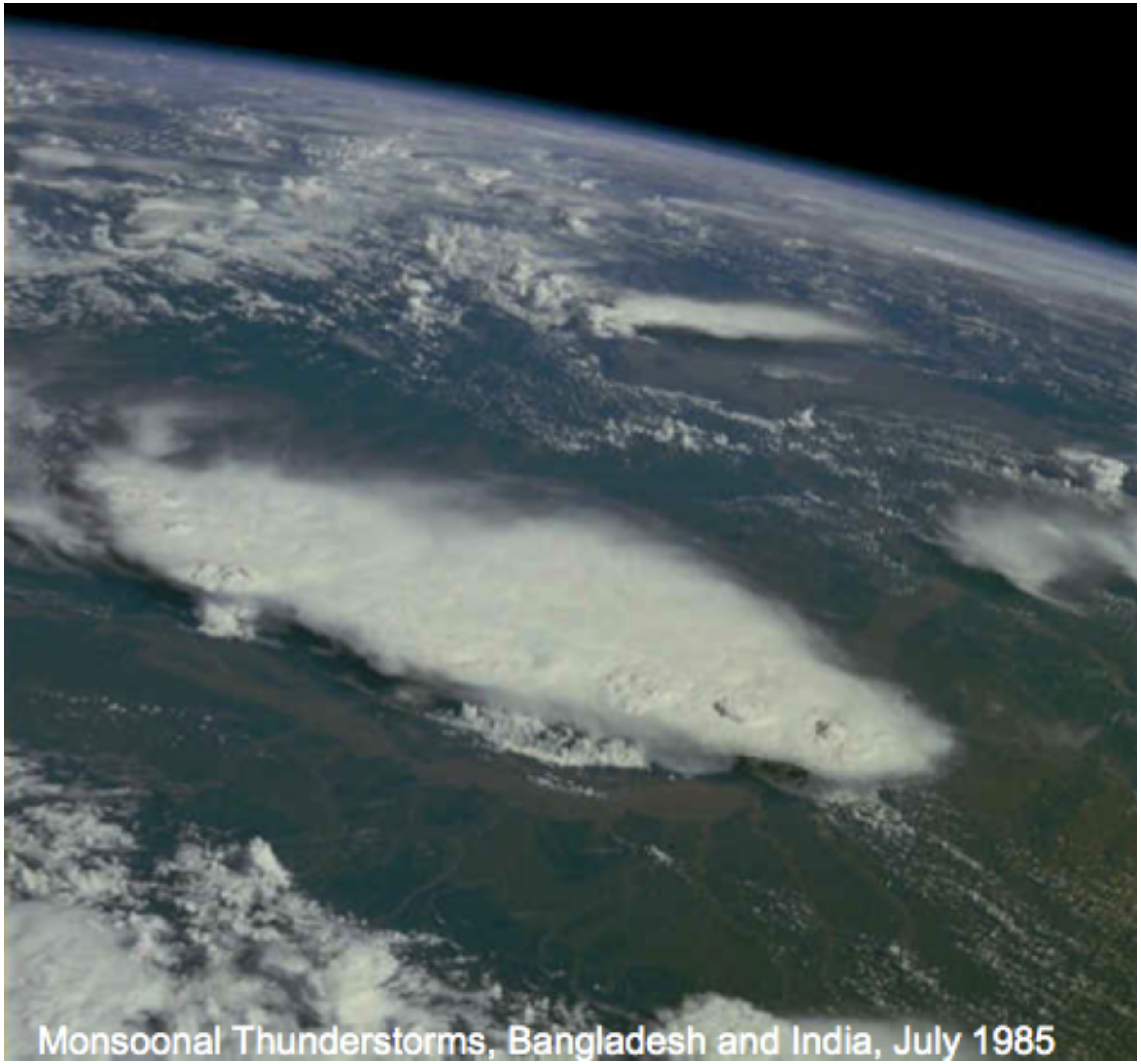

Convection is disorganized => “pop corn” state

Larger domain

Convection self-aggregates

*[Held Hemler Ramaswamy 92; Raymond, Zeng 2000; Bretherton, Blossey, Khairoutdinov, 2005; Sobel, Bellon, Bacmeister 2007; Muller, Held 2012; Emanuel, Wing, Vincent 2013; Wing Emanuel 2013; Jeevanjee Romps 2013; Khairoutdinov Emanuel, 2013; Shi Bretherton 2014; Tobin, Bony, Roca, 2012; Tobin et al, 2013; Muller Bony 2015; Mapes 2016; Holloway&Woolnough 2016; Wing Holloway Emanuel Muller 2017 (review)]*

# Self Aggregation: why do we care?



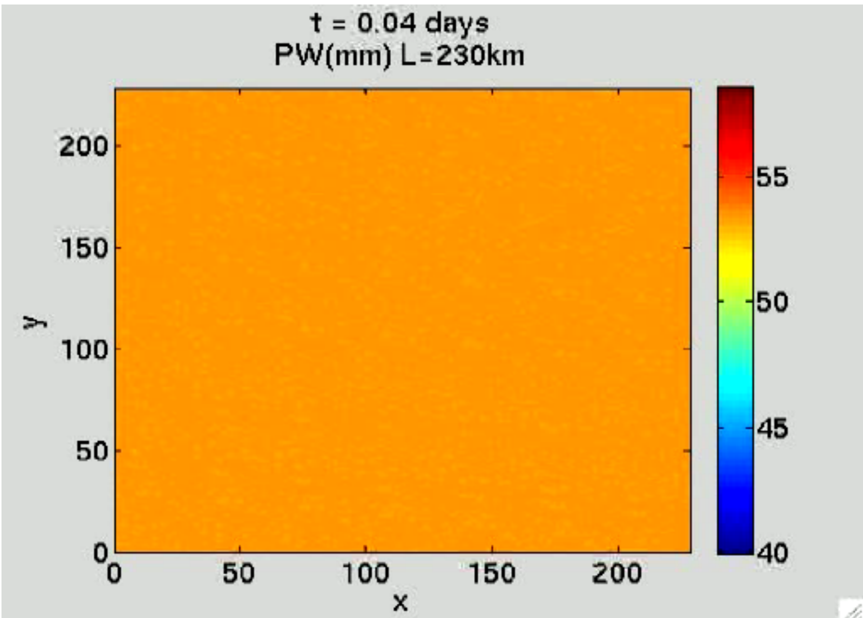
# Self Aggregation: why do we care?

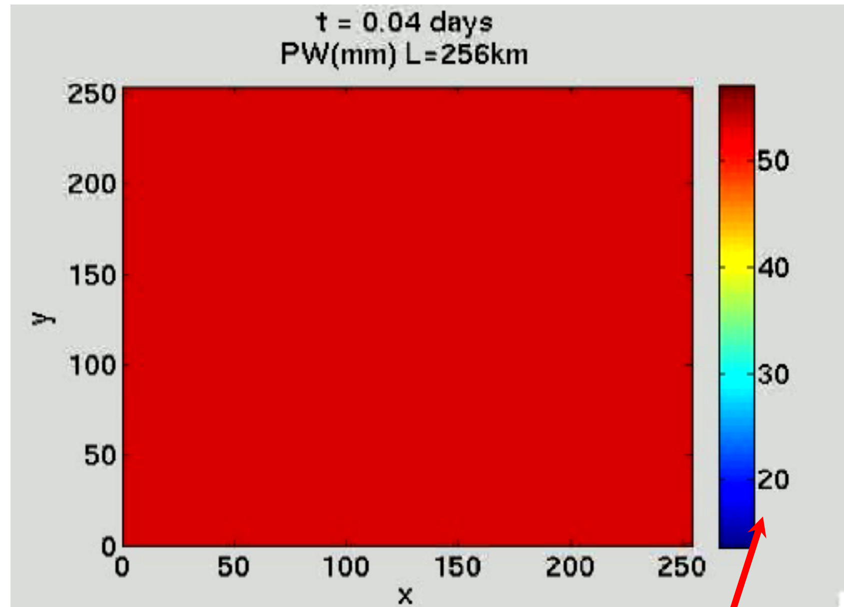
Top view

230km

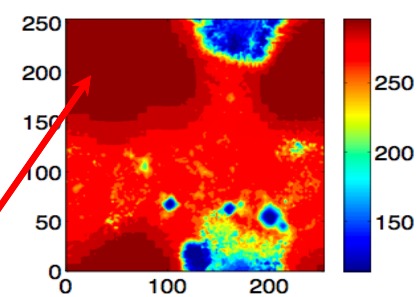
256km

WV:




OLR:



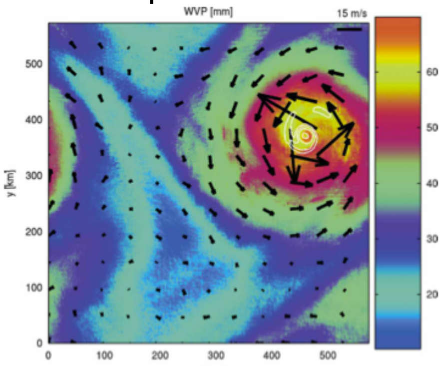

⇒ Thermodynamic and radiative properties dramatically affected

# Self Aggregation: why do we care?

Feedback responsible for self-aggregation - Role in cyclogenesis ?

