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Cloud-Resolving Models

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What is a cloud-resolving model?

Cloud-resolving model (CRM)

Cloud ensemble model (CEM)

Convection-permitting model (CPM)

Cloud system-resolving model (CSRM)

Storm-resolving model (SRM)

Convection-allowing model (CAM)

A model whose grid spacing is fine enough to allow explicit simulations of individual clouds

What are CRMs used for?

Exploration of cloud phenomenology
Process studies
Understanding convective cloud-related transient motions
Developing convective & cloud parameterizations
Tool for interpreting sparse & incomplete observations

Numerical laboratory

Outline

1. Basic Equations
2. Physics
   - Microphysics
   - Turbulence
   - Radiation
3. Numerics
   - Coordinate System/Grid
   - Boundary Conditions
4. History of CRM simulations
5. Convective Organization in RCE
6. Introduction to RCEMIP

Tao, W.-K. 2007: Cloud Resolving Modeling. *J. Met. Soc. Japan,* **85B**, 305-330.
Guichard, F. and F. Couvreux 2017: A short review of numerical cloud-resolving models, *Tellus A: Dynamic Meteorology and Oceanography*, **69:1**, 1373578, doi: 10.1080/16000870.2017.1373578.

Basic Equations

ΔA = the change in a forecast variable at a particular point in space

$$\frac{\Delta A}{\Delta t} = F(A)$$

F(A) describes the physical processes that can cause changes in the value of A

Δt equals the change in time

$$A^{forecast} = A^{initial} + F(A)\,\Delta t$$

Basic Equations

Need:

- Equation of state
- Prognostic equations for u, v, w
- Prognostic equations for a temperature variable (T, θ, θ_l)
- Prognostic equations for water variables (q_v, q_c, q_t, …)
- Continuity equation (conservation of mass)

Dynamics is *non-hydrostatic.* Fluctuations of w cannot be neglected.

Possible equation sets:

- Compressible Navier-Stokes equations
  - Most general, explicitly simulate turbulent motions
  - Numerically expensive to solve
- Anelastic
  - Assume pressure fluctuations balance rapidly and are negligible in comparison to density or temperature fluctuations
  - Filters out sound waves
- Boussinesq
  - Further assumes density fluctuations negligible in the continuity equation
  - Not valid for deep convection

Example: Anelastic Equations

Equation of state

$$T/\theta = \left(\frac{P}{P_o}\right)^{\frac{R_d}{C_p}}$$

Continuity equation

$$\rho_r \frac{\partial \bar{u}_j}{\partial x_j} + \bar{w} \frac{\partial \rho_r}{\partial z} = 0$$

Example: Anelastic Equations

Momentum equations

$$\frac{\partial \overline{u_i}}{\partial t} = -\frac{1}{\rho_r}\frac{\partial\left(\rho_r \overline{u_i u_j}\right)}{\partial x_j} - \frac{1}{\rho_r}\frac{\partial P}{\partial x_i} + \frac{g}{\theta_r}\left(\overline{\theta_{vl}} - \theta_r\right)\delta_{i,3} - \frac{1}{\rho_r}\frac{\partial\left(\rho_r \overline{u_i' u_j'}\right)}{\partial x_j} - 2\,\varepsilon_{i,j,k}\Omega_j\,\overline{u_k}$$

Advective fluxes

Pressure gradient force

Buoyancy

Turbulent fluxes

Coriolis

Example: Anelastic Equations

Thermodynamic equation

Advective fluxes

Turbulent fluxes

$$\frac{\partial\overline{\theta}}{\partial t} = -\frac{1}{\rho_r}\frac{\partial\left(\rho_r\,\overline{u_j\theta}\right)}{\partial x_j} - \frac{1}{\rho_r}\frac{\partial\left(\rho_r\,\overline{u_j'\theta'}\right)}{\partial x_j} + Q_{Rad} + Q_{m\Phi} + \left(\frac{\partial\overline{\theta}}{\partial t}\right)_{LS}$$

Radiative heating

Heating from microphysics

Large-scale advection

Example: Anelastic Equations

Prognostic equations for water variables

Advective fluxes

Turbulent fluxes

$$\frac{\partial \overline{r_x}}{\partial t} = - \frac{1}{\rho_r} \frac{\partial \left(\rho_r \overline{u_j r_x} \right)}{\partial x_j} - \frac{1}{\rho_r} \frac{\partial \left(\rho_r \overline{u_j' r_x'} \right)}{\partial x_j} + S_x + \left(\frac{\partial \overline{r_x}}{\partial t} \right)_{LS}$$

Microphysical sources/sinks

Large-scale advection

Physics Included in CRMs

Processes that operate on scales smaller than the model can resolve and exchanges of energy between the atmosphere and other sources

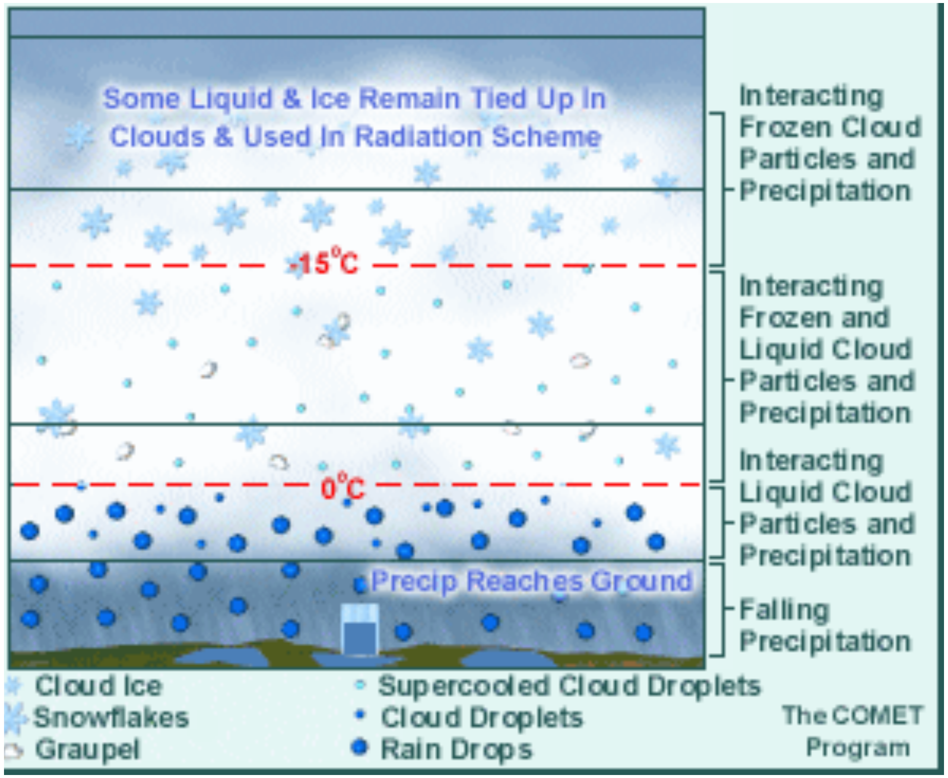
- Microphysics
- Turbulence
- Radiation

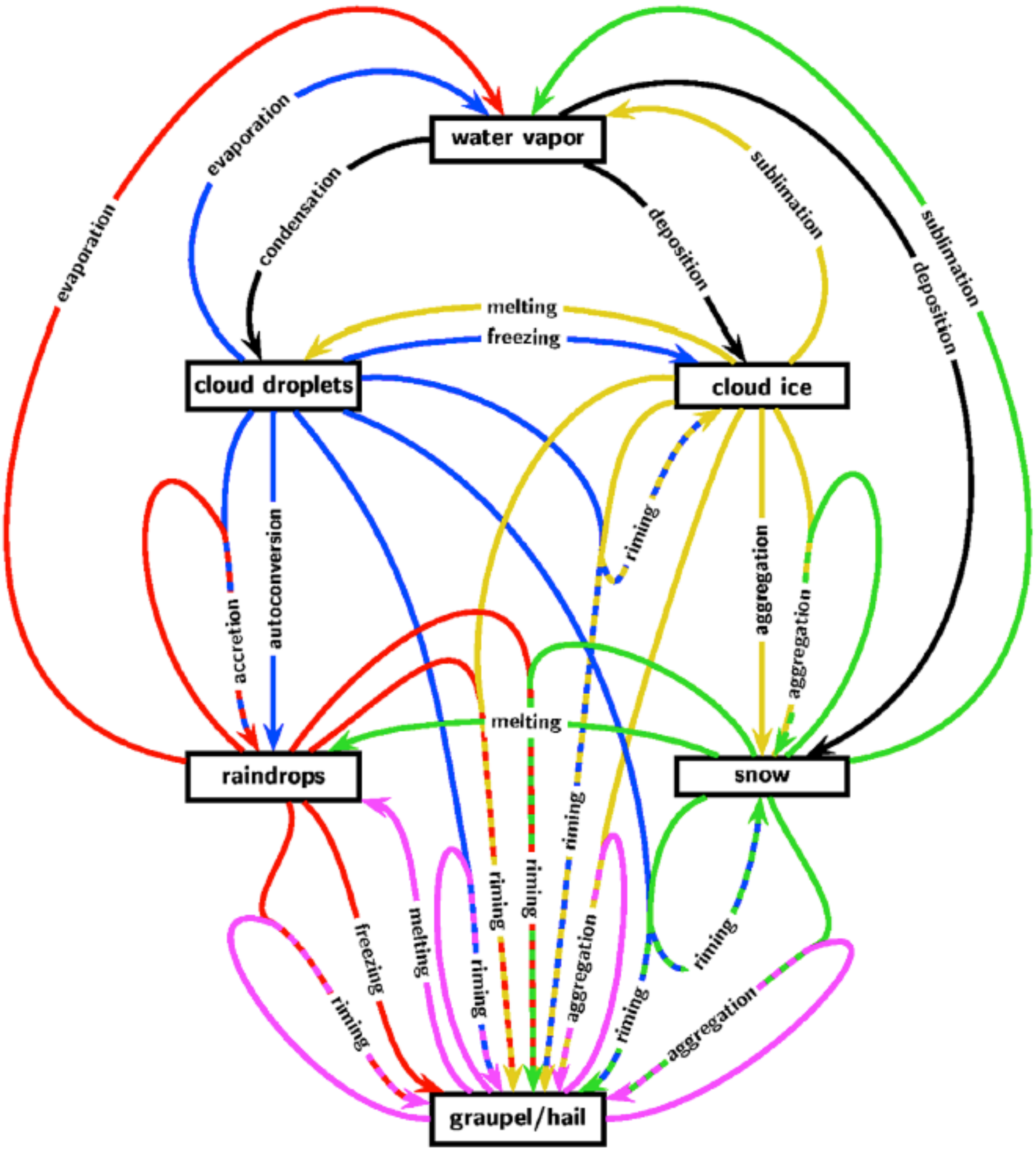
Microphysics

Separation of hydrometeors into

(i) Cloud water suspended within the air mass
(ii) Precipitating water falling with respect to the air mass

with prognostic equation for each type





Many complex exchanges between different types of hydrometeors:

