Mesoscale Organisation of Shallow Cumulus Convection : An Overview

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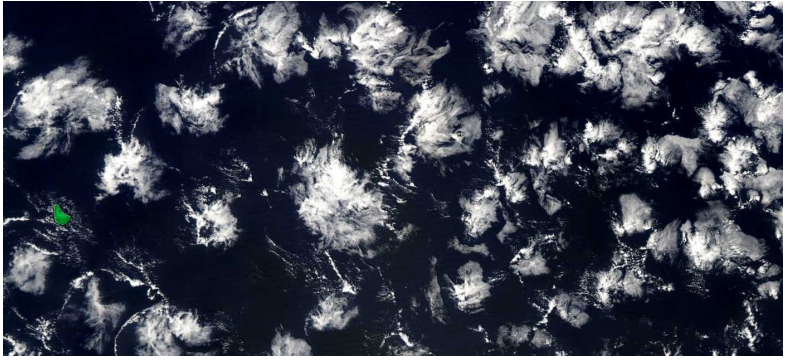
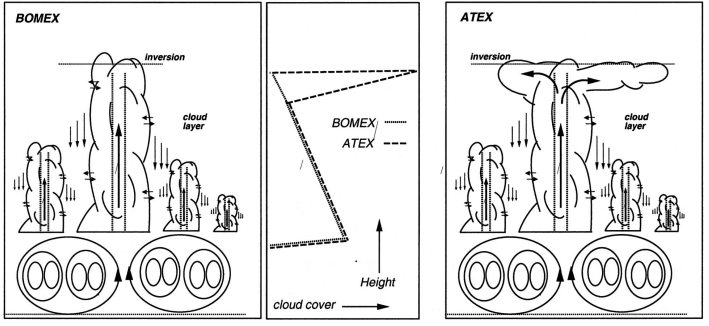


1.

A Bit of History

Previous GCSS/GASS Studies on Shallow Cumulus Convection

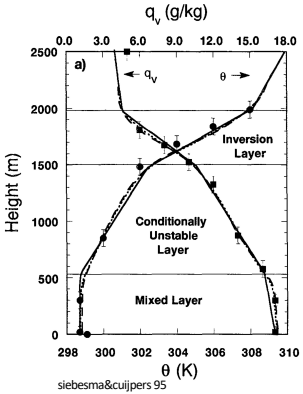


Siebesma et al 2003

Focused on the vertical structure….

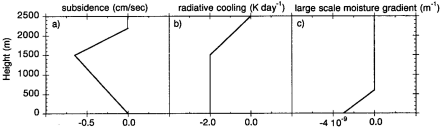
…and used a Scale-Separation View

Well observed steady state….



siebesma&cuijpers 95

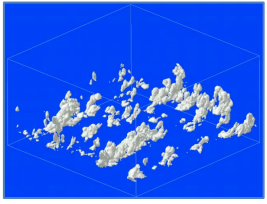
Well observed large scale forcings….

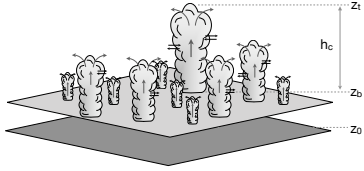


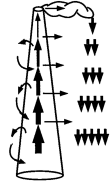
$$\frac{\partial \overline{\phi}}{\partial t} = \left(\frac{\partial \overline{\phi}}{\partial t}\right)_{\text{Large-Scale}} + \left(\frac{\partial \overline{\phi}}{\partial t}\right)_{\text{LES}} \simeq 0$$

Providing a simple but critical test for Large Eddy Simulations……

Leading to Conceptual Understanding and Parameterisations







- N independent entraining plumes
- Similar Cloud Base
- Many clouds: small and shallow…. Lesser clouds: high and deep.
- Low Cloud cover (~ 15 %)
- Quasi-equilibrium Closures
- Cumulus clouds randomly distributed

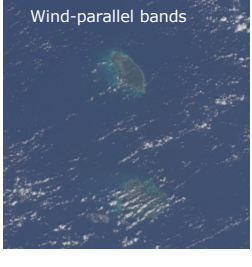
$$\frac{\partial \ln M}{\partial z} = \epsilon - \delta$$

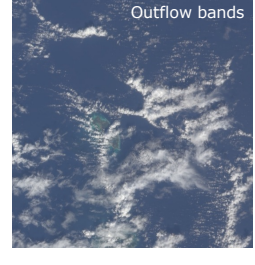
$$\frac{\partial \overline{\phi}}{\partial z} = -\epsilon(\phi_c - \overline{\phi})$$

