Long-term records of cirrus cloud properties for climate understanding

Amit Kumar Pandit[1], Jean-Paul Vernier[2, 3], Harish Gadhavi[4], M. Venkat Ratnam[5], K. Raghunath[5], T. Duncan Fairlie[3] & Bruce Doddridge[3]

1   Universities Space Research Association, Columbia, USA

2   National Institute of Aerospace, Hampton, USA.

3   NASA Langley Research Center, Hampton, USA

4   Physical Research Laboratory, Ahmedabad, India

5   National Atmospheric Research Laboratory, Gadanki, India

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Outline

✓ Cirrus Clouds & their formation mechanisms

✓ Role of Cirrus clouds in Earth's Climate

✓ Response of Cirrus cloud to Climate Change

       - Motivation, Objectives & Challenges

✓ Results

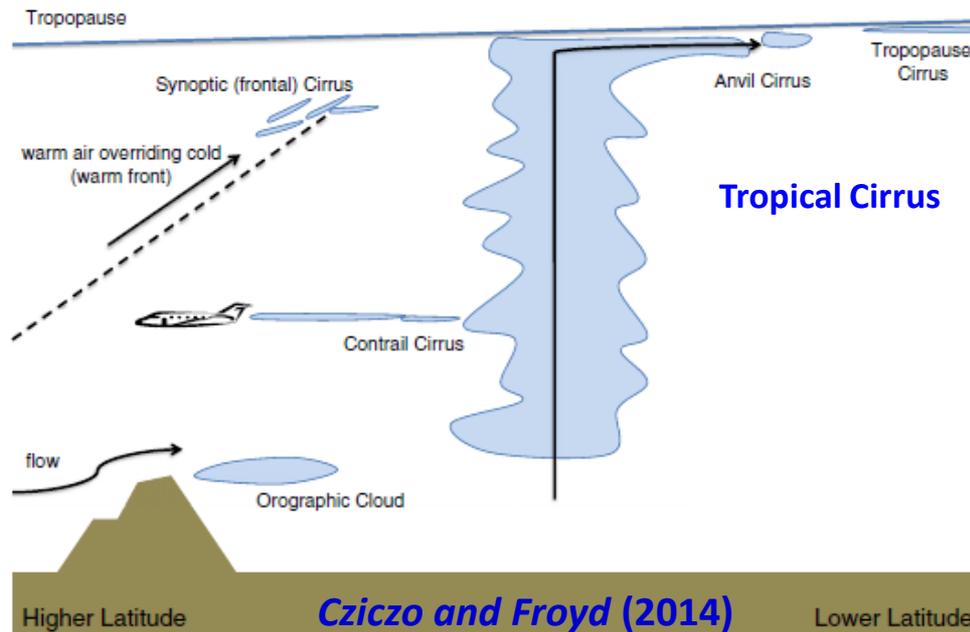   - Long-term trends in cirrus cloud properties.

✓ Summary

✓ Future plans

Cirrus Clouds & their Formation Mechanisms

Tirumala hills, Tirupati, India

Cirrus: Latin word meaning **curl of hair**. (First named by **Luke Howard** in 1802**).

Property	Mean	Range
Altitude (km)	9.0	4.0 to 20.0
Temperature (°C)	-50	-20 to -80
Thickness (km)	1.5	0.1 to 8.0
Concentration (L^{-1})	30.0	10^{-4} to 10^{4}
Ice content (gm^{-3})	0.025	10^{-4} to 1.2
Crystal size (μm)	250	1 to 8000

Sassen et al., (2002)

Tropopause

Synoptic (frontal) Cirrus

Anvil Cirrus

Tropopause Cirrus

warm air overriding cold (warm front)

Tropical Cirrus

Contrail Cirrus

flow

Orographic Cloud

Higher Latitude

Lower Latitude

Cziczo and Froyd (2014)

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Primary Nucleation Pathways

Kanji et al., 2017, Chapter 11, Meteorological monograph.

Role of Cirrus clouds in Earth's Climate

Tropical cirrus clouds (70%)

Global coverage: 50%

Sassen et al., (2008)

Solar-albedo effect

IR-green house effect

Courtesy: http://terra.nasa.gov/FactSheets/ EnergyBalance/

Tropical Tropopause Layer (TTL)

Ozone depletion
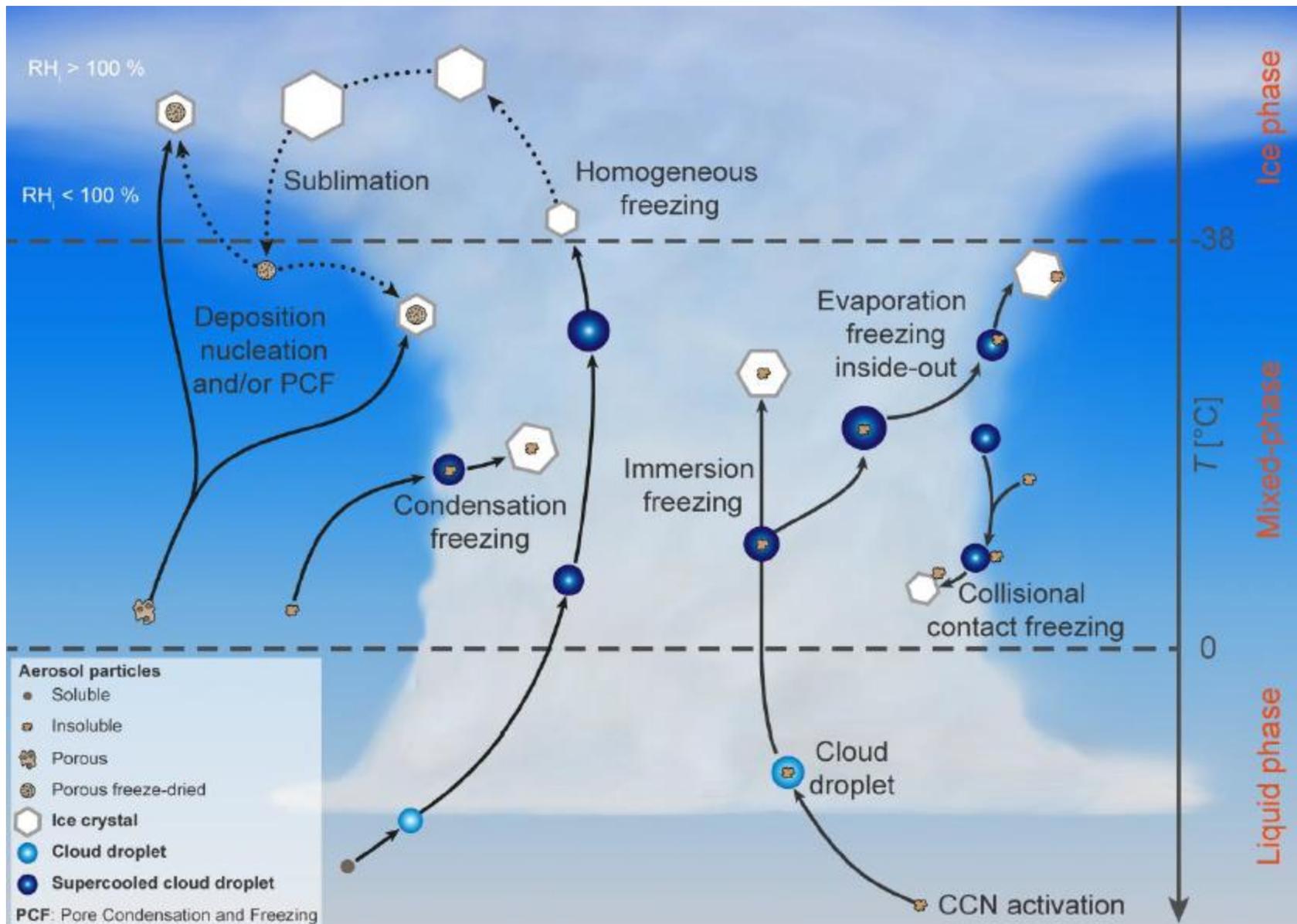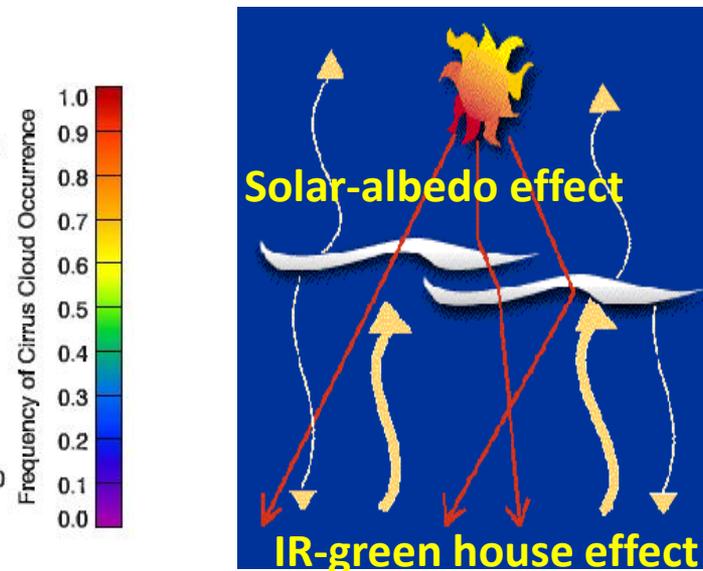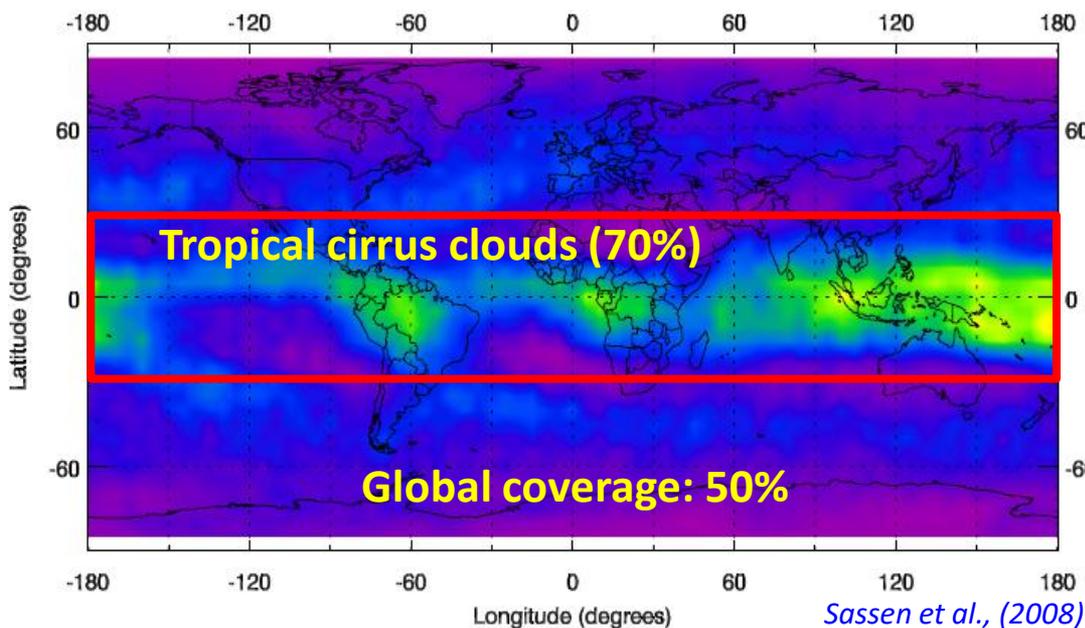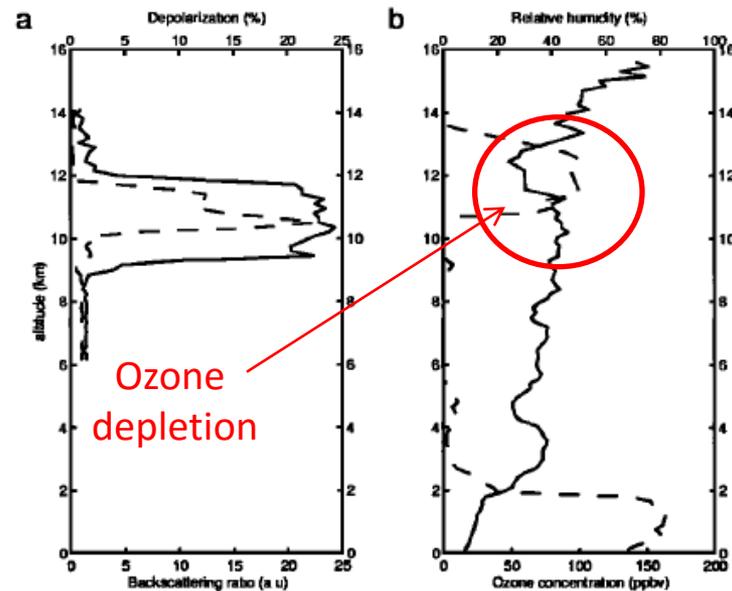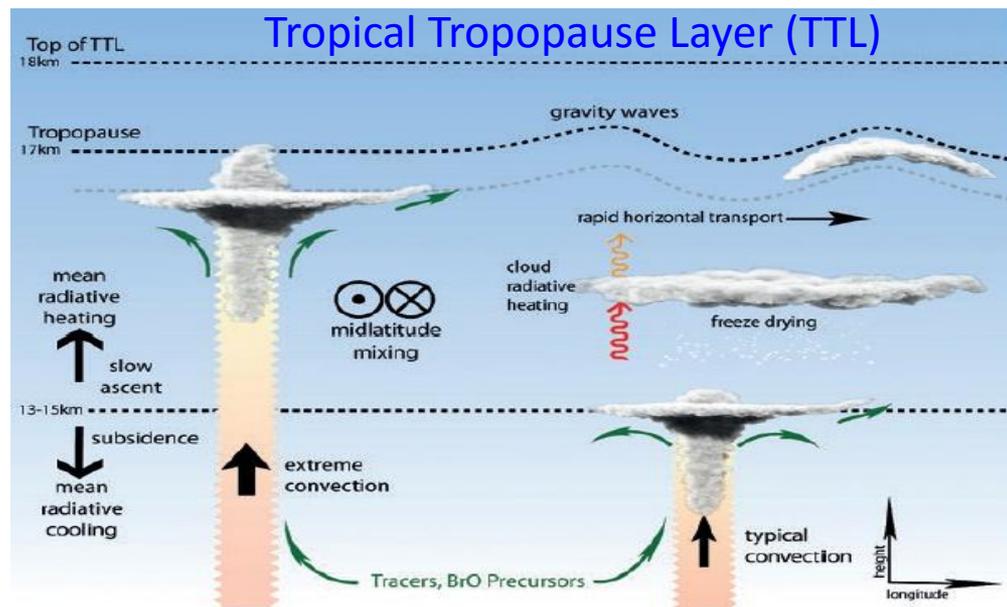
Roumeau et al., (2000)

