Wave-Driven Circulation in the Lower Thermosphere

A Dynamical Pathway for Whole-Atmosphere Coupling

https://www.nasa.gov/feature/goddard/2018/why-nasa-watches-airglow-the-colors-of-the-upper-atmospheric-wind

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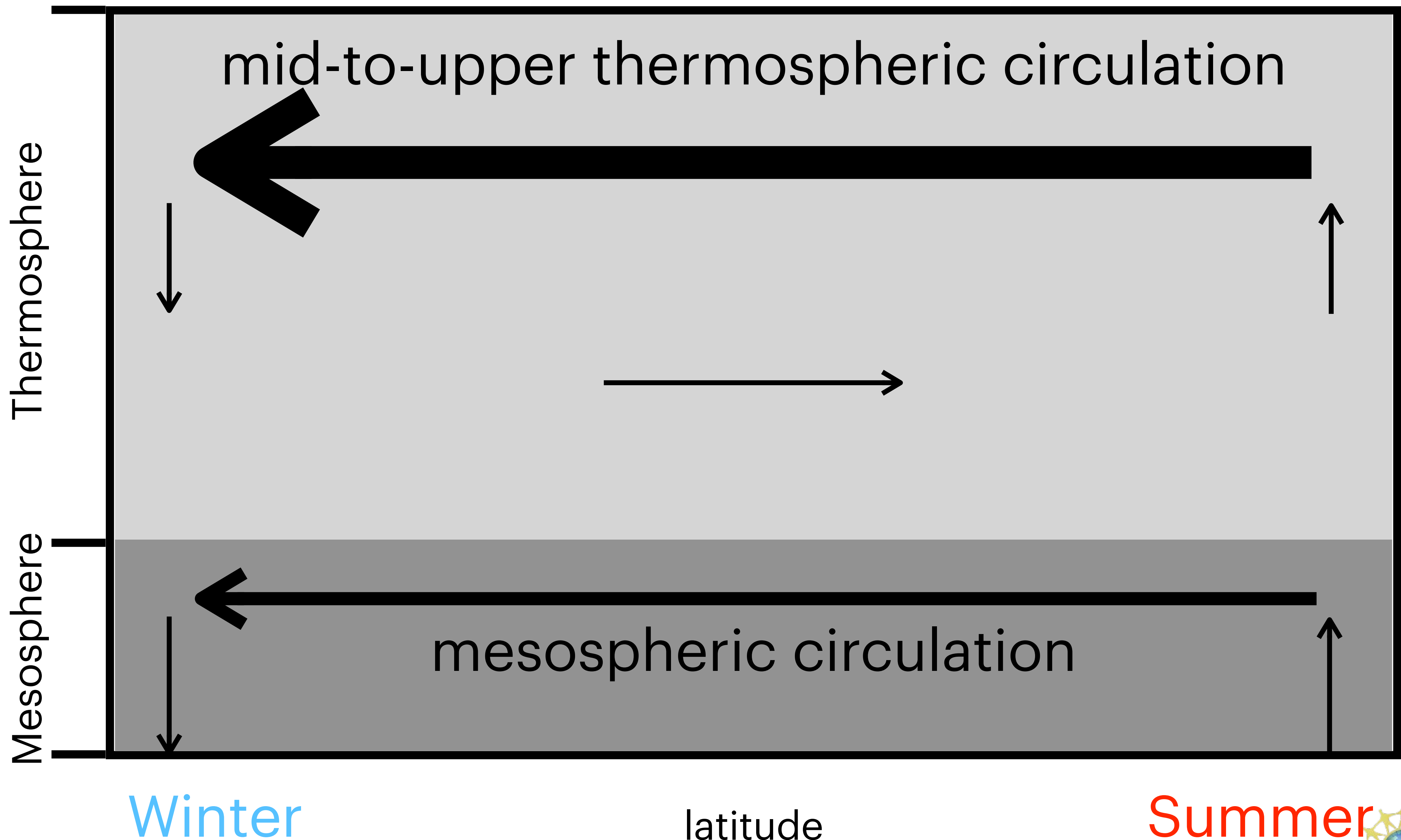
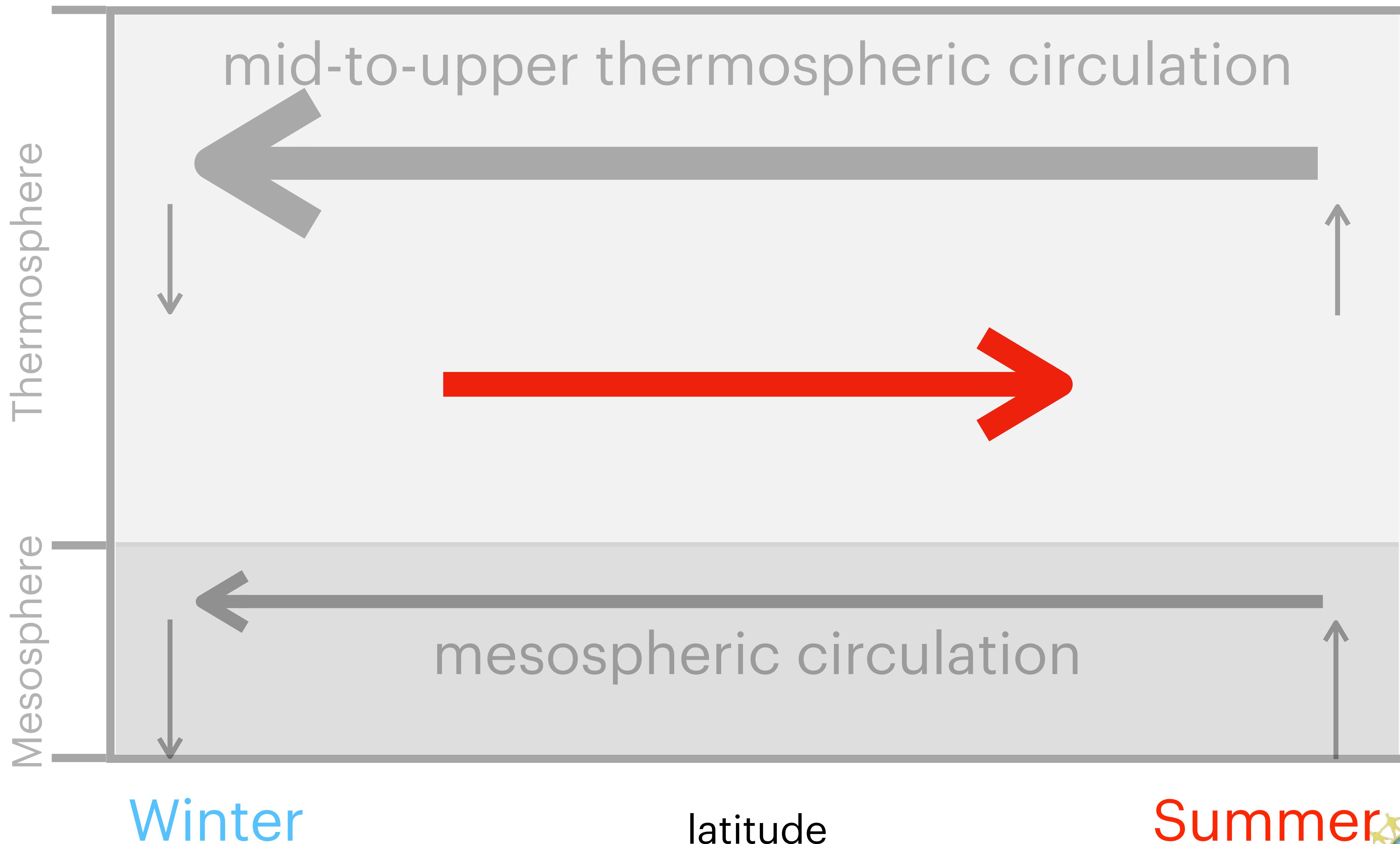
The authors acknowledge support from NSF and NASA

