Cloud properties from IR Sounders (AIRS – IASI): Synergies & Climate applications

Claudia Stubenrauch

Laboratoire de Météorologie Dynamique / IPSL, France

with contributions of A. Feofilov, S. Protopapadaki, G. Caria & GEWEX CA team

NASA Sounder Science Team meeting, 5 Oct 2020

Outline

- cloud properties from satellite observations (GEWEX Cloud Assessment)
- CIRS retrieval : clouds from IR Sounders
- diurnal cycle of UT clouds *(AIRS – IASI synergy)*
- UT cloud system approach:
  -> anvil properties – convection – environment
- vertical structure of UT cloud systems & environment
  (AIRS-CALIPSO-CloudSat synergy & machine learning)
  -> atmospheric radiative heating effects
- conclusions & outlook

Stubenrauch, C. J., Caria, G., Protopapadaki, S. E., and Hemmer, F.: **3D Radiative Heating of Tropical Upper Tropospheric Cloud Systems derived from Synergistic A-Train Observations and Machine Learning**, Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2020-613, in review, 2020

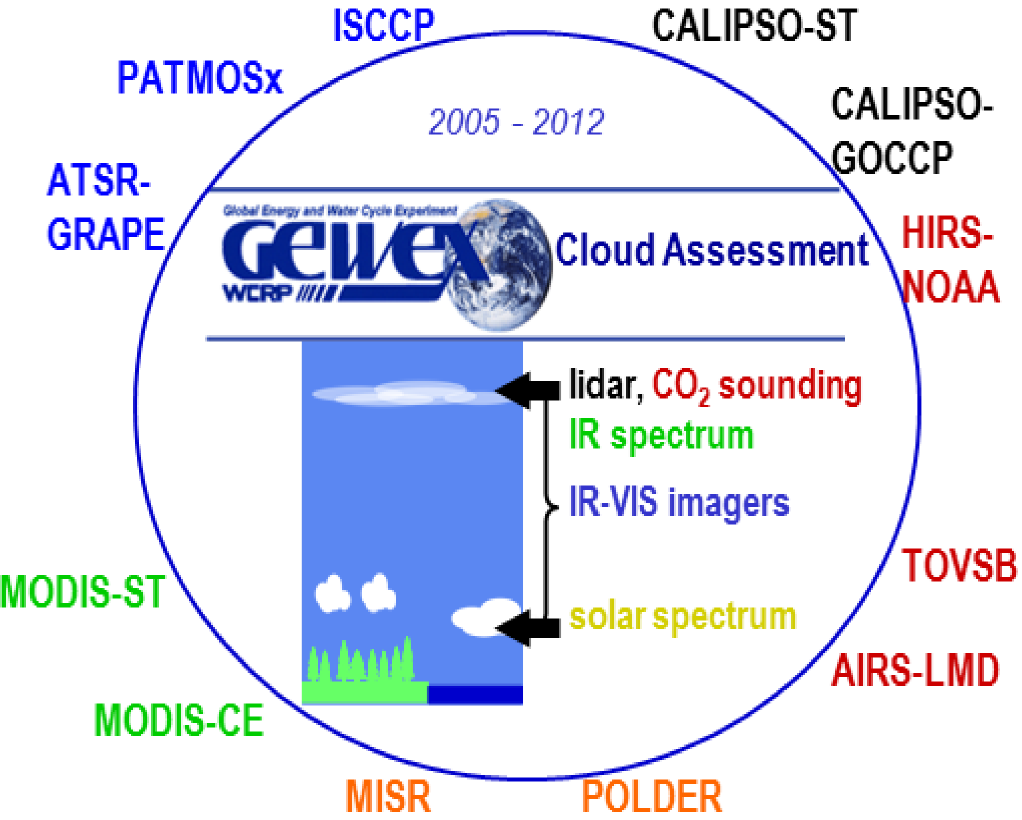
Protopapadaki, E.-S., Stubenrauch, C. J., and Feofilov, A. G., **Upper Tropospheric cloud Systems derived from IR Sounders: Properties of Cirrus Anvils in the Tropics**, Atmosph. Chem. Phys., 17, 3845-3859, doi:10.5194/acp-17-3845-2017, 2017

Feofilov, A. G. and Stubenrauch, C. J., **Diurnal variation of high-level clouds from the synergy of AIRS and IASI space-borne infrared sounders**, Atmos. Chem. Phys., 19, 13957-13972, doi:10.5194/acp-19-13957-2019, 2019

Stubenrauch, C. J., Feofilov, A. G., Protopapadaki, E.-S., & Armante, R.: **Cloud climatologies from the InfraRed Sounders AIRS and IASI: Strengths and Applications**, Atmosph. Chem. Phys., 17, 13625-13644, doi:10.5194/acp-17-13625-2017, 2017

Stubenrauch, C. J., & 21 co-authors: **Assessment of Global Cloud Datasets from Satellites: Project and Database initiated by the GEWEX Radiation Panel**, Bull. Amer. Meteor. Soc., doi:10.1175/BAMS-D-12-00117.1, 2013

Cloud properties from space



active **lidar – radar** : vertical cloud structure

passive **IR-NIR-VIS Radiometers**,

IR Sounders, **VIS-SWIR Radiometers**

exploit different parts of EM spectrum:

How does this affect

climatic averages & distributions?

