Possible Solar Cycle Response of Eddy Diffusion in the Mesosphere and Lower Thermosphere as inferred from SABER CO_2

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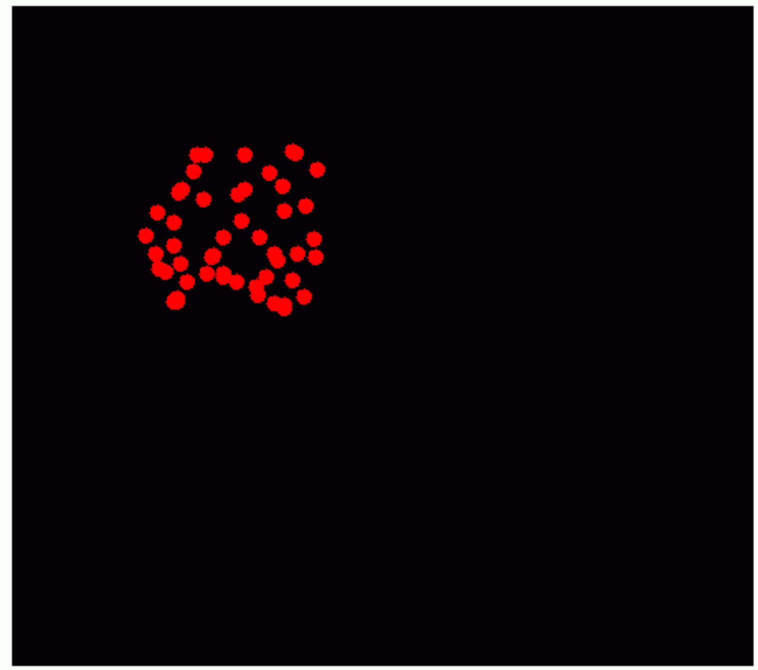
ISSUE OF DIFFUSIVE TRANSPORT DUE TO BREAKING GRAVITY WAVES

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.



http://cronodon.com/images/DiffusionAnim.gif

ISSUE OF DIFFUSIVE TRANSPORT DUE TO BREAKING GRAVITY WAVES

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:

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

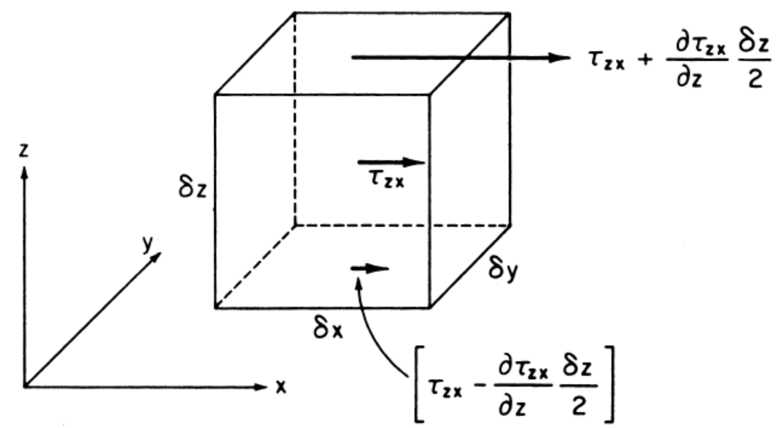


Fig. 1.4 The *x* component of the vertical shearing stress on a fluid element.

[*Holton*, 1973]

ISSUE OF DIFFUSIVE TRANSPORT DUE TO BREAKING GRAVITY WAVES

Dominant Diffusive Processes in the MLT:

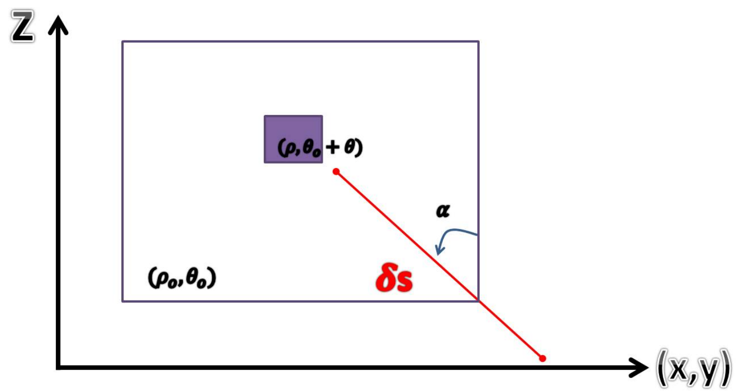
a. Molecular diffusion (D) is diffusion driven by the background temperature and the molecular weight of the chemical species. This is accounted for in laboratory experiments.

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

<u>Diffusive transport due to breaking gravity waves.</u>

Gravity waves drive the cold summer mesopause region.

Gravity waves drive the MLT residual circulation during solstice seasons.



DISPERSION RELATION:

$$\hat{\omega}^2 = (\omega - k\bar{u} - l\bar{v})^2 = \frac{N^2(k^2+l^2) + f^2\left(m^2 + \frac{1}{4H^2}\right)}{k^2+l^2+m^2+\frac{1}{4H^2}}$$

METHODS TO CALCULATE EDDY DIFFUSION COEFFICIENTS:

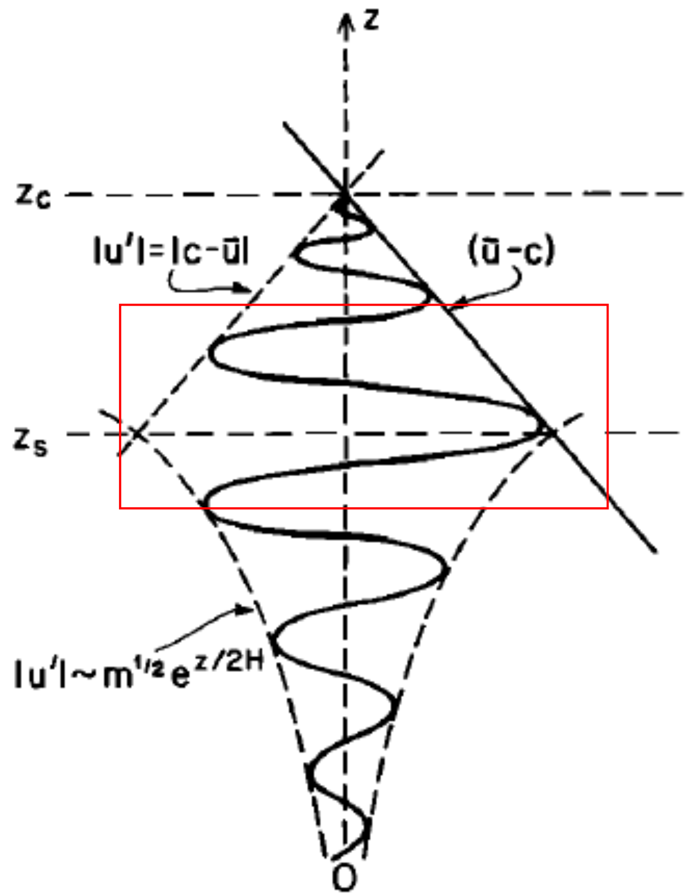
METHOD 1: Use wind-related parameters.

Lindzen [1981] Linear Saturation Theory

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

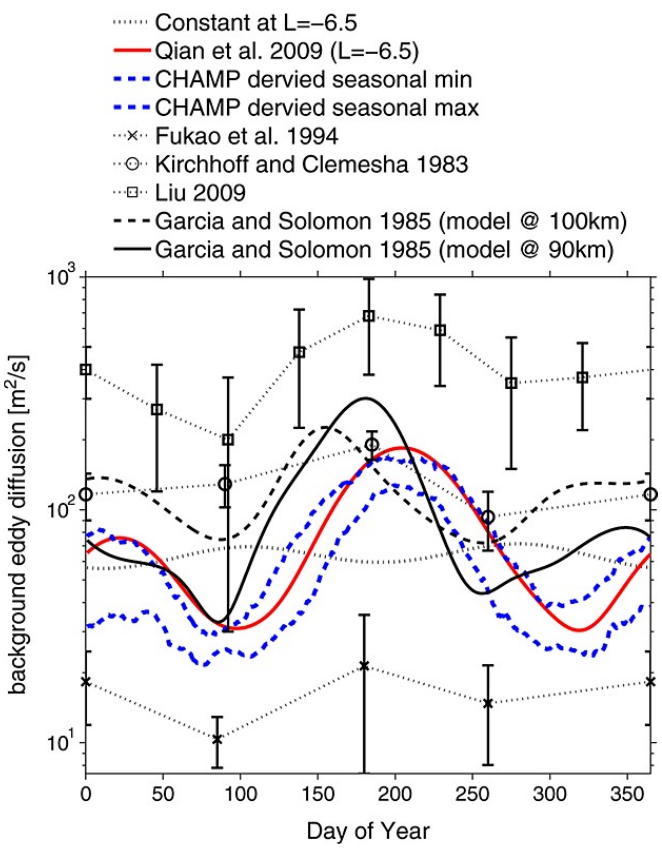
$$K_{zz} \approx \frac{k(\bar{u}-c)^4}{N^3}\left(\frac{1}{2H} - \frac{3}{2}\frac{1}{\bar{u}-c}\frac{\partial \bar{u}}{\partial z}\right)$$

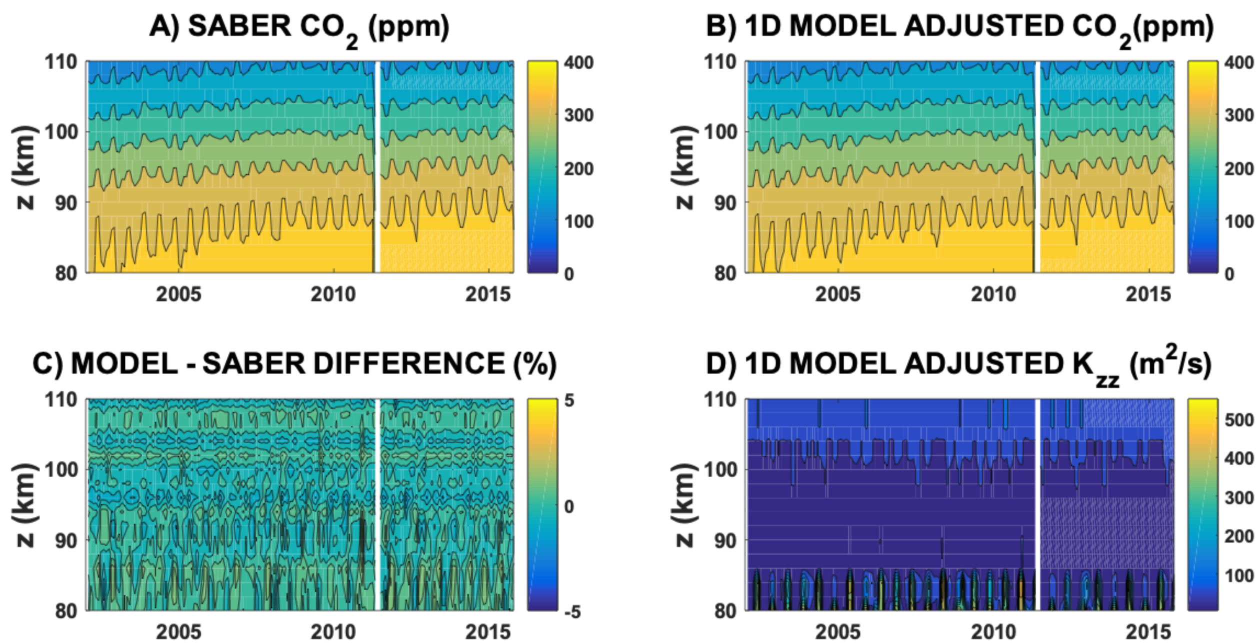
WARNING: These terms are difficult to observe globally.



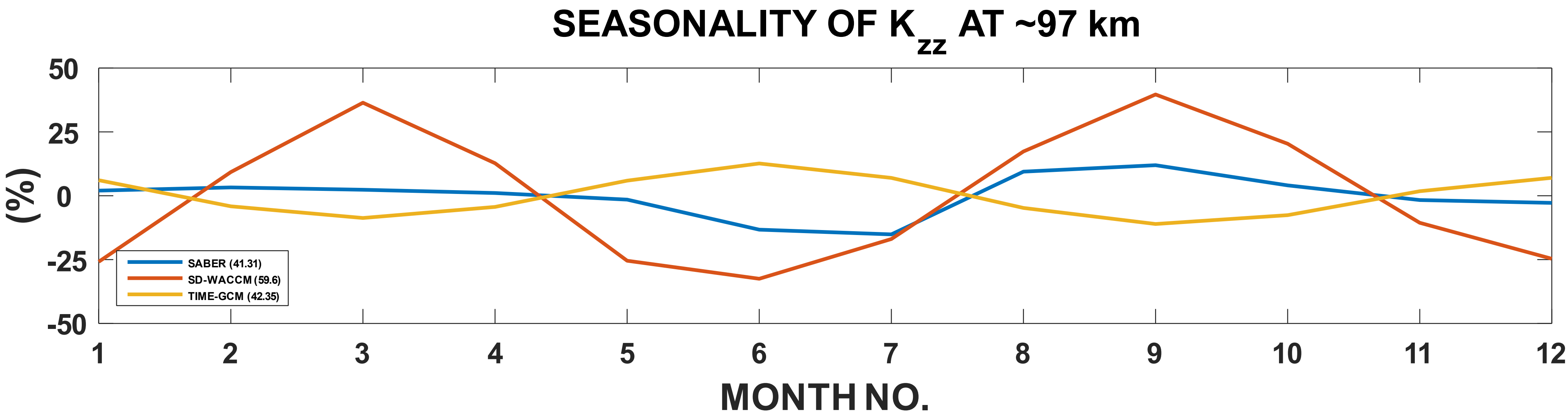
METHODS TO CALCULATE EDDY DIFFUSION COEFFICIENTS:

METHOD 2: Fit observed inert tracer profiles with simulated profiles.





