Towards a 3D view of Cloud Systems using Synergistic Satellite Observations & Machine Learning:

linking atmospheric heating to convective organization & process-oriented evaluation of parametrizations in climate models

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with contributions
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Journées GDR Défis théoriques pour les Sciences de Climat, 15-17 June 2022

Outline

- **Tools for a better understanding of our climate**
- **Cloud properties from space**
- **Building a 3D view of UT cloud systems for process studies**
  - ***Motivation & approach***
  - ***Clouds from IR sounder***
  - ***Cloud System Concept***
  - ***3D snapshots by expanding nadir vertical structure by using Machine Learning***
- **Evaluation & process-oriented analysis of mesoscale convective systems**
- **UT Cloud System Concept to assess GCM parameterizations**
  - ***example: test a more coherent bulk ice cloud scheme***
- **Radiative Impact of UT cloud systems in the tropics**
- **Conclusions, outlook & discussions**

What do we need for a better understanding of our climate

Observations at different scales :

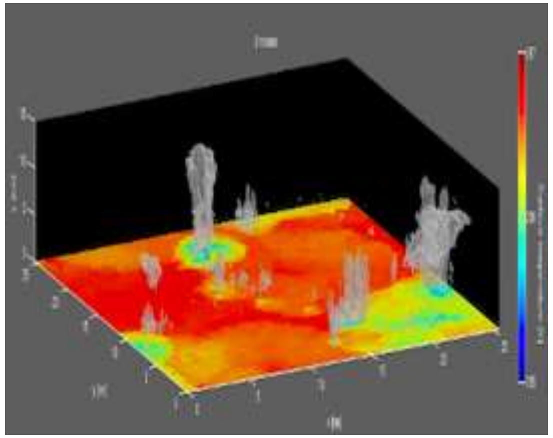
- in situ measurements
- field campaigns
- satellite retrievals

Satellite observations are global, but:

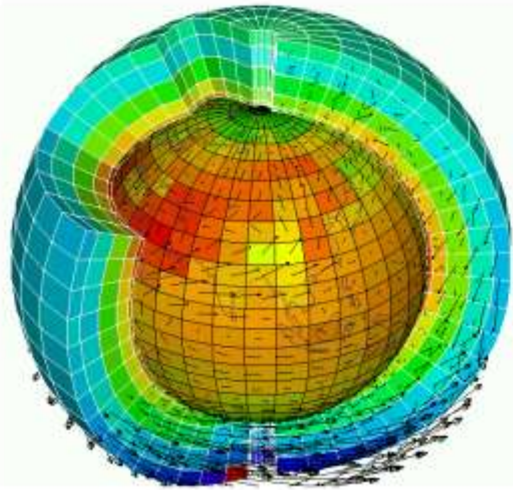
1) no direct measurements of key variables
   -> radiative transfer + retrieval
2) single instruments only provide partial view of the atmosphere
   -> build 3D view from synergistic instruments & Machine Learning

Models at different scales:

- 1D column model
- Large Eddy Simulation models
- Cloud Resolving Models
- Earth System Models



source: website of Caroline Muller



source: LMD website

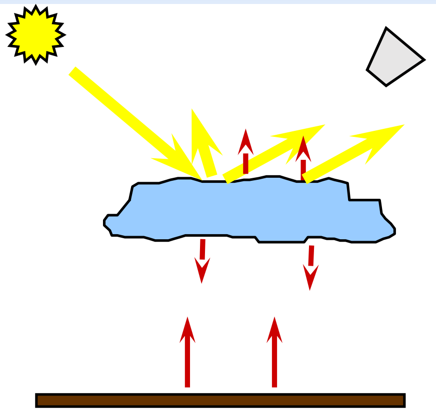
Atmospheric reanalyses:

using data assimilation & modelling

Analysis methods, theories, process studies, parameterizations, simulation experiments, trend analyses, etc

Cloud Properties from Space

Passive remote sensing (> 1970's) (multi-angle VIS & IR-NIR-VIS imagers, IR sounders):
radiometers measure emitted, reflected, scattered radiation



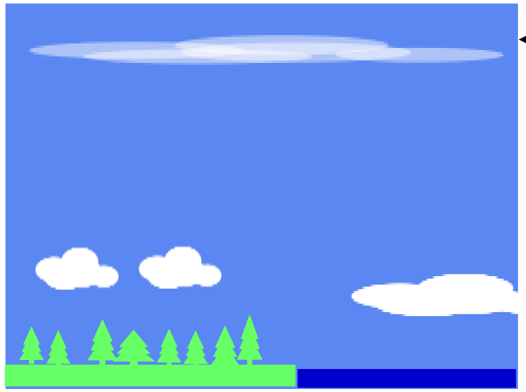
radiative transfer

cloud properties

Active instruments (A-Train, ≥ 2006):
CALIPSO lidar – CloudSat radar synergy -> information on all cloud layers; however: sparse sampling

Ci over low clouds : Interpretation of Cloud height

20% of all cloudy scenes (CALIPSO)



lidar, CO_2 sounding, IR spectrum

IR-VIS imagers

Solar spectrum

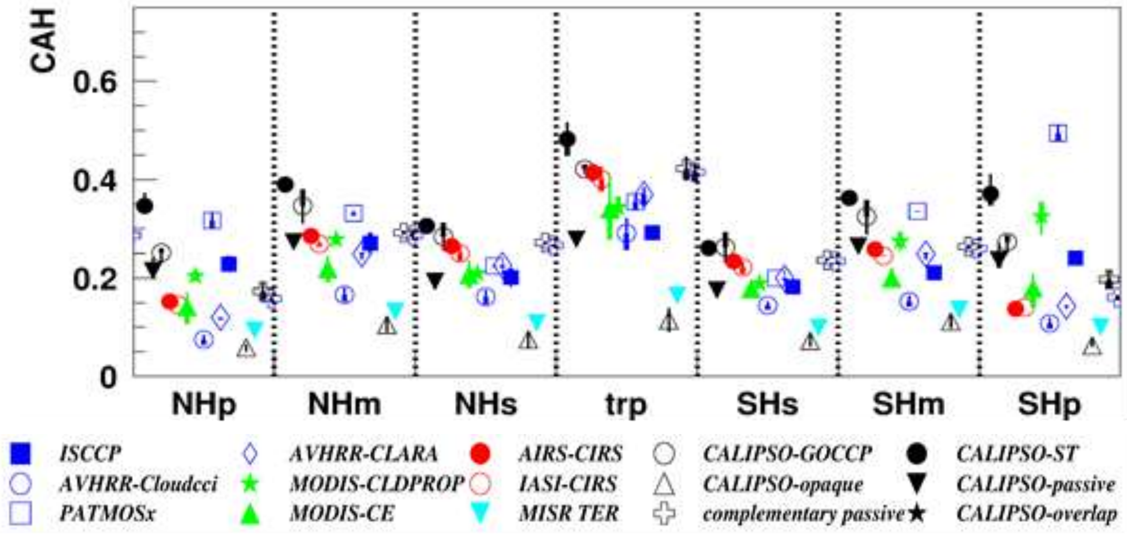
How does this affect climatic averages & distributions ?

GEWEX Cloud Assessment *(Stubenrauch et al. 2013)*

Updated GEWEX Cloud Assessment database

increasing sensitivity towards thin Ci:

VIS / VIS-IR / IR spectrum / IR sounder / lidar



Building a 3D view of UT cloud systems for process studies

Motivation & approach

Clouds from IR sounder

Cloud System Concept

3D snapshots by expanding nadir vertical structure
by using Machine Learning

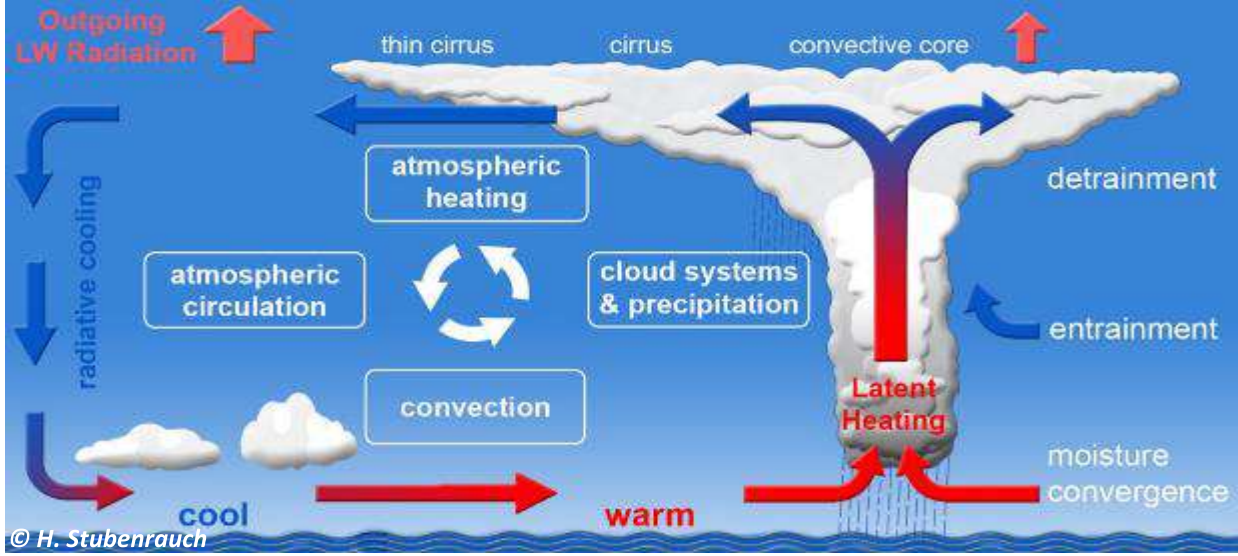
Motivation & approach

Climate warming :

change in tropical convective intensity & organisation ?