…. And to new campaigns: RICO : (van Zanten et al. JAMES 2011)……

Different Modes of Organization Observed during RICO

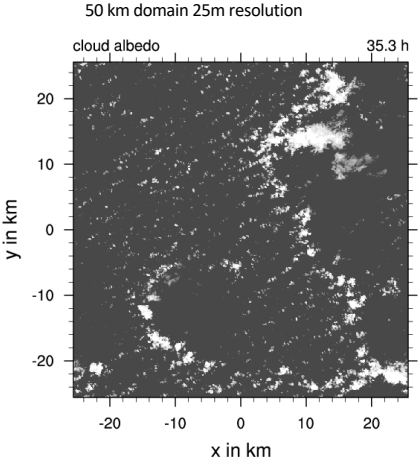
Zuidema, Girolamo, Snodgrass .....



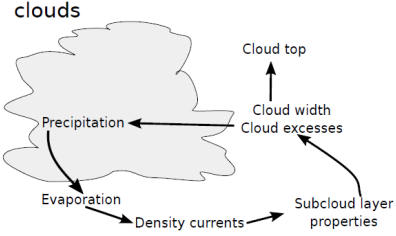


But Initially ignored by the modelers ..

Proposed Mechanism :
Cold Pools Dynamics promote scale growth of humidity fluctuations



Seifert & Heus ACP (2013)



Mechanism “borrowed” from deep convection :

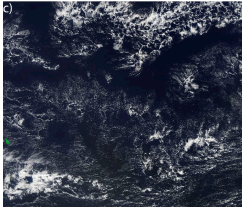
Tompkins	JAS 2001
Khairoutdinov&Randall	JAS 2006
Boing et al	JAS 2012

2.

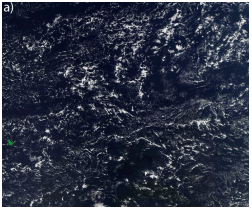
Observing Mesoscale Organization

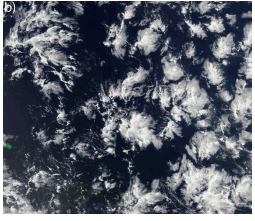
Classification of Shallow Mesoscale Organised Clouds (SMOCs)

Sugar

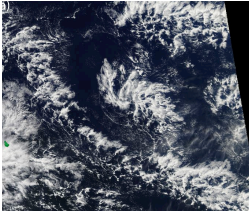


gravel





flowers



fish

Area 10^{o} x 10^{o} East of Barbados

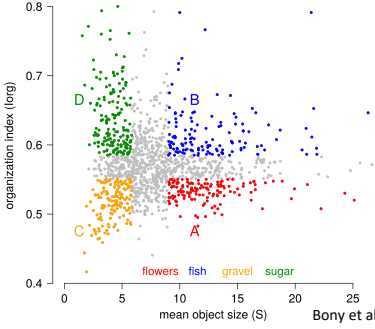
- Subjective eyeball-analysis of satellite images
  (Stevens et al QJRMS 2019)
- Supervised Neural Networks
  (Rasp et al BAMS 2020 ; Schulz ESSD 2022)
- Applying Organization Metrics on satellite images
  (Bony et al GRLS 2020 ; Jansen et al 2021)

Cloud Patterns in terms of existing organisation metrics

clustered

random

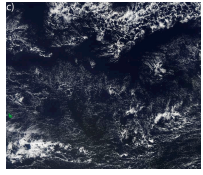
regular



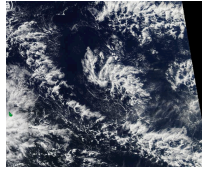
Bony et al 2020 GRL

Mean object size

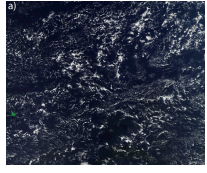
sugar



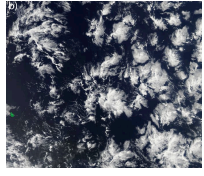
fish



gravel



flower

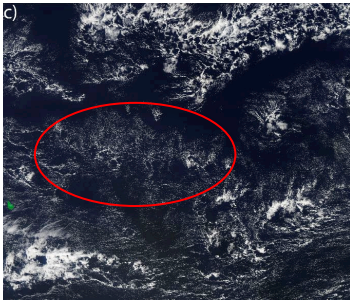


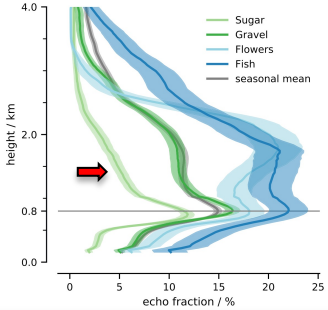
The specific patterns populate the tails of the pdf. Most of the images are mixtures or unidentified

