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Zonal Cloud Trends Obtained from Passive MODIS and Active CALIOP and CPR Sensors

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Objectives

- Filter CALIPSO and CloudSat clouds to minimize the impact of sensor degradations and to have more comparable sensitivity to clouds as in MODIS observations
- Compare zonal cloud trends obtained from MODIS and CALIPSO-CloudSat combined dataset
- Separate the cloud trends into ENSO and non-ENSO components

Cloud Selections in CALIPSO and CloudSat Measurements

Clouds are selected to minimize impacts of sensor degradation and for more comparable sensitivity to MODIS measurements. Only daytime observations are used since CloudSat daytime is only available after 2012.

- **CloudSat Clouds**
  - Clouds with radar reflectivity (Z) ≥ –25 dBZ

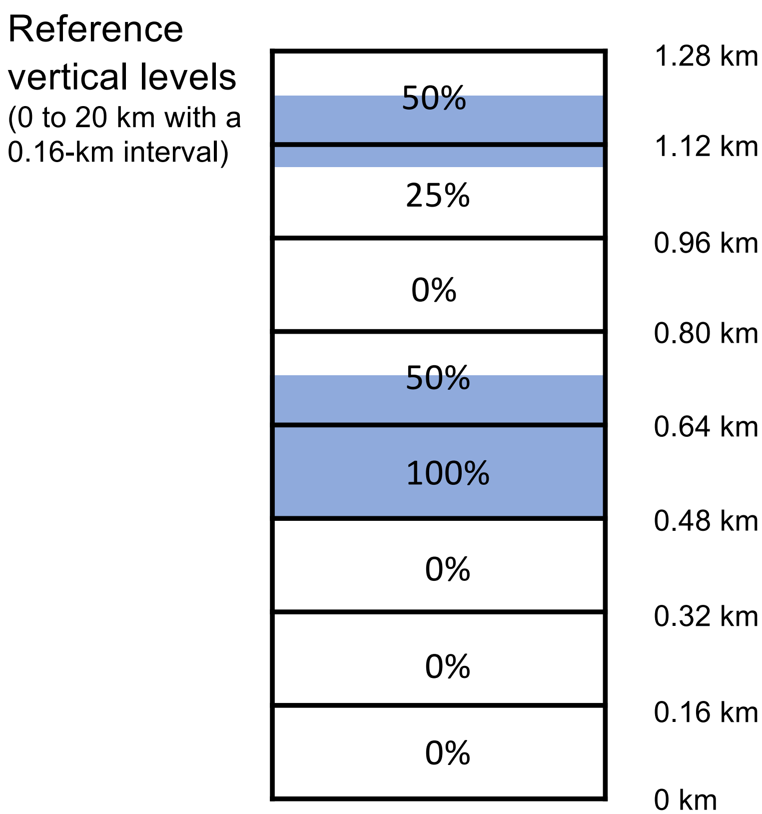
    Clouds with Z < -25 dBZ are excluded since these clouds could be detected in earlier mission due to the change in minimum detectable radar reflectivity .
- **CALIPSO clouds**
  - Horizontal averaging scale for cloud detections (HOR) ≤ 20 km

    CALIPSO clouds are detected either from a single beam (1/3 km) or spatial averaging of several beams (1, 5, 20, or 80 km). The 80-km clouds are excluded since these are mostly appeared over the Arctic and a strong decreasing trend is noted.
  - CAD (cloud-aerosol-discrimination) score ≥ 20

    The CAD score represents a confidence level of the detected clouds. When CAD < 20, there is no confidence due to highly attenuated CALIPSO signals.
  - Cloud optical depth (τ) ≥ 0.3

    MODIS misses clouds with τ < 0.3 (Kato et al. 2019). Therefore, for more consistent comparison, clouds with τ < 0.3 are also excluded in CALIPSO measurements. Also those thin clouds are more affected by the sensor degradation issues.
- **MODIS clouds: MODIS cloud parameters from CERES Single Scanner Footprint (SSF) Ed4 product**