-> size & emissivity structure of cirrus anvils

-> heating gradients -> large-scale circulation



GEWEX UTCC PROES *(https://gewex-utcc-proes.aeris-data.fr)*

Goals: - understand relation betw. convection, cirrus anvils & radiative heating

- provide observational metrics to probe processes involving UT cloud systems

To advance our understanding on UT cloud feedbacks, we are coupling

- **IR Sounder near-cloud-top properties,** *sensitive to cirrus (day & night) & good instantaneous coverage*
- **vertical structure & rain areas within UT clouds** (from CALIPSO-CloudSat & ML)
- **3D diabatic heating** (**radiative** from CALIPSO-CloudSat & ML & **latent** from TRMM & ML)
- **Cloud System Concept**, *relating cirrus anvil properties to convection*
- **metrics of convective organisation**, based on precipitating areas within UT clouds (from CloudSat & ML)
- **simulation experiments**, using observational 3D diabatic HR fields to force climate system & study changes in atmospheric circulation for different situations of convective organization

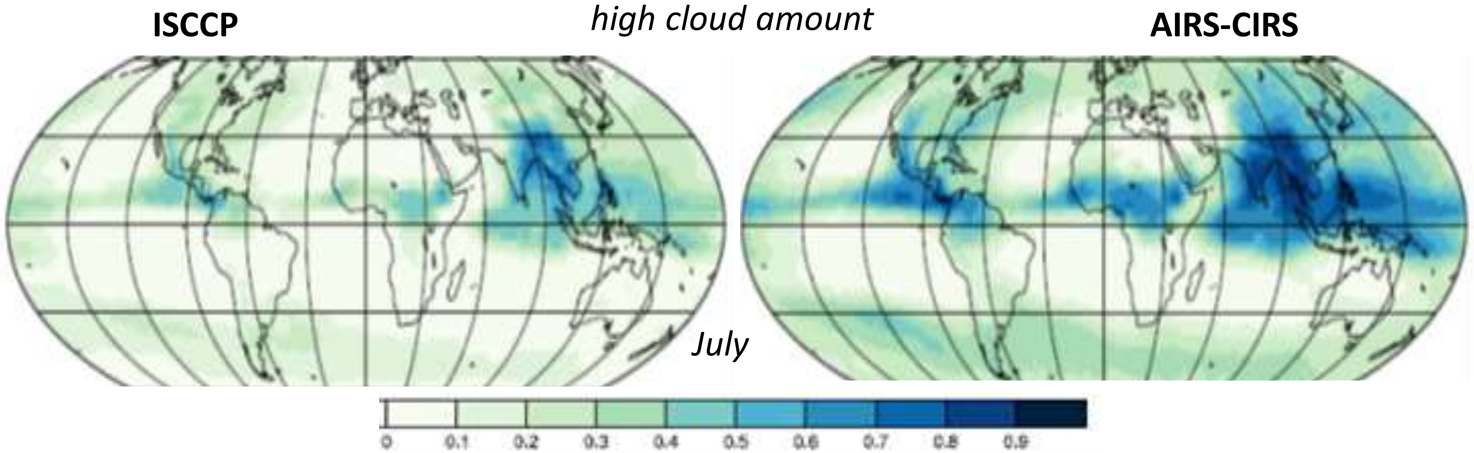
-> quantify dynamical response of climate system to atmospheric heating

Clouds from IR Sounder (CIRS) -> UT cloud types

HIRS
>1979 / ≥ 1995: 7:30/ 1:30 AM/PM

AIRS, CrIS
≥2002 / ≥ 2012 : 1:30 AM/PM

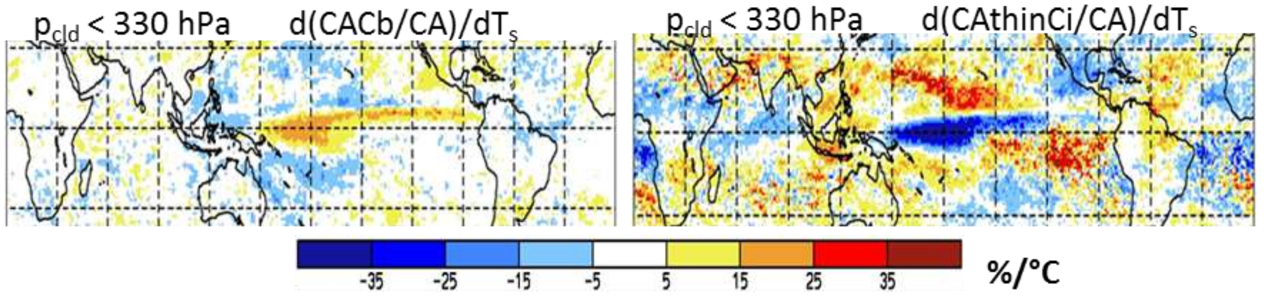
IASI (1,2,3), IASI-NG
≥2006 / ≥ 2012 / ≥ 2020 : 9:30 AM/PM

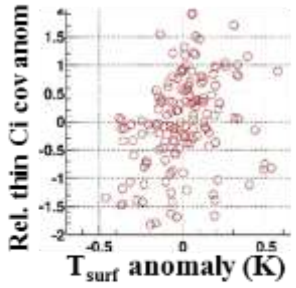


- **good IR spectral resolution -> sensitive to cirrus**
  similar performance day & night, $COD_{vis} > 0.1$, also in the case of lower clouds underneath
- long time series (HIRS, AIRS, IASI)
- good areal coverage
- distinction between opaque & semi-transparent UT clouds by using emissivity

(Stubenrauch et al., ACP, 2017)

How do tropical UT cloud types change with respect to T_{surf} ?





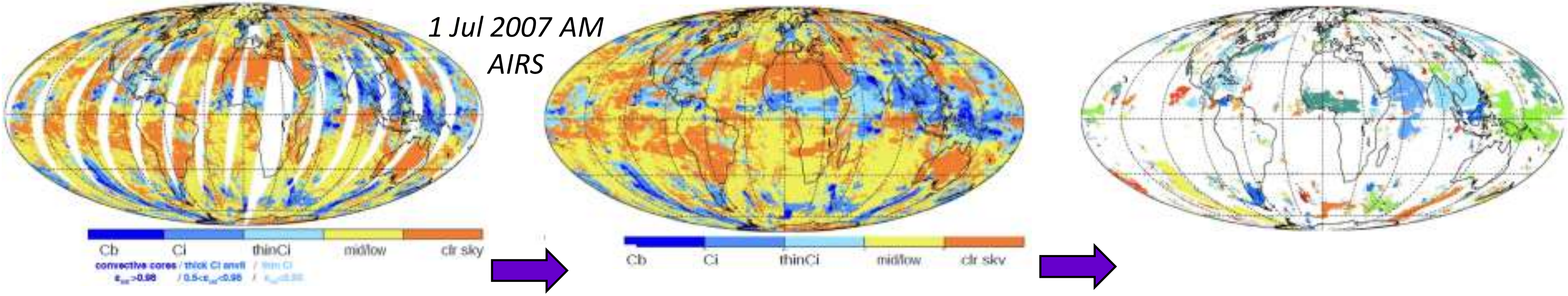
Changes in relative occurrence of Cb & thin Ci clouds per °C warming show different geographical patterns
-> change in heating gradients -> affects atmospheric circulation

From Cloud Retrieval to Cloud System Approach

clouds are **extended objects**, driven by dynamics -> **organized systems**

R E C O N S T R U C T I O N

1) group adjacent grid boxes with high clouds of similar height (p_{cld})