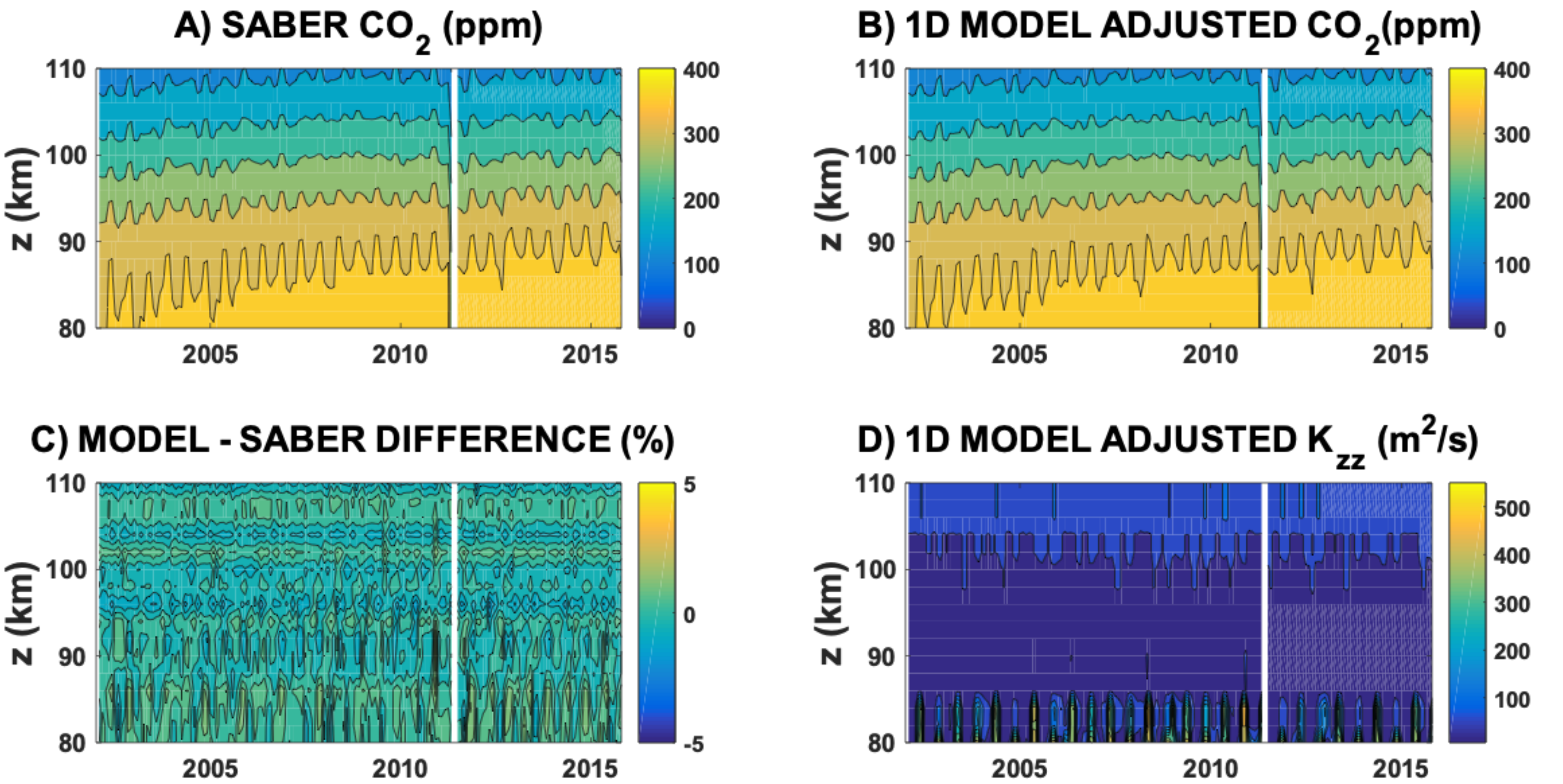
Global-mean CO_2's very long photochemical life-time (~1000 days) allows us to infer global-mean K_{zz} [Garcia et al, 2014; Salinas et al, 2016].



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?

<u>Objectives of the Study:</u>

- 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 CO_2 Day-time Observations

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

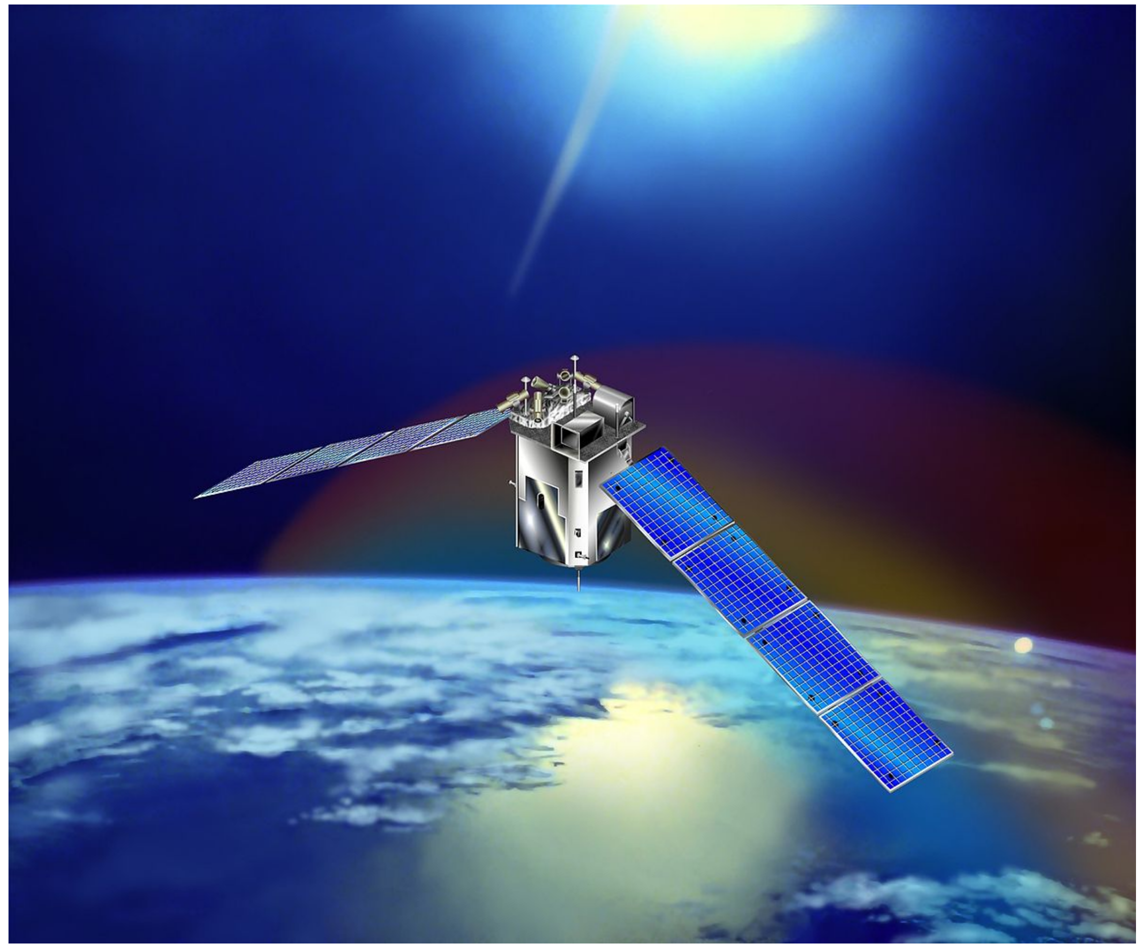
Satellite: Thermosphere – Ionosphere – Mesosphere Energetics and Dynamics (TIMED) Satellite

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.



SABER CO_2-DERIVED EDDY DIFFUSION COEFFICIENTS

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/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.

5-degree non-overlapping bins from 50S to 50N

SABER CO_2-DERIVED EDDY DIFFUSION COEFFICIENTS

How do we derive global-mean eddy diffusion coefficients (K_{zz}) from CO_2?

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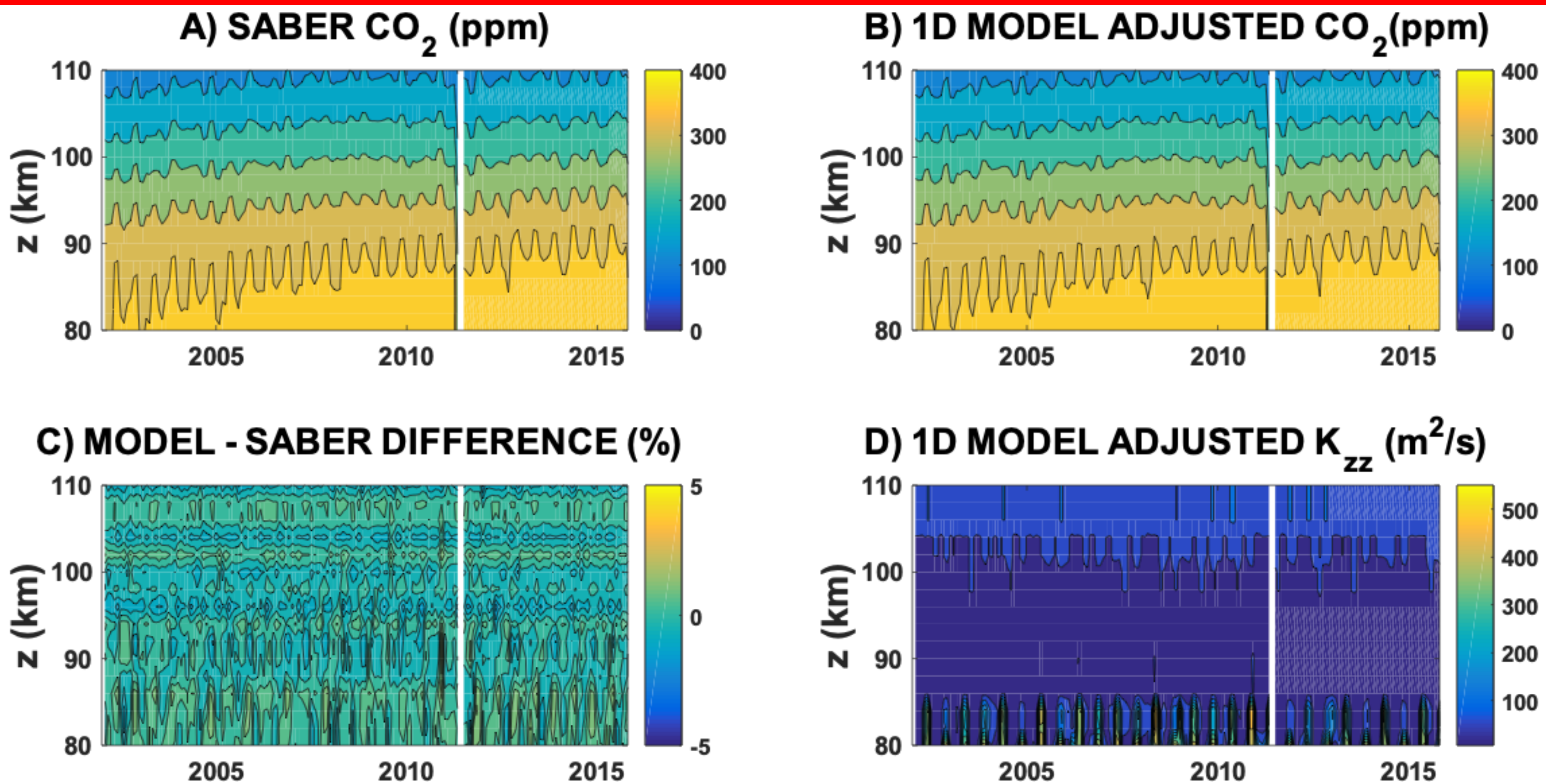
Simple iterative algorithm to solve for K_{zz} using SABER CO_2 and 1D model.