Add rotation => tropical cyclones

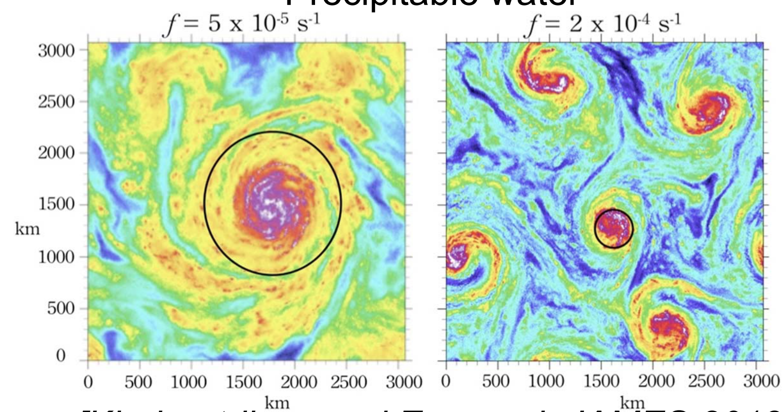
Precipitable water




*[Bretherton, Blossey, Khairoutdinov, JAS 2005]*

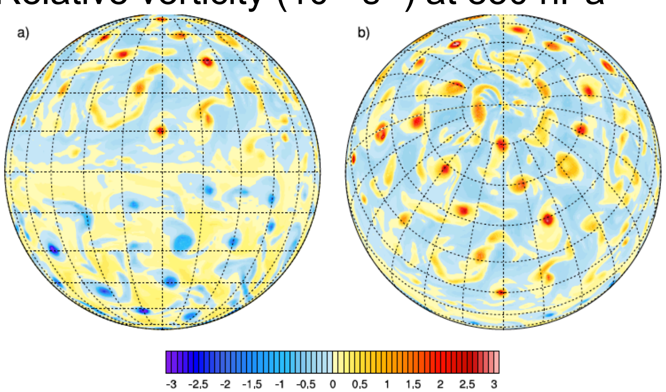
« TC World »

Precipitable water

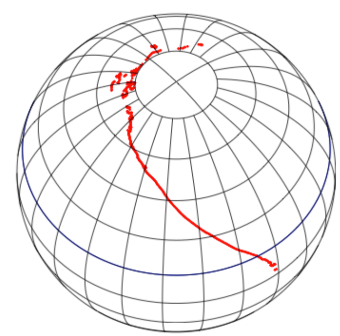



*[Khairoutdinov and Emanuel, JAMES 2013]*

Relative vorticity ($10^{-4}$ s$^{-1}$) at 850 hPa




Averaged trajectory of vortices. (blue circle=15N)



*[Shi and Bretherton, JAMES 2014]*

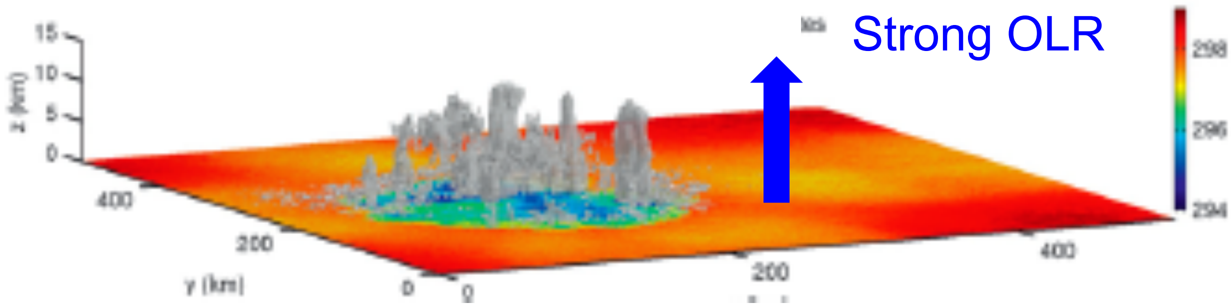
Self-aggregation of convection - Role in MJO ? *[Tobin et al, JAMES 2013]*

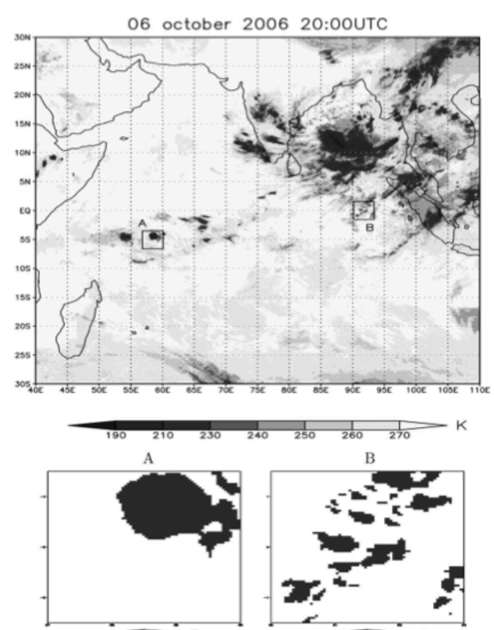
# Self Aggregation: why do we care?

Warm temperatures favor aggregation.
Cold temperatures as well.

*[Emanuel, Wing, Vincent, JAMES 2013
Abbot J. Clim. 2014]*

Self-aggregation regulates tropical climate?
Warmer temperatures => More aggregation => More LW cooling => <0 feedback




Brightness temperature

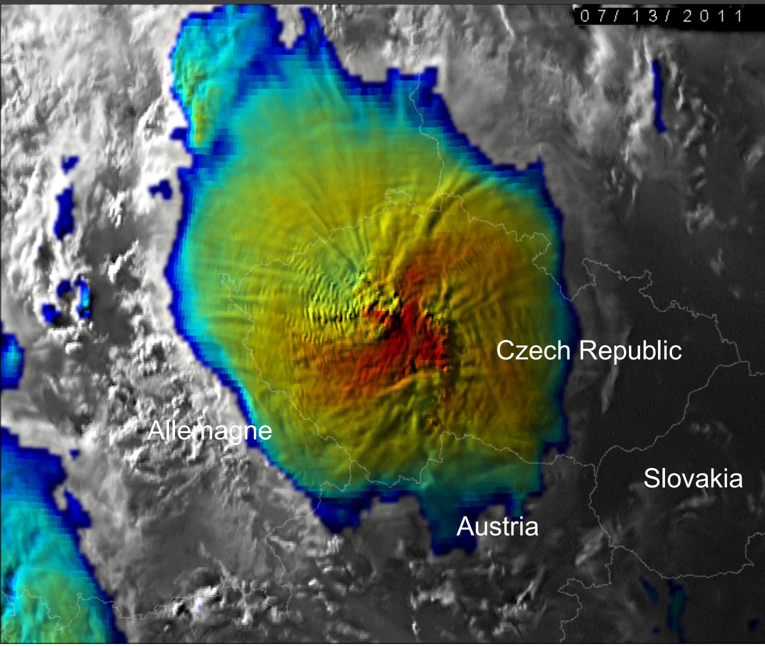
Radiative impact unclear.

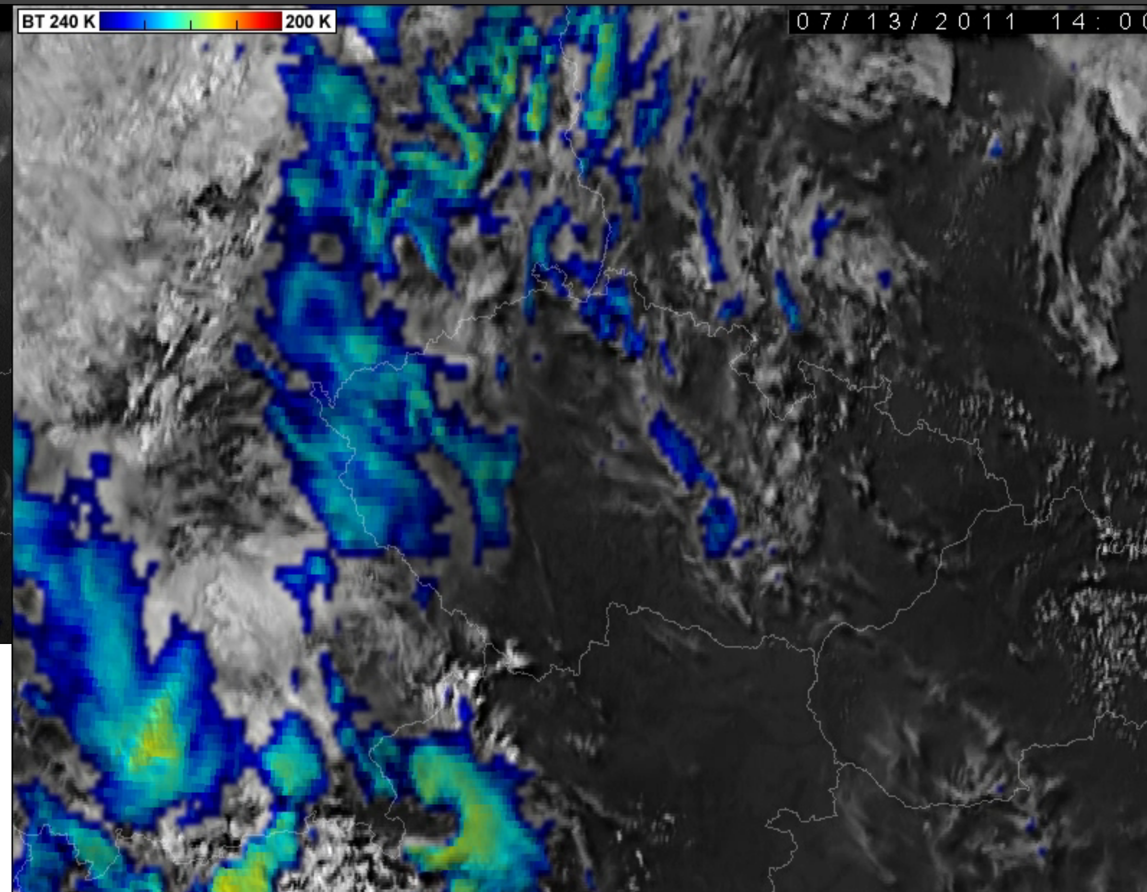
Observations suggest that SW warming may partly compensate LW cooling ?