Traditional View

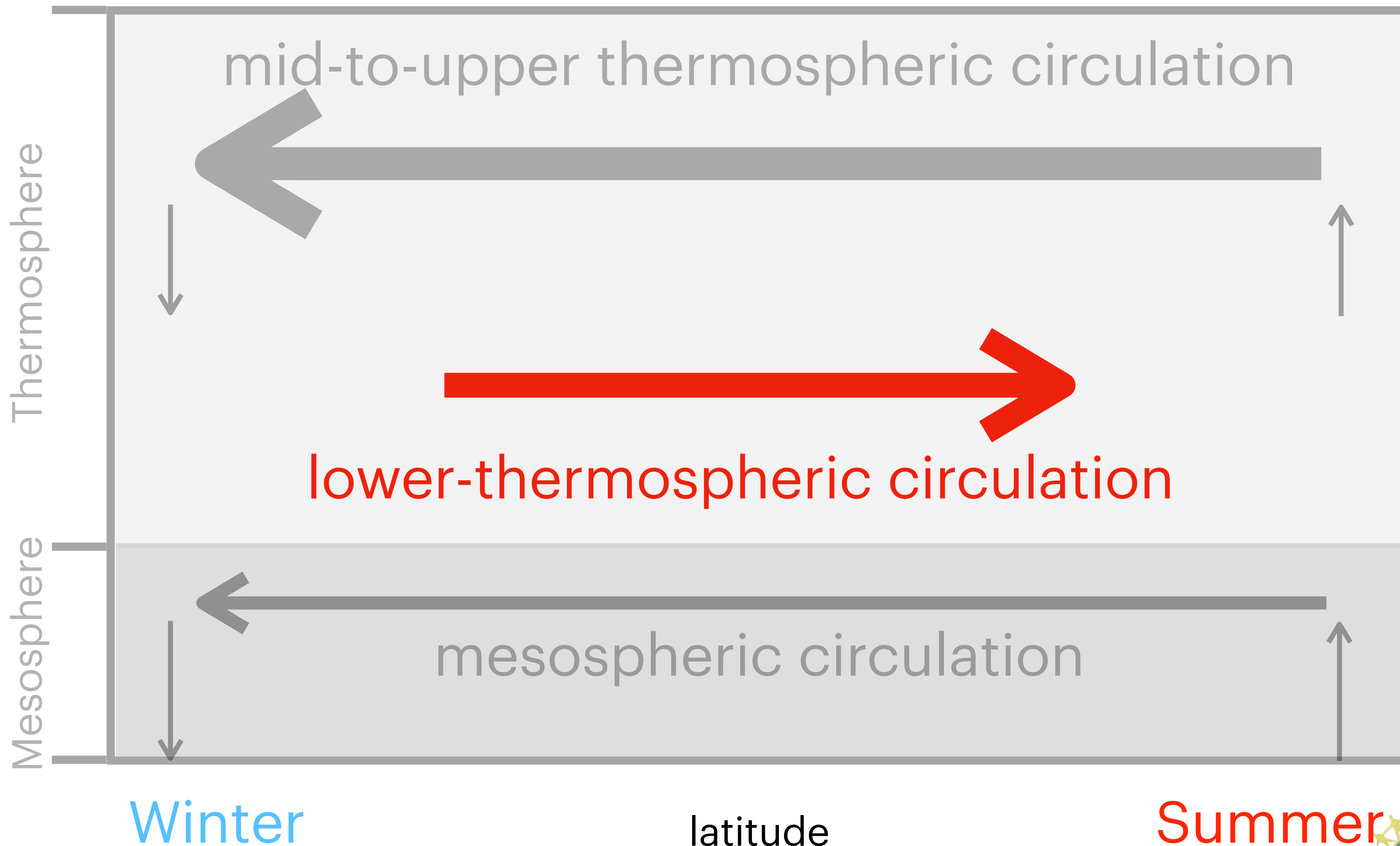
Lower atmosphere > Mesosphere circulation > Thermosphere



A reversed circulation sandwiched between the mesospheric and thermospheric circulations

