Simulating Microphysical and Dynamical Processes of Deep Convective Anvils

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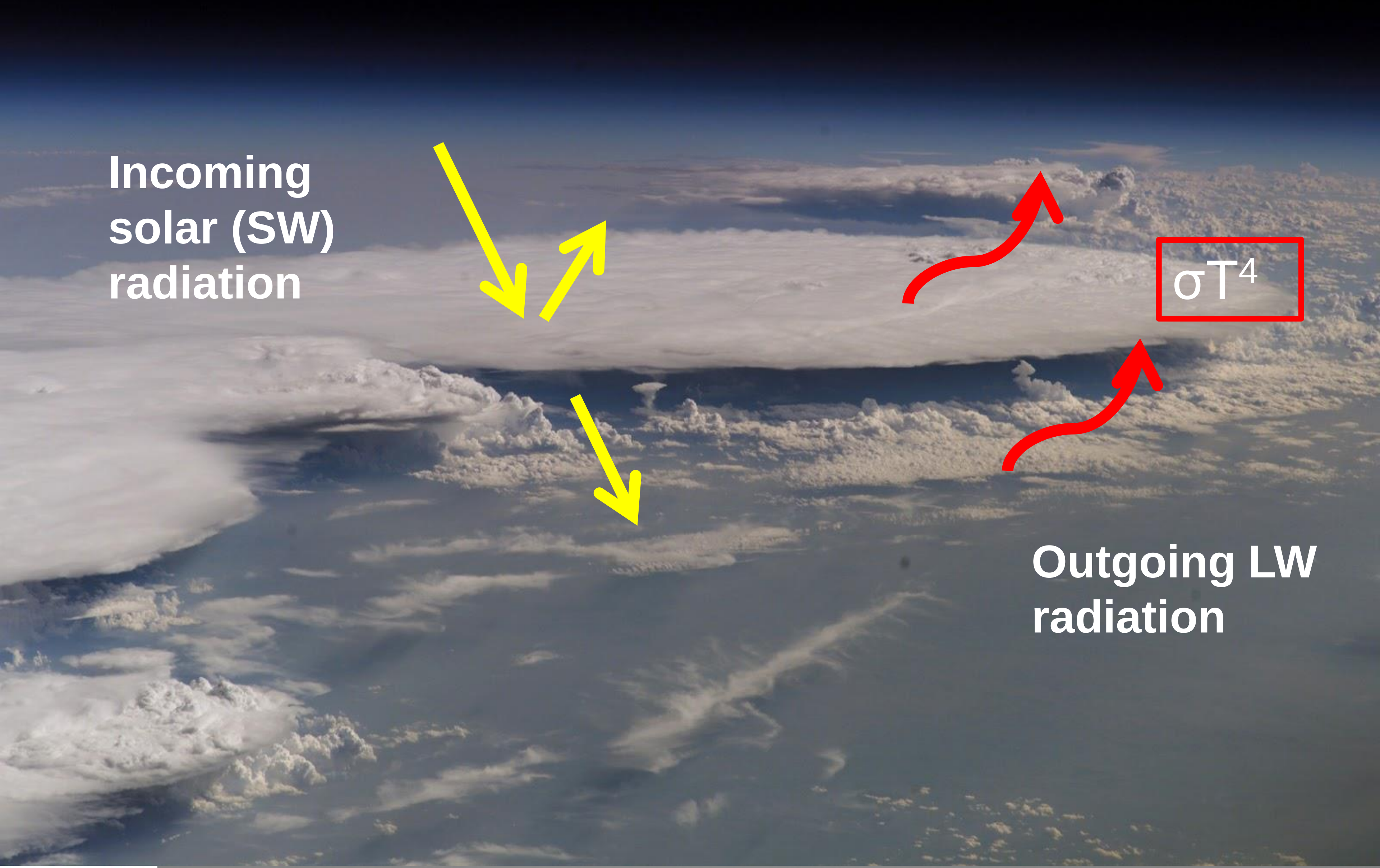
Convective Anvils → Radiative Impacts