Calculating Cloud Volume Fraction

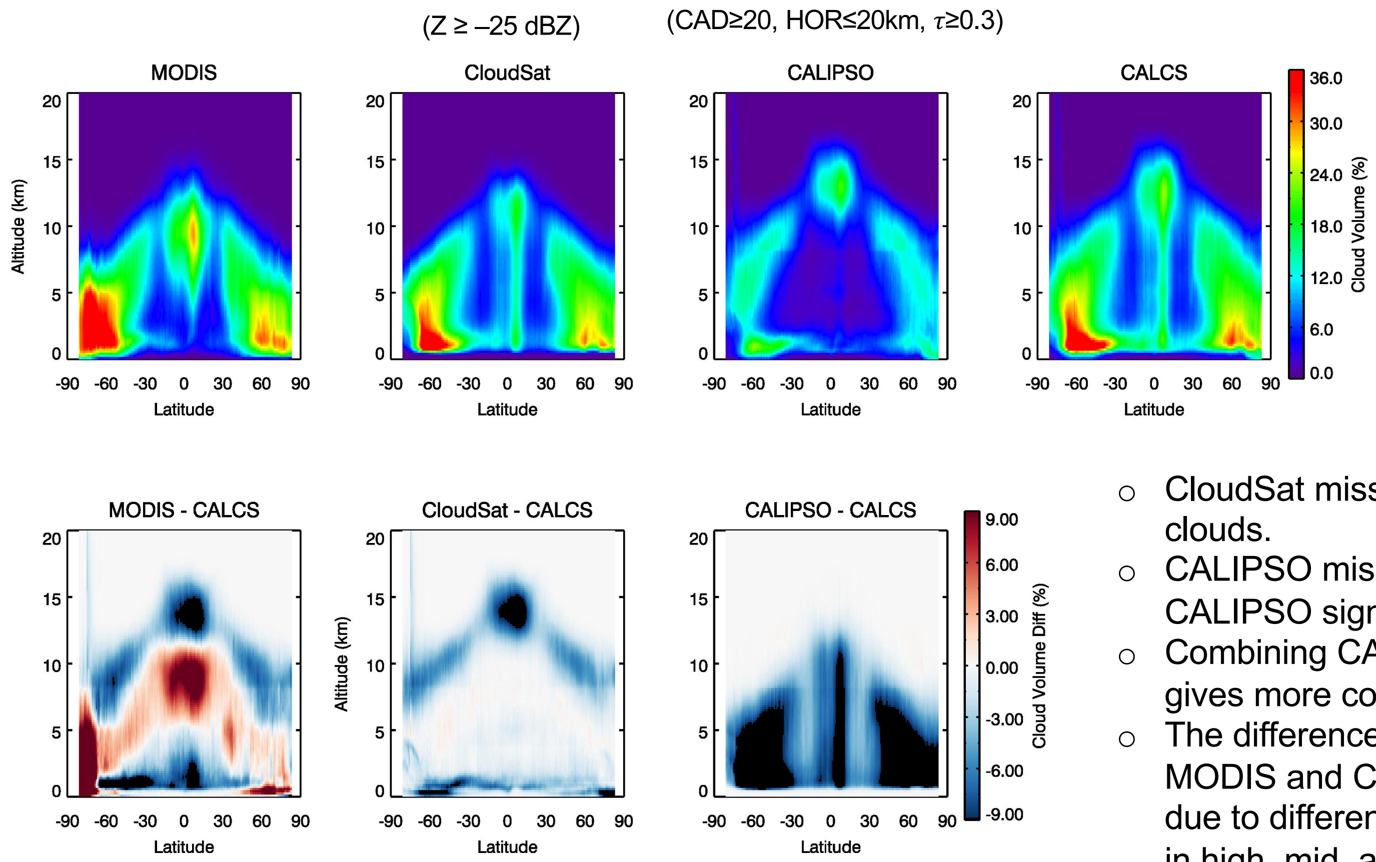


- **CALCS cloud volume fraction:**
  The cloud volume fraction profile is computed at a CALIPSO pixel resolution using merged cloud top and base heights of multiple cloud layers.

- **MODIS cloud volume fraction:**
  The cloud volume fraction profile is computed at a CERES footprint using cloud information in SSF product. Note that a single-layer cloud assumption is used for MODIS cloud retrieval. In the MODIS retrieval, cloud effective height (z_{eff}) is first derived and then cloud top and base heights are inferred using the geometrical depth (Δz) of the cloud layer. The value of Δz is inferred from the parametrized equation using cloud optical depth, phase, and altitude.

