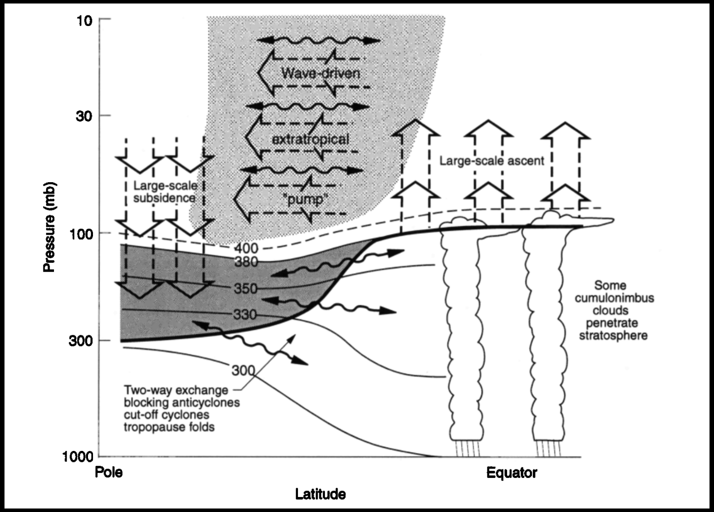
Some reflections on the history of key scientific advances and current challenges in understanding the tropical UTLS

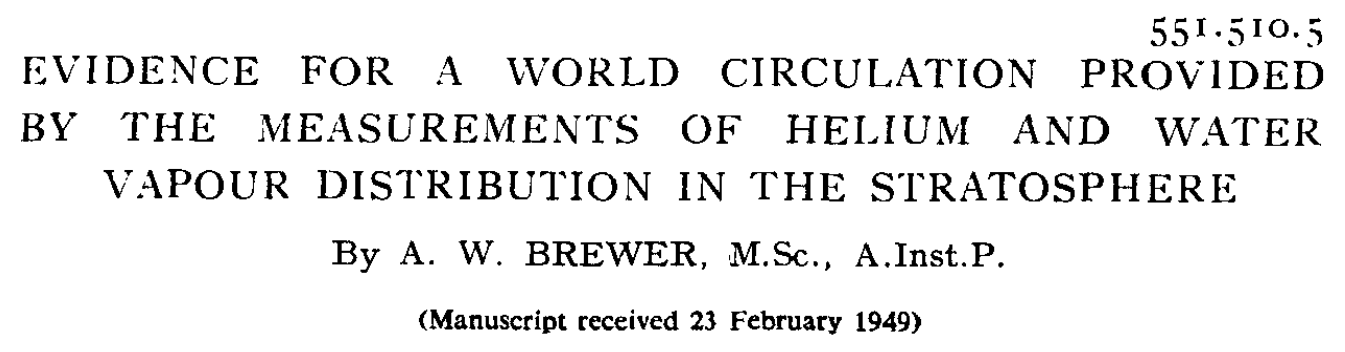
Susan Solomon,
Ellen Swallow Richards Professor of Atmospheric Chemistry and Climate Science,
MIT, Cambridge, MA

This talk

- Historical overview – O_3 and H_2O
- Connections to climate change
- Some Qs on current challenges and research needs



Holton et al., Rev. Geophys., 1995



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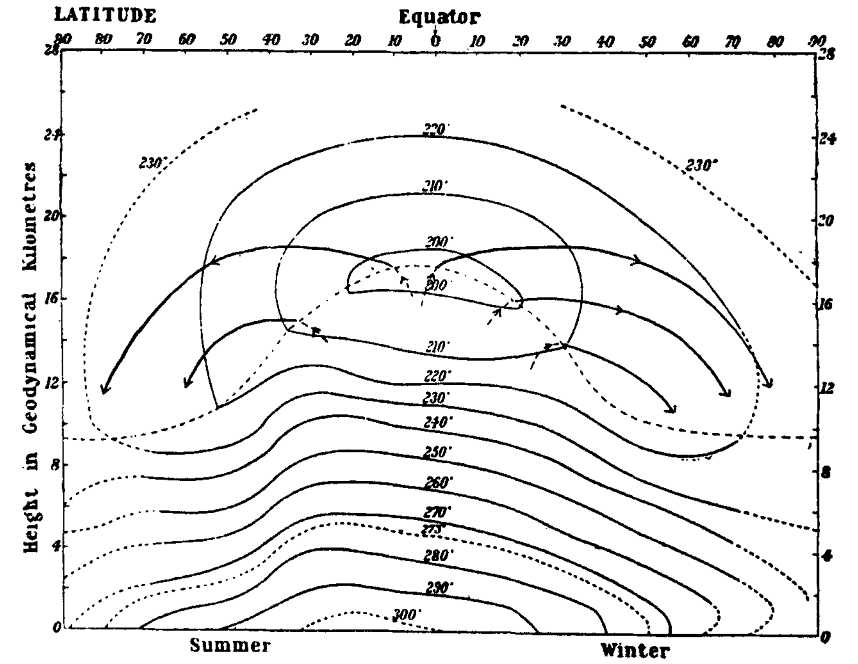
EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY THE MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

By A. W. BREWER, M.Sc., A.Inst.P.

(Manuscript received 23 February 1949)



Isotherms over the Globe

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

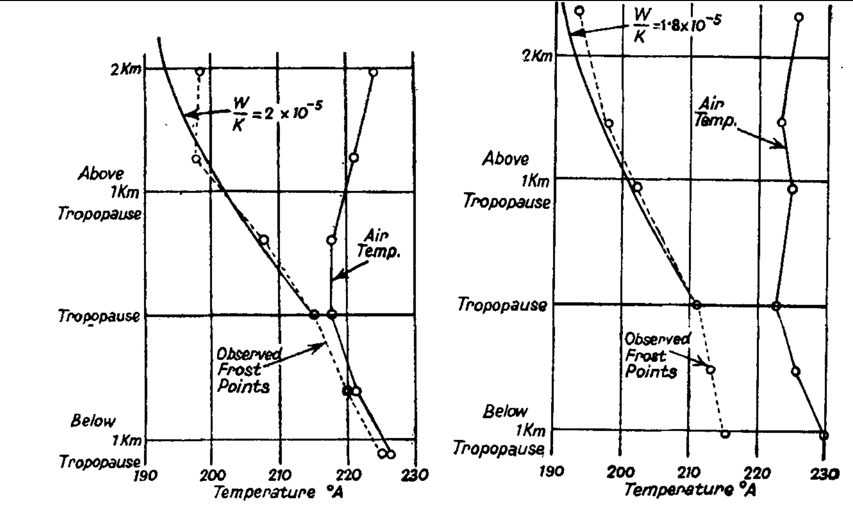
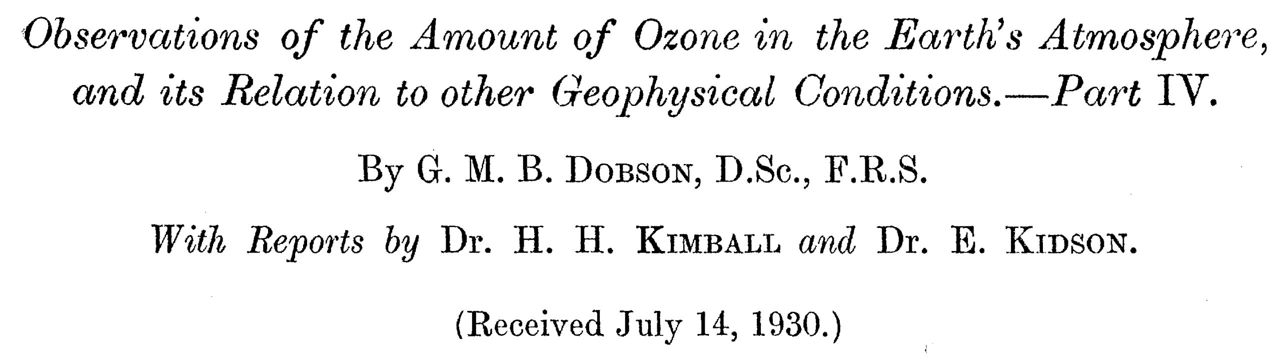


FIG. 3. 22 April 1945. Tropopause ht 34,000 ft.
FIG. 4. 7 Feb. 1945. Tropopause ht 30,000 ft.

FIGS. 1-4. Distribution of temperature and frost point near the tropopause on four ordinary occasions, compared with the calculated frost point curves for the lower stratosphere.

QJRMS, 1949

“how is the great dryness of the air only one or two km above the tropopause of southern England maintained?”



Observations of the Amount of Ozone in the Earth's Atmosphere, and its Relation to other Geophysical Conditions.—Part IV.

By G. M. B. Dobson, D.Sc., F.R.S.

With Reports by Dr. H. H. Kimball *and* Dr. E. Kidson.

(Received July 14, 1930.)

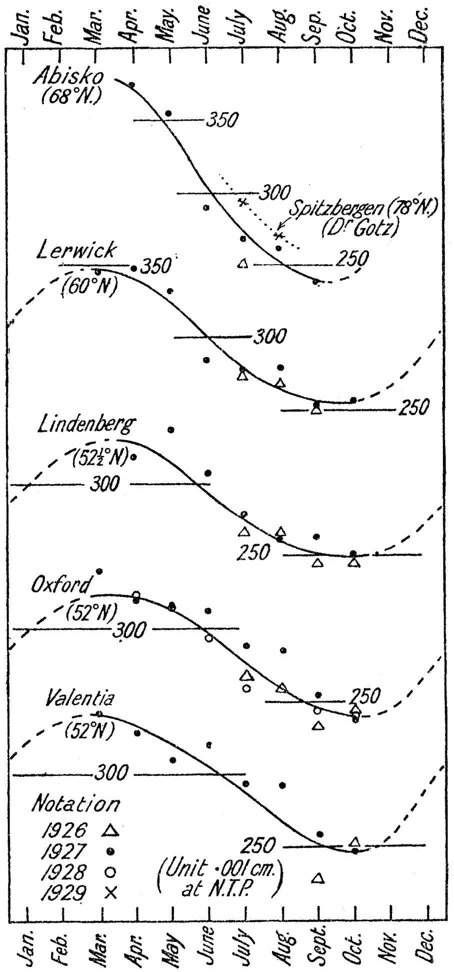


Fig. 1a.

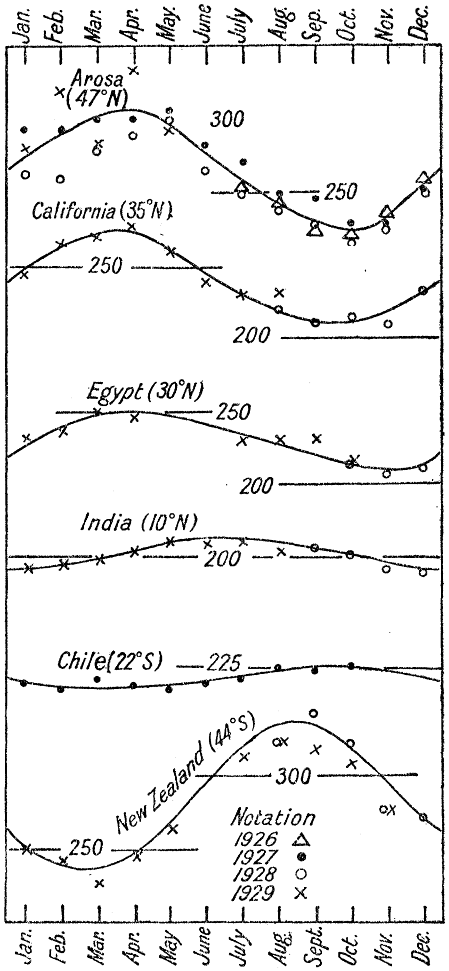


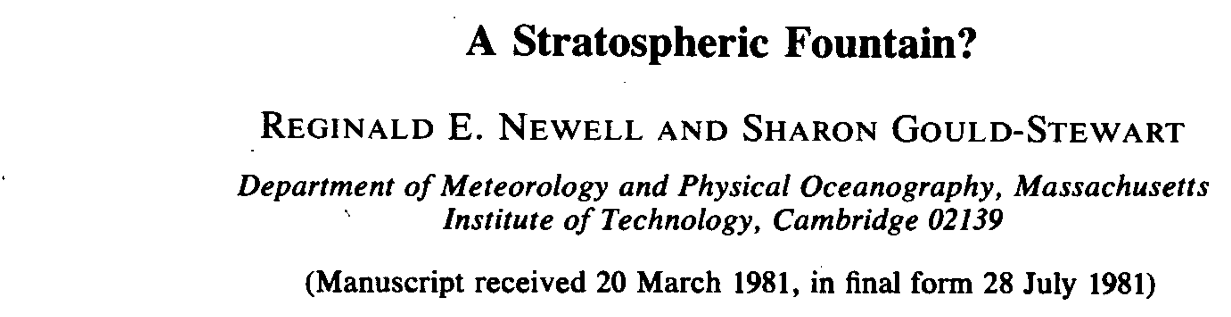
Fig. 1b.

Dobson puzzled over chemistry and transport.

Corpuscular radiation (energetic particles) as main O3 source at poles?

Vertical motions important to bring down ozone from above in mid-lats.

Proc. Roy. Soc., 1930

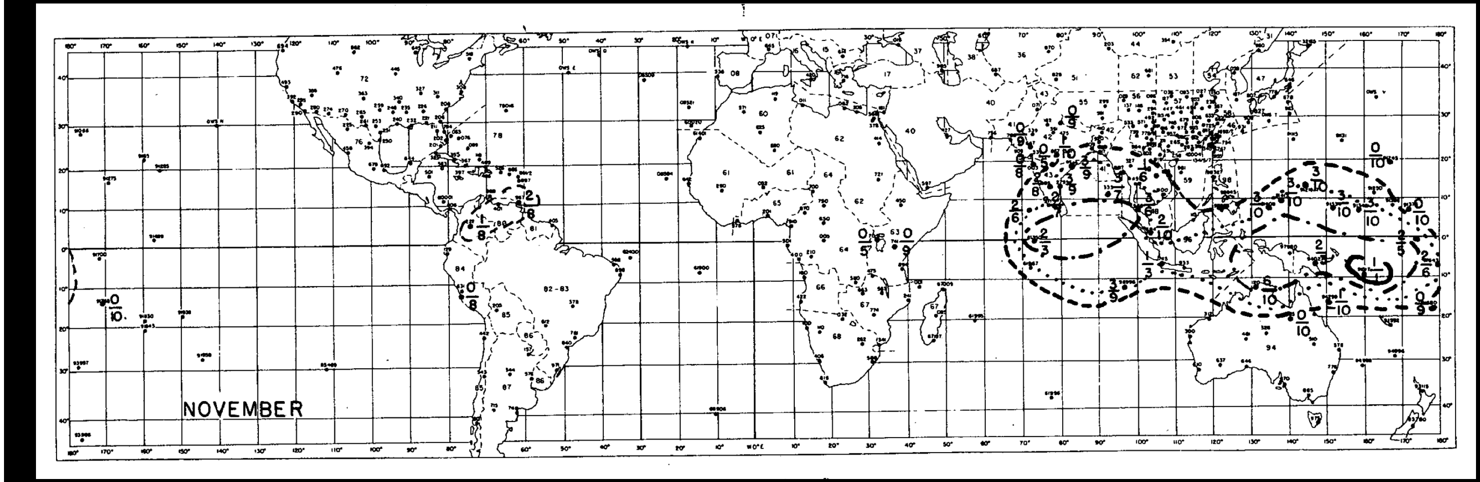


A Stratospheric Fountain?

REGINALD E. NEWELL AND SHARON GOULD-STEWART

Department of Meteorology and Physical Oceanography, Massachusetts Institute of Technology, Cambridge 02139

(Manuscript received 20 March 1981, in final form 28 July 1981)

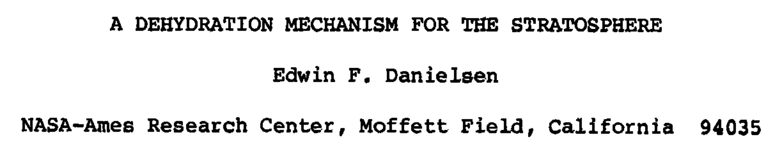


3.5 ppmv at 21 km (Kley et al.; Mastenbrook et al.) suggests T_{frost} < -82C at entry. Where is such air to be found?

Western tropical Pacific, Australia, Indonesia, monsoon region?
But….what is the absolute accuracy of the H_2O data?

JAS, 1981.

What is the role of clouds?



A DEHYDRATION MECHANISM FOR THE STRATOSPHERE

Edwin F. Danielsen

NASA-Ames Research Center, Moffett Field, California 94035

"Radiative heating at anvil base combined with cooling at anvil top drives a dehydration engine considered essential to explain the dry stratosphere…maximum potential attributed to Micronesia…"

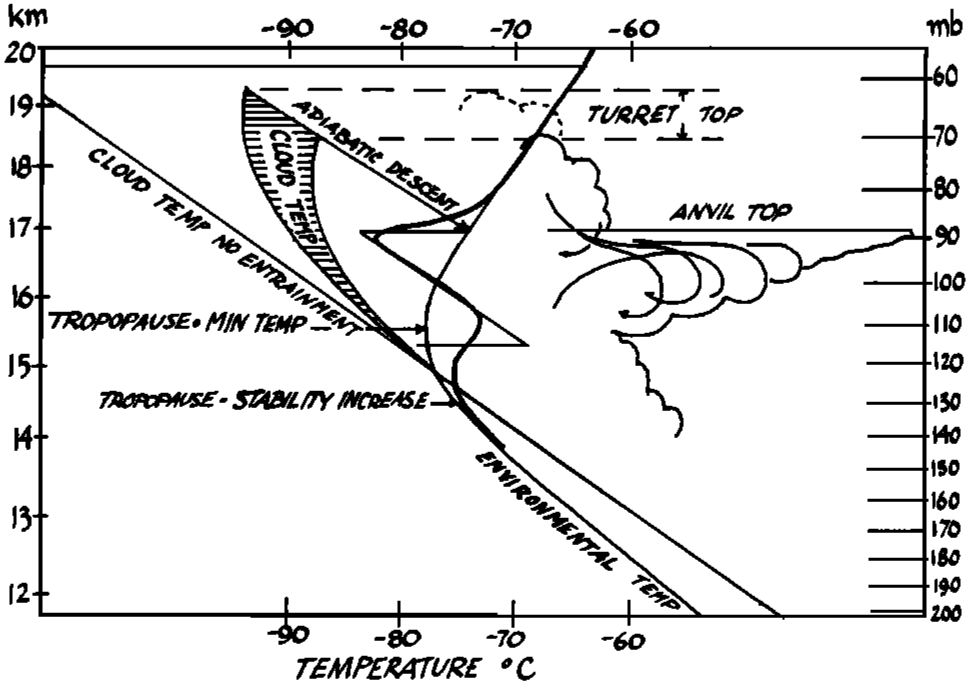
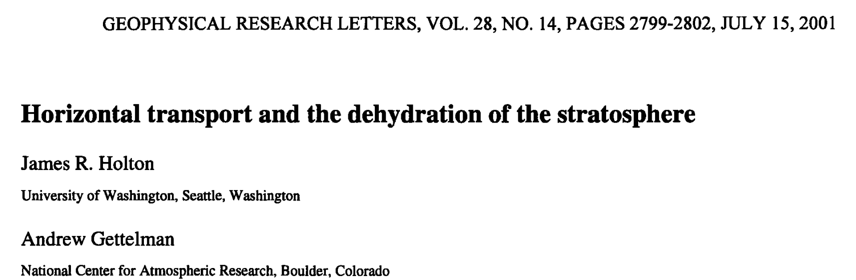


Fig. 2a. Anvil formation in stratosphere due to entrainment and mixing of stratospheric air in overshooting turret. Predicted temperature profile (heavy line) includes two minimums.

But is the air rising in the key region, or descending?

GRL, 1983.

