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Oxygen A-band spectrometry of cloud fields: recent advances

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Outline

Instruments

Oxygen A-band

Algorithm

ENSO on the record

Trend model and time series

Global and regional trends

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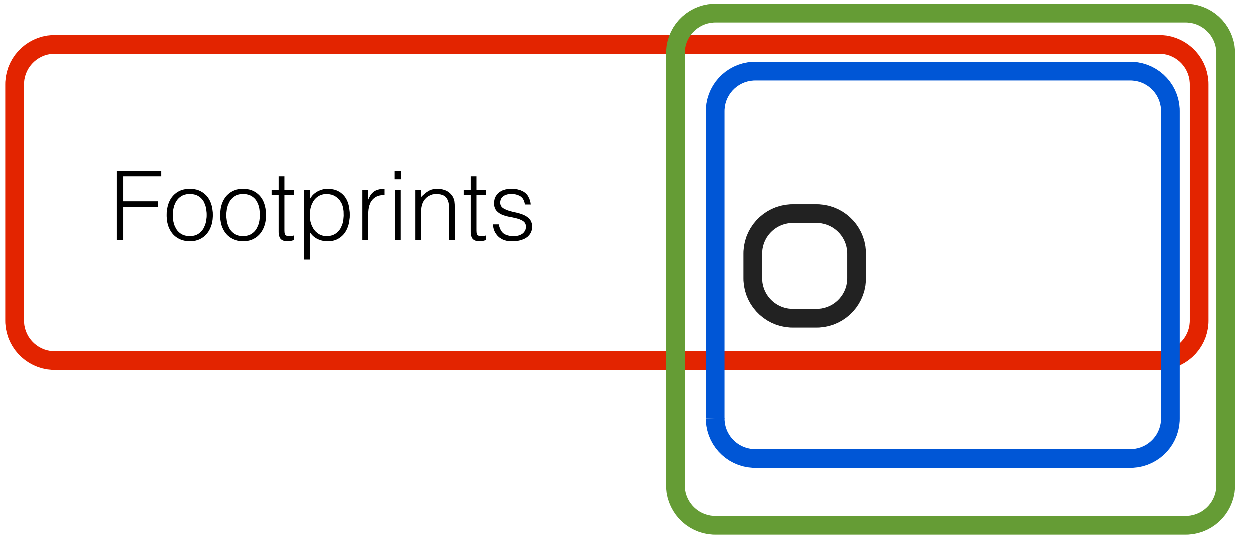
Aerosol height in the O_2 A-band:

case study

Instruments



GOME (320 x 40 km)
SCIAMACHY (60 x 40 km)
GOME-2 (80 x 40 km)

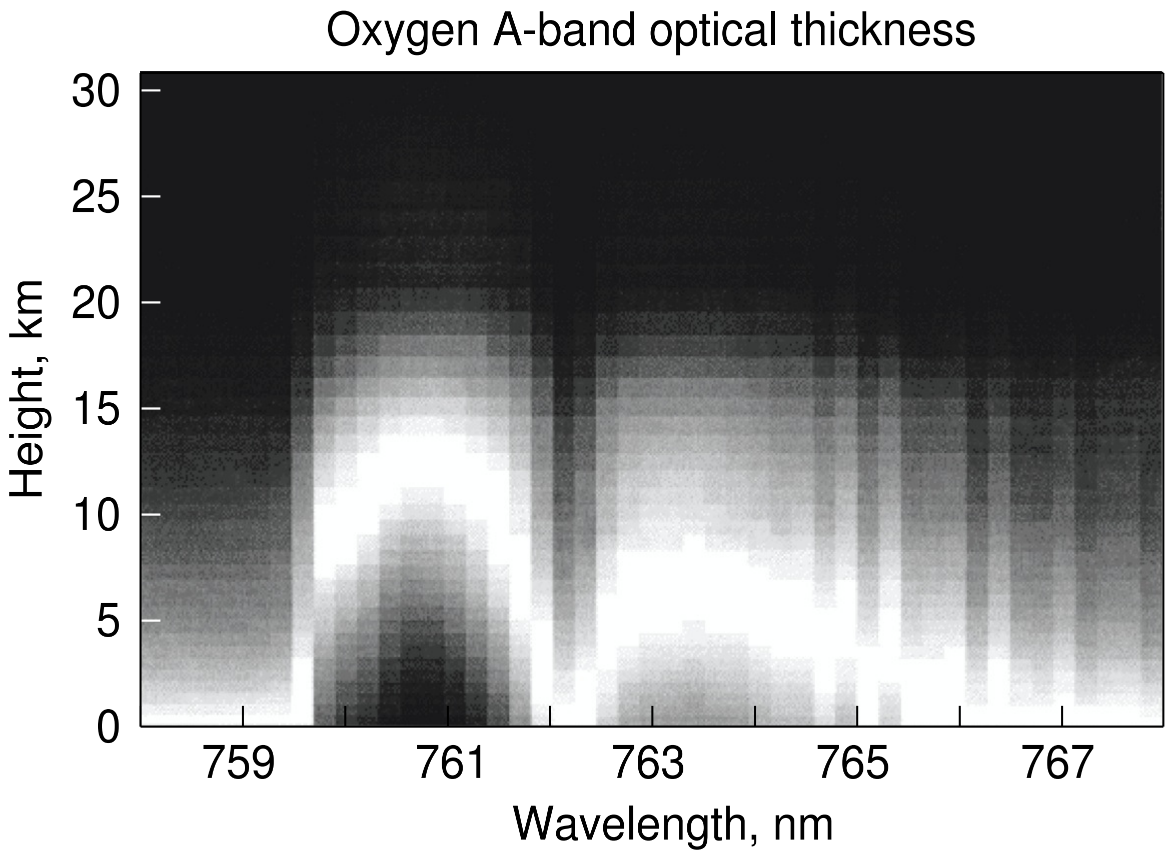
TROPOMI (7 x 7 km)
1.8 x 1.8 km O_2 A-band

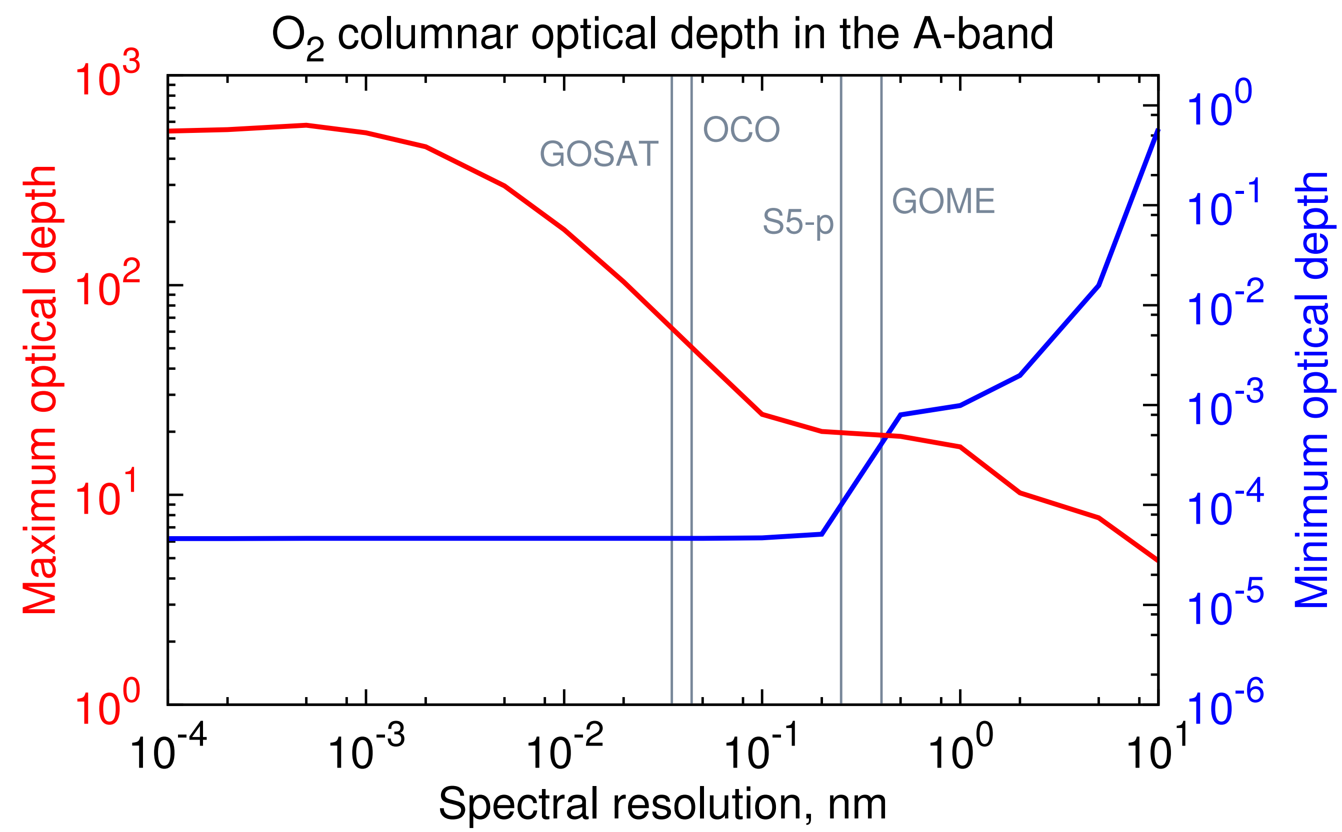
Today: Friday 17.12.2013

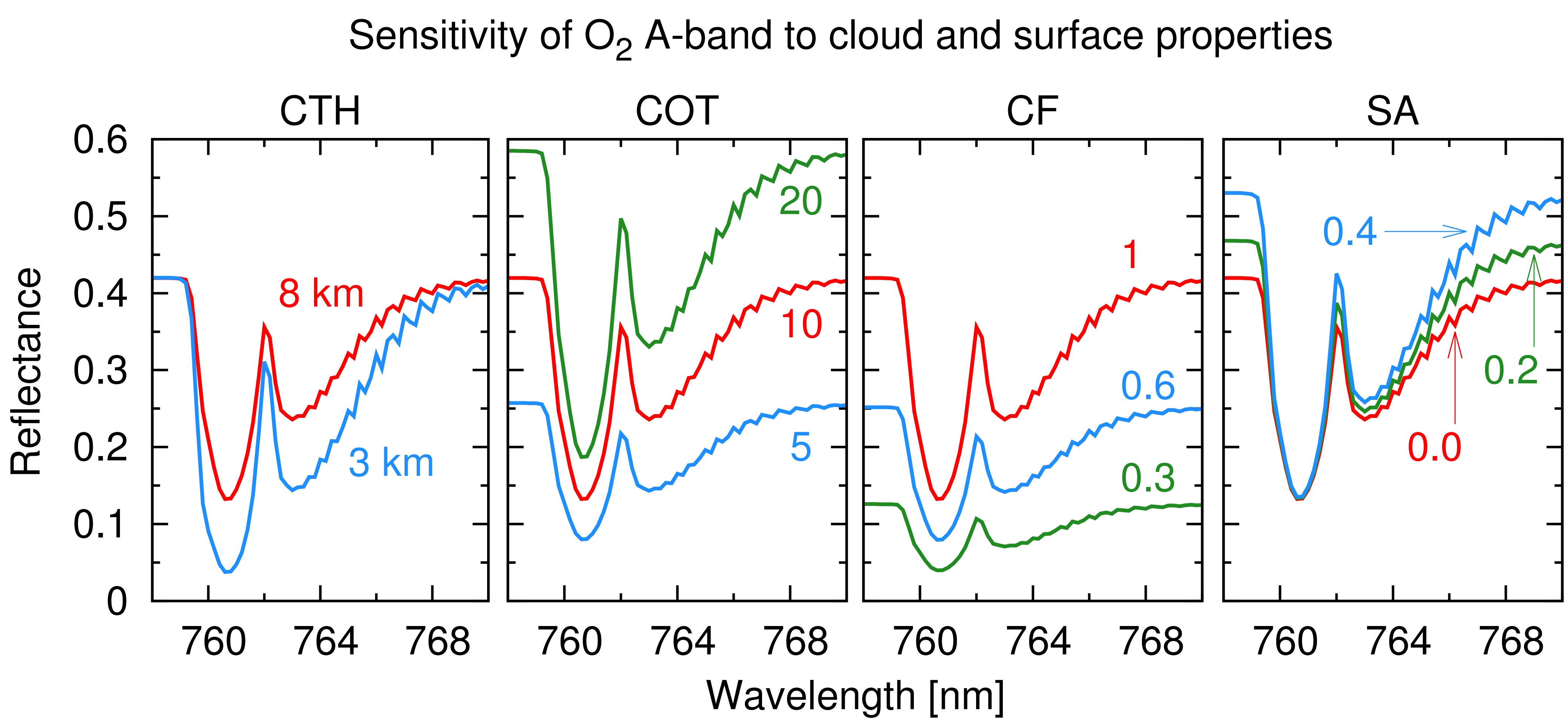
Timeline

	GOME ERS-2	**SCIAMACHY** ENVISAT	**GOME-2** METOPs	**TROPOMI** S-5 p
LT	10h30	10h00	9h30	13h30
Global coverage	3 days	6 days	1.5 days	1 day
Time span	1996 - 2010	2002 - 2012	2007 - 2021	2015 - 2022
Swath	960 km	1000 km	1920 km	2600 km
Spectral coverage	290-800 nm	240-2400 nm	290-800 nm	270-775 nm + SWIR
Spectral resolution	0.38 nm	0.44 nm	0.48 nm	0.25-0.55 nm
Polarization channels	3p	6p	15(s,p)	---

Oxygen A-band







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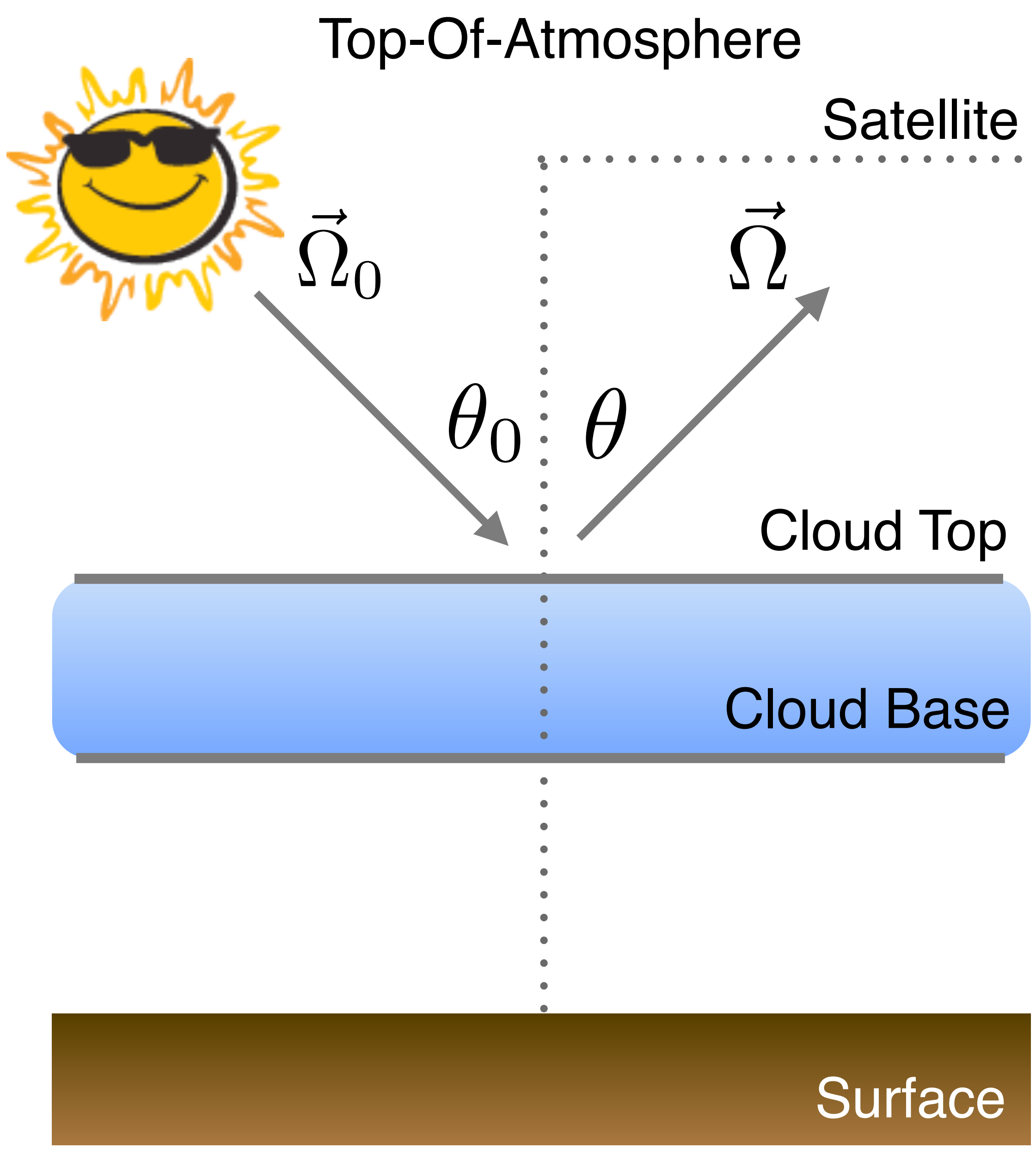
SACURA forward



$$R_{\mathrm{TOA}}(\lambda) = R_a(\lambda) + T_1(\lambda)\ R_b(\lambda)\ T_2(\lambda)$$

R_a

Above cloud

Aerosol + gas absorption & scattering in single scattering approximation

R_b, T_1, T_2

Inside cloud

Vertical gas profiles (correlated k)

Spherical polydispersed water droplets

LWC constant

Below cloud

Gas absorption & scattering

Diffuse approximation (no direct light)

$$\begin{cases} R_b(\theta, \theta_0) = R_\infty(\theta, \theta_0) - t\ K_0(\theta)K_0(\theta_0) + \dfrac{A\ t^2 K_0(\theta)K_0(\theta_0)}{1 - A\ (1-t)} \\ t = \dfrac{1}{\alpha + 0.75\ \tau\ (1-g)} \end{cases}$$

τ Optical thickness

g Asymmetry param.

K_0 Escape function

A Surface reflectance

Rozanov and Kokhanovsky, JQSRT (2004)

SACURA inverse

$\vec{I}$ Earthshine

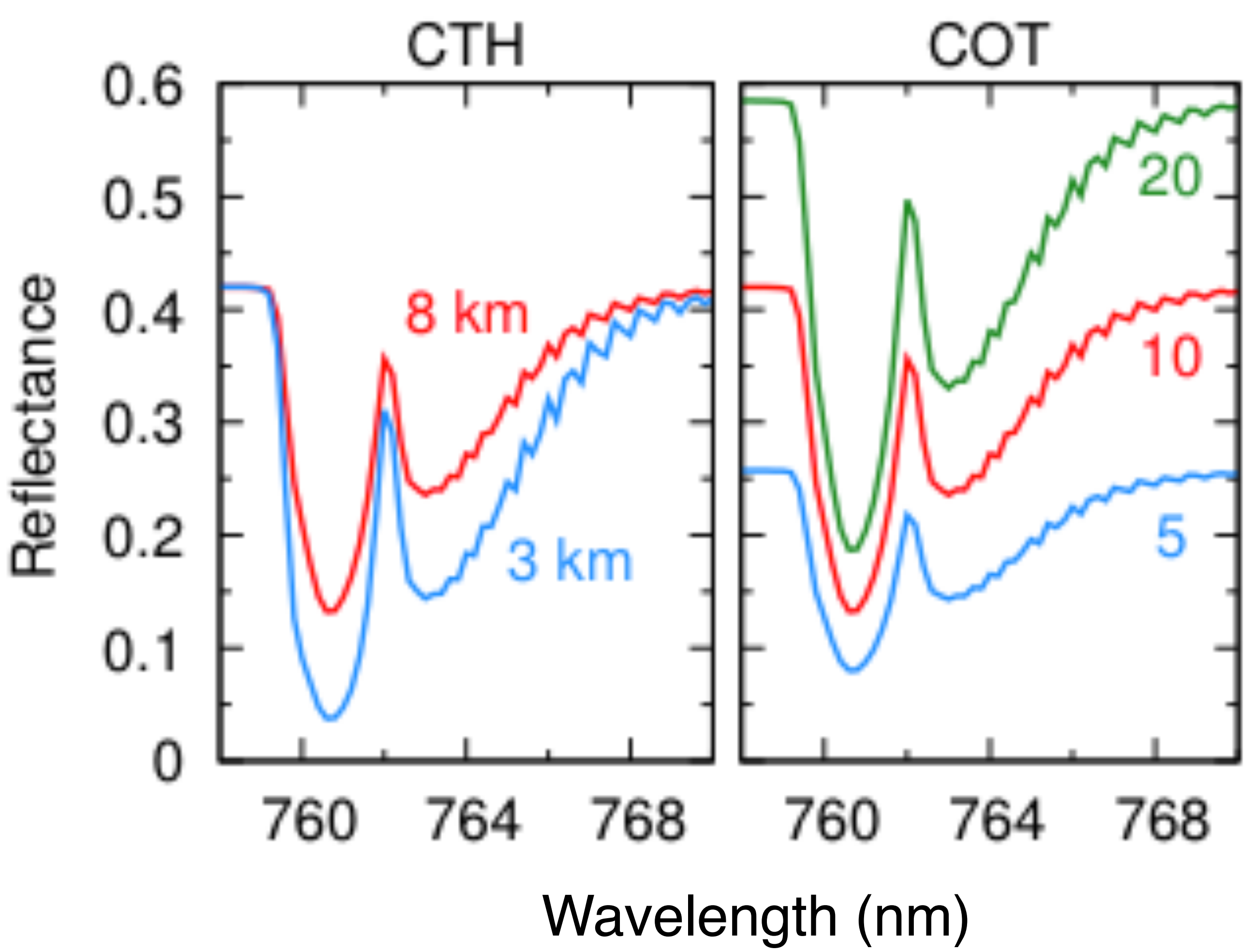
$\vec{E}_0$ Sun spectrum

$$\frac{\pi \ \vec{I}}{\cos\theta_0 \ \vec{E}_0} = \mathrm{CF} \ \vec{R}_{\mathrm{cl}} + (1 - \mathrm{CF}) \ \mathrm{SA}$$

SA = surface albedo

CF = OCRA cloud fraction

$$\underset{k}{\text{minimize}} \left\| \vec{R}_{\mathrm{cl}} - \vec{R}(h_k, l_k) - \frac{\partial \vec{R}(h_k, l_k)}{\partial h} \cdot (h - h_k) - \frac{\partial \vec{R}(h_k, l_k)}{\partial l} \cdot (l - l_k) \right\|^2$$



- ➡ 758 nm Cloud Optical Thickness
  Cloud Spherical Albedo
- ➡ 761 nm Cloud Top Height h
  Cloud Geometrical Thickness l
- ➡ 67 spectral points
- ➡ Reflectances normalized to R(758 nm)
- ➡ Effective single scattering albedo value throughout the cloud iteratively found (Yanovitskij, 1997)

Rozanov and Kokhanovsky, JGR (2004), Lelli et al., AMT (2012)

Validation with synthetic data

- Cloud top/bottom height ± 400 m
- Cloud optical thickness ±20% (COT > 5, Surface albedo < 0.4)
- Cloud spherical albedo ±10% (COT > 5)
- Clouds as Lambertian scattering layers not adequate
- Surface as Lambertian adequate for more than 70% of the cases
- Double-layered cloud for better filtering

Validation with real data

- Ground-based radar
- Satellite-based

  ATSR-2 (GRAPE, IR-technique)

  GOME/GOME-2 (FRESCO, O_2 A-band)

  GOME (ROCINN, O_2 A-band)

Validation: Rozanov and Kokhanovsky, JGR (2004), Rozanov et al. TGRS (2004), Kokhanovsky et al. ASR (2005), Nauss et al., Atm Res (2005), Kokhanovsky et al., ACP (2006), Lelli et al., AAPP (2011), Lelli et al., AMT (2012)