Response of Cirrus clouds to Warming

Cloud Climate Feedbacks

Rising High Clouds

Broadening of the Hadley Cell

Narrowing of Tropical Ocean Rainfall Zones

Rising High Clouds

Poleward Shift of Storms

Rising of the Melting Level

Less Low Clouds

More Polar Clouds

Equator   30°   60°   Pole

Are these responses are robust?
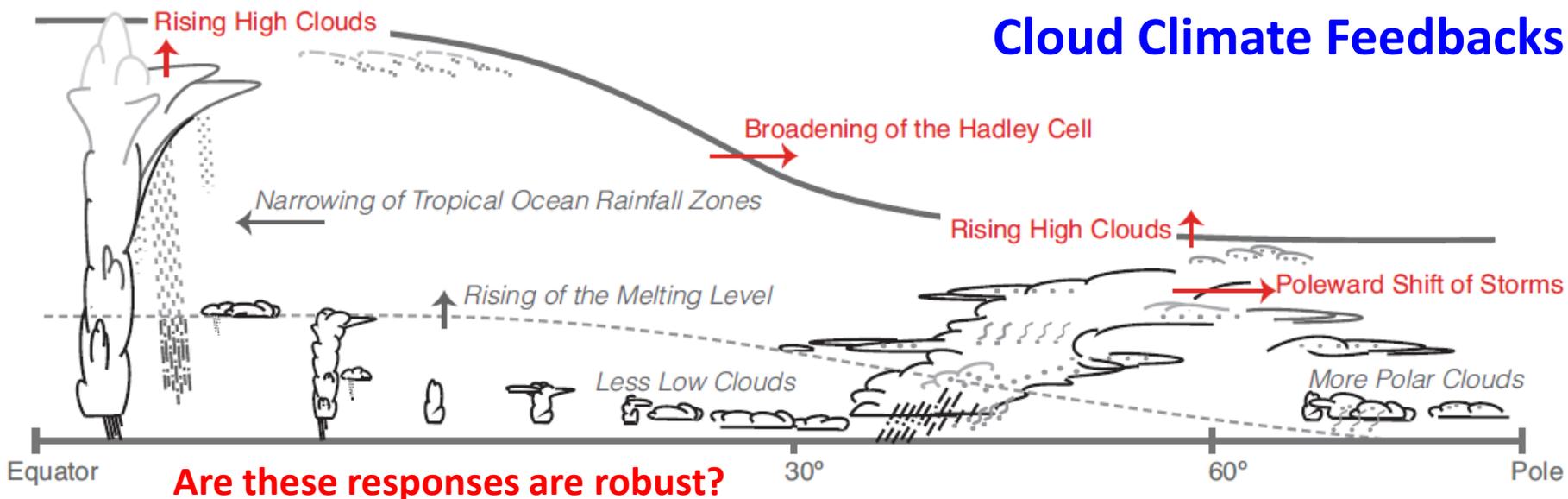
Chapter 7, IPCC AR5 Report, 2013

Tropics

Greenhouse Warming

Cloud Response — High clouds rise as troposphere deepens, increasing difference between cloud top and surface temperature.

Feedback Mechanism — High clouds more effectively trap infrared radiation, increasing surface warming.

CMIP5 CMIP3 CFMIP   LW SW Net

CFMIP & CMIP3 Models (by cloud level)

CFMIP Models (by cloud property)

Feedback (W m^{-2} °C^{-1})

1.5

1.0

0.5

0.0

-0.5

-1.0

Total   *High*   *Middle*   *Low*   *Amount*   *Height*   *Opacity*

Motivation & Objective

HadGEM2-A tropics

Current climate
+4K Scenario
optically thin clouds
optically thick clouds

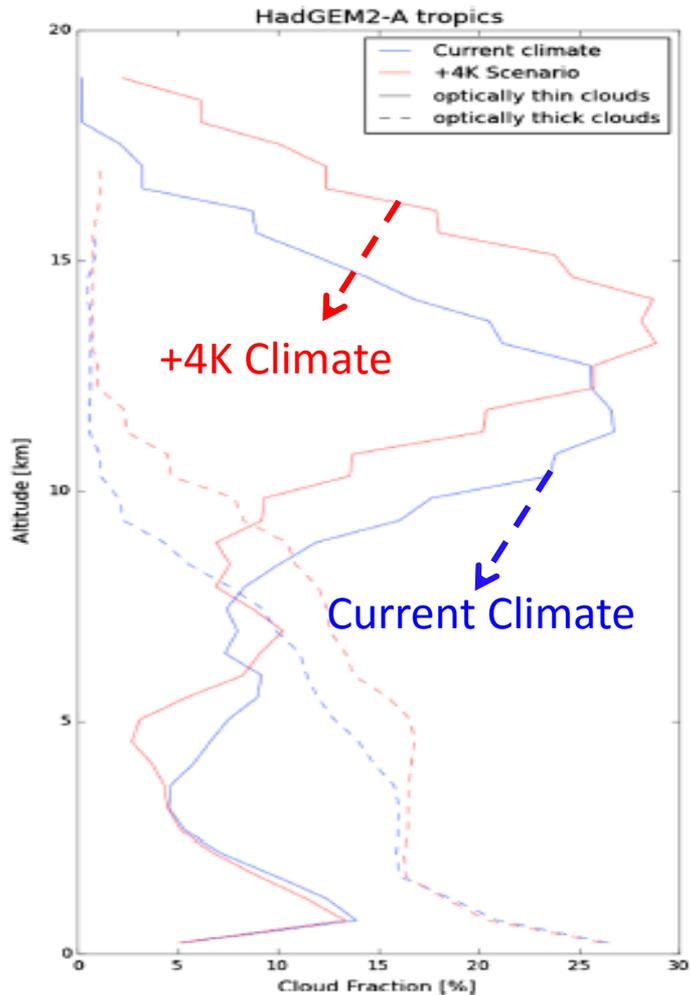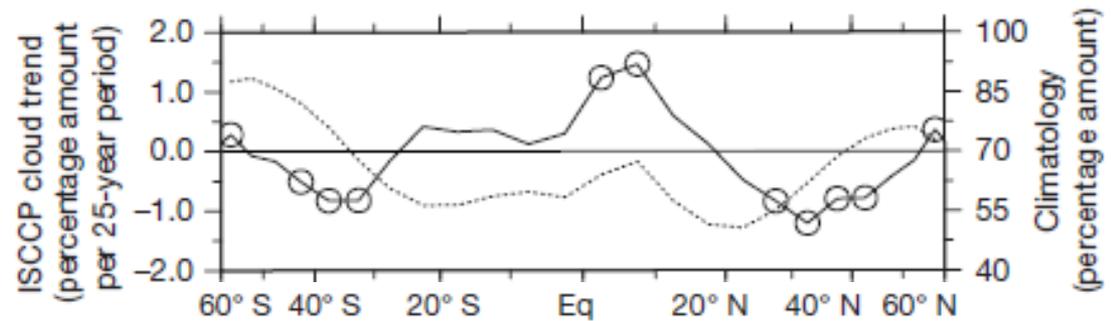+4K Climate

Current Climate

Figure 2. Synthetic lidar-like cloud fraction profiles for optically thin and thick clouds, based on output from the HadGEM2-A model + COSP/lidar for the current climate and the +4 K scenario in the tropics (30°S–30°N).

Chepfer et al., (2014), GRL
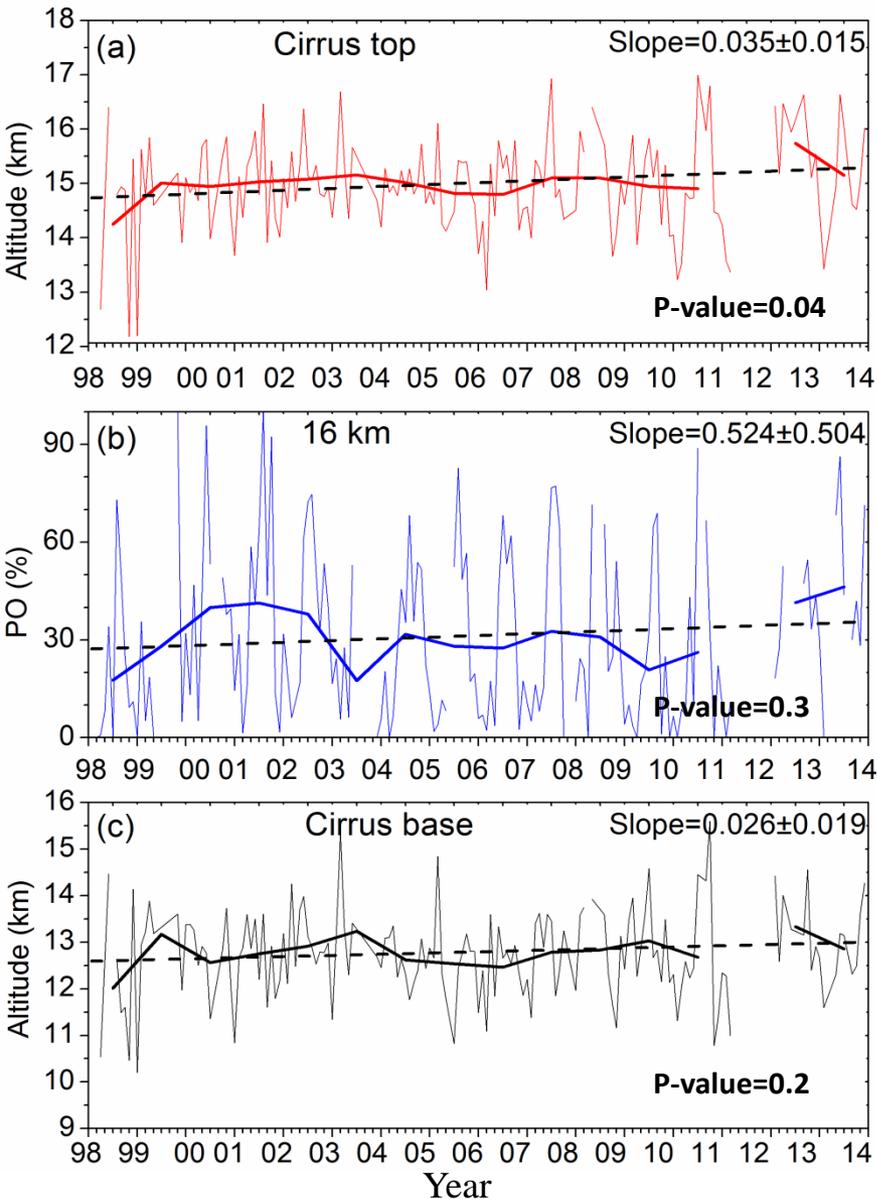

Norris et al., (2016), Nature

Norris et al., (2016) ignored clouds with optical depth less than 3.6 (Cirrus clouds).

