Interannual Variability of Stratospheric and Tropospheric Ozone Determined from Satellite Measurements

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Road Map

- History Behind Use of Satellites to Study Tropospheric Air Pollution

- Tropospheric Ozone Residual (TOR) Methodology and Climatology
  – Derivation and Validation of Long-Term Data Set

- Stratospheric and Tropospheric Interannual Variability in the Tropics:
  - Relationship between Stratospheric Ozone and the QBO
  - Interannual Variability of Tropospheric Ozone over West Africa

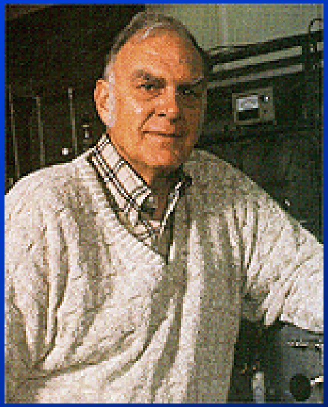
- Interannual Variability of Tropospheric Ozone over northern India and east China

- What's Next?

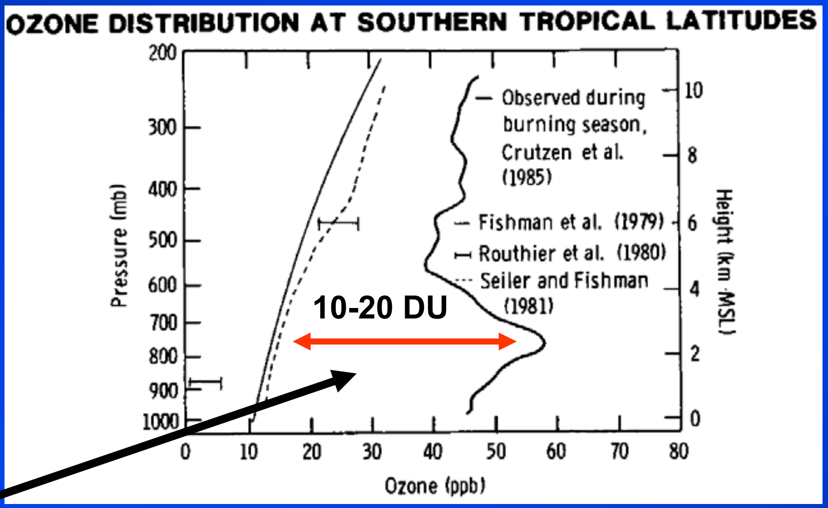
The Origin of Using Satellite Data to Study Tropospheric Ozone Can be Linked to Nobel-Prize Winning Research

from Nobel Prize press release:

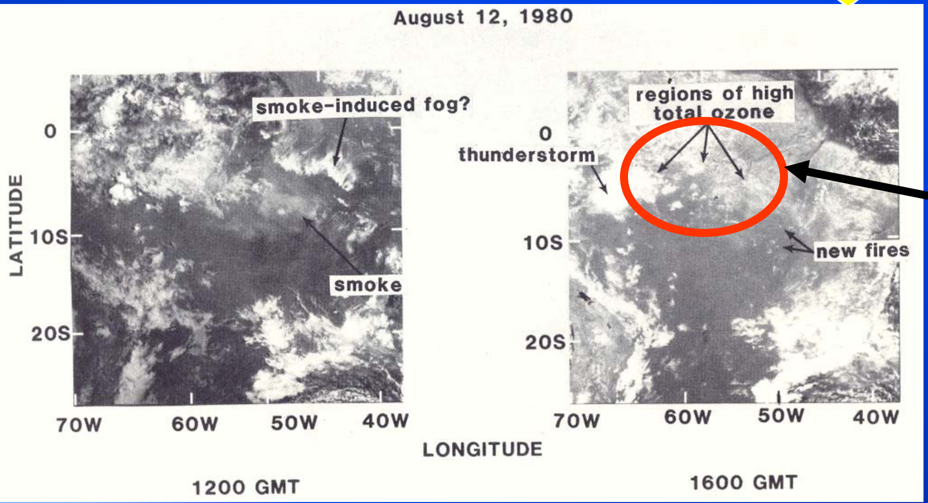
The Royal Swedish Academy of Sciences has decided to award the 1995 Nobel Prize in Chemistry to **Paul Crutzen, Mario Molina** and **F. Sherwood Rowland** for their work in atmospheric chemistry, particularly concerning **the formation** and decomposition **of ozone**.



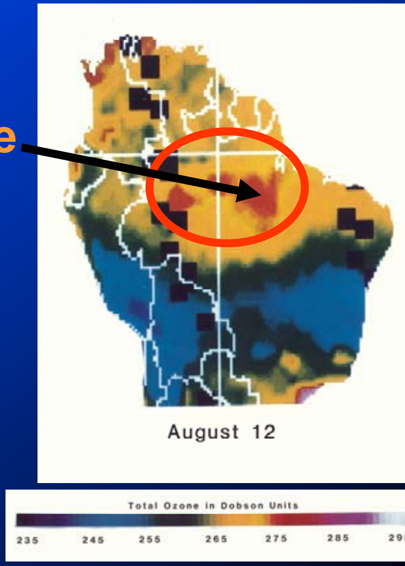
In the late 70's, Paul Crutzen led a team of NCAR scientists that made comprehensive measurements of trace gases where tropical biomass burning was occurring and found considerably higher concentrations than what had been published previously



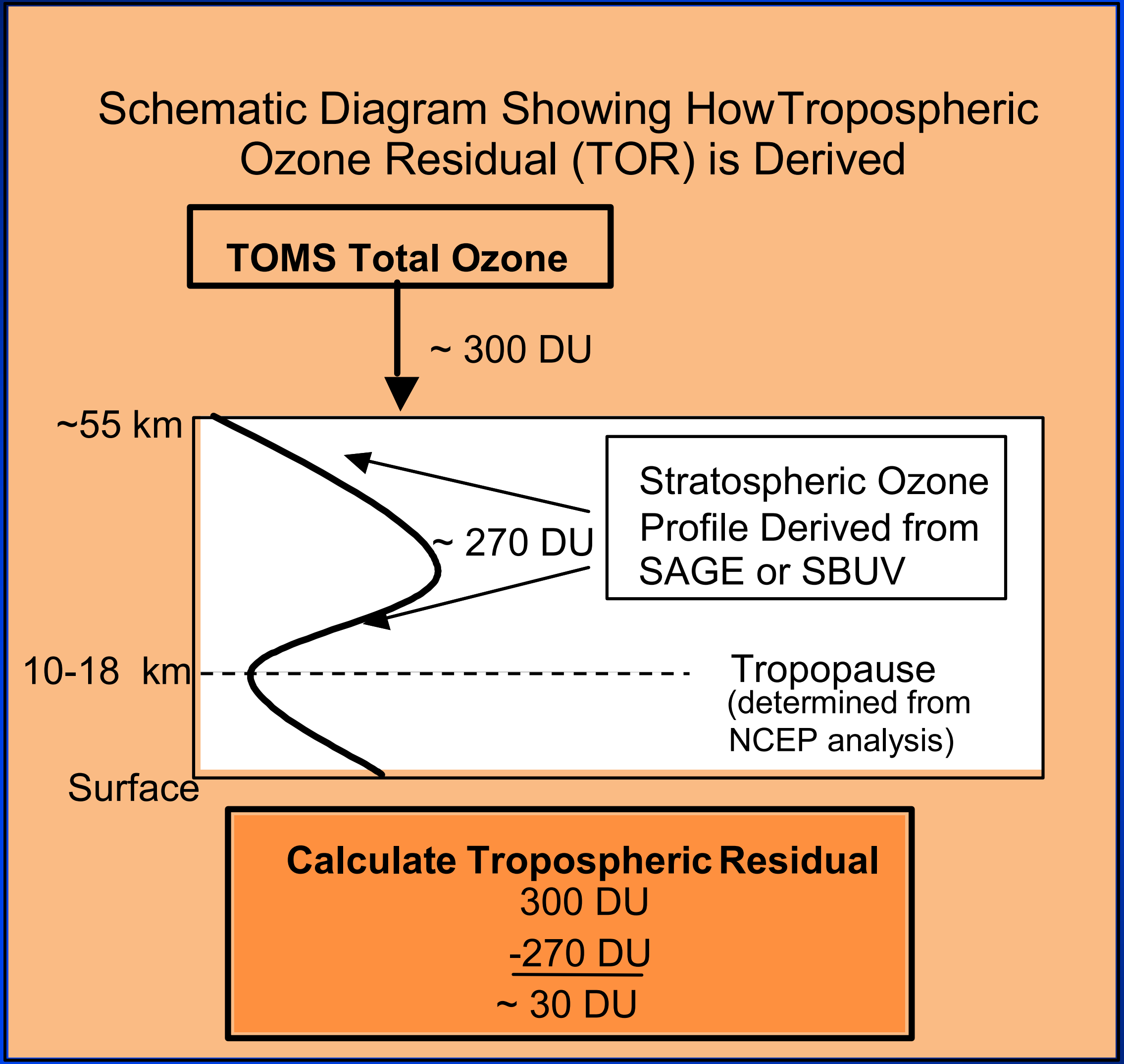
Can the 10-20 DU enhancement be identified with TOMS total ozone measurements?



Enhanced **Total Ozone** Observed in Conjunction with **Biomass Burning** in 1980 Episode



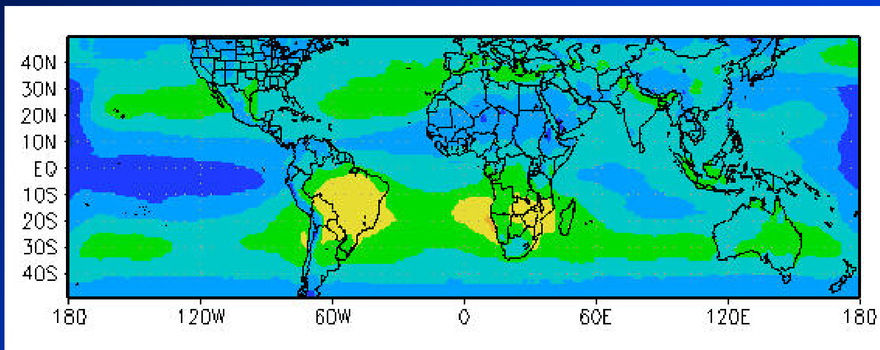
Separate Stratosphere from Troposphere to Compute Tropospheric Ozone Residual



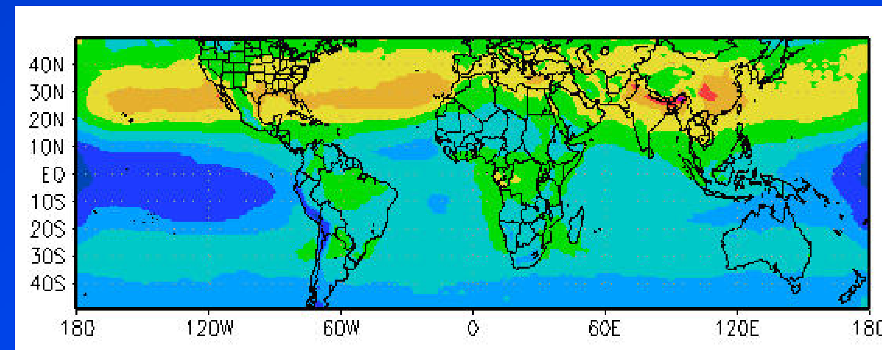
Not only do you generate a tropospheric ozone product, the TOR, but you also generate a stratospheric product, the SCO

Seasonal Depictions of Climatological Tropospheric Ozone Residual (TOR) 1979-2000

