Identifying the Climate Signals of Late 20th and Early 21st Century Volcanic Eruptions

Ben Santer*, Susan Solomon, David Ridley, John Fyfe, Jean-Francois Lamarque, Ryan Neely, Mark Zelinka, Mike Mills, and Celine Bonfils

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AGU Chapman Conference, Puerto de la Cruz, Tenerife, March 23rd, 2018

Structure

- Introduction
- Statistical issues
- Previous volcanic signal detection results
- New results
- Conclusions

My starting point

The Persistently Variable "Background" Stratospheric Aerosol Layer and Global Climate Change

S. Solomon,[1,2*] J. S. Daniel,[1] R. R. Neely III,[1,2,5,6] J.-P. Vernier,[3,4] E. G. Dutton,[5] L. W. Thomason[3]

Recent measurements demonstrate that the "background" stratospheric aerosol layer is persistently variable rather than constant, even in the absence of major volcanic eruptions. Several independent data sets show that stratospheric aerosols have increased in abundance since 2000. Near-global satellite aerosol data imply a negative radiative forcing due to stratospheric aerosol changes over this period of about –0.1 watt per square meter, reducing the recent global warming that would otherwise have occurred. Observations from earlier periods are limited but suggest an additional negative radiative forcing of about –0.1 watt per square meter from 1960 to 1990. Climate model projections neglecting these changes would continue to overestimate the radiative forcing and global warming in coming decades if these aerosols remain present at current values or increase.

12 AUGUST 2011 VOL 333 **SCIENCE** www.sciencemag.org

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Statistical issues

1. Removal of ENSO variability from climate variables

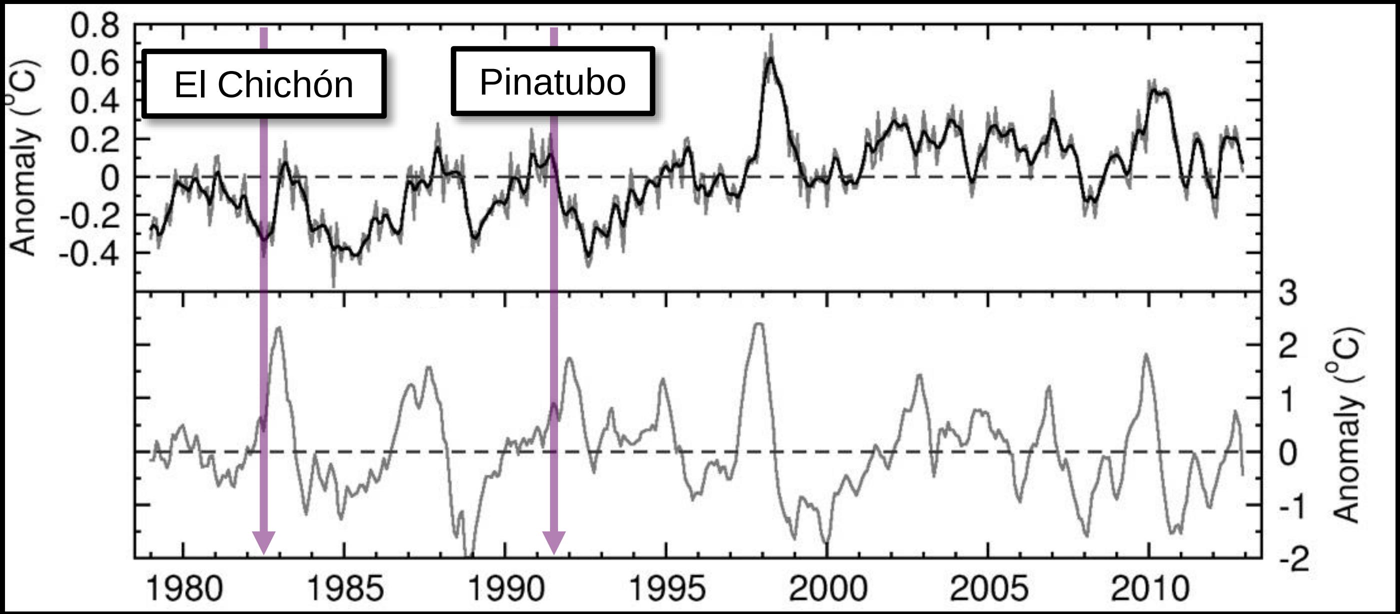
2. Dealing with volcanic forcing/climate relationships in volcanically active and volcanically quiescent periods (nonstationarity)

3. Interaction between volcanic eruptions and modes of internal variability

4. Assessing the statistical significance of relationships between volcanic forcing and climate

Issue 1: Removal of ENSO variability from climate variables

- Predictor variables used to estimate the ENSO and volcano temperature signals are correlated

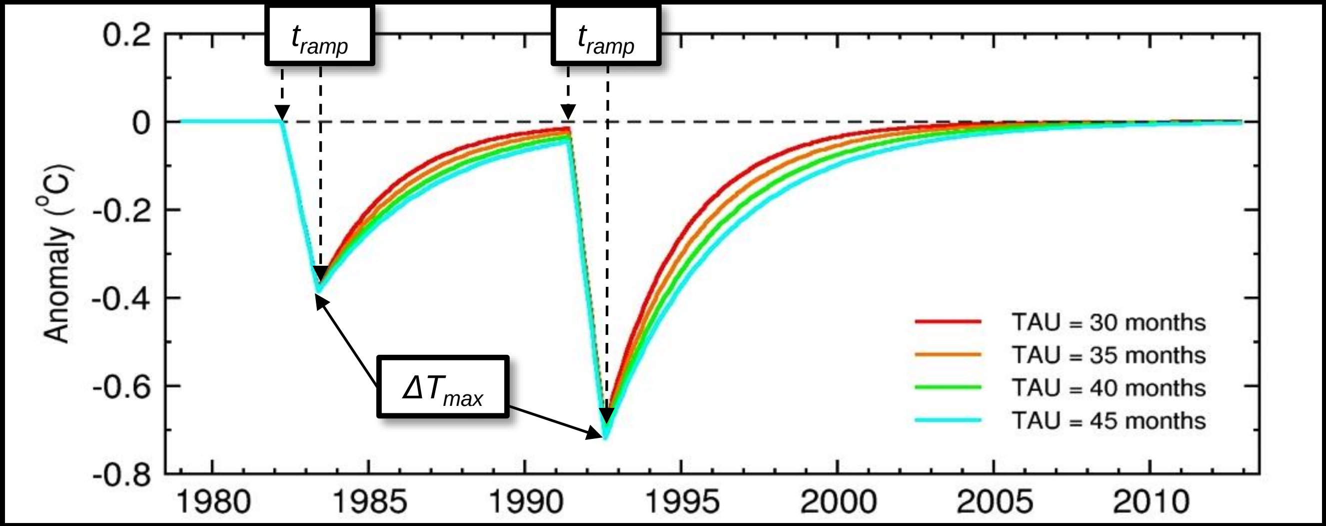


Lower tropospheric temperature (RSS)

Niño 3.4 SSTs (NOAA)

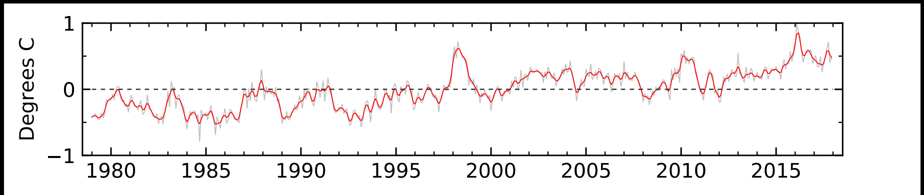
How do we estimate volcano signals in our iterative method?

- We use three parameters to characterize the tropospheric temperature response to volcanic forcing:
  - ΔT_{max} The maximum volcanically-induced cooling
  - t_{ramp} The time (in months) from the start of the eruption to ΔT_{max}
  - TAU Exponential decay time (in months) for the volcanic cooling signal
- ΔT_{max} and t_{ramp} are estimated directly from tropospheric temperature data



Removing ENSO and volcano signals from tropospheric temperature: An example

Tropospheric temperature (RSS)



Niño 3.4 SSTs (HadCRUT)

ENSO signal

Raw data minus ENSO signal

Estimated volcano signal

Residuals (raw data minus ENSO and volcano signals)

Subtract volcano signal from raw data; re-estimate ENSO signal; then iterate

Santer et al., JGR (2001)

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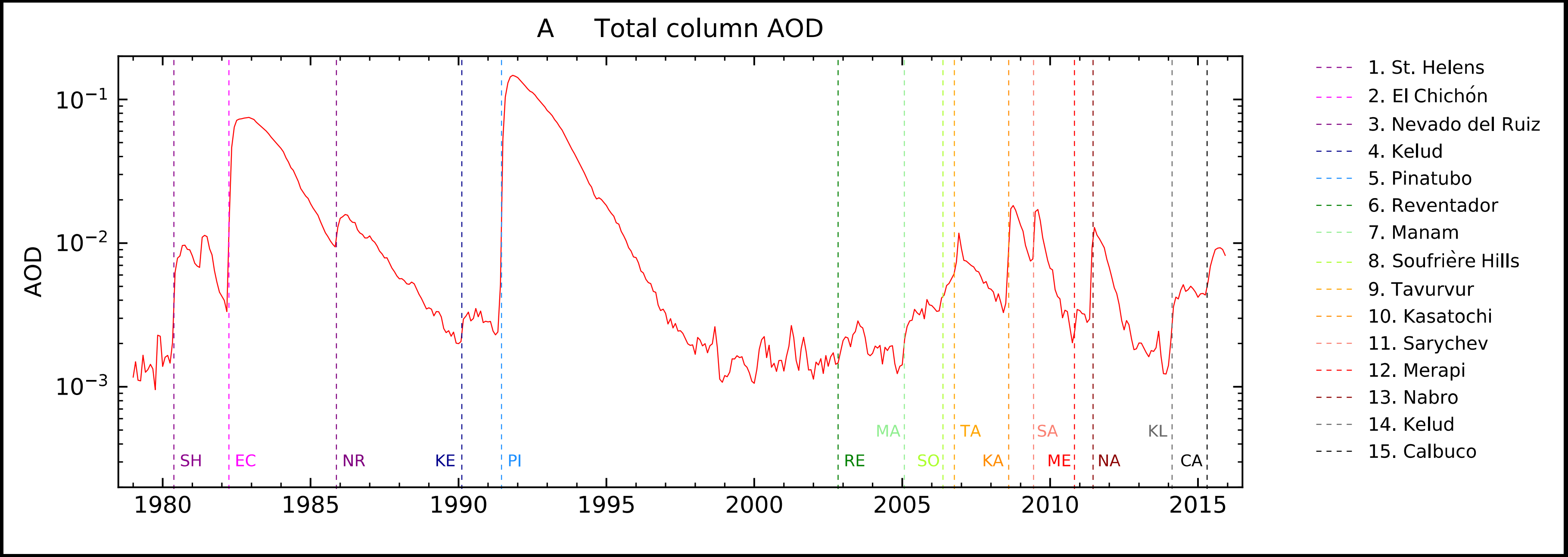
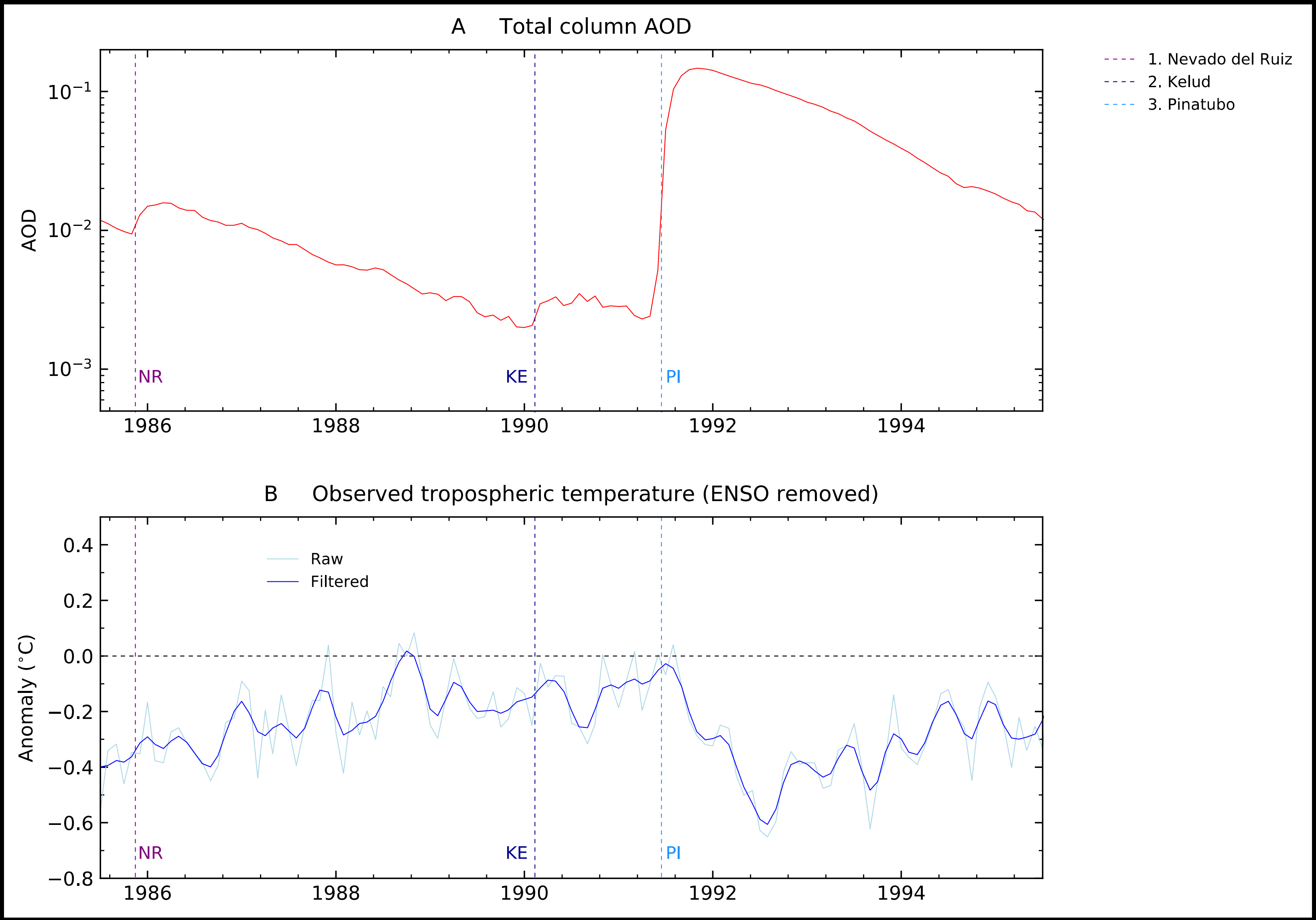
Issue 2: Dealing with changes over time in volcanic activity