July–August AOD 13–18 km ATAL
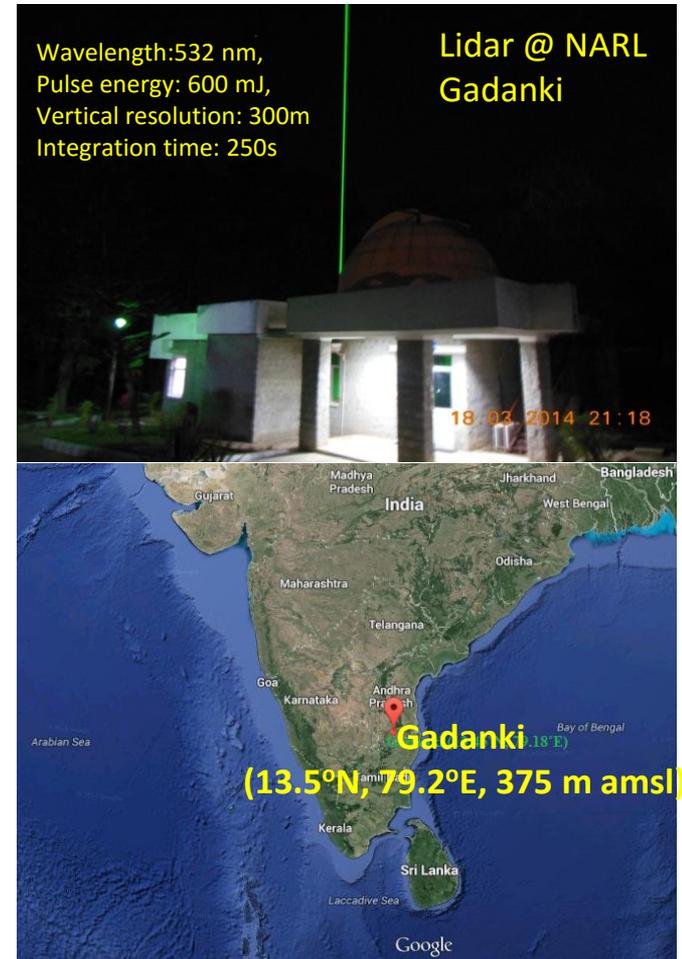
[5-105E;15-45N]

70sr

CALIOP

SAGE II

40sr
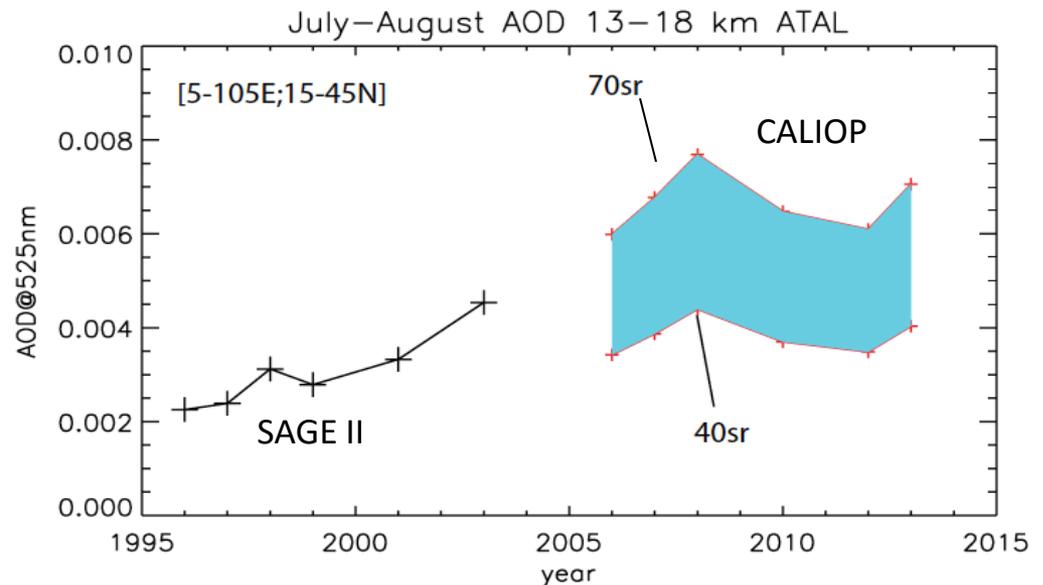
Vernier et al., (2015), JGR

Response of cirrus clouds to global warming and aerosol increase (ATAL)?

Cirrus cloud Trends

(a) Cirrus top — Slope=0.035±0.015 — P-value=0.04
(b) 16 km — Slope=0.524±0.504 — P-value=0.3
(c) Cirrus base — Slope=0.026±0.019 — P-value=0.2

Mean top and base altitude of cirrus clouds increased by 0.56 km and 0.41 km, respectively.
"UPWARD SHIFT IN CIRRUS CLOUDS"

Wavelength:532 nm,
Pulse energy: 600 mJ,
Vertical resolution: 300m
Integration time: 250s

Lidar @ NARL Gadanki

18.03.2014 21:18

Gadanki
(13.5ºN, 79.2ºE, 375 m amsl)

Rate of upward shift in tropical cirrus cloud altitude

HadGEM2-A tropics

Legend:
— Current climate
— +4K Scenario
— optically thin clouds
- - optically thick clouds

+4K Climate
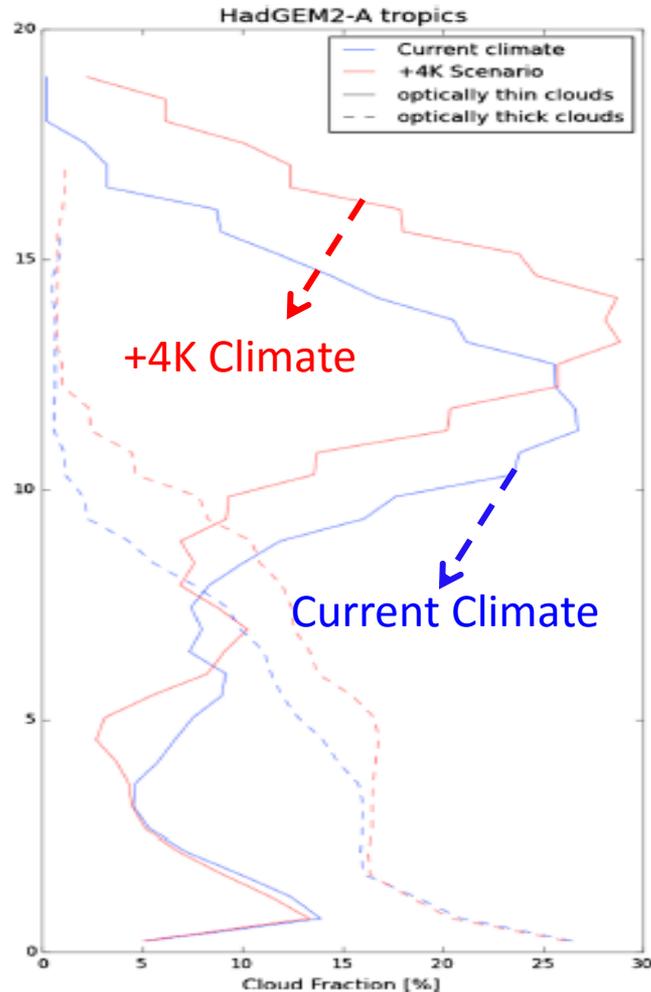
Current Climate

Altitude [km]

Cloud Fraction [%]

Figure 2. Synthetic lidar-like cloud fraction profiles for optically thin and thick clouds, based on output from the HadGEM2-A model + COSP/lidar for the current climate and the +4 K scenario in the tropics (30°S–30°N).

Chepfer et al., (2014)

Global climate model simulations predict an **upward shift** in cirrus cloud altitude everywhere with **highest shift of ~1.7 km over tropics in +4K climate** (*Chepfer et al.* (2014), GRL)

Rate of upward shift in cirrus cloud	Predicted (*Chepfer et al., 2014*)	Our study (*Pandit et al., 2014*)
Base altitude	~20 m/year	~26 m/year
Top altitude	~20 m/year	~35 m/year

Rate of increase in tropopause altitude ~ 20 m/year (*Rabindrababu et al.* (2014), JASTP).