Sugar

Vertical Structure obtained by making composites using observations of the Barbados Cloud Observatory (BCO)

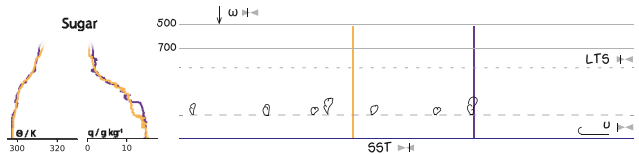
(Schulz et al. 2021 JGR)





No secondary peak in cloud fraction near the inversion

Frequency of occurrence 9%

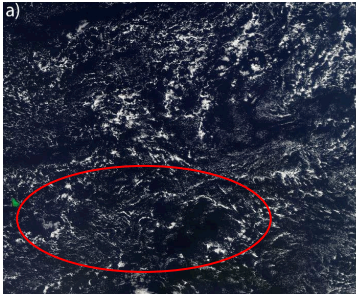


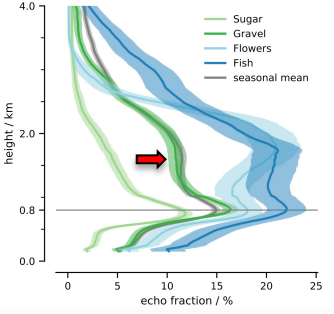
Unorganised random shallow cumulus clouds like simulated in BOMEX

Gravel

Vertical Structure obtained by making composites using observations of the Barbados Cloud Observatory (BCO)

(Schulz et al. 2021 JGR)





- Deeper Clouds
- Precipitating
- Cold pools
- Highest frequency of occurrence

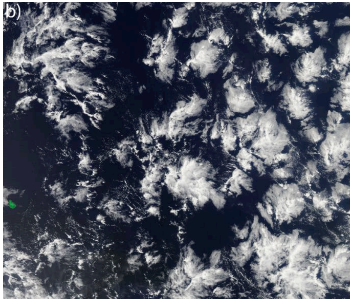
Frequency of occurrence 19%

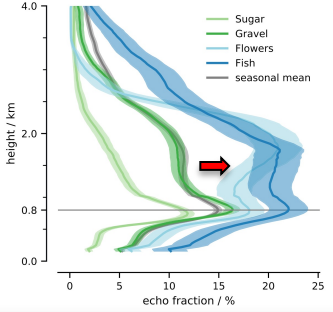
Associated with the the arc structures due to cold pools as observed already during RICO

Flowers

Vertical Structure obtained by making composites using observations of the Barbados Cloud Observatory (BCO)

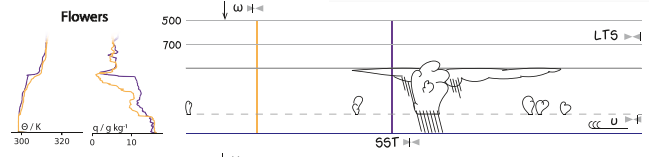
(Schulz et al. 2021 JGR)





- Strong Inversion
- Secondary peak in cloud fraction
- Outflow near Inversion
- Originating from the East (“Home of the scu”)

Frequency of occurrence 5 %

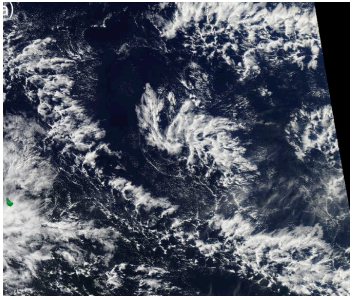


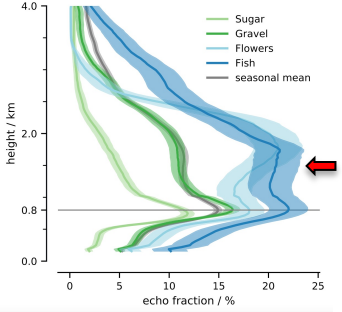
Associated with the cloud structures simulated in the ATEX intercomparison

Fish

Vertical Structure obtained by making composites using observations of the Barbados Cloud Observatory (BCO)

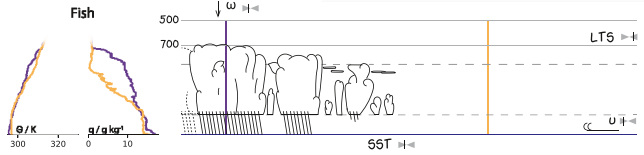
(Schulz et al. 2021 JGR)





