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Stochastic Convection Parameterizations

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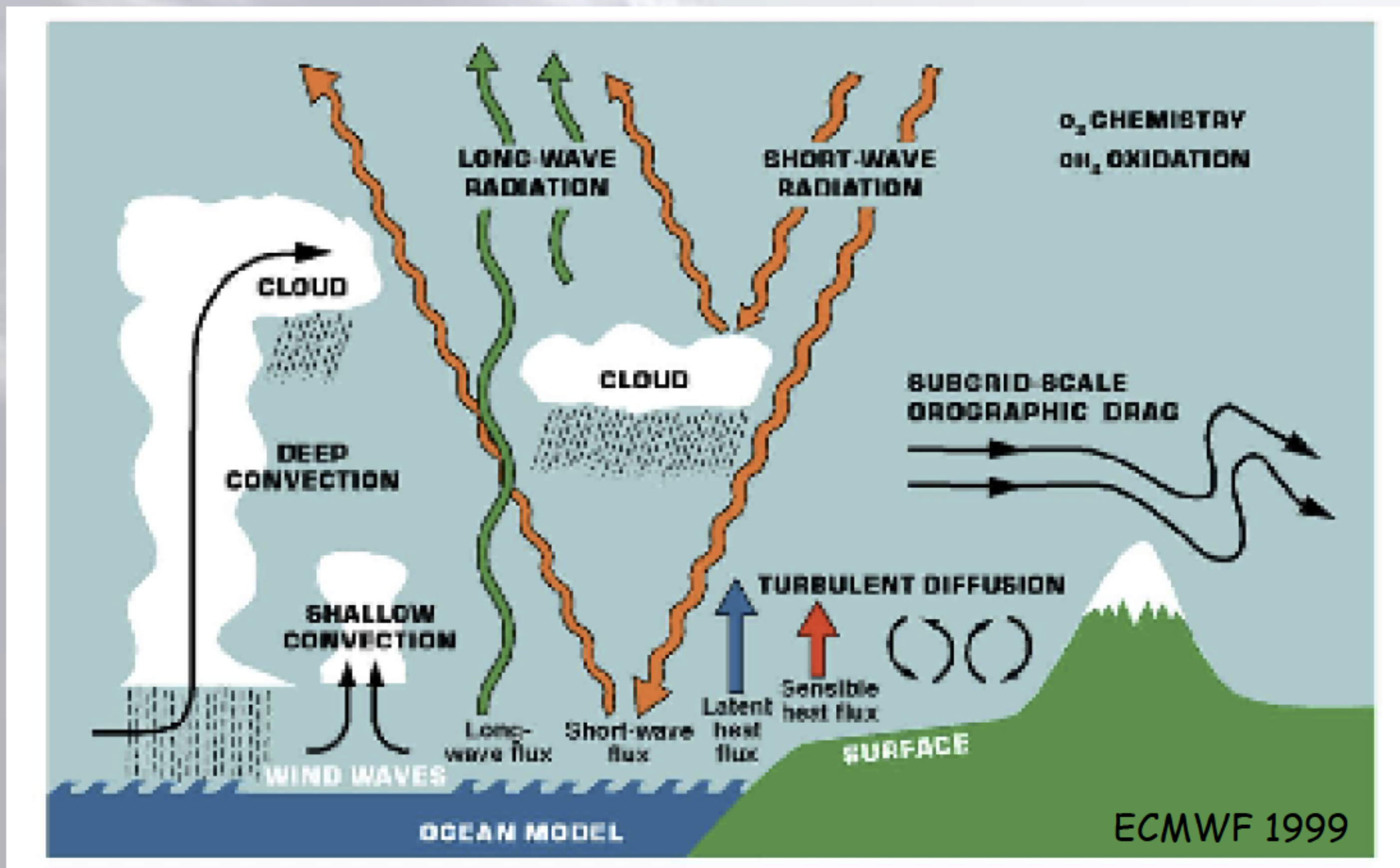
Small-scale Processes in Atmospheric Models

It is not a simple computational fluid dynamics problem ....



.... We need to represent radiation, clouds, turbulence, convection, gravity waves, surface interaction.

Physical Parameterizations

1) Small-scale fluid dynamics:

- Turbulence and Convection (dry and moist)
- Gravity waves
- Clouds (phase transition / latent heat)

➔ Would be mostly solved if NWP models had resolutions of around 1-10m

2) Small-scale physical processes (NOT just fluid dynamics):

- Radiation Interaction
- Cloud and aerosol microphysics

➔ Some of these equations are well-known but others not at all

3) Surface interaction can be (1) and (2) but also includes additional complexity (vegetation, biogeochemistry)

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Physical Parameterizations: Example of radiation vs turbulence/convection

Turbulence and convection parameterization:

$$\frac{\partial \phi}{\partial t} = -\frac{\partial}{\partial z}(w\phi) \Rightarrow \text{Reynolds decomposition and averaging} \Rightarrow \frac{\partial \phi}{\partial t} = -\frac{\partial}{\partial z}(\overline{w}\,\overline{\phi}) - \frac{\partial}{\partial z}(\overline{w'\phi'})$$

needs to be parameterized due to non-linearity wΦ

Radiation parameterization:

Theory leads to $$C_p \frac{\partial T}{\partial t} = -\frac{\partial}{\partial z}\left[F_R(T, q, l)\right]$$

But models have $$C_p \frac{\partial \overline{T}}{\partial t} = -\frac{\partial}{\partial z}\left[F_R(\overline{T}, \overline{q}, \overline{l})\right]$$

This is incomplete

Complex non-linearities

Stochastic approach

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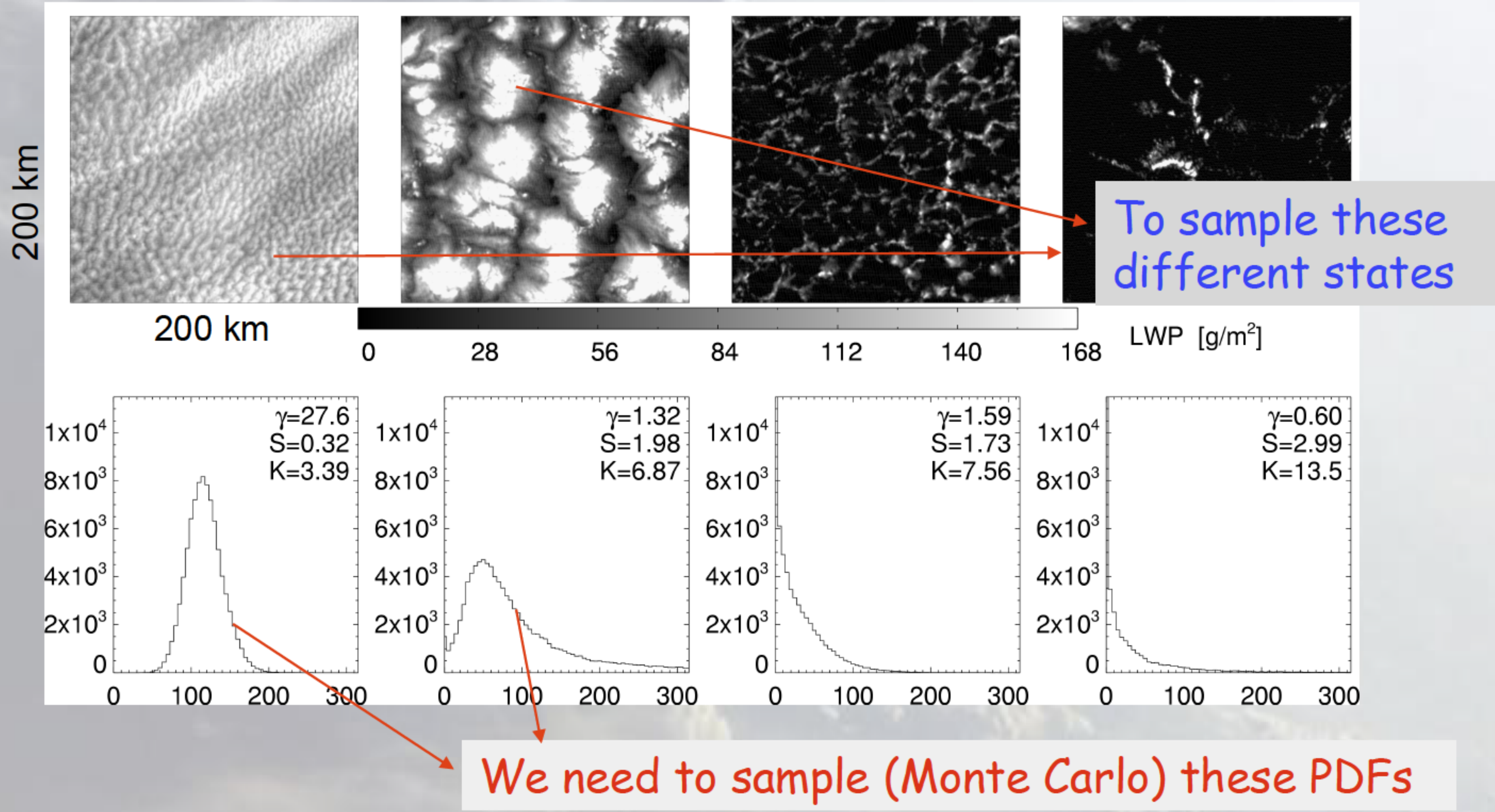
Need for stochastic approaches

Non-linearities in cloud-radiation interaction, cloud microphysics are too complex -> need stochastic approaches