Evidence for climate change in the satellite cloud record

Joel R. Norris[1], Robert J. Allen[2], Amato T. Evan[1], Mark D. Zelinka[3], Christopher W. O'Dell[4] & Stephen A. Klein[3]
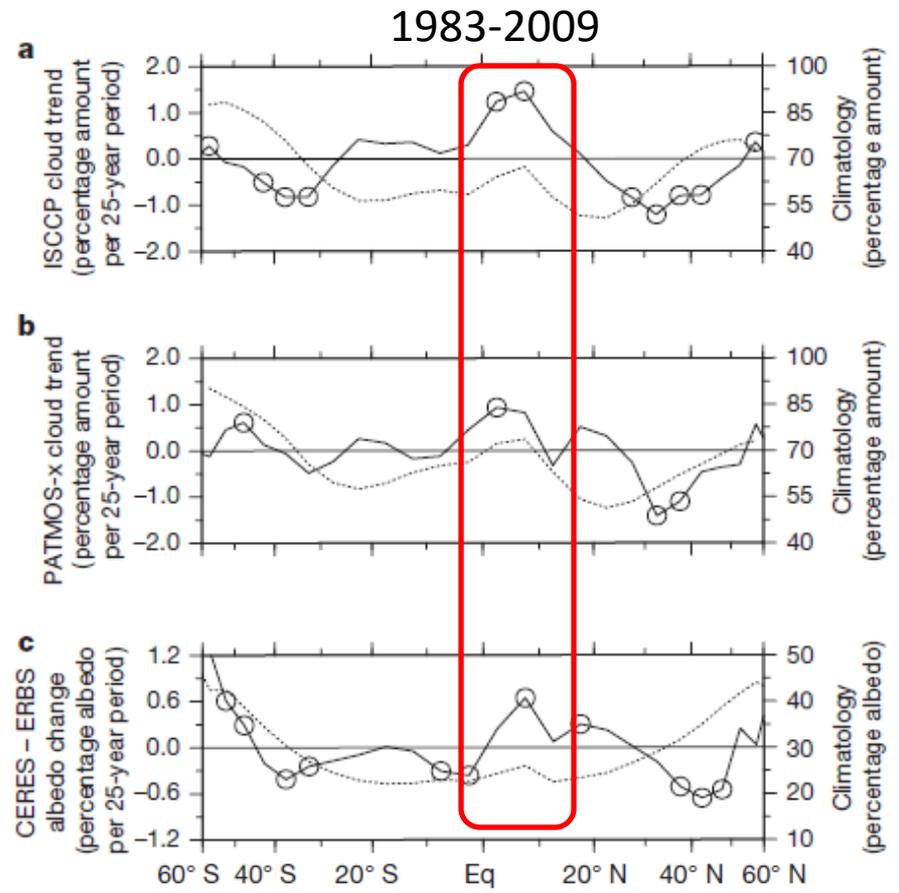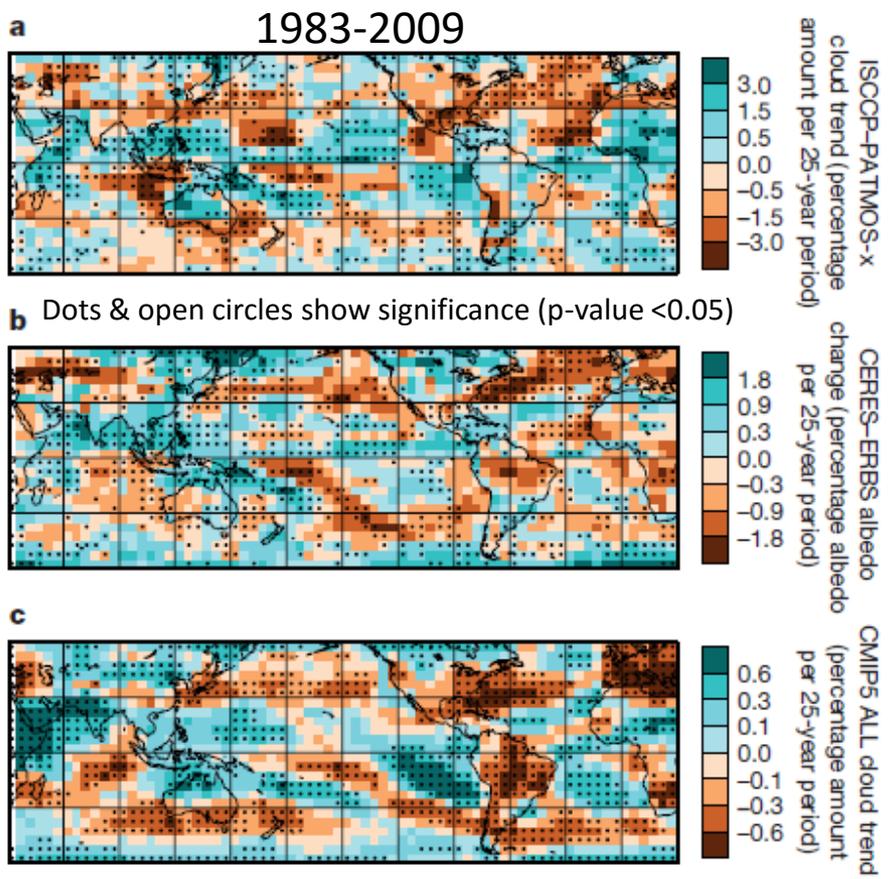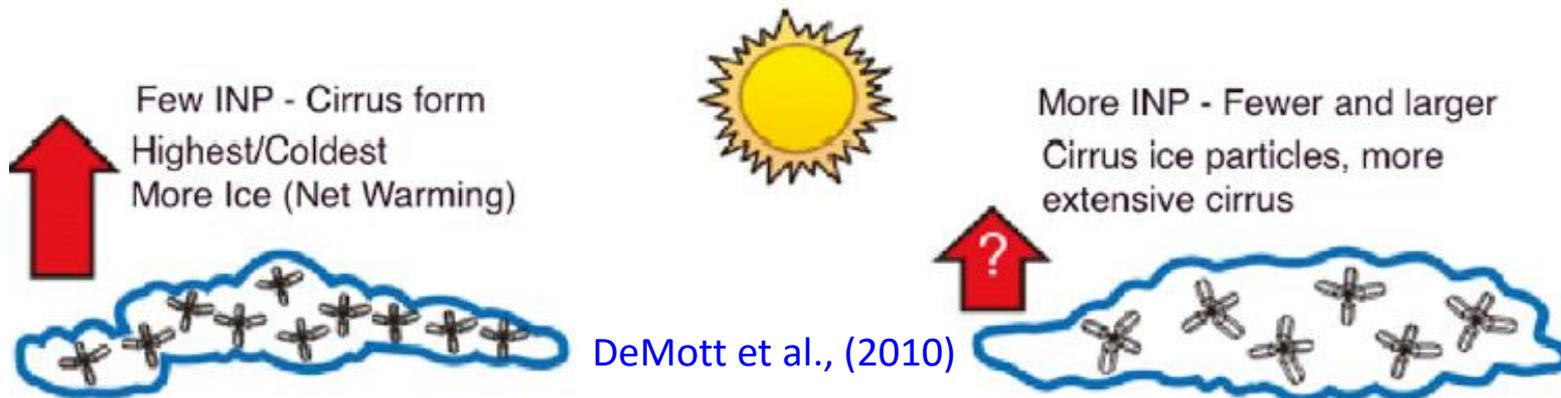
Only clouds with optical thickness greater than 3.6 were considered – No cirrus clouds.

Anthropogenic Impacts on Cirrus clouds

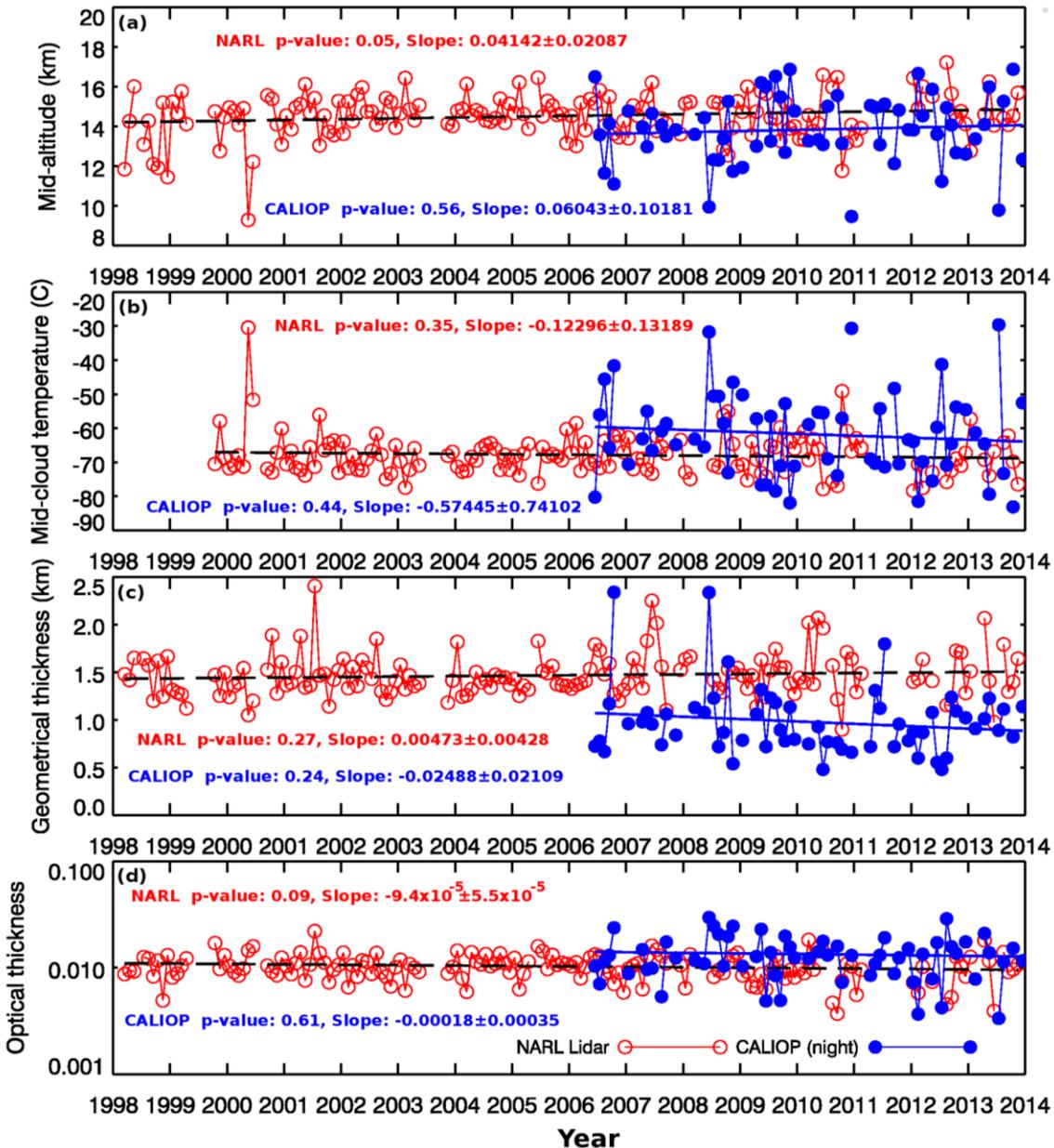| Cirrus-controlling factor	Assumed future changes	Natural cirrus changes	Likelihood of impact	Scale of impact
Meteorological changes				
Vertical wind (cooling rate) fluctuations[a]	Not known	More and smaller ice crystals[b]	High	Local
Relative humidity	Constant	Constant coverage	High	Regional
Tropopause altitude	Increase	Less ice water content[c]	High	Regional
Aerosol-induced changes				
Supercooled aerosols	Increase[d]	Moderate changes	Low	Local
Dust	Increase[d]	Depending on dynamical forcing[e]	High[f]	Local
Black carbon	Increase[d]	Depending on dynamical forcing[e]	Low	Local
Cloud-induced changes				
Contrail cirrus	Increase	Lower coverage[g]	Medium[h]	Regional
Deep convection	Not known	Higher coverage[b]	High[i]	Regional

Kärcher (2017), Curr. Clim. Change Rep.

- Anthropogenic activities can affect microphysical and macrophysical properties of cirrus
- Poor representation of these processes in Global Climate models (IPCC report, 2013)

Few INP - Cirrus form Highest/Coldest More Ice (Net Warming)

More INP - Fewer and larger Cirrus ice particles, more extensive cirrus

DeMott et al., (2010)

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Sub-visible cirrus clouds

Cirrus clouds are classified as
sub-visible (τ< 0.03),
thin (0.03< τ<0.3) and
thick cirrus clouds (τ>0.3) S
*Sassen and Cho, (1992).*

Mid-cloud altitude of sub-visible
cirrus are found to be increasing
@ 41 ± 21 m /year.

Optical thickness of sub-visible clouds
showed decreasing trend

Pandit, A. K., *Gadhavi, H. S., Venkat Ratnam,*
M., Raghunath, K., Rao, S. V. B., and Jayaraman,
A.: ***Long-term trend analysis and climatology of***
tropical cirrus clouds using 16 years of lidar
data set over Southern India, *Atmos. Chem.*
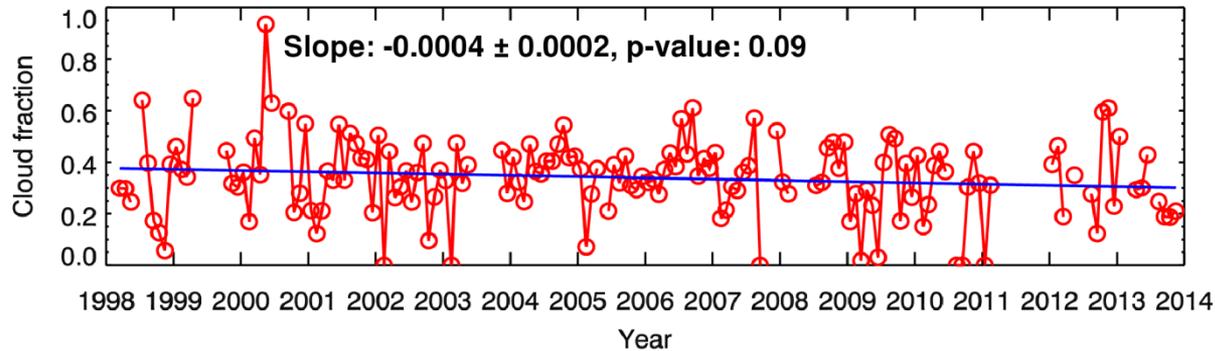*Phys., 15, 13833-13848,* *doi:10.5194/acp-15-*
13833-2015, 2015

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Sub-visible cirrus

Slope: 0.0005 ± 0.0003, p-value:0.1
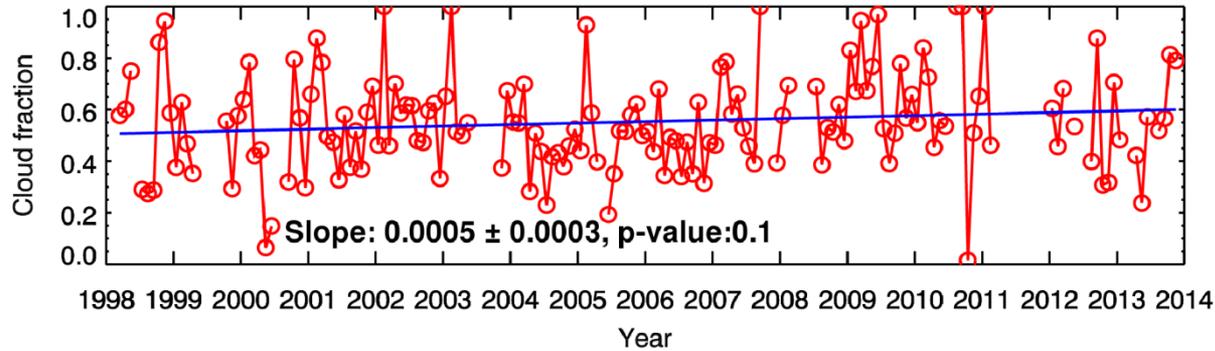
Fraction of sub-visible cirrus increased by 9.4 %.

