Trends and solar cycle signals of CO + CO$_2$ in the MLT

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motivation

• solar occultation observations of CO and CO$_2$ are available from the Atmospheric Chemistry Experiment (ACE) since 2004

• Emmert et al., 2012 showed that the trend of total carbon, CO$_X$ = CO + CO$_2$ in the MLT deduced from ACE is much larger than expected (8-9% per decade)

• can the observed trend by simulated by comprehensive numerical models?

• does solar cycle irradiance variability influence the estimate of the trend?
**CO\(_X\) trend from ACE observations**

- Emmert et al. (2012) analyzed ACE observations of \(CO_X = CO + CO_2\) for the period 2004-2011.
- They found that the trend of \(CO_X\) at ~90-105 km was significantly larger than the anthropogenic trend (green).
solar variability in CO$_2$ vs. CO$_x$

CO$_2$ and CO$_x$ solar signals

- CO$_2$ is clearly influenced by the solar cycle above 90-95 km
- but CO$_x$ exhibits negligible solar influence up to about 100-105 km (because CO$_2$ + hv $\rightarrow$ CO + O)
- (above 105 km, CO$_x$ is not conserved due to diffusive separation)
- estimating trend of CO$_x$ minimizes the impact of the solar cycle

from WACCM output 2004-2013
in this study:

• analyze updated ACE data for 2004-2013 to confirm Emmert et al.’s results

• use NCAR’s Whole Atmosphere Community Climate Model (WACCM) to attempt to simulate the ACE-derived trends

WACCM:

• a “high-top”, global chemistry-climate model that simulates explicitly the dynamics and chemistry of the atmosphere between the surface and ~140 km

• vertical diffusion is estimated from a parameterization of gravity waves that interacts with the underlying model climate
model climatology vs. observations

- ACE: CO and CO$_2$
- MIPAS (Michelson Interferometer for Passive Atmospheric Sounding): CO
- others
The behavior of CO and CO$_2$ above 80 km is captured very well by WACCM.
CO and CO$_2$: WACCM vs. ACE, MIPAS

- the long-term behavior of CO and CO$_2$ is also reproduced well (although WACCM CO$_2$ shows a low bias)
- there is a noticeable solar cycle signal in both CO and CO$_2$
CO\textsubscript{x}: WACCM vs. ACE

- CO\textsubscript{x} does not exhibit any solar cycle influence in either WACCM output or ACE observations at the altitudes shown (90-100 km)
calculation of solar cycle and trend

- analyze WACCM monthly-mean CO + CO₂ output in the mesosphere and lower thermosphere (MLT: 1-10⁻⁵ hPa)
- average data globally, de-seasonalize, and perform MLR to obtain trend profiles
- MLR predictors: time, 10.7 cm flux, and two QBO indices
- in the MLT, only two predictors \((t, f10.7)\) yield statistically significant regression coefficients
CO\textsubscript{x}: long-term trend (1980-2013)

- over a long period (34 years) the trend derived from WACCM has very low uncertainty
- it is everywhere very close to the (anthropogenic) trend at lower levels, about 5% per decade
- how does this change when shorter periods are considered?
CO$_x$ trend vs ACE: 2004-2013

- WACCM trend over a single decade (2004-2013) has greater uncertainty, but remains close to the trend in the lower atmosphere.

- It is statistically different from the ACE trend over the same period between about 85 and 100 km.

- Is this result sensitive to various sources of uncertainty?
variability of $\text{CO}_x$: ACE vs WACCM

- ACE $\text{CO}_x$ time series is “noisier” than WACCM time series
- what happens to the trend estimates if we add random noise to WACCM output?
CO\(_x\) (+ noise) trend vs ACE: 2004-2013

- add Gaussian random noise with s.d. equal to the s.d. of the original WACCM time series
- this increases the uncertainty of the WACCM trend
- the trend remains close to the that in the lower atmosphere
- the trend remains statistically different from the ACE trend between about 90 and 100 km
magnitude of SSI variability

- far UV radiation at 120-200 nm is important for CO$_2$ photolysis below $\sim 105$ km
- SORCE SSI variability is about 2 x larger than empirical models in this range
- what happens to the WACCM trend if we double SSI variability at 120-200 nm?
$\text{CO}_x (2 \times \text{SSI})$ trend vs ACE: 2004-2013

- doubling SSI variability at 120-200 nm has a negligible effect on the trend
- it increases slightly the uncertainty of the trend
- the trend remains statistically different from the ACE trend
sparse sampling by ACE

- occultation measurements are inherently sparse
- what happens if WACCM is sampled at the ACE geolocations?
CO$_x$ (ACE sampling) trend vs ACE

- sparse sampling on ACE geolocations increases the uncertainty of the WACCM trend
- but the trend remains statistically different from ACE and statistically indistinguishable from the trend at lower levels
is there a trend in vertical mixing?

- Emmert et al. (2012) showed that the ACE decadal trend at ~90-105 km is significantly larger than the trend derived from the NCAR (1D) global model (Roble, 1995)

- ACE and model can be partly reconciled if $K_{zz}$ increases at 15% per decade (dashed)

- what happens when $K_{zz}$ increases in WACCM?
estimating the impact of $K_{zz}$ in WACCM

- $K_{zz}$ in WACCM is calculated interactively by the small-scale gravity wave parameterization—it cannot be changed easily.

- however, we have WACCM runs with $Pr = 2$ and $Pr = 4$, and we know that $K_{zz} \sim Pr^{-1}$; therefore, $K_{zz}$ varies by a factor of $\sim 2$ between these runs.

- these two simulations can be used to estimate the effect of $K_{zz}$ if one assumes the change in CO + CO$_2$ is linear in $K_{zz}$. 
effect of $K_{zz}$ on the trend of $CO_x$

- a $\sim33\%$ per decade increase in $K_{zz}$ could reconcile the $CO_x$ trend in WACCM and ACE
effect of $K_{zz}$ on the trend of CO$_2$

- ACE CO$_2$ trend is very large above 90 km (but similar to recent results using SABER data by Yue et al., GRL, 2015)
- WACCM CO$_2$ trend is comparable to that at lower levels
- however, a ~33% per decade increase in $K_{zz}$ could also reconcile the CO$_2$ trend in WACCM and ACE
- is it possible to find independent confirmation for a trend in $K_{zz}$?
effect of $K_{zz}$ on H$_2$O

- H$_2$O responds sensitively to changes in $K_{zz}$
- in the range of altitude outlined at left, 85-95 km, a $\sim$33% per decade increase in $K_{zz}$ leads to 15-30% trends in H$_2$O
- change is even greater at higher altitudes, but the m.r. of H$_2$O is very small there (< 0.5 ppmv)
- H$_2$O might provide independent confirmation of a trend in $K_{zz}$

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conclusions

• the CO$_X$ trend calculated with WACCM in the MLT does not differ significantly from the (anthropogenic) CO$_2$ trend in the lower atmosphere (~5% per decade)

• this is much smaller than the trend derived from ACE observations (up to ~9% per decade at 90-105 km, 2004-2013)

• examination of a variety of possible sources of uncertainty cannot reconcile WACCM and ACE trends

• WACCM and ACE could be reconciled if vertical mixing has increase rapidly over the period of analysis (2004-2013)

• it might be possible to obtain independent confirmation of changes in $K_{zz}$ from water vapor (SABER?, ACE?, MLS?)