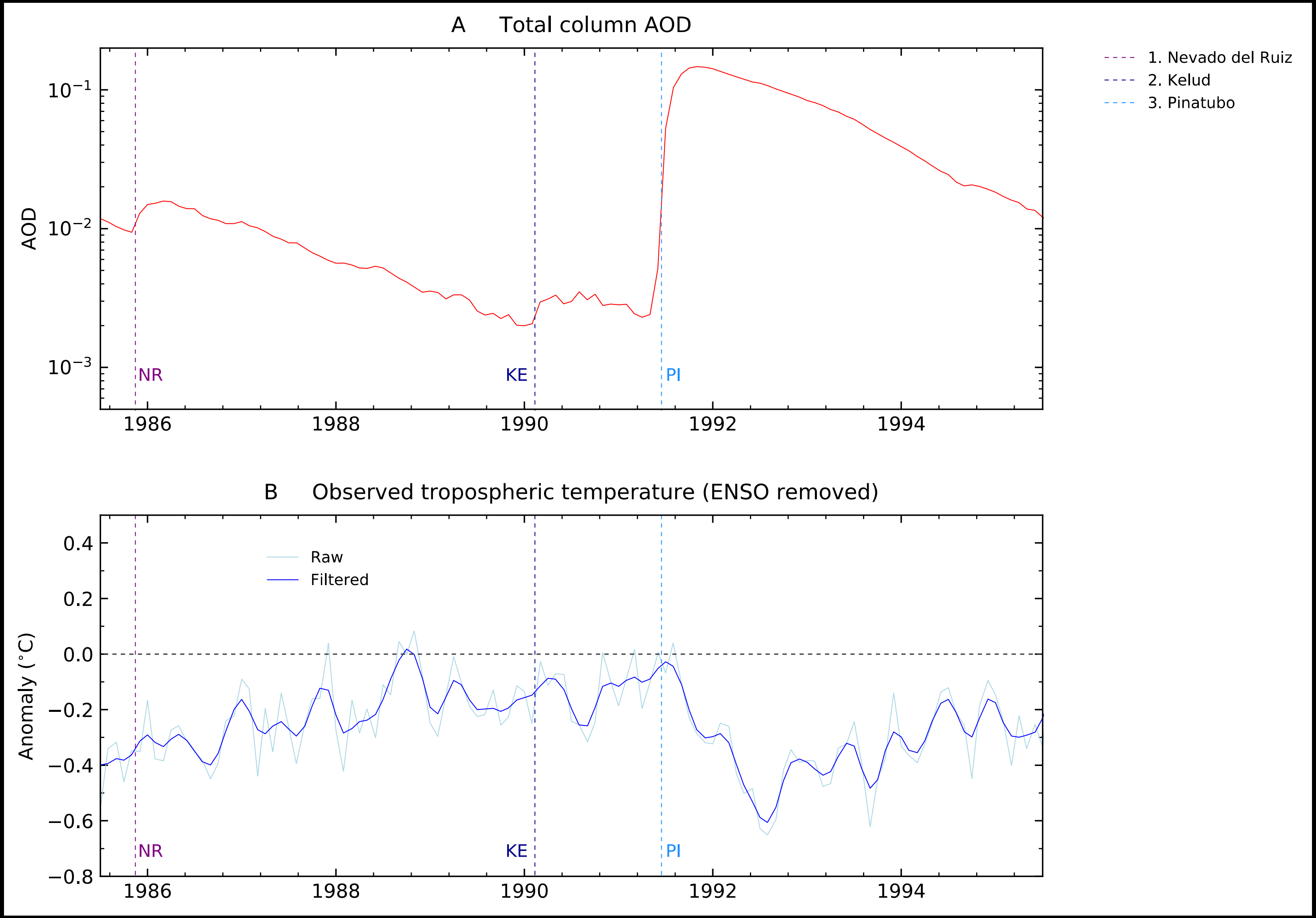


Mills et al., JGR (2016)

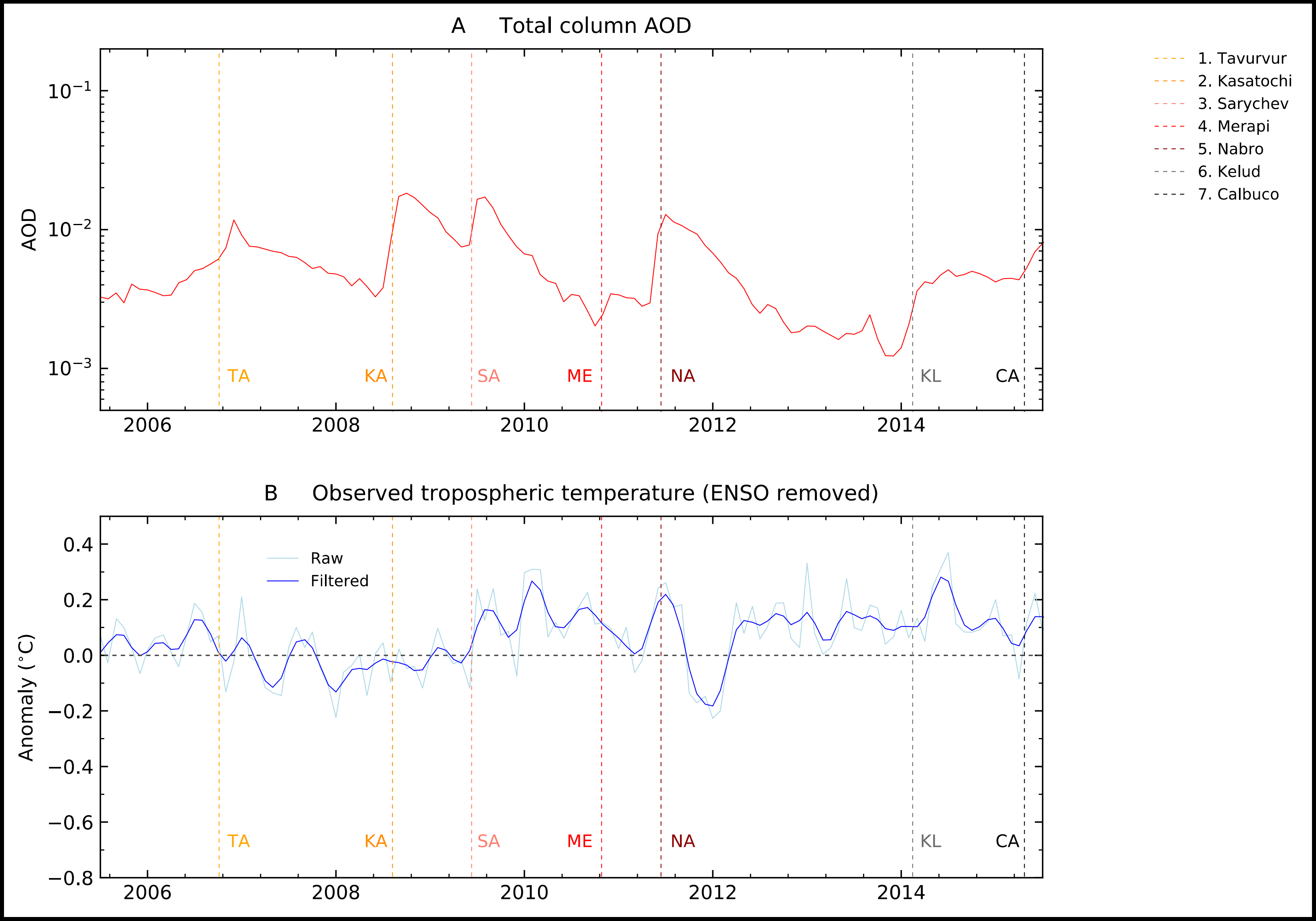
Explaining the “moving window” correlation analysis



Explaining the “moving window” correlation analysis



Explaining the “moving window” correlation analysis



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Issue 4: Assessing the statistical significance of volcanic climate signals

1. Calculate r_i\{SAOD,X\}, the correlation between the i^{th} 60-month segment of observed SAOD and X (observed climate data)

2. Use an AR-1 statistical model to generate k different realizations of synthetic observational climate time series, $X_k(t)^*$ (k = 1, 2, … 10,000)

3. Calculate $r_{i,k}$\{SAOD,X*\}, the correlation between observed SAOD and $X_k(t)^*$. Repeat for each 60-month window and each $X_k(t)^*$ realization.

4. Compare the actual correlation, r_i\{SAOD,X\}, with the null distribution of $r_{i,k}$\{SAOD,X*\} values

5. Determine the probability that the actual correlation between aerosol optical depth and the climate variable of interest could be due to chance.