Condensation, autoconversion, accretion, evaporation, melting, riming, ice initiation, deposition, snow aggregation, sedimentation

Guichard and Couvreux 2017

Microphysics Approaches

Bulk: particle-size distributions specified
Bin: particle-size distribution explicitly represented

Single-moment: prognostic equations for mixing ratios of different hydrometeors
Double-moment: prognostic equations for mixing ratios and particle number concentrations of different hydrometeors

Variety in

- Specification of hydrometeor types (particle size distributions, mass-diameter relationships)
- Types of processes considered
- Formulation of processes

Turbulence

Sub-grid-scale turbulent motions parameterized based on local arguments with turbulent fluxes expressed as a function of local gradients:

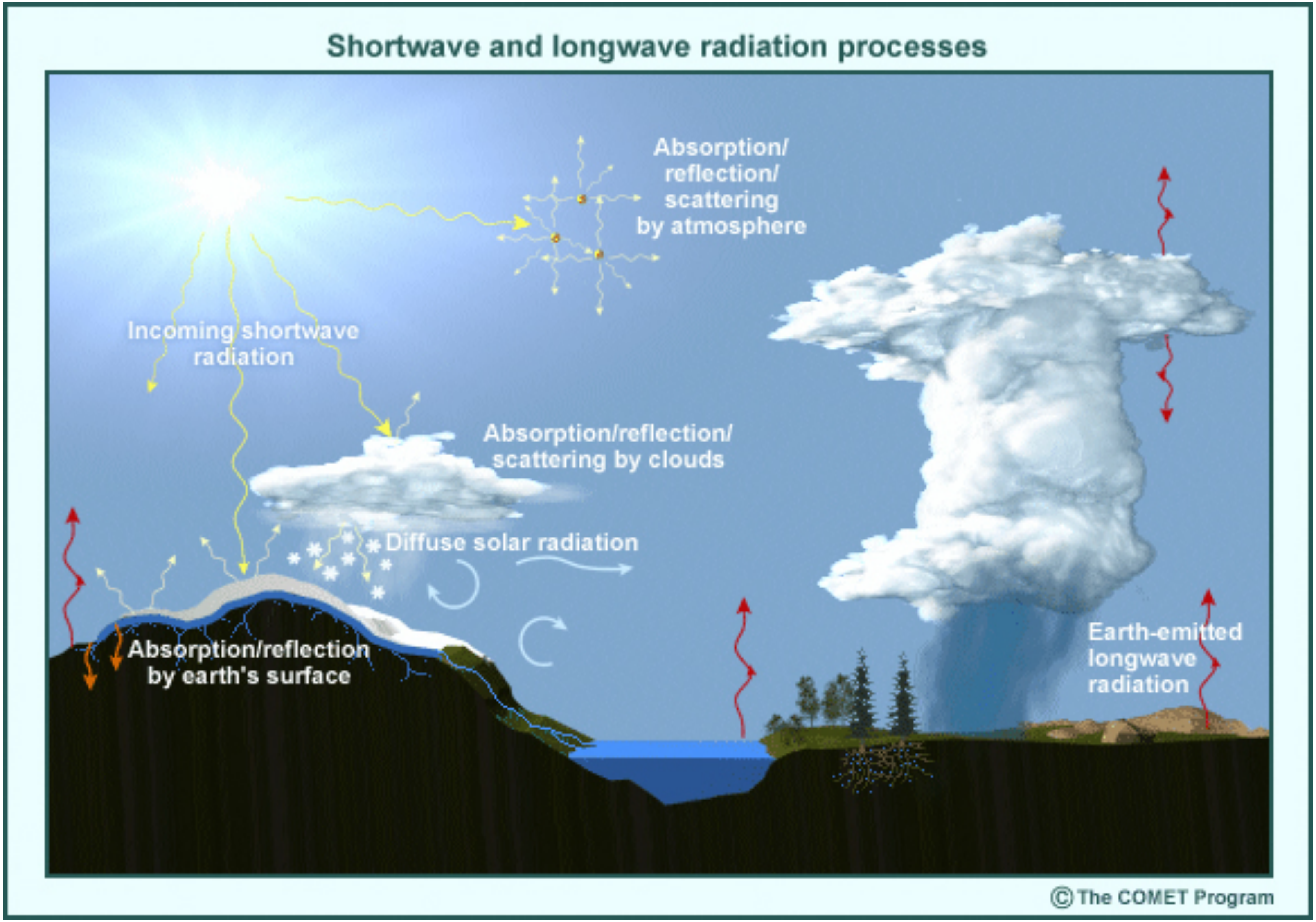
$$\overline{u_i \alpha} = - K \frac{\partial \bar{\alpha}}{\partial x_i}$$

where K is an eddy-diffusivity coefficient

Two different types of schemes:

- Smagorinksy-type
    - Assumes buoyancy and shear productions of TKE balance molecular dissipation
    - Eddy diffusivity proportional to local velocity and temperature gradients and function of a Richardson number
- More sophisticated involving prognostic equation for turbulent kinetic energy (TKE)

Radiation


Shortwave and longwave radiation processes
Absorption/
reflection/
scattering
by atmosphere
Incoming shortwave
radiation
Absorption/reflection/
scattering by clouds
Diffuse solar radiation
Absorption/reflection
by earth's surface
Earth-emitted
longwave
radiation
© The COMET Program

Radiation Approaches

- **Simplest:** constant cooling rate (~1 K/day)
  - Excludes any convective-radiative interactions
- **Simple**: prescribed cooling rate profiles
- **Explicit radiative transfer scheme**
  - Separate formulations of longwave and shortwave radiation
  - Account for cloud reflection, absorption and scattering of radiation
  - Many diverse flavors and ranges of accuracy

Radiation Approaches

- Broadband:
  - Consider a limited number of spectral bands

- Two-stream approximation:
  - Radiative flux divergence in each band is expressed as difference between upwelling and downwelling flux
  - Upwelling and downwelling fluxes computed independently for each column

- Impact of clouds
  - Radiative impact of precipitating hydrometeors usually neglected
  - Radiative properties of cloud liquid drops and ice crystals (+ sometimes drizzle and snow) taken into account
  - Depends on size distribution, shape, and concentration of hydrometeors

Cloud-Radiation Impact

- Shortwave radiation schemes include, for each separate band, a formulation of cloud optical properties

- Often expressed as function of cloud water path and of an effective radius

- Longwave radiation, in simplest case
  - Neglects scattering
  - Clouds treated as grey bodies with emissivity dependent on cloud water path

Numerics

- Coordinate system
- Grid Spacing/Resolution
- Boundary conditions
- Advection and time-stepping schemes
  - Simple or complex
  - Centered or not
  - Implicit or explicit
  - More or less diffusive
  - More or less conservative & accurate

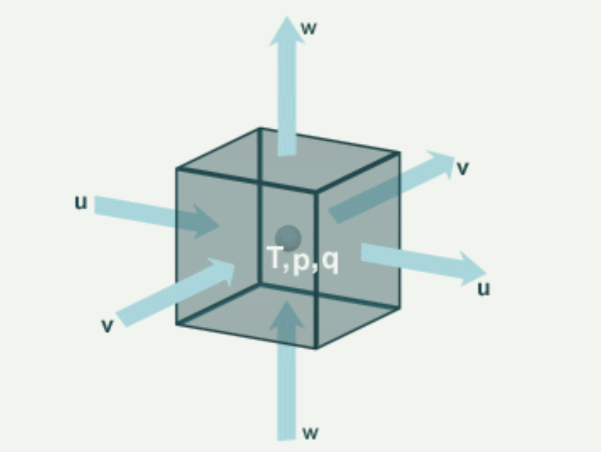
Coordinate System & Grid

Coordinate system:

- Most use height as a vertical coordinate
- Vertical grid is often stretched (finer grid spacing in lower levels)
- Horizontal grid usually regular

Grid:

- Staggered grid often used
- Arakawa-C common:
  - Scalar variables defined at grid center
  - Wind components defined at edges



Example of 3-D Grid Box in a Grid Point Model

Initial and Boundary Conditions

Top boudary conditions

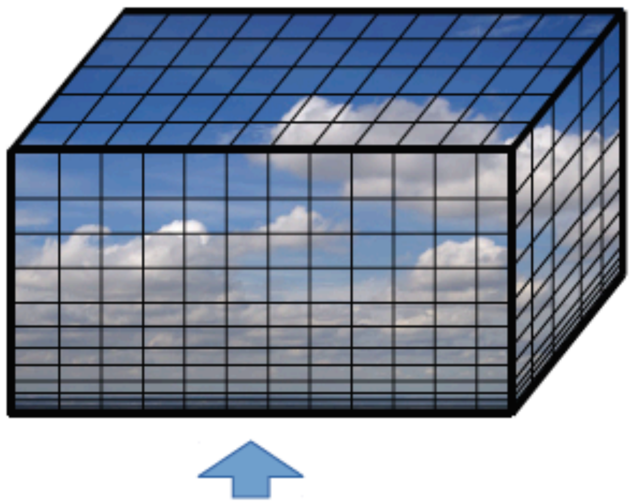
- wall above a sponge layer
- radiative condition

Initial atmospheric conditions

T , q , U , V (x ,y , z , t_0)

