Changes in UT clouds *deduced from IR sounders*
&
synergistic dataset
to link convective organization & atmospheric heating

Claudia Stubenrauch,

Giulio Mandorli(until Nov 2024), *Xiaoting Chen*

Laboratoire de Météorologie Dynamique / IPSL, Paris, France

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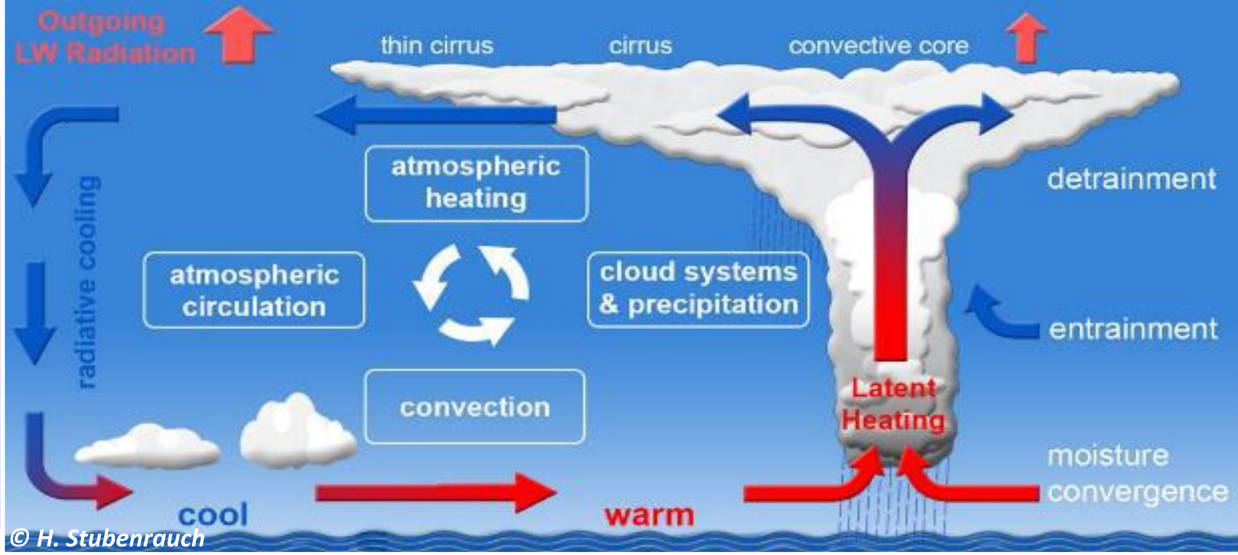
Motivation & approach



Climate warming :

can we detect changes in UT clouds so far?

change in tropical convective intensity & organisation ?

-> size & emissivity structure of cirrus anvils

-> heating gradients -> large-scale circulation

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

- **cloud-top properties**: from IR Sounder, ***sensitive to Ci*** *(day-night) & good instantaneous coverage (Stubenrauch et al. ACP 2017)*
- **Eulerian Cloud System Concept**: *relating cirrus anvil properties to convection (Protopapadaki et al. ACP 2017)*
- **vertical structure & rain areas within UT clouds**: from CALIPSO-CloudSat & ML *(Stubenrauch et al. 2023)*
- **3D diabatic heating**: **radiative** from CALIPSO-CloudSat & ML & **latent** from TRMM & ML
- **Lagrangian Convection Tracking**: based on cold T_B^{IR} *(Fiolleau et al. 2020)* & precipitation *(Takahashi et al. 2021)*
- **metrics of convective organisation**: *(Mandorli & Stubenrauch 2023)*
- **simulation experiments**: study changes in atmospheric circulation for different situations of convective organization

-> quantify dynamical response of climate system to atmospheric heating

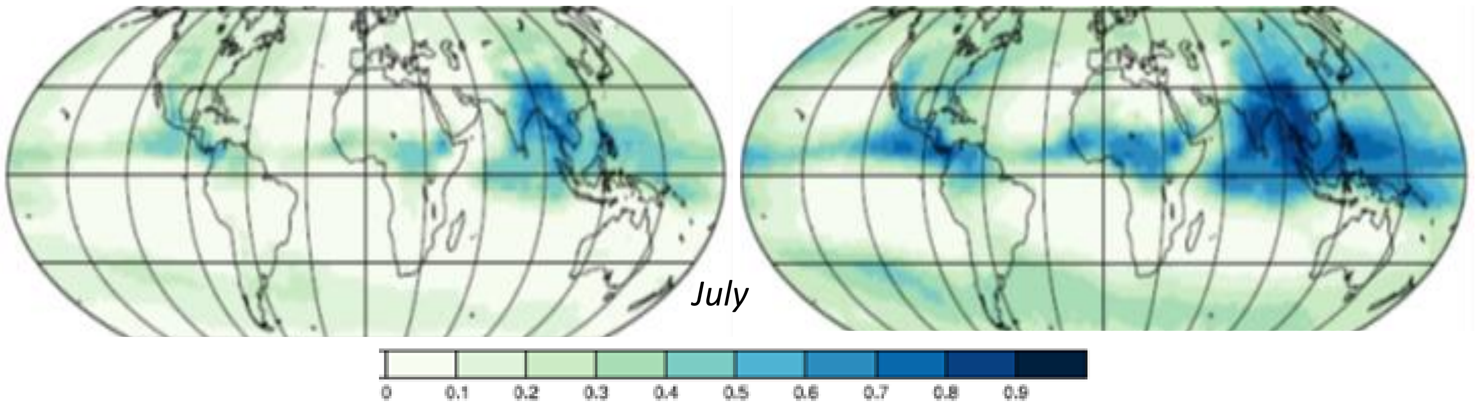
Clouds from IR Sounder (CIRS)

AIRS
≥2002 : 1:30 AM/PM

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

Stubenrauch et al., ACP, 2017

ISCCP *high cloud amount* **AIRS-CIRS**

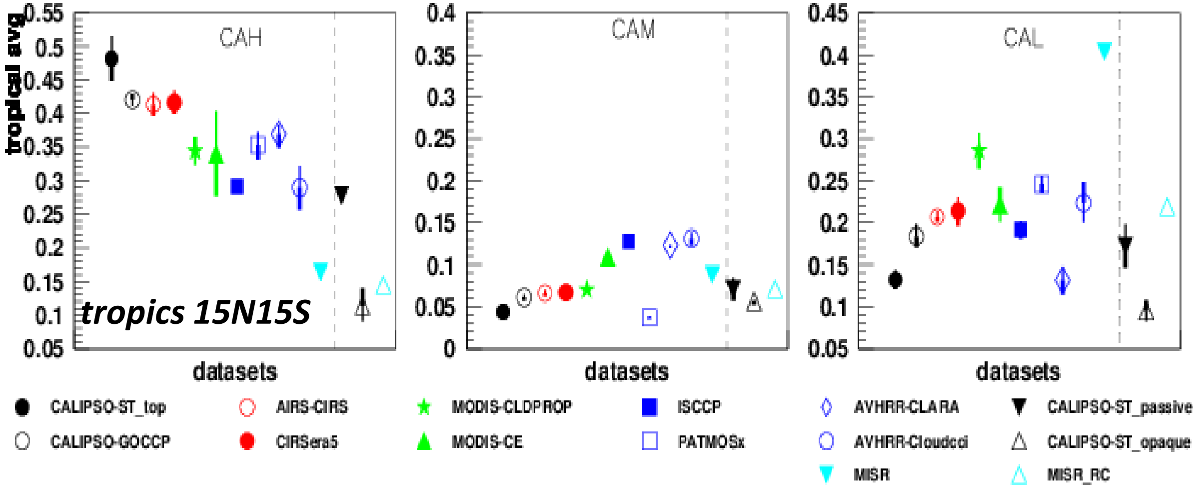


- **good IR spectral resolution -> sensitive to cirrus**
  similar performance day & night, COD_{vis} > 0.1,
  also in the case of lower clouds underneath
- good areal coverage
- distinction between opaque & semi-transparent UT clouds by using emissivity

CIRS data produced & distributed by AERIS: 2003-2018 *(ERA-Interim ancillary data)* *https://cirs.aeris-data.fr/*

Retrieval adapted to ERA5 ancillary data & new production: **2003-2024** *(ERA5 ancillary data, AIRS L1C data)*

evaluation still in progress, in particular for 2024 due to Aqua time drifting



results similar sensitivity to Cirrus slightly below CALIPSO
slight improvements over land during day
compared to L3 data from updated GEWEX Cloud Assessment Database
Stubenrauch et al. 2024 *https://gewexca.aeris-data.fr/*

Can we detect changes in UT clouds due to warming in our current climate ?

