

1                                   **The Response of Tropical Tropospheric Ozone to ENSO**

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47           **Abstract**

48           We have successfully reproduced the Ozone ENSO Index (OEI) in the Goddard Earth  
49 Observing System (GEOS) chemistry-climate model (CCM) forced by observed sea surface  
50 temperatures over a 25-year period. The vertical ozone response to ENSO is consistent  
51 with changes in the Walker circulation. We derive the sensitivity of simulated ozone to  
52 ENSO variations using linear regression analysis. The western Pacific and Indian Ocean  
53 region shows similar positive ozone sensitivities from the surface to the upper  
54 troposphere, in response to positive anomalies in the Niño 3.4 Index. The eastern and  
55 central Pacific region shows negative sensitivities with the largest sensitivity in the upper  
56 troposphere. This vertical response compares well with that derived from SHADOZ  
57 ozonesondes in each region. The OEI reveals a response of tropospheric ozone to  
58 circulation change that is nearly independent of changes in emissions and thus it is  
59 potentially useful in chemistry-climate model evaluation.

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61           **Introduction**

62           The El Niño-Southern Oscillation (ENSO) is the dominant mode of tropical  
63 variability on interannual timescales [*Philander, 1989*]. ENSO has been long known to  
64 cause significant perturbations to the coupled oceanic and atmospheric circulations  
65 [*Bjerknes, 1969; Enfield, 1989*]. Changes in sea surface temperatures in the Pacific Ocean  
66 can notably impact the Walker Circulation, displacing areas of convective activity, and have  
67 also been shown to dominate the interannual variability of the Hadley cell [*Quan, 2004*].  
68 These changes in circulation cause changes in the temperature and moisture fields across  
69 the tropical Pacific, and influence the constituent distributions in the troposphere [*Chandra*

70 *et al.*, 1998; 2002; 2009; *Sudo and Takahashi*, 2001; *Ziemke et al.*, 2003; *Zeng and Pyle*,  
71 2005; *Doherty et al.*, 2006; *Lee et al.*, 2010; *Randel and Thompson*, 2011] and in the  
72 stratosphere [*Randel and Cobb*, 1994].

73 *Ziemke et al.* [2010] used tropospheric column ozone (TCO) measurements to show  
74 that the ENSO related response of tropospheric ozone over the western and eastern Pacific  
75 dominated interannual variability. The ENSO impact is so clearly seen in tropospheric  
76 ozone columns that an Ozone ENSO Index (OEI) that largely mimics the Niño 3.4 Index is  
77 formed by subtracting the eastern and central tropical Pacific region TCO (15°S-15°N,  
78 110°W-180°W) from the western tropical Pacific-Indian Ocean region (15°S-15°N, 70°E-  
79 140°E), removing the seasonal cycle and smoothing with a 3-month running average.  
80 *Ziemke et al.* [2010] suggested that chemistry-climate models forced with observed sea  
81 surface temperatures should reproduce this observed pattern in tropospheric ozone. Here  
82 we will show that in the GEOS CCM tropical tropospheric ozone responds to the  
83 perturbation in atmospheric dynamics that is due to the ENSO signature in tropical SSTs.  
84 In addition, we use the Southern Hemisphere Additional Ozonesondes (SHADOZ)  
85 measurements to evaluate the vertical structure of the simulated response to ENSO.

86

## 87 **Model Simulation and Measurements**

88 We examine the response of simulated tropospheric ozone to the observed sea  
89 surface temperature changes using the Goddard Earth Observing System (GEOS) version 5  
90 general circulation model [*Rienecker et al.*, 2008] coupled to the comprehensive Global  
91 Modeling Initiative (GMI) stratosphere-troposphere chemical mechanism [*Duncan et al.*,  
92 2007; *Strahan et al.*, 2007]. The GMI combined stratosphere-troposphere chemistry

93 mechanism includes 117 species, 322 chemical reactions, and 81 photolysis reactions.  
94 Integration of the chemical mass balance equations use the SMVGEAR II algorithm  
95 described in *Jacobson (1995)*. The mechanism includes a detailed description of O<sub>3</sub>-NO<sub>x</sub>-  
96 hydrocarbon chemistry necessary for the troposphere (*Bey et al., 2001*), with more recent  
97 updates described in *Duncan et al. (2007)*. The simulation used in this study was forced  
98 with observed sea surface temperatures and sea ice concentrations from 1985 to 2009  
99 (*Rayner et al., 2003*, updated on a monthly basis), but the seasonally-varying mixing ratio  
100 boundary conditions and emissions for trace gases are for 2005 conditions. The simulation  
101 produces the variability in constituent distributions due to sea surface temperature  
102 changes that we evaluate here.