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nature geoscience

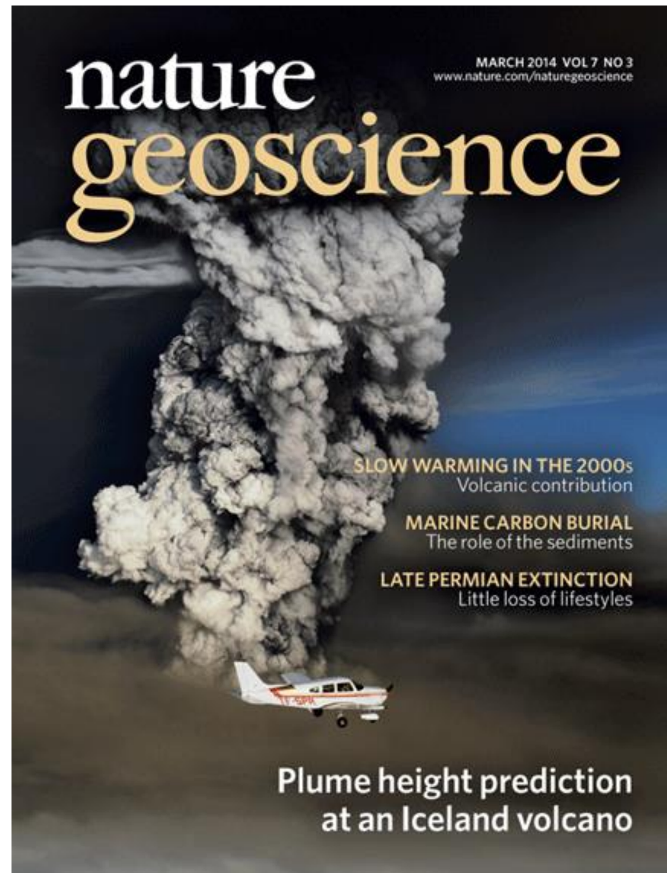
LETTERS

PUBLISHED ONLINE: 23 FEBRUARY 2014 | DOI: 10.1038/NGEO2098

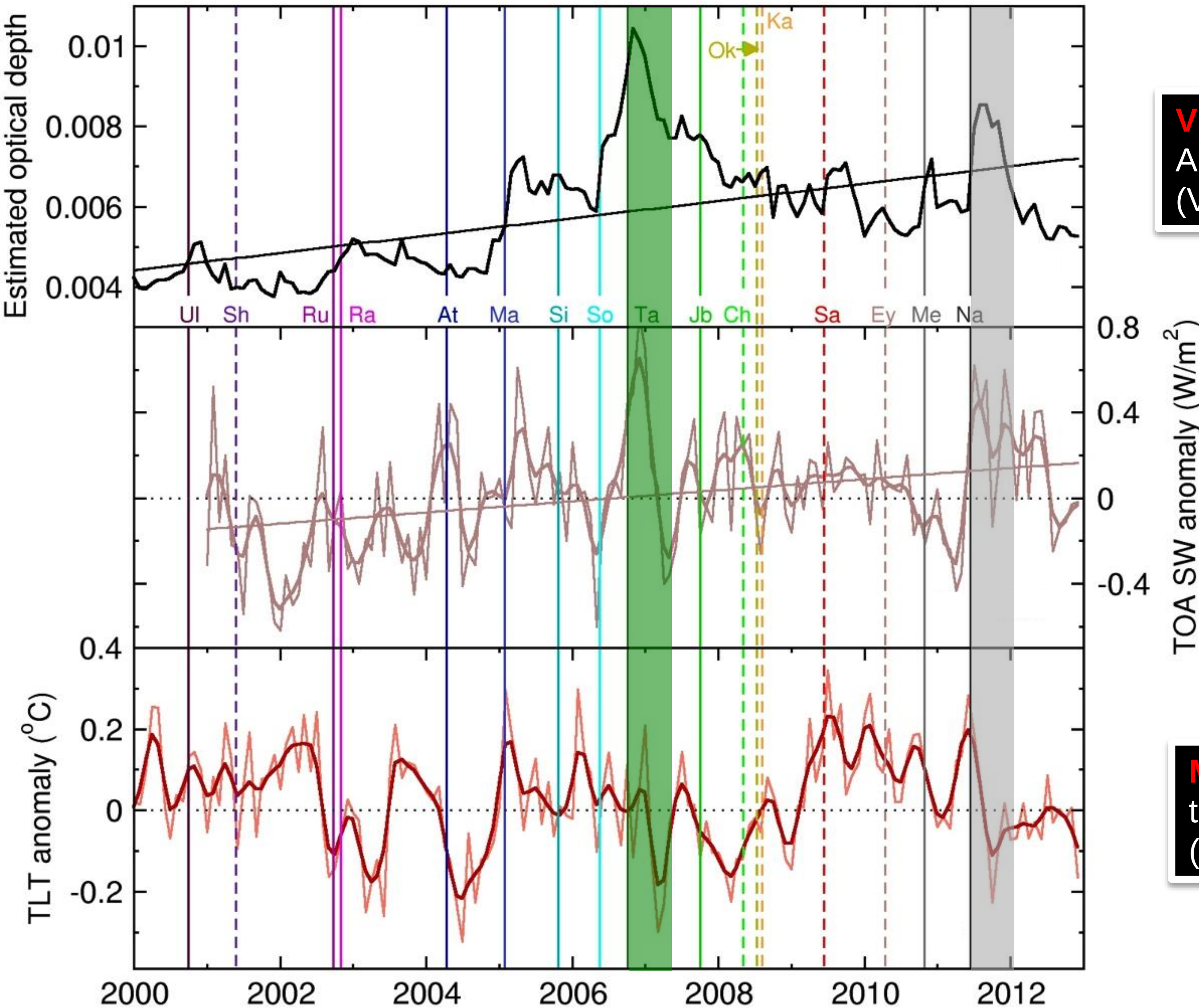
Volcanic contribution to decadal changes in tropospheric temperature

Benjamin D. Santer[1*], Céline Bonfils[1], Jeffrey F. Painter[1], Mark D. Zelinka[1], Carl Mears[2], Susan Solomon[3], Gavin A. Schmidt[4], John C. Fyfe[5], Jason N. S. Cole[5], Larissa Nazarenko[4], Karl E. Taylor[1] and Frank J. Wentz[2]

Despite continued growth in atmospheric levels of greenhouse gases, global mean surface and tropospheric temperatures have shown slower warming since 1998 than previously[1–5]. Possible explanations for the slow-down include internal climate variability[3,4,6,7], external cooling influences[1,2,4,8–11] and observational errors[12,13]. Several recent modelling studies have examined the contribution of early twenty-first-century volcanic eruptions[1,2,4,8] to the muted surface warming. Here we present a detailed analysis of the impact of recent volcanic forcing on tropospheric temperature, based on observations as well as climate model simulations. We identify statistically significant correlations between observations of stratospheric aerosol optical depth and satellite-based estimates of both tropospheric temperature and short-wave fluxes at the top of the atmosphere. We show that climate model simulations without the effects of early twenty-first-century volcanic eruptions overestimate the tropospheric warming observed since 1998. In two simulations with more realistic volcanic influences following the 1991 Pinatubo eruption, differences between simulated and observed tropospheric temperature trends over the period 1998 to 2012 are up to 15% smaller, with large uncertainties in the magnitude of the effect. To reduce these uncertainties, better observations of eruption-specific properties of volcanic aerosols are needed, as well as improved representation of these eruption-specific properties in climate model simulations.



Early 21st century volcanic eruptions have signatures across the electromagnetic spectrum



VISIBLE: Stratospheric Aerosol Optical Depth (Vernier *et al*., 2011)

SHORT-WAVE: CERES net clear-sky SW radiation

MICROWAVE: MSU lower tropospheric temperature (with ENSO removed)

Follow-up paper (Santer et al., 2015): Volcanic signals are also detectable in the hydrological cycle

Observed multivariable signals of late 20th and early 21st century volcanic activity

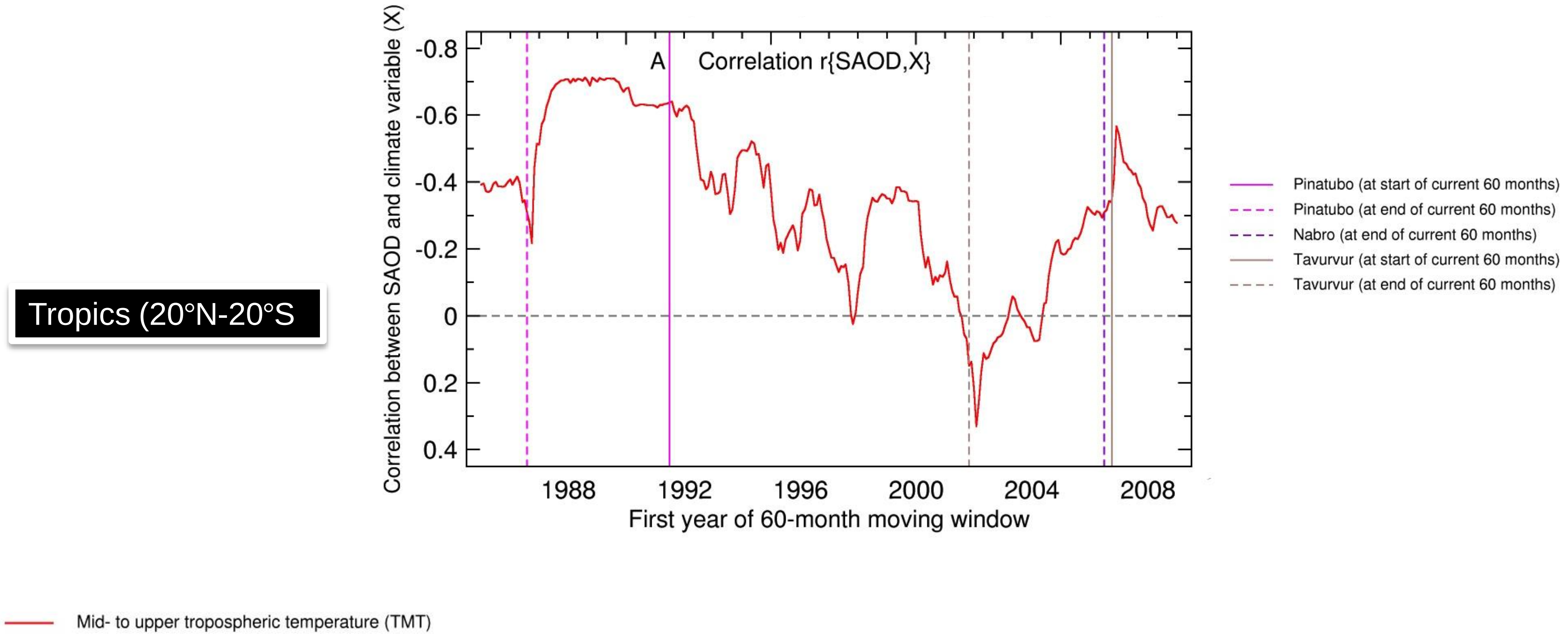
Benjamin D. Santer[1], Susan Solomon[2], Céline Bonfils[1], Mark D. Zelinka[1], Jeffrey F. Painter[1], Francisco Beltran[1], John C. Fyfe[3], Gardar Johannesson[1], Carl Mears[4], David A. Ridley[2], Jean-Paul Vernier[5], and Frank J. Wentz[4]

[1]Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, Livermore, California, USA, [2]Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, [3]Canadian Centre for Climate Modelling and Analysis, Environment Canada, Victoria, British Columbia, Canada, [4]Remote Sensing Systems, Santa Rosa, California, USA, [5]NASA Langley Research Center, Hampton, Virginia, USA

Abstract The relatively muted warming of the surface and lower troposphere since 1998 has attracted considerable attention. One contributory factor to this "warming hiatus" is an increase in volcanically induced cooling over the early 21st century. Here we identify the signals of late 20th and early 21st century volcanic activity in multiple observed climate variables. Volcanic signals are statistically discernible in spatial averages of tropical and near-global SST, tropospheric temperature, net clear-sky short-wave radiation, and atmospheric water vapor. Signals of late 20th and early 21st century volcanic eruptions are also detectable in near-global averages of rainfall. In tropical average rainfall, however, only a Pinatubo-caused drying signal is identifiable. Successful volcanic signal detection is critically dependent on removal of variability induced by the El Niño–Southern Oscillation.

Do volcanic climate eruptions produce significant climate signals?

Tropics (20°N-20°S



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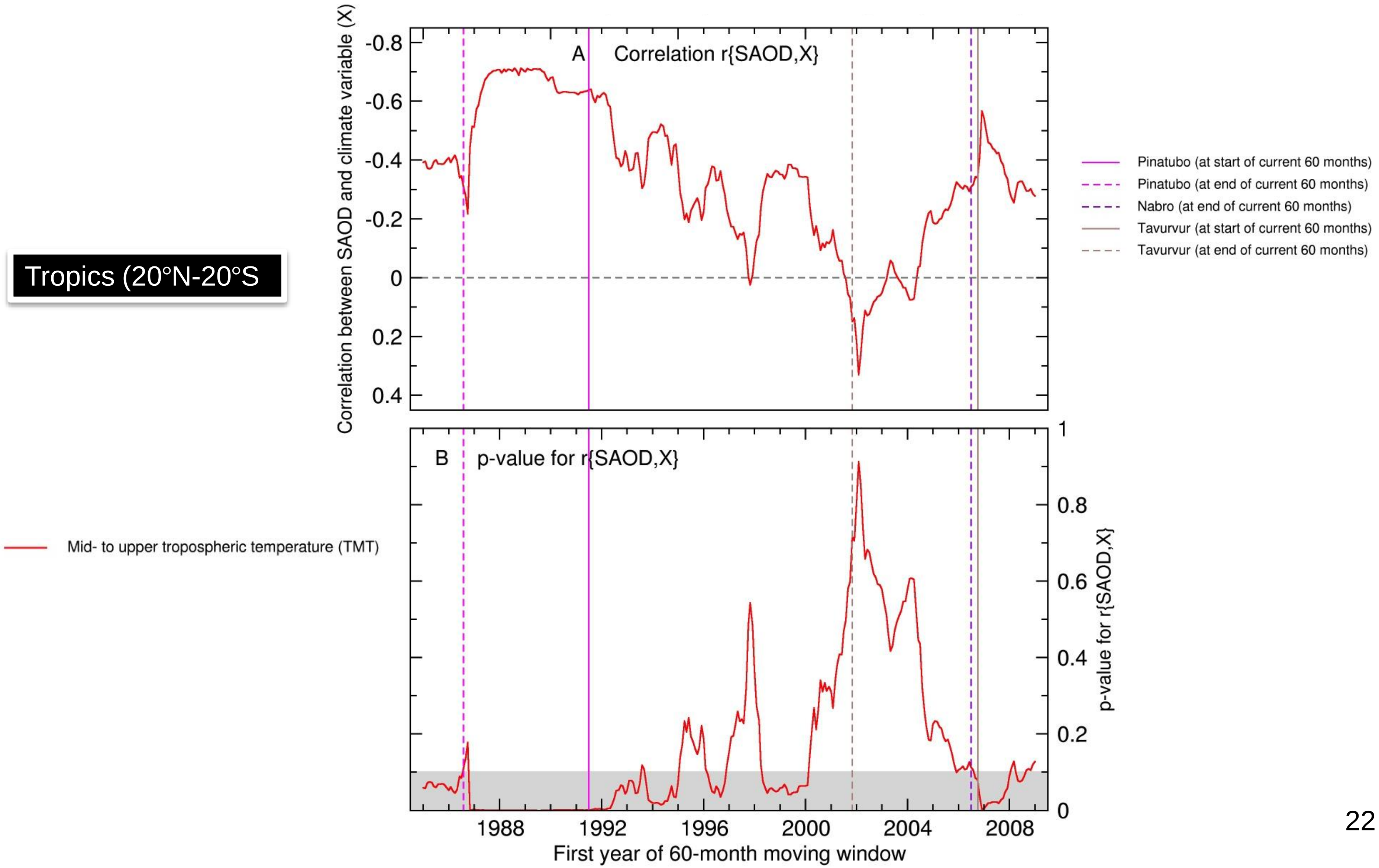