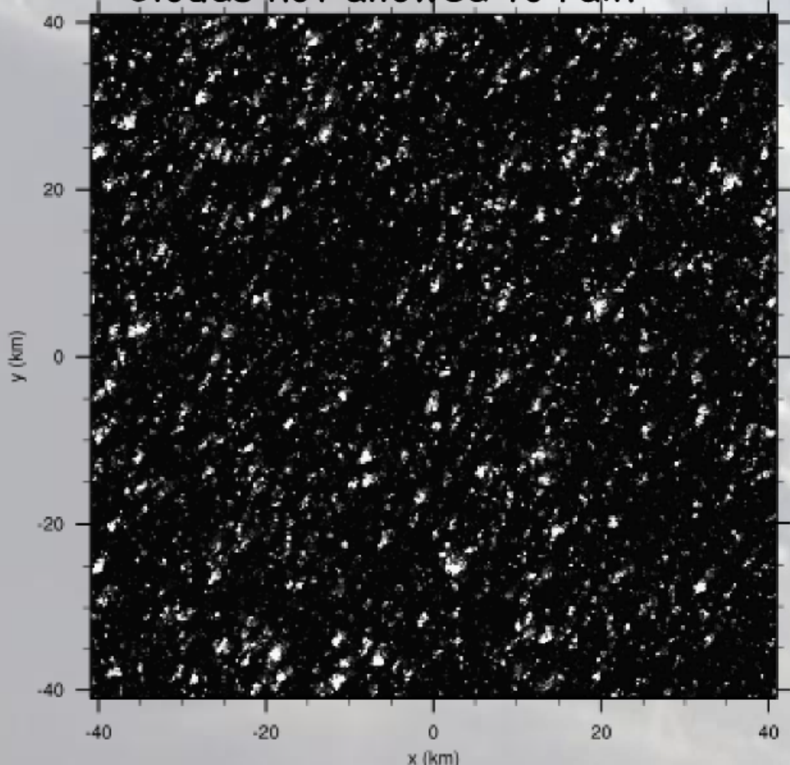


Kawai & Teixeira, JCLI, 2010

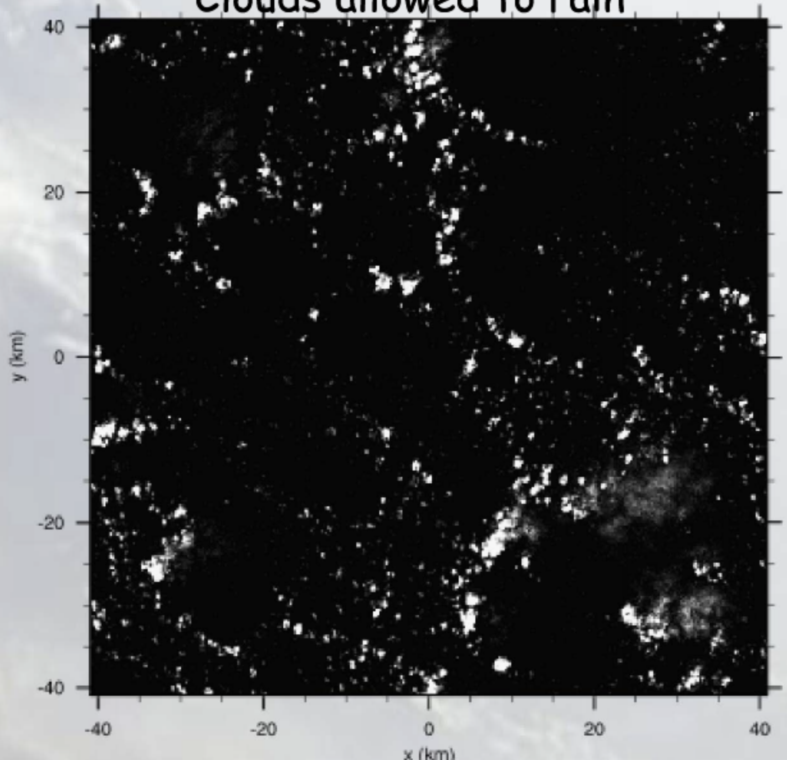
Large-Eddy Simulation (LES) models

- High-resolutions (~ 10-50m) in all 3 dimensions
- Resolutions good enough to represent key dynamics in convection
- Closures still needed for scales < 10m (but simpler to do)

Clouds not allowed to rain



Clouds allowed to rain



Matheou et al., MWR, 2011

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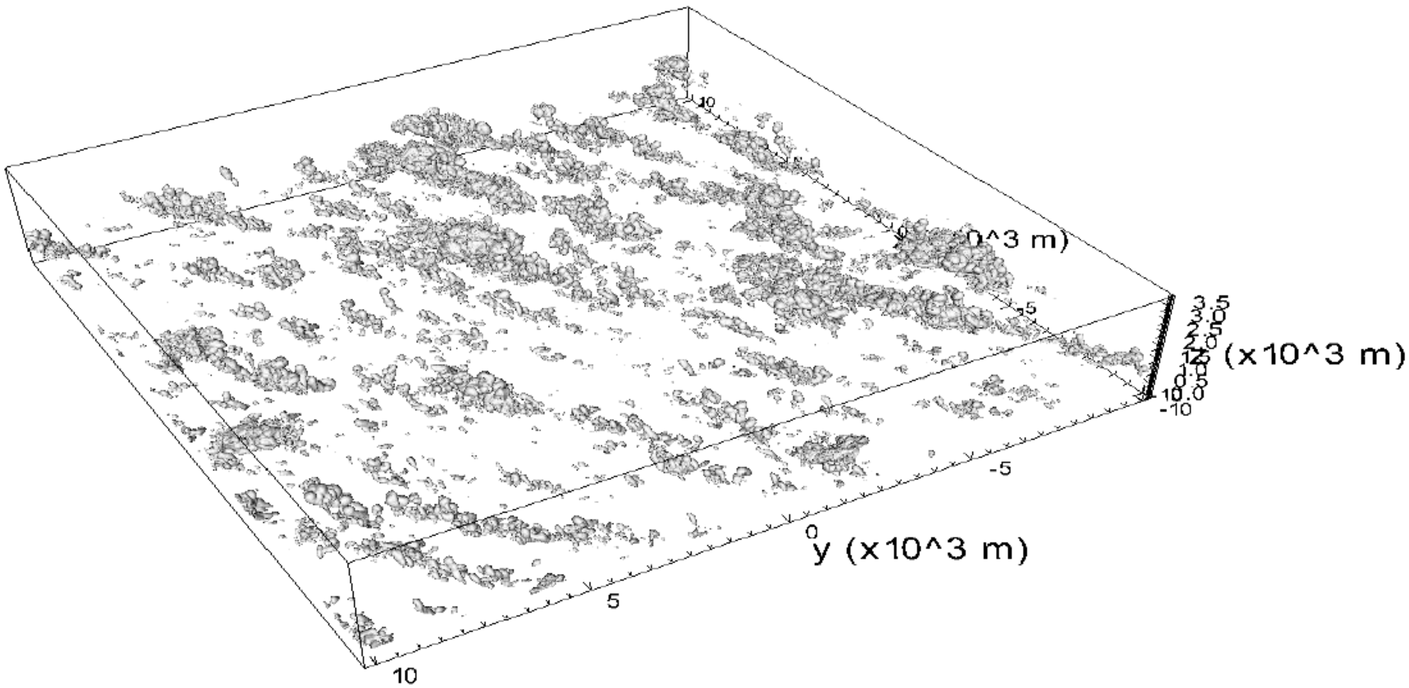
Moist convection