- Most humid
- Secondary peak in cloud fraction
- Large scale structure
- Originating from the North (extratropical disturbance)

Frequency of occurrence 9 %



Associated with the shallow cumulus on top of an humid extratropical disturbance

Take home messages

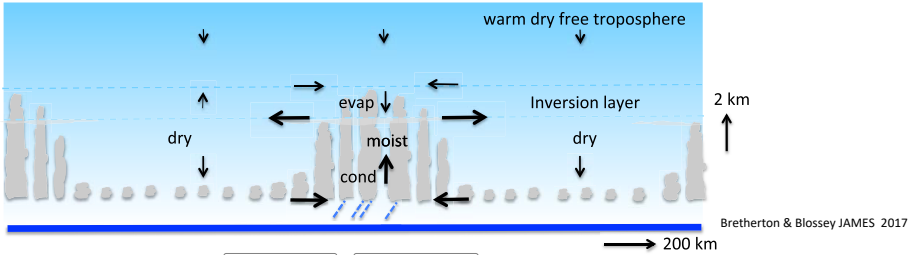
- Trade-wind low clouds tend to organise.
- The unorganised (sugar) popcorn shallow cumulus convection more the exception than the rule.
- Many parameterizations of shallow cumulus convection have been based on Large-Eddy-Simulations (LES) of this unorganised ”sugar”-mode.
- Estimates of (low but positive) cloud feedback strength of subtropical cumulus clouds are based on LES of this unorganised “sugar”-mode (i.e the CGILS intercomparison study)
- Have we been betting on the wrong horse?
- Can we even ride the other horses?

3.

Key Internal and External Processes Driving Mesoscale Organisation

Spontaneous scale growth of humidity fluctuations (bottom up)

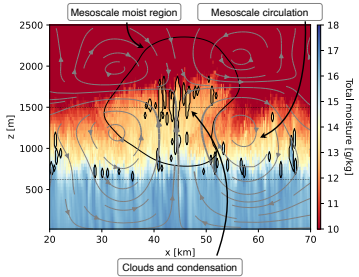
Schematics :



Bretherton & Blossey JAMES 2017

Simulation :

BOMEX



- No precipitation
- No interactive radiation

Janssens et al 2022 Submitted to JAS

Minimum Model Of Scale Growth of Moisture (1)

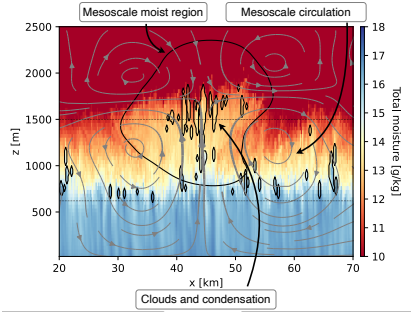
Weak Temperature Gradient (WTG) Assumption:

$$\partial_t q'_{t_m} \sim -w'_m \Gamma_{q_t}$$

w` => increase q'_t
(provided a negative humidity gradient)

$$\partial_t \theta'_{lv_m} \approx -w'_m \bar{\Gamma}_{\theta_{lv}} - \partial_z F'_{\theta_{lv_m}} \approx 0$$

Leading to stronger w′ anomalies
(provided a positive θ_{vl} gradient



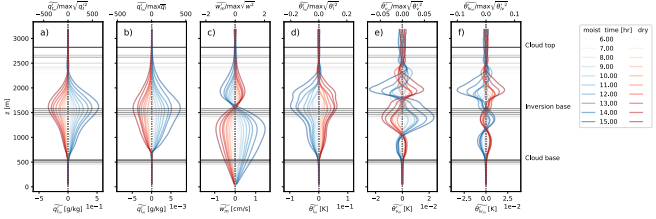
$$C'_m \propto q'_{t_m}$$

Leading to stronger condensation anomalies

$$C'_m \simeq \partial_z F'_{q_{lm}} \sim -\partial_z F'_{\theta_{vl}}$$

Leading to stronger heat flux anomalies

Minimum Model Of Scale Growth of Moisture (2)



Janssens et al 2022
Also:
Bretherton & Blossey 2017
Narenpitak et al 2021

Linear Instability Model

$$\frac{\partial \langle q'_{t,m} \rangle}{\partial t} \simeq \frac{\langle q'_{t,m} \rangle}{\tau_{q_{t,m}}}$$

$$\tau_{q'_{tm}} = \frac{1}{C\overline{\theta_l} w^* \frac{\partial}{\partial z}\left(\frac{\Gamma_{q_T}}{\Gamma_{\theta_{lv}}}\right)}.$$