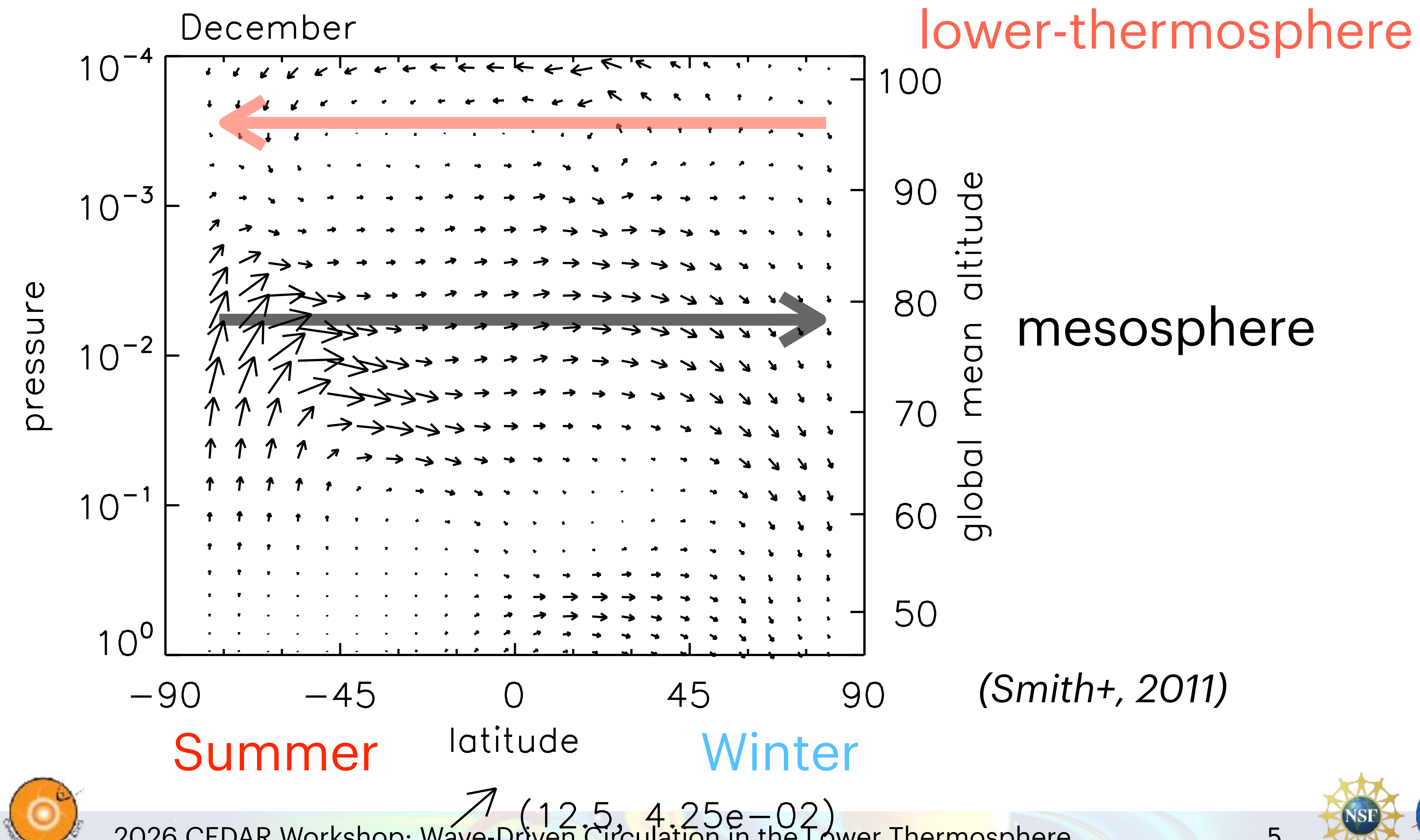


A reversed circulation sandwiched between the mesospheric and thermospheric circulations