Thin cirrus

Slope: -0.0004 ± 0.0002, p-value: 0.09

Fraction of thin cirrus decreased by 7.6 %.

Thick cirrus

Slope: -0.00009 ± 0.00018, p-value: 0.6
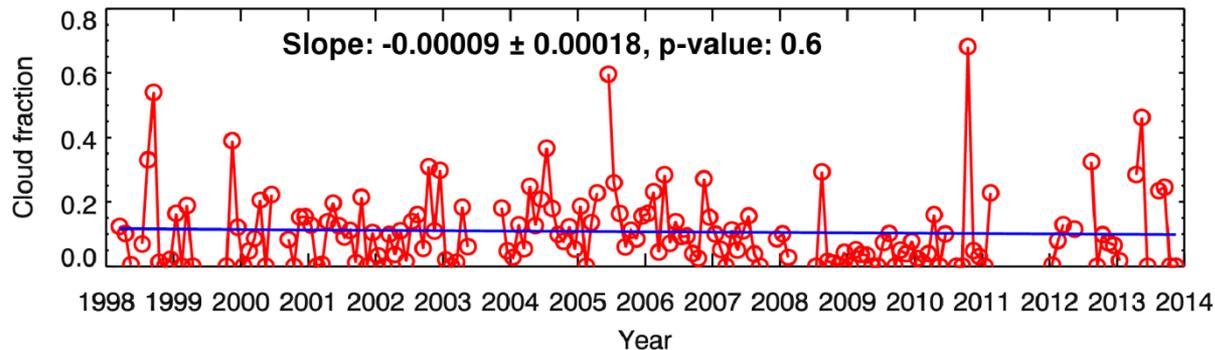
Fraction of thick cirrus decreased by 1.8 %.- statistically insignificant.

Pandit et al., (2015), ACP

Stratospheric Aerosol and Gas Experiment (SAGE)-II

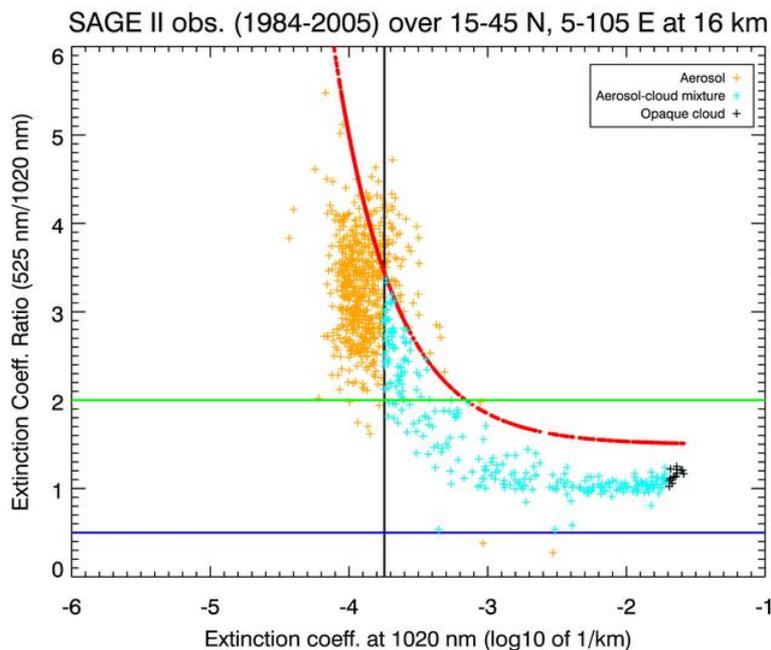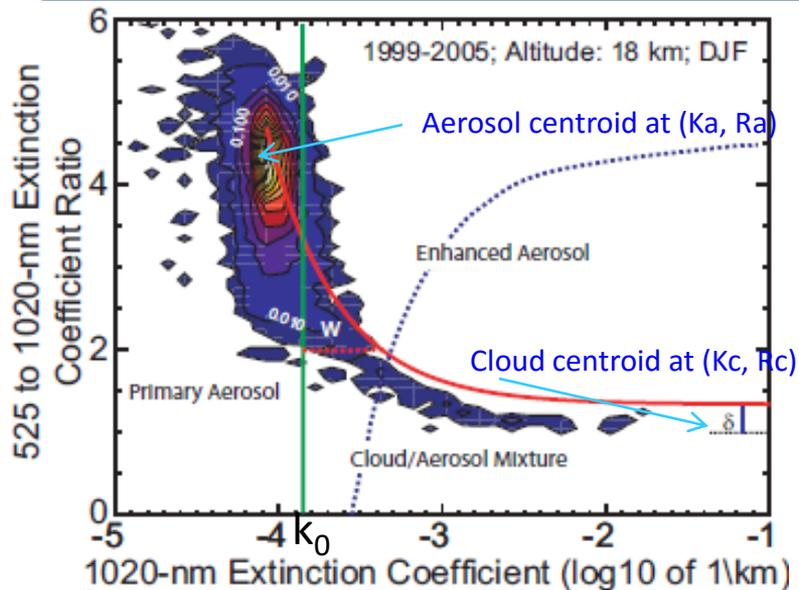https://www.nasa.gov/centers/langley/news/factsheets/SAGE.html
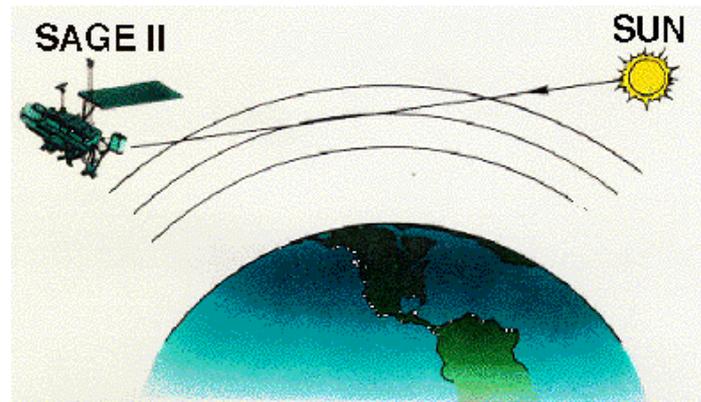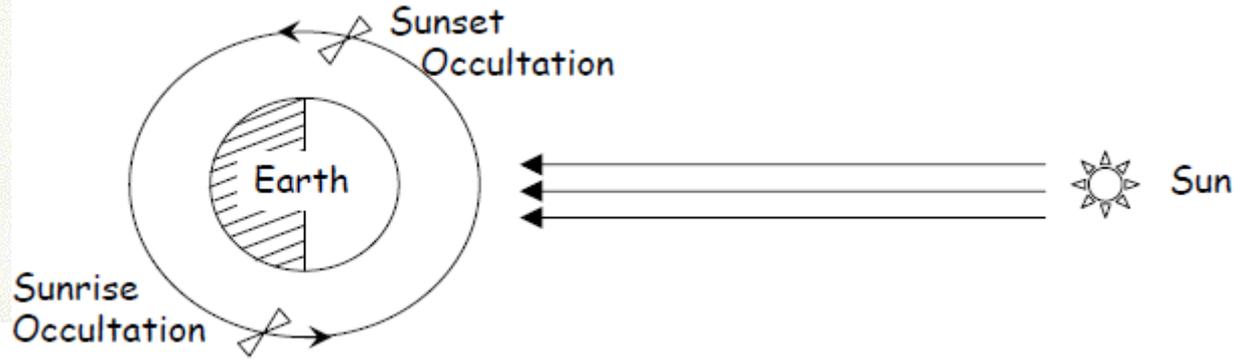
✓ SAGE II: A seven channel space-borne Sun-photometer onboard Earth Radiation Budget Satellite
✓ Measures sunlight during space-craft's sunrise or sunset.
✓ Wavelengths: **385**, 448, **453, 525**, 600, 940 and **1020 nm**

Parameter	Specifications
Spatial coverage	80 N to 80 S, 180 E to 180 W
Spatial resolution (vertical)	0.5 km
Temporal coverage	24 Oct 1984 to 31 Aug 2005
Data products	Vertical profiles of ozone number density, **aerosol extinction coefficient**, NO2 number density and water vapour mixing ratio.

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SAGE-II Aerosol-Cloud Discrimination

1999-2005; Altitude: 18 km; DJF

Aerosol centroid at (Ka, Ra)

Enhanced Aerosol

Cloud centroid at (Kc, Rc)

Primary Aerosol

Cloud/Aerosol Mixture

525 to 1020-nm Extinction Coefficient Ratio

1020-nm Extinction Coefficient (log10 of 1\km)

SAGE II obs. (1984-2005) over 15-45 N, 5-105 E at 16 km

Aerosol +
Aerosol-cloud mixture +
Opaque cloud +

Extinction Coeff. Ratio (525 nm/1020 nm)

Extinction coeff. at 1020 nm (log10 of 1/km)

SAGE II extinction profiles at 525 &1020 nm

Calculate extinction ratio (525nm/1020nm)

$$k_0 = k_a + 3*\Delta k_a$$

$$R = \frac{aR_c k_c + (1-a)R_a k_a}{ak_c + (1-a)k_a} + \delta \qquad a = \frac{(k-k_a)}{(k_c-k_a)}$$
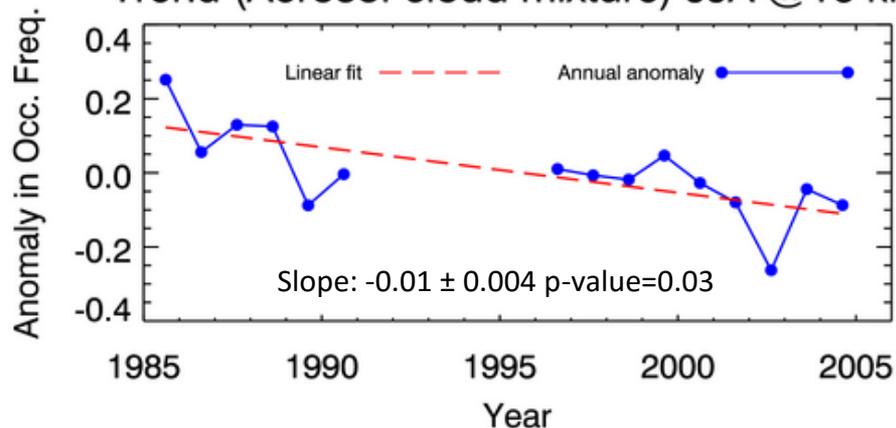
Aerosol-Cloud mixture