Still true at warmer T?

*[Tobin, Bony, Roca, J.Clim 2012
Tobin et al, JAMES 2013]*

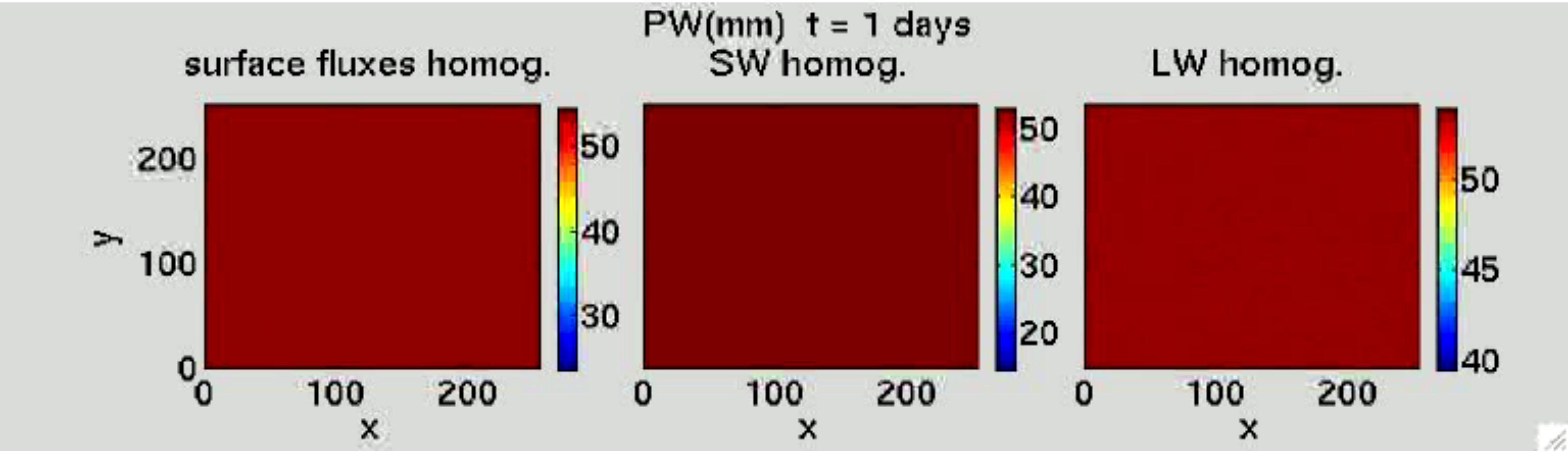
# Self-Aggregation of Convection




Physical mechanism responsible?

# Sensitivity study

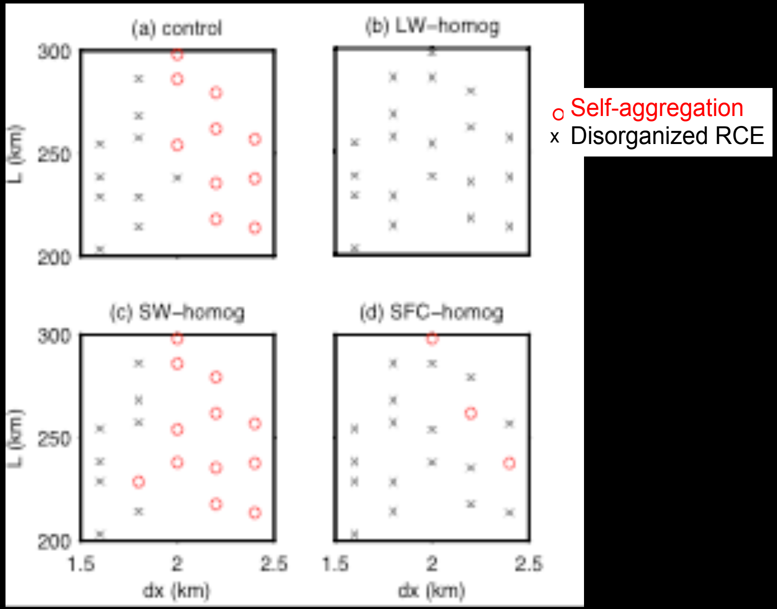



⇒ LW interactive radiation crucial

# Sensitivity study

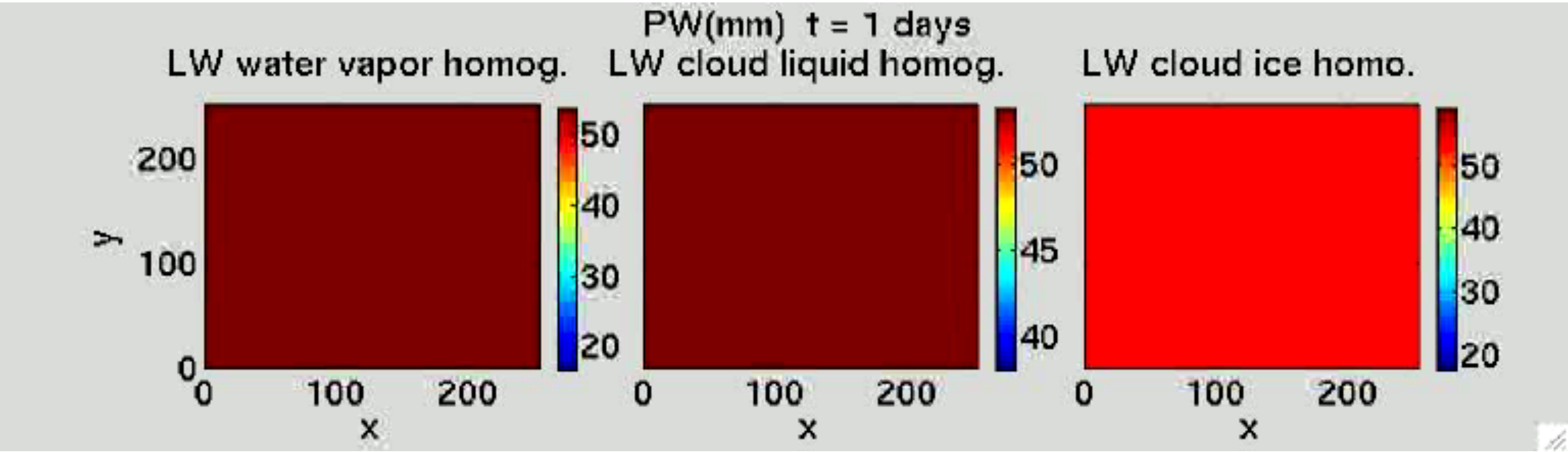
Feedbacks leading to aggregation

Results from sensitivity experiments in which various feedbacks are turned off




=> interactive LW radiative cooling crucial

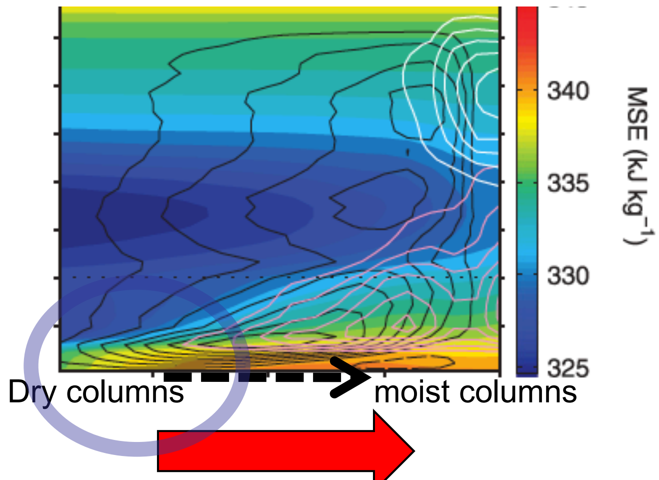
# Sensitivity study



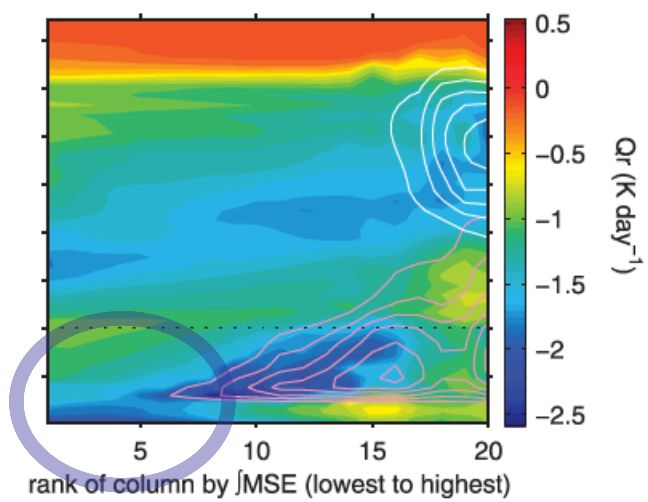

⇒ low cloud LW radiation crucial

# Why is the LW cooling from low clouds crucial?

*Circulation with aggregation during the onset of aggregation :*
*Streamfunction (dark lines)*
*Moist Static Energy (colors)*