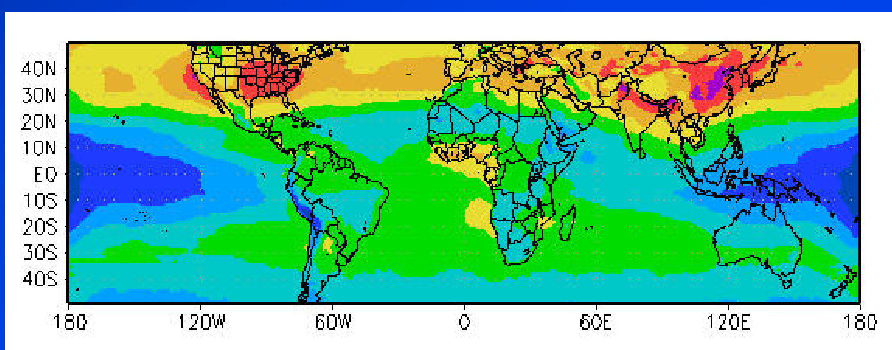
December - February



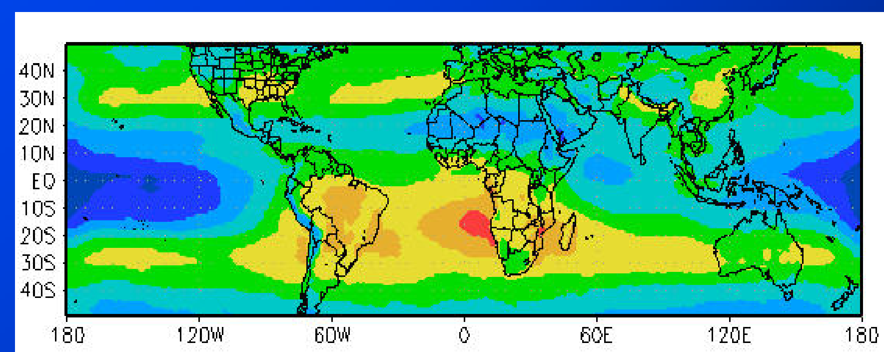
March - May

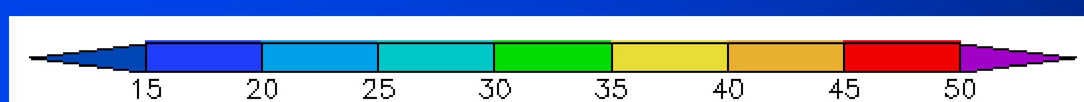


June - August



September - November

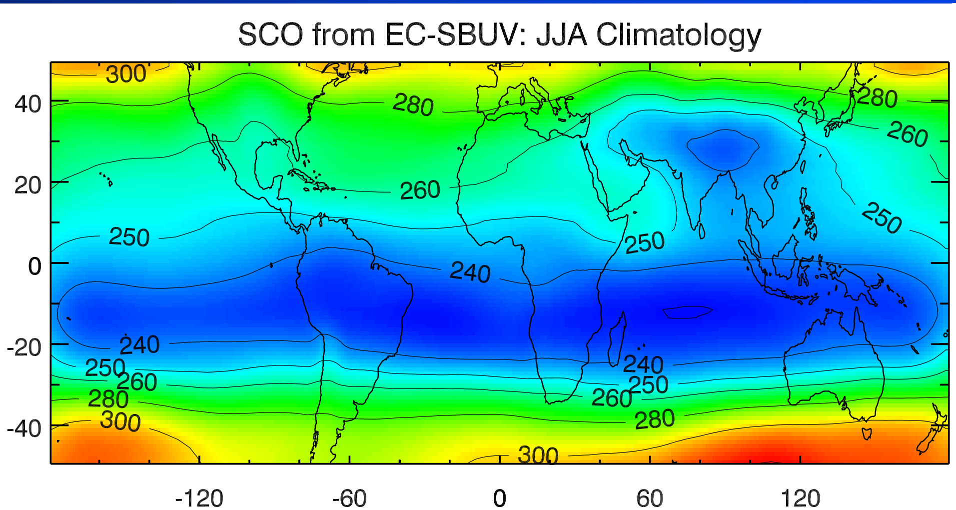


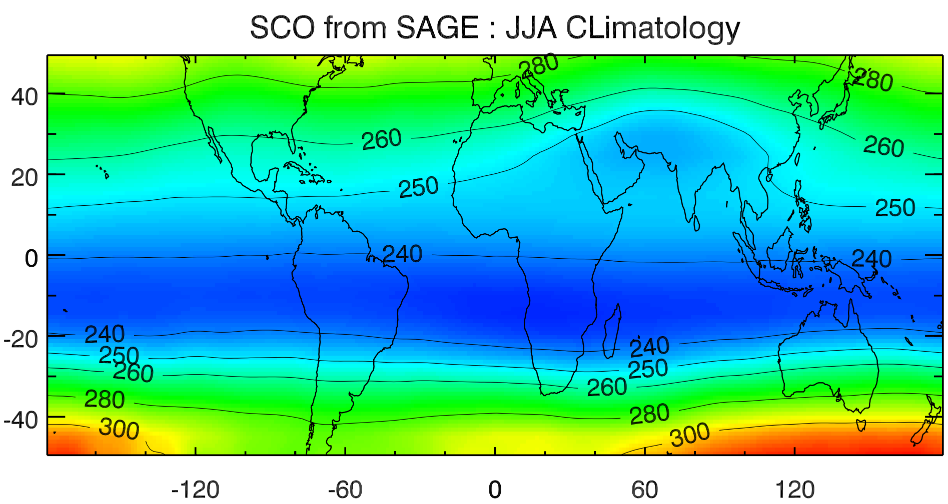


Dobson Units (DU)

from Fishman, Wozniak, Creilson, *Atmos. Chem. Phys.*, 3, 2003

Comparison of JJA Stratospheric Column Ozone Distributions Derived from Empirically-Corrected V6 SBUV and SAGE II Measurements Exhibits Strong Similarities



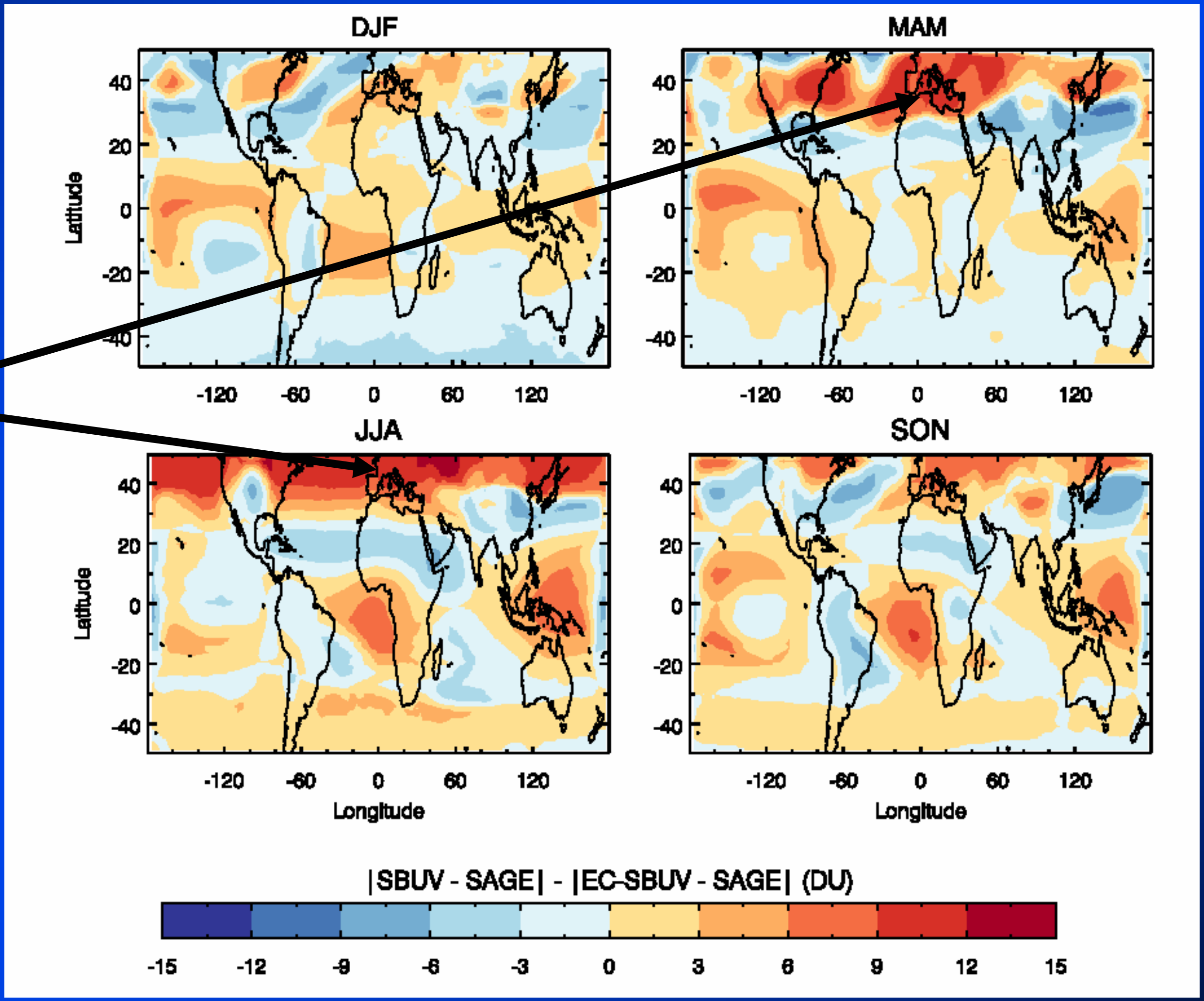


SBUV

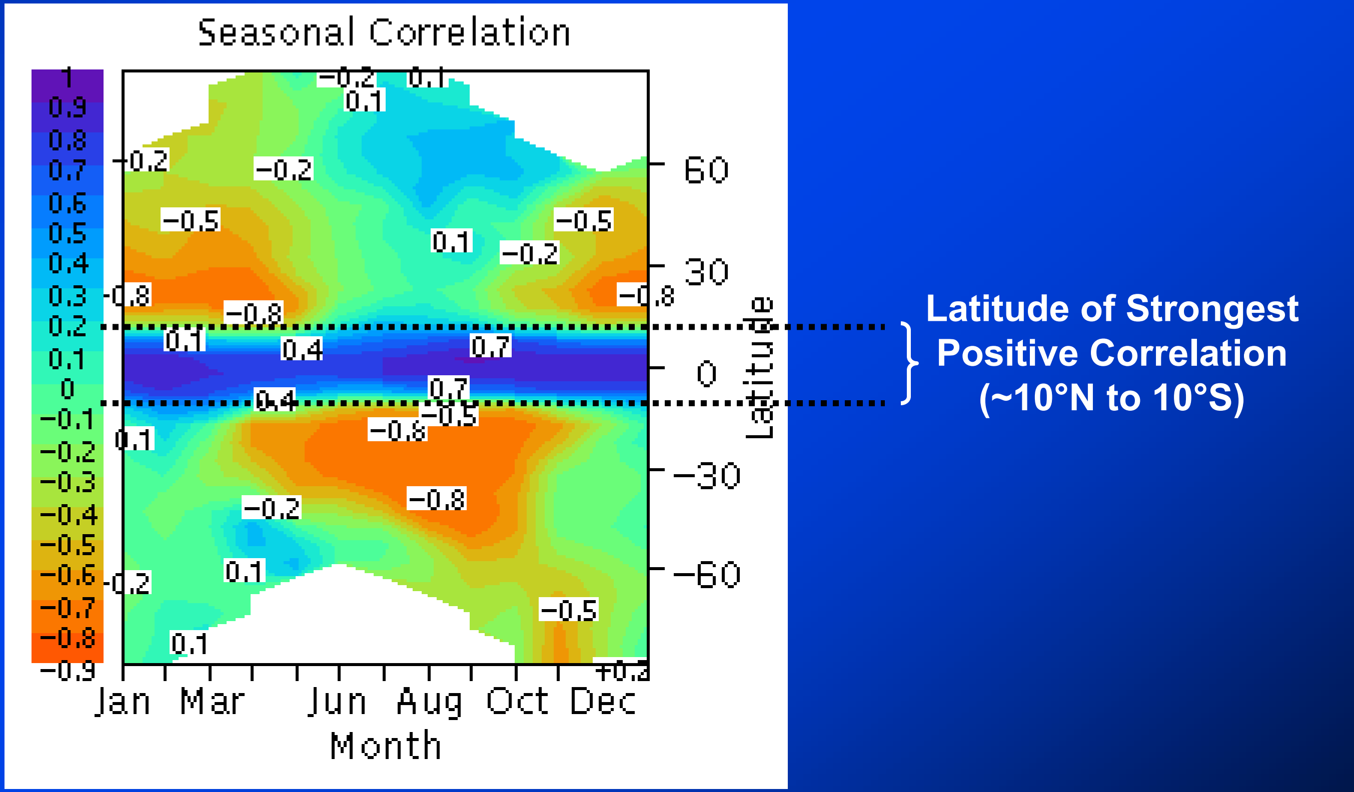
SAGE

Seasonal Depiction Showing Areas of Improvement from V6 SBUV to EC-SBUV (relative to SAGE)

Northern Hemisphere Spring and Summer show greatest improvement



Earlier Research Established Strong Positive Equatorial Correlative Pattern Between TOMS Total Ozone and the QBO



(from Kinnersley and Tung (1998))

Interannual Relationship between EC-SBUV SCO and the QBO Shows Strikingly Similar Pattern to Prior Work by Kinnersley and Tung