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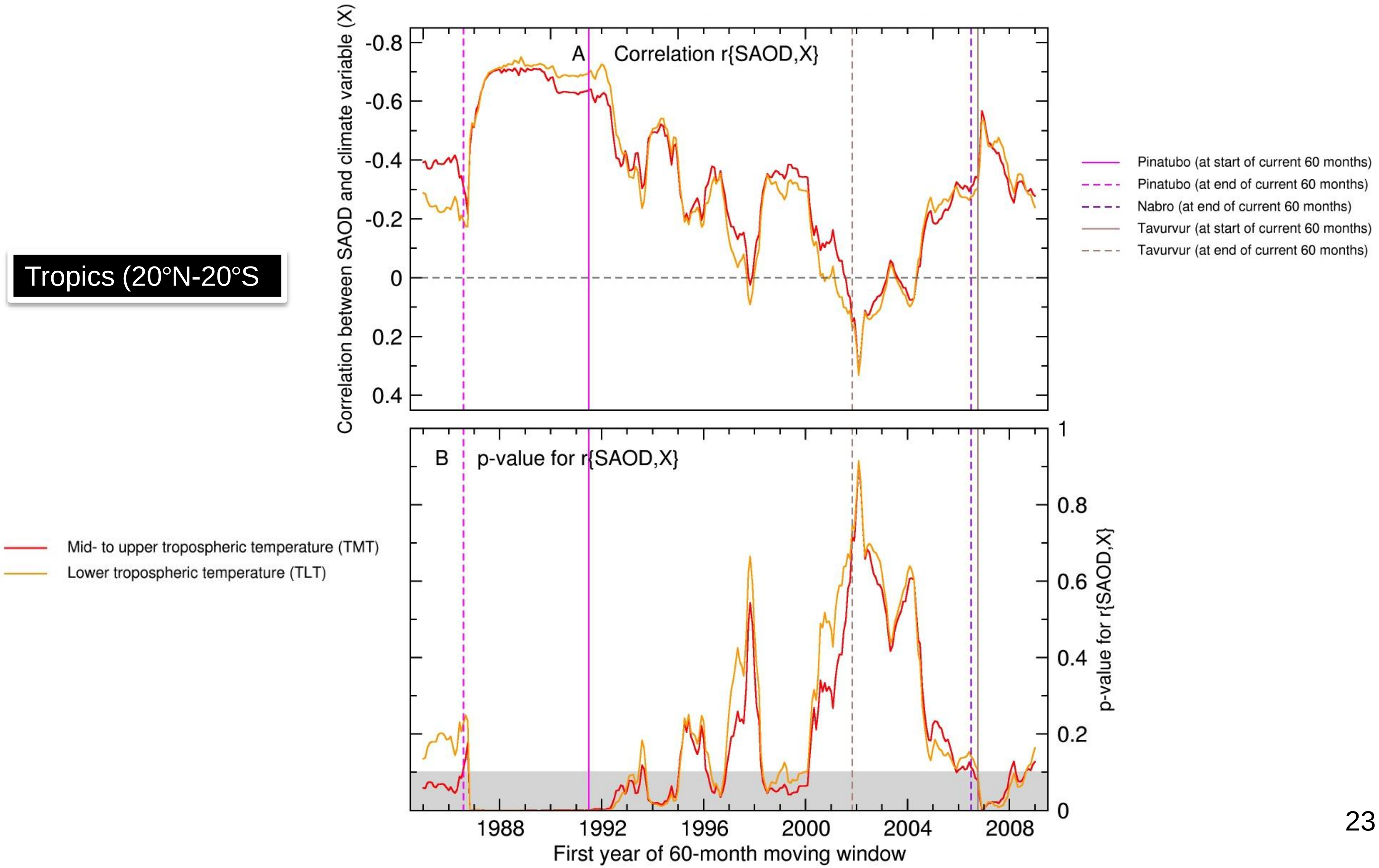

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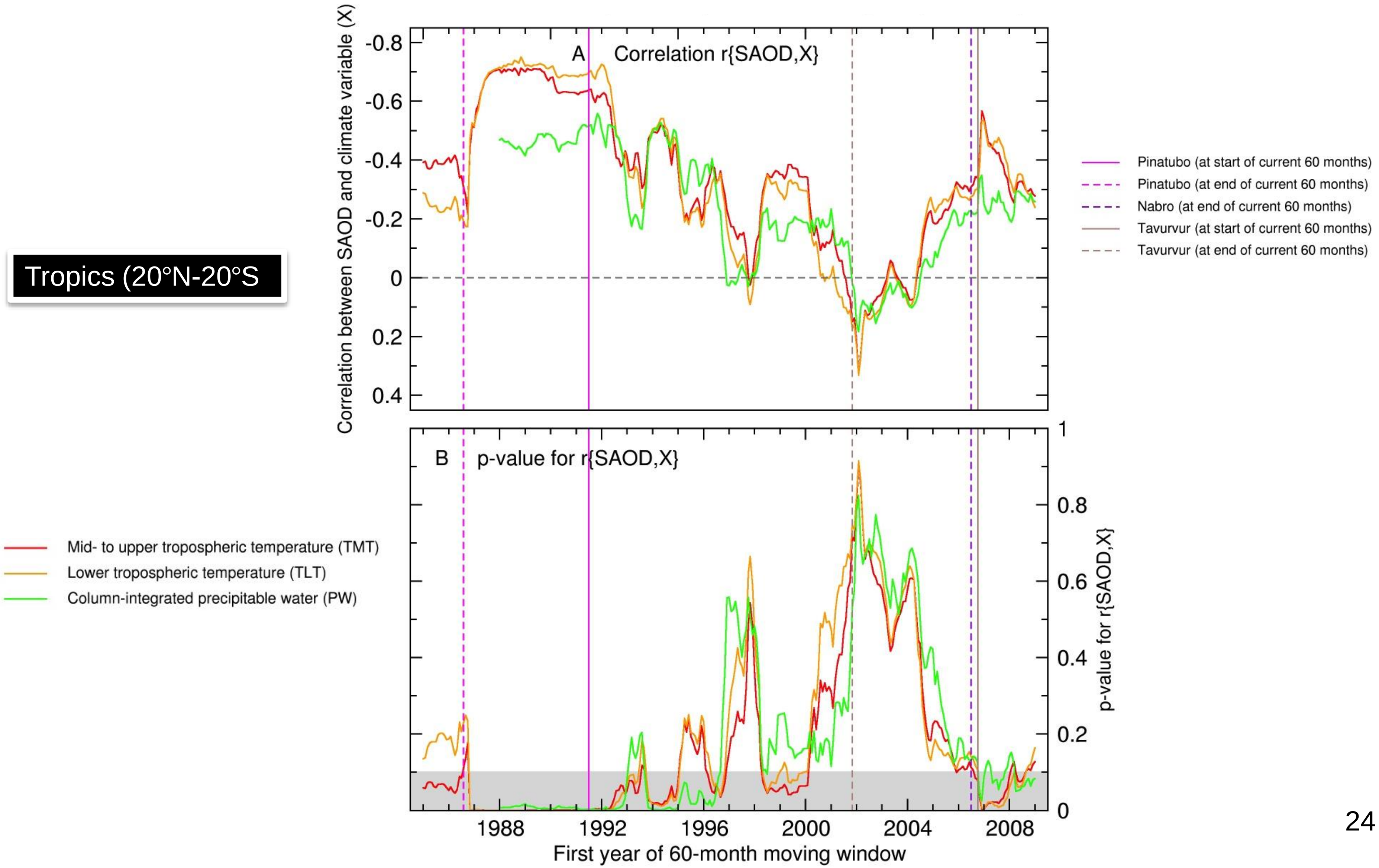

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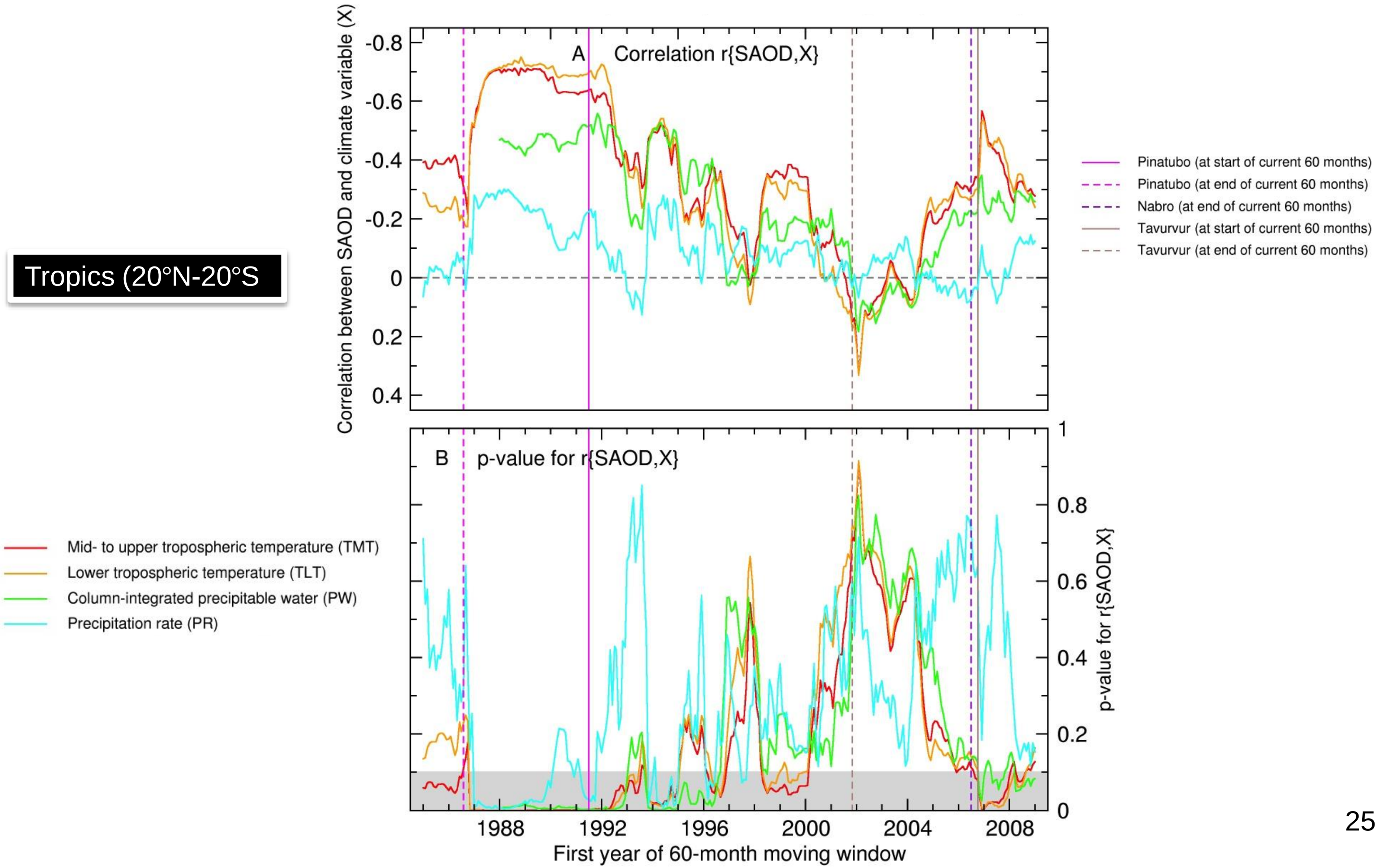

Do volcanic eruptions produce significant climate signals?