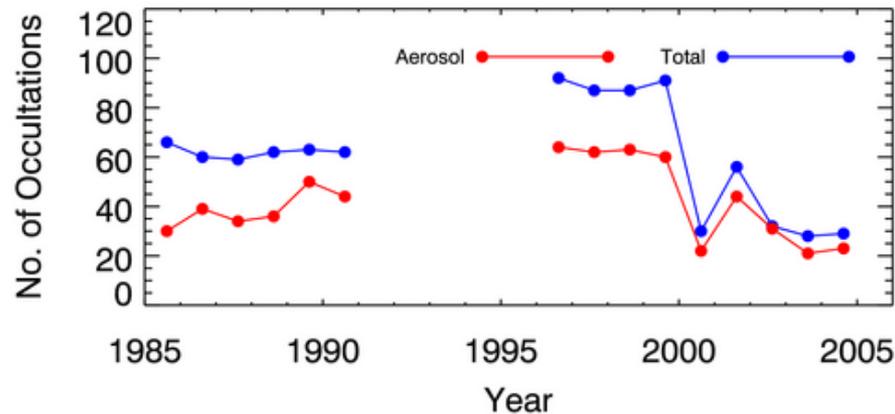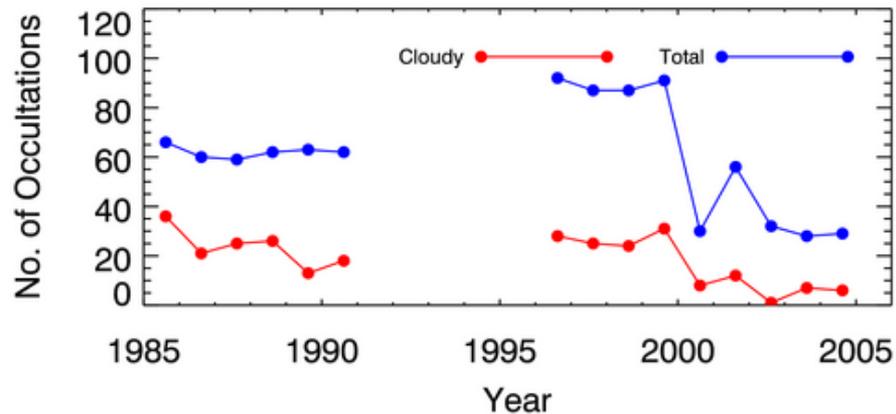Calculate monthly frequency of occurrence of aerosol-cloud mixture over tropics

$k_a = 10^{-4}$, $R_a = 4.5$, $k_c = 0.1$, $R_c = 1.0$, $\delta = 0.4$

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Thomason and Vernier, (2013), ACP

Trend (Aerosol-cloud mixture) JJA @16 km

Slope: -0.01 ± 0.004 p-value=0.03

Trend (Aerosol) JJA @16 km

Slope: 0.01 ± 0.004 p-value=0.03
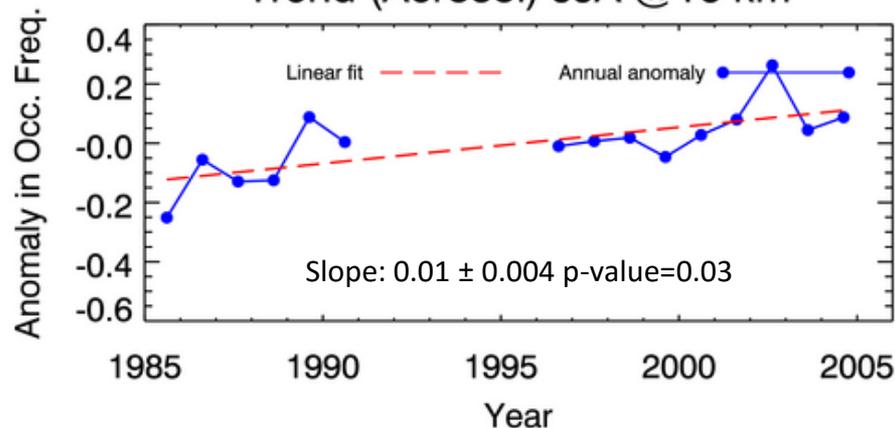
Long-term Trends: Cirrus cloud occurrence frequency
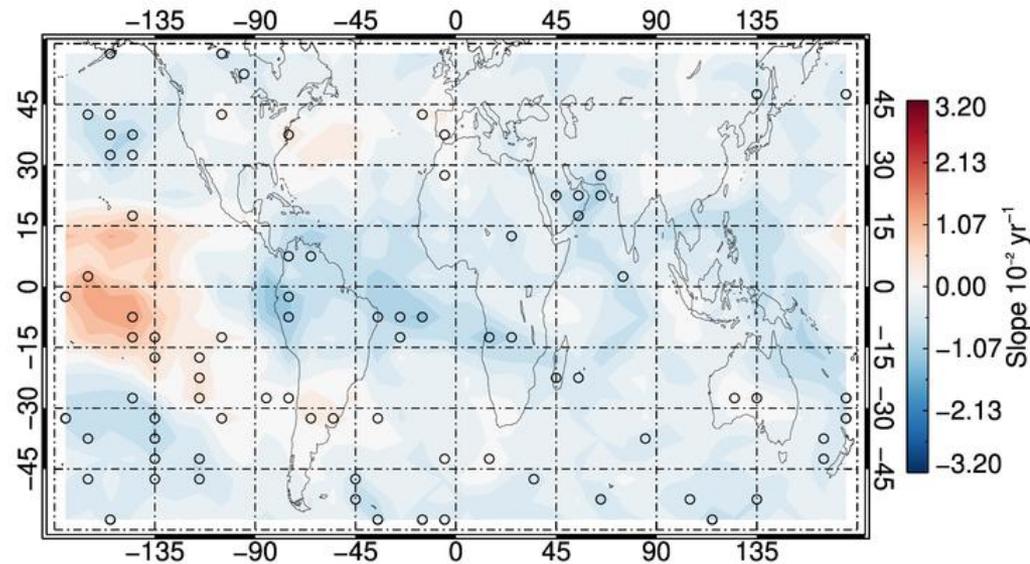

1983-2009

Norris et al., 2016, Nature
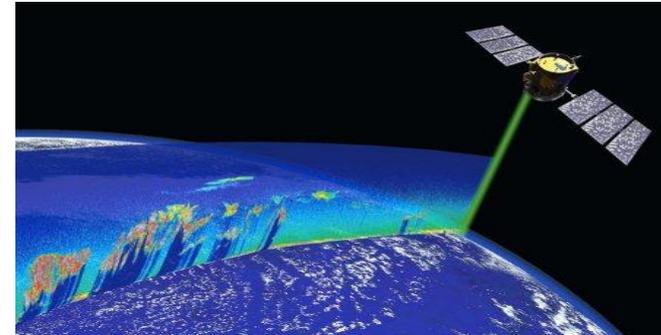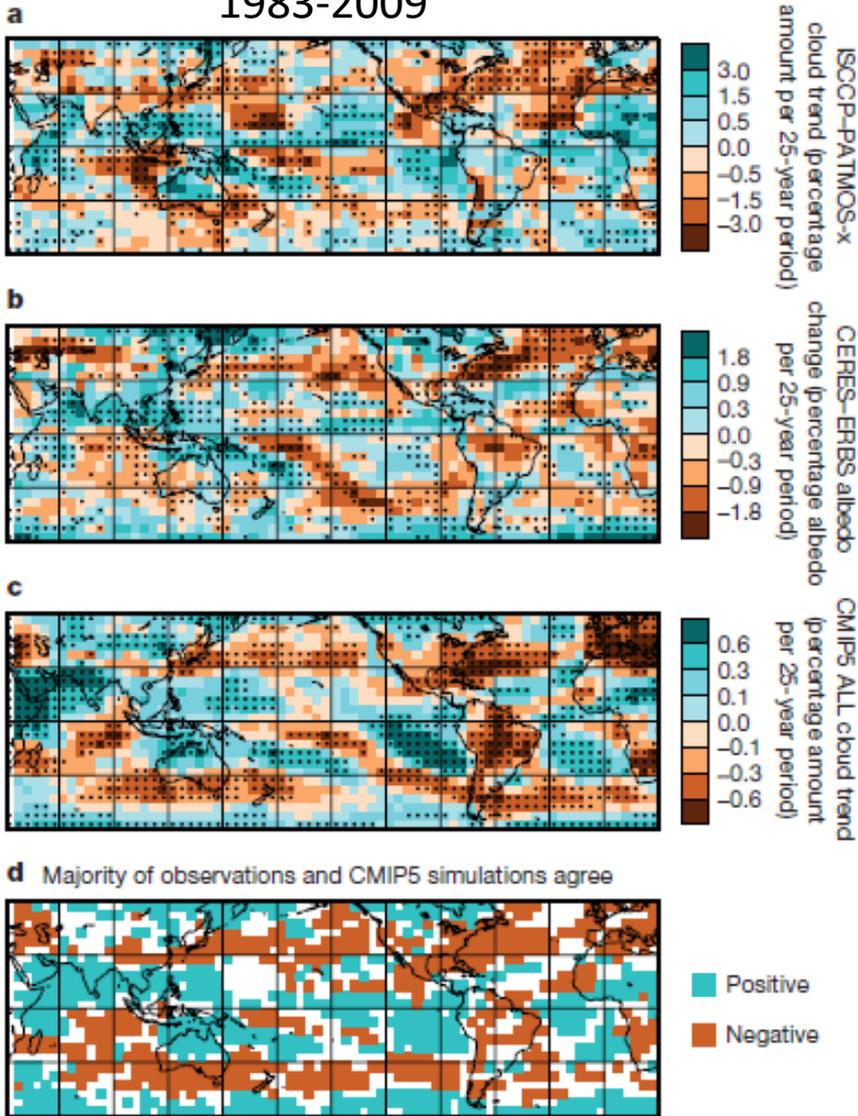
http://science-edu.larc.nasa.gov/images/spotlight/1-CALIPSO_cropped448W-336H.jpg

Data used: CALIOP, L2, CLAY, 2007-2017, 10˚ lon. x 5˚ lat.

Clouds layers with their base temperature less than -40 ˚C are considered.

Dots & open circles show significance (p-value <0.05)

Summary

- ✓ An upward shift of cirrus clouds at a rate higher than that predicted by the climate models is observed in the last 16 years.
- ✓ Only sub-visible cirrus clouds exhibited upward shift in their altitude.
- ✓ Optical thickness of sub-visible and thick cirrus clouds showed decreasing trends.
- ✓ No significant trend was obtained from the CALIOP data over Gadanki.
- ✓ SAGE-II data show increasing trend in the occurrence frequency of aerosol and decreasing trend in aerosol-cloud mixture
- ✓ CALIOP observations show increase in cirrus cloud occurrence in Western-equatorial pacific.