Representing moist convection with stochastic plumes leads to more realistic results



LES provides detailed statistics about cloud structure

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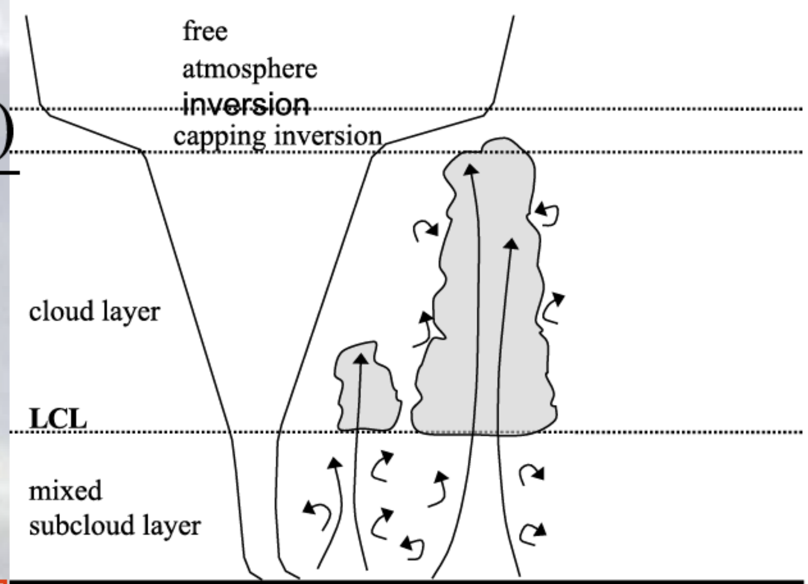
Mass Flux Model for Cumulus Mixing

$$\left(\frac{\partial \bar{\phi}}{\partial t}\right)_{conv} = -\frac{\partial \overline{w'\phi'}}{\partial z} \approx -\frac{\partial M(\phi_u - \bar{\phi})}{\partial z}$$



Originally proposed by Arakawa 1969, Betts 1973

$$\frac{\partial \phi_u}{\partial z} = -\varepsilon(\phi_u - \bar{\phi}) \text{ for } \phi \in \{\theta_l, q_t\}$$

$$M = \sigma_u w_u$$

$$\frac{1}{2}\frac{\partial w_u^2}{\partial z} = -b\varepsilon\, w_u^2 + a\frac{g}{\theta_0}\left(\theta_{v,u} - \overline{\theta_v}\right)$$

Lateral entrainment rate: $\varepsilon = \frac{1}{w_u \tau} \approx \frac{1}{h_c}$

Constant τ: Neggers et al 01; Cheinet and Teixeira, 03.