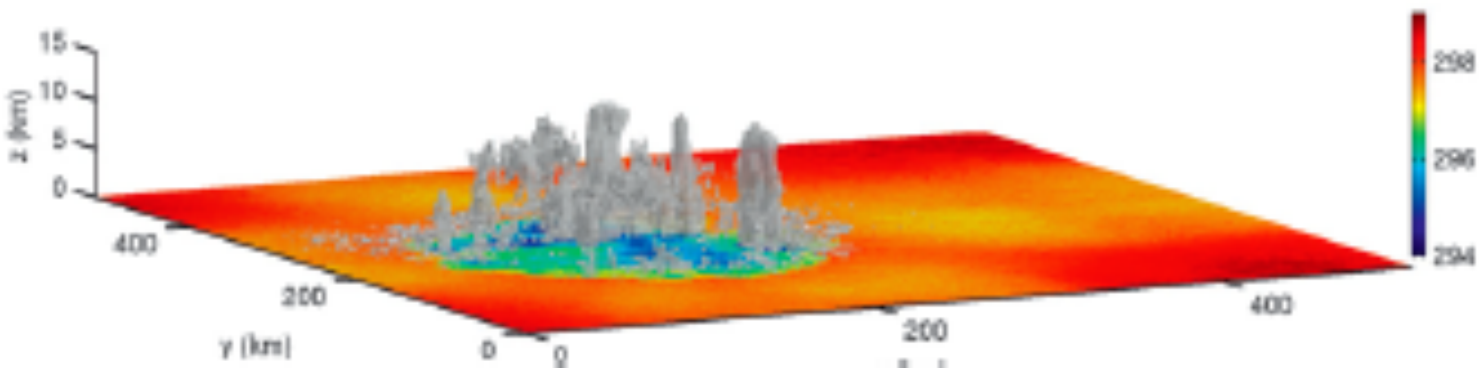

Near-surface MSE transport from dry to moist region
=> up gradient MSE transport
*Why flow so low?*




Very strong low-level cooling in the dry region at the top of low clouds
=> subsidence

*[Bretherton, Blossey, Khairoutdinov, 2005; Muller&Held 2012]*

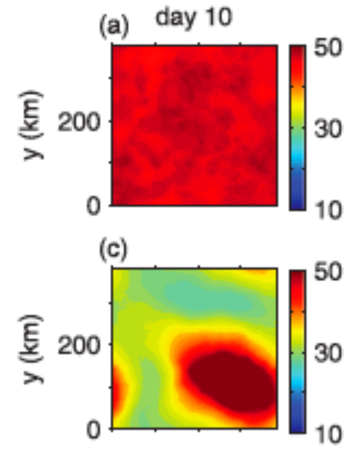
Where are the low clouds?



No low cloud LW

With low cloud LW

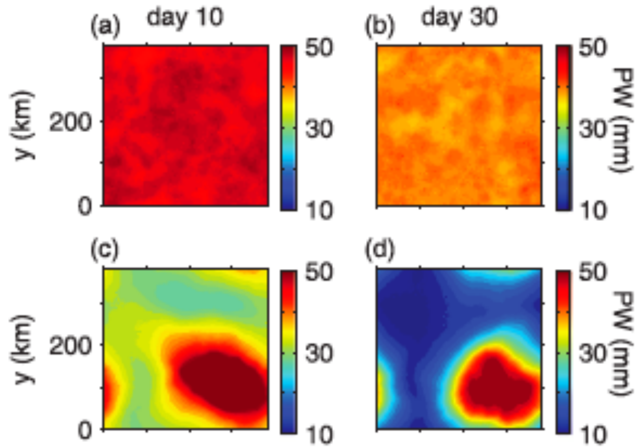
Remove low cloud LW after 10 days



No low cloud LW

With low cloud LW

Remove low cloud LW after 10 days



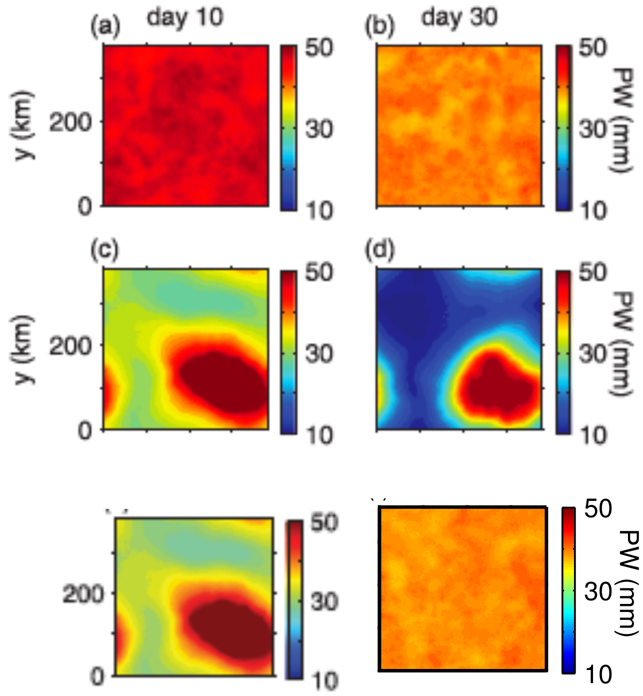

⇒ **Mechanism responsible for ONSET (low clouds LW)**
**Different from mechanism responsible for MAINTENANCE** *clear sky* + *high clouds*

No low cloud LW

With low cloud LW

Remove low cloud LW after 10 days

Remove all LW after 10 days




*[Muller & Held JAS 2012]*

⇒ high cloud LW + clear-sky LW radiation also contribute positively to aggregation

# Self-Aggregation of atmospheric convection in idealized simulations

Literature confusing…

- Cloud radiative processes, in particular in the longwave, have been shown to play a crucial role in the self-aggregation of convection. *[Muller&Held, JAS 2012]*

- Clear sky radiation has also been identified as a key ingredient in theoretical models of self-aggregation. *[Emanuel, Wing, Vincent JAMES 2013; Beucler&Cronin JAMES 2016]*

- Moisture feedbacks lead to aggregation in theory *[Craig&Mack JGR 2013]*

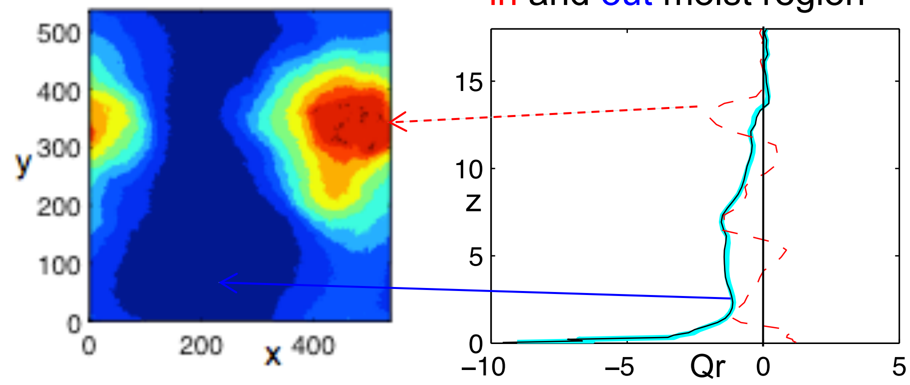
- Cold pools have been shown to impact the aggregation as well. *[Jeevanjee, Romps, GRL 2013]*

**Our question: What aspect of each physical process matters for aggregation?**

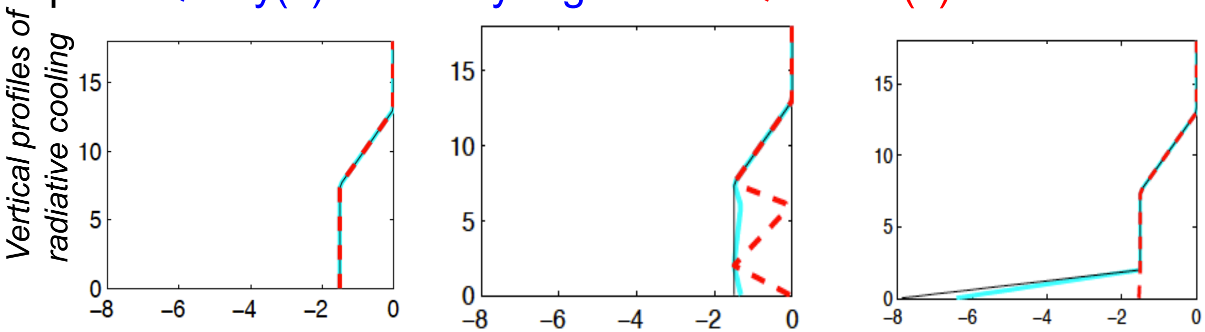
We address this question with idealized experiments

# Self-Aggregation: physical processes

Control run that aggregates :




Impose Qr-dry(z) in the dry region and Qr-moist(z) in the moist region




$$\frac{\partial T}{\partial t} = Qr(T, qv, qcloud \ldots)$$

Qr-dry(z)