- academic vertical profiles
- sounding data

Horizontally homogeneous with random noise or warm bubbles or cold pools added



Lateral boundary conditions

- periodic
  with prescribed larger-scale advection added and/or nudging of horizontal-mean fields towards given profiles
- open
- wall

Surface boundary conditions

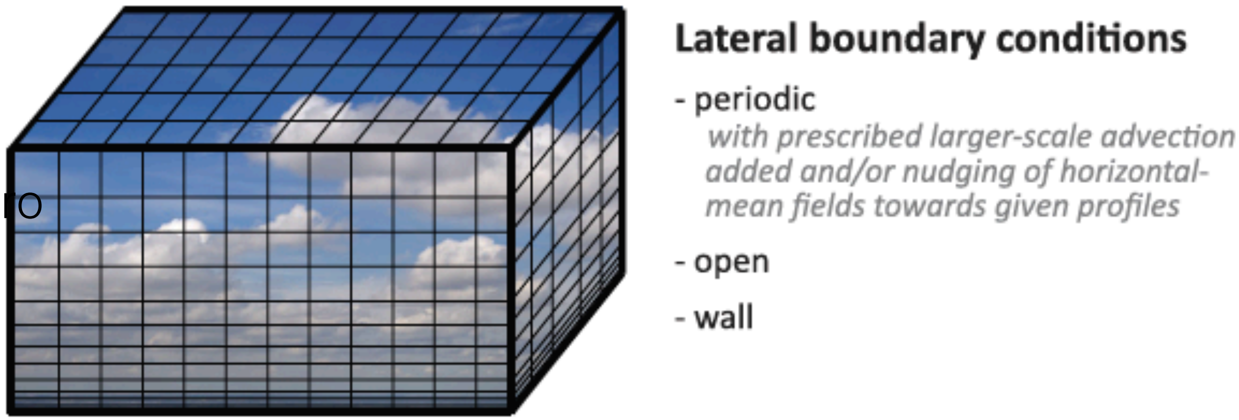
- prescribed surface fluxes
- prescribed surface temperature (+ soil moisture when over land)
- provided by a coupled surface model (soil temperature and moisture then initialized)

Guichard and Couvreux 2017

Lateral Boundary Conditions

Periodic:

- Good for larger-scale convection with regular spatial patterns
- Consider as part of larger homogeneous system
- Net horizontal flux divergence and mean vertical velocity must be zero (or large-scale profiles prescribed)



Open:

- Better for features like mature squall lines
- Larger scales of motion respond to convection within domain
- Need to define characteristics of air entering domain and minimize wave reflection

Guichard and Couvreux 2017

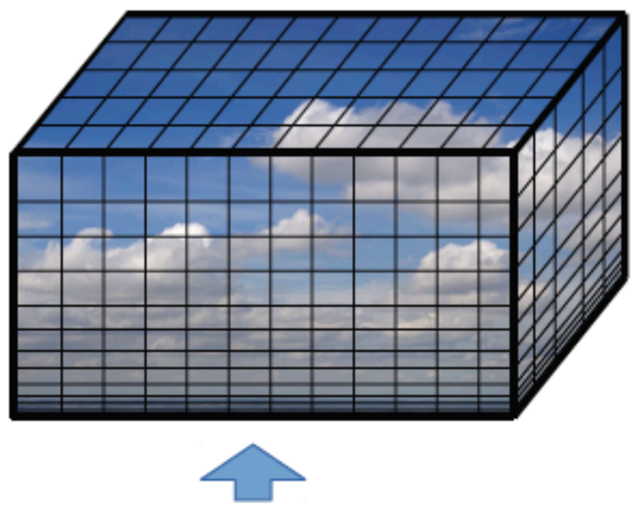
Top & Bottom Boundary Conditions

Top:

- Usually rigid lid (w=0)
- Sponge layer below domain top to damp wave reflection (nudge towards prescribed profiles)

Top boudary conditions

- wall above a sponge layer
- radiative condition



Surface boundary conditions

- prescribed surface fluxes
- prescribed surface temperature (+ soil moisture when over land)
- provided by a coupled surface model (soil temperature and moisture then initialized)

Bottom:

- Usually rigid (w=0)
- Common to prescribe SST
- Mixed layer ocean or land surface model can be coupled
- Surface fluxes can be prescribed or calculated with bulk formula

Guichard and Couvreux 2017

History of CRM Simulations

	Major Highlights
1960's	Loading, Buoyancy and Entrainment

2D anelastic cloud model developed to study cloud development under the influence of the surrounding environment: Ogura & Phillips 1962

Tao 2007

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1970's	Slab- vs Axis-symmetric Model Cloud Seeding Cloud Dynamics & Warm rain

3D non-hydrostatic models of deep precipitating convection, dx~1 km: Steiner 1973, Wilhelmson 1974, Miller & Pearce 1974, Sommeria 1976, Klemp & Wilhelmson 1978a, Cotton & Tripoli 1989, Schlesinger 1978, Clark 1979

Most focused on single convective cells

Development of semi-implicit time-splitting scheme: Klemp and Wilhemson 1978a

Dynamics of supercells: Klemp and Wilhelmson 1978b, Wilhelmson and Klemp 1978

Tao 2007

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Development of cloud ensemble modeling to study collective feedback of clouds on the large-scale tropical environment, goal to improve convective parameterizations:
Soong & Tao 1980, Soong & Ogura 1980, Tao & Soong, 1986, Lipps & Helmer 1986, Tao et al. 1987, Krueger 1988…

Morphology & life cycle of individual storms
Explore mechanisms in wider mature squall lines
…Nakajima & Matsuno 1988, Rotunno et al 1988, Fovell & Ogura 1988, Tao & Simpson 1989…

Tao 2007

History of CRM Simulations

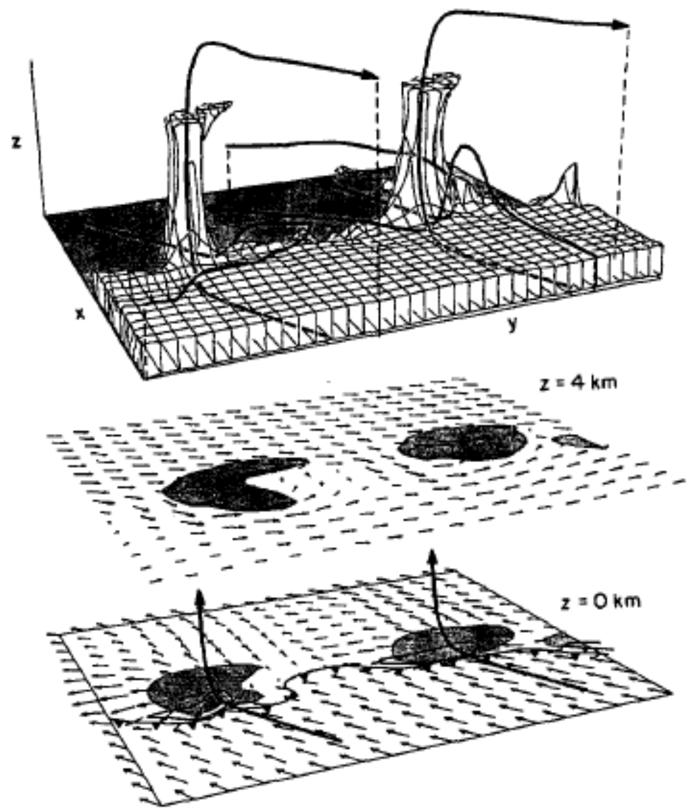

FIG. 17. Top: a three-dimensional perspective view of the $\theta_e = 335$ K surface for a portion ($56 \leq x \leq 116$ km, $14 \leq y \leq 82$ km) of a line containing two supercells. Below there is the $z = 4$ km horizontal plane exhibiting line-relative flow vectors at every other grid point (a length of two grid intervals = 20 m s^{-1}); the shaded regions encompass places where rainwater exceeds 0.1 g kg^{-1}; the circular contour encompasses updraft greater than 10 m s^{-1}. The flow in the horizontal plane at the surface is denoted similarly except, the updraft contour (at $z = 350$m) encompasses values greater than 1 m s^{-1} and the barbed line denotes the cold-air boundary defined by the -1 K perturbation.

Rotunno et al. 1988

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GCSS: Browning et al 1993, Moncrieff et al 1997
Force CRMs by field observations: Tripoli & Cotton 1989, Bernardet & Cotton 1998, Xu & Randall 1996, Grabwoski et al 1996

Tao 2007

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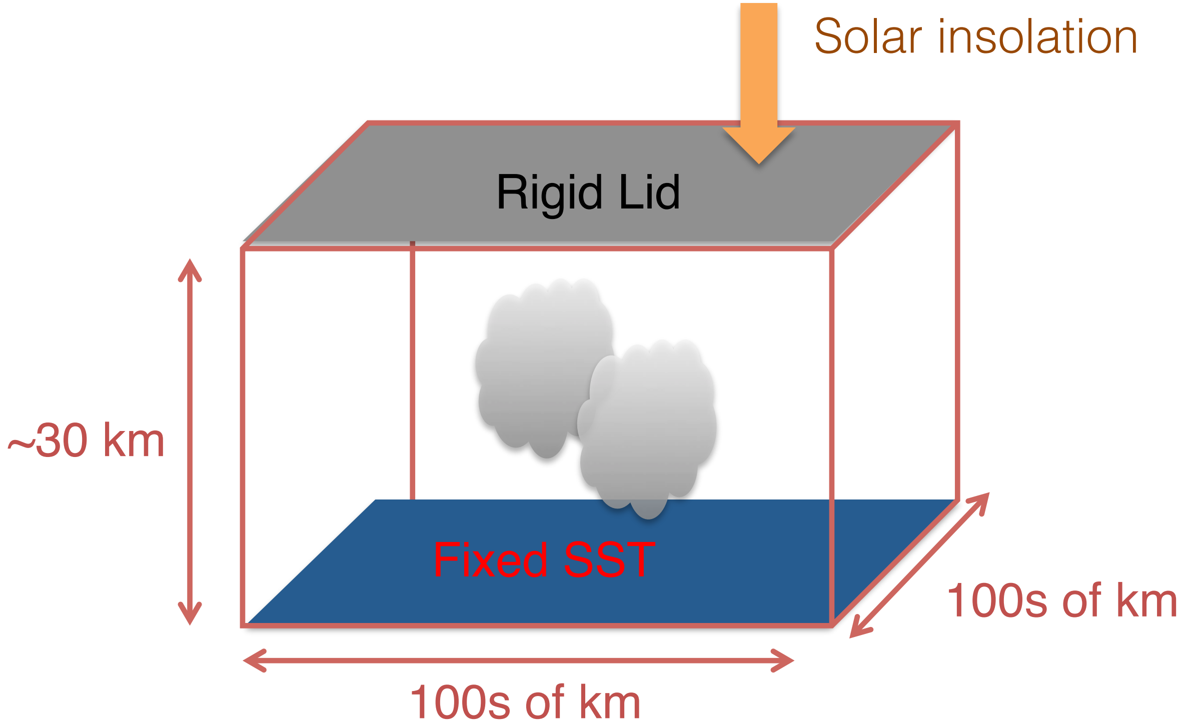
2000's	Land and Ocean Processes Multi-scale Interactions Energy and Water Cycle Cloud Aerosol-Chemistry Interactions Cumulus Parameterization Improvements