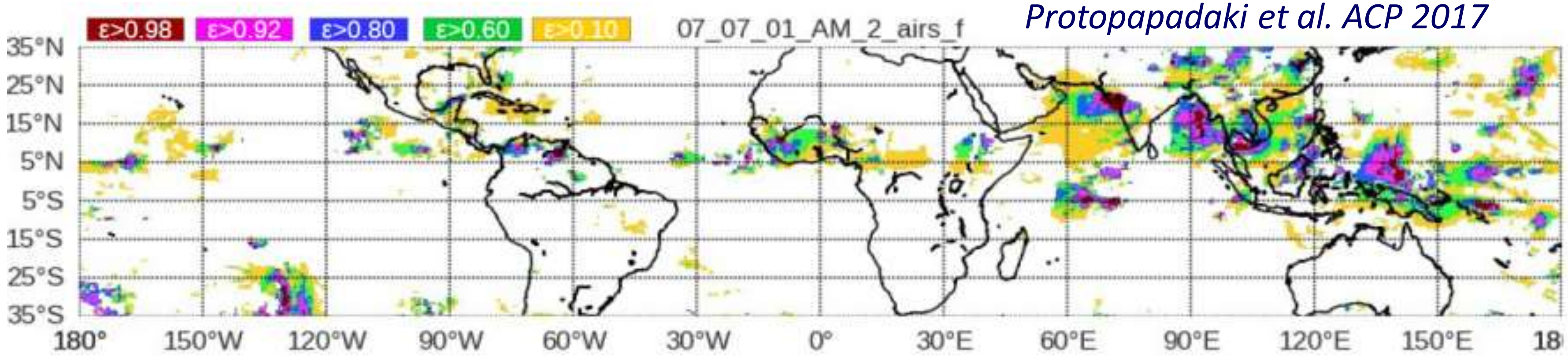


fill data gaps using PDF method

build UT cloud systems

2) use ε_{cld} to distinguish convective core, thick cirrus, thin cirrus *(only IR sounder)*

Protopapadaki et al. ACP 2017

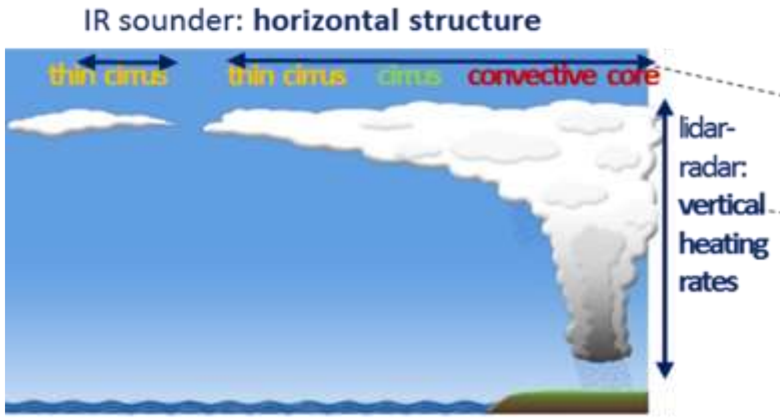


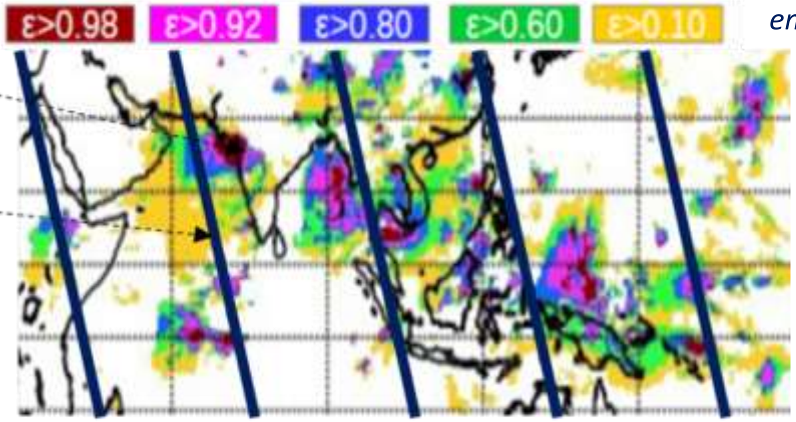
based on p_{cld} & ε_{cld}

30N-30S: UT clouds cover 35%; UT cloud systems cover 20 – 25% *(depending on definition)*
Mesoscale convective systems cover 15 – 20% ; ***Cloud System Approach allows to link convection to anvils***

3D snapshot reconstruction using synergistic data & Machine Learning

add vertical structure & precipitation





emissivity structure of UT cloud systems

vertical structure & precipitation:

1) CloudSat-lidar on narrow nadir tracks

2) TRMM radar : small coverage at specific LT

LT within 20 min of 1h30 AM

expand vertical structure & precipitation info across UT cloud systems & environment by machine learning:

1) develop optimized 'non-linear regression & classification models' based on neural networks, training on collocated data *(AIRS-CloudSat-lidar 2007-2010, AIRS-TRMM 2004-2015, IASI-TRMM 2007-2015)*

2) apply these models on the whole CIRS data record *(2003-2019)*

use derived atmospheric properties ***(similar for AIRS & IASI)*** **:**

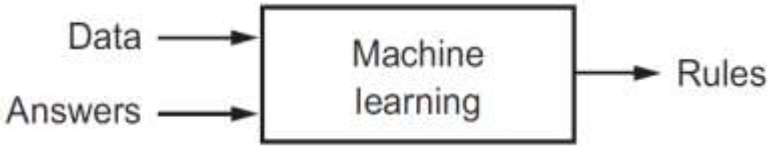
X : CIRS cloud variables & ERA-Interim atmosphere

F(X) : CloudSat-lidar radiative heating rates, Z_{top} & Z_{top}-Z_{base}, rain rate, cloud layering from NASA FLXHR v4, GEOPROF, PRECIP-column

TRMM latent heating rates from NASA SLH v6

X

F(X)



Vertical structure & rainy areas within UT cloud systems in tropics

use ML approach to develop regression & classification models

↓

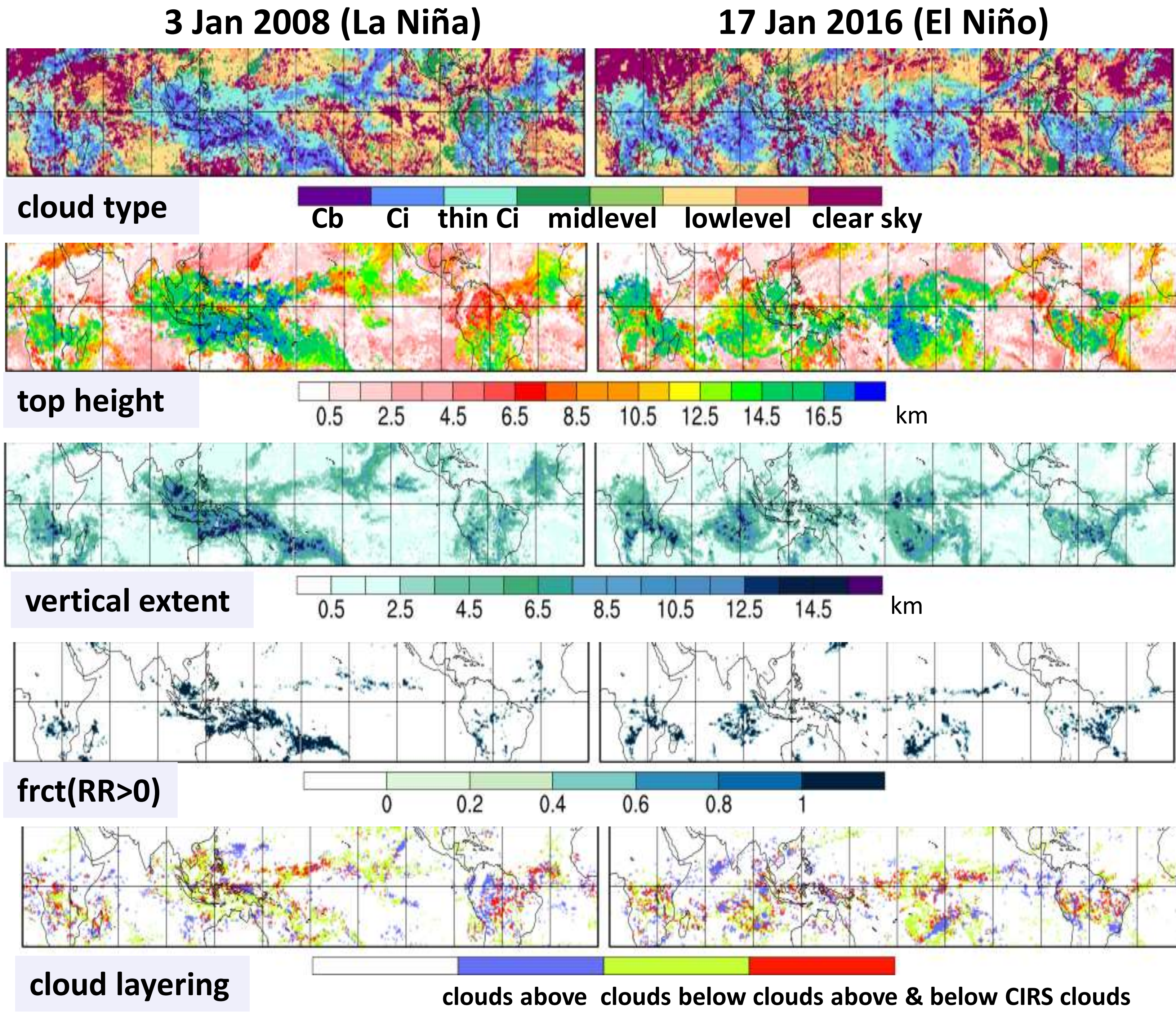
Z_{top}, Z_{top}-Z_{base}, Cloud Layering & Rain Rate classification