Incoming solar (SW) radiation

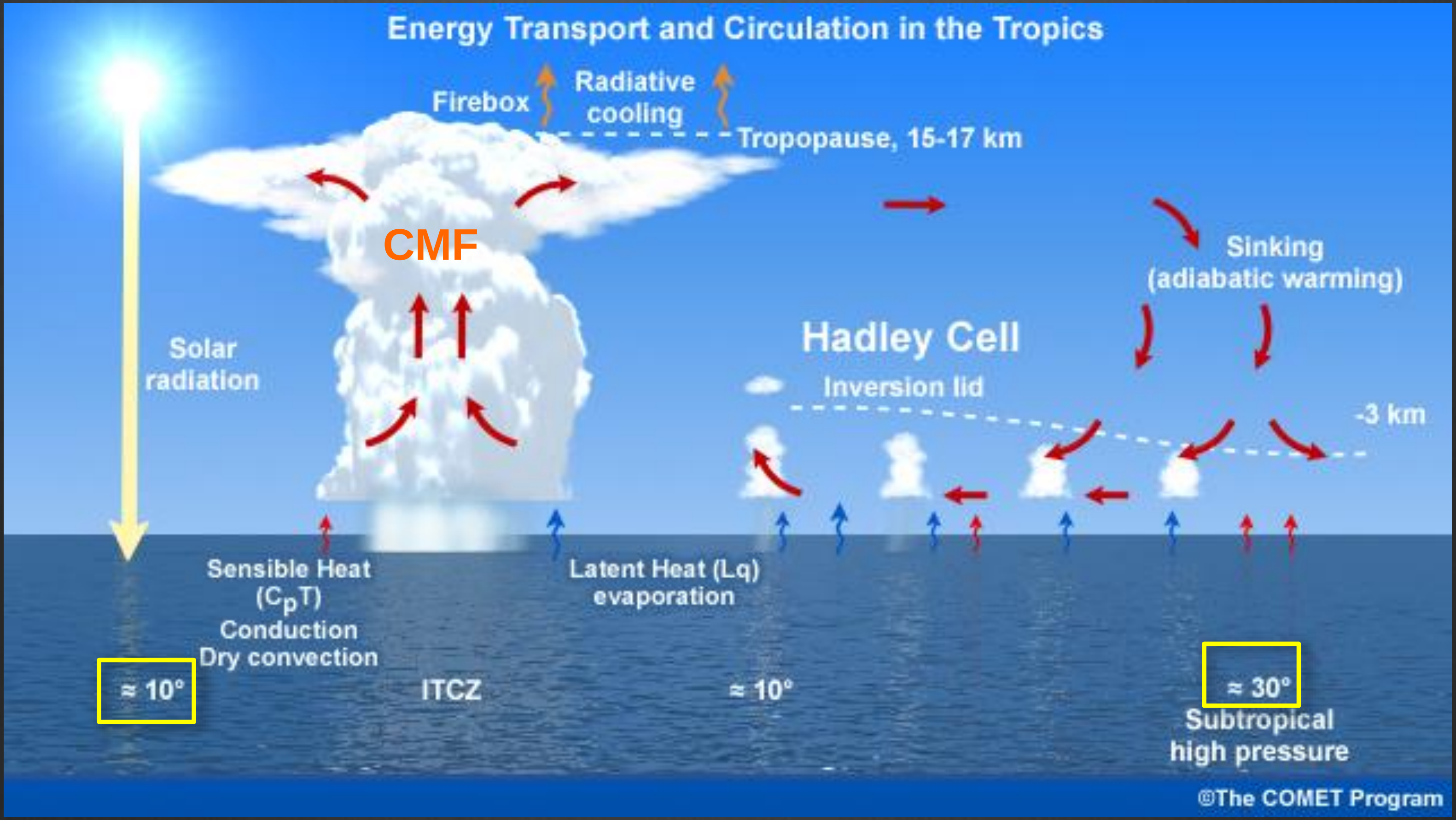
σT^4

Outgoing LW radiation

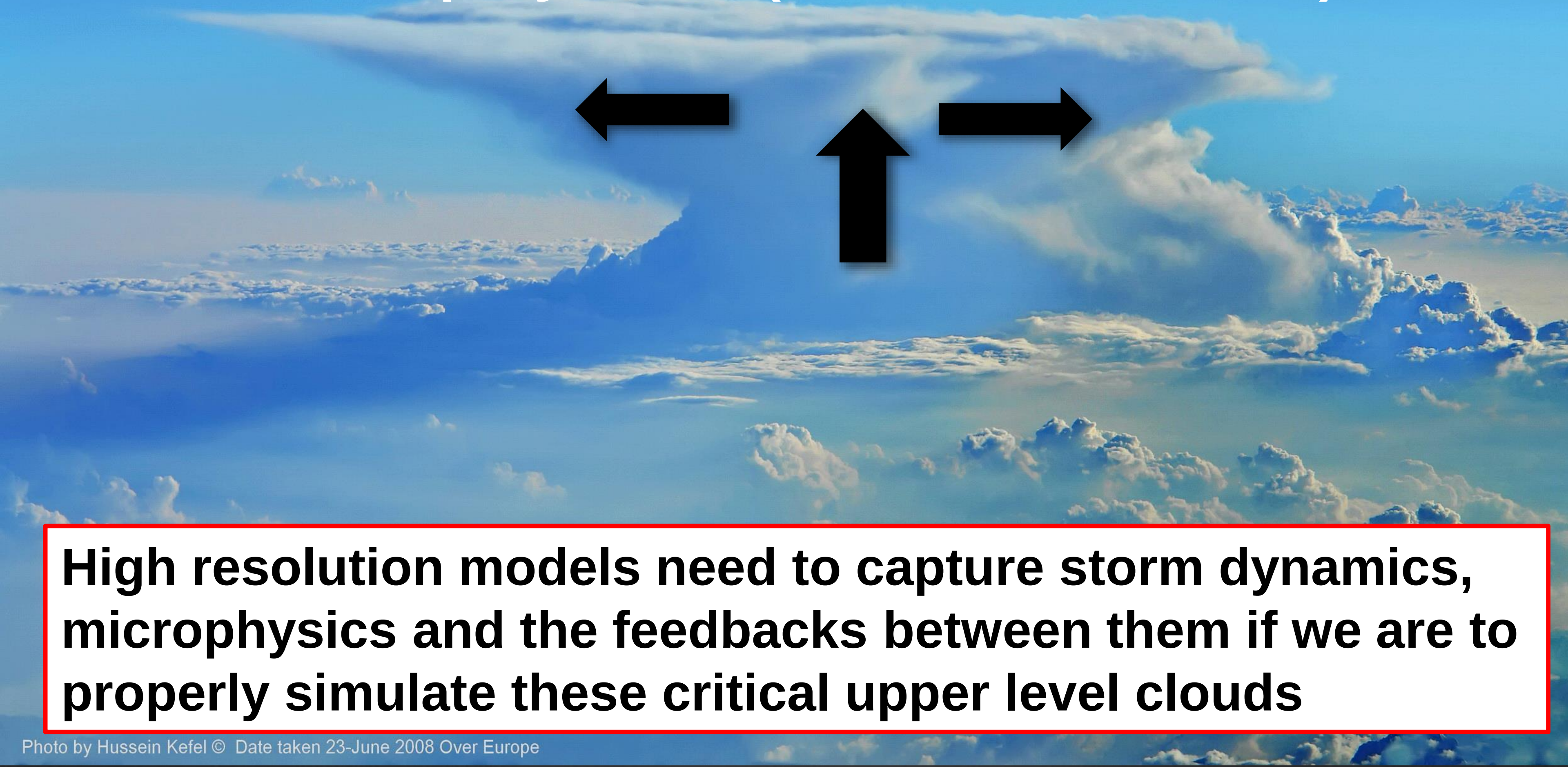
Convective Anvils → Detrainment of Water Vapor and Momentum

Supercell anvil - photographed from NASA's DC-8 airborne science laboratory as it flew at an altitude of 40,000 feet southwest of Oklahoma City, Ok., during a DC3 mission flight May 19. (NASA / Frank Cutler)

Convective Anvils → Large-Scale Circulation



Convective Anvils → Integrally Dependent on Storm Dynamics and Microphysics (and Radiation)



High resolution models need to capture storm dynamics, microphysics and the feedbacks between them if we are to properly simulate these critical upper level clouds

