Study of Long-term Trend in Aerosol Optical Thickness (AOT) Observed from Operational AVHRR Satellite Instrument

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CICS/ESSIC/UMCP & NOAA/NESDIS/STAR

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(Reference: Zhao et al., *JGR*, in press)

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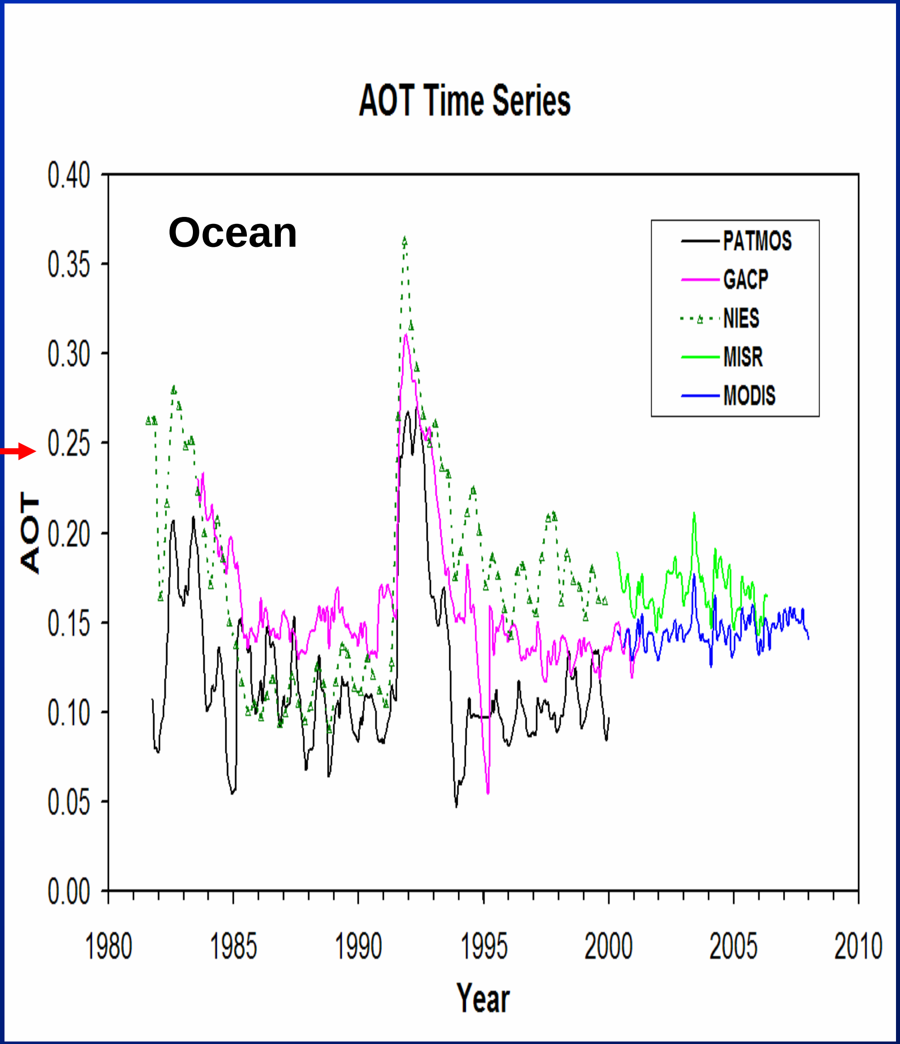
Introduction

- Recent retrospective processing of historical AVHRR satellite records makes the global long-term trend analysis of tropospheric aerosol possible.

- There are evident differences in the global monthly mean aerosol optical thickness (AOT) from the historical satellite aerosol data (same for the current satellite aerosol data), which may produce different AOT trend.

- Causes of the Difference
  - Difference in calibration
  - Difference in retrieval algorithms
    - ✓ aerosol model assumptions
    - ✓ surface treatment
    - ✓ cloud screening



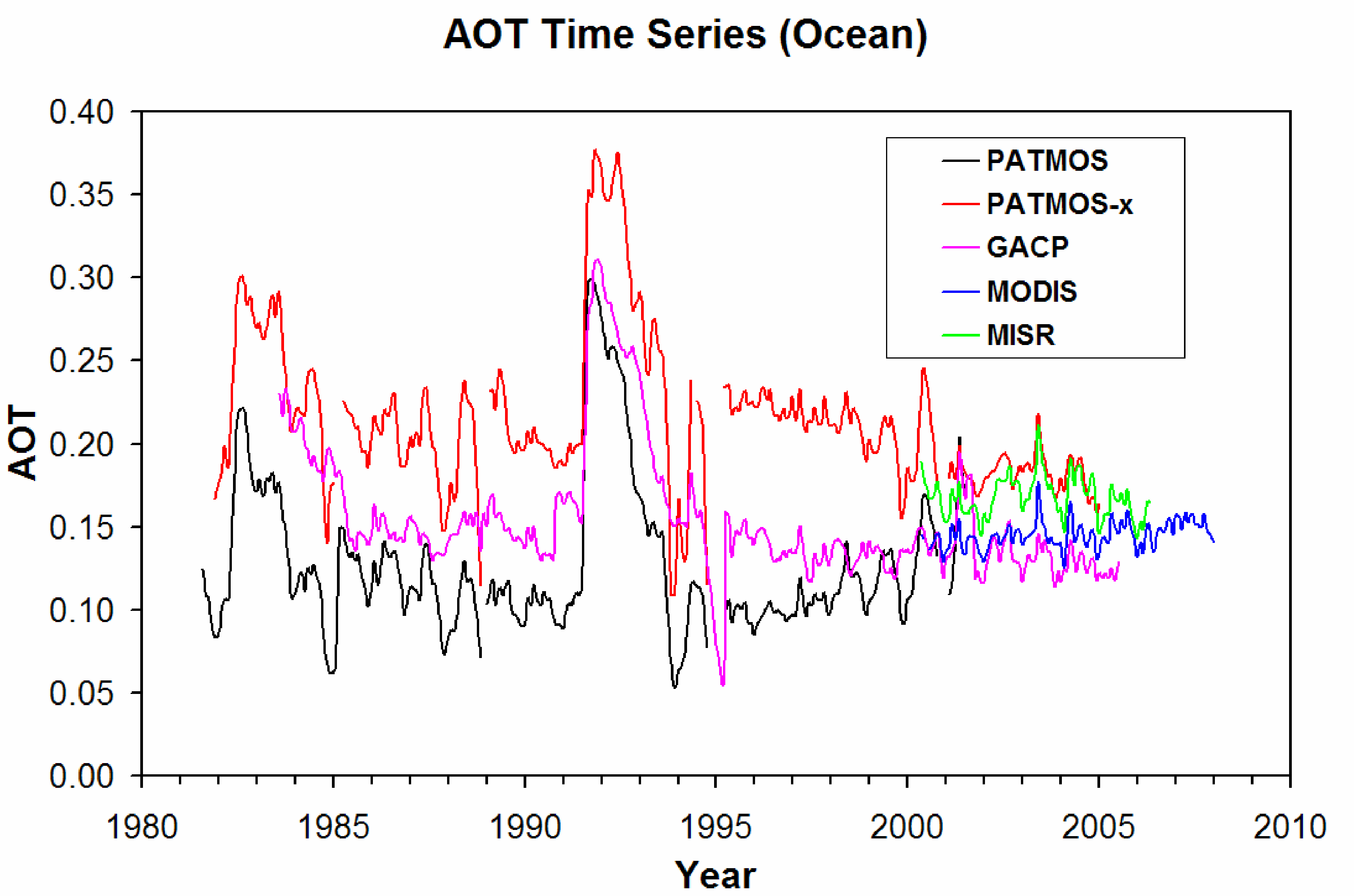
Objectives

- Analyze the effect of instrument calibration and aerosol retrieval algorithm on the long-term trend of AOT by using AVHRR PATMOS and PATMOS-x aerosol products.
- Derive the long-term trend of AOT over both global and regional scales over ocean for the last two decades and examine the potential impact of anthropogenic emissions on the aerosol loading in the troposphere.

NOAA/NESDIS AVHRR Aerosol Products

- **PATMOS Aerosol Product:**
  - AOT (0.63μm) over cloud free ocean.
  - 1°x1° equal area grid.
  - Pentad and monthly products from 1981-2001.
  - Single-channel algorithm.
  - Vicarious calibration
  - CLAVR-1 cloud screening.

- **PATMOS-x Aerosol Product:**
  - AOTs (0.63 & 0.83μm) over cloud free ocean.
  - 0.5°x0.5° and 0.25°x0.25° equal area grid.
  - Daily and monthly products from 1981-present.
  - Independent two-channels algorithm.
  - Vicarious calibration + SNO inter-satellite calibration.
  - CLAVR-x cloud screening.



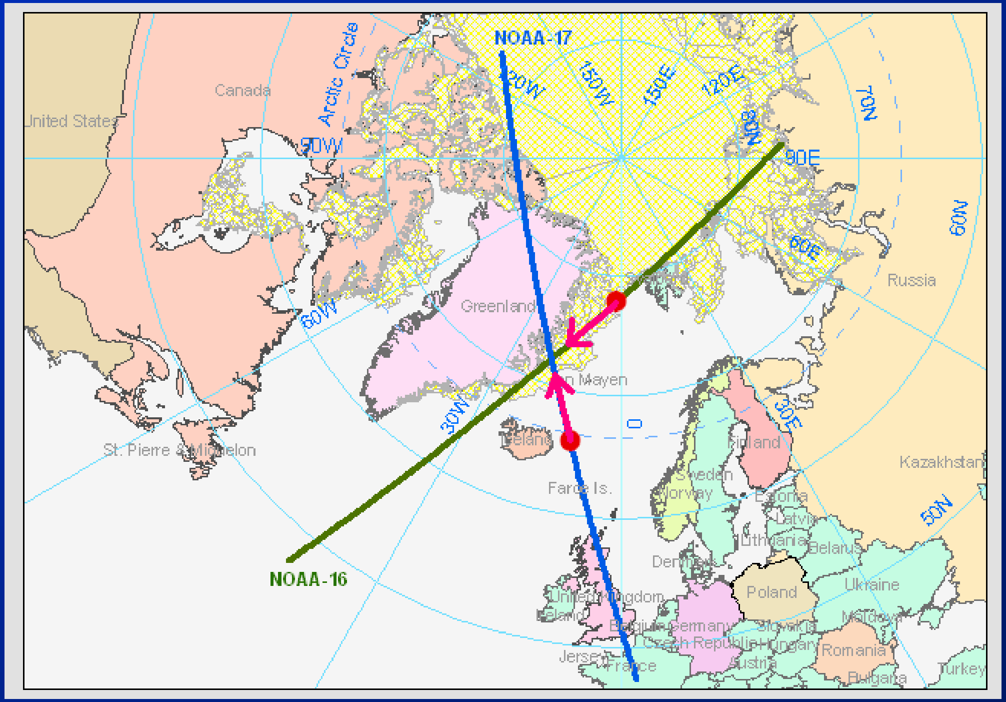
AOT Time Series (Ocean)
AOT
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1980
1985
1990
1995
2000
2005
2010
Year
PATMOS
PATMOS-x
GACP
MODIS
MISR

Simultaneous Nadir Overpass (SNO) Calibration

SNO Method [Cao et al., 2004; Heidinger et al., 2002]:

- Find the orbits of different satellites that have intersections.
- Use time and location information to determine simultaneity between two pixels.
- Use MODIS as reference to retrospectively recalibrate the AVHRR observations from all the NOAA/POES satellites.