103         A record of TCO for the 2005 – 2010 period was derived from the combination of  
104 NASA's Aura satellite Ozone Monitoring Instrument (OMI) and the Microwave Limb  
105 Sounder (MLS) using the method described in *Ziemke et al. [2006]*. These TCO values  
106 extend the time series developed using Nimbus 7 TOMS, Earth Probe TOMS and NOAA  
107 SBUV. The TCO measurements for 2005 – 2010 are used in Figure 1a. A complete  
108 description of the methods used to construct the OEI can be found in *Ziemke et al. [2010]*.  
109 Here we use the index derived from TCO measurements for 1985 - 2009 to match the  
110 simulation. The OEI time series begins in 1979 and is updated periodically. The data can  
111 be obtained from the Goddard tropospheric ozone website at <http://toms.gsfc.nasa.gov>,

112         We use ozonesonde measurements from five SHADOZ stations [*Thompson et al.,*  
113 2003] (<http://croc.gsfc.nasa.gov/shadoz>): two in the western region (Java and Kuala  
114 Lumpur) and three in the eastern region (American Samoa, Hilo, and San Cristobal). The  
115 data for Watukosek, Java (7.6°S, 112.7°E), Kuala Lumpur, Malaysia (2.7°N, 101.7°E), Pago

116 Pago, American Samoa (14.2°S, 170.6°W), and Hilo, Hawaii (19.4°N, 155.0°W) cover the  
117 1998 to 2009 time period, whereas the San Cristobal (0.9°S, 89.6°W) record is slightly  
118 shorter, covering 1998 to 2008.

119 We used the ENSO index based on the Niño 3.4 region and available from the NOAA  
120 sea-surface temperature website (<http://www.cpc.ncep.noaa.gov/data/indices/>), also  
121 used by *Ziemke et al.* [2010].

122

## 123 **Results and Discussion**

124 *Ziemke et al.* [2010] used a combination of satellite observations and simulations to  
125 show that the observed tropical longitudinal structure in total column ozone was due  
126 almost entirely to structure in the TCO. They identified a dipole in tropical TCO between  
127 the western Pacific-Indian Ocean region and eastern and central Pacific region (15°S-15°N,  
128 70°E-140°E, and 15°S-15°N, 110°W-180°W, respectively). The difference between the  
129 mean TCO in these two regions, shown as black rectangles on Figure 1, is called the Ozone  
130 ENSO Index (OEI). Also shown in Figure 1 is the TCO response to the Niño 3.4 Index  
131 computed using linear regression analysis for both measurements and the GEOS chemistry-  
132 climate model (CCM) simulation. Regression of the TCO against Niño 3.4 Index yields a  
133 sensitivity coefficient or slope (DU/K) that represents the TCO change congruent with a 1K  
134 increase in the Niño 3.4 Index. For reference, a typical El Niño/La Nina cycle represents  
135 about a 3K range with about a 5K range for a more extreme cycle. OMI/MLS derived TCO  
136 measurements [*Ziemke et al.*, 2006] for the 6 years covering 2005 to 2010 are used to  
137 calculate the sensitivity coefficient (DU/K) in Figure 1a. Significant positive TCO  
138 sensitivities are located throughout the western region with significant negative TCO

139 sensitivities over the eastern region. Shaded regions show sensitivities that are not  
140 significant at the 95% level taking into account any autocorrelation of the residual. Figure  
141 1b shows a similar 6-year period (in this case 2004 to 2009) from GEOS CCM simulated  
142 TCO. The overall pattern is similar to that derived from OMI/MLS TCO with a slightly  
143 negative offset in the simulation. Over the Indonesian region, the meridional extent of the  
144 positive anomalies is smaller in Figure 1b than 1a, which could partially be due to the short  
145 record. Also, shown (Figure 1c) is the sensitivity calculated using 25 years of the  
146 simulation (from 1985 to 2009). Another significant feature that appears in both  
147 measurements and simulation is positive TCO sensitivities in the central Pacific Ocean near  
148 30°S.