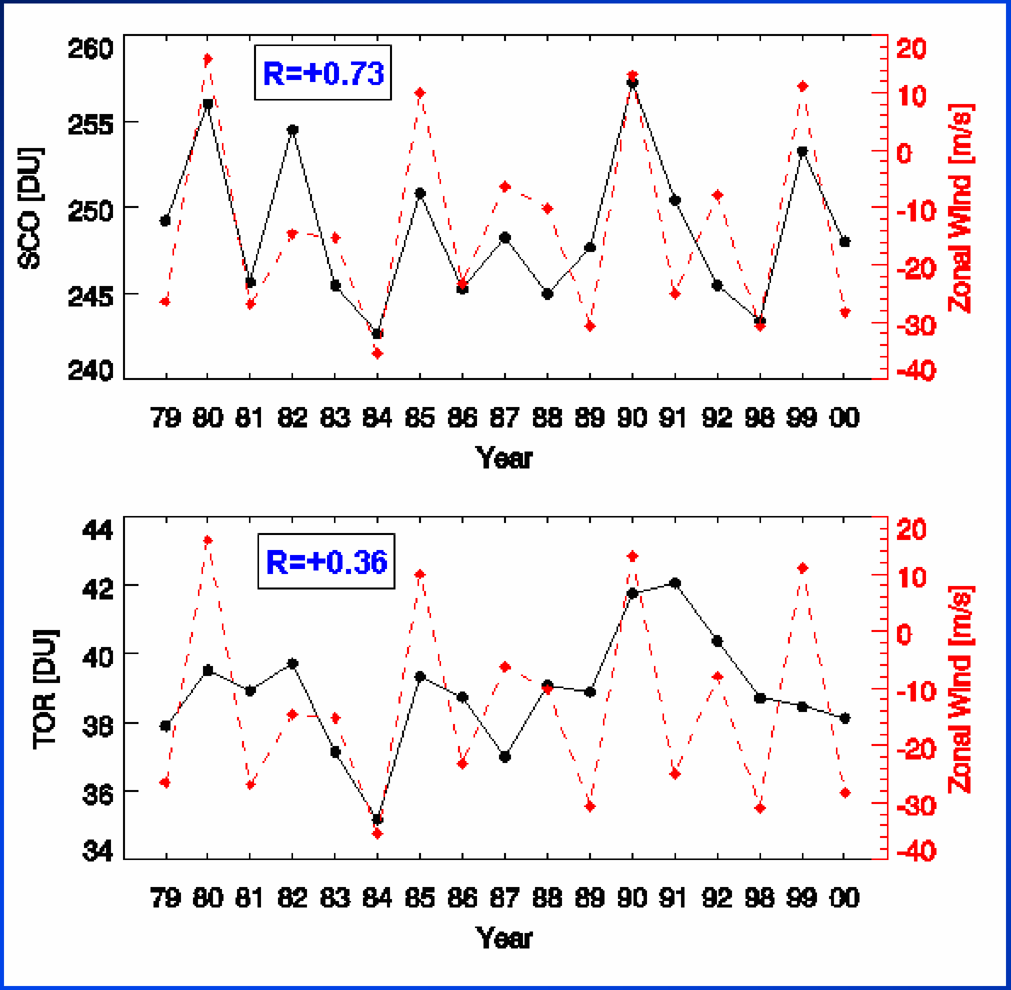
Region	Lat	Monthly SCO Correlations											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	N=>	18	18	17	18	17	17	17	18	18	18	17	17
West Africa (20W-30E)	15-20N	-.23	-.34	-.37	**-.48**	-.39	-.12	.07	-.20	-.20	-.20	-.10	-.17
	10-15N	.18	.03	-.06	-.09	.12	.27	.44	.09	.10	.05	.16	.13
	5-10N	**.55**	.46	.40	.31	**.53**	**.57**	.71	**.53**	**.56**	**.54**	**.55**	**.52**
	E-5N	.64	.63	.67	.60	.71	.73	.82	.73	.74	.72	.70	.65
	E-5S	**.53**	.65	.68	.66	.74	.73	.83	.70	.64	.63	.70	**.54**
	5-10S	.36	**.56**	**.56**	**.57**	.62	**.49**	**.59**	.34	.26	.33	**.56**	.27
	10-15S	.11	.37	.31	.25	.18	.02	-.15	**-.49**	-.35	-.37	-.10	-.14
	15-20S	-.10	.13	.01	-.16	-.31	-.31	**-.55**	**-.78**	**-.68**	**-.65**	**-.51**	-.38
India (60-120E)	15-20N	-.28	-.17	-.40	-.45	-.48	-.27	.11	-.04	.04	.15	-.08	-.31
	10-15N	.21	.23	-.02	-.17	.05	.18	.38	.21	.36	.40	.23	-.08
	5-10N	.60	.64	**.49**	.41	**.52**	**.52**	.64	**.53**	.67	.70	.73	.44
	E-5N	.65	.69	.67	.69	.67	.63	.78	.72	.80	.79	.87	.65
	E-5S	.62	.66	.68	.73	.71	.65	.78	.73	.79	.74	.83	**.58**
	5-10S	**.54**	.59	**.57**	.66	.62	.35	**.50**	.35	**.47**	**.48**	.67	.34
	10-15S	.30	.41	.27	.34	.22	-.21	-.33	**-.48**	-.42	-.26	-.04	-.27
	15-20S	.02	.20	-.06	-.13	-.23	-.45	**-.64**	**-.69**	**-.68**	**-.56**	**-.57**	**-.49**
Pacific (160-100W)	15-20N	-.34	-.19	-.37	-.36	**-.53**	-.17	.02	-.09	-.17	-.03	-.06	-.18
	10-15N	-.02	.08	-.03	-.11	-.13	.17	.32	.17	.12	.23	.27	.11
	5-10N	.34	.44	.40	.28	.30	**.49**	.65	**.51**	**.47**	**.55**	.69	**.54**
	E-5N	**.53**	.63	.65	**.57**	**.56**	.69	.79	.67	.59	.65	.79	.65
	E-5S	**.50**	.64	.73	.67	.63	.72	.78	.66	**.54**	**.58**	.71	.59
	5-10S	.29	**.49**	.63	**.56**	**.53**	**.55**	.45	.35	.21	.26	.42	.34
	10-15S	.02	.25	.38	.19	.19	.10	-.35	**-.49**	**-.51**	-.43	-.29	-.09
	15-20S	-.14	.08	.15	-.22	-.25	-.32	**-.71**	**-.80**	**-.80**	**-.69**	**-.63**	-.33

Similar Strong Positive Correlation In Region of Interest

SCO Relationship Appears Independent of Longitude

Positive Correlation and level of significance of at least .01:
Positive Correlation and level of significance of at least .05:
Negative Correlation and level of significance of at least .01:
Negative Correlation and level of significance of at least .05:

Stratospheric and Tropospheric Interannual Variability in the Tropics: Strong Difference between July QBO Correlations

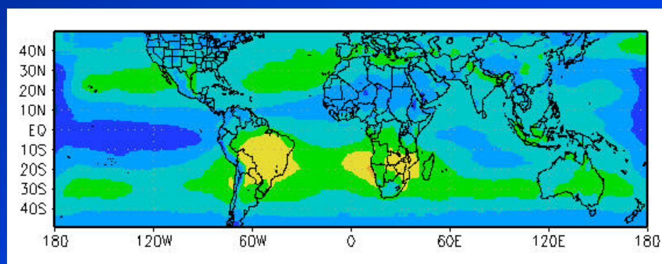


Stratospheric ozone over west Africa strongly correlated with quasi-biennial oscillation (QBO)

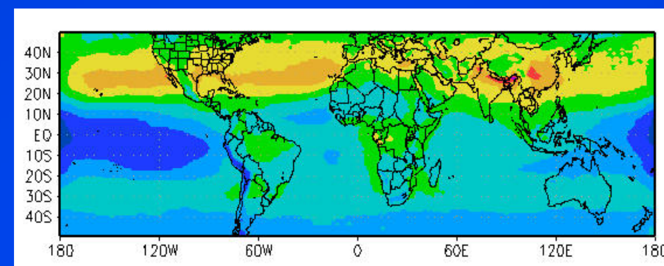
Correlation of TOR with QBO is much less significant

Looking Further at Tropospheric Ozone… We See More Regional Enhancements and Different Climate-Ozone Relationships

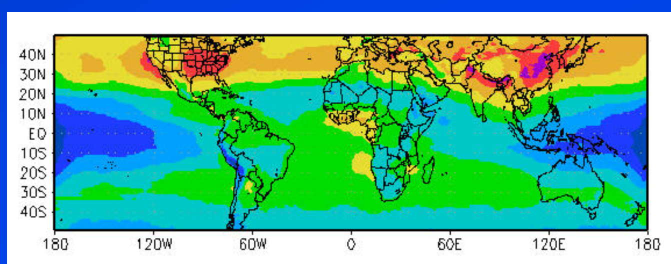
December - February



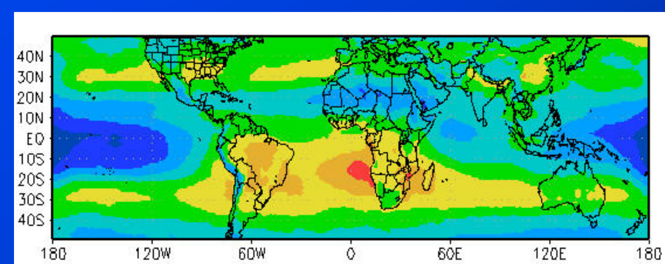
March - May

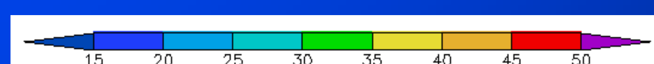


June - August



September - November



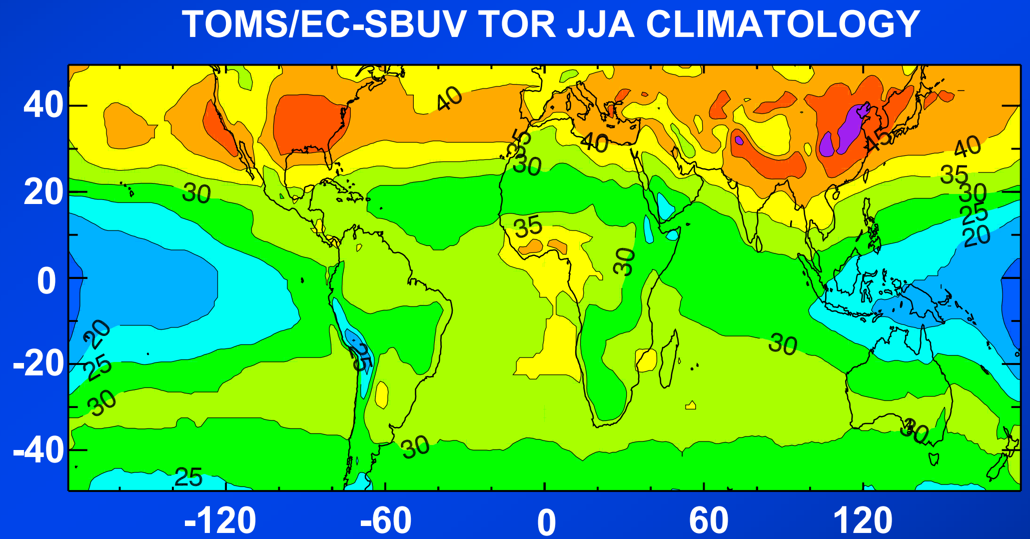


Dobson Units (DU)

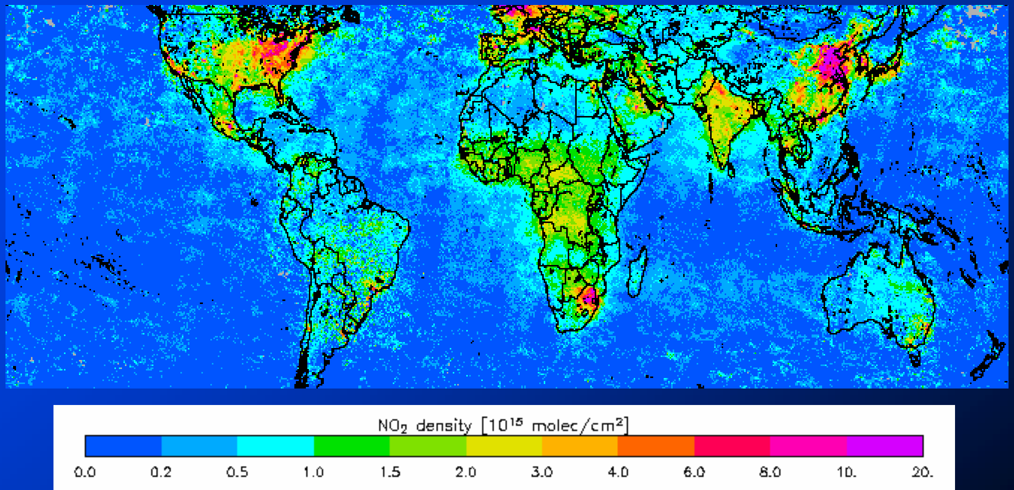
How do we know what we are seeing is in the troposphere?

Striking Similarity Between Global Distributions of TOR and Tropospheric NO_2

June-August Climatological TOR Distribution in Dobson Units (DU)

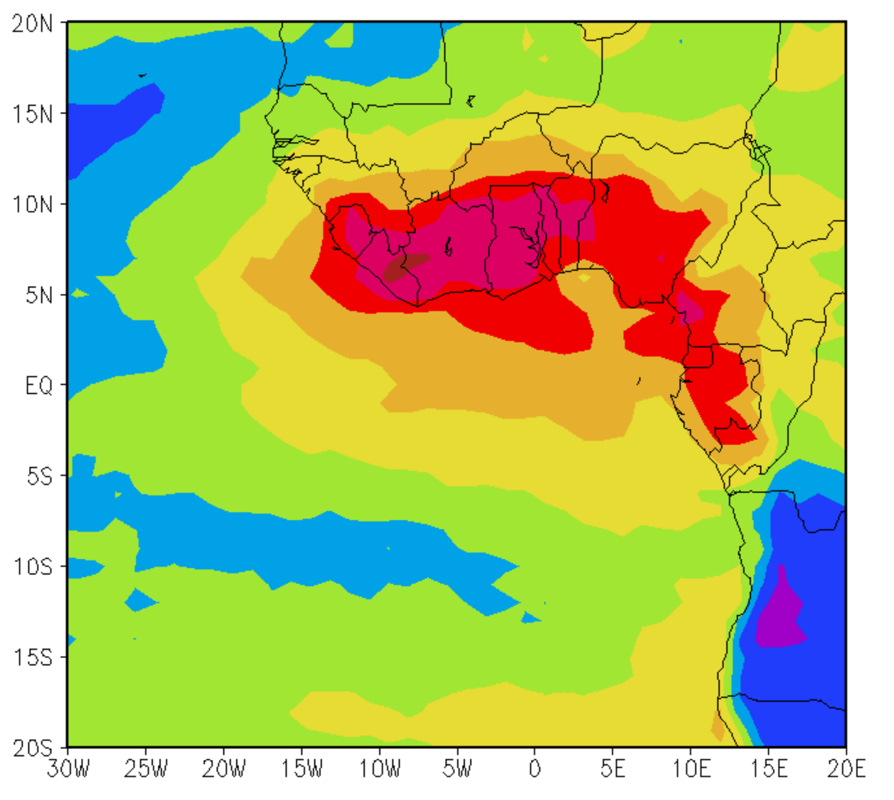


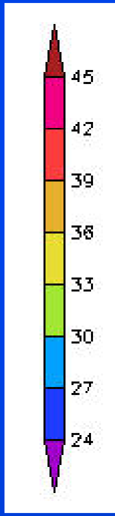
2003 Tropospheric NO_2 Distribution from SCIAMACHY (10^{15} molec. cm^{-2})



Significant Interannual Variability is also Evident between North and South of the ITCZ in West Africa: Potential Linkage to Phase of ENSO