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

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

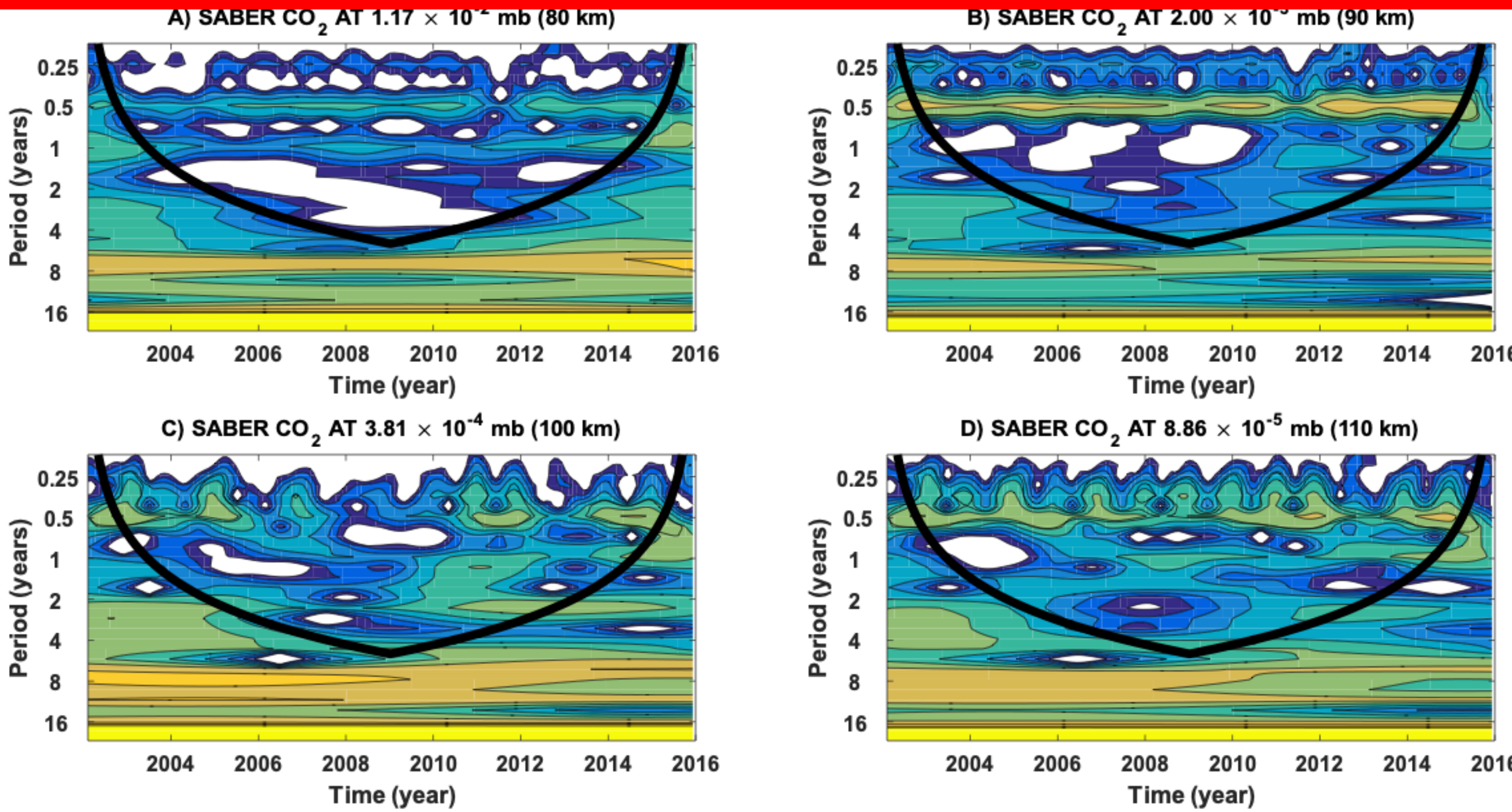
1. Set $w = 0$.
2. Set model CO_2 lower boundary to SABER CO_2.
3. Adjust K_{zz} in the model.
4. Calculate Root-Mean-Square (RMS).

SABER CO_2-DERIVED EDDY DIFFUSION COEFFICIENTS



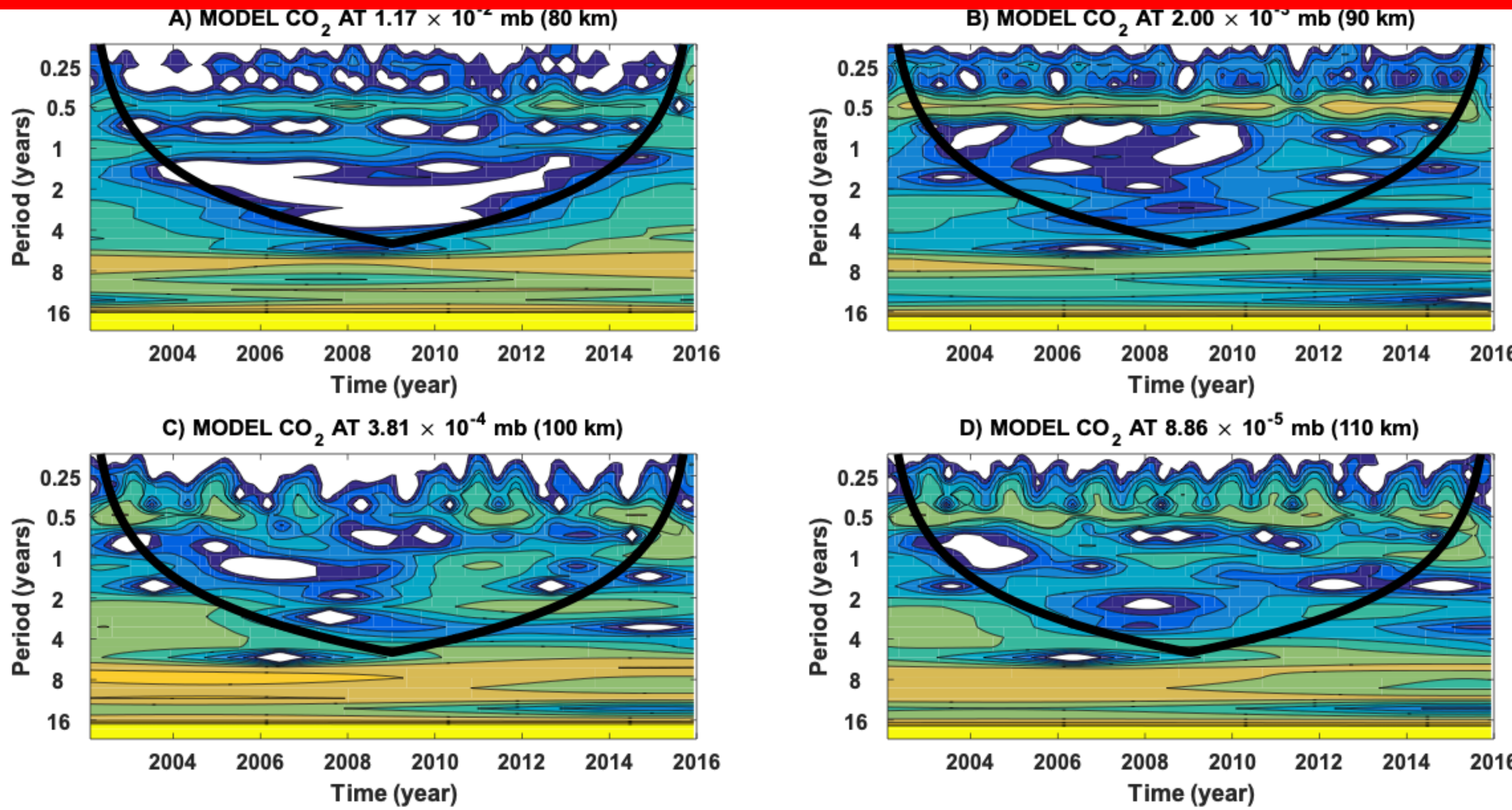
This is the first ever satellite-based global-mean K_{zz} that spans more than 1 solar cycle.

SABER CO_2-DERIVED EDDY DIFFUSION COEFFICIENTS



Wavelet spectra of SABER CO_2 is captured by modeled CO_2. This was not achieved in Salinas et al [2016].

SABER CO_2-DERIVED EDDY DIFFUSION COEFFICIENTS



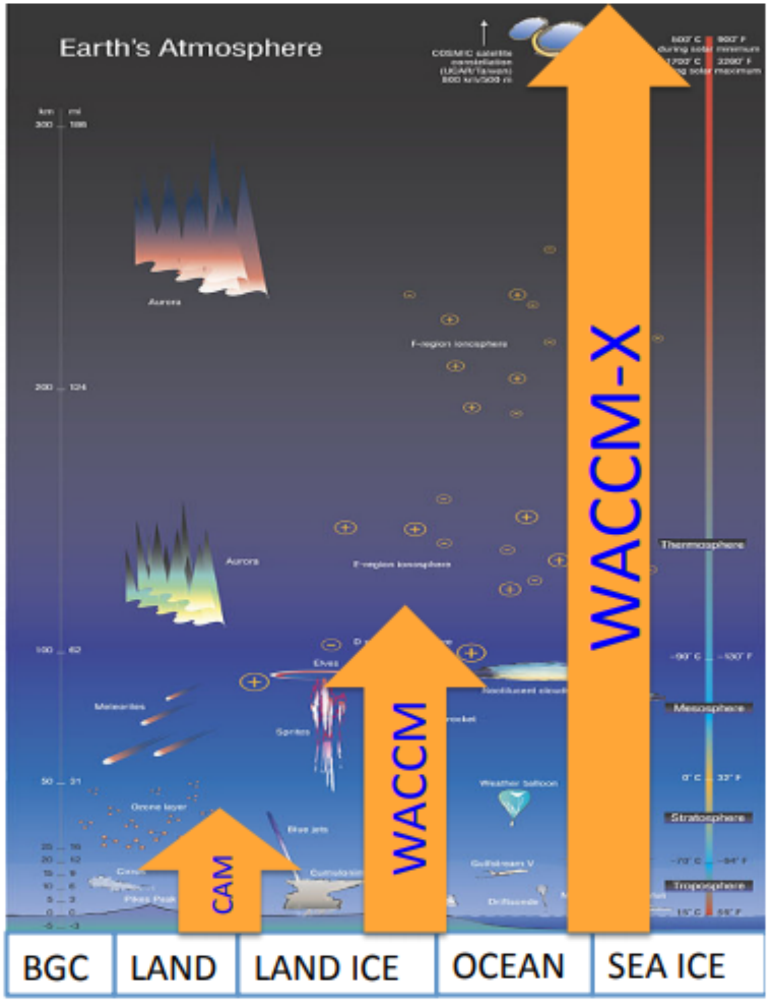
Wavelet spectra of SABER CO_2 is captured by modeled CO_2. This was not achieved in Salinas et al [2016].

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].

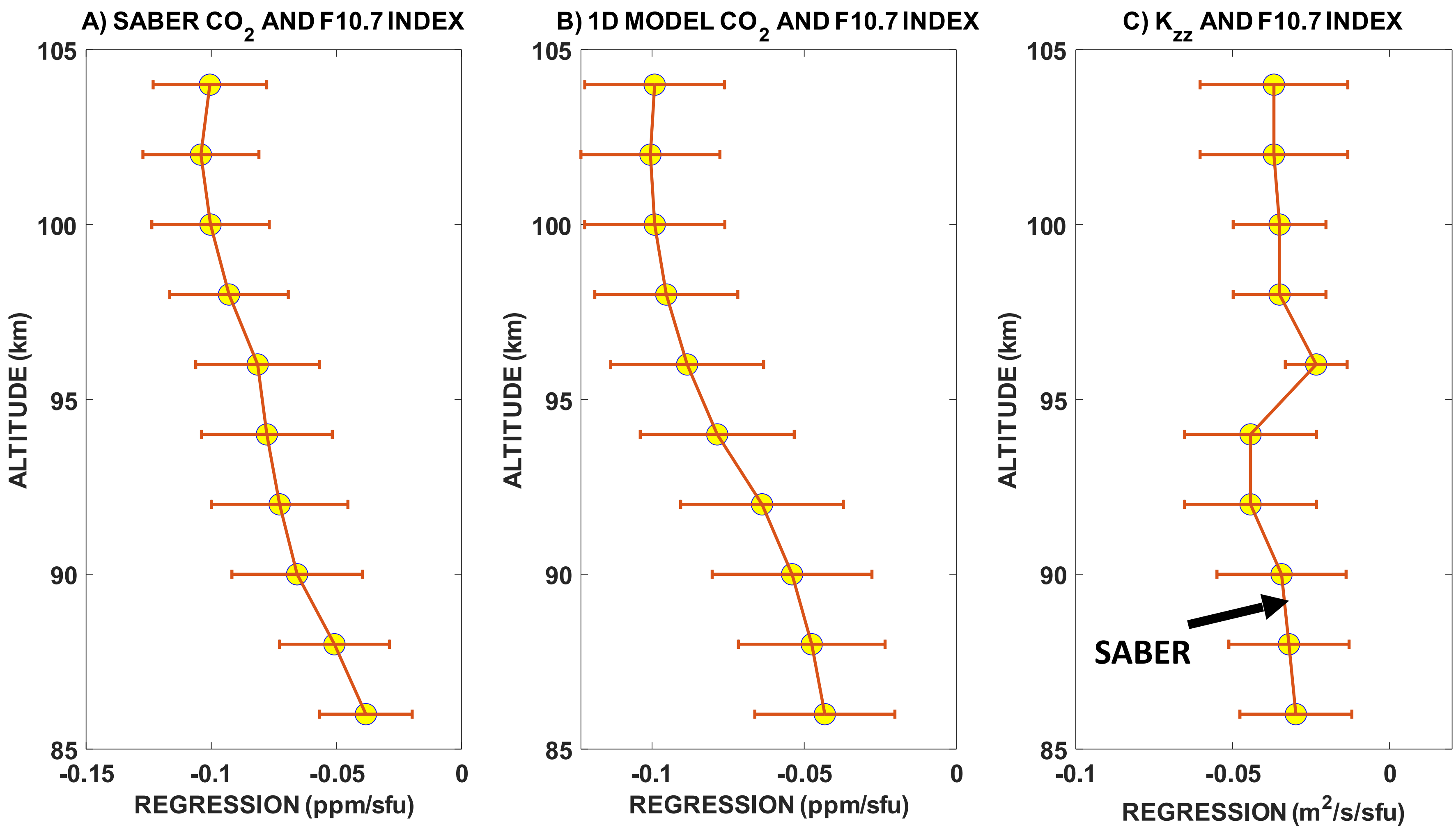
Multiple linear regression of de-seasonalized time-series with mean, trend, F10.7 index, QBO and ENSO:

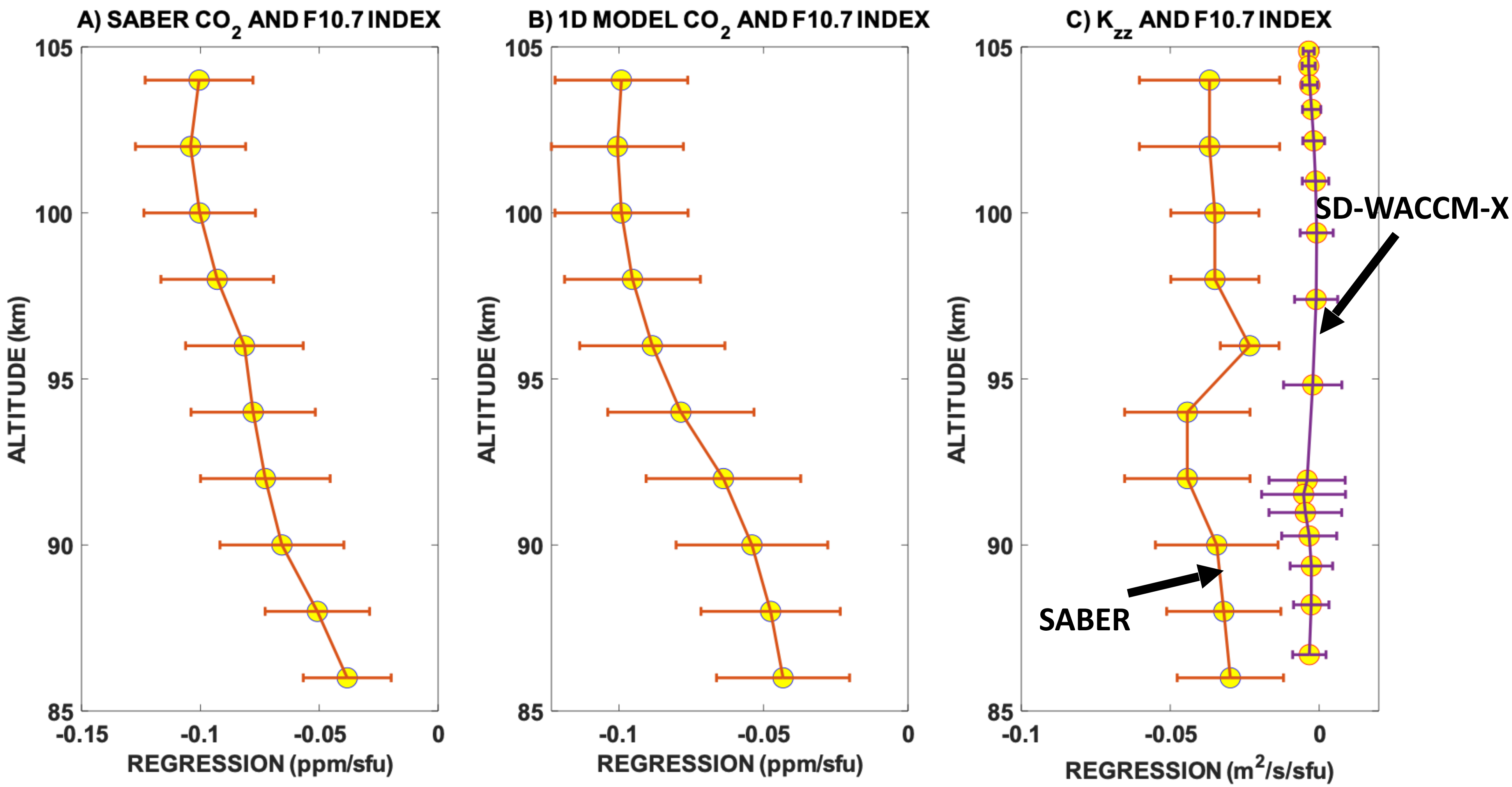
$$N = A + Bt + C \times F10.7 + D \times 30mb\_QBO + E \times ENSO$$

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

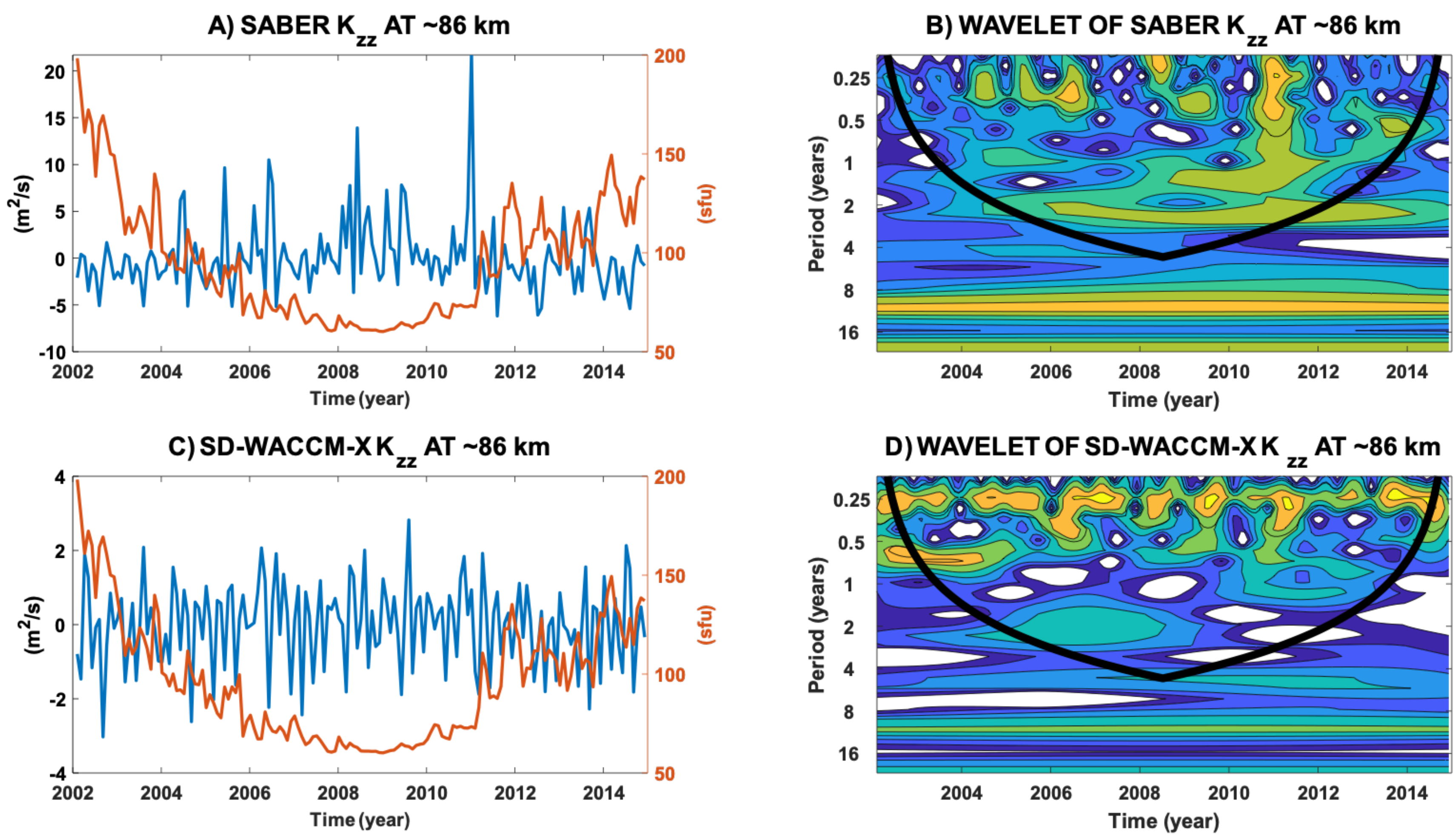
Results

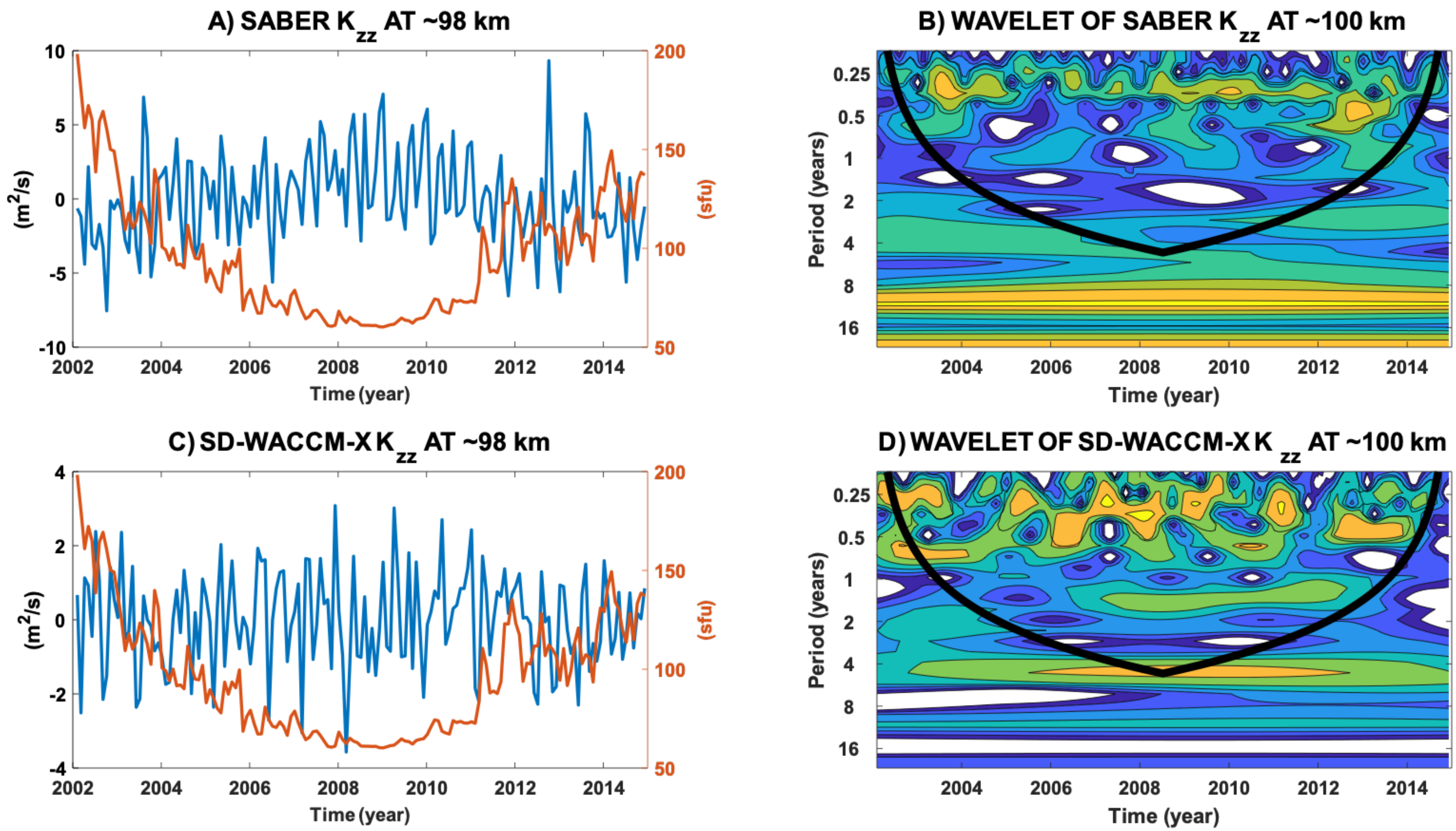
Solar Cycle Response of SABER CO_2-derived K_{zz}


A) SABER CO_2 AND F10.7 INDEX
B) 1D MODEL CO_2 AND F10.7 INDEX
C) K_{zz} AND F10.7 INDEX
ALTITUDE (km)
105
100
95
90
85
-0.15
-0.1
-0.05
0
REGRESSION (ppm/sfu)
REGRESSION (m^2/s/sfu)
SABER

