Possible Solar Cycle Response of Eddy Diffusion in the Mesosphere and Lower Thermosphere as inferred from SABER CO$_2$

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Diffusion is the transport of chemical species from a region of high volume mixing ratio to a region of low volume mixing ratio by small-scale random motions [Seinfeld and Pandis, 2012].

PROBLEM: We cannot computationally resolve all scales of motion especially the smallest scales.
Diffusion is the transport of chemical species from a region of high volume mixing ratio to a region of low volume mixing ratio by small-scale random motions [Seinfeld and Pandis, 2012]. The formulation for diffusion is based off of the formulation for shear:

\[
\frac{\partial}{\partial z} \left( K_x \frac{\partial \mu}{\partial z} \right)
\]
Dominant Diffusive Processes in the MLT:

a. Molecular diffusion ($D$) is diffusion driven by the background temperature and the molecular weight of the chemical species. This is accounted for in laboratory experiments.

b. Eddy diffusion ($K_{zz}$) is diffusion driven by turbulent motion (e.g. breaking gravity waves). This is difficult to observe or derive.
Diffusive transport due to breaking gravity waves.

Gravity waves drive the cold summer mesopause region.

Gravity waves drive the MLT residual circulation during solstice seasons.

\[ 
\omega^2 = (\omega - k\bar{u} - l\bar{v})^2 = \frac{N^2(k^2 + l^2) + f^2(m^2 + \frac{1}{4H^2})}{k^2 + l^2 + m^2 + \frac{1}{4H^2}} 
\]
**METHODS TO CALCULATE EDDY DIFFUSION COEFFICIENTS:**

**METHOD 1: Use wind-related parameters.**

Lindzen [1981] Linear Saturation Theory

Eddy diffusion coefficient is related to zonal wind, wind shear and static stability via the vertical wave number.

\[ K_{zz} \approx \frac{k(\bar{u} - c)^4}{N^3} \left( \frac{1}{2H} - \frac{3}{2} \frac{1}{\bar{u} - c} \frac{\partial \bar{u}}{\partial z} \right) \]

**WARNING:** These terms are difficult to observe globally.
Global-mean CO$_2$’s very long photochemical life-time (~1000 days) allows us to infer global-mean $K_{zz}$ [Garcia et al, 2014; Salinas et al, 2016].
Models that utilize Lindzen’s gravity wave parameterization:

1. Specified Dynamics – Whole Atmosphere Community Climate Model (SD-WACCM)
2. Thermosphere Ionosphere Mesosphere Electrodynamics – General Circulation Model (TIME-GCM)

Seasonality of SABER CO$_2$-derived $K_{zz}$ may be due to gravity waves.
QUESTION: What is the solar cycle response of eddy diffusion in the MLT region?
Objectives of the Study:

- To determine the solar cycle response of SABER CO$_2$-derived global-mean eddy diffusion coefficients.

- To compare the solar cycle response of SABER CO$_2$-derived global-mean eddy diffusion coefficients and of SD-WACCM-X global-mean eddy diffusion coefficients.
SABER CO$_2$-derived Eddy Diffusion Coefficients
SABER/TIMED CO₂ Day-time Observations

Instrument: Sounding of the Atmosphere using Broadband Emission Radiometry (SABER)

Satellite: Thermosphere – Ionosphere – Mesosphere Energetics and Dynamics (TIMED) Satellite

Public release in 2016. Data coverage is 2002 to present.

Measured parameter: Infrared Limb Measurements (4.3 and 15 μm channels)

CO₂ Retrieval Algorithm: [Rezac et al, 2015a; 2015b]

1. Model the vibration of a CO₂ molecule due to Infrared Radiation.
2. Determine the corresponding radiances.
Calculate global-mean CO₂ for each month from February 2002 to December 2015. Then, use a simple iterative algorithm to solve for $K_{zz}$ using SABER CO₂ and 1D model.

SABER/TIMED CO₂ Profiles

Retrieval Algorithm: [Rezac et al, 2015]

- Calculate bi-monthly zonal-mean CO₂ profiles.
- Calculate cosine-of-latitude weighted zonal-mean CO₂ profiles.
- Calculate global-mean CO₂ profiles.

5-degree non-overlapping bins from 50S to 50N.
How do we derive global-mean eddy diffusion coefficients ($K_{zz}$) from CO$_2$?

Calculate global-mean CO$_2$ for each month from February 2002 to December 2015.

Simple iterative algorithm to solve for $K_{zz}$ using SABER CO$_2$ and 1D model.