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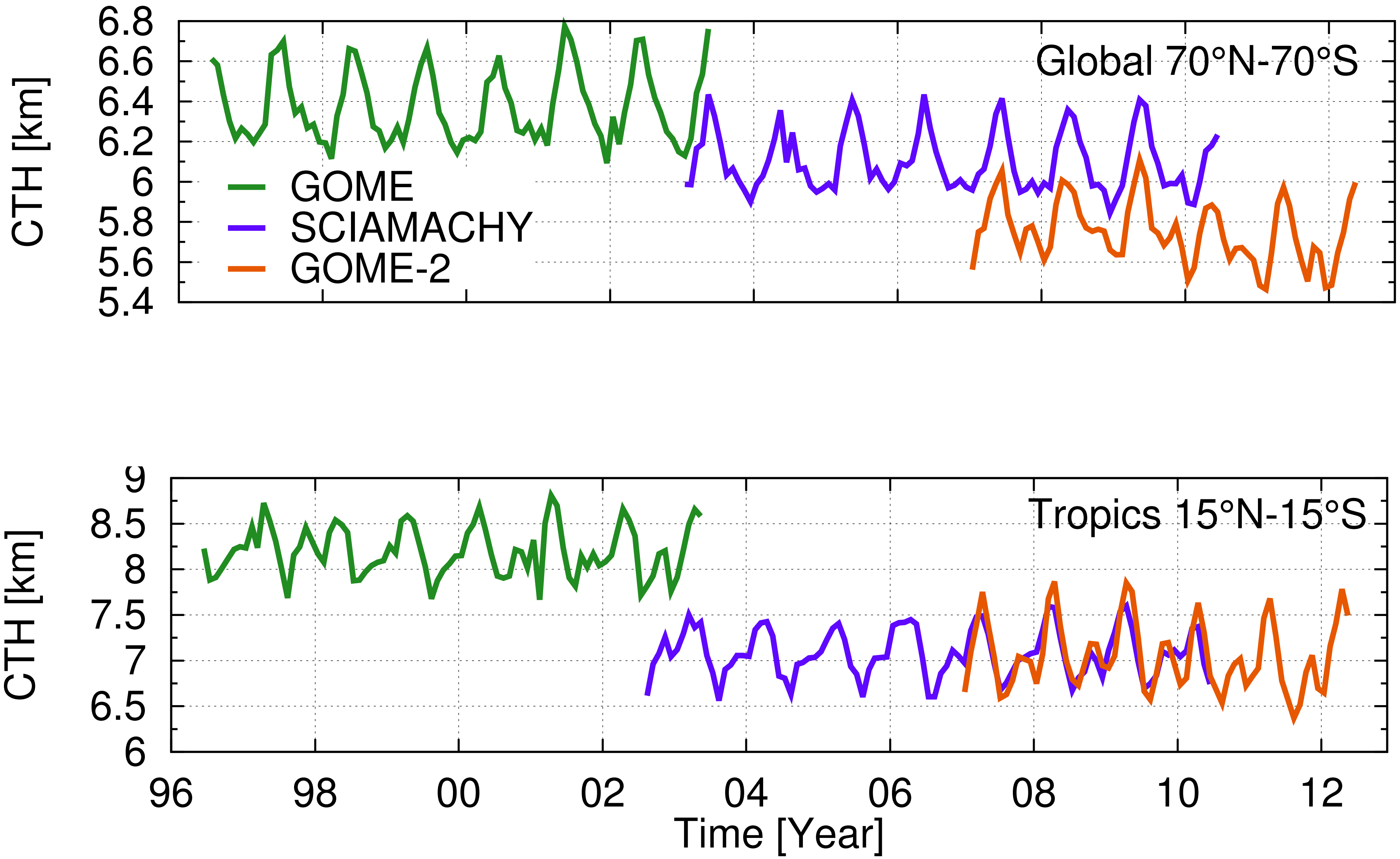
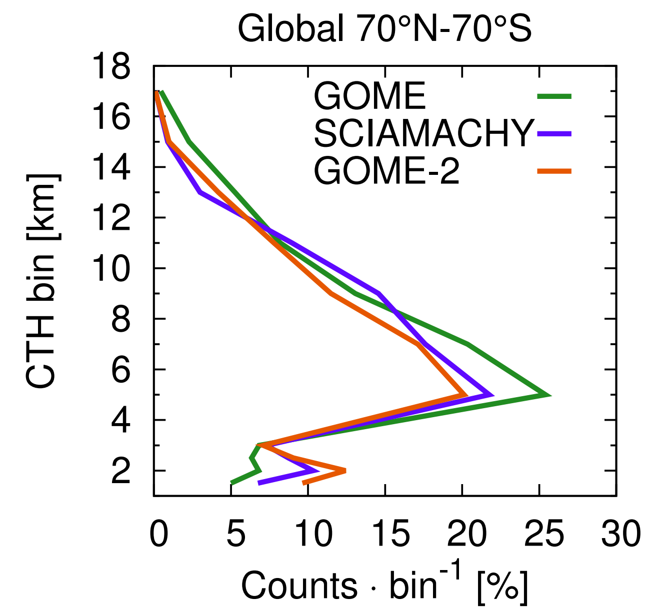
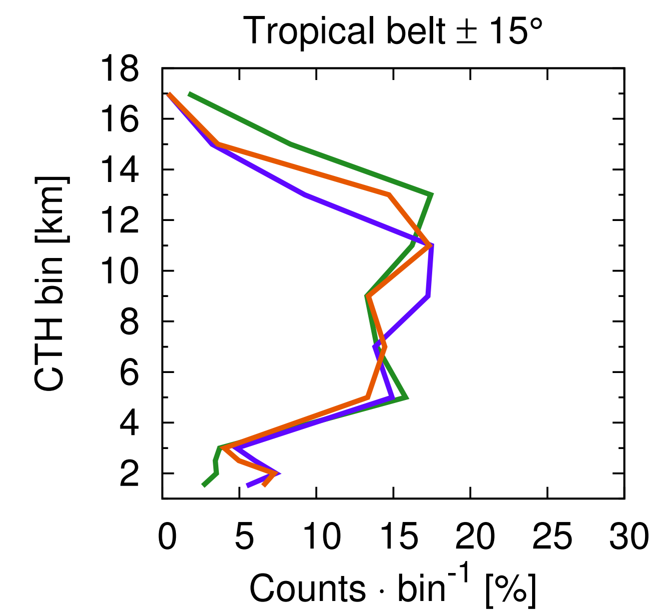
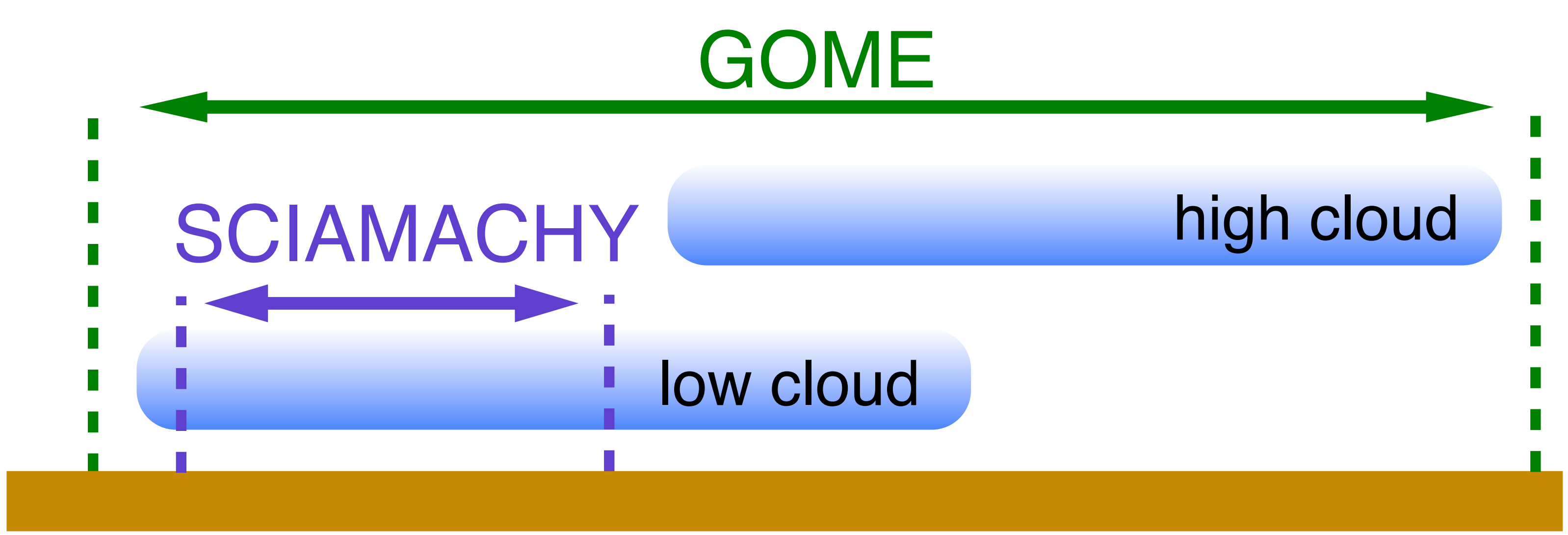
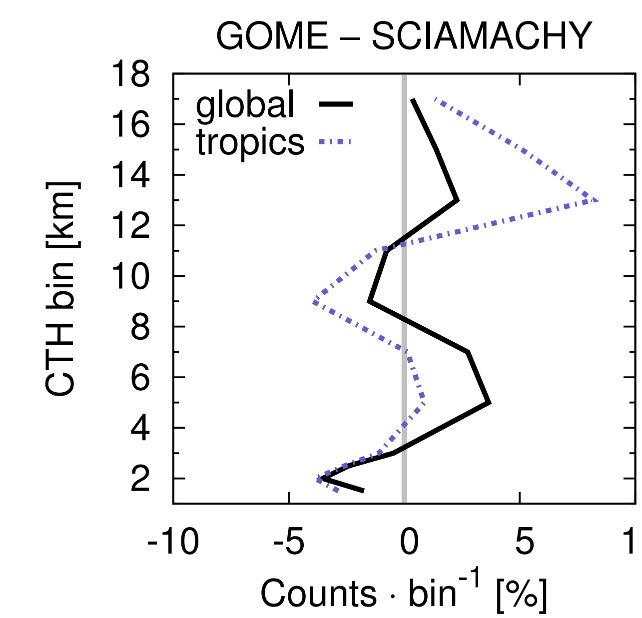
CTH time series