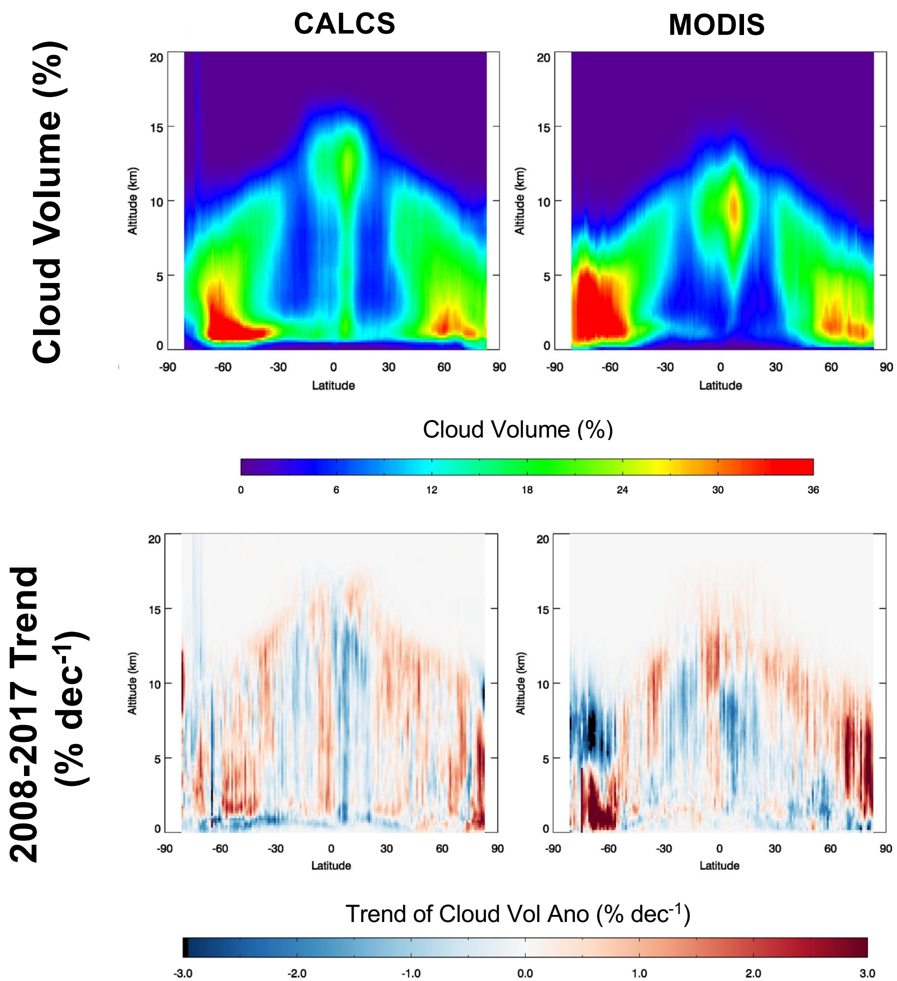
Zonal Distributions of Cloud Volume Fraction from MODIS, CloudSat, CALIPSO, and CALIPSO+CloudSat (CALCS)

2008, Daytime



- CloudSat misses thin cirrus and low clouds.
- CALIPSO misses mid/low clouds when the CALIPSO signal is fully attenuated.
- Combining CALIPSO+CloudSat (CALCS) gives more complete picture of clouds.
- The differences in cloud amounts from MODIS and CALCS seem to be mostly due to different cloud heights. Differences in high, mid, and low clouds are compensating.