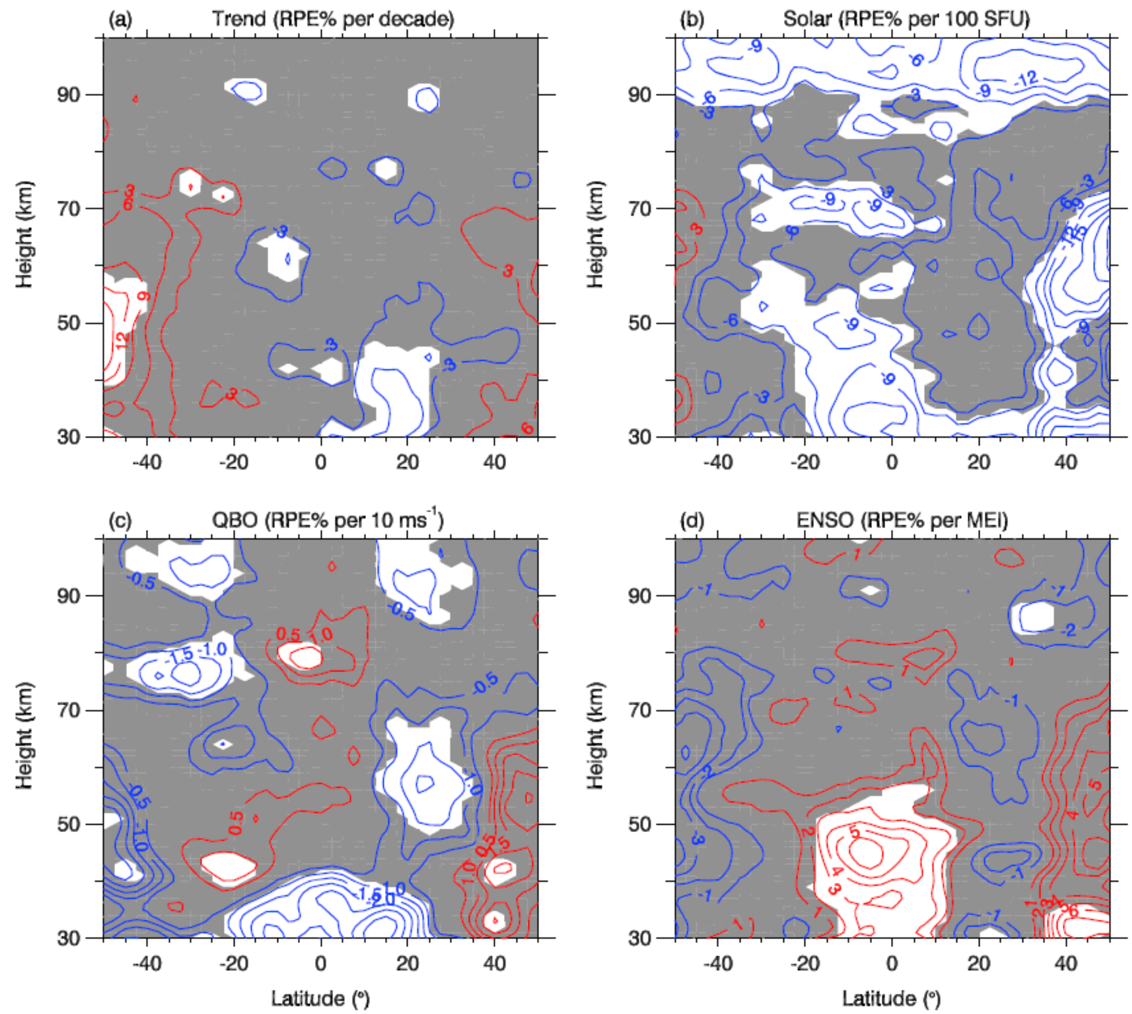


A) SABER CO2 AND F10.7 INDEX
B) 1D MODEL CO2 AND F10.7 INDEX
C) Kzz AND F10.7 INDEX
ALTITUDE (km)
105
100
95
90
85
-0.15
-0.1
-0.05
0
REGRESSION (ppm/sfu)
REGRESSION (m2/s/sfu)
SD-WACCM-X
SABER


A) SABER K zz AT ~86 km
20
15
10
5
0
-5
-10
(m2/s)
200
150
100
50
(sfu)
2002
2004
2006
2008
2010
2012
2014
Time (year)
B) WAVELET OF SABER K zz AT ~86 km
0.25
0.5
1
2
4
8
16
Period (years)
2004
2006
2008
2010
2012
2014
Time (year)
C) SD-WACCM-X K zz AT ~86 km
4
2
0
-2
-4
(m2/s)
200
150
100
50
(sfu)
2002
2004
2006
2008
2010
2012
2014
Time (year)
D) WAVELET OF SD-WACCM-X K zz AT ~86 km
0.25
0.5
1
2
4
8
16
Period (years)
2004
2006
2008
2010
2012
2014
Time (year)

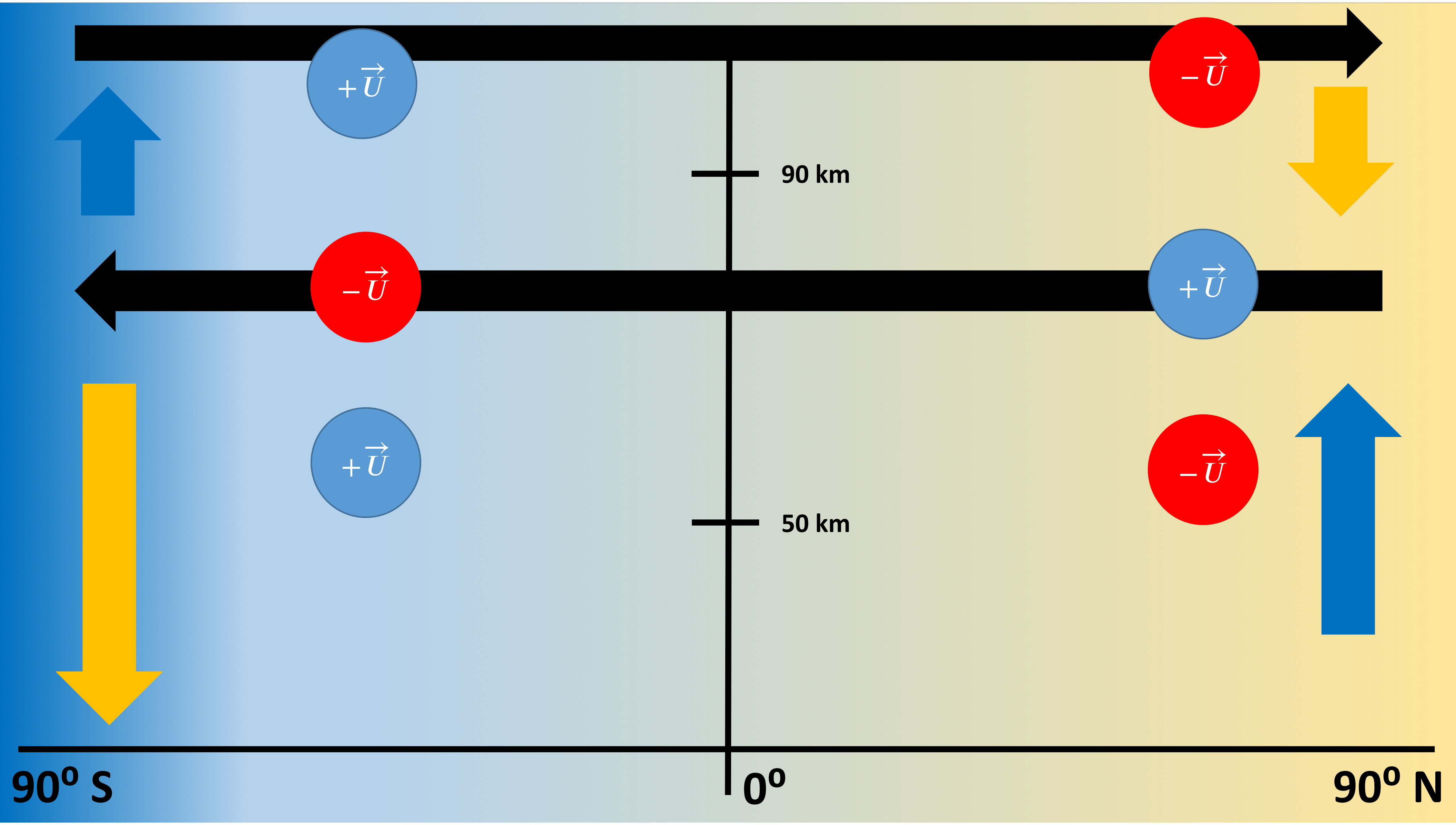

A) SABER K
zz
AT ~98 km
B) WAVELET OF SABER K
zz
AT ~100 km
C) SD-WACCM-X K
zz
AT ~98 km
D) WAVELET OF SD-WACCM-X K
zz
AT ~100 km
(m²/s)
(sfu)
Period (years)
Time (year)
10
5
0
-5
-10
4
2
-2
-4
200
150
100
50
0.25
0.5
1
2
4
8
16
2002
2004
2006
2008
2010
2012
2014

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.

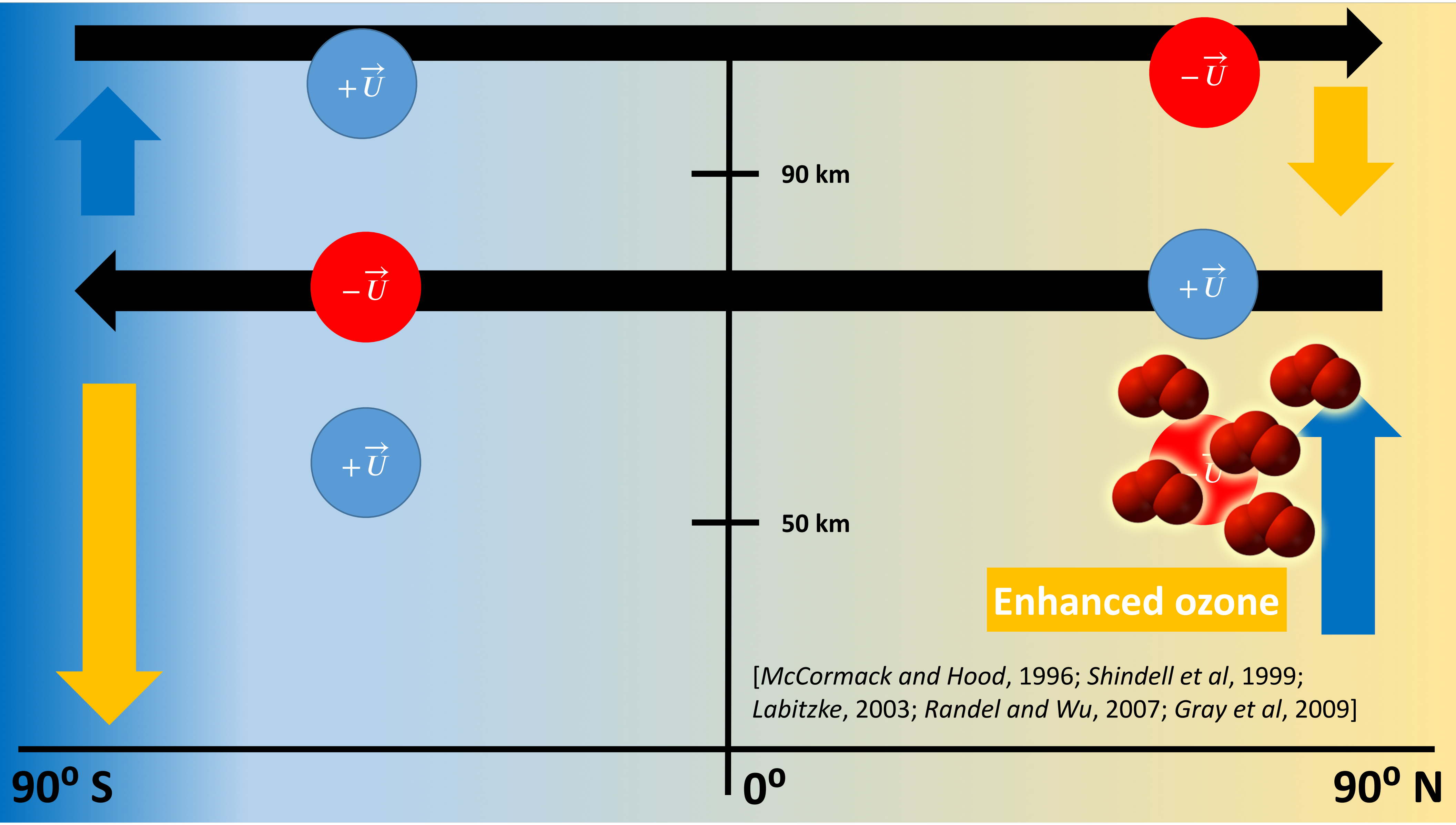


Liu et al [2017]