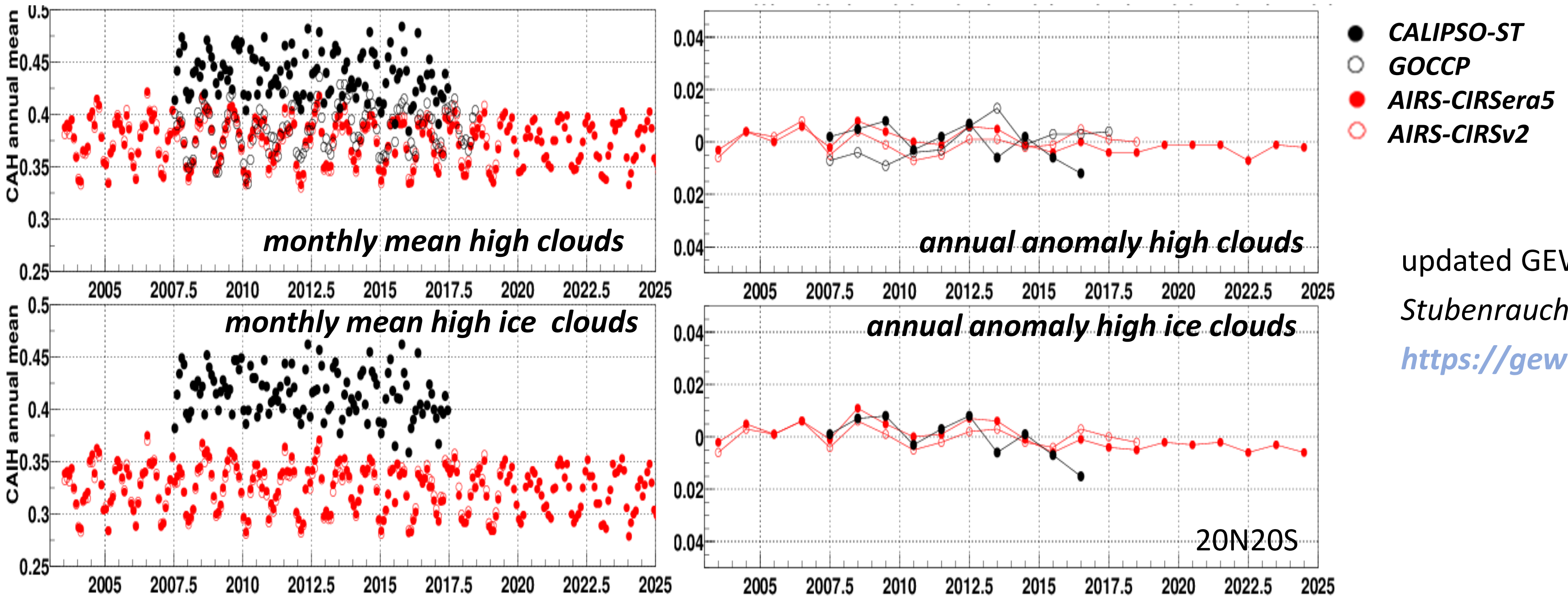
30N30S

2004-2023

preliminary

Changes in tropical UT clouds

- changes are very small and therefore very difficult to detect
- ENSO signal often stands out as major driver of variability in climate records *(Liu et al. 2021)*



updated GEWEX cloud assessment database

Stubenrauch et al. 2024

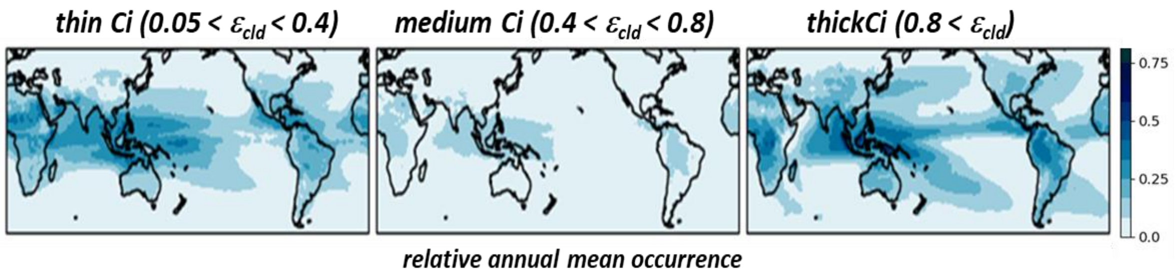
https://gewexca.aeris-data.fr/

- CIRS: very slight decrease of annual high ice cloud amount
- This decrease stems from reduction during months with maximum amount (reduction of variability)

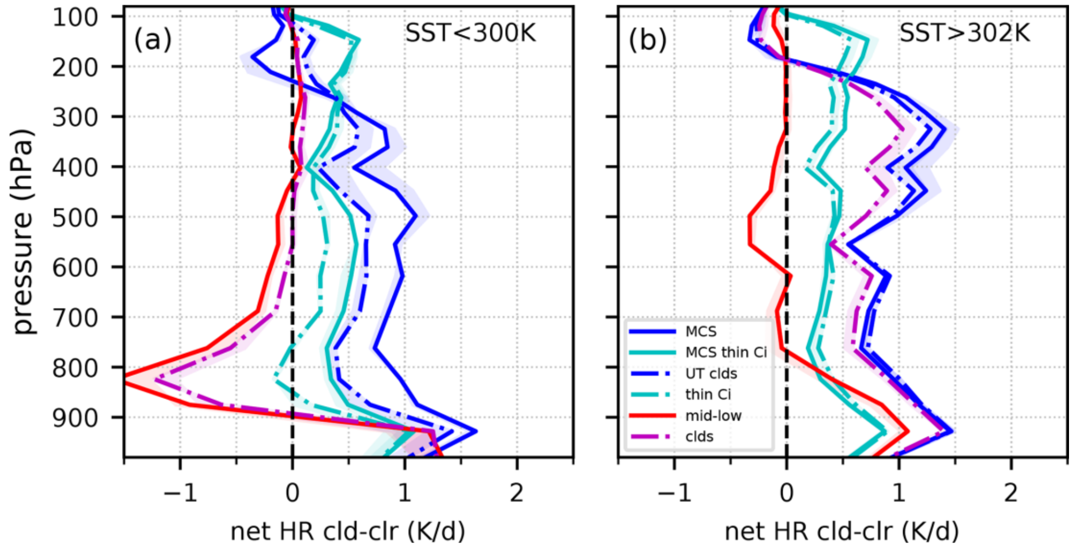
Which type of UT clouds are these ?