Schematic View of the Overpass of Two NOAA Satellites



Benefits:

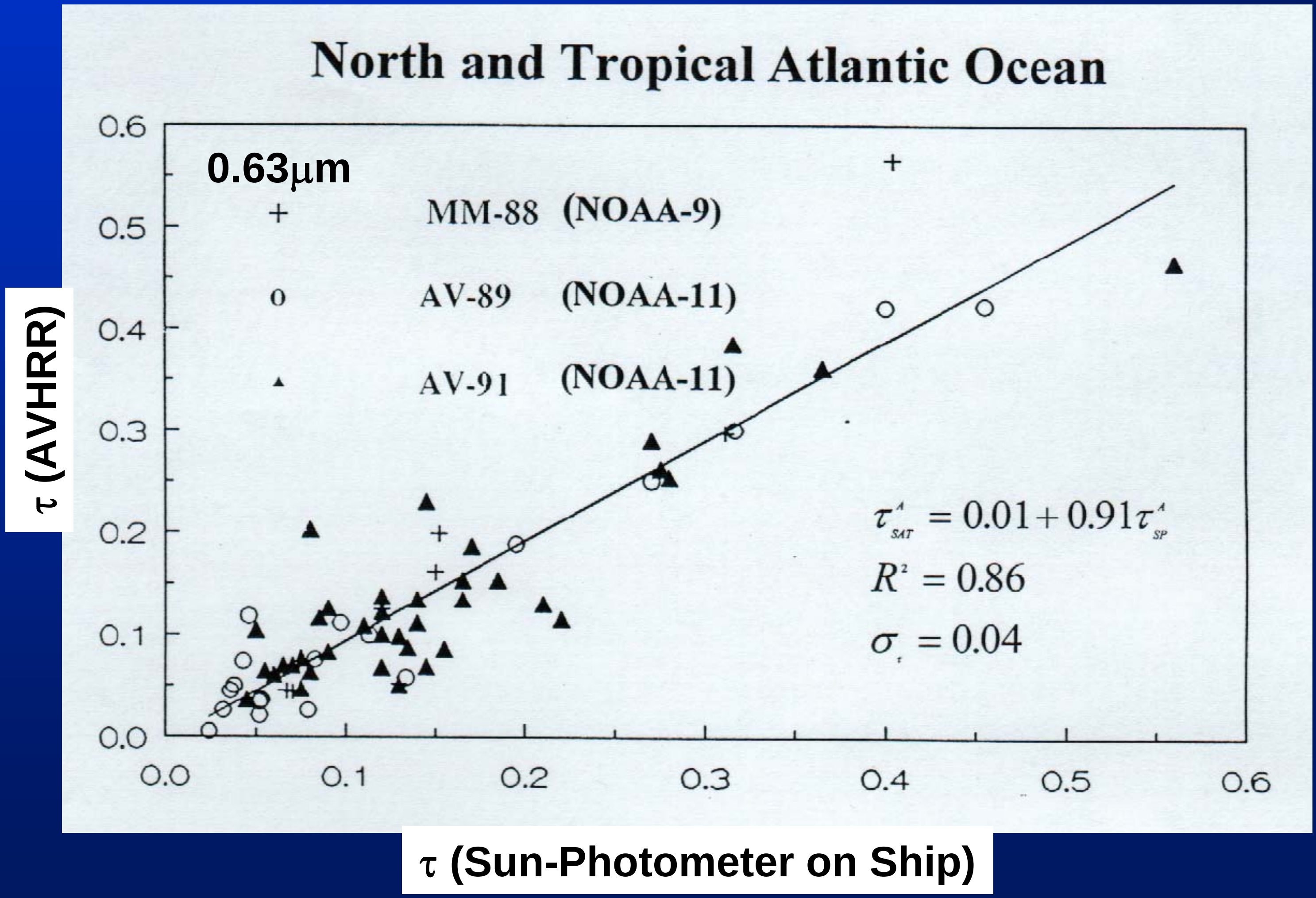
1. **AVHRR calibration is improved and its uncertainty become close to MODIS.**
2. **A consistent calibration is applied to all the AVHRR observations from different satellite platforms – critical for long-term trend detection.**

NOAA/NESDIS AVHRR Aerosol Retrieval Algorithm

Algorithm (Ocean)	AOT Products	Description
one channel [Stowe et al., 1997]	τ_1 (0.63μm) (PATMOS)	One-mode lognormal size distribution; no absorption; lambertian surface with diffuse glint correction.
independent two channel [Ignatov & Stowe, 2002]	τ_1 (0.63μm) τ_2 (0.83μm) (PATMOS-x)	Ono-mode lognormal size distribution; no absorption; ocean surface BRDF (V=1m/s); tuned to match the one-channel retrieval.
revised independent two channel [Zhao et al., 2004]	τ_1 (0.63μm) τ_2 (0.83μm) (PATMOS-x based new data)	Bi-mode lognormal size distribution; weak absorption; ocean surface BRDF (V=6m/s); adjusted according to the AERONET validation.

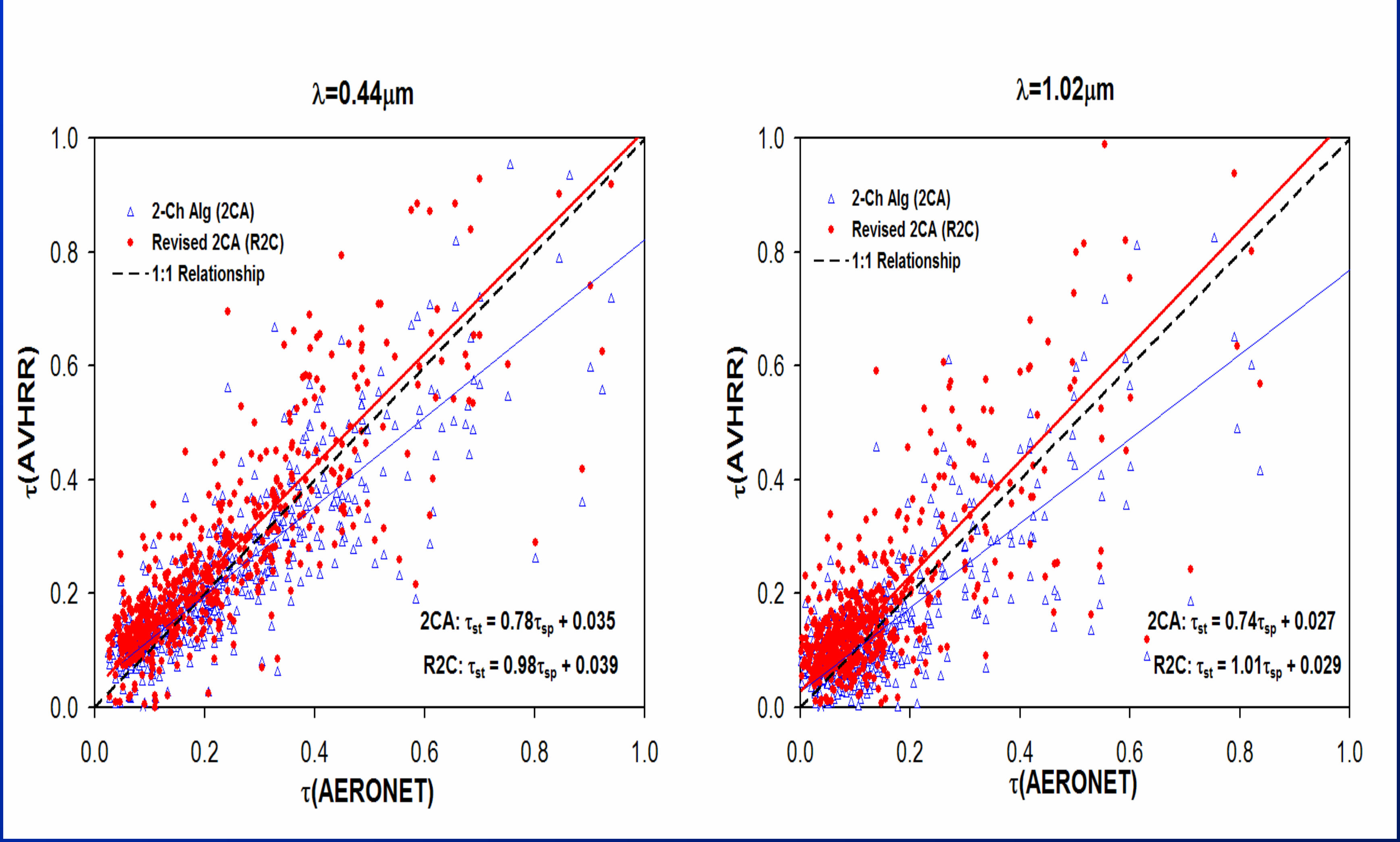
Validation of AVHHR Single Channel Algorithm

(Stowe et al., 1997; JGR)



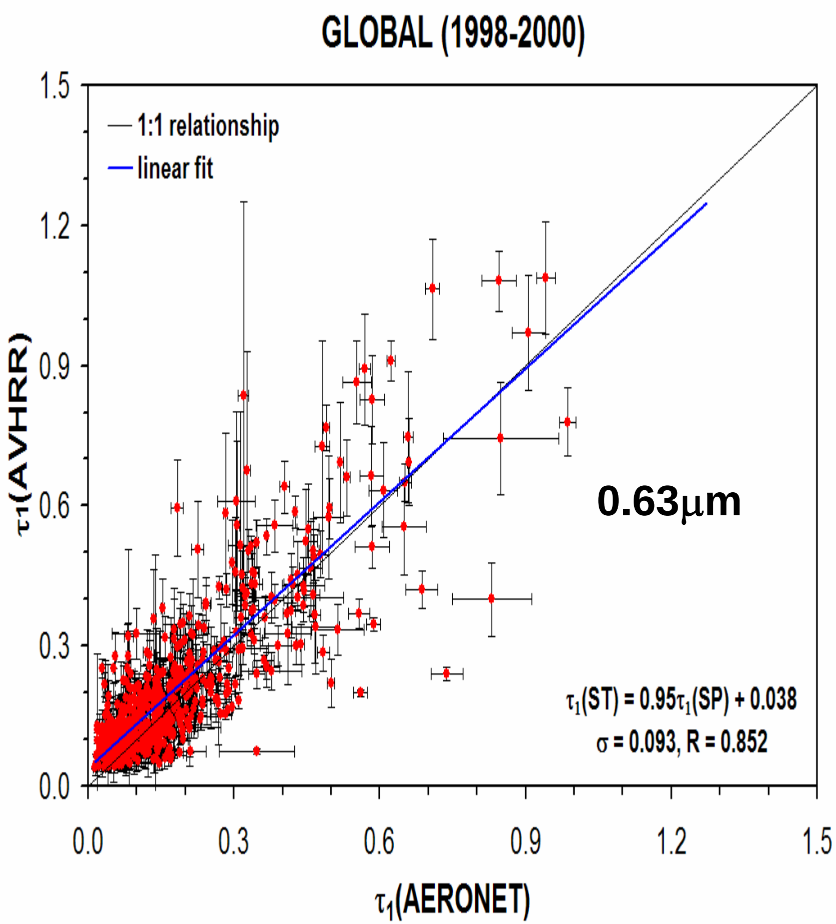
Validation of AVHRR Two Channel Algorithm and Revised Two Channel Algorithm

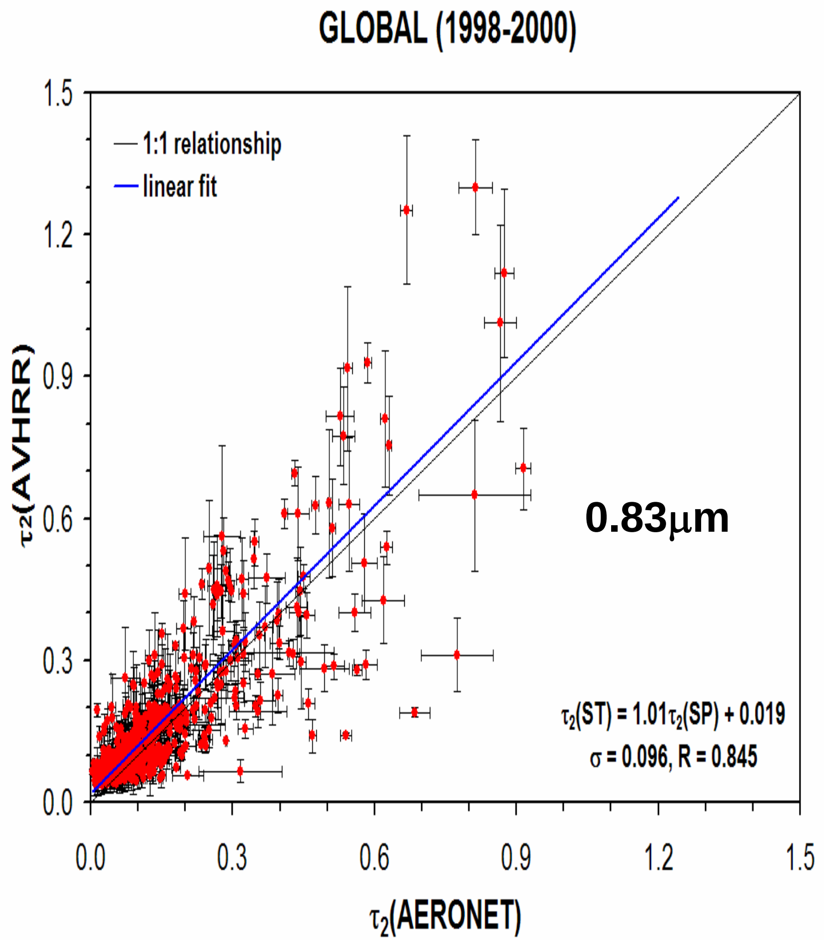
(Zhao et al., 2004; JGR)