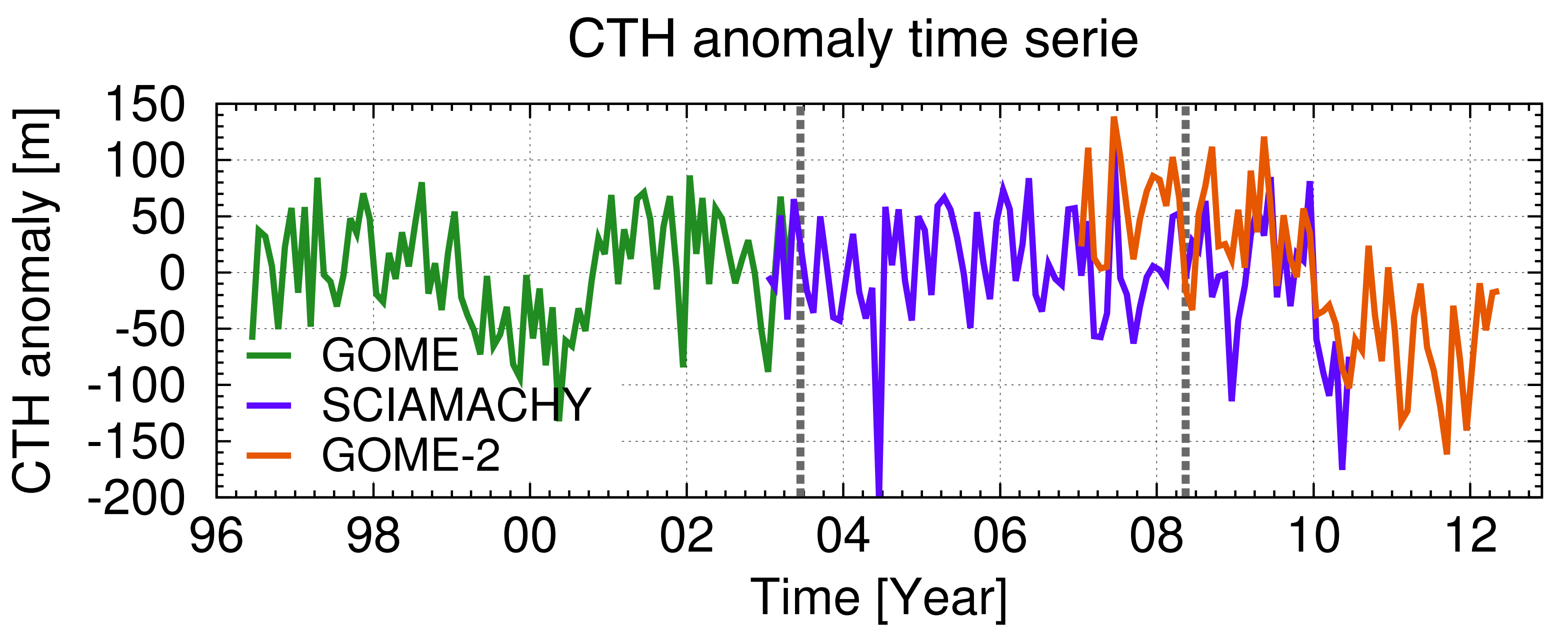


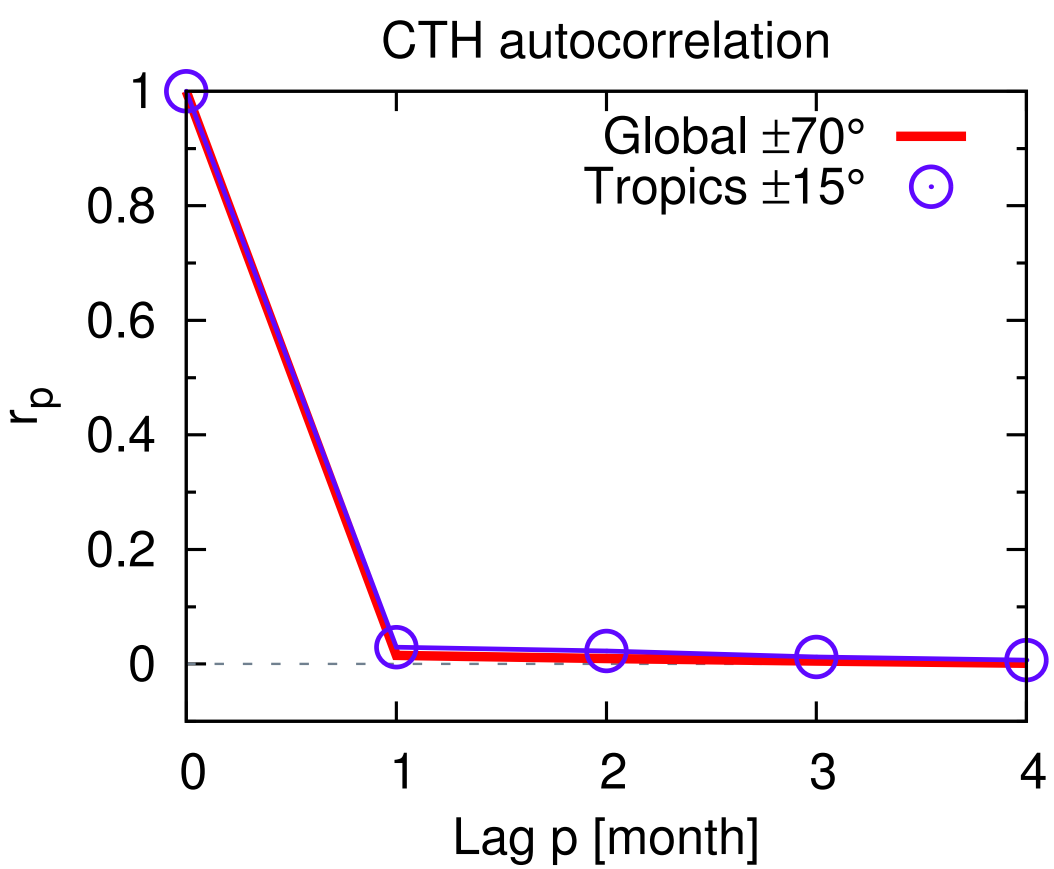


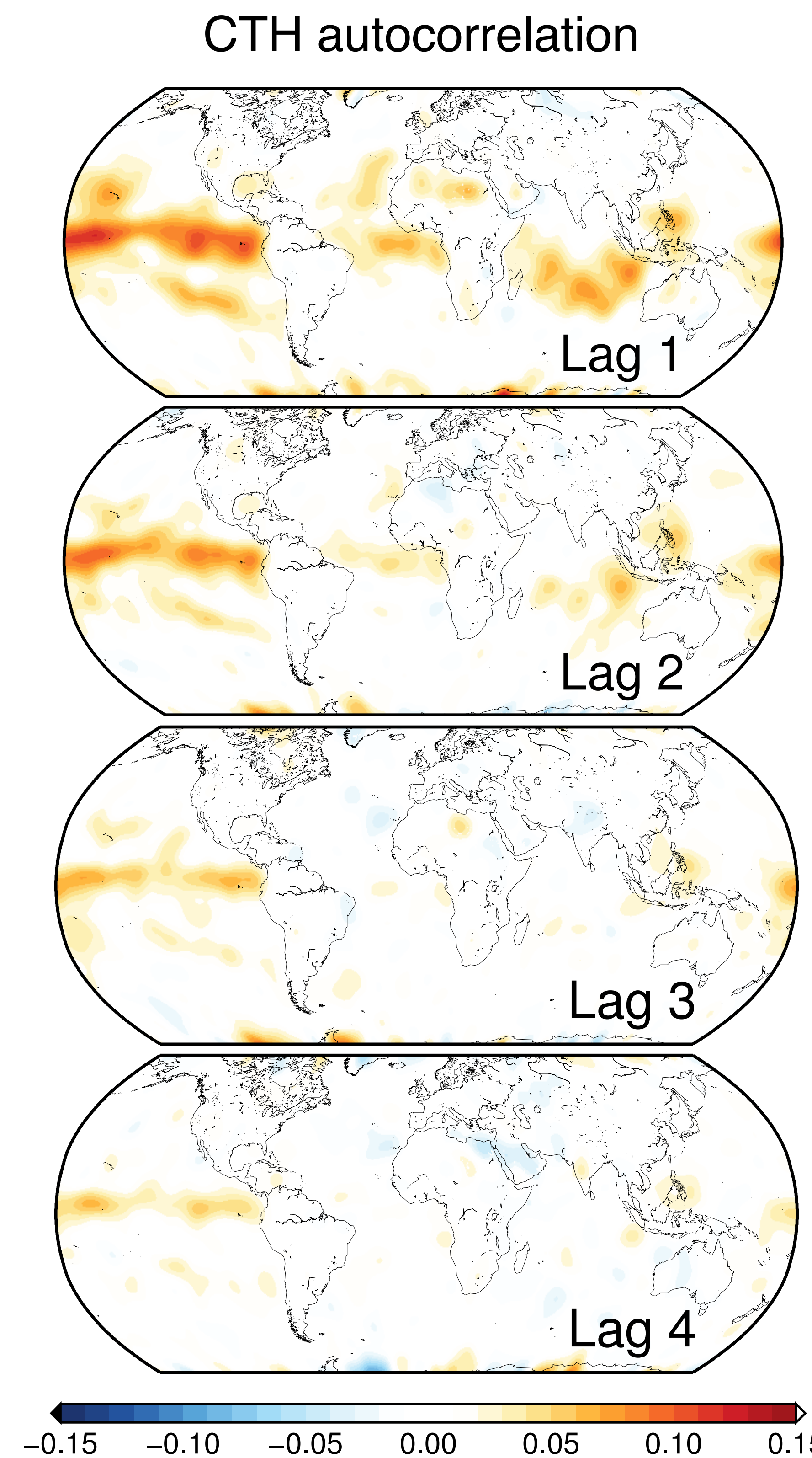




CTH anomaly and trend model

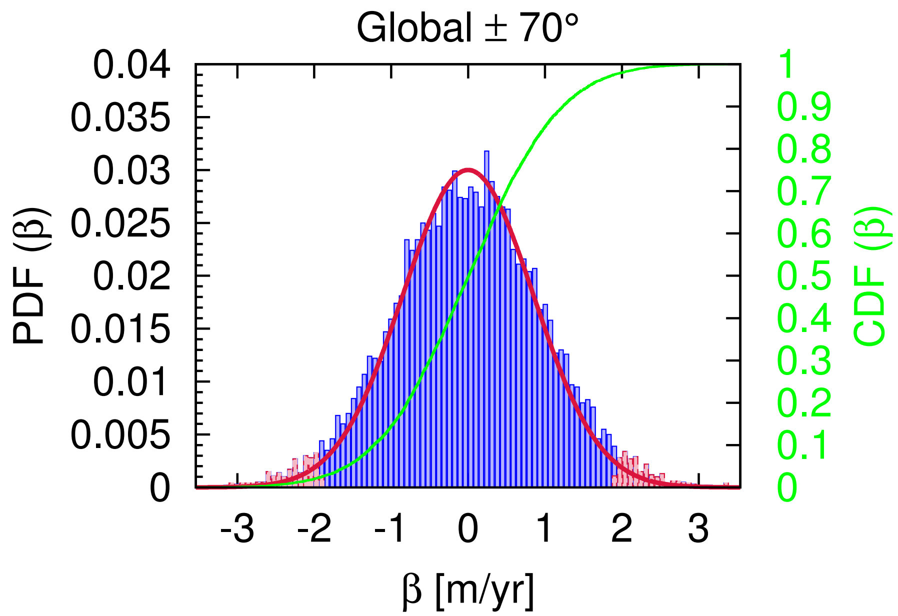


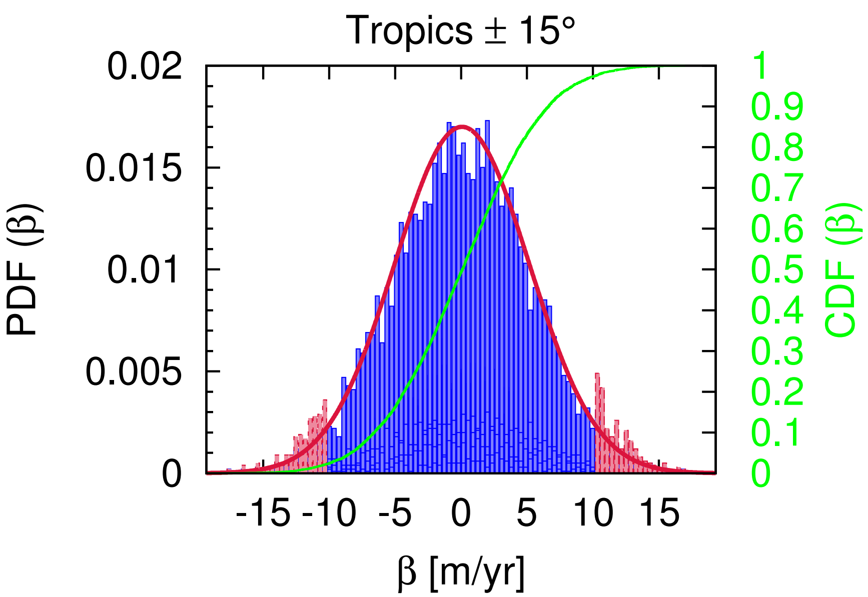


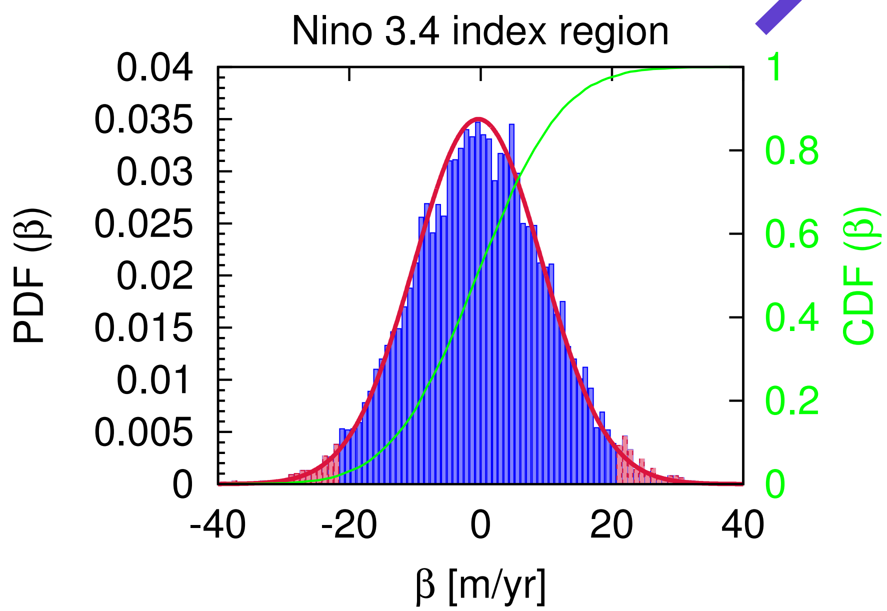


CTH anomaly and trend model

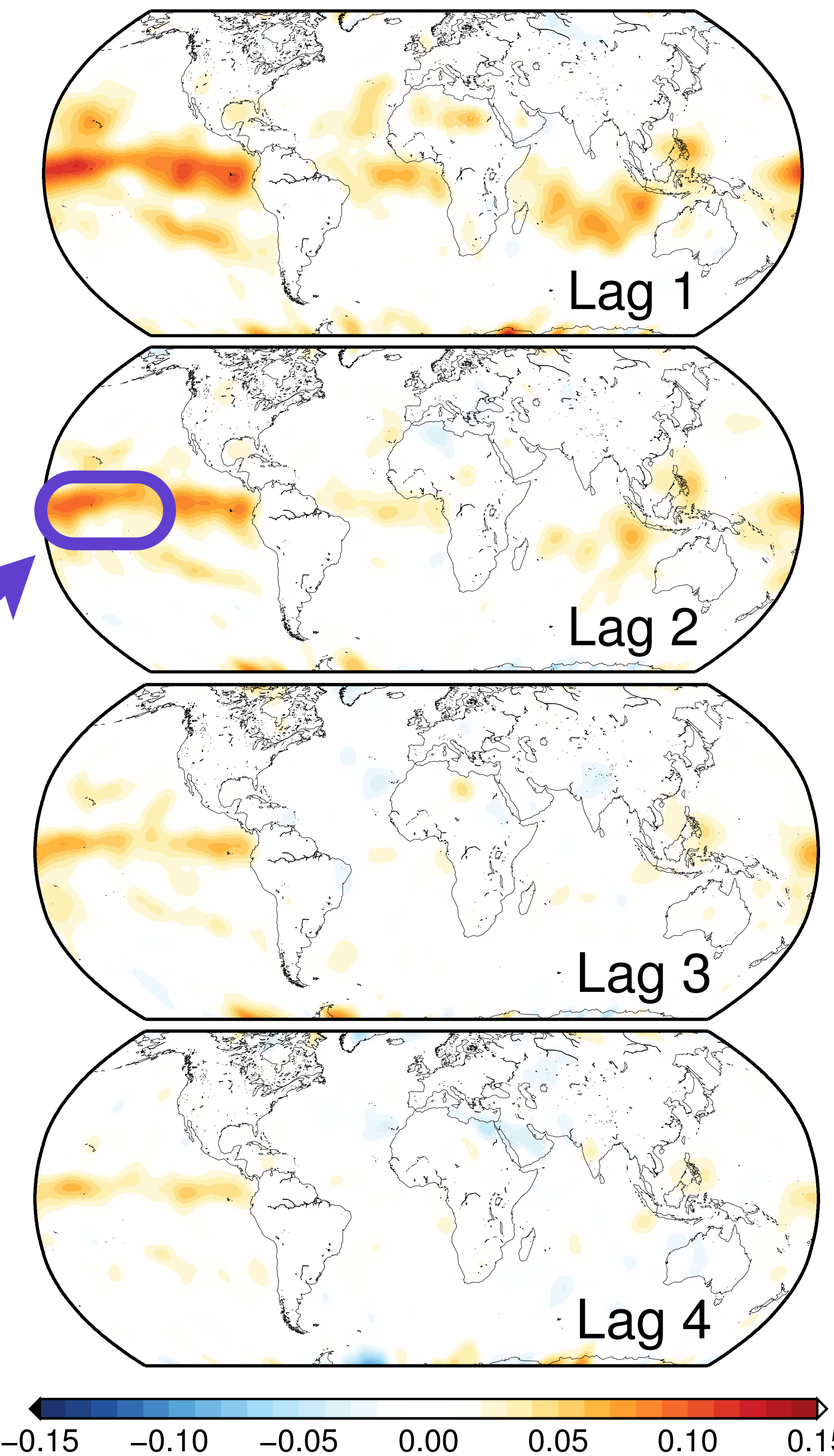
Bootstrapping (Efron and Tibshirani, 1993; Mudelsee, 2010)