Horizontal transport: the fountain gets lost in the swimming pool



GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 14, PAGES 2799-2802, JULY 15, 2001

Horizontal transport and the dehydration of the stratosphere

James R. Holton
University of Washington, Seattle, Washington

Andrew Gettelman
National Center for Atmospheric Research, Boulder, Colorado

“Horizontal processing of air by passage through the Western Pacific cold trap is an effective means to explain the extreme aridity of the equatorial stratosphere and to explain the presence of thin cirrus”

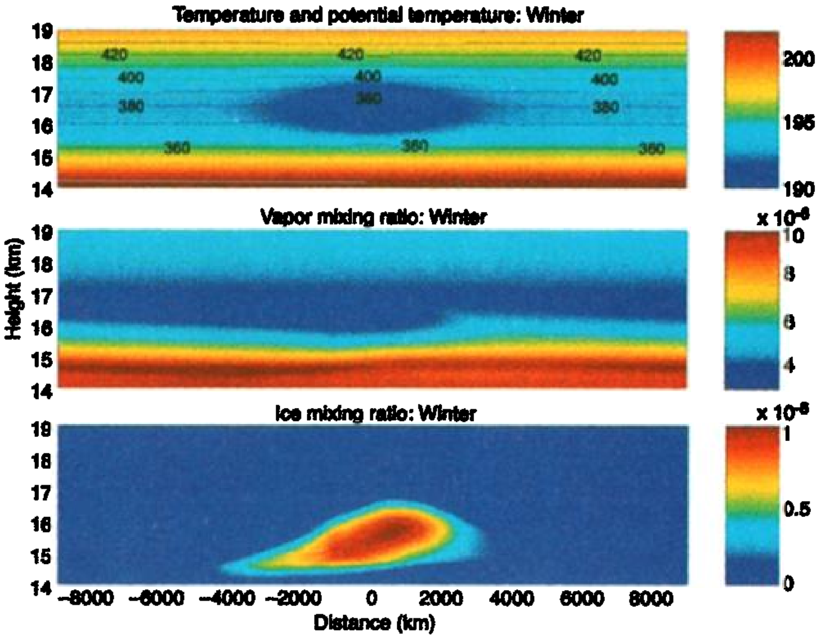
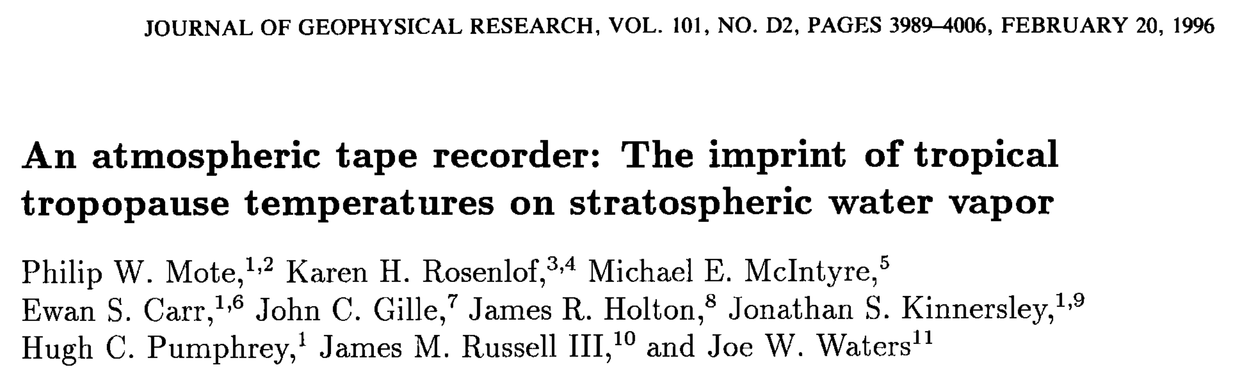


Plate 1. Longitude-height cross sections showing the specified temperature distribution (color), potential temperature (isolines, K), water vapor mixing ratio (ppmv), and ice mixing ratio for Northern Hemisphere winter.

→ implications for interpretation of observations of local hygropause, cold point, tropopause

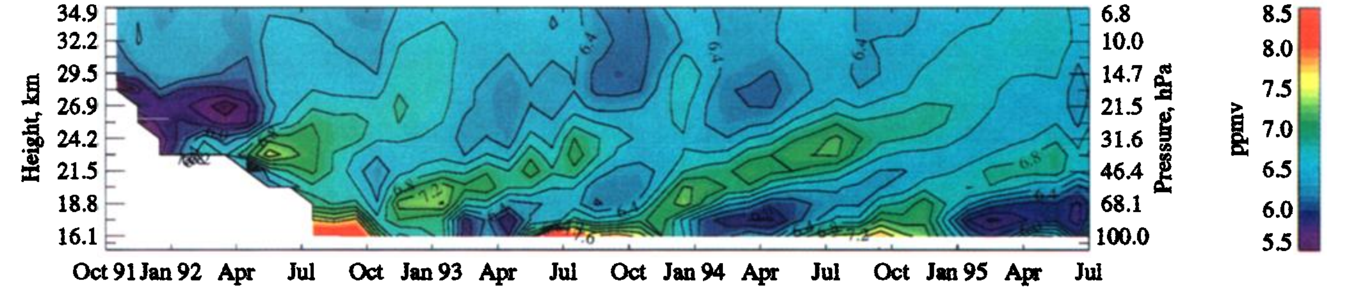
GRL, 2001.



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. D2, PAGES 3989–4006, FEBRUARY 20, 1996

An atmospheric tape recorder: The imprint of tropical tropopause temperatures on stratospheric water vapor

Philip W. Mote,[1,2] Karen H. Rosenlof,[3,4] Michael E. McIntyre,[5]
Ewan S. Carr,[1,6] John C. Gille,[7] James R. Holton,[8] Jonathan S. Kinnersley,[1,9]
Hugh C. Pumphrey,[1] James M. Russell III,[10] and Joe W. Waters[11]

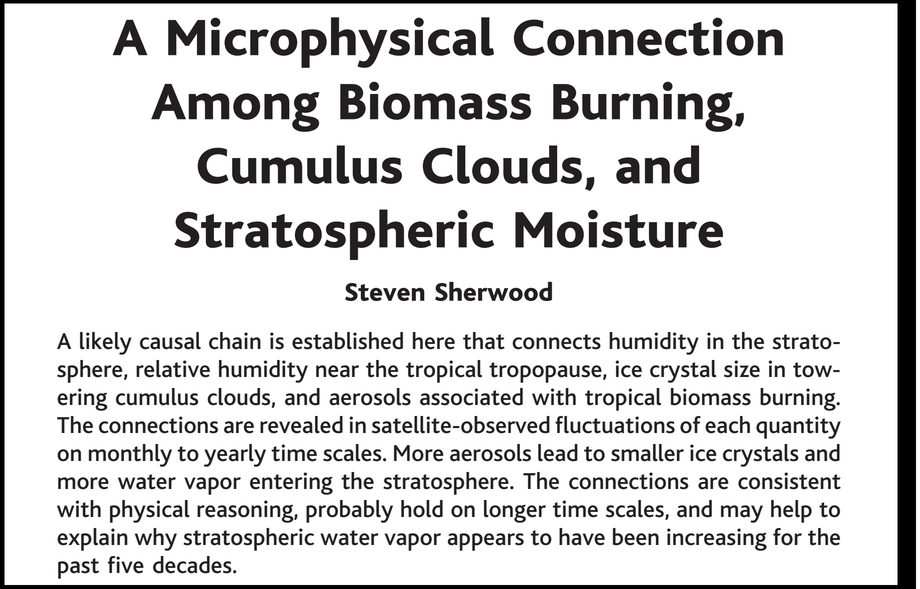


HALOE data

Air transported upward by the global-scale mean circulation retains, for 18 months or more, a distinct "memory" of the tropical tropopause conditions it encountered

JGR, 1996.

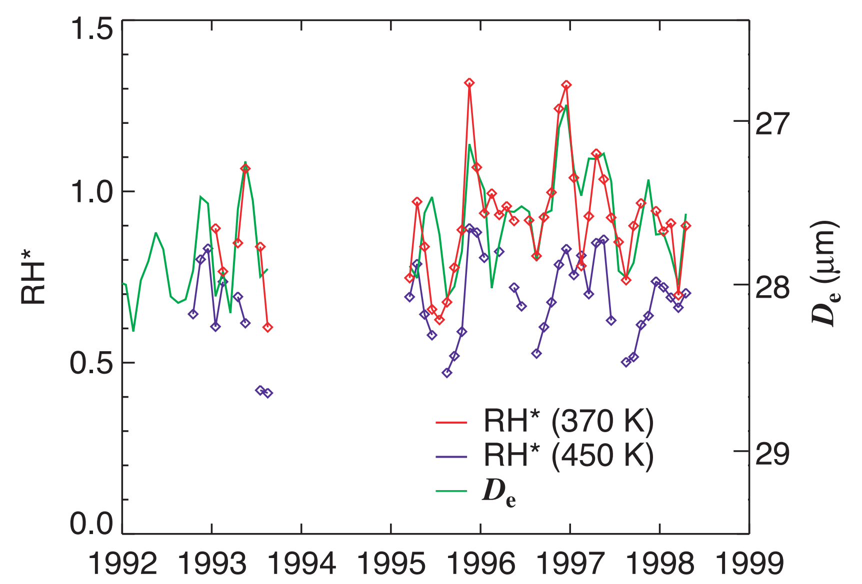
What is the role of aerosols and clouds in the UTLS?

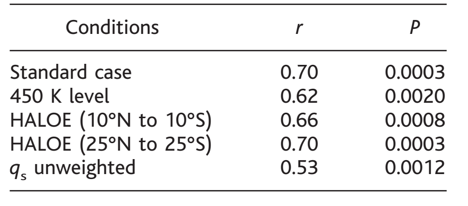


A Microphysical Connection Among Biomass Burning, Cumulus Clouds, and Stratospheric Moisture

Steven Sherwood

A likely causal chain is established here that connects humidity in the stratosphere, relative humidity near the tropical tropopause, ice crystal size in towering cumulus clouds, and aerosols associated with tropical biomass burning. The connections are revealed in satellite-observed fluctuations of each quantity on monthly to yearly time scales. More aerosols lead to smaller ice crystals and more water vapor entering the stratosphere. The connections are consistent with physical reasoning, probably hold on longer time scales, and may help to explain why stratospheric water vapor appears to have been increasing for the past five decades.





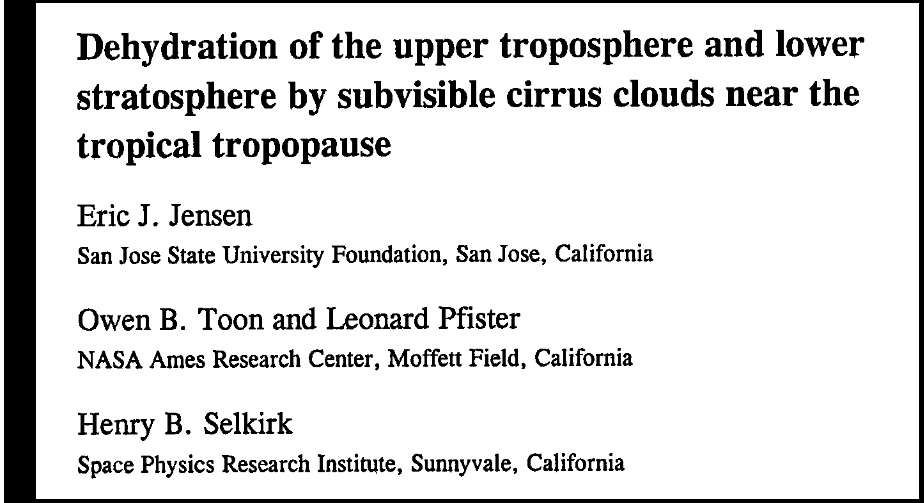
Conditions	*r*	*P*
Standard case	0.70	0.0003
450 K level	0.62	0.0020
HALOE (10°N to 10°S)	0.66	0.0008
HALOE (25°N to 25°S)	0.70	0.0003
q_s unweighted	0.53	0.0012

Relationship between RH and particle size

Qs: How important is the coupling short-term, compared to other factors? Are aerosols and H_2O coupled in the long term on a global scale? What about other aerosol (e.g. volcanic, soot, etc)?

Science, 2002.

What is the role of clouds in the UTLS?



Dehydration of the upper troposphere and lower stratosphere by subvisible cirrus clouds near the tropical tropopause

Eric J. Jensen
San Jose State University Foundation, San Jose, California

Owen B. Toon and Leonard Pfister
NASA Ames Research Center, Moffett Field, California

Henry B. Selkirk
Space Physics Research Institute, Sunnyvale, California

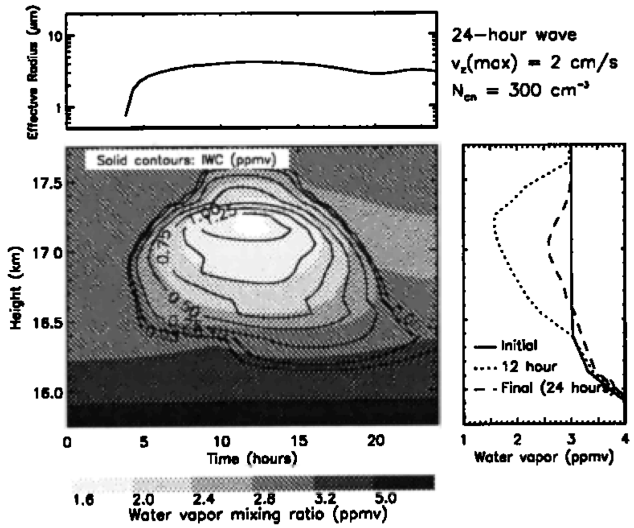
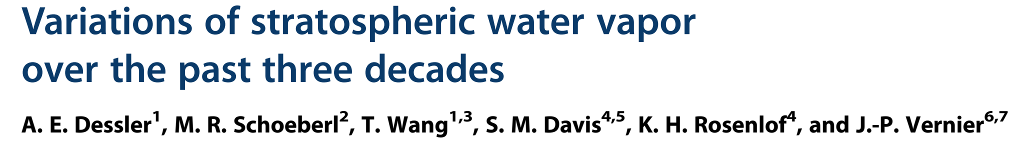


Figure 3. Simulated cloud and water vapor fields for 24-hour wave with 300 cm^{-3} H_2SO_4 aerosols. In this case ice crystals have enough time to fall several hundred meters before sublimation occurs.

Wave-induced cooling, and time scale is important → slow growth in cirrus required (i.e., over large rather than small systems) in order for particles to get big enough to dehydrate.

GRL, 1996.



Variations of stratospheric water vapor over the past three decades

A. E. Dessler[1], M. R. Schoeberl[2], T. Wang[1,3], S. M. Davis[4,5], K. H. Rosenlof[4], and J.-P. Vernier[6,7]

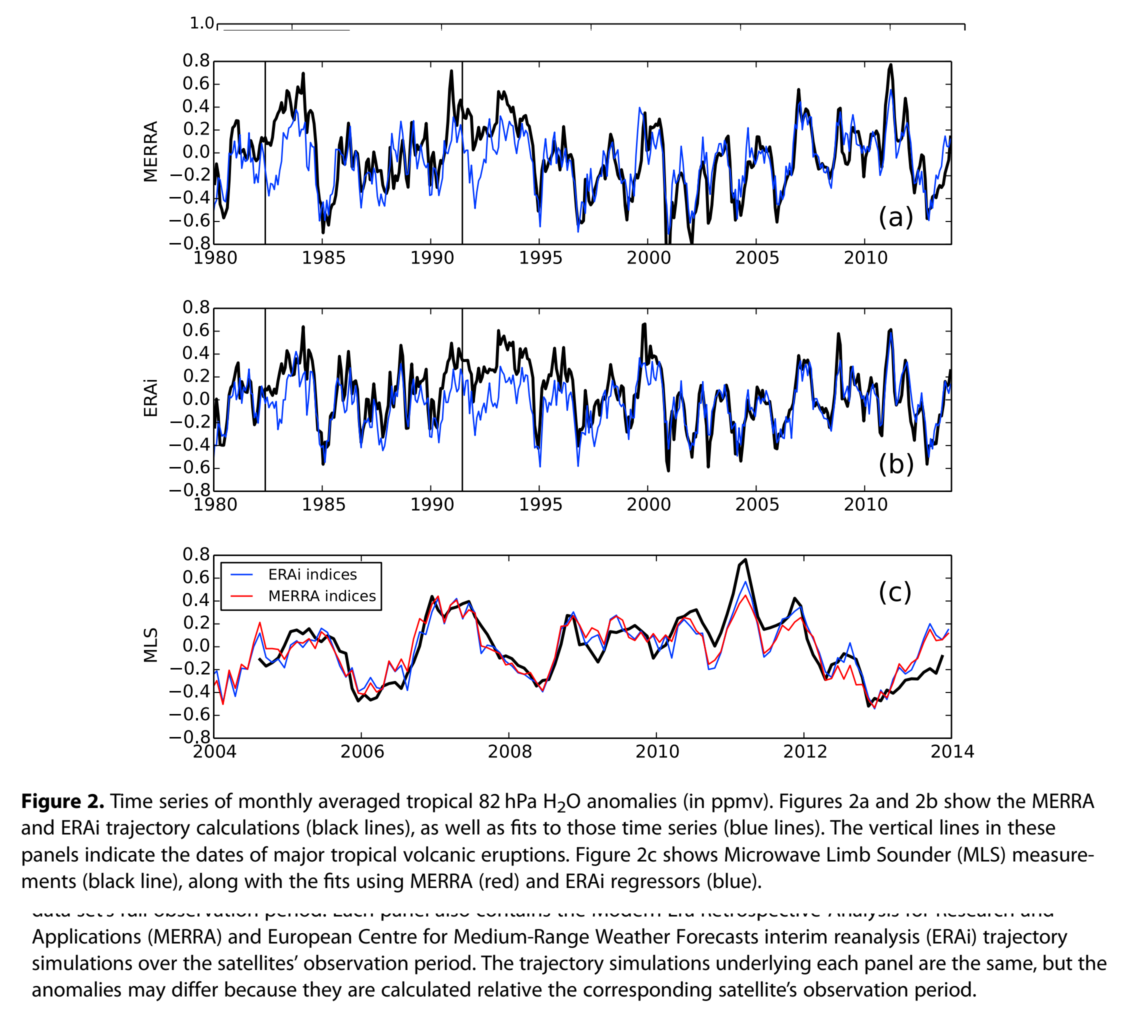


Figure 2. Time series of monthly averaged tropical 82 hPa H_2O anomalies (in ppmv). Figures 2a and 2b show the MERRA and ERAi trajectory calculations (black lines), as well as fits to those time series (blue lines). The vertical lines in these panels indicate the dates of major tropical volcanic eruptions. Figure 2c shows Microwave Limb Sounder (MLS) measurements (black line), along with the fits using MERRA (red) and ERAi regressors (blue).

Applications (MERRA) and European Centre for Medium-Range Weather Forecasts interim reanalysis (ERAi) trajectory simulations over the satellites' observation period. The trajectory simulations underlying each panel are the same, but the anomalies may differ because they are calculated relative the corresponding satellite's observation period.

>1300 trajectories initialized below cold point, allowed to rise.

- QBO, BDC, and mid-troposphere indices fit *anomalies* well

- post-volcanic discrepancies→role of aerosol in microphysics

- Qs: absolute accuracy of reanalyses temps? Microphysics? Role of unresolved waves? Mixing?

JGR, 2014.