149         The OEI is the difference between the western region average monthly TCO and that  
150 computed for the eastern region. The deseasonalized time series of OEI, smoothed with a 3-  
151 month running average, is shown in Figure 2 for the measurements (black curve) and  
152 simulation (red curve). The Niño 3.4 Index multiplied by 3 is shown as the blue curve.  
153 There is excellent agreement between all three times series: The correlation of the  
154 measurement derived OEI with ENSO is 0.84 and that of the simulation derived OEI with  
155 ENSO is 0.86. During El Niño, the positive phase of ENSO, the OEI anomaly is positive,  
156 corresponding to increased ozone over the western region and decreased ozone over the  
157 eastern region. This can be most clearly seen during the very strong 1997-1998 El Niño  
158 with an anomaly of 9 DU for OEI obtained from simulated tropospheric ozone columns  
159 compared with 11 DU from observations.

160         The correspondence of observed and simulated OEI prompted us to examine the  
161 vertical structure of the dynamically driven ozone changes simulated with the GEOS CCM,

162 again using linear regression analysis. Regression of the simulated tropical ozone field  
163 against the Niño 3.4 Index yields a sensitivity coefficient in ppbv/K. We average tropical  
164 tropospheric ozone between 15°S and 15°N and regress the deseasonalized ozone field  
165 with Niño 3.4 Index at each longitude and pressure level to construct Figure 3a. Since ENSO  
166 is known to produce a significant change in the Walker circulation, we overlay the anomaly  
167 in the streamfunction obtained by regressing the zonal wind and vertical velocity against  
168 the Niño 3.4 Index. The ozone and circulation anomalies generally have inflection points  
169 just to the west of the international date line, with lower ozone values and anomalous  
170 upwelling to the east and higher ozone values and anomalous downwelling to the west. The  
171 Walker circulation response is seen clearly in the streamfunction anomaly, which  
172 corresponds very well to the pattern of ozone sensitivity. Figure 3a shows that the  
173 simulated sensitivity of ozone to the Niño 3.4 Index in the western region as defined by  
174 *Ziemke et al.* [2010] is ~1 to 2 ppbv/K from the surface to the tropopause with relative  
175 maxima in the upper troposphere around 60°E and in the mid-troposphere around 130°E.  
176 Negative values of ozone sensitivity in the eastern region are largest in the upper  
177 troposphere approaching -15 ppbv/K near the tropopause.

178 We also examine the latitude dependence of the ozone and circulation response in  
179 the two key regions identified by *Ziemke et al.* [2010]. The sensitivity coefficients (ppbv/K)  
180 formed from linearly regressing deseasonalized average ozone in the eastern region  
181 (180°W-110°W) and western region (70°E-140°E) against the Niño 3.4 Index for each  
182 latitude and altitude are given in Figures 3b and 3c respectively. Again we overlay the  
183 anomalous circulation shown by the streamfunction obtained this time by regressing the  
184 meridional wind and vertical velocity against the Niño 3.4 Index. The dashed black curve

185 shows the mean model tropopause in each region. In the eastern region a stronger mean  
186 ascending branch of Walker circulation is seen near the equator. This simulated eastern  
187 region response of the circulation is consistent with the observed rawinsonde station data  
188 analyzed by *Oort and Yienger* [1996] and produces a corresponding tropospheric ozone  
189 response. The region of decreased ozone generally broadens in latitude as altitude  
190 increases with values from -3 ppbv/K in the equatorial mid-troposphere to -15 ppbv/K  
191 near the tropical tropopause. The positive ozone anomalies with increased tropical SSTs in  
192 the midlatitudes of Figure 3b could be consistent with increased stratosphere-troposphere  
193 exchange of ozone. *Zeng and Pyle* [2005] also found an increase in the stratosphere-  
194 troposphere exchange of ozone in their CCM simulation of the impact of ENSO. Other  
195 studies suggested observational evidence for this impact in observations above Colorado  
196 [*Langford et al.*, 1998; *Langford*, 1999]. The recent analysis of *Voulgarakis et al.* [2011] has  
197 also simulated enhanced stratosphere-troposphere exchange of ozone following the strong  
198 1997-1998 El Niño event.

199 *Chandra et al.* [1998] found that downward motion, suppressed convection, and a  
200 drier troposphere contribute to the ozone increase over the tropical western Pacific and  
201 Indonesian region. The combination of downward motion and suppressed convection  
202 bring ozone produced in the upper troposphere down [*Sudo and Takahashi*, 2001], and  
203 reduce the upward transport of low ozone air over ocean surfaces, increasing ozone values  
204 in the low to mid troposphere. Additionally, the drier troposphere increases the chemical  
205 lifetime of ozone, which also acts to increase tropospheric ozone concentrations [*Kley et al.*,  
206 1996]. These results are consistent with the GEOS CCM simulation and are shown in Figure  
207 3c by the anomalous downward component in the circulation.