CALIPSO high cloud anomalies (sparse sampling & short time series) inconsistent between both retrievals

Radiative effects of UT clouds depend on their optical depth /emissivity



Stubenrauch et al. 2021



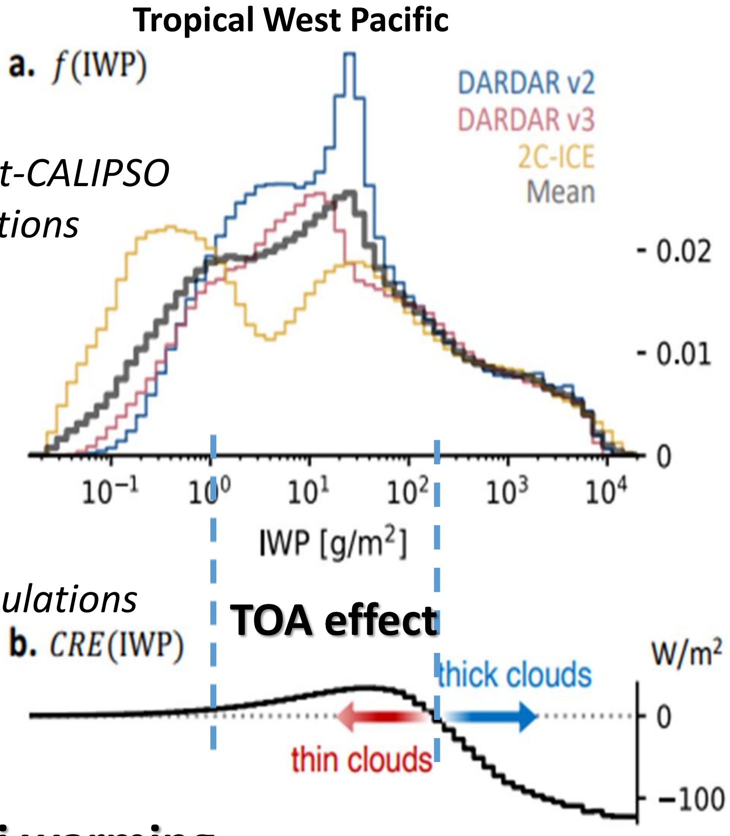
MCSs heat atmosphere below & cool atmosphere above 200 hPa
thin Ci heat the atmosphere, in particular above 200 hPa

Net Cooling of lower atmosphere (low clouds) over cool ocean
Net Warming of atmospheric column (UT clouds) over warm ocean

Sokol et al. 2024

CloudSat-CALIPSO observations

CRM simulations Ts=300K



thin Ci warming

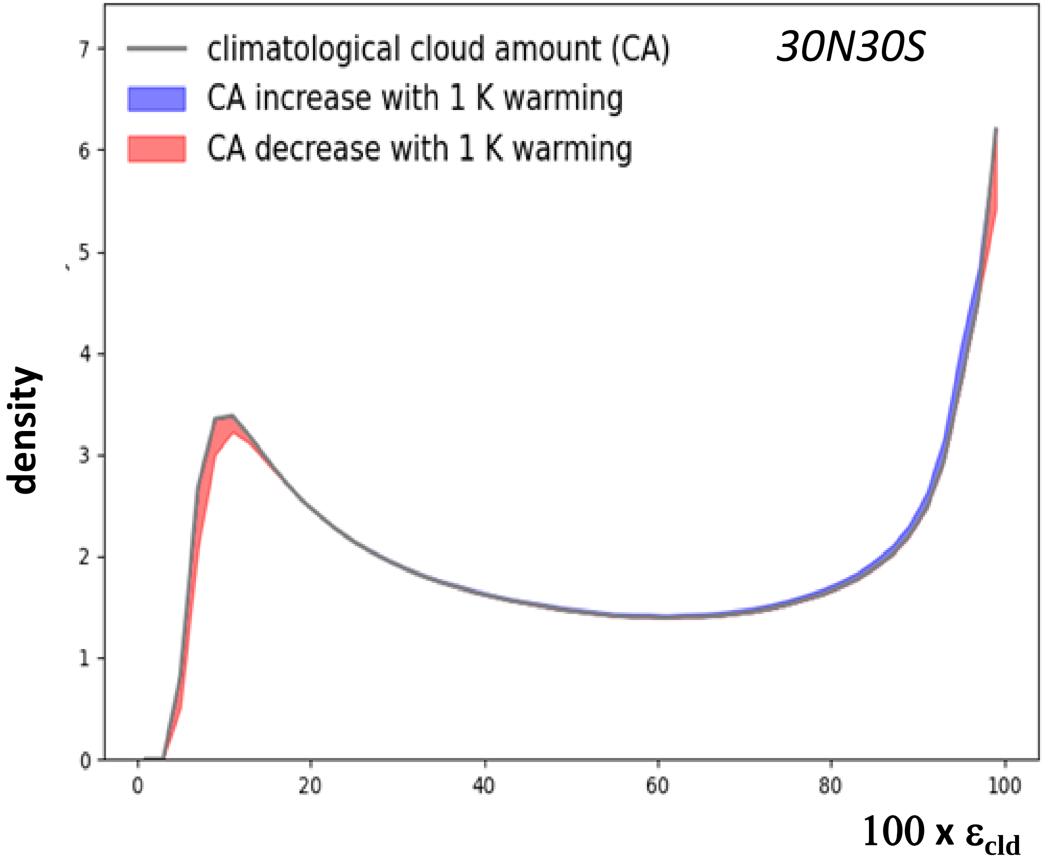
$1 < IWP < 200\ gm^{-2}$ $\tau_{cld} < 6$ $0.2 < \varepsilon_{cld} < 0.8$

thick Ci cooling

$IWP > 200\ gm^{-2}$ $\tau_{cld} > 6$ $\varepsilon_{cld} > 0.8$

Changes in UT clouds dependent on their emissivity

- *AIRS-CIRSera5 2004-2023*
- *UT clouds: $p_{cld} < 350$ hPa*
- *linear trend in time per emissivity interval*
- *assuming dTs/dt = 0.5 K/decade*



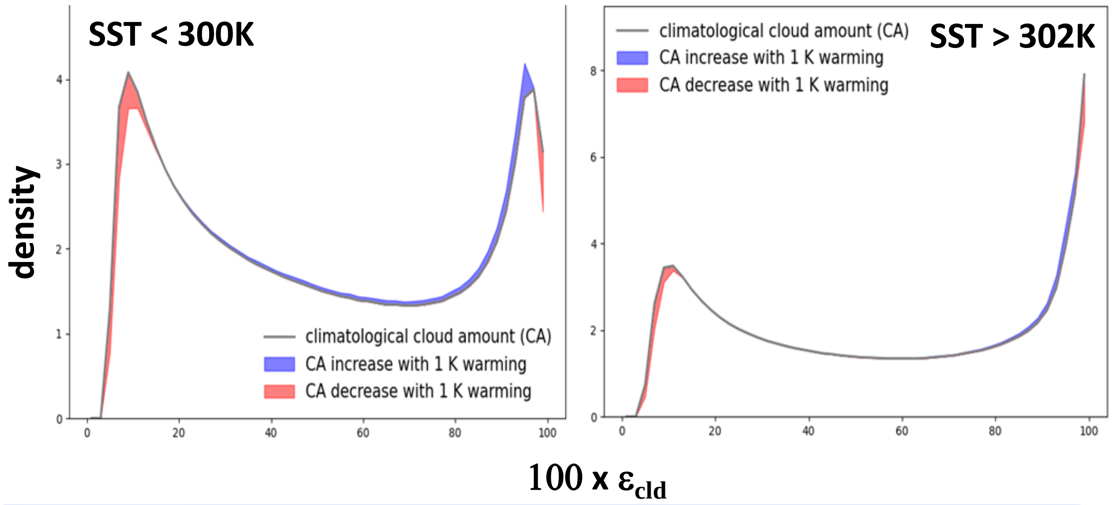
tropical UT cloud emissivity distribution is shifting:
very thin & very thick UT clouds decrease towards middle

Changes in UT cloud types: cool & warm regions

- Do opaque clouds thin out or do convective towers / thick anvils shrink ?
- Get very thin Ci thicker or do they disappear ?
- Where is this happening ?