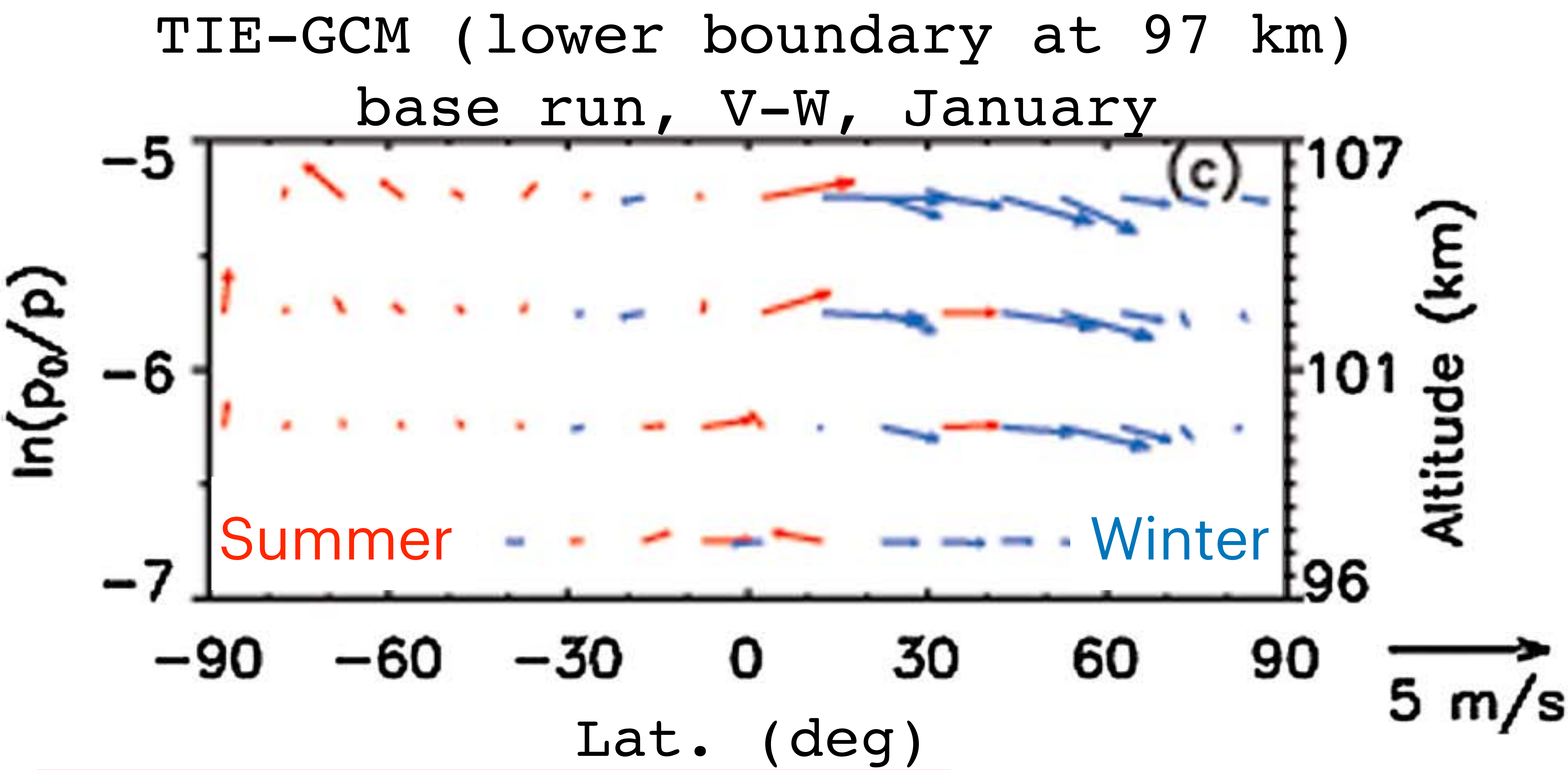
It was first predicted by whole atmosphere model simulation

Smith et al. (2011), WACCM simulations of the mean circulation and trace species transport in the winter mesosphere, J. Geophys. Res.



(Smith+, 2011)

Not all models can reproduce the lower-thermospheric circulation…



(Qian & Yue, 2017)

only models "with lower atmospheric components" can reproduce

Our Scientific Journey Over the Past 5 Years

<u>Discovery</u>

Can we observe the lower-thermospheric circulation?

<u>Mechanism</u>

What drives the lower-thermospheric circulation?

<u>Impacts</u>

Why does it matter for the whole thermosphere?