Stubenrauch et al., WCRP report 2012, BAMS 2013

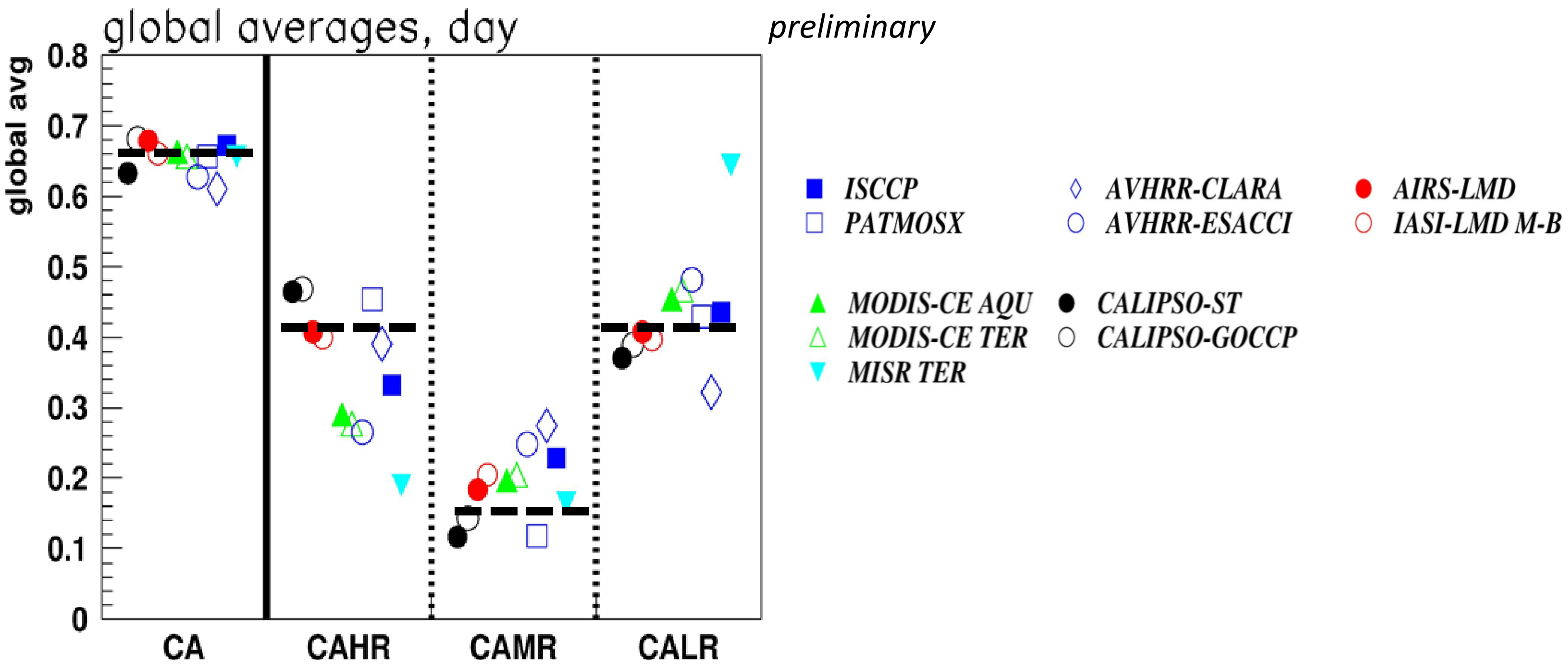
http://climserv.ipsl.polytechnique.fr/gewexca
Data archive until 2009

Update of database in 2020:
https://gewexca.aeris-data.fr/

- **Passive remote sensing: only information on uppermost cloud layers**
- **'radiative' cloud height** (middle or middle between top & height at which cloud reaches opacity)
- **perception of cloud scenes depends on instrument** (IR – VIS spectrum)

=> cloud property accuracy scene dependent :
most difficult scenes: thin Ci overlying low clouds, low contrast with surface thin Ci, low cld, polar regions

Cloud Assessment update: rel. CA stratified by height



results similar to GEWEX Cloud Assessment:

CA: 0.68 ± 0.03

40% are high clouds & 40% single-layer low-level clouds

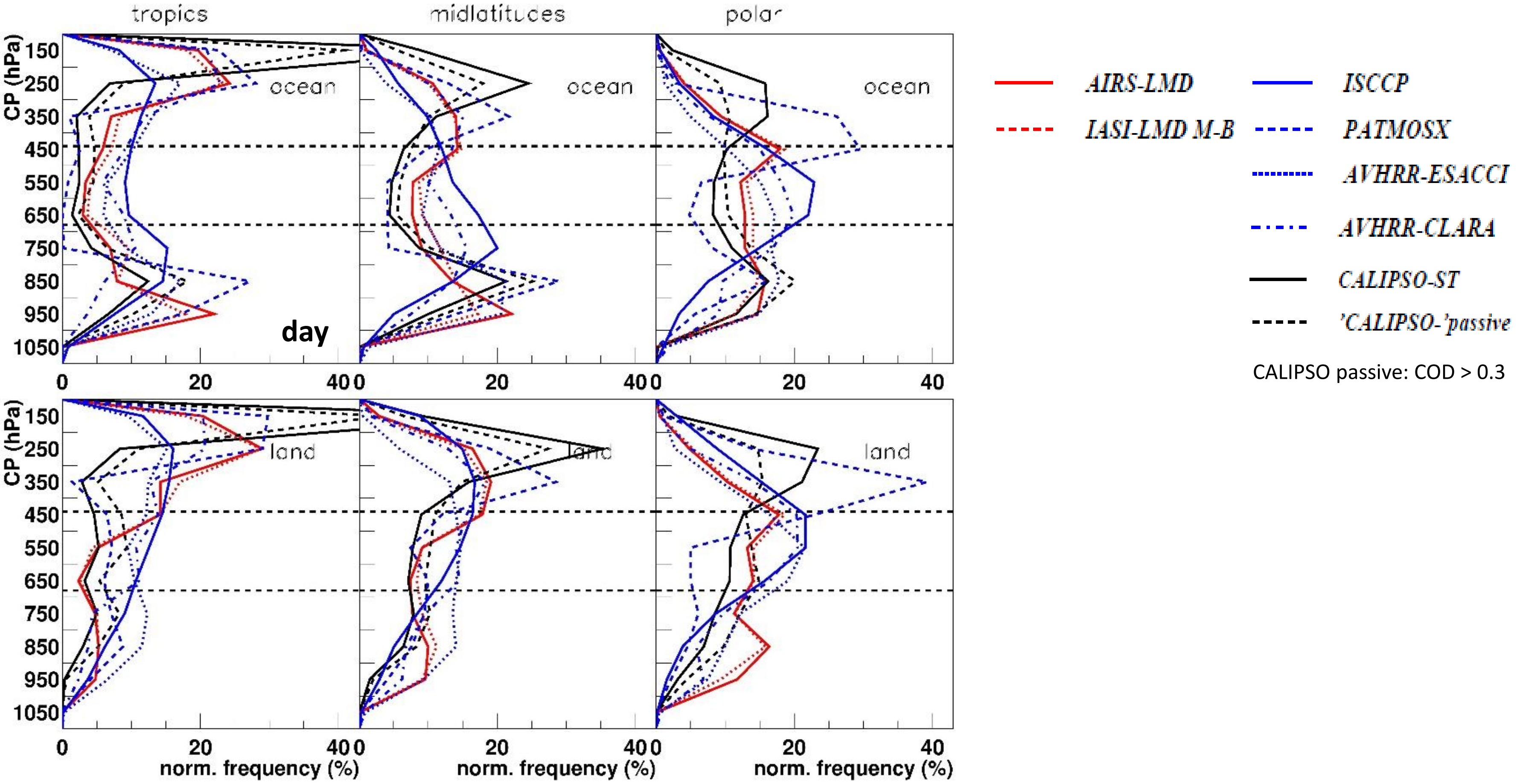
- **sensitivity to thin cirrus decreases from**
  lidar – IR Sounders – IR spectral difference –VIS only

  VIS only : sensitive to cirrus with COD>2 (MISR)

-> CALR also includes clouds obscured by cirrus with COD < 2

[CAM+CAL](MISR) = [CAM+CAL](CALIPSO-ST_COLUMN)