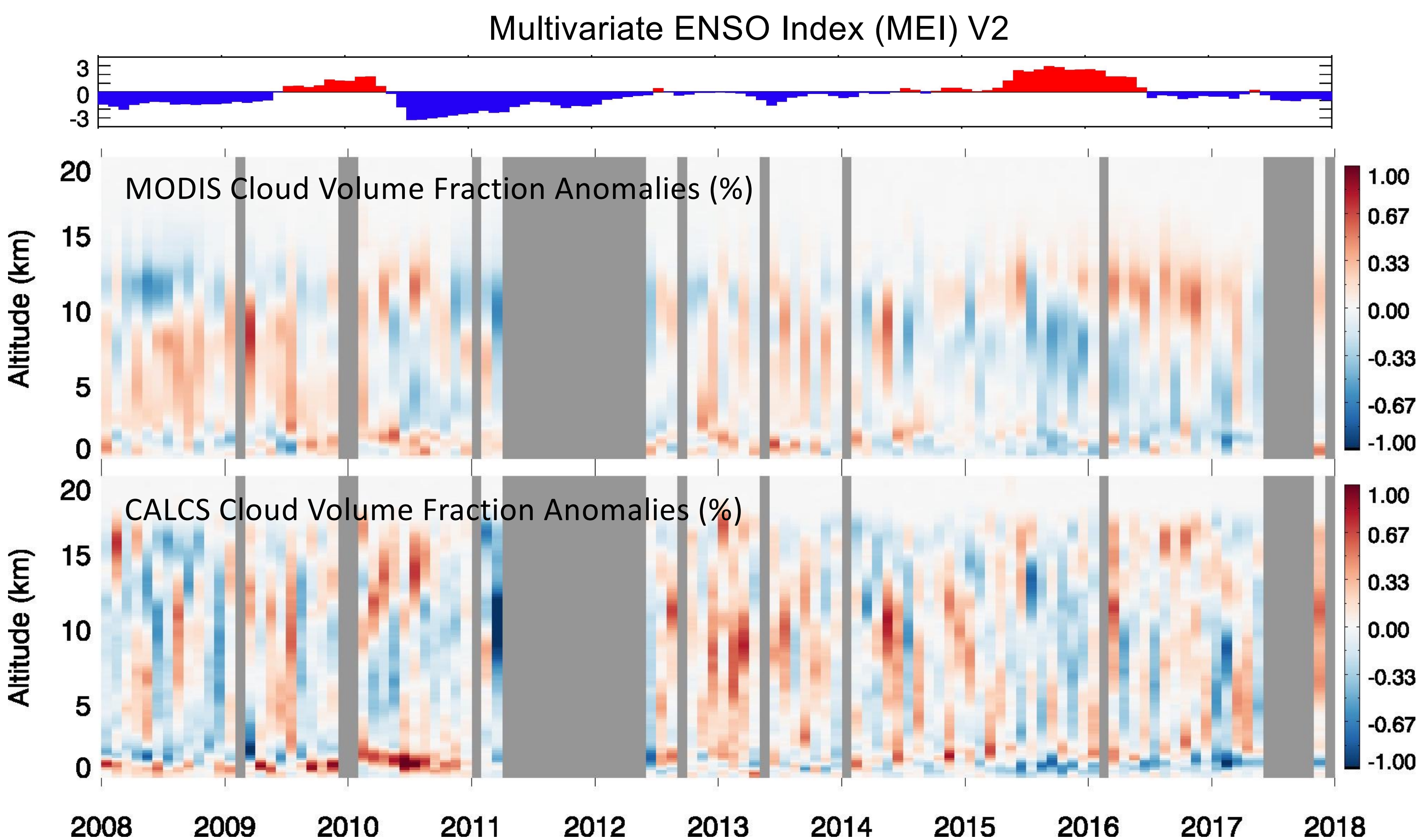
Zonal Cloud Trends from CALIPSO+CloudSat (CALCS) and MODIS for 2008-2017



- **Consistent features:**
  Both CALCS and MODIS indicate an increase of uppermost clouds and a decrease underlying clouds over 60°S–60°N.

- **Inconsistent features:**
  Cloud altitudes in CACS and MODIS trends over the Antarctic are different: Probably due to the limitations of the MODIS cloud height retrievals in temperature inversion or skin temperature issues. Also, it can be related to the chemical composition of polar stratospheric clouds (i.e., non hydrometeors), which cannot be detected by MODIS.