Climate Coupling: Water vapor

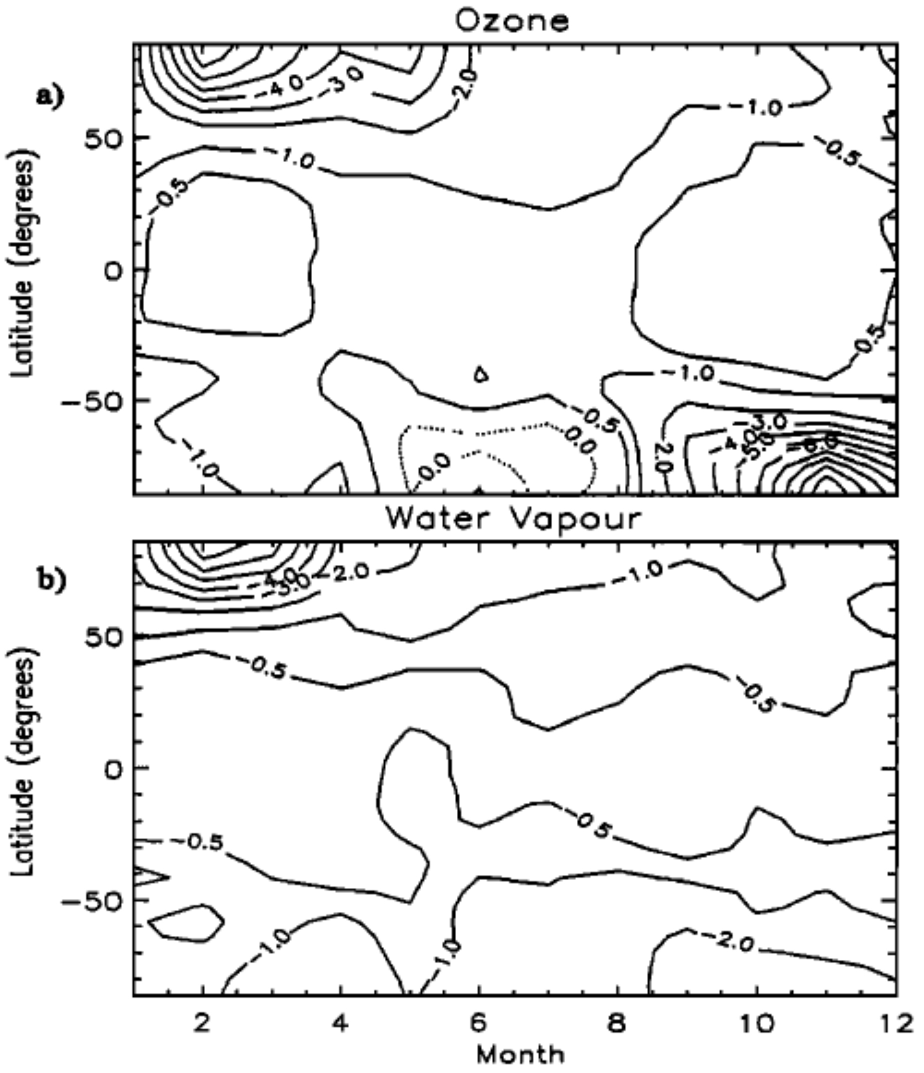


Figure 2. Zonally averaged temperature change between 15-30 km as a function of latitude and month for the OZONE (a) and WATER (b) scenarios. The contours are at 1.0 K intervals with an extra contour at -0.5 K.

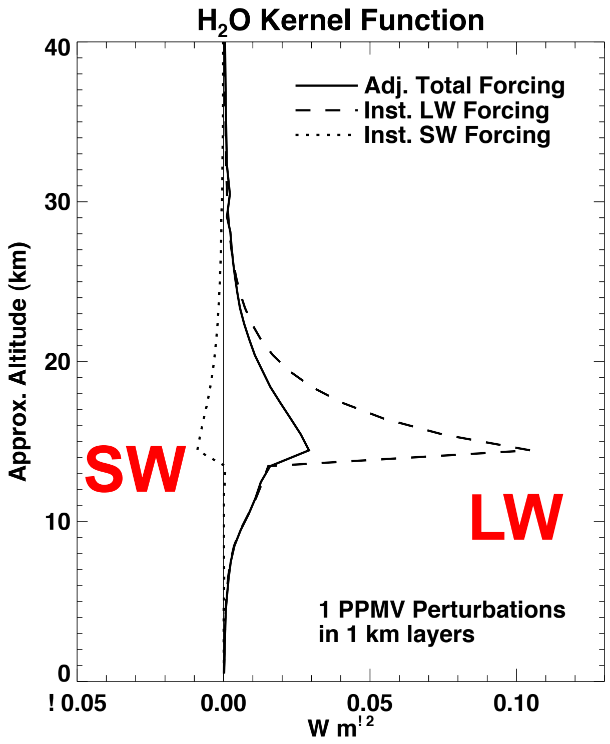
Seminal work by Forster & Shine, 1999

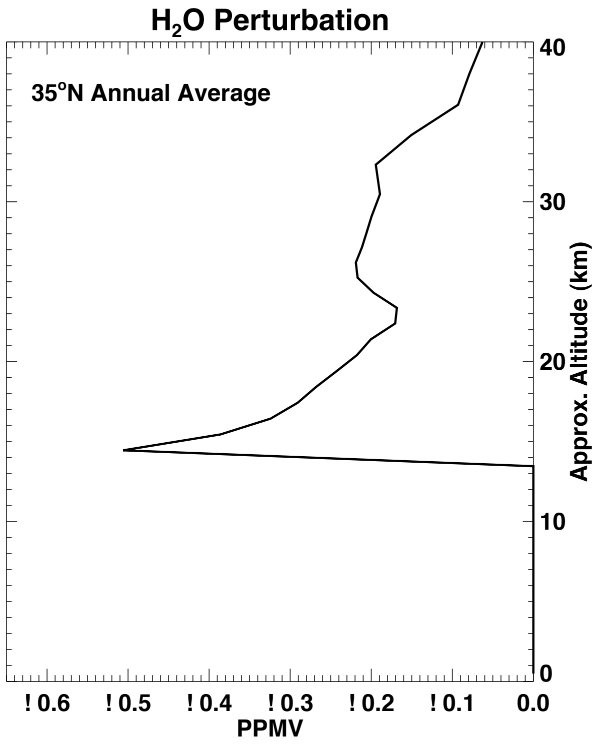
Noted an observed increase in stratospheric H_2O in limited balloon record from 1980 to 1998, and showed significant effects for <u>stratospheric</u> temperature trends since 1980.

Also said: *"the changes in stratospheric water vapour may have contributed, since 1980, a radiative forcing which enhances that due to carbon dioxide alone by 40%"*

GRL, 1999.

Narrow Region Packs a Wallop





Line-by-line IR radiative transfer (Portmann), includes stratospheric adjustment

Contributions to radiative forcing per ppmv change at given levels -> strongly peaked very near tropopause

Change in H2O near 40°N
Post-2000 minus pre-2000
Effect on hiatus?

Net: product of left and right panels! Very narrow!

Solomon et al., Science, 2010;

See earlier work by Randel et al., JGR, 2006 and later by Dessler, PNAS, 2013.

Stratospheric water vapor feedback

A. E. Dessler[a,1], M. R. Schoeberl[b], T. Wang[a], S. M. Davis[c,d], and K. H. Rosenlof[c]

[a]Department of Atmospheric Sciences, Texas A&M University, College Station, TX 77843; [b]Science and Technology Corporation, Columbia, MD 21046; [c]National Oceanic and Atmospheric Administration Earth System Research Laboratory, Boulder, CO 80305; and [d]Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, CO 80309

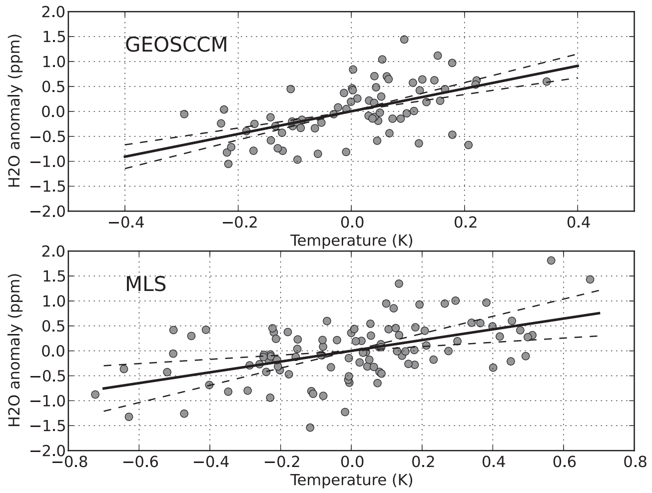


Fig. 3. Scatter plots of (*Upper*) GEOSCCM annual-average lowermost stratospheric H_2O (200-hPa mixing ratio, averaged between 50°N and 90°N) vs. extratropical tropospheric temperature (500-hPa temperature, averaged between 30°N and 90°N) and (*Lower*) the corresponding scatterplot of MLS monthly average H_2O vs. MERRA temperatures. For these plots, the GEOSCCM data have been filtered to remove long-term (>10 y) variations. The solid line is the least-squares fit, and the dashed lines are the 95% confidence interval.

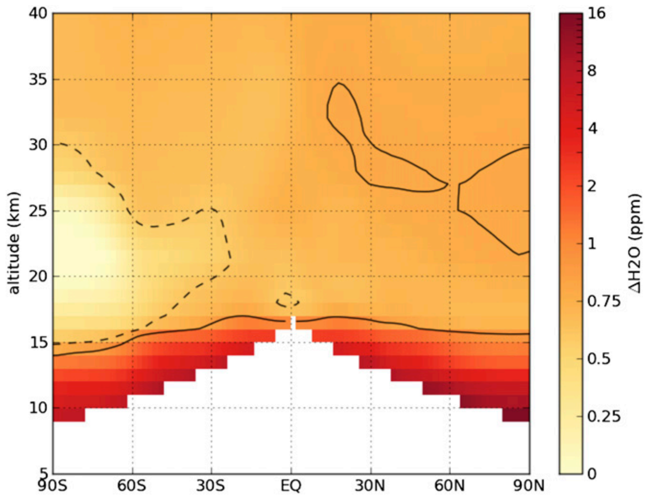


Fig. 4. Change in zonal average stratospheric H_2O in ppm over the 21st century from the GEOSCCM; the contribution from methane oxidation has been subtracted. Note that the color scale is nonlinear; white areas indicate the troposphere. The dashed and solid lines are the 0.6 and 0.8 ppm contours, respectively.

PNAS, 2013.

Obsvd and modelled variability in water vapor and UTLS temperatures→ a 10-30% contribution to climate sensitivity from stratospheric input of H2O

Has been studied with some other models….enough models?
Warm bias in CMIP5 TTL (Hardiman et al., J. Clim., 2015).

Asian Monsoon Transport of Pollution to the Stratosphere

William J. Randel,[1]* Mijeong Park,[1] Louisa Emmons,[1] Doug Kinnison,[1] Peter Bernath,[2,3] Kaley A. Walker,[4,3] Chris Boone,[3] Hugh Pumphrey[5]

Transport of air from the troposphere to the stratosphere occurs primarily in the tropics, associated with the ascending branch of the Brewer-Dobson circulation. Here, we identify the transport of air masses from the surface, through the Asian monsoon, and deep into the stratosphere, using satellite observations of hydrogen cyanide (HCN), a tropospheric pollutant produced in biomass burning. A key factor in this identification is that HCN has a strong sink from contact with the ocean; much of the air in the tropical upper troposphere is relatively depleted in HCN, and hence, broad tropical upwelling cannot be the main source for the stratosphere. The monsoon circulation provides an effective pathway for pollution from Asia, India, and Indonesia to enter the global stratosphere.

Spectacular evidence of transport of key constituents (not just HCN) in the Asian monsoon region.

Q: Roles of deep convection? Mixing?

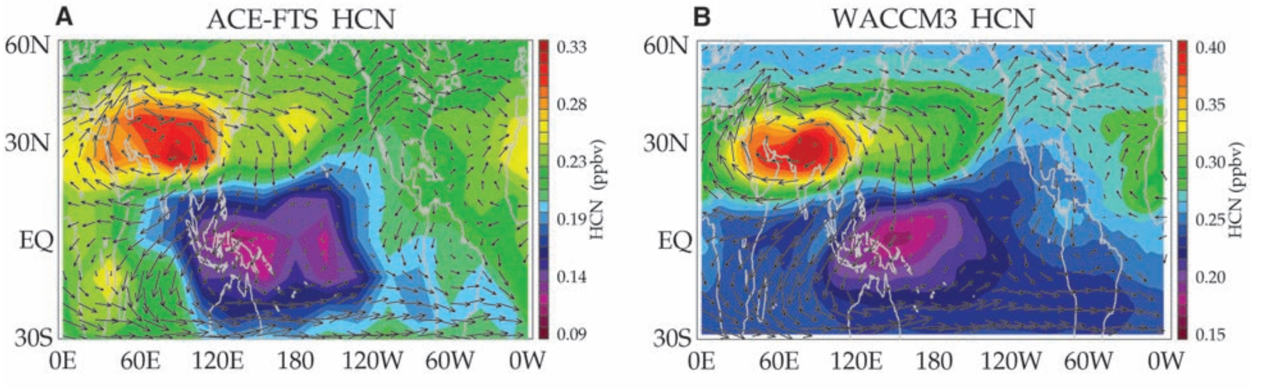
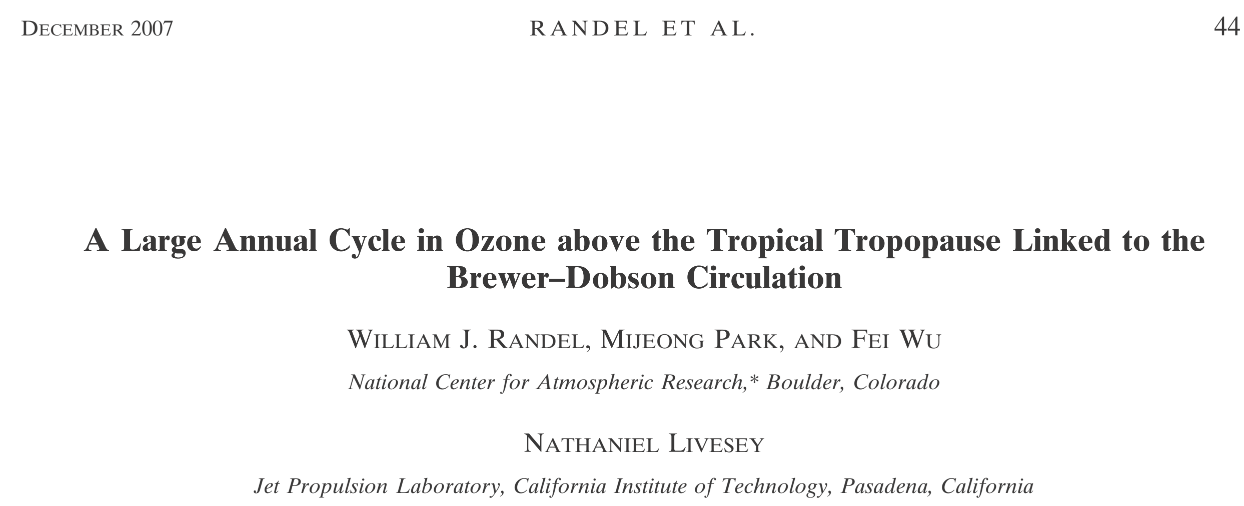


Fig. 1. Time average mixing ratio [parts per billion by volume (ppbv)] of HCN near 13.5 km during boreal summer (June to August) derived from (**A**) ACE-FTS observations and (**B**) WACCM chemical transport model calculations. Arrows in both panels denote winds at this level derived from meteorological analysis, showing that the HCN maximum is linked with the upper tropospheric Asian monsoon anticyclone.

JGR, 1996.

Controls on ozone in the tropical UTLS



DECEMBER 2007 RANDEL ET AL. 44

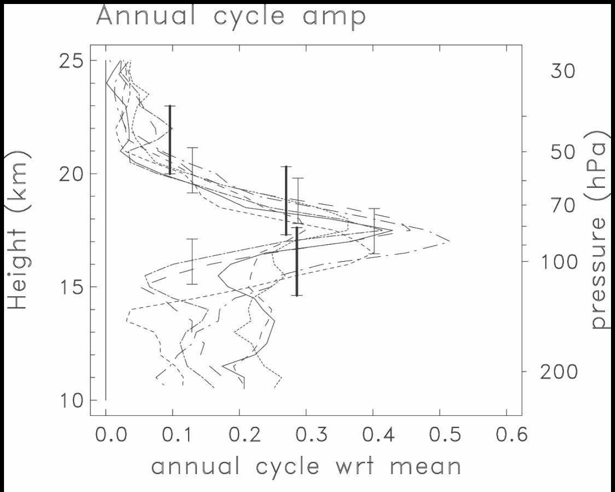
A Large Annual Cycle in Ozone above the Tropical Tropopause Linked to the Brewer–Dobson Circulation

WILLIAM J. RANDEL, MIJEONG PARK, AND FEI WU

National Center for Atmospheric Research, Boulder, Colorado*

NATHANIEL LIVESEY

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California



Steep vertical gradients in lifetime, abundance, seasonal cycle make the tropical UTLS unique for ozone.
Qs: Role of deep convection? Lightning? Horizontal mixing?

JAS, 2007.

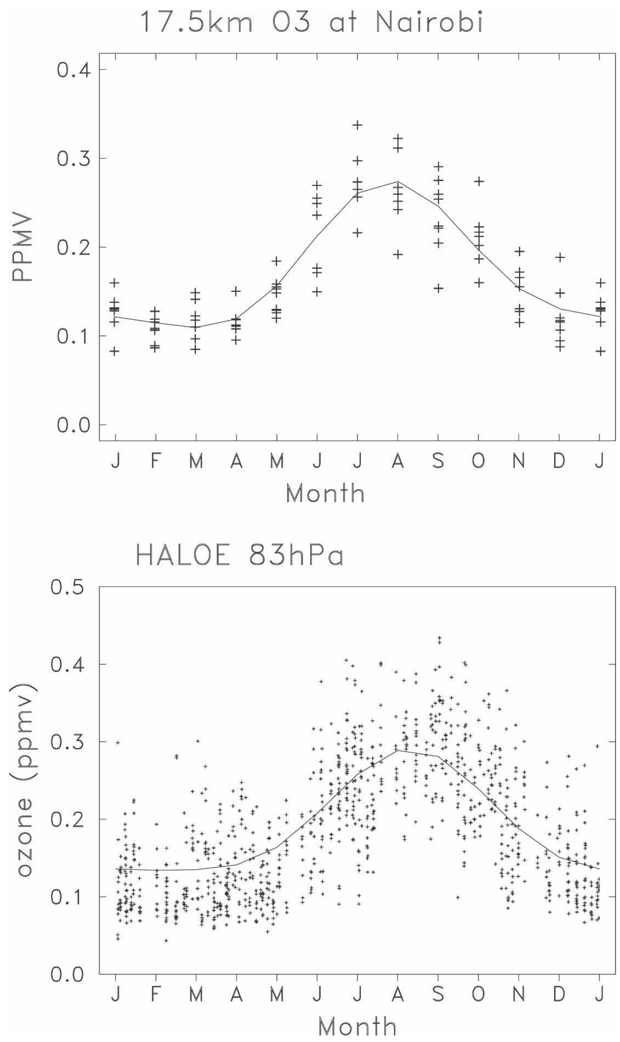
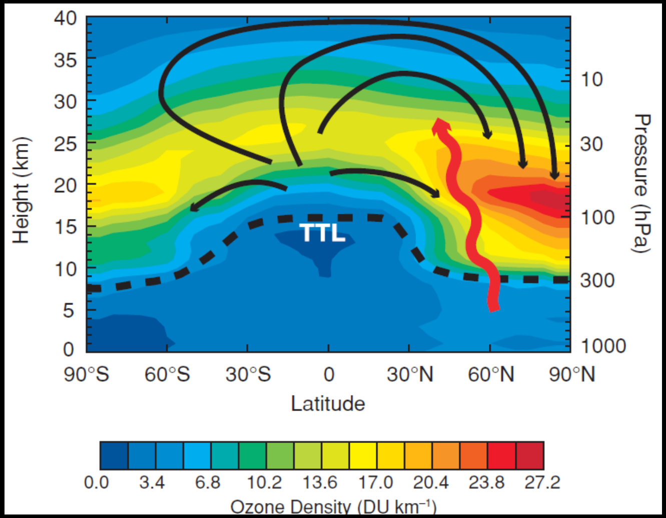
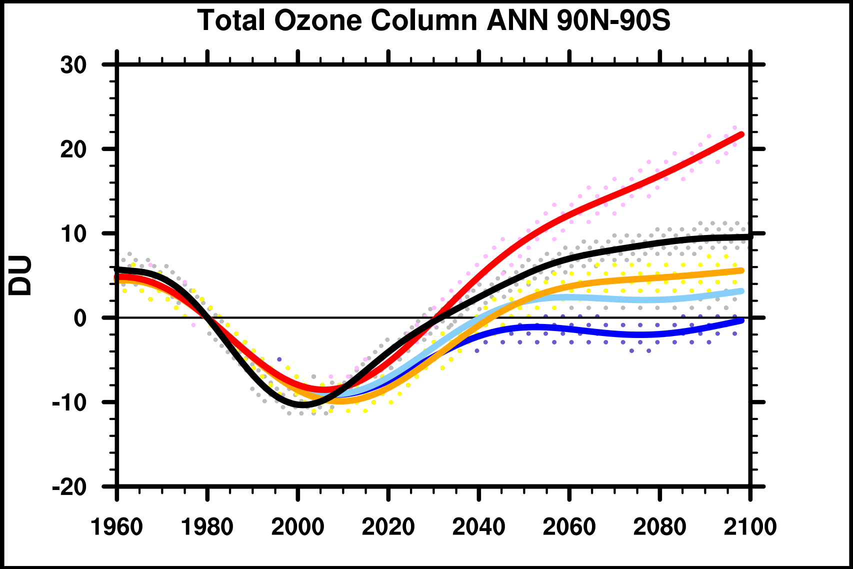


FIG. 1. (top) Ozone mixing ratio (ppmv) at 17.5 km derived from ozonesonde measurements over Nairobi during 1998–2006, plotted according to month of the observation. (bottom) HALOE ozone observations at 83 hPa over 10°N–S, combining all observations over 1992–2005. The thin line in each panel shows the harmonic seasonal cycle fit to the individual points.