Validation of Revised AVHRR Two Channel Algorithm

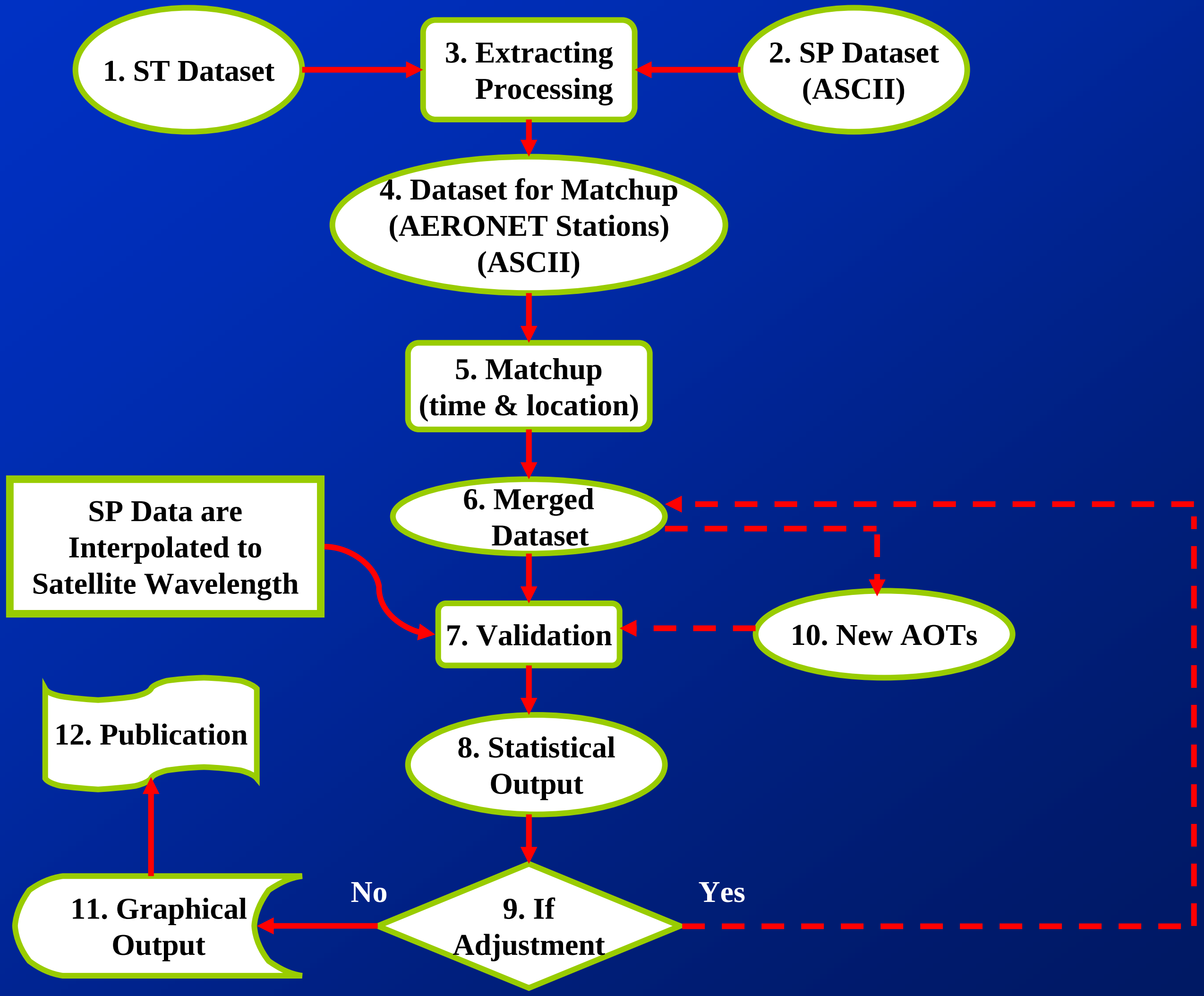
(Zhao et al., 2004)





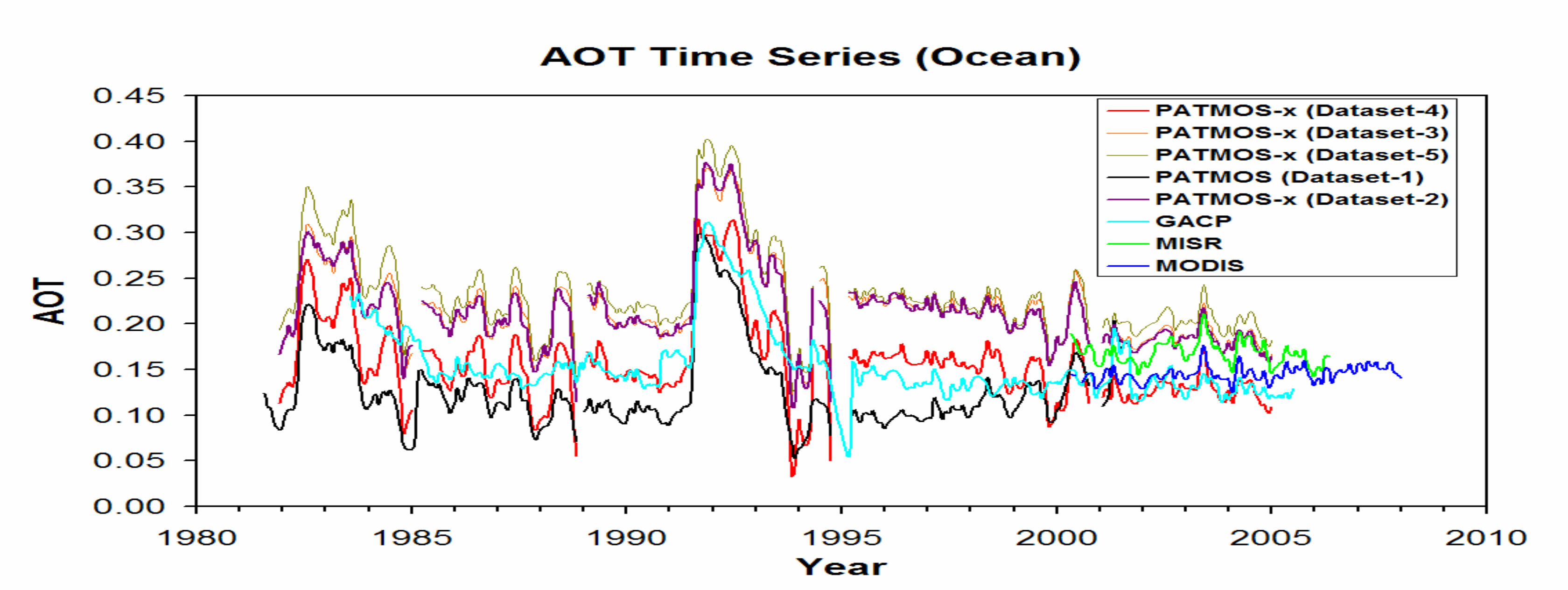
Flow Chart for Aerosol Validation

(Zhao et al., 2002, JAS; 2004, JGR)



Dataset Used for Long-term Trend Analysis

Datasets	Products	Retrieval Resolution	Time Coverage	Algorithm	Notes
1	τ_1	Pixel level (GAC data)	1981-2001	One-channel	PATMOS, Old Calibration
2	τ_1 and τ_2	Pixel level (GAC data)	1981-2004	Two-channel	PATMOS-x, with SNO Calibration
3	τ_1 and τ_2	Grid level (0.5^ox0.5^o)	1981-2004	Two-channel	PATMOS-x based, with SNO Calibration
4 (reference)	τ_1 and τ_2	Grid level (0.5^ox0.5^o)	1981-2004	Revised Two-channel	PATMOS-x based, with SNO Calibration
5	τ_1	Grid level (0.5^ox0.5^o)	1981-2004	One-channel	PATMOS-x based, with SNO Calibration



Cases Designed for Long-term Trend Analysis

Case 1 (Dataset 2 & 3 Comparison):

Effect of spatial resolution on AOT trend (orbital pixel level versus orbital grid level retrieval).

Case 2 (Dataset 4 & 5 Comparison):

Effect of aerosol retrieval algorithm on AOT trend (revised two-channel versus one-channel algorithm).

Case 3 (Dataset 1 & 5 Comparison):

Effect of calibration on AOT trend (SNO versus no-SNO).

AOT Long-term Trend Analysis

Define Some Terminology:

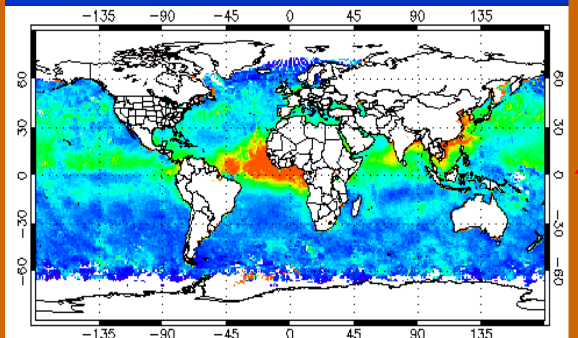
- **Linear long-term trend (LLT):**
  - The AOT LLT is the slope of linear regression line for the time series of monthly, or seasonally, or annually averaged AOT.
  - LLT is in the unit of absolute (or percentage) changes per decade or per year.

- **Significance of AOT LLT:**
  - Defined as $|LLT/\sigma|$, σ is the standard deviation of the AOT LLT.
  - Trend is examined at 95% confidence level (or 5% significance level), which is corresponding to $|LLT/\sigma| > 2$.

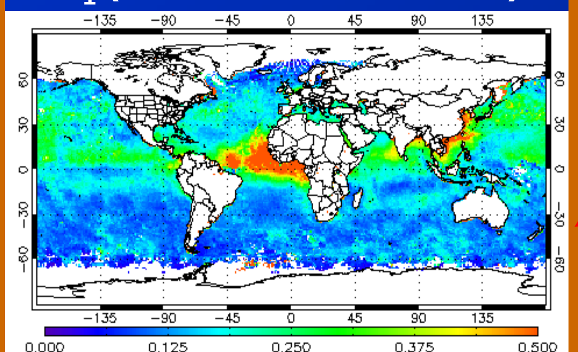
Case 1 - Effect of Spatial Resolution

AOT

τ_1 (Dataset-2, March 2004)



τ_1 (Dataset-3, March 2004)

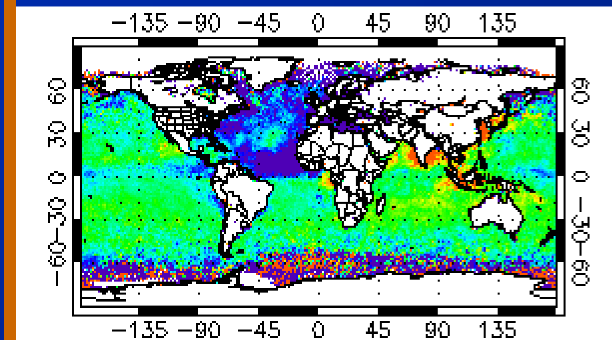


pixel level retrieval

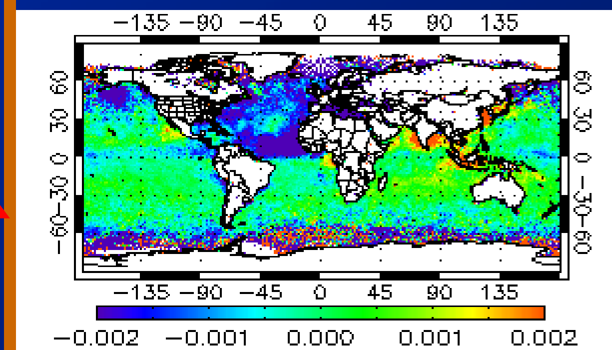
grid level retrieval

LLT

Dataset-2



Dataset-3



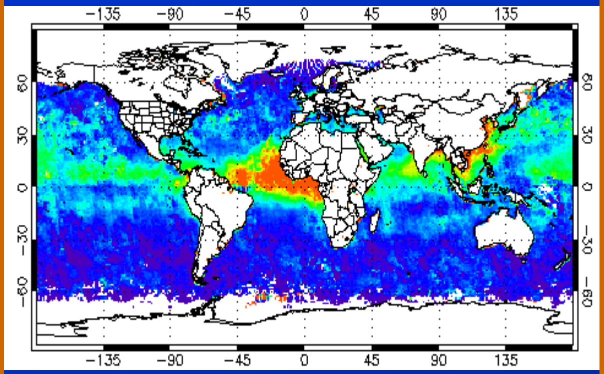
Conclusions:

1. The difference in the monthly averaged AOT value and its LLT between the pixel and grid level retrieval can be neglected.
2. Grid level retrieval will not degrade AOT LLT and is good for efficient re-processing.