Photo by Hussein Kefel © Date taken 23-June 2008 Over Europe

Challenges in Representing Dynamics

(1) Numerous Processes and Feedbacks

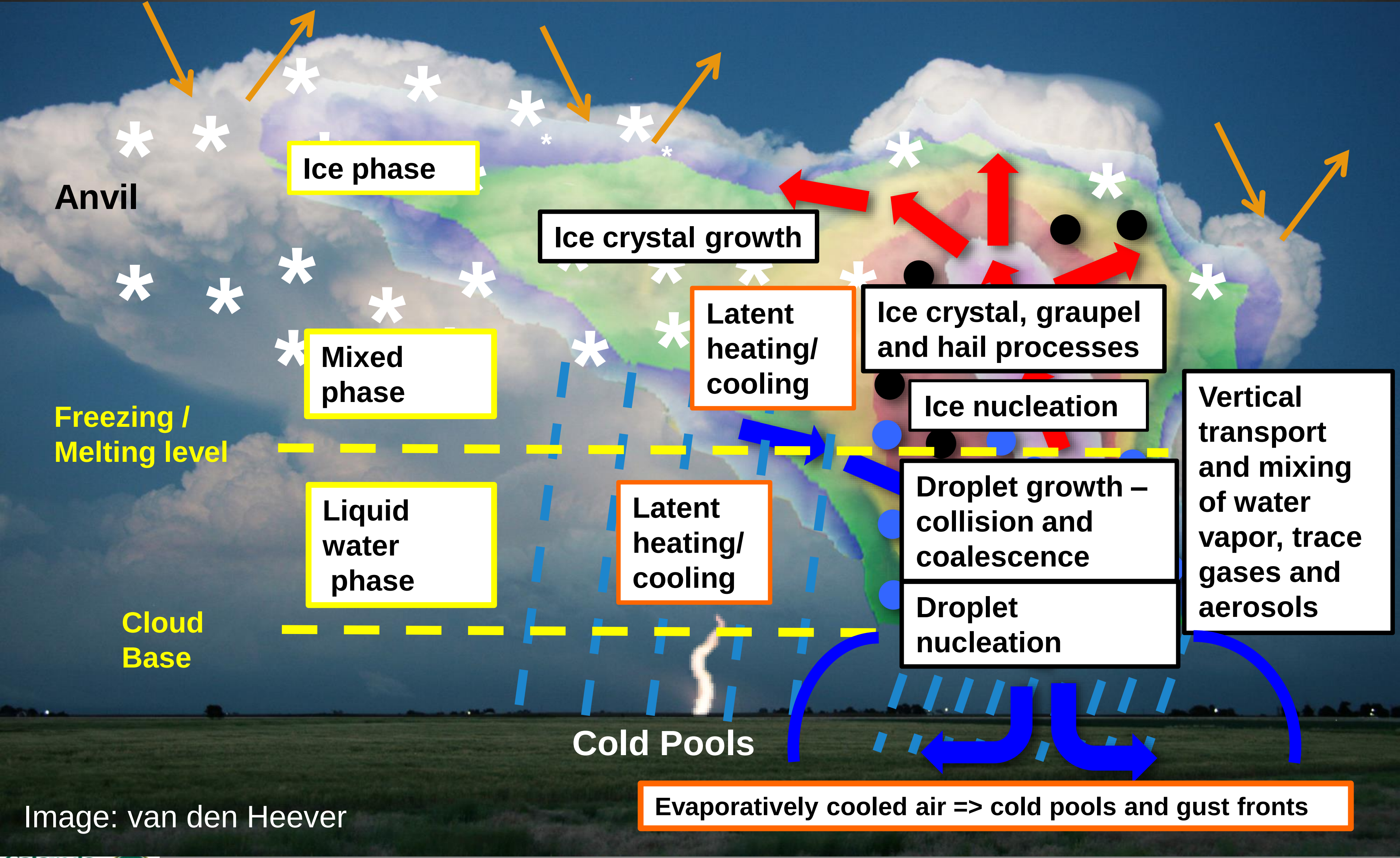
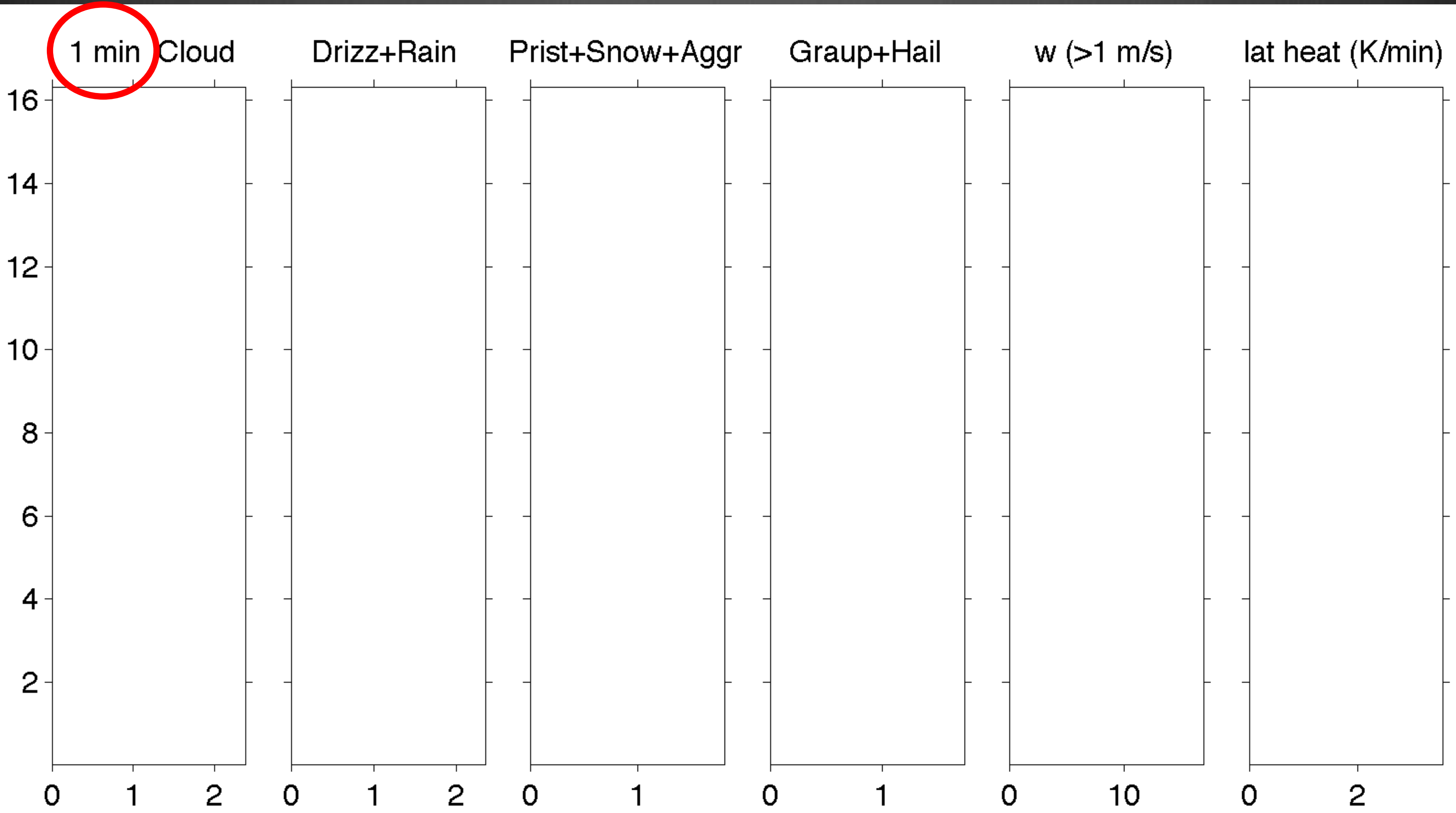


Image: van den Heever

Challenges in Representing Dynamics

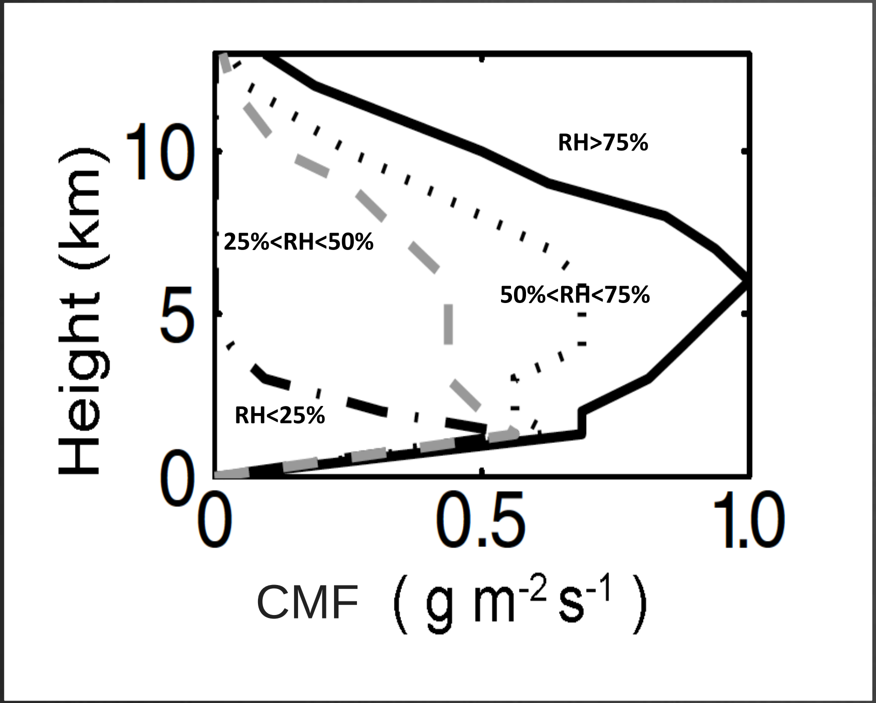
(2) Dynamics – Microphysics Feedback Process Rates

Profiles of cloud mixing ratios (g/kg) and vertical velocity (m/s) averaged over the updraft in a developing deep convective storm at 1 minute time intervals