Ozone recovery – but not for the tropics?

Stronger B-D circulation in a warmer world → reduced ozone in the tropics, and a new mechanism for 21st century ozone loss in an unexpected region.





Pawson et al., chapter 2, ozone assessment, 2014

A large ozone-circulation feedback and its implications for global warming assessments

Peer J. Nowack[1*], N. Luke Abraham[1,2], Amanda C. Maycock[1,2], Peter Braesicke[1,2†], Jonathan M. Gregory[2,3,4], Manoj M. Joshi[2,3†], Annette Osprey[2,3] and John A. Pyle[1,2]

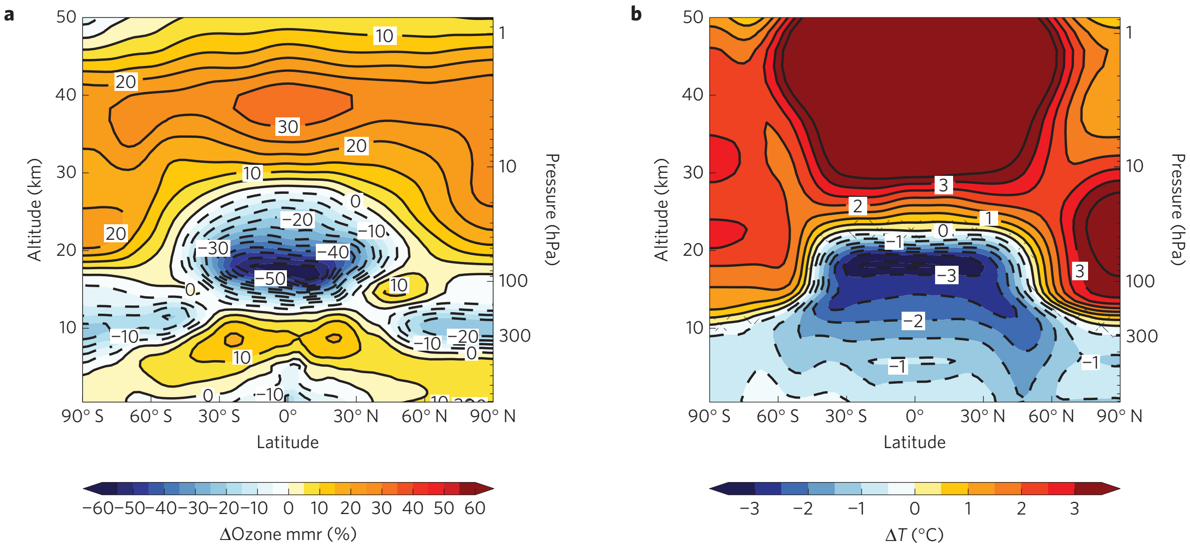


Figure 3 | Annual and zonal mean differences in ozone and temperature. Shown are averages over the last 50 years of each experiment. **a**, The percentage differences in ozone between simulations B and A. By definition, these are identical to the differences in the climatologies between B/B1/B2 and C1/C2/A/A1/A2. Note that the climatologies of experiments B1/B2 and other 2D and 3D versions of each set of experiment are only identical after zonal averaging. **b**, The absolute temperature anomaly (°C) between experiments B and C1. Apart from some areas around the tropopause (hatched out), all differences in **b** are statistically significant at the 95% confidence level using a two-tailed Student's *t*-test.

Nature Clim. Chg., 2015

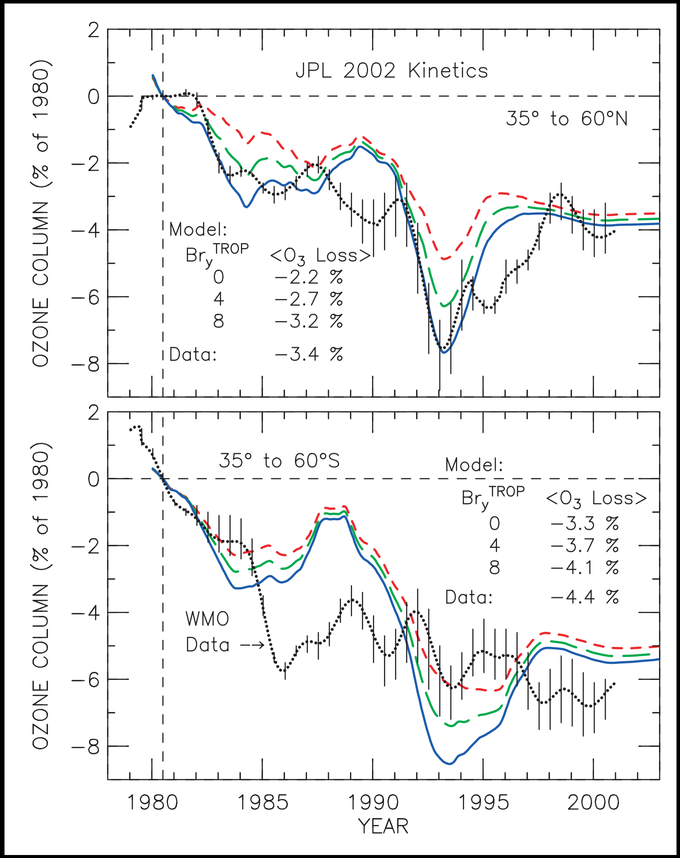
Stronger B-D circulation in a 4xCO2 world→ reduced ozone at TTL, cooling, effects on cirrus and H_2O.

A *negative* climate feedback in a fully coupled warmer world?

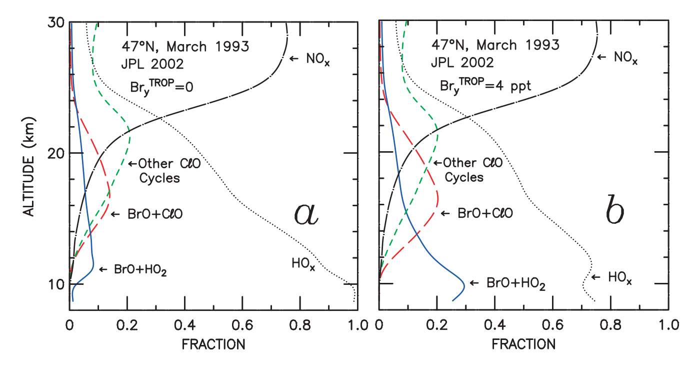
The UTLS, and ozone elsewhere: VSLS


Sensitivity of ozone to bromine in the lower stratosphere

R. J. Salawitch,[1] D. K. Weisenstein,[2] L. J. Kovalenko,[3] C. E. Sioris,[4] P. O. Wennberg,[3] K. Chance,[4] M. K. W. Ko,[5] and C. A. McLinden[6]



GRL, 2005.



Importance of very short lived Cly, Bry inputs to stratosphere

Qs: Balance between organic and other forms such as BrO, variability (e.g., ENSO).

See also Carpenter and Liss, JGR, 2000; Solomon et al., JGR, 1994.

Widening of the tropical belt in a changing climate

DIAN J. SEIDEL[1], QIANG FU[2],
WILLIAM J. RANDEL[3], THOMAS J. REICHLER[4]

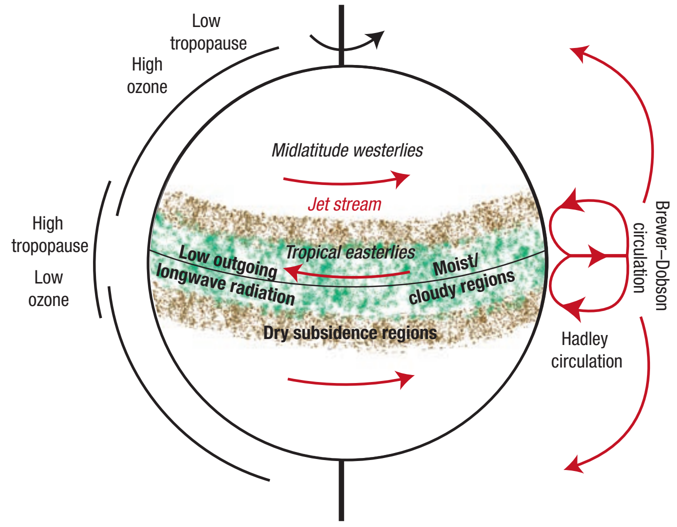
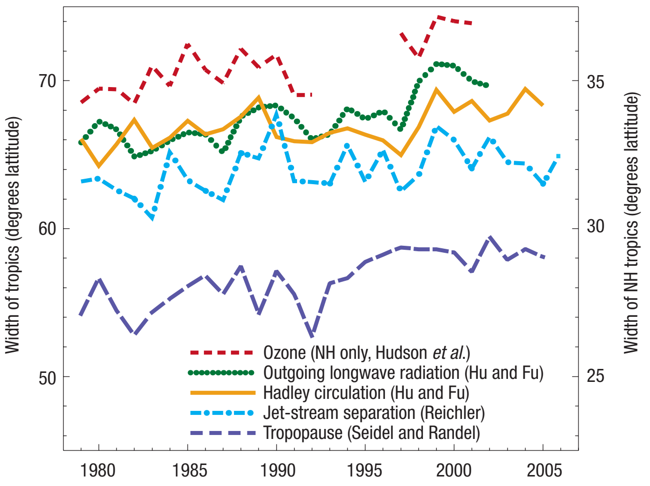


Figure 1 What climatological features distinguish the tropics? Some of the atmospheric structure, circulation, and hydrological features shown in this schematic diagram of the Earth have moved poleward in recent decades, indicating a widening of the tropical belt and the Hadley circulation.

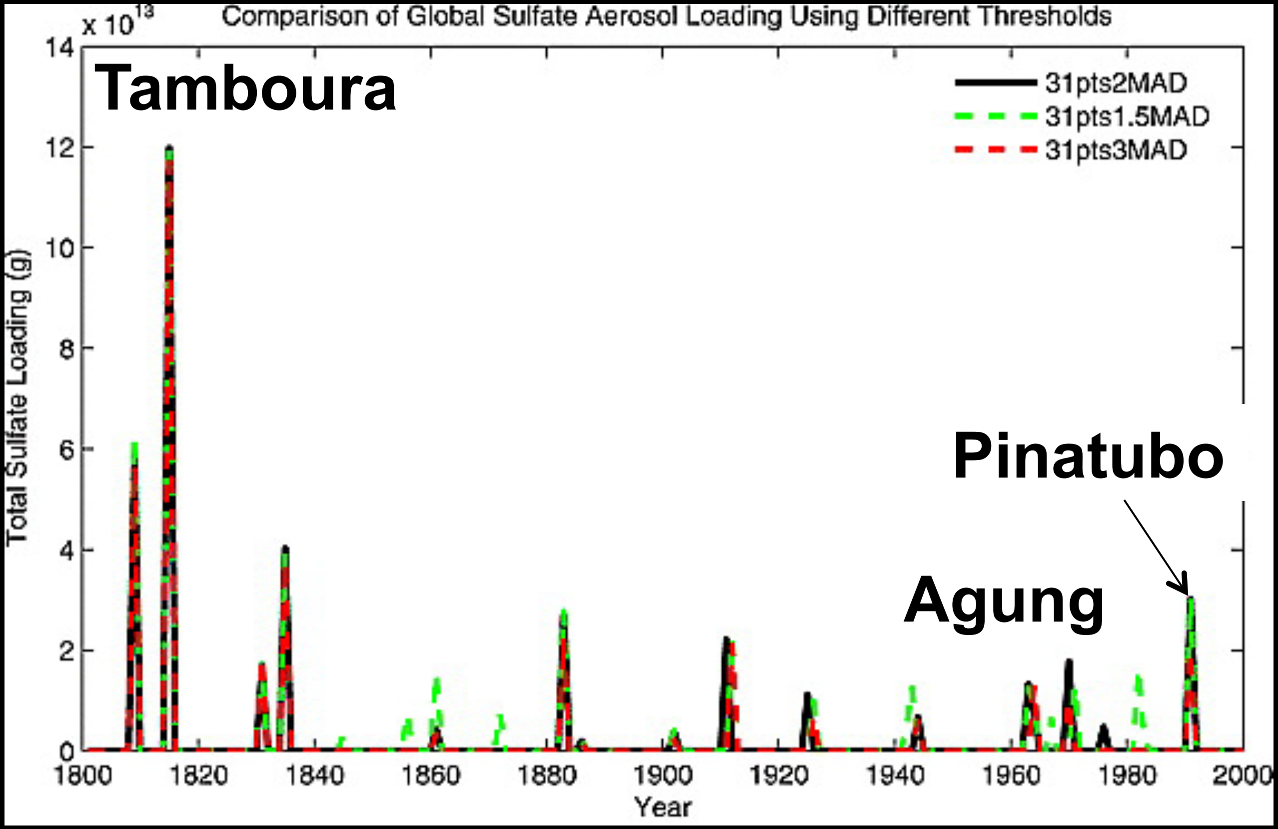


Nature Geosci., 2008

Substantial implications for surface CC if real

Forcing vs internal variability?
Robustness of the trend metrics? (Rosenlof and Davis, J. Clim., 2012)?
GHG? Black carbon, trop ozone? Ozone hole?

Volcanic forcing of climate over the past 1500 years: A key index for climate models

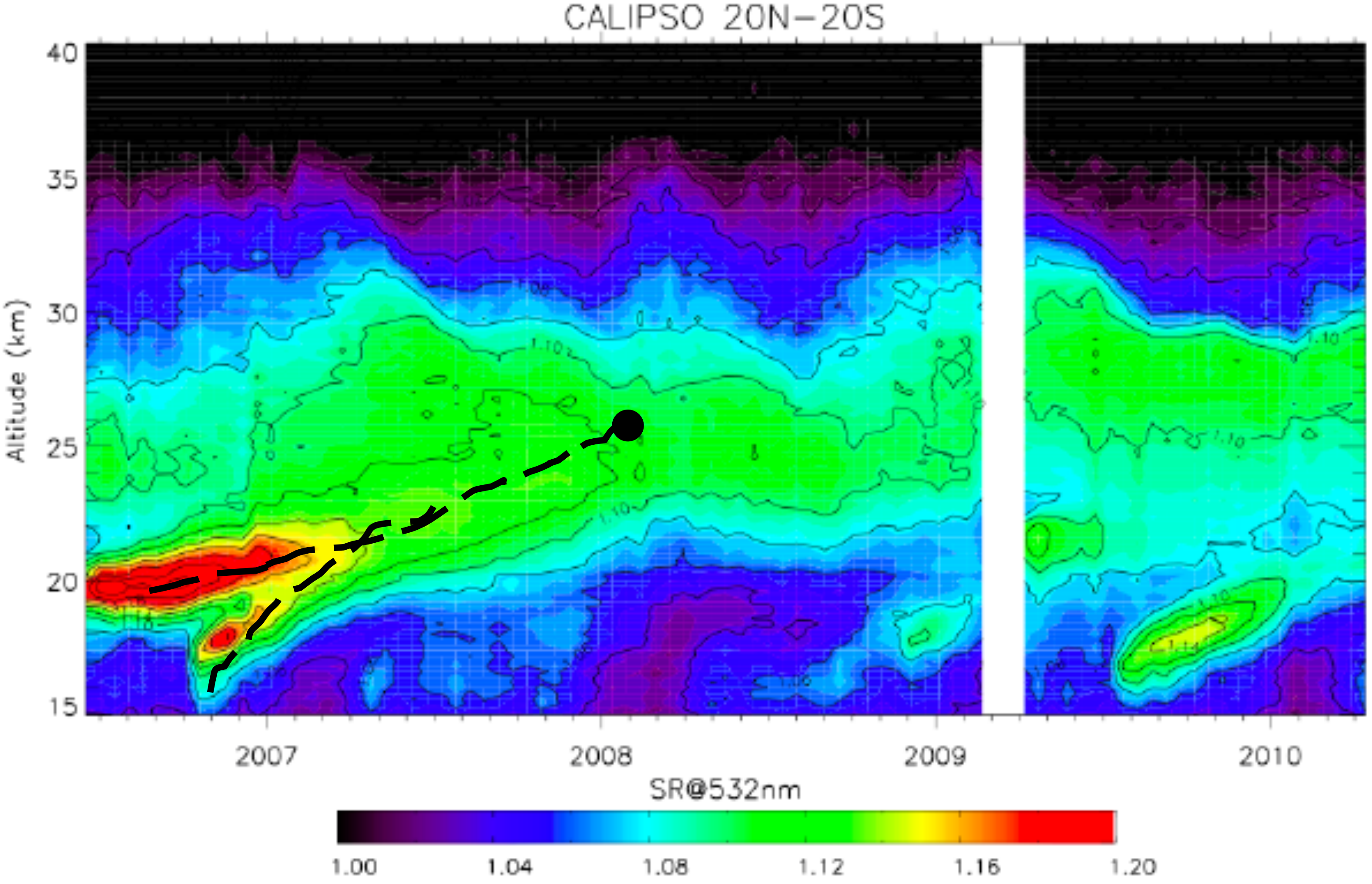


Large tropical eruptions, injected material directly into stratosphere …is that what it takes to influence climate?

What about since Pinatubo?