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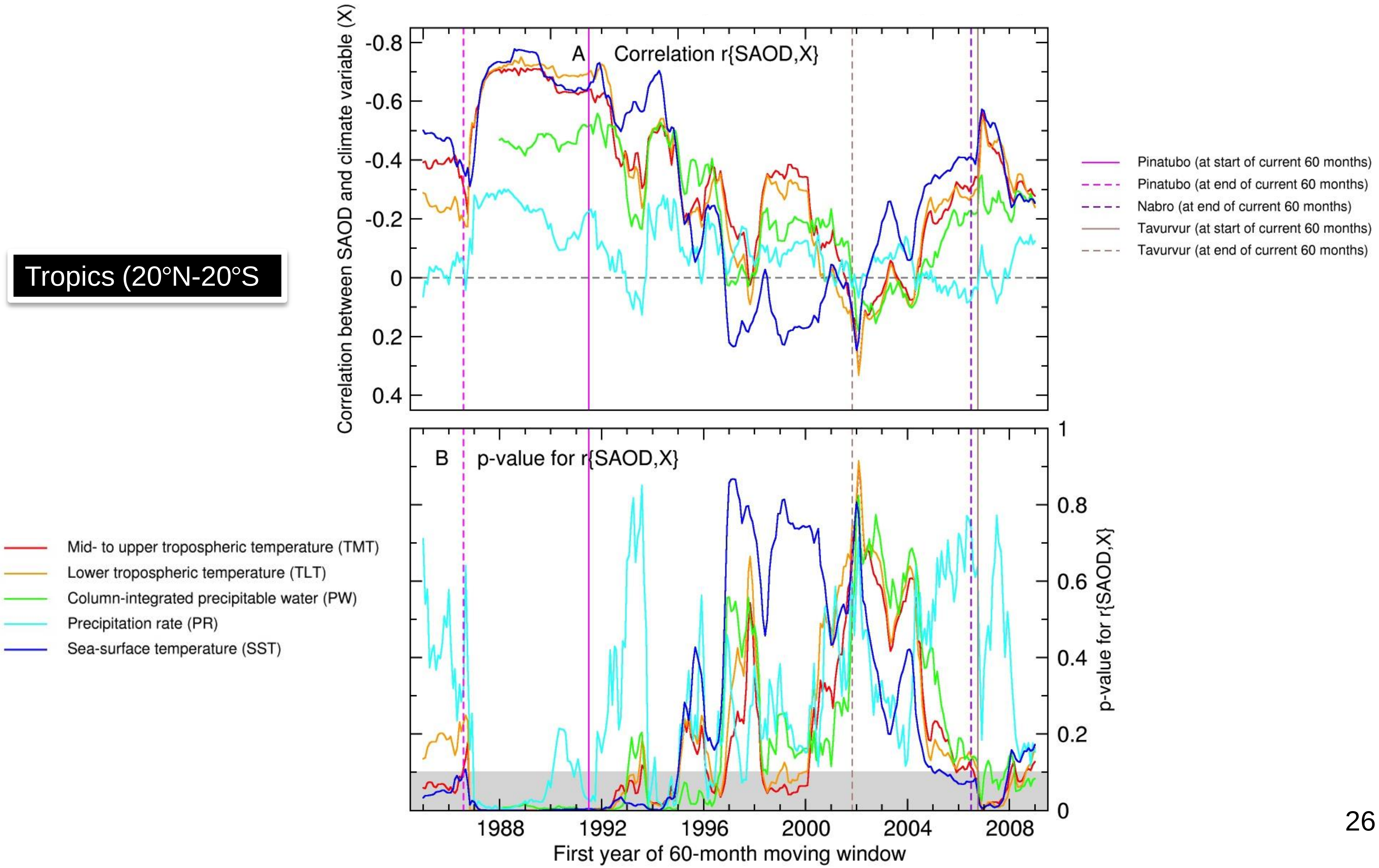
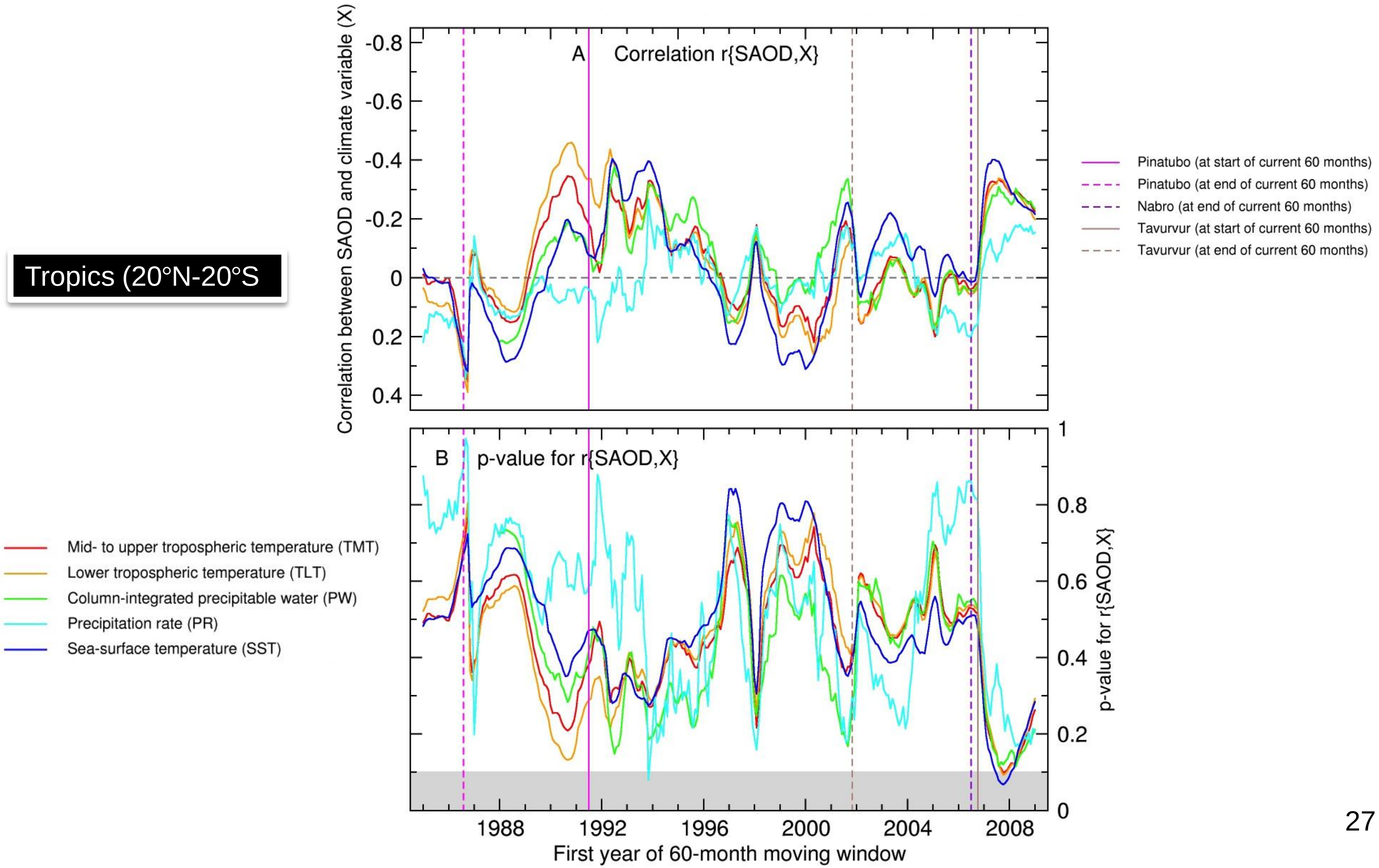
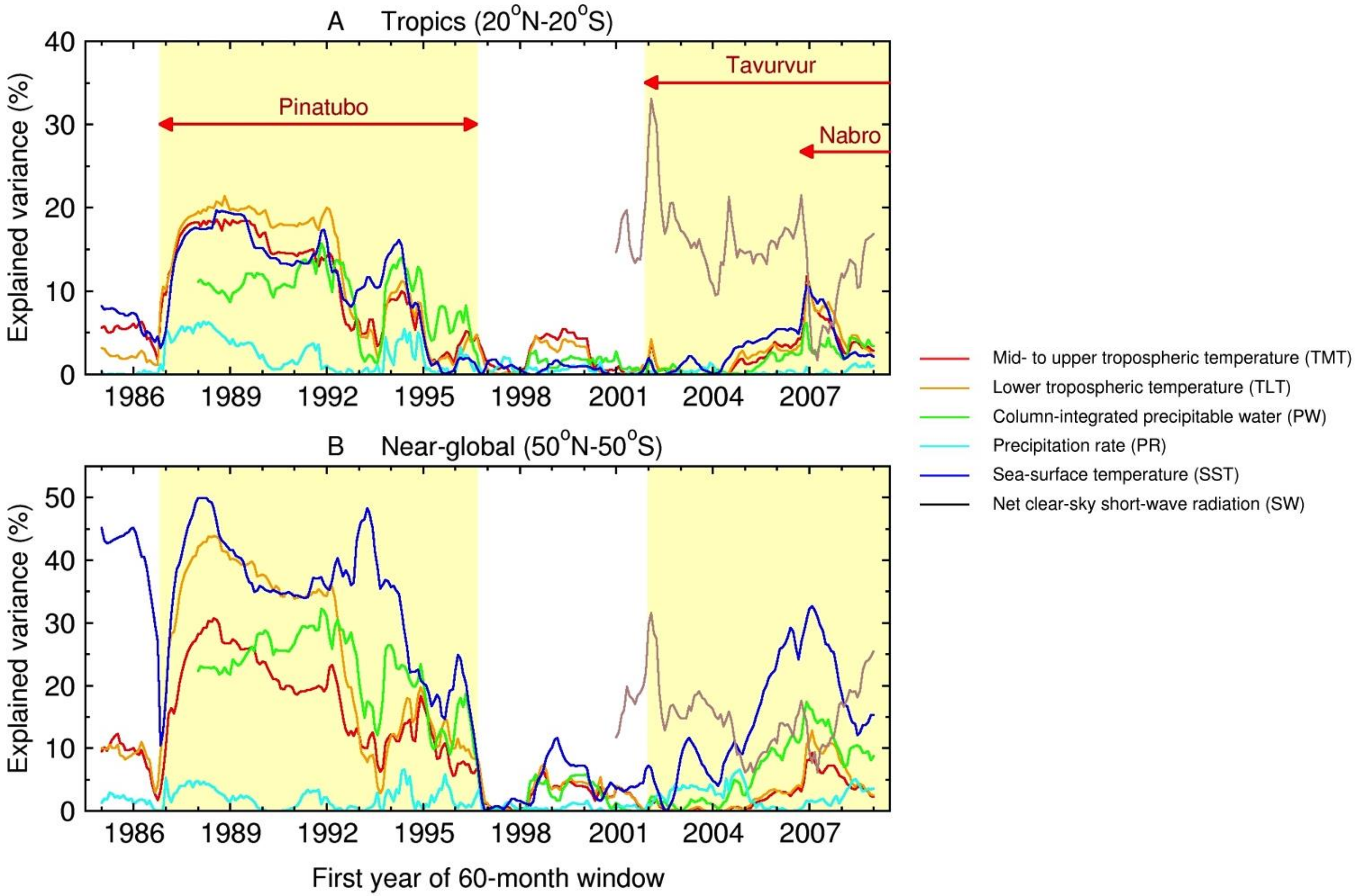


Removing ENSO effects is key to the identification of volcanic climate signals

Tropics (20°N-20°S



How much of the temporal variance of temperature, moisture, and SW radiation is explained by SAOD?



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Mills et al., *JGR* (2016)

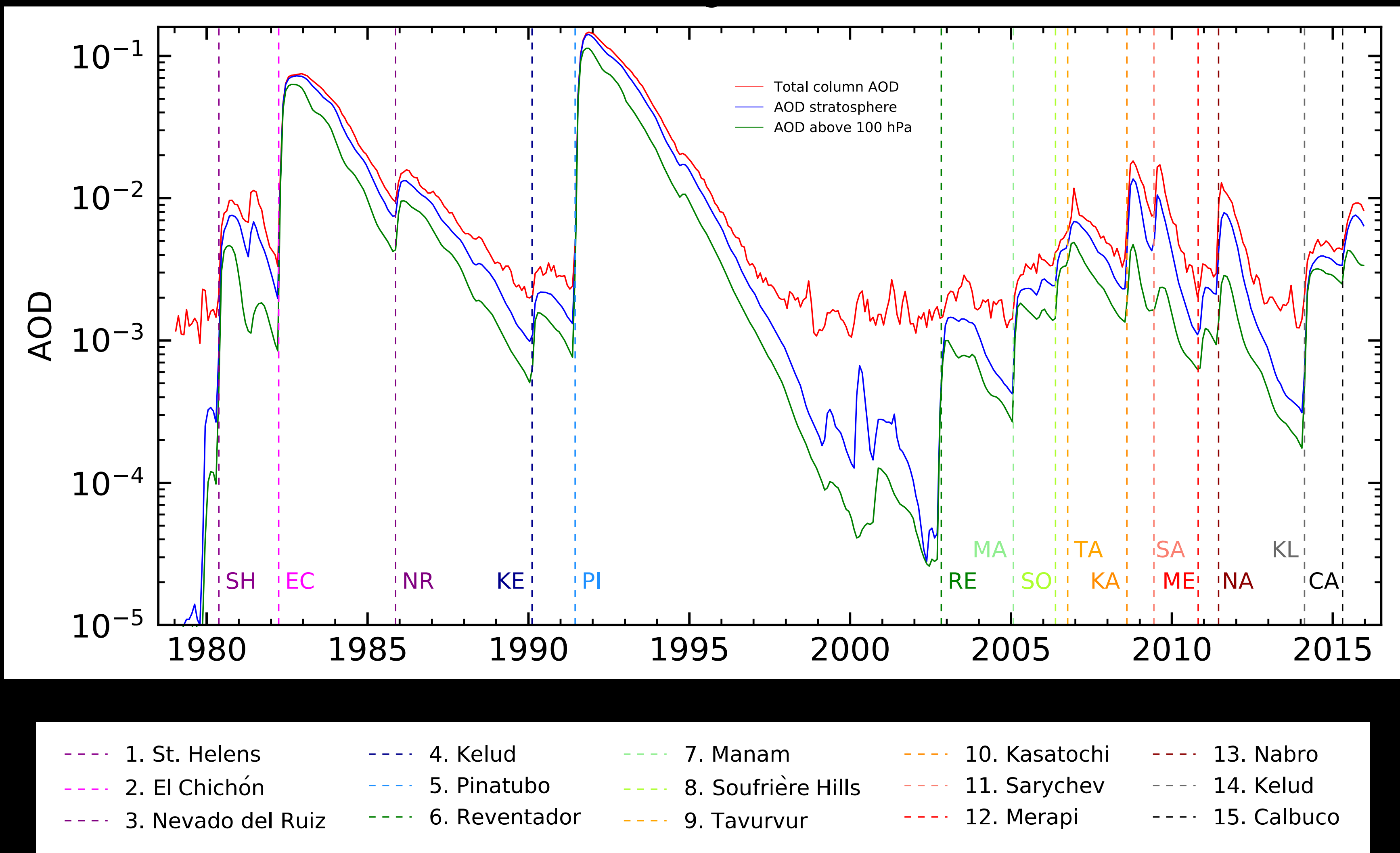
Global volcanic aerosol properties derived from emissions, 1990–2014, using CESM1(WACCM)