accuracy 65 - 70%

leads to snapshots of horizontal structures !

different structures for

La Niña - El Niño



derive convective organization from rainy areas within UT clouds

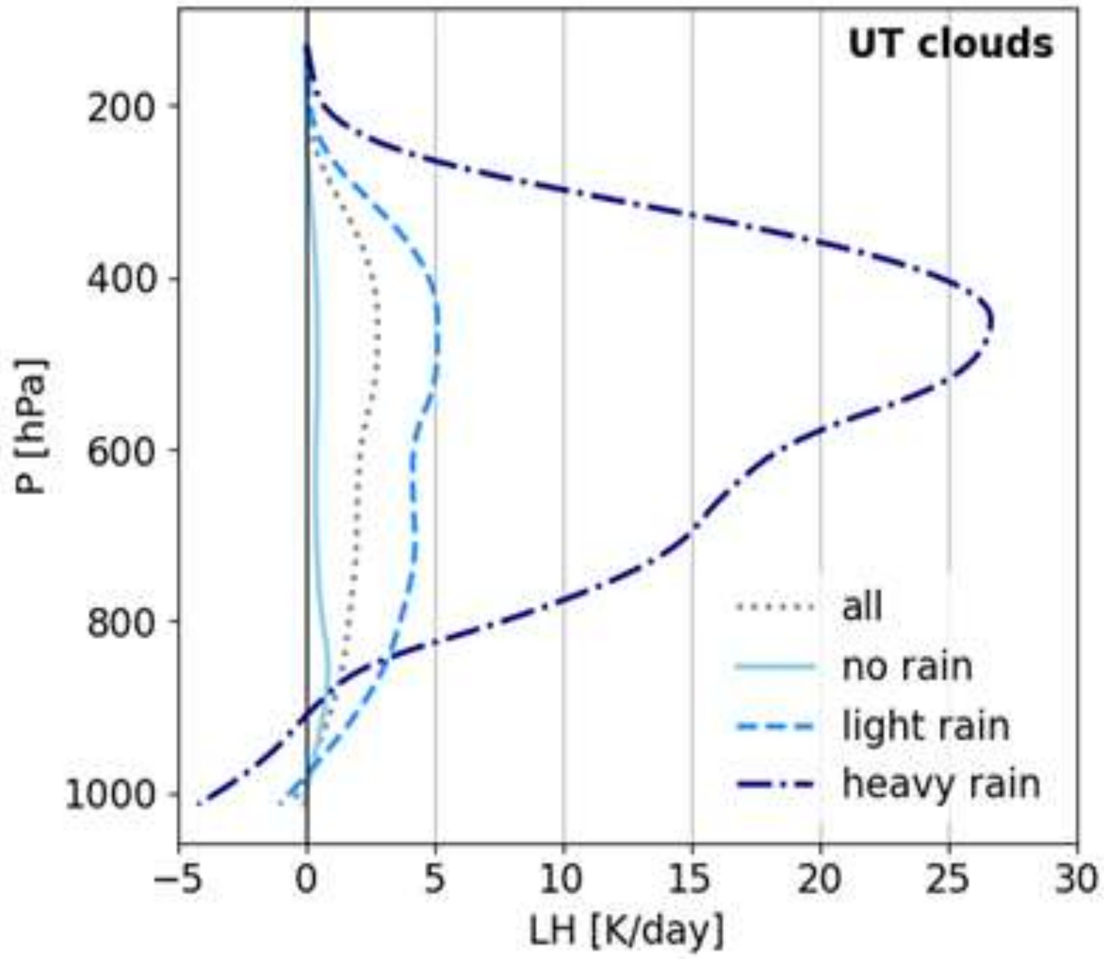
Multiple layers: mostly lower clouds underneath Ci / thin Ci
structures prolongated by very thin Ci above lower clouds