208           We evaluate the simulated vertical ozone response to ENSO using data collected by  
209 the SHADOZ network [*Thompson et al.*, 2003]. There are SHADOZ stations in and around  
210 the two key regions shown in *Ziemke et al.* [2010]. In Figure 4 we compare the simulated  
211 ENSO related vertical ozone sensitivity to that obtained using observations from two  
212 western region SHADOZ locations (Java and Kuala Lumpur) and three eastern region  
213 SHADOZ locations (American Samoa, Hilo, and San Cristobal) for 1998-2009. Although in  
214 the eastern region only American Samoa is within the box defined by *Ziemke et al.* [2010],  
215 the other two locations are just north (Hilo) and east (San Cristobal) of the region and still  
216 located in the area significantly correlated with ENSO. We deseasonalized each  
217 ozonesonde record prior to averaging them within each region and then regress the  
218 resulting values against the Niño 3.4 Index. In the western region (red diamonds), values  
219 are nearly all statistically significant and positive (2 standard deviation interval shown  
220 from regression). In the eastern region (blue diamonds) SHADOZ reveals significant large  
221 negative values in the upper troposphere similar to those simulated. In the low to mid  
222 troposphere ozone anomalies are generally not significantly different from zero. Also,  
223 plotted on Figure 4 are the ozone sensitivities from the GEOS CCM simulation (solid curves)  
224 sampled at the same locations as the SHADOZ stations. In the western region the GEOS CCM  
225 simulation underestimates the magnitude of the positive anomalies, while in the upper  
226 troposphere of the eastern region the negative anomalies are larger than those derived  
227 from SHADOZ stations. Overall these patterns in SHADOZ regional composites are similar  
228 to those obtained by *Lee et al.* [2010] for two individual stations (Kuala Lumpur and San  
229 Cristobal), and more recently for several stations used by *Randel and Thompson* [2011].  
230

231 **Conclusions**

232           We have demonstrated that the relationship between tropical SST anomalies and  
233 the response of tropical tropospheric ozone is clearly reproduced in the GEOS CCM  
234 simulation forced with time varying observed SSTs. Such agreement requires both a  
235 realistic response of the circulation to the SST and realistic simulated horizontal and  
236 vertical ozone gradients. The OEI represents an essential physical relationship that coupled  
237 chemistry-climate models should reproduce and is potentially useful in future chemistry-  
238 climate model evaluations. Tropical tropospheric ozone changes appear to be congruent  
239 with anomalous changes to the Walker circulation cell.

240           The impact of changes in biomass burning is not considered in this simulation.  
241 Although, previous work (*e.g.*, *Thompson et al.*, 2001) has shown its importance in ozone  
242 production, time-dependent emissions are not critical for reproducing the OEI. *Ziemke et*  
243 *al.* [2009] used emissions appropriate for the 2006 El Niño event; their results suggest that  
244 the change in emissions accounts for no more than 20% of the OEI response. Simulations  
245 indicate that ozone anomalies produced from interannual variability in biomass burning  
246 are transported throughout the tropics over the 3 month averaging period that is used in  
247 constructing the OEI. Only a strong local increase in one region but not the other will  
248 impact the OEI.

249           This analysis demonstrates that ENSO-related changes in the circulation, thermal  
250 structure and composition drive tropical ozone variability. Future work will include a  
251 detailed budget analysis to determine the relative contributions of dynamical, chemical,  
252 and thermal changes to the sensitivity of ozone and related species to ENSO.

253

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260

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354 Figure Captions

355 Figure 1. Comparison of the tropospheric column ozone sensitivity (DU/K) to the Niño 3.4  
356 Index for a) 6 years of MLS/OMI measurements, b) 6 years of GEOS CCM simulation, c) 25  
357 years of GEOS CCM simulation. Shaded regions are not significant at the 95% level. The  
358 black rectangles show two regions used in calculating the Ozone ENSO Index.

359

360 Figure 2. Comparison of GEOS CCM simulation and *Ziemke et al.* [2010] measurement  
361 derived Ozone ENSO Index (OEI) with Niño 3.4 Index (multiplied by 3) for the 1985 to  
362 2009 time period.