Thank you

Extra Slides

Images of Shapes of Ice-crystals using CPI
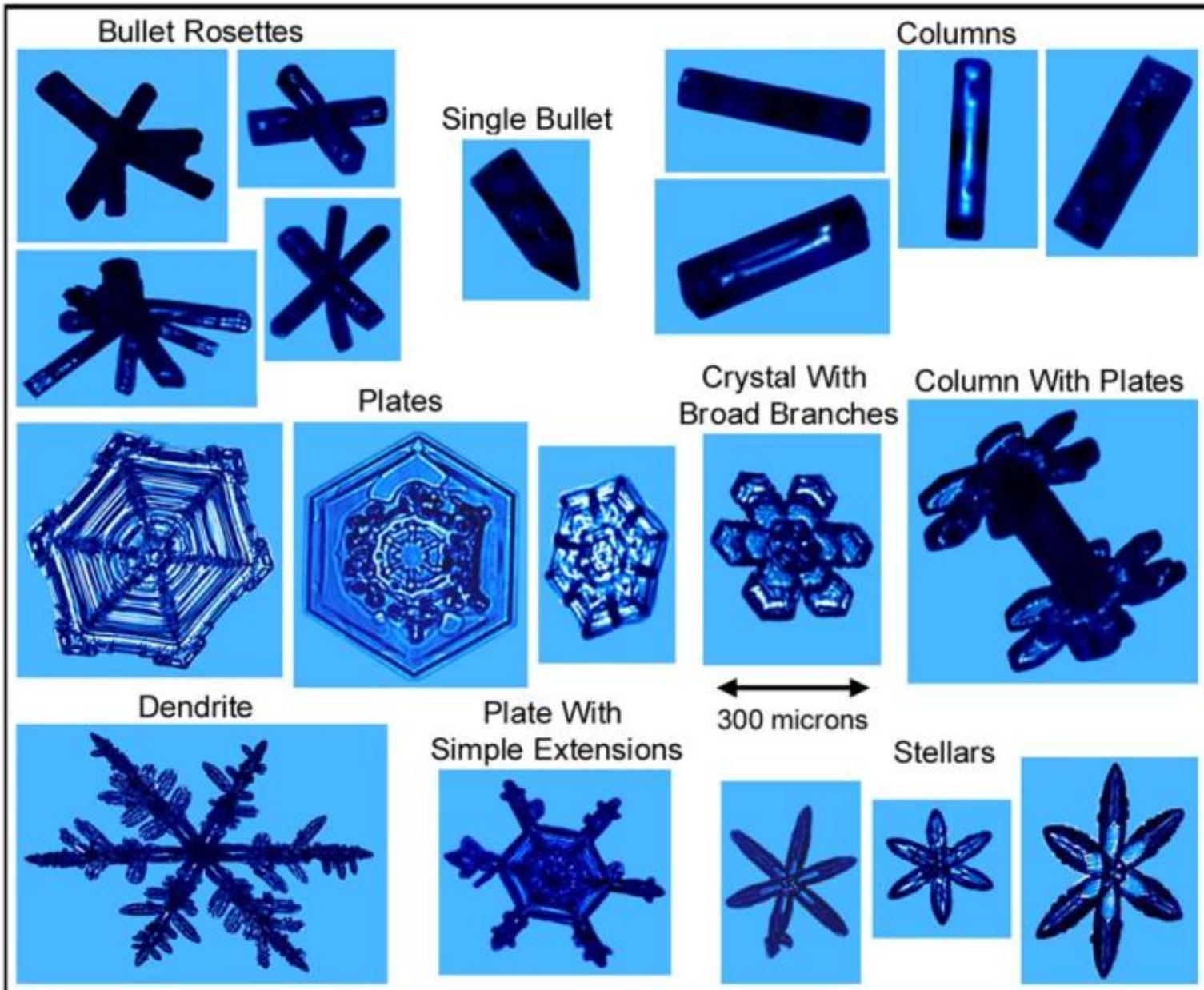
Specifications of Mie Lidar @ NARL Gadanki

Lidar beam

18.03.2014 21:18

Image courtesy: Dr. K. Raghunath

Rayleigh Telescope

Mie Telescope

Beam steering mirror

Data acquisition system

PMT

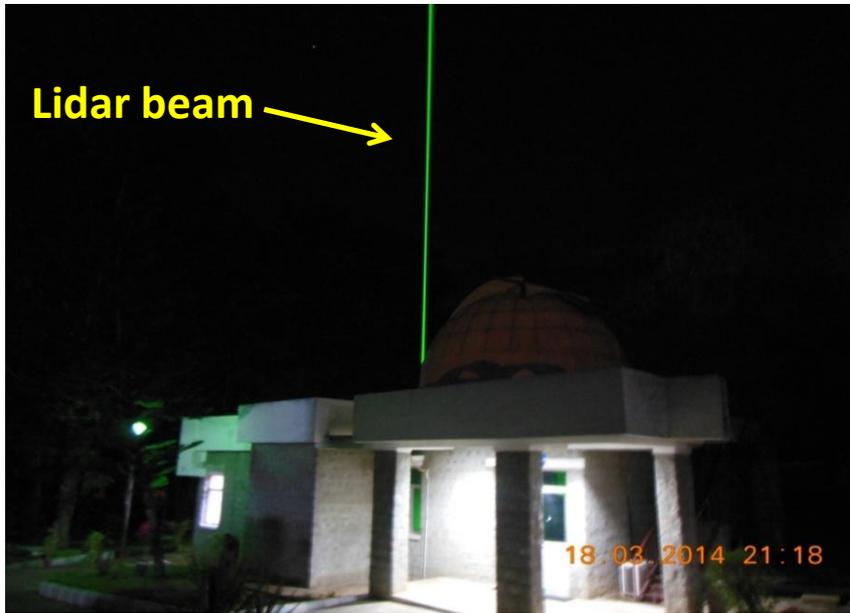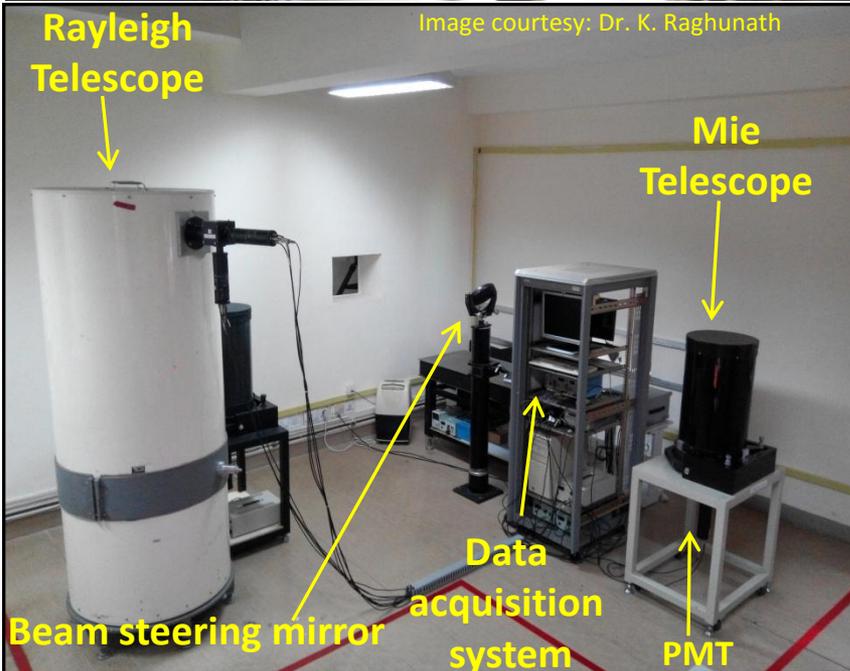| TRANSMITTER	
Laser Source	Nd:YAG (Continuum, USA)
Operating wavelength	**532 nm** (green)
Average energy per pulse	550 mJ (600 mJ since 2007)
Pulse width	7 ns
Pulse repetition rate	20 Hz (50 Hz since 2007)
Beam divergence	<0.1 mrad
RECEIVER	
Telescope type and diameter	Schmidt –Cassegrain , 35 cm
Field of view	1mrad
IF filter (FWHM)	1.13 nm
Detector	PMT (Hamamatsu)
SIGNAL PROCESSING	
4 –Channel PC based photon counting system	Co & Cross-polarized PMT MCS real-time software
Bin width (range resolution)	**2 µs (300 m)**
Integration time	**250 s**

Operational since 1998: One of the longest data record over a tropical station - good for climate studies

Preparation of Lidar Cloud Database

4 min averaged profiles for each year
LEVEL-1 PROFILE DATA

Quality checks based on threshold signal at 5 km altitude bin
LEVEL-2 PROFILE DATA

Detection of cloud base & top altitudes using
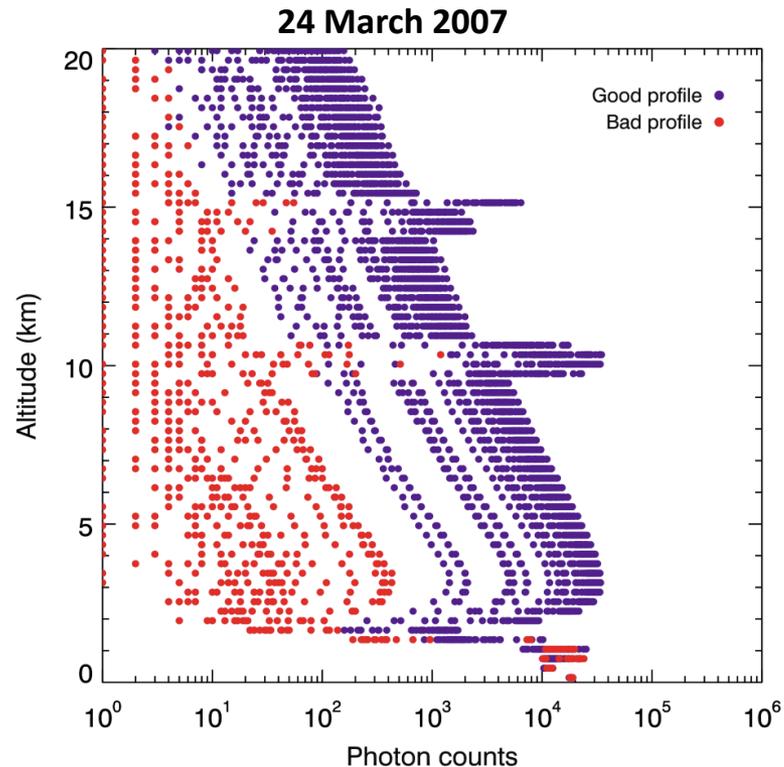**WCT algorithm**
LEVEL-1 CLOUD DATA

Identification of faulty & ambiguous detections by WCT algorithm

Manual correction of faulty detections
LEVEL-2 CLOUD DATA

• For climate studies long-term, highly stable, well-calibrated, precise and accurate data are pre-requisite.

• Data must undergo through stringent quality checks.

24 March 2007

Level-2 cloud data set contains **cloud base height, top height, date** and **time** information.

Cirrus cloud detection: Wavelet Covariance Transform method

Wavelet Covariance Transform (WCT) method *(Brooks, 2003)*

$$W_P(a,b) = \frac{1}{a} \int_{z_b}^{z_t} P(z) h\left(\frac{z-b}{a}\right) dz$$
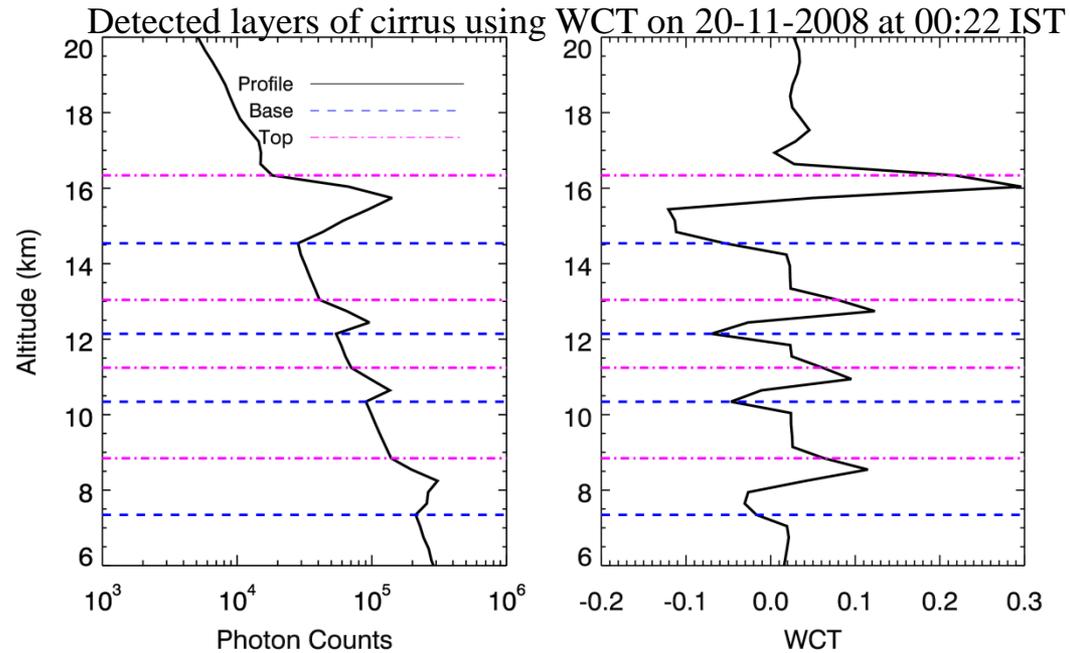
where,

a = *dilation (3.0)*, b = *translation*,

z = altitude bins, $P(z)$ = Lidar raw profile, z_b & z_t= lower & upper limit of the profile and

