Instantaneous Radiative Forcing from Tropospheric Ozone on Regional and Global Scales Estimated from Satellite Measurements

Helen M. Worden, NCAR, Kevin W. Bowman, Annmarie Eldering, and Susan S. Kulawik, JPL, CalTech

ABSTRACT

Ozone is the third most important greenhouse gas, according to assessments of The Intergovernmental Panel on Climate Change (IPCC). The 2007 IPCC average value from model estimates for the radiative forcing due to anthropogenic tropospheric ozone is 0.35 W/m^2, with predictions ranging from 0.25 to 0.65 W/m^2. While much of the uncertainty is due to the lack of reliable measurements for pre-industrial ozone, it is also related to the spatial and temporal variability of tropospheric ozone, which is much higher than longer-lived greenhouse gases such as CO2.

We show satellite estimates of instantaneous radiative forcing, defined here as the reduction in outgoing longwave radiation (OLR), due to tropospheric ozone. Using spectrally resolved infrared (IR) radiances from the Tropospheric Emission Spectrometer (TES) and corresponding atmospheric retrievals, we compute the outgoing flux for the 9.6 µm ozone absorption band and examine principal components of radiance variability. To focus on particular regions, we use jacobians of radiance sensitivity to the vertical distribution of ozone that are calculated by the retrieval algorithm.

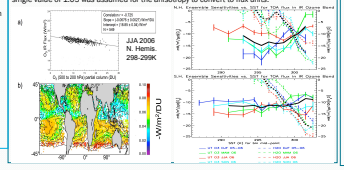
Accounting for sea surface temperature (SST), we calculate a 2006 average clear-sky OLR reduction from upper tropospheric ozone of 0.48 ± 0.14 W/m^2 (with measurement uncertainty) for ocean scenes with latitudes 45°S to 45°N. These results are the first global measurements that partition the greenhouse gas contribution from tropospheric ozone and represent new observational constraints for climate model predictions of present and future radiative forcing and forcing sensitivity.

METHODS

Global ensemble estimates

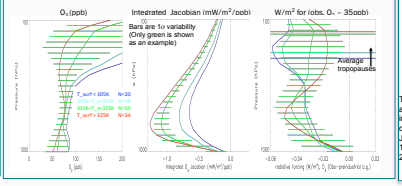
Reference: H. Worden et al., Nature Geoscience, 2008.

Using clear-sky, ocean TES spectra, binned by SST (sea-surface temperature), we compute linear regressions of the LW outgoing flux for the 985-1080 cm^{-1} ozone band vs. corresponding estimates of the 500-200 hPa ozone column (DU) to obtain the OLR sensitivity to upper tropospheric ozone in W/m^2/DU as a function of season, hemisphere and SST. A single value of 1.05 was assumed for the anisotropy to convert to flux units.



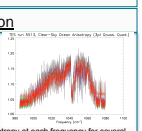
Radiance Jacobians

For a subset of TES data, we stored the Jacobian matrices in W/m^2/cm^{-1}/sr/ppb for ozone (1585 frequencies x 64 pressure levels) for the final iteration of the retrieval. These can be used to compute the instantaneous radiative forcing from ozone in each TES observation including land and cloud scenes. Results in this poster are for JJA, 2006, 15°-45°N, 20°-60°E. Example below shows averages for clear-sky land, daytime observations.



Angular Flux integration

To obtain flux in W/m^2 from nadir radiances for different surfaces and clouds, we need an estimate of anisotropy for each scene. By computing a forward model radiance using the retrieved atmospheric state at 50.77° off-nadir, we perform a 3-pt Gaussian integration to obtain the hemispherical flux and estimate the anisotropy for each TES observation.



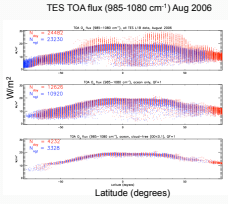
Above plot shows anisotropy at each frequency for several clear-sky ocean scenes, (colors are for latitude ranges)

Table shows average anisotropy integrated over the ozone band for JJA, 2006, 15°-45°N, 20°-60°E.

Scene Type	Average anisotropy	Standard deviation	N (# cases)
Clear-sky ocean	1.095	0.005	182
Clear-sky land (night)	1.087	0.010	130
Clear-sky land (day)	1.111	0.009	142
Trans. Cld ocean	1.115	0.023	65
Trans. Cld land (night)	1.103	0.019	201
Trans. Cld land (day)	1.137	0.025	70
Opaque Cld	1.087	0.031	96

PRINCIPAL COMPONENT ANALYSIS

Following the approach of Huang & Yung, JGR, 2005, we can use a Singular Value Decomposition (SVD) to determine the primary sources of variability in the spectra. First, we remove the largest sources of variability: land and clouds.