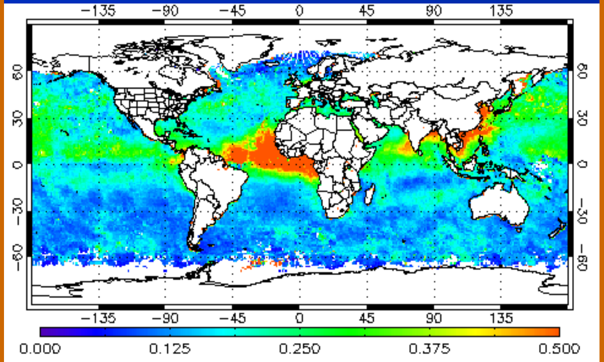
Case 2 - Effect of Aerosol Retrieval Algorithm

AOT

τ_1 (Dataset-4, March 2004)



τ_1 (Dataset-5, March 2004)

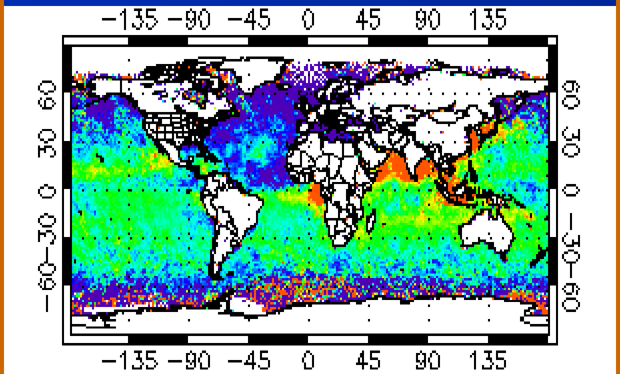


revised two channel retrieval

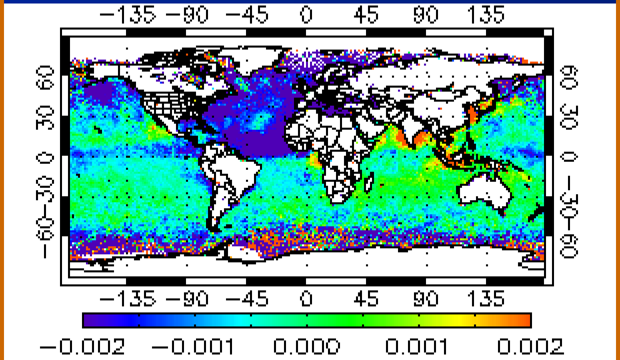
one channel retrieval

LLT

Dataset-4



Dataset-5



LLT of global mean AOT is ~ -0.01 per decade

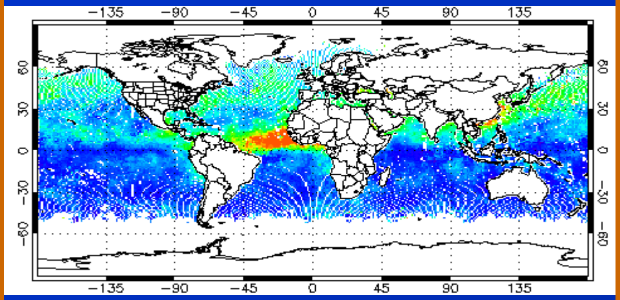
LLT of global mean AOT is ~ -0.01 per decade

Conclusions: 1) AOTs of Dataset-4 are somewhat lower than Dataset-5, especially over middle- & high-latitudes oceans. 2) Difference in the LLT are mainly in the regions under the influence of industrial and biomass burning pollutions and desert particles. 3) However, the effect on the LLT of globally and monthly averaged AOT can still be neglected.

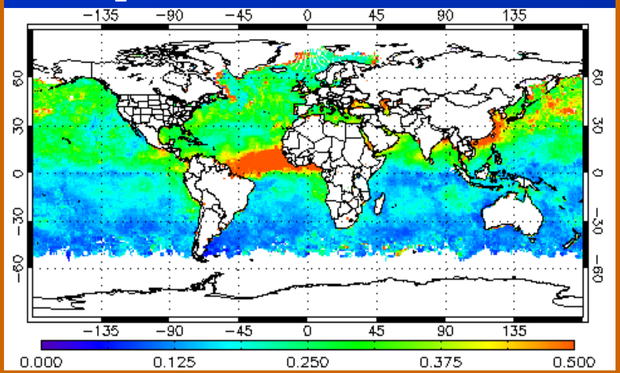
Case 3 - Effect of Calibration

AOT

τ_1 (Dataset-1, April 1985)



τ_1 (Dataset-5, April 1985)

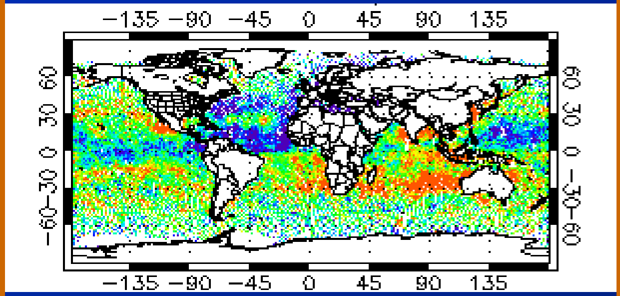


no SNO calibration

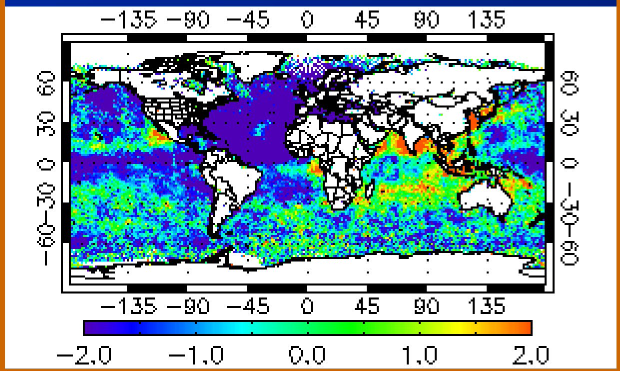
with SNO calibration

Significance of LLT

Dataset-1



Dataset-5



LLT of global mean AOT is ~ +0.001 per decade

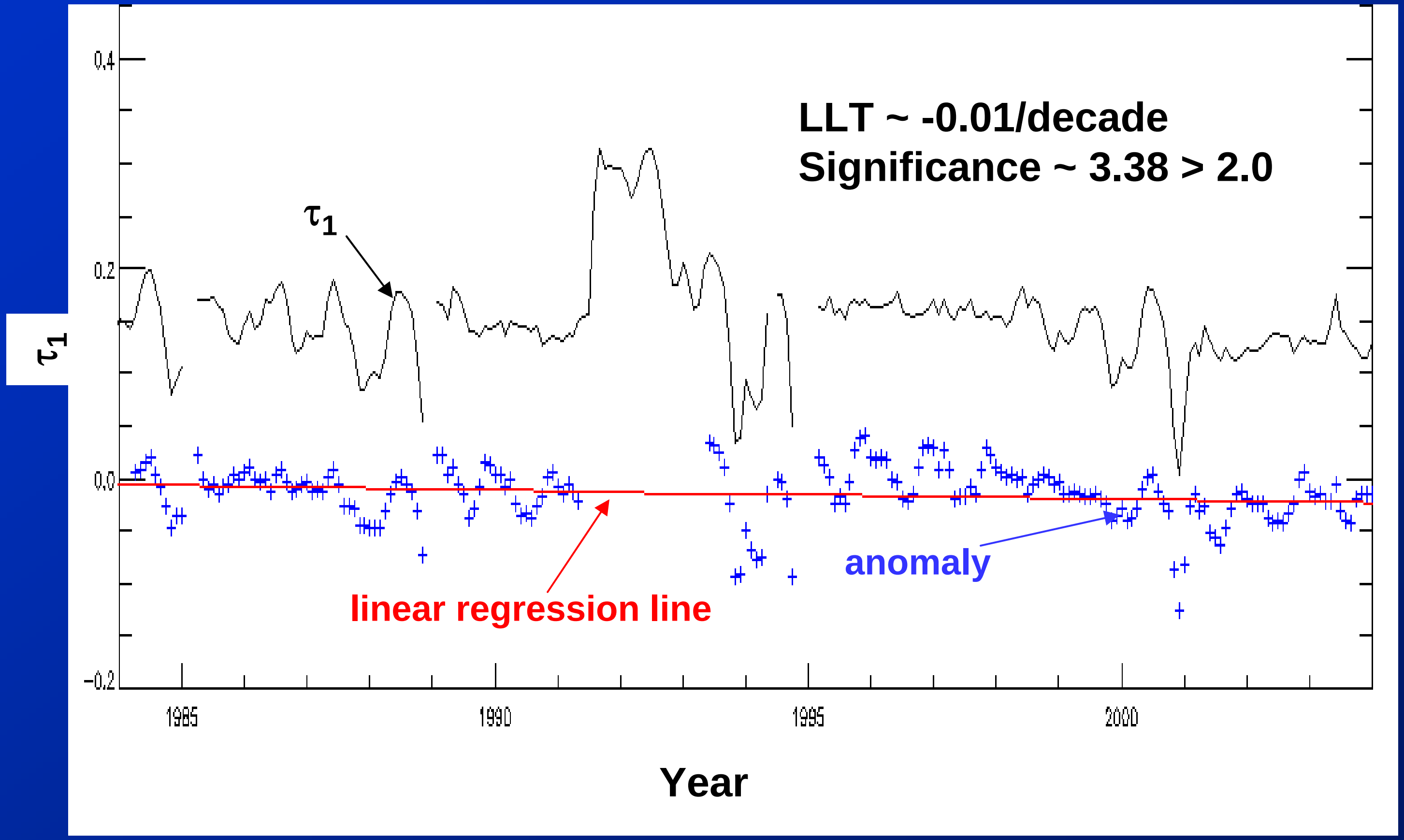
LLT of global mean AOT is ~ -0.01 per decade

Conclusions: 1) AOT with new SNO calibration is higher in general over global ocean than that without the SNO calibration; 2) The effect of calibration on the AOT long-term trend is more evident over broad open oceans; 3) The calibration effect on the LLT of globally and monthly averaged AOT can change the sign of the trend.