Constant h: Siebesma 97

σ_u is the udraft/core area fraction - not to be confused with cloud fraction

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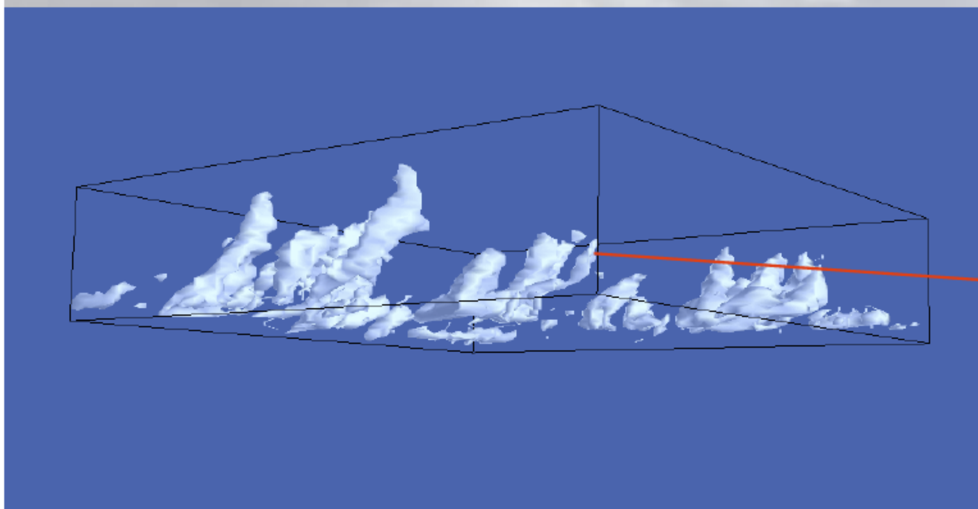
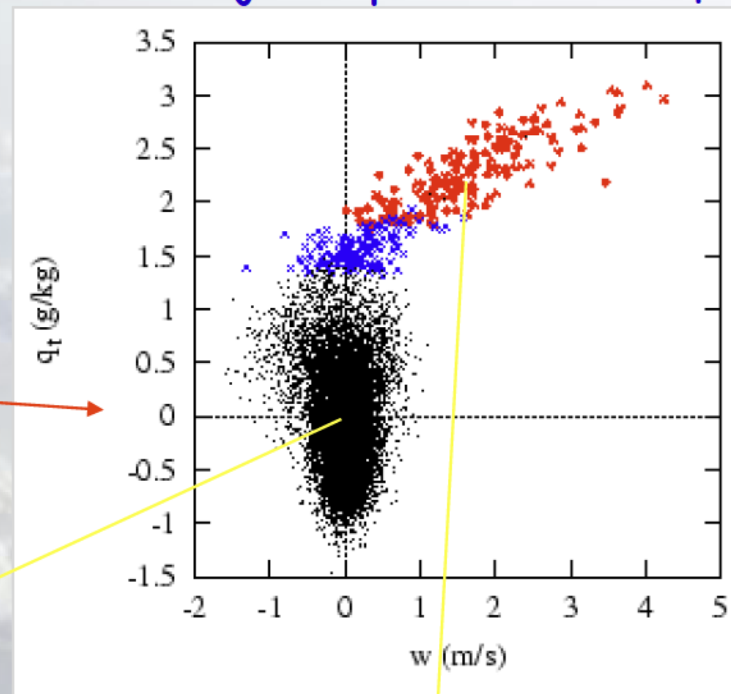
LES models and Eddy-Diffusivity/Mass-Flux (EDMF) Parameterization

Large Eddy Simulation (LES) model – BOMEX shallow cumulus case



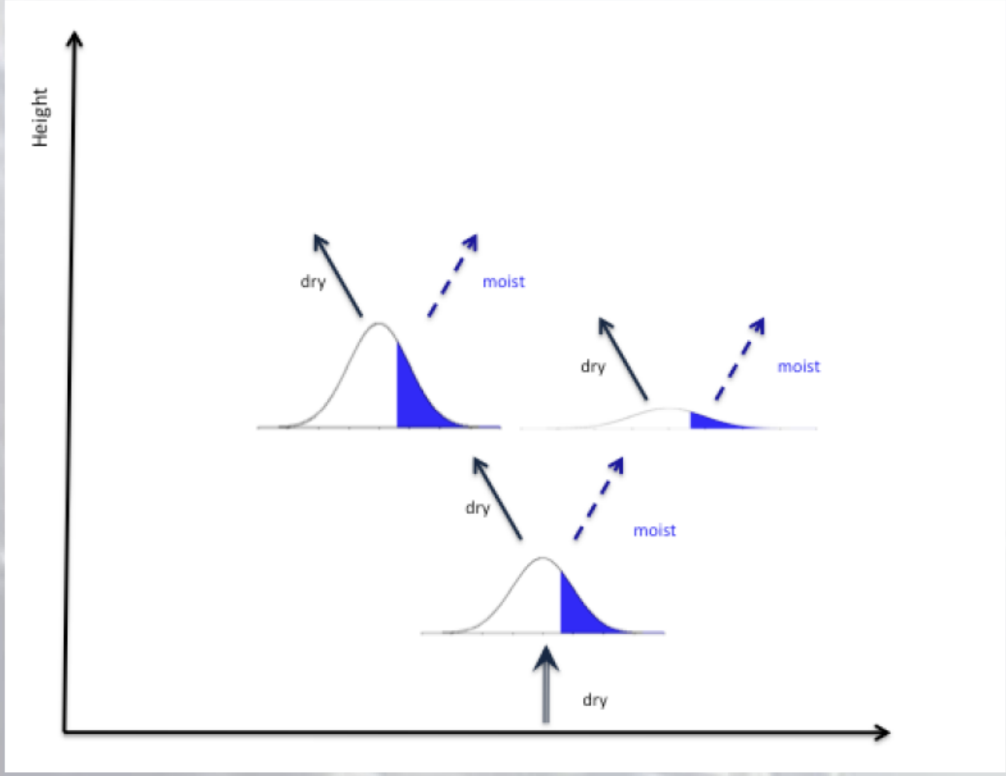
Bimodal joint pdf of w and qt



Well mixed sub-cloud layer:
Eddy-Diffusivity (ED) mixing

Cloud core updrafts:
Mass-Flux (MF) transport

Stochastic Plume EDMF: using PDF of updraft properties



Suselj et al., JAS, 2012

1) Estimate PDF of plume/updraft properties (T, q, w)
2) Sample PDF to generate a variety of plumes (diff. properties)
3) Integrate different plumes in the vertical