Rain rate classification– Latent heating coherence

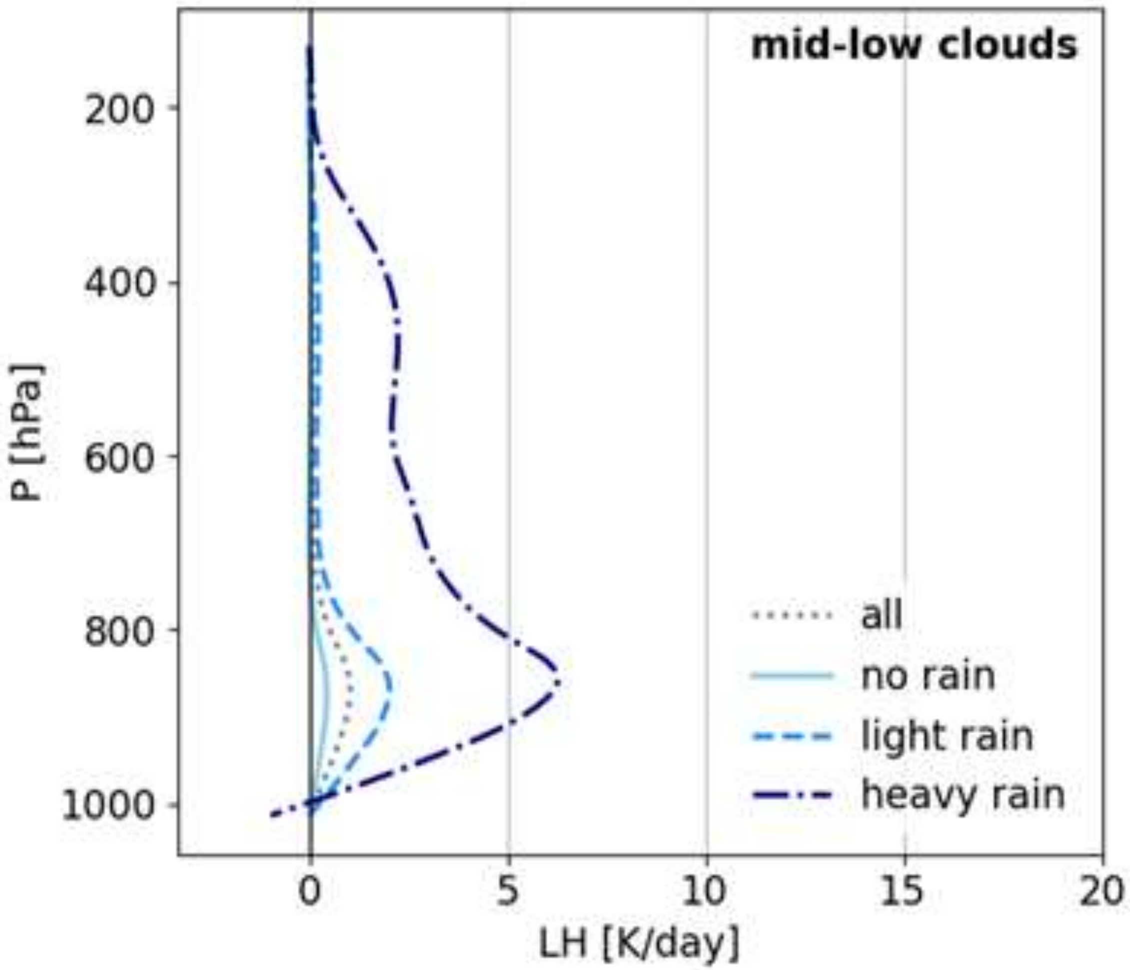
AIRS ML & CloudSat

TRMM

LH for heavy rain about 10 times larger than tropical average from UT clouds



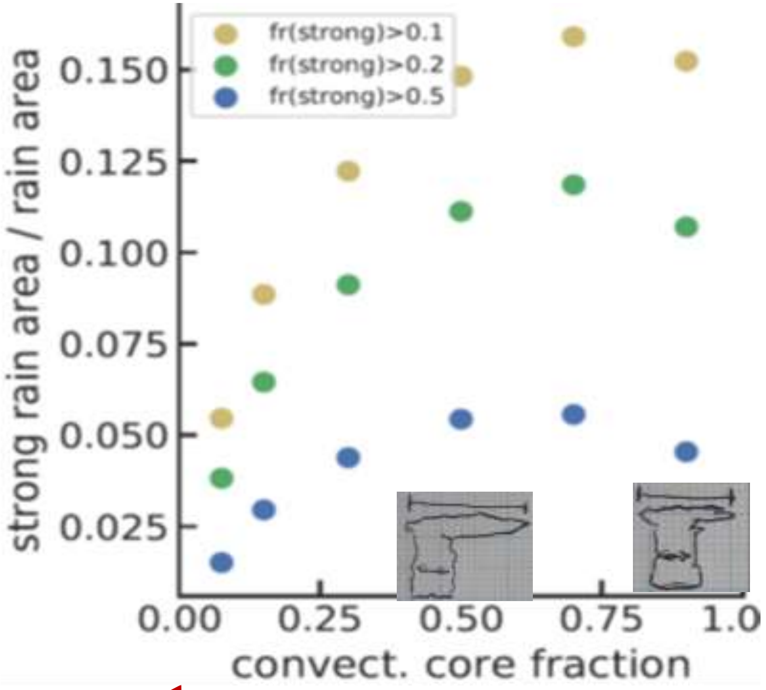
LH of mid- / lowlevel clouds smaller & in lower troposphere



Stubenrauch et al., ACP 2022, to be submitted

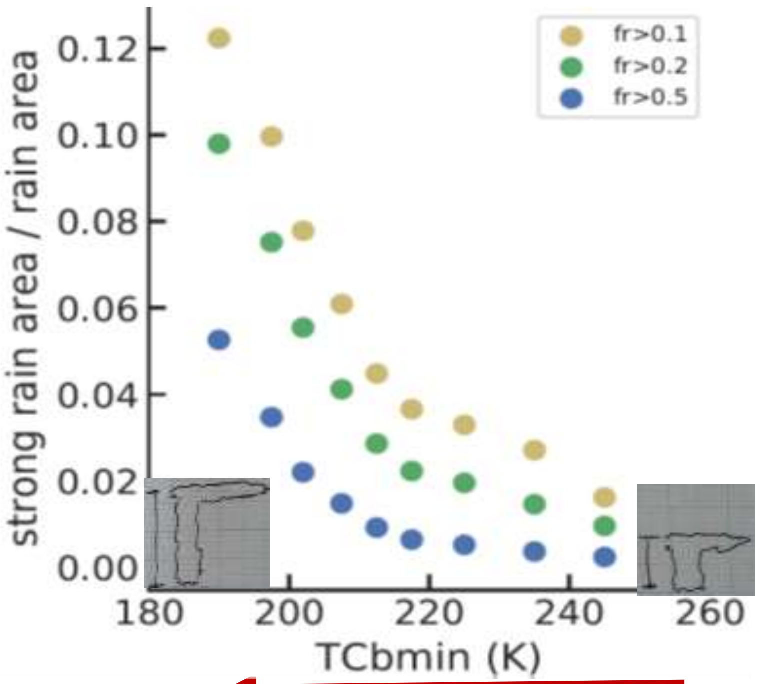
Process-oriented behaviour of mesoscale convective cloud systems

convective core fraction :
proxy for life stage

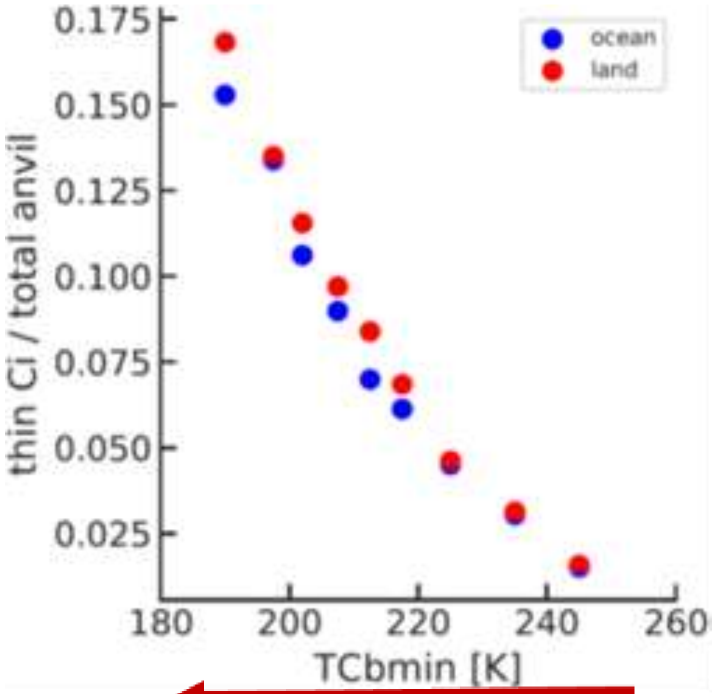


increasing age of system

min T within core of mature systems:
proxy for convective depth



increasing convective depth



increasing convective depth

max. rain intensity
after first development of anvils

Deeper convection leads to larger heavy rain areas

Deeper convection leads to larger areas of thin Ci around anvils

in agreement with other studies *(Roca et al. 2014, Takahashi et al. 2021, …)*
-> reliability of ML derived rain

Deeper convection in warmer tropical regions

Stubenrauch et al., ACP 2022, to be submitted

Stubenrauch et al., ACP 2021

UT Cloud System Concept to assess GCM parameterizations

Cloud System Concept relates anvil properties to processes shaping them

-> process-oriented evaluation of detrainment / convection / microphysics parameterizations

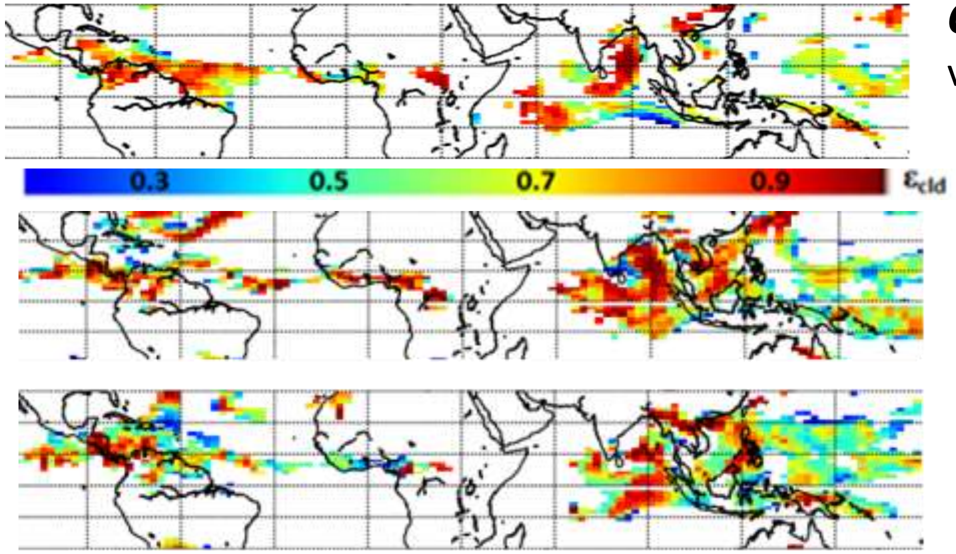
Example: Towards coherent bulk ice cloud scheme deduced from thermodynamics in LMDZ

v_m strongly influences UT cloud occurrence & properties & has potential to influence climate sensitivity

D_e affects the radiative properties of UT clouds : ε = f(De, IWC)

CIRS simulator *(M. Bonazzola)* & cloud system analysis

spatial res. 2.5° x 1.25°



Current LMDZ model: **v_m = f(IWC), De = f(T)**

v_m tuned to achieve balance (x 0.3)

