Multi-Year Trends in MODIS & MISR Observed Cloud Fraction over the Extratropical Oceans

Andrew Geiss
Roger Marchand
02.03.2016
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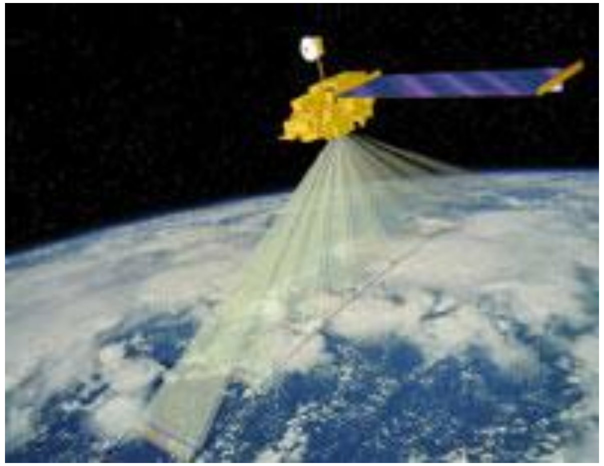
Instruments: MISR



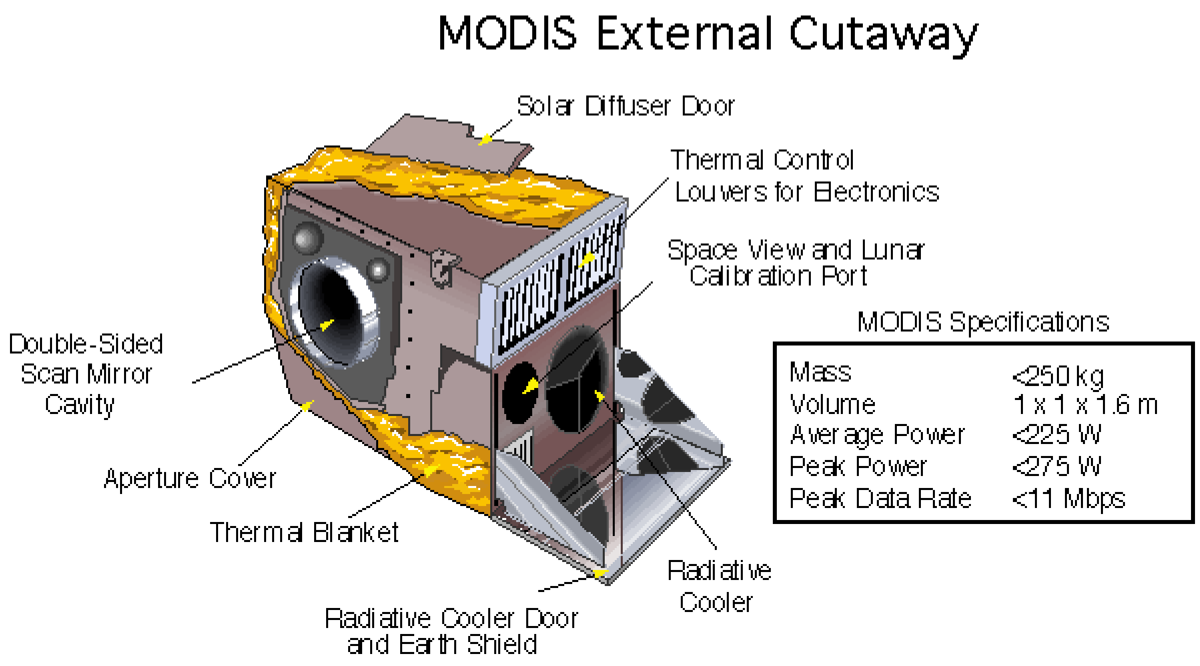
Multi-angle Imaging Spectro-Radiometer

Cloud top heights retrieved via multi-angle imaging

Cloud optical depth over ocean

Monthly CTH-OD Cloud Fraction joint histograms

Instruments: MODIS

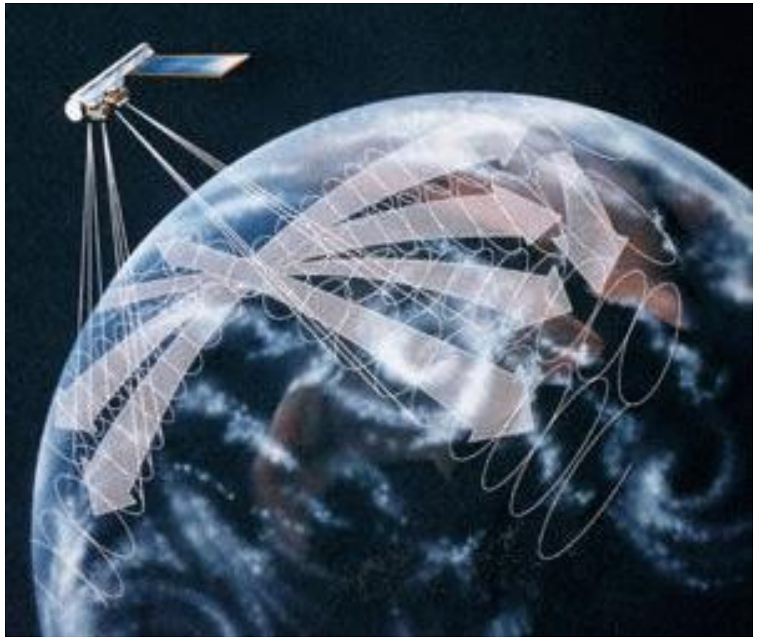


MODerate resolution Imaging Spectro-radiometer

36 bands, Cloud top pressure estimated via IR bands

Monthly cloud top pressure versus optical depth Cloud Fraction joint histograms

Instruments: CERES



Clouds and the Earth’s Radiant Energy System

Broadband radiometer measuring TOA fluxes

I will use monthly estimates of albedo

Methodology

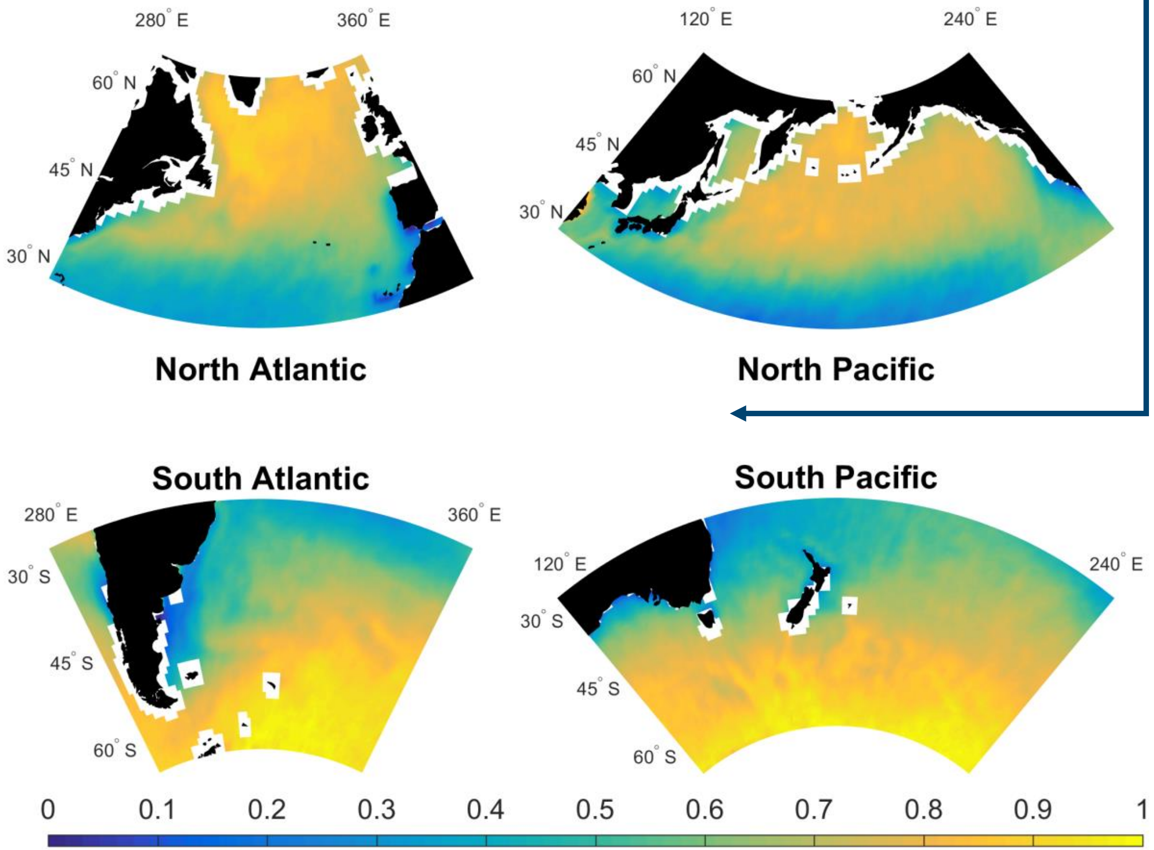
Compute linear temporal trends on cloud fraction datasets.

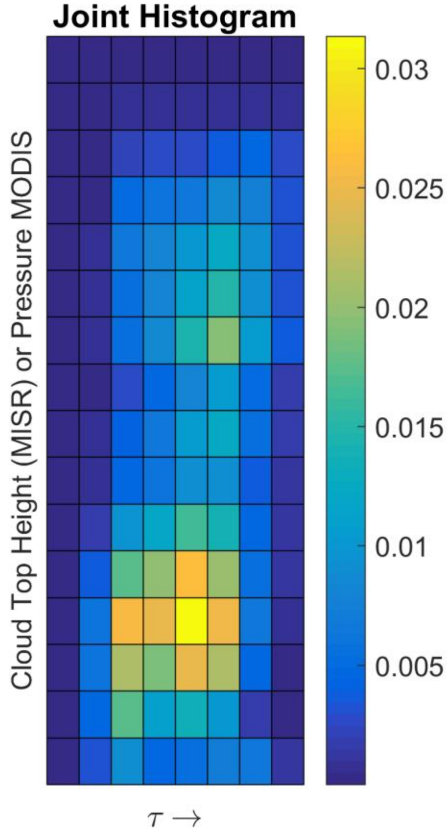
Windowed bootstrap resampling is used to determine 95% confidence intervals.

Robustness of overall result can be tested via Bretherton et al. 1998

Bretherton C, Widmann M, Dymnikov V, Wallace J, and Blade I (1998) The Effective Number of Spatial Degrees of Freedom…

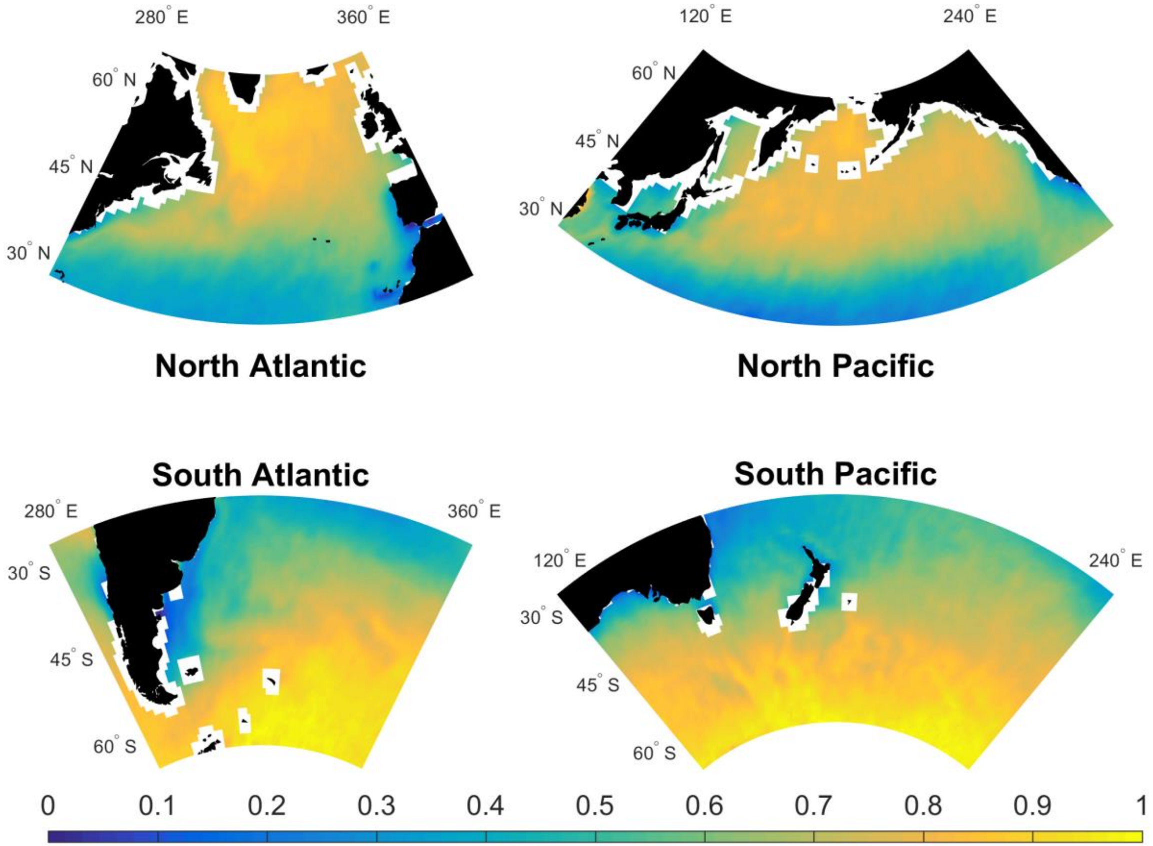
Data

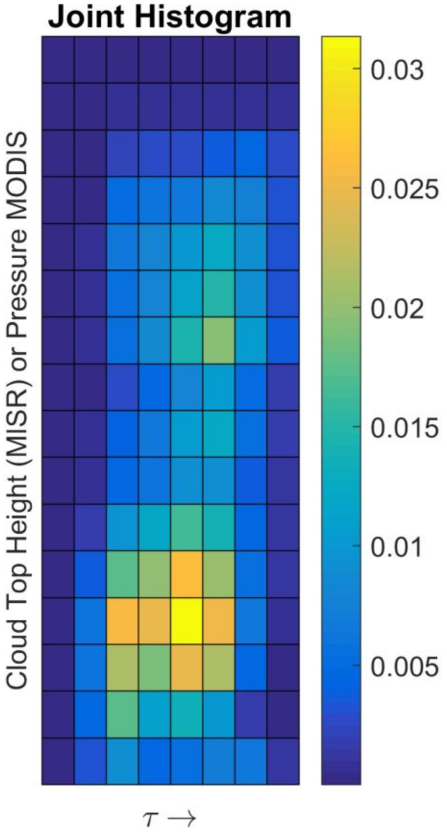




Limit analysis to four extratropical ocean basins (example shows 15yr mean total cloud fraction using monthly data)

Data





Limit analysis to four extratropical ocean basins

An example cloud top height / pressure versus optical depth cloud fraction joint histogram

Poleward Shift of the Storm Tracks

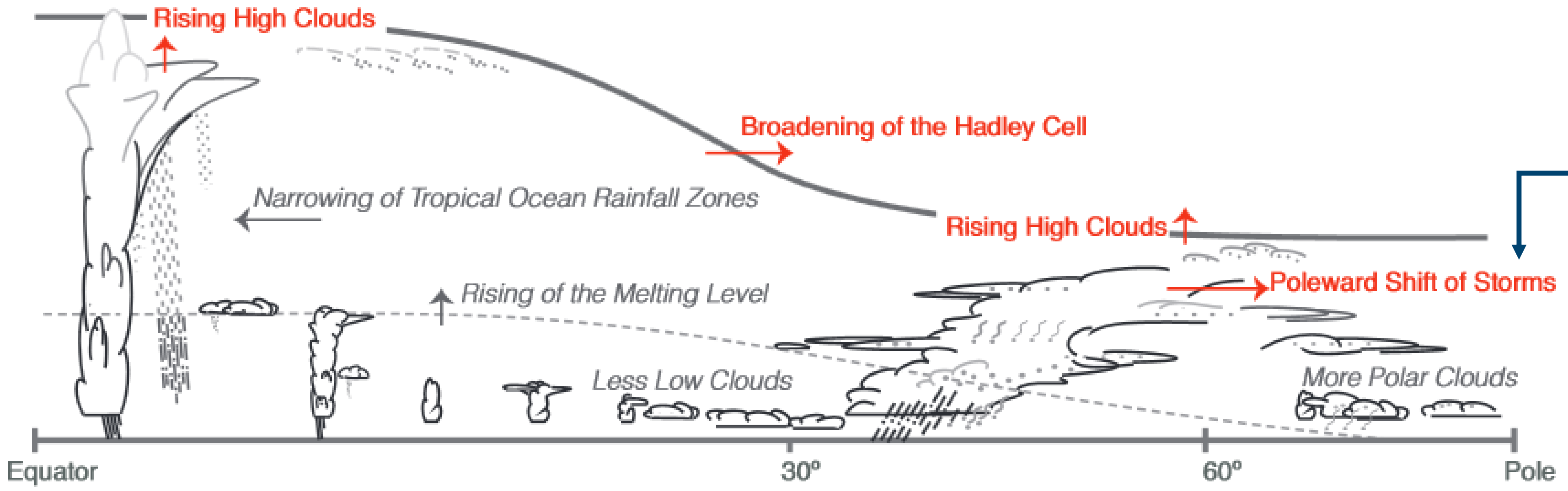
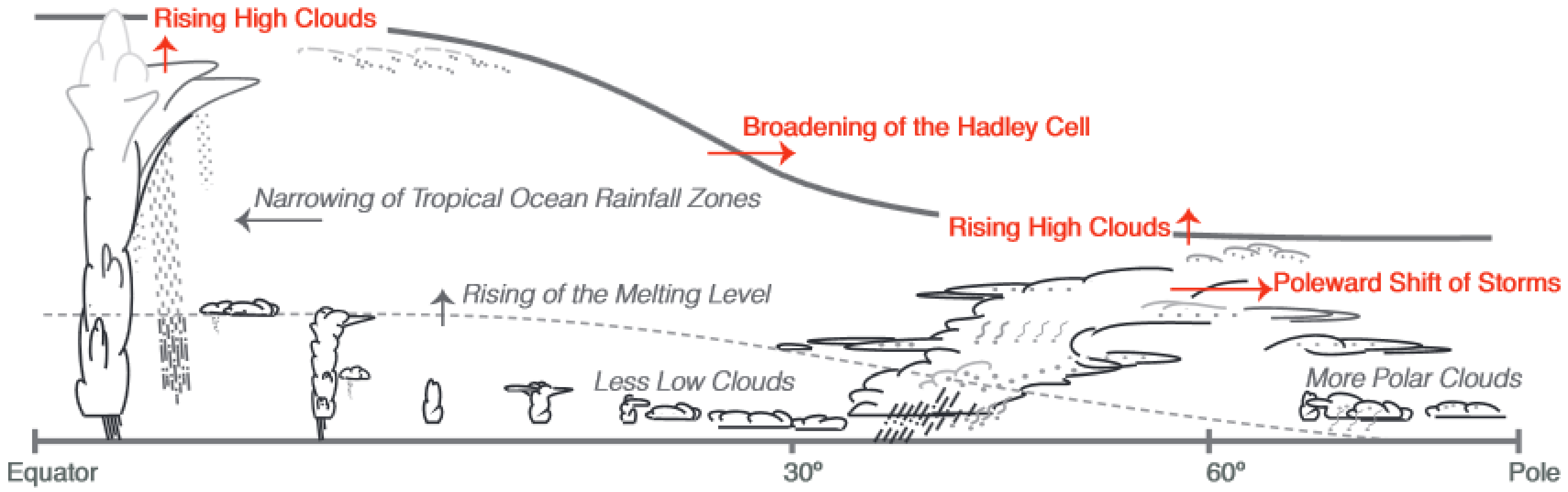


Figure 7.11 | Robust cloud responses to greenhouse warming (those simulated by most models and possessing some kind of independent support or understanding). The tropopause and melting level are shown by the thick solid and thin grey dashed lines, respectively. Changes anticipated in a warmer climate are shown by arrows, with red colour indicating those making a robust positive feedback contribution and grey indicating those where the feedback contribution is small and/or highly uncertain. No robust mechanisms contribute negative feedback. Changes include rising high cloud tops and melting level, and increased polar cloud cover and/or optical thickness (*high confidence*); broadening of the Hadley Cell and/or poleward migration of storm tracks, and narrowing of rainfall zones such as the Intertropical Convergence Zone (*medium confidence*); and reduced low-cloud amount and/or optical thickness (*low confidence*). Confidence assessments are based on degree of GCM consensus, strength of independent lines of evidence from observations or process models and degree of basic understanding.

A poleward shift of the storm tracks is expected (with high certainty) under global warming.

Boucher et. al. (2013) 'Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth…'

Poleward Shift of the Storm Tracks



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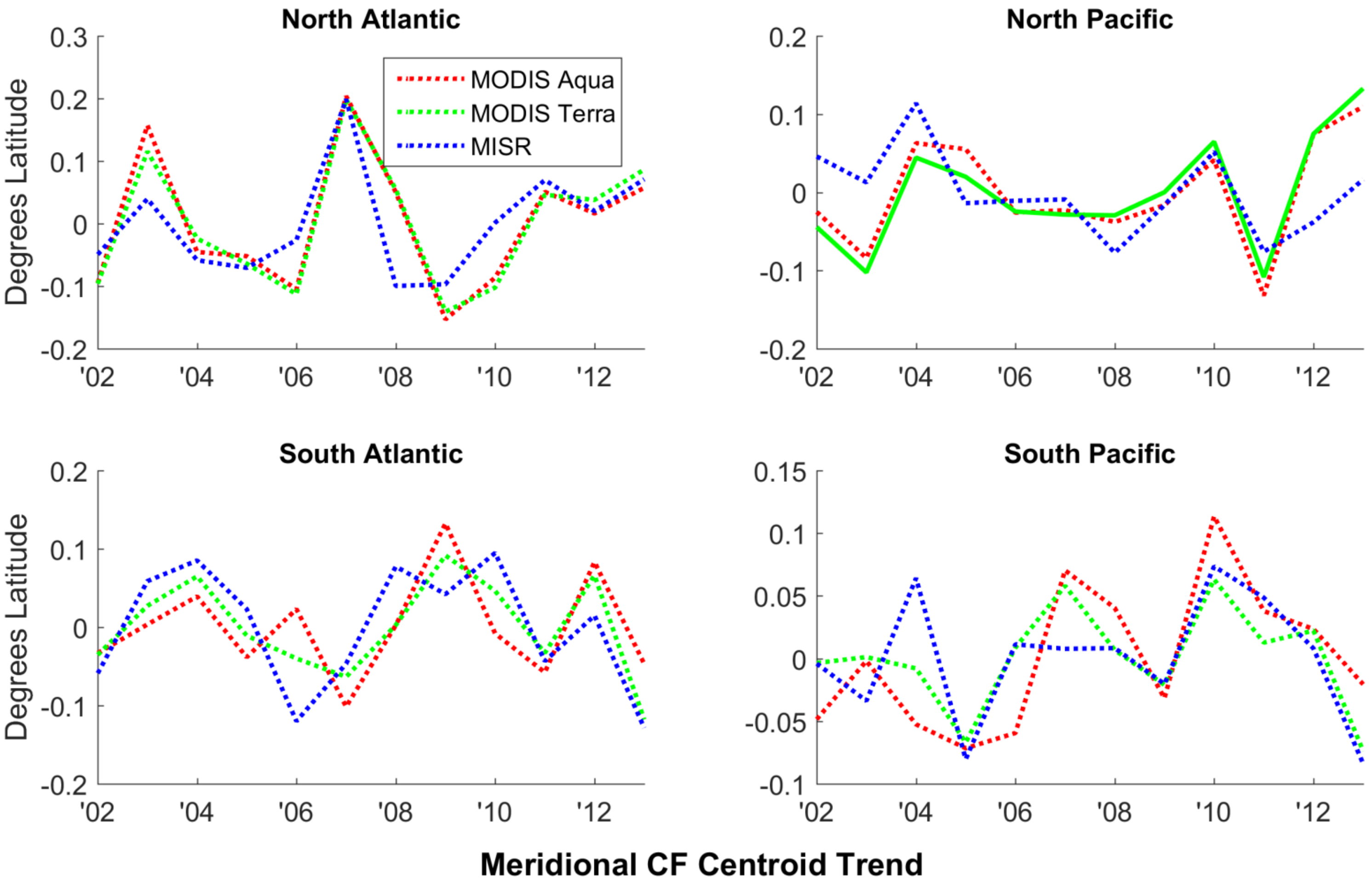
A poleward shift of the storm tracks is expected (with high certainty) under global warming.

Can this prediction be verified by observation?

Boucher et. al. (2013) ‘Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth…’

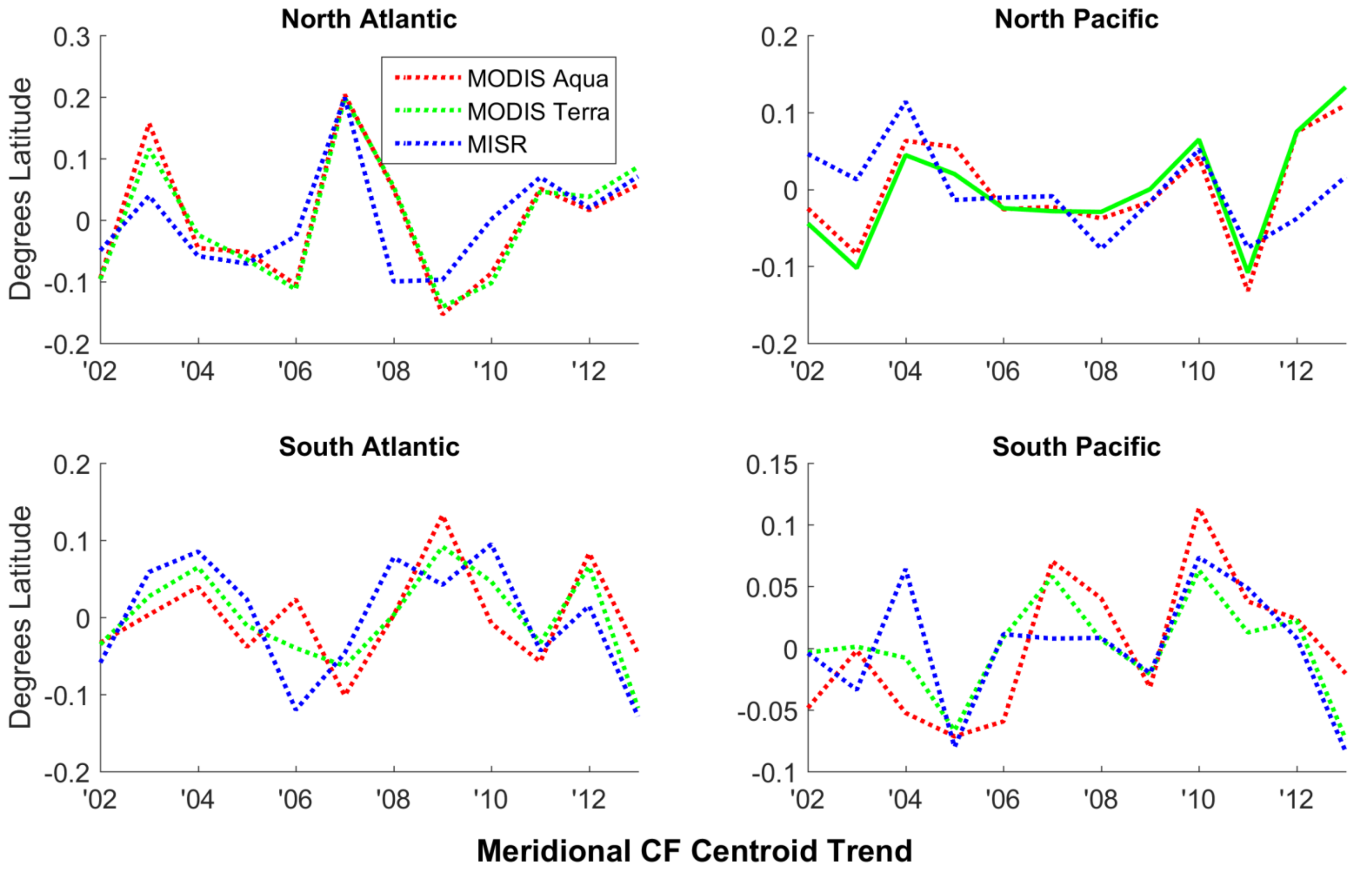
Meridional CF Centroid



Bender et al. 2011 identified a poleward shift in the location of the storm tracks in ISCCP (International Satellite Cloud Climatology Project) total cloud fraction.