Tao 2007

Simulations of RCE

1D: Moeller 1963, Manabe & Strickler 1964, Satoh & Hayashi 1992, Renno et al 1994
2D: Nakajima & Matsuno 1988, Held et al 1993, Islam et al 1993, Sui et al 1994, Randall et al 1994, Grabowski et al 1996
3D: Islam et al 1993, Robe & Emanuel 1996, Tompkins & Craig 1998, and many more…



CRM simulations of RCE

Widely used in studies of tropical convection

- Predictability of mesoscale rainfall
  - e.g.,: Islam et al 1993
- Rainfall over tropical islands
  - e.g., Cronin et al. 2015
- Base state for tropical cyclone studies
  - e.g.,Nolan et al. 2007, Chavas and Emanuel 2014
- Behavior of convection as temperature is changed
  - e.g., Muller et al. 2011, Romps 2011, Singh and O'Gorman 2013, 2014, 2015
- Precipitation extremes
  - e.g., Muller 2013, Singh and O'Gorman 2014
- Studies of convective organization
  - e.g., Held et al. 1993, Tompkins and Craig 1998, Bretherton et al 2005

CRM simulations of RCE

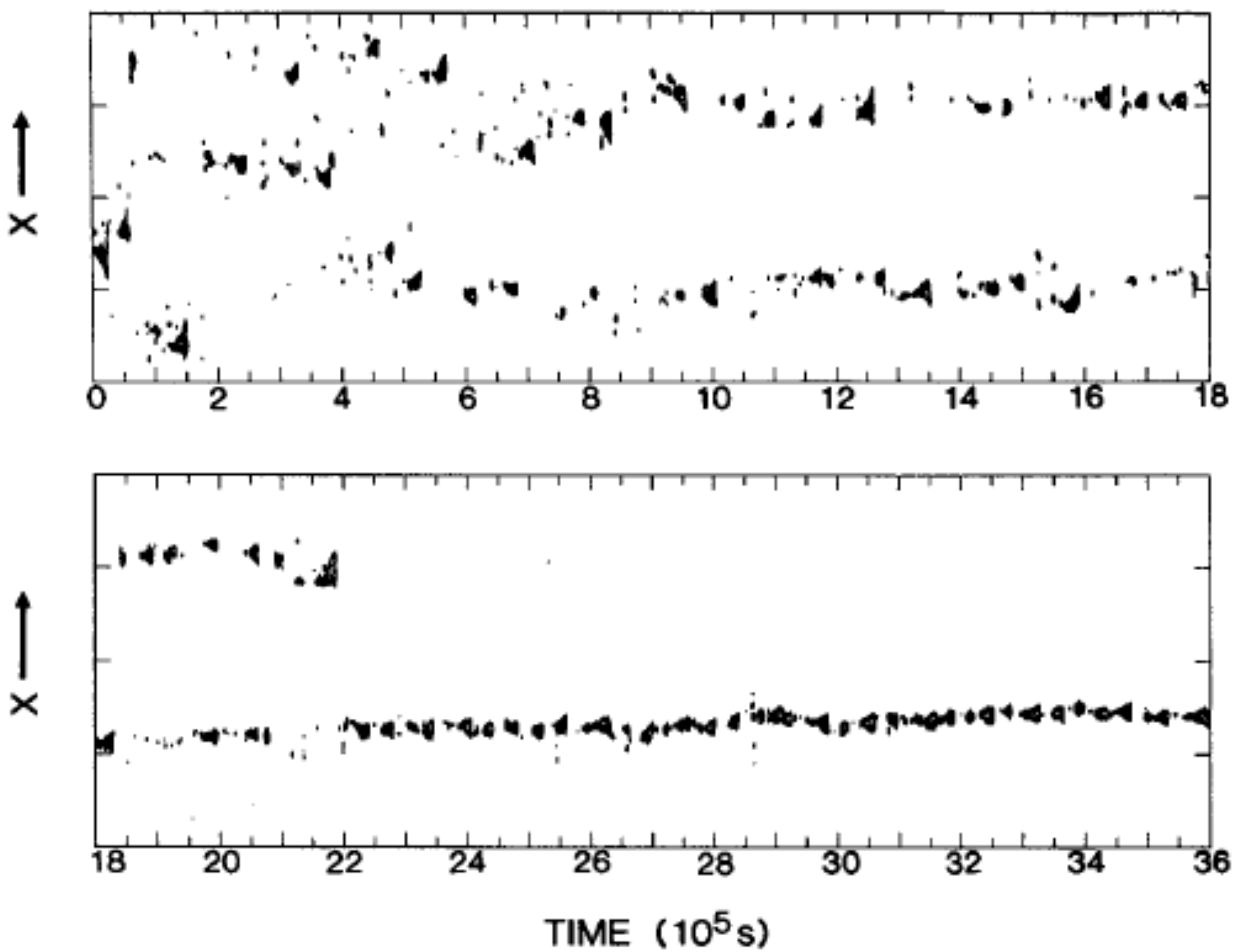


FIG. 4. Precipitation as a function of time and x in the case in which the mean wind is constrained to vanish.

Held et al. 1993

Self-aggregation: spontaneous transition from randomly distributed to organized convection despite homogeneous boundary conditions

Moist regions get moister, dry regions get drier

- Self-aggregation begins as a dry patch that expands.
- Convection is suppressed in the dry patch and becomes increasingly localized into a single cluster.

Results from interactions between convection and environment involving clouds, water vapor, radiation, surface fluxes, and circulation

Localization of convection first seen: Held et al 1993

Reviews: Wing et al 2017, Wing 2019

Occurs in a wide range of model configurations

2D CRMs: Held et al 1993, Grabowski and Moncrieff 2001, Grabowski and Moncreiff 2002, Stephens et al 2008, Yang 2018a, Yang 2018b, Brenowitz et al 2018

Small-domain square 3D CRMs: Tompkins and Craig 1998, Bretherton et al 2005, Khairoutdinov and Emanuel 2010, Muller and Held 2012, Jeevanjee and Romps 2013, Wing and Emanuel 2014, Abbot 2014, Muller and Bony 2015, Holloway and Woolnough 2016, Hohenegger and Stevens 2016, Tompkins and Semie 2017, Hohenegger and Stevens 2018, Becker et al. 2018, Bao and Sherwood 2018, Ruppert and Hohenegger 2018, Colin et al 2019

Elongated channel 3D CRMs: Tompkins 2001 ,Posselt et al 2008, Posselt et al 2012, Stephens et al 2008, Wing and Cronin 2016, Cronin and Wing 2017, Wing et al 2018, Beydoun and Hoose 2019

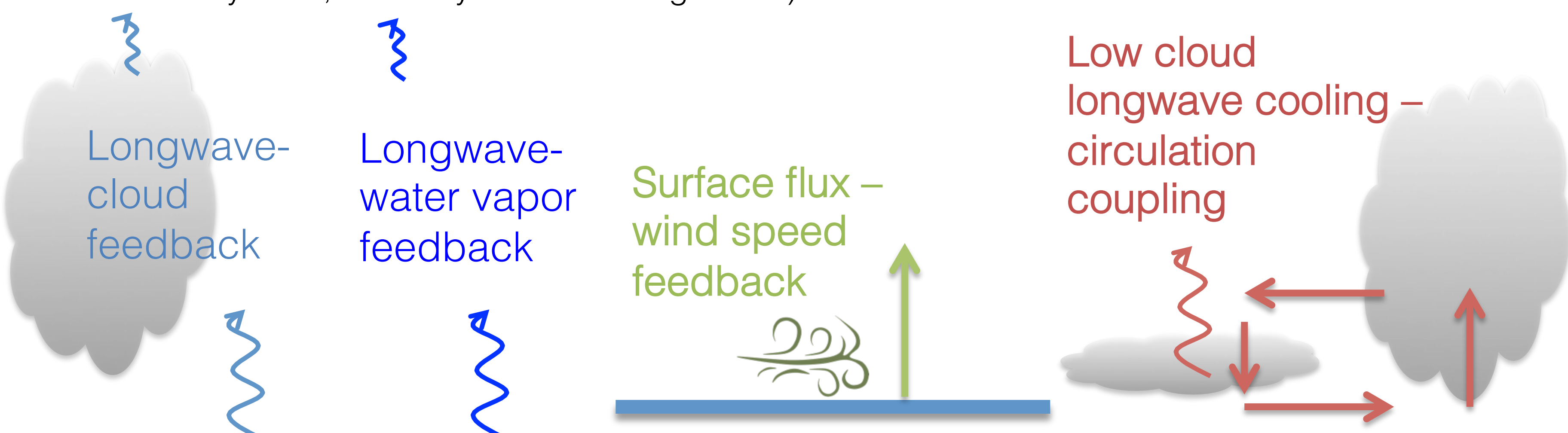
Regional/global models with parameterized convection: Su et al 2000, Held et al 2007, Popke et al 2013, Becker and Stevens 2014, Reed et al 2015, Arnold and Randall 2015, Reed and Medeiros 2016, Coppin and Bony 2015, Silvers et al 2016, Hohenegger and Stevens 2016, Bony et al 2016, Pendergrass et al 2016, Becker et al 2017, Coppin and Bony 2017, Arnold and Putnam 2018, Coppin and Bony 2018, Wing et al 2018