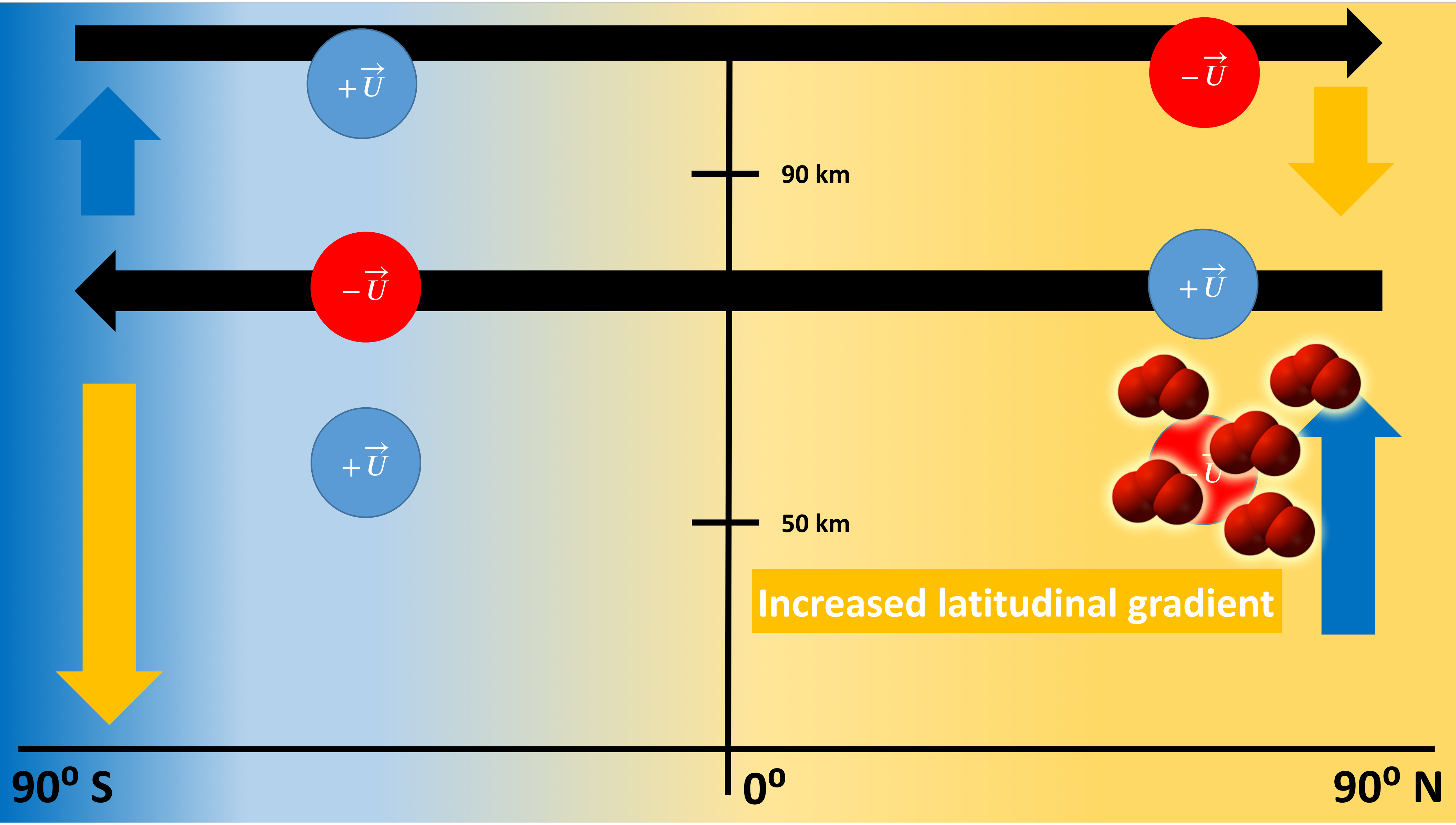
Possible physical mechanism???



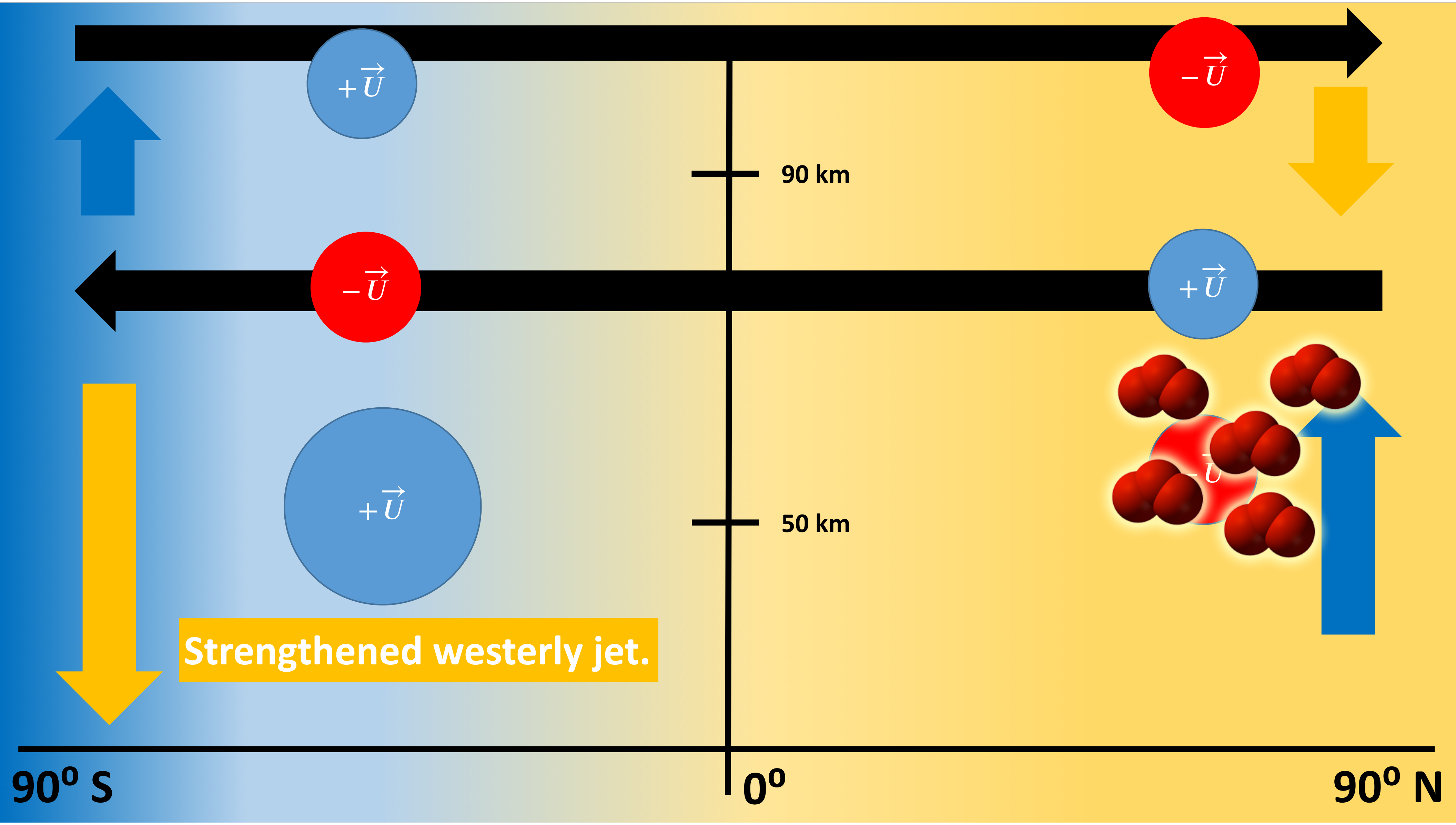
$+\vec{U}$
$-\vec{U}$
90 km
$-\vec{U}$
$+\vec{U}$
$+\vec{U}$
$-\vec{U}$
50 km
90^o S
0^o
90^o N



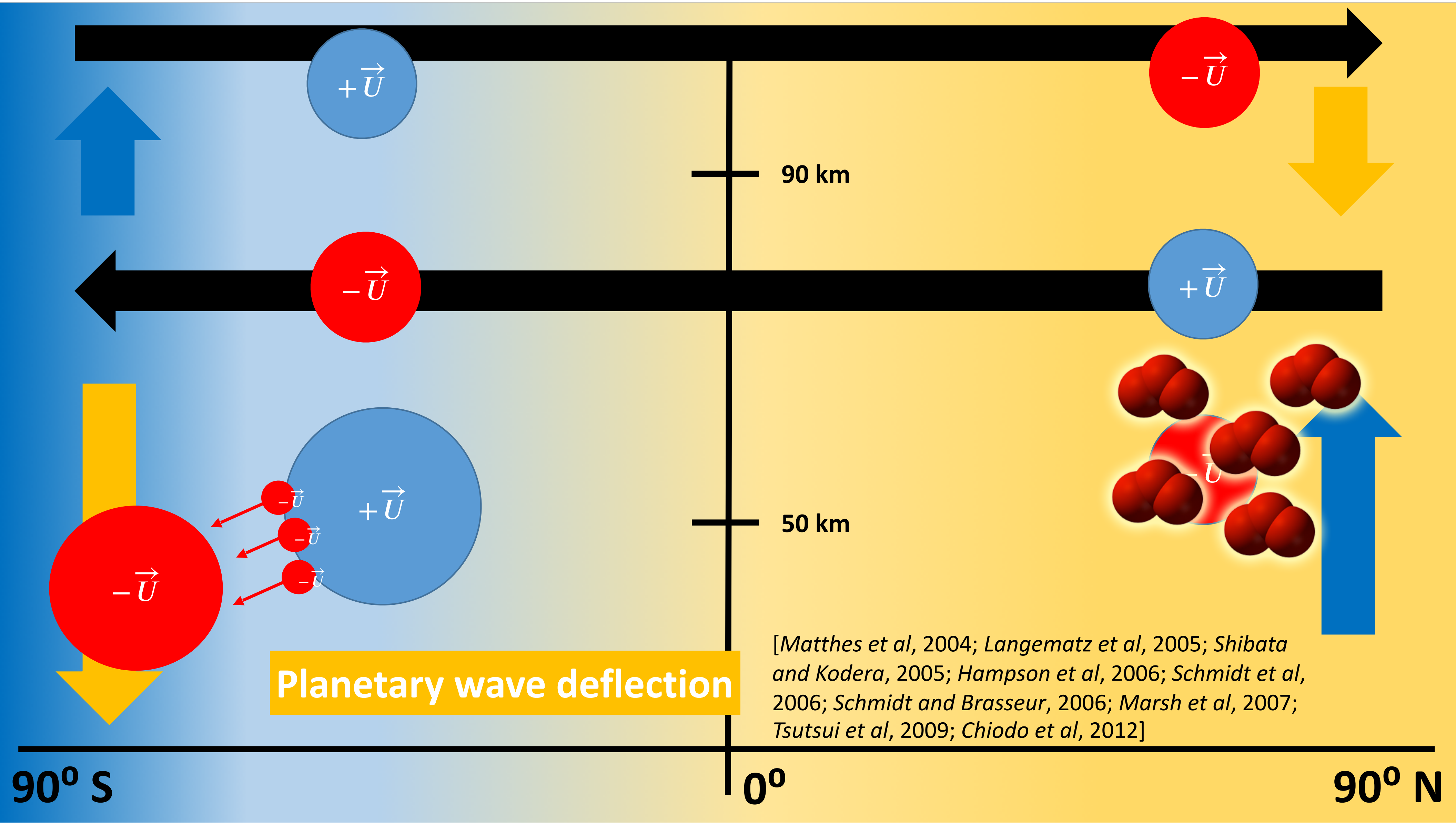
$+\vec{U}$
$-\vec{U}$
90 km
$-\vec{U}$
$+\vec{U}$
$+\vec{U}$
50 km
Enhanced ozone
[*McCormack and Hood*, 1996; *Shindell et al*, 1999; *Labitzke*, 2003; *Randel and Wu*, 2007; *Gray et al*, 2009]
90° S
0°
90° N

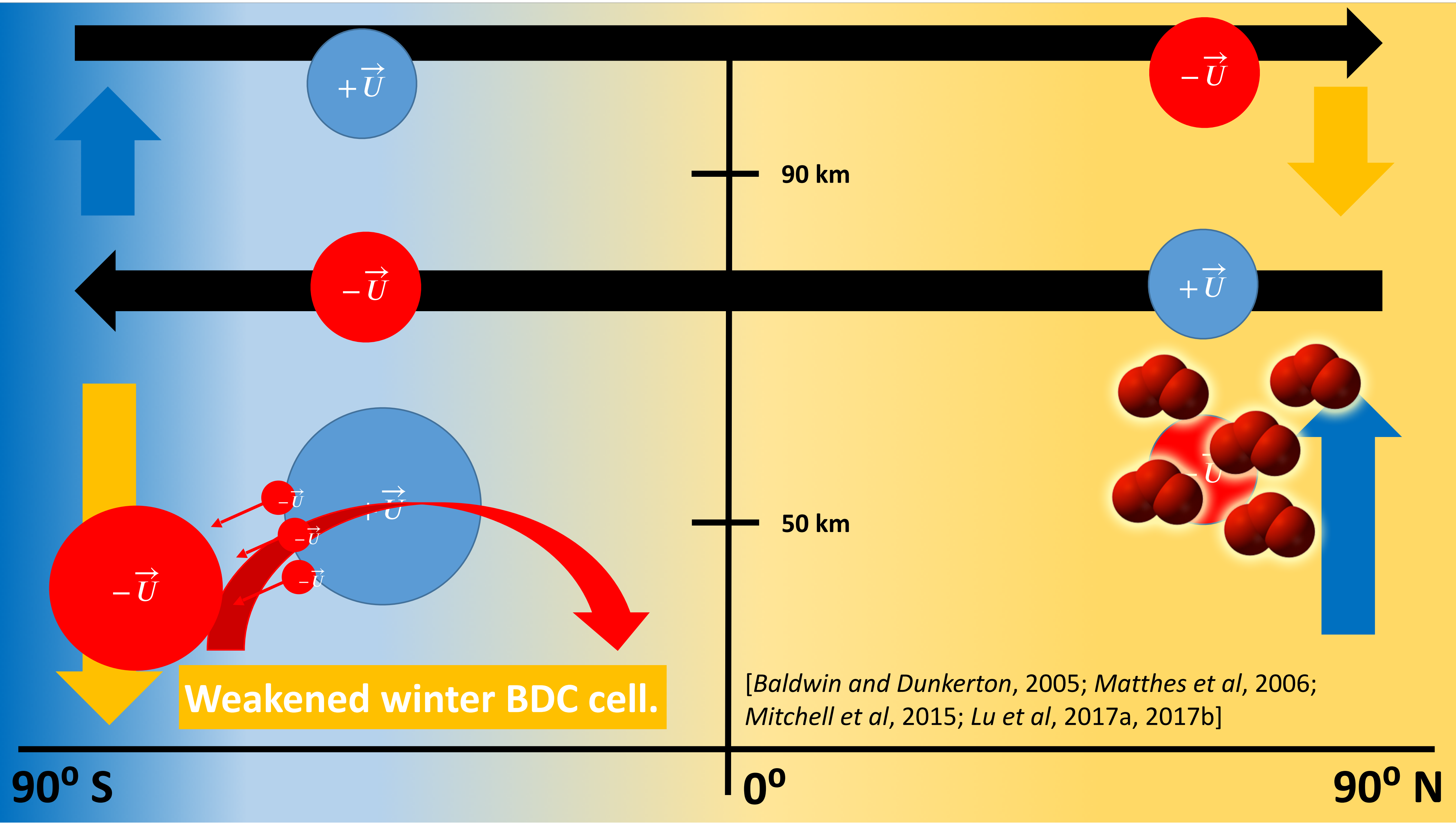


$+\vec{U}$
$-\vec{U}$
90 km
$-\vec{U}$
$+\vec{U}$
$+\vec{U}$
50 km
Increased latitudinal gradient
90° S
0°
90° N