SABER CO$_2$-DERIVED EDDY DIFFUSION COEFFICIENTS

1D Photochemical-Transport Model [Allen et al, 1981; Liang et al, 2007]

$$\frac{\partial \mu}{\partial t} + w \frac{\partial \mu}{\partial z} - \frac{1}{\rho_0} \frac{\partial}{\partial z} \left( \rho_0 K_{zz} \frac{\partial \mu}{\partial z} \right) - \frac{1}{\rho_0} \frac{\partial}{\partial z} \left( \rho_0 D_{\mu} \frac{\partial \mu}{\partial z} \right) = P - L$$

Set $w = 0$.
Set model CO$_2$ lower boundary to SABER CO$_2$.
Adjust $K_{zz}$ in the model.
Calculate Root-Mean-Square (RMS).
SABER CO$_2$-DERIVED EDDY DIFFUSION COEFFICIENTS

A) SABER CO$_2$ (ppm)

B) 1D MODEL ADJUSTED CO$_2$ (ppm)

C) MODEL - SABER DIFFERENCE (%)

D) 1D MODEL ADJUSTED K$_{zz}$ (m$^2$/s)

This is the first ever satellite-based global-mean K$_{zz}$ that spans more than 1 solar cycle.
Wavelet spectra of SABER CO$_2$ is captured by modeled CO$_2$. This was not achieved in Salinas et al [2016].
Wavelet spectra of SABER CO₂ is captured by modeled CO₂. This was not achieved in Salinas et al [2016].
Whole Atmosphere Community Climate Model – eXtended (WACCM-X)

Physics-based whole atmosphere general circulation model (surface to 700 km) based off of the NCAR Community Earth System Model (CESM) and the NCAR HAO Thermosphere Ionosphere General Circulation Model (TGCM).

Gravity wave parameterization: Lindzen Linear Saturation Scheme [Garcia et al, 2007; Richter et al, 2010]

Ran from 2002 to 2014 in Specified Dynamics mode. This involves nudging the model to MERRA reanalysis from the surface to around 50 km.
TIME-SERIES ANALYSIS

Wavelet transform is used to determine the oscillations present in the data [Torrence and Compo, 1998].

Multiple linear regression of de-seasonalized time-series with mean, trend, F10.7 index, QBO and ENSO:

\[ N = A + Bt + C \times F10.7 + D \times 30mb\_QBO + E \times ENSO \]

F-test is done to determine statistical significance (90%).
Results

Solar Cycle Response of SABER CO$_2$-derived $K_{zz}$
Liu et al [2017] also showed a generally negative solar cycle response in gravity wave potential energy throughout the MLT region as extracted from SABER temperatures.
Possible physical mechanism???
Enhanced ozone

[McCormack and Hood, 1996; Shindell et al, 1999; Labitzke, 2003; Randel and Wu, 2007; Gray et al, 2009]
Increased latitudinal gradient
Strengthened westerly jet.
Planetary wave deflection

[Matthes et al, 2004; Langematz et al, 2005; Shibata and Kodera, 2005; Hampson et al, 2006; Schmidt et al, 2006; Schmidt and Brasseur, 2006; Marsh et al, 2007; Tsutsui et al, 2009; Chiodo et al, 2012]
Weakened winter BDC cell.

[Baldwin and Dunkerton, 2005; Matthes et al, 2006; Mitchell et al, 2015; Lu et al, 2017a, 2017b]
Reduced westerly gravity waves.
Enhanced winter mesospheric jet.

[Kodera and Kuroda, 2002; Kodera et al, 2003]
Poleward and downward residual circulation.

[Keckhut et al, 2005; Hampson et al, 2005; Li et al, 2011; Cullens et al, 2015; Gan et al, 2017]
Downwelling-induced adiabatic warming.

[Keckhut et al, 2005; Hampson et al, 2005; Li et al, 2011; Cullens et al, 2015; Gan et al, 2017]
Easterly anomaly in the subtropical jet extends into the lower thermosphere [Salinas et al, 2018].
Reduction in westerly gravity waves reduces eddy diffusion [Salinas et al, 2018].
Summary

• The multiple linear regression coefficients between the SABER CO$_2$-derived $K_{zz}$ and the F10.7 are consistently negative and statistically significant throughout the MLT region but upon checking the time-series, the clearest response is found in the lower thermosphere at ~98 km.

• The multiple linear regression coefficients between the SD-WACCM-X $K_{zz}$ and the F10.7 are also consistently negative but are weak and not statistically significant throughout the MLT region.
Conclusion

• SABER CO$_2$-derived $K_{zz}$ suggests that the 11-year solar cycle affects eddy diffusion in the lower thermosphere by reducing it during solar maximum and enhancing it during solar minimum.

• SD-WACCM-X’s simulation of eddy diffusion’s response to the 11-year solar cycle needs to be enhanced.
Future Work

• What are the mechanisms behind these changes?

• What are the seasonal dependencies of this solar cycle response?
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