Produces more realistic results than purely deterministic parameterization

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Stochastic Nature of Parameterizations in Ensemble Prediction

For parameterizations:

Ensemble and deterministic prediction are essentially different

<u>In ensemble prediction systems:</u>

- Parameterizations should be viewed as stochastic
- But within the context of current parameterizations
  (without imposing artificial stochastic terms)

<u>Parameterizations:</u>

- Typically used to predict the evolution of grid-mean quantities
- Can also provide estimates of higher moments
  (can be used to constrain random sampling)

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Stochastic parameterizations in ensemble systems: a methodology

Methodology for stochastic parameterizations

A variable after being updated by a parameterization (e.g. moist convection) can be written:

$$\phi_{conv}^{stoch} = \overline{\phi}_{conv} + \varepsilon$$

$\overline{\phi}_{conv}$ - mean value of the variable after convection
ϕ_{conv}^{stoch} - stochastic value after convection
ε - normally distributed stochastic variable with
mean $\mu(\varepsilon) = 0$
standard deviation $\sigma(\varepsilon) = \sigma_{\phi,conv}$
$\sigma_{\phi,conv}$ - standard deviation due to moist convective processes

After discretizing the first term on the rhs, the following equation is obtained

$$\phi_{conv}^{stoch} = \overline{\phi} + \Delta t \left(\frac{\Delta \overline{\phi}}{\Delta t} \right)_{conv} + \varepsilon$$

$\overline{\phi}$ - mean value before the moist convection parameterization

Teixeira & Reynolds, MWR, 2008

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Stochastic convection: a simple approach

Assuming standard deviation proportional to convection tendency leads to:

$$\frac{\phi_{conv}^{stoch} - \bar{\phi}}{\Delta t} = \left(1 + \eta\beta\right)\left(\frac{\Delta\bar{\phi}}{\Delta t}\right)_{conv}$$

β - constant of proportionality

η - normally distributed stochastic variable with mean $\mu(\eta) = 0$

and standard deviation $\sigma(\eta) = 1$

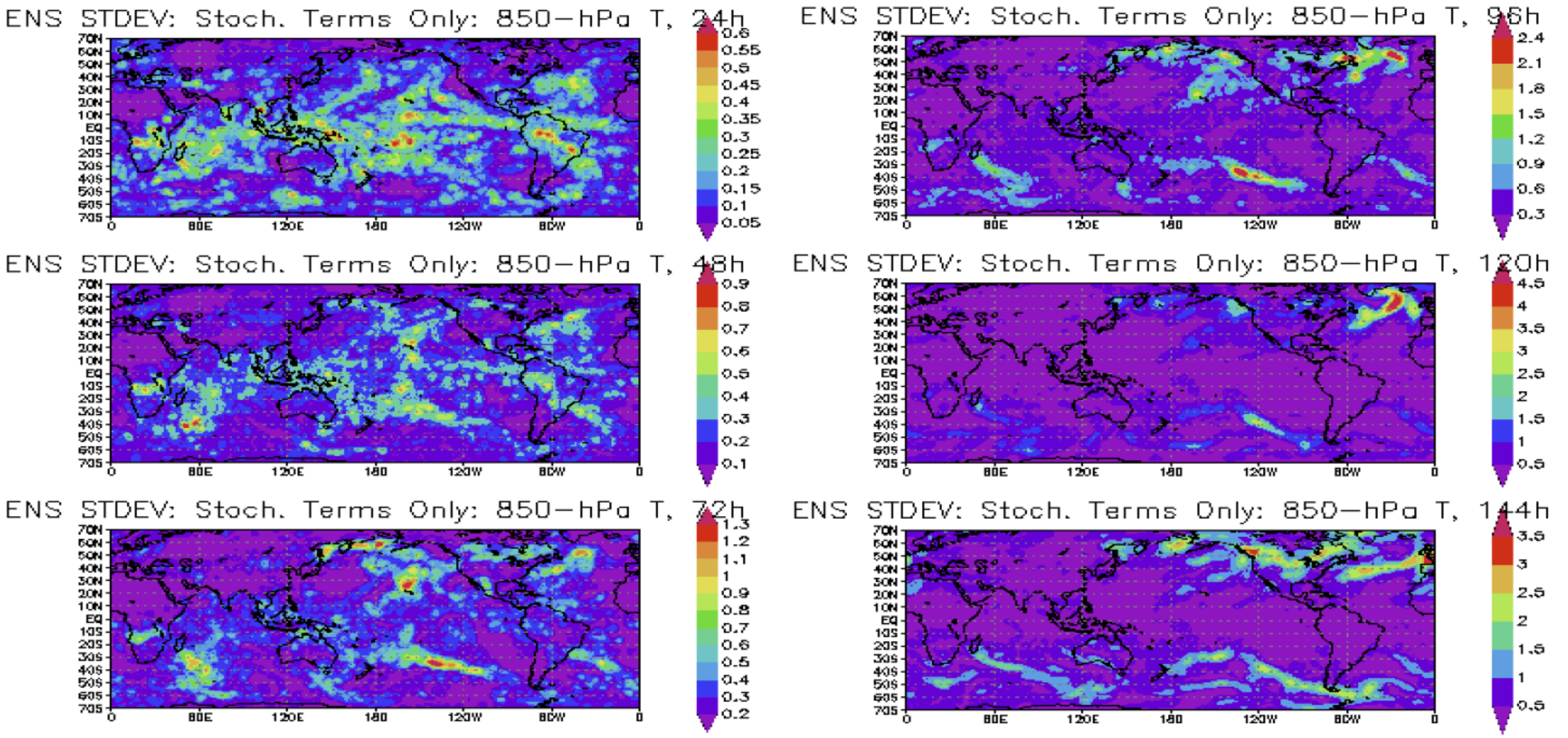
(Teixeira & Reynolds, MWR, 2008)