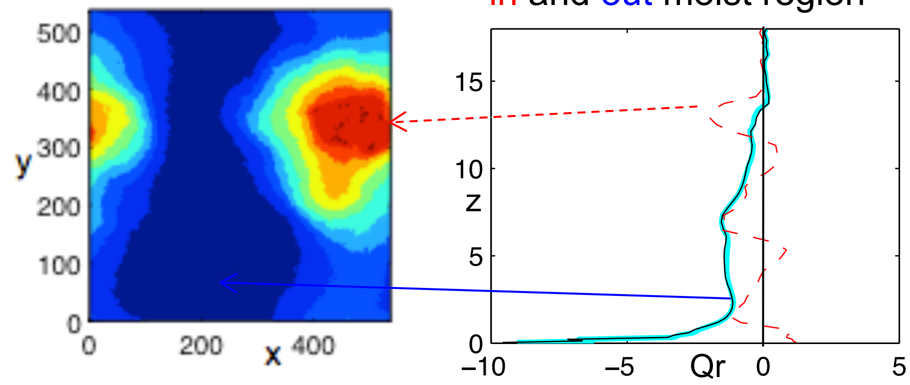
Qr-moist(z)

# Self-Aggregation: physical processes

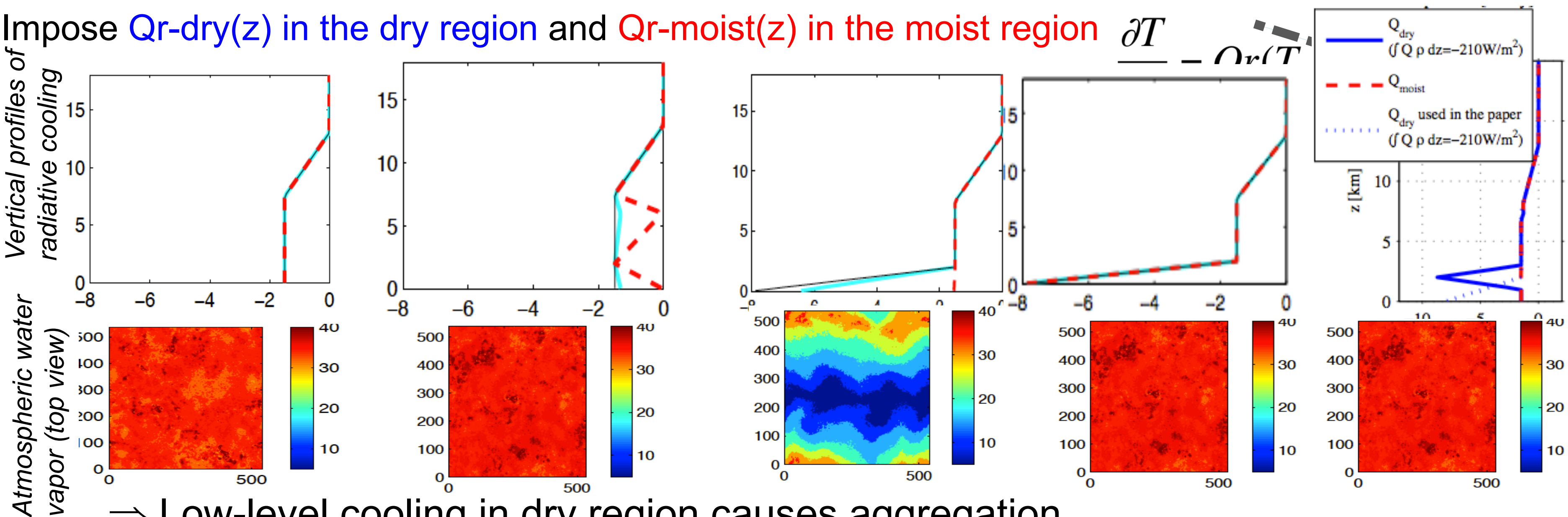
Control run that aggregates :

*Atmospheric water vapor*

Radiative cooling profiles (K/day)
in and out moist region




Impose Qr-dry(z) in the dry region and Qr-moist(z) in the moist region

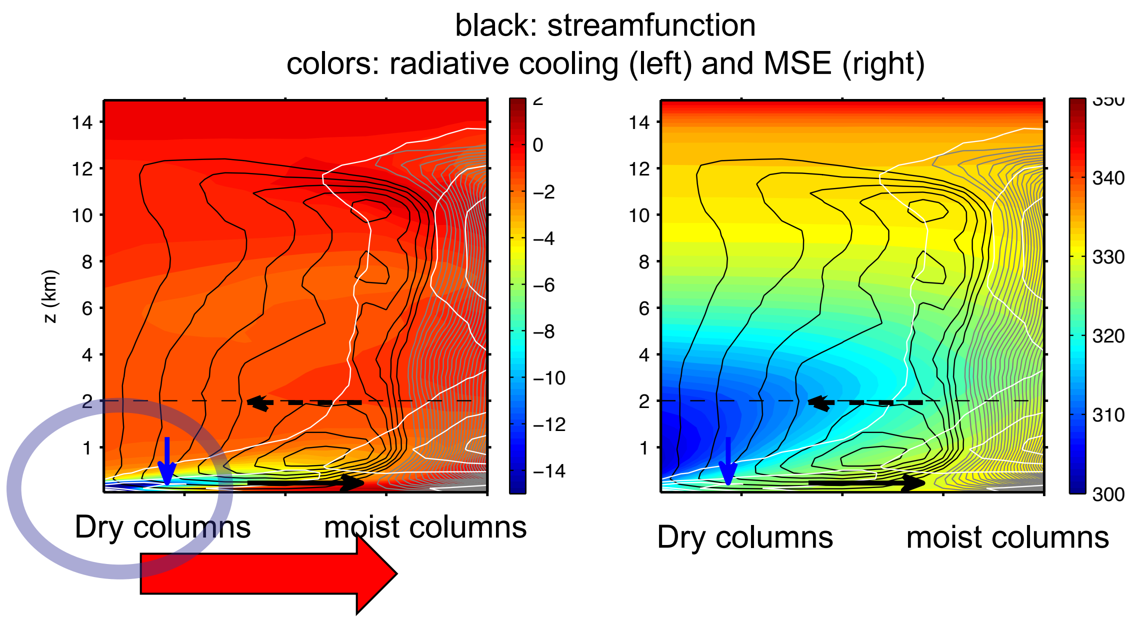



⇒ Low-level cooling in dry region causes aggregation

More precisely: Variability in low-level cooling causes aggregation

Due to low clouds

# Why does differential radiative cooling lead to aggregation?




=> upgradient MSE transport

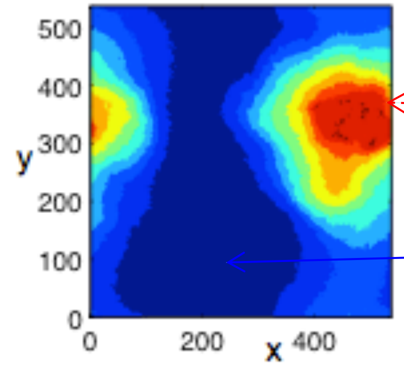
As before, low-level cooling => near-surface energy transport

*Is that the whole story?...*

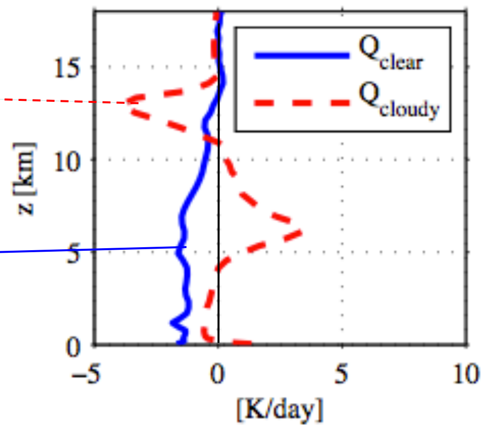
Why LW cooling from high clouds crucial for maintenance?

Remove low cloud radiative cooling

*Atmospheric water vapor*




Radiative cooling profiles (K/day) in and out high clouds

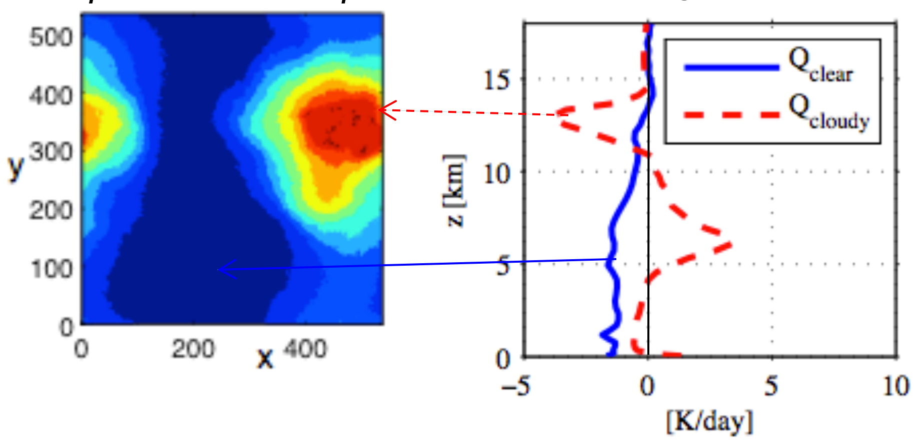


**Why LW cooling from high clouds crucial for maintenance?**

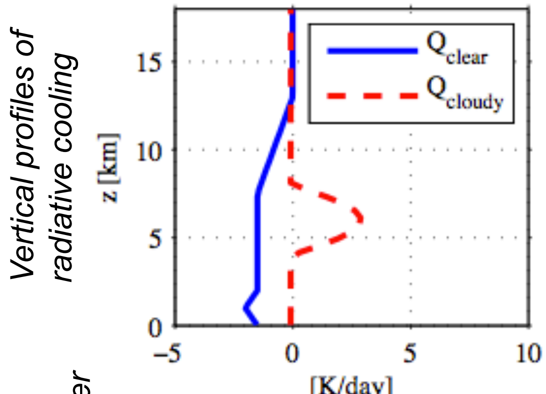
Remove low cloud radiative cooling :

