Seasonality and Solar Cycle Response of SABER CO$_2$-derived and WACCM-X Eddy Diffusion Coefficients in the Mesosphere and Lower Thermosphere Region

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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 [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 [Seinfeld and Pandis, 2012].

The formulation for diffusion is based off of shear theory:

\[
\frac{\partial}{\partial z} \left( K_x \frac{\partial \mu}{\partial z} \right)
\]

Fig. 1.4 The x component of the vertical shearing stress on a fluid element.

[Holton, 1973]
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.
ISSUE OF DIFFUSIVE TRANSPORT DUE TO BREAKING GRAVITY WAVES

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.
PROBLEM: Deriving accurate global-mean eddy diffusion coefficients due to breaking gravity waves is hindered by the small scale nature of diffusion and gravity waves.
This work will help remedy this problem by using satellite observations of a tracer, Carbon Dioxide.
CO₂ is chemically inert in the MLT region. With a photochemical lifetime of ~1000 days, it can be used as a tracer for a wide range of motions [Smith et al, 2011; Garcia et al, 2014].
SABER/TIMED CO$_2$ 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)

CO$_2$ Retrieval Algorithm: [Rezac et al, 2015a; 2015b]

1. Model the vibration of a CO$_2$ molecule due to Infrared Radiation.
2. Determine the corresponding radiances.
Objectives of the Study:

• To derive global-mean eddy diffusion coefficients from global-mean SABER CO$_2$.

• To compare the seasonality of SABER CO$_2$-derived global-mean eddy diffusion coefficients and of WACCM-X global-mean eddy diffusion coefficients.

• To compare the solar cycle response of SABER CO$_2$-derived global-mean eddy diffusion coefficients and of WACCM-X global-mean eddy diffusion coefficients.
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]

WACCM-X runs:
1. March Equinox Solar Minimum
2. March Equinox Solar Maximum
3. June Solstice Solar Minimum
4. June Solstice Solar Maximum
Salinas et al. [2016; 2018] have already compared and analyzed our SABER CO$_2$-derived $K_{zz}$ with TIE-GCM and SD-WACCM $K_{zz}$. Salinas et al. [2016] showing our SABER CO$_2$-derived $K_{zz}$ with $K_{zz}$ from gravity wave parameterizations.
SABER CO$_2$-derived Eddy Diffusion Coefficients
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/TIMED CO$_2$ Profiles

Retrieval Algorithm: [Rezac et al, 2015]

- Calculate bi-monthly zonal-mean CO$_2$ profiles.
- Calculate cosine-of(latitude weighted zonal-mean CO$_2$ profiles.
- Calculate global-mean CO$_2$ profiles.

Updated version of Salinas et al [2016].
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.

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

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

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

Updated version of Salinas et al [2016].
This is the first ever satellite-based global-mean $K_{zz}$ that spans more than 1 solar cycle.
Seasonality of Eddy Diffusion
Comparison with WACCM-X
WACCM-X Eddy Diffusion Coefficient Adjustments

Are these adjustments supported by our SABER CO$_2$-derived $K_{zz}$?
Do these $K_{zz}$ adjustments yield a global-mean CO$_2$ profile consistent with SABER CO$_2$?
WACCM-X underestimates global-mean CO$_2$ because of weaker global-mean K$_{zz}$ below 80 km.
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GW Breaking by Static Instability or Molecular Diffusion?

Our SABER CO$_2$-derived $K_{zz}$ suggests further enhancement of $K_{zz}$ in the mesosphere.

Hanli Liu CEDAR Prize Lecture
https://www2.hao.ucar.edu/sites/default/files/users/whawkins/LiuCedarWaccmX2018.pdf
GW Breaking by Static Instability or Molecular Diffusion?

Our SABER CO₂-derived $K_{zz}$ agrees with a peak in $K_{zz}$ at the mesosphere.

Hanli Liu CEDAR Prize Lecture
https://www2.hao.ucar.edu/sites/default/files/users/whawkins/LiuCedarWacmx2018.pdf
Why is there a peak in the MLT region?

WACCM-X may not be simulating enough breaking gravity waves due to static instability at around 80 km?
Solar Cycle Response of Eddy Diffusion
This provides 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].
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This provides first ever wavelet spectra of $K_{zz}$ that spans more than 1 solar cycle.
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WACCM-X $K_{zz}$ has a general negative response to the 11-year solar cycle above ~92 km.
Solar cycle response of Austral winter global-mean $K_{zz}$ is consistent with solar cycle response of zonal-mean $K_{zz}$ in Salinas et al [2018].
Conclusions

• SABER CO$_2$-derived $K_{zz}$ suggests further enhancement in WACCM-X $K_{zz}$ at 80 km.

• SABER CO$_2$ does support adjusting the peak $K_{zz}$ down to the MLT region.

• Both SABER CO$_2$-derived and WACCM-X $K_{zz}$ have a negative response to the 11-year solar cycle.
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