Simple vertical correlation: single random number per column

No horizontal or temporal correlations:

- Simpler
- Perturbations assumed much smaller than grid-size
- Variance already possesses a certain degree of correlation
- Physically unclear how to construct correlations

US Navy NOGAPS ensemble spread due to stochastic physics only: 850 hPa Temperature



(Teixeira & Reynolds, MWR, 2008)

- Perturbations grow in time
- At 24 h: mostly in Tropics/Sub-tropics
- At 144 h: mostly in Mid-latitudes
- Similar for U at 250 and 850 hPa, Z at 500 hPa

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Simple stochastic convection approach in Navy's ensemble prediction system

NOGAPS stochastic convection after 5 to 10 days:

- Saturation in Tropics
- Synoptic (sub-synoptic) peak in NH Extra-tropics

Stochastic Convection:

- Is able to produce substantial ensemble spread in the Tropics
- Produces sizeable impact in ensemble spread in the extratropics

Initial-condition + stochastic convection show promising increase in ensemble spread and decrease in number of outliers in the Tropics

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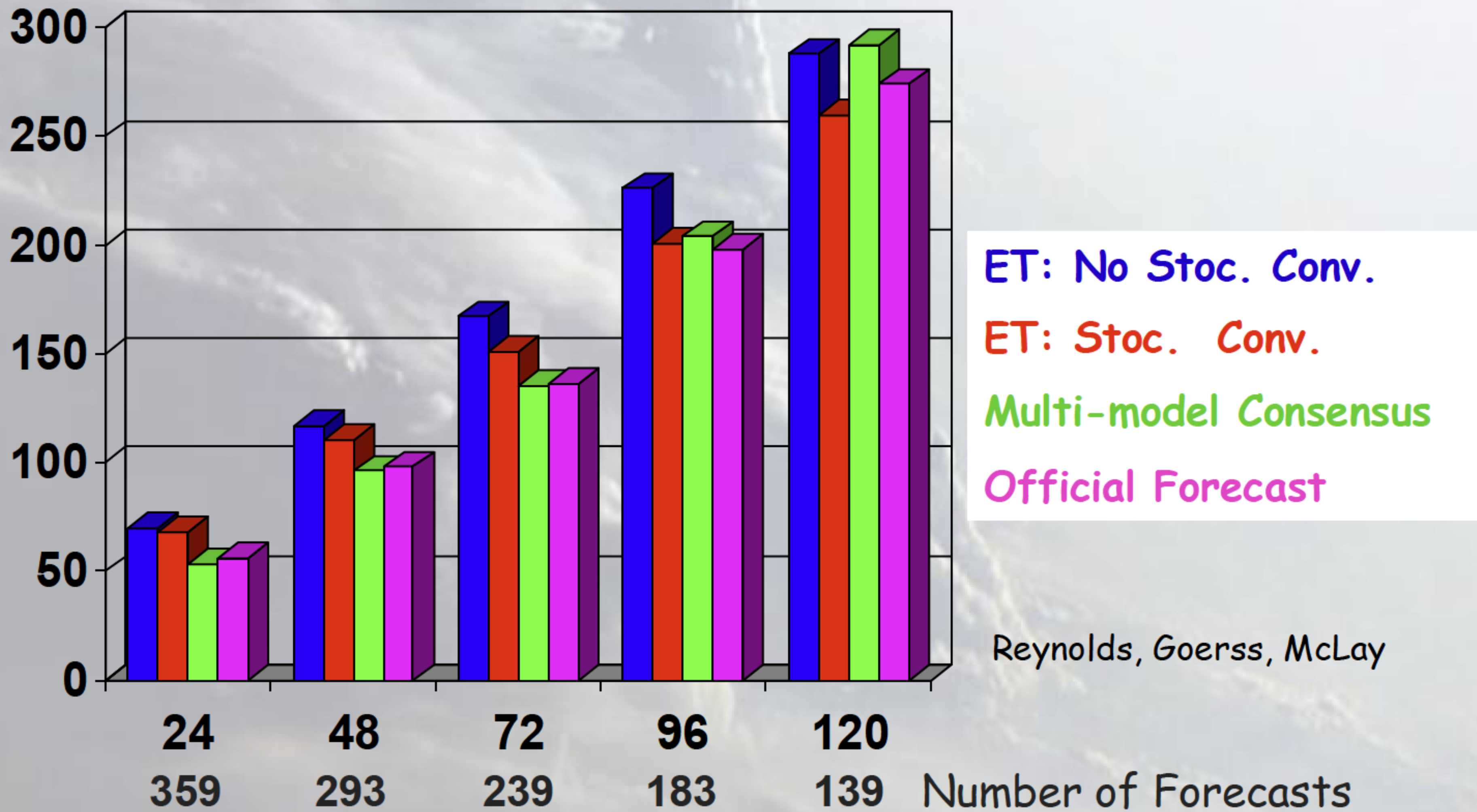
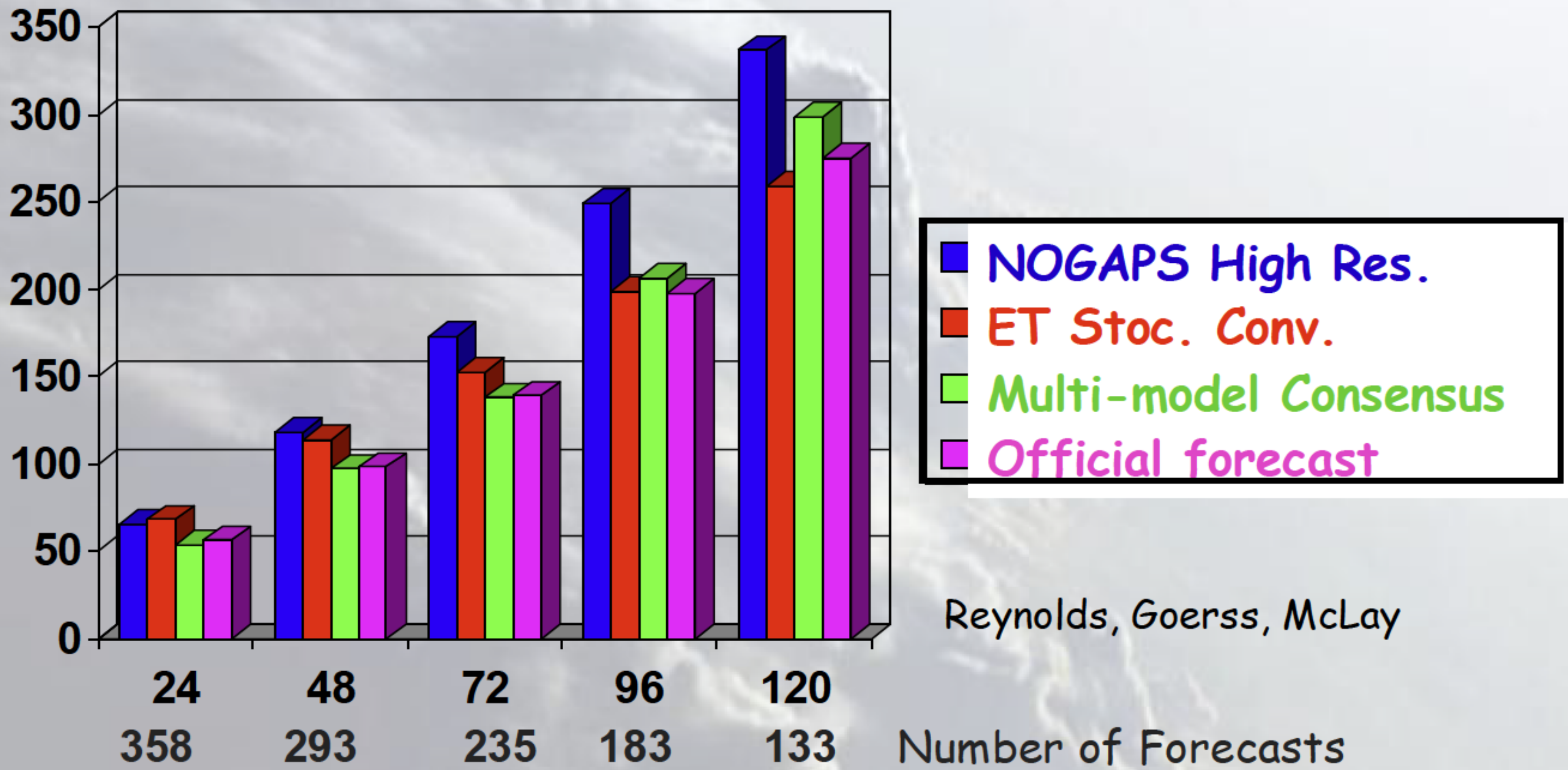
Atlantic 2005 - TC Forecast Error (nm)

Stochastic Convection significantly improves NOGAPS ET performance



Reynolds, Goerss, McLay

Atlantic 2005 - TC Forecast Error (nm)



NOGAPS ET with stochastic convection better than high-res deterministic model, and competitive with official forecast at 96 and 120 hours

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Summary

- Sub-grid scale physical processes possess complex non-linearities
- Some parameterizations need to be stochastic (e.g. radiation-cloud interaction, cloud microphysics) EVEN in deterministic models
- Moist convection parameterizations using plumes (mass-flux) are more realistic if stochastic
- Simple stochastic convection parameterizations produce improvements in hurricane forecasts with NOGAPS ensemble system
- Stochastic physics and resolution independent parameterizations