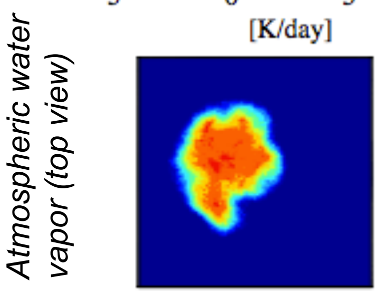
*Atmospheric water vapor*

Radiative cooling profiles (K/day) in and out high clouds



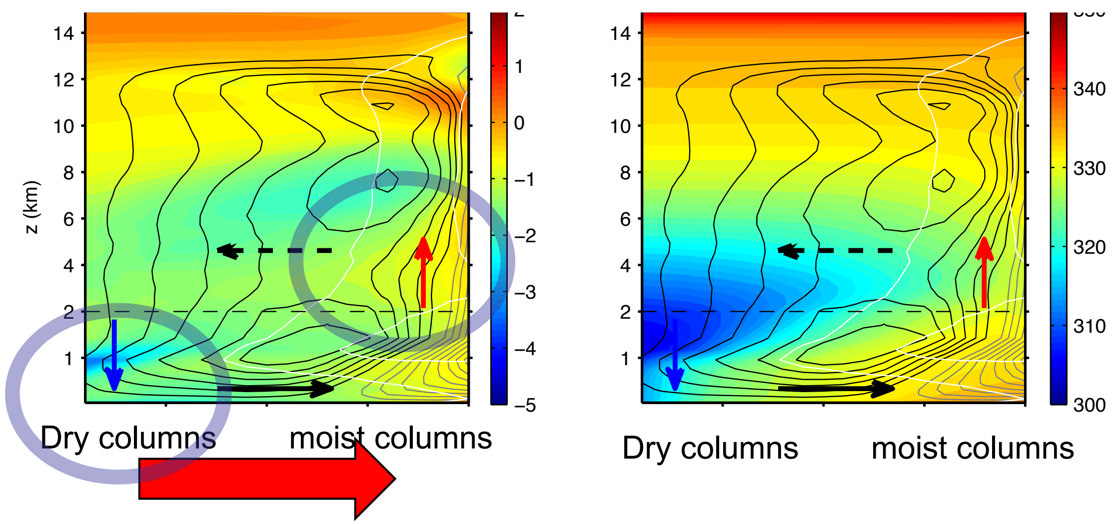

Impose Qr-clear(z) in the dry region and Qr-cloudy(z) in the moist region



# Why does differential radiative cooling lead to aggregation?

black: streamfunction
colors: radiative cooling (left) and MSE (right)

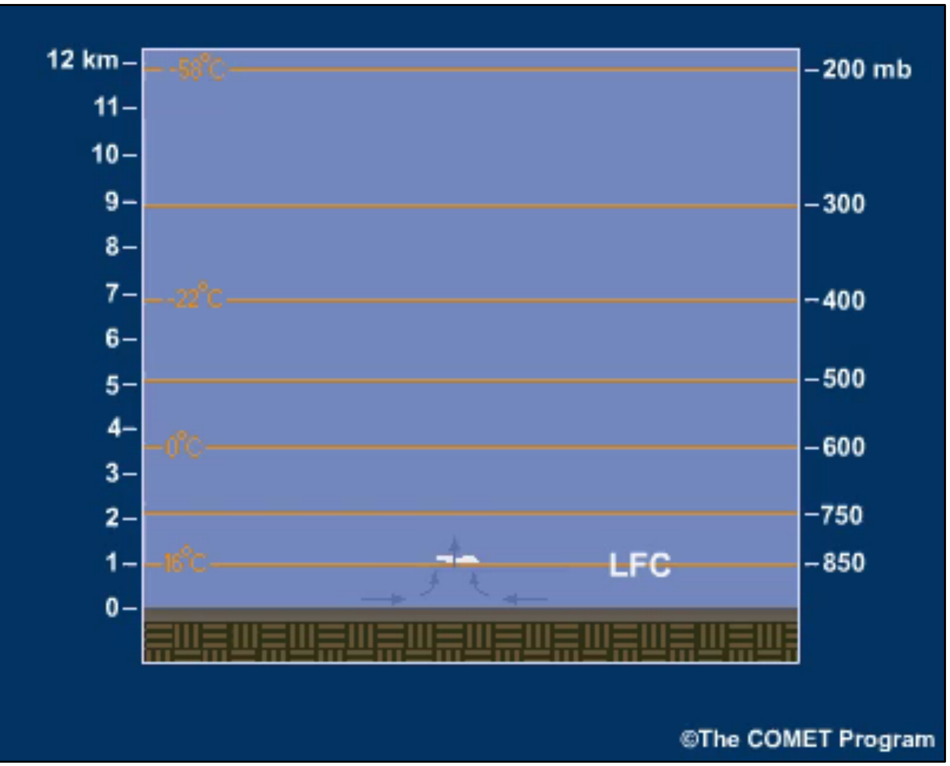


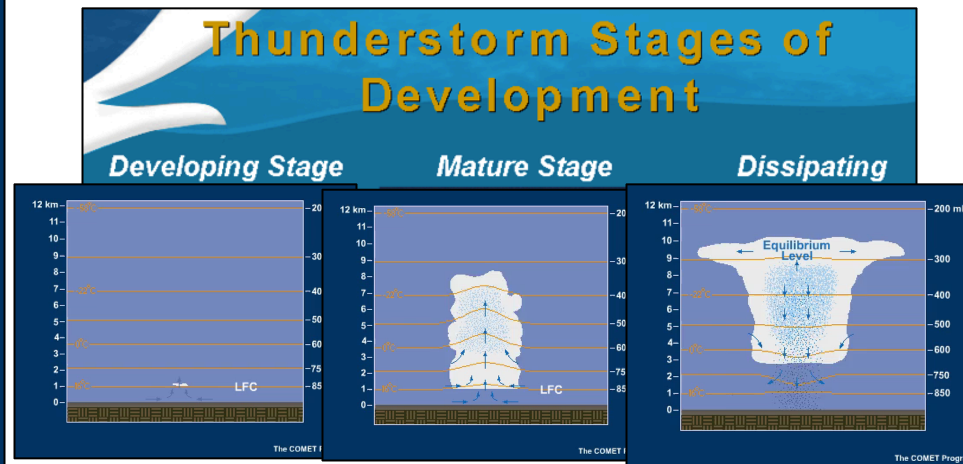

=> upgradient MSE transport

Low-level cooling in dry region and mid-level warming in moist region
=> near-surface energy transport

*And now, is that the whole story?...*

*Role of cold pools?* *[Jeevanjee&Romps 2013 GRL]*

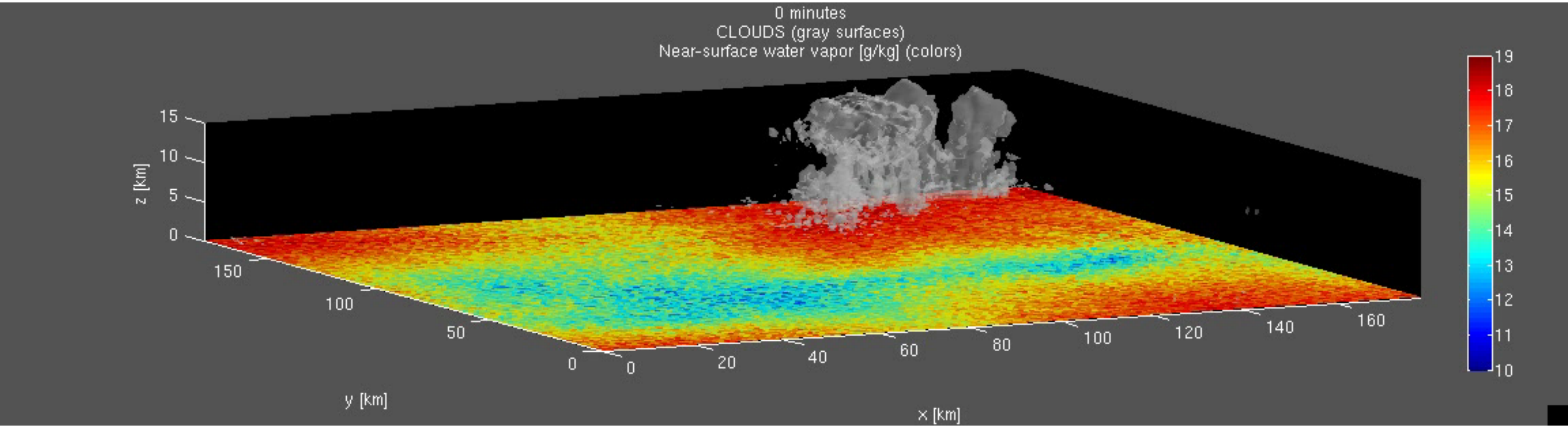



Evaporative driven downdrafts and cold pools

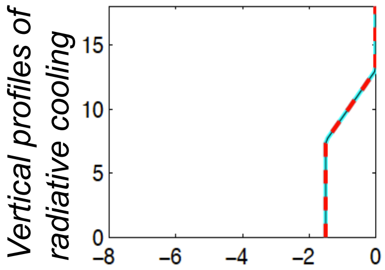
# Self-Aggregation: physical processes

*Clouds over near-surface humidity*




Simulation without cold pools with fixed radiation aggregates !