Global models with explicit convection: Satoh and Matsuda 2009, Satoh et al 2016, Ohno and Satoh 2018, Wing et al 2018

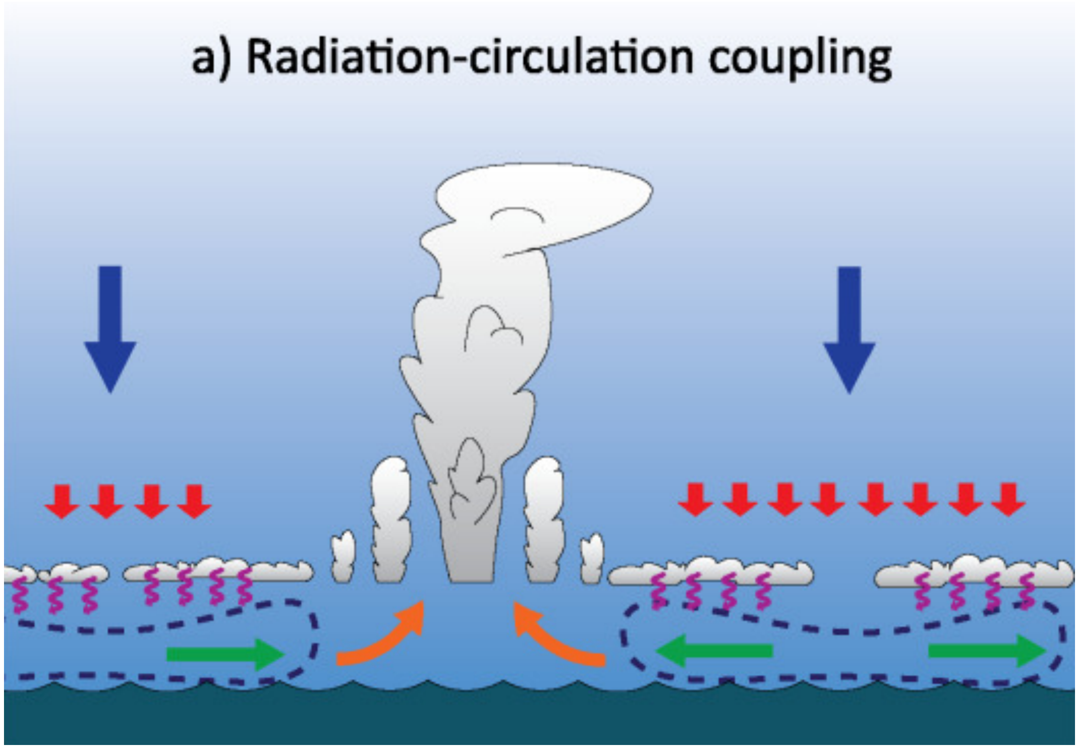
Rotating RCE: Bretherton et al 2005, Nolan et al 2007, Khairoutdinov and Emanuel 2013, Shi and Bretherton 2014, Zhou et al 2014, Boos et al 2016, Reed and Chavas 2015, Davis 2015, Wing et al 2016, Merlis et al 2016, Zhou et al 2017, Muller and Romps 2018, Khairoutdinov and Emanuel 2018

Mechanisms of Self-aggregation

- Longwave – water vapor feedback (Wing and Emanuel 2014, Emanuel et al., 2014)
- Longwave – cloud feedback (Bretherton et al., 2005, Posselt et al. 2012, Wing and Emanuel 2014, Muller and Bony 2015, Wing and Cronin 2016, Arnold and Randall 2015, Holloway and Woolnough 2016)
- Low cloud longwave cooling – circulation (Muller and Held 2012, Coppin and Bony 2015, Muller and Bony 2015)
- Surface flux – wind speed feedback (Bretherton et al., 2005, Wing and Emanuel 2014, Wing and Cronin 2016, Coppin and Bony 2015)
- Moisture-convection feedback (Tompkins 2001, Craig and Mack 2013, Muller and Bony 2015, Holloway and Woolnough 2016)



Cloud-Circulation Coupling

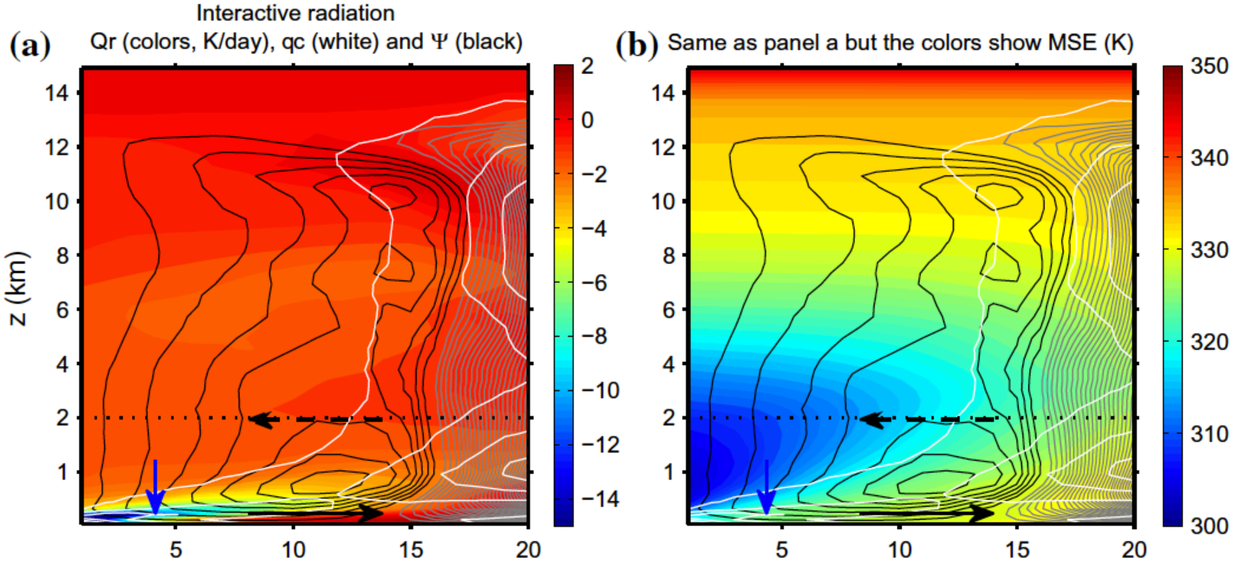


Subsidence in dry region promotes formation of low-level clouds with radiative cool the lower troposphere

Low-level cooling drives shallow circulations that increase the subsidence in dry areas and of "radiatively-driven cold pools" that force the convection to aggregate outside of these cold/dry areas

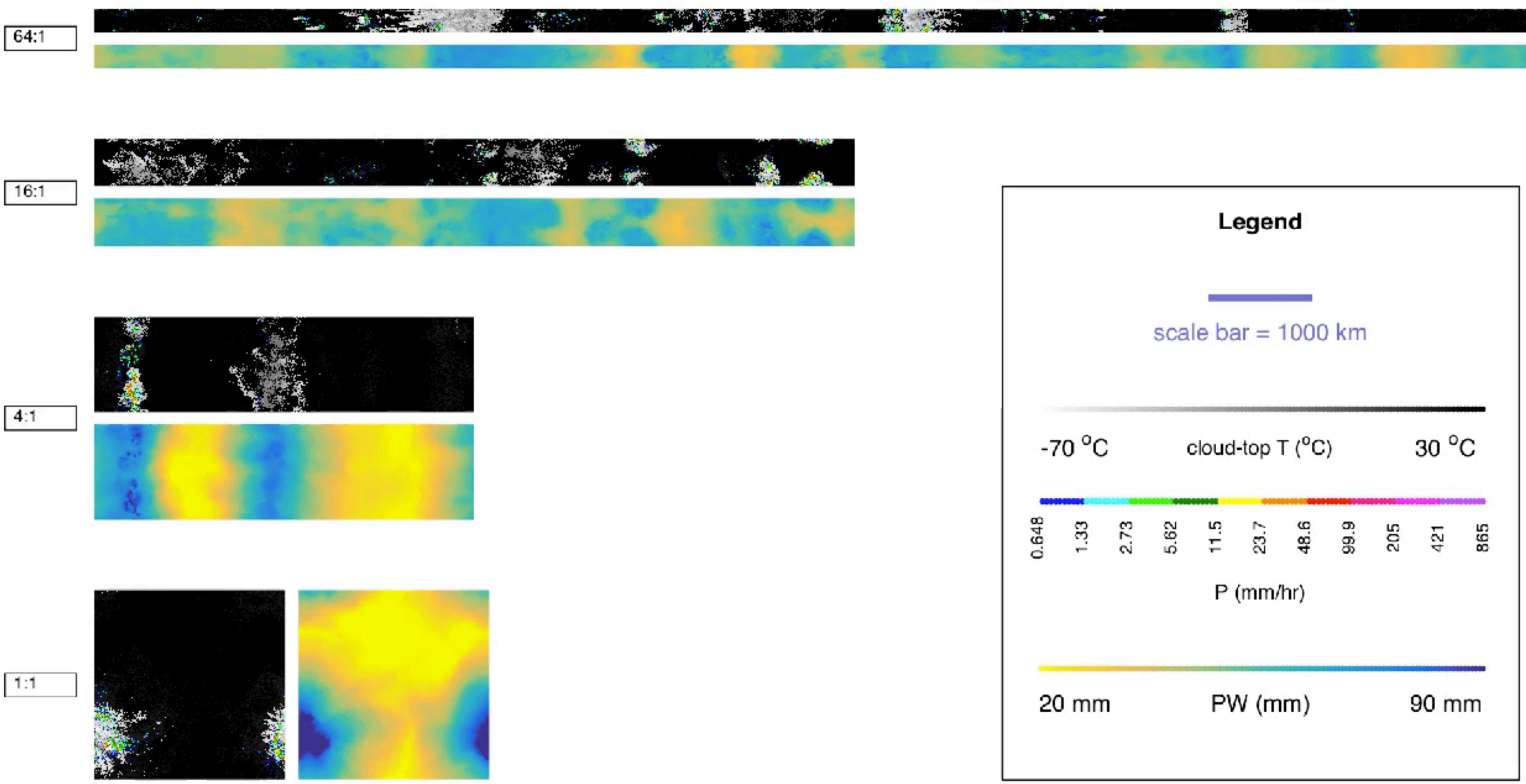
Coppin and Bony (2015)