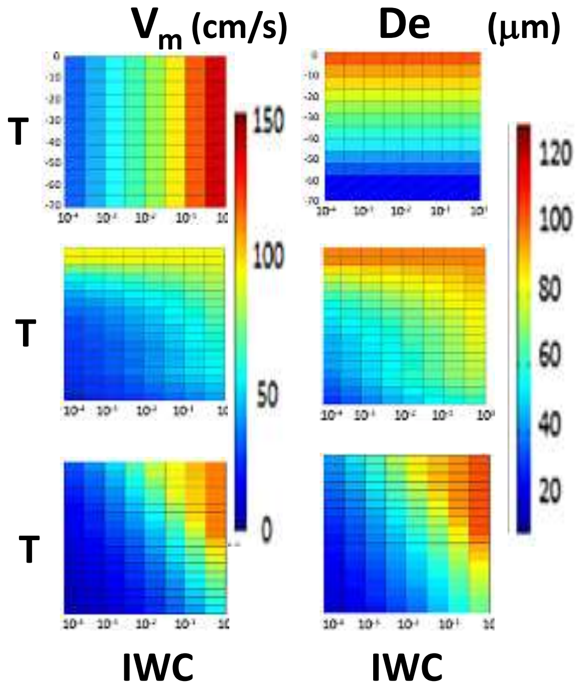
observations: **v_m = f(IWC,T), De = f(IWC,T)**

empirical: **v_m = f(IWC,T), De = f(v_m)**

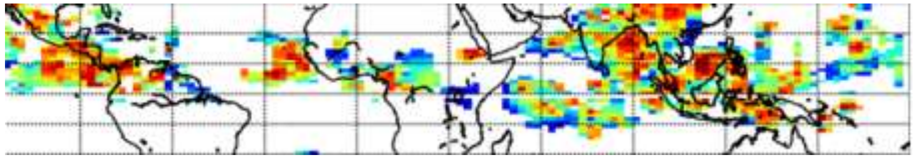
Deng & Mace (2008), Heymsfield et al. 2003

PSDM: **v_m, De from moments of ice crystal size distributions as f(IWC,T)**

Field et al. (2007), Furtado et al. 2015, Baran et al. 2016



horizontal cloud system emissivity structure sensitive to v_m, De

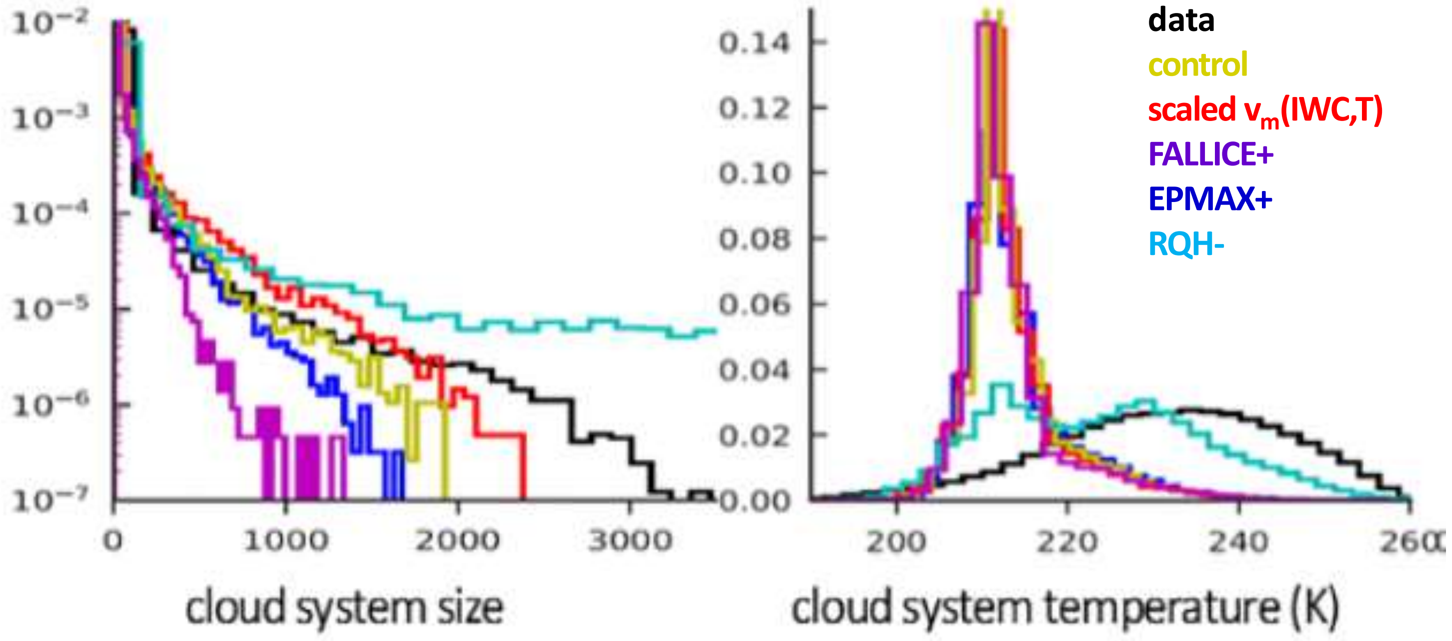


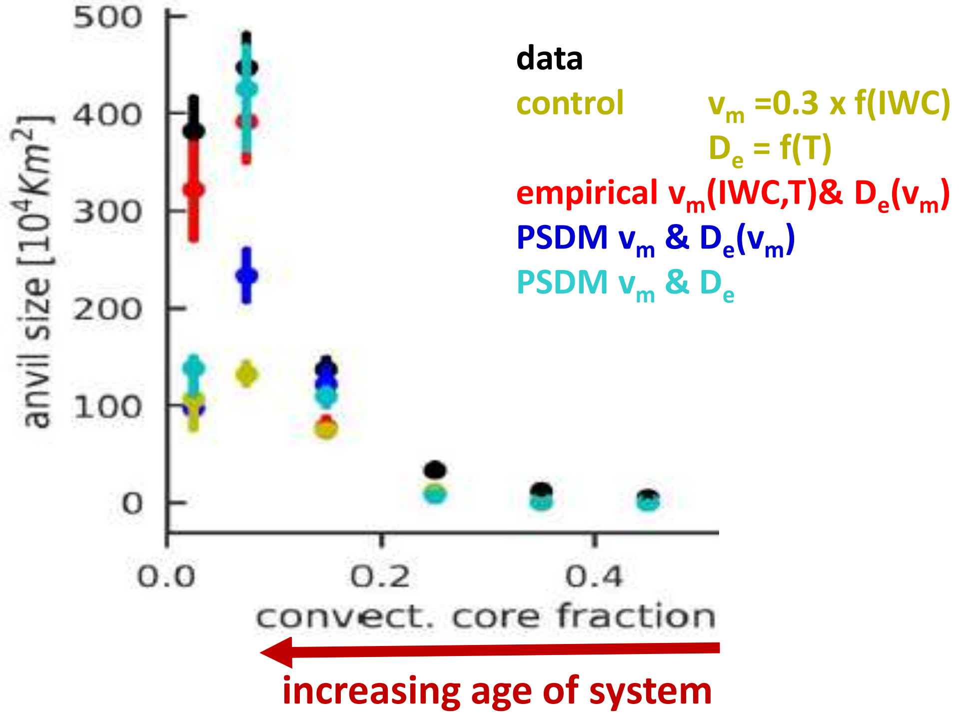
AIRS snapshot 3 July 2008 AM

UT cloud system & process-oriented behavior

Stubenrauch et al., JAMES 2019

Sensitivity Study





Introduction of IWC-T dependence:
-> improved size distribution
Decrease of RQH:
-> larger anvils (& more thin Ci)

Decrease of RQH :
-> improved T distribution

more realistic v_m –D_{eff} :
-> more realistic anvil size development

new cloud system & process-oriented diagnostics additional powerful evaluation tools

AIRS-CloudSat-lidar nadir track statistics (2007 – 2010)