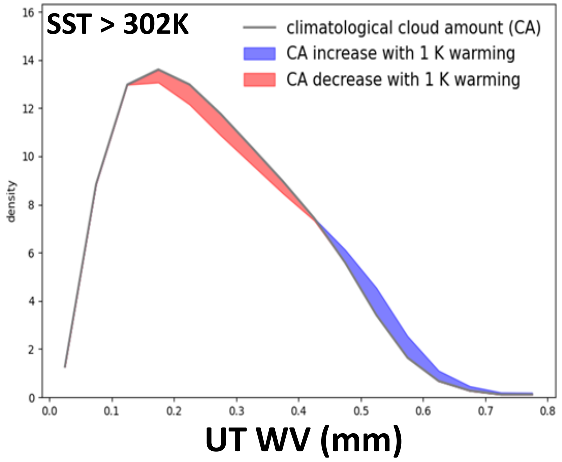
30N30S, AIRS-CIRSera5 2004-2023

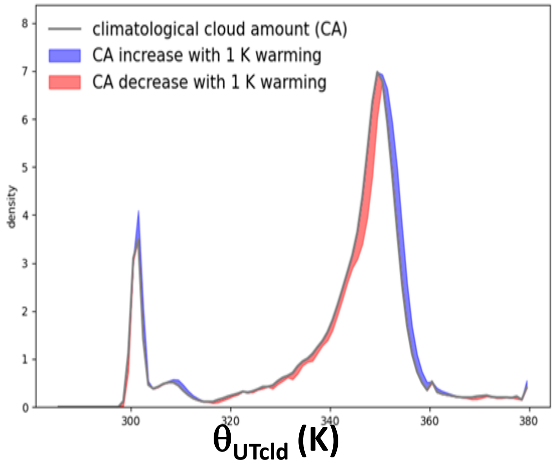
UT cloud changes similar in cool & warm regions



Cb -> clouds of slightly smaller ε_{cld} :
- ➢ **smaller, more intense convective cells ?**

UT WV & θ_{UTcld} shift towards larger values in warm regions





Increase in θ_{UTcld} :
- ➢ UT cloud tops lifted higher
- ➢ **enhanced convection** (as T_{UTcld} slightly warms)

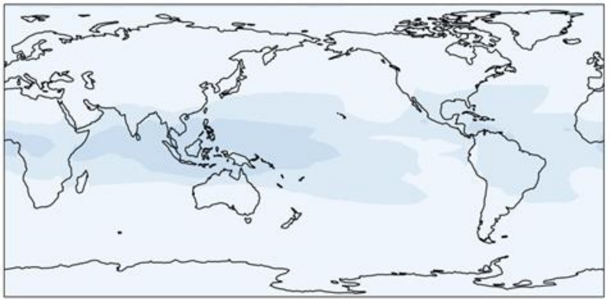
Geographical changes in UT cloud type occurrence

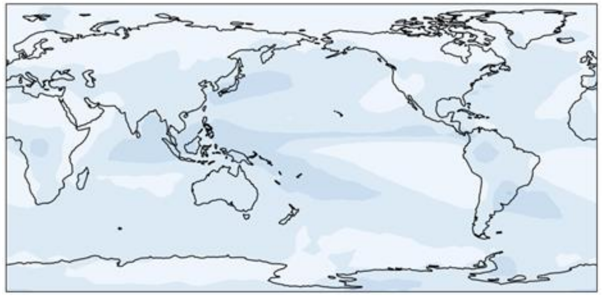
30N30S, AIRS-CIRSera5 2004-2023

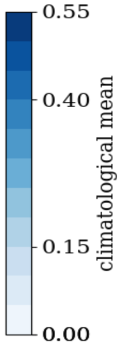
very thin | very thick

UT cloud occurrence

0.05 < ε_{cld} < 0.20 | **0.95 < ε_{cld}**

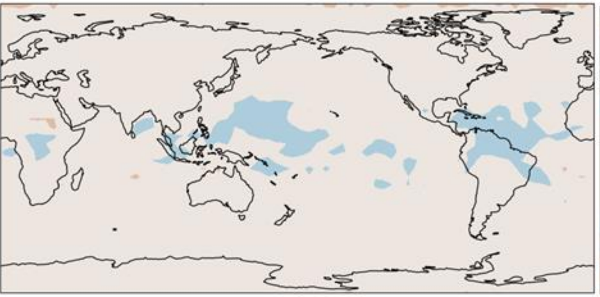


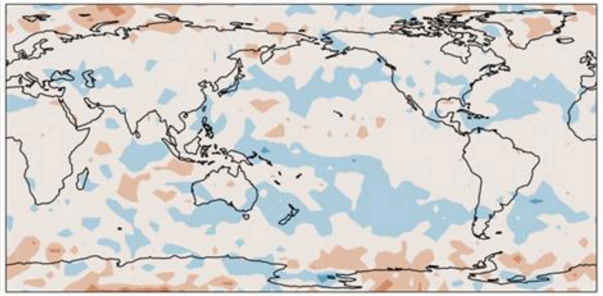


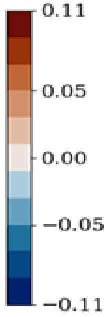


UT cloud changes / 1K

0.05 < ε_{cld} < 0.20 | **0.95 < ε_{cld}**







- very thin UT clouds decrease in regions of deep convection
- ITCZ with very thick UT clouds seems to narrow

Synergistic dataset to describe UT cloud systems

3D / 4D

Colocation reduces the combined dataset to overlap of individual datasets

↓

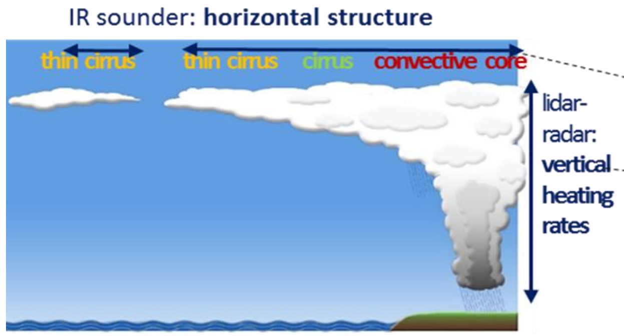
use ANN regression / classification for expansion

Artificial Neural Network

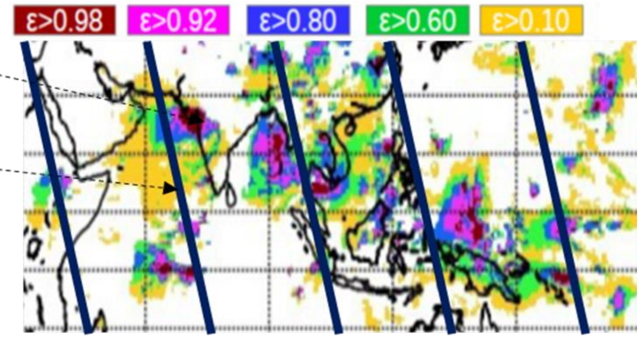
in space & time

3D snapshot reconstruction using synergistic data & Machine Learning

add heating rates & precipitation



emissivity structure of UT cloud systems



rad. heating & precipitation:

CloudSat-lidar on ***narrow nadir tracks***

Latent Heating: **LT within 20 min of 1h30 AM**

TRMM radar : ***small coverage at specific LT***

expand vertical structure & precipitation across AIRS / IASI swaths via ANN:

1) develop regression & classification models,

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 *(2004-2018)*

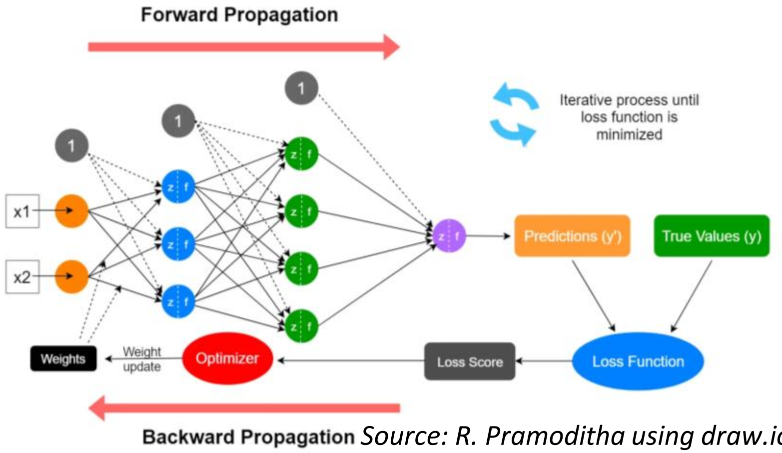
use derived atmospheric properties *(similar for AIRS & IASI)* **:**