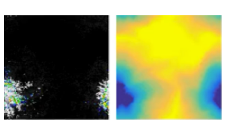
Cloud-Circulation Coupling



Muller and Held (2012)

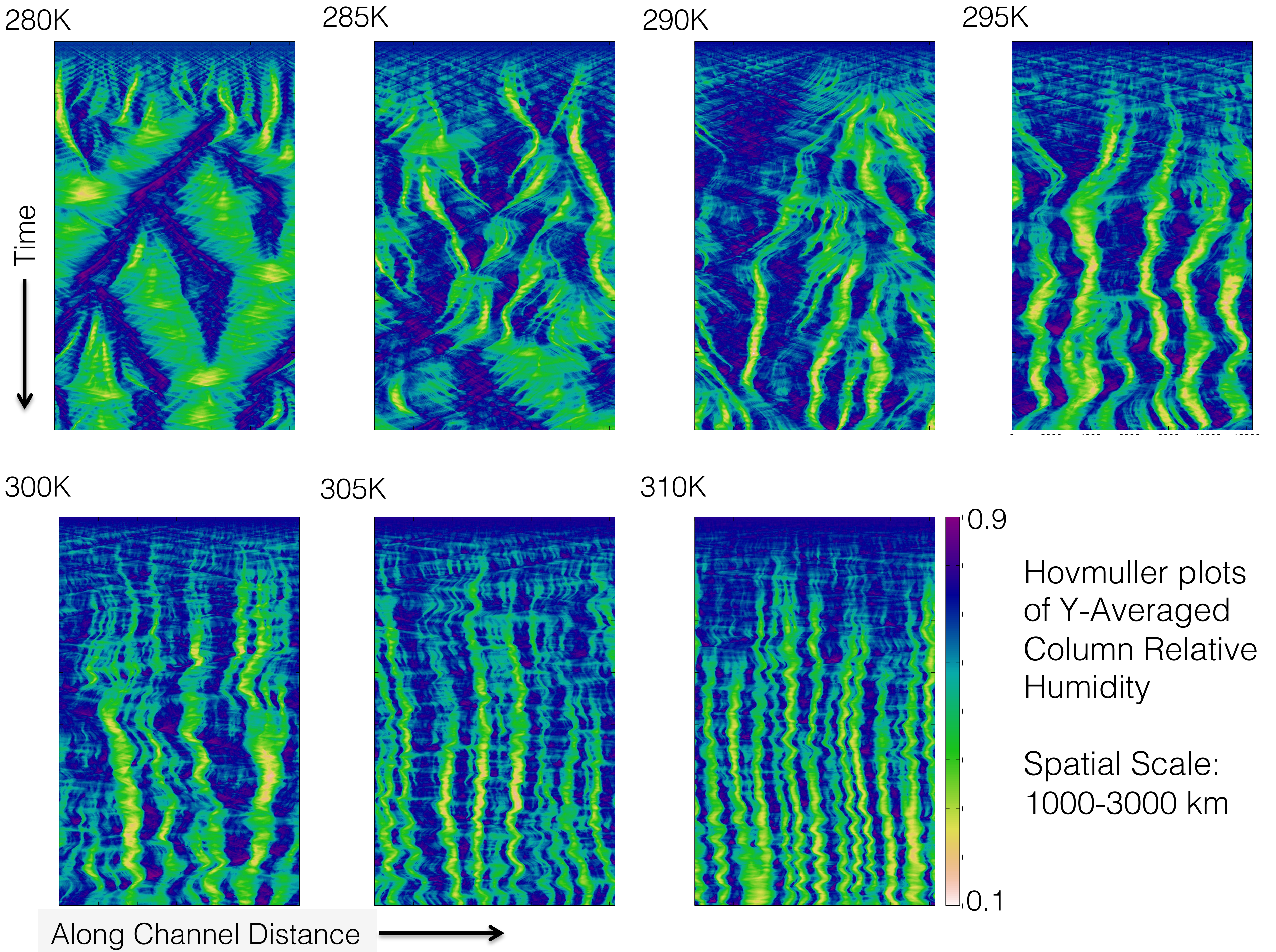
Plots of 1) cloud-top T + surface rain rate and 2) precipitable water for four aspect ratios, day 70, hour 01



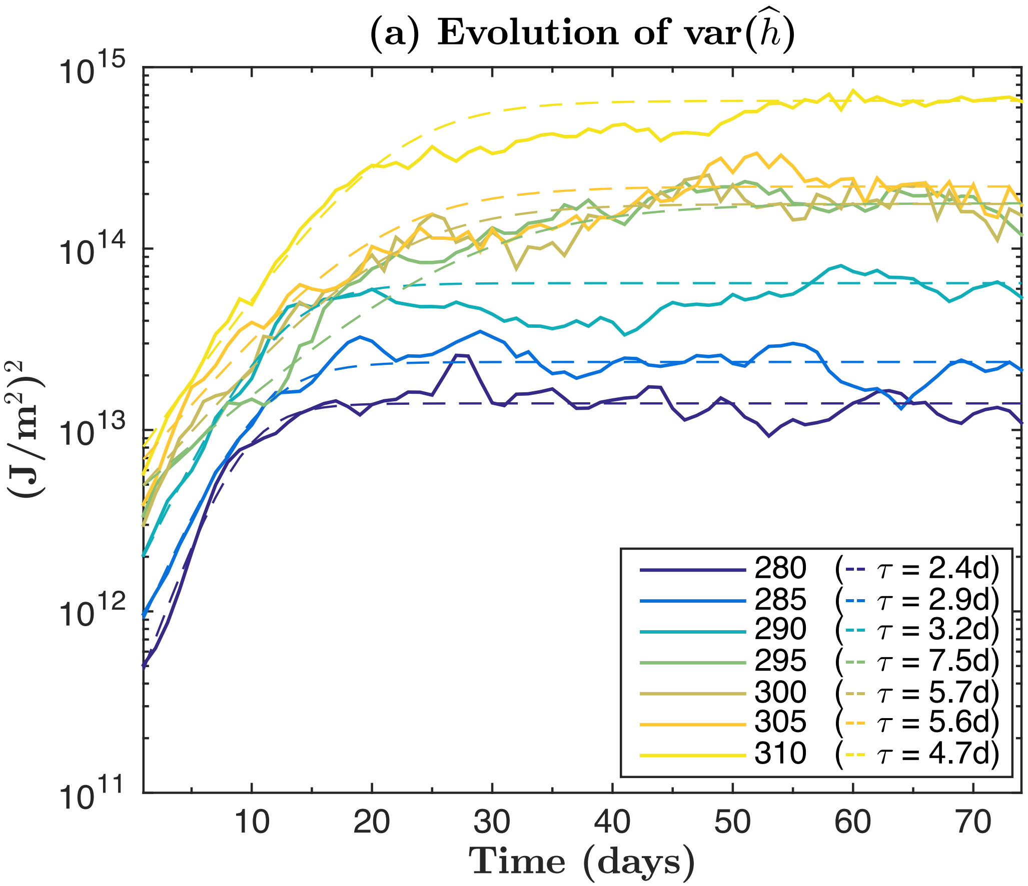


→ Most 3D simulations

Wing and Cronin (2016)


280K
285K
290K
295K
300K
305K
310K
Time
0.9
0.1
Hovmuller plots of Y-Averaged Column Relative Humidity
Spatial Scale: 1000-3000 km
Along Channel Distance

Increase in FMSE variance with aggregation



$$h = c_p T + gz + L_v q_v - L_f q_{ice}$$

FMSE conserved, column integral unchanged by convection

Large increase in column FMSE variance with aggregation

→Processes that increase var(h) favor self-aggregation

Wing and Cronin (2016)