ENSO Time Series versus Cloud Volume Fraction Anomalies (%) over 60°S–60°S



Decomposition of Cloud Trends into ENSO and non-ENSO Components

Monthly Cloud Volume Fraction Anomaly (%) Time series

Third-order regression model using Multivariate ENSO Index (MEI)

$$\Delta C = \underbrace{c_0 + c_1\,\mathrm{MEI} + c_2\,\mathrm{MEI}^2 + c_3\,\mathrm{MEI}^3}_{\text{ENSO Component}} + \underbrace{\varepsilon}_{\text{non-ENSO Component}}$$

ENSO Component ($\widehat{\Delta C_i}$) of time sies

↓

Cloud trend of ENSO component

non-ENSO Component of time series (ε_i)

↓

Cloud trend of non-ENSO component

Total Cloud Trend

Monthly cloud anomaly predicted from the regression model

$$\widehat{\Delta C_i} = c_0 + c_1 MEI_i + c_2 MEI_i^{\,2} + c_3 MEI_i^{\,3}$$

Total sum of squares (TSS)

$$TSS = \sum_{i=1}^{n} (\Delta C_i - \overline{\Delta C})^2$$

Residual sum of squares (RSS)

$$RSS = \sum_{i=1}^{n} \left(\Delta C_i - \widehat{\Delta C_i}\right)^2 = \sum_{i=1}^{n} (\varepsilon_i)^2$$

Coefficient of determination

$$R^2 = 1 - RSS/TSS$$

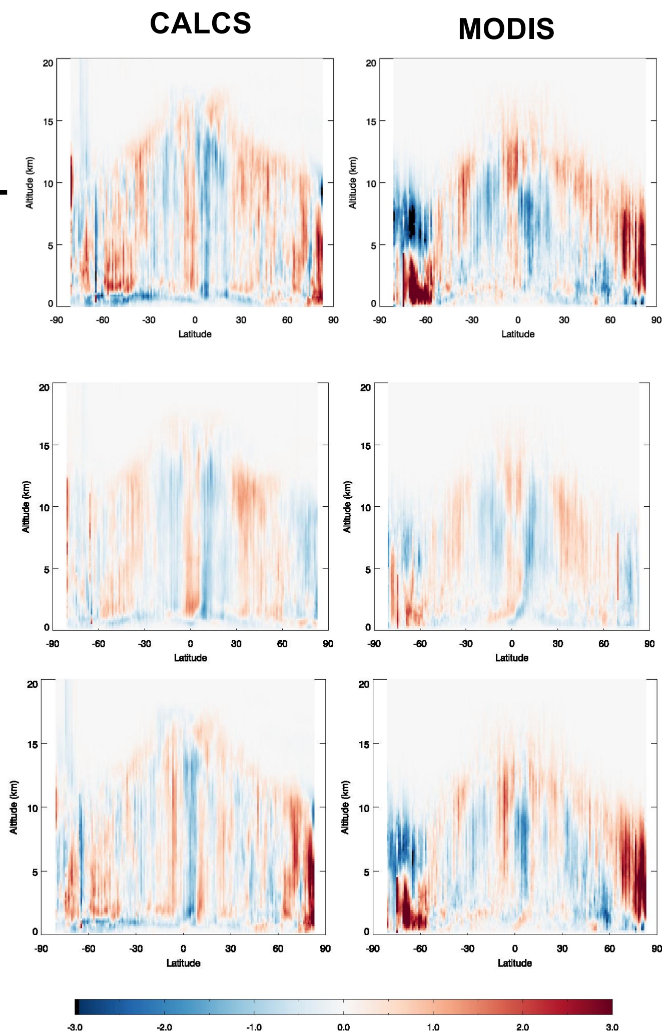
Using the regression model, cloud anomaly time series are are separated into ENSO and non-ENSO components. Then the trends of them can be obtained.

Decomposing 2008-2017 Cloud Trends into the ENSO and non-ENSO Components

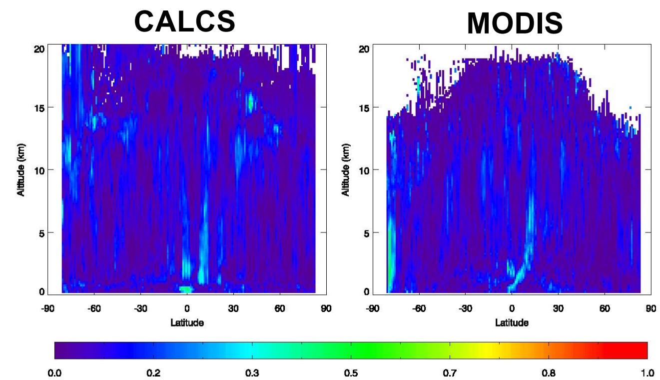
Total cloud trends (% dec^{-1})