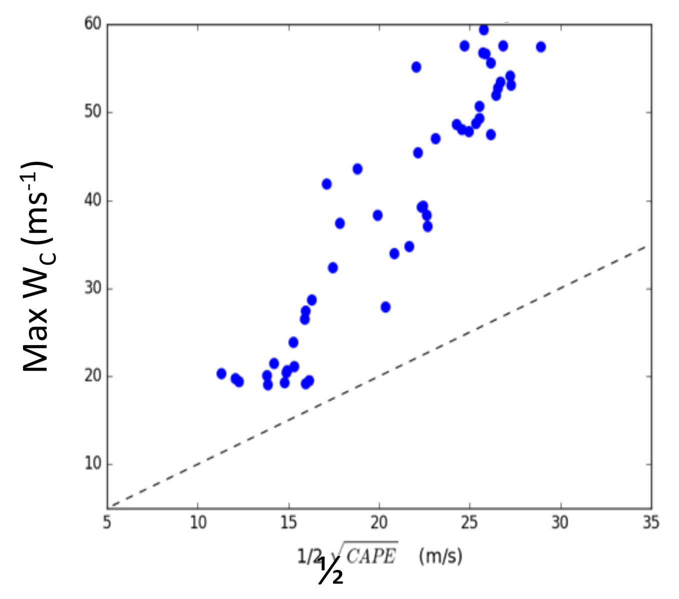


Challenges in Representing Dynamics

(3) Environmental Impacts



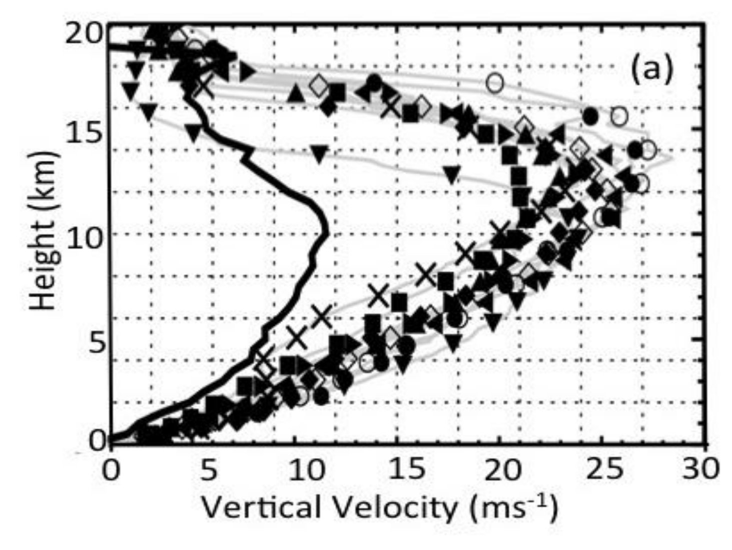
CMF as a function of relative humidity (modified after De Rooy et al 2013)



Maximum vertical velocity as a function of CAPE

Explicit Simulations of Vertical Velocity

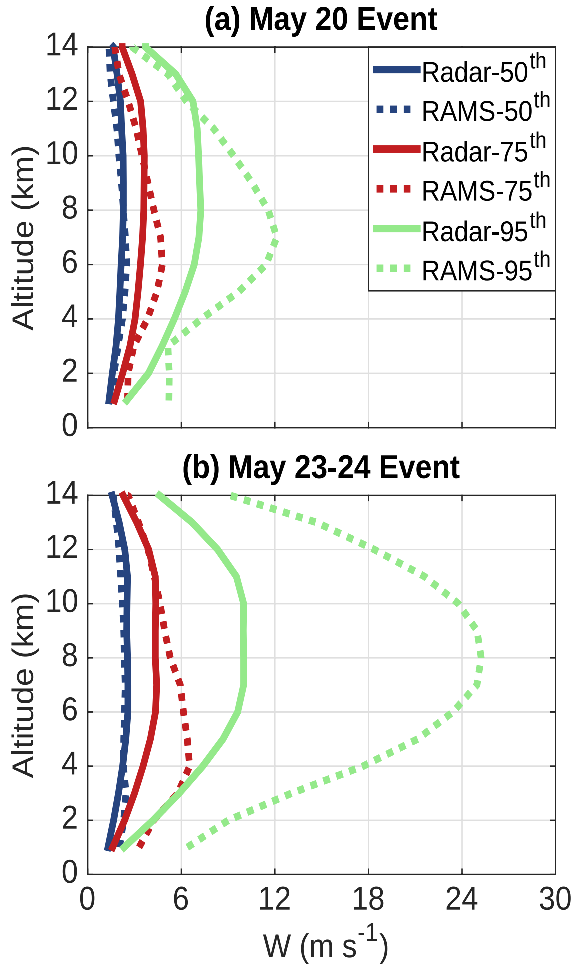
Tropical Convection (TWP-ICE)



CRMs (symbols) compared with radar observations (solid curve) (after Varble et al 2014).

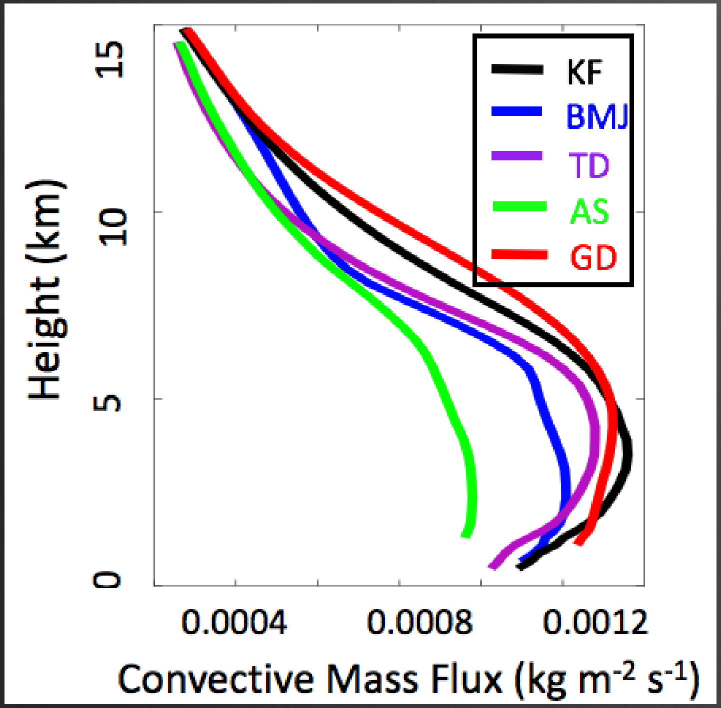
Simulated vertical velocity is both larger and located higher up than Doppler derived vertical velocity

Midlatitude Squall Lines (MC3E)

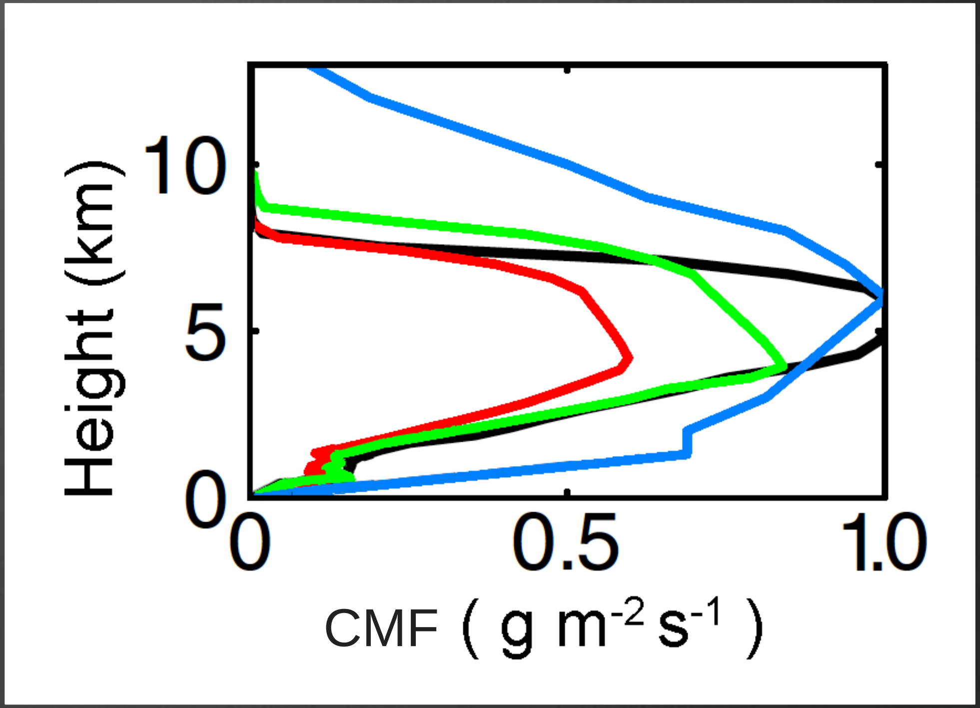


50th, 75th, and 95th percentiles of radar derived and simulated vertical velocities within convective updrafts for (a) May 20 and (b) May 23-24 MC3E squall lines (after Marinescu et al 2016)