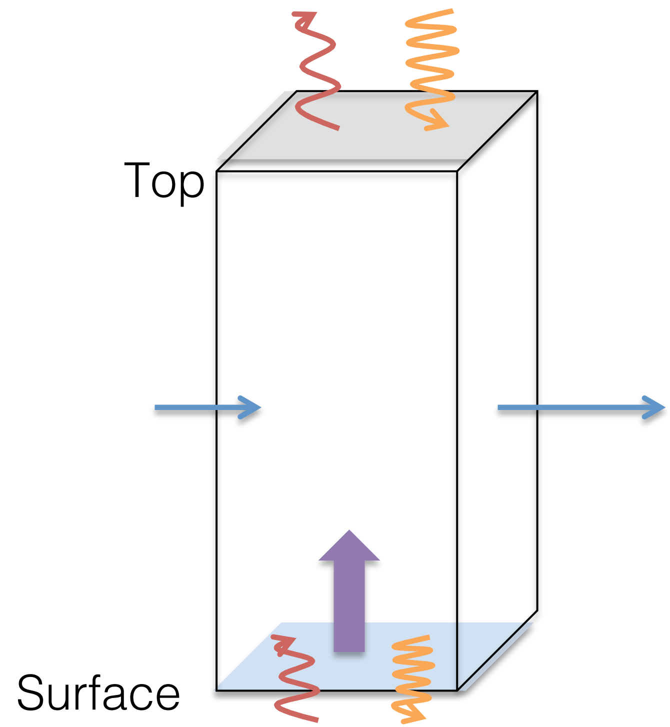
Mechanisms of Self-Aggregation

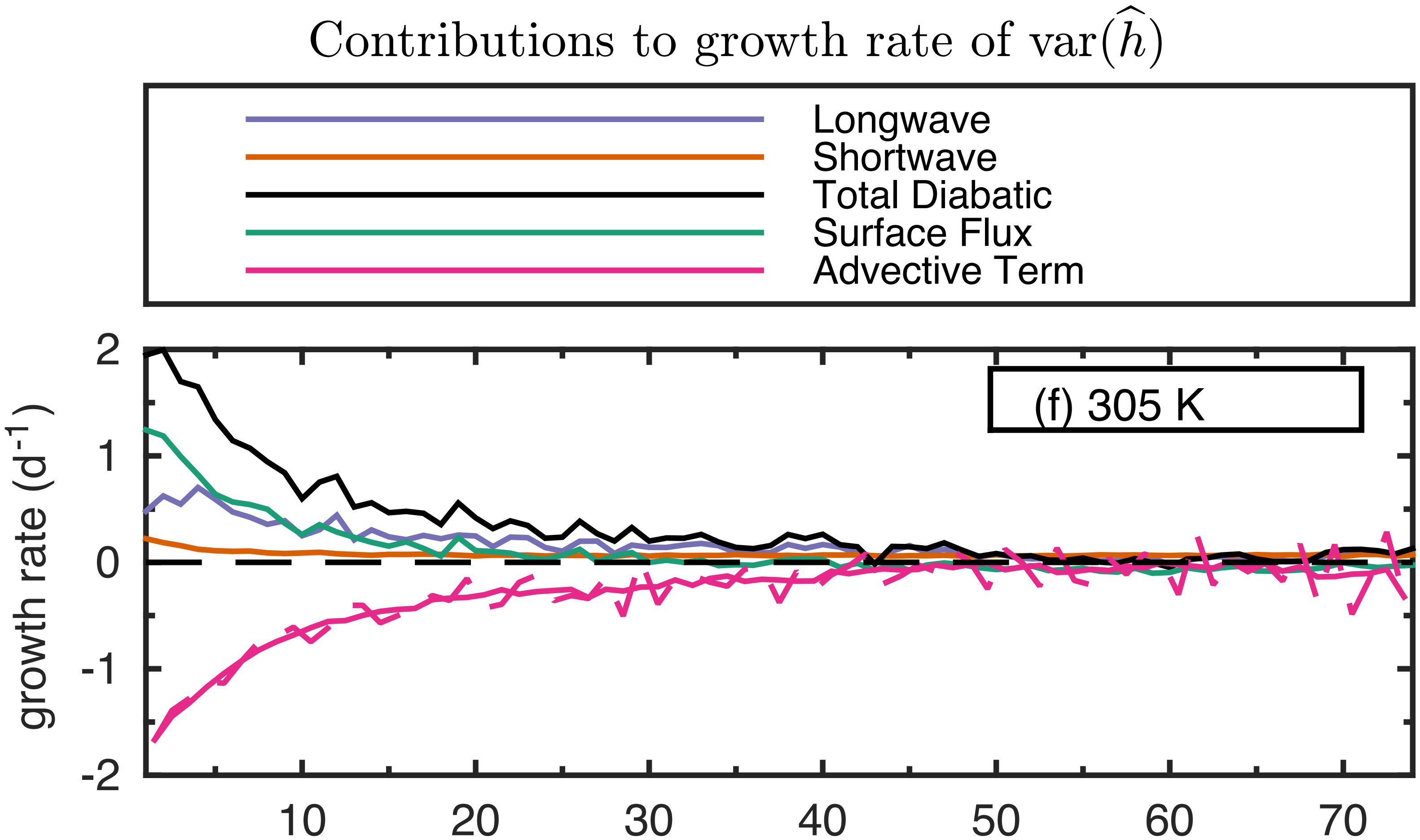
Framework: Budget for spatial variance of column integrated frozen moist static energy, following Wing and Emanuel (2014)
- Consider anomalies from the horizontal mean (primes)

$$\frac{1}{2}\frac{\partial \hat{h}'^2}{\partial t} = \hat{h}'\mathrm{SEF}' + \hat{h}'\mathrm{NetSW}' + \hat{h}'\mathrm{NetLW}' - \hat{h}'\nabla_h \cdot \widehat{\vec{u}h}$$

Feedback term:
FMSE anom * Source/sink anom

Positive Feedback: Process increases FMSE of already moist region
Negative Feedback: Process decreases FMSE of moist region

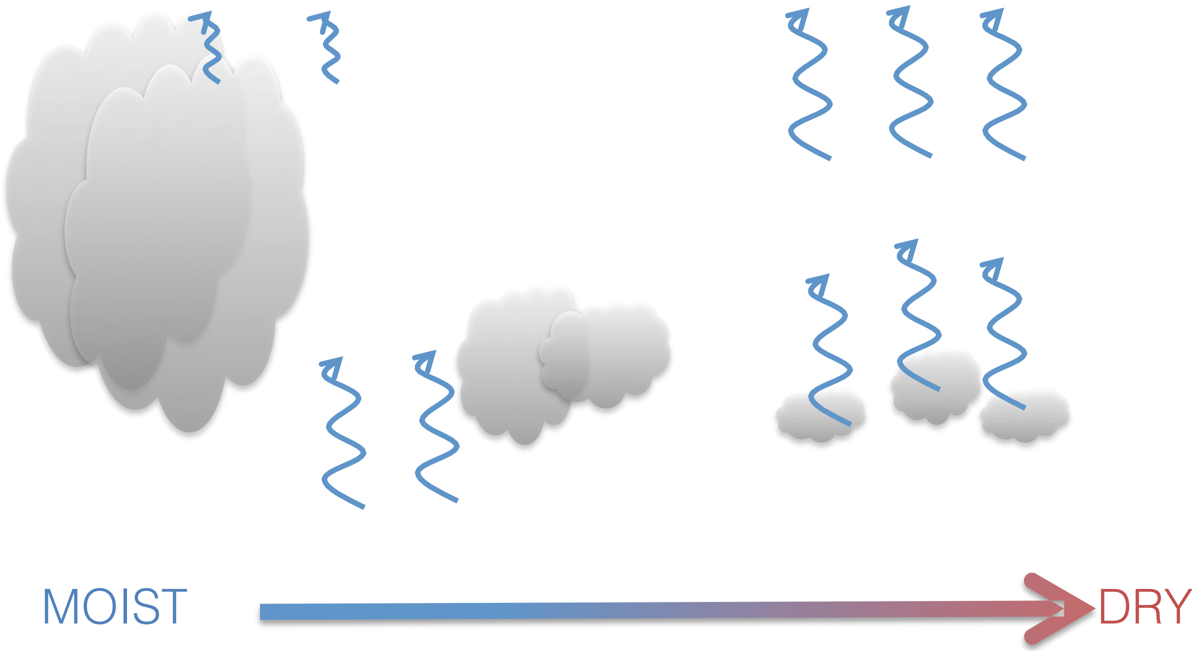




Longwave and surface flux feedbacks drive initial development of aggregation

Wing and Cronin (2016)