BUT Recall:
no self-aggregation with fixed radiation



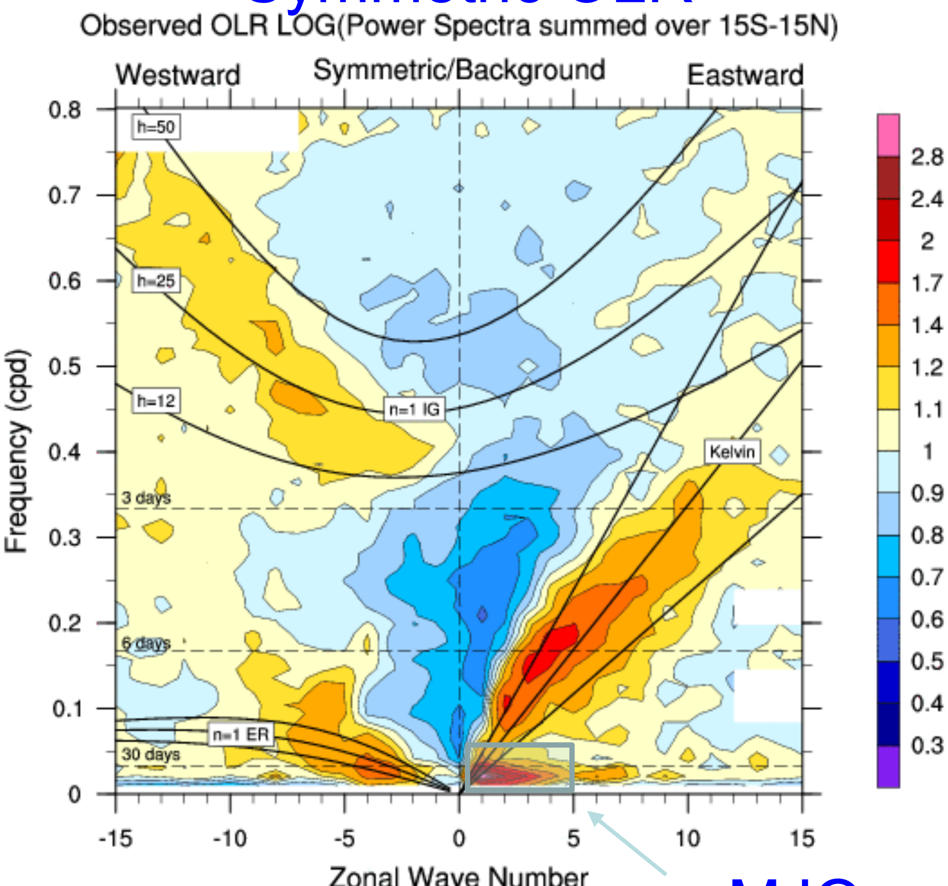

⇒ not same feedback

« moisture memory » feedback is responsible for aggregation *[Tompkins JAS 2001, Craig&Mack JGR 2013]*, no downdraft to kill the cloud

*[Muller & Bony GRL 2015]*

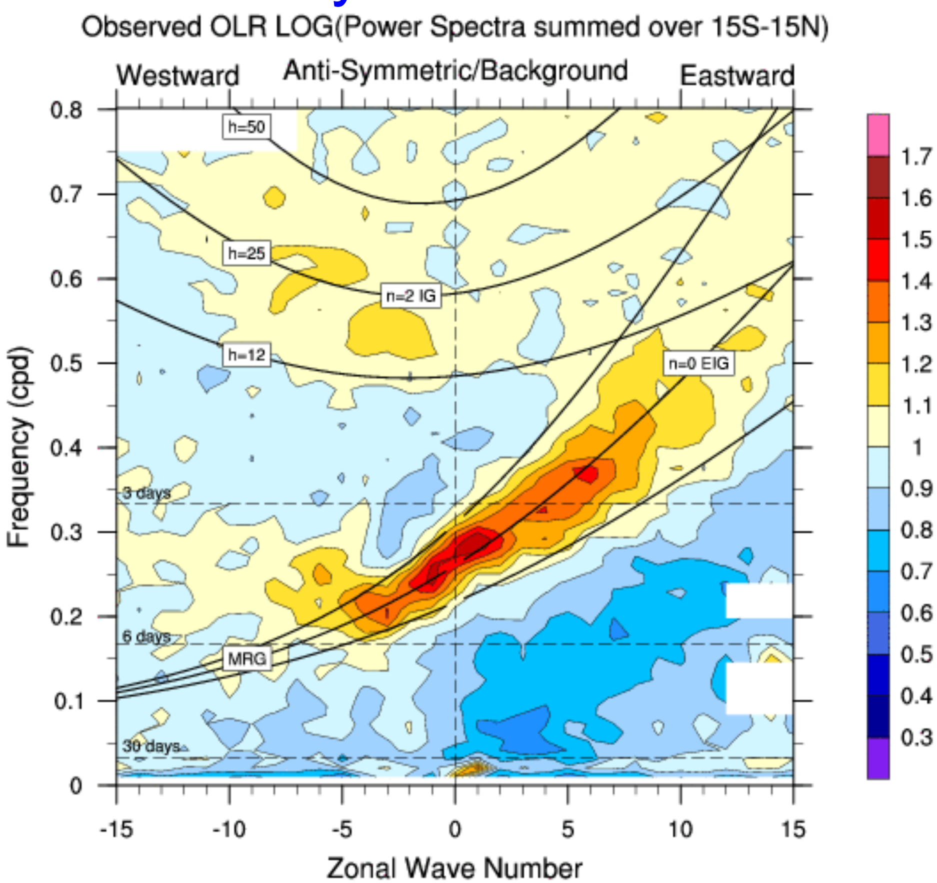
# Equatorial Intraseasonal Variability

## Symmetric OLR




MJO

## Anti-symmetric OLR

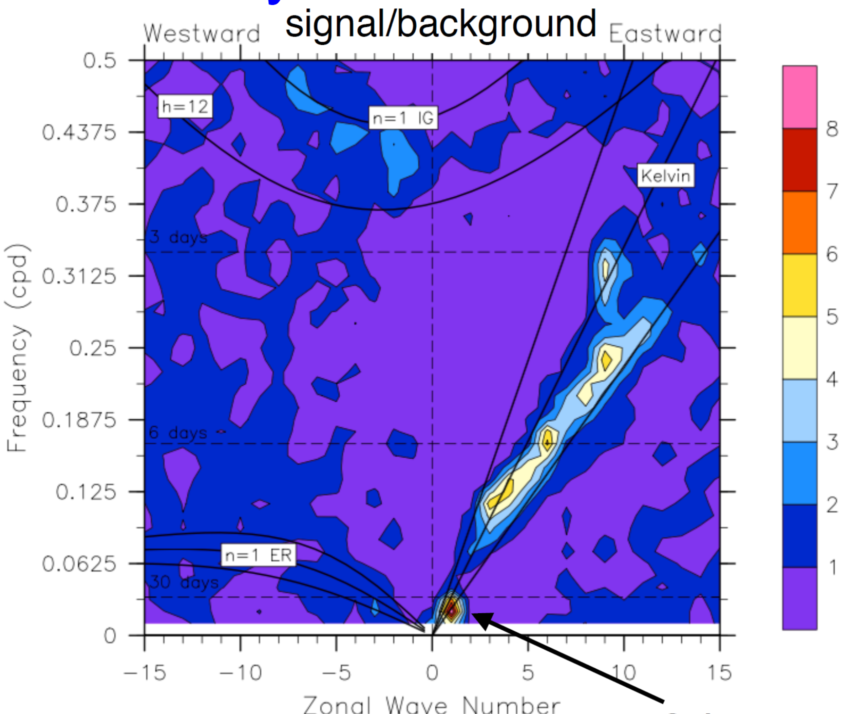



Courtesy Marat Khairoutdinov & Kerry Emanuel

# Cloud-permitting model run on aqua-planet with constant SST (bounded at +/-46° latitude)

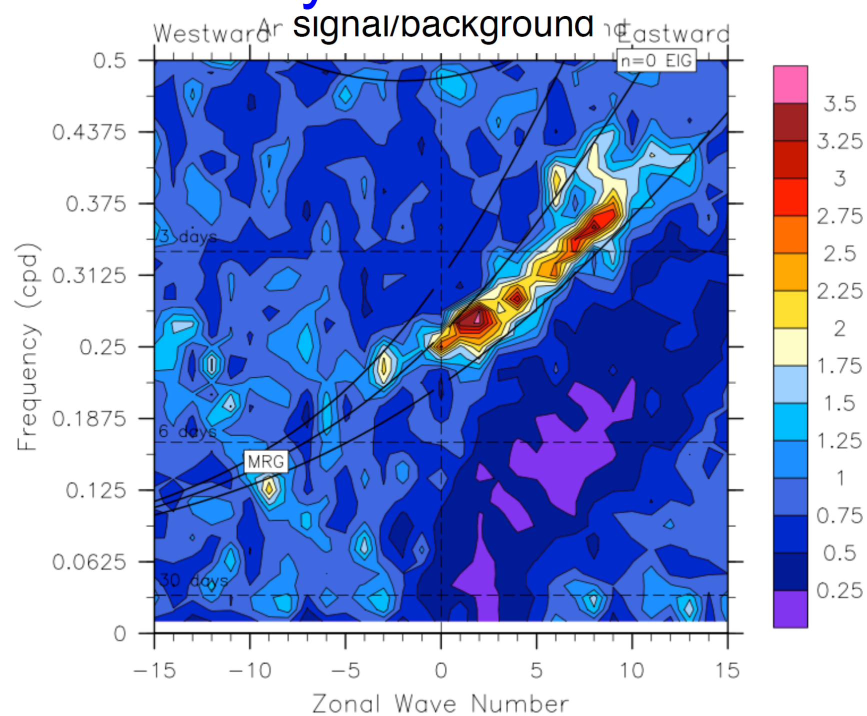
(Marat Khairoutdinov)