Cloud Pressure histograms



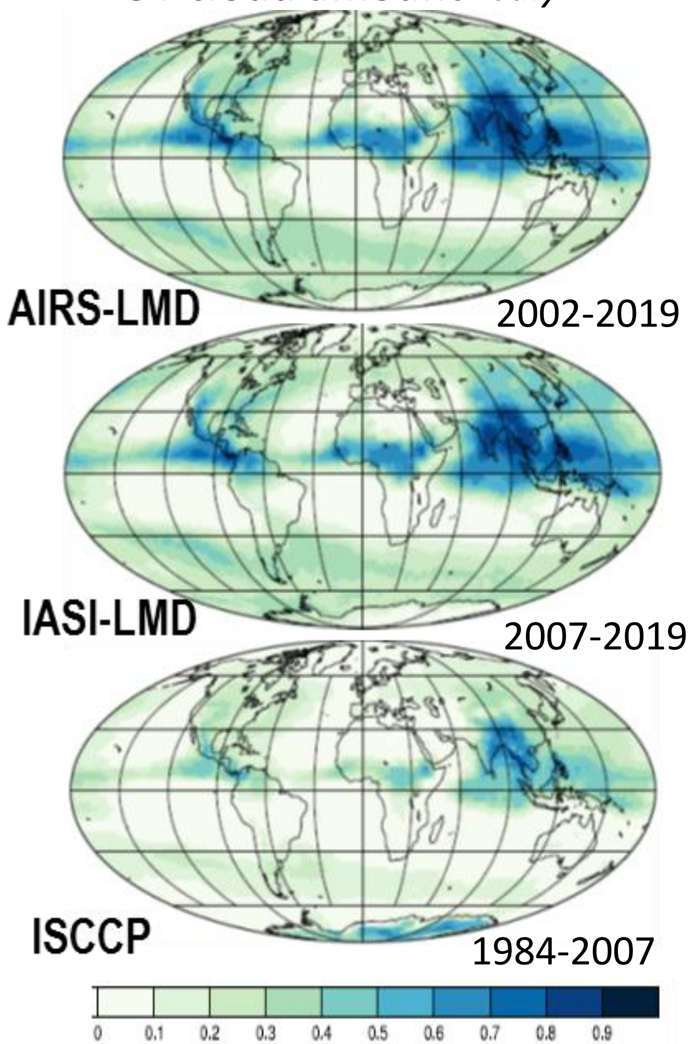
- Only CALIPSO provides cloud top height -> p_{cld}(CALIPSO) < p_{cld}(passive)
- Bimodal p_{cld} distributions, esp. over tropical ocean; less low clouds over land
- rel. good agreement AIRS / IASI & PATMOSX & CALIPSO
- ISCCP misses high clouds; low clouds higher than those of other datasets
- New datasets (ESACCI & AVHRR-CLARA) need still some refinement
  (misidentification of high clouds & of low clouds , respectively, as midlevel clouds)

Cloud retrieval from IR Sounders (CIRS)

Stubenrauch et al., J. Clim. 1999, 2006; ACP 2010, ACP 2017

HIRS	AIRS, CrIS	IASI (1,2,3), IASI-NG
>1979 : 7:30/ 1:30 AM/PM	≥2002 / ≥ 2012 : 1:30 AM/PM	≥2006 / ≥ 2012 / ≥ 2020 : 9:30 AM/PM

UT cloud amount *July*



from GEWEX Cloud Assessment Database

- **good IR spectral resolution -> sensitive to cirrus**

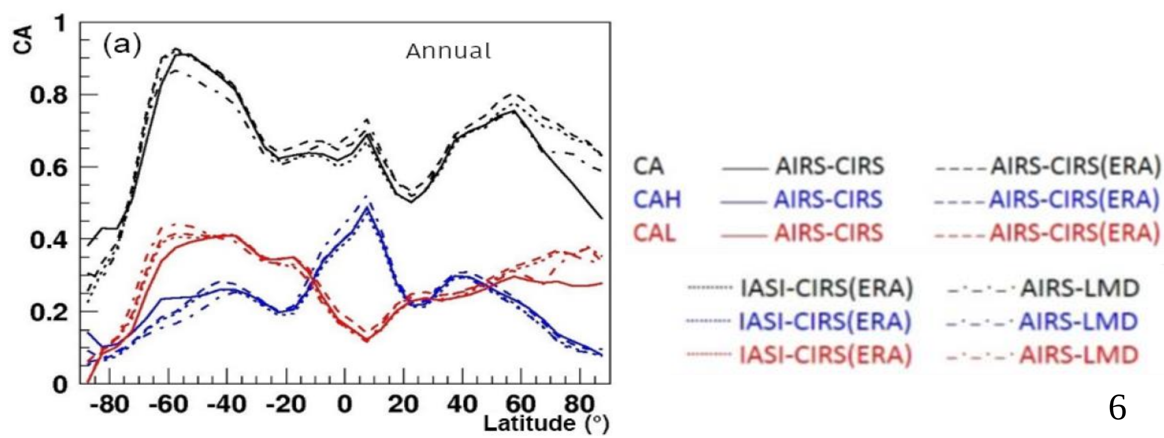
similar performance day & night, COD_{vis} > 0.2, also above low clouds

- ε_{cld}, p_{cld} from min χ^2 (8 CO_2 channels) + T_{cld}, z_{cld} + uncertainties
- a posteriori cloud detection (spectral $\boldsymbol{\varepsilon_{cld}}$ coherence); ε_{cld} > 0.1
- evaluation for AIRS with CALIPSO-CloudSat
- AIRS / IASI common ancillary data *(ERA-Interim)*
- **CIRS can be easily adapted to any IR Sounder**

effect of ancillary data on cloud properties:

- *small effect between NASA AIRS and ERA-Interim*

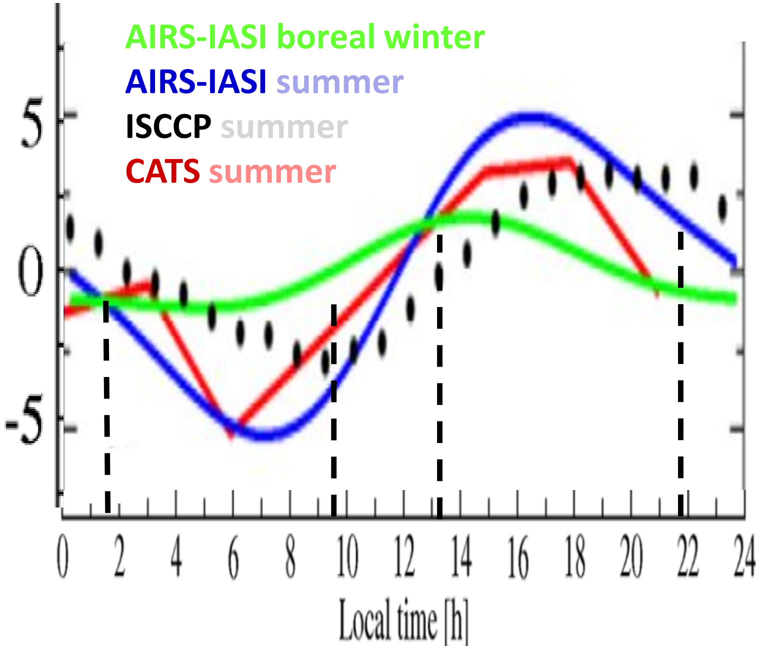
CAL is more affected than CAH (linked to T_{surf})