Gao et al., Journal of Geophysical Research: Atmospheres Volume 113, Issue D23, D23111, 13 DEC 2008 DOI: 10.1029/2008JD010239
http://onlinelibrary.wiley.com/doi/10.1029/2008JD010239/full#jgrd14895-fig-0008

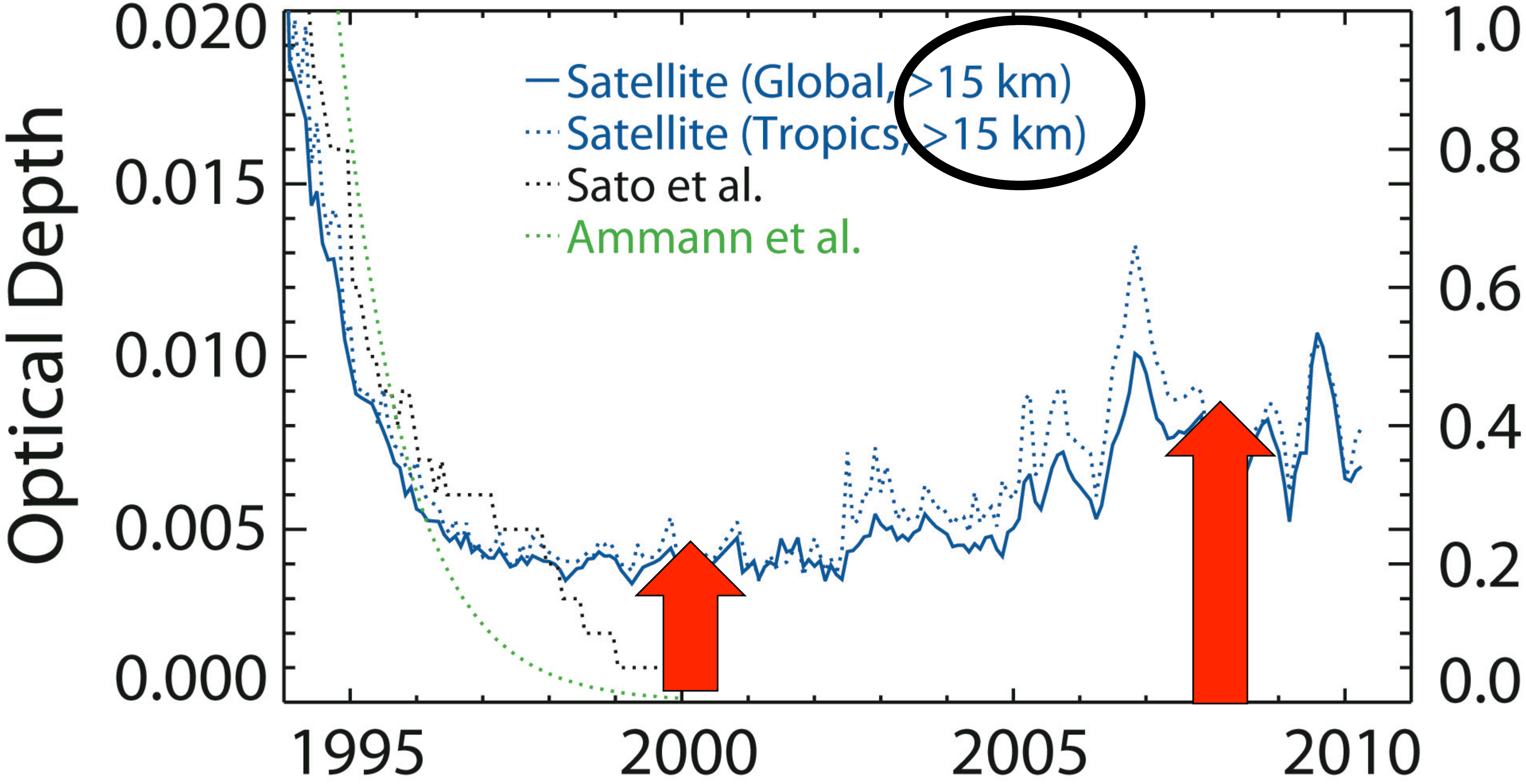
Input of volcanic material post 2000 from a ‘swarm’ of volcanoes



20N-20S altitude versus time slice

Vernier et al., GRL, 2011
Solomon et al., Science, 2011

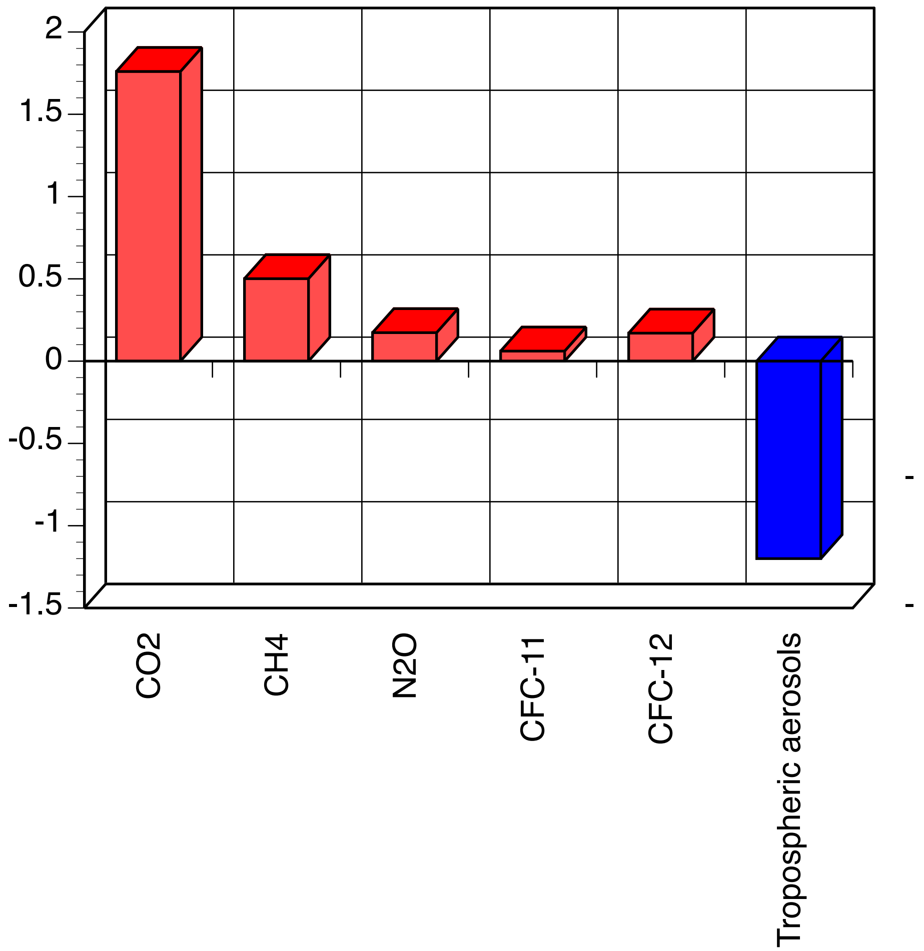
Global Aerosol Optical Depth



Standard climate models (e.g. CMIP5) had incorrect forcing. Volcanic contribution to the hiatus estimated at -0.05°C, about 1/3 of the effect *(Solomon et al., Science, 2011)*. Contribution between tropopause and 15 km also important (*Ridley et al., GRL, 2015*).

Change in Radiative Budget (W m^{-2})

1750 to 2010

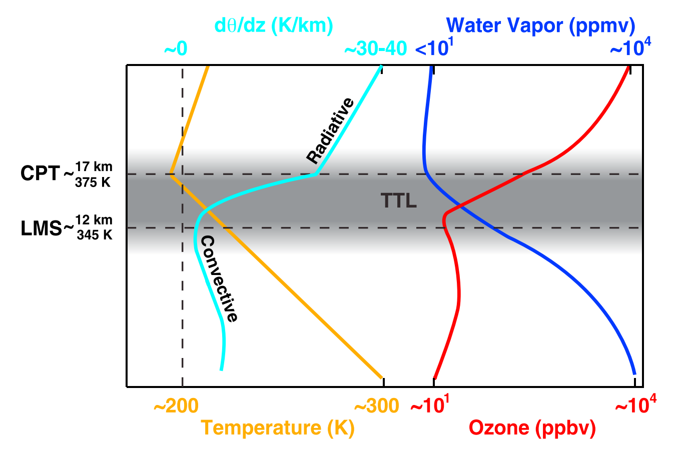


Overarching conclusion: on decadal timescales, different forcing agents need to be considered. The stratosphere plays an important role on shorter time scales in particular.

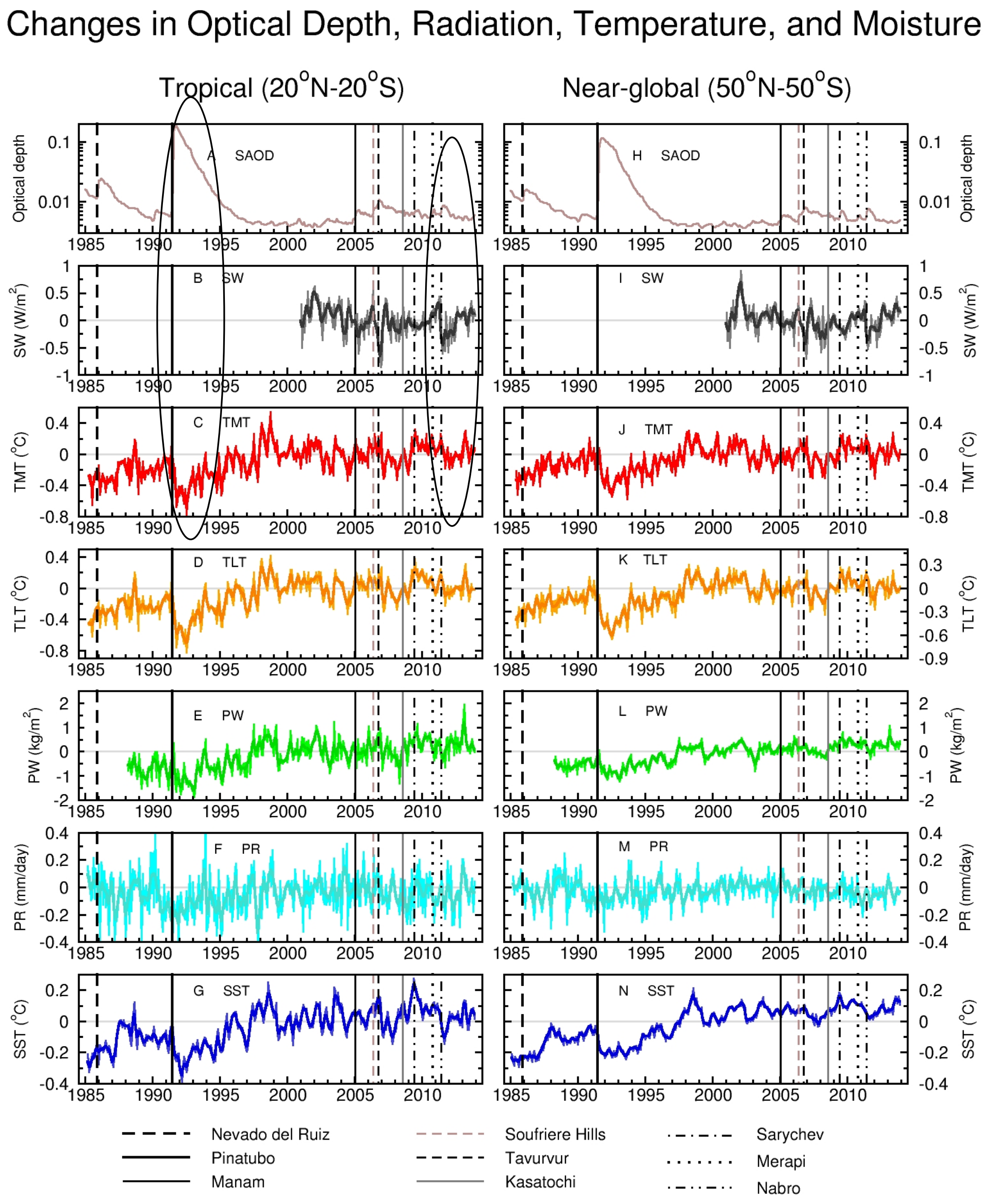
Some closing thoughts

Why we care about the tropical UTLS: key roles of tropical H_2O, volcanoes, and O_3 in the climate system, the importance of ozone itself for tropical UV, VSLS and ozone, tropical widening (if it is real), and more

Closing remarks: How can we better address decades-old and new challenges? What new tools do we have and how could we use them to address H_2O and O_3 changes, drivers, and climate impacts? How can we better quantify sulfur inputs (background and volcanic)? Understanding of cirrus clouds?



Pan et al., JGR, 2013.



Changes in multiple climate variables from recent volcanoes.

Multi-variate analysis

Santer et al., GRL, 2014

Tropical “Tape Recorder”

- Dryness of the stratosphere and implication that most air enters in the tropics dates to Brewer (1949)
- Concept of a tape recorder introduced by Mote et al. in 1990s
- Cold tropical tropopause introduces seasonally very dry air, esp. in the ‘warm pool’ region; often called cold point or dehydration region
- Some wet air comes in seasonally, including in the monsoon region

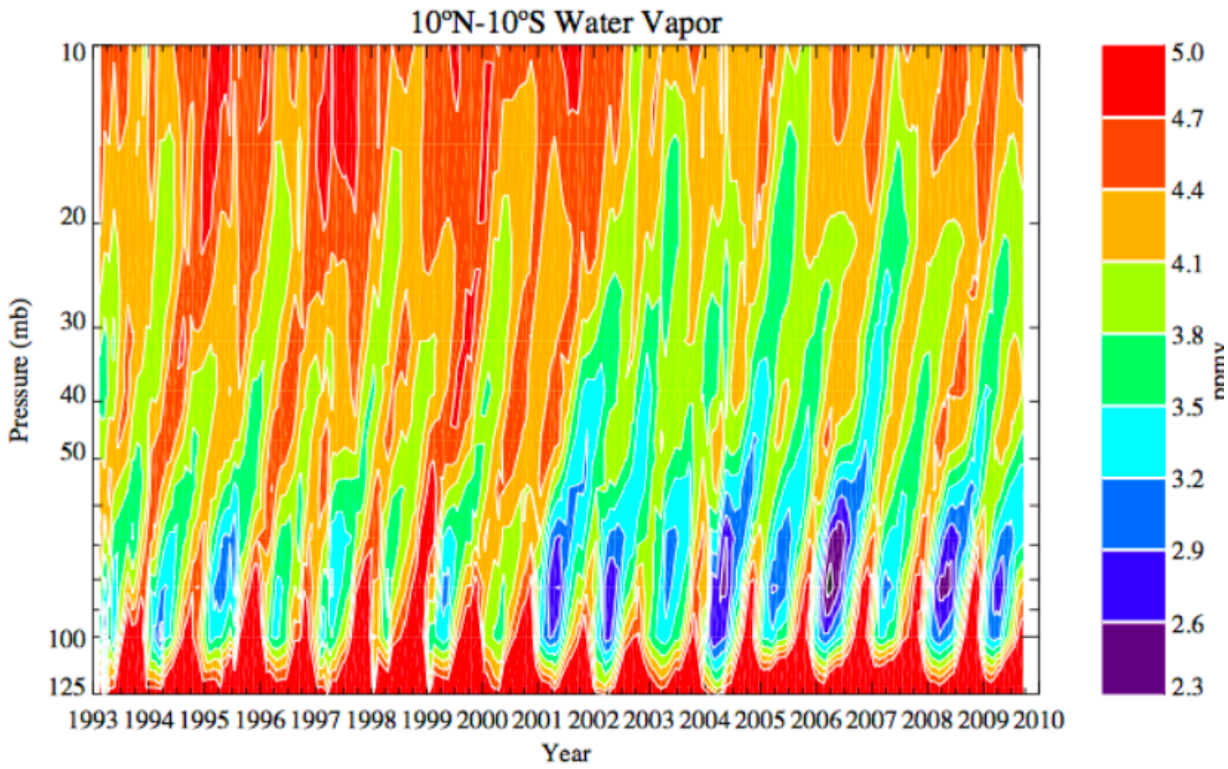


Figure 4.1.4. Tropical water vapor (10°N-10°S, monthly averages) plotted versus ti
showing upward propagation of the water vapor tape recorder (Mote et al., 1995). This
combination of UARS HALOE and Aura MLS measurements. During the period of
overlap (from mid 2004 through the end of 2005), differences were computed for matc
profiles at each pressure level. That average shift was applied to the HALOE measurem
at each level; for 82 hPa it is on the order of 0.5 ppmv. The key feature to note here is
change to lower values of the water vapor minimum (hygropause) at the end of 2000,
upward propagation of those lower values in subsequent years. This is an update of Fi
10 from Rosenlof and Reid (2008).

Importance of waves

Direct impacts of waves on tropical cold point tropopause temperature

Ji-Eun Kim[1,2] **and M. Joan Alexander**[2]

[1]Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, Colorado, USA, [2]NorthWest Research Associates, CoRA Office, Boulder, Colorado, USA

"waves in the tropical tropopause layer lower cold point temperature by 1.6 K on average relative to the seasonal mean"

Q: Role of waves at various time/space scales for water vapor transport?

GRL, 2015.

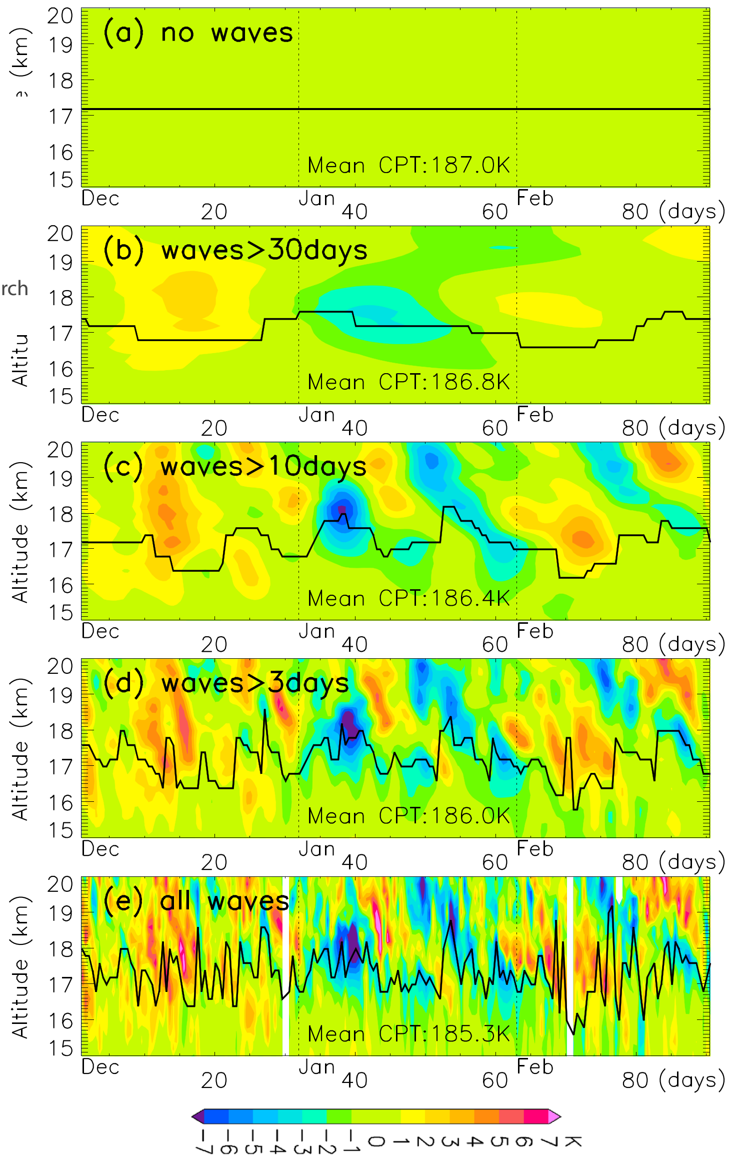
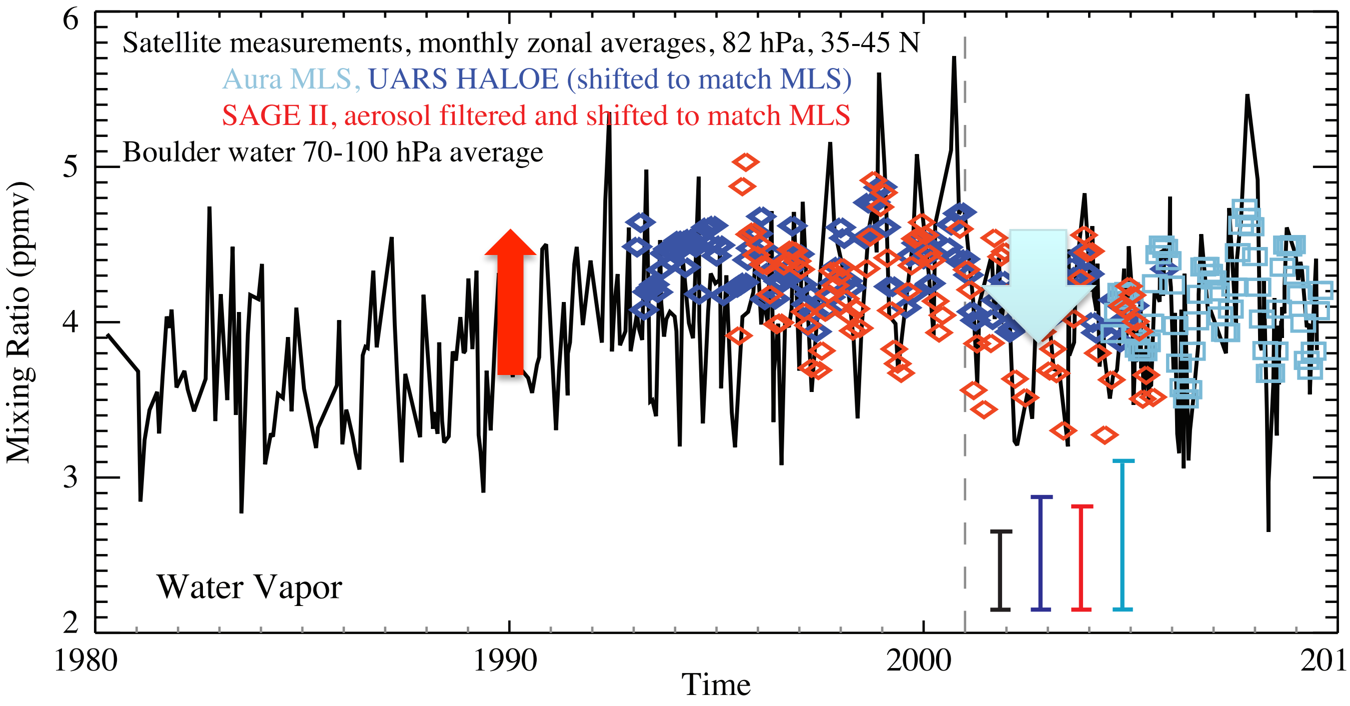


Figure 2. Time-height sections of temperature anomalies for December 2012 to February 2013 at 171°E, 7°N from Majuro radiosonde observations. The horizontal thick black curve indicates the cold point tropopause. Higher-frequency waves are gradually added from Figures 2a–2e. (a) Mean temperature anomalies (zero by definition). Fourier-filtered temperature anomalies including wave periods longer than (b) 30 days, (c) 10 days, and (d) 3 days. (e) All waves observed by the radiosonde are included. The mean CPT temperature for each case is listed on the bottom of each panel.