Implicit Representation of Vertical Velocity – Cumulus Parameterization



CMF from a simulation of the same convective storms using the same model (WRF) but different convective parameterizations



Averaged profiles of CMF for different models including a CRM (blue), the ECMWF IFS (green) using an RH dependent scheme, and two other forecast models with mass fluxes independent of RH (modified after De Rooy et al 2013)

Forces Driving Vertical Velocity (W)

$$\frac{\partial w}{\partial t} = -\vec{V}\cdot\vec{\nabla} w - \frac{1}{\rho}\frac{\partial p}{\partial z} + \boxed{B} + D$$

Time rate of change

Advection (vertical and horizontal transport)

Pressure gradient force

Buoyancy

Diffusion

$$B = g\frac{q'_r}{q_{r0}} \approx g\left(\frac{q'}{q_0} + 0.61 r_v - r_c\right)$$

This is the term representing microphysics – dynamics feedbacks

Potential Sources of Error in Simulating W

$$\frac{\partial w}{\partial t} = -\vec{V} \cdot \vec{\nabla} w - \frac{1}{\rho}\frac{\partial p}{\partial z} + B + D$$

1. Discretization of continuous fluids – systematic errors due to inability to capture nonlinearities → advection and PGF
2. Microphysics (in B) and turbulence / diffusion – sub-grid scale processes – need parameterizations
3. Representation of perturbations and associated base state challenging

Focus Today

$$\underbrace{\frac{\partial w}{\partial t}}_{\text{Time rate of change}} = \underbrace{-\vec{V}\cdot\vec{\nabla}w}_{\text{Advection (vertical and horizontal transport)}} \underbrace{-\frac{1}{\rho}\frac{\partial p}{\partial z}}_{\text{Pressure gradient force}} + \underbrace{B}_{\text{Buoyancy}} + \underbrace{D}_{\text{Diffusion}}$$

Today's focus

$$B = g\frac{q'_r}{q_{r0}} \approx g\left(\frac{q'}{q_0} + 0.61 r_v - r_c\right)$$

Many of the issues in numerical models have been attributed to inaccuracies associated with this term (includes latent heating and microphysical processes)

Relationship between W and Microphysics

Prognostic equation for condensate (liquid water and ice)

Think of as radar Z

$$\frac{\partial r_c}{\partial t} = -\vec{U}_h \cdot \vec{\nabla}_h r_c - [w - v_t]\frac{\partial r_c}{\partial z} + M + D$$

Small compared to other terms

Condensate tendency

Horizontal advection / transport

Vertical advection / transport (includes condensate terminal fall speeds)

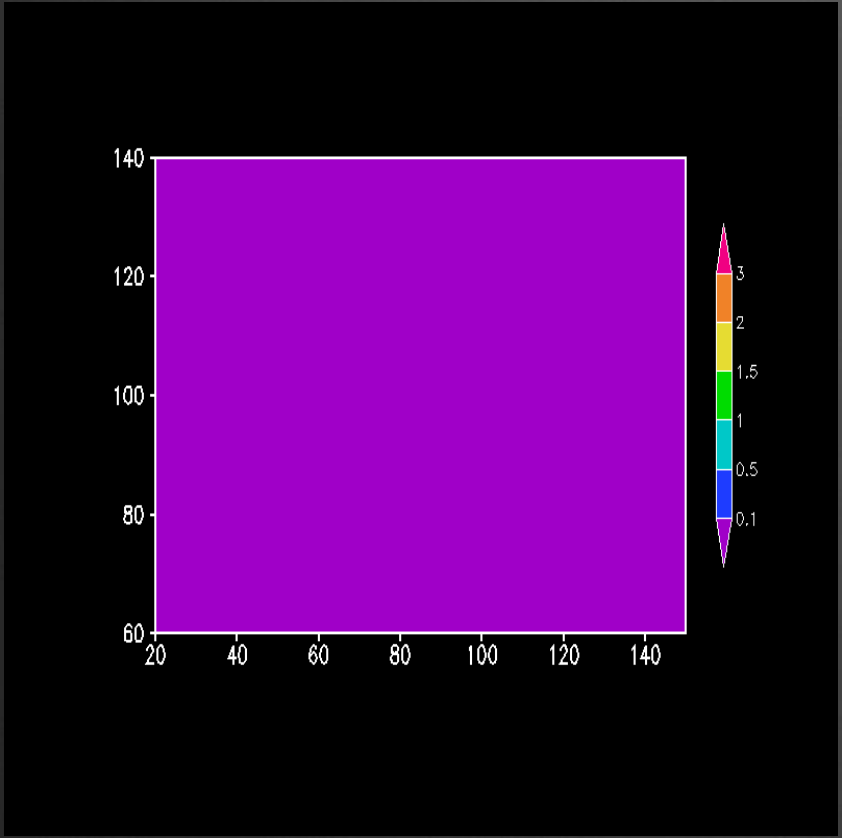
Microphysical processes

Difficult to measure

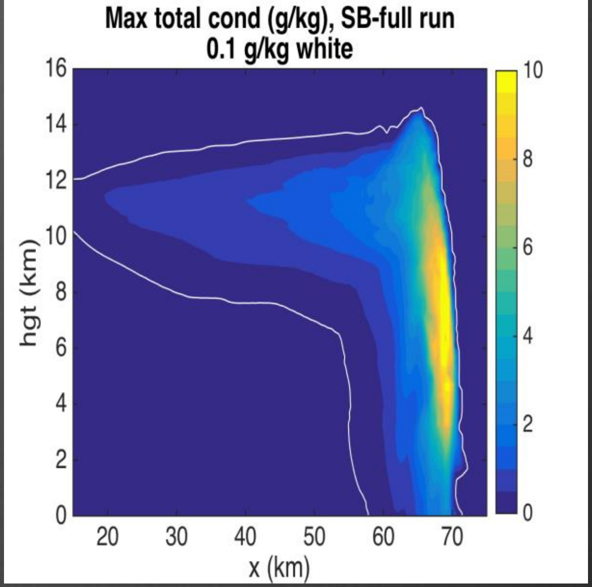
Diffusion

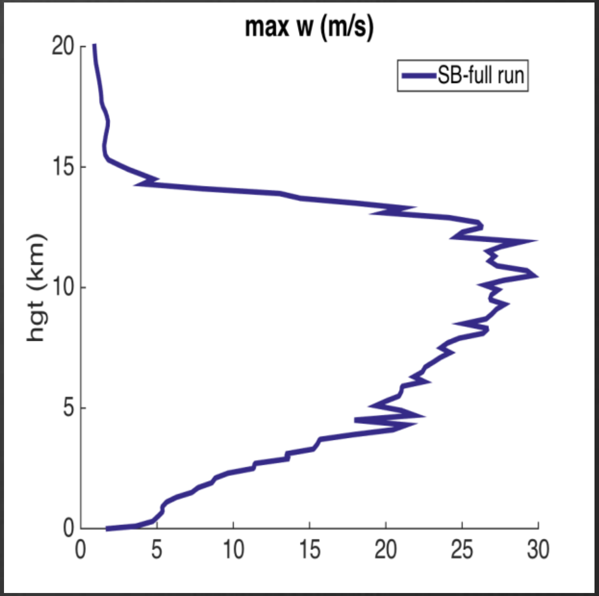
Spatial and temporal derivatives in condensate mass – could be measured using appropriate radar platforms