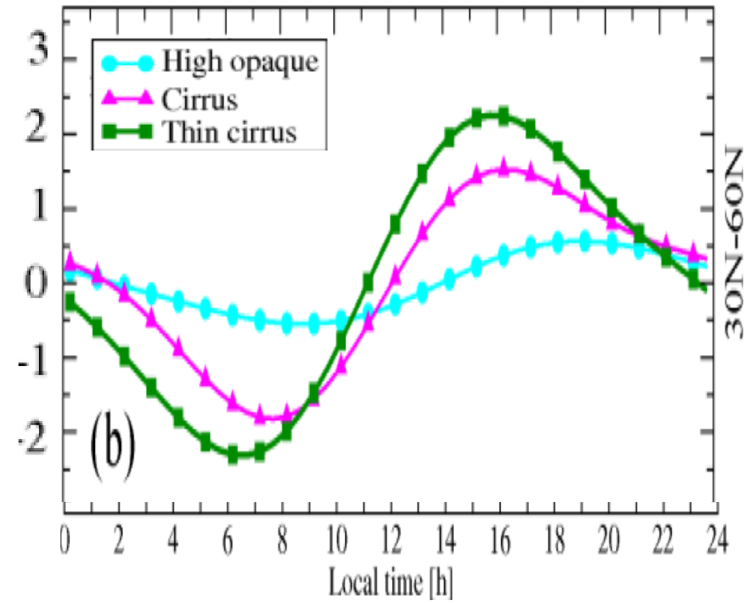


Diurnal cycle of UT clouds:
good temporal resolution vs sensitivity / day-night coherence

NH midlatitudes land during summer

Feofilov & Stubenrauch ACP 2019





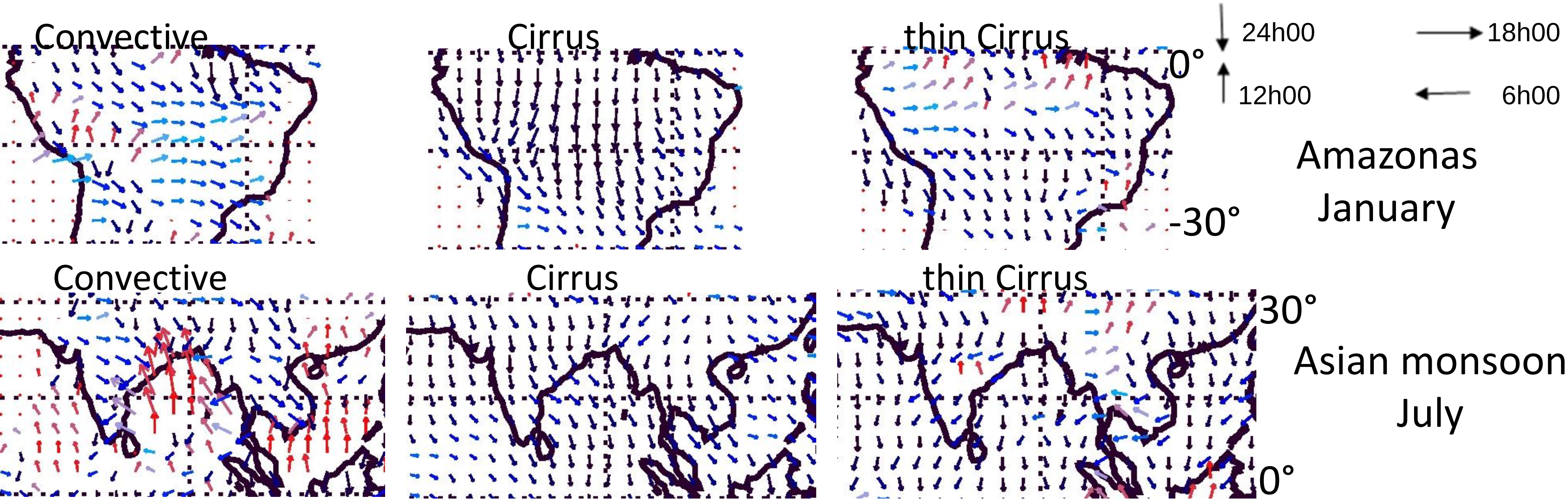
- IR sounders ≈ CATS *Noël et al. ACP 2018*

- ISCCP is driven towards the diurnal cycle of optically thicker clouds
- For process studies consider diurnal cycle of different cloud types

Diurnal cycle of UT cloud types in tropics

Use of same ancillary data necessary to get coherent diurnal cycle -> ERA-Interim

Database of mean amount, diurnal amplitude & peak time per cloud type, 1° x 1°, monthly, 2008-2015



Continents:

deep convection max in early evening

anvils (Cirrus) continue development during night

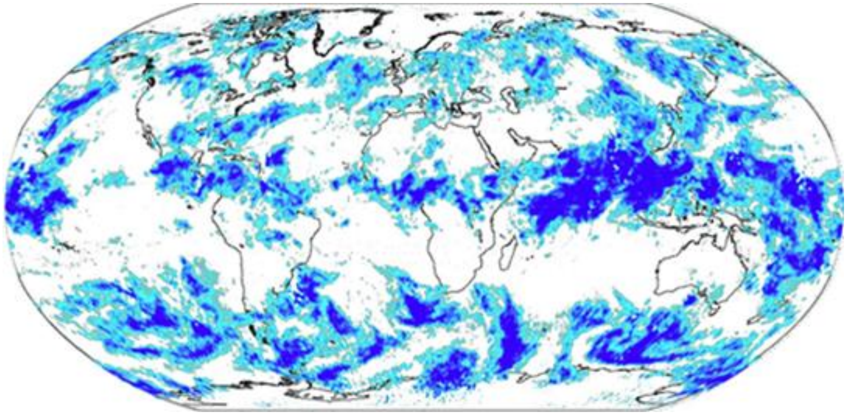
thin Cirrus different regimes, partly from dissipation of convective systems

Asian maritime:

convection around noon / cirrus evening / thin Cirrus night

UT clouds cover 30% of the Earth

& 40% of tropics



Snapshot AIRS-CIRS
UT clouds: dark -> light blue, according to decreasing ε_{cld}

UT clouds play a vital role in climate system by modulating Earth's energy budget & UT heat transport

They often form **mesoscale systems** extending over several hundred kilometres, as outflow of convective / frontal systems or in situ by large-scale forcing

Climate warming : change in convective intensity & coverage, height of convective systems & emissivity structure of the anvils ? This then affects the heating gradients!