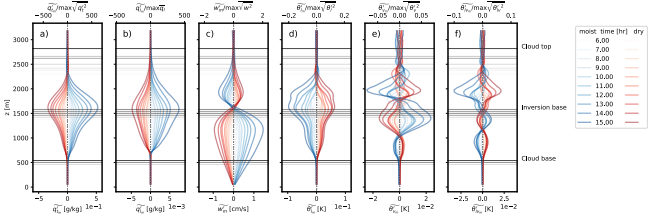
C ~ 0.3

Scale Growth of $q'_{t,m}$, $q'_{l,m}$, w'_m

No Scale growth of θ'_{lv}

No scale growth in subcloud layer

Minimum Model Of Scale Growth of Moisture (3)



Janssens et al 2022
Also:
Bretherton & Blossey 2017
Narenpitak et al 2021

Linear Instability Model

$$\frac{\partial \langle q'_{t,m} \rangle}{\partial t} \simeq \frac{\langle q'_{t,m} \rangle}{\tau_{q_{t,m}}}$$

$$\tau_{q'_{t_m}} = \frac{1}{C\overline{\theta_l} w^* \frac{\partial}{\partial z}\left(\frac{\Gamma_{q_t}}{\Gamma_{\theta_{l_v}}}\right)}.$$

C ~ 0.3

Conclusions

- BOMEX : $\tau \sim 4$ hrs (but depends strongly on numerics)
- Instability if $\tau > 0$
- Such instabilities allways develop spontaneously in shallow cumulus.
- Models show no scale growth in subcloud layer. Observations do (see presentation Geet George?)
- **Shallow cumulus is inherently unstable to length scale growth**

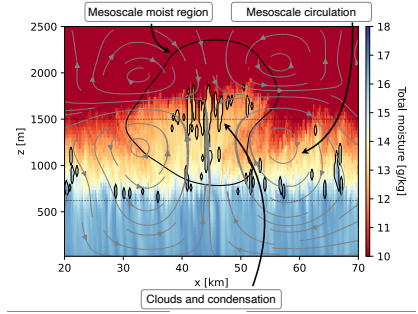
What about other internal scale growth mechanisms?

- Heterogeneous radiative cooling *(Klinger et al 2017, Naumann et al 2019)*

  Could potentially reinforce the instability growth mechanism.

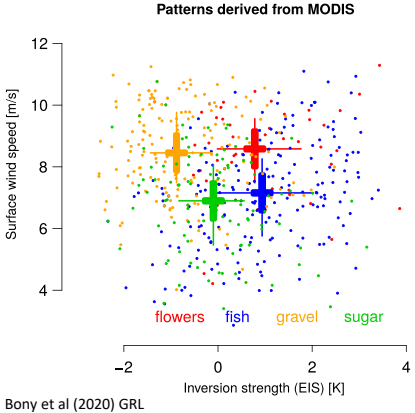
- Evaporation of precipitation (cold pools) *(Seifert & Heus 2013 , Zuidema et al 2017)*)

  Could destroy the mesoscale patterns by the instability growth mechanism, but introduces scale growth of cloud free areas through the cold pool generation and support cloud clustering at colliding gust fronts.



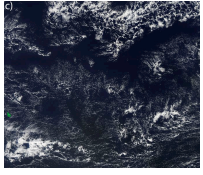
And what about ***external*** scale growth mechanisms……..

External Mechanisms: Correlations with "External" Cloud Controlling Factors

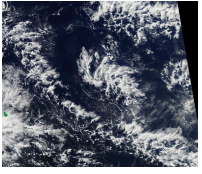


Bony et al (2020) GRL

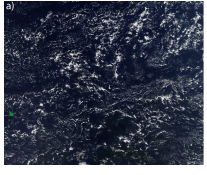
sugar



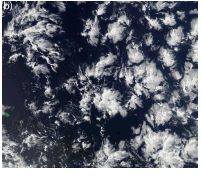
fish



gravel



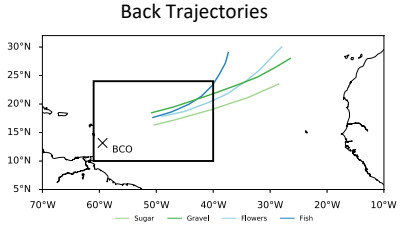
flower



- ***Sugar*** : low winds, unstable env
- ***Flower***: strong winds , stable env
- ***Gravel***: strong winds , unstable env
- ***Fish:*** weak winds, stable env.