Many different water vapor datasets, one story: a marked change after 2000



- **Change in tropical transport is also suggested by ozone data**
- **Limited data before the mid-1990s suggest increasing H2O up to 2000**

Dhomse et al.: Water Vapor and Eddy Heat Flux

-> What about extratropical wave driving…?

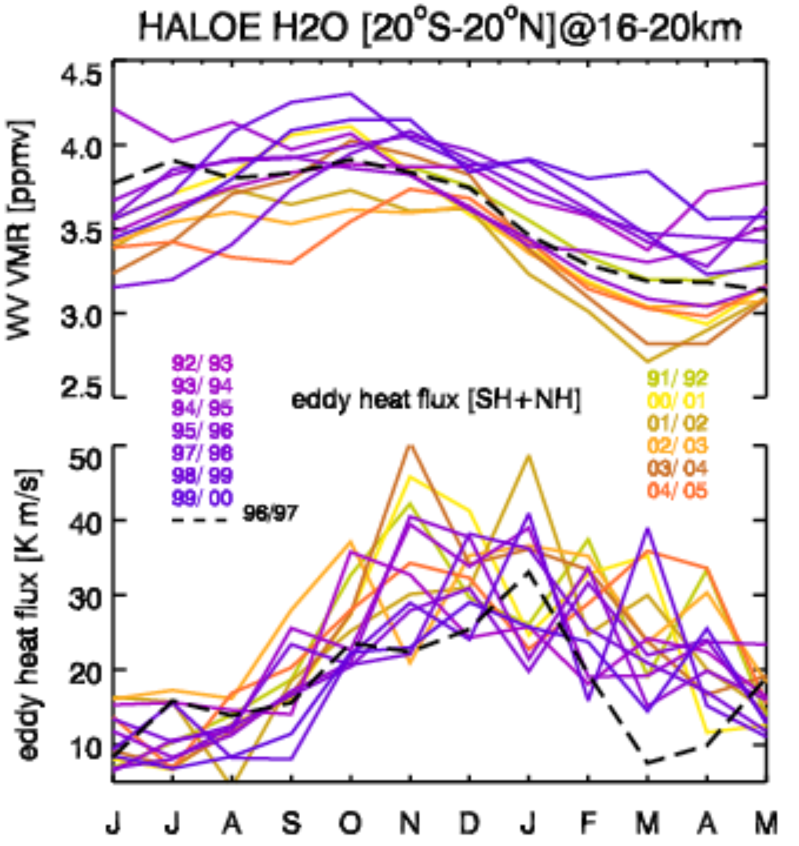


Fig. 1. Annual cycle of monthly mean tropical water vapor VMRs from HALOE V19 data averaged between 16 km and 20 km and between 20° S and 20° N (top) and monthly mean mid-latitude eddy heat flux at 50 hPa averaged from 45° to 75° with area weights and added from both hemispheres (bottom). Years with higher and lower wave activity are shown in yellow-red and blue-violet lines, respectively.

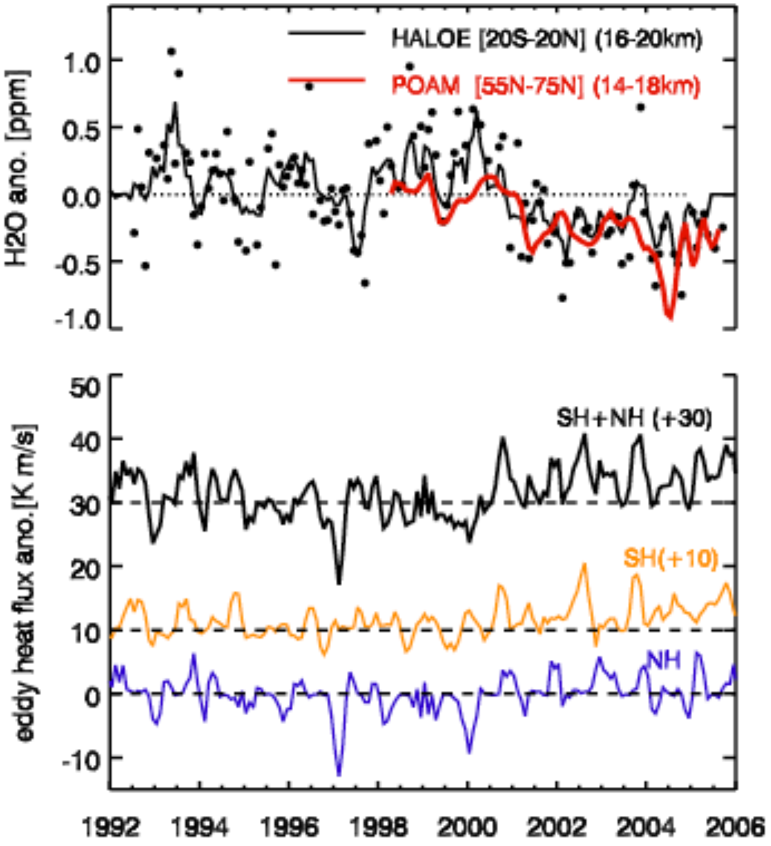
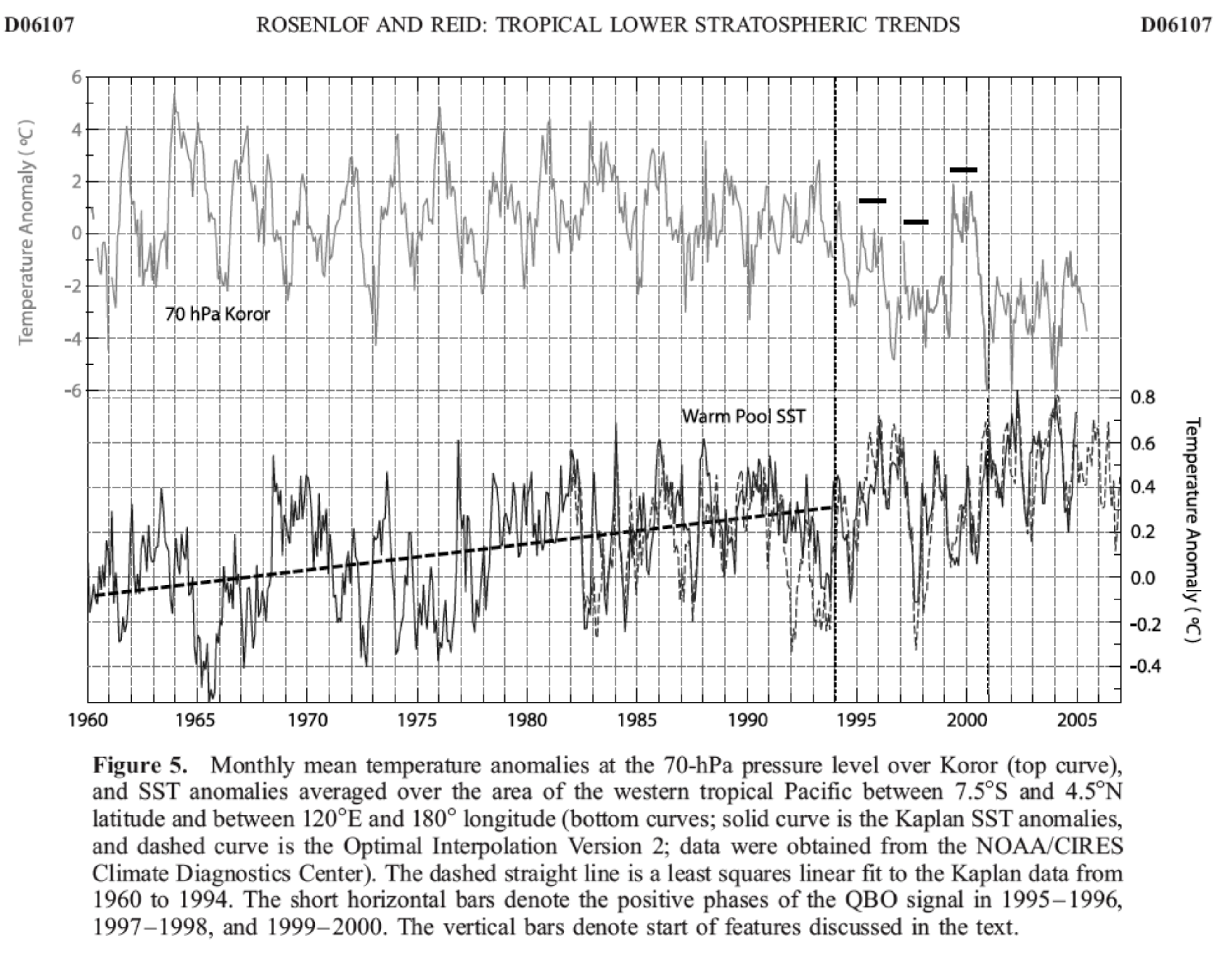


Fig. 3. Top panel: monthly mean H_2O vapor anomalies from HALOE (16–20 km, 20° S–20° N) in the tropics (black line) and POAM III (14–18 km) at middle to high NH latitudes (red line). Both lines represent three month mean water vapor VMRs, while black circles are monthly mean HALOE values (Update from Randel et al., 2006). Bottom panel: Time series of monthly mean 50 hPa eddy heat flux anomalies in each hemisphere and globally (added from both hemispheres).

Recent Tropical Pacific Temperatures, SSTs, and related

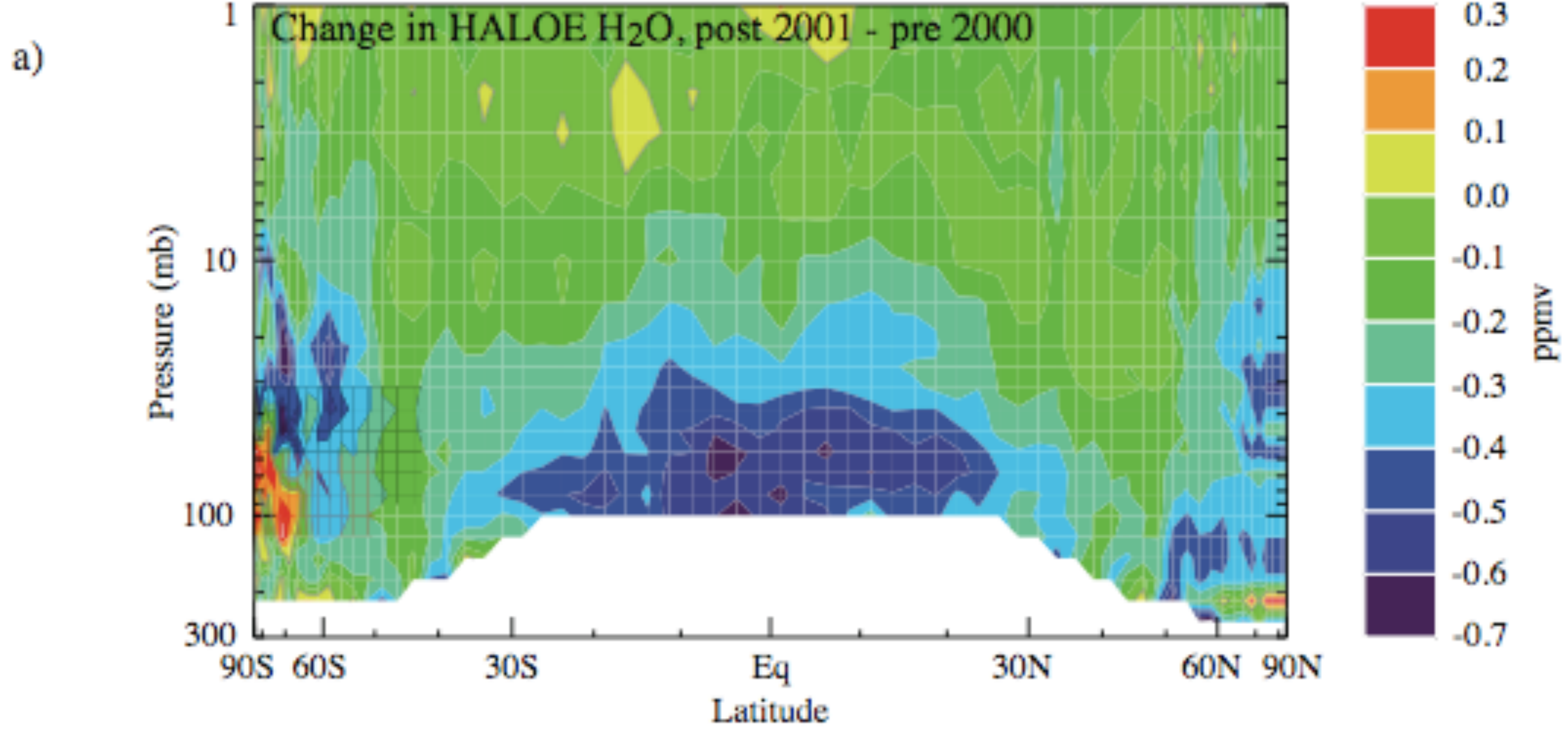


D06107 ROSENLOF AND REID: TROPICAL LOWER STRATOSPHERIC TRENDS D06107

Figure 5. Monthly mean temperature anomalies at the 70-hPa pressure level over Koror (top curve), and SST anomalies averaged over the area of the western tropical Pacific between 7.5°S and 4.5°N latitude and between 120°E and 180° longitude (bottom curves; solid curve is the Kaplan SST anomalies, and dashed curve is the Optimal Interpolation Version 2; data were obtained from the NOAA/CIRES Climate Diagnostics Center). The dashed straight line is a least squares linear fit to the Kaplan data from 1960 to 1994. The short horizontal bars denote the positive phases of the QBO signal in 1995–1996, 1997–1998, and 1999–2000. The vertical bars denote start of features discussed in the text.

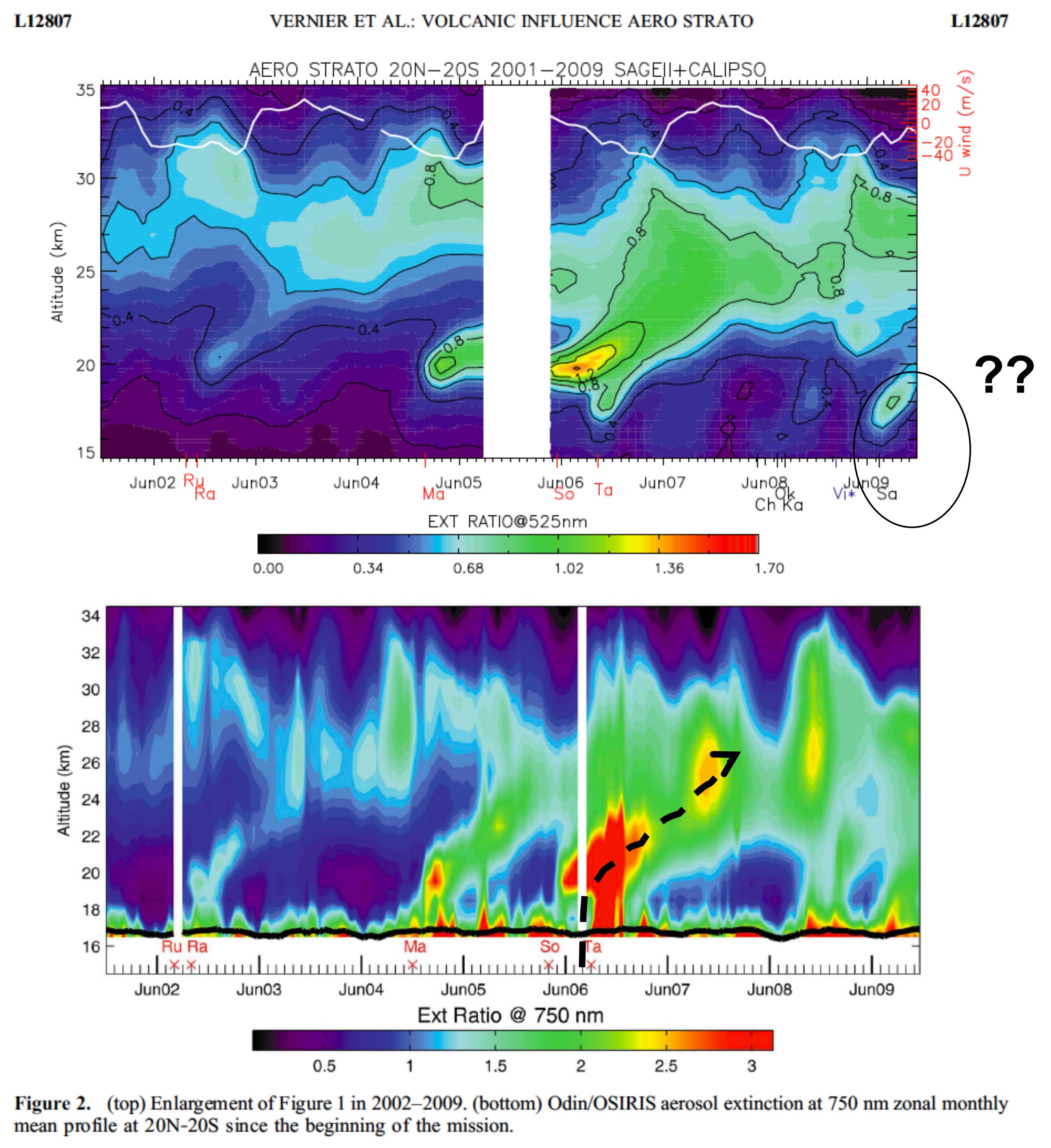
Relationship between colder cold points and SSTs in the western Pacific; Rosenlof and Reid; Dameris and Deckert; and others….