X : CIRS cloud variables & ERA-Interim atmosphere, surface

F(X) : CloudSat-lidar radiative heating rates, Z_{top} & Z_{top}-Z_{base}, cloud layering, rain rate

from *NASA* *FLXHR v4* *GEOPROF,* *PRECIP-column*

TRMM latent heating rates from *NASA SLH v6*



Source: R. Pramoditha using draw.io

snapshots of horizontal structures

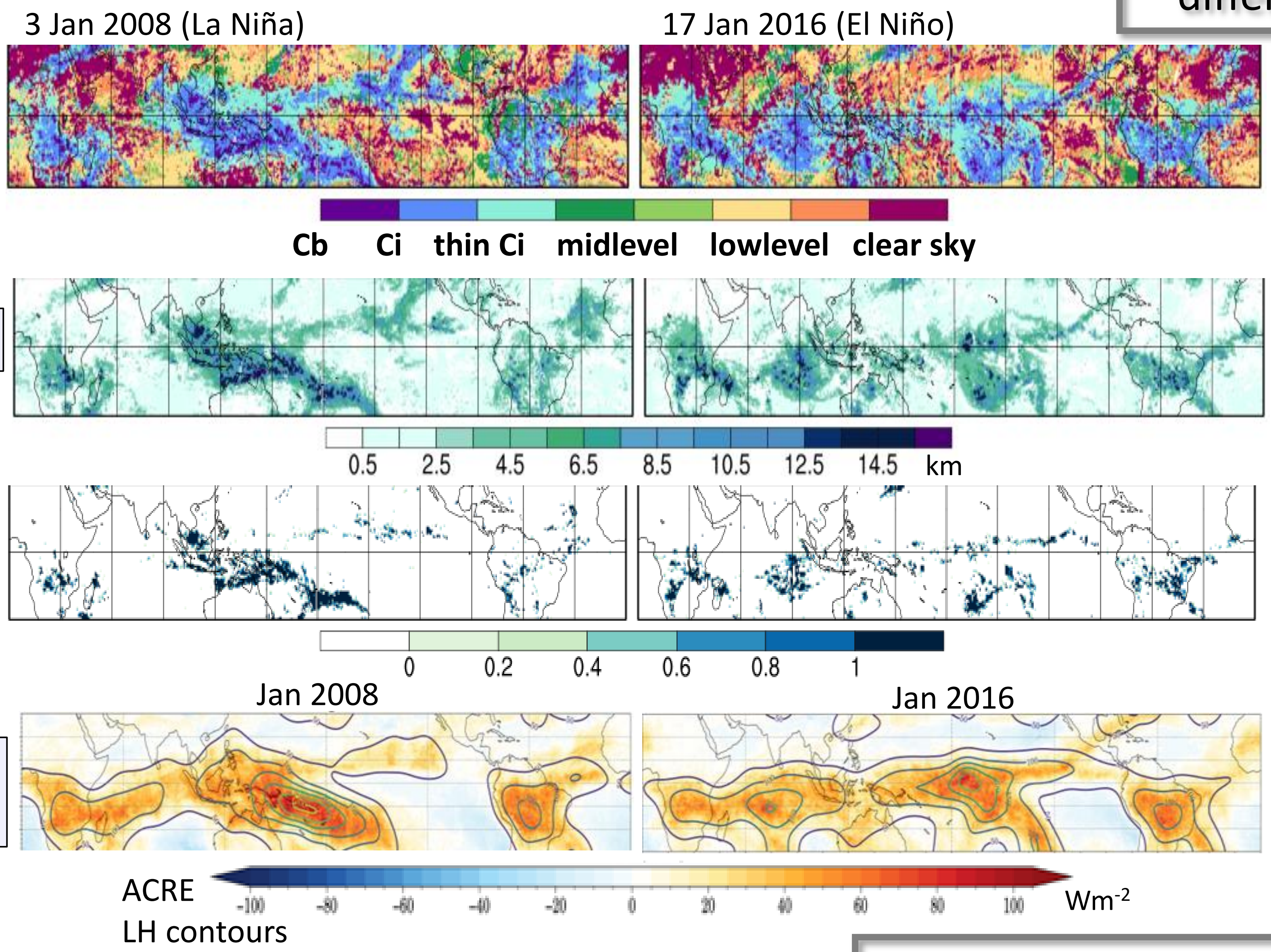
different for La Niña - El Niño

cloud type

vertical extent

RainRate > 0 fraction

radiative & latent heating



ANN

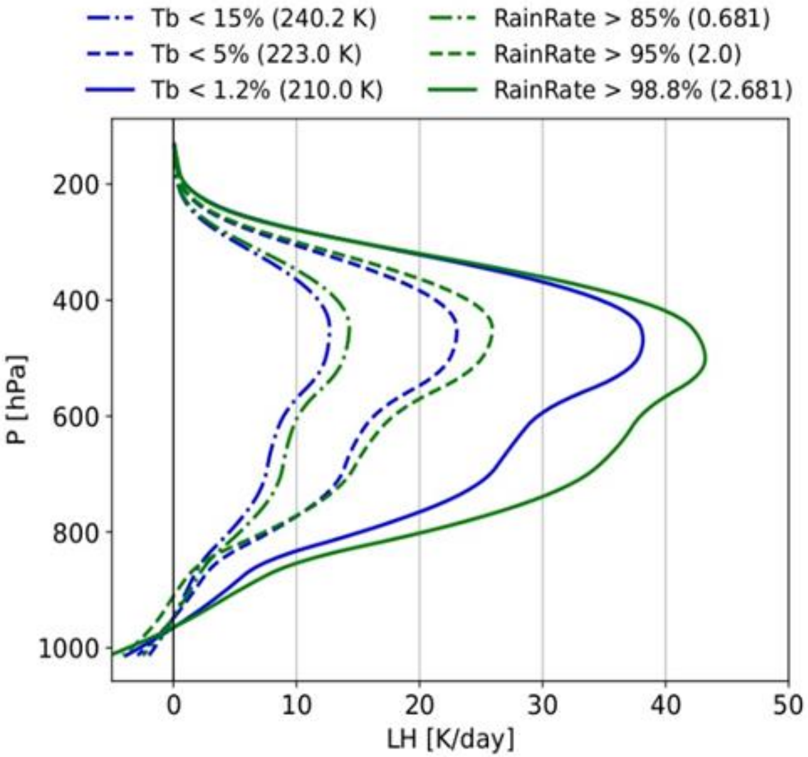
vertically integrated LH & ACRE well aligned !

Stubenrauch et al. ACP 2023

Tropical deep convective organization

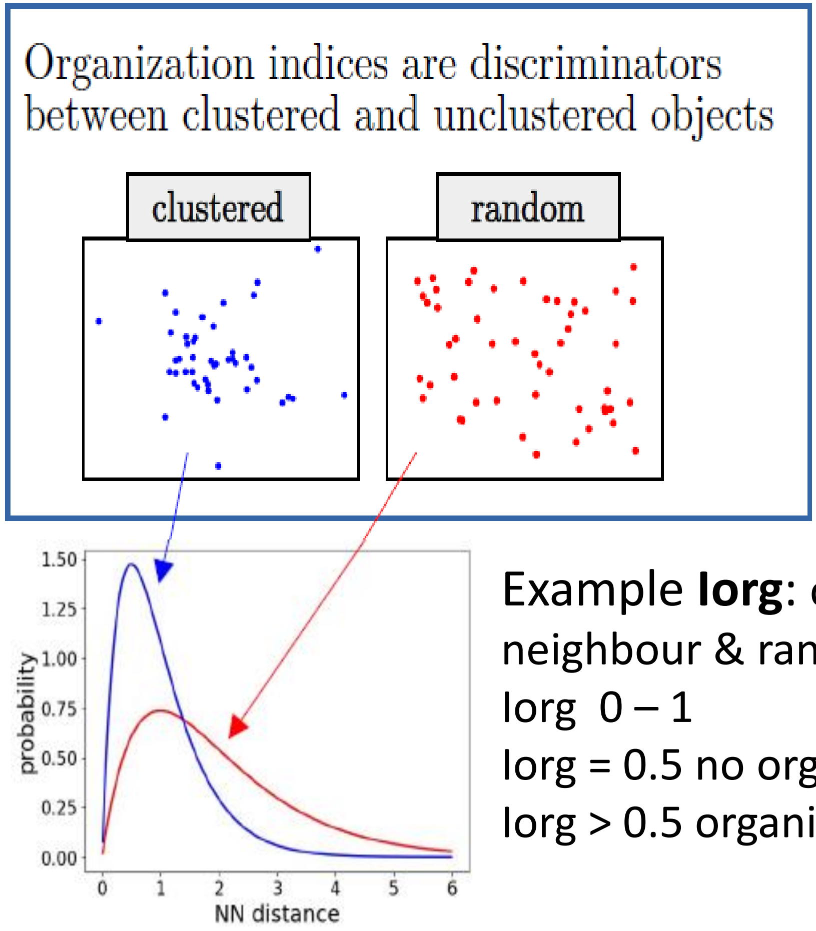
derived from spatial distribution of convective objects

1) How to define convective objects



ML rainrate classification more powerful to identify large LH than T_B^{IR}!