$$h\left(\frac{z-b}{a}\right) = \begin{cases} +1, \ b - \dfrac{a}{2} \leq z \leq b, \\ \\ -1, \ b \leq z \leq b + \dfrac{a}{2}, \\ \\ 0, \quad elsewhere \end{cases}$$

is a step function known as ***Haar function.***

Detected layers of cirrus using WCT on 20-11-2008 at 00:22 IST

Criteria used for a layer to be a cirrus cloud layer:
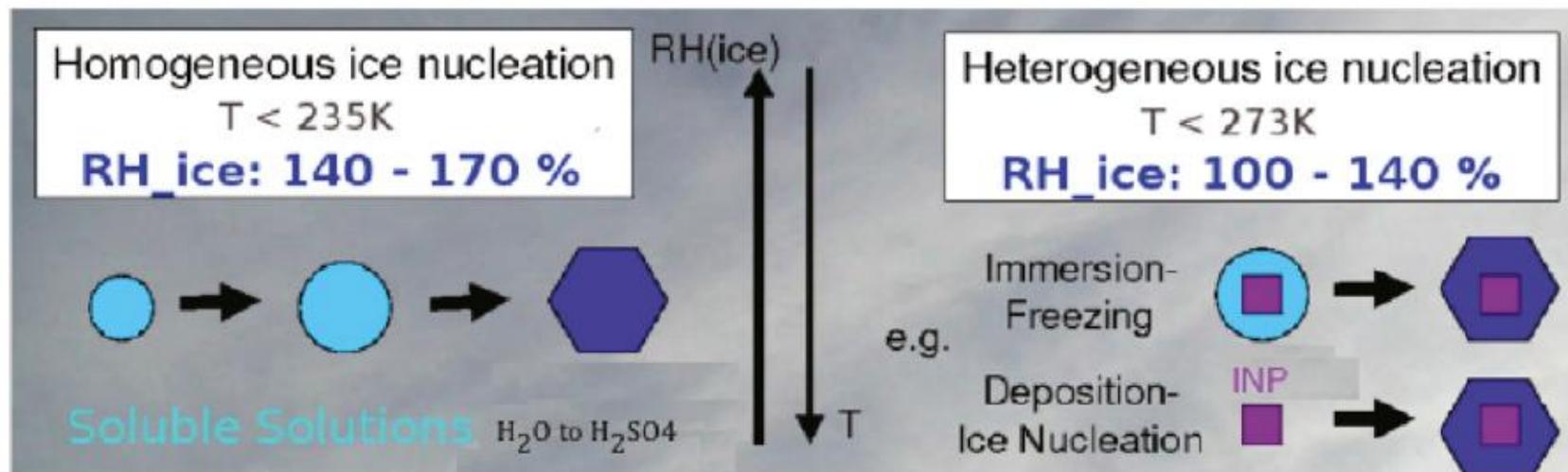
• WCT corresponding to the raw Lidar profile exceeds a pre-defined threshold.

AND

• Cloud base temperature less than -20 ℃ (*Liou, 1986*) which corresponds to base height above 8 km.

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Ice Nucleation Mechanisms

Homogeneous Nucleation	Heterogeneous Nucleation
Occurs at high RHi and low temperature	Occurs at lower RHi and higher temperature
Smaller and large number of ice-crystals	Larger and small number of ice-crystals
Large updraft velocity favourable	Depends on size, chemical composition, surface and morphology of ice-nuclei
Example: Aqueous solutions of sulphates, nitrates, ammonium, and organic compounds	Example: Mineral dust and biological particles
Well represented in Global Climate models	Poorly represented in Global Climate models

Homogeneous ice nucleation
T < 235K
RH_ice: 140 - 170 %

RH(ice)

Heterogeneous ice nucleation
T < 273K
RH_ice: 100 - 140 %

Immersion- Freezing

e.g.

Deposition- Ice Nucleation

INP

Soluble Solutions H_2O to H_2SO4

T

Heymsfield et al., (2017)

Both of these mechanisms compete with each other

Long-term Trends over Gadanki contd.: Summary

| Parameter	Sub-visible cirrus		Thin cirrus		Thick cirrus	
	Trend per year	p-value	Trend per year	p-value	Trend per year	p-value
Mid-cloud altitude (km)	0.0414 (0.0604)*	0.05 (0.56)	0.00959 (-0.00264)	0.64 (0.98)	-0.00632 (-0.08724)	0.78 (0.32)
Mid-cloud temperature (°C)	-0.1229 (-0.5745)	0.35 (0.44)	-0.00262 (-0.12121)	0.98 (0.88)	-0.0787 (0.62862)	0.61 (0.35)
Geometrical thickness (km)	0.00473 (-0.0249)	0.27 (0.24)	0.01544 (-0.00917)	0.15 (0.82)	-0.00671 (-0.03852)	0.76 (0.66)
Optical thickness	-9.4×10^{-5} $(-2. \times 10^{-4})$	0.09 (0.6)	$3. \times 10^{-4}$ (-1.937×10^{-3})	0.58 (0.5)	-0.0148 (-9.92×10^{-3})	0.01 (0.83)
Cloud fraction (%)	0.59	0.1	-0.48	0.09	-0.11	0.6

- Mid-cloud altitude of sub-visible cirrus are found to be increasing @ 41 ± 21 m /year.

- Optical thickness of sub-visible and thick cirrus clouds showed decreasing trends.

- Fraction of sub-visible cirrus increased by 9.4 % while fraction of thin cirrus decreased by 7.6 % in the last 16 years.
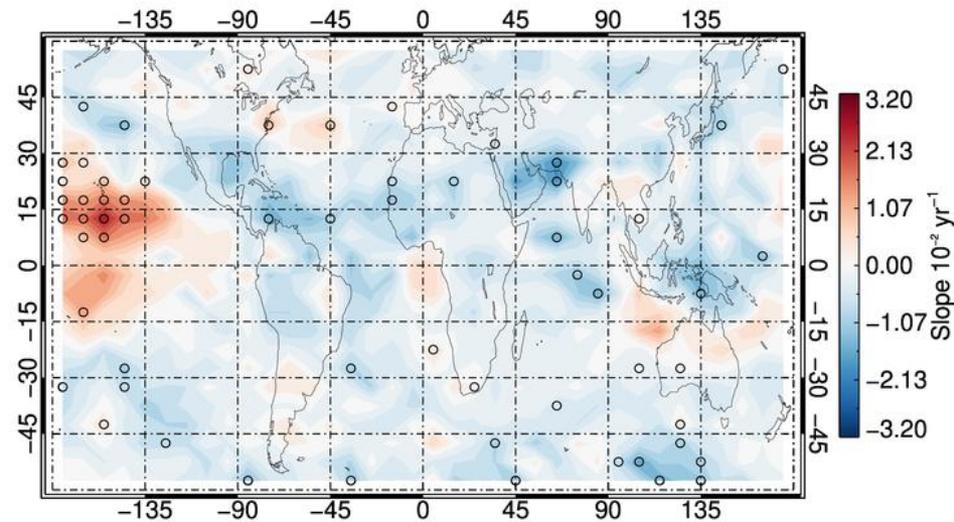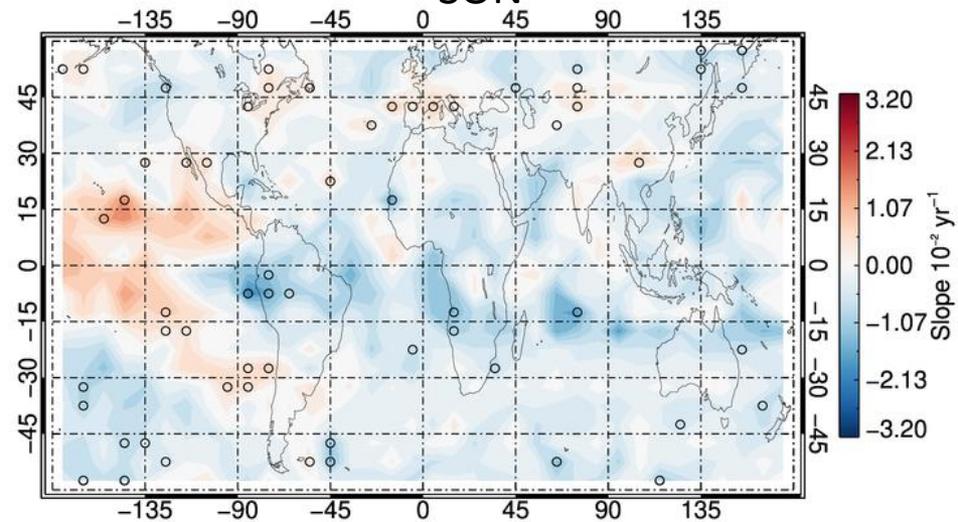
Long-term Trends: Cirrus cloud occurrence frequency

DJF
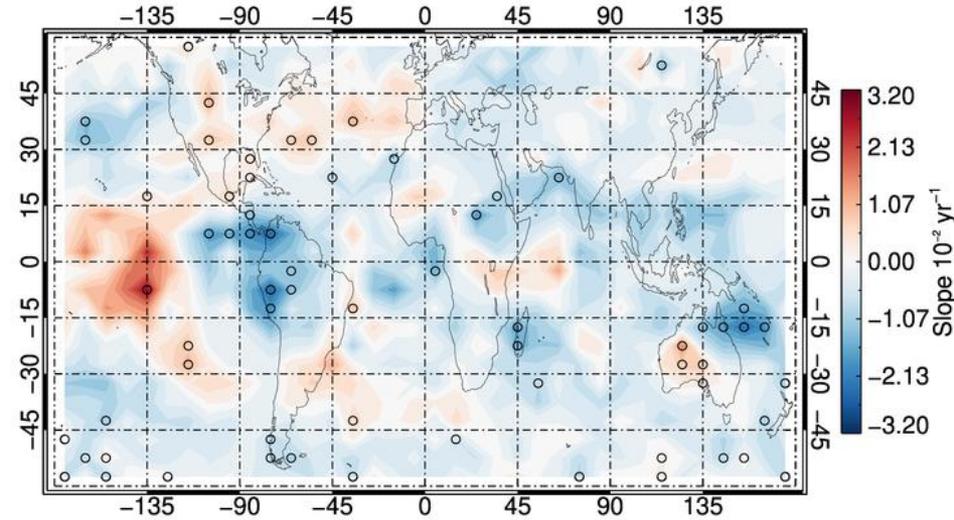
MAM
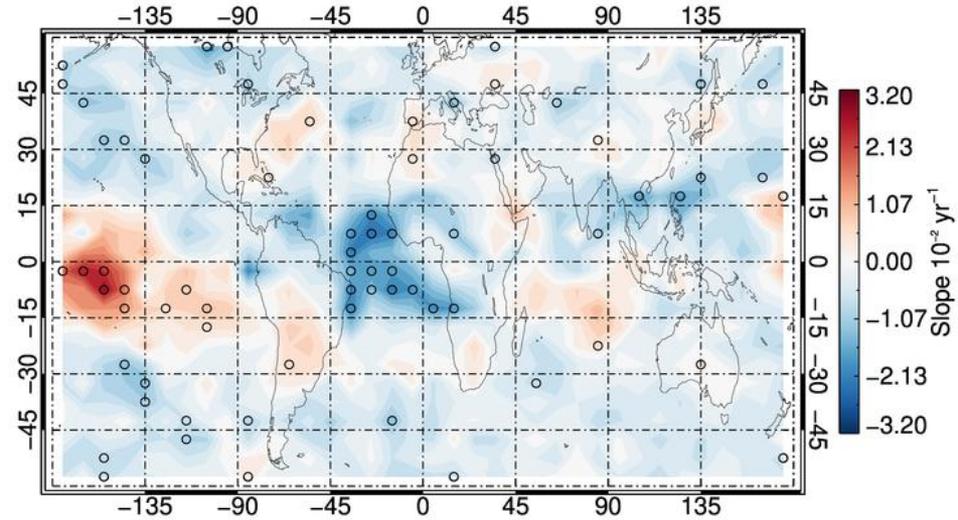
JJA

SON

CALIOP L2, Clay, v3, 2007-2017, 5 deg. lat. x 10 deg. lon.