363

364 Figure 3. Sensitivity coefficient (ppbv/K) formed from linearly regressing deseasonalized  
365 tropical (15°S-15°N, a), eastern region (180°W-110°W, b), and western region (70°E-  
366 140°E, c) average ozone against Niño 3.4 Index. Overlaid is the anomalous circulation  
367 shown by the streamfunction obtained by regressing the zonal wind and vertical velocity  
368 (a), or meridional wind and vertical velocity (b,c) against Niño 3.4 Index. The dashed black  
369 curve on all panels shows the mean model tropopause.

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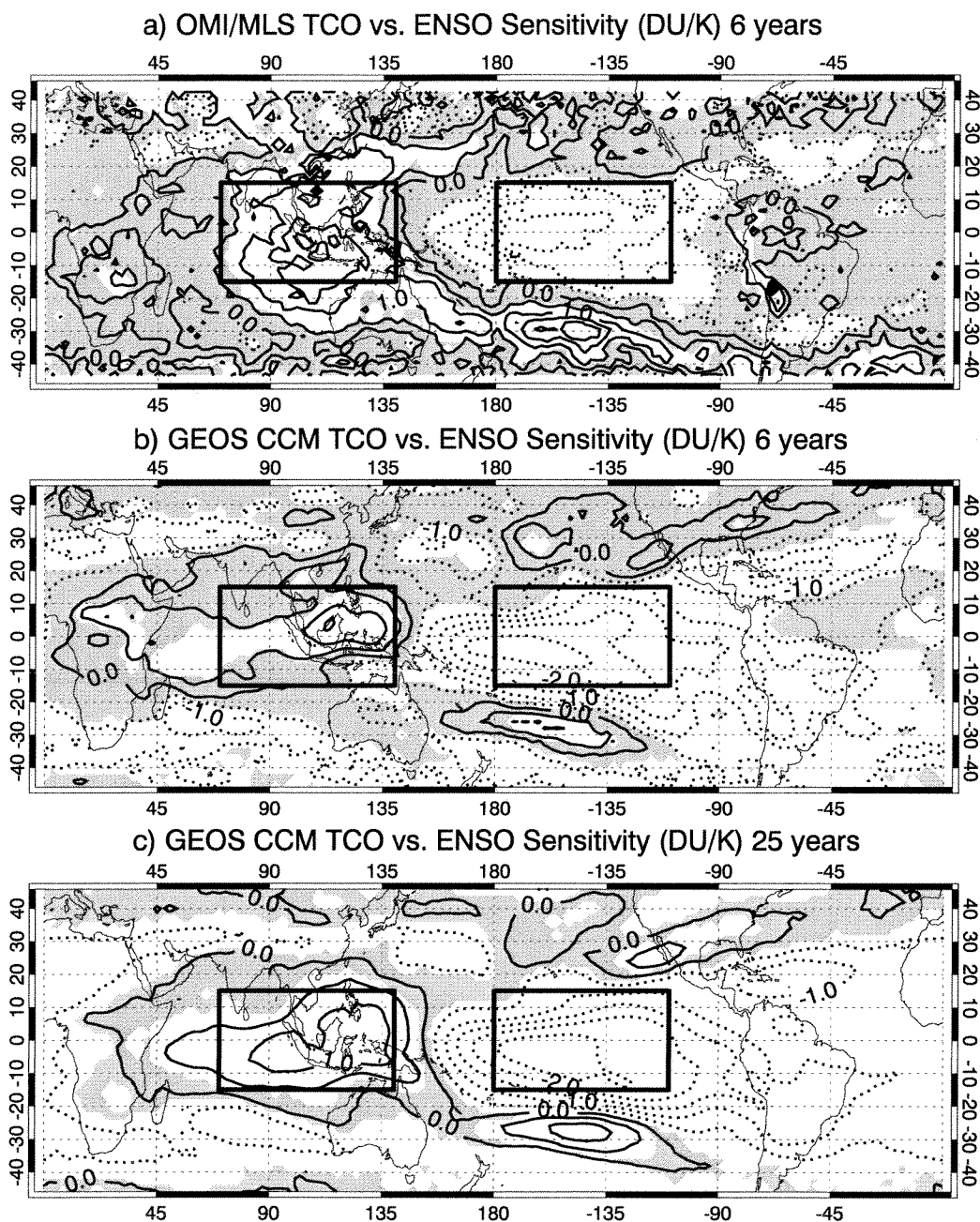
371 Figure 4. Vertical structure of ozone sensitivity (ppbv/K) to Niño 3.4 Index derived from  
372 SHADOZ ozonesondes over the western (red diamonds) and eastern (blue diamonds)  
373 regions of the tropical Pacific. GEOS CCM sensitivities sampled for the SHADOZ locations  
374 are shown as solid curves.