2) How to define organization metrics



Indices:

Iorg (Tompkins et al. 2017)

ROME (Retsch et al. 2020)

COP (White et al. 2018)

SCAI (Tobin et al. 2013)

Example **Iorg**: considers : cumulative nearest neighbour & random distribution

Iorg 0 – 1

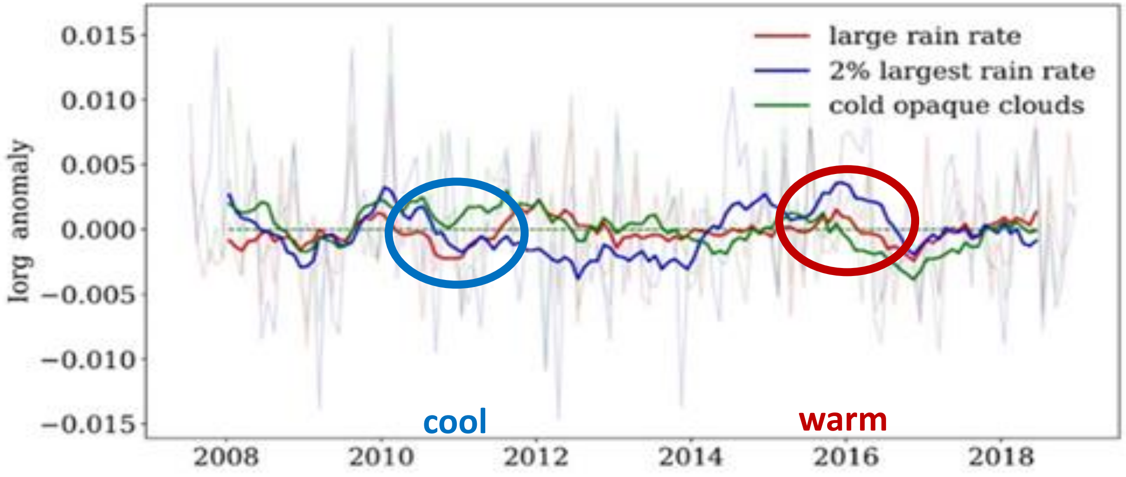
Iorg = 0.5 no organization

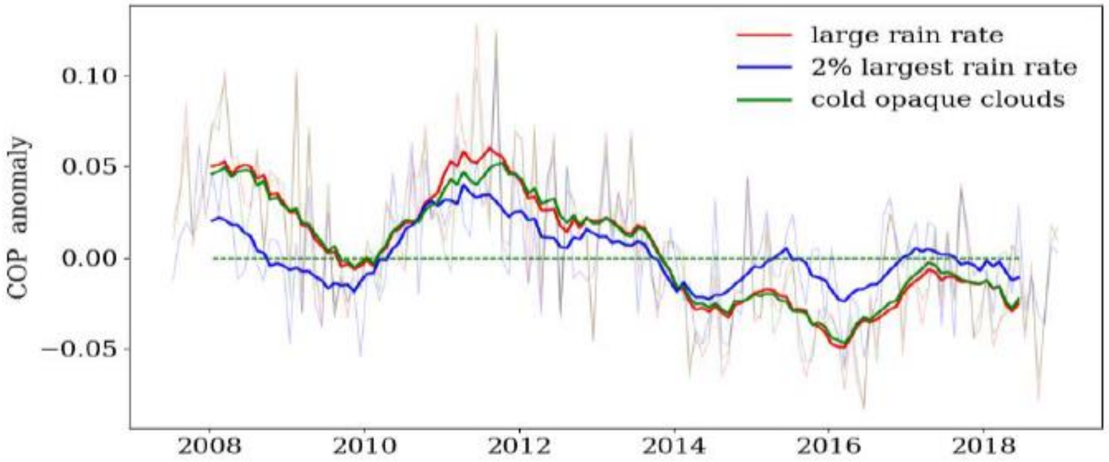
Iorg > 0.5 organization

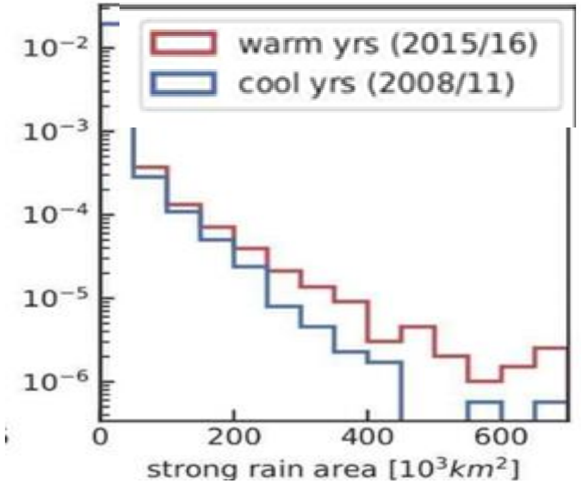
Inter-annual variability of tropical deep convective organization

convective organization not easy to quantify

Stubenrauch et al. ACP 2023







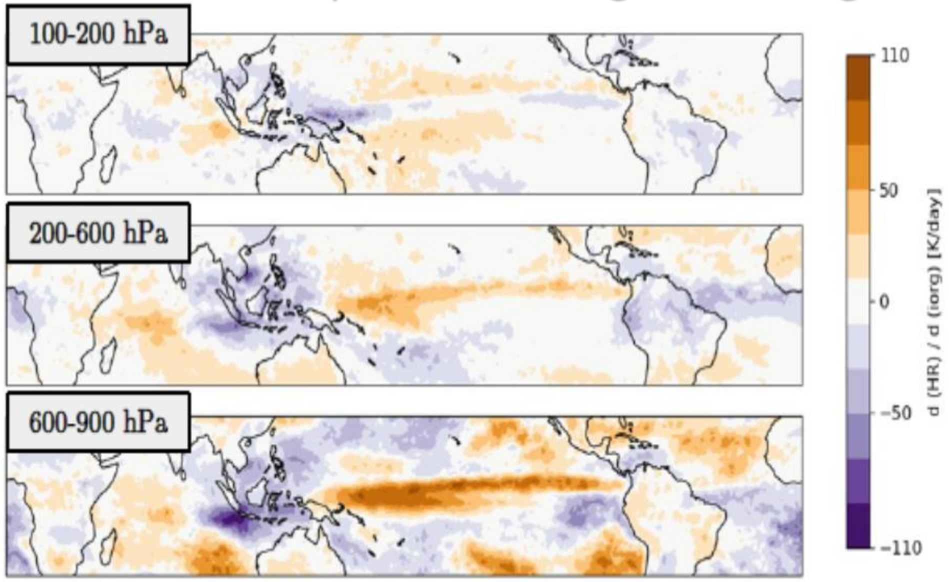
Size distribution of strong rain areas a better proxy ?

systematic assessment of indices:

Mandorli & Stubenrauch GMD 2024

DOI:10.5194/gmd-17-7795-2024

ACRE pattern changes wrt Iorg



Inter-annual variability of indices not coherent: *signal too small*

Pattern changes in ACRE wrt indices may be more robust

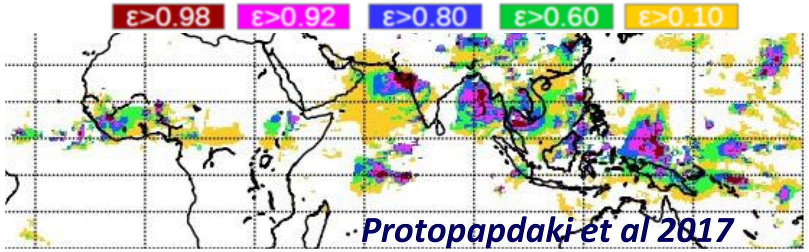
(large signals, similar to ENSO)

& single index to describe convective organization may not be sufficent

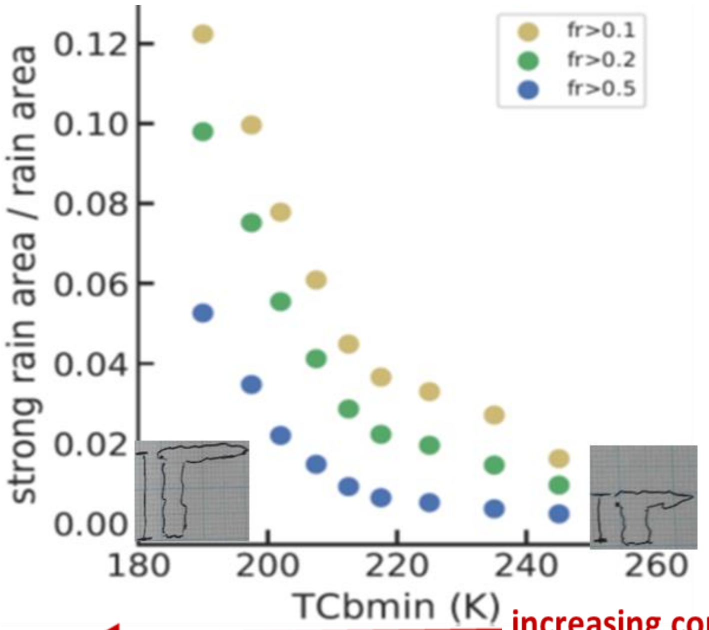
Process-oriented behaviour of mesoscale convective cloud systems

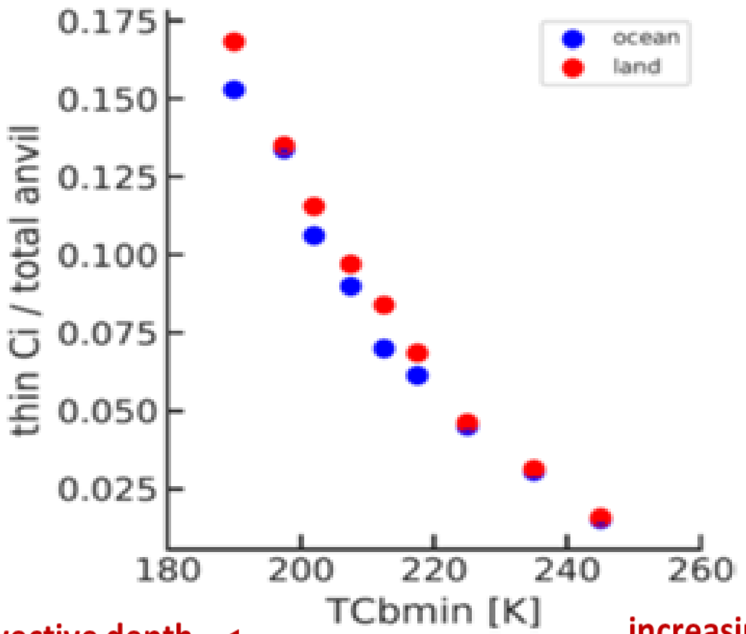
Stubenrauch et al. ACP 2023
Stubenrauch et al. JAMES 2019

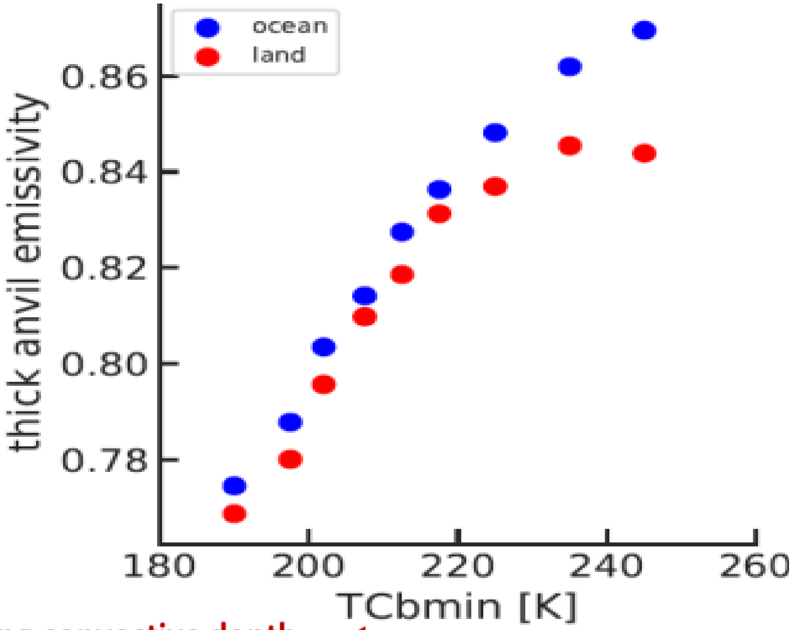
Eulerian Cloud System Concept using p_{cld} & ε_{cld}



proxy for convective depth: min T within core of mature systems
Mature MCSs: convective core fraction 0.2-0.4







increasing convective depth

increasing convective depth

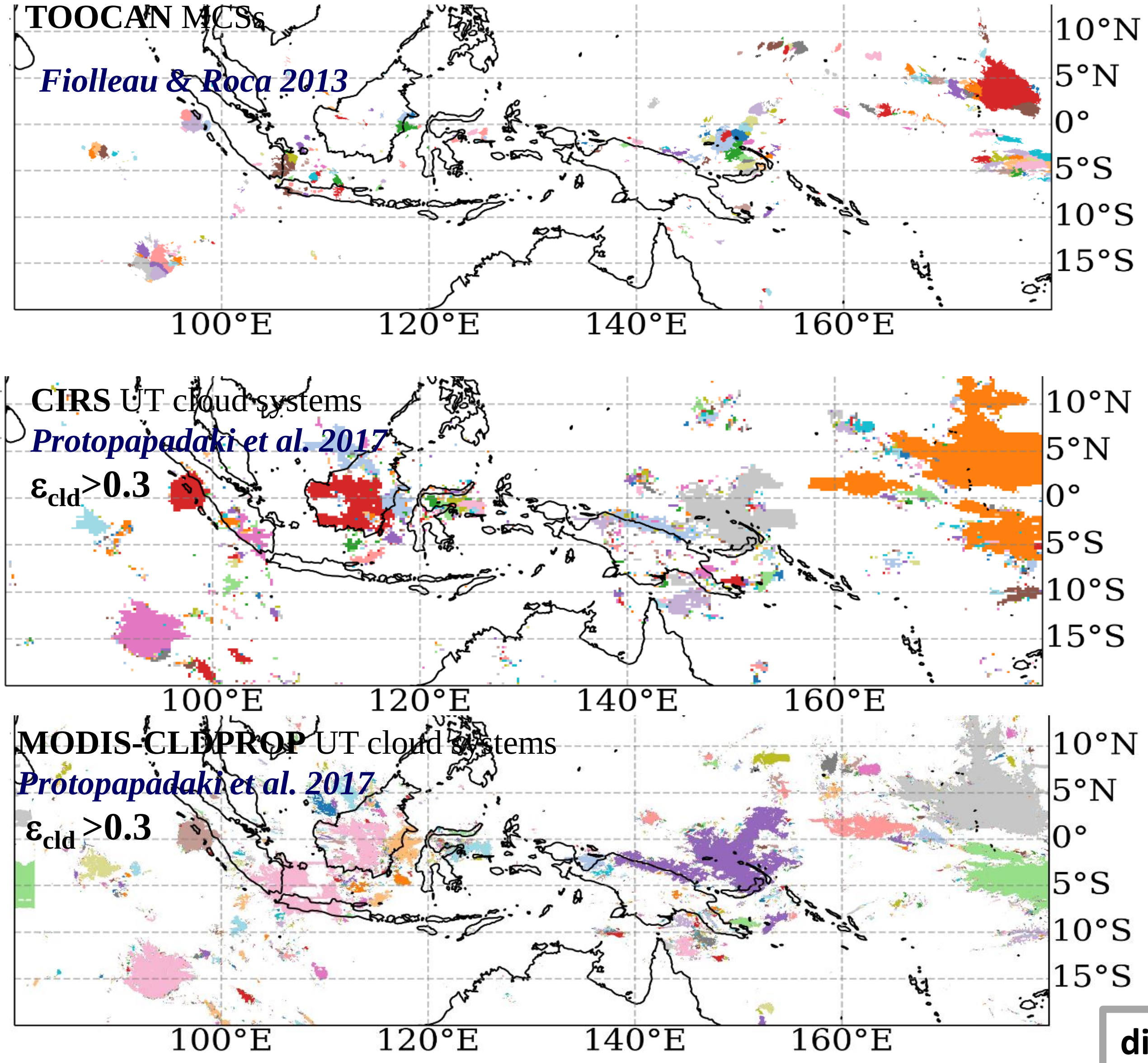
Deeper convection leads to:

larger heavy rain areas | larger areas of surrounding thin Ci | slightly thinner anvils

CIRS-ML Synergy with Lagrangian convection tracking

combine MCSs from tracking to anvil properties

Snapshot at 1:30PM , 4 Jan 2016



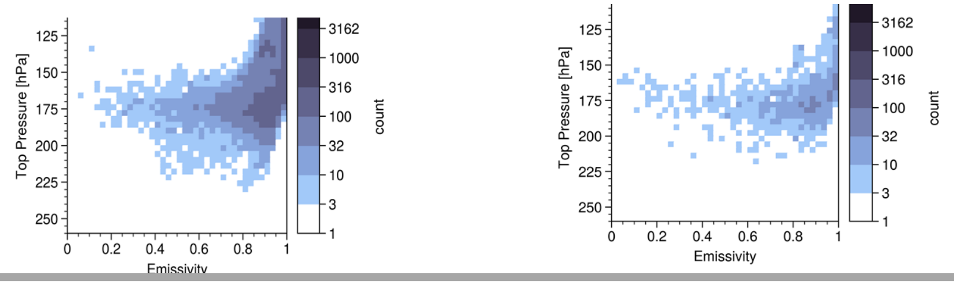
How is Cirrus & its heating related to deep convection & its organization ?

***TOOCAN**: cold mesoscale convective systems*
fine spatial & temporal resolution
tracking yields life time & stage, maturity size

-> cold T_B (& precipitation) tracking miss anvil parts

***CIRS-ML**: large envelopes of UT cloud systems with additional information (HR, LH, thin Ci & anvil properties)*

***MODIS**: much better spatial resolution than CIRS: still large envelopes of UT cloud systems !*



dissipating stage: *long-living MCSs* thicker & higher than *short-living MCSs*

Conclusions & Outlook

- **Synergy of different satellite instruments provides a more complete picture of clouds**
- **complete 3D snapshots & longer time series by ML (CIRS-ML)**
  -> convective organization & process studies
- **Eulerian Cloud System Concept allows**
  - to study relationships between convection & anvils
  - process-oriented evaluation of GCM parameterizations
- **Synergy of UT cloud envelopes & Lagrangian MCS Concept adds life time & life stage**
  - to study relationship between convection & thinner parts of anvils
- **CIRS data recently reprocessed** *(changing ancillary data from ERA-Interim to ERA5)* **: 2003-2024**
  after evaluation will be distributed via *https://cirs.aeris-data.fr/*
- ***Data record shows interesting features in UT cloud changes***
- ***To reprocess the more complete CIRS-ML dataset, colocation and retraining of ANNs necessary***

CIRS-ML 3D cloud structure dataset distributed at *https://gewex-utcc-proes.aeris-data/fr/data*

2004-2018: on AIRS swath at 1:30 AM & PM, spatial resolution of 0.5°, netCDF format

general

UTC time
T_{surf}
p_{surf}
solar zenith
$p_{tropopause}$

CIRS cloud retrieval

T_{cld}
p_{cld}
ε_{cld}
most frequent scene:
UT cld, mid-low cld, clr sky
cld type fractions:
Cb, Ci, thin Ci, mid-low

Stubenrauch et al. ACP 2017

vertical structure

z_{cldtop}
$z_{cldtop} - z_{cldbase}$
for each cld type

Rain Rate classification

Rain Rate indicator
fractions of
no, light, heavy rain

radiative heating

SW heating rate
LW heating rate
at 22 pressure levels

clr sky monthly mean
SW heating rate
LW heating rate
at 22 pressure levels

CIRS-ML trained on CloudSat-CALIPSO GEOPROF, PRECIP-column & FLXHR

Stubenrauch et al. ACP 2023

Stubenrauch et al. ACP 2021

TOOCAN Tracking of organized convection (> 2012) at ***https://toocan.ipsl.fr/***

Fiolleau & Roca 2013

Discussion points for complete 3D / 4D description of UT cloud systems

- Colocation: which data should be taken, in particular for radiative heating rates ?

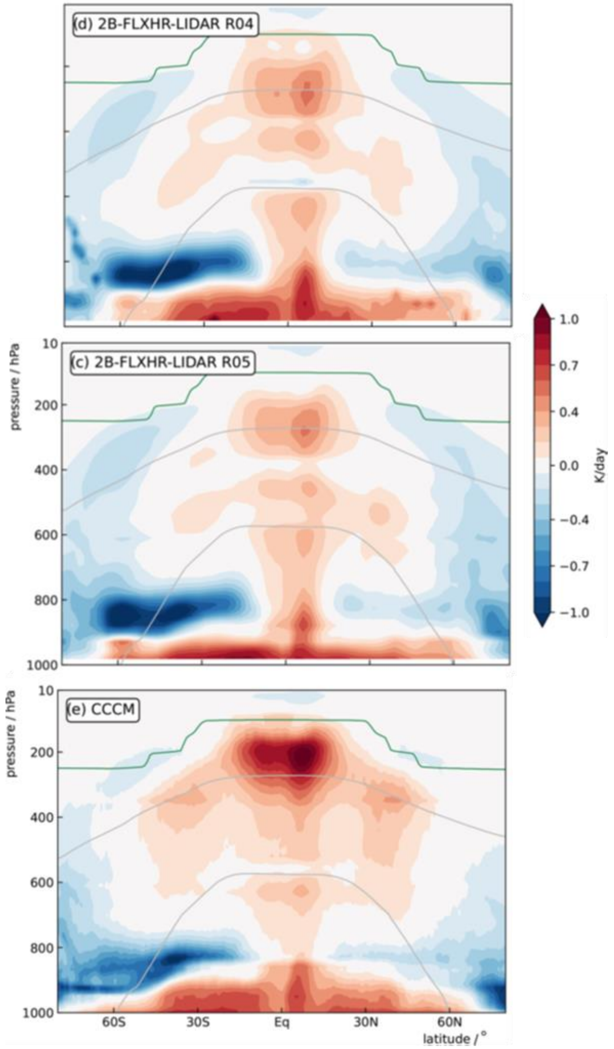
- ANN prediction good for means, but not for extremes:
  are there better methods to combine with latent heating ?

- Cloud system data: would this dataset be useful to distribute?

- AIRS data drifting *(2:30AM/PM in Jan 2025)* & will end in 2026
  similar ANN approach with other cloud data ?
  ISCCP-NG + EarthCare + GPM + … ?

GEO-RING of advanced multi-spectral imagers since 2018

CloudSat-CALIPSO observations



Voigt et al. 2024

DOI: 10.5194/acp-24-9749-2024