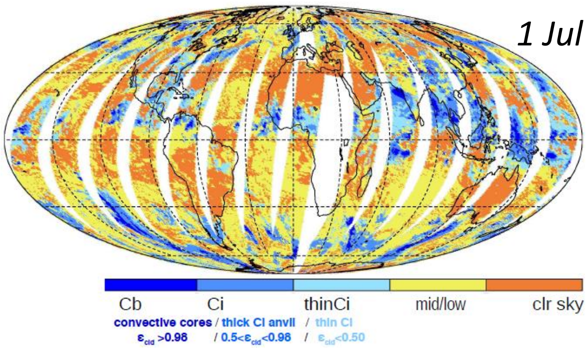
⬇

Goals: - understand relation between convection, cirrus anvils & radiative heating
- provide obs. based metrics to evaluate detrainment processes in models

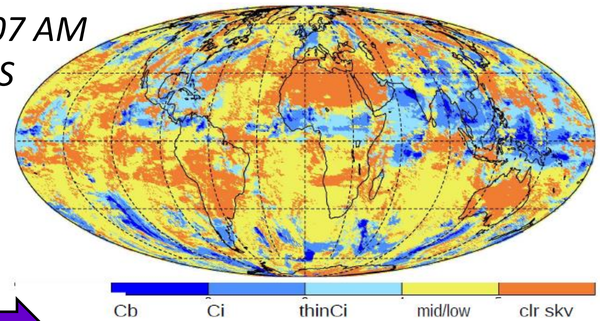
From cloud retrieval to cloud systems

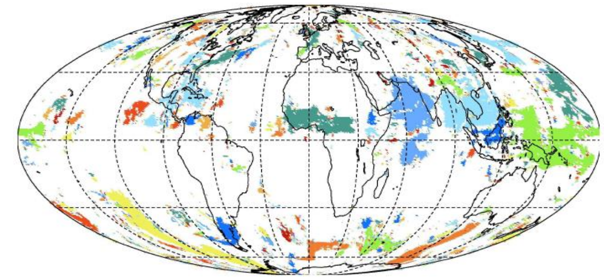
clouds are **extended objects**, driven by dynamics -> **organized systems**

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



1 Jul 2007 AM
AIRS



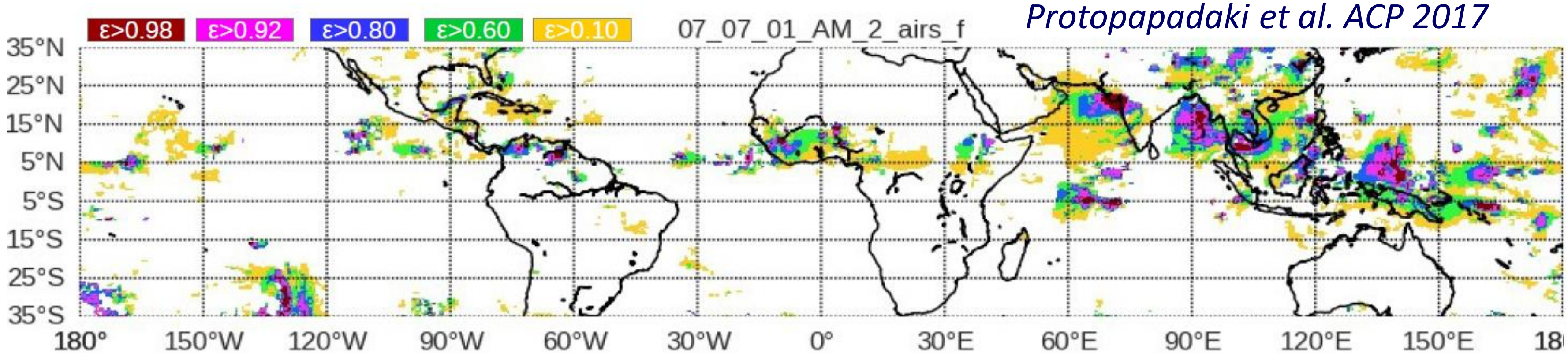


fill data gaps using PDF method

build UT cloud systems

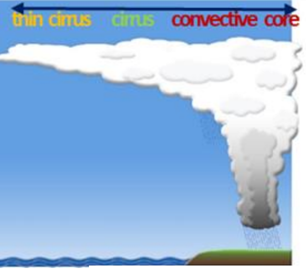
2) use ε_{cld} to distinguish convective core, thick cirrus, thin cirrus *(only IR sounder)*

Protopapadaki et al. ACP 2017

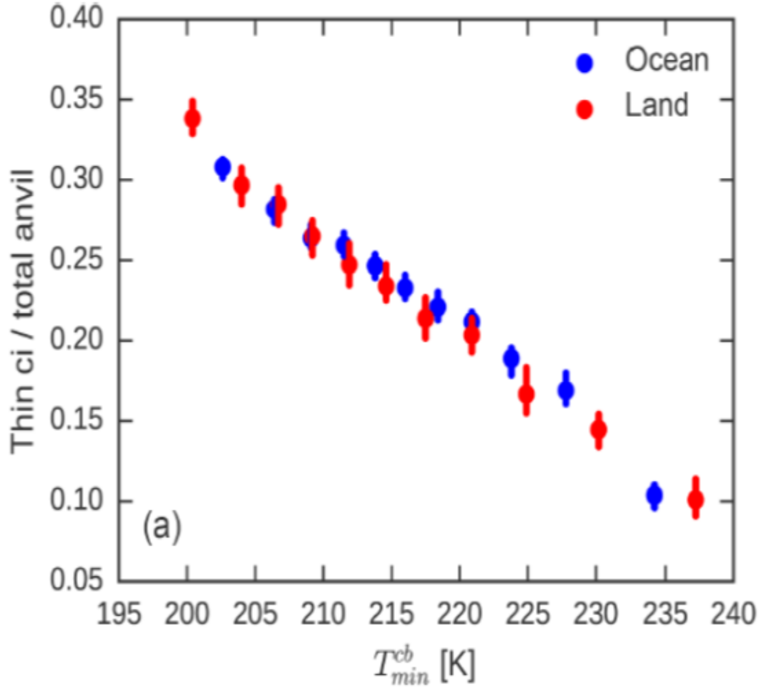


30N-30S: UT cloud systems cover 25%, those without convective core 5%
50% of these originate from convection *(Luo & Rossow 2004, Riihimaki et al. 2012)*

link anvil structure to convective depth



Protopapadaki et al. ACP 2017



15 years ***tropical mature convective cloud systems***;
convective core: ε_{cld}>0.98; fraction within system 0.1 – 0.3

Deeper convection leads to relatively more thin cirrus within & around larger anvils (similar land / ocean)

increasing convective depth

Why ?

H1: UT environmental predisposition (at higher altitude larger RH, T stratification)

H2: UT humidification from cirrus outflow

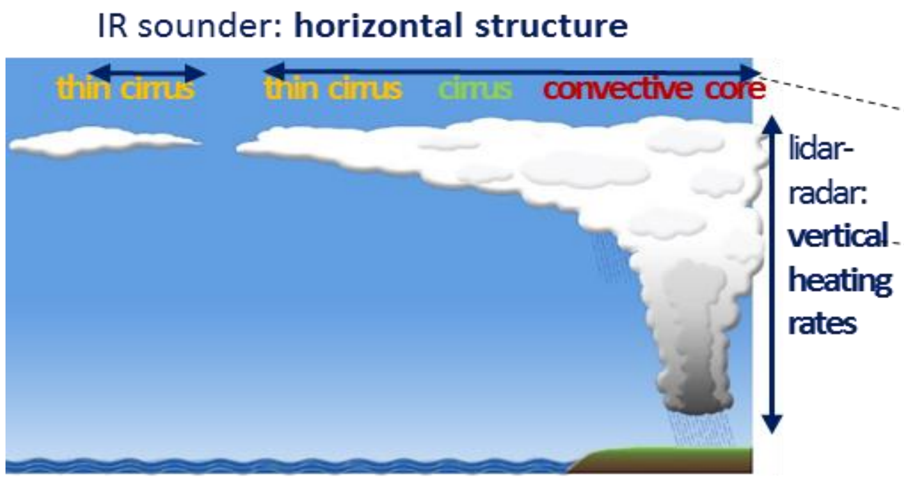
Does the relationship change in a warmer climate ?