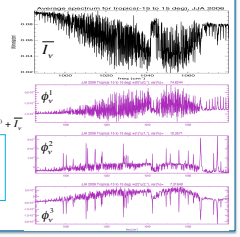
SVD for JJA 2006 TES spectra, cloud-free, ocean, tropics

Average radiance spectrum for JJA 2006 tropics 985-1080 cm^{-1}

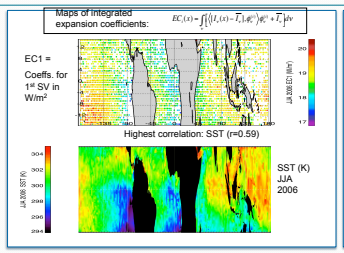
1st 3 Singular Vectors (93.7% of variance)

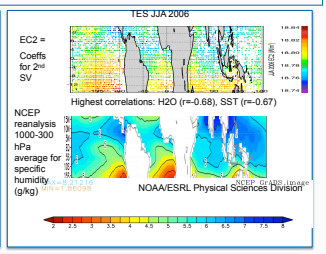
$$I_\nu(x) = \sum_i \langle I_\nu(x) - \overline{I}_\nu, \phi_\nu^{(i)} \rangle \phi_\nu^{(i)} + \overline{I}_\nu$$

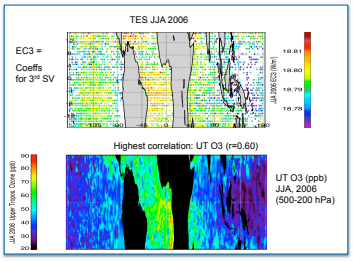
Primary variability from:
- ϕ_ν^1 SST
- ϕ_ν^2 water vapor
- ϕ_ν^3 upper trop. O3



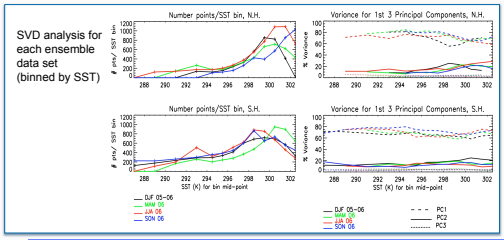
Maps of integrated expansion coefficients: $EC_i(x) = \int_\nu \langle I_\nu(x) - \overline{I}_\nu, \phi_\nu^{(i)} \rangle \phi_\nu^{(i)} + \overline{I}_\nu \, d\nu$

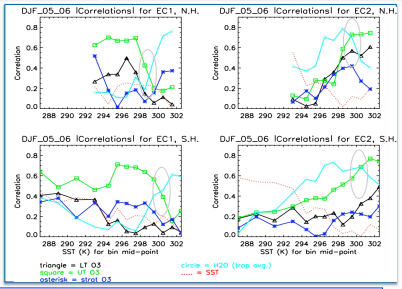






SVD analysis for each ensemble data set (binned by SST)

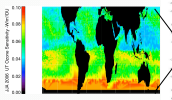




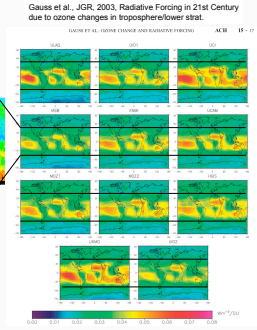
SVD analysis for spectra binned by season, hemisphere and SST. Left panel shows number of observations per bin and the % variance of the 1st 3 principle components. Right panel shows the correlations of expansion coefficients corresponding to the first two singular vectors for SVDs of TES spectra in each SST bin. Top plots show results for the northern hemisphere (N.H.) and bottom plots show the southern hemisphere (S.H.) for Dec. 2005 to Feb. 2006 (DJF_05_06). Note the relatively low correlation of EC1 with SST since data are binned by SST (2K bins up to 294 K, then 1K bins). Ovals denote the crossover points between upper tropospheric (UT) ozone and water vapor dominance of the correlation.

GLOBAL RESULTS FOR 2006 CLEAR-SKY OCEAN TES OBSERVATIONS USING ENSEMBLE ESTIMATES

Normalized Radiative Forcing (W/m^2/DU)



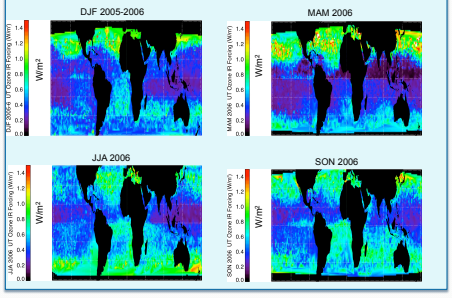
Gauss et al., JGR, 2003, Radiative Forcing in 21st Century due to ozone changes in troposphere/lower strat.