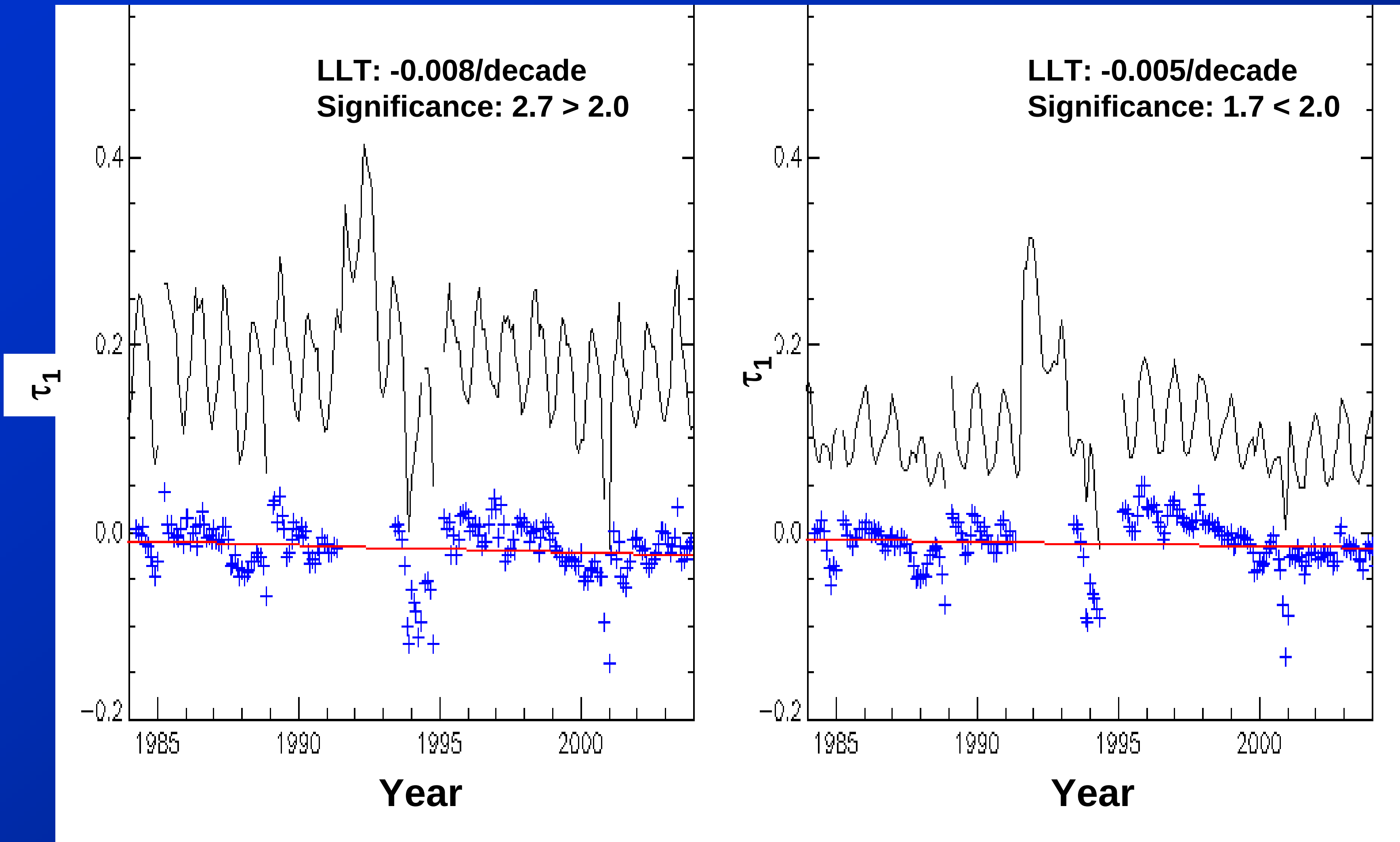
Results of Global Long-term Trend

Time-Series and Trend of Monthly Mean AOT

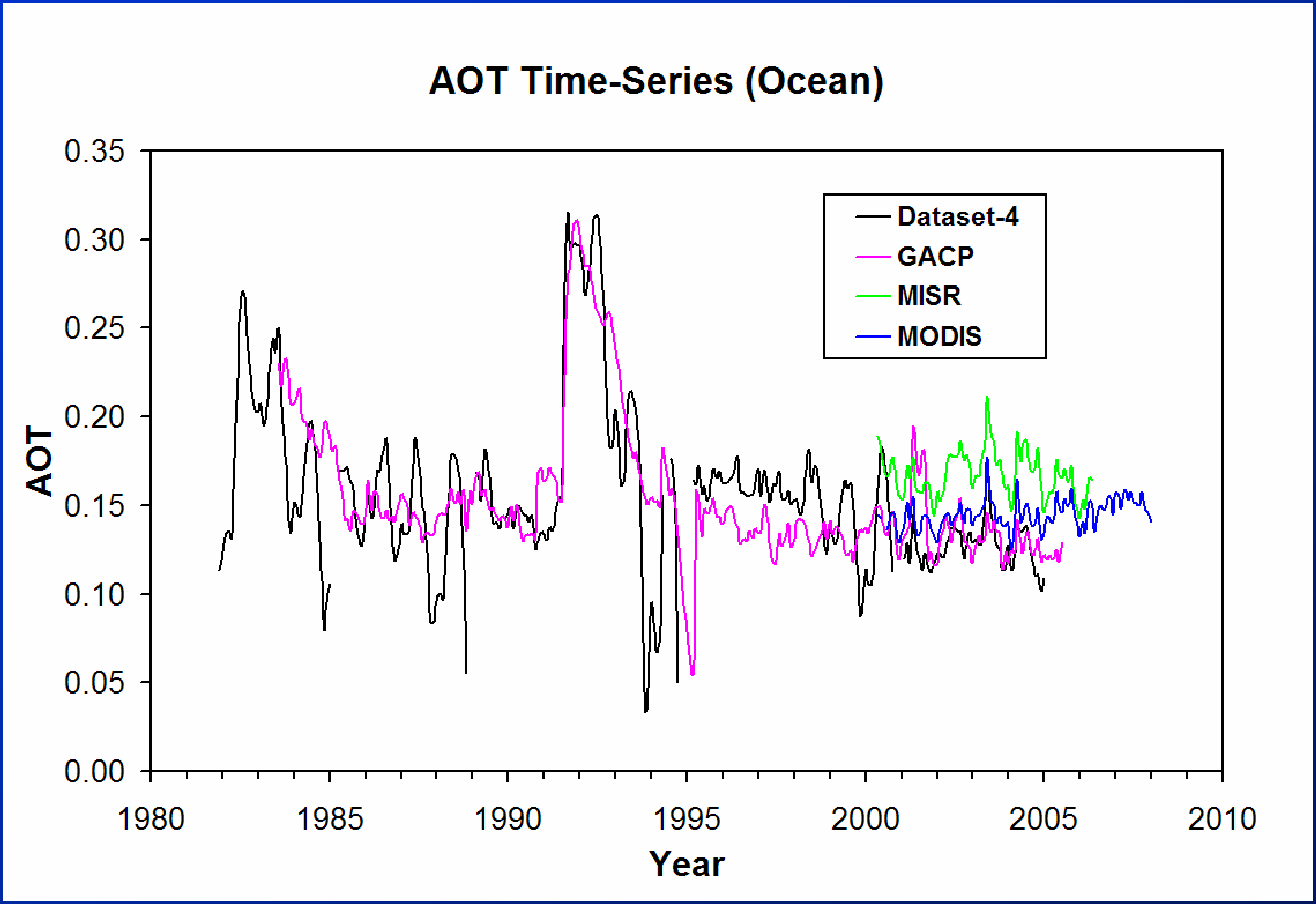
(reference Dataset-4)



North Hemisphere | South Hemisphere

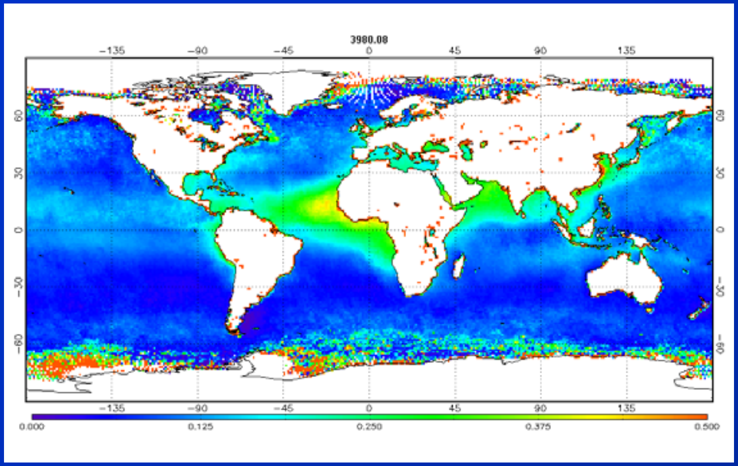


Comparison of AOT Time-Series

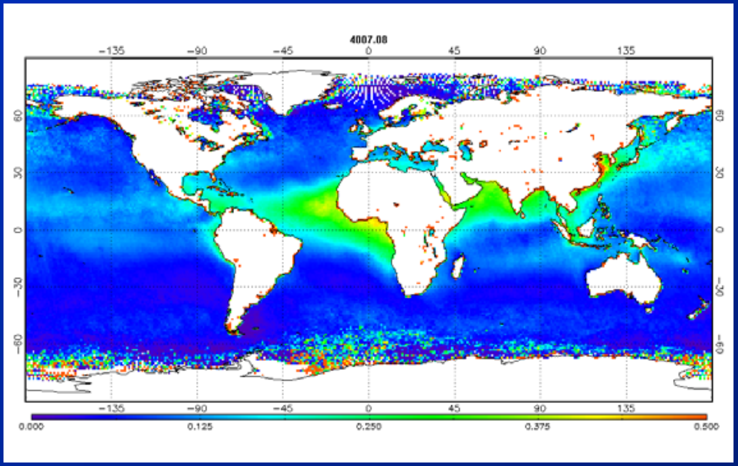


Average AOT for Two Quiescent Periods of Volcano

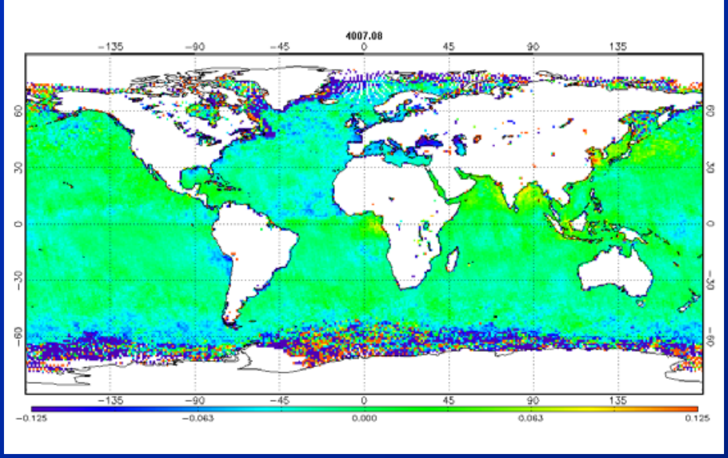
Period 1: Jul 1988-Jun 1991



Period 2: Jan 2002-Dec 2004



Period 2-1 Difference



In Period 2:

- Decrease of AOT over the North Atlantic
- Significant decrease over the Black Sea
- Increase over the South, South-East coast of Asia

Period 2-1 Difference (GACP)

Period 2-1 Difference (Dataset-4)