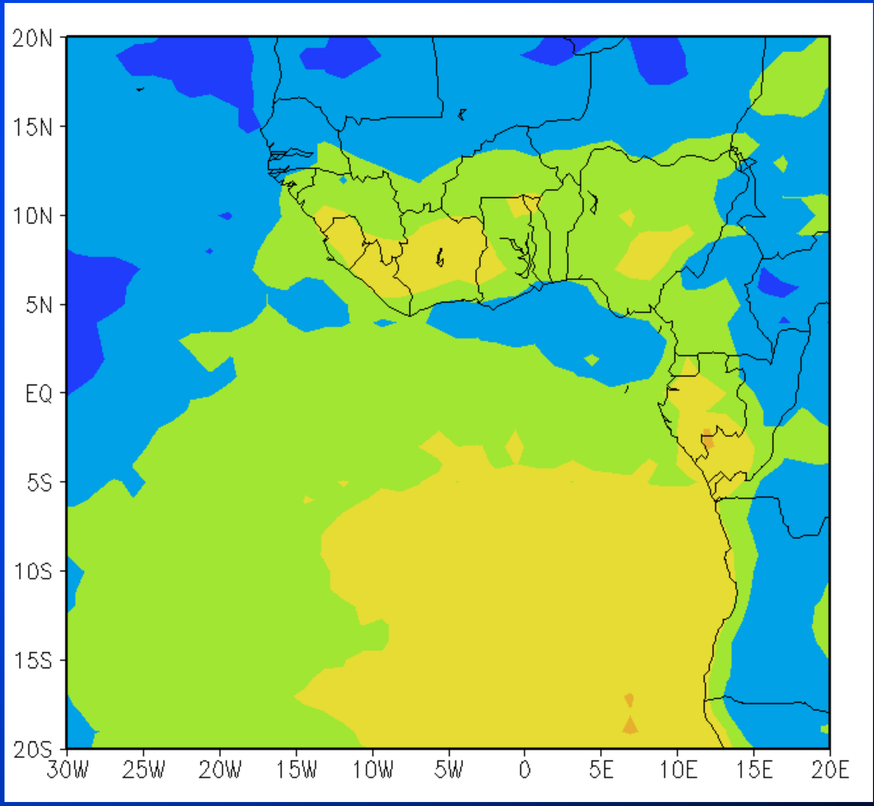
North-South TOR: June 1982





Dobson Units

North-South TOR: June 1984

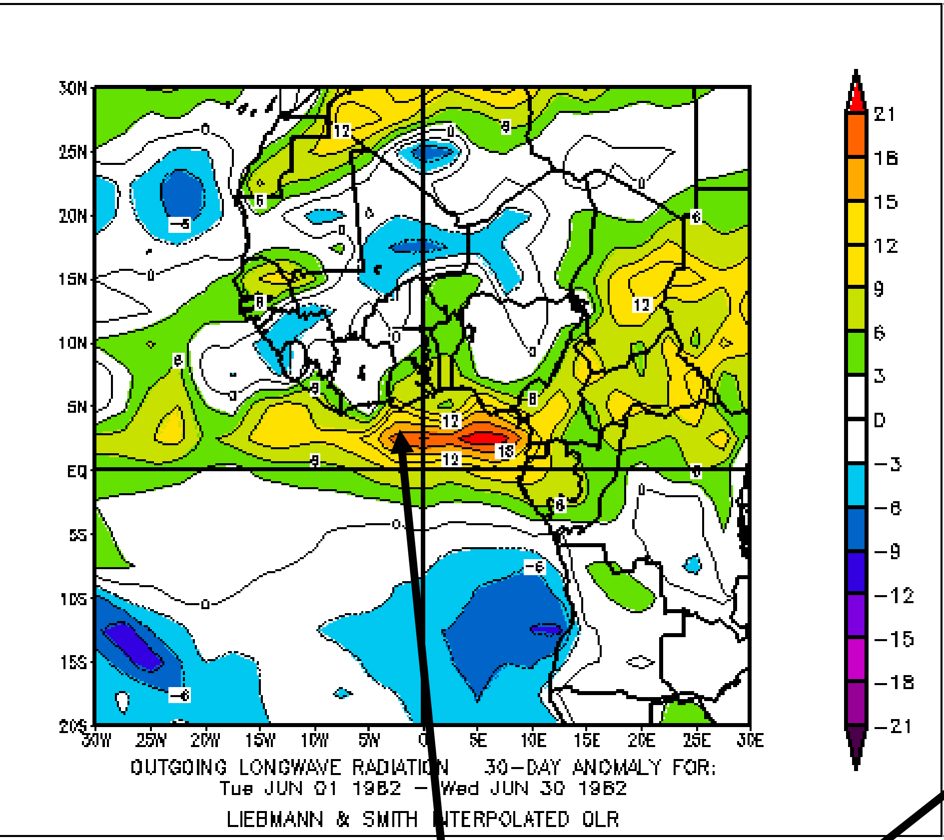


Strong El Niño

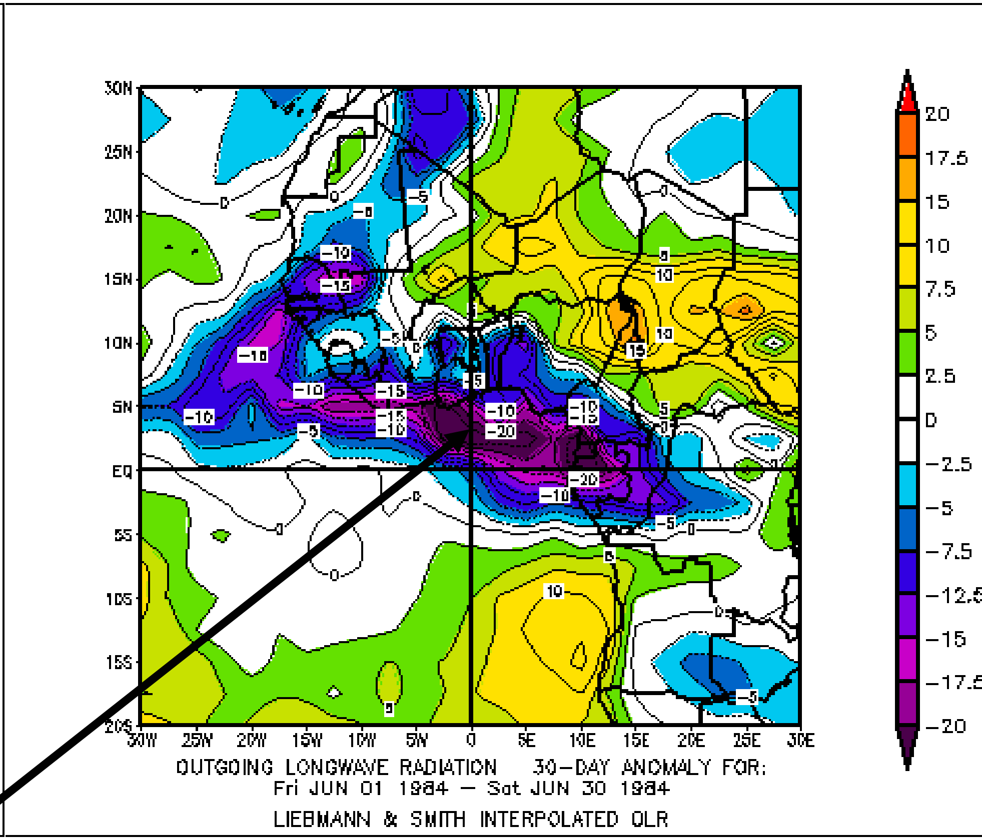
Strong La Niña

Strong Difference Seen in Outgoing Longwave Radiation Between June of 1982 (El Niño) and June of 1984 (La Niña)

OLR – June 1982

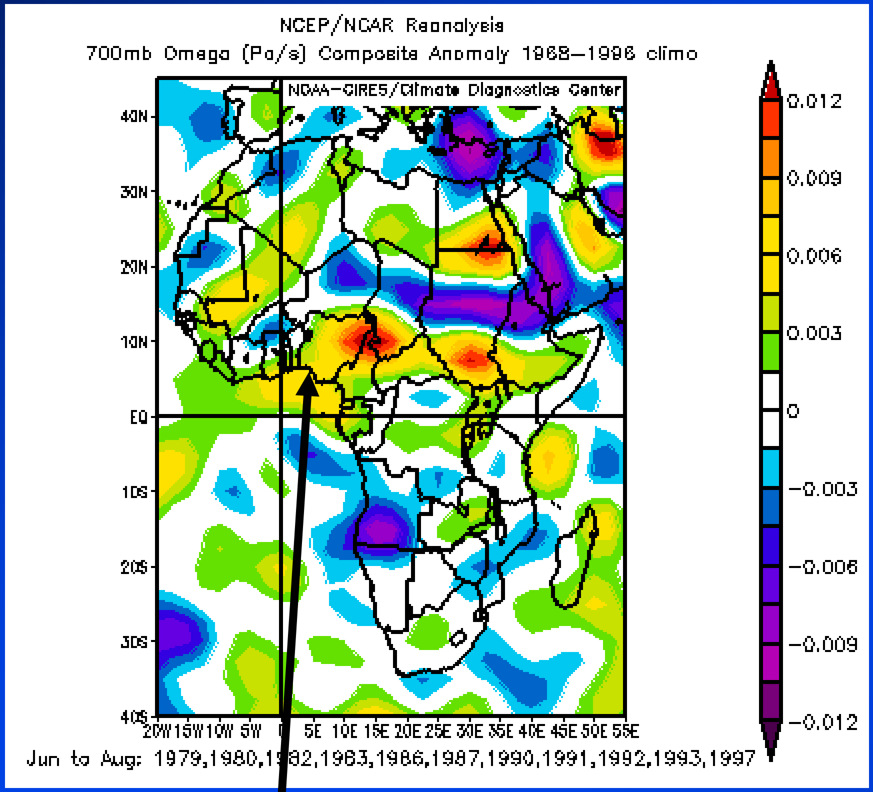


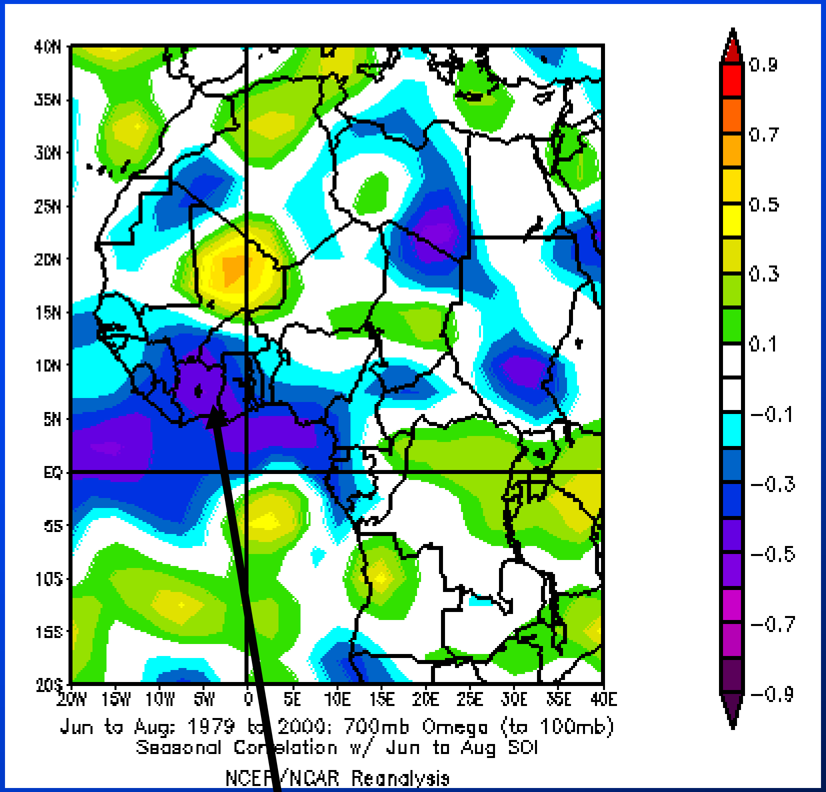
OLR – June 1984



Positive Versus Negative Anomaly over the Same Region

Strong Relationship Between Omega at 700mb and the SOI Indicative of Enhanced Subsidence Over this Region During El Niño

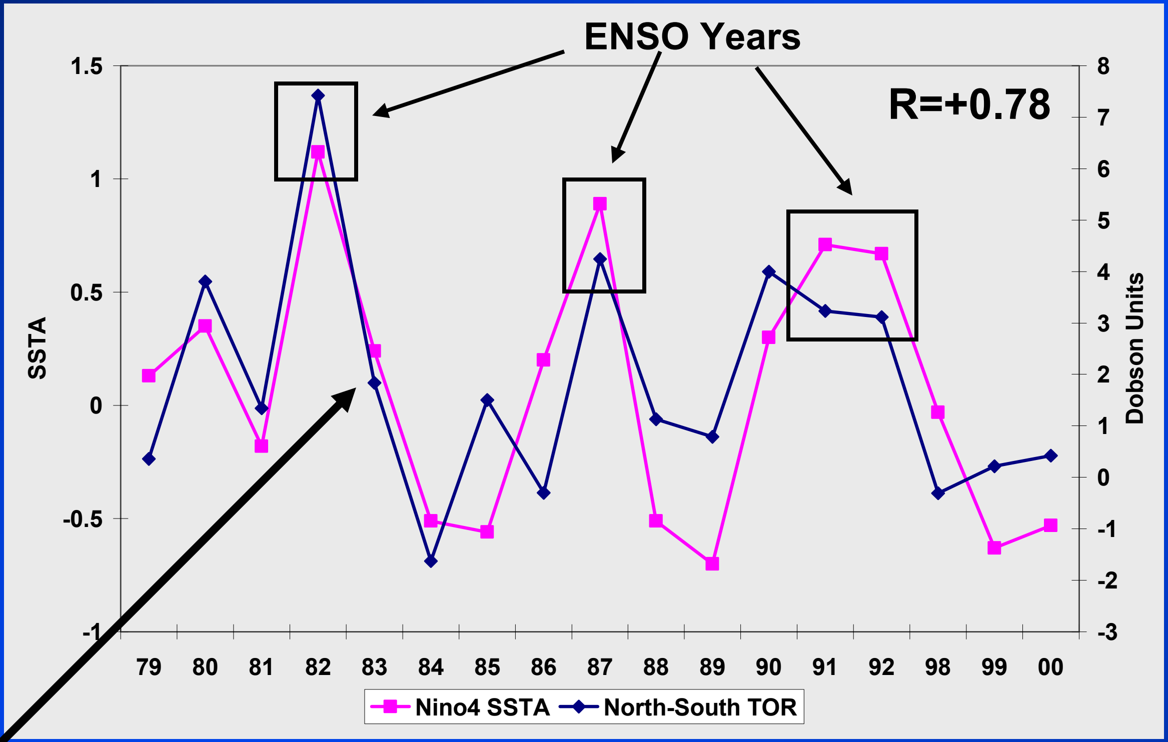




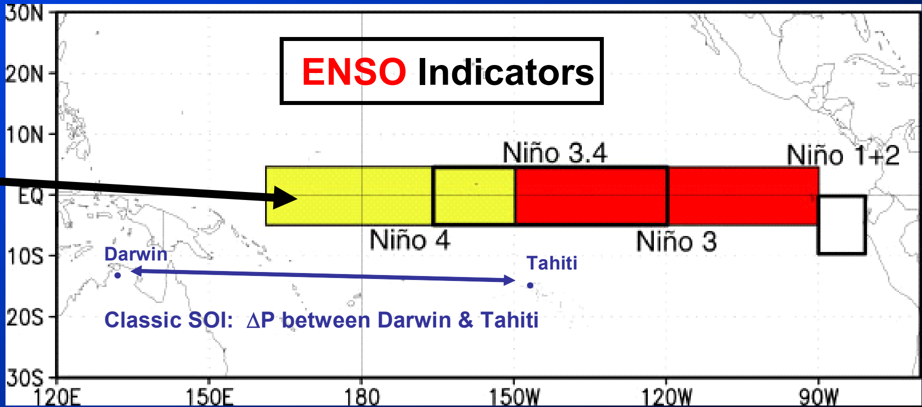
Positive anomalies evident during El Niño summers