Michael J. Mills[1], Anja Schmidt[2], Richard Easter[3], Susan Solomon[4], Douglas E. Kinnison[1], Steven J. Ghan[3], Ryan R. Neely III[2,5], Daniel R. Marsh[1], Andrew Conley[1], Charles G. Bardeen[1], and Andrew Gettelman[1]

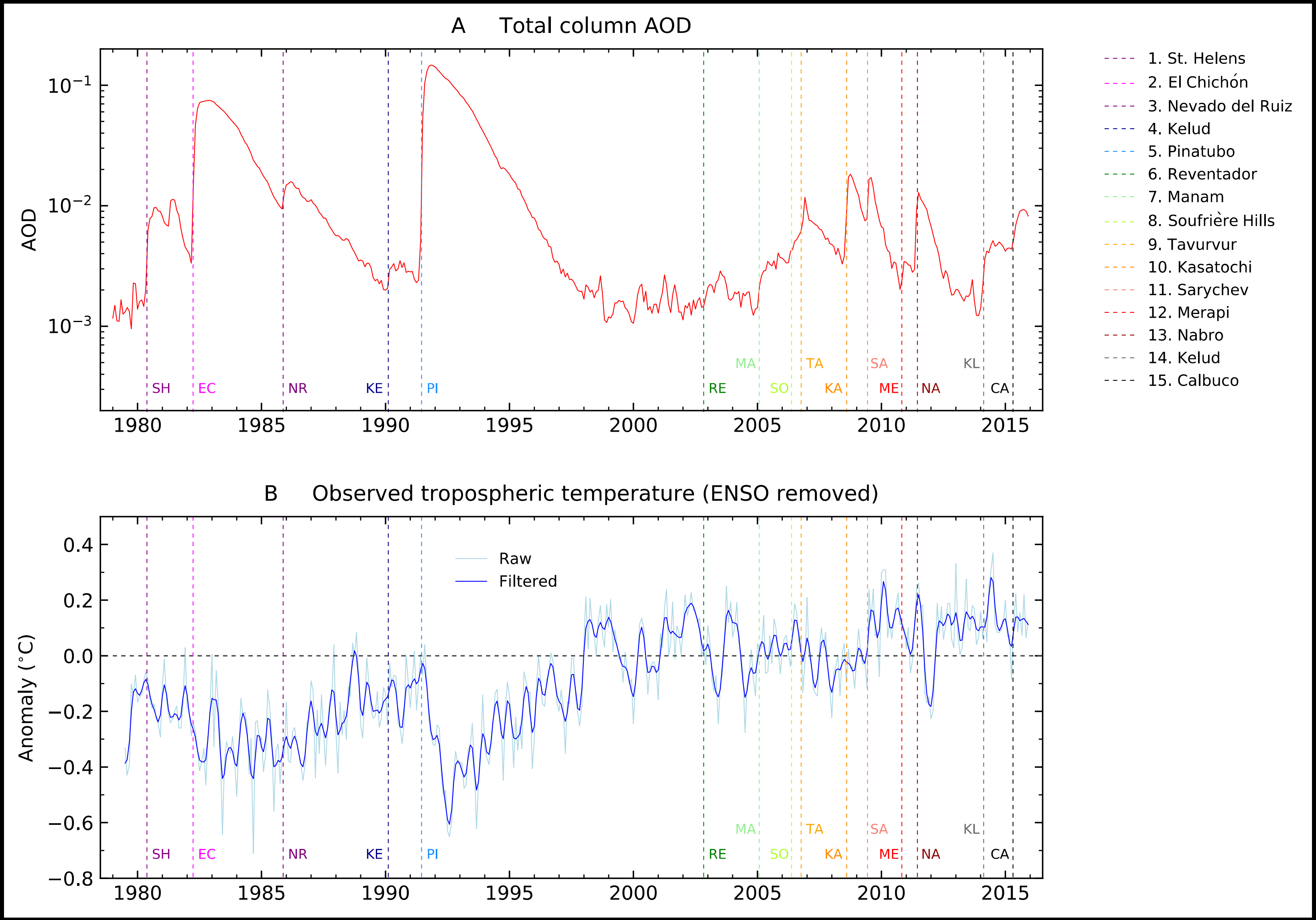
[1]Atmospheric Chemistry Observations and Modeling Laboratory, National Center for Atmospheric Research, Boulder, Colorado, USA, [2]School of Earth and Environment, University of Leeds, Leeds, UK, [3]Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, Washington, USA, [4]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, [5]National Centre for Atmospheric Science, University of Leeds, Leeds, UK

Abstract Accurate representation of global stratospheric aerosols from volcanic and nonvolcanic sulfur emissions is key to understanding the cooling effects and ozone losses that may be linked to volcanic activity. Attribution of climate variability to volcanic activity is of particular interest in relation to the post-2000 slowing in the rate of global average temperature increases. We have compiled a database of volcanic SO_2 emissions and plume altitudes for eruptions from 1990 to 2014 and developed a new prognostic capability for simulating stratospheric sulfate aerosols in the Community Earth System Model. We used these combined with other nonvolcanic emissions of sulfur sources to reconstruct global aerosol properties from 1990 to 2014. Our calculations show remarkable agreement with ground-based lidar observations of stratospheric aerosol optical depth (SAOD) and with in situ measurements of stratospheric aerosol surface area density (SAD). These properties are key parameters in calculating the radiative and chemical effects of stratospheric aerosols. Our SAOD calculations represent a clear improvement over available satellite-based analyses, which generally ignore aerosol extinction below 15 km, a region that can contain the vast majority of stratospheric aerosol extinction at middle and high latitudes. Our SAD calculations greatly improve on that provided for the Chemistry-Climate Model Initiative, which misses about 60% of the SAD measured in situ on average during both volcanically active and volcanically quiescent periods.

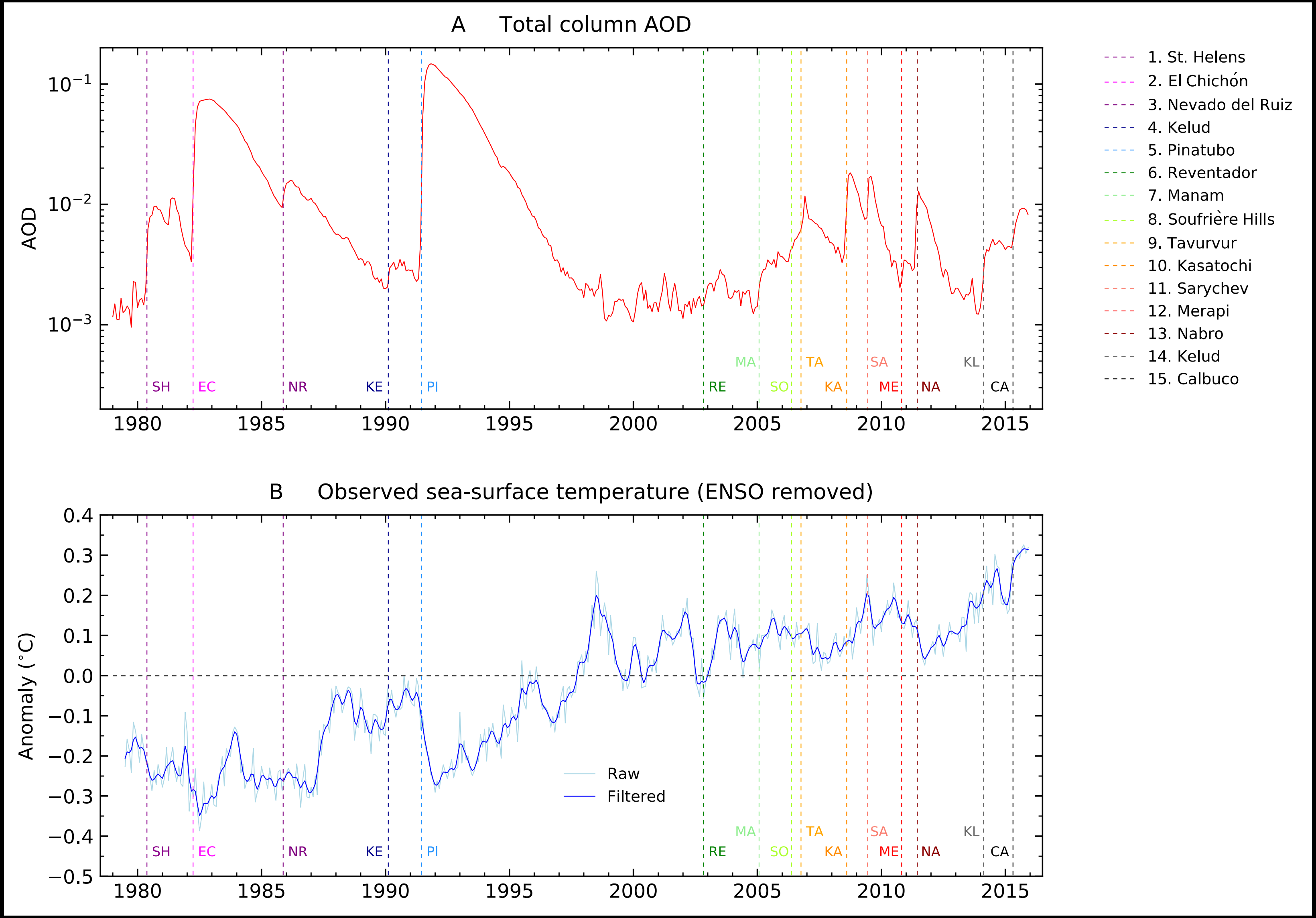
AOD in the Mills et al. simulations



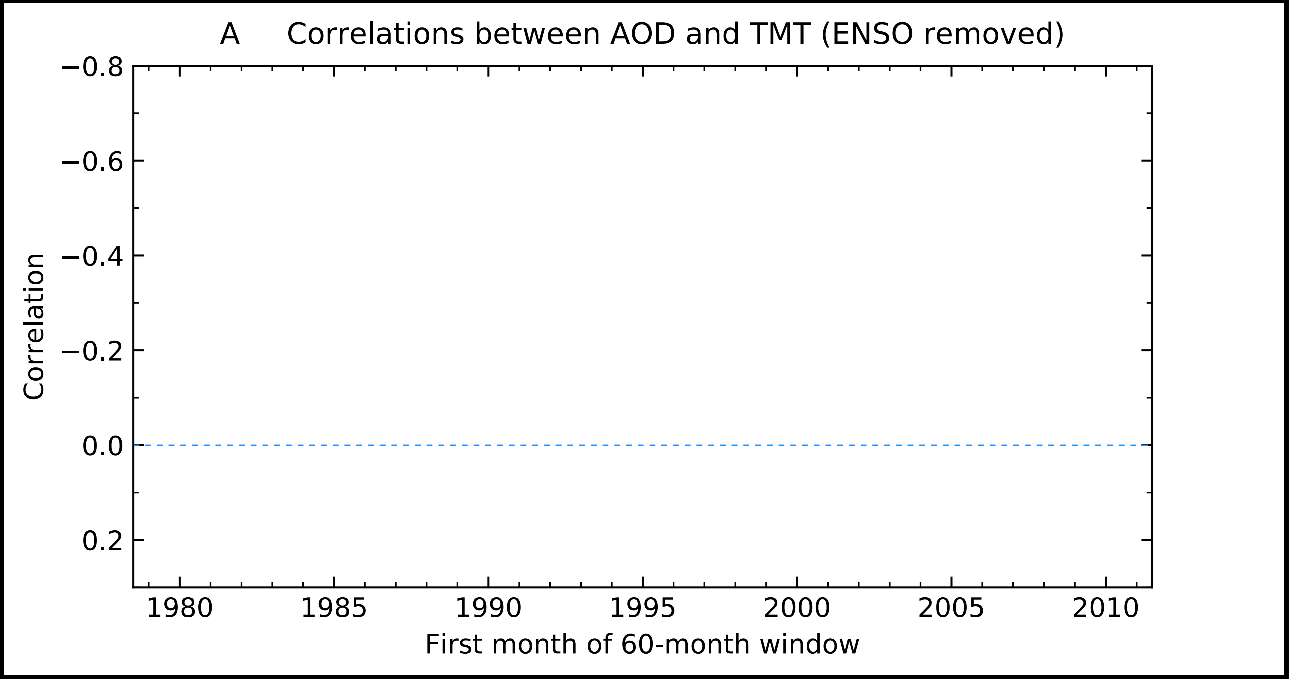
Changes in global-mean aerosol optical depth (WACCM) and tropospheric temperature (OBS)



Changes in global-mean aerosol optical depth (WACCM) and sea-surface temperature 50°N-50°S (OBS)