Bender F, V Ramanathan, T Tselioudis (2011) ‘Change in Extratropical Storm Track Cloudiness 1983-2008: Observational Support…’ Climate Dynamics

Meridional CF Centroid



This is the anomaly in the meridional centroid of total cloud fraction (latitude weighted by cloud fraction):

$$\phi_c = \frac{\sum \phi \, \overline{C(\phi)}}{\sum \overline{C(\phi)}}$$

Bender F, V Ramanathan, T Tselioudis (2011) ‘Change in Extratropical Storm Track Cloudiness 1983-2008: Observational Support…’ Climate Dynamics

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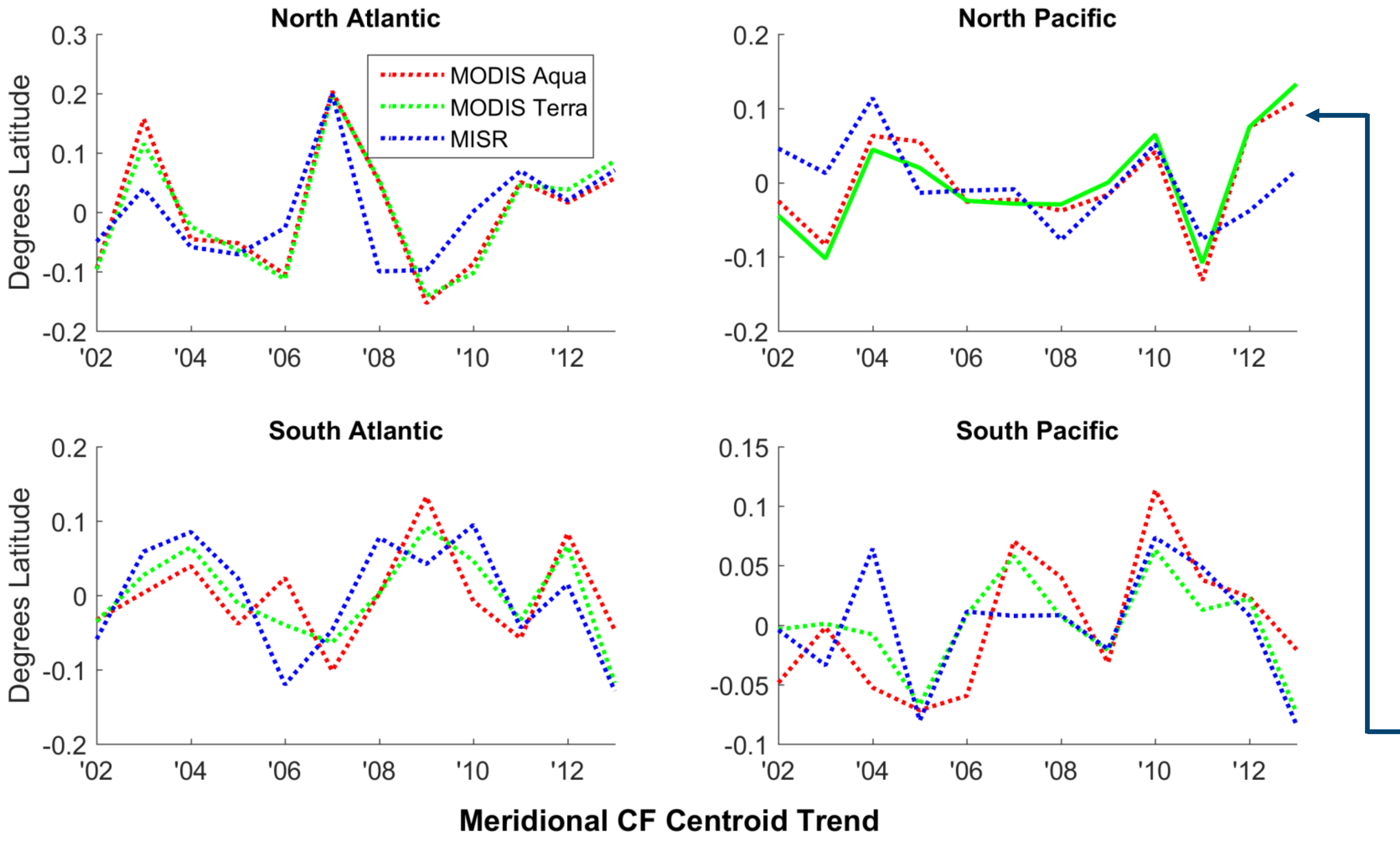

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Only one instrument in one basin shows a significant trend (solid)

Bender F, V Ramanathan, T Tselioudis (2011) ‘Change in Extratropical Storm Track Cloudiness 1983-2008: Observational Support…’ Climate Dynamics

Results 1

Are poleward trends present in MISR and MODIS CF data over the lifetime of EOS?

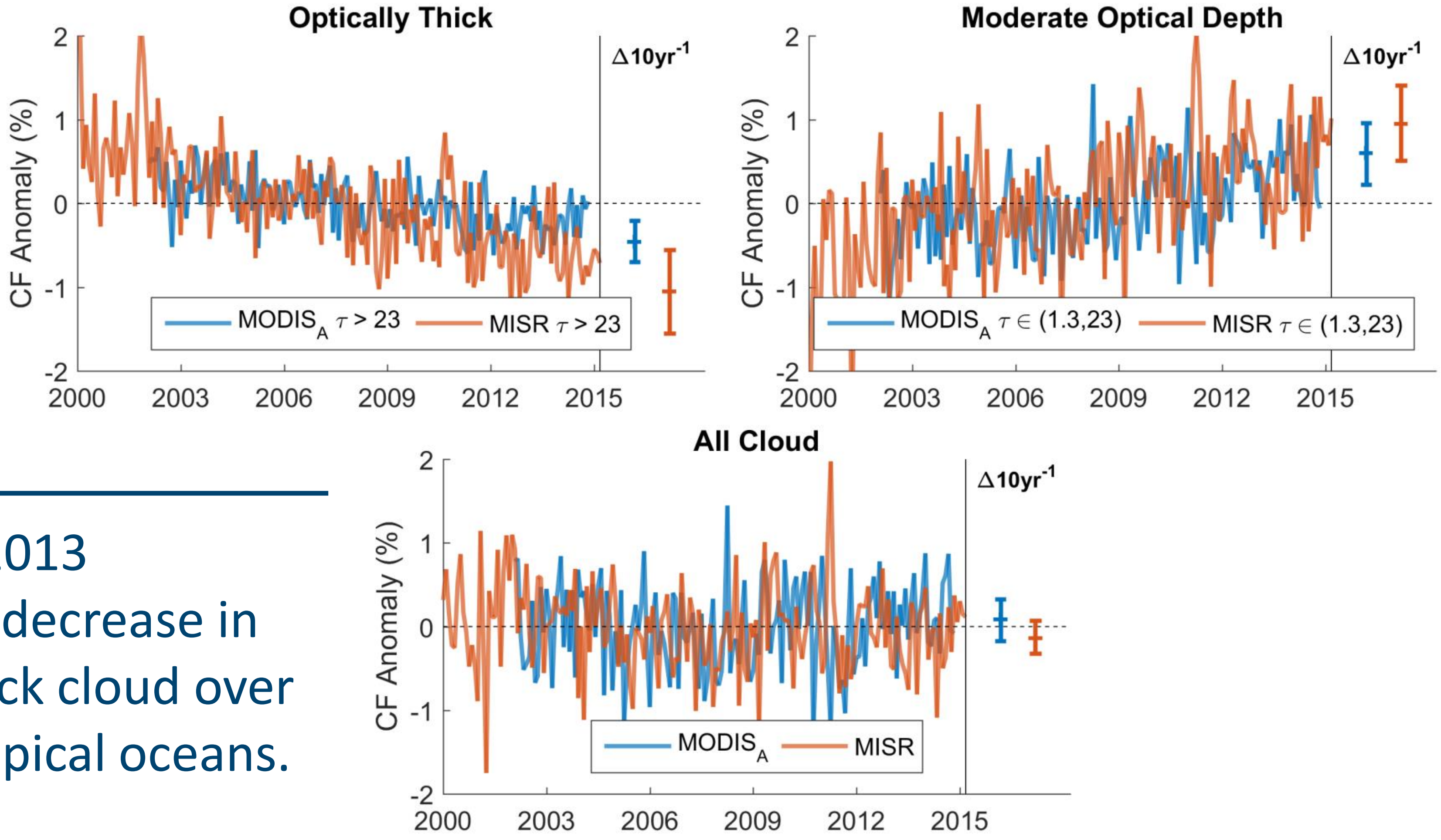
No.

Either the trends present in ISCCP data are not present in EOS data

…or the poleward shift has not continued 2002-2013

…or the trends are not resolvable on shorter time-scales

Trends in CTH-OD Histogram Categories



Marchand 2013 identified a decrease in optically thick cloud over the extratropical oceans.

Marchand R (2013) Trends in ISCCP, MISR, and MODIS cloud-top-height and optical-depth histograms. Journal of Geophysical Research 118:1-9

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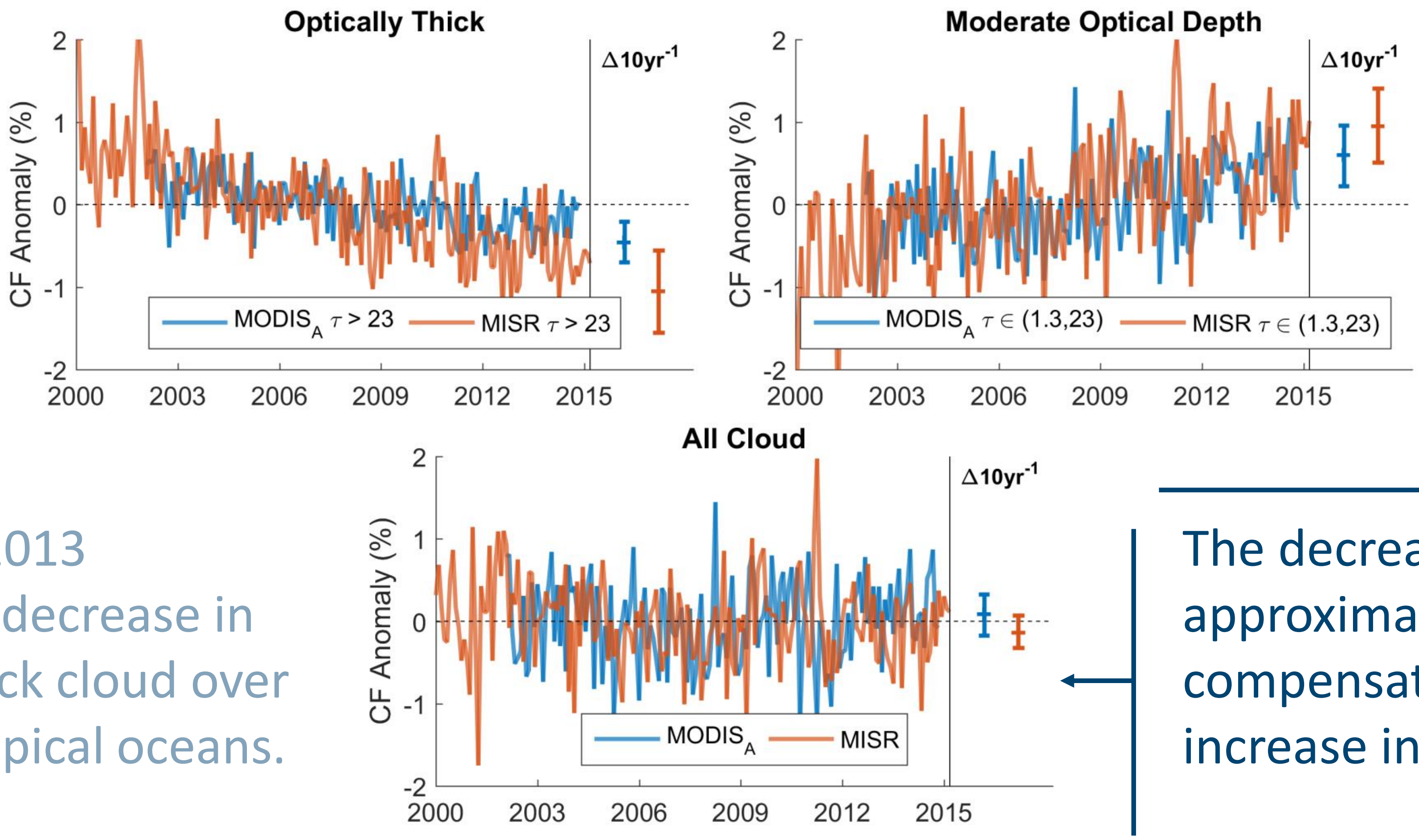
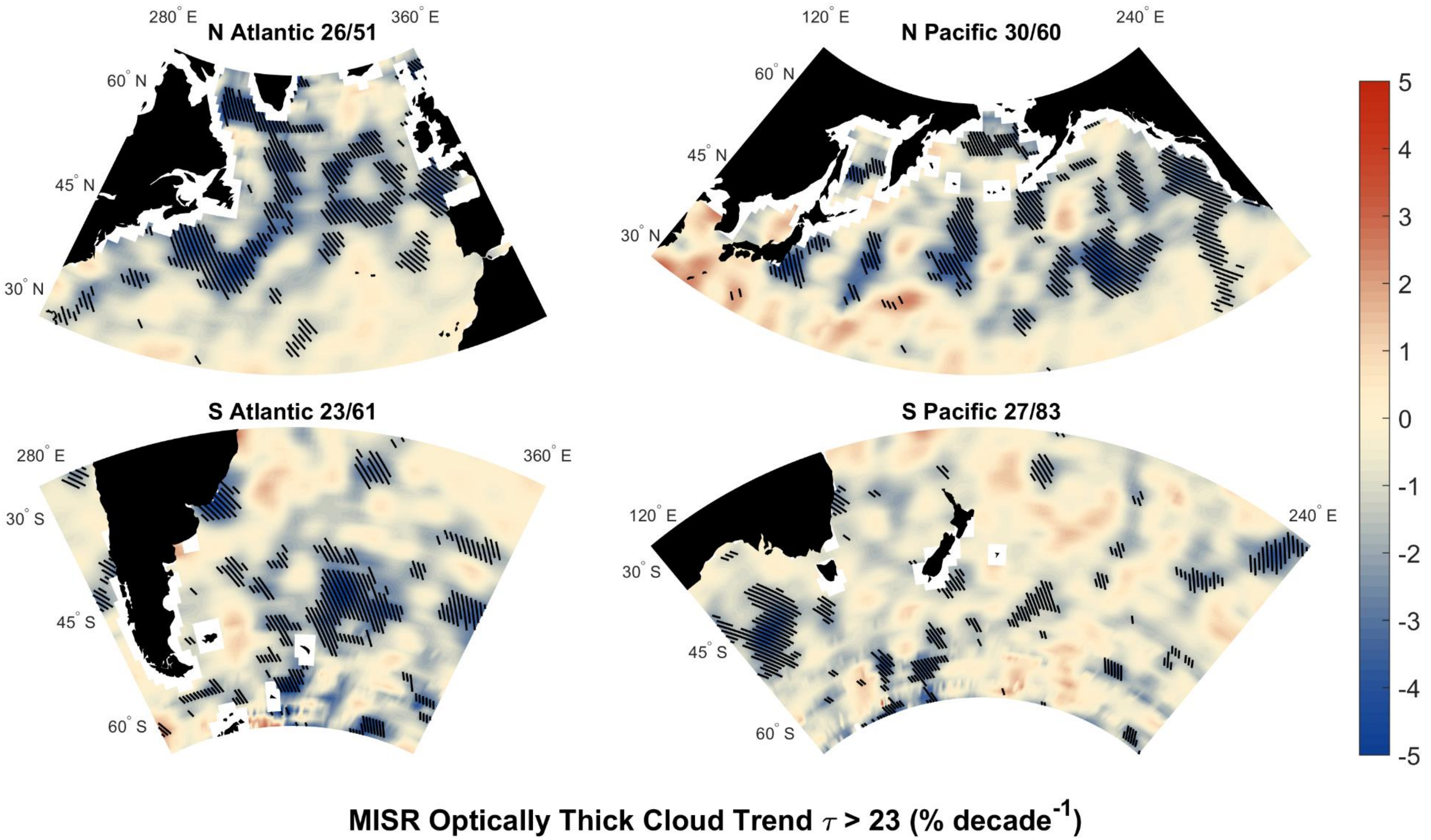


Marchand 2013 identified a decrease in optically thick cloud over the extratropical oceans.

The decrease has been approximately compensated by an increase in thinner cloud.

Marchand R (2013) Trends in ISCCP, MISR, and MODIS cloud-top-height and optical-depth histograms. Journal of Geophysical Research 118:1-9

Trends in Optically Thick Cloud

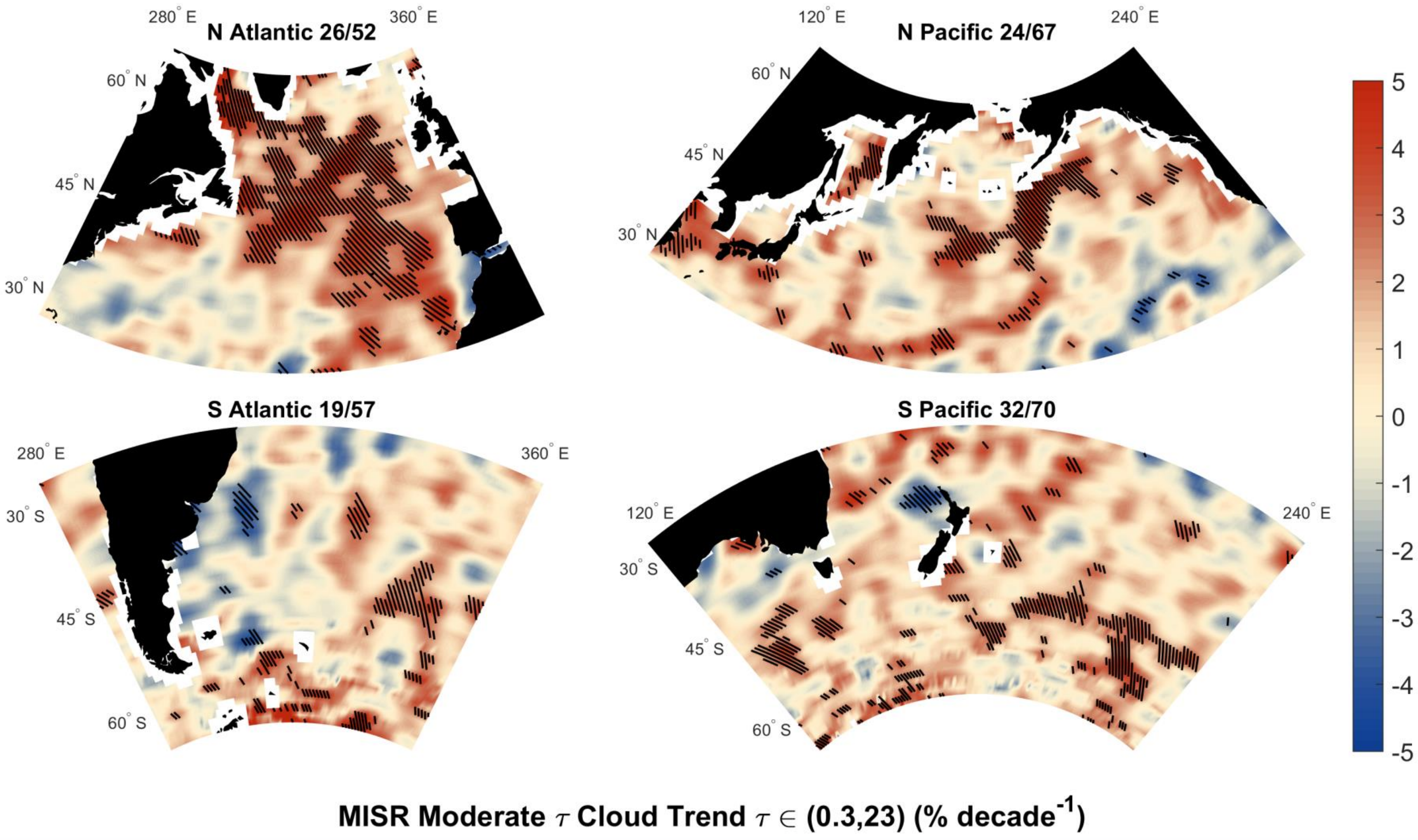


Here is the spatial distribution of the trend in optically thick cloud.

Hatching represents statistical significance at the 95% level.

There is clearly spatial structure (e.g. in the northern hemisphere storm tracks).

Trends in Cloud of Moderate Optical Depth



Here is the spatial distribution of the trend in cloud with optical depth between .3 - 23.

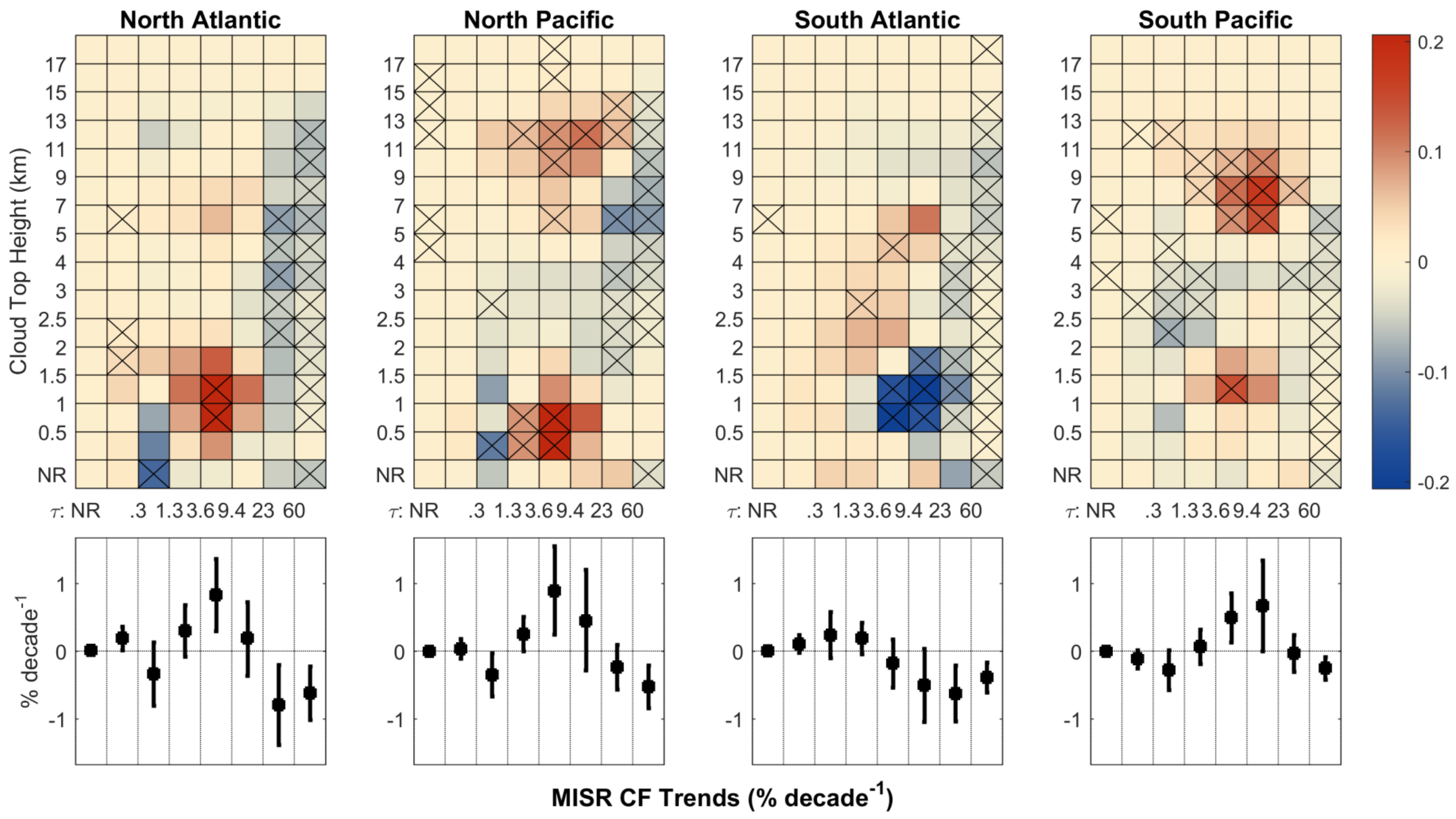
Objectives

Characterize changes in cloud fraction

Cross-instrument verification

Determine the cause of the changes

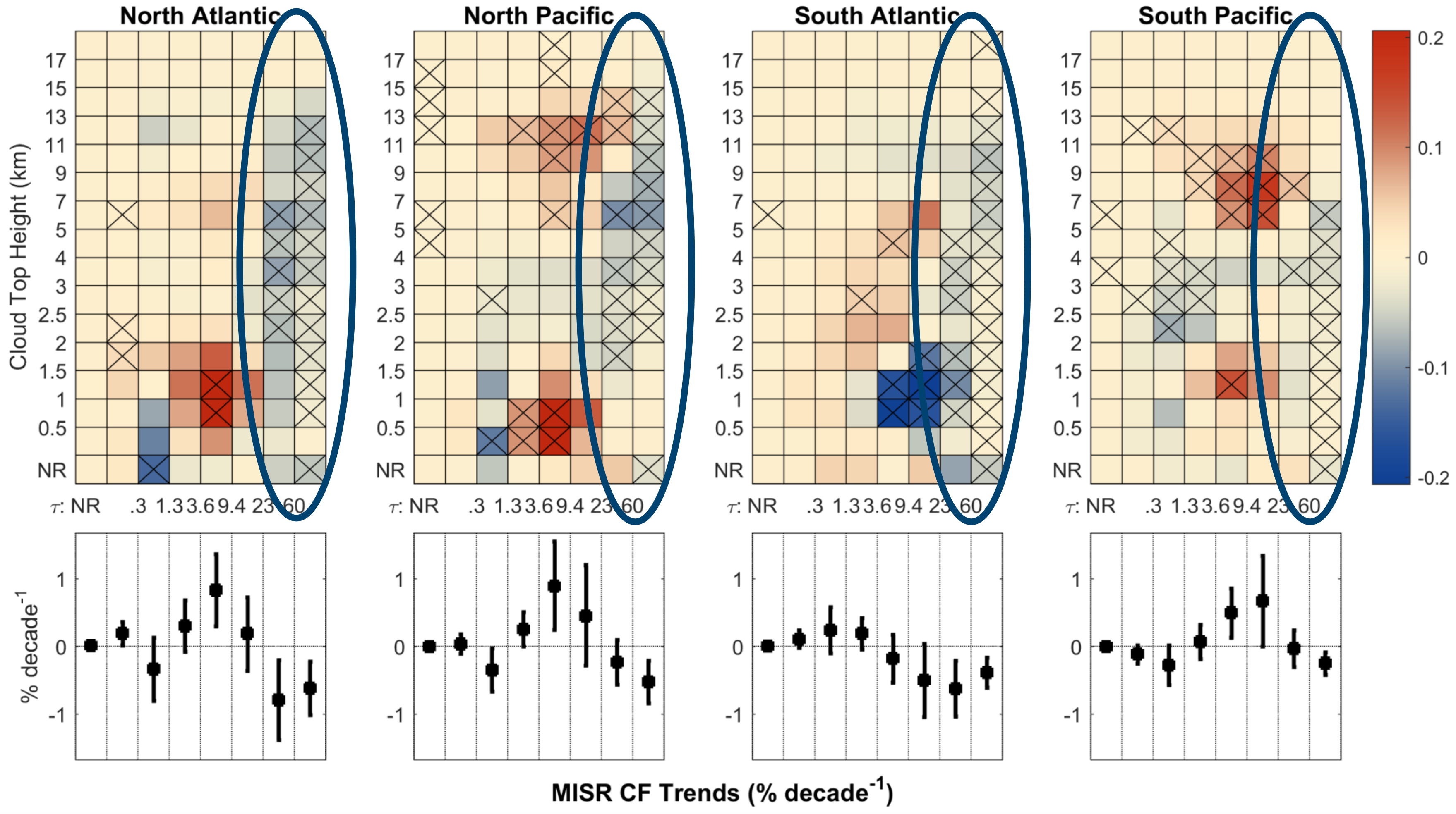
Trends in MISR Joint-Histograms



These are trends in spatially averaged cloud fraction joint histograms. X's denote significance