CRM Simulated Anvil Characteristics

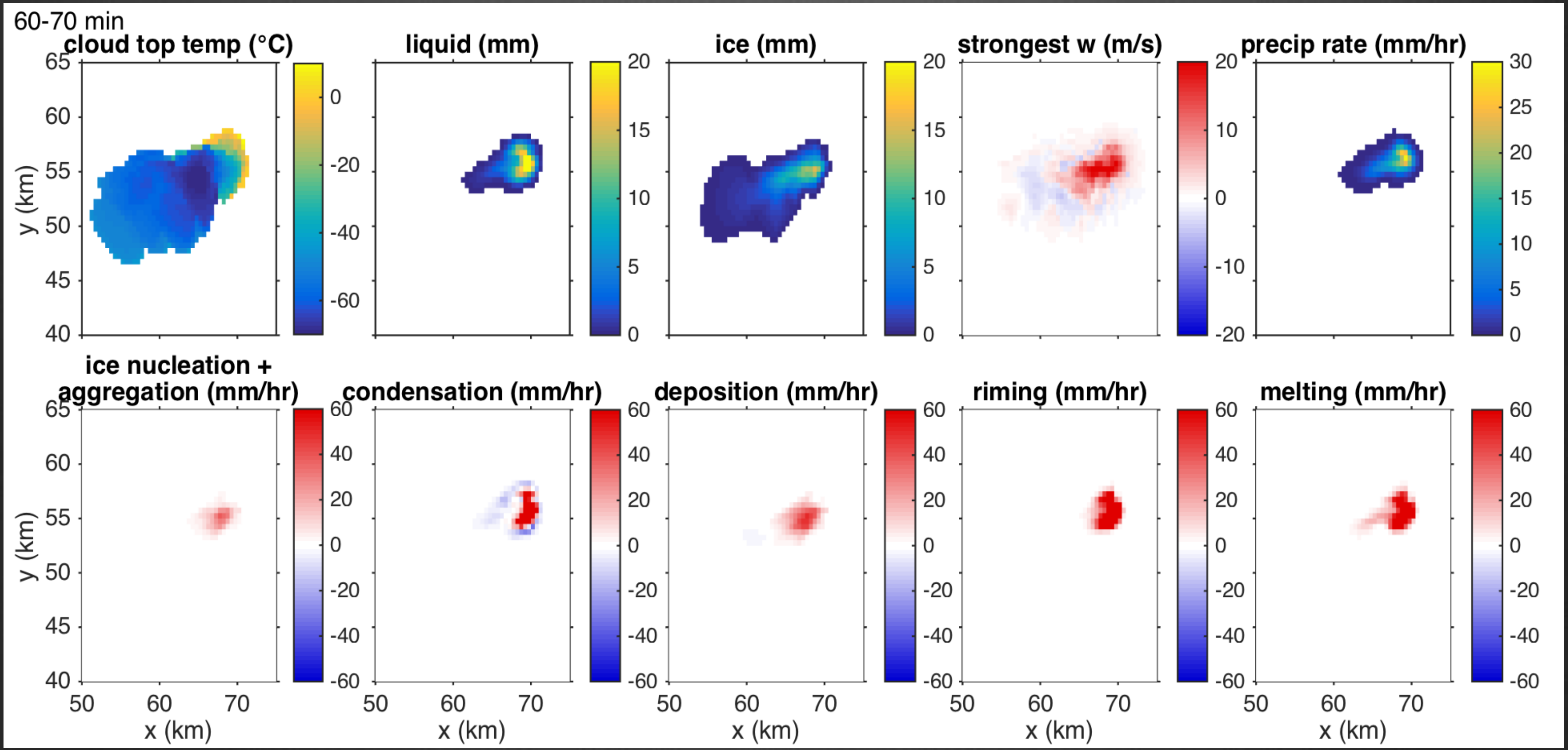


Plan view of ice water path (mm, shaded) and vertical velocity at 9.7 km (black contours, 5 and $10\ \mathrm{ms}^{-1}$)





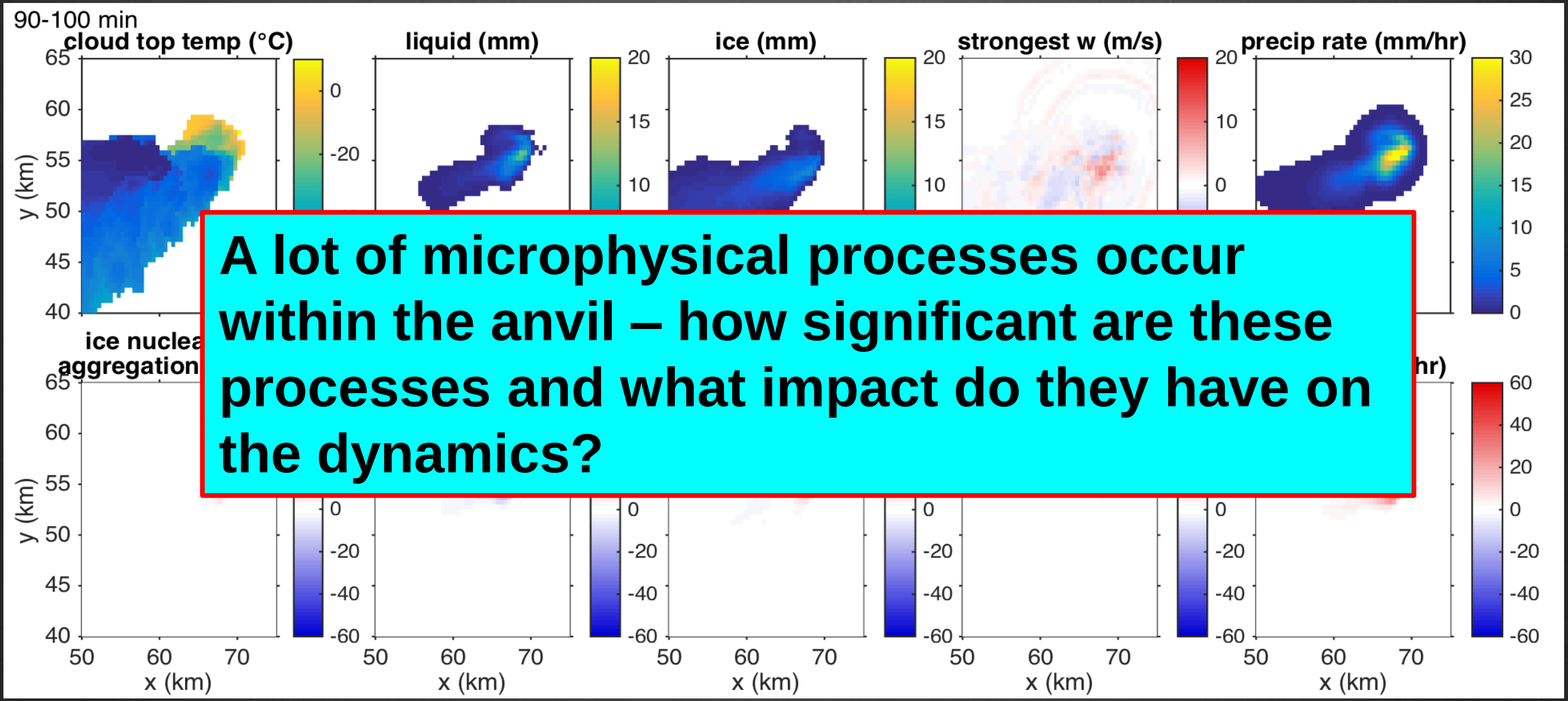
Convective Anvil Process Rates – Mature Phase