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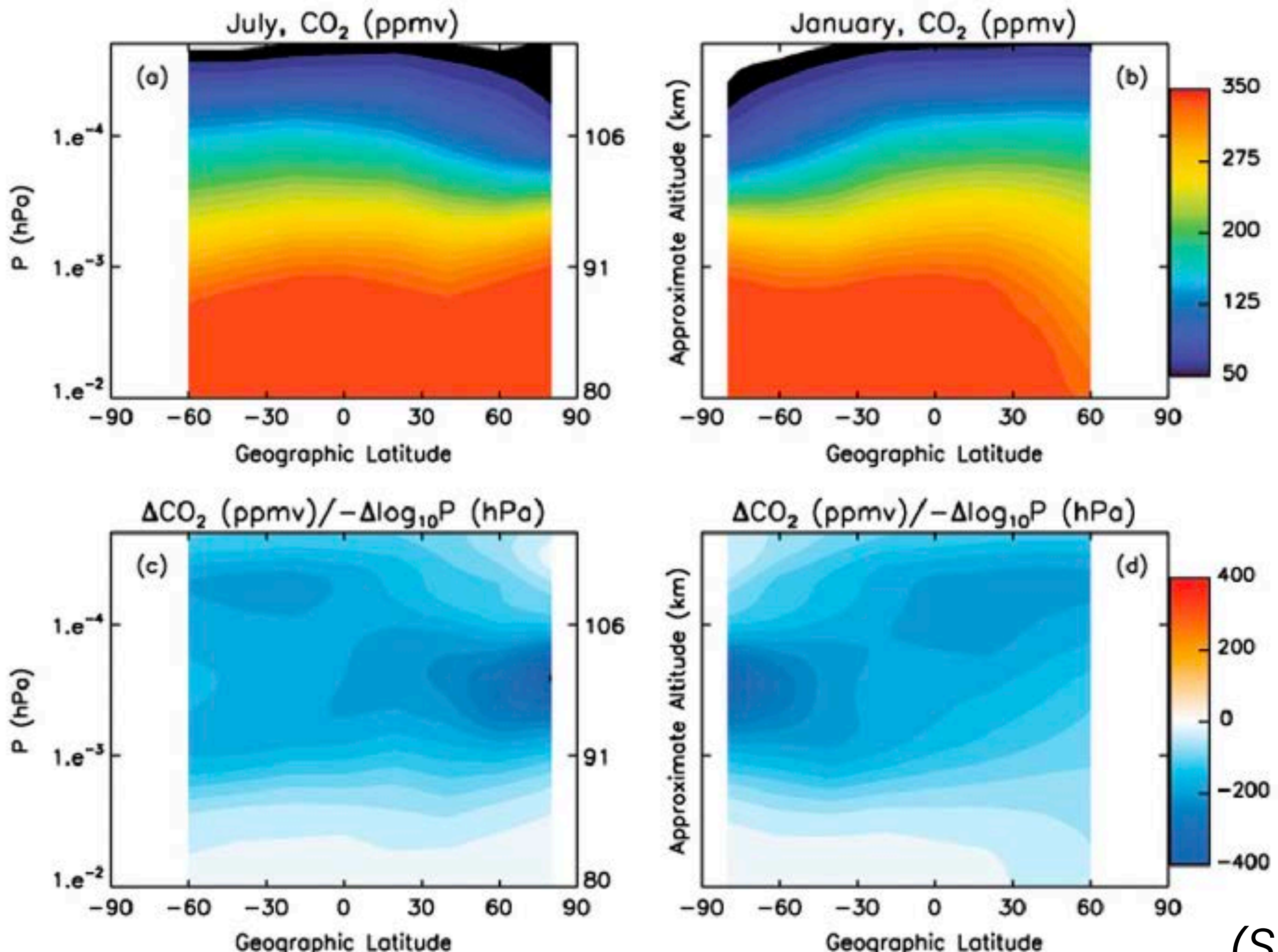
Yes, but the first clues came from indirect observations