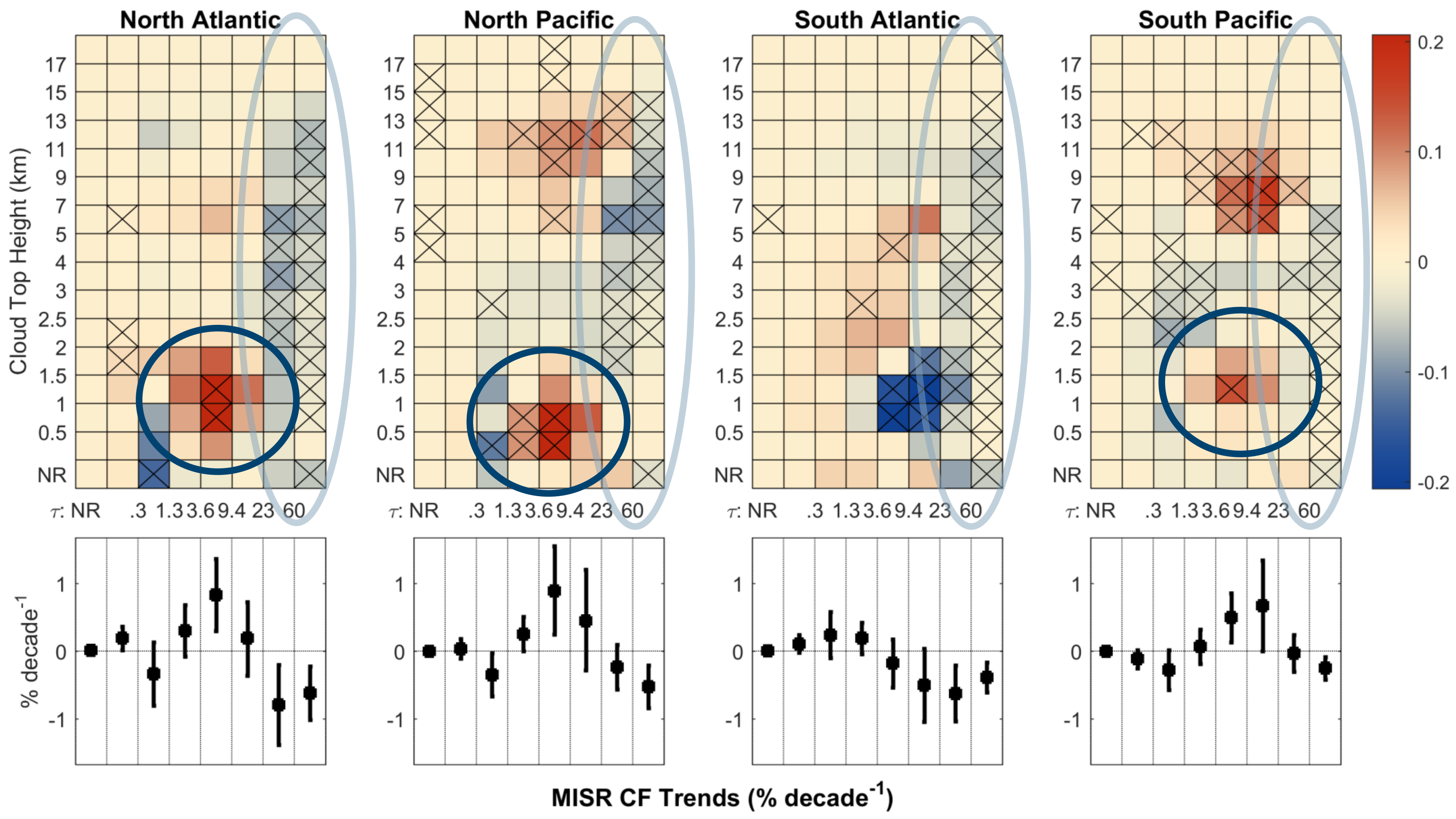
This is the result of summing over all cloud top height bins

Trends in MISR Joint-Histograms



The change in optically thick cloud is ubiquitous, occurring in each basin at most levels.

Trends in MISR Joint-Histograms



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3 basins show an increase in low-thin cloud

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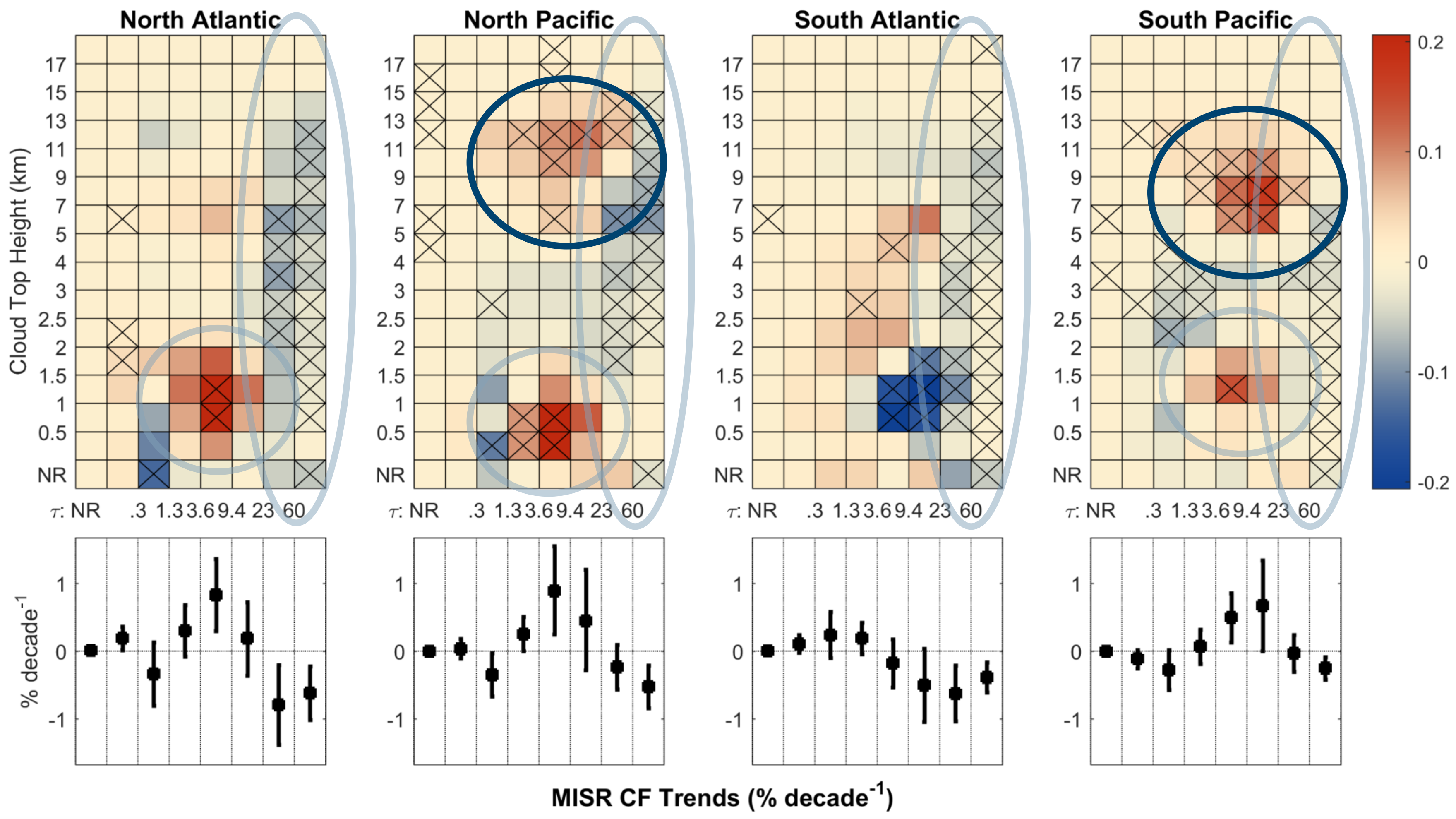
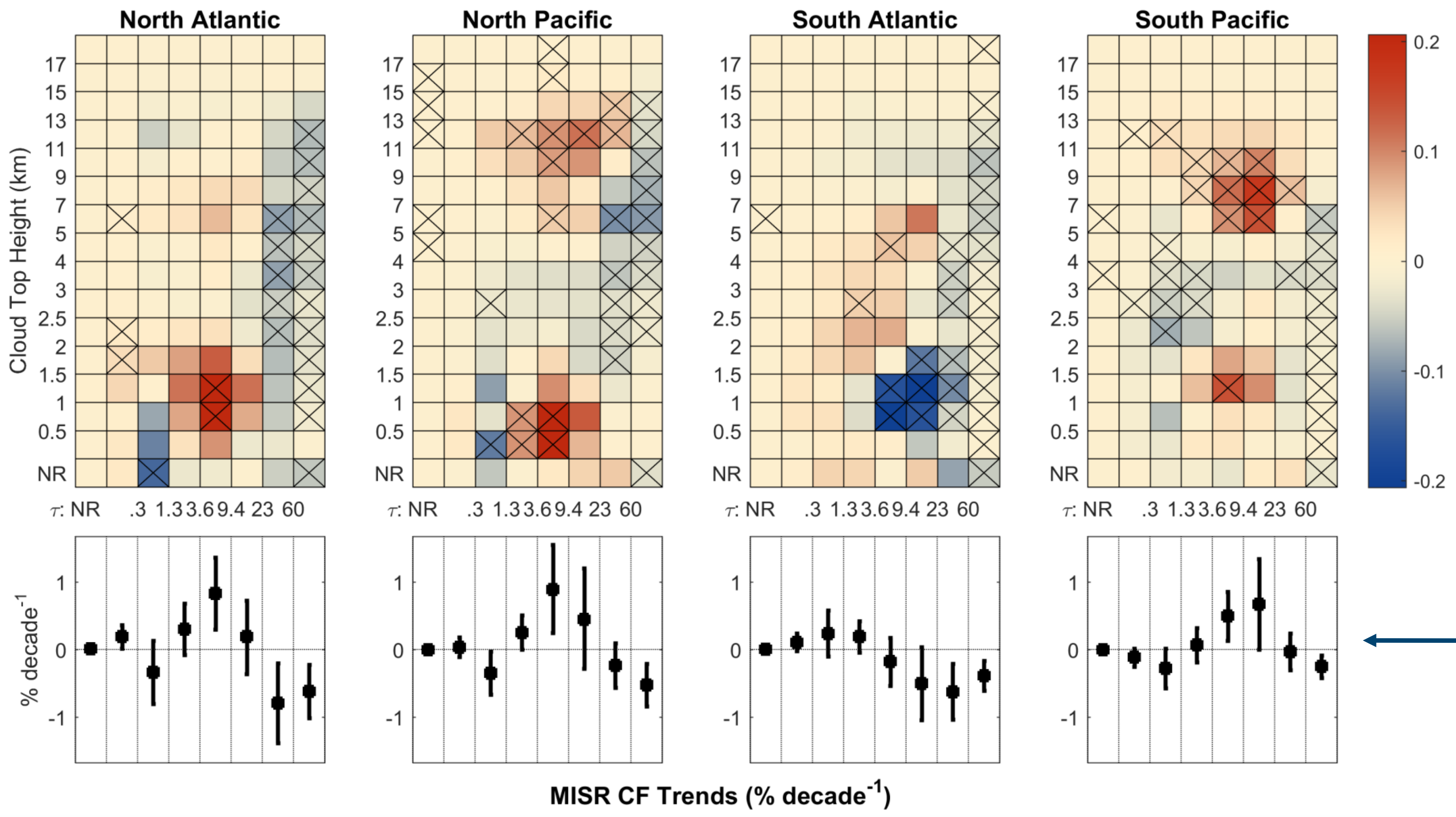


The change in optically thick cloud is ubiquitous, occurring in each basin at most levels.

3 basins show an increase in low-thin cloud

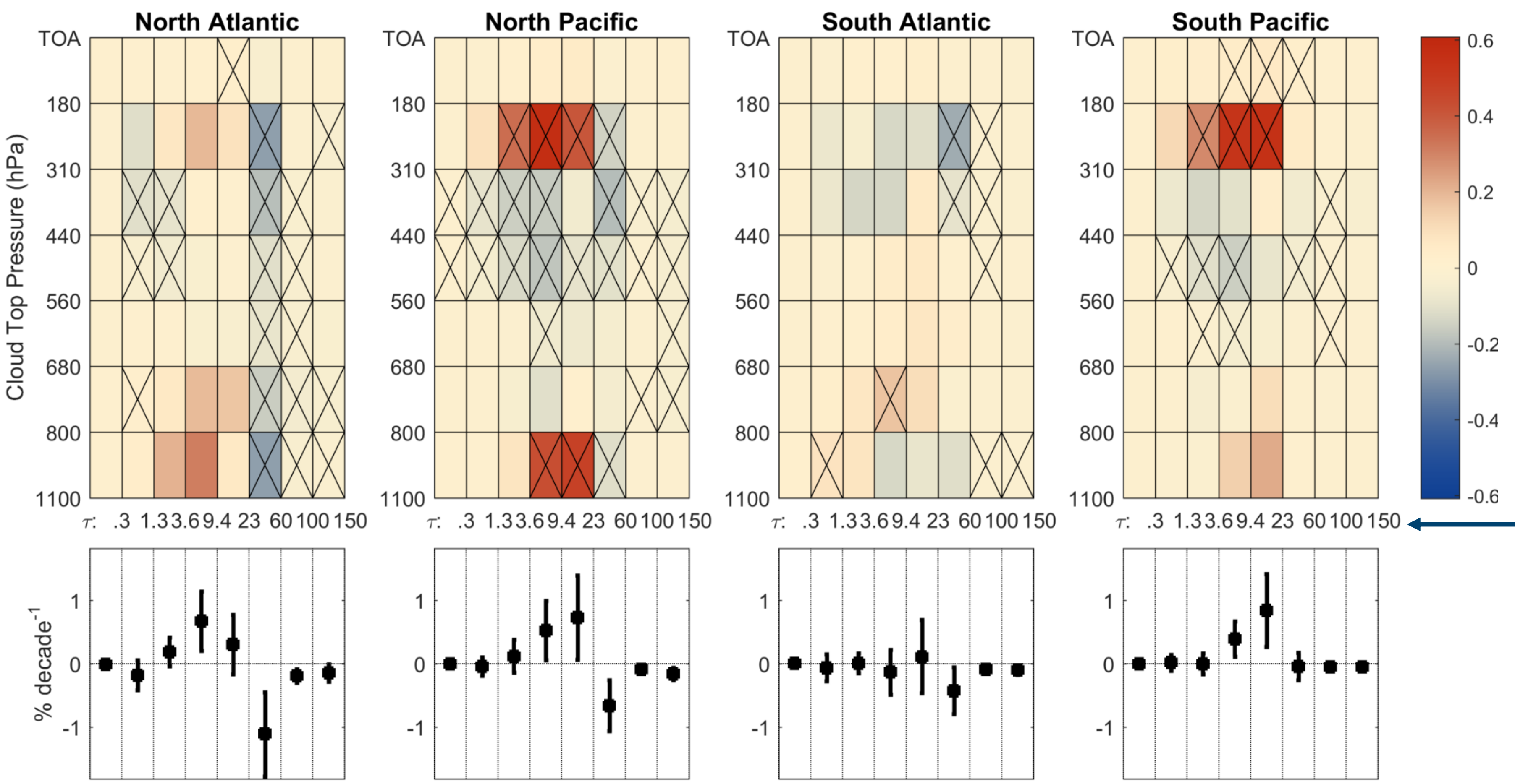
The Pacific shows an increase in high thin cloud

Trends in MISR Joint-Histograms



Overall, the changes with respect to optical depth seem to indicate decreased albedo

Trends in MODIS Joint-Histograms

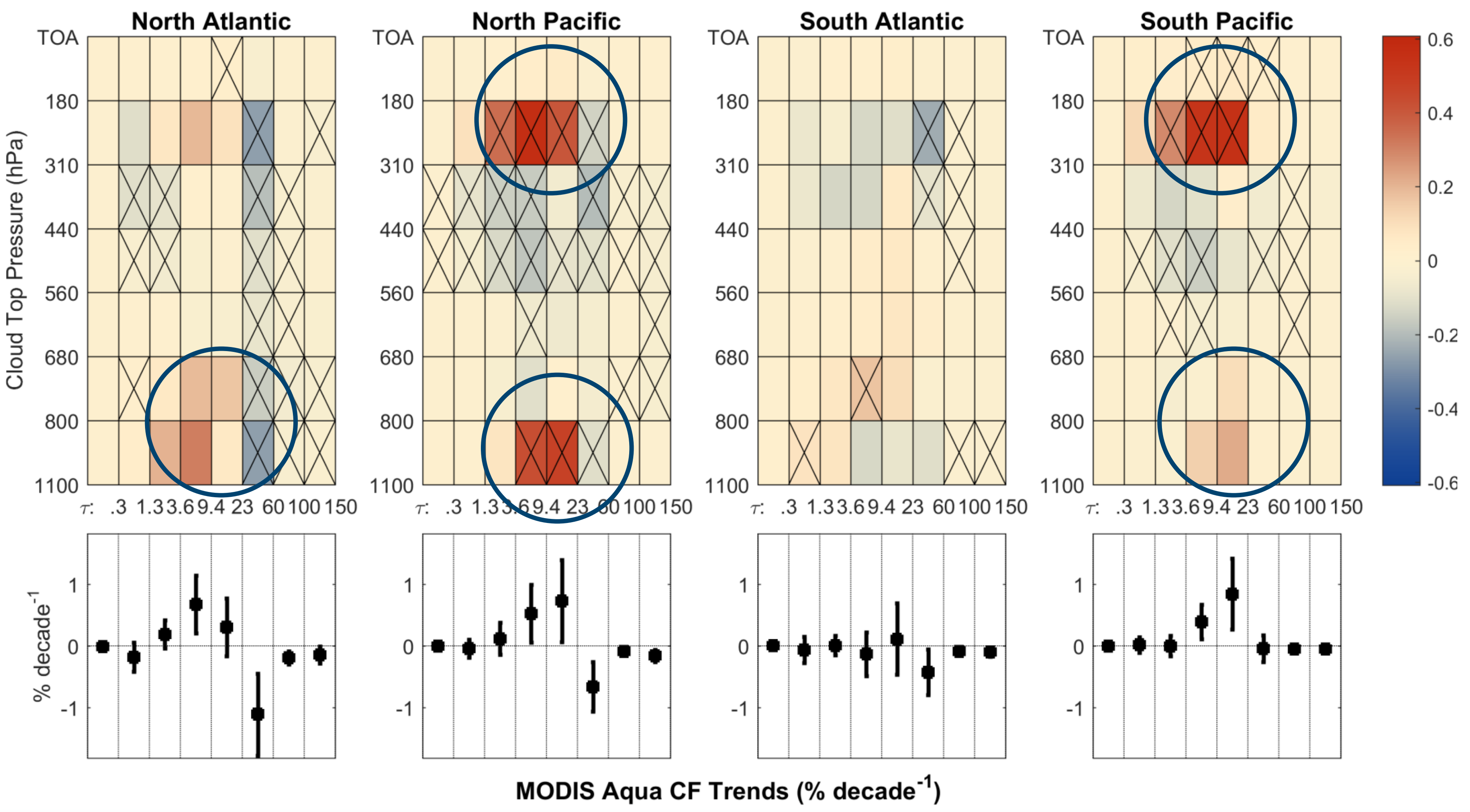


MODIS Aqua CF Trends (% decade^{-1})

Here is the same plot using MODIS-Aqua data.

Note the differences in binning!

Trends in MODIS Joint-Histograms



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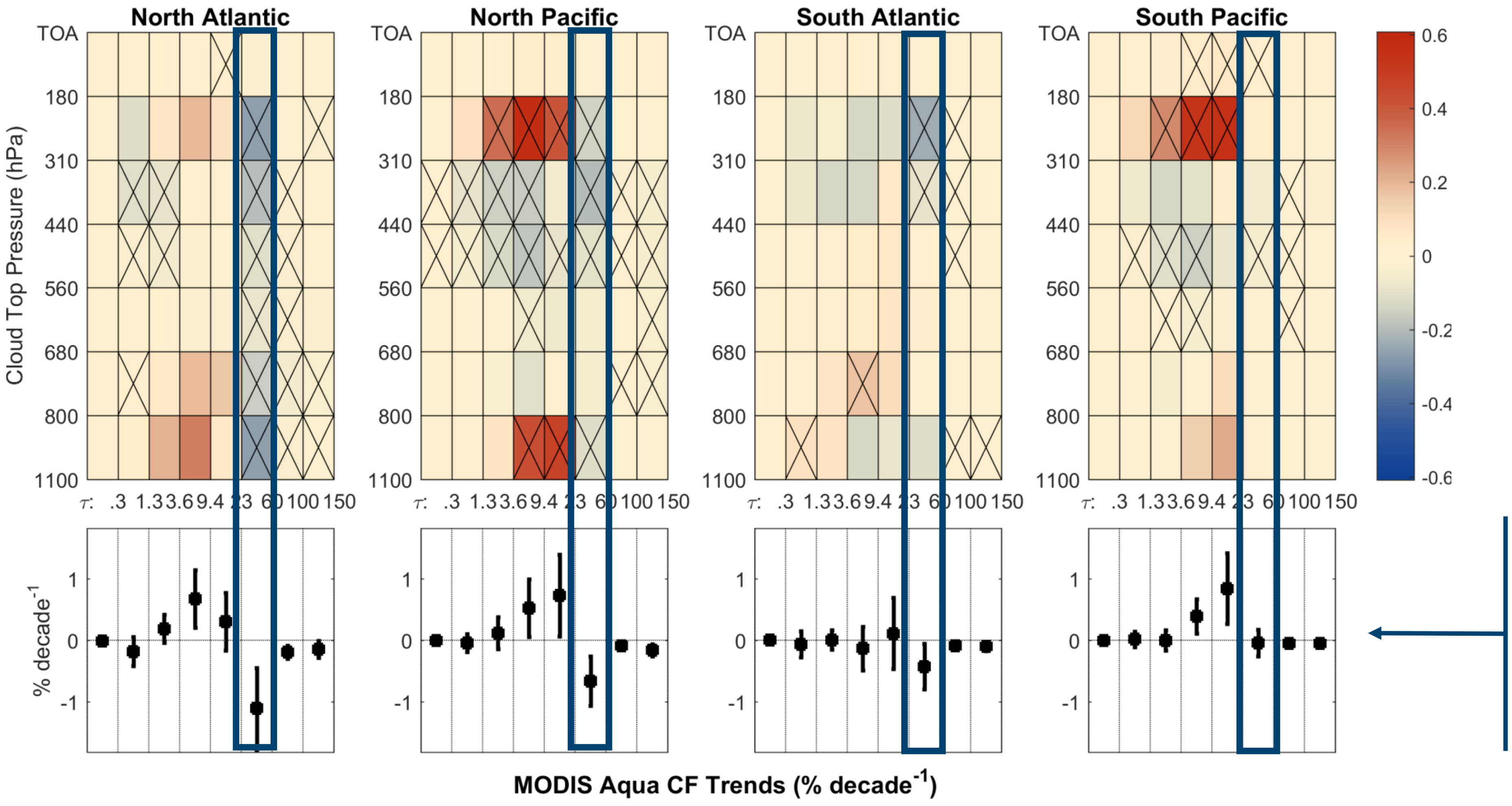
The same patterns are present in cloud of moderate optical depth

Trends in MODIS Joint-Histograms



Here is the same plot using MODIS-Aqua data.

The same patterns are present in cloud of moderate optical depth

The change in optically thick cloud is limited to one bin

Cloud Optical Depth and Albedo

There is a relationship between cloud optical depth and albedo.

The figure at the left shows both observational (AVHRR and ERBE) and model estimates of this relationship.

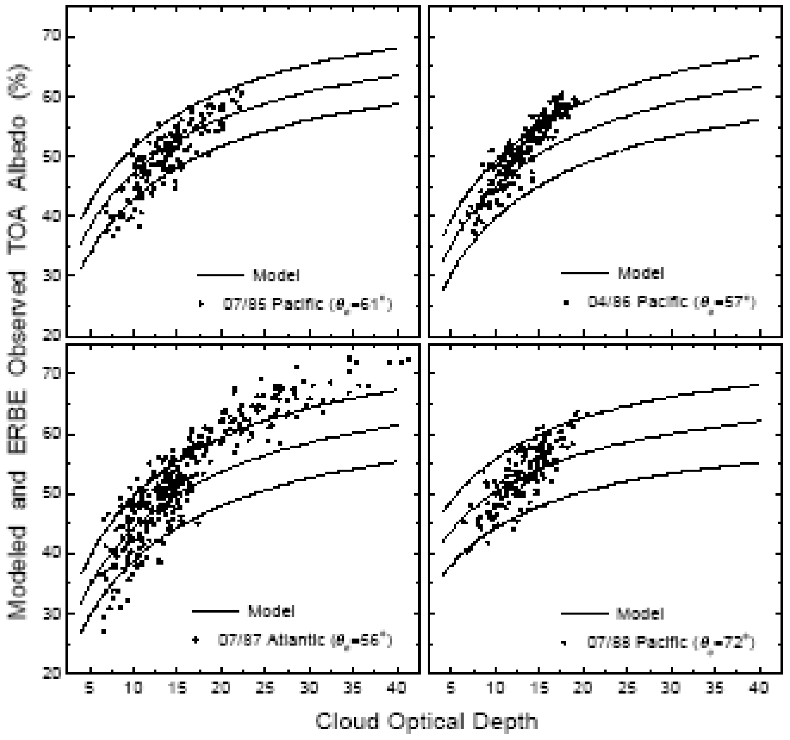


Figure 3. TOA albedos (%) from ERBE observations and model computations. Dashed lines indicate the uncertainties of model computations, which are described in the text.