Trends (% dec^{-1}) of the ENSO Component

Trends (% dec^{-1}) of the non-ENSO Component



Coefficient of Determination (R^2)

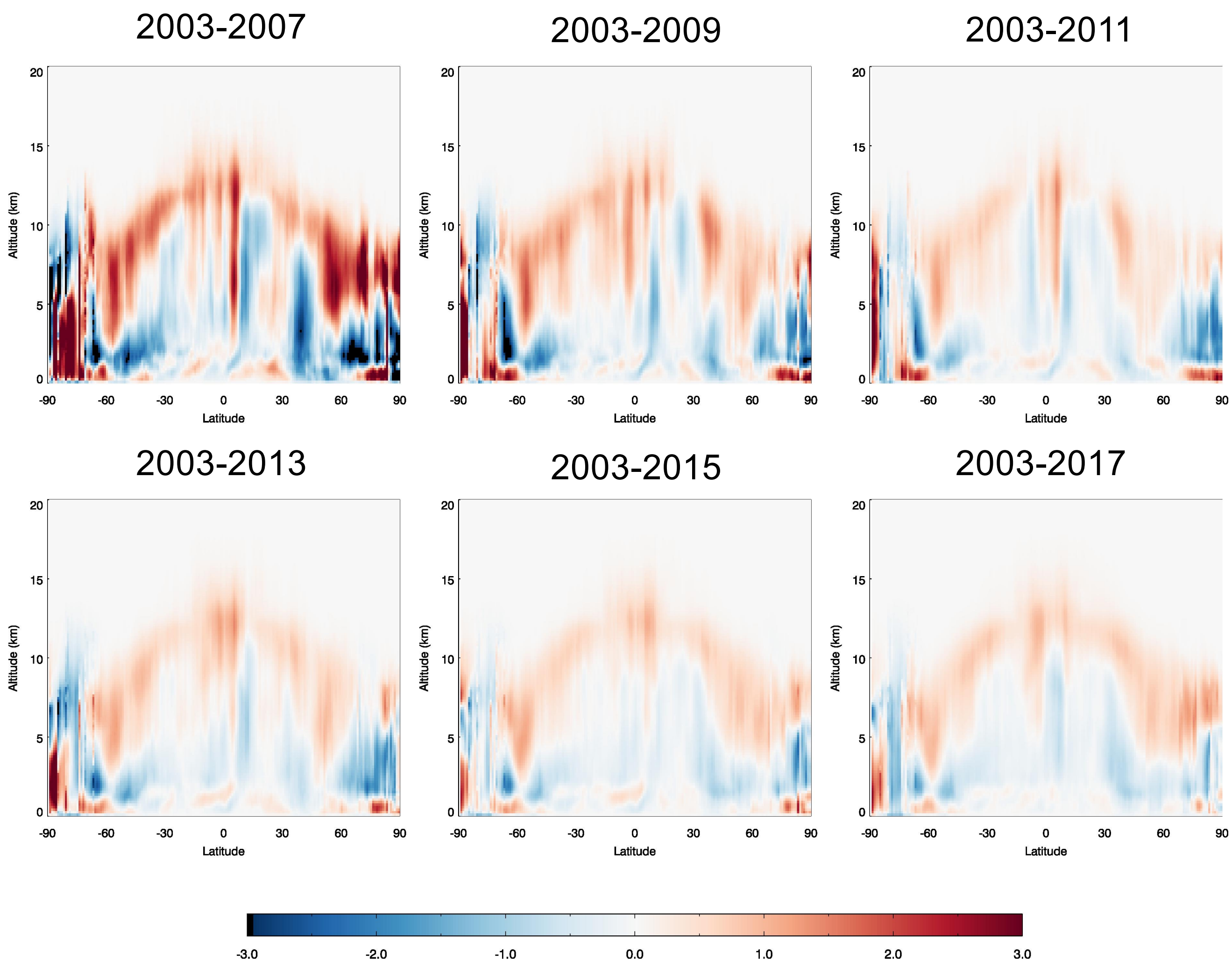


Less than 30% of total variation of cloud anomalies are explained by the regression model using MEI ($R^2 < 0.3$).