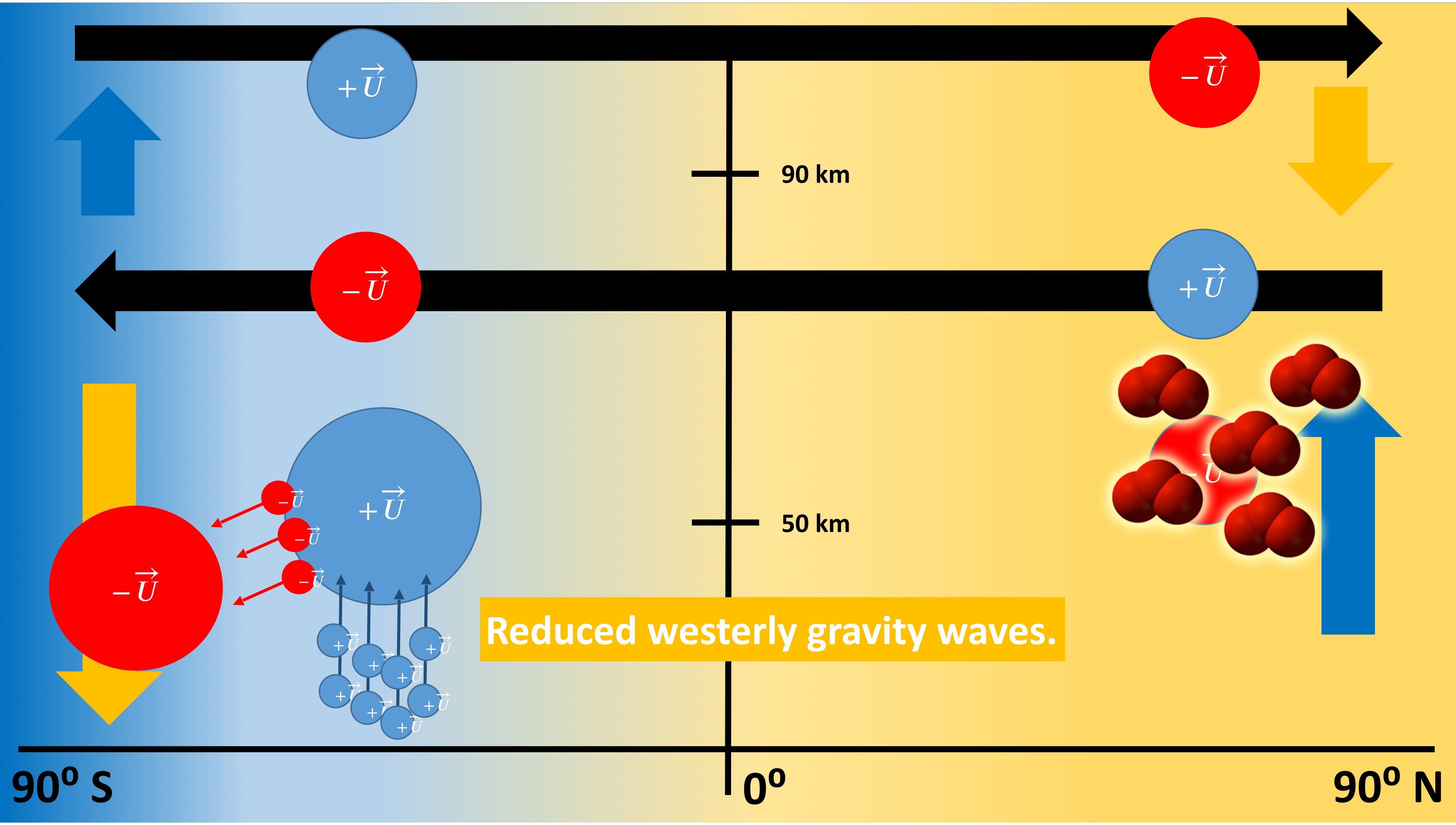


$+\vec{U}$
$-\vec{U}$
90 km
$-\vec{U}$
$+\vec{U}$
$+\vec{U}$
50 km
Strengthened westerly jet.
90° S
0°
90° N

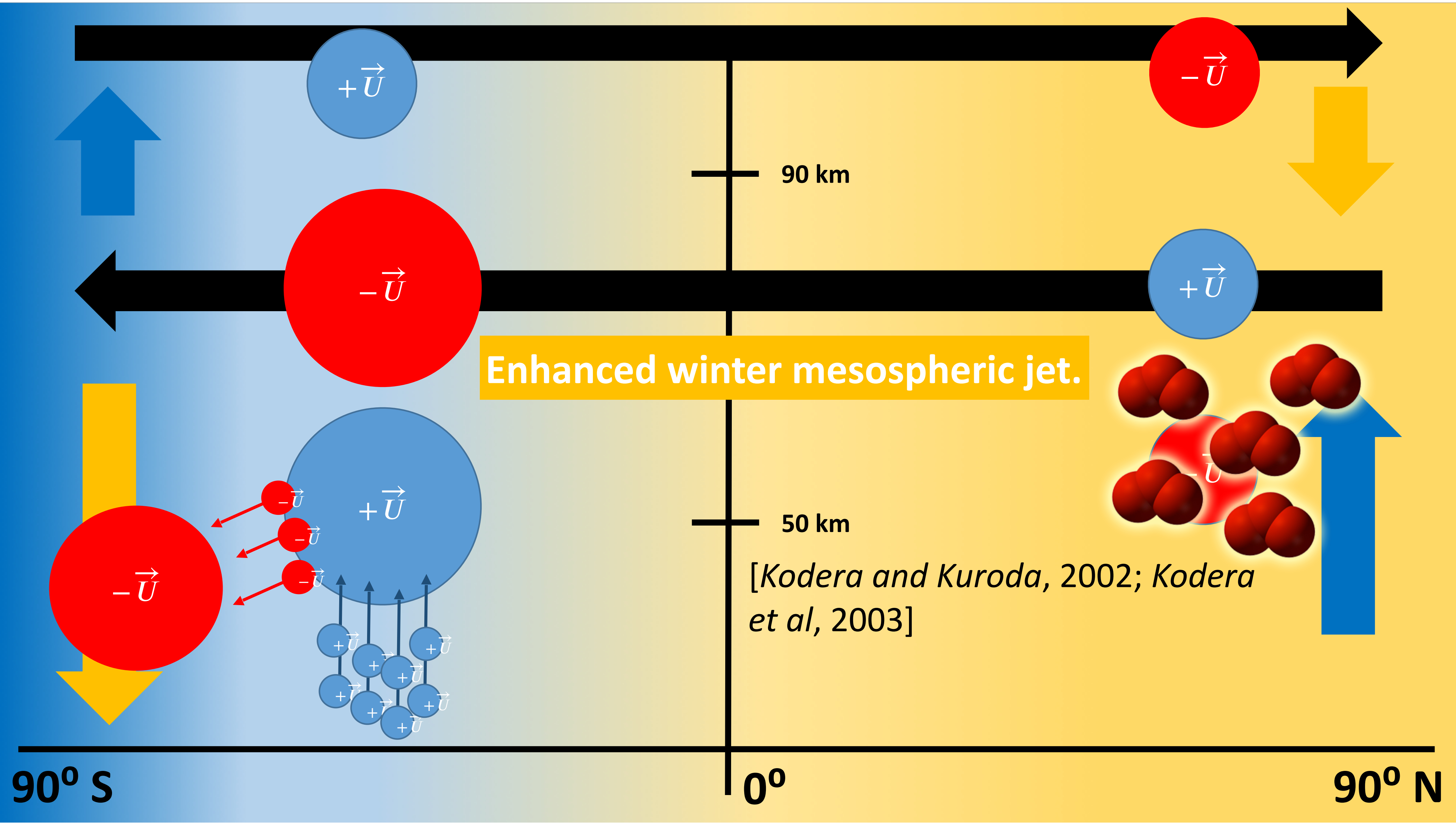

$+\vec{U}$
$-\vec{U}$
90 km
$-\vec{U}$
$+\vec{U}$
$+\vec{U}$
$-\vec{U}$
50 km
Planetary wave deflection
[*Matthes et al*, 2004; *Langematz et al*, 2005; *Shibata and Kodera*, 2005; *Hampson et al*, 2006; *Schmidt et al*, 2006; *Schmidt and Brasseur*, 2006; *Marsh et al*, 2007; *Tsutsui et al*, 2009; *Chiodo et al*, 2012]
90^o S
0^o
90^o N



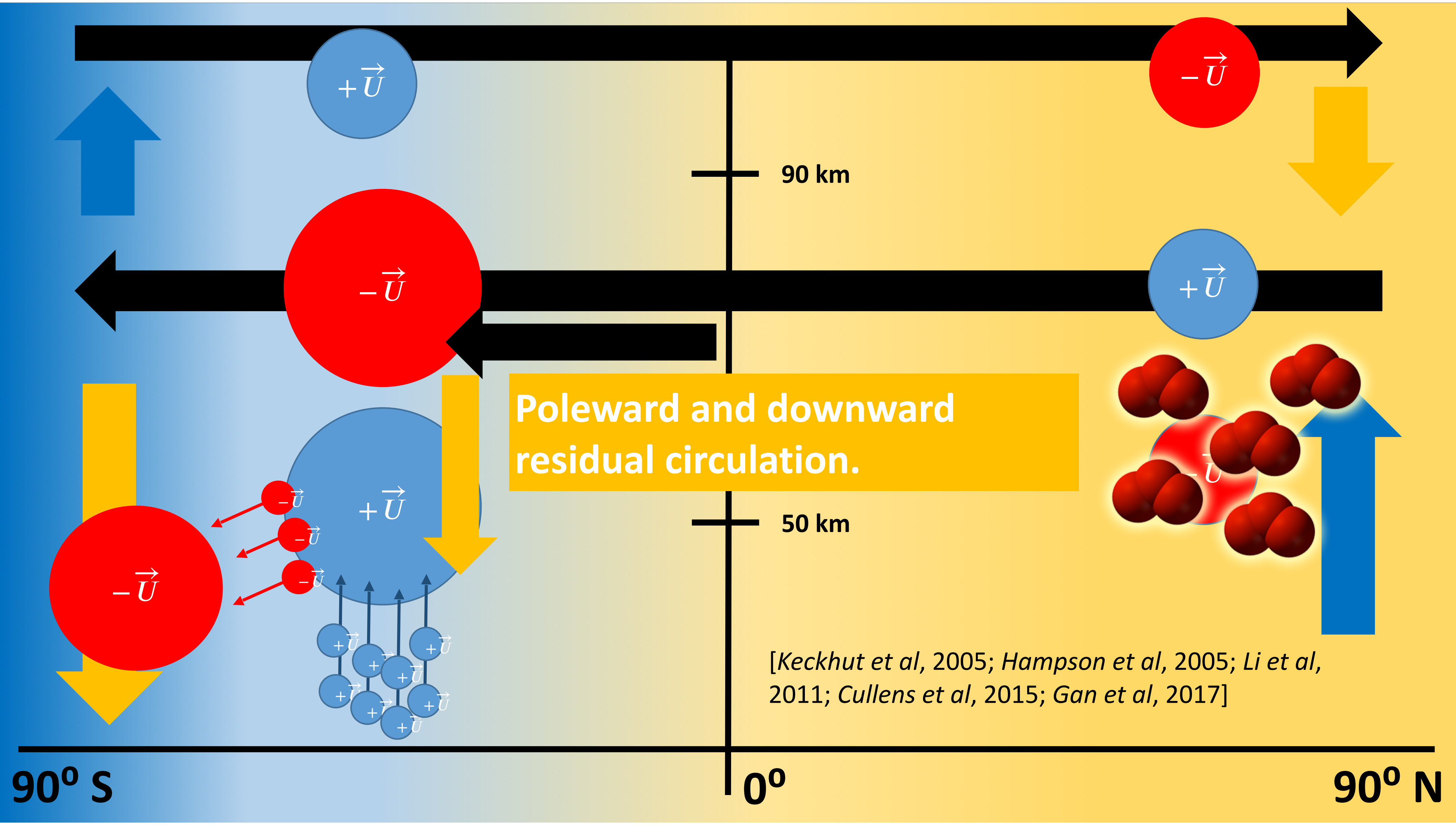
$+\vec{U}$
$-\vec{U}$
90 km
$-\vec{U}$
$+\vec{U}$
$-\vec{U}$
$+\vec{U}$
50 km
$-\vec{U}$
Weakened winter BDC cell.
[*Baldwin and Dunkerton*, 2005; *Matthes et al*, 2006; *Mitchell et al*, 2015; *Lu et al*, 2017a, 2017b]
90° S
0°
90° N