Ackerman, S. Chang, F. ‘Relationship between TOA albedo and cloud optical depth as deduced from models and collocated AVHRR and ERBE…’

Cloud Optical Depth and Albedo

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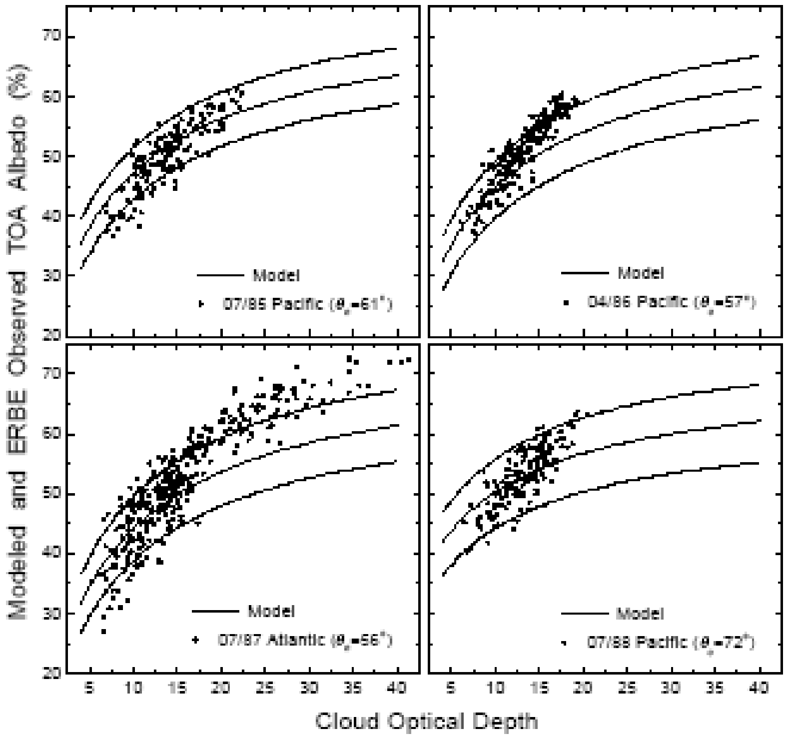
I will make a simple estimate of the change in albedo caused by the observed changes in cloud fraction and compare to CERES albedo data via:

$$\alpha = \frac{\tau}{(\tau + 7)}$$



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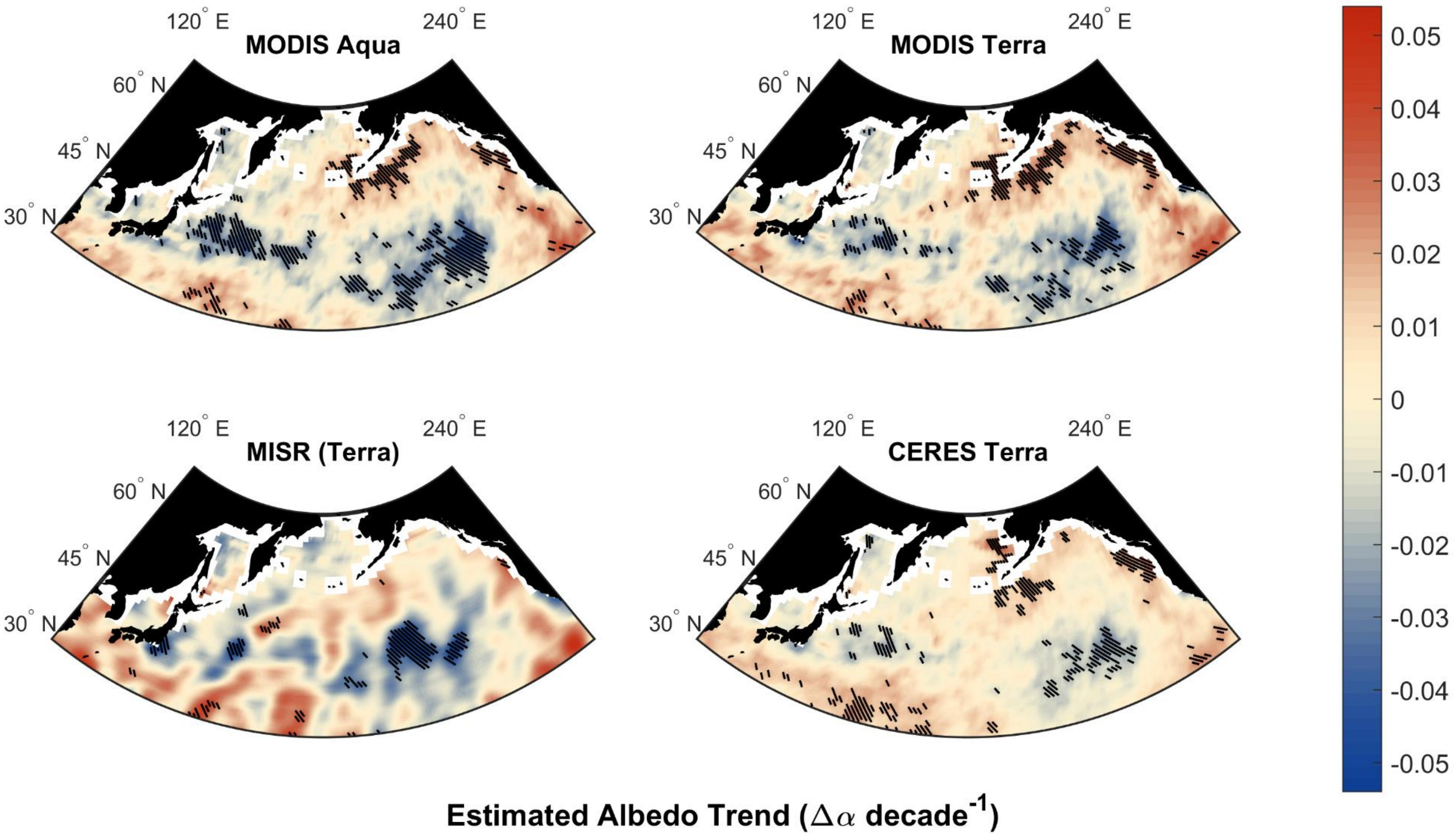
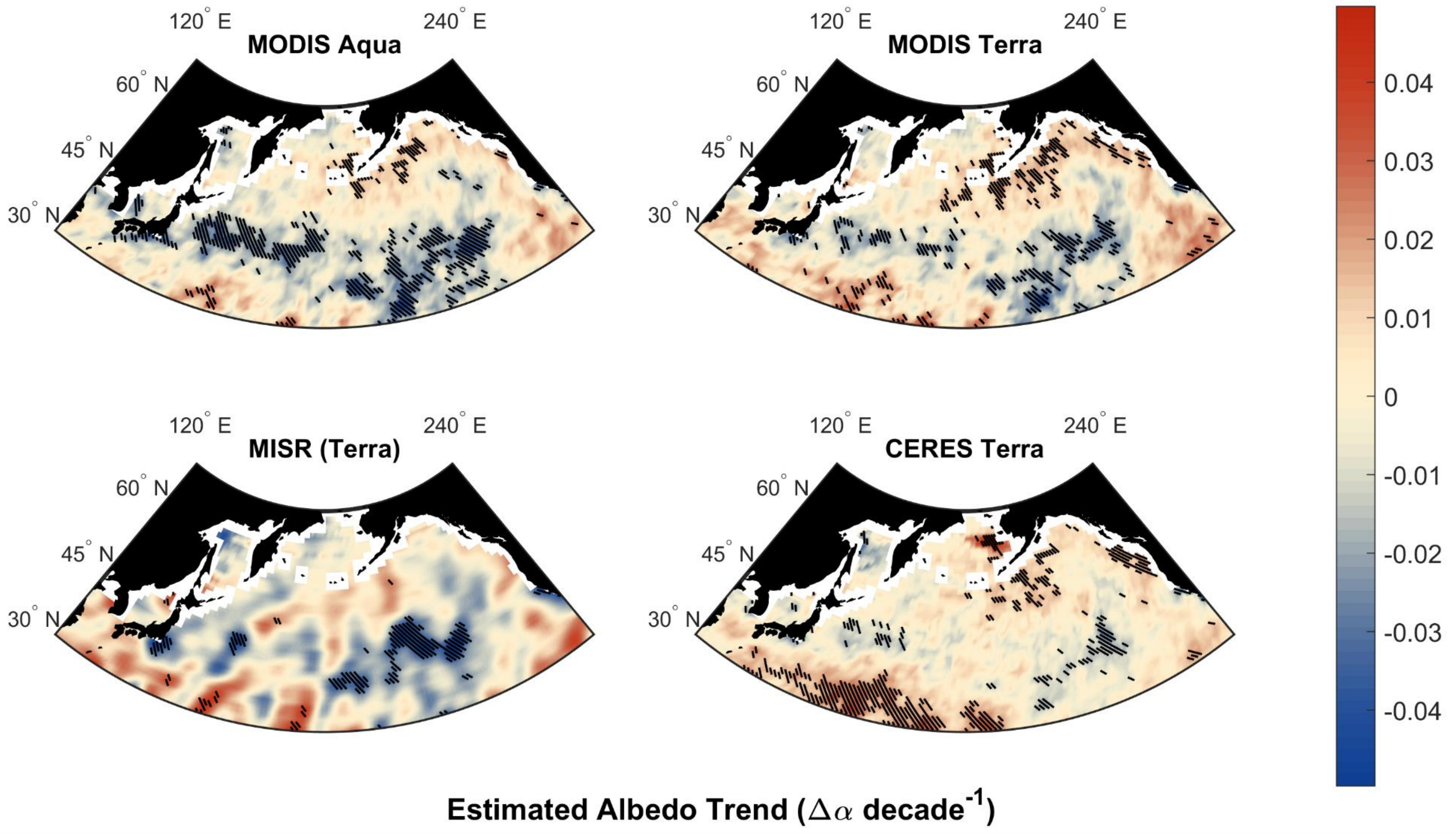
Changes in Albedo



These are the resulting trends in albedo.

There is generally good agreement between the four instruments.

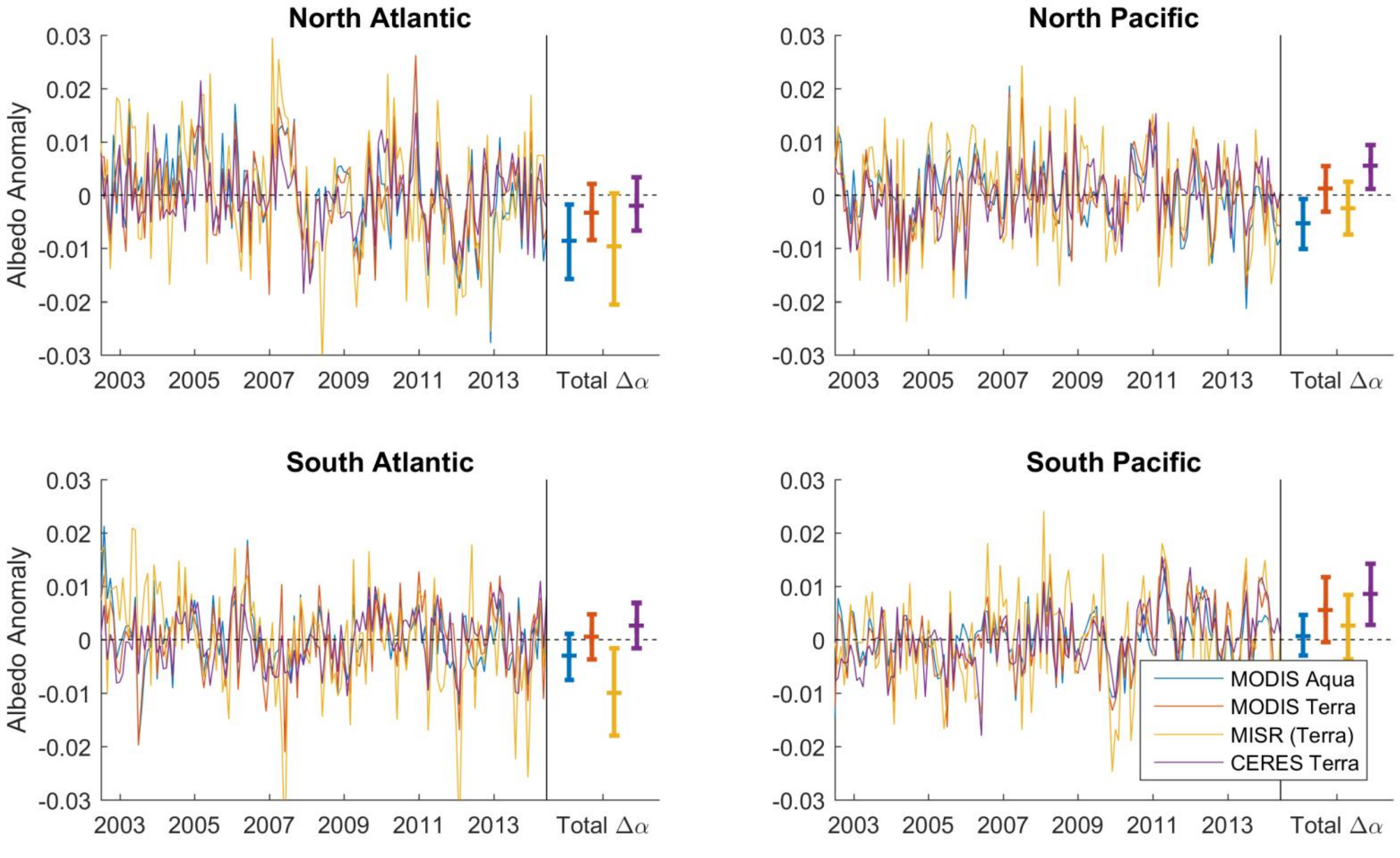
Changes in *Cloud* Albedo



These are the resulting trends in *cloud* albedo.

Even the regional changes appear to be dominated by changes in cloud albedo, not total cloud fraction.

Albedo Time-Series

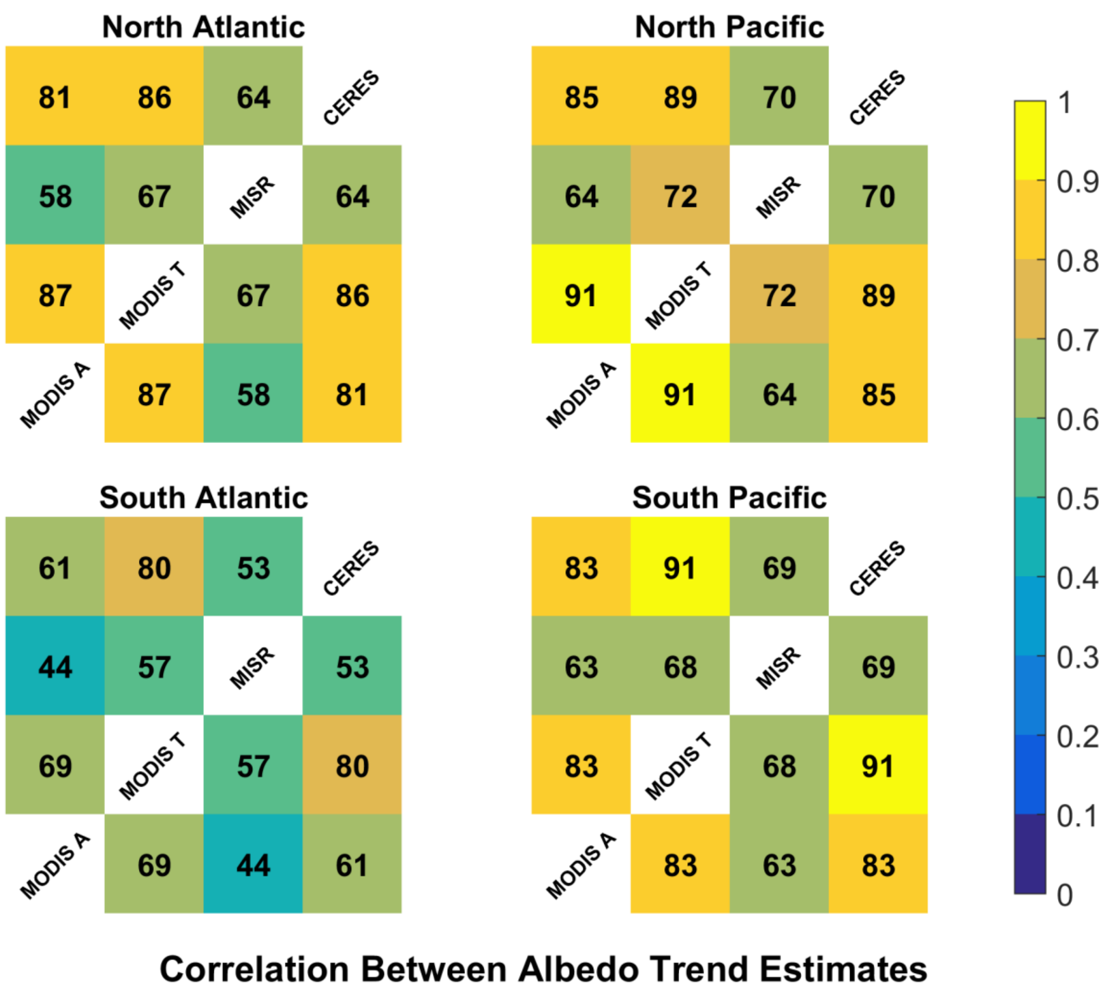


Basin Averaged Cloud Albedo Anomaly and Trends (α)

Time-series of basin averaged albedo, with trends plotted to the right.

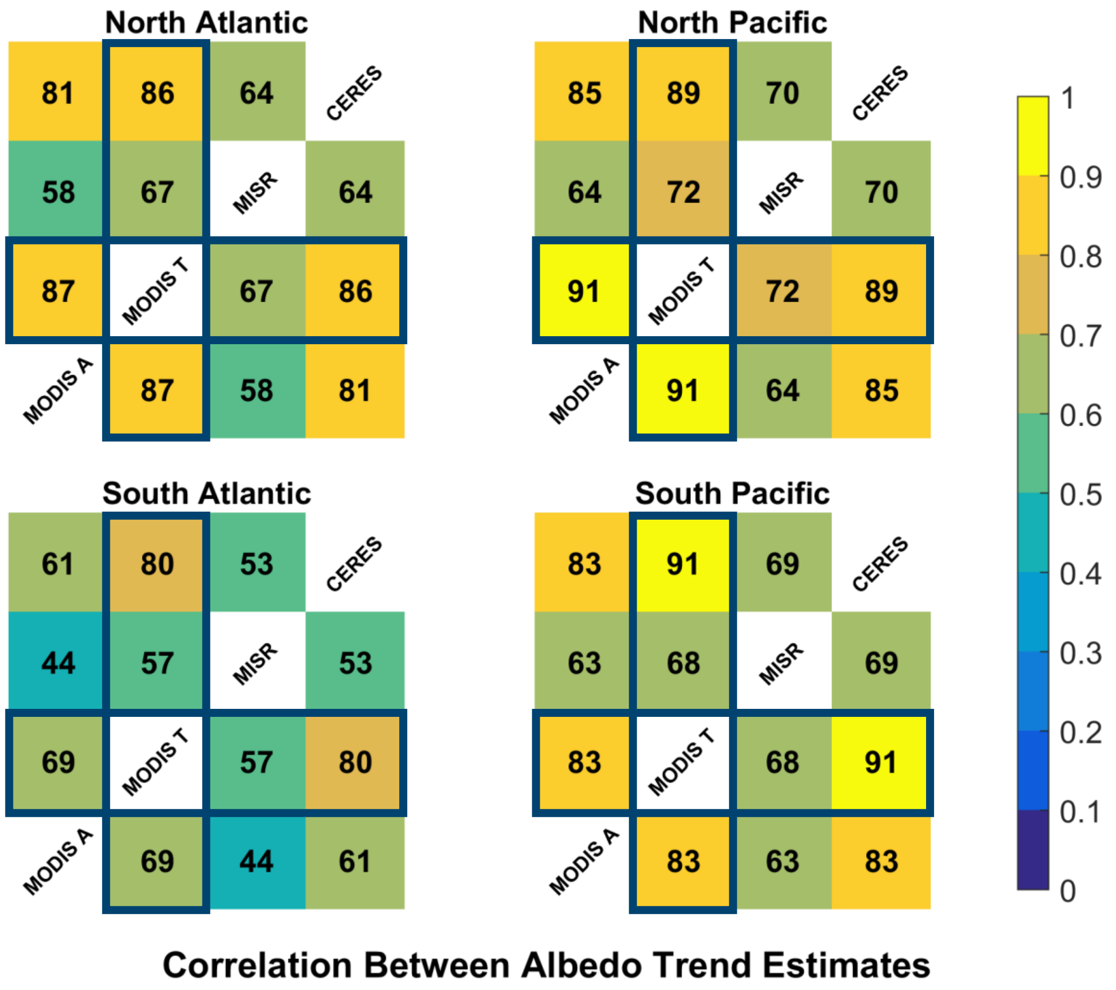
There is no significant and consistent trend in any ocean basin.

Comparison of α Estimates



This shows spatial correlations between trends in albedo estimated by each instrument

Comparison of α Estimates



This shows spatial correlations between trends in albedo estimated by each instrument

MODIS Terra is expected to have the best correlation with CERES because of concurrent sampling

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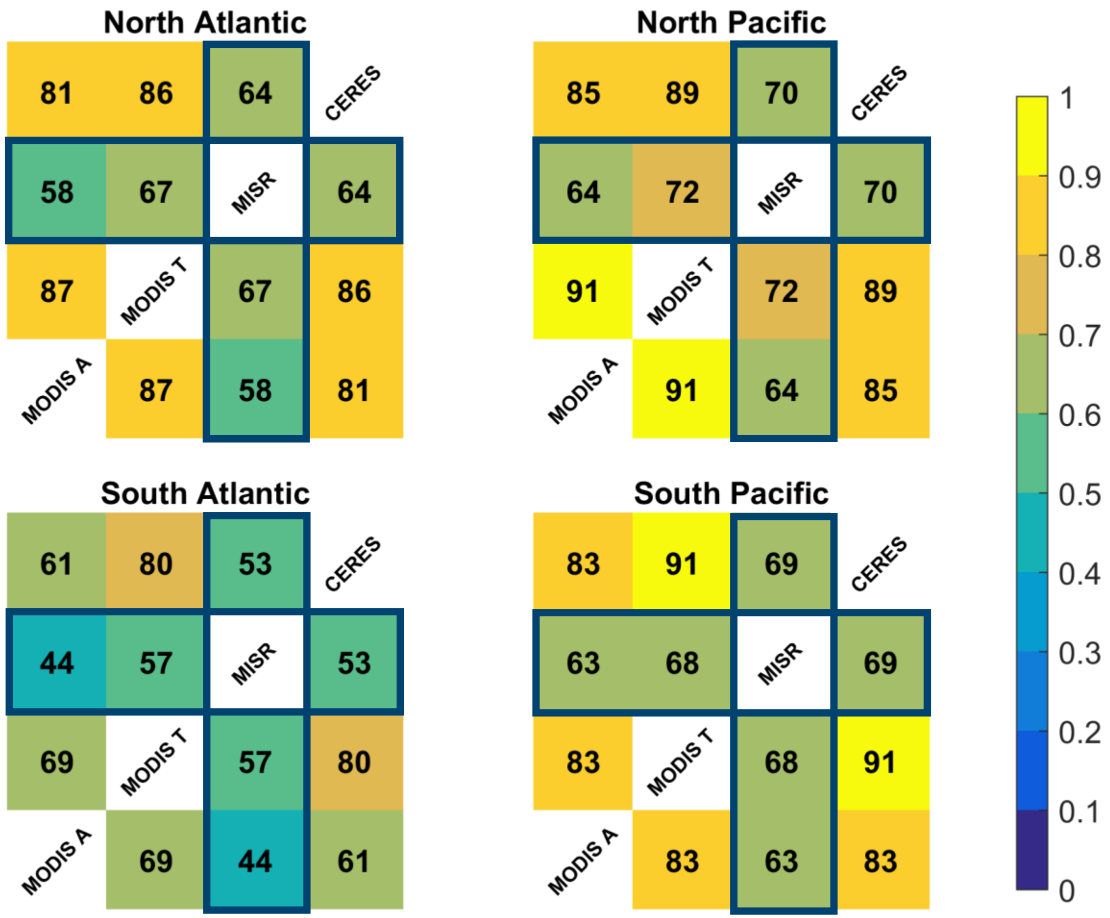

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MISR's resolution and retrieval algorithm differs the most from the other instruments so it will have the lowest correlations

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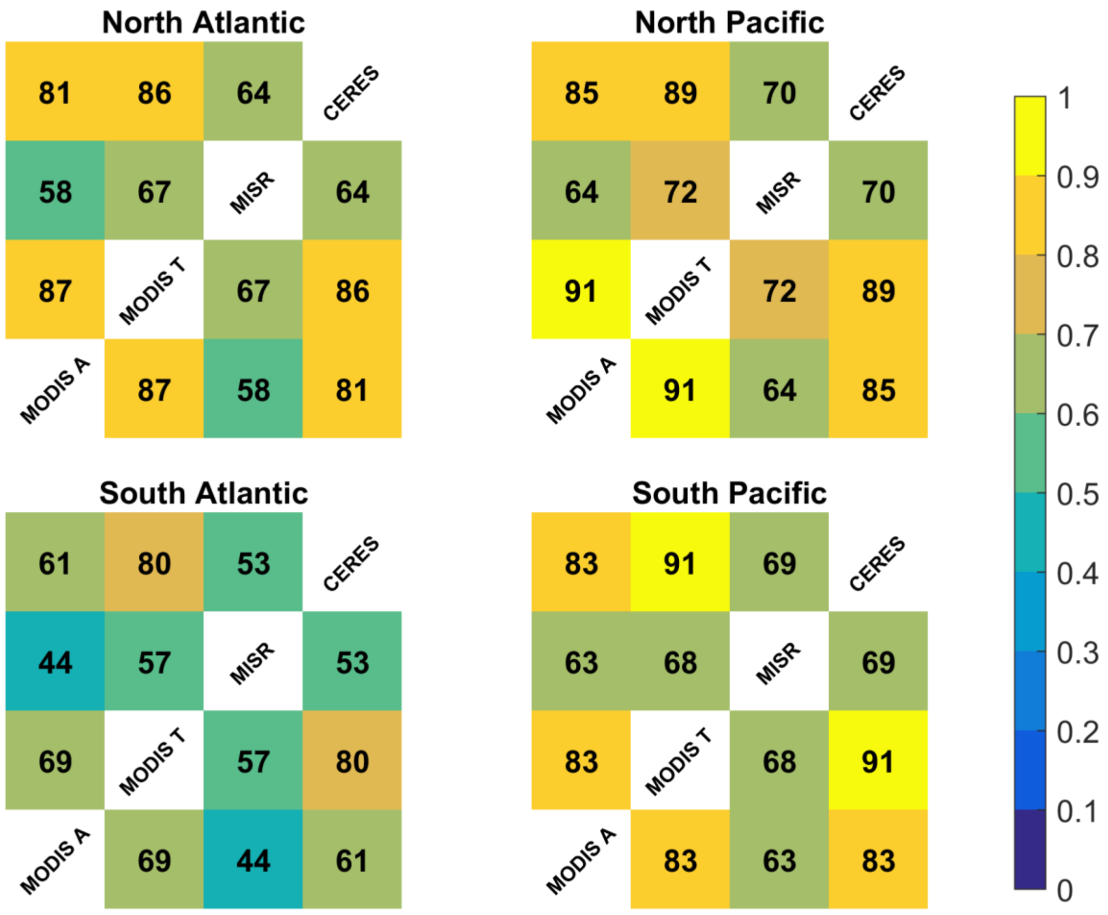

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MODIS Terra is expected to have the best correlation with CERES because of concurrent sampling

MISR's resolution and retrieval algorithm differs the most from the other instruments so it will have the lowest correlations

…but overall there is good agreement!