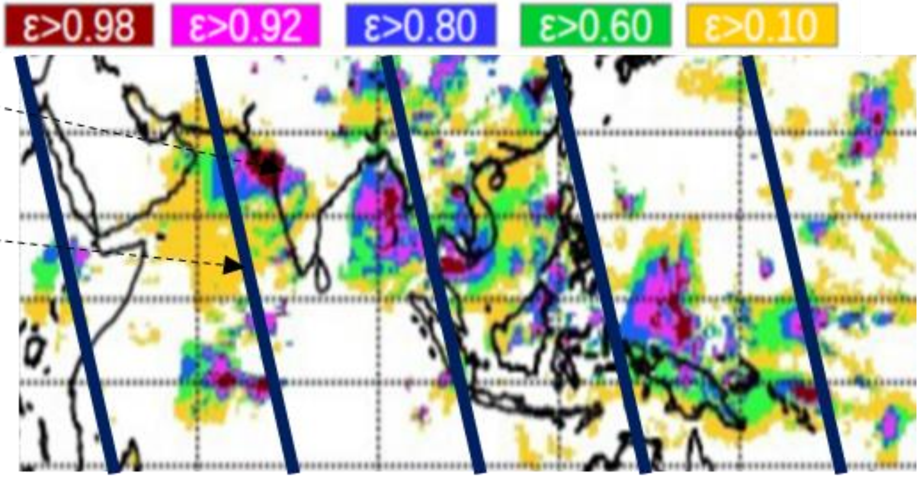
CRM

GCM

Goal: link anvil heating rates to convective depth

via a complete 3-D description of UT cloud systems & their environment





start from retrieved cloud properties:

CloudSat-CALIPSO nadir tracks: NASA vertical structure, radiative HR (FLXHR V4)

AIRS / IASI orbits: CIRS cloud properties

meteorological re-analyses: ERA-Interim atmospheric & surface properties

expand nadir track info across UT cloud systems & environment by machine learning:

1) develop optimized 'non-linear regression models',
which relate most suitable cloud, atmospheric & surface properties to HR,
by training neural networks on collocated data (2007-2010)

2) apply these models on the whole AIRS-CIRS data record (2003-2018)

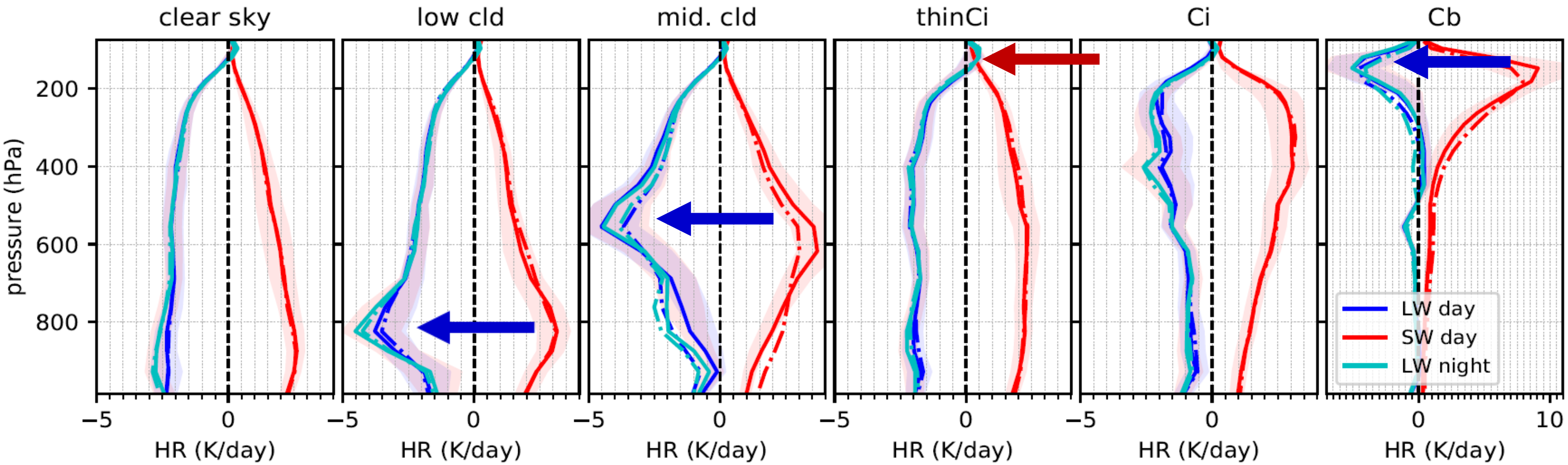
predicted radiative HRs over tropics (30N-30S)

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

scenes determined by AIRS

Stubenrauch et al. 2020

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)

radiative LW heating rates: specific layers

Example: Jan 2008 (La Niña)