Volcanic signal detection: AOD and "ENSO removed" tropospheric temperature



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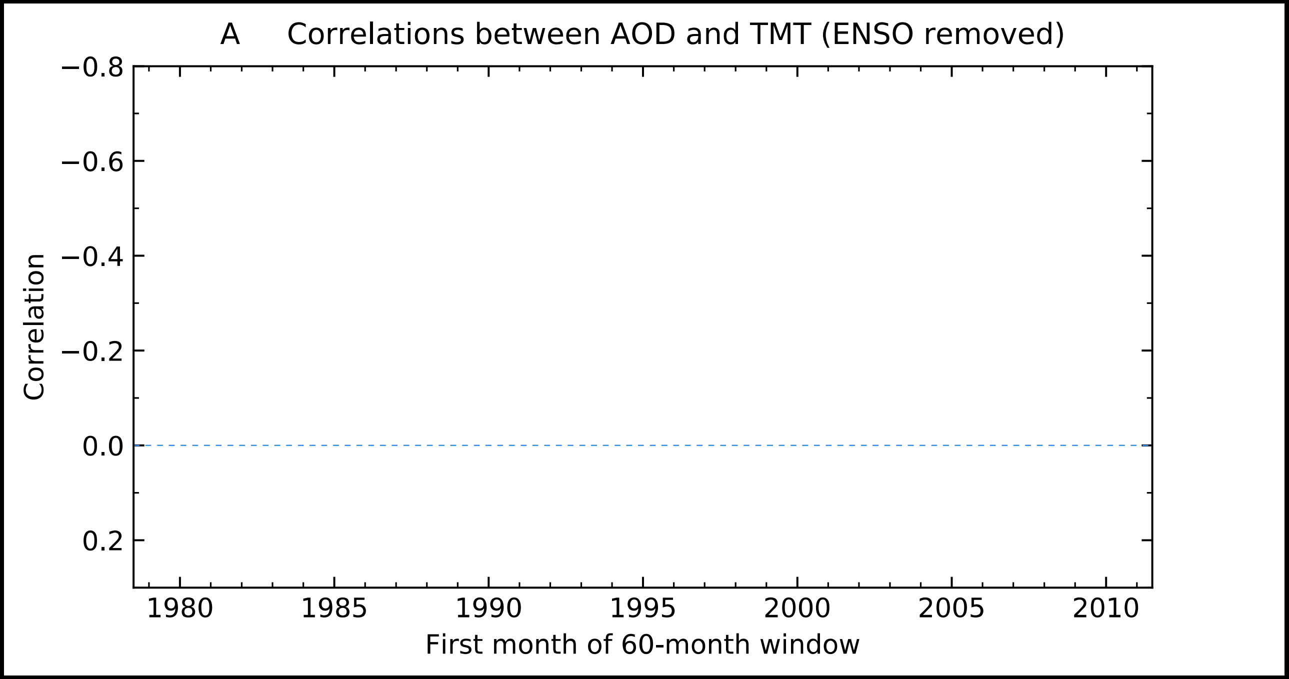

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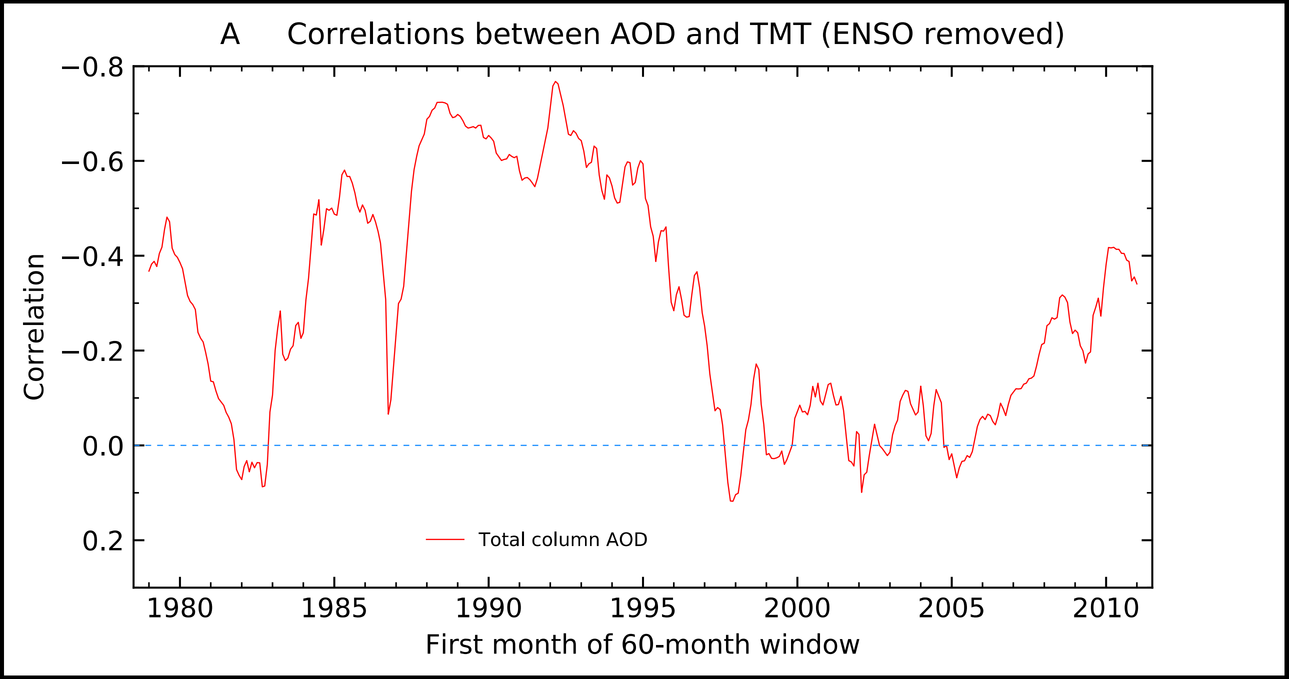

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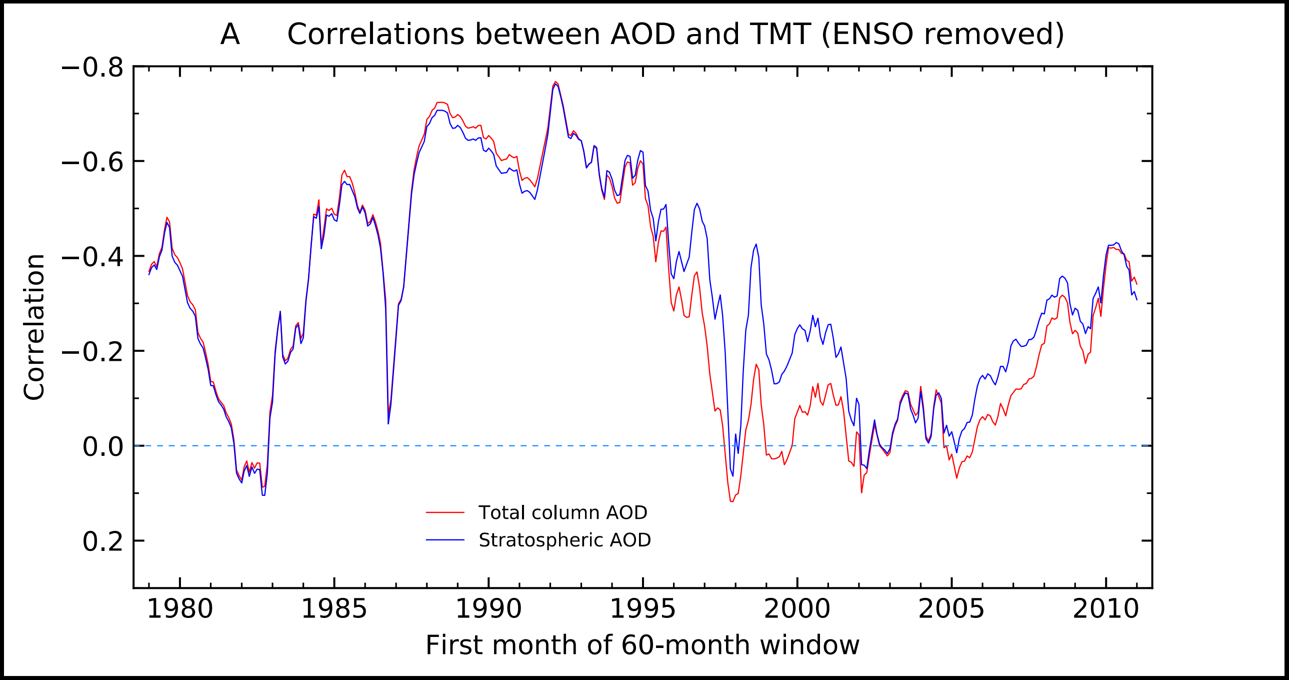

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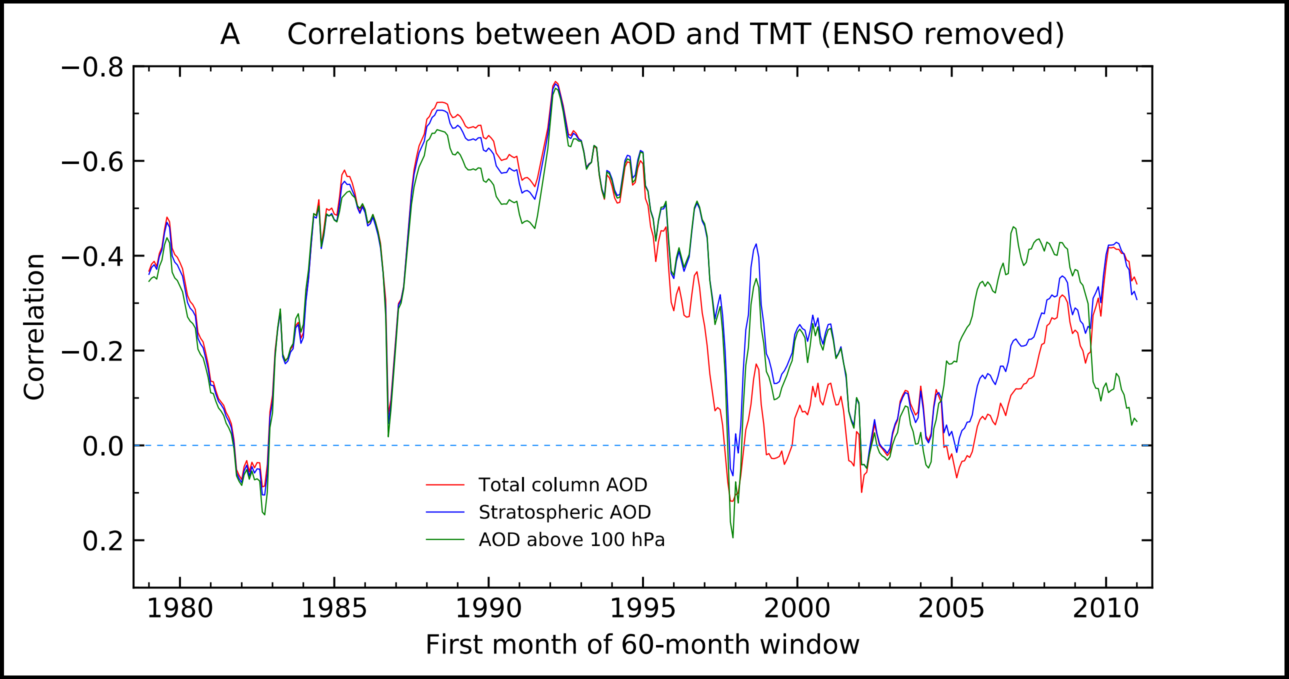
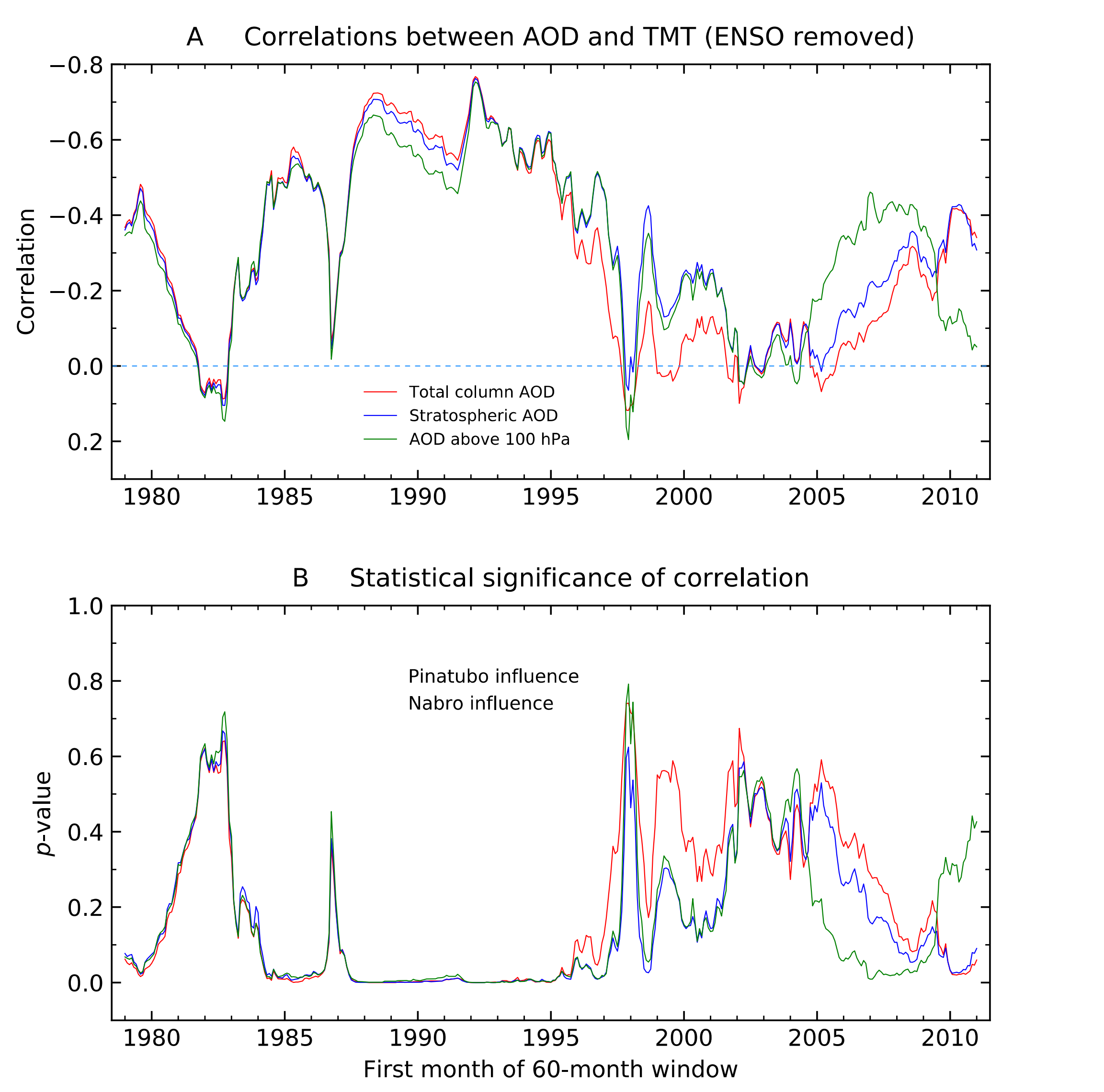
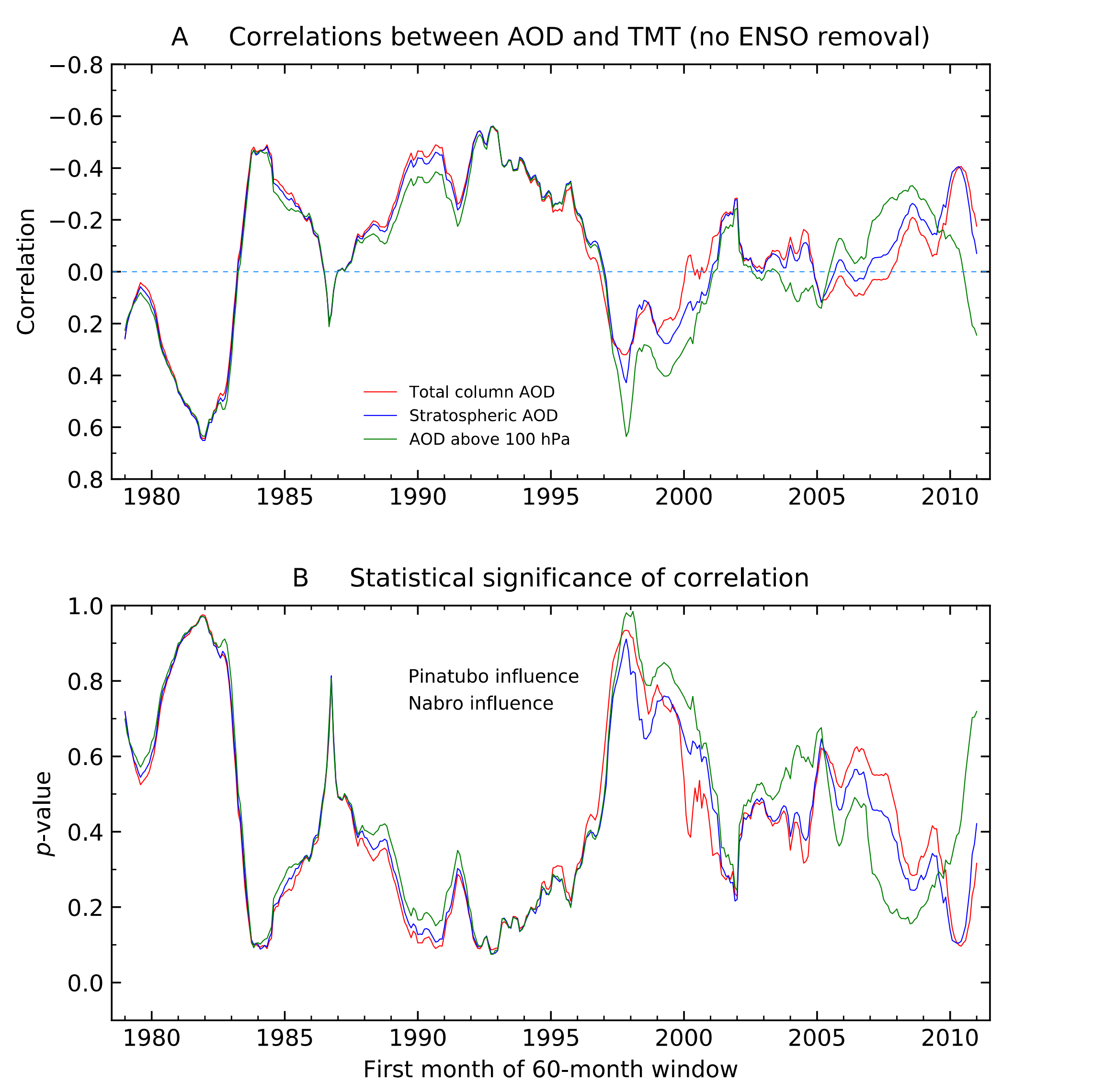