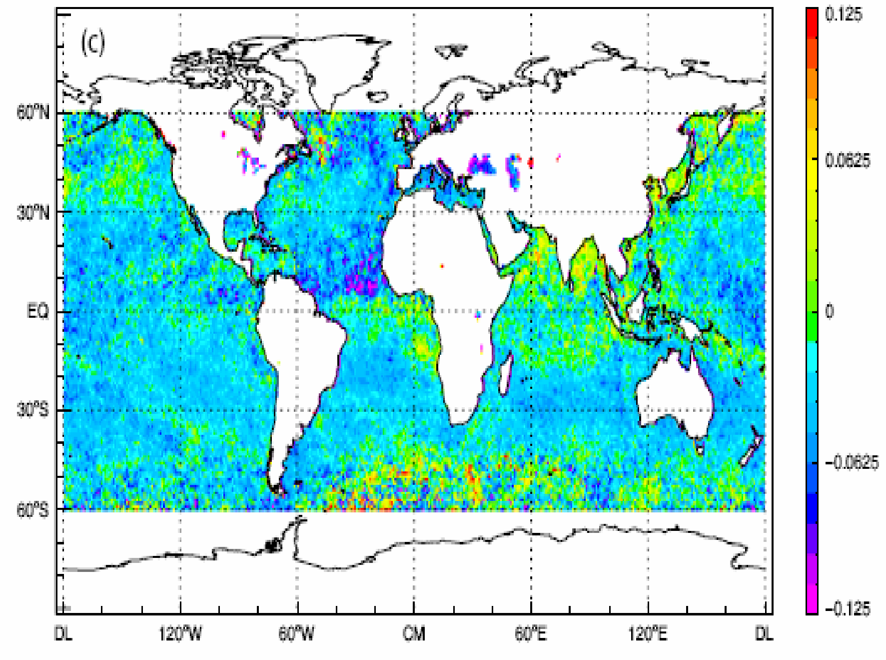
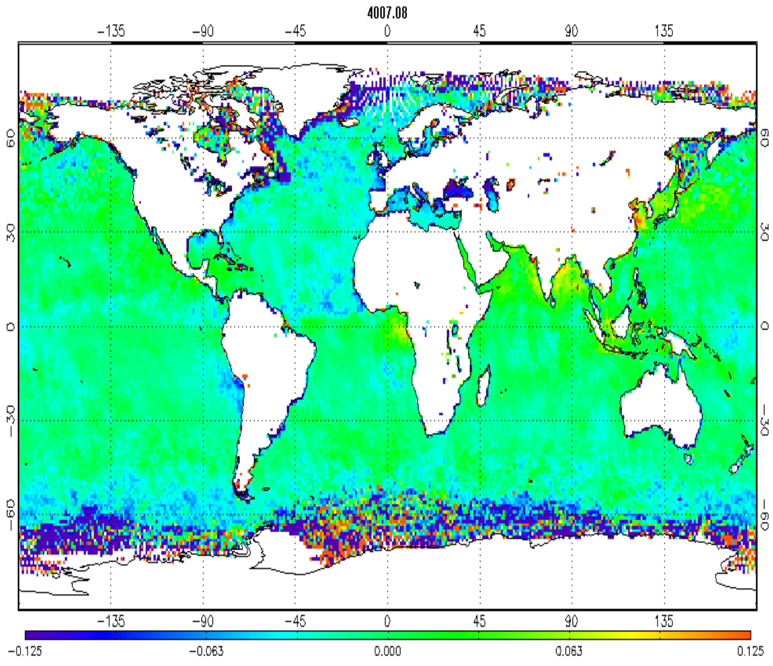
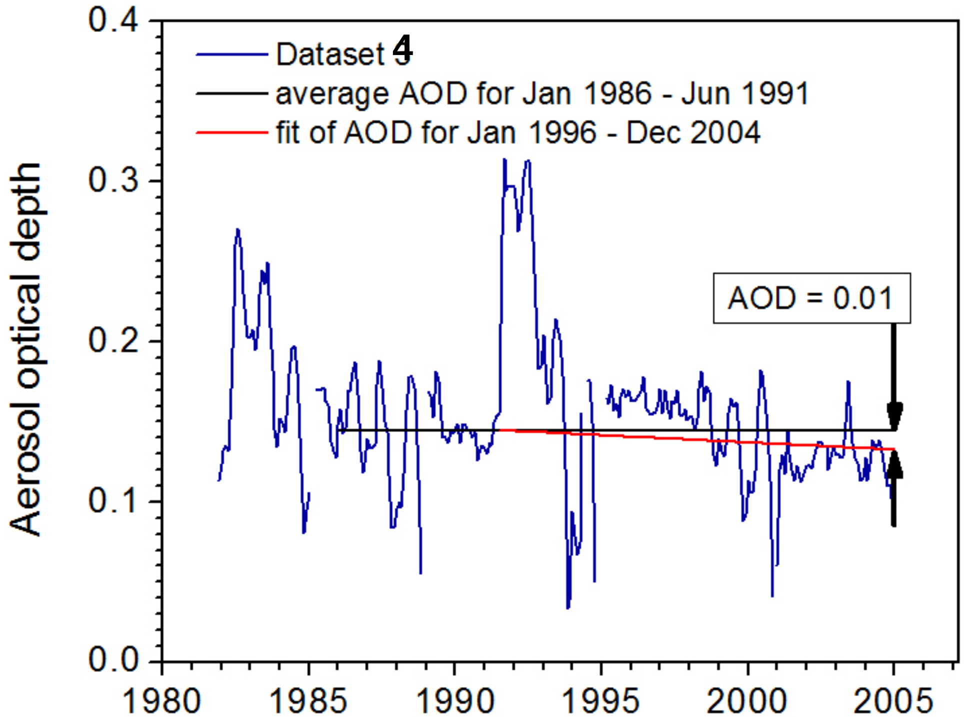
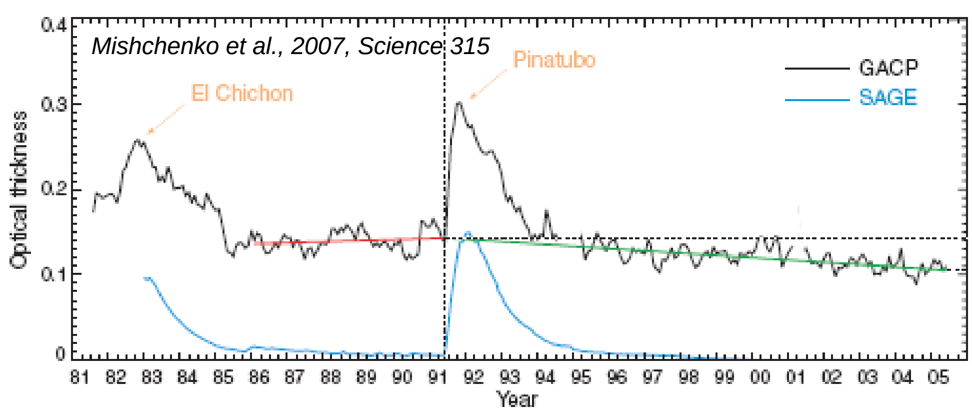


Fig. 2. (a) AOT averaged over the period July 1988 – June 1991. (b) AOT averaged over the period July 2002 – June 2005. (c) Difference between the AOT averages in panels (b) and (a).



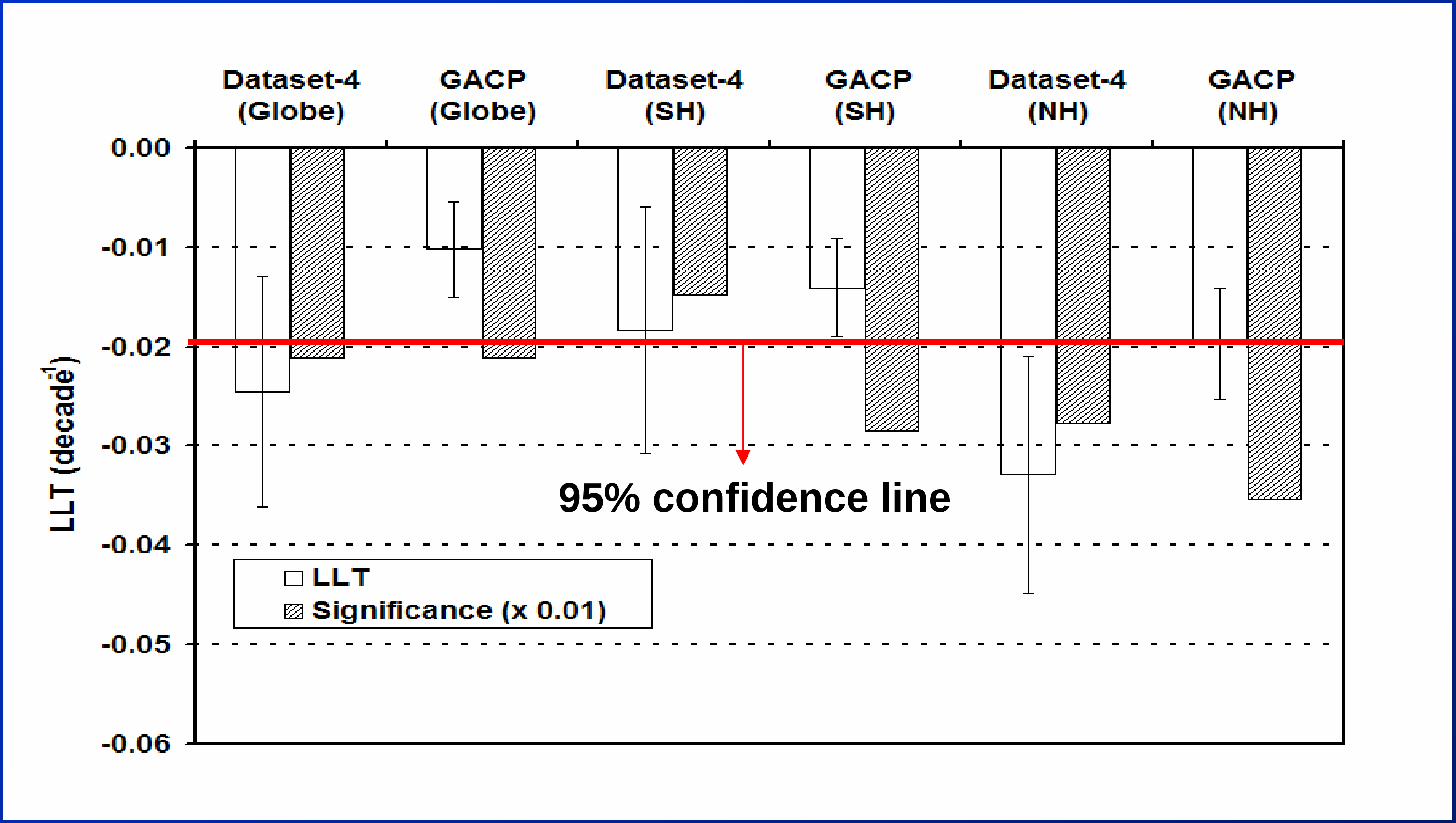
Analysis of two quiescent periods





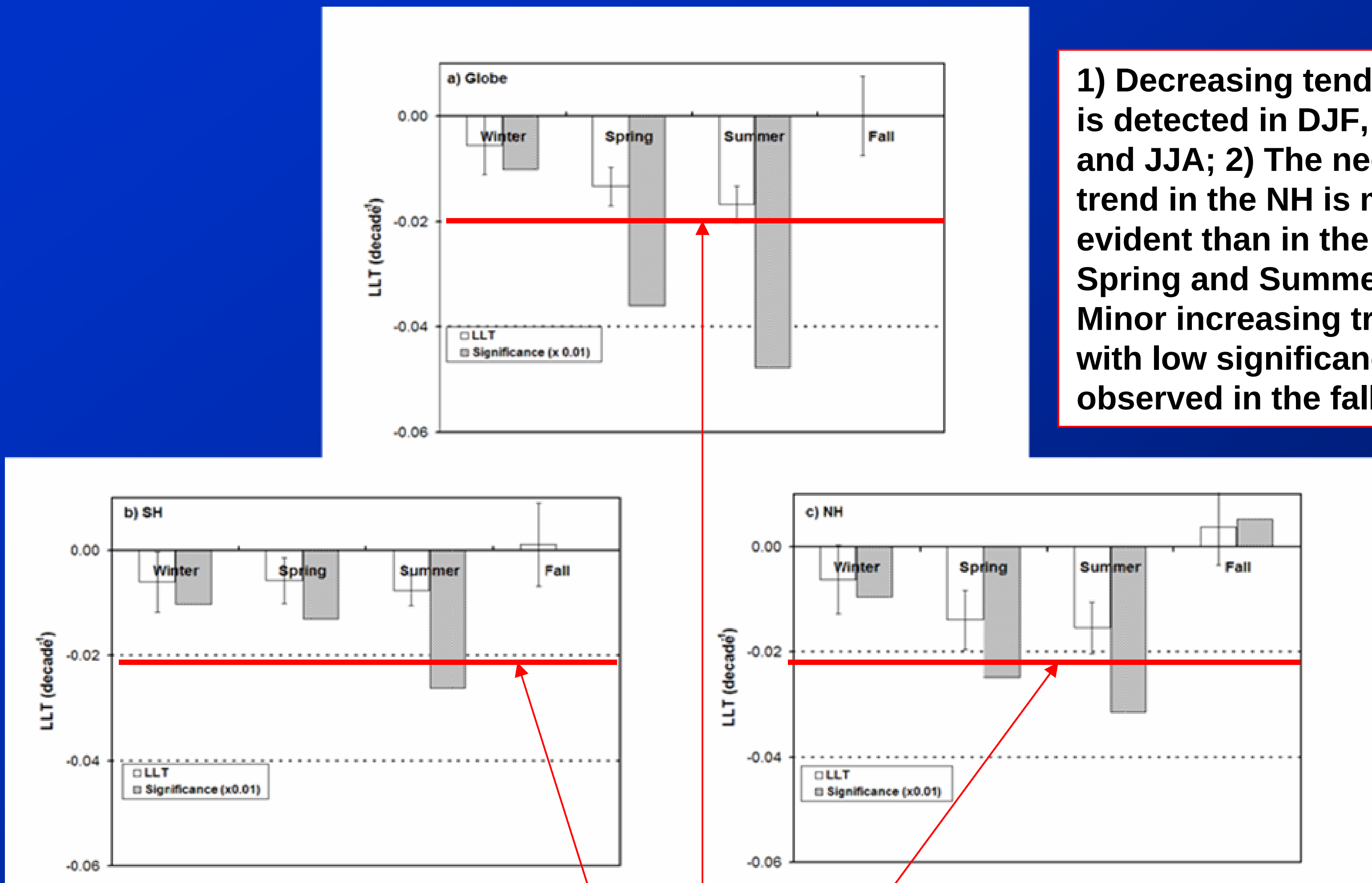
- Repeated the analysis of Mishchenko et al. (2007) for Dataset 4:
- Analyzed change for Jan 1986-Jun 1991 and Jun 1996 – Dec 2004.
- No significant change between Jan 1986-Jun 1991. Average AOD is **0.145** (black line).
- Linear fit (red line) predicts an AOD of **0.133** at the end of the period.
- **Change in AOD is 0.01** between Jun 1991 – Dec 2004. (three times smaller than obtained by Mishchenko et al., but significant!)