Observed changes in stratospheric water



The structure of the obsvd change in H2O (1996-2000 versus 2001-2004) shows its origin in the tropics (this is not from methane oxidation)

Solomon et al., 2010



L12807 VERNIER ET AL.: VOLCANIC INFLUENCE AERO STRATO L12807

Figure 2. (top) Enlargement of Figure 1 in 2002–2009. (bottom) Odin/OSIRIS aerosol extinction at 750 nm zonal monthly mean profile at 20N-20S since the beginning of the mission.

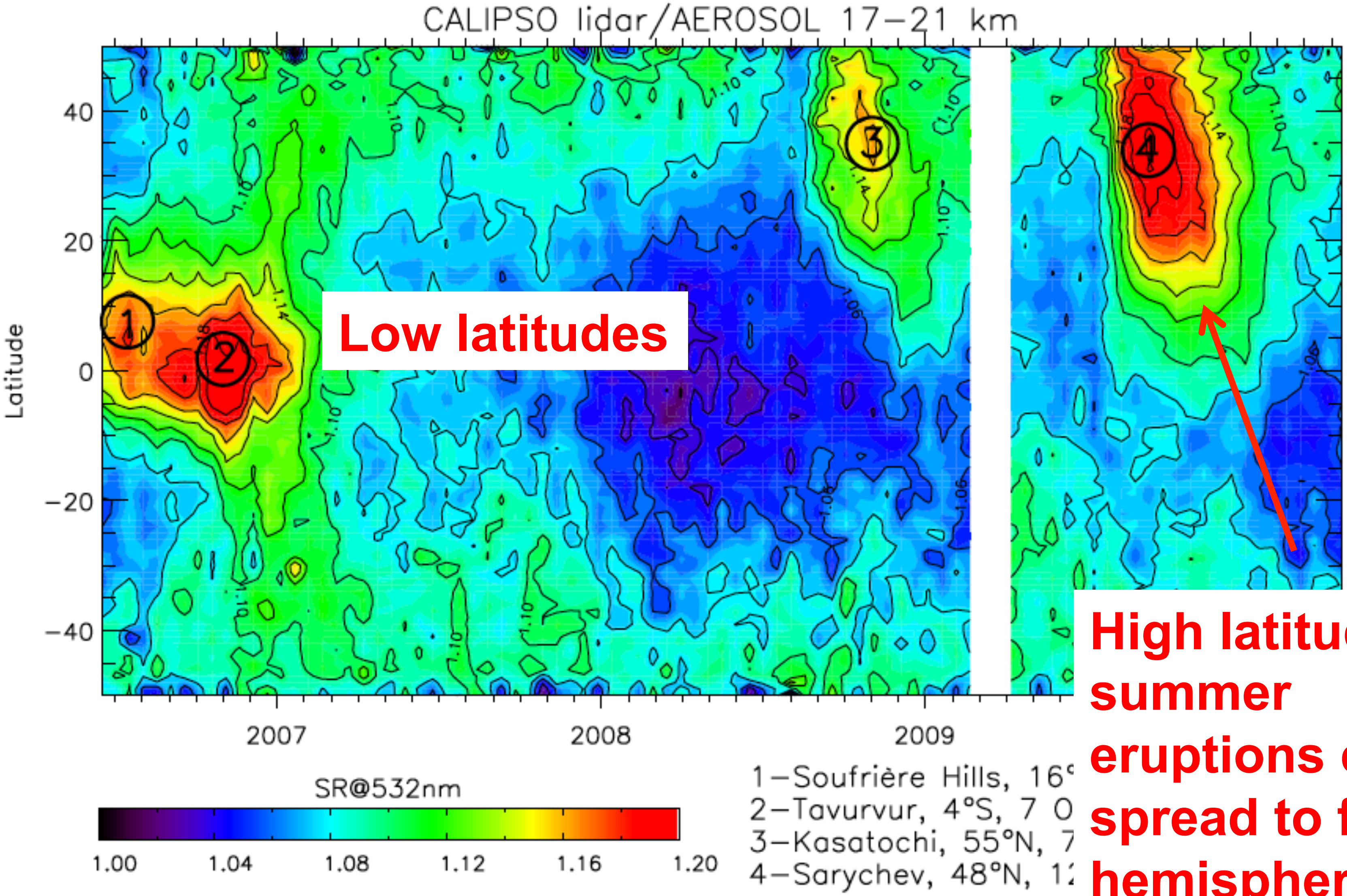
Independent instruments, same basic outcome

Significant effects from eruptions previously neglected.

Upward transport is important.

Vernier et al., GRL, 2011

Several recent eruptions influenced stratospheric aerosol



Low latitudes

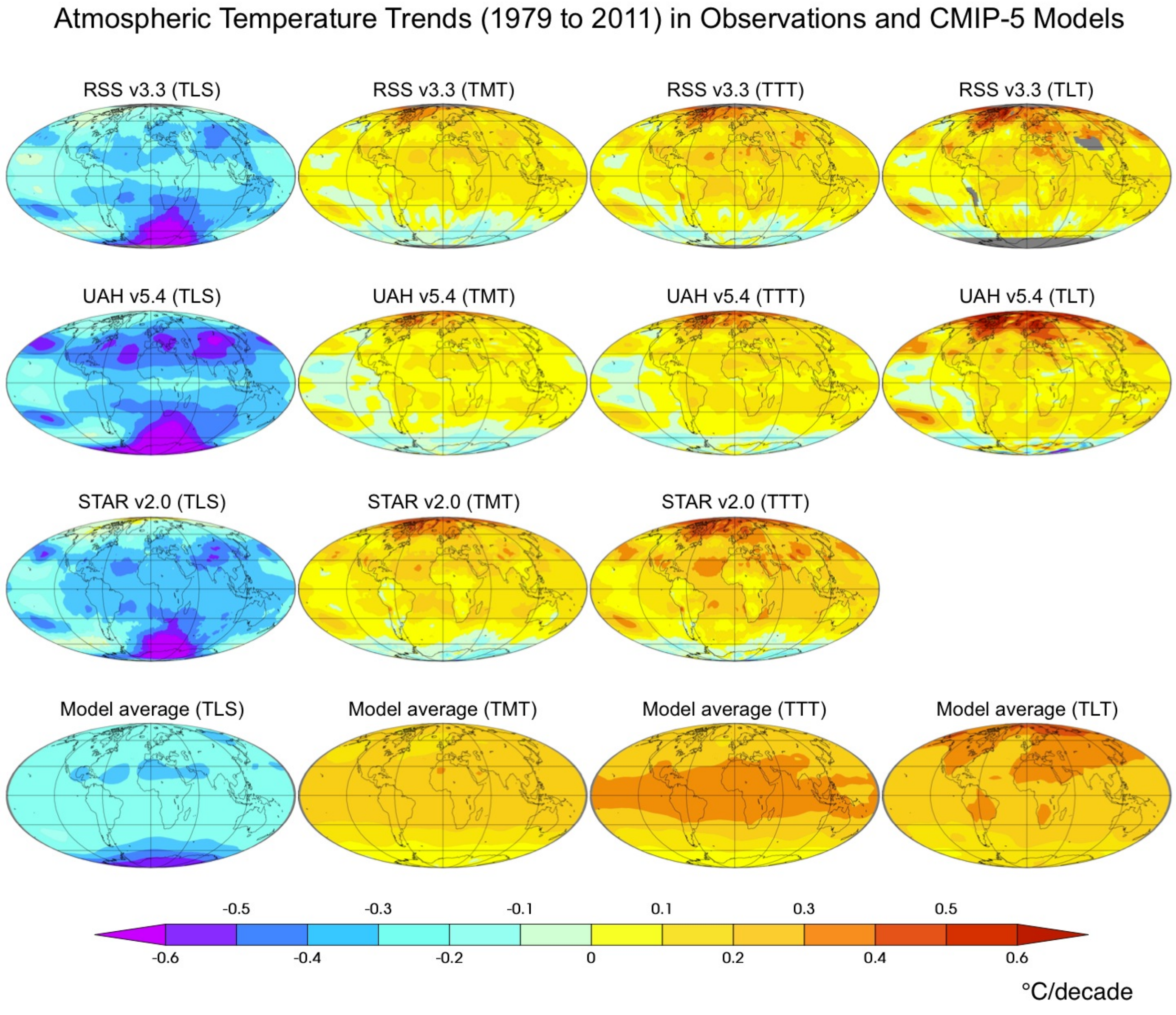
High latitude summer eruptions can spread to fill hemisphere

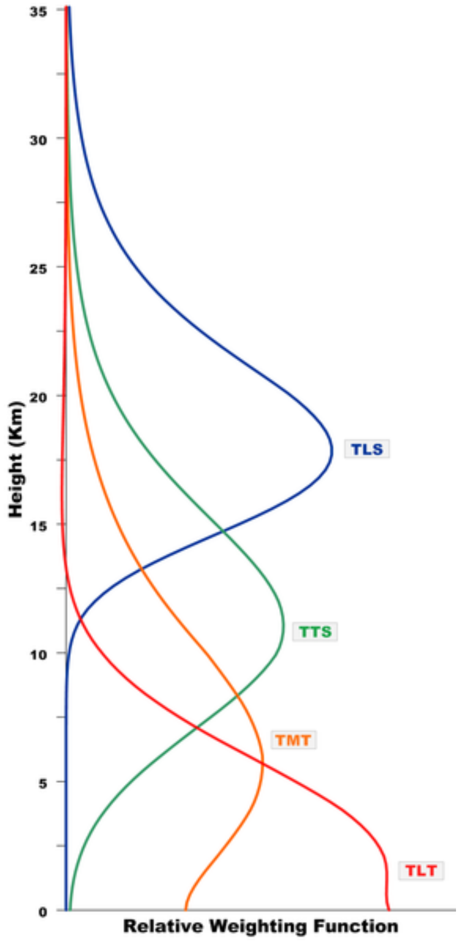
Latitude versus time slice in lower stratosphere

Solomon et al., Science, 2011

Interlude: Models and reality

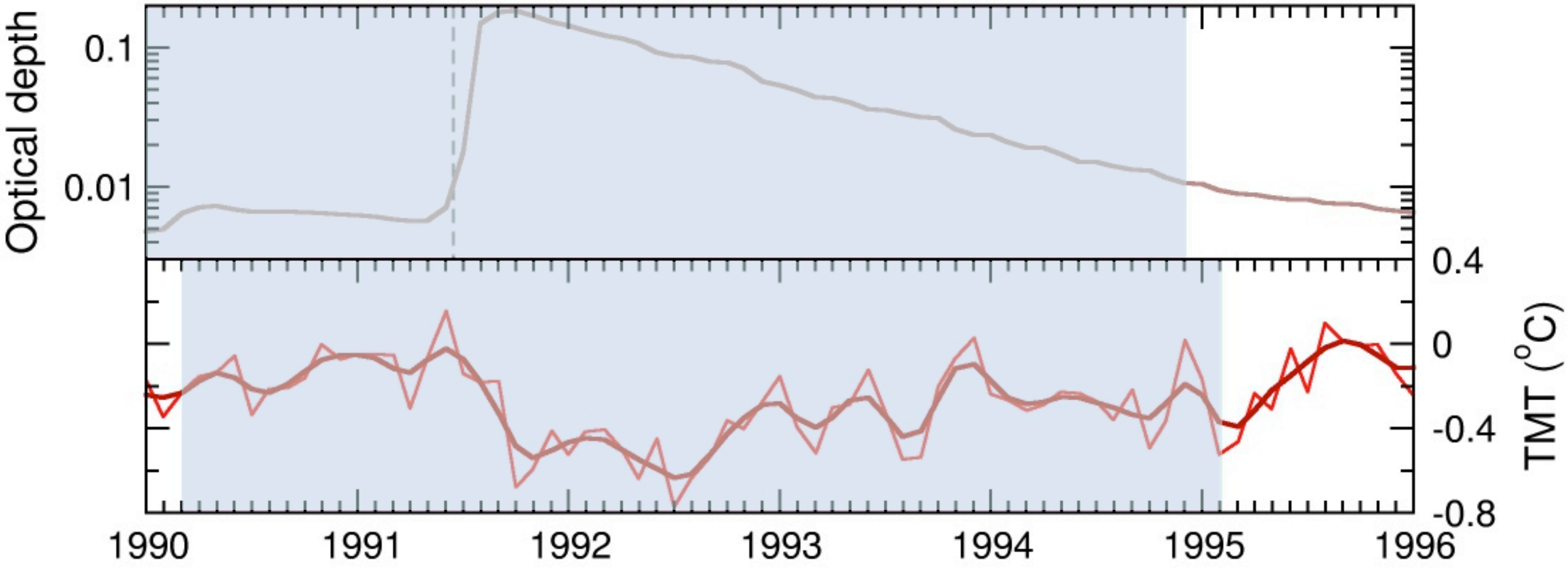
Stratosphere Upper Trop Mid Trop Lower Trop


Atmospheric Temperature Trends (1979 to 2011) in Observations and CMIP-5 Models



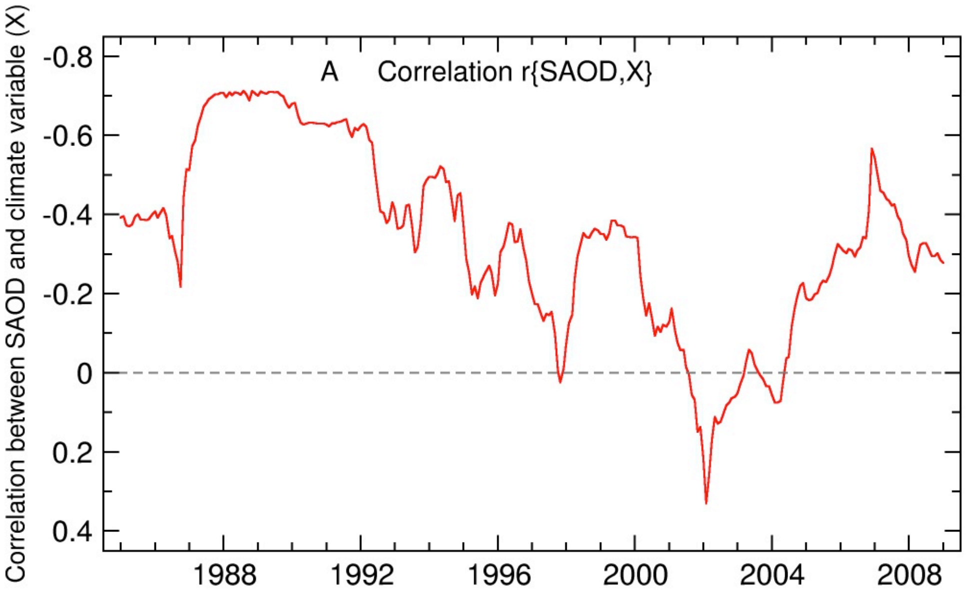
From Santer et al., PNAS, 2013.

“Moving window” correlations between 60-month segments of SAOD and temperature



Santer et al., GRL, 2014

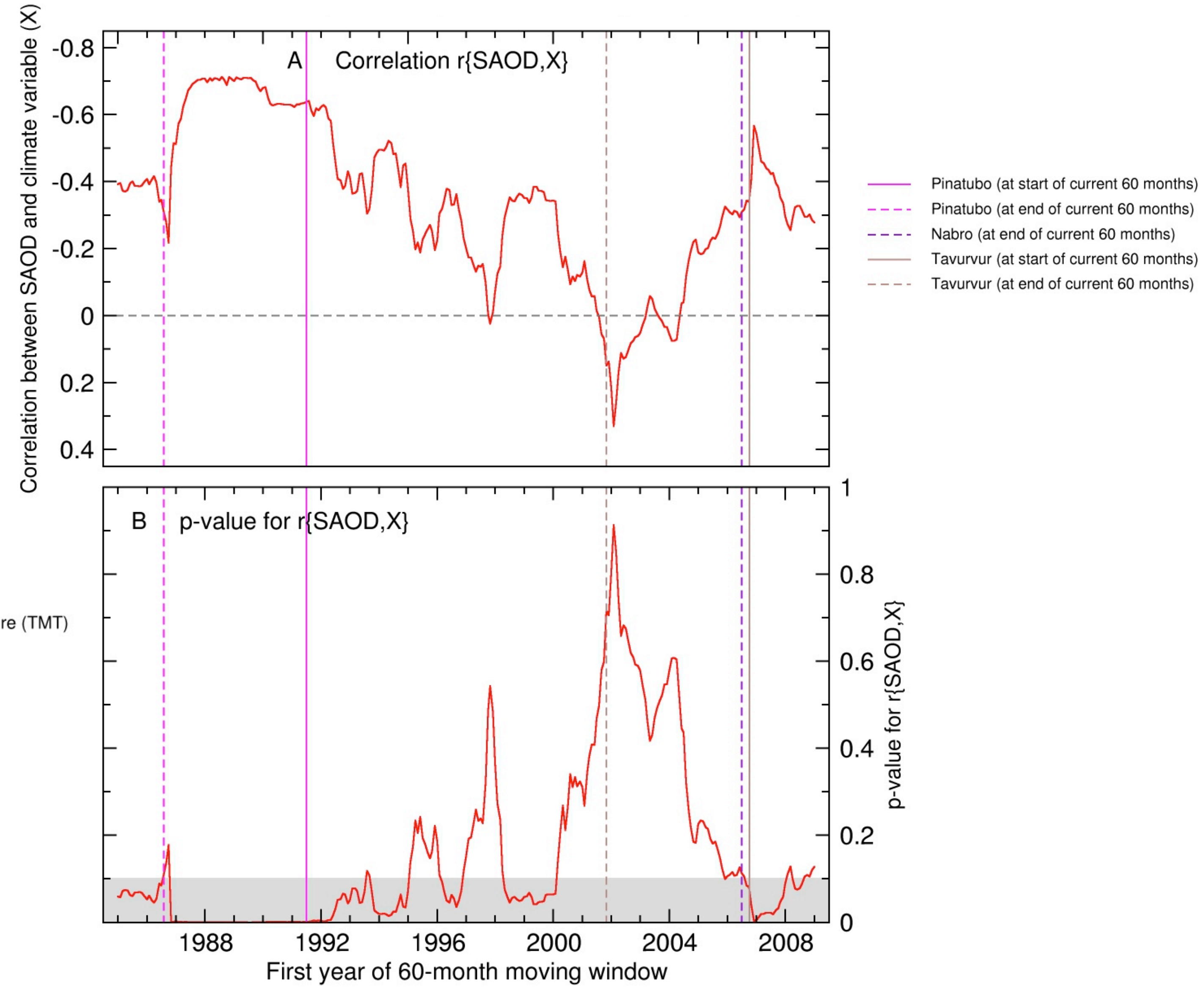
Statistical significance of volcanic climate signals in the tropics (20°N-20°S)



— Mid- to upper tropospheric temperature (TMT)

Santer et al., GRL,
2014

Statistical significance of volcanic climate signals in the tropics (20°N-20°S)