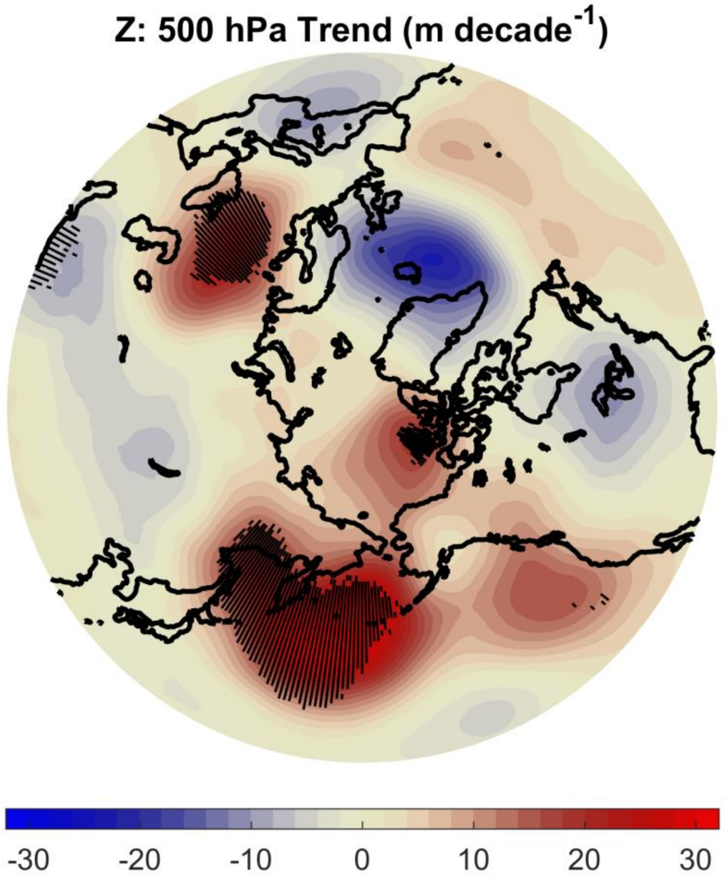
Conclusion 2

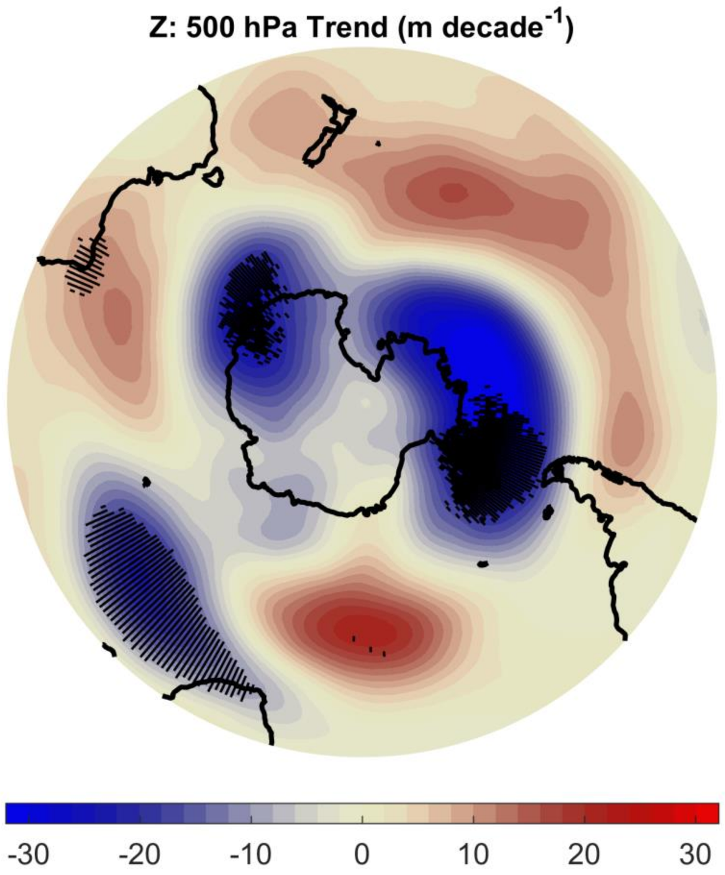
Cloud fraction changes have coherent structure both in physical space and CTH vs OD space

Similar trends have been observed across multiple instruments and platforms

There has not been a statistically significant change in mean cloud albedo

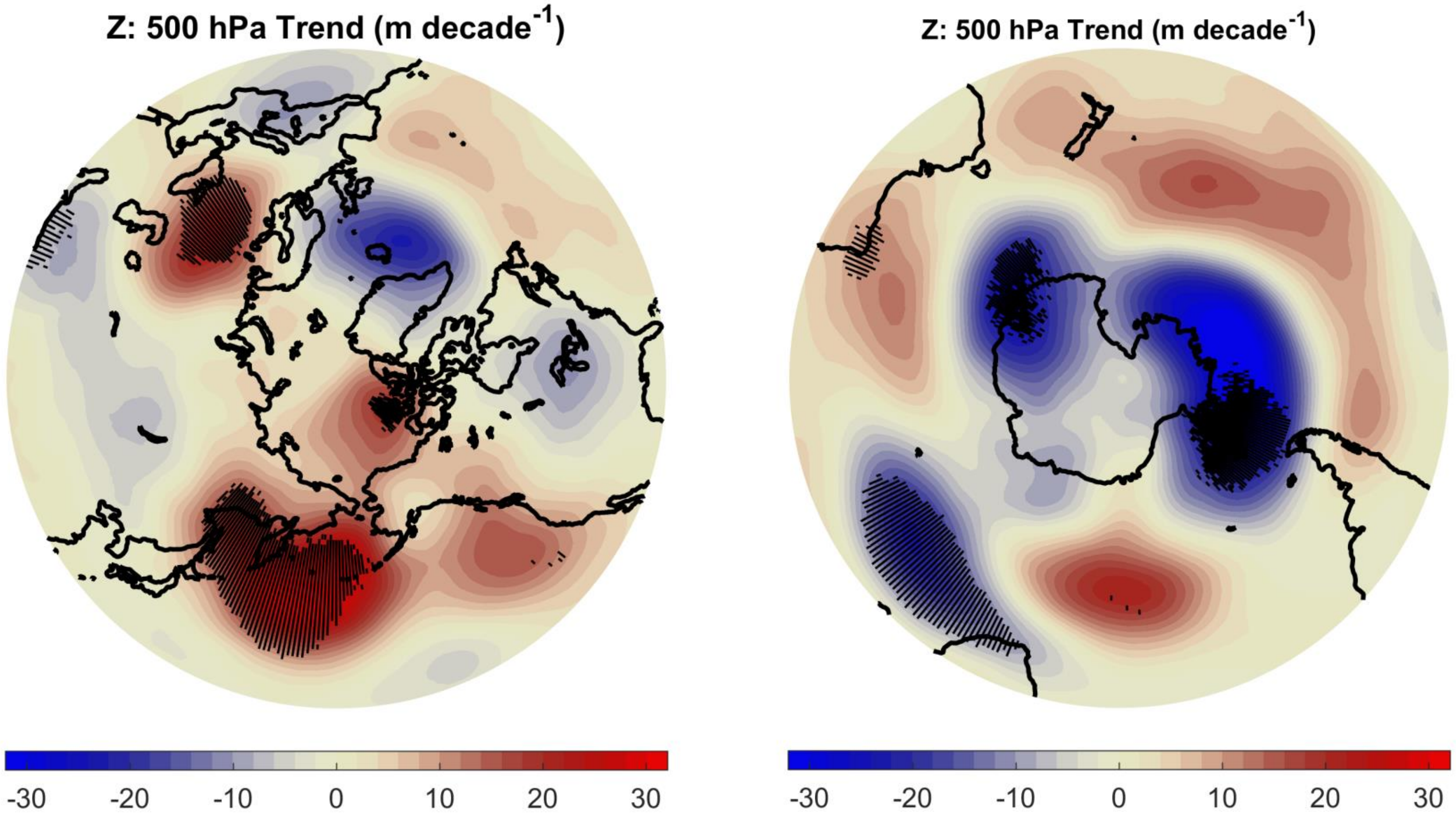
Comparison to ERA Interim





The cloud fraction trends have coherent spatial structure. Are they caused by changes in the meteorology?

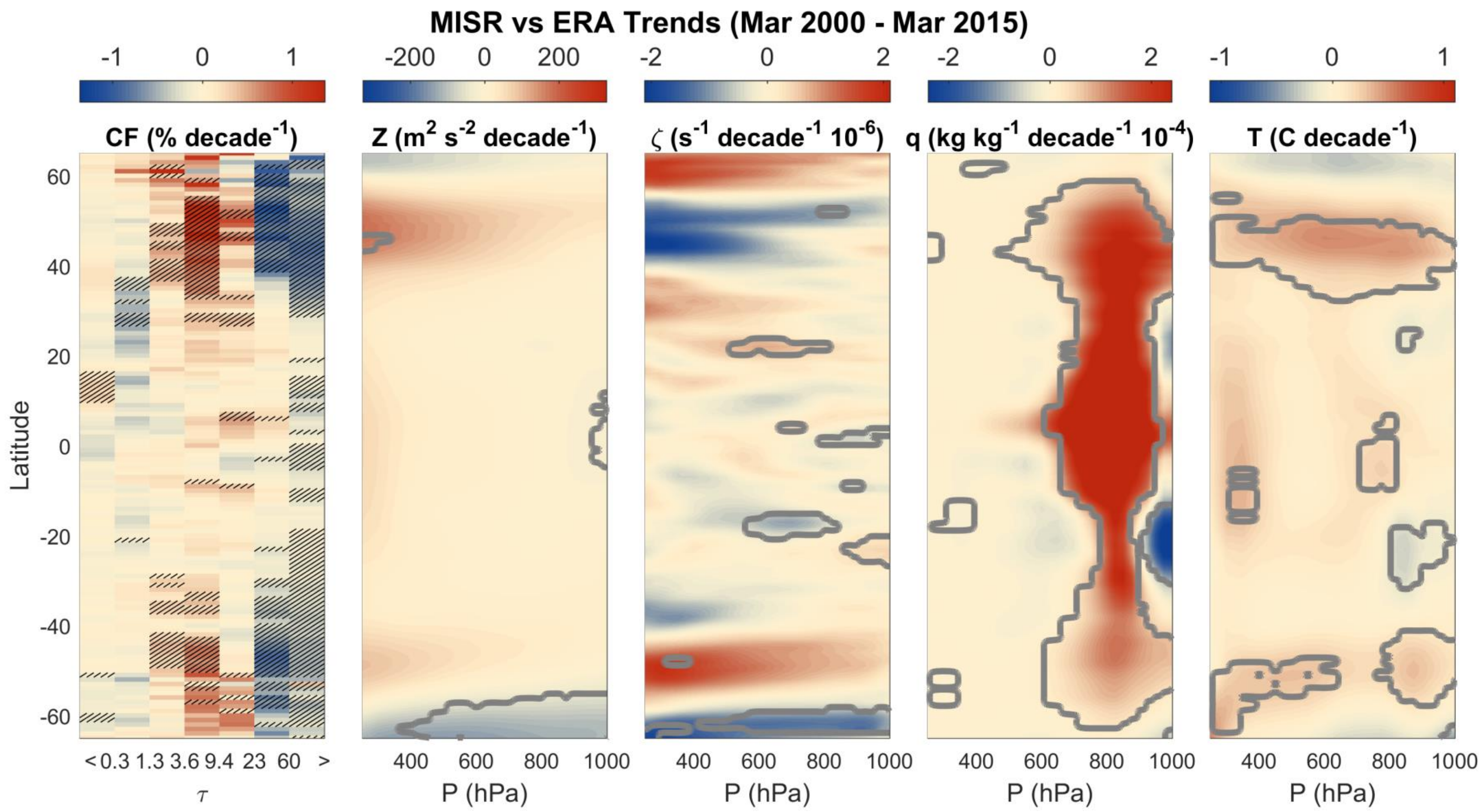
Comparison to ERA Interim



The cloud fraction trends have coherent spatial structure. Are they caused by changes in the meteorology?

These are trends in ECMWF reanalysis 500 hPa geopotential height over the same period

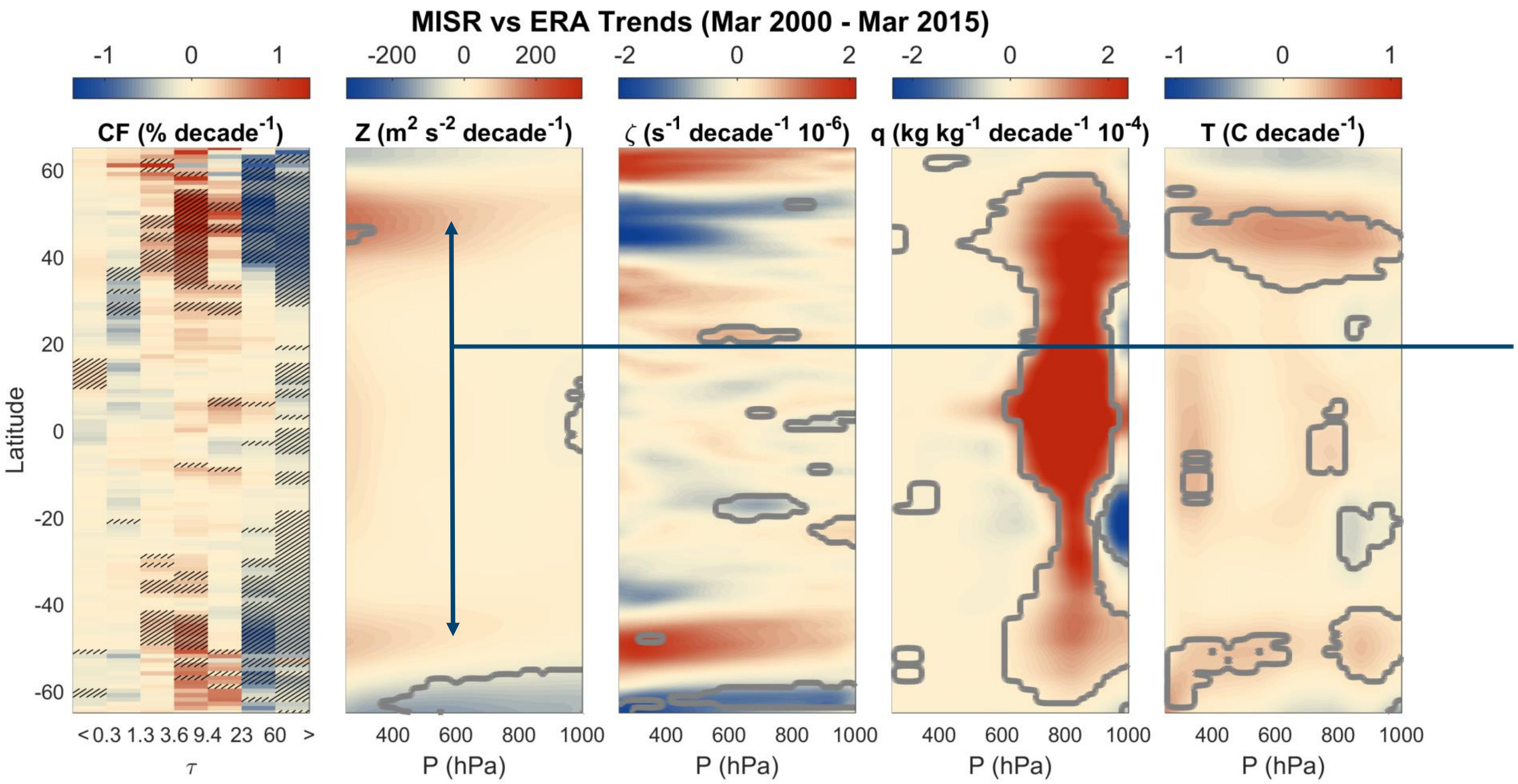
A Simple Approach



I will compare the changes in cloud fraction to changes in 7 ERA-Interim reanalysis variables

A simple technique is to compute trends in the zonal mean.

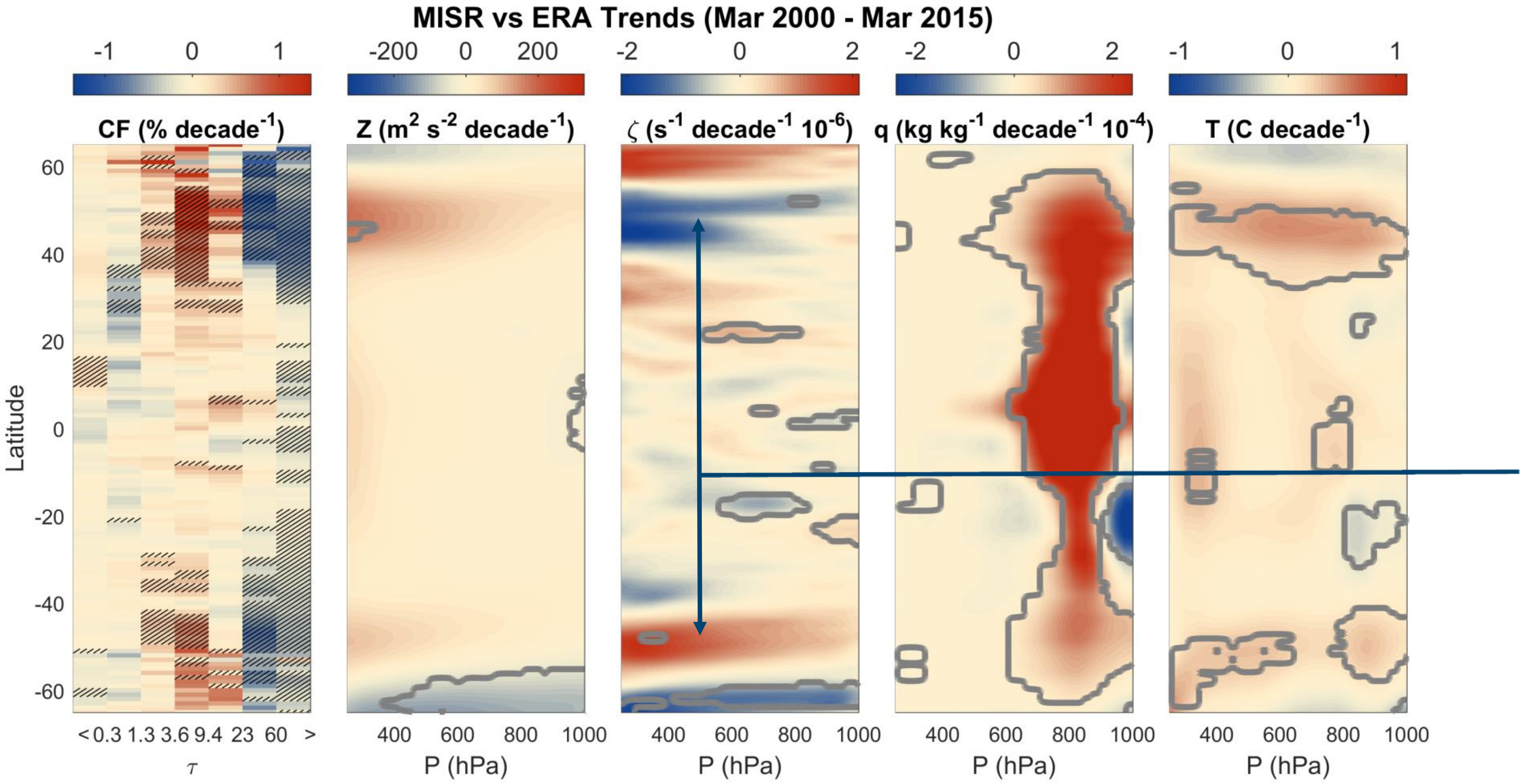
A Simple Approach



This change in the CF joint histogram is associated with:

High pressure

A Simple Approach

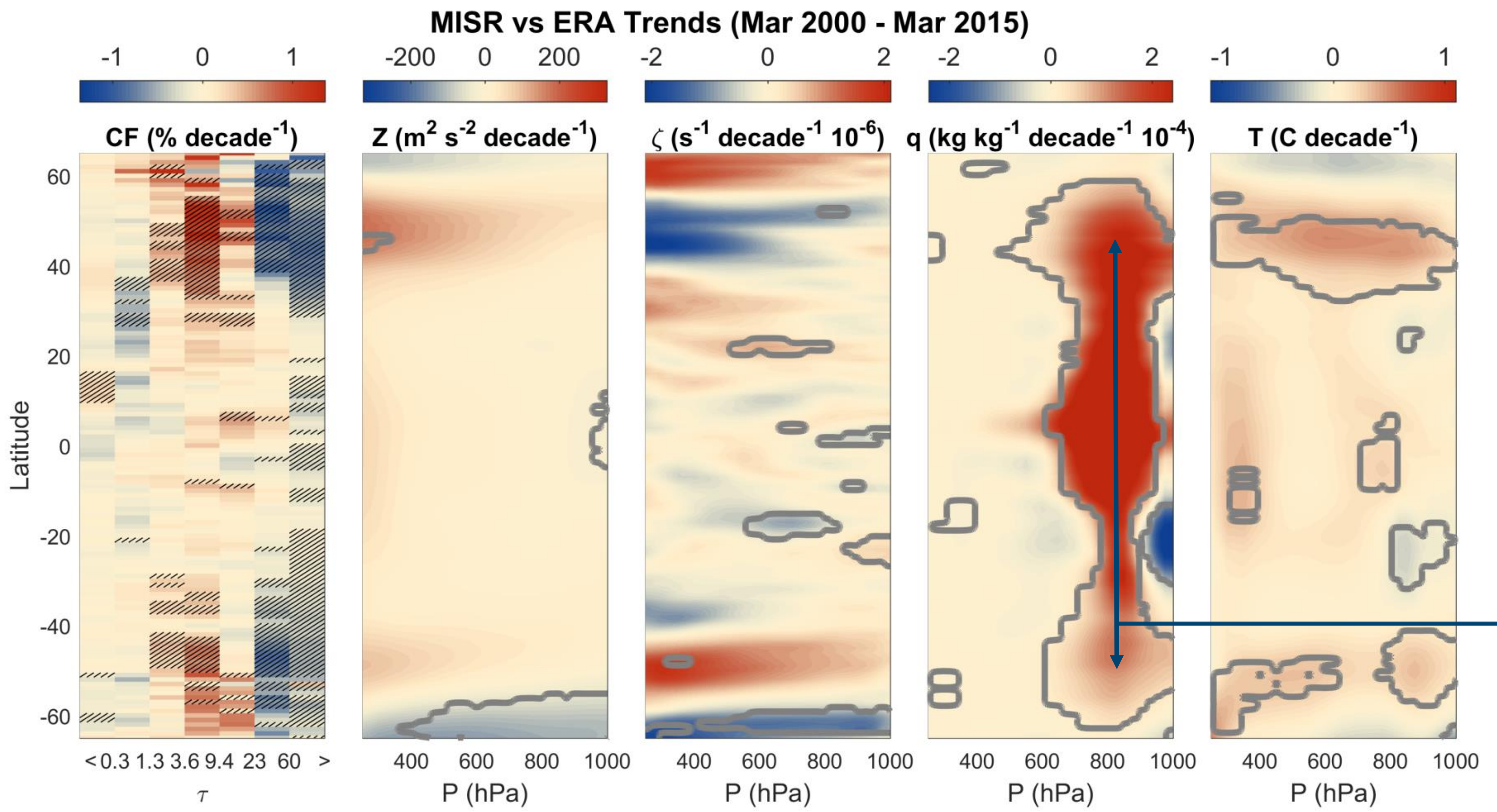


This change in the CF joint histogram is associated with:

High pressure

Anticyclonic flow

A Simple Approach



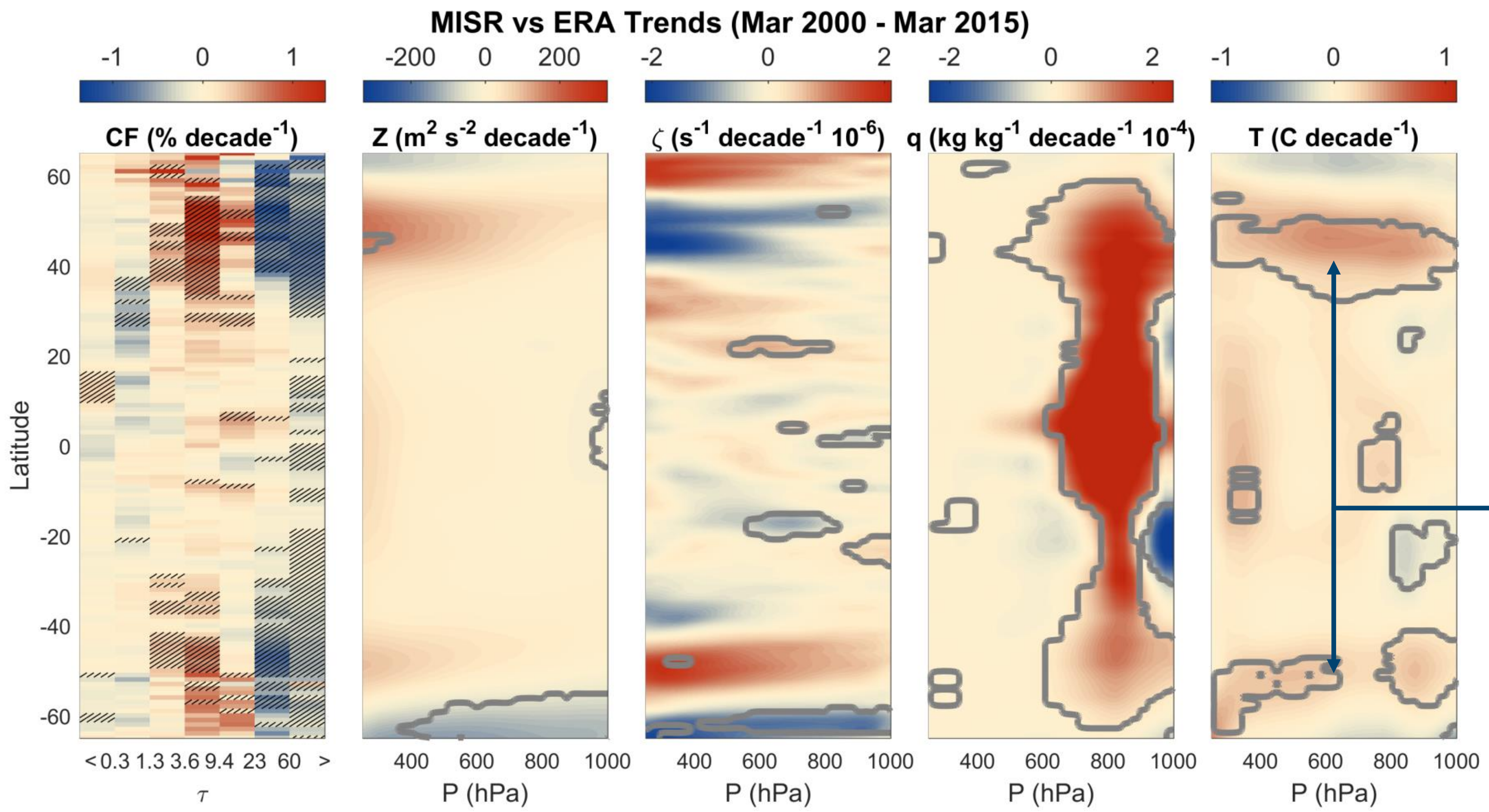
This change in the CF joint histogram is associated with:

High pressure

Anticyclonic flow

High q at low levels

A Simple Approach



This change in the CF joint histogram is associated with:

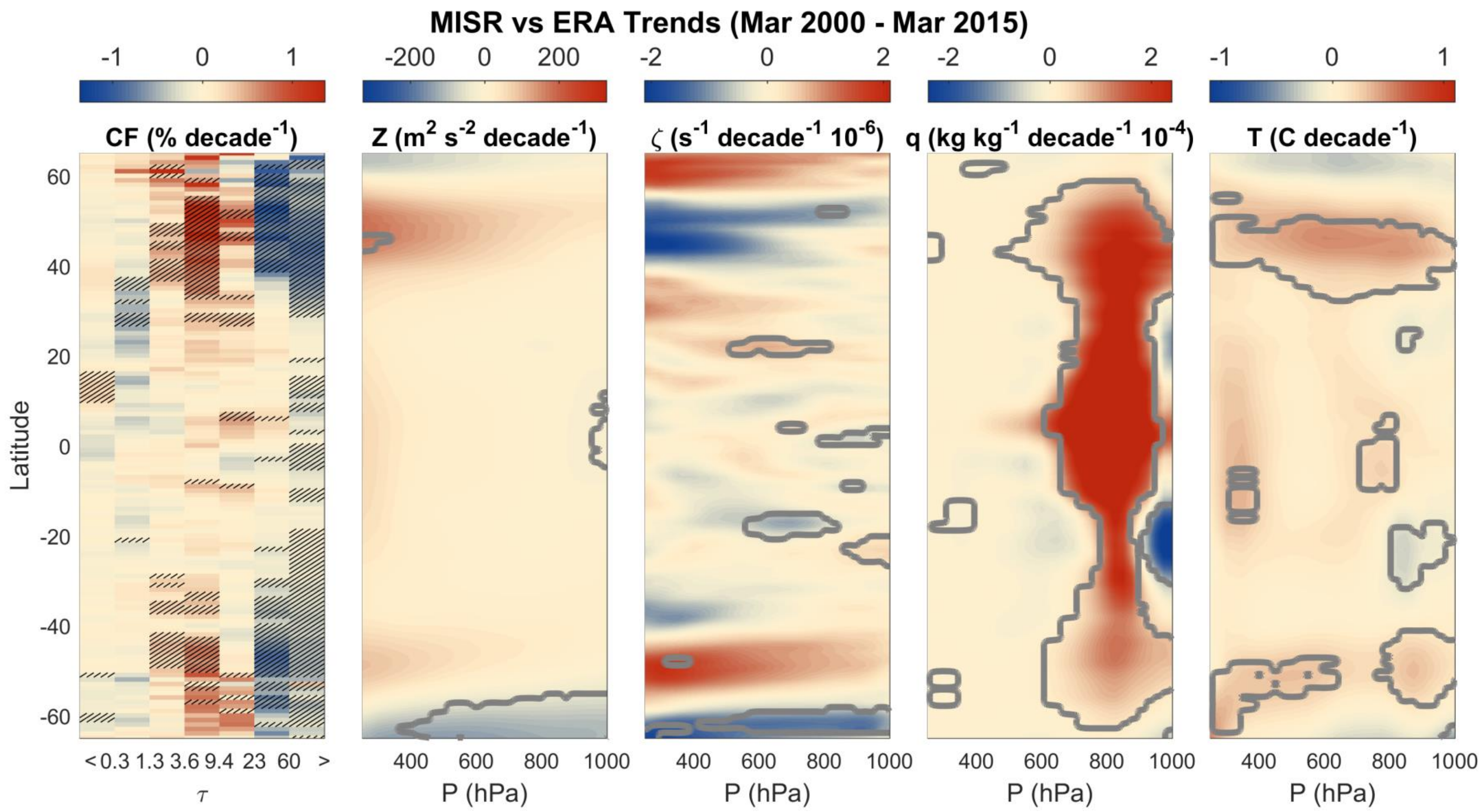
High pressure

Anticyclonic flow

High q at low levels

High temperature

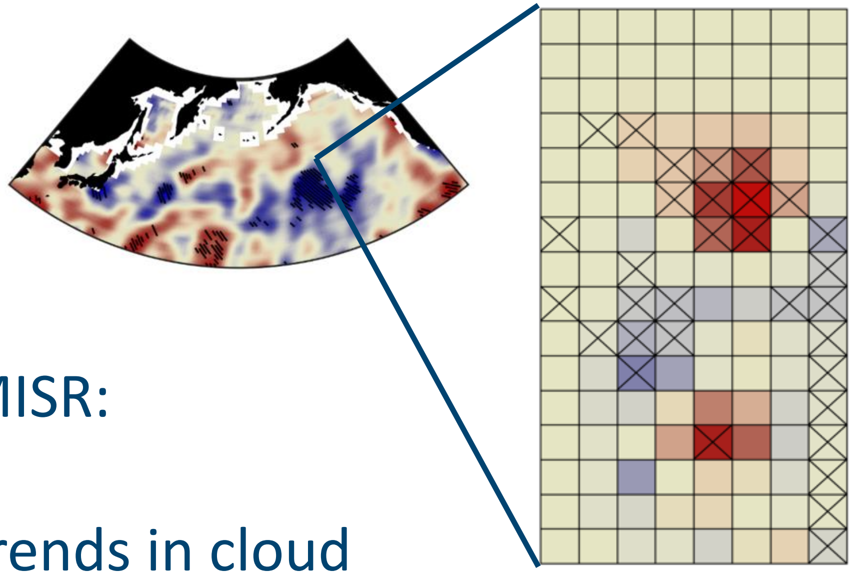
A Simple Approach



This suggests that changes in cloud optical depth are associated with increased *intensity* or frequency of extratropical highs

…but this analysis ignores all of the zonal structure

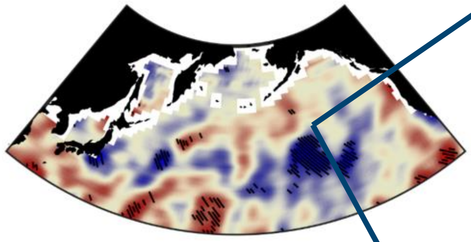
MCA Description

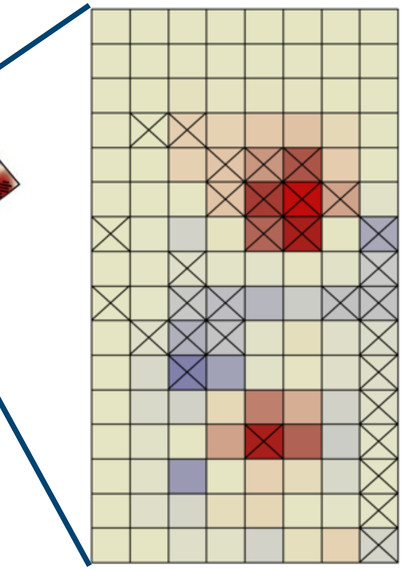


MISR:

Trends in cloud fraction defined w.r.t. λ, ϕ, z, and τ.

MCA Description





MISR:

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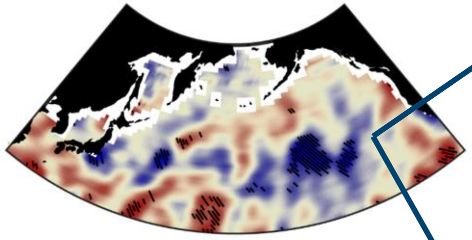
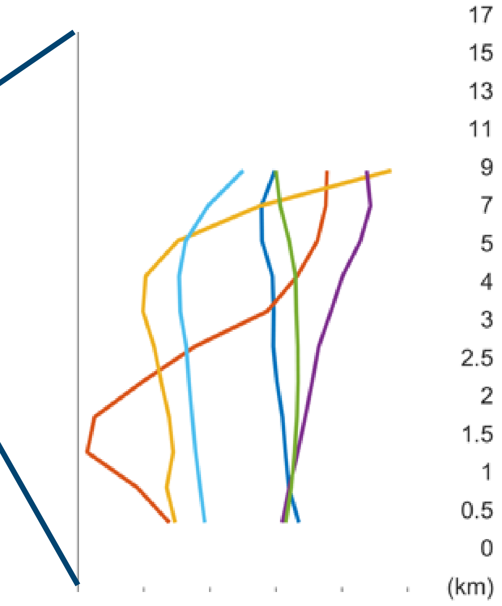
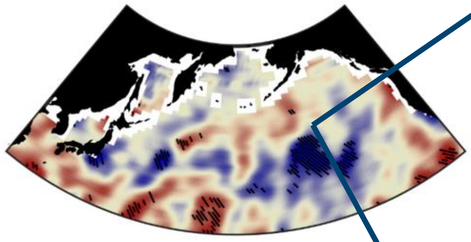


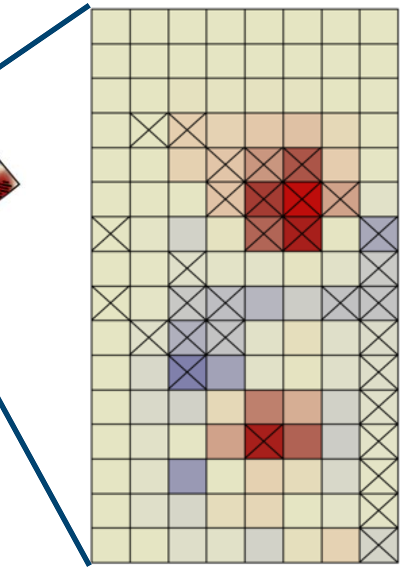


ERA-Interim:

Trends in 7 variables
defined w.r.t. λ, ϕ, and z. (I will treat the 7 variables as an additional dimension).

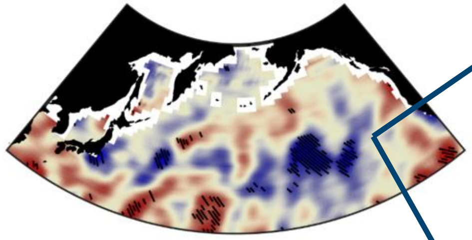
MCA Description

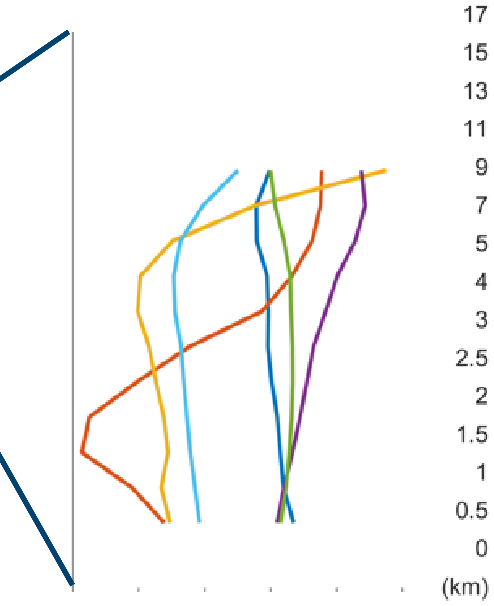




MISR:

Trends in cloud fraction defined w.r.t. λ, ϕ, z, and τ.





ERA-Interim:

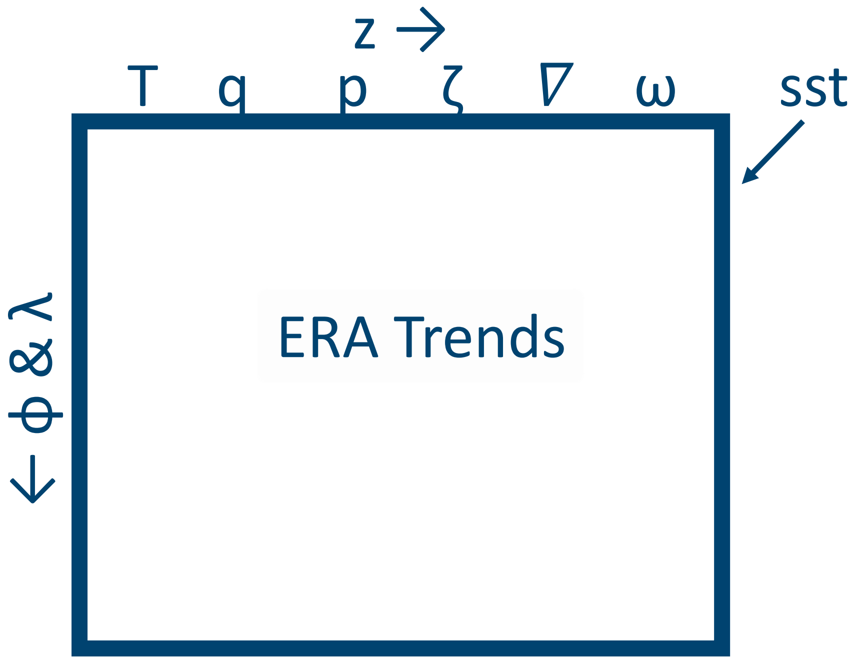
Trends in 7 variables defined w.r.t. λ, ϕ, and z. (I will treat the 7 variables as an additional dimension).

Now I need to reshape these in to 2D matrices and compute a covariance matrix. I will use λ and ϕ as a shared dimension

MCA Description

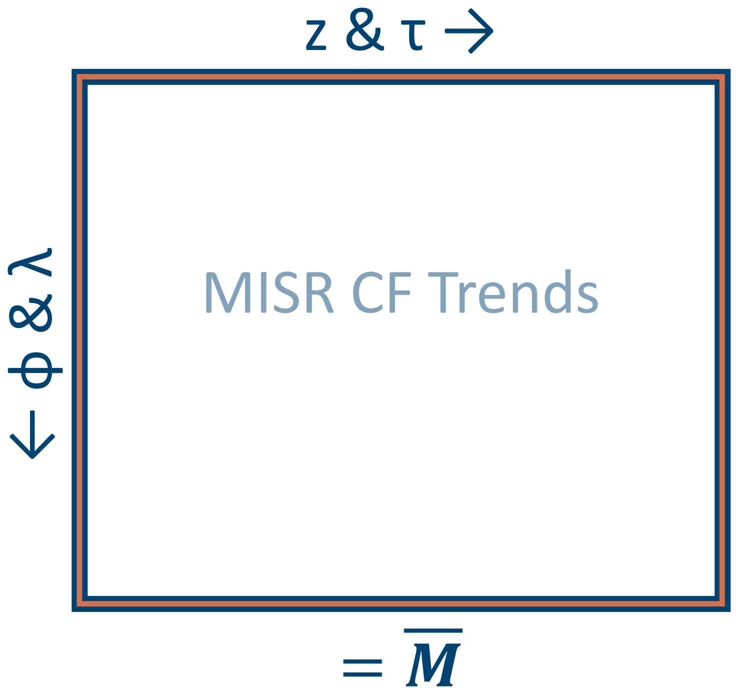
$= \overline{\boldsymbol{M}}$

These are the resulting 2D matrices containing trends



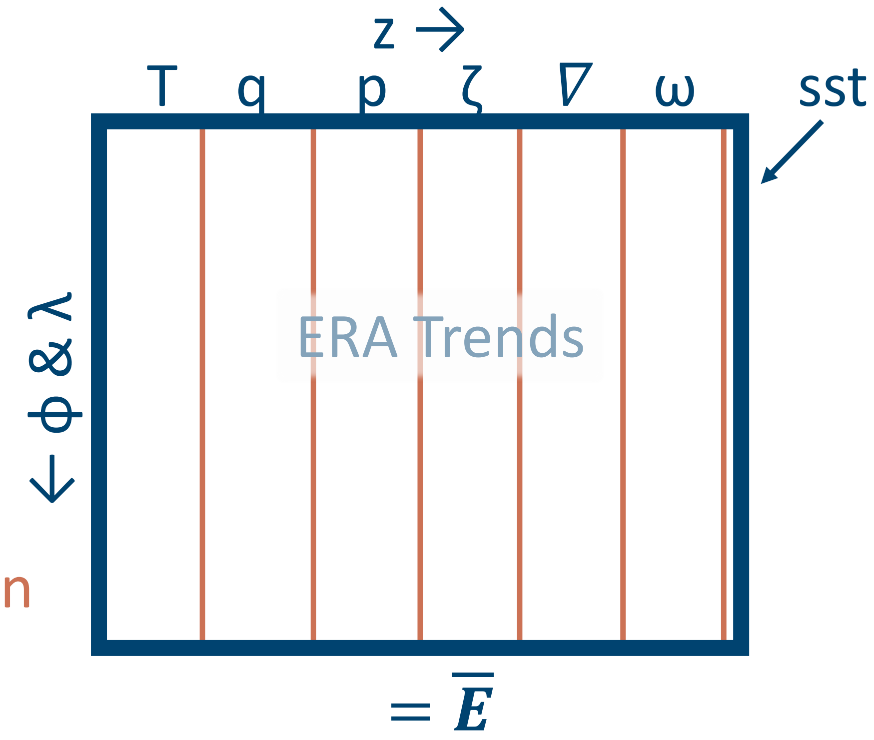
$= \overline{\boldsymbol{E}}$

MCA Description

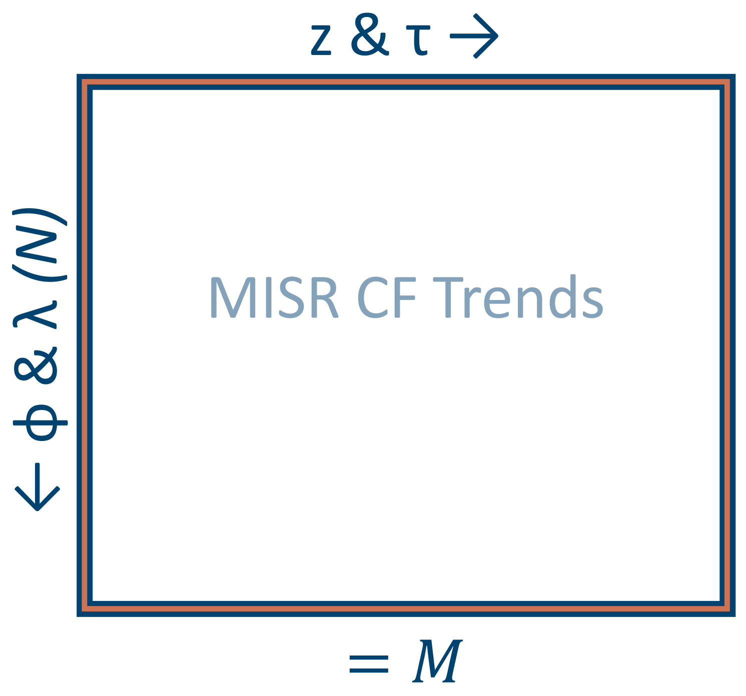


These are the resulting 2D matrices containing trends

Pre-normalize with respect to variable (separate normalization within each red box)



MCA Description



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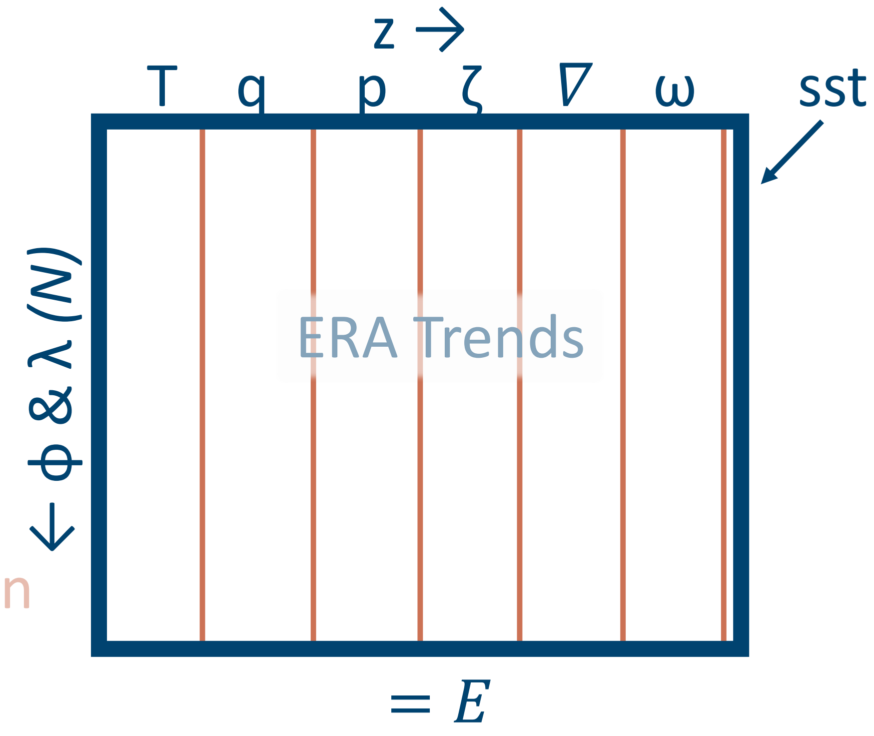
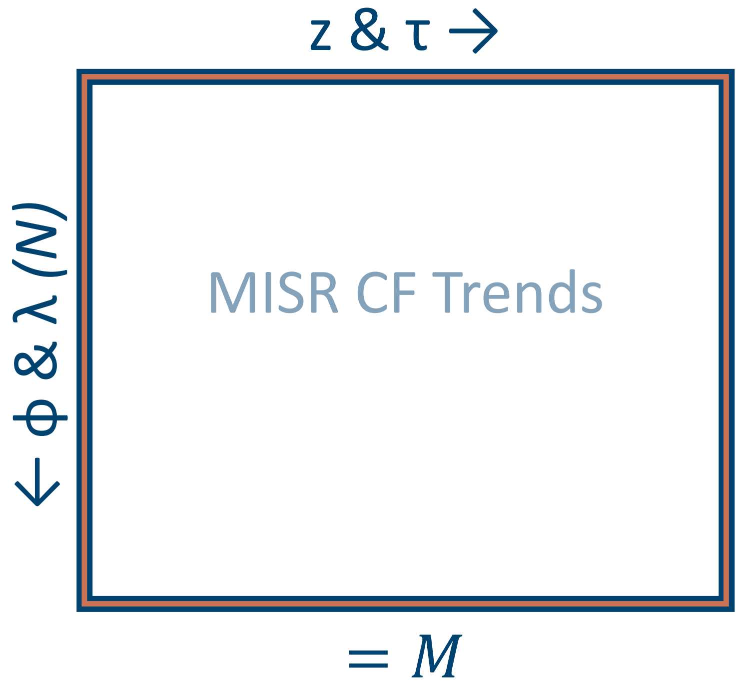


Now compute covariance: $C_{ME} = M^T E / N$ …and perform SVD: $U\Sigma V = C_{ME}$

MCA Description



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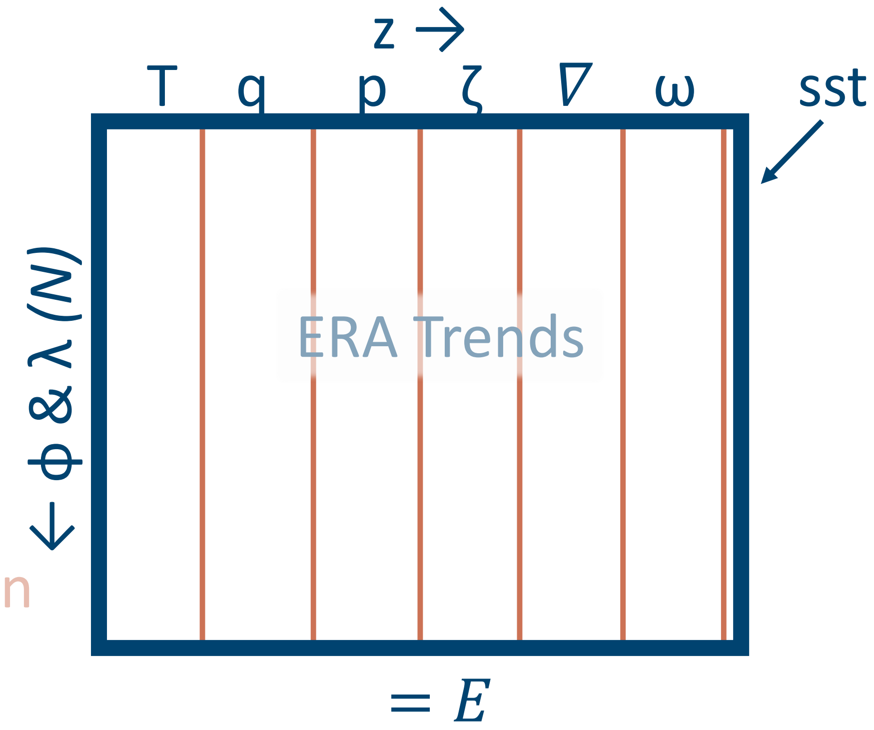
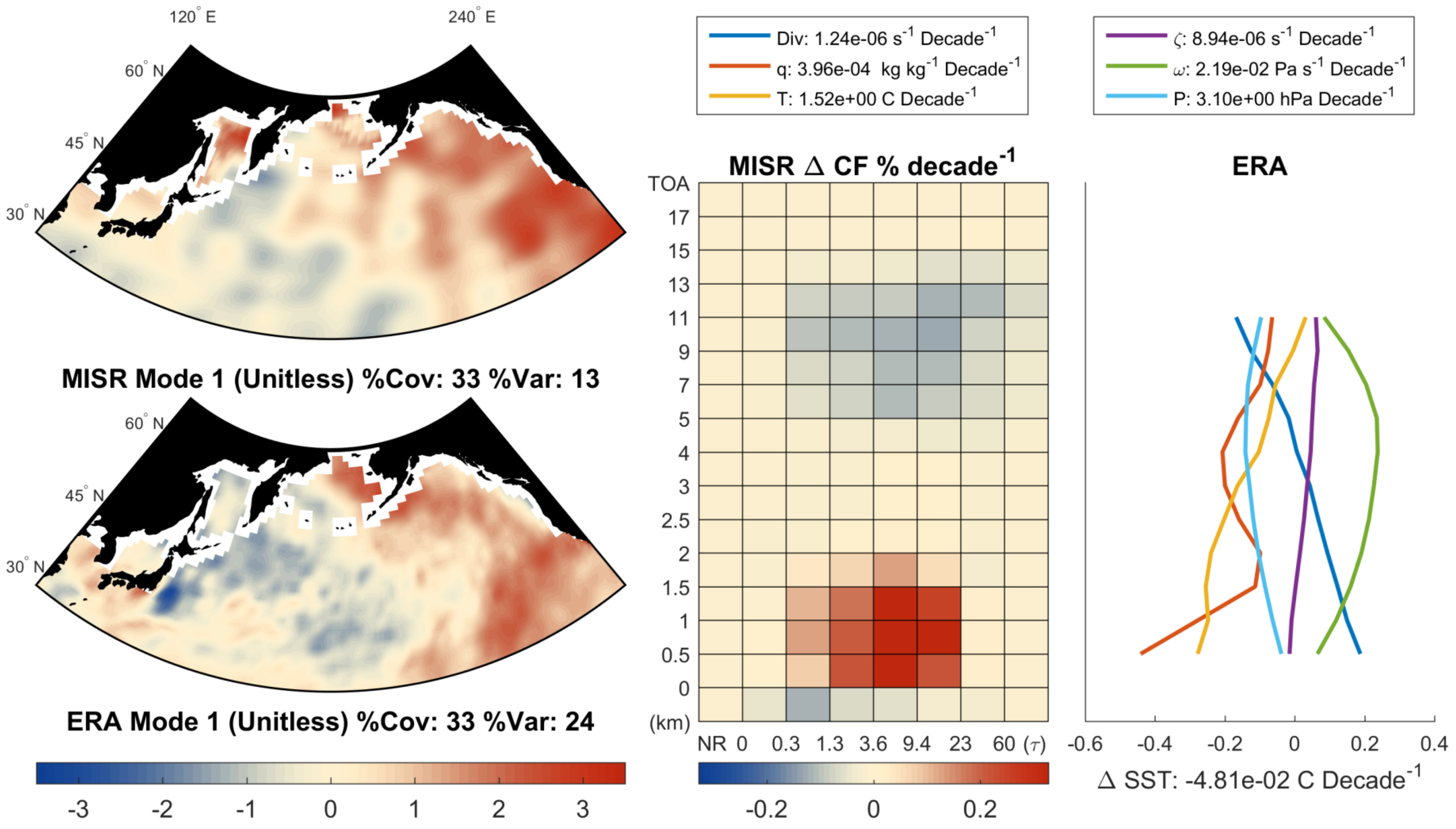
Pre-normalize with respect to variable (separate normalization within each red box)