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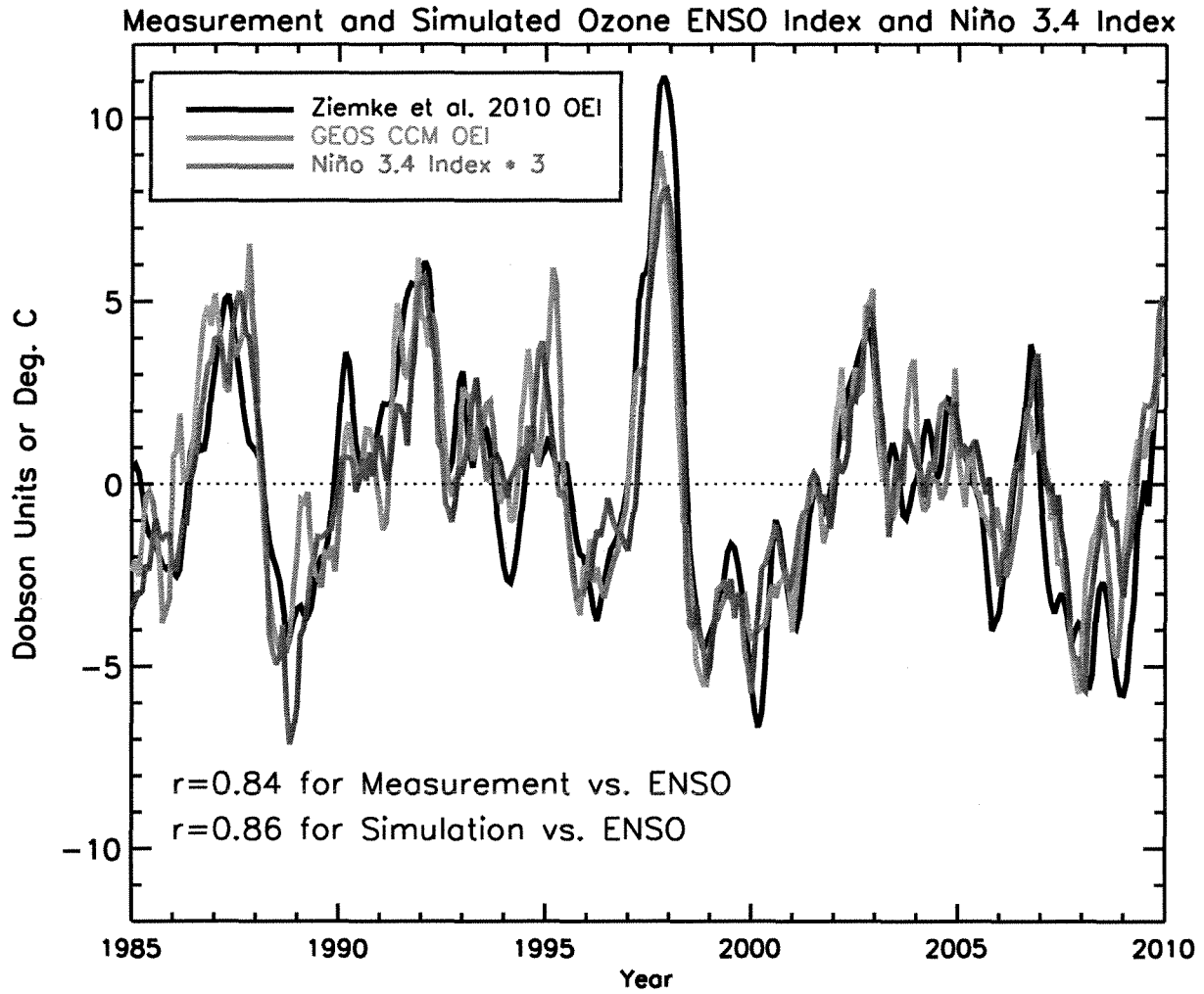
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377 Figures