<u>Non-ENSO Component</u>

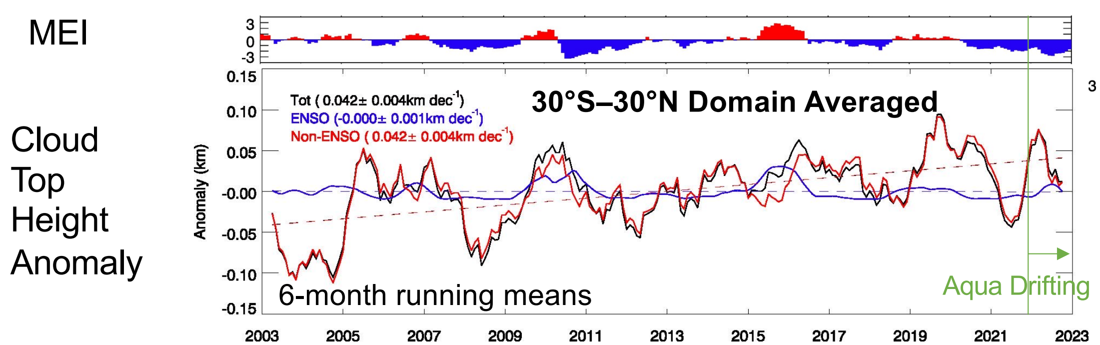
1) Arctic cloud increase related to the sea ice loss (Kay and Gettleman 2009; Wu and Lee 2012; Sato et al. 2012)
2) Non-ENSO signals in the cloud trends are positive in the uppermost cloud layer and negative in the underlying (mid, low) clouds. This indicates rising high clouds as the response to temperature warming (Wetherald and Manabe 1988; Zelinka and Hartmann 2010; Voigt et al. 2019; Aerenson et al. 2022; Richardson et al. 2022)

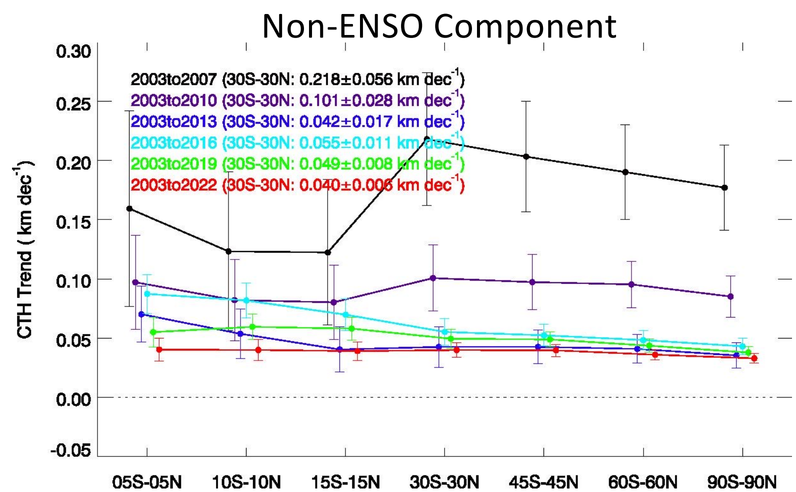
Non-ENSO Component of MODIS Aqua Cloud Trends (2003–2017)



- The 10-year period may not be long enough for detecting rising high cloud features (Takahashi et al., 2019; Davies et al. 2017; Chepfer et al. 2018).
- Therefore, a longer periods are considered using MODIS measurements.
- All periods generally show positive trends in uppermost clouds and negative trends in the underlying clouds.

Trends of Cloud Top Height for High Clouds (10-18 km) from MODIS Using a Longer Record (2003-2022)





- The domain averaged CTH anomalies show slight increasing trend, but the magnitude largely differ by the period.
- A longer record will reduce the uncertainty of the trend estimate.
- The magnitude of CTH trends seems to be comparable in earlier studies (Aerenson et al. 2022; Richardson et al. 2022).

Summary

- When CloudSat+CALIPSO clouds are filtered for known sensitivity differences, trends agree well with MODIS cloud trends for 2008–2017.
- When the clouds are decomposed into ENSO and non-ENSO components, the non-ENSO component is related to 1) the cloud increase over the Arctic and 2) rising high clouds over 60°S–60°N. MODIS and CALCS consistently capture these features.
- When a longer MODIS record is used, rising high clouds are observed, but the magnitude varies depending on periods.

Thank you for your attention!

Please contact to seung-hee.ham@nasa.gov if you have any questions.