Now compute covariance: $C_{ME} = M^T E / N$ …and perform SVD: $U\Sigma V = C_{ME}$

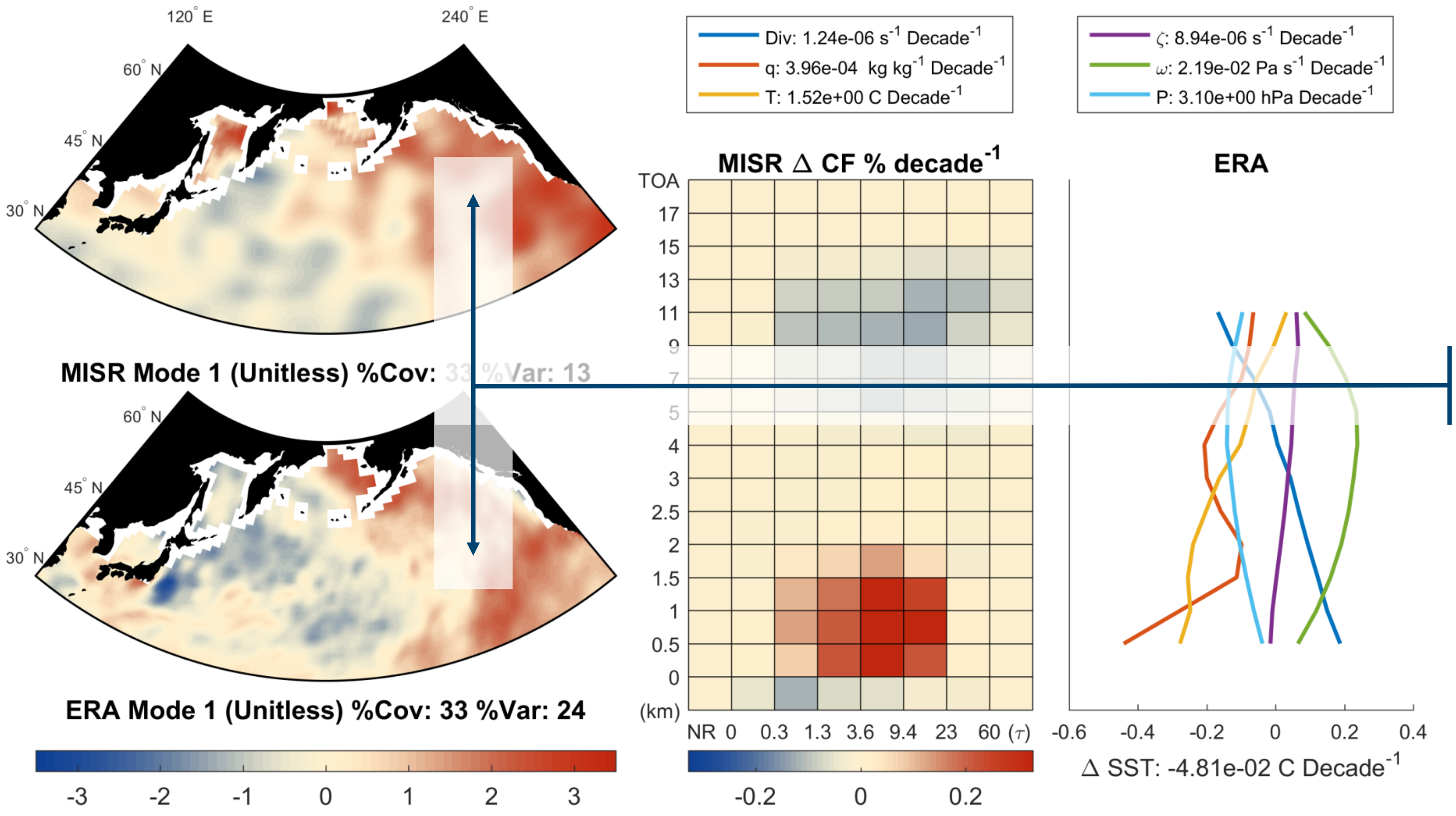
…so U contains MISR joint histogram patterns …and V contains ERA profiles

MCA Results: North Pacific Mode 1



The patterns resulting from the MCA can be projected on to the original data to determine spatial structure

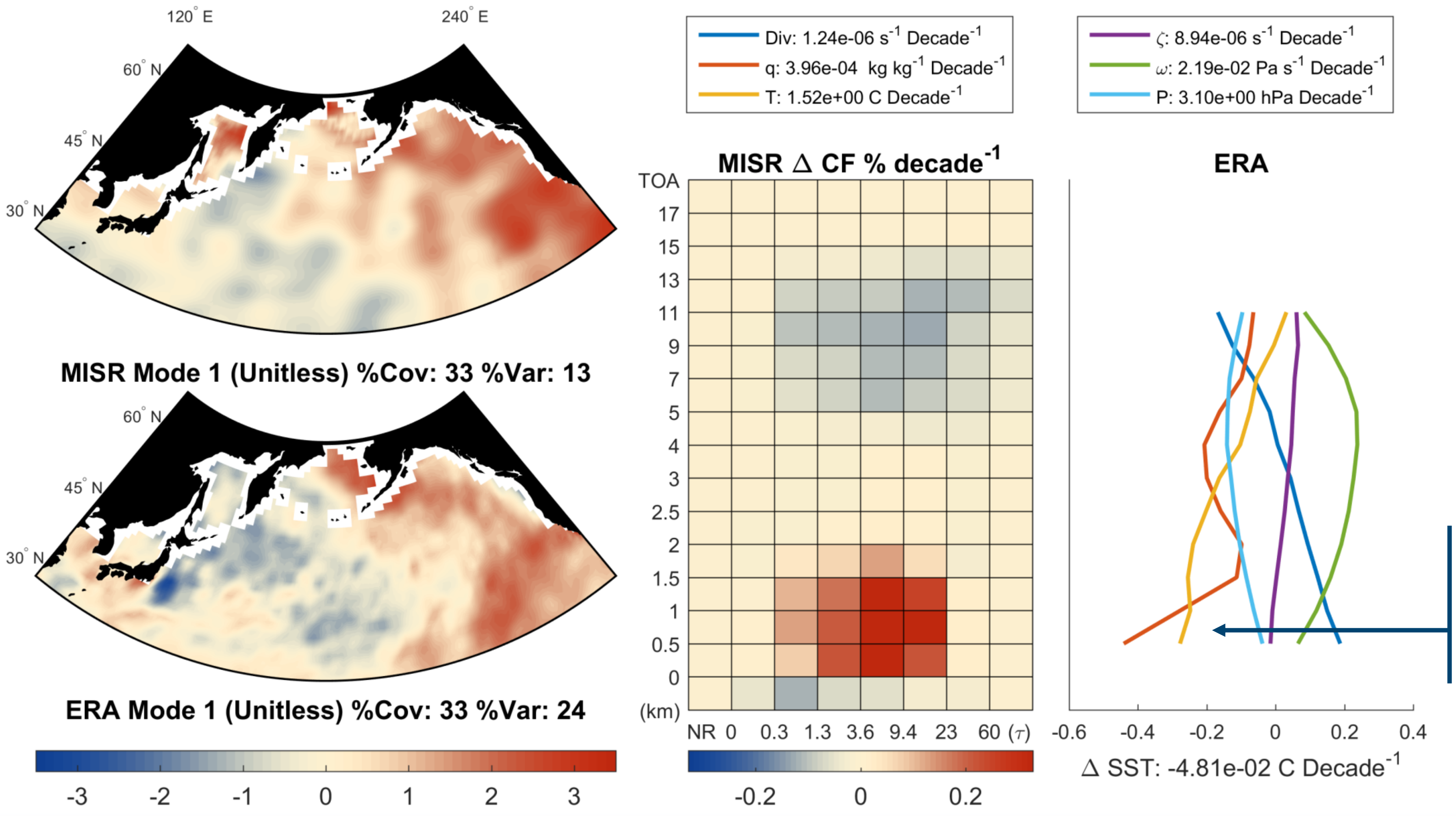
MCA Results: North Pacific Mode 1



The patterns resulting from the MCA can be projected on to the original data to determine spatial structure

The first mode resembles a PDO/ENSO like pattern

MCA Results: North Pacific Mode 1

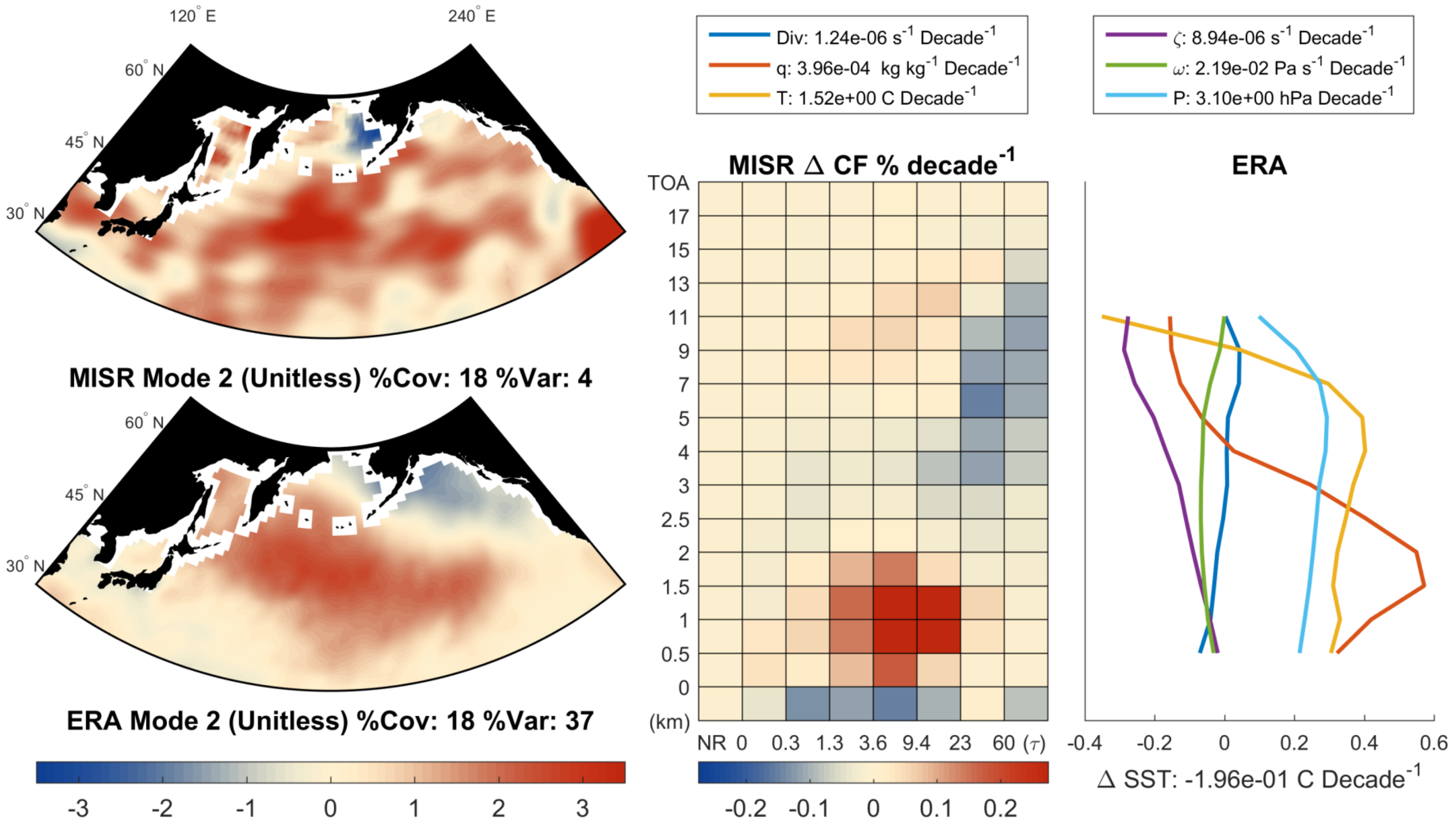


The patterns resulting from the MCA can be projected on to the original data to determine spatial structure

The first mode resembles an PDO/ENSO like pattern

The biggest changes are in the thermodynamic variables at the surface

MCA Results: North Pacific Mode 2



The second mode in the North Pacific is maximized in the storm track region

This is a closer match to what was seen in the zonal mean

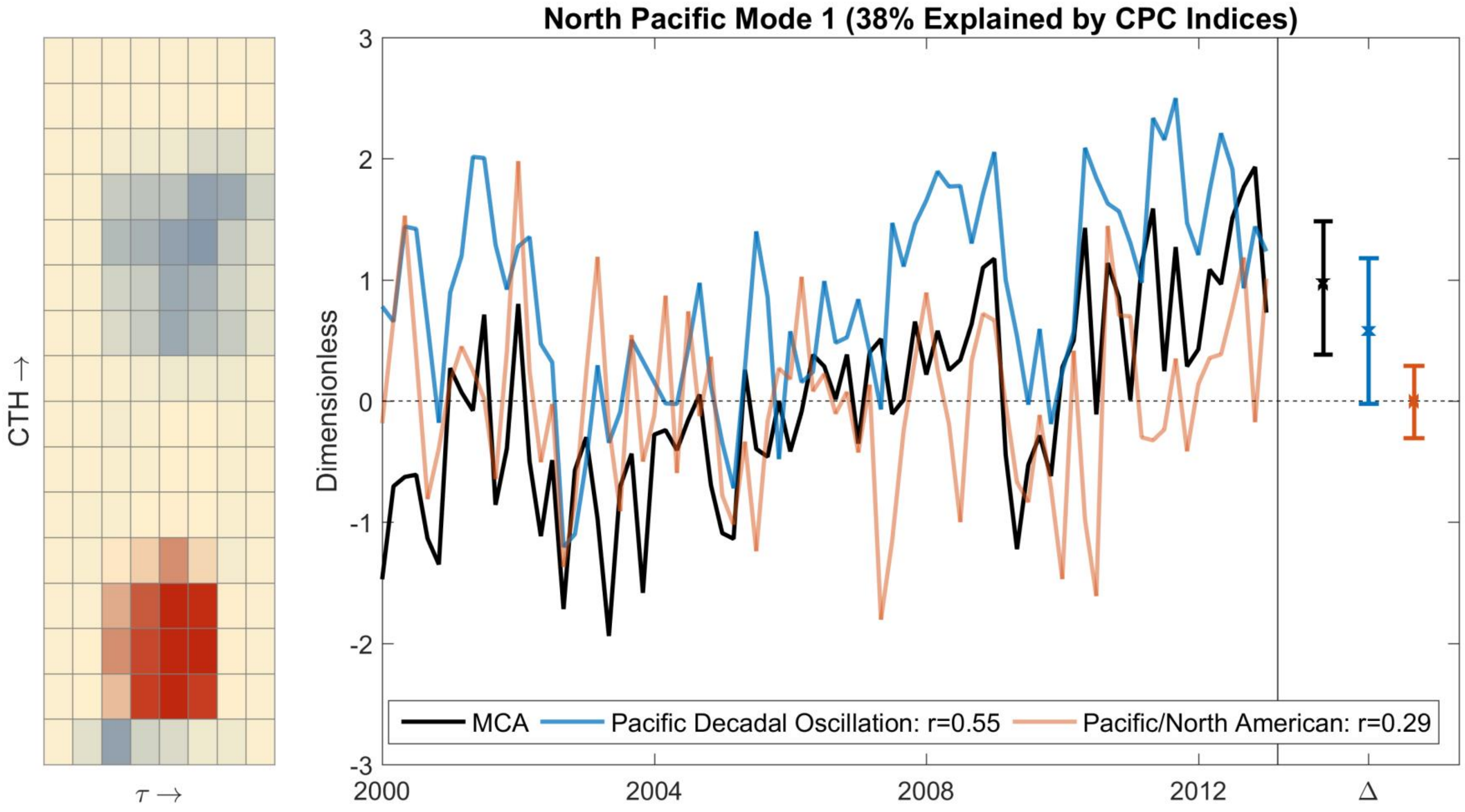
Comparison to Climate Signals

The first mode in the North Pacific resembles the PDO pattern.

NOAA CPC maintains a number of climate indices

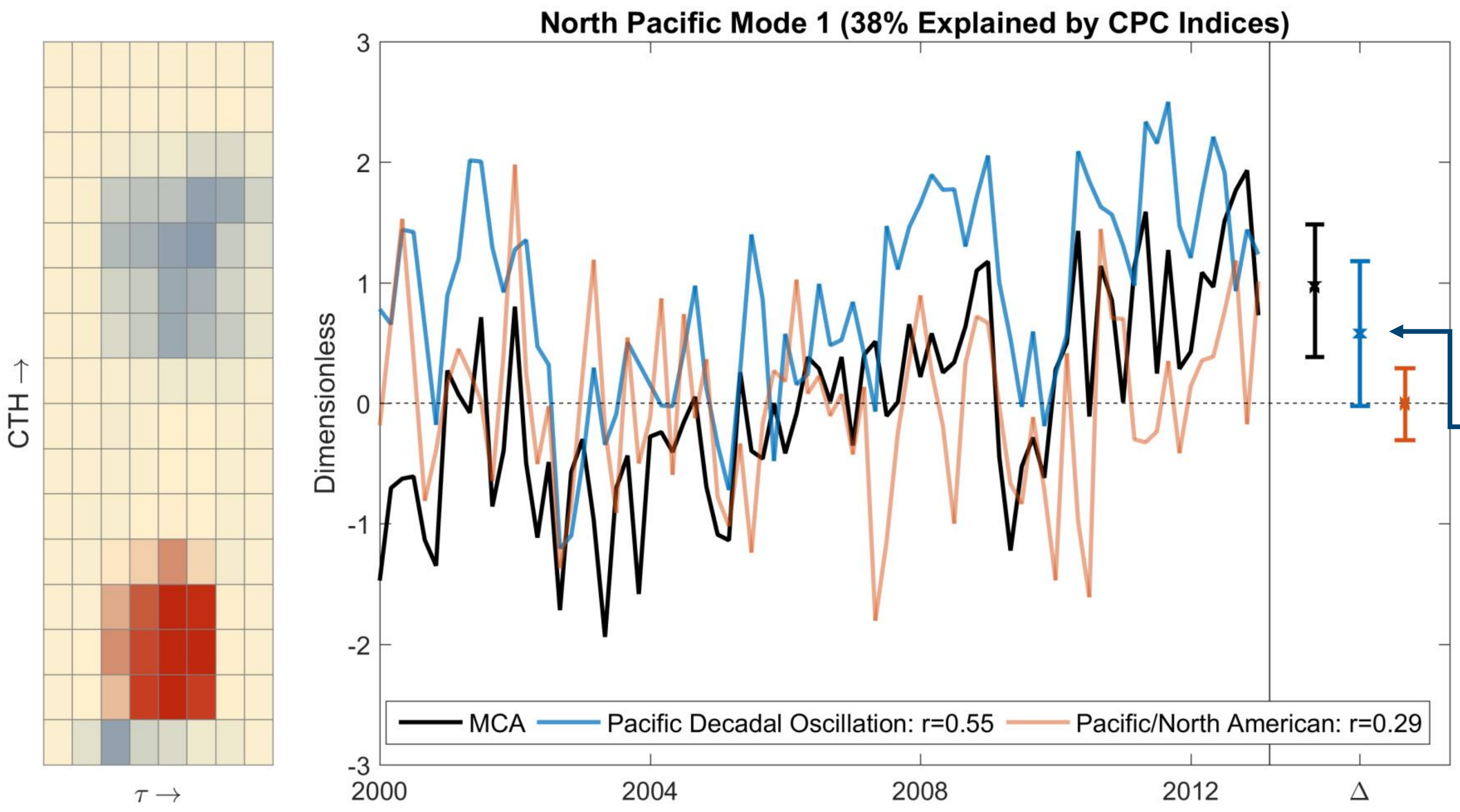
I can project the MISR spatial and CTH-OD patterns on to the original data to obtain associated time series and compare to CPC indices

Comparison to Climate Signals



The PDO index is very well correlated with the first MCA mode.

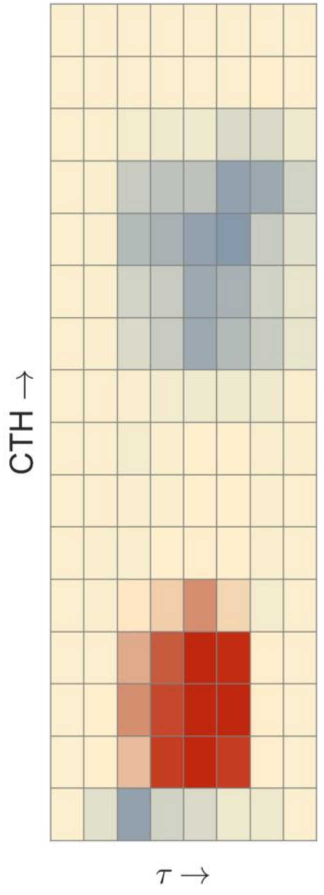
Comparison to Climate Signals

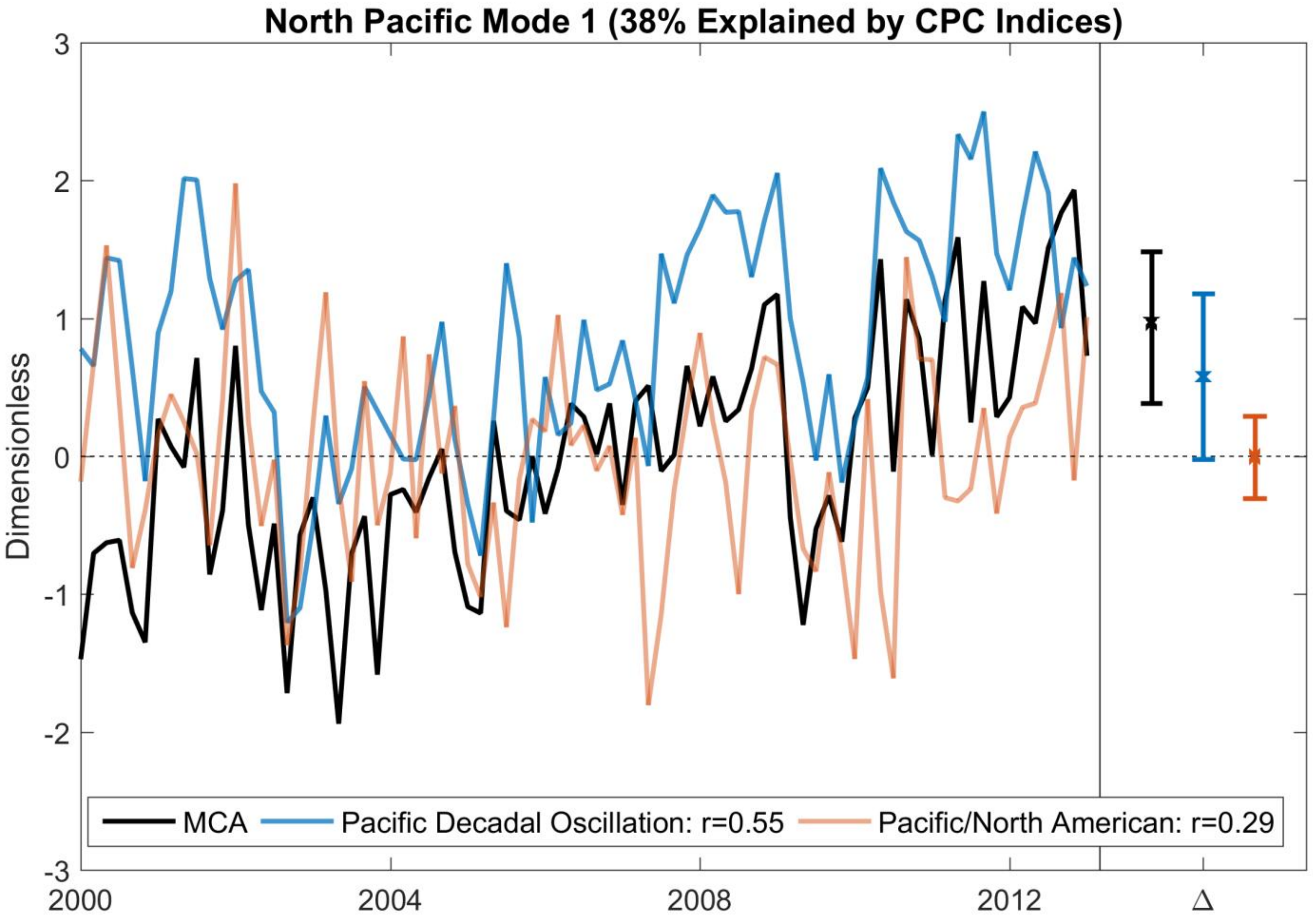


The PDO index is very well correlated with the first MCA mode.

And the PDO has undergone a trend during this period!