1. W > 20 m/s
2. Condensation, riming, and melting signals are strong within the convective core, and ice depositional growth and melting are important in the anvil

van den Heever et al GEWEX PROESS 22-23 October 2018 Paris

Convective Anvil Process Rates - Dissipating Stage

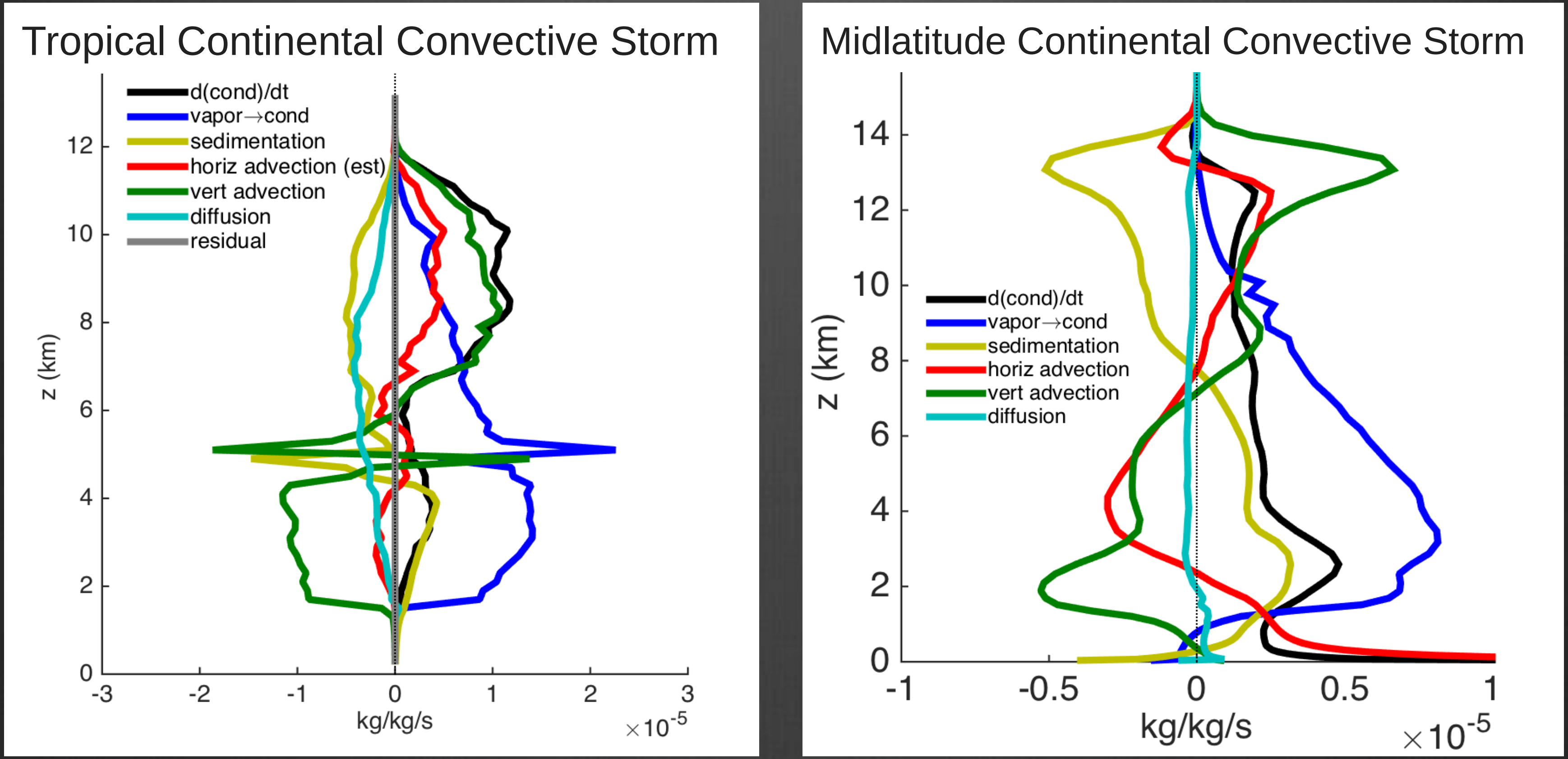


A lot of microphysical processes occur within the anvil – how significant are these processes and what impact do they have on the dynamics?

1. W < 20 m/s
2. Evaporation and melting are prevalent within the core while patterns of both ice depositional growth and sublimation are evident in the anvil region.

Condensate Budgets

$$\frac{\partial r_c}{\partial t} = -\vec{U}_h \cdot \vec{\nabla}_h r_c - [w - v_t]\frac{\partial r_c}{\partial z} + M + D$$



Tropical Continental Convective Storm

Midlatitude Continental Convective Storm

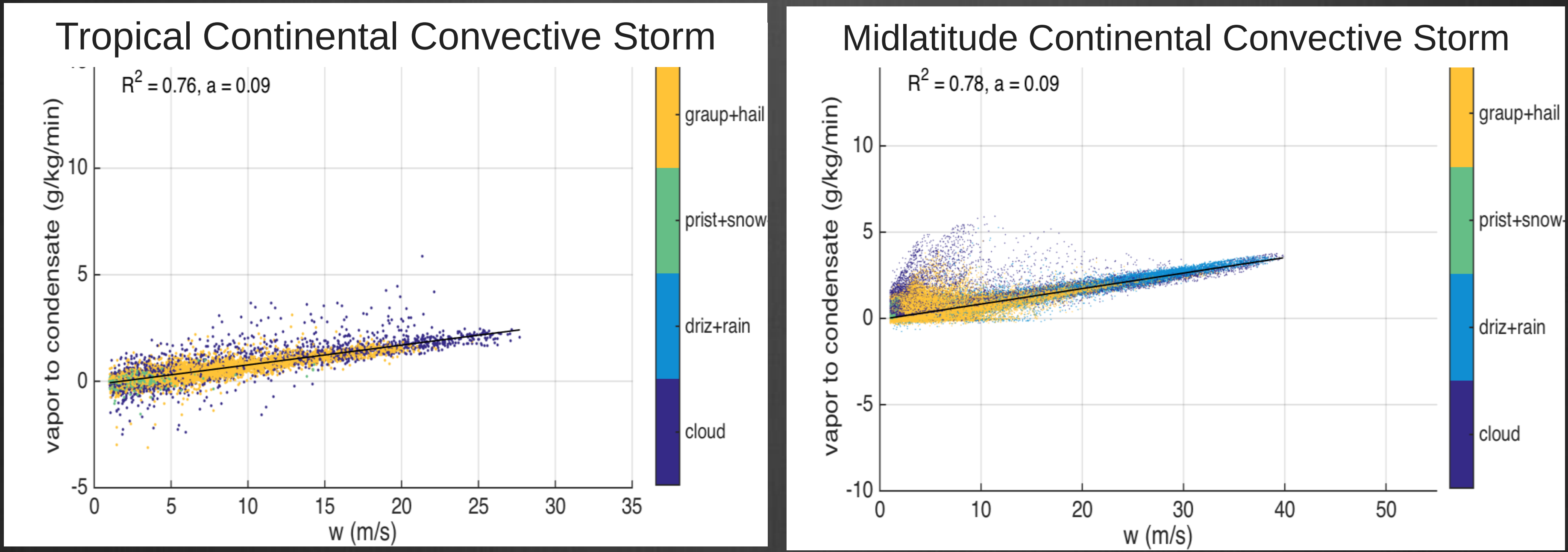
Contributions of different terms in condensate equation to time changes in condensate mixing ratio in simulations of different convective storms. Budget terms are analyzed over grid points with $w > 1$ m s^{-1} for both cases.imp

Linear Correlations Between W and Micro

Microphysics contributions important – but how are they related to W, if at all?