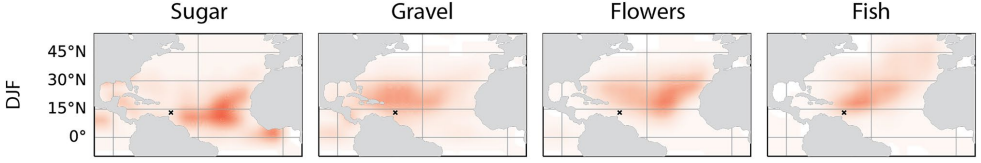
External Mechanisms: Correlations with External Dynamical Conditions

- ***Fish*** : Remnant of an extratropical disturbances?
- ***Flowers*** : Manifestation of closed cell structures from the Stratocumulus regions of the Eastern part of the Atlantic Ocean?



Schulz et al 2021

Frequency of occurrence:



Schulz et al 2021

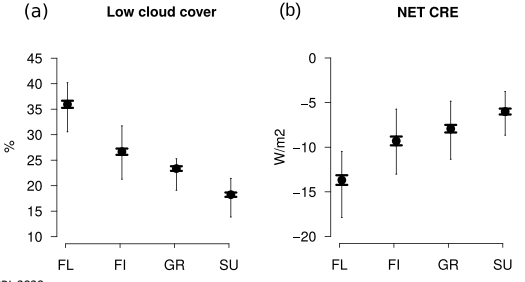
Take home messages

- Shallow Cumulus is fundamentally unstable for scale growth (of humidity)
- But there are also other (scale growth) mechanisms
  - Internal : heterogeneous radiative cooling, Cold pool formation through precipitation
  - External: correlations of mesoscale cloud structures with large scale factors (SST, EIS, surface wind) or large dynamics.
- At present it is unclear which are the dominant processes and how/if they interact.

4.

Does mesoscale organization matter for cloud feedback?

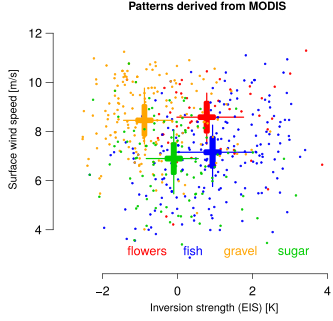
Cloud Feedback and External Cloud Controlling Factors



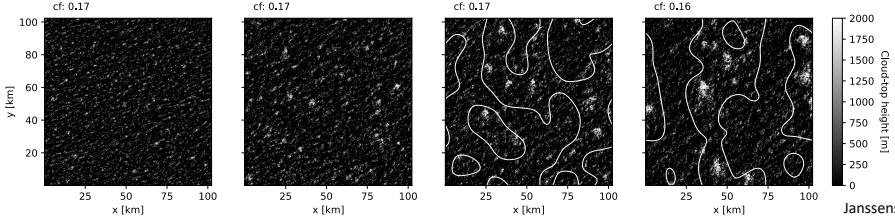
Bony et al GRL 2020

- Flower and Fish correlate with stronger EIS than Sugar and Fish.
- Most Climate models predict increasing EIS over the subtropical oceans with global warming
- Would suggest an increase in frequency of occurrence for Fish and flower => negative cloud feedback?

- Flower and Fish have the largest cloud cover and the strongest CRE .



Cloud Feedback and Internal Scale Growth



Self-aggregation of BOMEX

Janssens et al 2022

cf = 0.17 cf = 0.17 cf = 0.17 cf = 0.16

- Cloud Fraction remarkably robust during the self-aggregation process.
- But this specific case does not show inversion-layer outflows (i.e. flowers, fish) which might show a stronger relation between self-aggregation and cloud fraction

More general : Is cloud fraction determined by external cloud-controlling factors or is cloud fraction also (partially) controlled internally by the self-aggregation process?

5.

Simulation Capabilities of Mesoscale Cloud Patterns and their response to climate perturbations

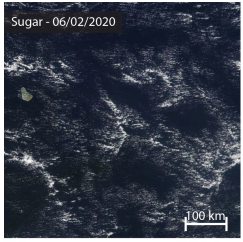
EUREC4A Field Campaign

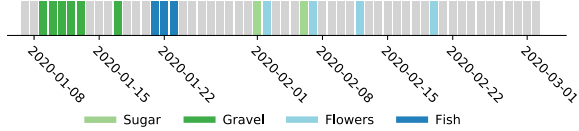
Jan-feb 2020. Goal : to study the interplay between trade-wind clouds and their environment.