Comparison to Climate Signals



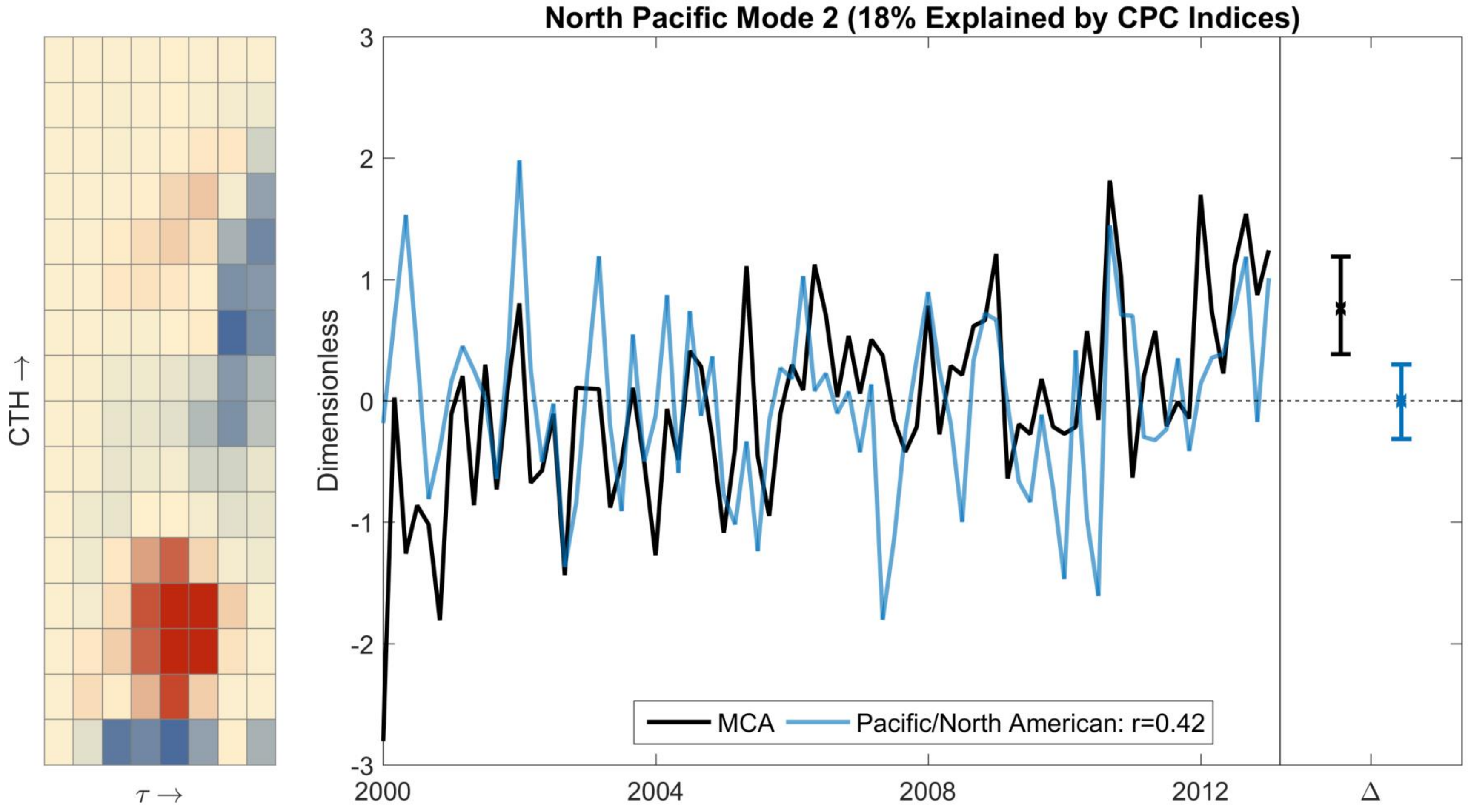


The PDO index is very well correlated with the first MCA mode.

And the PDO has undergone a trend during this period!

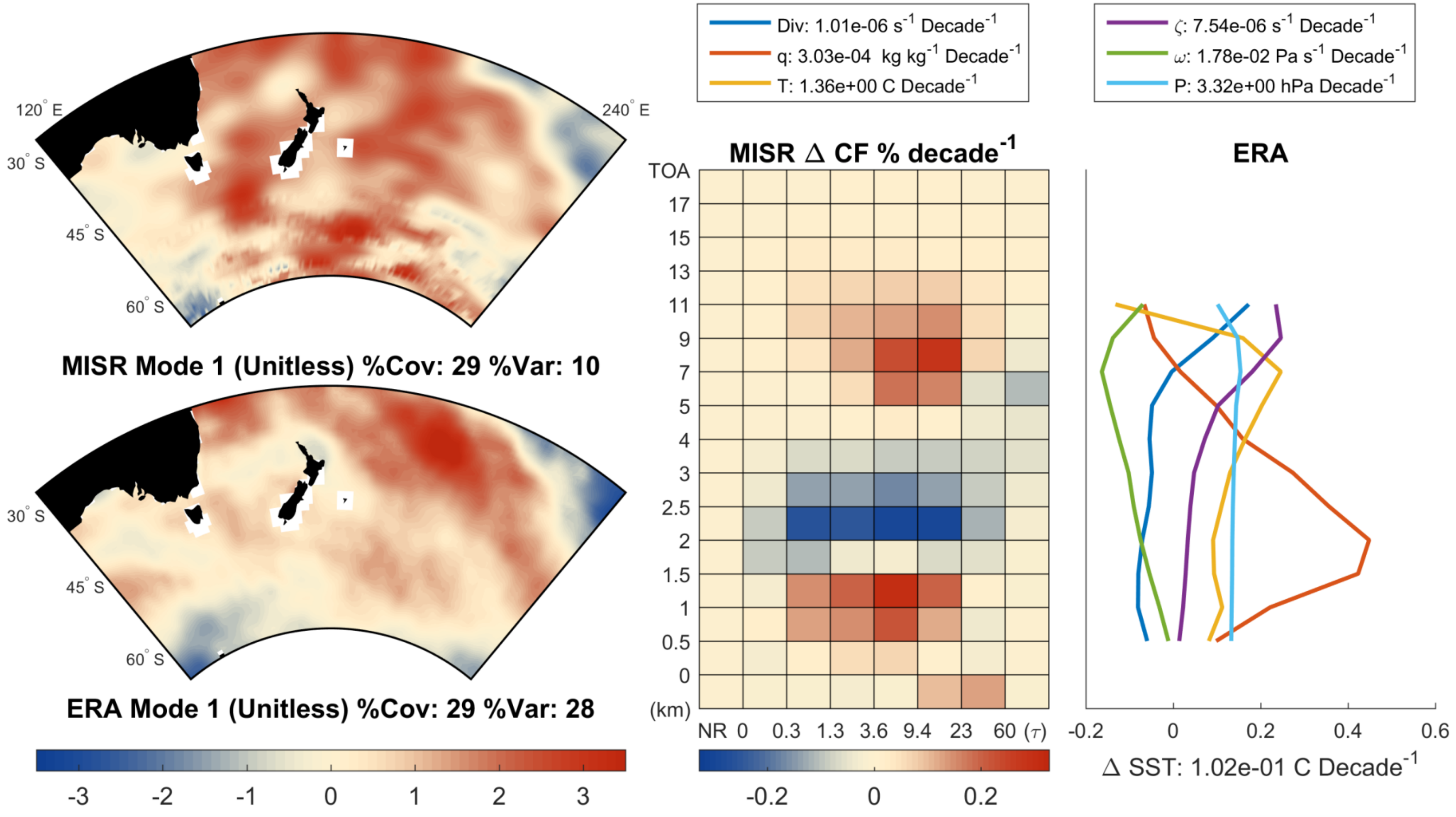
The PNA describes some of the changes on a shorter time scale

Comparison to Climate Signals



The second mode is maximum in the storm tracks and is well correlated with the Pacific / North American mode

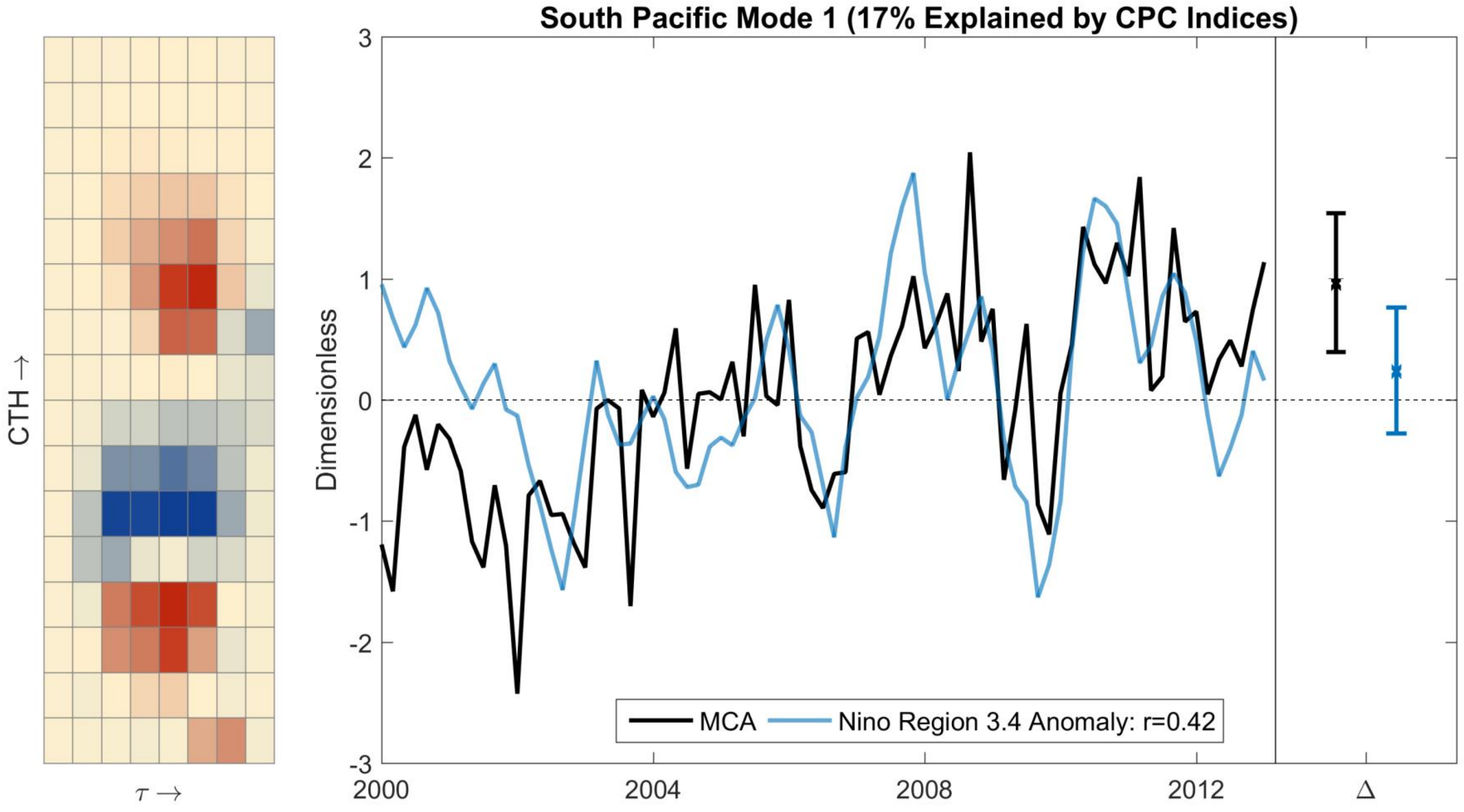
MCA Results: South Pacific Mode 1



This is the first mode in the South Pacific

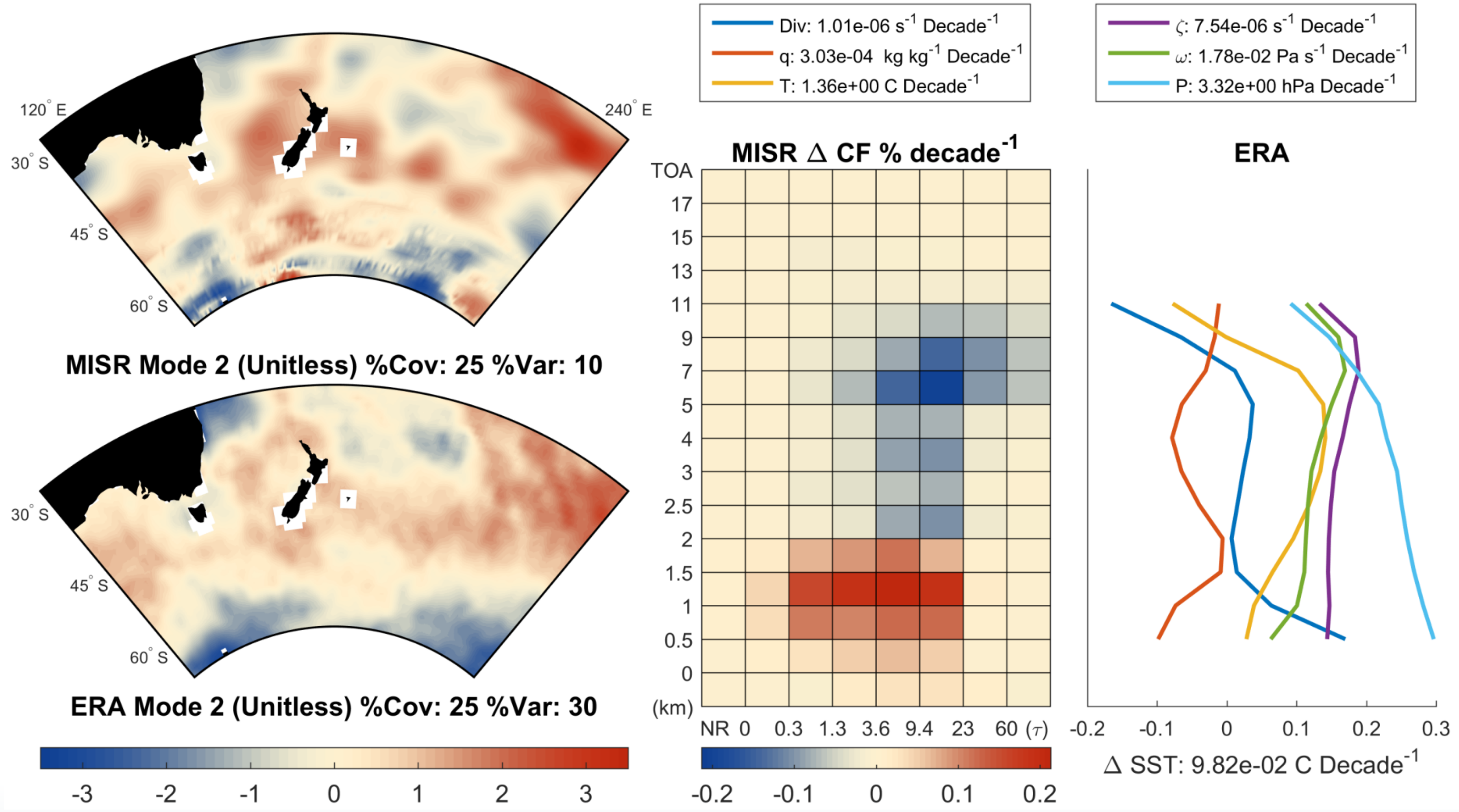
Again, most of the change in optically thick cloud is in subsequent modes

MCA Results: South Pacific Mode 1



This mode is well correlated with ENSO

MCA Results: South Pacific Mode 2

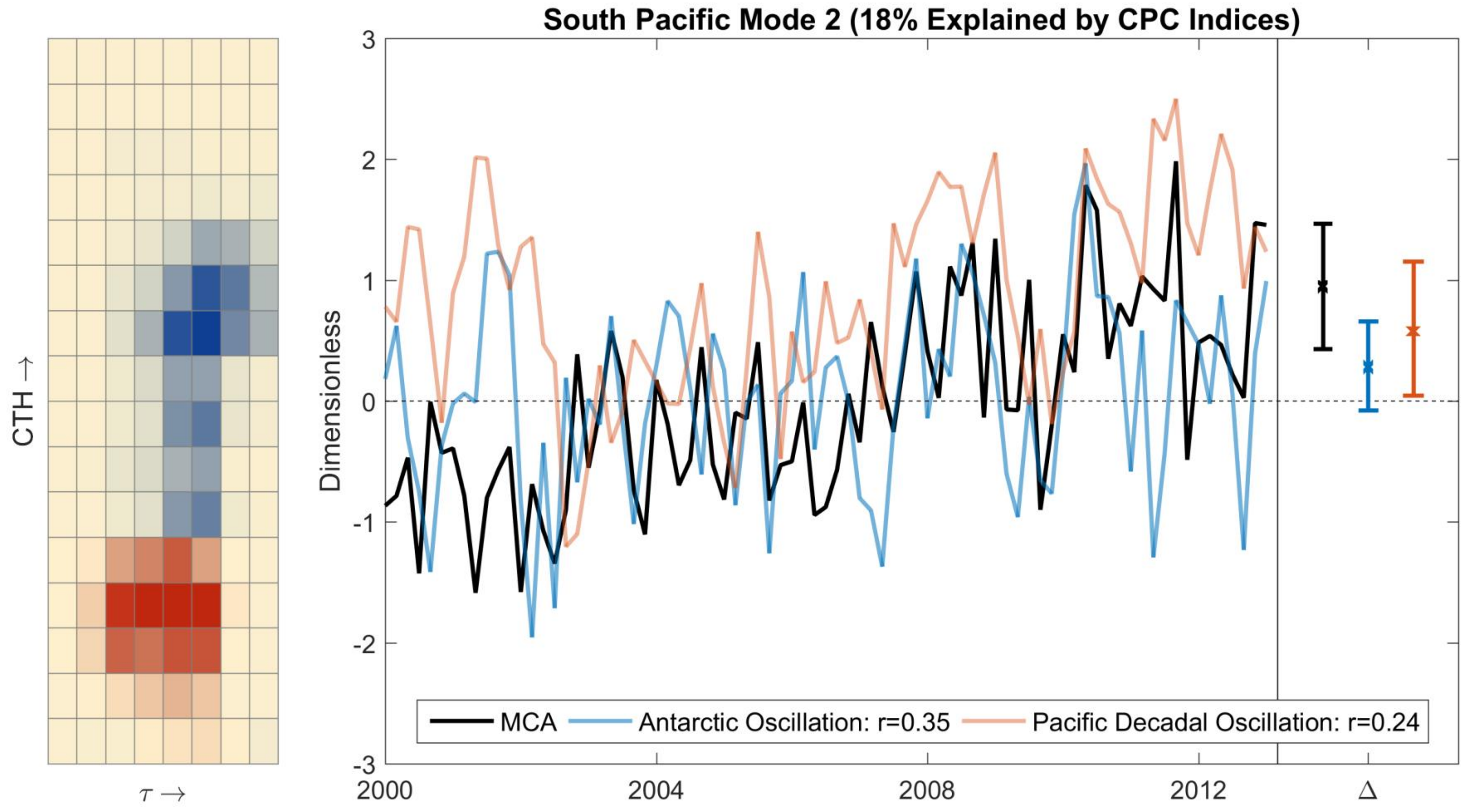


The second mode is maximized in the storm track region

This mode contains some of the change in optically thick cloud

It is clearly associated with mid-latitude highs

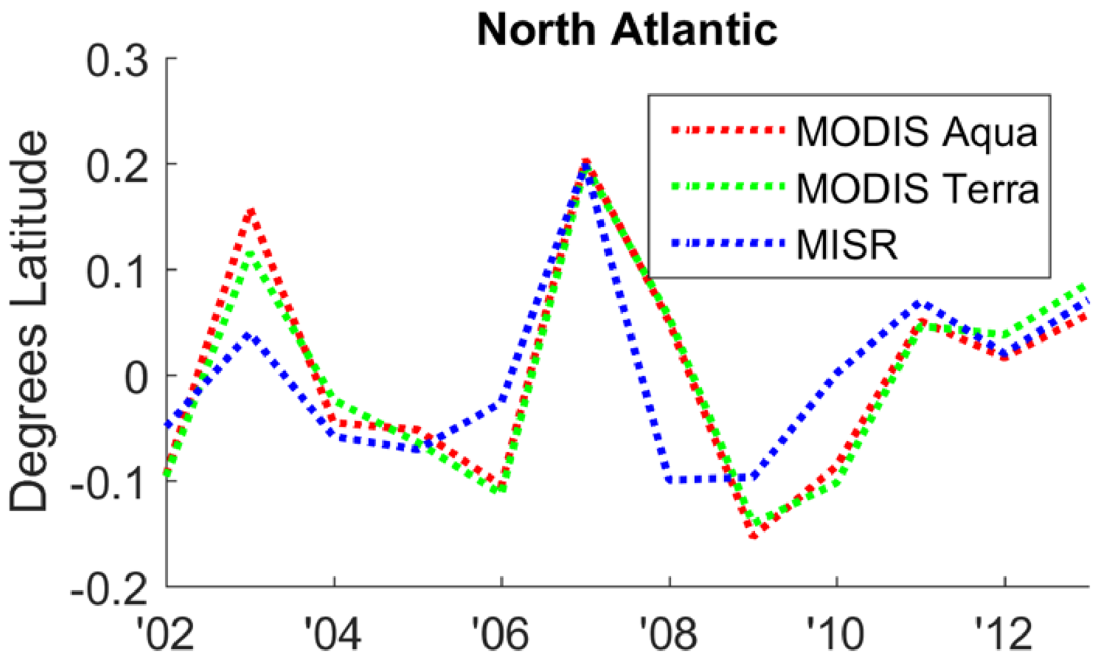
MCA Results: South Pacific Mode 2



This MCA mode is mostly associated with the Southern Annular Mode which has increased in intensity over the last decade

Overview

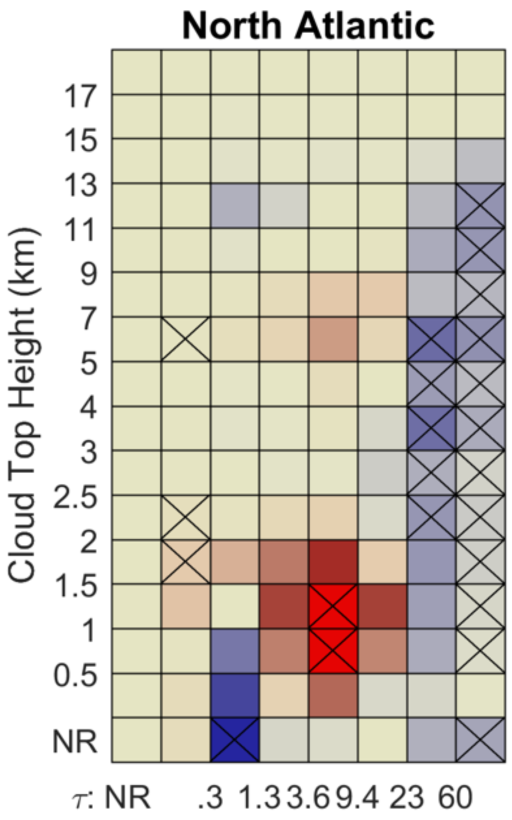
MODIS and MISR have not observed any significant poleward shift of the storm tracks over the last decade….



Overview

MODIS and MISR have not observed any significant poleward shift of the storm tracks over the last decade

But optically thick cloud has decreased in the extra-tropics, and the amount of lower thinner cloud has increased during this time

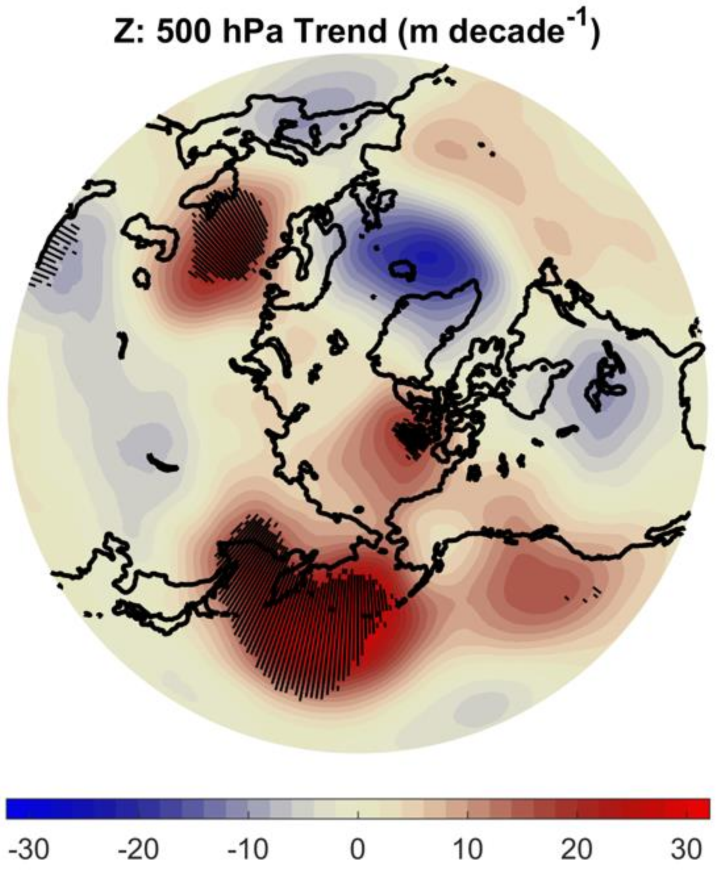


Overview

MODIS and MISR have not observed any significant poleward shift of the storm tracks over the last decade

But optically thick cloud has decreased in the extra-tropics, and the amount of lower thinner cloud has increased during this time

This change is associated with enhanced midlatitude highs



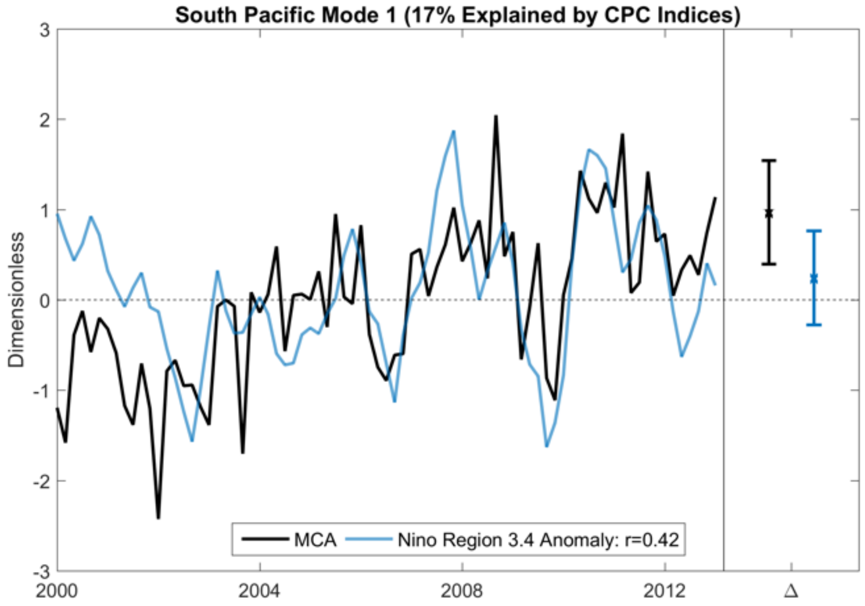
Overview

MODIS and MISR have not observed any significant poleward shift of the storm tracks over the last decade

But optically thick cloud has decreased in the extra-tropics, and the amount of lower thinner cloud has increased during this time

This change is associated with enhanced midlatitude highs

The trend is likely driven by trends in known climate signals



Future Work / Applications

Examine changes on shorter time scales

Determine shortwave and longwave cloud forcing associated with known climate variability

Assessment tool for representation of cloud in climate models

Thanks for Listening!

Questions?