Strong inverse correlation over region of enhanced TOR

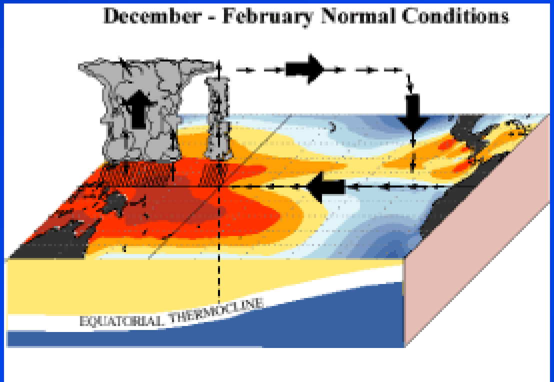
North-South (5N-5S) June TOR Differential Versus Nino Region 4 SSTA: Strong Correlation Evident



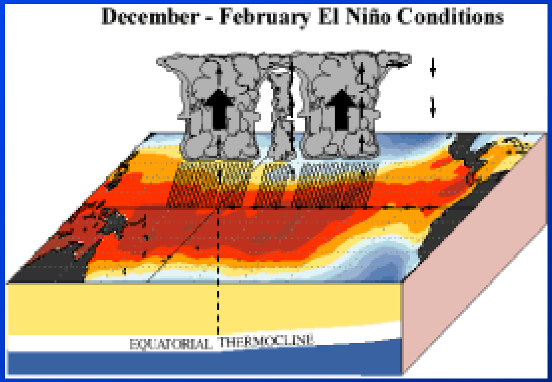
Interannual variability of TOR is strongly correlated to ENSO cycle



Studies have also discovered a relationship between Ozone Pollution over Northern India and both Population & Phase of ENSO



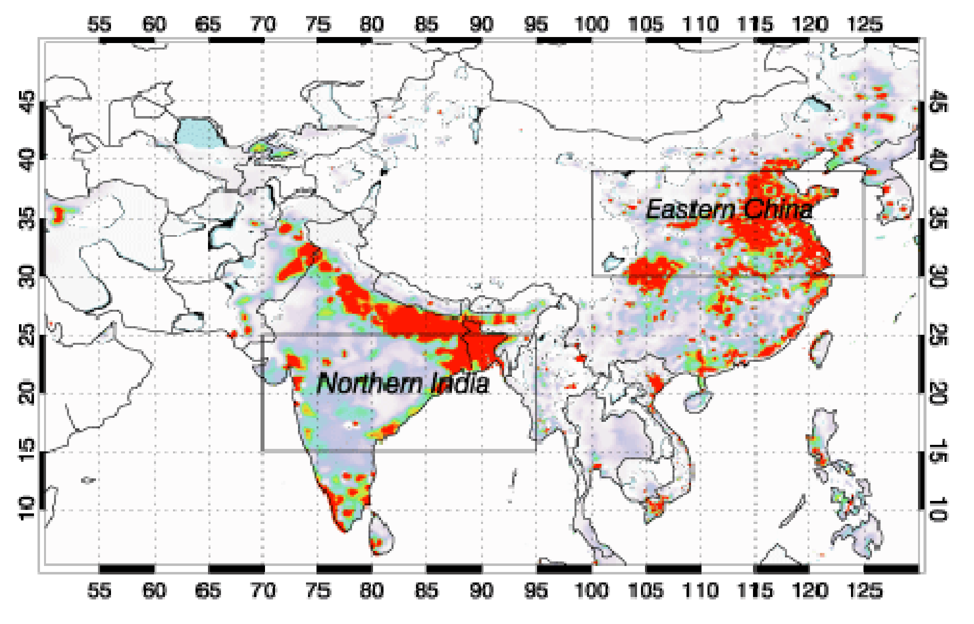
Normal Conditions



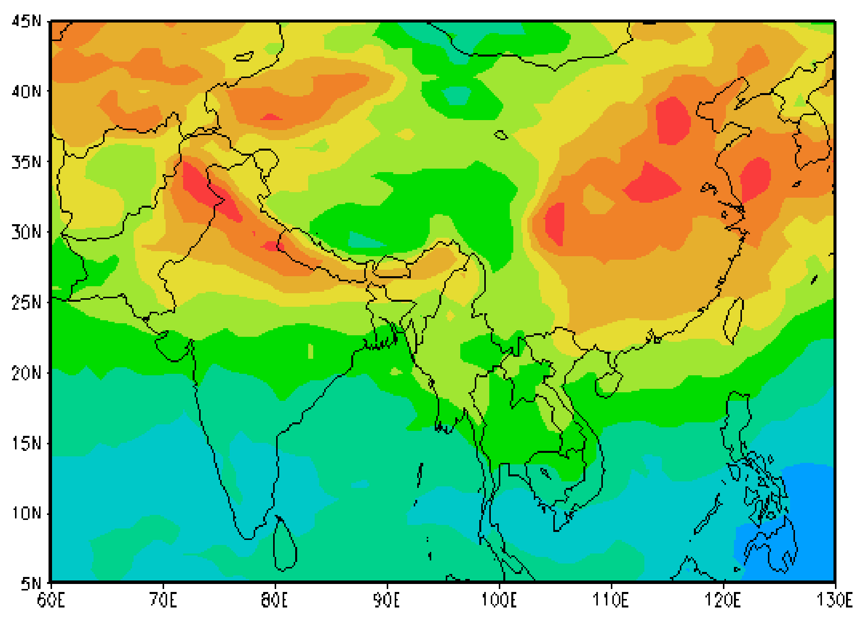
Typical El Niño

Population and Ozone Pollution Strongly Correlated in India and China

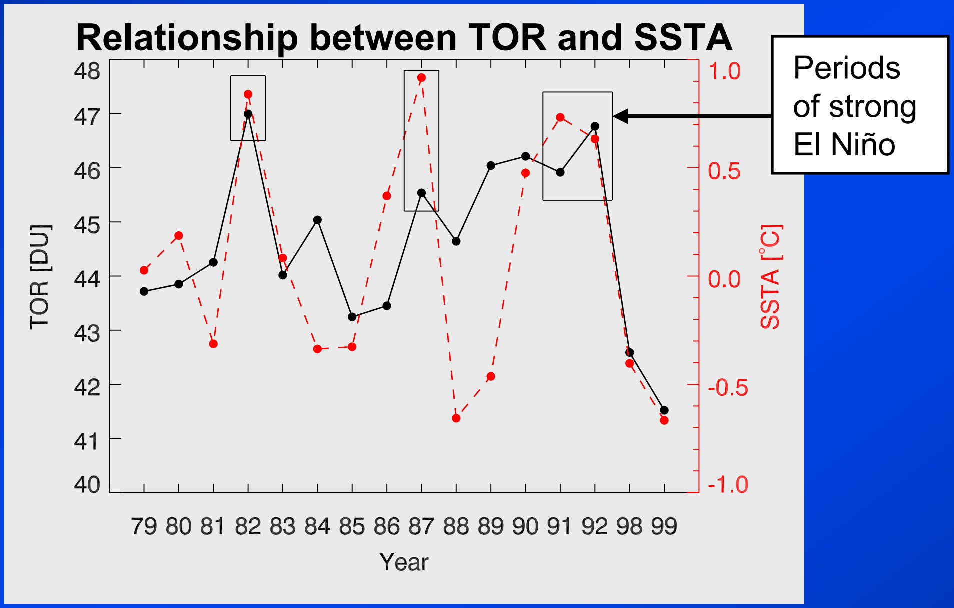
Population Density

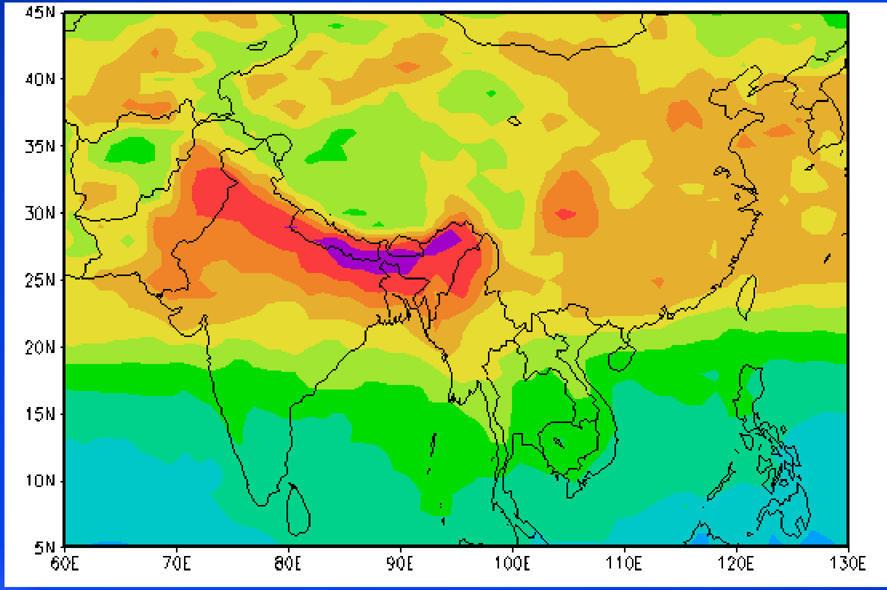


Summertime TOR Depiction

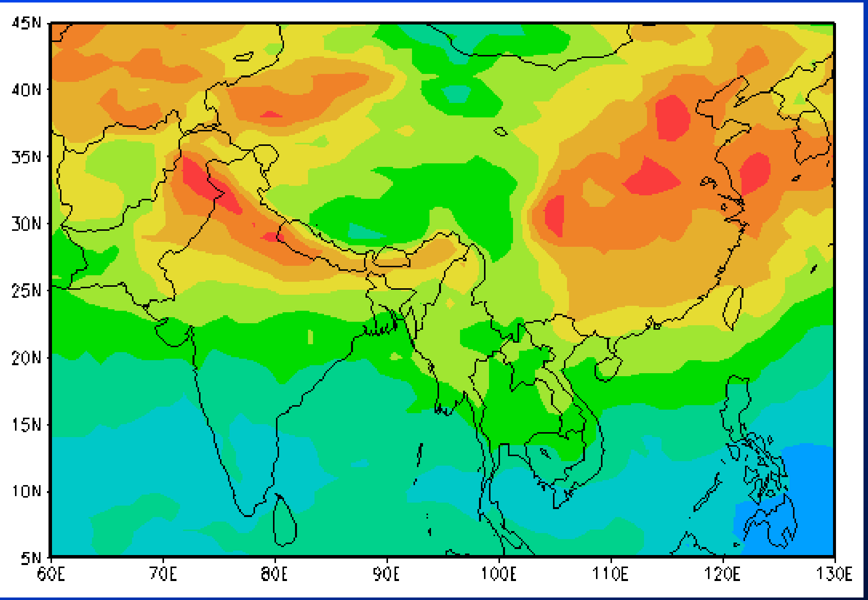


Interannual variability of TOR over Northern India strongly correlated with ENSO and strength of monsoonal flow





June 1982 - Strong El Niño Year



June 1999 - Strong La Niña Year

Distinct Seasonal Difference Evident between India and China ENSO Correlations: Strong Summer India Relationship NOT Seen over China

INDIA

Month	SOI		ENSO SST Region			
	Mon	Seas	1&2	3	3.4	4
January	-0.06	-0.09	0.15	0.06	0.03	0.05
February	-0.34	-0.48	0.12	0.28	0.34	0.23
March	0.03	0.02	-0.14	-0.13	-0.06	0.11
April	-0.15	-0.14	-0.14	0.05	0.12	0.24
May	0.22	0.24	-0.2	0.08	0.13	0.3
June	-0.43	**-0.55**	-0.11	0.27	0.41	0.44
July	-0.48	**-0.56**	0.06	0.4	**0.59**	0.68
August	-0.44	**-0.53**	0.12	0.45	**0.57**	0.66
September	0.13	0.19	-0.25	-0.25	-0.23	0.04
October	**0.5**	0.43	-0.36	-0.43	-0.47	**-0.54**
November	0.28	0.1	0.12	0.04	-0.01	-0.13
December	**0.5**	0.3	-0.02	-0.09	-0.16	-0.16