Comparison of LLT and the Corresponding Significance for the Annual Mean τ_1 between our Dataset-4 and the NASA/GACP Data



The above comparisons of two AVHRR AOT retrievals with independent calibration, cloud screening, and retrieval algorithm give a consistent negative sign of tendency in global averaged AOT but their magnitude is different.

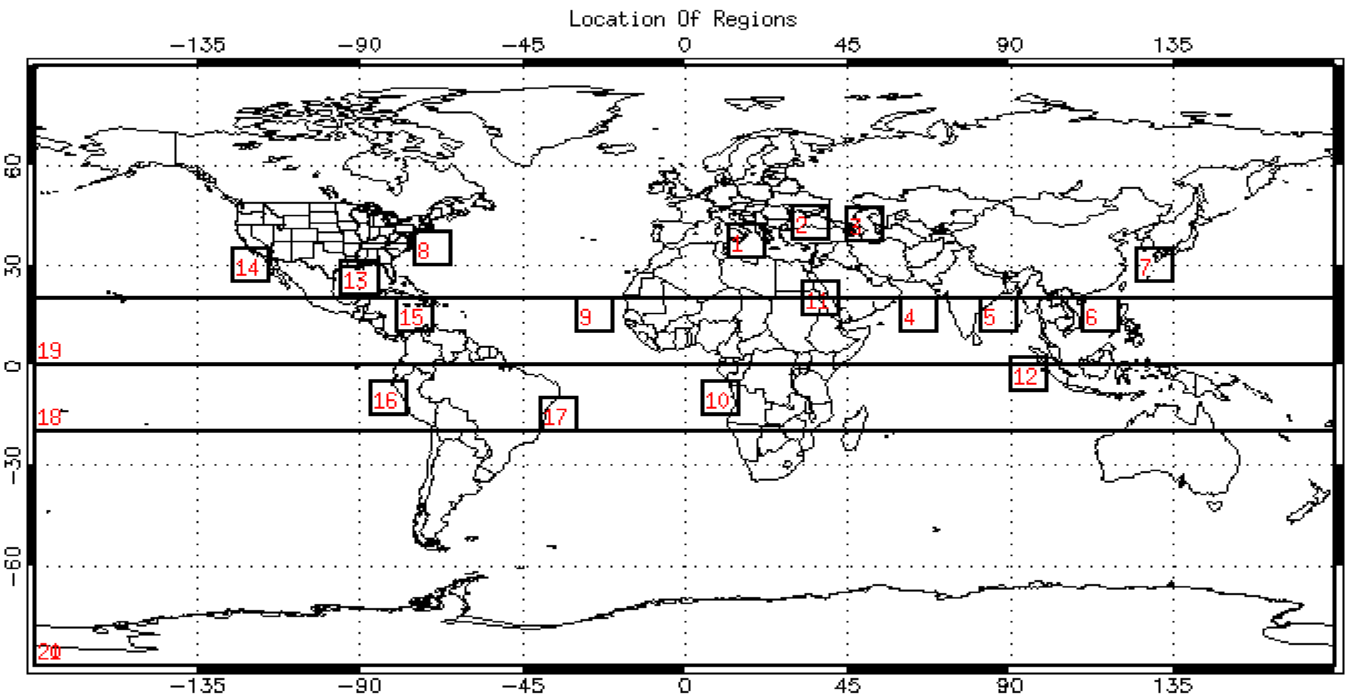
LLT and the Corresponding Significance of Seasonal Mean τ_1



95% confidence line

1) Decreasing tendency is detected in DJF, MAM, and JJA; 2) The negative trend in the NH is more evident than in the SH in Spring and Summer; 3) Minor increasing trend with low significance is observed in the fall season.

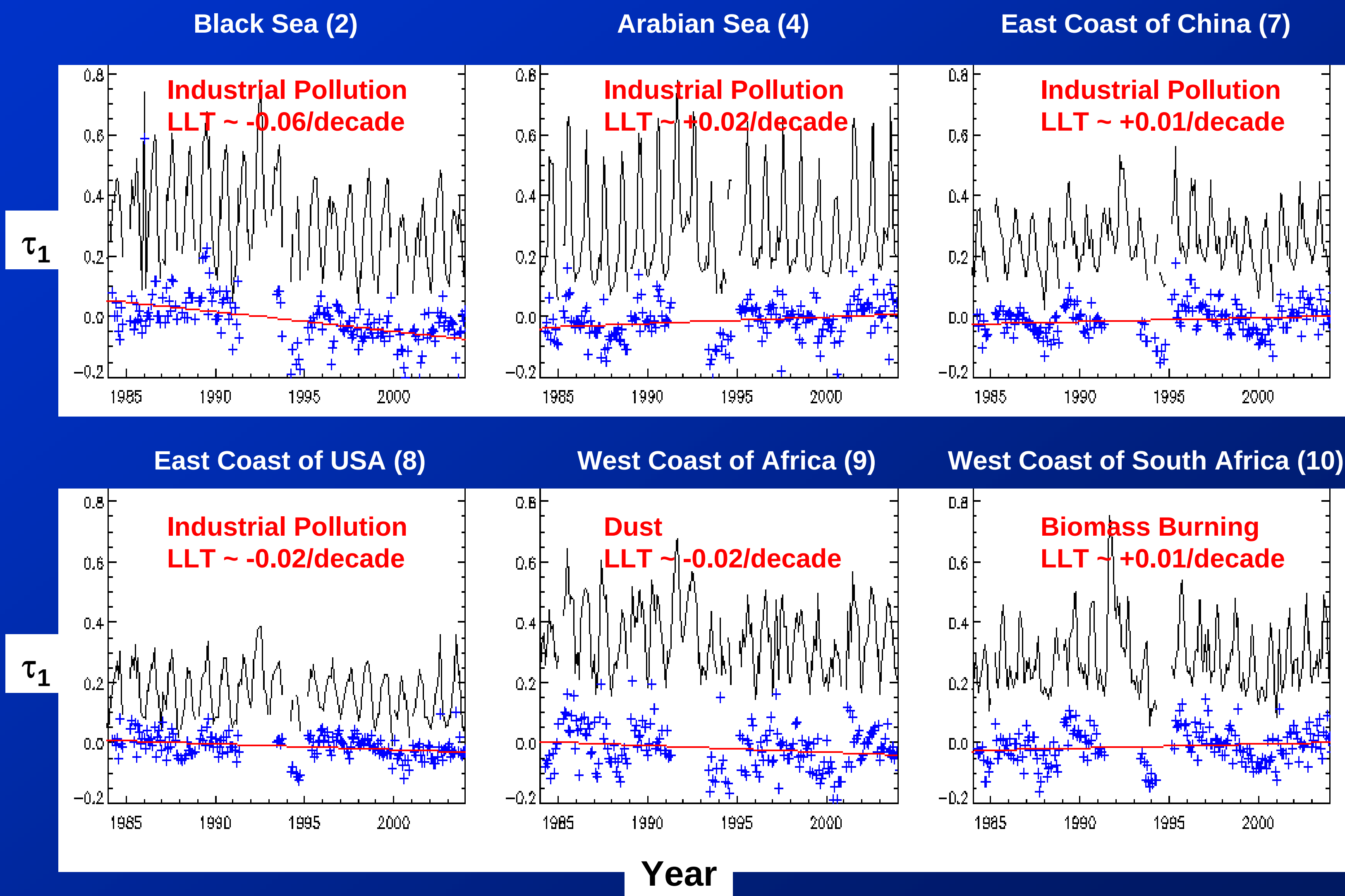
Locations Selected for the Study of Regional AOT Long-term Trend