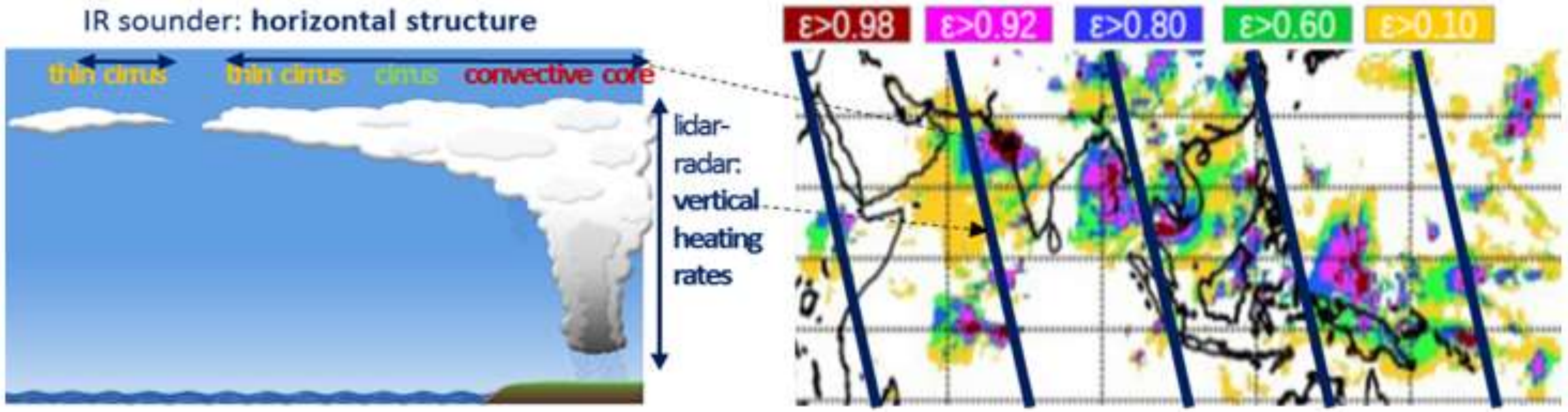
↓ ML

15 year AIRS swath statistics (2004 – 2018)

Radiative Impact of UT cloud systems in tropics

Section 4 of *Stubenrauch, C. J., G. Caria, S. E. Protopapadaki, and F. Hemmer, 3D Radiative Heating of Tropical Upper Tropospheric Cloud Systems derived from Synergistic A-Train Observations and Machine Learning, Atmos. Chem. Phys., DOI: 10.5194/acp-21-1015-2021 (2021)*

AIRS-CIRS–ERA–CloudSat-CALIPSO–TRMM synergy & Machine Learning -> 15 yr cloud vertical structure & rain structure across cloud systems

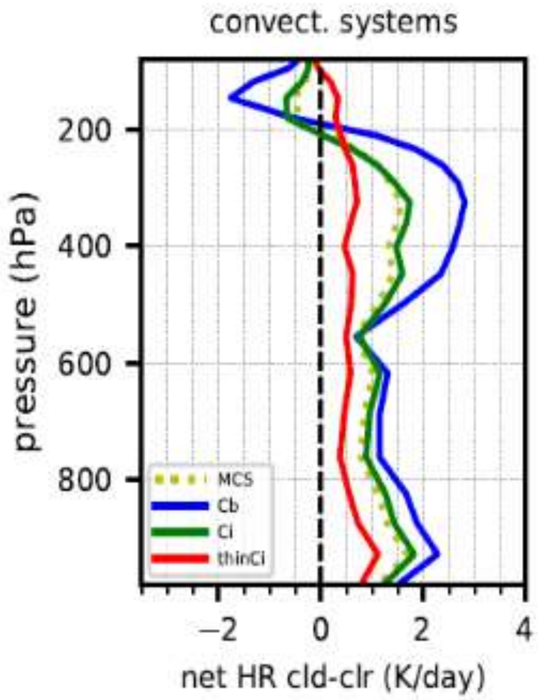


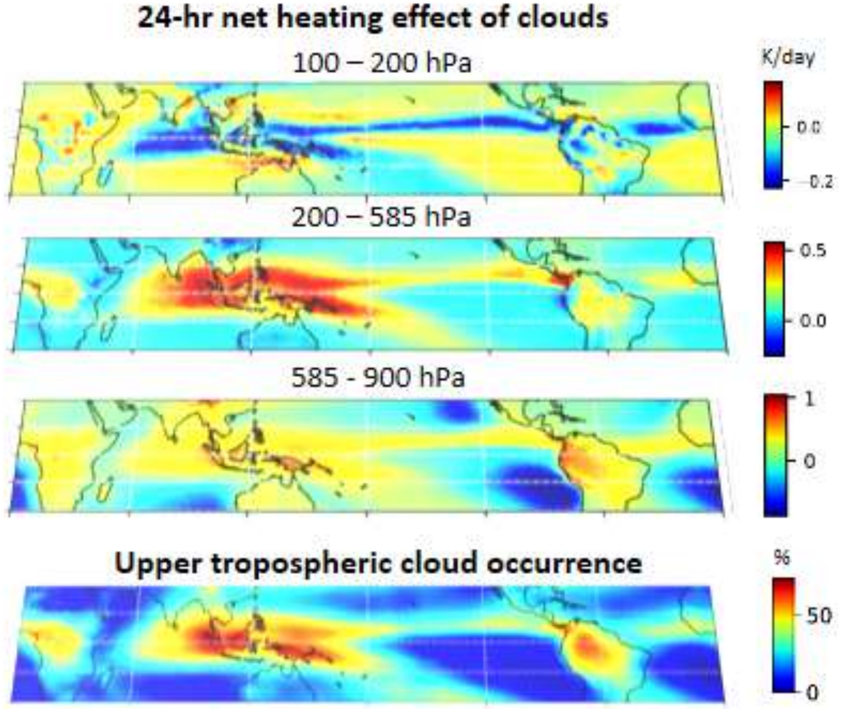
Cloud System Concept + 3D HR fields :

1) relation between convection – cirrus anvil

2) process-oriented GCM evaluation

3) dynamical response to atmospheric heating



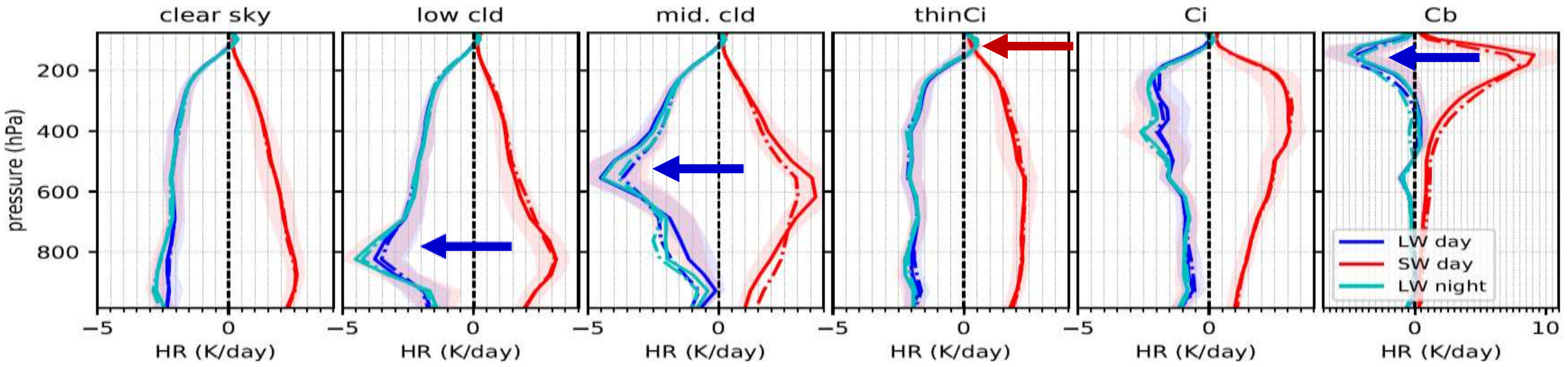


radiative HRs for different scenes over tropics (30N-30S)

apply 8 ANN models *(Cb, Ci, mid/low clds, clr sky over ocean / land)* to AIRS-ERA data

scenes determined by AIRS

Jan 2008 1:30 AM & 1:30PM **SW, LW means, 30% & 70% quantiles** **. _ . _ . FLXHR on nadir tracks**



Clear sky: tropospheric LW cooling (day & night) & **SW warming** (day)

Clouds introduce sharp vertical gradients :