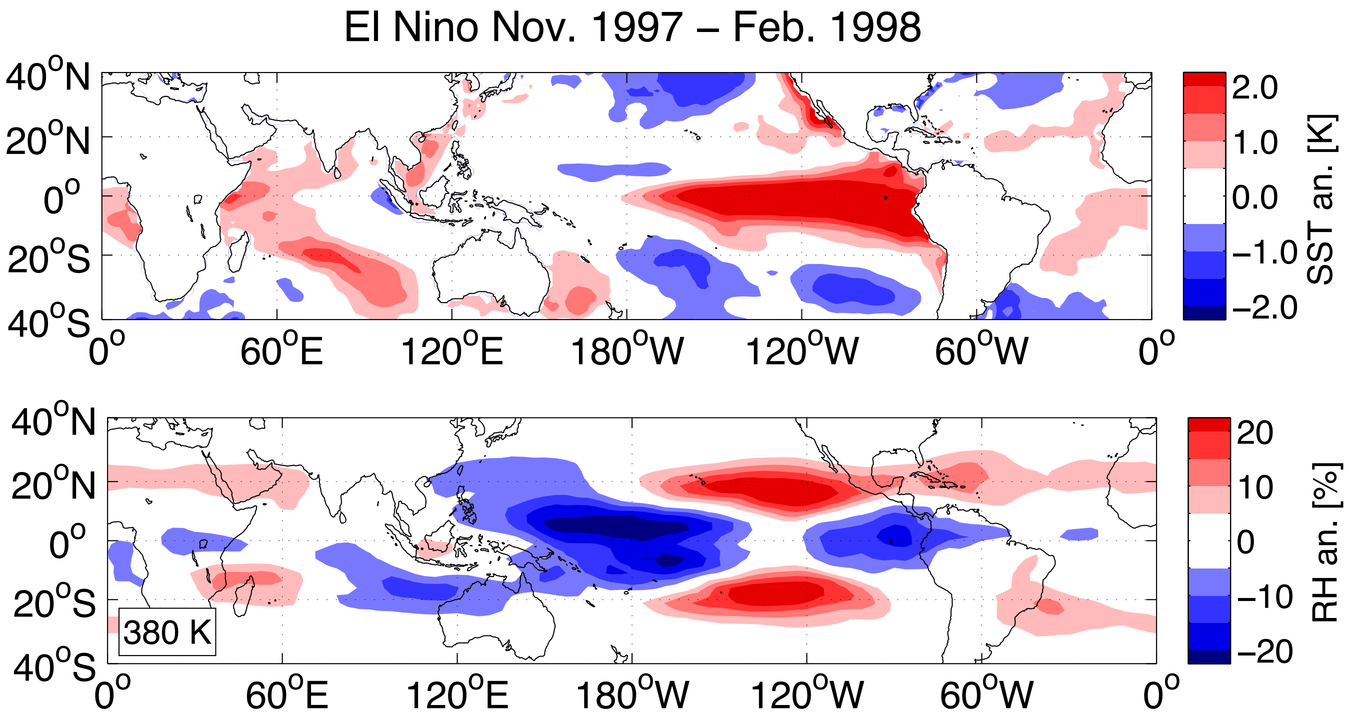




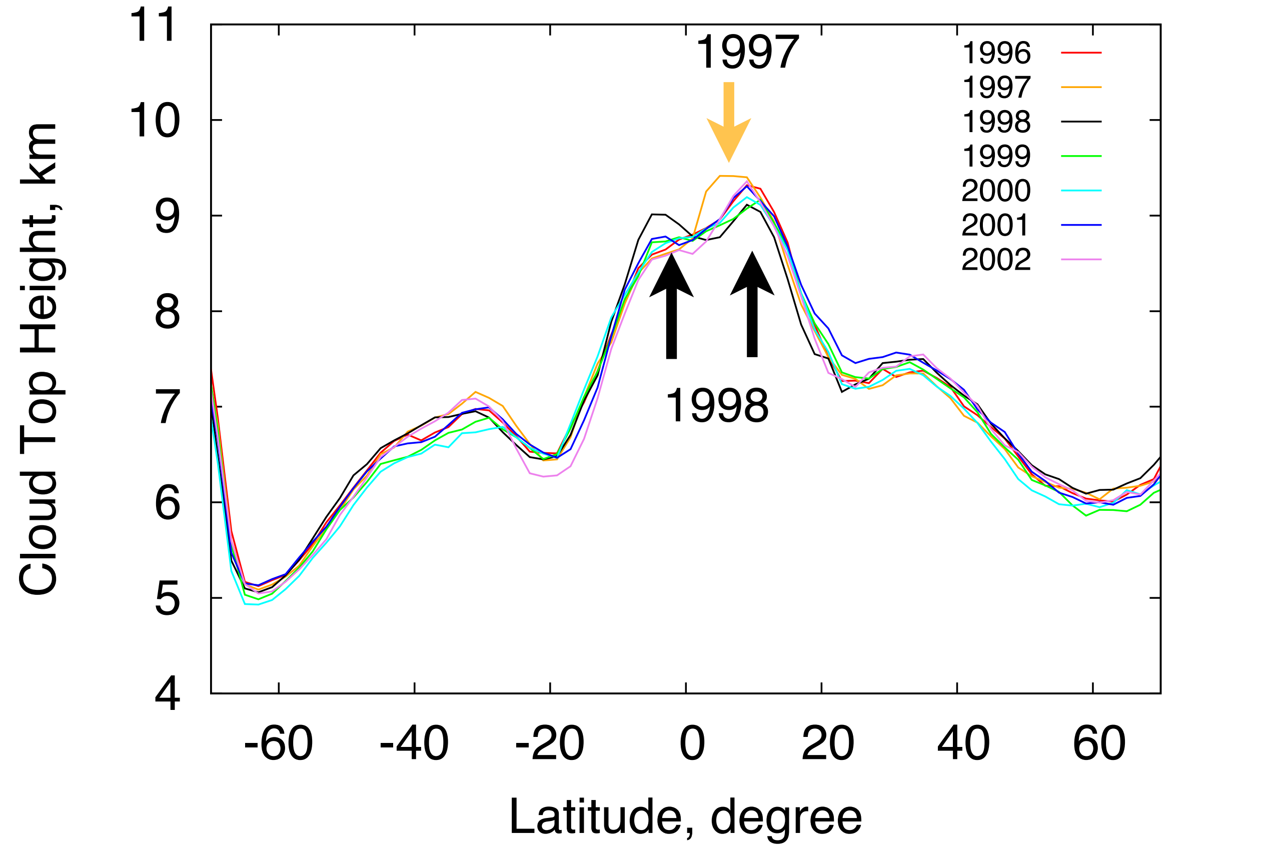
CTH autocorrelation

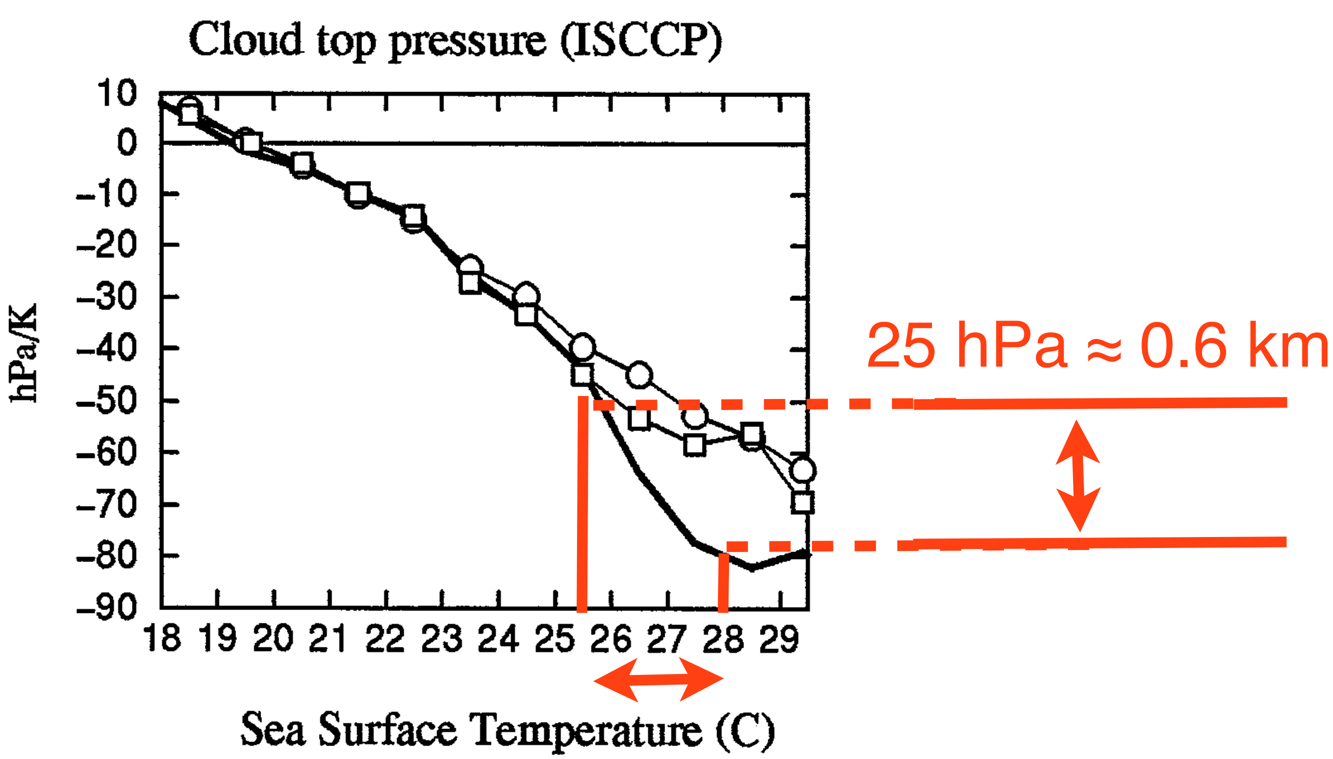


El Niño - Southern Oscillation

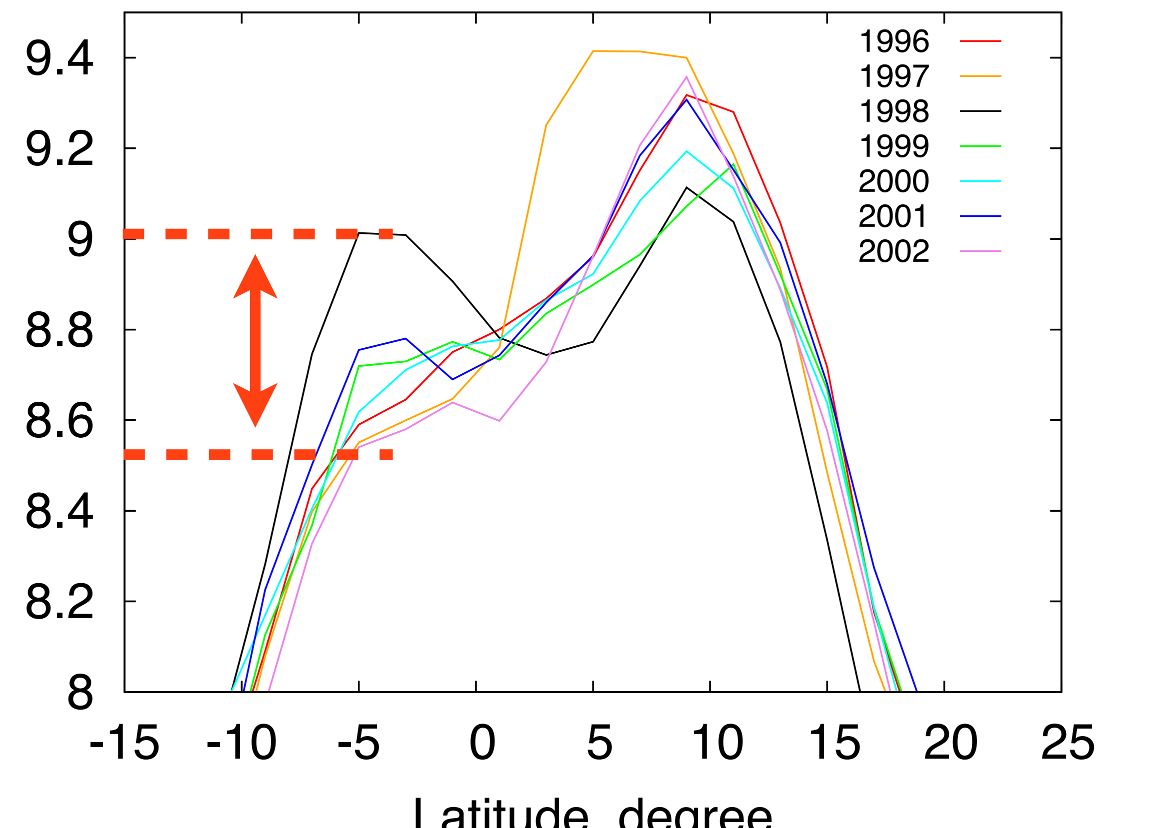


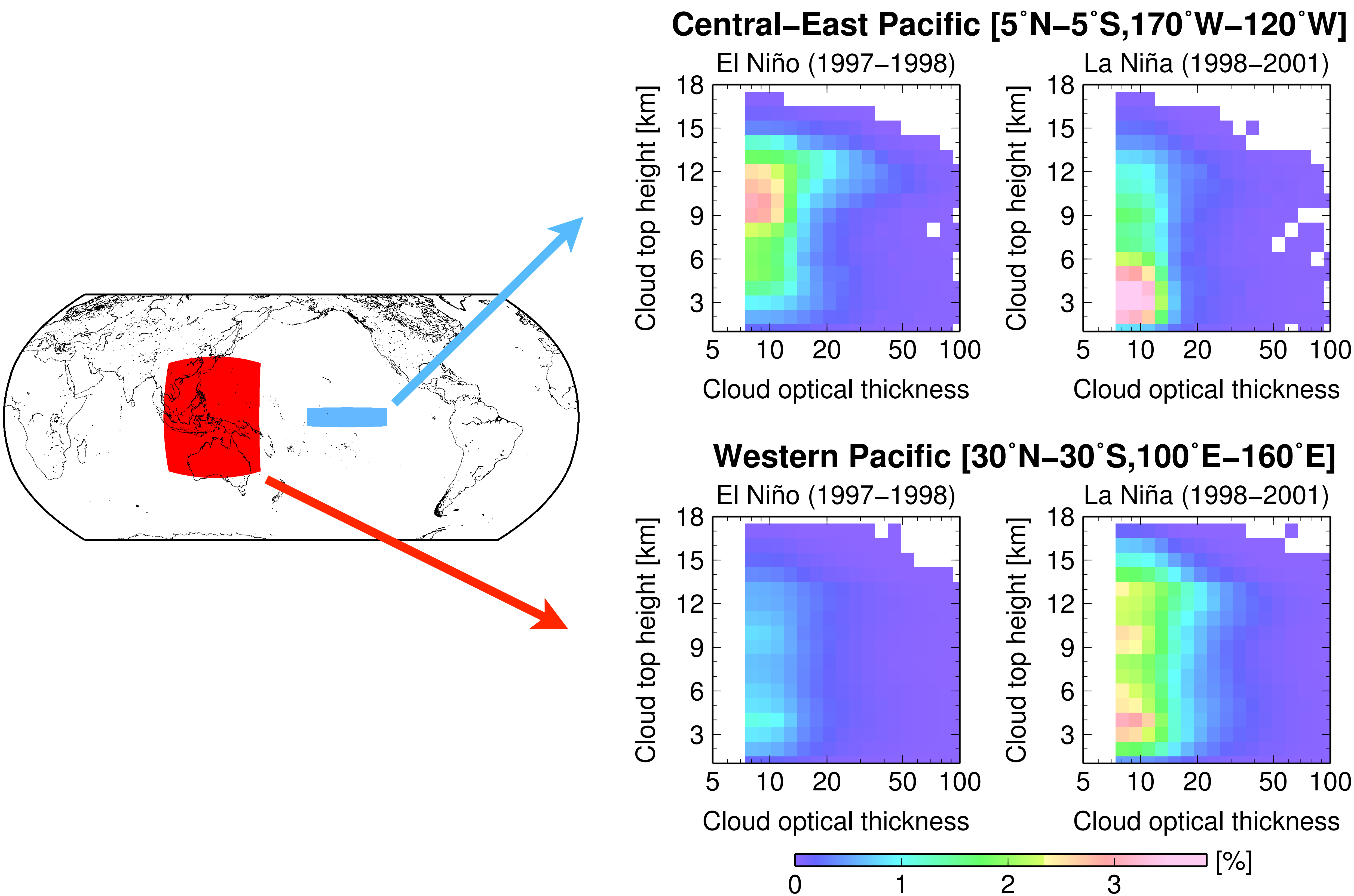
Aschmann et al. ACP, 2011

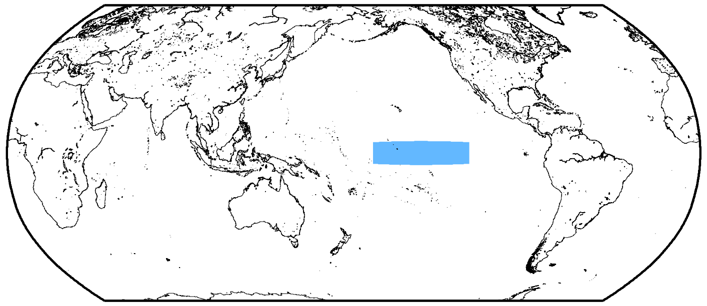


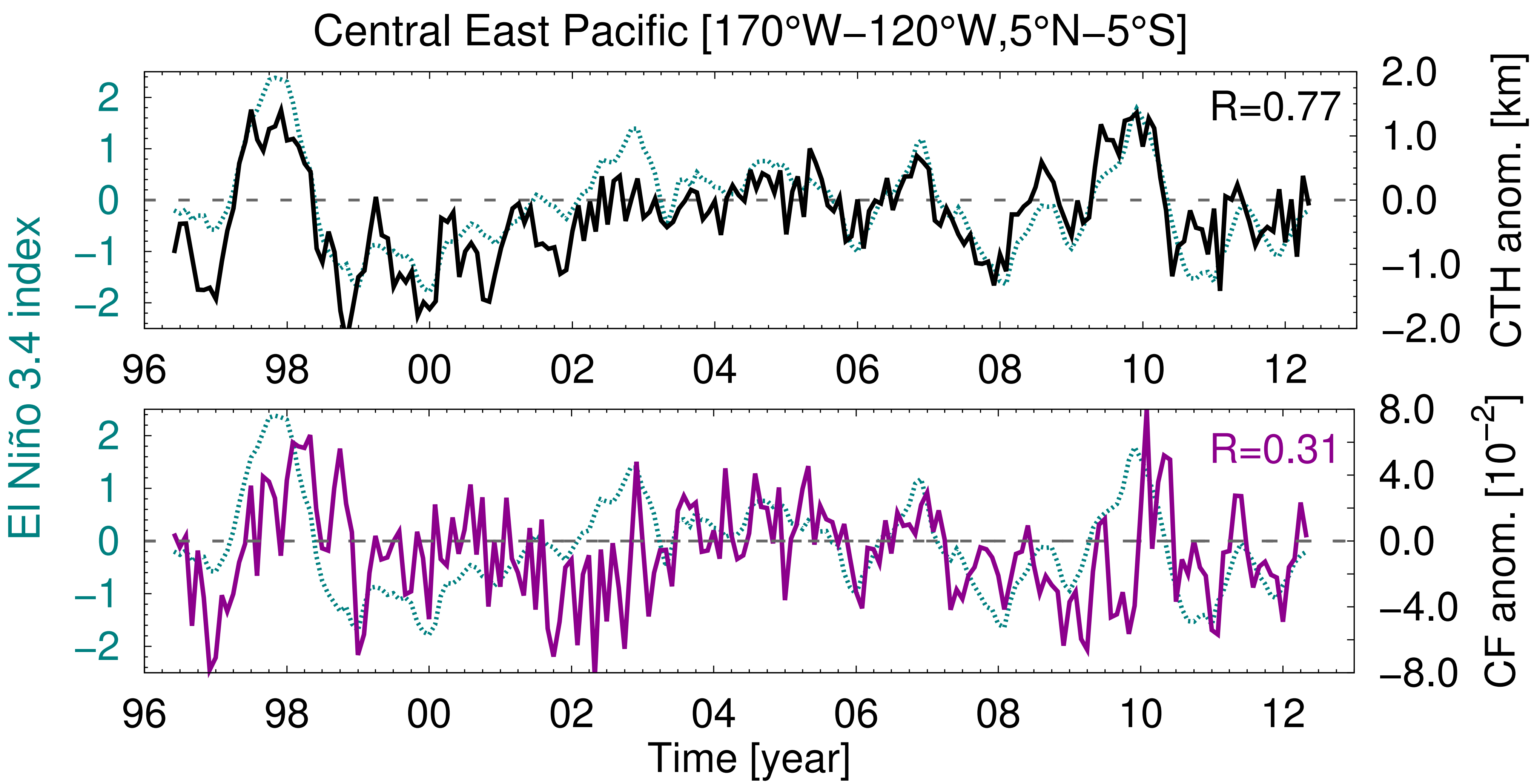


Bony et al. JCLIM, 1997

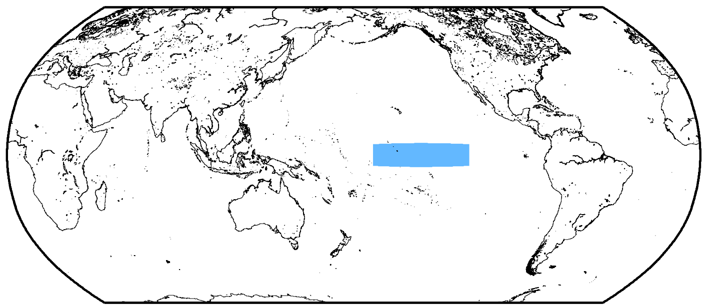


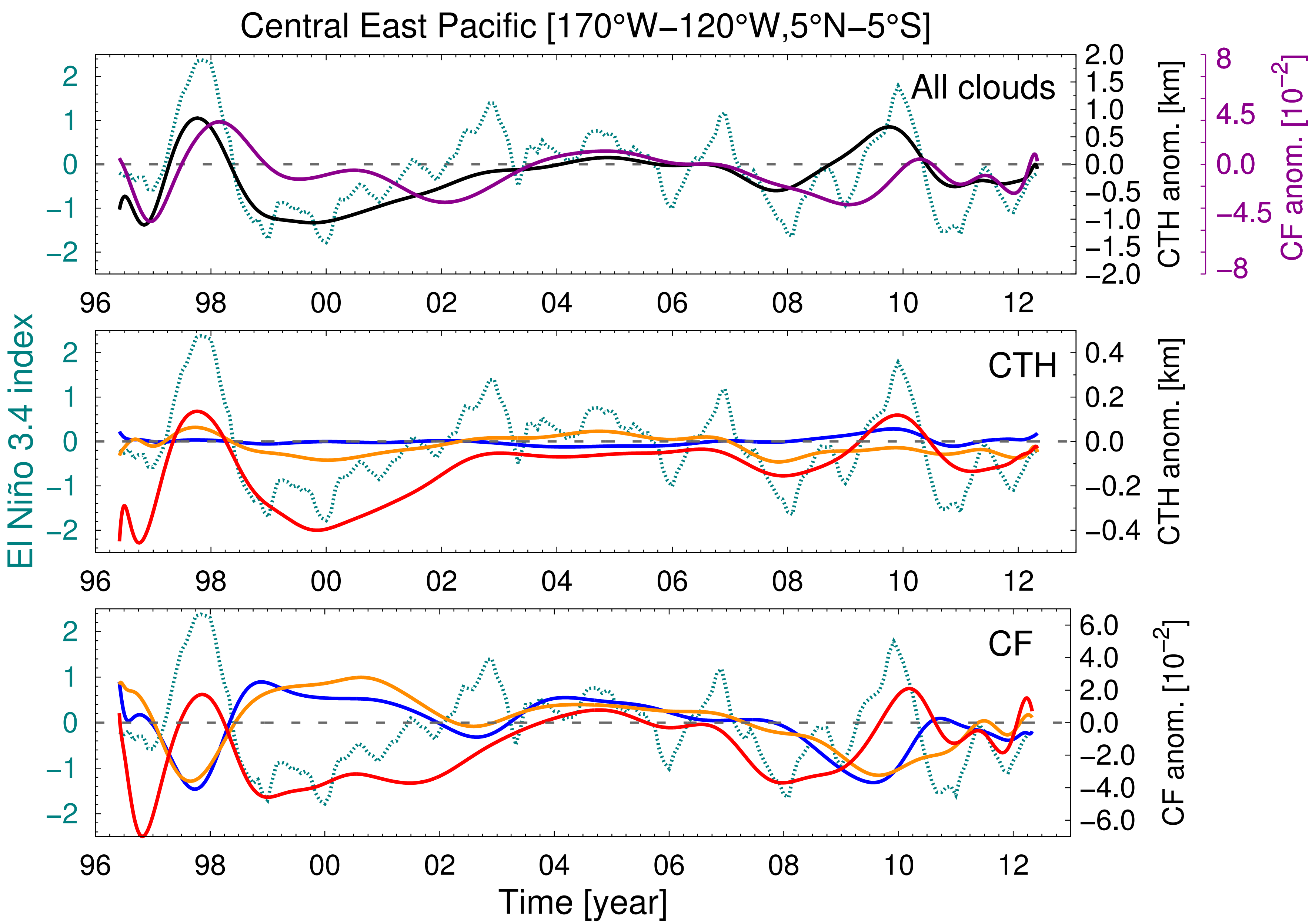

Central–East Pacific [5˚N–5˚S,170˚W–120˚W]
El Niño (1997–1998)
La Niña (1998–2001)
Western Pacific [30˚N–30˚S,100˚E–160˚E]
El Niño (1997–1998)
La Niña (1998–2001)
Cloud top height [km]
18
15
12
9
6
3
5
10
20
50
100
Cloud optical thickness
[%]
0
1
2
3




Central East Pacific [170°W–120°W,5°N–5°S]
R=0.77
R=0.31
El Niño 3.4 index
CTH anom. [km]
CF anom. [10^{-2}]
Time [year]
96
98
00
02
04
06
08
10
12
2.0
1.0
0.0
−1.0
−2.0
8.0
4.0
0.0
−4.0
−8.0
2
1
0
−1
−2

ENSO





Correlation coefficients

All clouds

CTH **+ 0.77**

CF **+ 0.31**

Cloud Top Height

HIGH clouds **+ 0.55**

MID clouds **+ 0.56**

LOW clouds **+ 0.29**

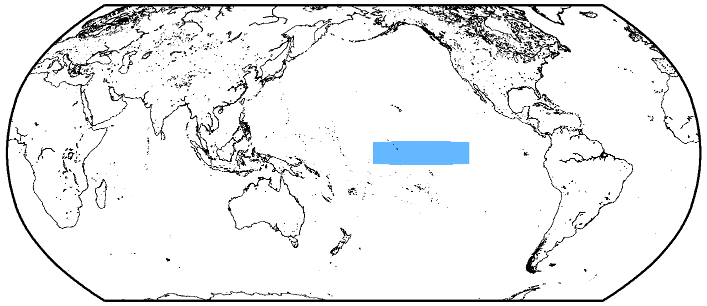
Cloud Fraction

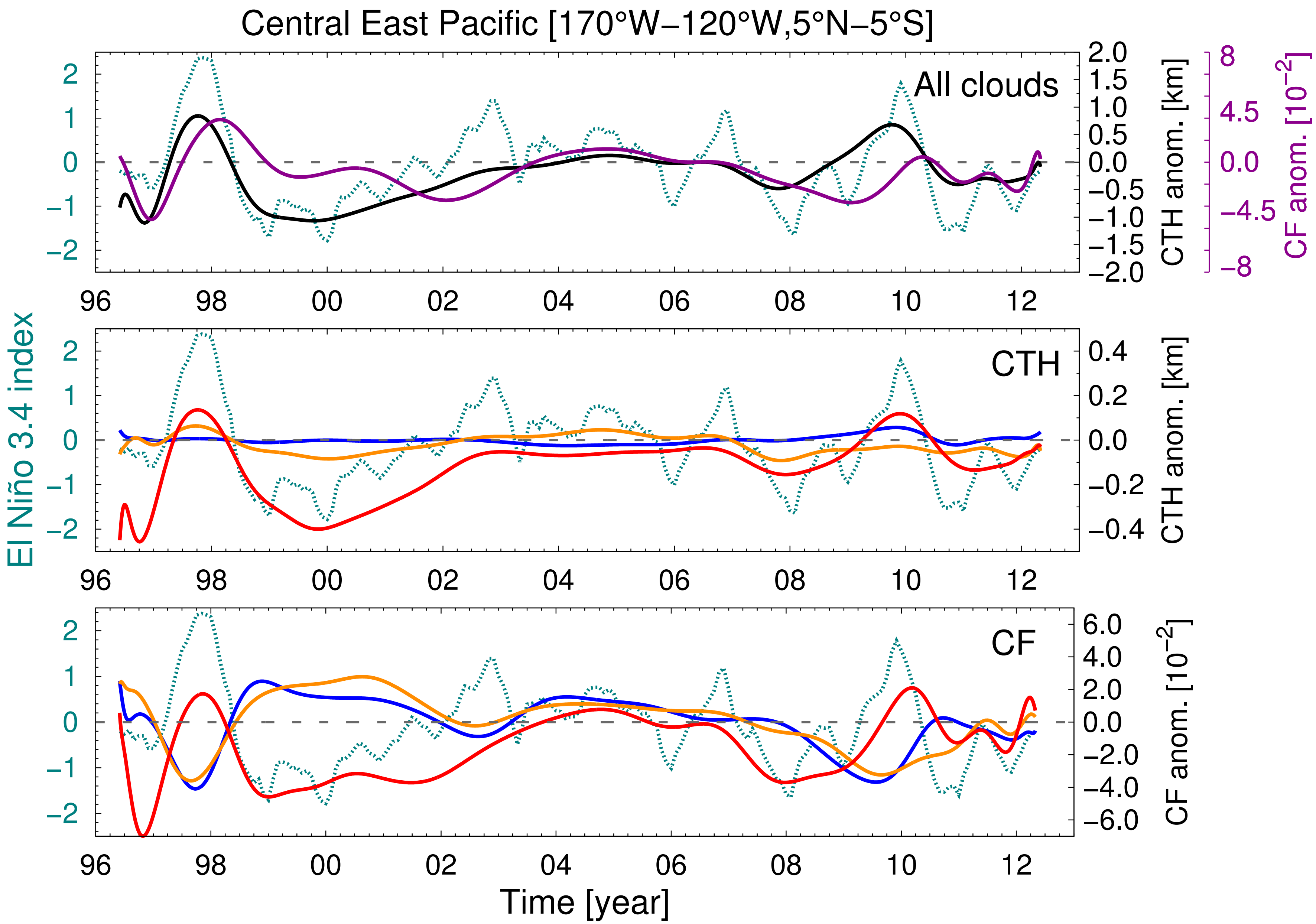
HIGH clouds **+ 0.53**

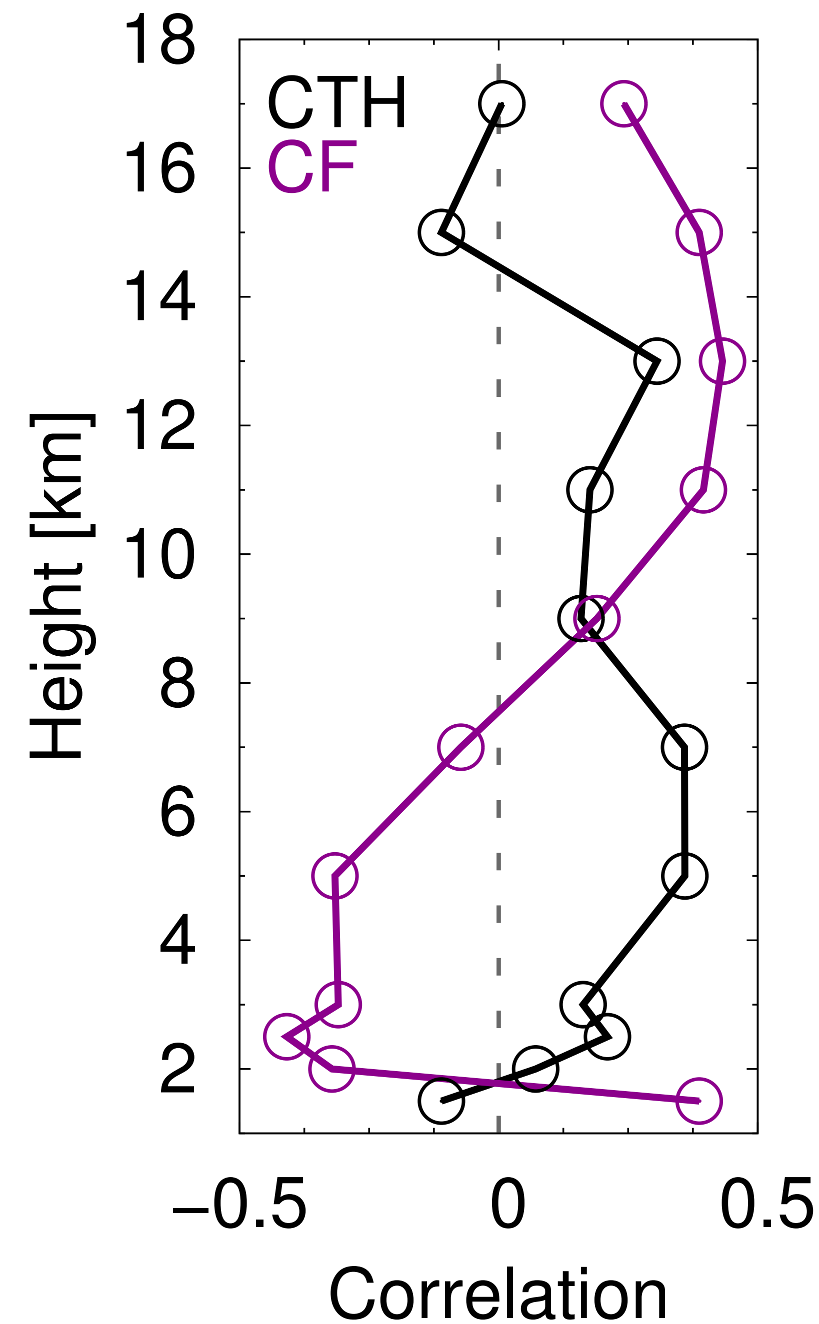
MID clouds **- 0.31**

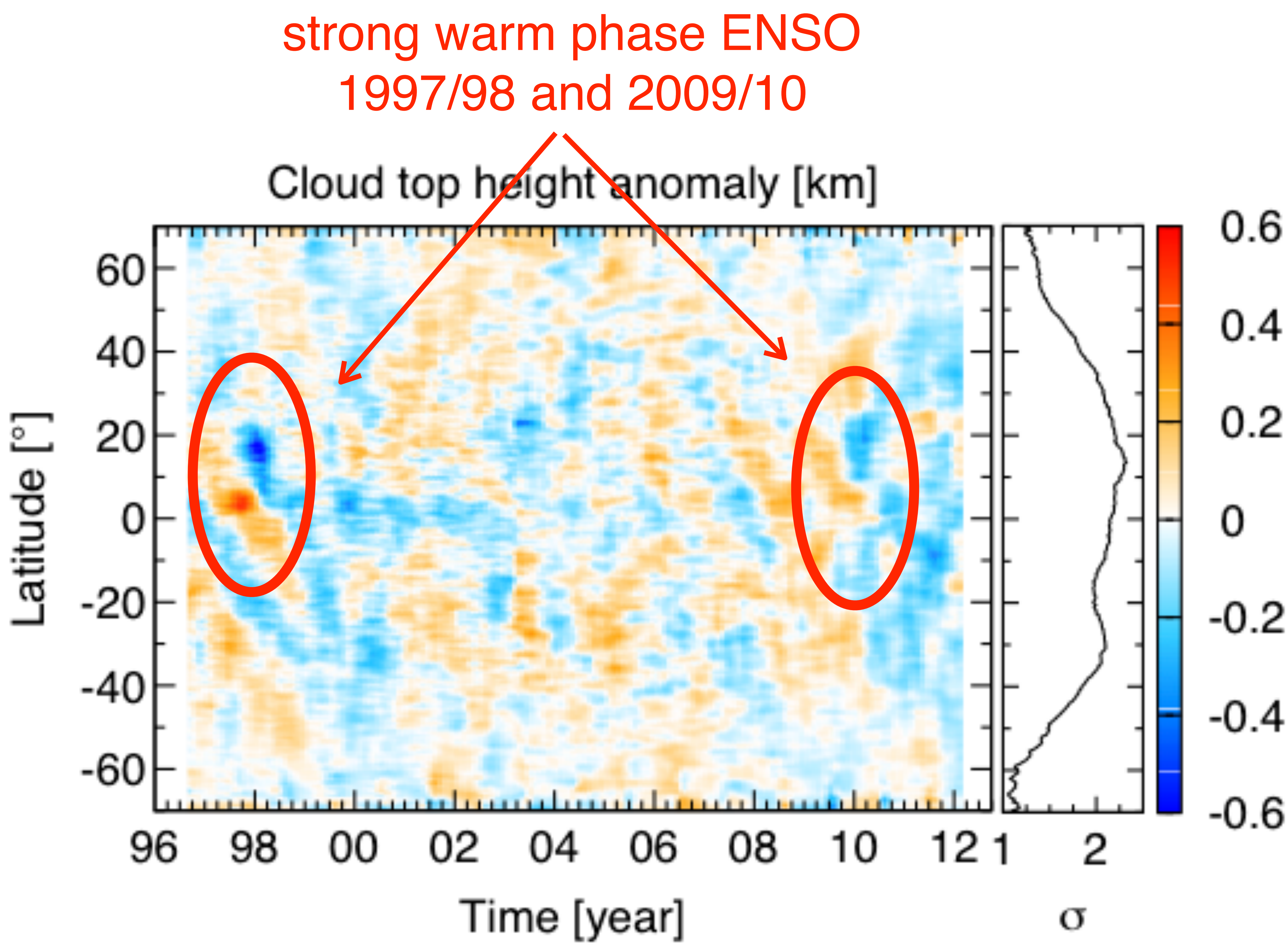
LOW clouds **- 0.55**

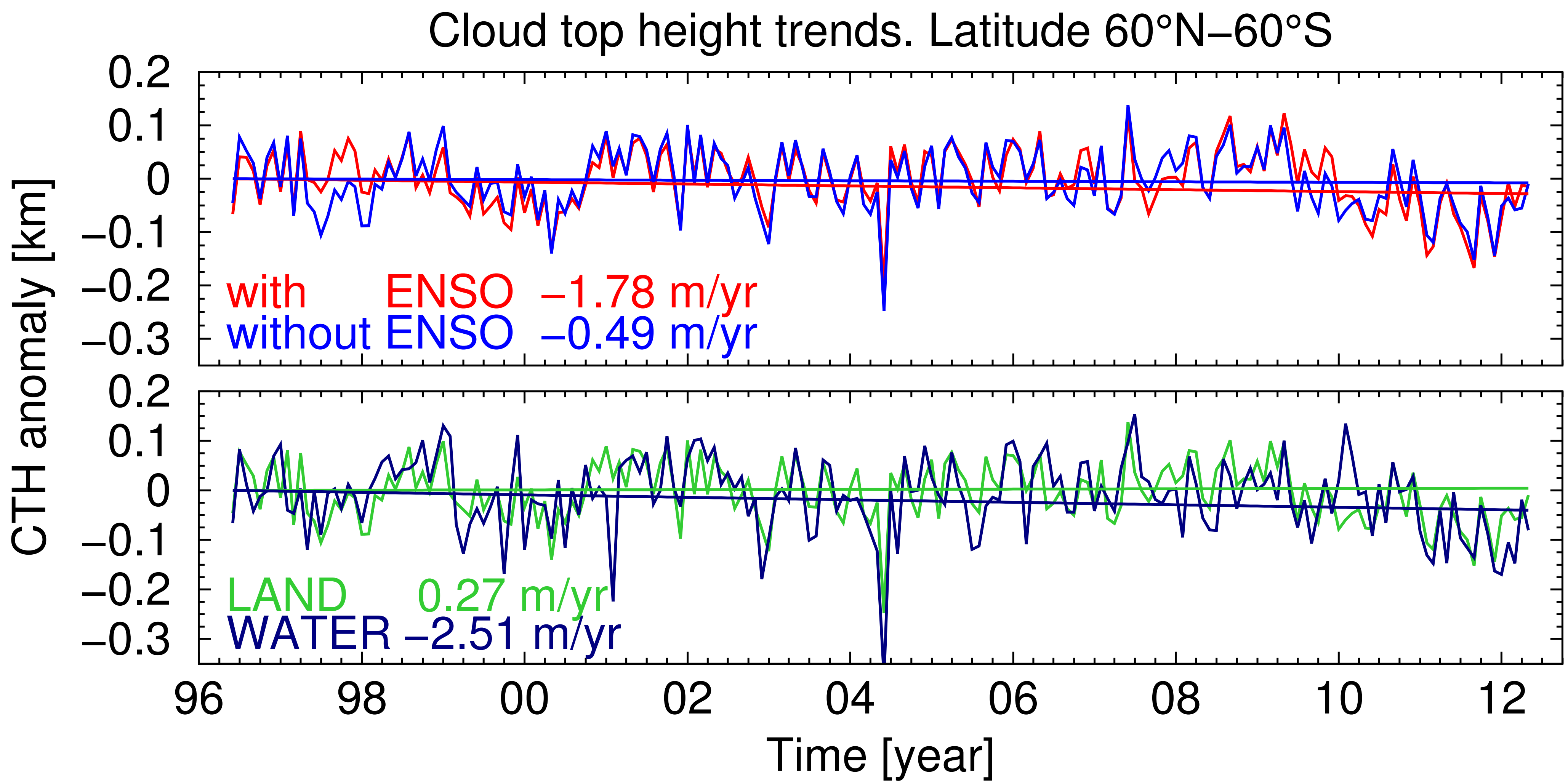
ENSO




Central East Pacific [170°W–120°W,5°N–5°S]
All clouds
CTH
CF
El Niño 3.4 index
CTH anom. [km]
CF anom. [10^{-2}]
Time [year]
96 98 00 02 04 06 08 10 12


CTH
CF
Height [km]
Correlation
−0.5 0 0.5


strong warm phase ENSO
1997/98 and 2009/10
Cloud top height anomaly [km]
Latitude [°]
60
40
20
0
-20
-40
-60
96
98
00
02
04
06
08
10
12
1
2
Time [year]
σ
0.6
0.4
0.2
0
-0.2
-0.4
-0.6

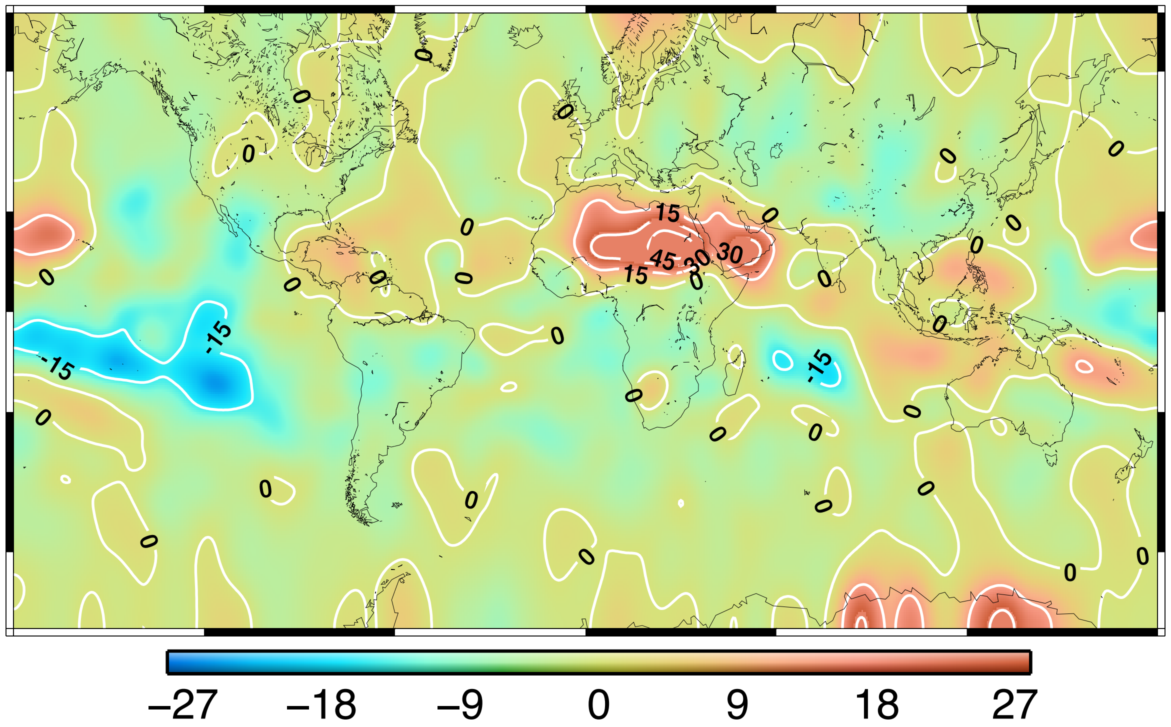


Base period [year month^{-1}]	MISR	MISR corr.	MODIS	GOME	GSG	
03/03 – 11/02	–40.1[b]	+54.3[c]	+60.9[c]	–	–10.7	+8.4
96/06 – 03/05	–	–	–	–47.9[d,e]	–67.2[e]	+25.2[e]
96/06 – 12/05	–	–	–	–	–17.8	–4.9