Volcanic signal detection: AOD and "ENSO removed" tropospheric temperature



Volcanic signal detection: AOD and tropospheric "raw" temperature

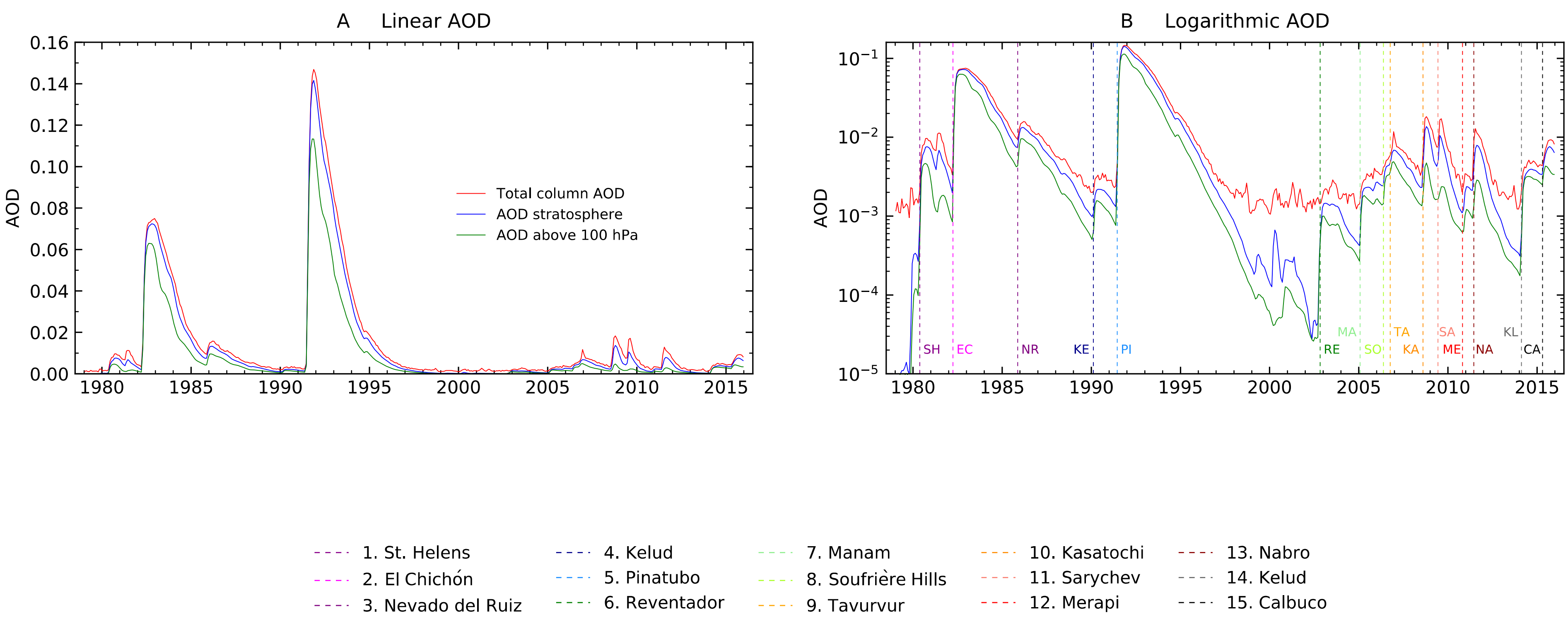


Conclusions

- Multivariate climate signals of late 20th and early 21st century volcanic activity are statistically identifiable in observations:
  - SST and tropospheric temperature
  - Column-integrated water vapor
  - Rainfall
  - Net clear-sky short-wave radiation at top of the atmosphere
- Signals are identifiable for El Chichón, Pinatubo, and for the post-2005 period
- Systematic errors in volcanic (and other) external forcings affect interpretation of differences between modeled and observed climate changes
- In the SO_2-forced CESM1-WACCM simulations, model-generated volcanic aerosol optical depth can be used to identify significant signals in observed climate data
- Such simulations provide a useful test-bed for quantification of contributions from stratospheric and tropospheric volcanic aerosol to observed volcanic climate signals

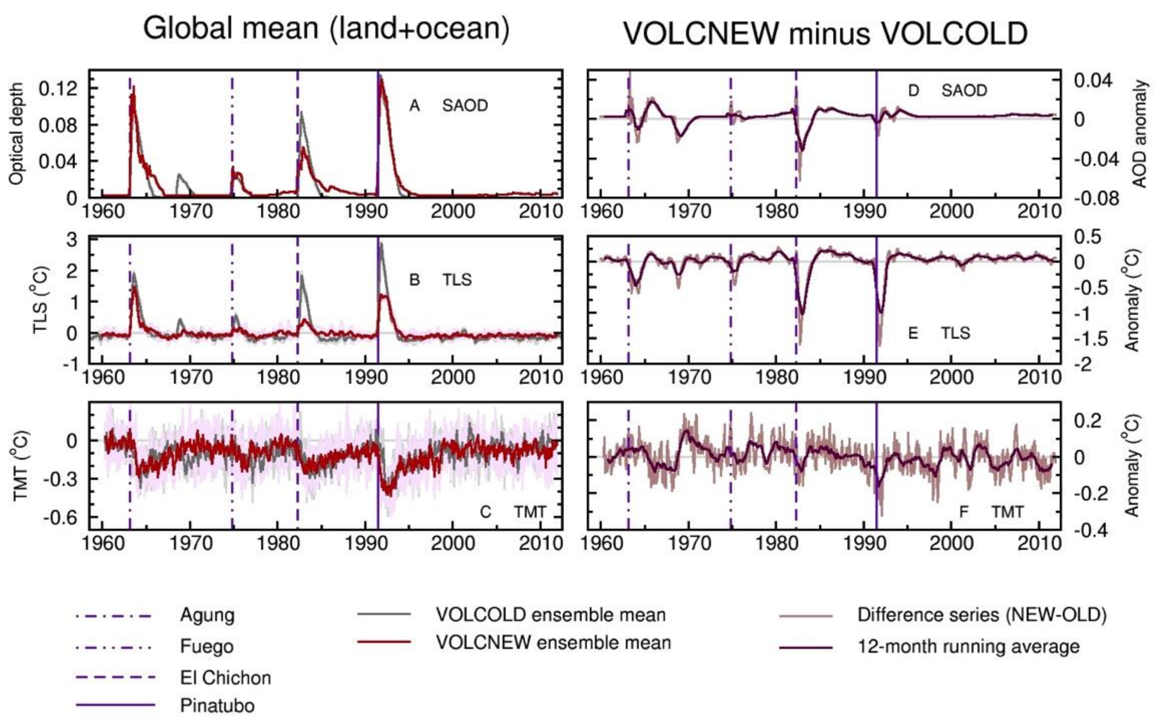
Two science questions

1. Why can we identify the observed climate signals of “small” volcanic eruptions in the post-2005 period?



Two science questions

2. In the last four days, we have seen estimates of spatio-temporal changes in volcanic activity based on observations, reanalyses, and SO_2-driven model simulations. How different are these estimates? How much of the temporal variance of observed “ENSO removed” climate variables do they explain?



Work with Ryan Neely, J.-F. Lamarque, Jerry Meehl, Susan Solomon, and David Ridley

EXTRA SLIDES

- EXTRA SLIDES

Schematic of iterative method for removing ENSO and volcano signals (Santer *et al*., 2001)

T_t Raw tropospheric temperature data

Select ENSO index, X_t (SOI, Niño 3.4, Niño 3)

- Estimate regression coefficient b for { X_t , T_t } (Iteration 1)
- Estimate regression coefficient b for { X_t , T_t^* } (Iterations > 1)
- Estimate lag j (in months) at which $b = b_{max}$

Iterate until convergence

Compute ENSO signal in T_t or T_t^*

- $E_t = a_j + b_j X_t$

Subtract ENSO signal E_t from raw temperature data

- $Z_t = T_t – E_t$

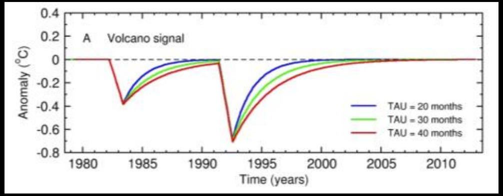
For selected TAU, estimate volcano parameters from Z_t

- ΔT_{max} Maximum volcano-induced cooling
- t_{ramp} Time (in months) to maximum cooling

Estimate volcano signal V_t from Z_t

Subtract V_t from original temperature data T_t

- $T_t^* = T_t - V_t$



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