LW warming by trapping surface emissions and cooling above by excess emission

during day: SW warming within the cloud; SW and LW effects nearly compensate

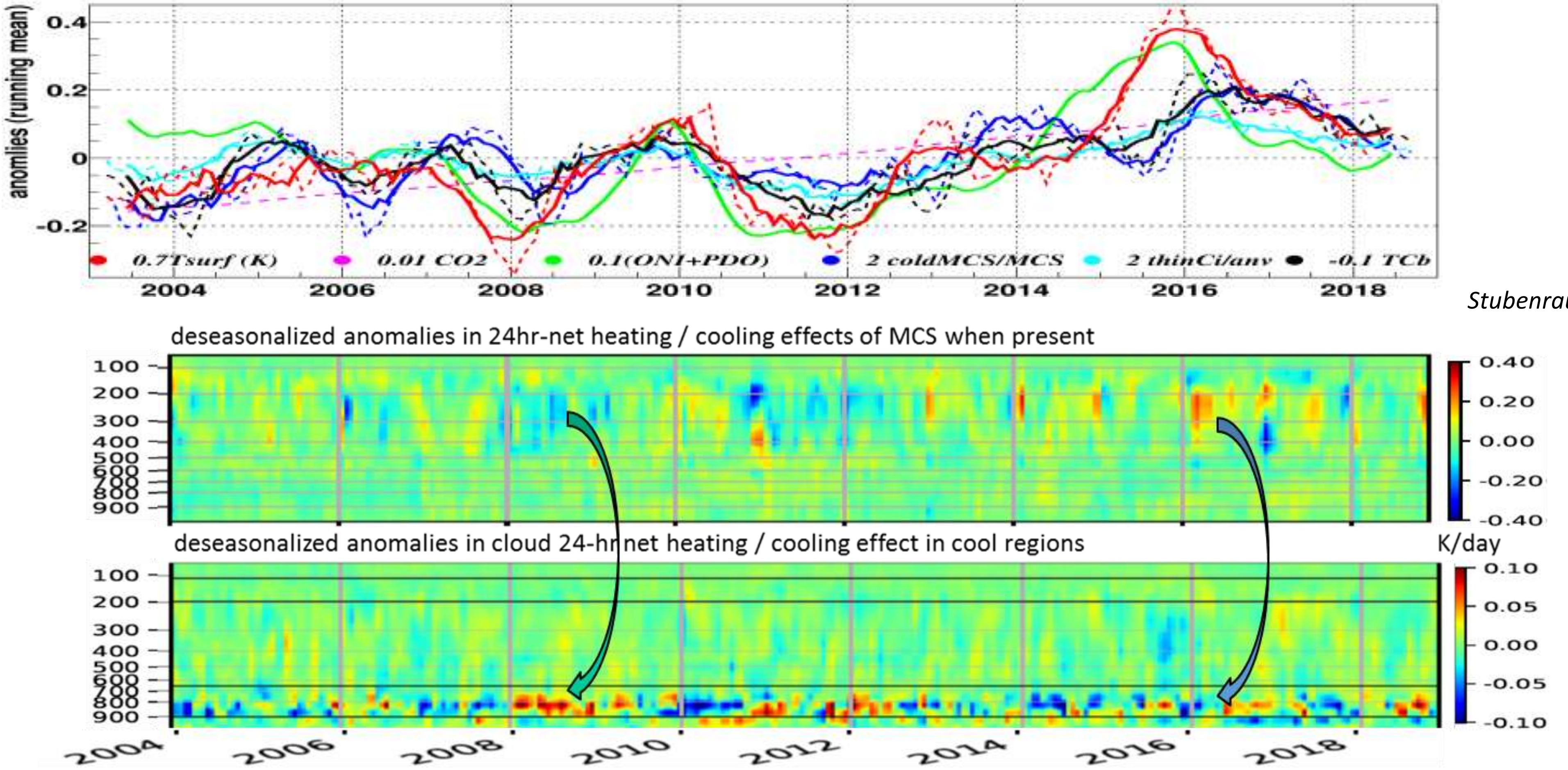
UT: warming by thin Ci, strong cooling above Cb & thick Ci anvil

MT: warming by Cb, thick Ci anvil

LT: warming by Cb, cooling above low clouds (also underneath Ci & thin Ci)

MCS & Heating pattern changes related to tropical T_{surf} anomalies

- **MCSs get colder (deeper) with tropical surface warming** : **dT_{Cb}/dT_{surf} = -3.4 ± 0.2 K/K (r=0.78)**



Stubenrauch et al., ACP 2021

- in warm periods (El Niño) deeper warming of upper & mid troposphere & cooling above the systems
- **correlation** (r=0.71) **between MCS heating in upper & mid troposphere**
  & (low-level) cloud cooling in lower atmosphere in cool regions **} energy constraint**

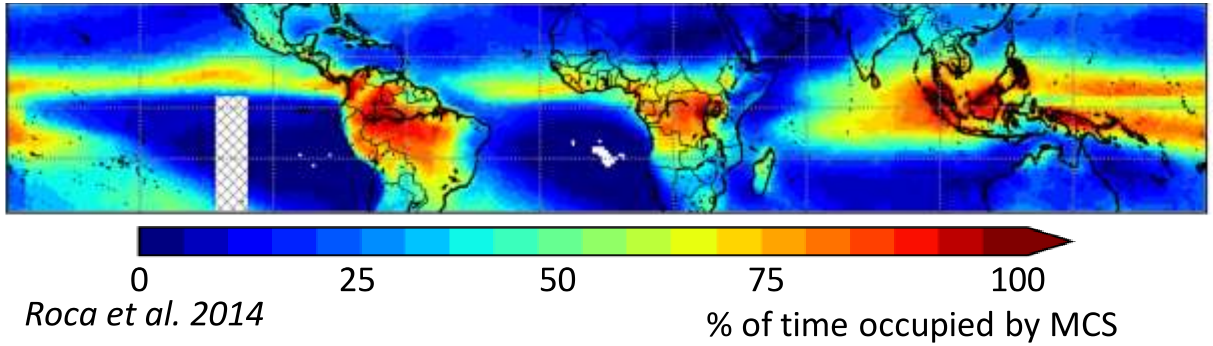
Conclusions

- **The synergy of different satellite instruments gives a more complete picture of clouds**
- **complete 3D snapshots (necessary for process studies) & longer time series can be constructed by Machine Learning applied on cloud & atm. variables**
- **Though the ML models introduce additional uncertainties, complete 3D snapshots allow to study horizontal structure -> convective organization**
- **Time series correlation of ML radiative heating demonstrates energetic constrains between convective & subsidence regions**
- **Cloud System Concept allows**
  - **to study relationships between convection & anvils**
  - **process-oriented evaluation of GCM parameterizations**

Complementary databases & analyses

***Thomas Fiolleau**, UTCC PROES meeting 2018 & Journées Convection 2022*

Mesoscale Convective Systems from geostationary IR imagers 2012-2016



Roca et al. 2014

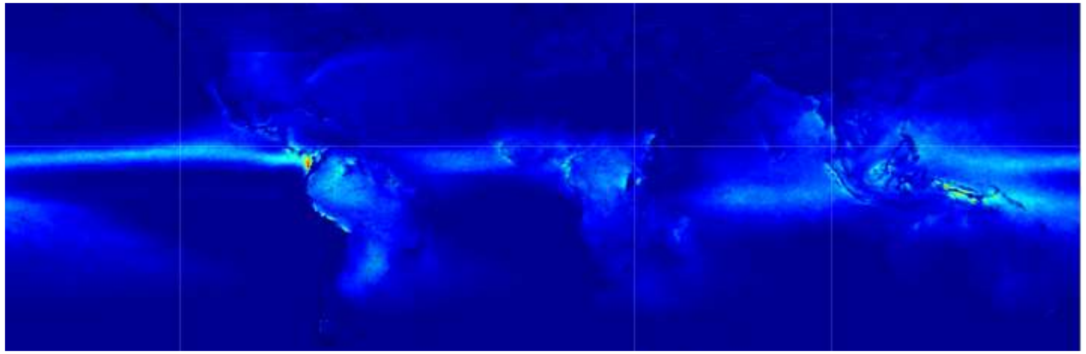
Lifetime duration
max extension, minimum T_B^{IR}
initiation, dissipation
propagated distance

Pattern recognition, tracking, $T_B^{IR} < 235K$

Short-lived systems (<12h) only explain <30% of rainfall over ocean & <40% over land

***Jean François Rysman**, UTCC PROES meeting 2018 & Journées Convection 2022*

Deep Convection & Convective Overshooting from microwave sounders ≥ 1999



Rysman et al. 2017

DEEPSTORM *Rysman et al. 2021*

daily, 0.25°
Occurrence of DC, CTH, IWP trained with CloudSat

ML analysis to study link between convective intensity & environment :

UT humidity & vertical velocity interact to amplify convective intensity

Outlook & discussion

HR fields & convective organization metrics & Cloud System Concept will be used to quantify the dynamical response of the climate system to atmospheric diabatic heating
(bypassing cloud parameterizations in the climate model) *PhD project in cooperation with L. Li, LMD*

Synergies with complementary datasets & modelling to be further explored
like MCS life time duration from geostationary data (*Fiolleau et al. 2020, https://toocan.ipsl.fr*)

When expanding datasets via ML, the evaluation with collocated training / validation data is not sufficient; one needs to carefully evaluate relationships and time series

Possible improvements due to better exploitation of ML techniques & variables ?

In order to foster cooperations with ML & M community
foresee a workshop in 2024 within the framework of this GDR on the thematic:

« Nouvelles synergies entre l'analyse des données et la modélisation:
améliorer et contraindre les modèles par les observations «
?