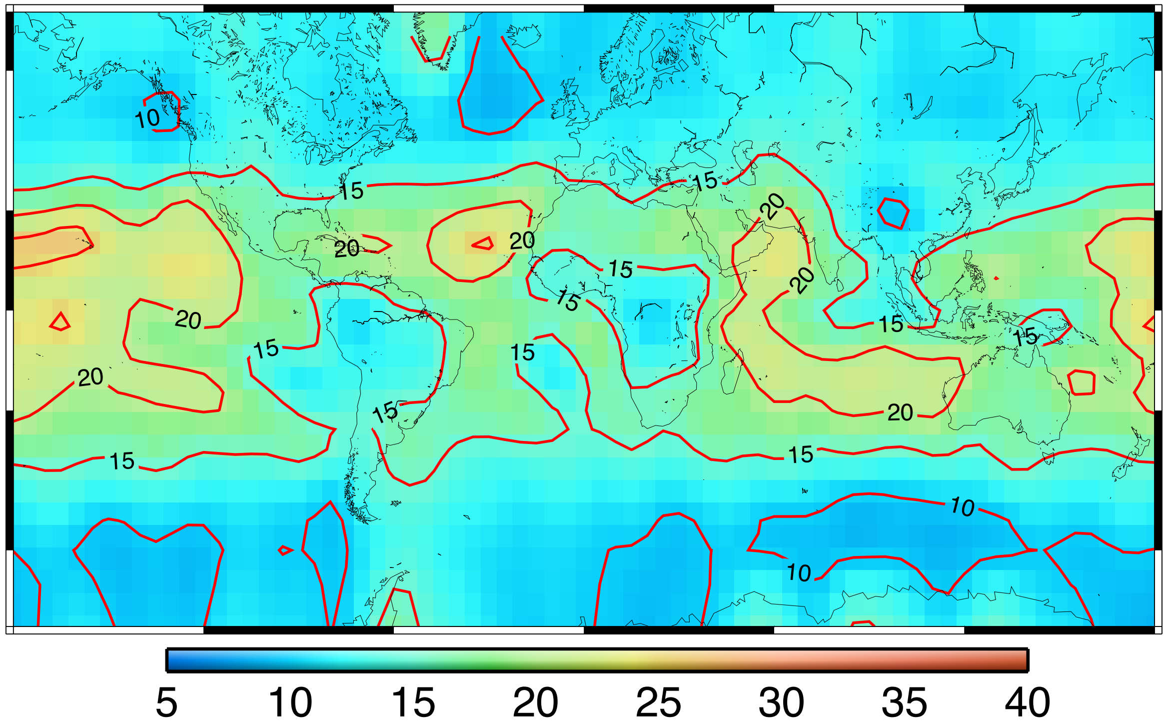
[a] The GSG trends are recalculated for the length of the referenced dataset and latitude belt ±60°.
[b] Davies and Molloy (2012).
[c] Evan and Norris (2012).
[d] Loyola et al. (2010).
[e] Extrapolated to decade.

CTH trends

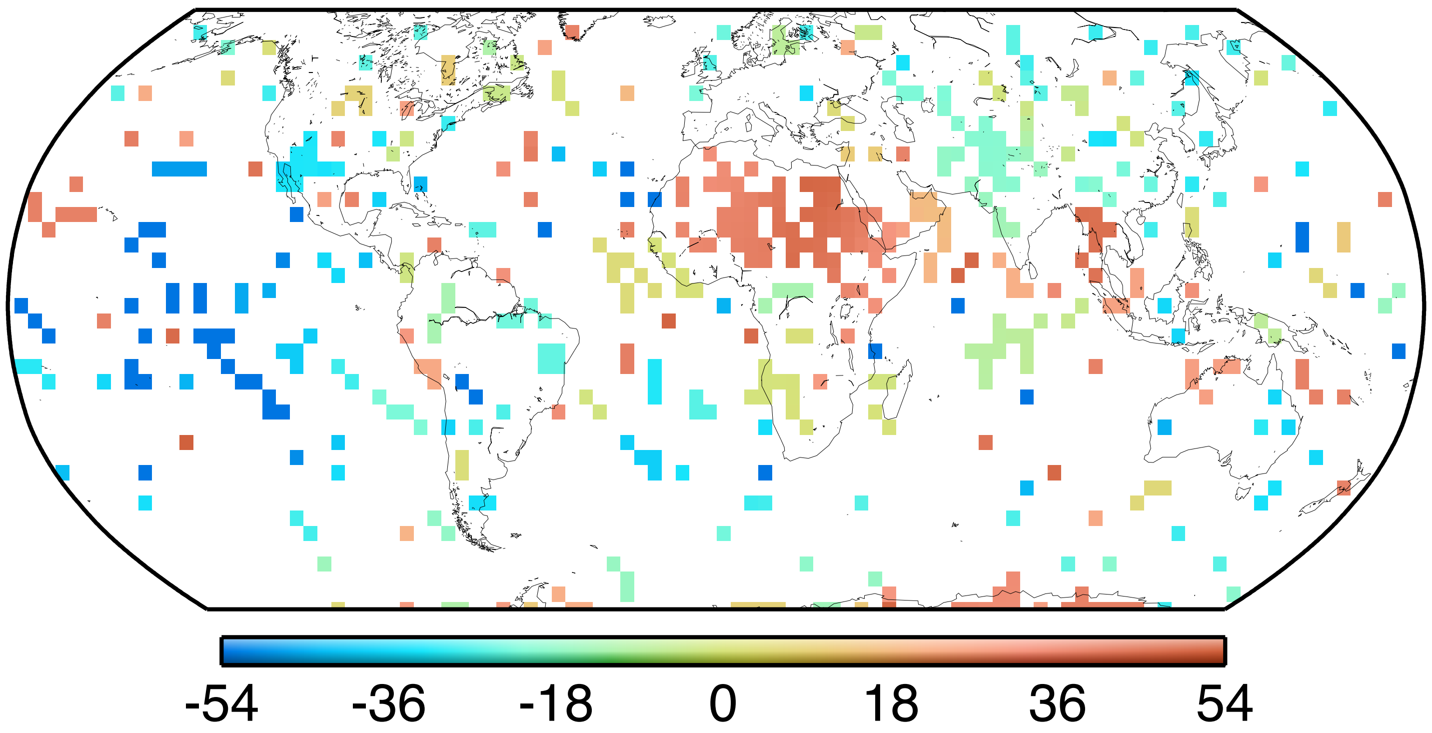
Trend β [m/yr]



Trend β standard deviation [m/yr]



Significant trend β [m/yr]

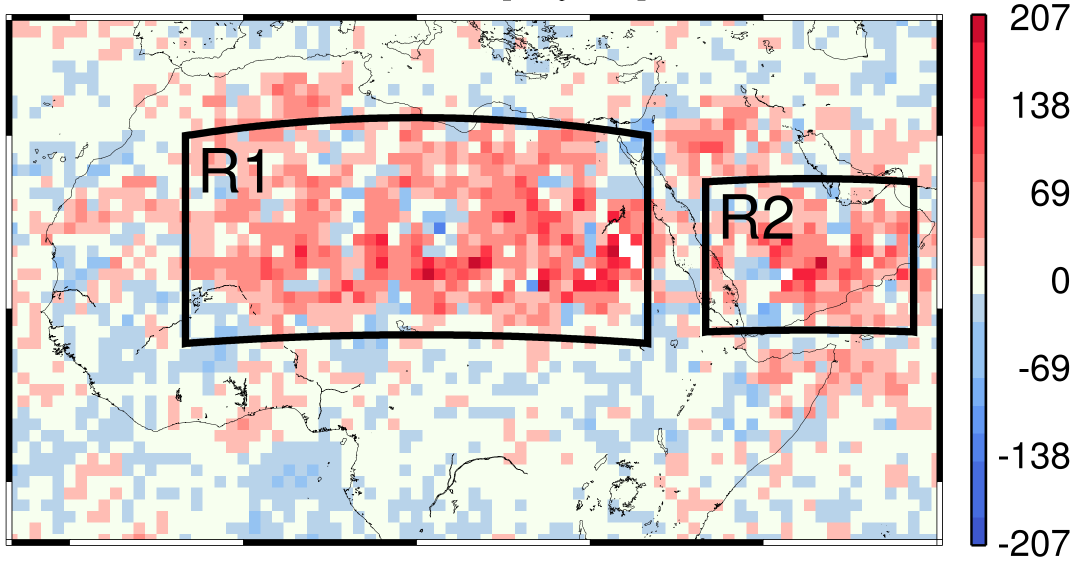


CTH, H_2O trends

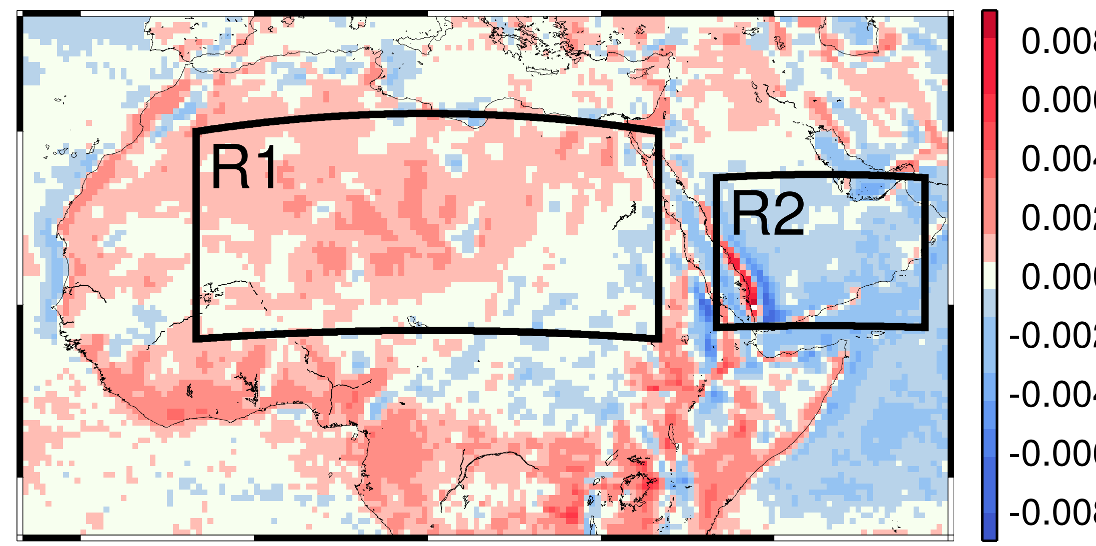
All values are given per year^{-1}. Reference values: CF 0.4, COT 15.

Region	CTH [m]	H_2O [g/m^2]	CF [%]	COT [%]
Sahara (R1)	+31.77	+0.0005	−0.066	+0.02
Arabia (R2)	+26.64	−0.0011	−0.088	+0.09

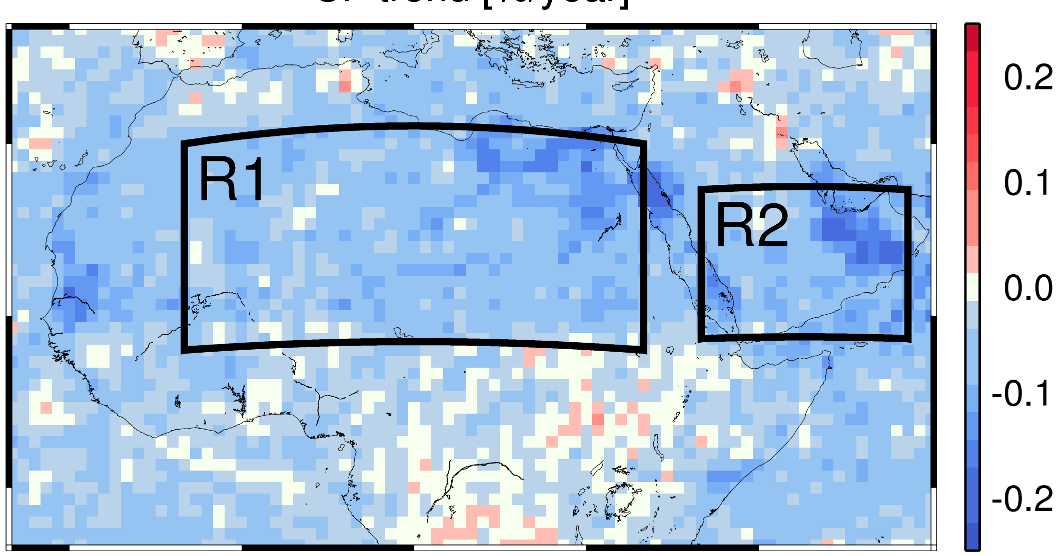
CTH trend [m/year]



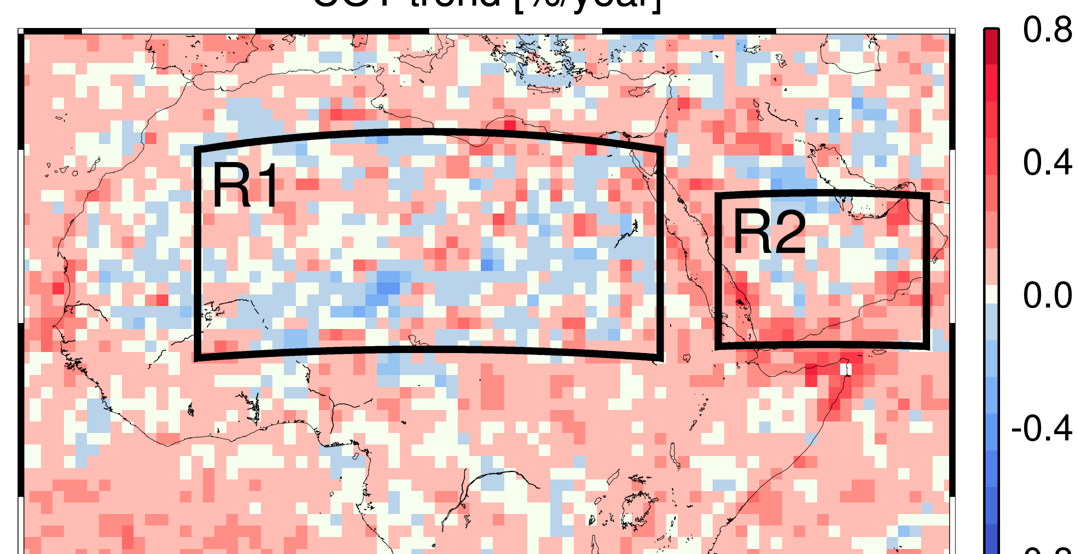
H_2O trend [g/m^2/year]



CF trend [%/year]



COT trend [%/year]



Water vapor data: Noël et al., GRL (1999), Noël et al., ACP (2004), Mieruch et al., ACP (2008)

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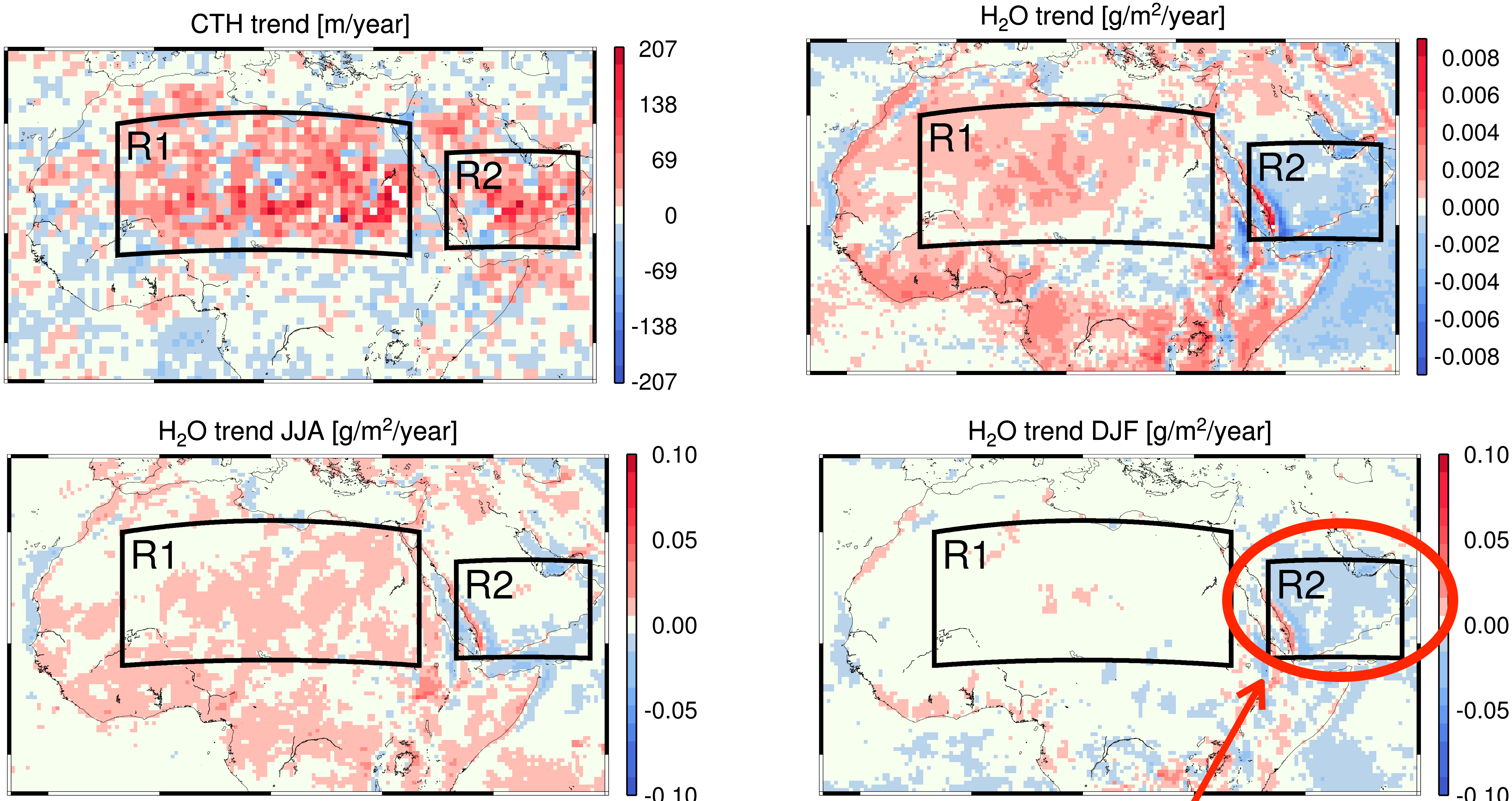
CTH, H_2O trends



Soot production

Winter phase of Indian Monsoon

Negative radiative forcing
at the surface

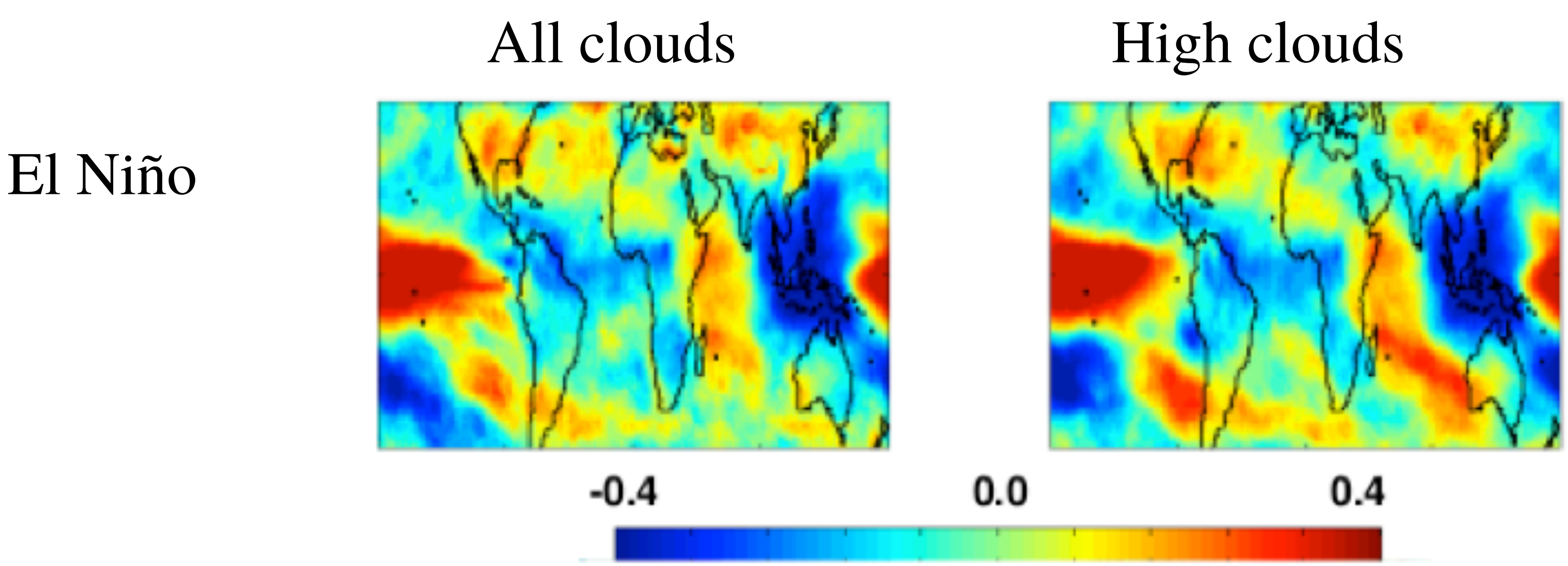
Nakajima, T. and Schulz, M. (2009)

Next task?