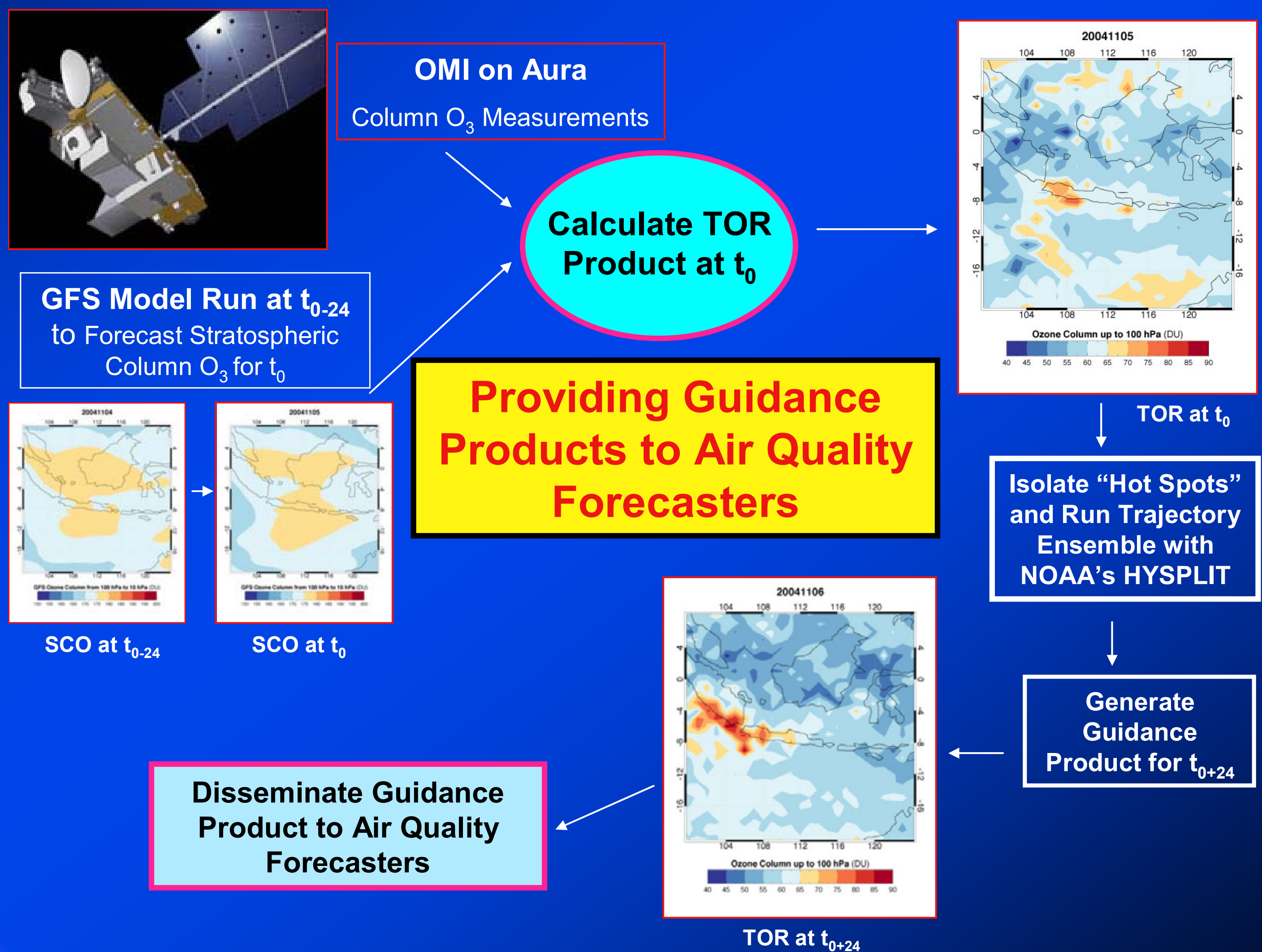
(Significant correlations at .05 level are shaded)

CHINA

Month	SOI		ENSO SST Region			
	Mon	Seas	1&2	3	3.4	4
January	-0.22	-0.14	0.12	0.15	0.17	0.19
February	-0.19	-0.09	0.27	0.21	0.19	0.29
March	-0.1	-0.01	-0.21	-0.03	0.15	0.26
April	-0.4	-0.38	-0.05	0.13	0.26	0.27
May	-0.09	-0.07	0.06	0.39	0.39	0.18
June	0.4	0.39	0.17	0.04	0.02	0.04
July	0.31	0.34	-0.38	-0.17	-0.08	-0.07
August	0.06	-0.16	-0.14	-0.07	-0.11	-0.19
September	0.2	0.21	-0.09	-0.28	-0.34	-0.35
October	0.31	0.29	0.16	-0.04	-0.15	-0.4
November	-0.04	-0.19	0.35	0.24	0.18	0.08
December	-0.05	-0.09	0.28	0.35	0.3	0.19

What's Next?

Improved residual technique utilizing OMI total ozone and GFS ozone profile information



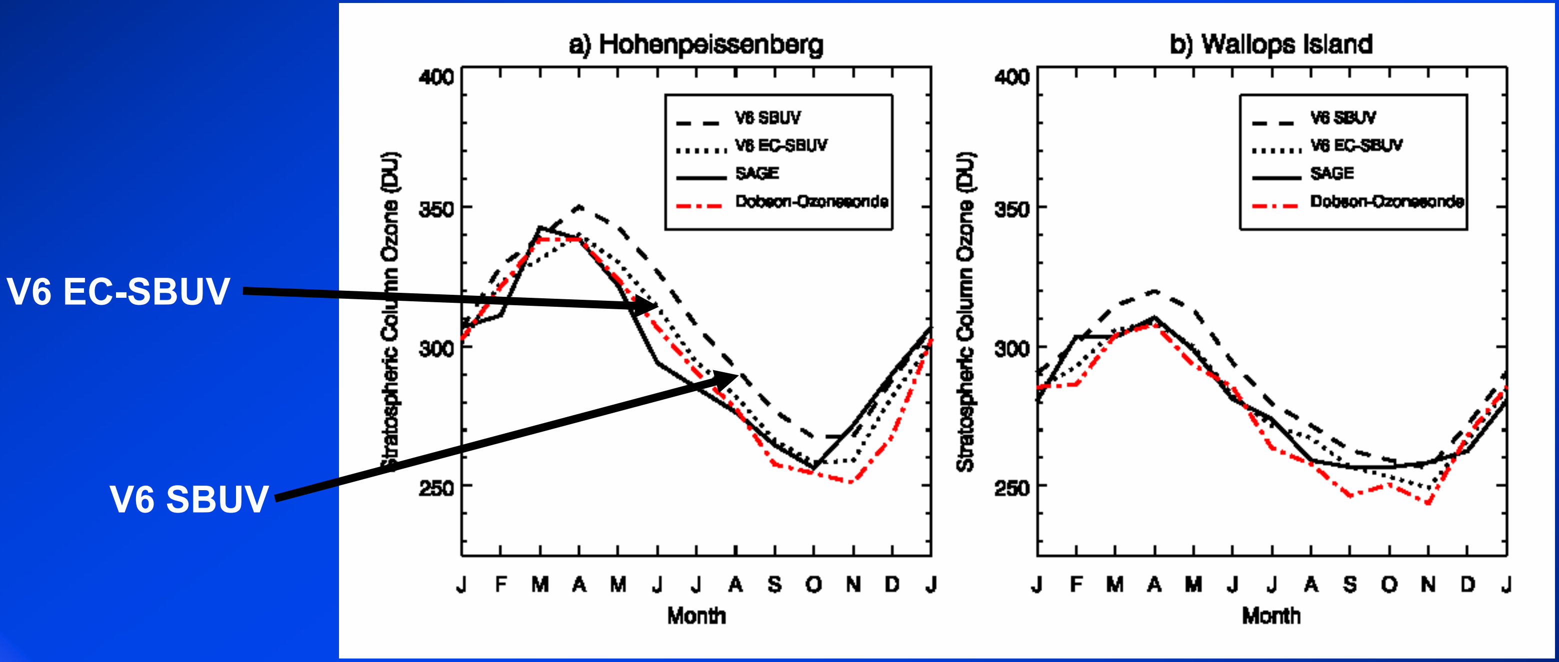
SUMMARY

- Pioneering Research into Tropospheric Ozone Leads to Discovery of Tropospheric Signal in TOMS
  - 20 Years of Tropospheric Ozone (TOR) Data now available at http://asd-www.larc.nasa.gov/TOR/data.html
- Distinct Differences in West African Tropospheric versus Stratospheric Ozone-Climate Relationships:
  - Tropospheric-ENSO; Stratospheric-QBO
- Strong Correlation between Asian Pollution and Population
  - Interannual Variability over India Linked to Phase of ENSO
  - However, similar TOR-ENSO relationship not seen over China
- **Next Step**:
  - Extending current tropospheric ozone record by way of OMI-GFS residual product
  - Linking satellite observations and surface measurements through prevailing meteorology

GOAL: CONTINUATION AND IMPROVEMENT OF LONG-TERM TROPOSPHERIC OZONE RECORD

Back-Up Slides

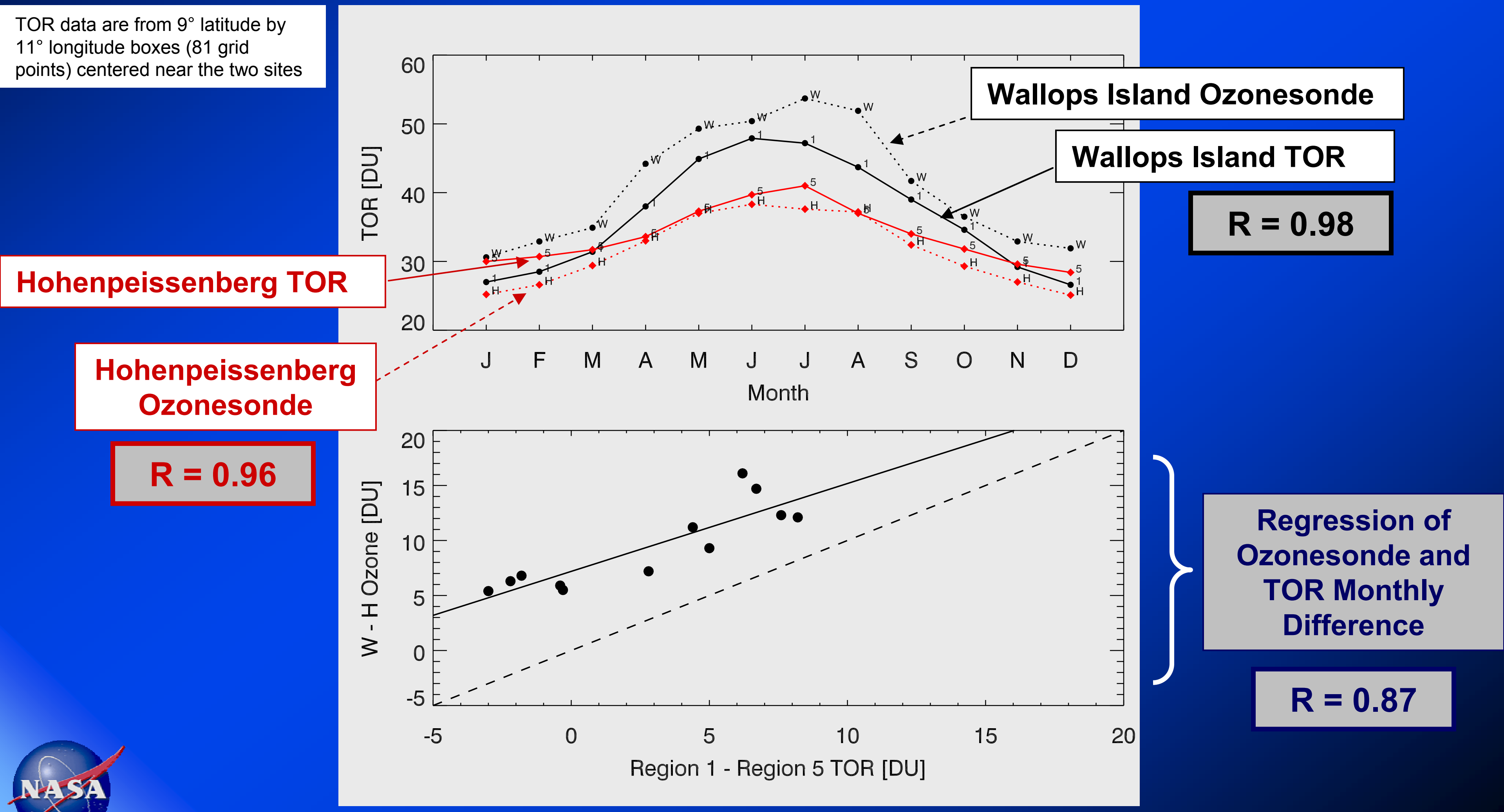
Seasonal Cycle of Stratospheric Column Ozone at Hohenpeissenberg and Wallops Island: EC-SBUV SCO More Closely Mirrors SAGE and Dobson-Ozonesonde Network than Archived V6 SBUV



How do we validate TOR measurements?