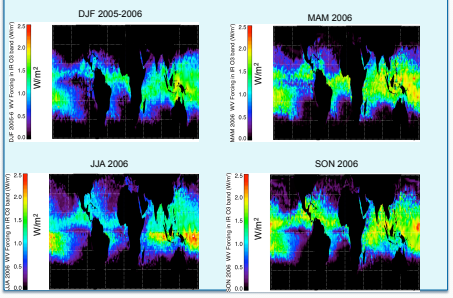
TES global, annual avg = 0.055 W/m^2/DU (0.017 st.dev.) 45°S to 45°N

Model range = 0.042 - 0.052 W/m^2/DU
LW clear, inst., all latitudes, trop only (no strat)

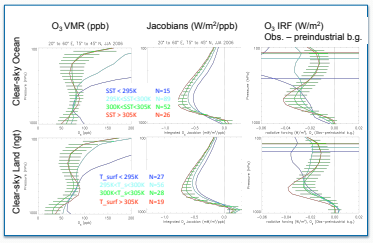
Seasonal dependence of UT Ozone OLR reduction



Seasonal dependence of OLR reduction due to water vapor in IR ozone band



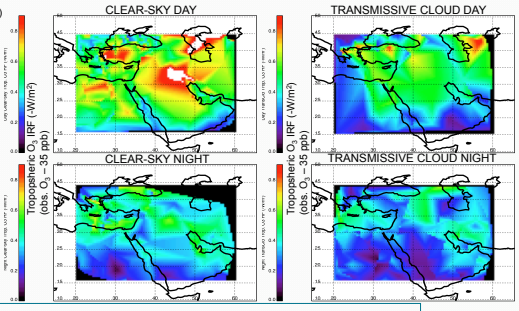
REGIONAL RESULTS FOR 15°-45°N, 20°-60°E, JJA 2006 TES OBSERVATIONS USING RADIANCE JACOBIANS



Instantaneous IR radiative forcing for tropospheric ozone (observed – pre-industrial background) JJA 2006, 15° to 45°N, 20° to 60°E

Scene Type	P_cld > 800 hPa		P_cld 800-600 hPa		P_cld 600-450 hPa		P_cld < 450 hPa	
	RF (-W/m^2)	N	RF (-W/m^2)	N	RF (-W/m^2)	N	RF (-W/m^2)	N
Opaque Clouds	0.30 ± 0.14	18	0.26 ± 0.10	27	0.12 ± 0.09	31	0.06 ± 0.04	20
Trans. Clouds Ocean	0.47 ± 0.15	5	0.37 ± 0.13	32	0.28 ± 0.16	19	0.27 ± 0.13	9
Trans. Clouds Land (ngt)	0.40 ± 0.05	2	0.27 ± 0.13	43	0.25 ± 0.11	107	0.25 ± 0.12	49
Trans. Clouds Land (day)	0.38 ± 0.14	10	0.47 ± 0.19	34	0.37 ± 0.23	23	0.21 ± 0.17	3
Clear-sky Ocean	0.44 ± 0.15	182						
Clear-sky Land (night)	0.34 ± 0.13	130						
Clear-sky Land (day)	0.60 ± 0.20	142						
Clear-sky (all) *IPCC tar avg.*	0.46 ± 0.19 *0.345*	454						
Clear+Cloudy *IPCC tar avg.*	0.37 ± 0.20 *0.255*	887						

- Assumed pre-industrial background for tropospheric ozone is 35 ppb (IPCC-TAR)
- Opaque = cloud OD > 1.386 (transmission < 25%)
- Trans. = 0.1 < cloud OD < 1.386 (transmission from 90% to 25%)
- Clear-sky = cloud OD < 0.1 (transmission > 90%)
- N = number of scenes
- Jacobian(W/m^2/ppb) x sqrt(3) is added up to the chemical tropopause (chem. tropopause = nearest level below therm. tropopause - 800 m)
- Errors are ± 1 σ
- Anisotropy for angular integration is computed for each TES scene
- IPCC values from TAR (2001) are for global LW forcing (avg. did not change for 2007 report)



CONCLUSIONS

Using TES radiance spectra and corresponding atmospheric retrievals, we can partition the reduction in OLR due to tropospheric ozone. This can be done using either ensemble estimates of normalized forcing (W/m^2/DU) or direct calculations with radiance Jacobians computed at retrieval convergence and integrated to W/m^2/ppb. We examine the sources of variability in TES data subsets using principle component analysis, giving insight into the orthogonal nature of tropospheric water vapor and ozone for dominating the variability in ozone band spectra. Comparisons with model results should include both normalized forcing and principle components. Using Jacobians at the solution point for each retrieval, we can investigate the radiative role of ozone in the presence of larger sources of variability, such as surface type, clouds and water vapor in the tropics.

http://tes.jpl.nasa.gov