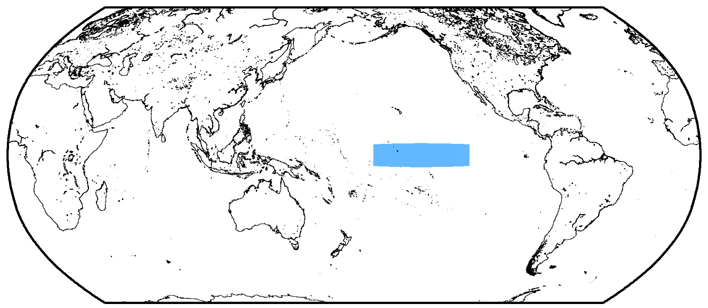
EC-Earth (Hazeleger et al., 2012, 2011) Atmospheric only run

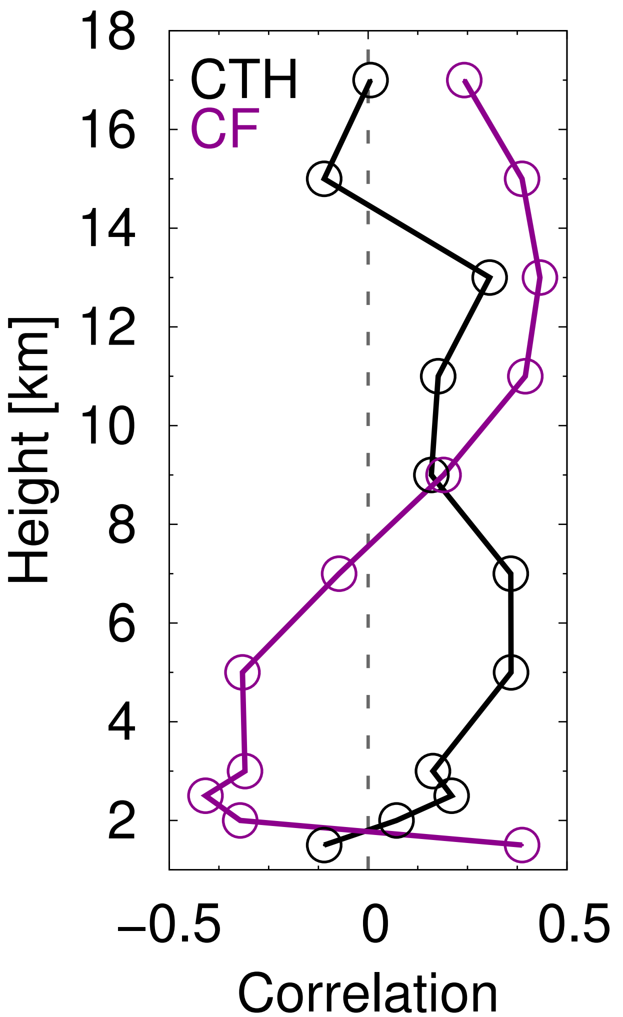
at T255L62 (0.7deg) forced with CMIP5 GHG, aerosols, O3m insolation and volcanoes, SST and sea-ice from ERA-Interim

Spatial correlation of cloud cover with ENSO index



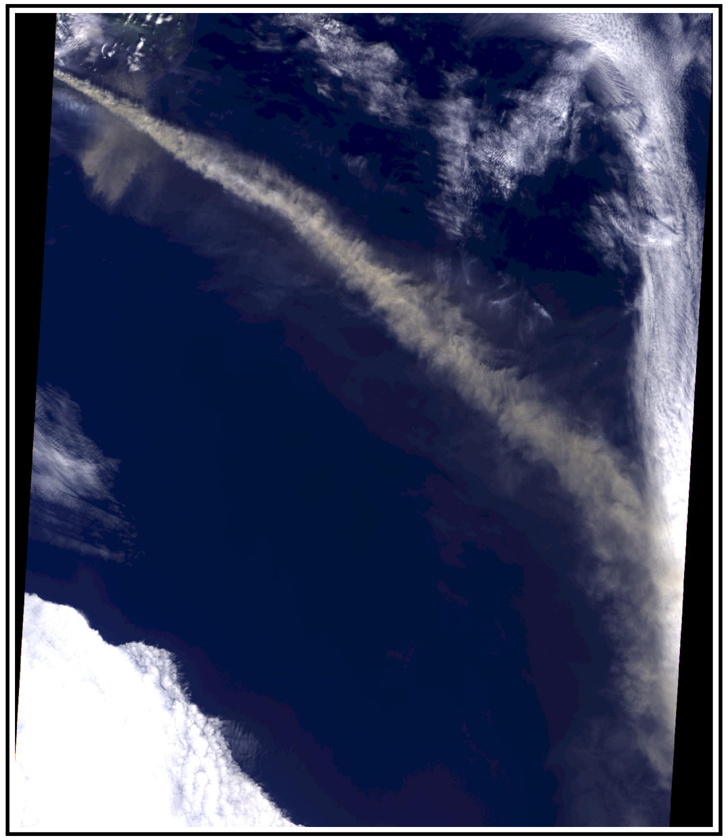
Courtesy of U.Willén (SMHI, Sweden)