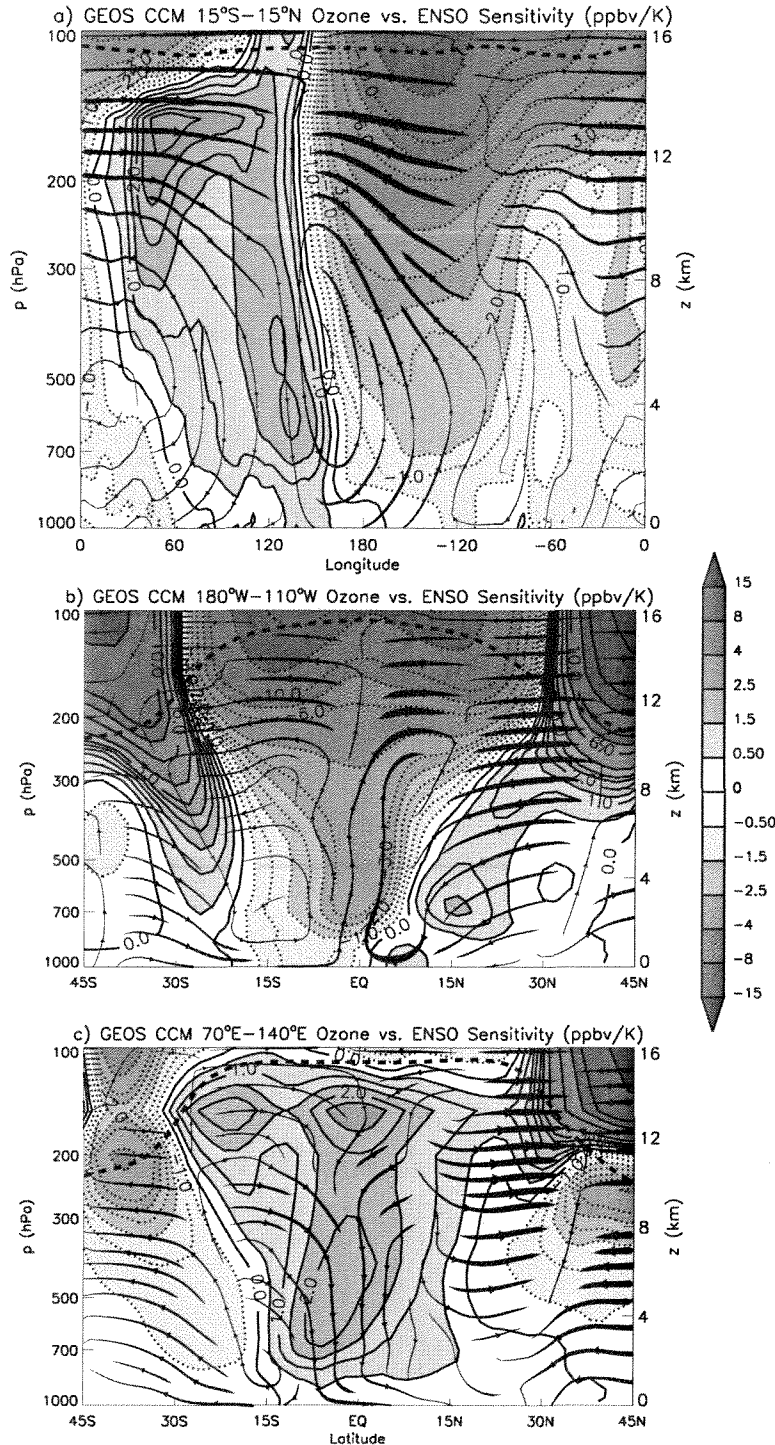
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Figure 1. Comparison of the tropospheric column ozone sensitivity (DU/K) to the Niño 3.4 Index for a) 6 years of MLS/OMI measurements, b) 6 years of GEOS CCM simulation, c) 25 years of GEOS CCM simulation. Shaded regions are not significant at the 95% level. The black rectangles show two regions used in calculating the Ozone ENSO Index.