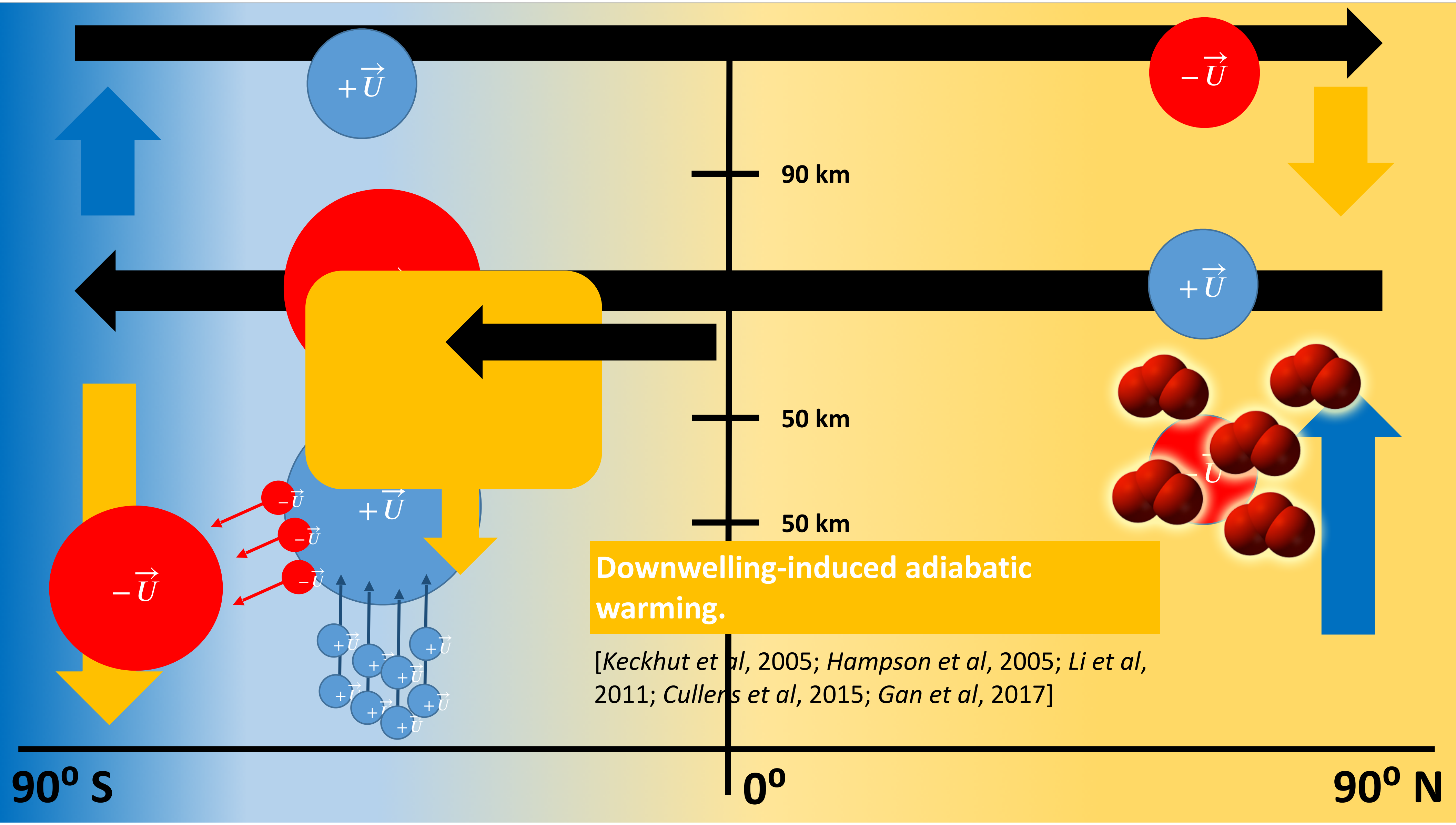
$+\vec{U}$
$-\vec{U}$
90 km
50 km
Reduced westerly gravity waves.
90⁰ S
0⁰
90⁰ N



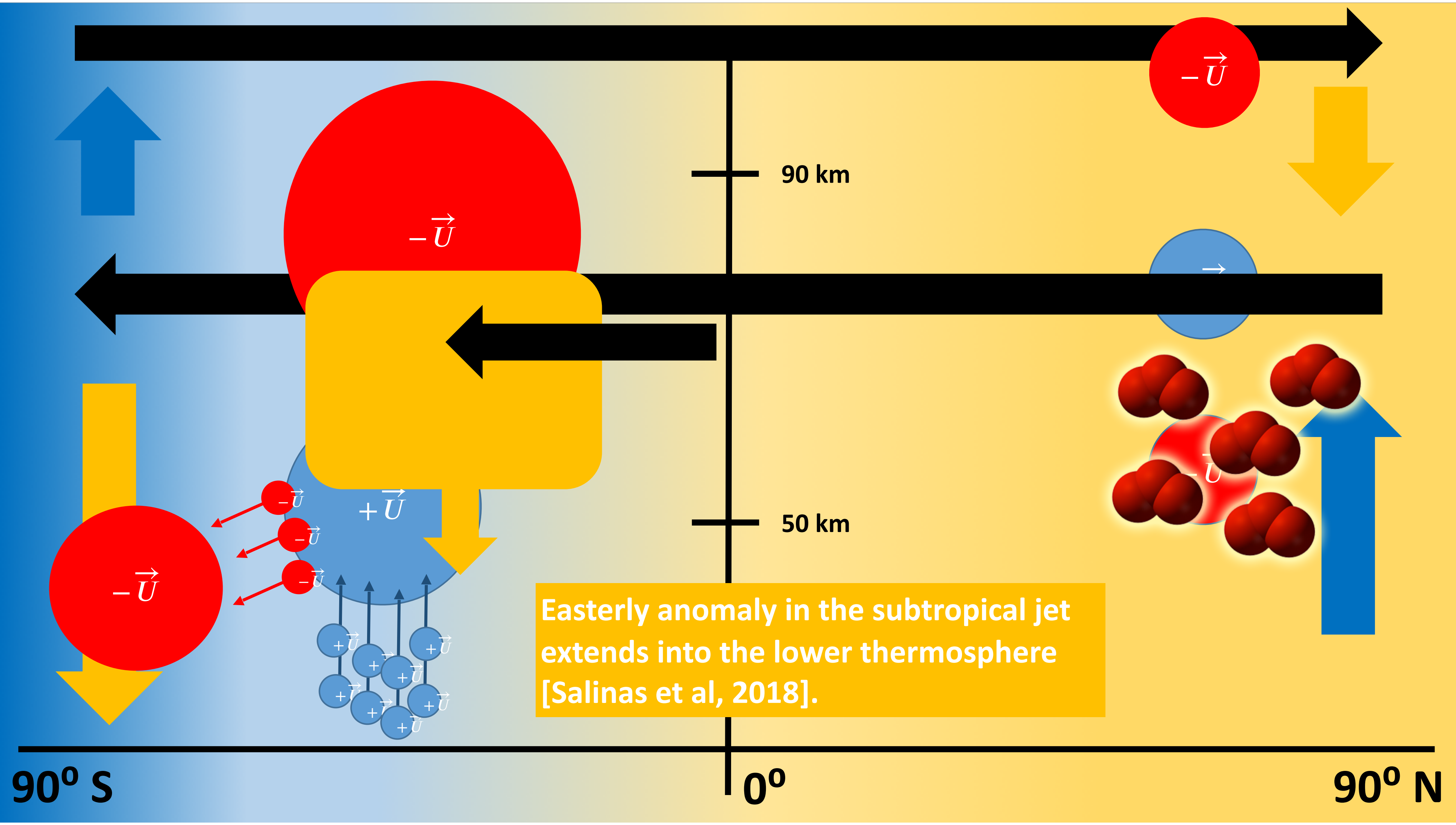
$+\vec{U}$
$-\vec{U}$
90 km
Enhanced winter mesospheric jet.
50 km
[*Kodera and Kuroda*, 2002; *Kodera et al*, 2003]
90^{o} S
0^{o}
90^{o} N



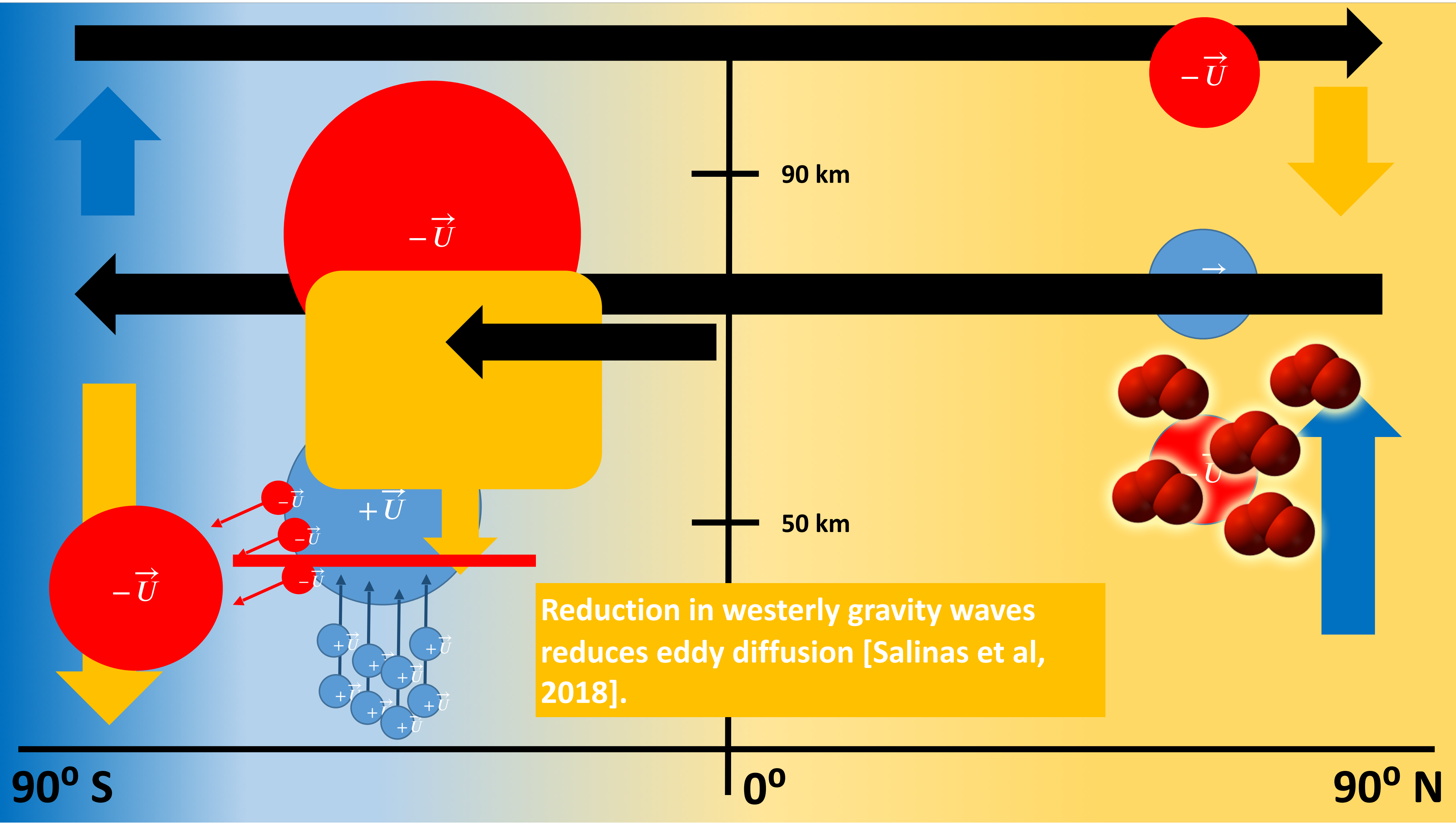
$+\vec{U}$
$-\vec{U}$
90 km
50 km
Poleward and downward residual circulation.
[*Keckhut et al*, 2005; *Hampson et al*, 2005; *Li et al*, 2011; *Cullens et al*, 2015; *Gan et al*, 2017]
90° S
0°
90° N



$+\vec{U}$
$-\vec{U}$
90 km
50 km
50 km
Downwelling-induced adiabatic warming.
[*Keckhut et al*, 2005; *Hampson et al*, 2005; *Li et al*, 2011; *Cullens et al*, 2015; *Gan et al*, 2017]
90⁰ S
0⁰
90⁰ N



90 km
50 km
Easterly anomaly in the subtropical jet extends into the lower thermosphere [Salinas et al, 2018].
90⁰ S
0⁰
90⁰ N



90 km
50 km
Reduction in westerly gravity waves reduces eddy diffusion [Salinas et al, 2018].
90⁰ S
0⁰
90⁰ N

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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