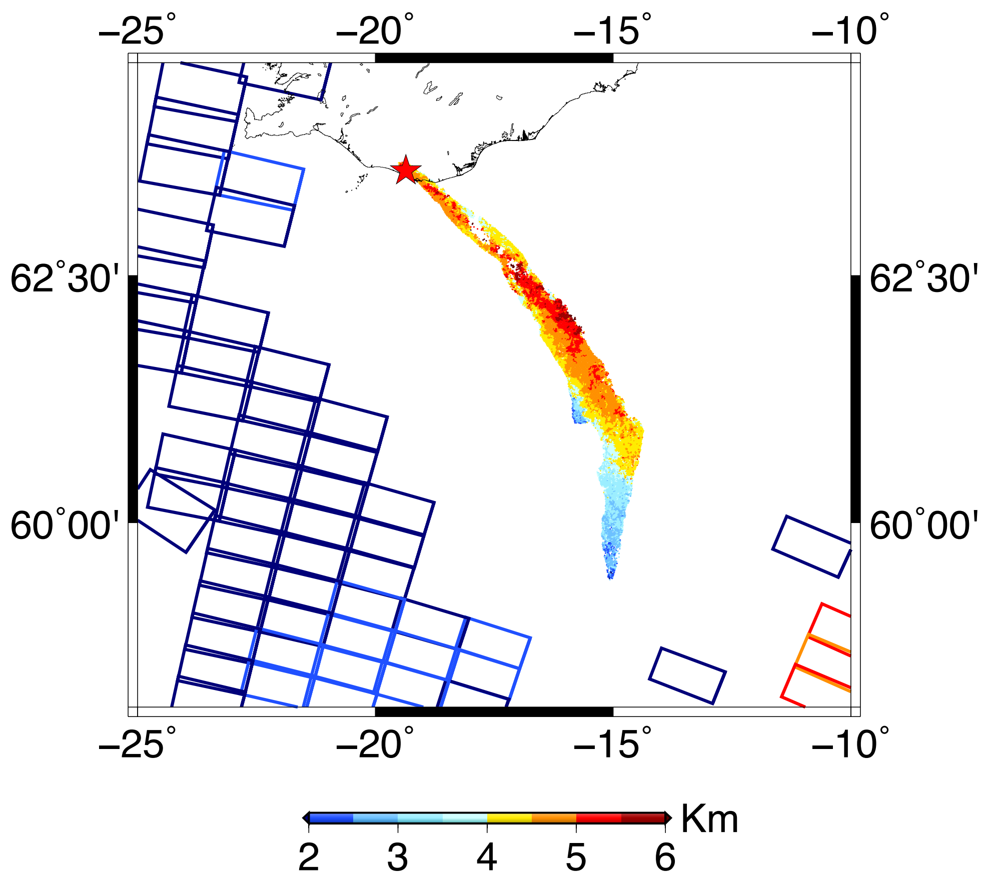


ALH in the O_2 A-band

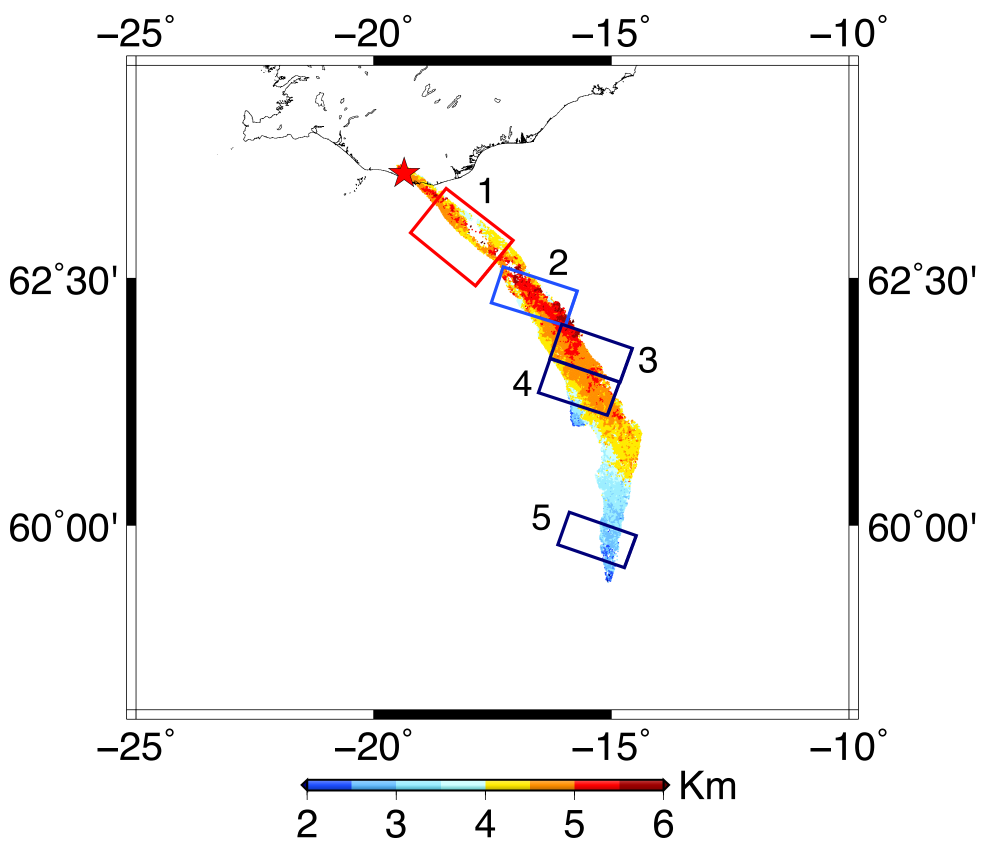
MISR RGB image 7 May 2010



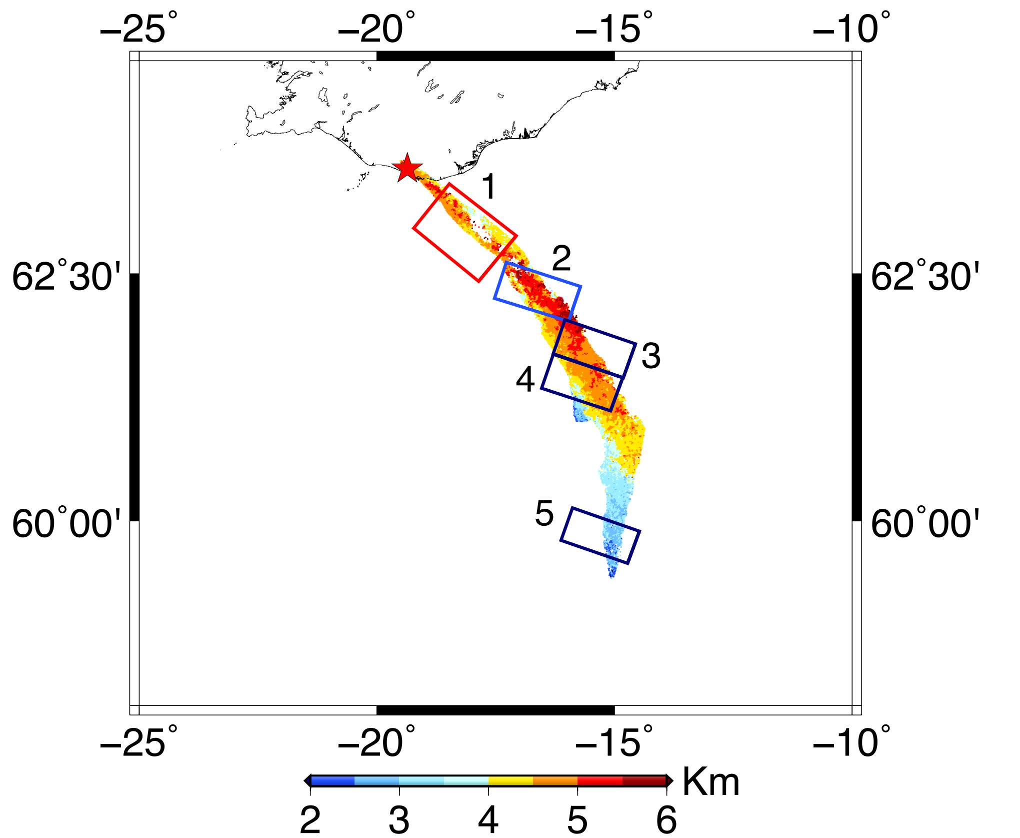
OCRA plume fraction

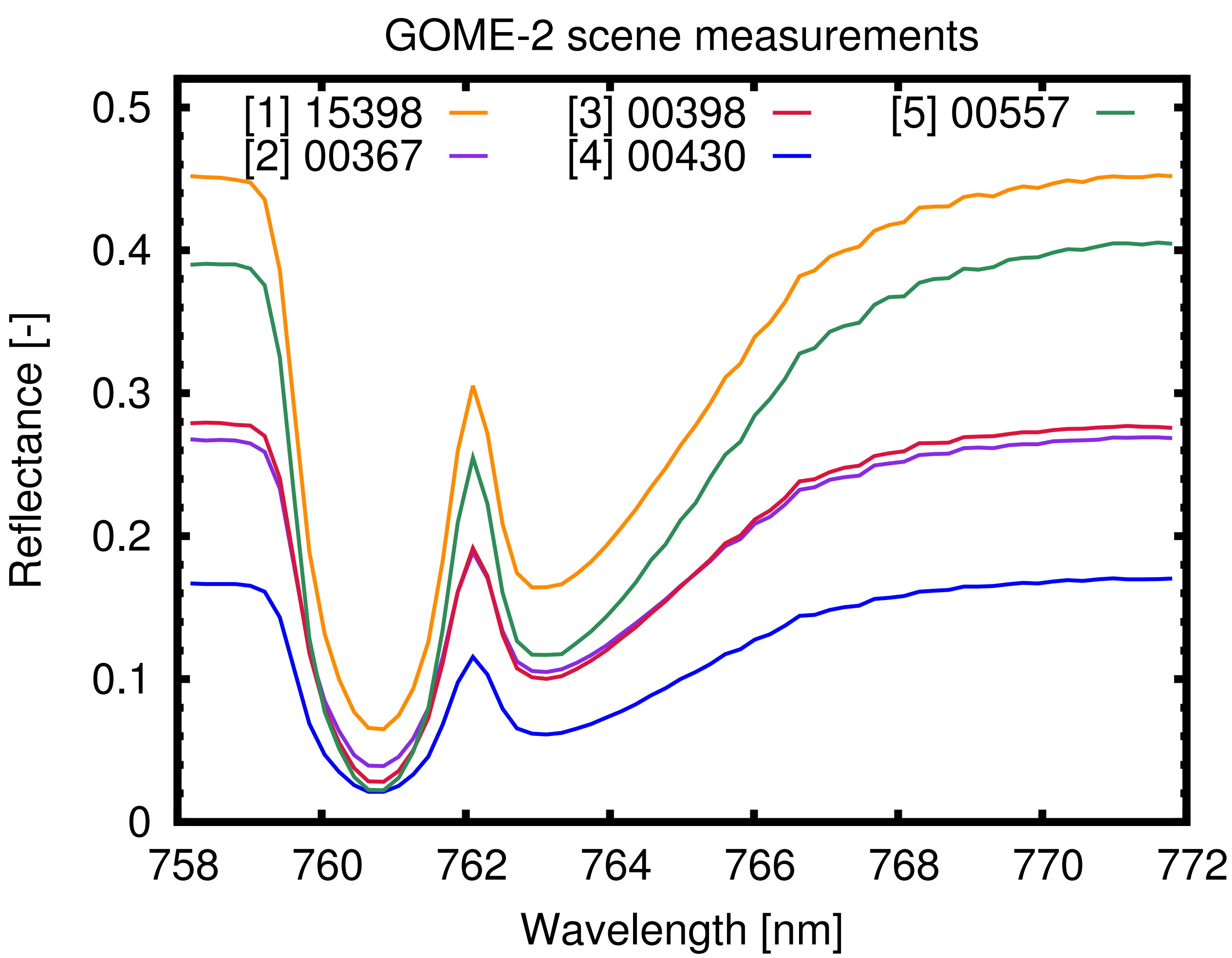


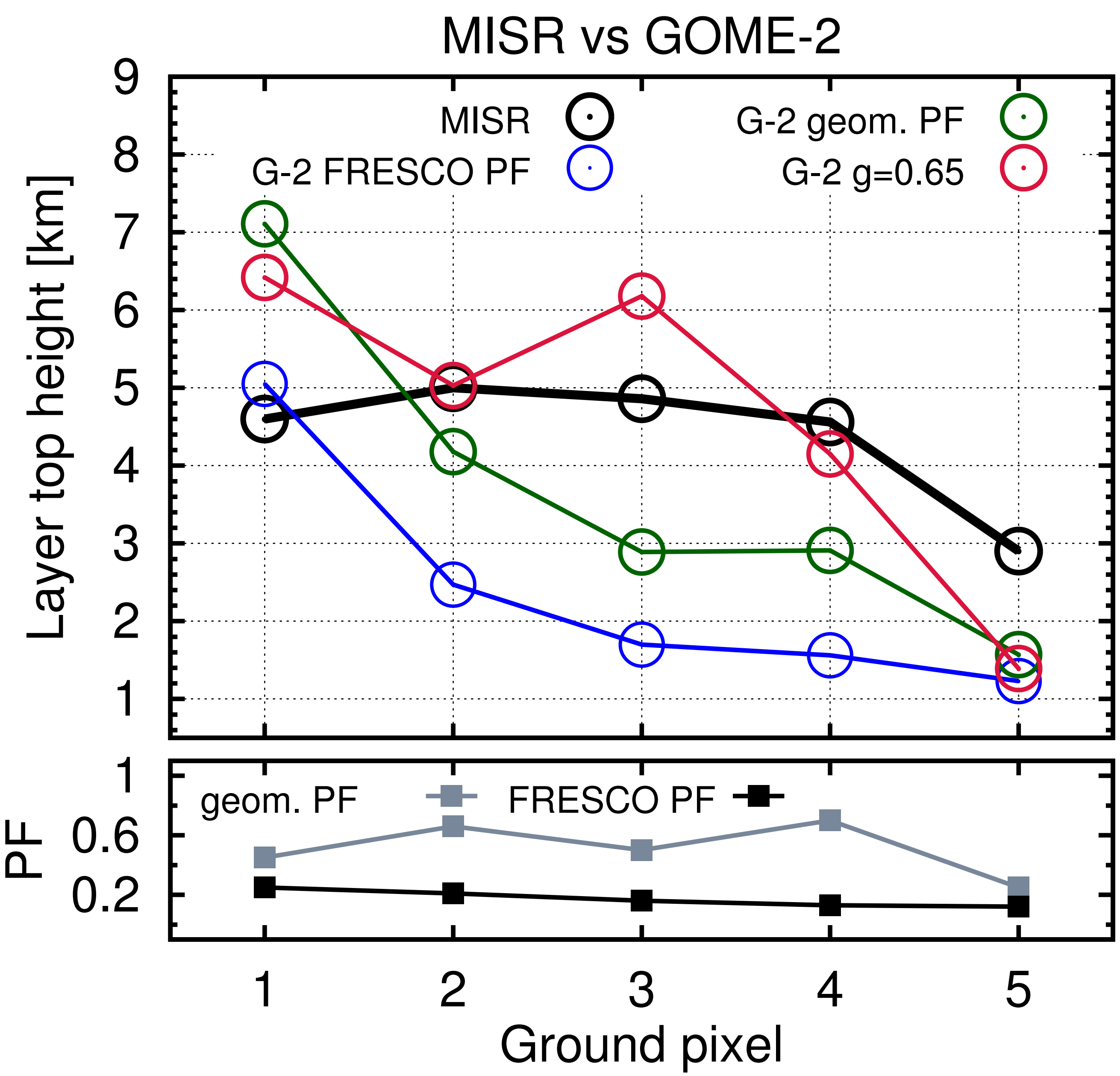
FRESCO plume fraction



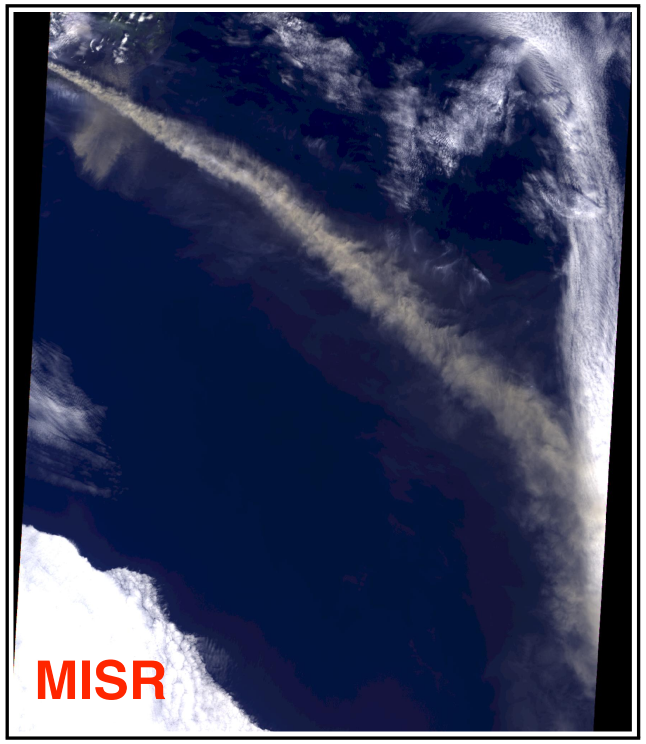
ALH in the O_2 A-band

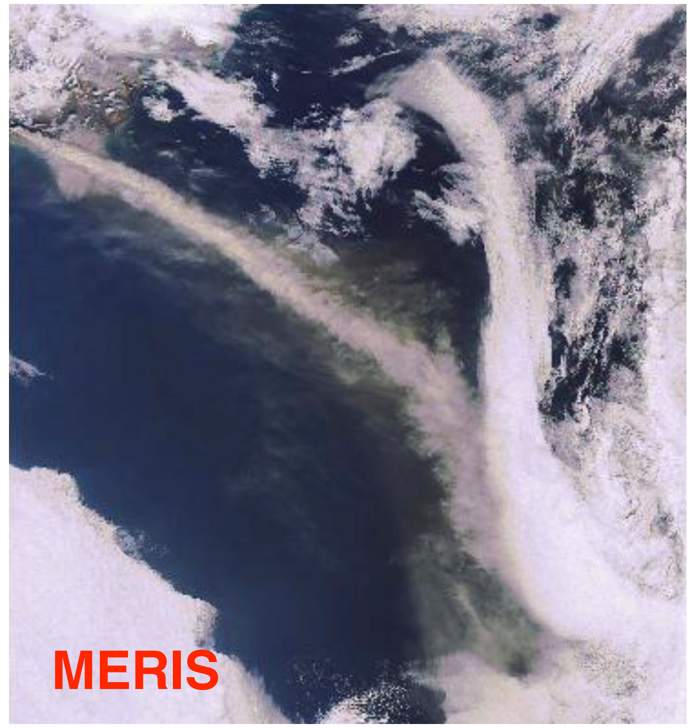


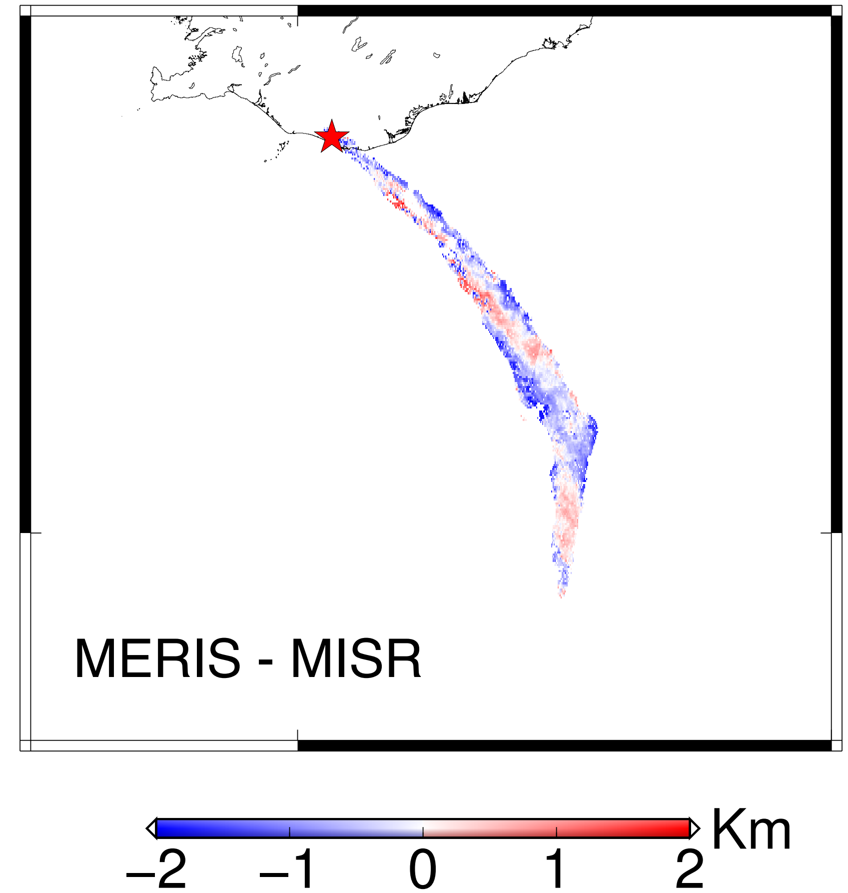


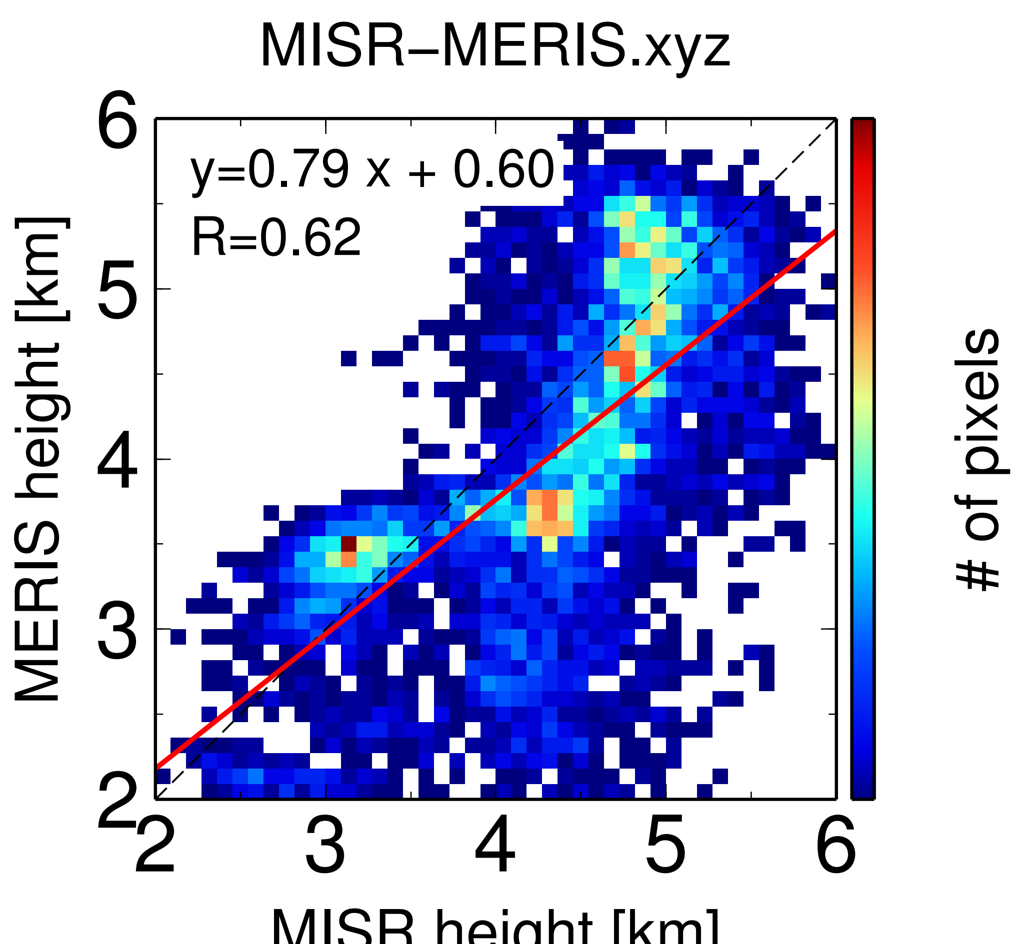


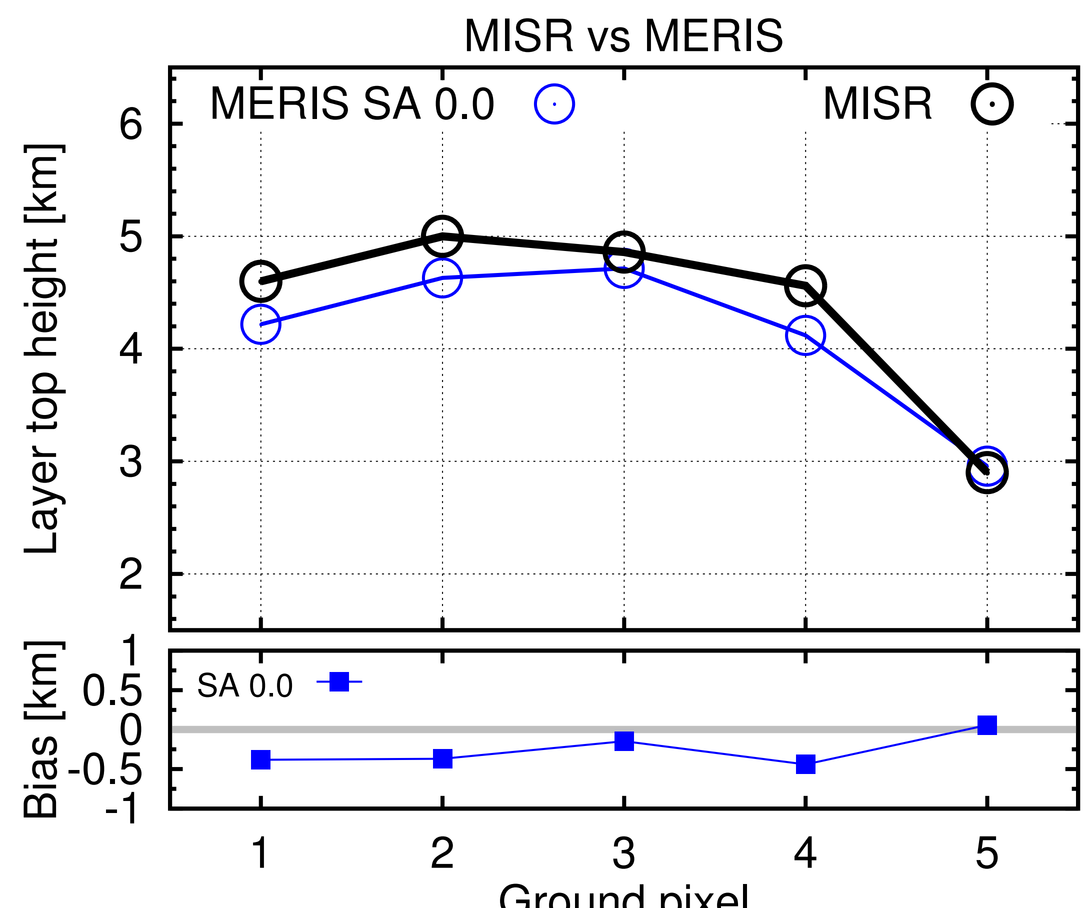
ALH in the O_2 A-band











Conclusions

Summary

1. Cloud top height (at monthly sampling) is **not persistent** and the trend is **normally** distributed
2. ENSO pulls clouds to lower altitudes (**negative** feedback)
3. Global CTH trends of **opposite sign** over **ocean** / **land**
4. **No clear synoptic patterns** (yet) of statistical significance (at 95% CI)
5. Increase (decrease) in H_2O >>> Soot production
   >>> significant (not significant) CTH trend

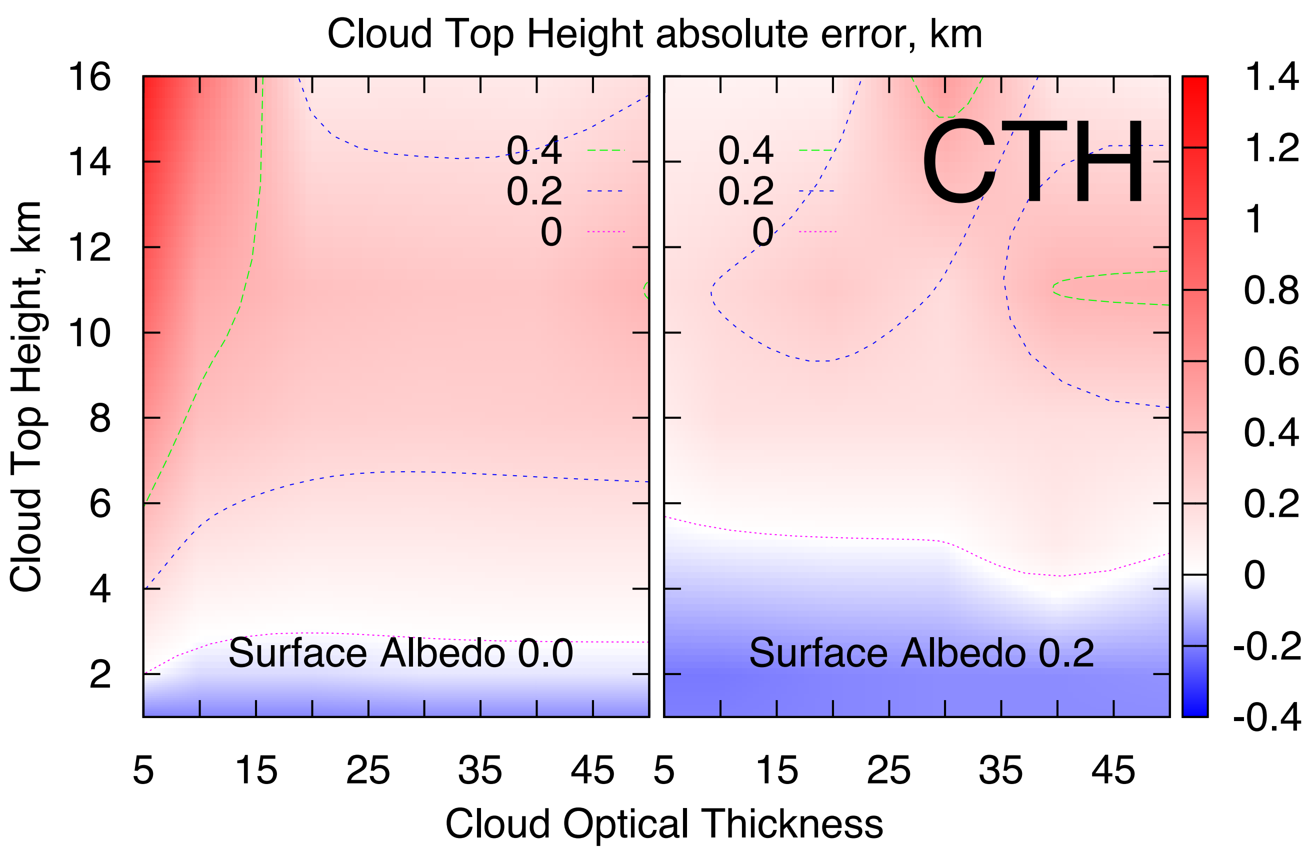
Have your say: Lelli et al., 2013, ACPD

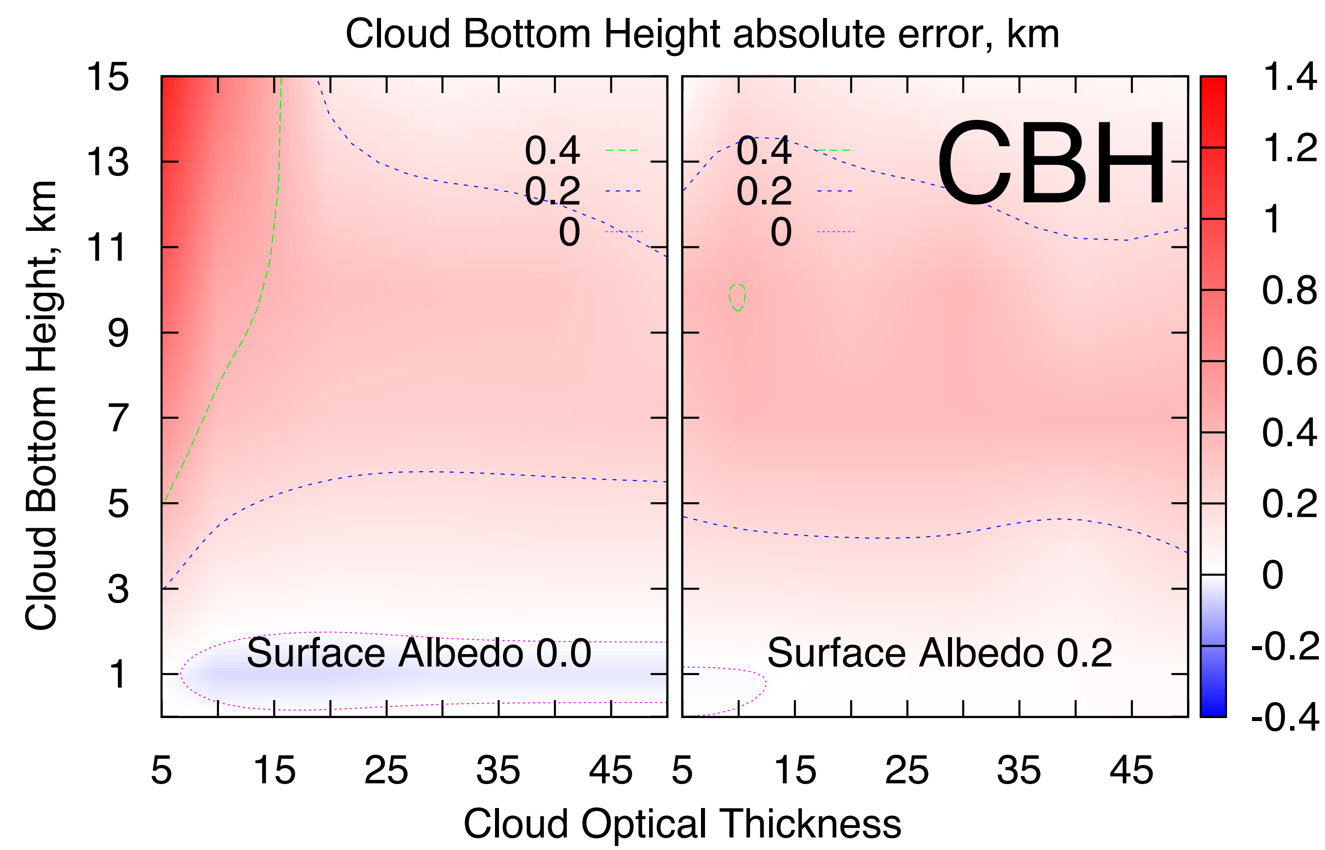
Outlook

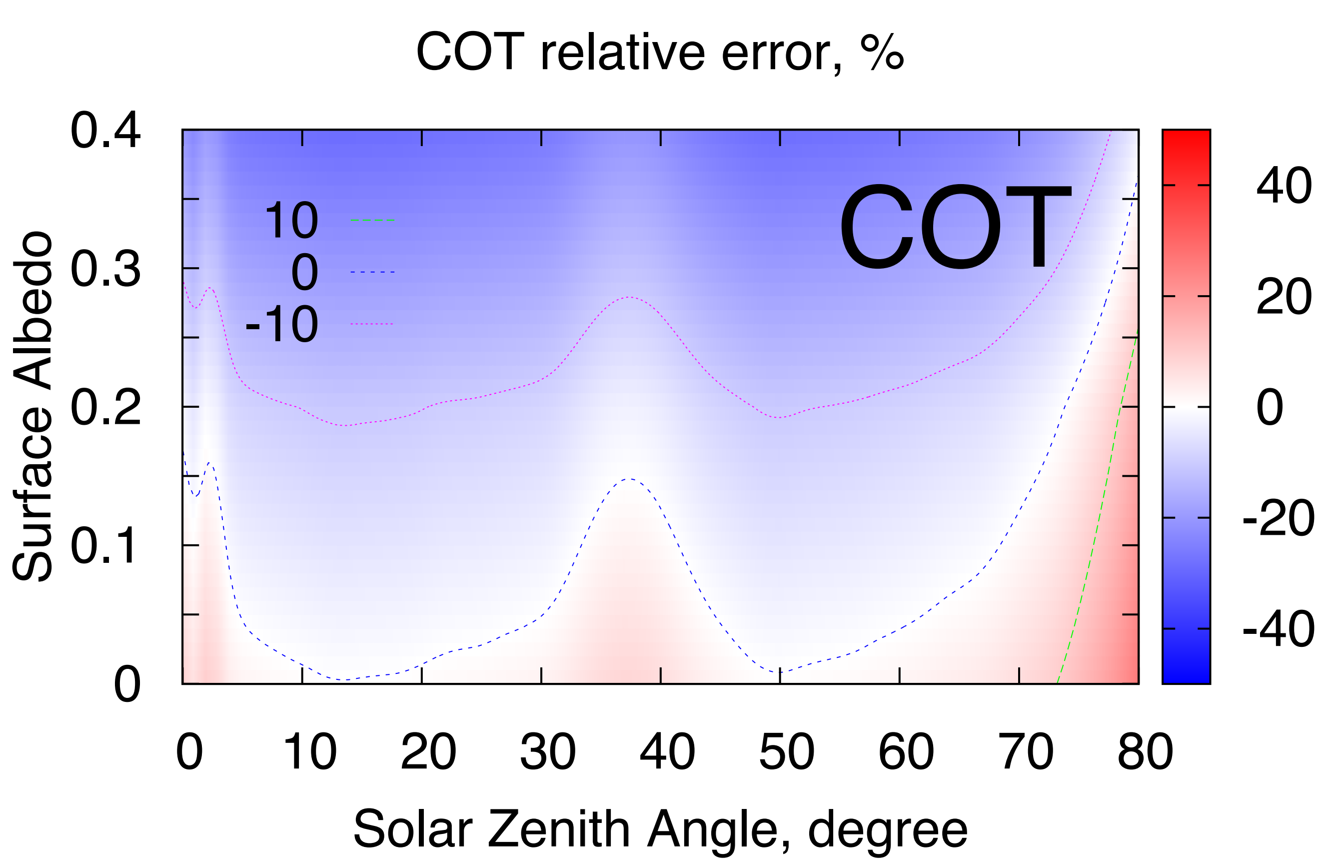
1. Cloud record **extension**: MetOp-B/C, Sentinel 5-p (beyond 2020)
2. Increased **spatial resolution** >>> more single-layered clouds
3. **Plane parallel** model to be improved >>> 3D + adjacency effects
4. Untangle **meteorology**: process- and attribution-oriented study