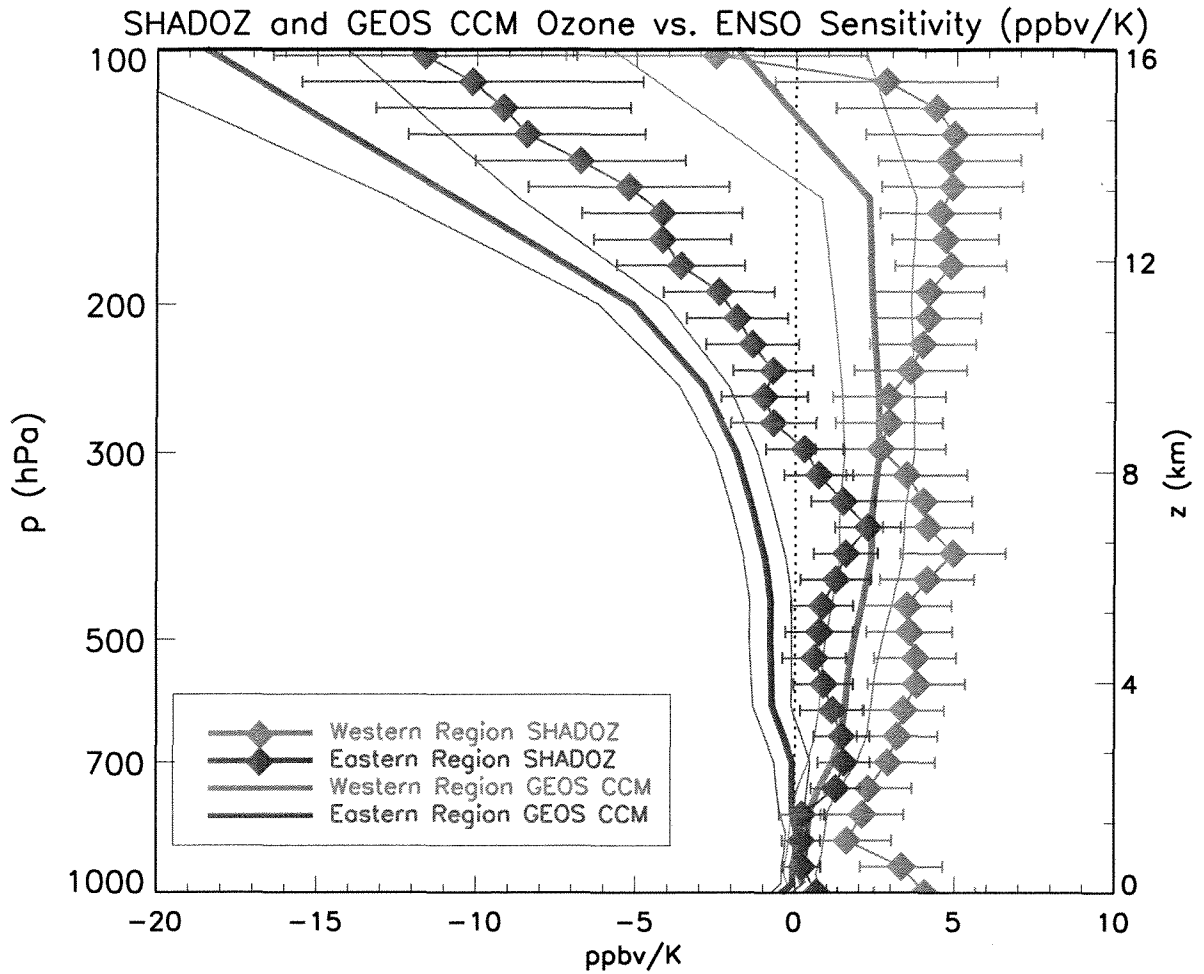


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Figure 2. Comparison of GEOS CCM simulation and *Ziemke et al.* [2010] measurement derived Ozone ENSO Index (OEI) with Niño 3.4 Index (multiplied by 3) for the 1985 to 2009 time period.



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 402 Figure 3. Sensitivity coefficient (ppbv/K) formed from linearly regressing deseasonalized  
 403 tropical (15°S-15°N, a), eastern region (180°W-110°W, b), and western region (70°E-  
 404 140°E, c) average ozone against Niño 3.4 Index. Overlaid is the anomalous circulation  
 405 shown by the streamfunction obtained by regressing the zonal wind and vertical velocity  
 406 (a), or meridional wind and vertical velocity (b,c) against Niño 3.4 Index. The dashed black  
 407 curve on all panels shows the mean model tropopause.



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Figure 4. Vertical structure of ozone sensitivity (ppbv/K) to Niño 3.4 Index derived from SHADOZ ozonesondes over the western (red diamonds) and eastern (blue diamonds) regions of the tropical Pacific. GEOS CCM sensitivities sampled for the SHADOZ locations are shown as the solid curves.