Santer et al., GRL, 2014

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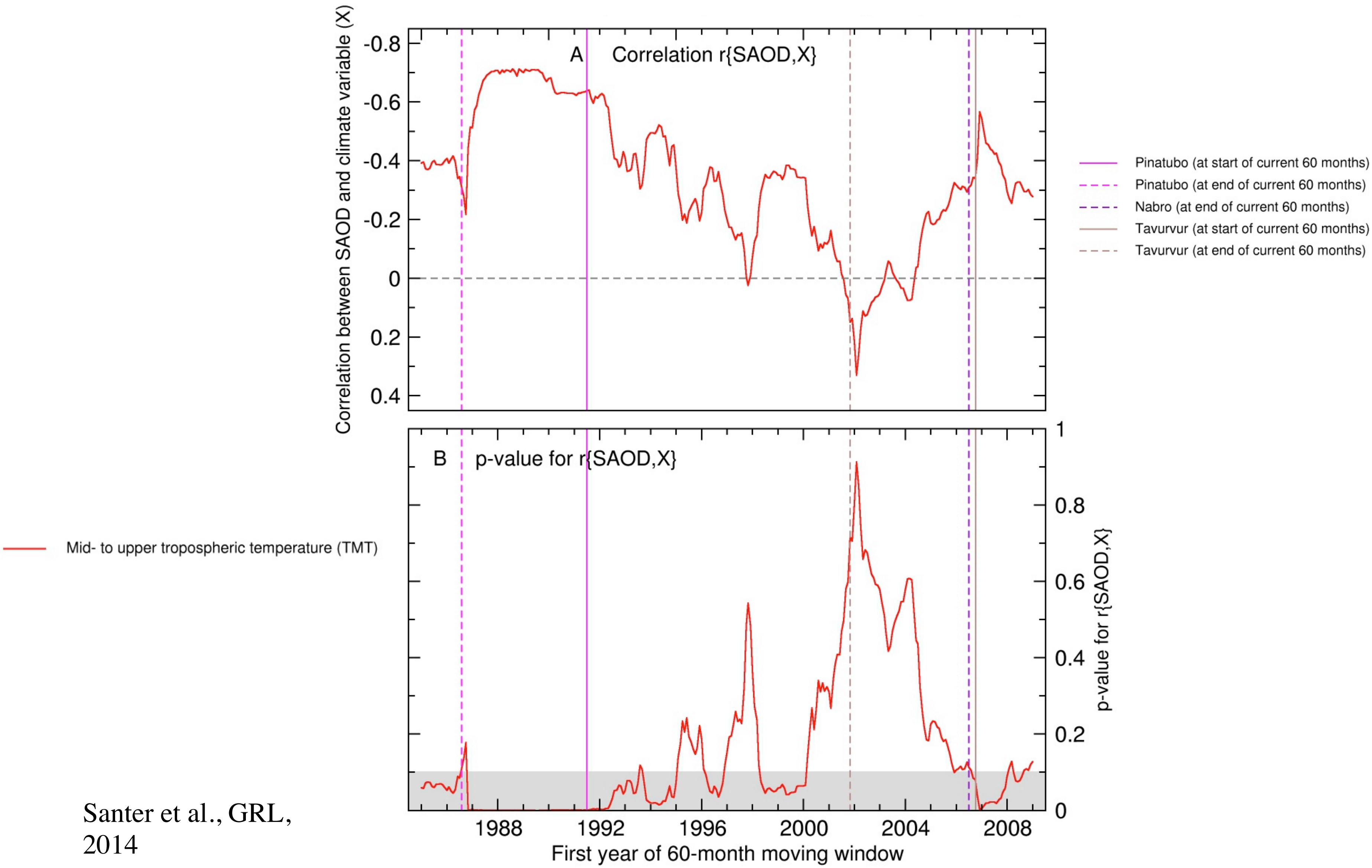

Santer et al., GRL, 2014

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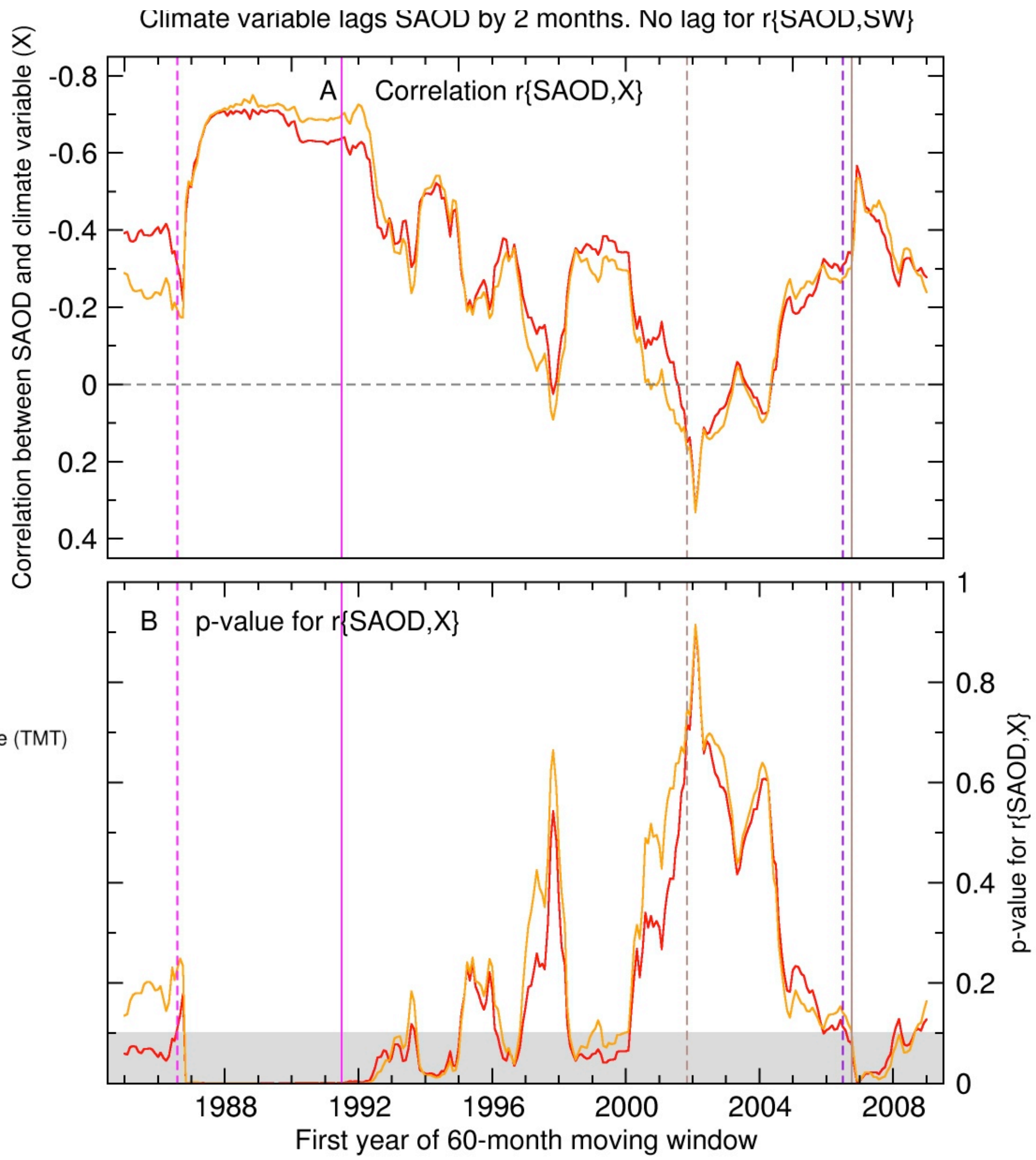
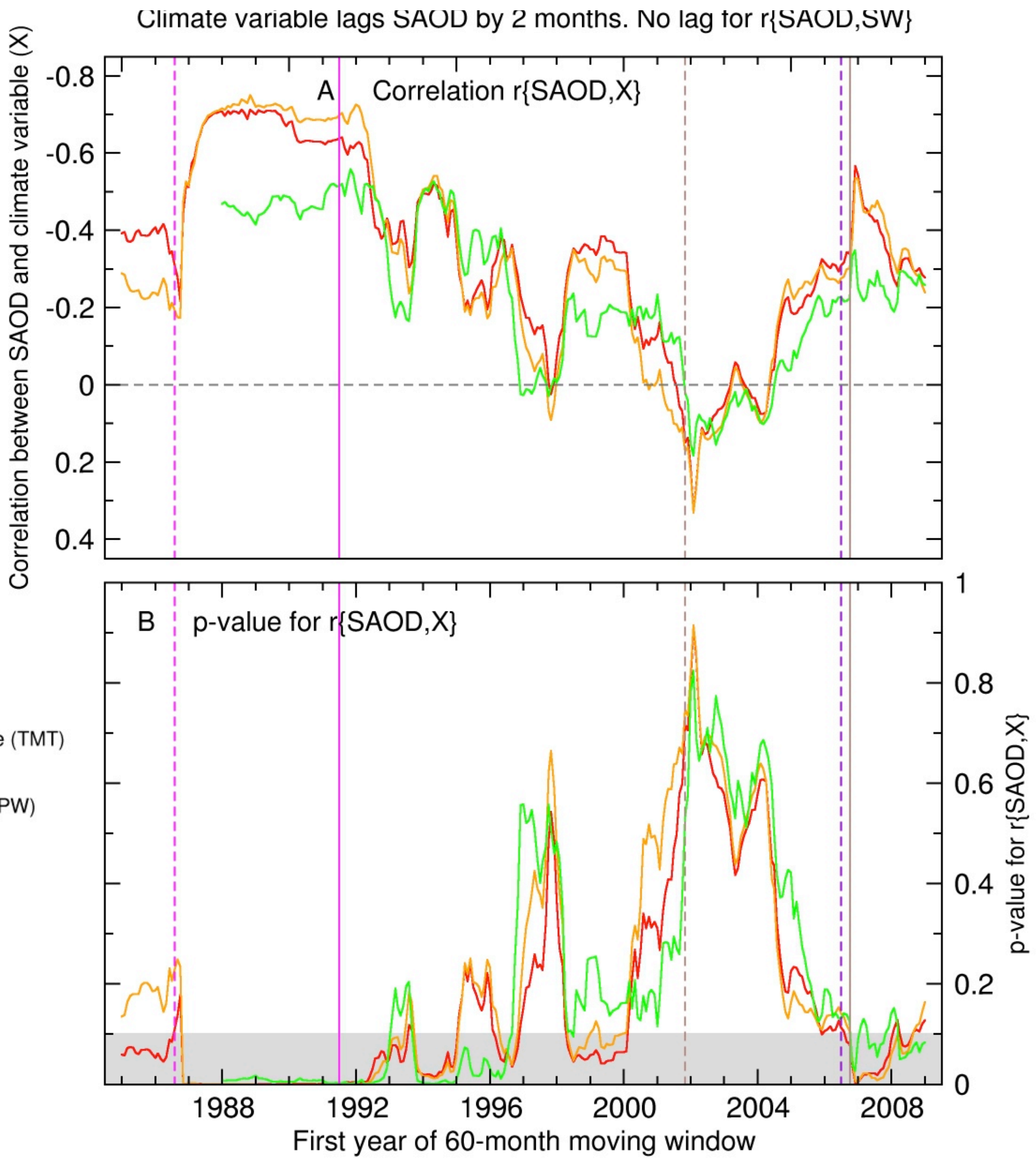


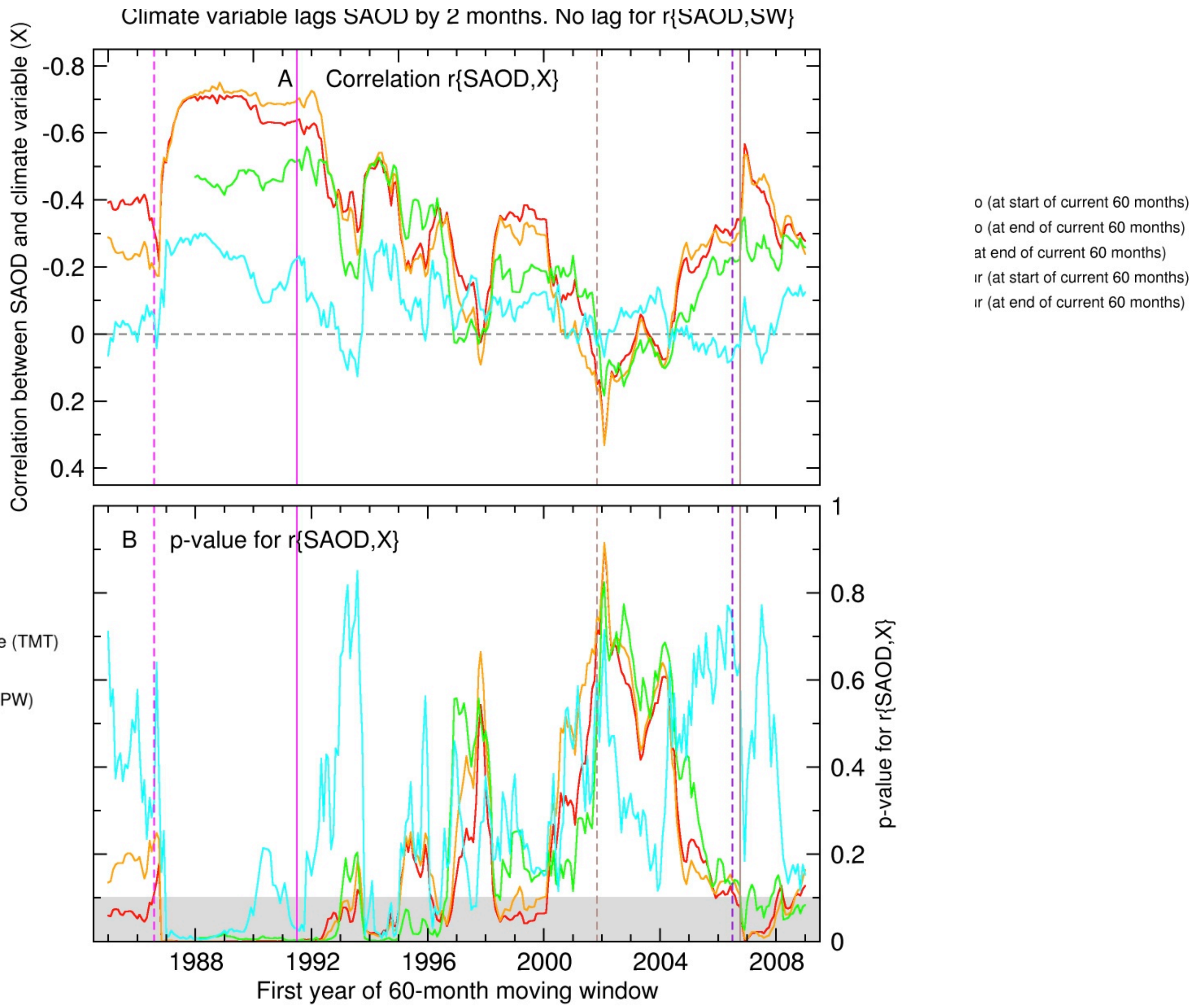
Santer et al., GRI
2014

Statistical significance of volcanic climate signals in the tropics (20°N-20°S)



Santer et al., GRI
2014

Statistical significance of volcanic climate signals in the tropics (20°N-20°S)



Santer et al., GRL
2014

Schmidt et al. Nature Geoscience commentary on Santer et al. 2014

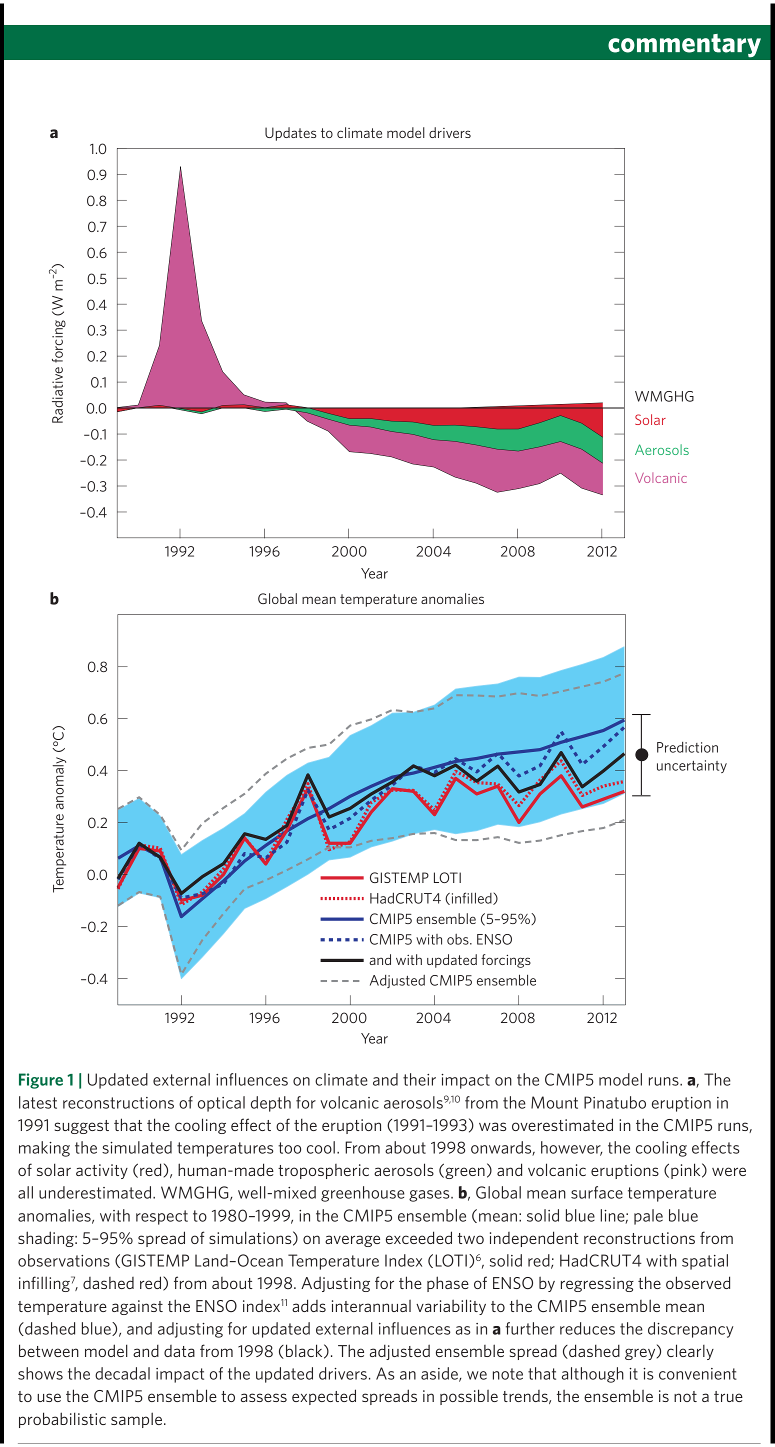


Figure 1 | Updated external influences on climate and their impact on the CMIP5 model runs. **a**, The latest reconstructions of optical depth for volcanic aerosols[9,10] from the Mount Pinatubo eruption in 1991 suggest that the cooling effect of the eruption (1991–1993) was overestimated in the CMIP5 runs, making the simulated temperatures too cool. From about 1998 onwards, however, the cooling effects of solar activity (red), human-made tropospheric aerosols (green) and volcanic eruptions (pink) were all underestimated. WMGHG, well-mixed greenhouse gases. **b**, Global mean surface temperature anomalies, with respect to 1980–1999, in the CMIP5 ensemble (mean: solid blue line; pale blue shading: 5–95% spread of simulations) on average exceeded two independent reconstructions from observations (GISTEMP Land–Ocean Temperature Index (LOTI)[6], solid red; HadCRUT4 with spatial infilling[7], dashed red) from about 1998. Adjusting for the phase of ENSO by regressing the observed temperature against the ENSO index[11] adds interannual variability to the CMIP5 ensemble mean (dashed blue), and adjusting for updated external influences as in **a** further reduces the discrepancy between model and data from 1998 (black). The adjusted ensemble spread (dashed grey) clearly shows the decadal impact of the updated drivers. As an aside, we note that although it is convenient to use the CMIP5 ensemble to assess expected spreads in possible trends, the ensemble is not a true probabilistic sample.

“Climate models projected stronger warming over the past 15 years than has been seen in observations. Conspiring factors of errors in volcanic and solar inputs, representations of aerosols, and El Niño evolution, may explain most of the discrepancy.”