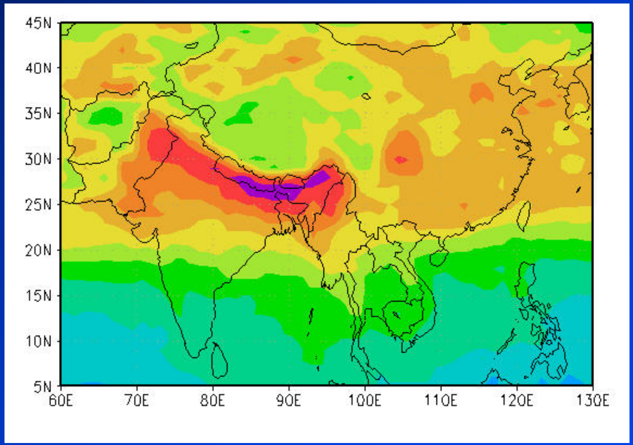
Comparison of Satellite TOR with Ozonesonde Measurements at two Mid-latitude Sites

TOR data are from 9° latitude by 11° longitude boxes (81 grid points) centered near the two sites

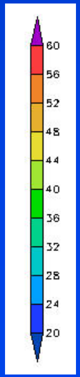


from Creilson et al., 2003

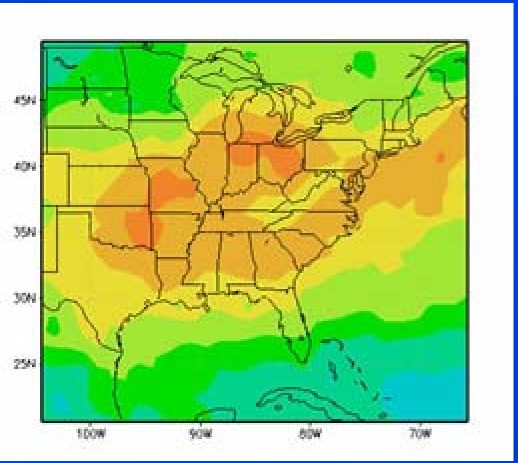
Asian Pollution Event Stronger than Historic 1988 Eastern United States Episode



TOR June 1982

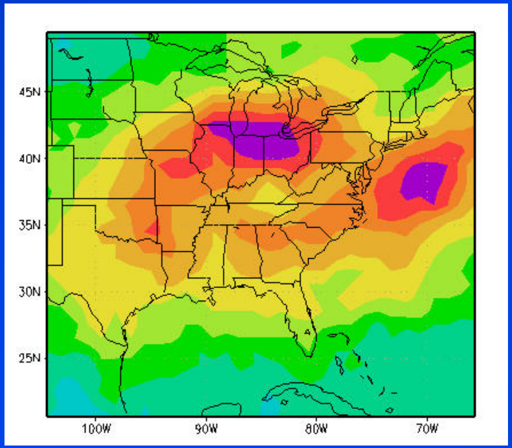


Dobson Units (DU)

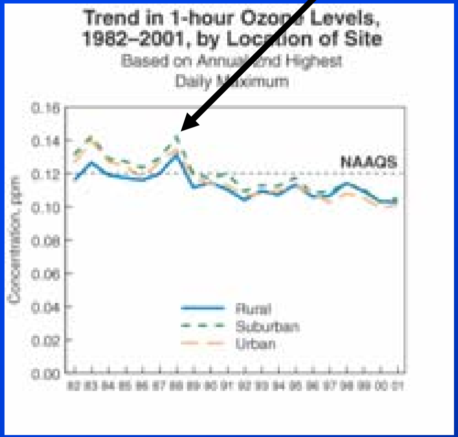


TOR July 1988

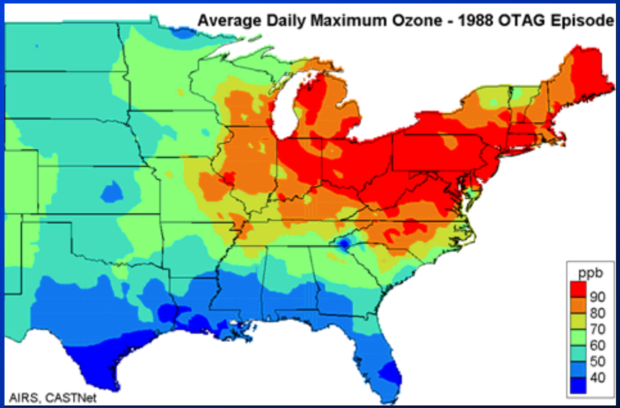
1988 Worst Year



TOR July 3-15 1988

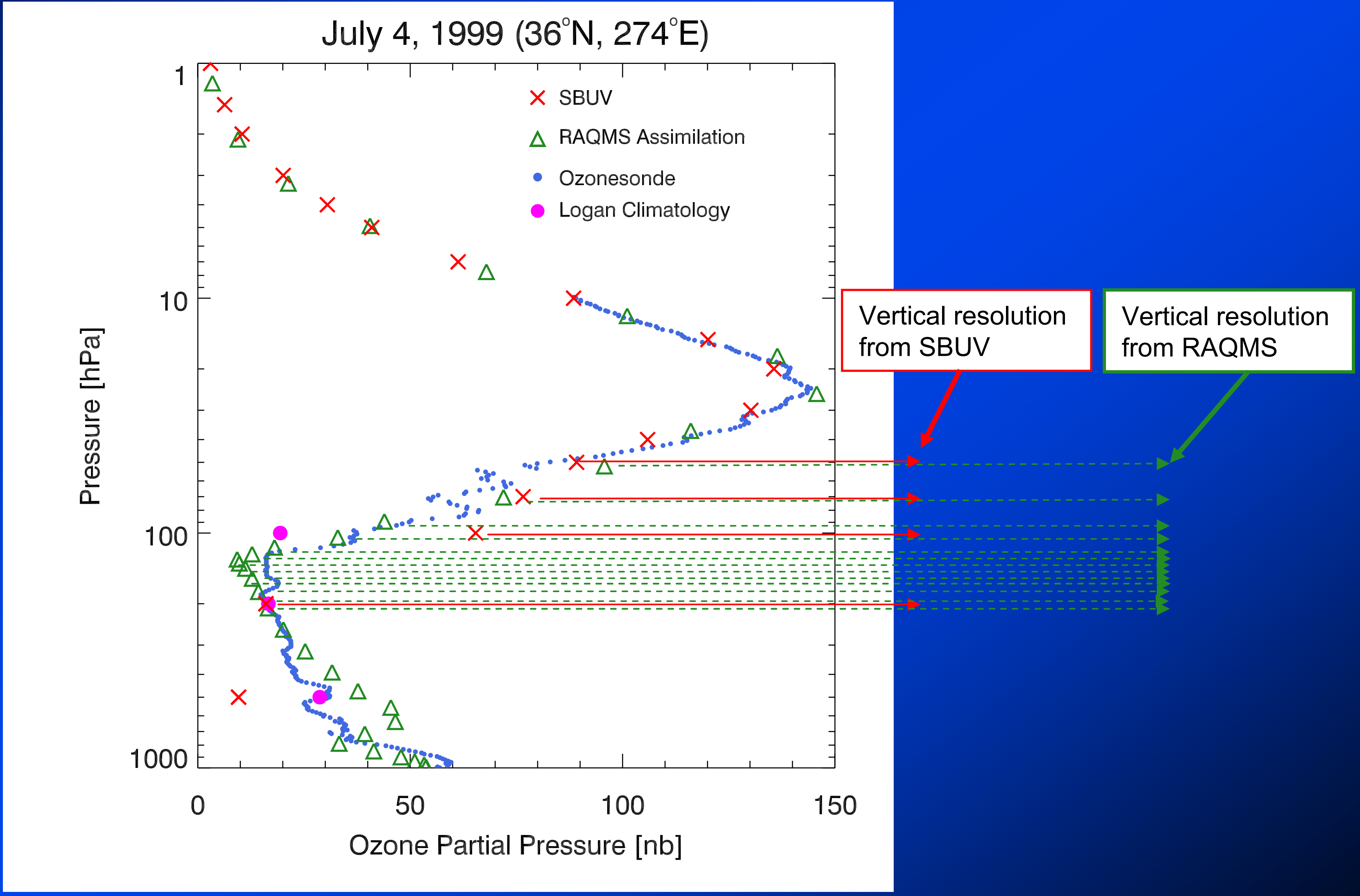


U.S. Surface Ozone Levels-1982-2001



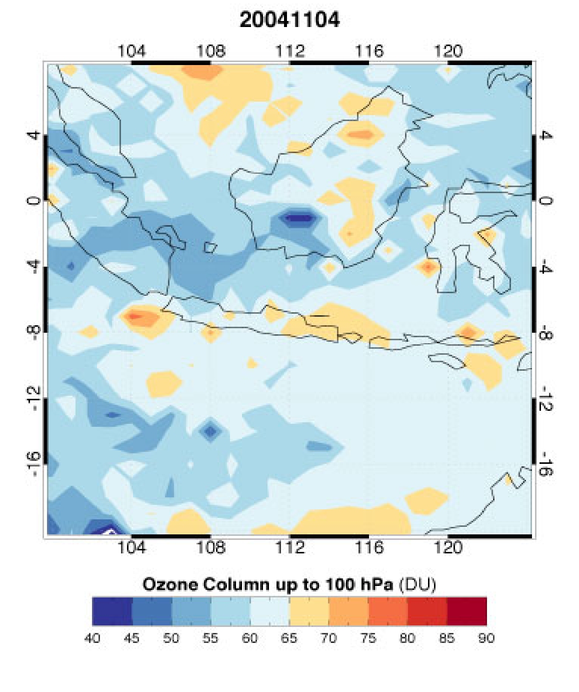
Surface O_3 July 3-15 1988

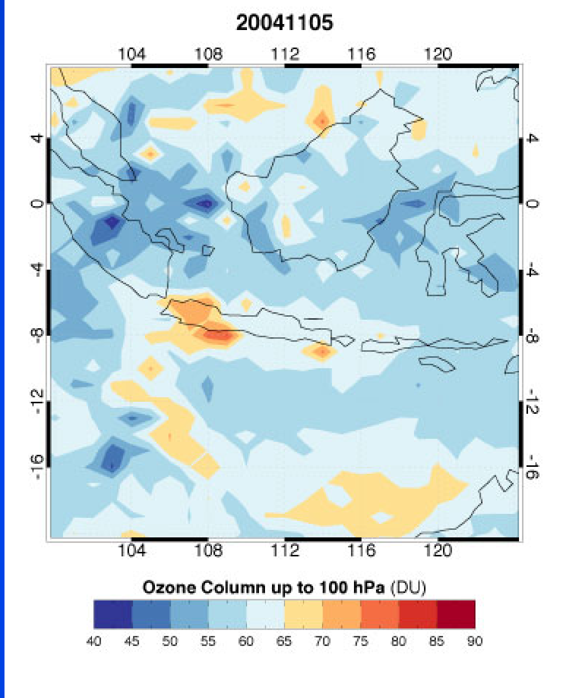
Assimilated Data Provide Much Better Information in Upper Troposphere and Lower Stratosphere Compared to Nadir-viewing Satellites: Critical for Residual Techniques

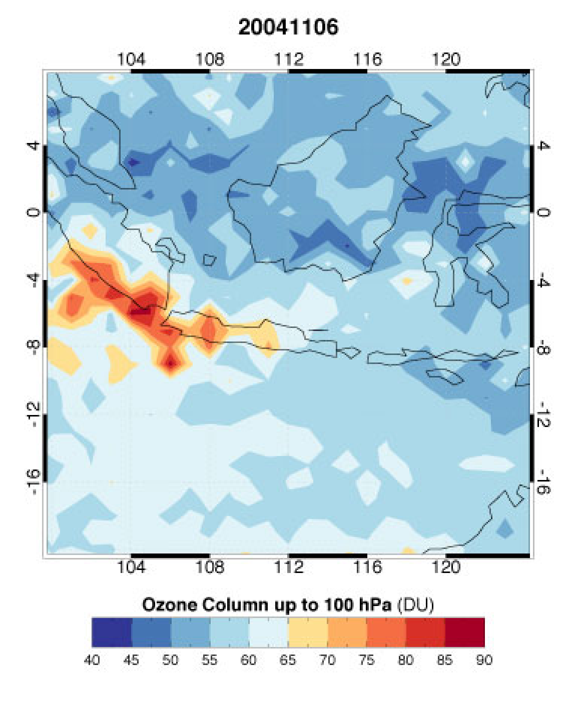


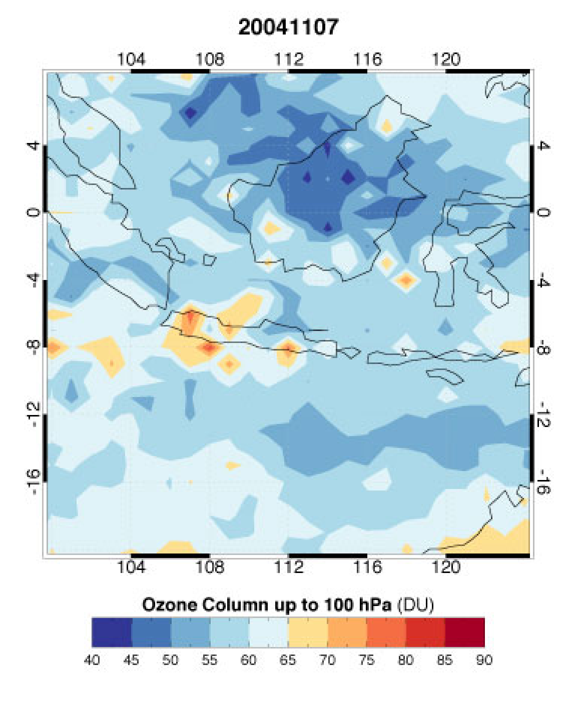
Calculated TOR

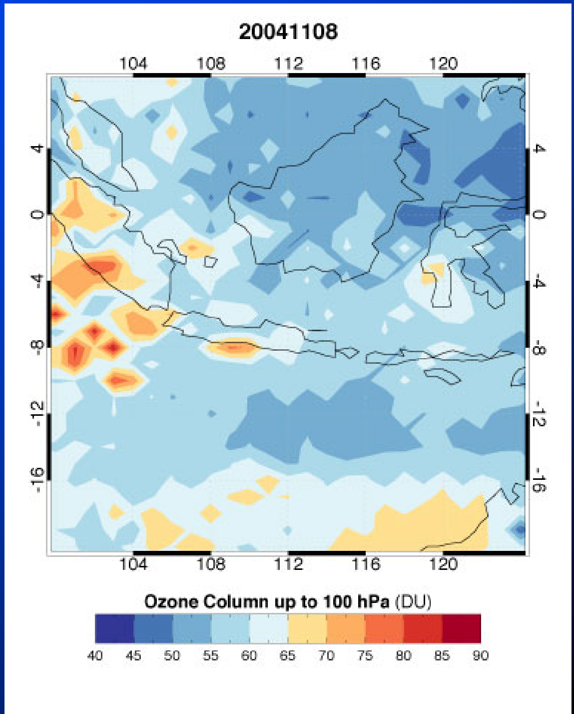
4-8 Nov 2004











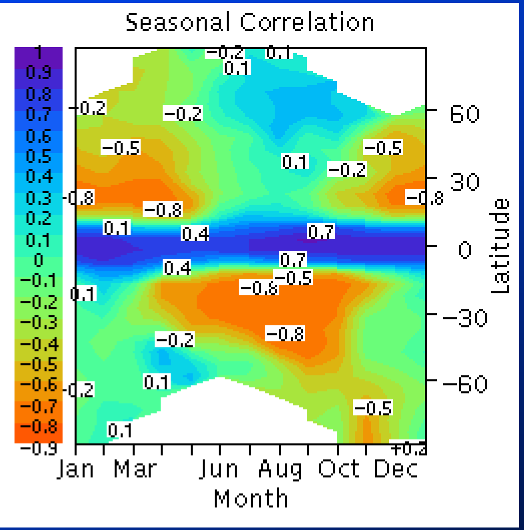
Stratospheric and Tropospheric Interannual Variability in the Tropics: Relationship between Stratospheric Ozone and the QBO