Strong robust linear fit – even in mixed phase regions

Slopes are similar - independent of region and storm type

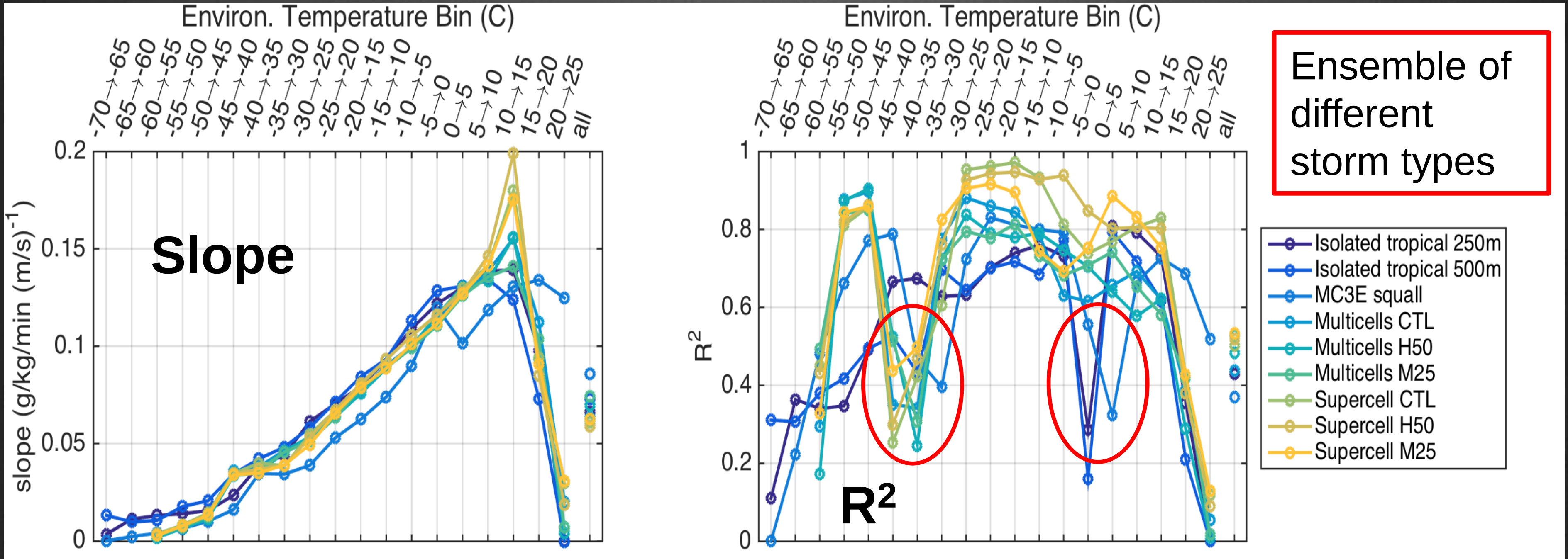


Tropical Continental Convective Storm

Midlatitude Continental Convective Storm

Scatter plots of vertical velocity *w* and microphysical contributions to condensate mixing ratio changes *M* for (left panel) the different convective storms. Scatter plots for all model grid points where w > 1 m s^{-1} and where the environmental temperature is between -15°C and -10°C.

Linear Correlations Between W and Micro



Slope

R²

Ensemble of different storm types

Associated with freezing level and homogeneous freezing

(Left panel) Slope and (right panel) variance explained by a linear fit between *w* and *M* as a function of environmental temperature in 5°C temperature bins, for a range of different convective types as indicated in the legend.

Strong robust linear relationship between w and M

$$w = a(T)M$$

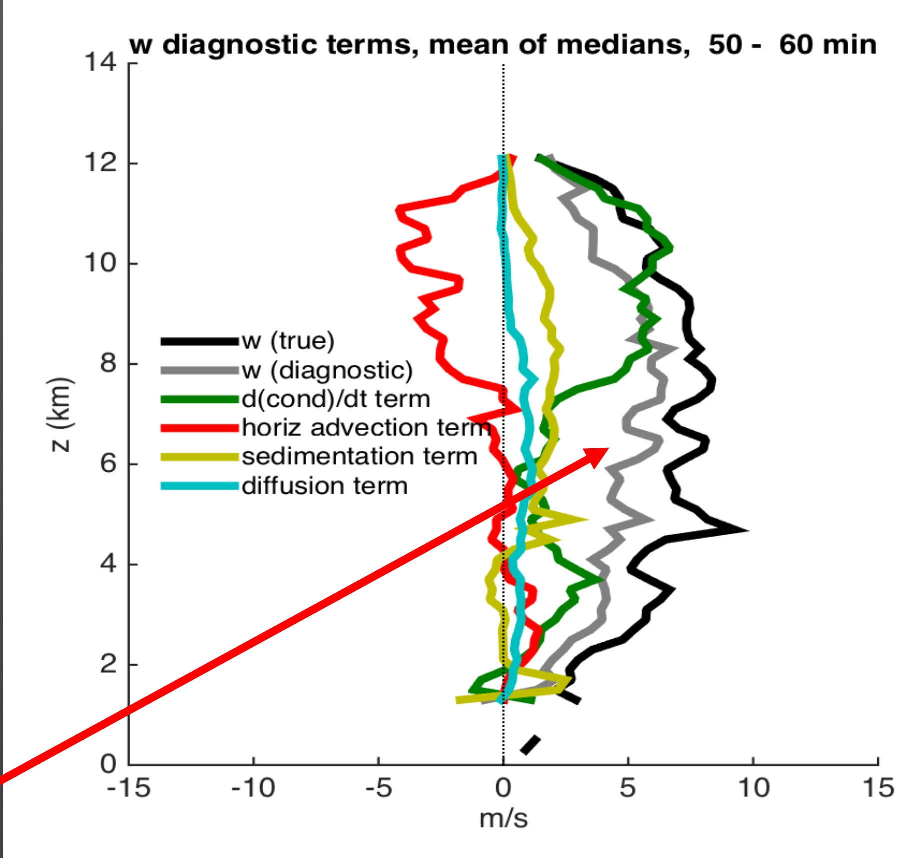
Using this Relationship to Diagnose W

From condensate equation:

$$w = \frac{\dfrac{\partial r_c}{\partial t} + \overrightarrow{U_h} \cdot \overrightarrow{\nabla_h} r_c - S - D}{\alpha - \dfrac{\partial r_c}{\partial z}}$$

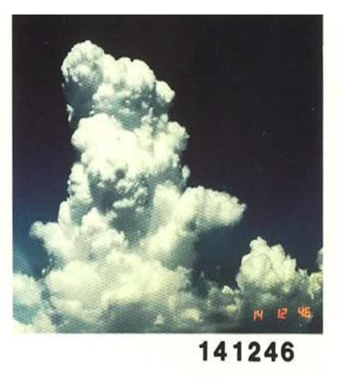
$$S = v_t \frac{\P r_c}{\P z}$$

Diagnosed W within ~2 ms^{-1} of true W

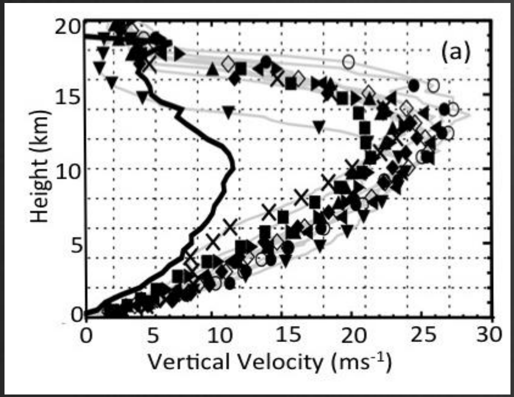


Application of diagnostic equation to the isolated tropical continental convective storm simulation. Actual w in black and diagnosed w in gray.

Pathways Forward



Vertical transport
is critical



Poorly represented in
forecast and climate models

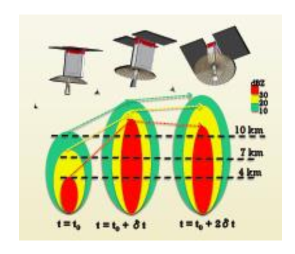
Global database of convective mass flux

Solutions:

1. EarthCARE (2020) → instantaneous Doppler velocities

2. Convoy of Miniature Radars

Temporal and spatial derivatives of condensate



$$w = \frac{\frac{\partial r_c}{\partial t} + \overrightarrow{U}_h \cdot \overrightarrow{\nabla}_h r_c - S - D}{\alpha - \frac{\partial r_c}{\partial z}}$$

3 2 1

Short $\Delta t = 30\ secs$
Resolves changes to intense updrafts

Long Δt=90 secs
Resolves weaker updrafts

Study different parts of the CMF intensity spectrum and quantify duration of the vertical transport

Single Doppler Measurement → characterization of instantaneous vertical speed but with no information about how long such a speed is sustained

Global database of CMF → evaluate and development representation of CMF in numerical models → better prepared for water, energy and emergency management

Complete radar satellite
Raincube, May 2018
~ $5M instrument and satellite