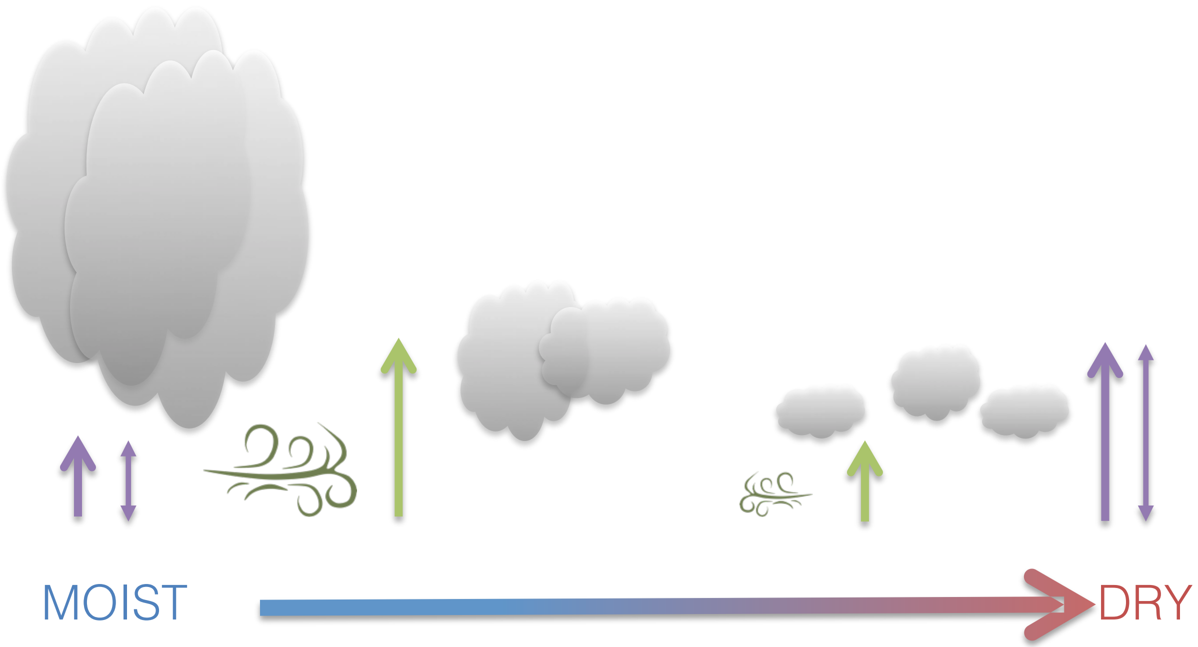
Positive Longwave Radiation Feedback



Small atmos. LW cooling

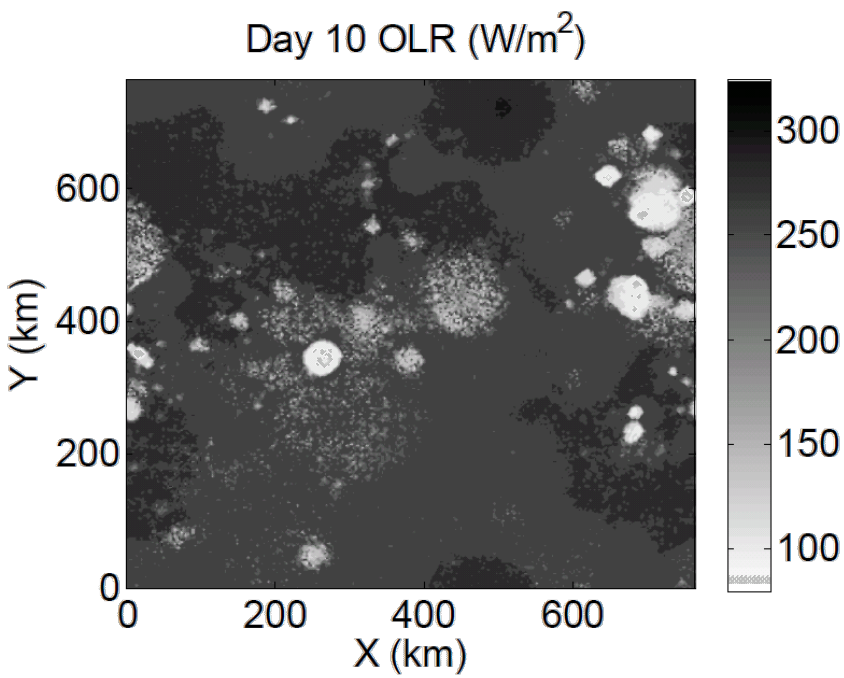
LARGE atmos. LW cooling

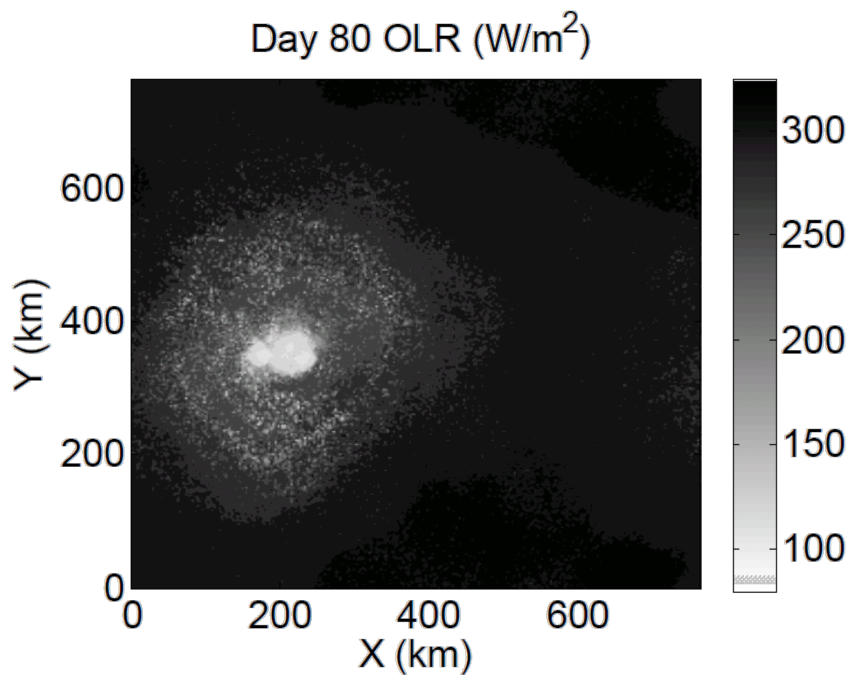
Positive Surface Enthalpy Flux Feedback



Small surface fluxes	Large surface fluxes
Large surface fluxes	Small surface fluxes
Large surface fluxes	Small surface fluxes

In RCE, organization of convection takes the form of "self-aggregation"





Spontaneous clustering of convection in homogeneous environment driven by radiative and surface flux feedbacks

Wing and Emanuel (2014)

A brief summary of self-aggregation

Studies agree that…

- Convection preferentially occurs in humid, high MSE regions
- As convection aggregates, dry regions get drier and moist regions get moister, increasing humidity and MSE variance
- Self-aggregation affects domain-mean climate*
- Feedbacks between longwave radiation and clouds/water vapor are essential for triggering and maintaining self-aggregation
- Surface flux feedbacks favor the development of aggregation, but aren't always essential
- The self-aggregated state exhibits strong hysteresis

But many things remain uncertain…

- Relative contributions of direct and circulation-mediated effects of radiative forcing
- Behavior with mean winds/vertical wind shear
- Behavior with interactive surface
- Behavior over land
- Control of spatial scale
- *Nature of temperature dependence*
- *Impact on climate sensitivity*
- *Robustness to different dynamical models & physics schemes*

Introduction to RCEMIP

Despite its simplicity, there aspects of the physics of RCE that are not fully understood

RCE is useful for:

- Understanding tropical dynamics in simplified setting
- Including in hierarchy of modeling
- Connecting to theory/analytic models
- Model development/evaluation/comparison

"Time-honored idealization for understanding the tropical atmosphere and its sensitivity to relevant forcings" Bretherton et al. (2005)

Motivation for RCEMIP

1. Assessing the sensitivity of simulations of RCE is hindered by the absence of a common baseline

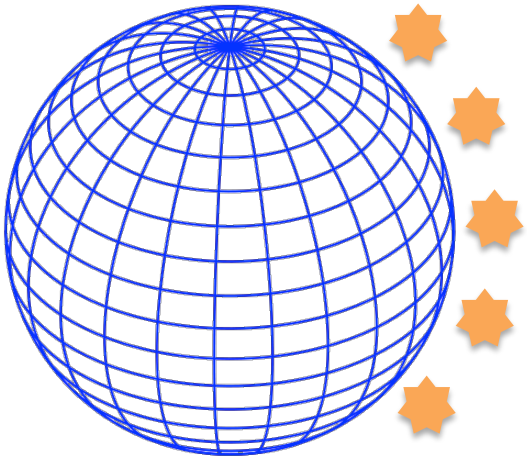
2. Can help answer some of biggest, most important questions in climate science
   - *Changes in clouds and convection with warming*
   - *Cloud feedbacks and climate sensitivity*
   - *Aggregation of convection and its role in climate*

3. No other framework accessible by so many of the model types
   - *Can test models with parameterized convection against those that simulate it directly*

RCE Setup

Homogenous boundary conditions and forcing

Interactive radiation with specified O_3 profile and CO_2, CH_4, N_2O concentrations.



Same solar insolation everywhere

Solar constant = 551.58 Wm^{-2}
Tropical mean insolation-weighted zenith angle = 42.05°
➔ Tropical annual mean insolation of 409.6 Wm^{-2}

Same SST everywhere

Interactively calculated surface fluxes

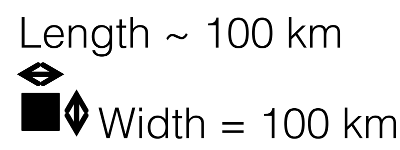
No rotation. No land or sea ice.

- Initialize with same temperature and moisture sounding at every grid point and zero wind.
- Generate convection by prescribing random noise.
- Run to equilibrium.

Two Sets of Simulations:

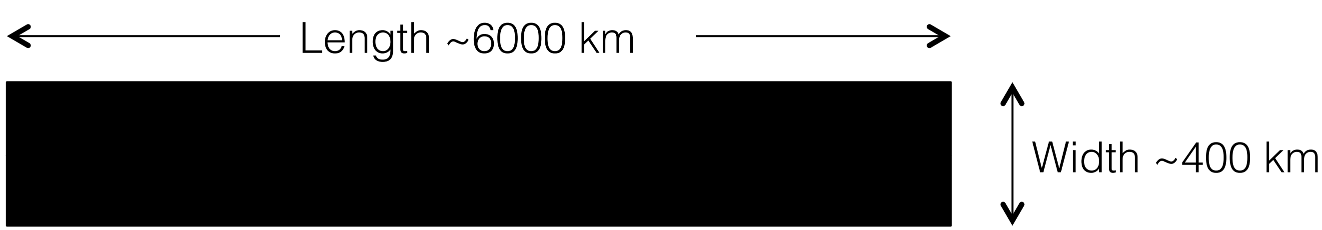
1. RCE_small (295 K, 300 K, 305 K)

- 100 km square for CRMs, 1 km horiz spacing
- Single column or small Earth for GCMs
- 200 m horiz spacing for LES
- Initialize from analytic tropical sounding



2. RCE_large (295 K, 300 K, 305 K)

- 6000 km x 400 km rectangle for CRMs, 3 km horiz spacing
- Global for GCMs, GCRMs (CMIP6 config.)
- Initialize from mean sounding from **RCE_small**



Expected Participation from ~40 Models

CRMs (16), GCMs (12), LES (6), GCRMs (2), SCMs (8)

GCMs	CRMs	LES	GCRMs	SCMs
CAM5	**DAM**	CM1	**NICAM**	**CNRM CM6**
CAM6	**CM1**	DALES	**MPAS**	**GEOS5**
CNRM-CM6	GFDL FV3	**ICON**		IPSL-CM5A
ECHAM6	**ICON-LEM**	MESONH		IPSL-CM6
GEOS5	**ICON-NWP**	MicroHH		MIT SCM
GFDL FV3	**Meso-NH**	**SAM**		SCAM5
ICON-A	MicroHH			SCAM6
IPSL-CM5A-LR	**SAM**			**UKMO GA7**
IPSL-CM6	**SCALE**			
SP-CAM	**UCLA-CRM**			
SPX-CAM	**UKMOi v11.1 RA1-T**			
UKMO GA7	**UKMOi v11.1 RA1-T-nohrad**			
	UKMOi v11.1 RA1-T-nocloud			
	UKMOi v11.1 CASIM			
	WRF 3.9.1			
	WRF 3.5.1			

Your RCEMIP Analysis

Objective: Determine which simulations exhibit self-aggregation and assess the degree and scale of self-aggregation

Today

Task 1: Examine the basic state and evolution of the simulations to RCE using 0D and 1D data

Task 2: Examine spatial variations of convection using 2D data

Thursday/Friday

Design and use a metric of aggregation

Diagnose the spatial scale of aggregation

Task 1: Evolution to RCE

1. Equilibrium and Energy Balance
2. Vertical Profiles

→ Start with one RCE_small simulation

3. SST Dependence → Consider simulations at other SSTs

4. Small vs. Large Simulations → Now compare to RCE_large simulations

Task 2: Spatial Variations

1. Small Simulations

2. Large Simulations

Does the convection look aggregated?

Thurs/Fri: Assess Degree of Aggregation

1. Design and use a metric of aggregation
   - Explore its sensitivities

2. Diagnose the spatial scale of aggregation

It is easy to see with your eyes whether convection is aggregated – but can you measure it quantitatively and objectively?