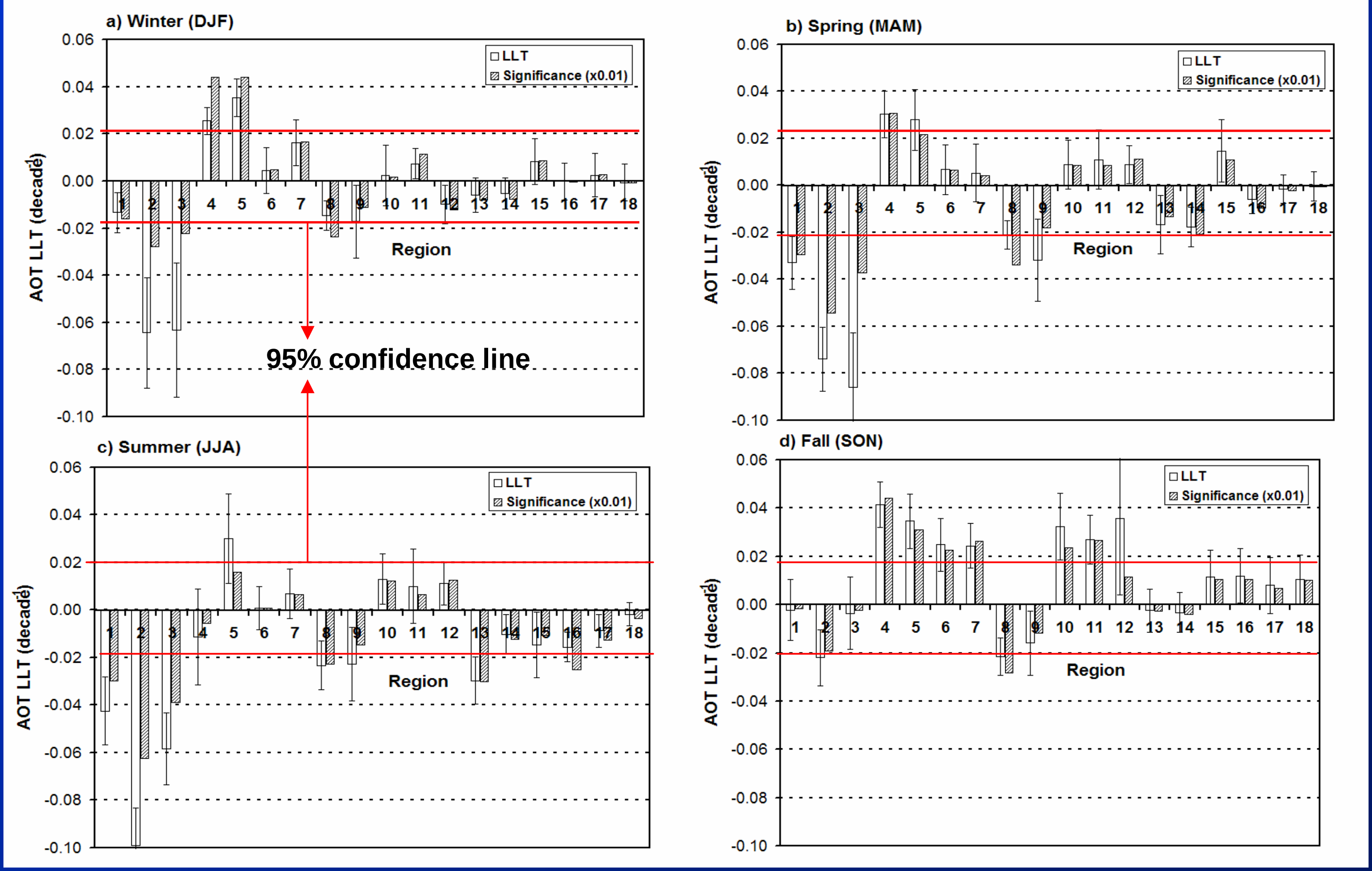
R1:	lon=[12.0, 22.0]	lat=[32.0, 42.0]	R2:	lon=[30.0, 40.0]	lat=[37.5, 47.5]
R3:	lon=[45.0, 55.0]	lat=[37.0, 47.0]	R4:	lon=[60.0, 70.0]	lat=[10.0, 20.0]
R5:	lon=[82.0, 92.0]	lat=[10.0, 20.0]	R6:	lon=[110.0, 120.0]	lat=[10.0, 20.0]
R7:	lon=[125.0, 135.0]	lat=[25.0, 35.0]	R8:	lon=[-75.0, -65.0]	lat=[30.0, 40.0]
R9:	lon=[-30.0, -20.0]	lat=[10.0, 20.0]	R10:	lon=[5.0, 15.0]	lat=[-15.0, -5.0]
R11:	lon=[32.5, 42.5]	lat=[15.0, 25.0]	R12:	lon=[90.0, 100.0]	lat=[-7.5, 2.5]
R13:	lon=[-95.0, -85.0]	lat=[21.0, 31.0]	R14:	lon=[-125.0, -115.0]	lat=[25.0, 35.0]
R15:	lon=[-80.0, -70.0]	lat=[10.0, 20.0]	R16:	lon=[-87.0, -77.0]	lat=[-15.0, -5.0]
R17:	lon=[-40.0, -30.0]	lat=[-20.0, -10.0]	R18:	lon=[-180.0, 180.0]	lat=[-20.0, 20.0]
R19:	lon=[-180.0, 180.0]	lat=[0.0, 90.0]	R20:	lon=[-180.0, 180.0]	lat=[-90.0, 0.0]
R21:	lon=[-180.0, 180.0]	lat=[-90.0, 90.0]			

Results of Regional Long-term Trend

Time Series of Monthly Mean τ_1 and the Corresponding LLT for Selected Regions



Regional LLT and the Corresponding Significance of Seasonal Mean τ_1



(see Zhao et al., JGR, in press, for detailed explanation)

Summary and Conclusions

- The application of a consistent calibration on the AVHRR radiances is important for the detection of global long-term trend in AOT. The MODIS based SNO calibration is useful for an accurate and consistent calibration of AVHRR observation and beneficial for aerosol trend detection.

- The effect of aerosol algorithm (such as aerosol model assumption) on AOT long-term trend is more evident in regional scale. More representative aerosol model should be used in the aerosol retrieval algorithm.

- A decreasing trend (-0.01/decade) is obtained for the globally and monthly averaged τ_1.

- The regional long-term trend of monthly mean τ_1 is more variable but is consistent with the tendency of emissions.
  - A negative trend (-0.10/decade) is observed over the regions influenced by industrial pollutions from the developed countries.
  - A negative trend (-0.03/decade) is observed over the regions influenced by Saharan dust particles.
  - A positive trend (up to +0.04/decade) is observed over the regions influenced by industrial pollutions from fast developing countries or biomass burning pollutions.

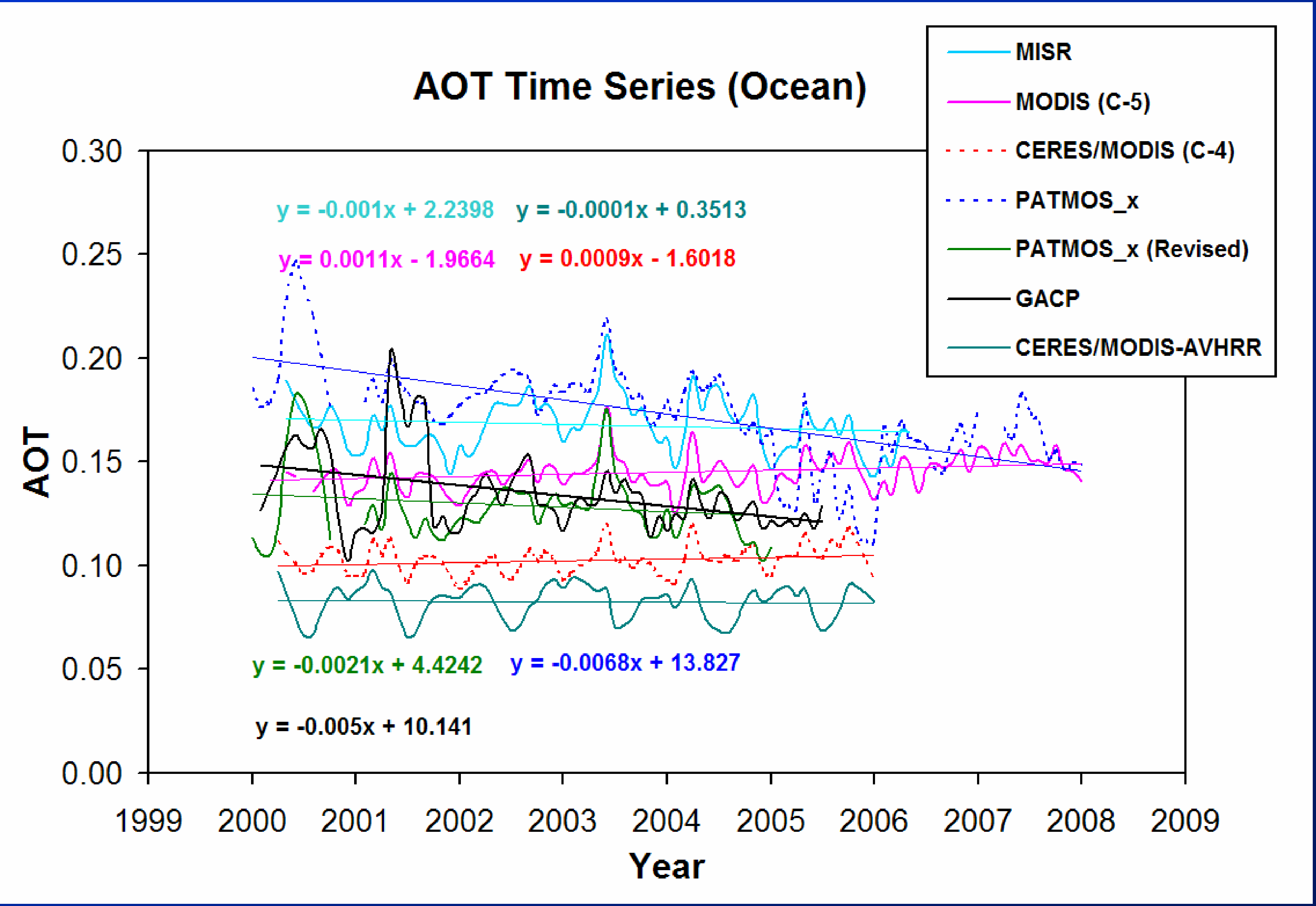
Important Issues and Discussions

1) There are differences in AOD tendency from different satellite sensors, especially the difference in the sign of tendency.
   - Causes?
   - Solution?

2) Given the accuracy of current satellite aerosol observations, what is the length of observations needed for a reliable AOT trend detection? Or how can we produce a AOT dataset with sufficient length for trend detection?

3) Is the linear model the best way to evaluate AOT trend?

Example of Difference in AOT Tendency?



- ✓ Cause?
  - Calibration?
  - Aerosol model assumption?
  - Sampling?
  - Cloud screening?
    - residual clouds
    - misclassify heavy smoke as cloud
    - misclassify heavy dust as cloud

- ✓ Solution?
  - Inter-satellite comparison of cloud screening using CALIPSO
    - study misclassification
  - Sensitivity studies based on reprocessing
    - study effect of residual clouds on trend

What is the Length of Data Record Needed for A Reliable AOT Trend Detection?
(How Can We Produce a AOT Dataset with a Sufficient Length for Trend Detection?)

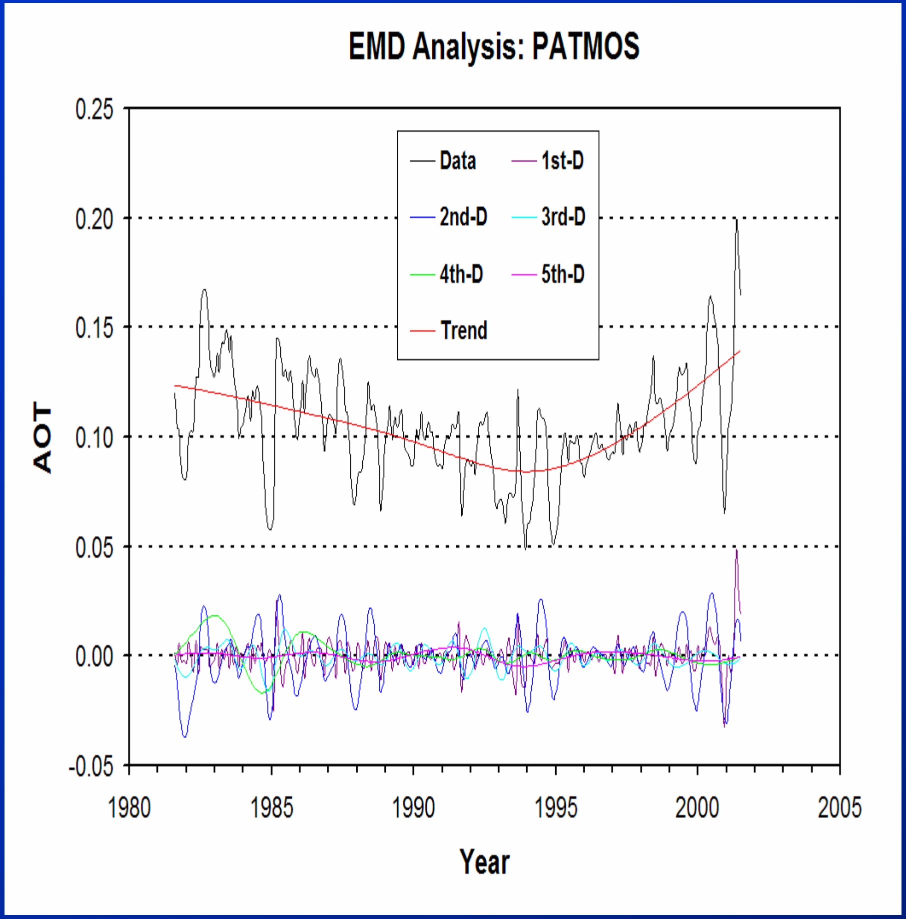
- Statistical Analysis (e.g., Weatherhead et al., JGR, 1998)
  - 30 – 50 years?

- Data Synthesis
  - Inter-satellite calibration (e.g., SNO)
  - Inter-satellite comparison in the context of trend
    - examine cloud contamination, cloud misclassification.
  - Algorithm validation in the context of trend
    - examine the contamination elements: cloud, surface.

Is the linear model the best way to evaluate AOT trend? (or Do we need more advanced trend analysis tool?)

Example

(EMD; Huang et al., 1998, 1999)



- Advantage
  - determine real trend
  - not strongly dependent on the length of data record
  - in-depth examining the variability of data records.

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