## Symmetric OLR




MJO (40-50 days)

## Anti-symmetric OLR

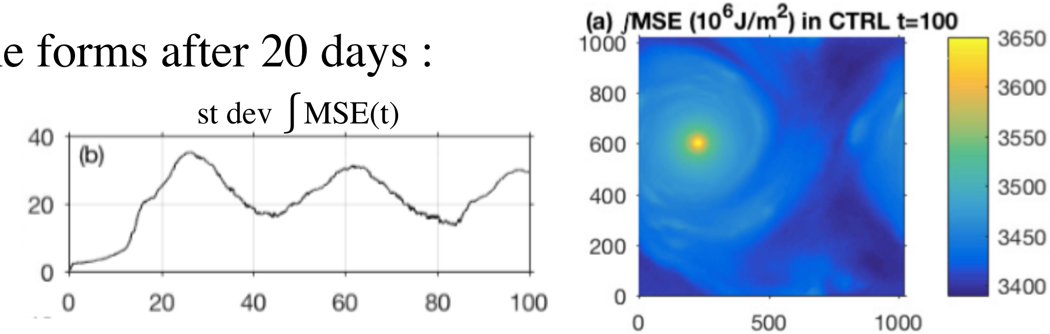



Courtesy Marat Khairoutdinov & Kerry Emanuel

# Self-aggregation and cyclogenesis ?

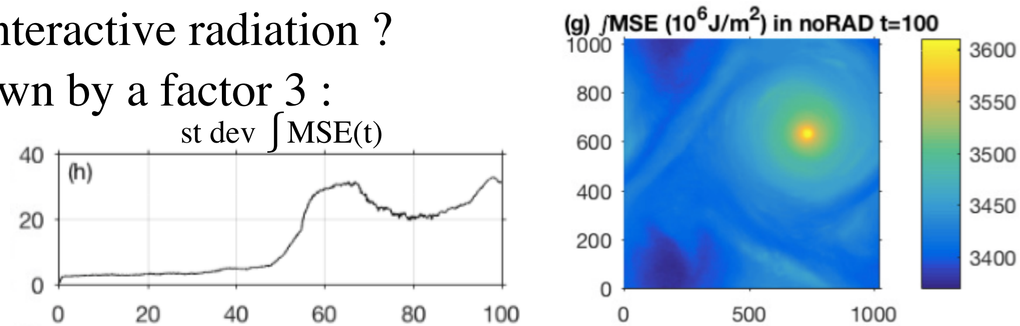
## Self-aggregation accelerates tropical cyclogenesis

CONTROL RUN : A cyclone forms after 20 days :

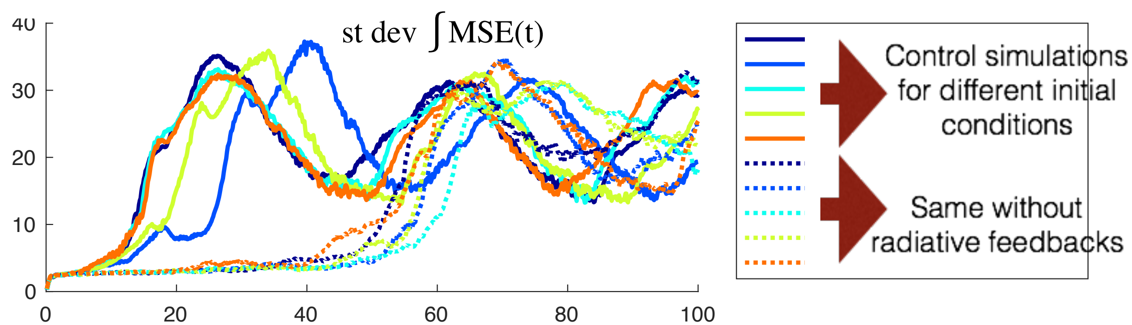



What happens if we remove interactive radiation ?

⇒ Cyclogenesis is slowed down by a factor 3 :

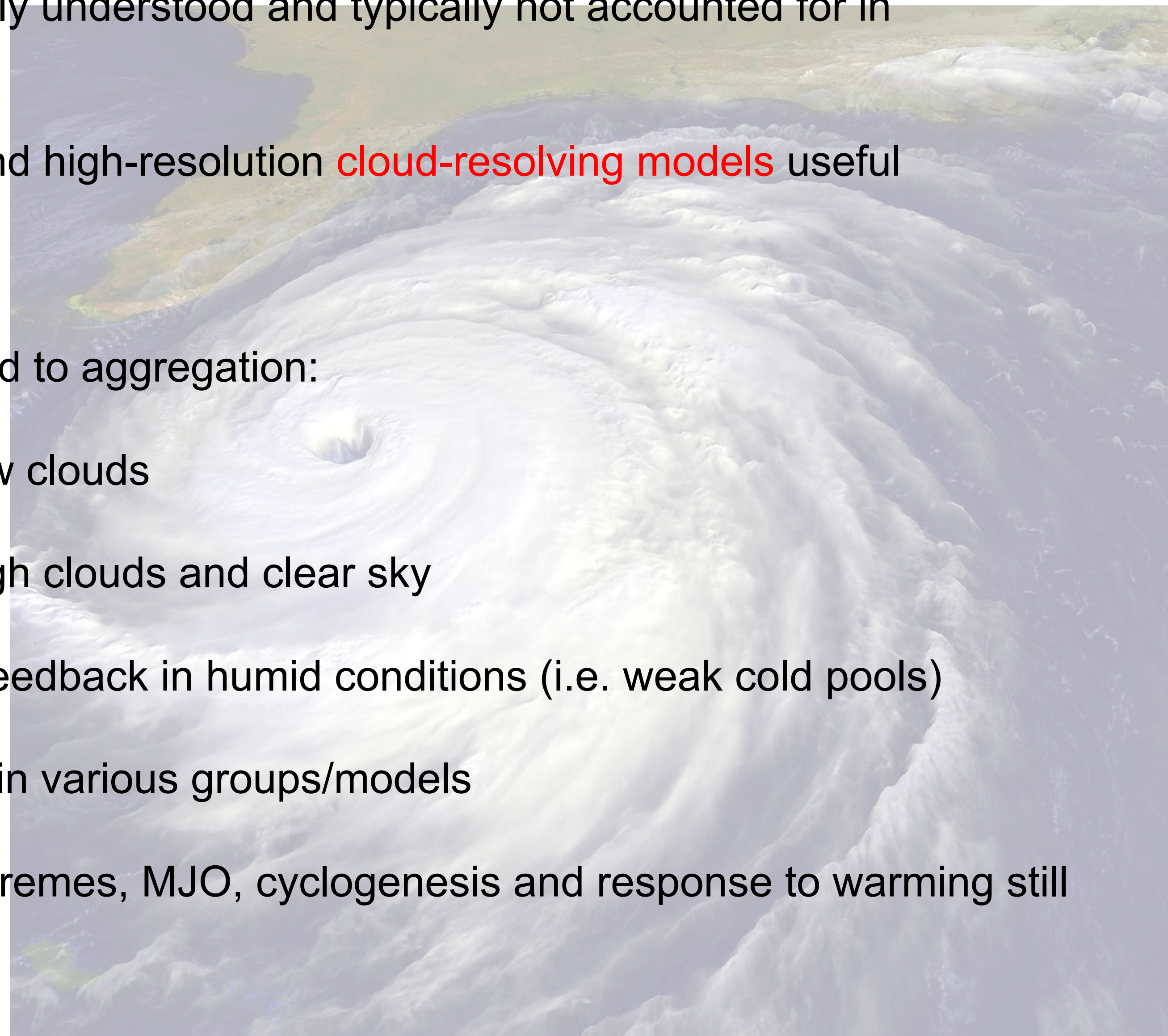



This result is robust to intial conditions :




⇒ Self-aggregation accelerates cyclogenesis by a factor 2 or 3

*Muller&Romps, in prep*



⇒ Organization still not fully understood and typically not accounted for in parameterizations

⇒ Observations, theory and high-resolution cloud-resolving models useful

Various feedbacks can lead to aggregation:

LW rad cooling from low clouds

LW rad cooling from high clouds and clear sky

« moisture-memory » feedback in humid conditions (i.e. weak cold pools)

⇒Observed in various groups/models

Impact on precipitation extremes, MJO, cyclogenesis and response to warming still unclear

# Lectures Outline :

**Cloud fundamentals -** global distribution, types, visualization and link with large scale circulation

**Cloud Formation and Physics -** thermodynamics, cloud formation, instability, life cycle of an individual cloud

**Organization of deep convection at mesoscales -** MCSs, MCCs, Squall lines, Tropical cyclones, Processes, Self-aggregation

**Response of the hydrological cycle to climate change -** mean precip, precip extremes

**Clouds in a changing climate –** climate sensitivity, cloud effect, cloud feedback, FAT