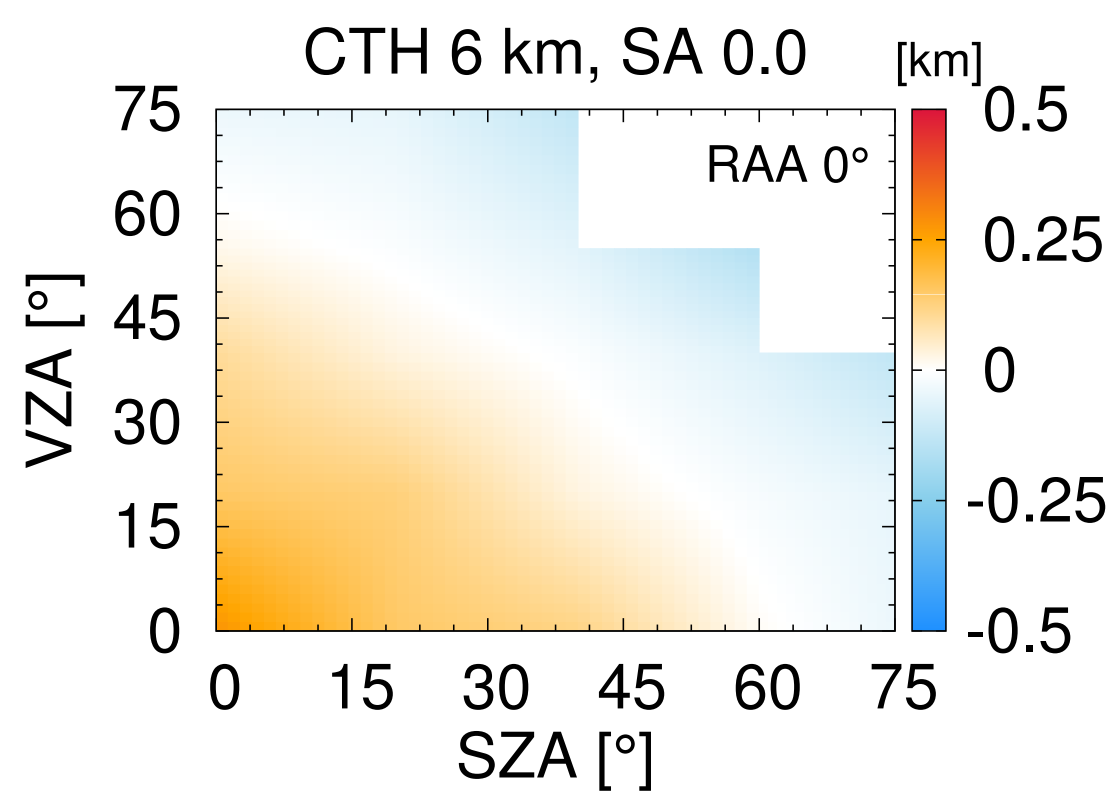
Backup slides

Validation (1): model errors





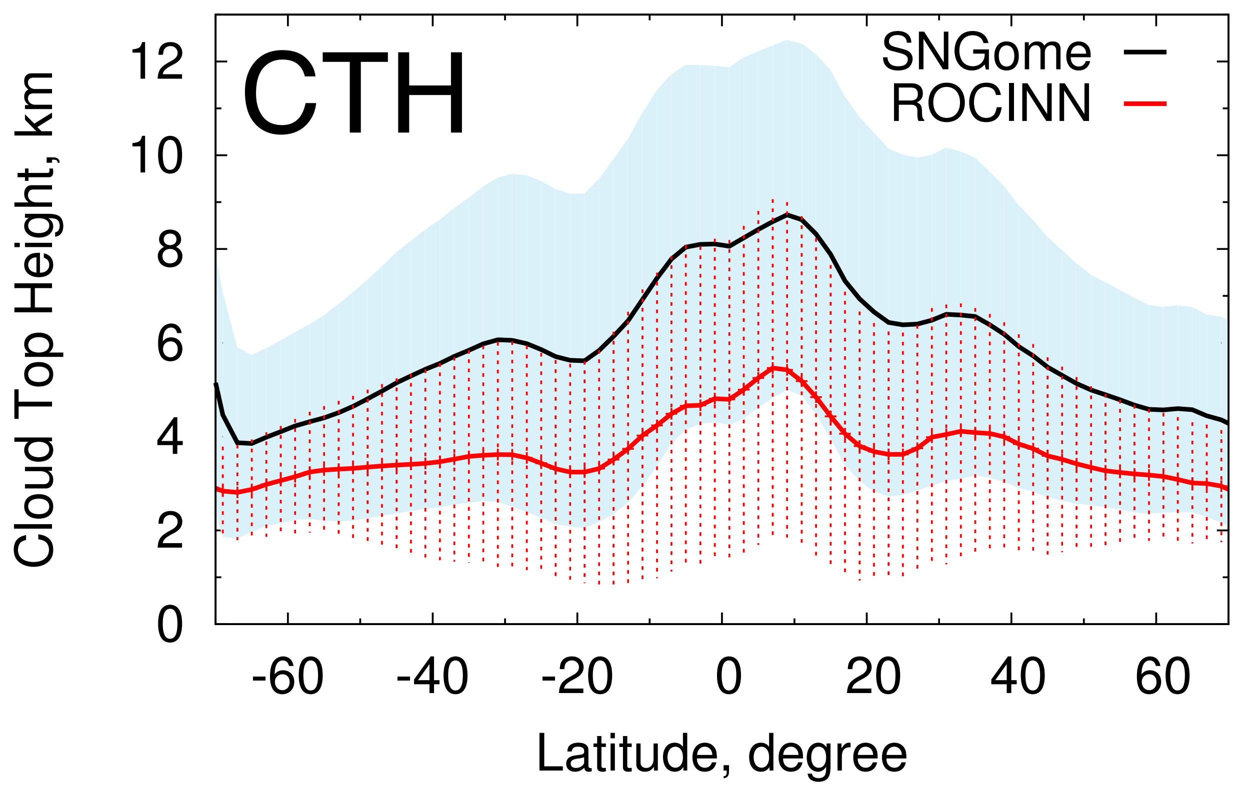




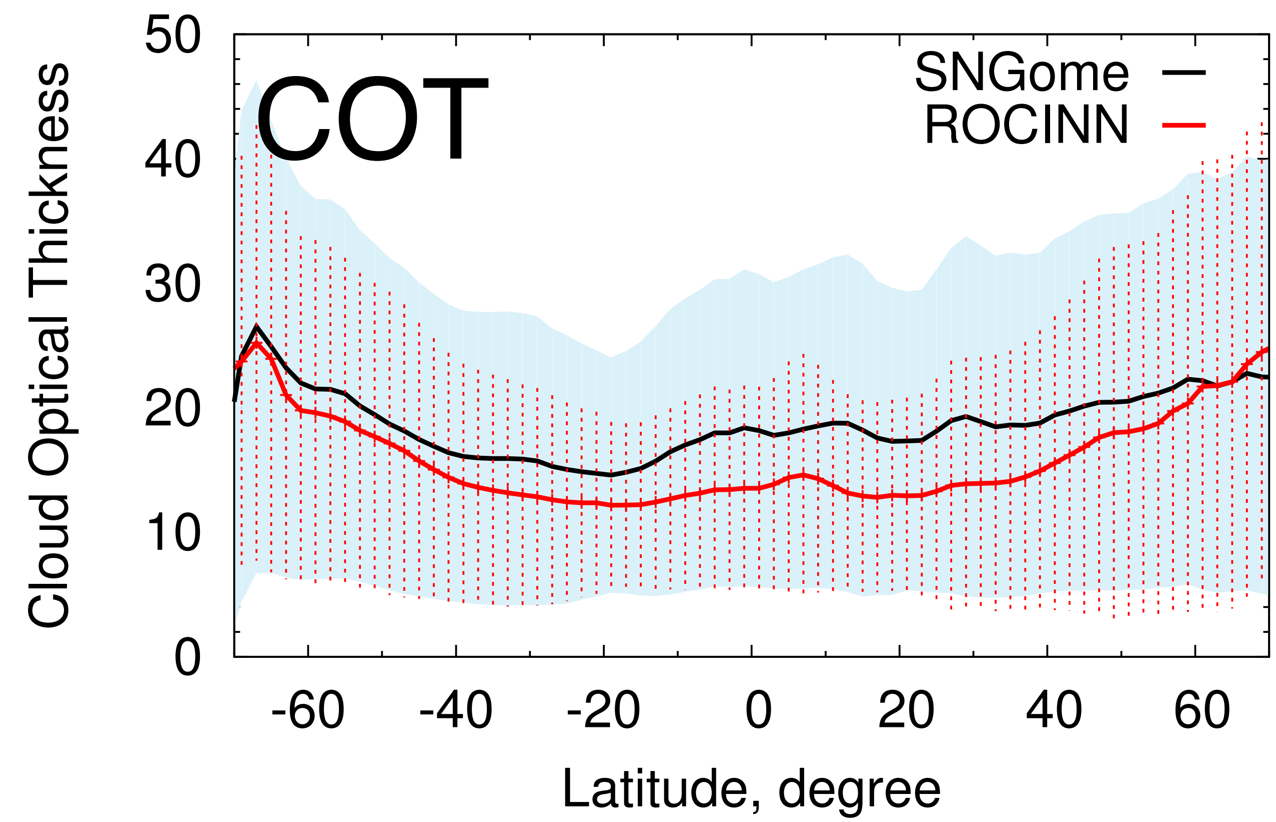
Universität Bremen

Validation (3): GOME - ROCINN

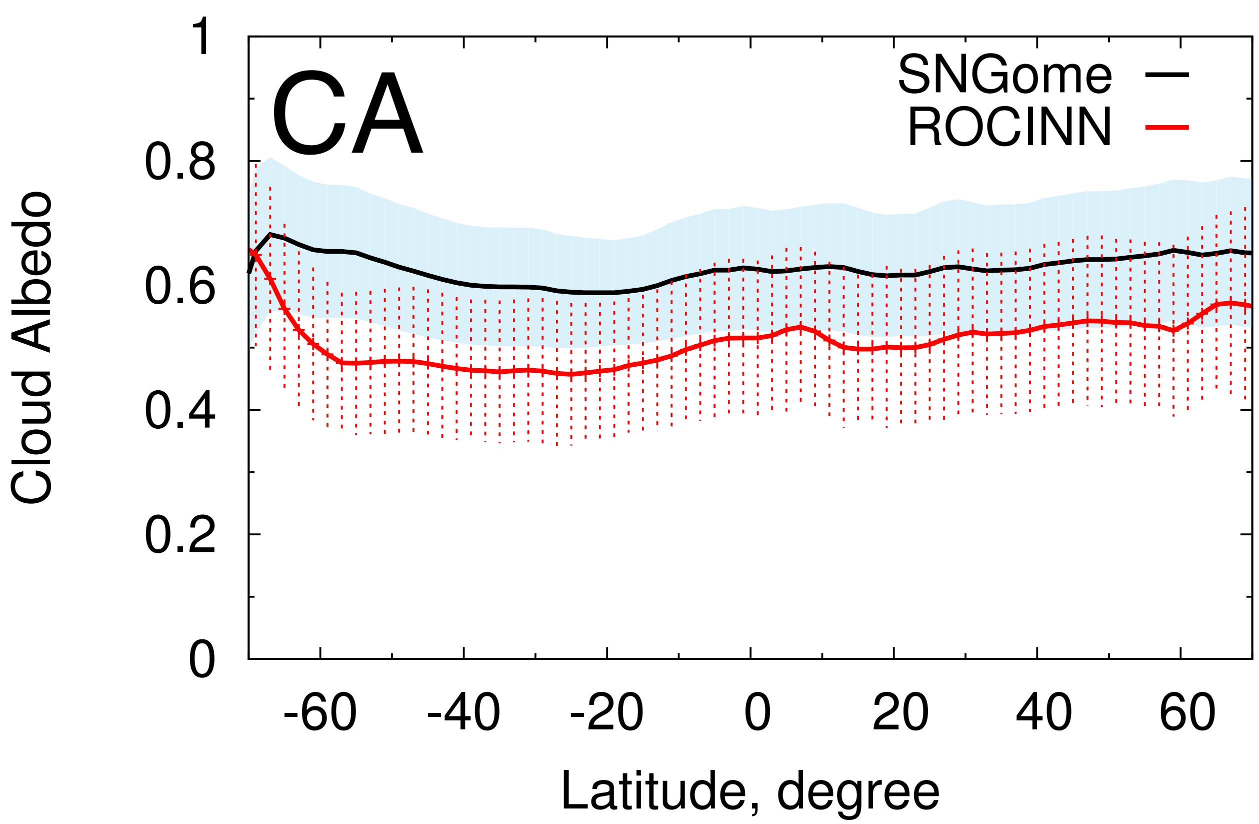
Zonal means (06/1996-05/2003)



Zonal means (06/1996-05/2003)



Zonal means (06/1996-05/2003)



PRO

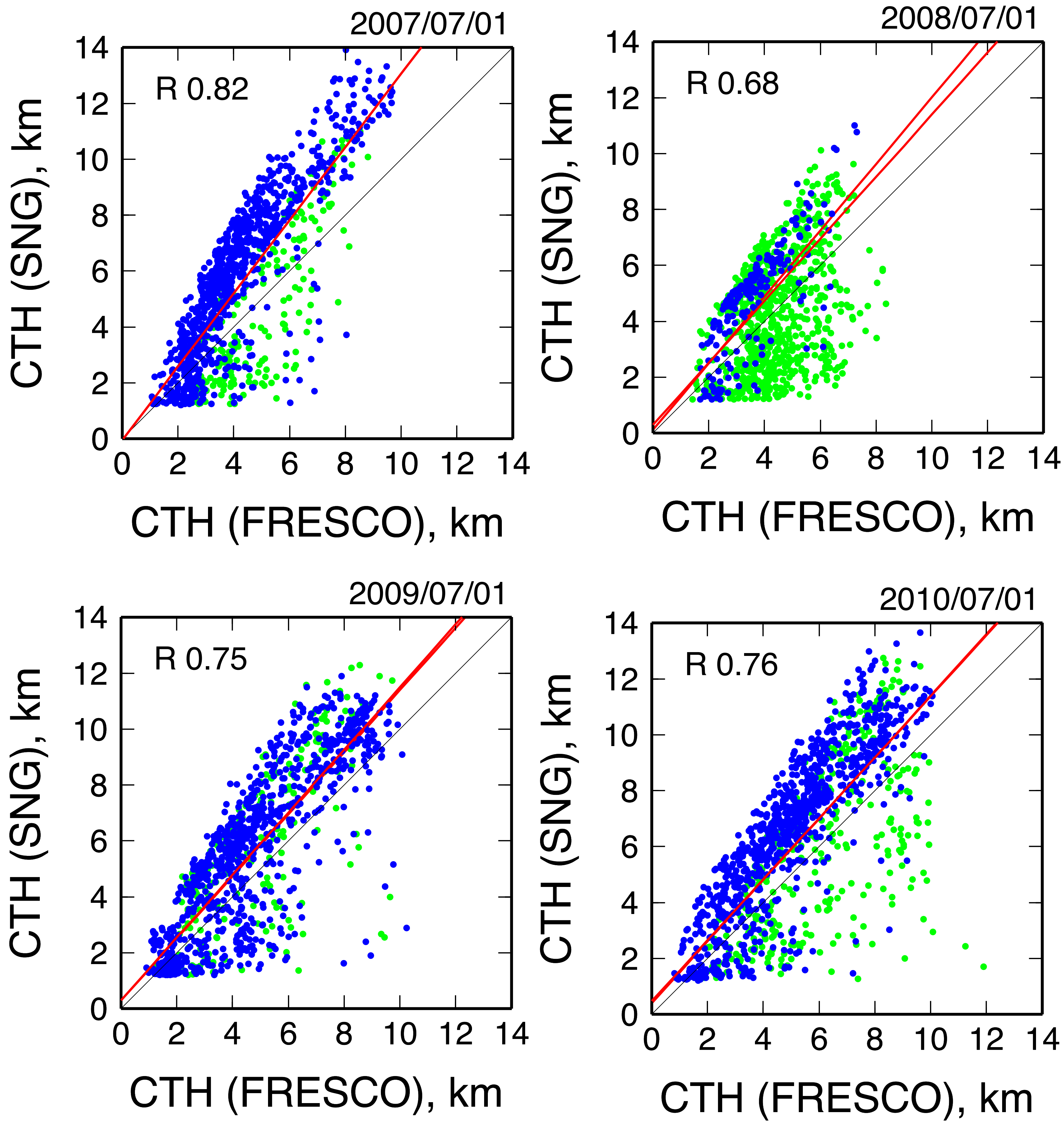
- Increase in global AOT
    - Water: ATSR-2, Twomey effect
        - Gassó, JGR, 2008, Thomas et al., ACP, 2010
        - Bulgin et al., GRL, 2010
    - Land: not very clear yet

CONTRA

- *Cloud Albedo effect* (horizontal/vertical variability)
- SNGome only optically thick clouds (COT > 5)

Lelli et al., AMT, 2012

Validation (4) GOME-2: FRESCO



WATER

LAND

FRESCO = Fast **RE**trieval **S**cheme for **C**loud **O**bservables

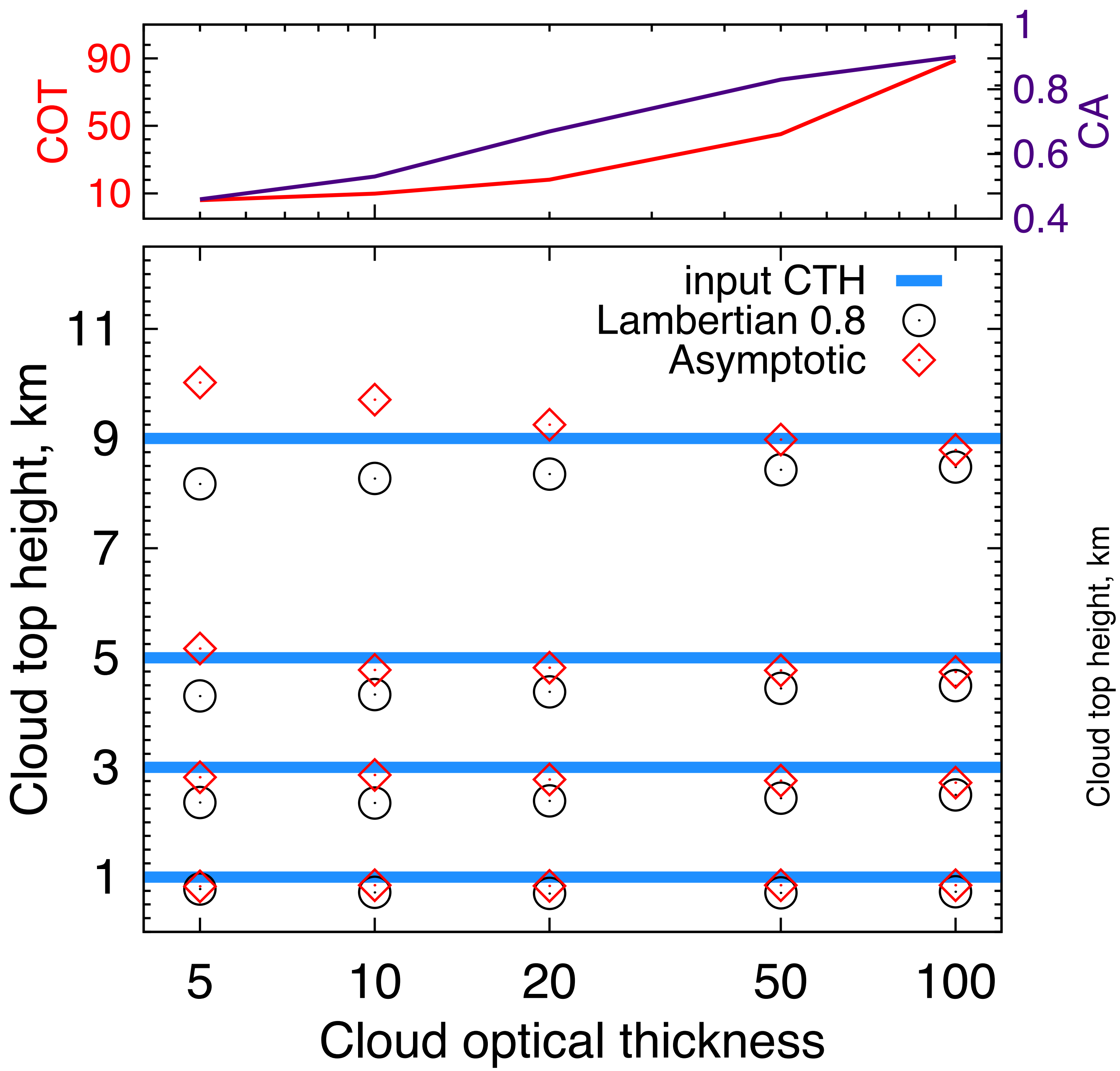
O_2A-band algorithm (KNMI)

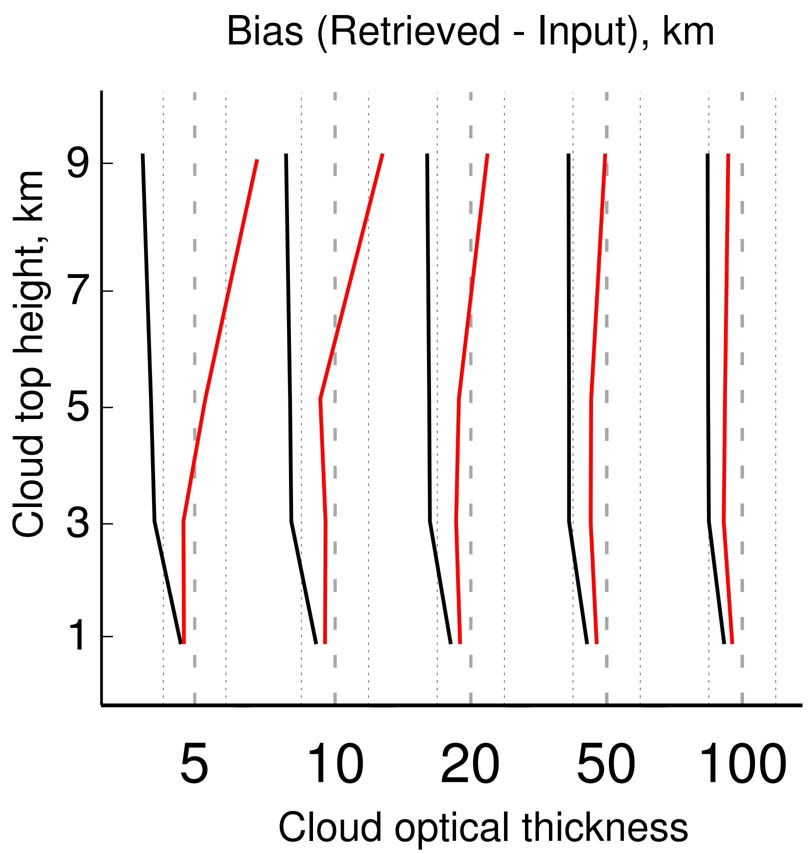
fixed cloud albedo (= 0.8)

$$\mathrm{CF}\ R_{\mathrm{cl}} + (1 - \mathrm{CF})\ \mathrm{SA}$$

FRESCO SA and CF instead of **OCRA**

Clouds as Lambertian diffusers?

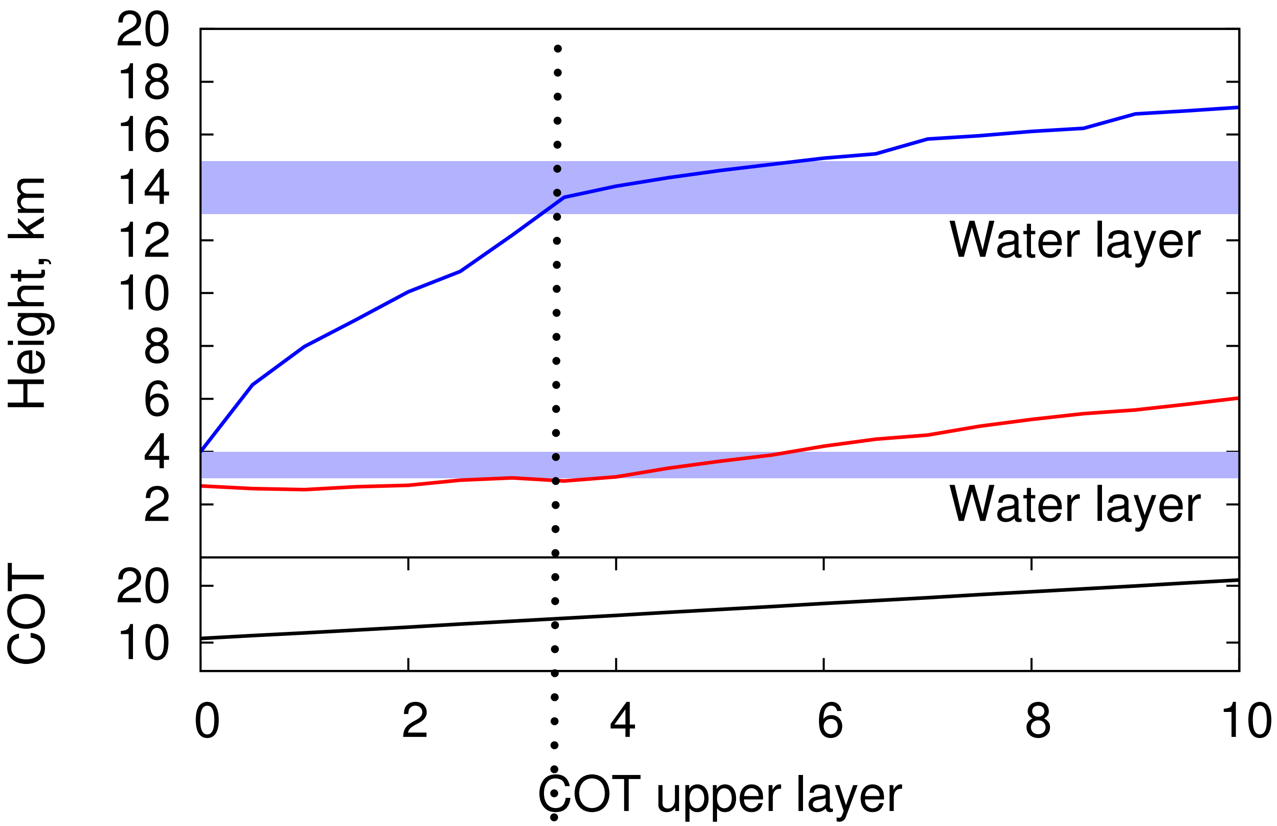




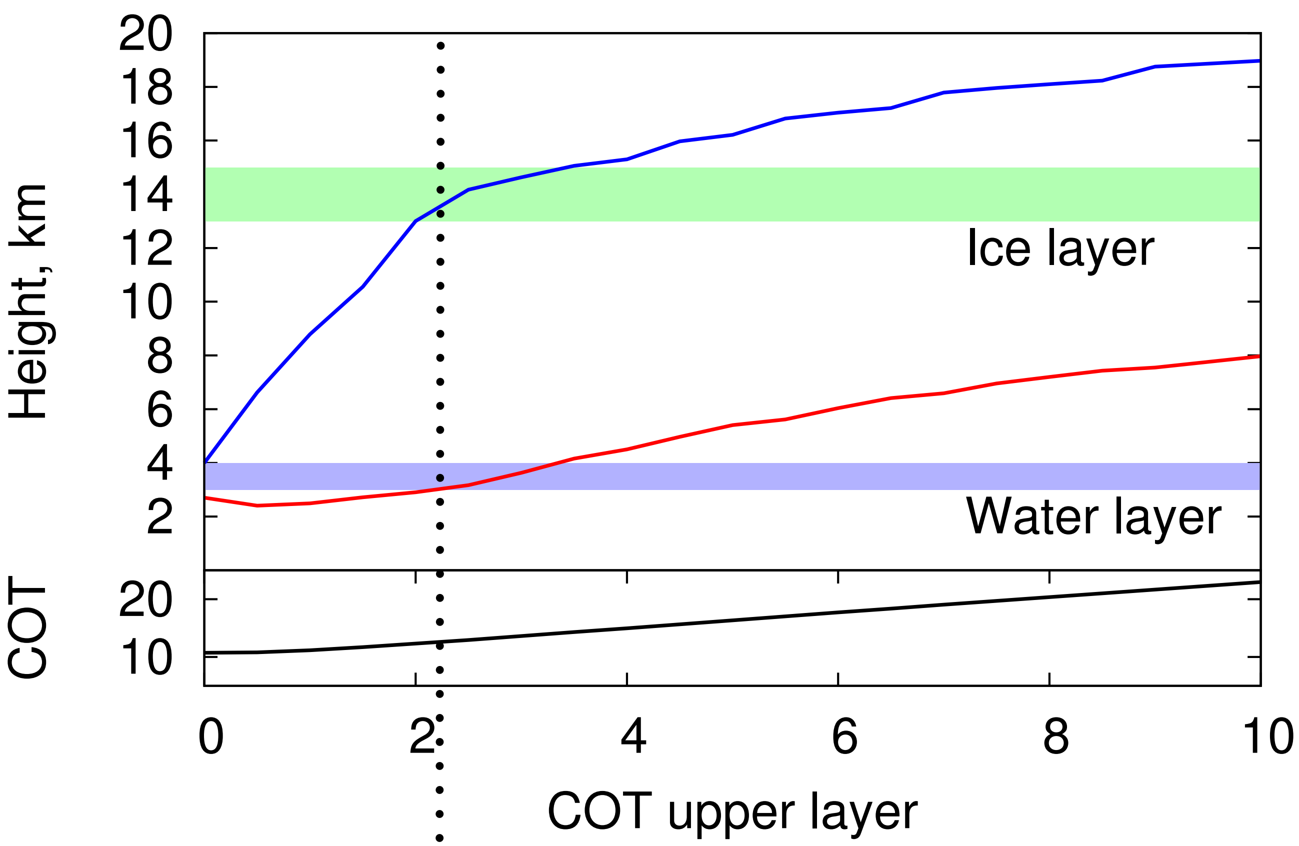
Double-layered cloud system

SZA = 30°

Water cloud, 6 µm, modified gamma distribution.



Ice crystals, fractal, 50 µm side length



Flag 5

CTH
CBH

Flag 3

Geometrical Thickness

Flag 5

CTH
CBH

Flag 3

Geometrical Thickness

Quality flagging

Value	Description	Flag value	GOME (%)	GOME-2 (%)
0	No retrieval	0	23.88	6.11
1	Only cloud bottom height convergence	1	34.6	20.51
2	Only cloud top height convergence	2	13.71	25.15
3	Geometrical thickness limit	3	5.69	2.11
4	No convergence	4	0.002	0.004
5	Cloud top and bottom height convergence	5	22.10	46.1