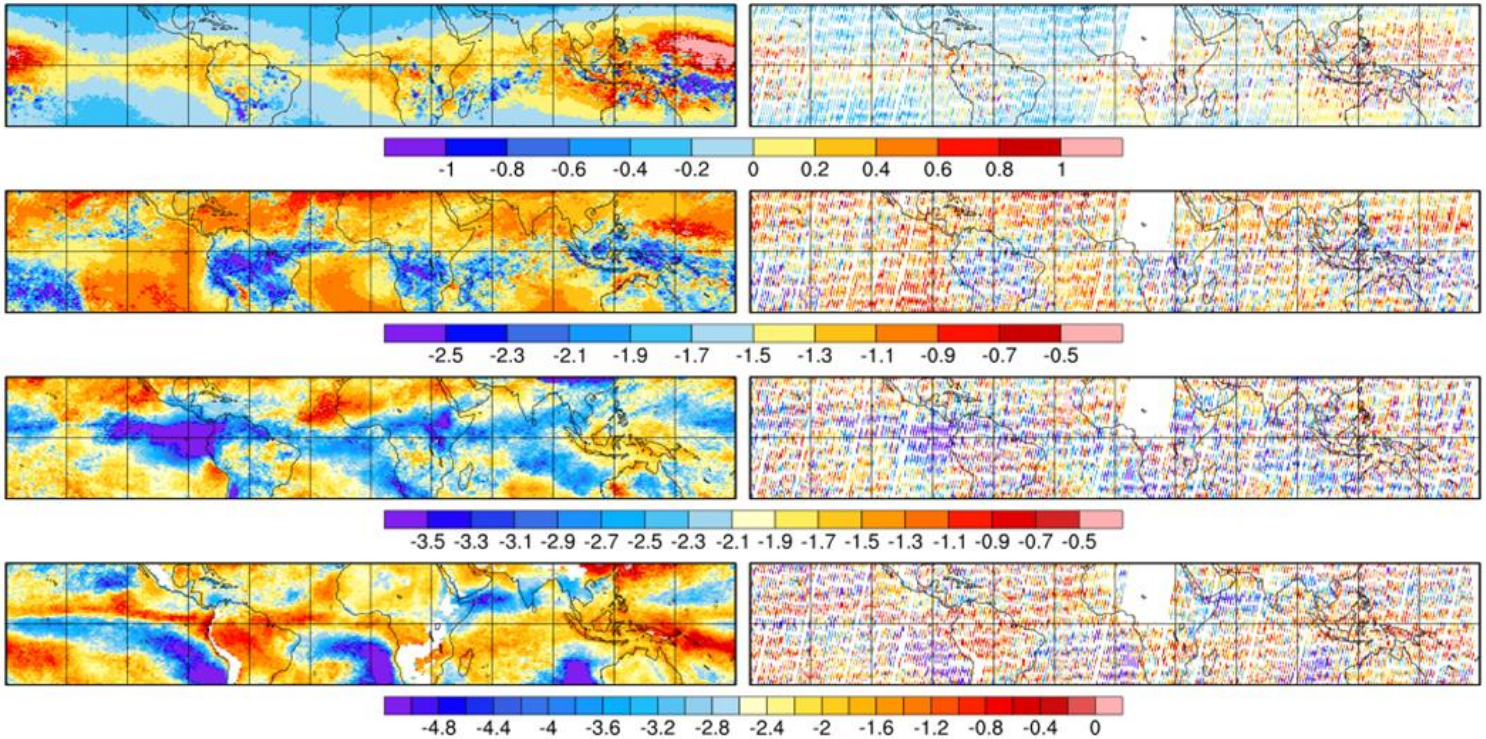
predicted LW HR | **CloudSat-CALIPSO FLXHR on nadir tracks**

106 – 131 hPa

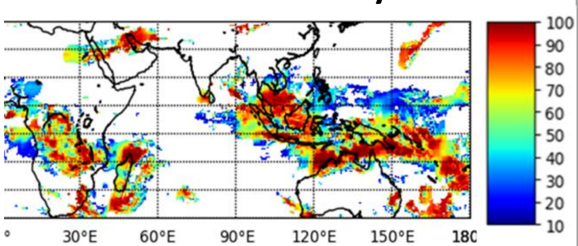
200 - 223 hPa

525 - 585 hPa

850 – 900 hPa



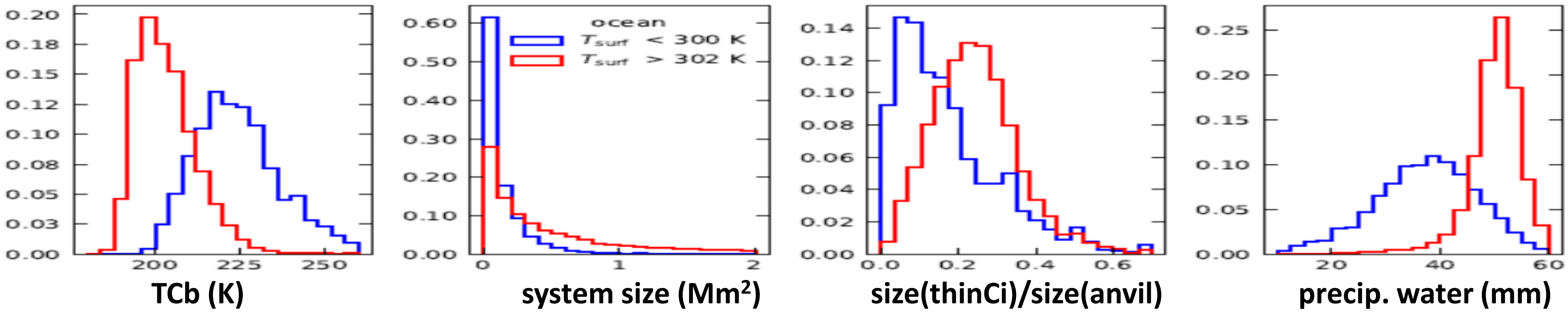
ε structure of UT cloud systems



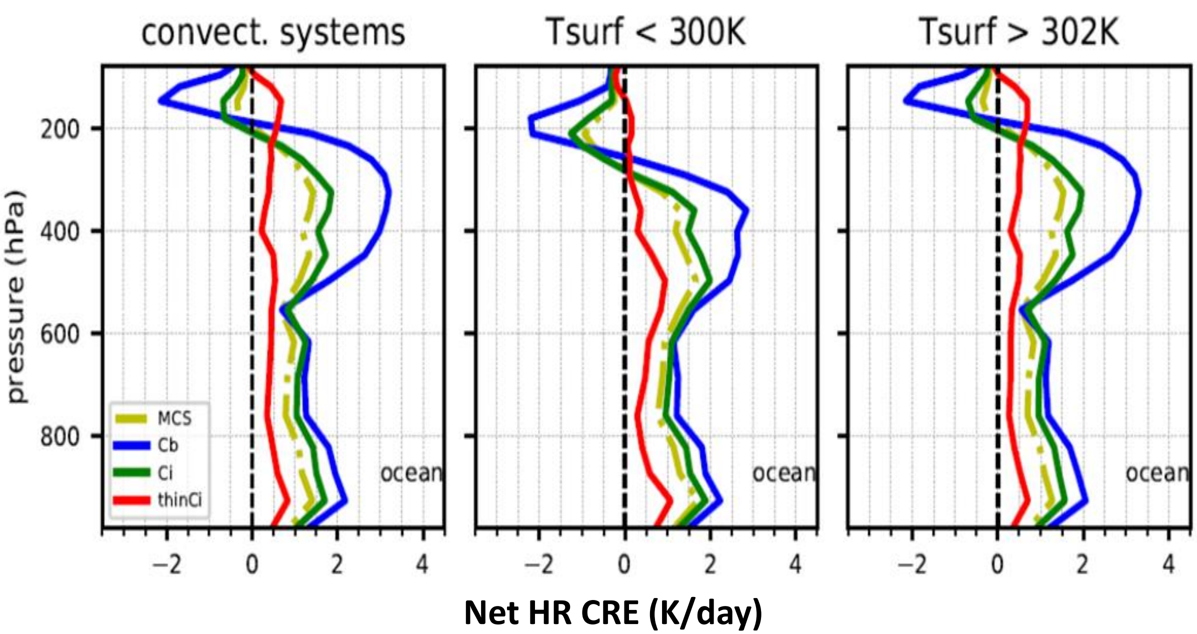
- **predicted HRs** over whole tropical band similar to nadir track, but giving a **much more complete picture -> process studies**