Unique opportunity to test model capability to represent the observed mesoscale cloud patterns and to explore the underlying mechanisms

Bony et al. (Surv. Geophys., 2017), Stevens et al. (ESSD, 2021), ESSD special issue : https://essd.copernicus.org/articles/special_issue1122.html

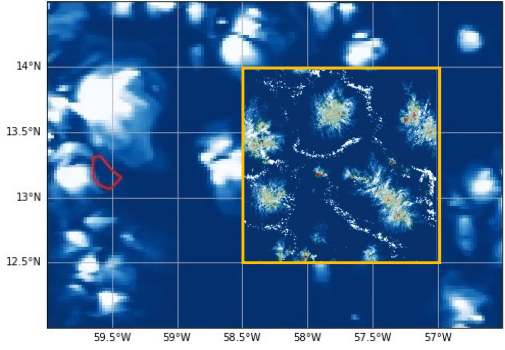
All 4 cloud patterns were observed during EUREC4A





Different Models see different aspects of these patterns

Feb 3th 14:00 UTC



Allesandro Savazzi (TU Delft)

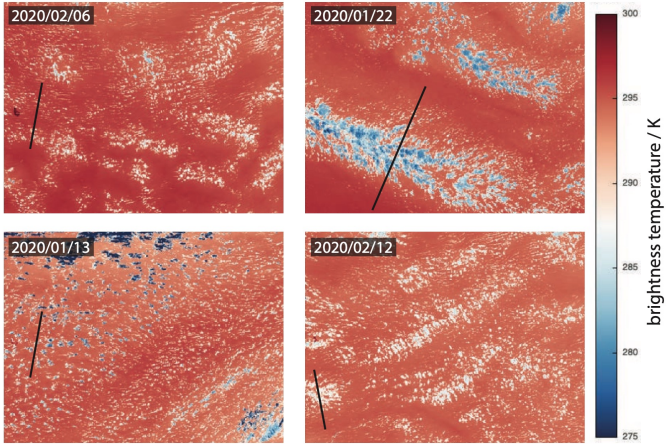
LEM (DALES) embedded in SRM (HARMONIE)

- Storm Resolving Models:
  - resolution: 500m ~ 5km
  - Domain size : 500km ~ 5000km
  - Resolving the larger mesoscale structures (fish, flowers)
  - Individual clouds remain unresolved
  - Turbulence needs to be parameterized

- Large Eddy Models:
  - resolution: 50m ~ 500m
  - Domain size : 50km ~ 500km
  - Resolving the smaller mesoscale structures (sugar, gravel)
  - Individual clouds resolved
  - Turbulence (partially) resolved

So we need the whole model hierarchy

Simulating the whole 2 Months period……..



Schultz 2022 Phd Thesis 2022

ICON-LEM

Res : 624m
Domain: 60W-45W ; 7.5N– 17N
Period: 9-1-2020 / 14-2-2020

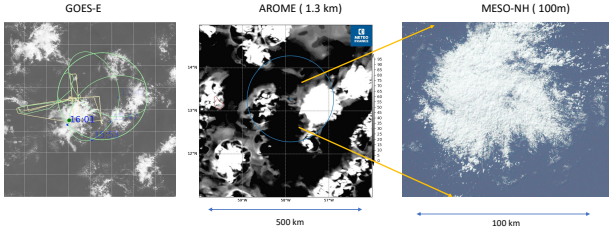
Overall mesoscale structures well represented

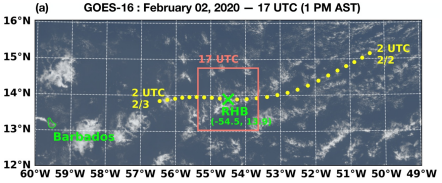
Fish and Flowers are underrepresented, possibly due to the misrepresentation of the inversion structure

Gravel and Sugar are overrepresented

Opposite behaviour for Storm Resolving Models (flowers and fish over represented at the cost of gravel and sugar

Or Zooming in ……..





Eulerian:

AROME:

- Domain 9.7N-22.9N ; 75.3W-51.7W
- Res: 1.3 km
- Period : jan-feb 2020
- Beucher et al. et al submitted QJRMS

Meso-NH:

- Domain 12.5N-13.5N ; 57.9W-56.1W
- Res: 100m
- Period : 02-02-2020
- Dauhut et al submitted QJRMS

Langrangian: SAM : sugar-flower transition

Narenpitak et al 2021 (JAMES)

Evaluation and Process Understanding……

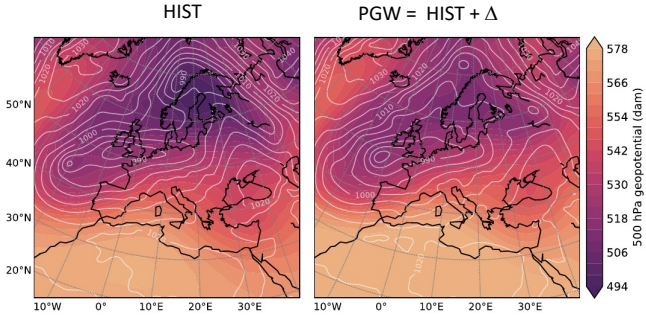
But what about radiative response of these mesoscale cloud patterns to global warming ?