Region	Lat	Monthly SCO Correlations											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	N=>	18	18	17	18	17	17	17	18	18	18	17	17
West Africa (20W-30E)	15-20N	-.23	-.34	-.37	**-.48**	-.39	-.12	.07	-.20	-.20	-.20	-.10	-.17
	10-15N	.18	.03	-.06	-.09	.12	.27	.44	.09	.10	.05	.16	.13
	5-10N	**.55**	.46	.40	.31	**.53**	**.57**	.71	**.53**	**.56**	**.54**	**.55**	**.52**
	E-5N	.64	.63	.67	.60	.71	.73	.82	.73	.74	.72	.70	.65
	E-5S	**.53**	.65	.68	.66	.74	.73	.83	.70	.64	.63	.70	**.54**
	5-10S	.36	**.56**	**.56**	**.57**	.62	**.49**	**.59**	.34	.26	.33	**.56**	.27
	10-15S	.11	.37	.31	.25	.18	.02	-.15	**-.49**	-.35	-.37	-.10	-.14
	15-20S	-.10	.13	.01	-.16	-.31	-.31	**-.55**	**-.78**	**-.68**	**-.65**	**-.51**	-.38
India (60-120E)	15-20N	-.28	-.17	-.40	-.45	-.48	-.27	.11	-.04	.04	.15	-.08	-.31
	10-15N	.21	.23	-.02	-.17	.05	.18	.38	.21	.36	.40	.23	-.08
	5-10N	.60	.64	**.49**	.41	**.52**	**.52**	.64	**.53**	.67	.70	.73	.44
	E-5N	.65	.69	.67	.69	.67	.63	.78	.72	.80	.79	.87	.65
	E-5S	.62	.66	.68	.73	.71	.65	.78	.73	.79	.74	.83	**.58**
	5-10S	**.54**	.59	**.57**	.66	.62	.35	**.50**	.35	**.47**	**.48**	.67	.34
	10-15S	.30	.41	.27	.34	.22	-.21	-.33	**-.48**	-.42	-.26	-.04	-.27
	15-20S	.02	.20	-.06	-.13	-.23	-.45	**-.64**	**-.69**	**-.68**	**-.56**	**-.57**	**-.49**
Pacific (160-100W)	15-20N	-.34	-.19	-.37	-.36	**-.53**	-.17	.02	-.09	-.17	-.03	-.06	-.18
	10-15N	-.02	.08	-.03	-.11	-.13	.17	.32	.17	.12	.23	.27	.11
	5-10N	.34	.44	.40	.28	.30	**.49**	.65	**.51**	**.47**	**.55**	.69	**.54**
	E-5N	**.53**	.63	.65	**.57**	**.56**	.69	.79	.67	.59	.65	.79	.65
	E-5S	**.50**	.64	.73	.67	.63	.72	.78	.66	**.54**	**.58**	.71	.59
	5-10S	.29	**.49**	.63	**.56**	**.53**	**.55**	.45	.35	.21	.26	.42	.34
	10-15S	.02	.25	.38	.19	.19	.10	-.35	**-.49**	**-.51**	-.43	-.29	-.09
	15-20S	-.14	.08	.15	-.22	-.25	-.32	**-.71**	**-.80**	**-.80**	**-.69**	**-.63**	-.33

}E

Positive Correlation and level of significance of at least .01:
Positive Correlation and level of significance of at least .05:
Negative Correlation and level of significance of at least .01:
Negative Correlation and level of significance of at least .05:

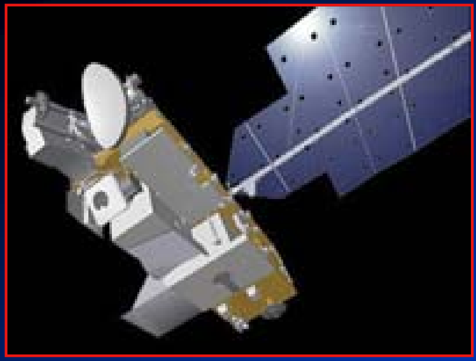
Strong equatorial (E) correlative pattern consistent with known total ozone/QBO relationship



(from Kinnersley and Tung (1998))

from Fishman et al., 2005 (submitted)

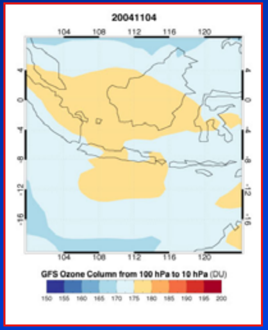
Providing Guidance Products to Air Quality Forecasters



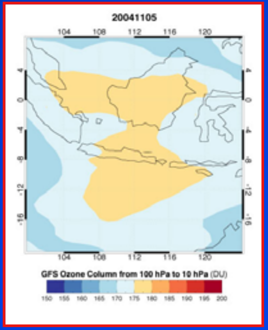
OMI on Aura

Column O_3 Measurements

GFS Model Run at t_{0-24}
to Forecast Stratospheric Column O_3 for t_0

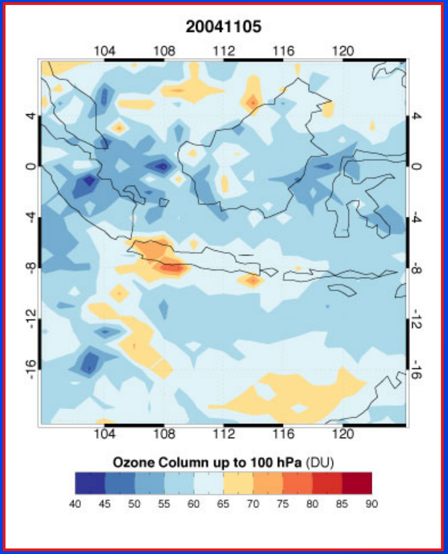


SCO at t_{0-24}



SCO at t_0

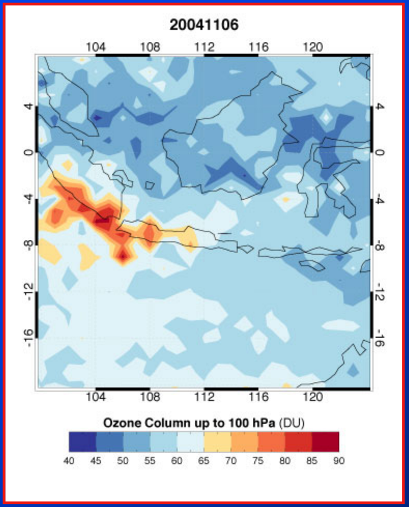
Calculate TOR Product at t_0



TOR at t_0

Isolate "Hot Spots" and Run Trajectory Ensemble with NOAA's HYSPLIT

Generate Guidance Product for t_{0+24}



TOR at t_{0+24}

Disseminate Guidance Product to Air Quality Forecasters

Distinctive Seasonal Difference between India and China ENSO Correlations: Strong Summer India Relationship Not Seen over China

INDIA

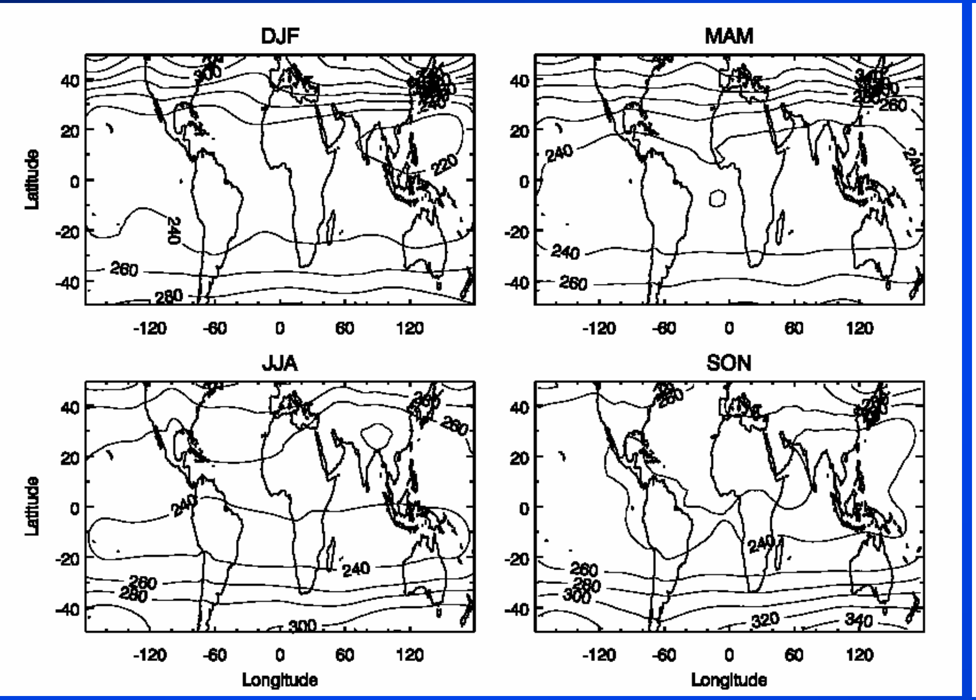
Month	SOI		ENSO SST Region			
	Mon	Seas	1&2	3	3.4	4
January	-0.06	-0.09	0.15	0.06	0.03	0.05
February	-0.34	-0.48	0.12	0.28	0.34	0.23
March	0.03	0.02	-0.14	-0.13	-0.06	0.11
April	-0.15	-0.14	-0.14	0.05	0.12	0.24
May	0.22	0.24	-0.2	0.08	0.13	0.3
June	-0.43	**-0.55**	-0.11	0.27	0.41	0.44
July	-0.48	**-0.56**	0.06	0.4	**0.59**	**0.68**
August	-0.44	**-0.53**	0.12	0.45	**0.57**	**0.66**
September	0.13	0.19	-0.25	-0.25	-0.23	0.04
October	**0.5**	0.43	-0.36	-0.43	-0.47	**-0.54**
November	0.28	0.1	0.12	0.04	-0.01	-0.13
December	**0.5**	0.3	-0.02	-0.09	-0.16	-0.16

(Significant Correlations at .05 level are shaded)

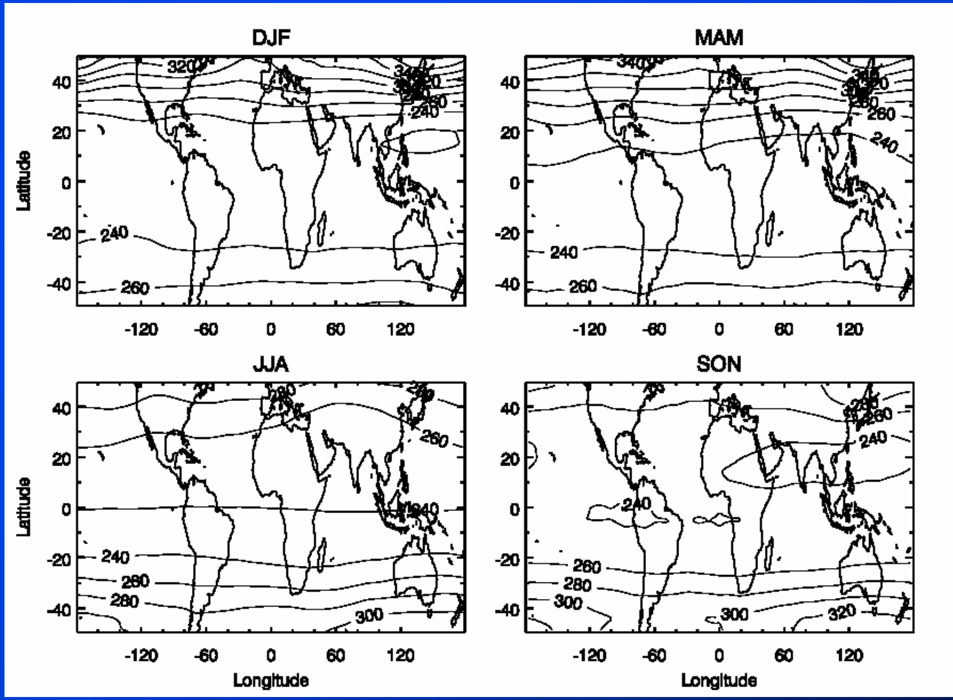
CHINA

Month	SOI		ENSO SST Region			
	Mon	Seas	1&2	3	3.4	4
January	-0.22	-0.14	0.12	0.15	0.17	0.19
February	-0.19	-0.09	0.27	0.21	0.19	0.29
March	-0.1	-0.01	-0.21	-0.03	0.15	0.26
April	-0.4	-0.38	-0.05	0.13	0.26	0.27
May	-0.09	-0.07	0.06	0.39	0.39	0.18
June	0.4	0.39	0.17	0.04	0.02	0.04
July	0.31	0.34	-0.38	-0.17	-0.08	-0.07
August	0.06	-0.16	-0.14	-0.07	-0.11	-0.19
September	0.2	0.21	-0.09	-0.28	-0.34	-0.35
October	0.31	0.29	0.16	-0.04	-0.15	-0.4
November	-0.04	-0.19	0.35	0.24	0.18	0.08
December	-0.05	-0.09	0.28	0.35	0.3	0.19

Comparison of Seasonal Stratospheric Column Ozone Distributions Derived from Empirically-Corrected SBUV and SAGE II Measurements (1985-2000) Exhibits Strong Similarities



SBUV



SAGE

from Wozniak et al., 2005 (submitted)