UT: strong warming by thin Ci, strong cooling above Cb & thick Ci anvil
MT: warming by Cb& thick Ci, cooling above lower clouds
LT: warming by Cb, cooling above low clouds (also underneath Ci & thin Ci)

Mesoscale Convective Systems: warm & cool regions

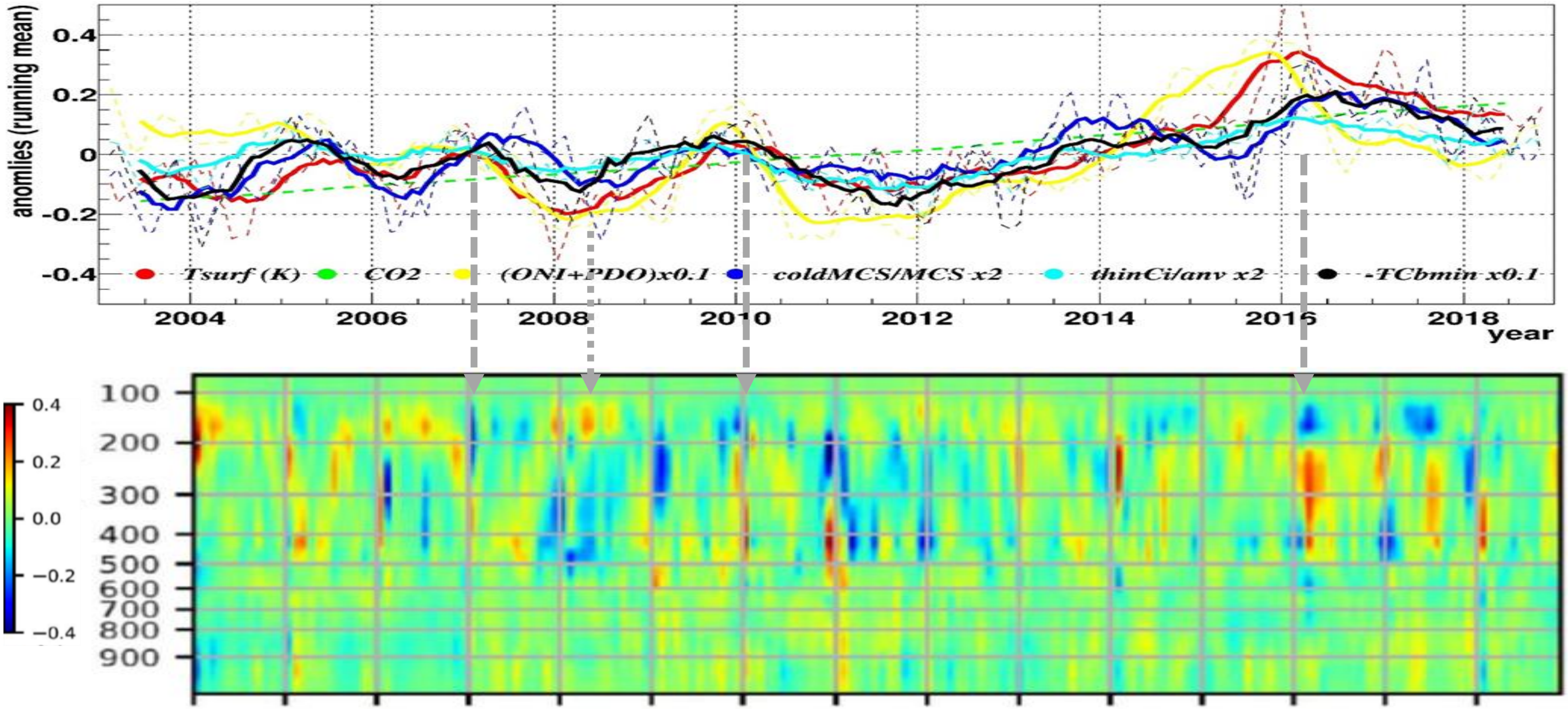


Regions of higher SST (> 302K): more humid
colder, larger convective systems, with more thin Cirrus sourrounding anvil



regions of higher SST:
higher systems with more UT thin Ci heating (opposed by strong cooling above Cb) & more Cb / Ci heating in mid & low atm
-> affects hor. & vert. gradients

Changes in relation to global Tsurf anomaly



1:30 AM deseasonalized anomalies in LW heating / cooling effect of MCS when present

- **d[cov$_{\text{cold MCS}}$/cov$_{\text{MCS}}$]/dT$_s$ = +25 ± 2 % /°C** 48% of MCSs are cold MCS (T < 210K)
- timeseries of global T_{surf} anomaly mostly reflects ENSO / PDO variations & CO_2 increase
- colder MCSs in warmer periods (El Niño)
  -> deeper warming of upper & mid troposphere & cooling above the systems

Summary

- **IR Sounders reliably identify cirrus** (day & night, COD>0.2); height = 0.5(top+app base)
- **Amplitude & phase of UT cloud diurnal cycle estimated within 20% / 1.5h**
- **Data availability:**

  IASI cloud L2 data distributed by AERIS https://iasi.aeris-data.fr/cloud/ & quicklooks
  AIRS cloud L2 data distributed by AERIS https://en.aeris-data.fr/cloud-airs-data/ (quicklooks in preparation)
  Diurnal amplitude & phase of UT clouds https://doi.org/10.13140/RG.2.2.13038.15681
  & L3 data will be in updated GEWEX Cloud Assessment database https://gewexca.aeris-data.fr/

- **synergetic UT cloud system approach based on IR sounder data powerful tool to study relation between convection & anvil properties:**

  more cold convective systems with relatively more surrounding thin Ci in warmer regions -> vertically deeper heating and additional heating from thin Ci (0.7 K/day)

  Heating patterns follow well ENSO, with more colder MCSs in warmer periods (El Niño) leading to deeper warming of upper & mid troposphere & cooling above the systems

- **machine learning applied on cloud & atmospheric variables & training on 4 yrs radar-lidar -> 15 yr cloud vertical structure across cloud systems -> process studies**

  predicted LW & SW heating rates mostly within 0.25 K/day

  Though the predictions introduce additional uncertainties, we are able to study the structure of the cloud systems & their environment !

Outlook

- ***train ANN to predict latent heating from TRMM*** *(in progress by Giacomo Caria)*

- ***use 3D diabatic HR fields to study changes in atmospheric circulation in response to forcing*** *(collaboration with L. Li, LMD)*

- ***use 3D rad. HRs to evaluate new ice cloud scheme (& effect of SSP(IWC, T))***
  (collaboration M. Bonazzola, A. Baran) *Stubenrauch et al. JAMES 2019*

- **CIRS retrieval may be applied to CrIS**

GEWEX UTCC PROES (PROcess Evaluation Study on Upper Tropospheric Clouds & Convection)
working group to advance our understanding on UT cloud feedbacks

https://gewex-utcc-proes.aeris-data/fr

if you want to join this group, please email claudia.stubenrauch@lmd.ipsl.fr

Thank you to the Sounder Teams for their continuous effort to check, calibrate & distribute the data !