EUREC4A-MIP: Pseudo-Global Warming (PGW) Approach (2)

Concept:

1. Run LES and SRM on large domains with realistic boundary conditions (ERA5) : HIST
2. Repeat the simulations with an added perturbation field from climate simulations : PGW = HIST + Δ

Δ = SCEN - CTR



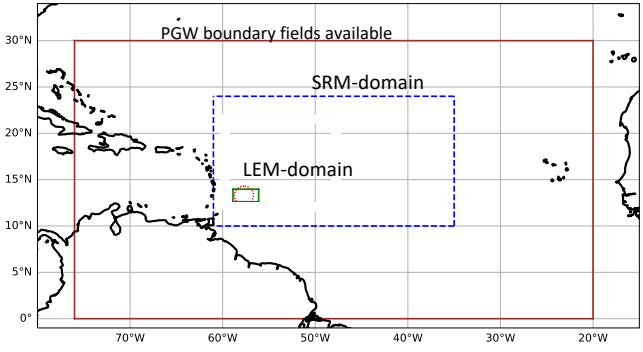
Objectives

- Assess model capability of reproducing observed model structures
- Process Understanding
- Assess sensitivity of the radiative response of mesoscale cloud patterns to warming

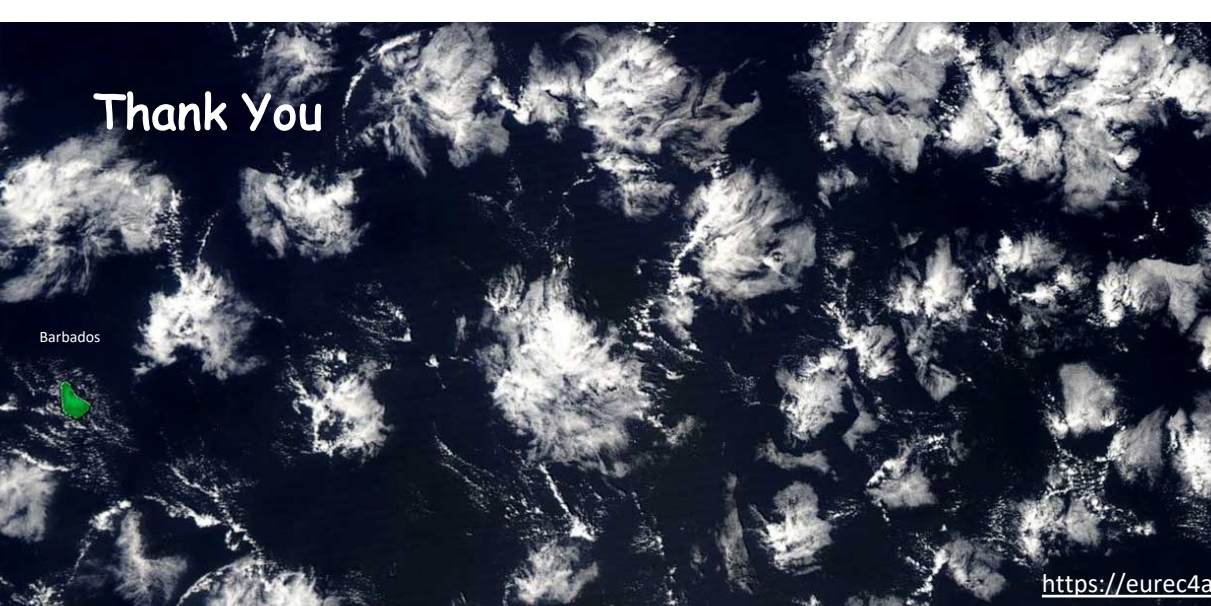
EUREC4A-MIP: Pseudo-Global Warming (PGW) Approach (3)

Applying PGW for the EUREC4A period for :

- SRM's : Jan-Feb 2020 over a large domain at resolutions 1-5 km
- LEM's : Feb 1-10 2020 over a smaller domain (300x150km^2) at resolutions 100-500m
- Climate Perturbation Fields Δ derived from +4K SST global GCM runs (30yr) minus CTRL (30yr)
- Climate Perturbation fields Δ available from GFDL model (medium ECS), HADGEM (high ECS) and low ECS (NorESM)
- For more details see the webpage : https://eurec4a.eu
- Join the break out session today…



Thank You



https://eurec4a