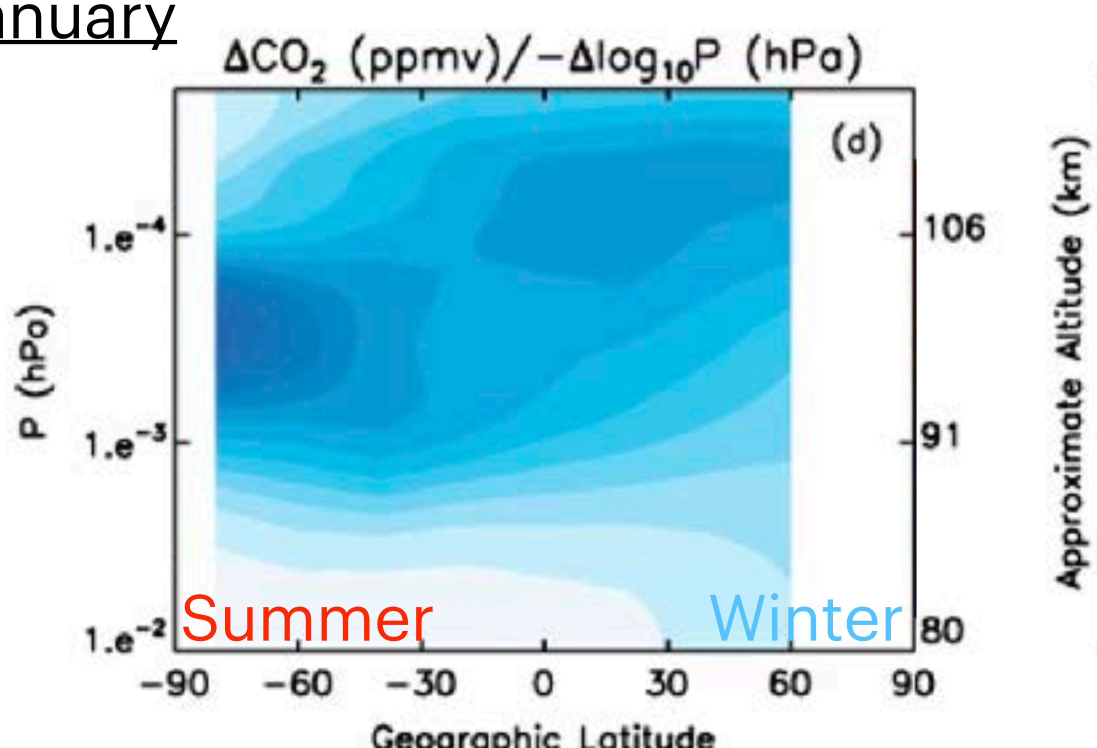
CO_2 in mesosphere and lower thermosphere is chemically inert gas, and can be used to track air-parcel movement



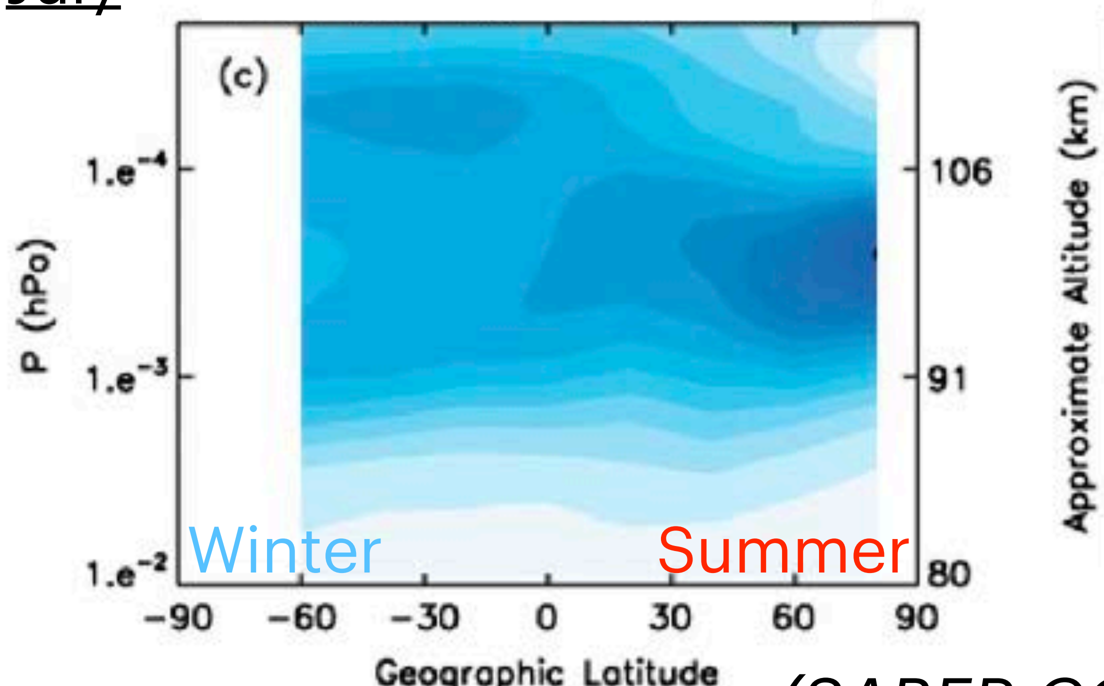
(SABER CO_2; Qian+, 2017)

There exist maximum vertical gradients of CO_2 at summer mesosphere and winter lower-thermosphere

January



July



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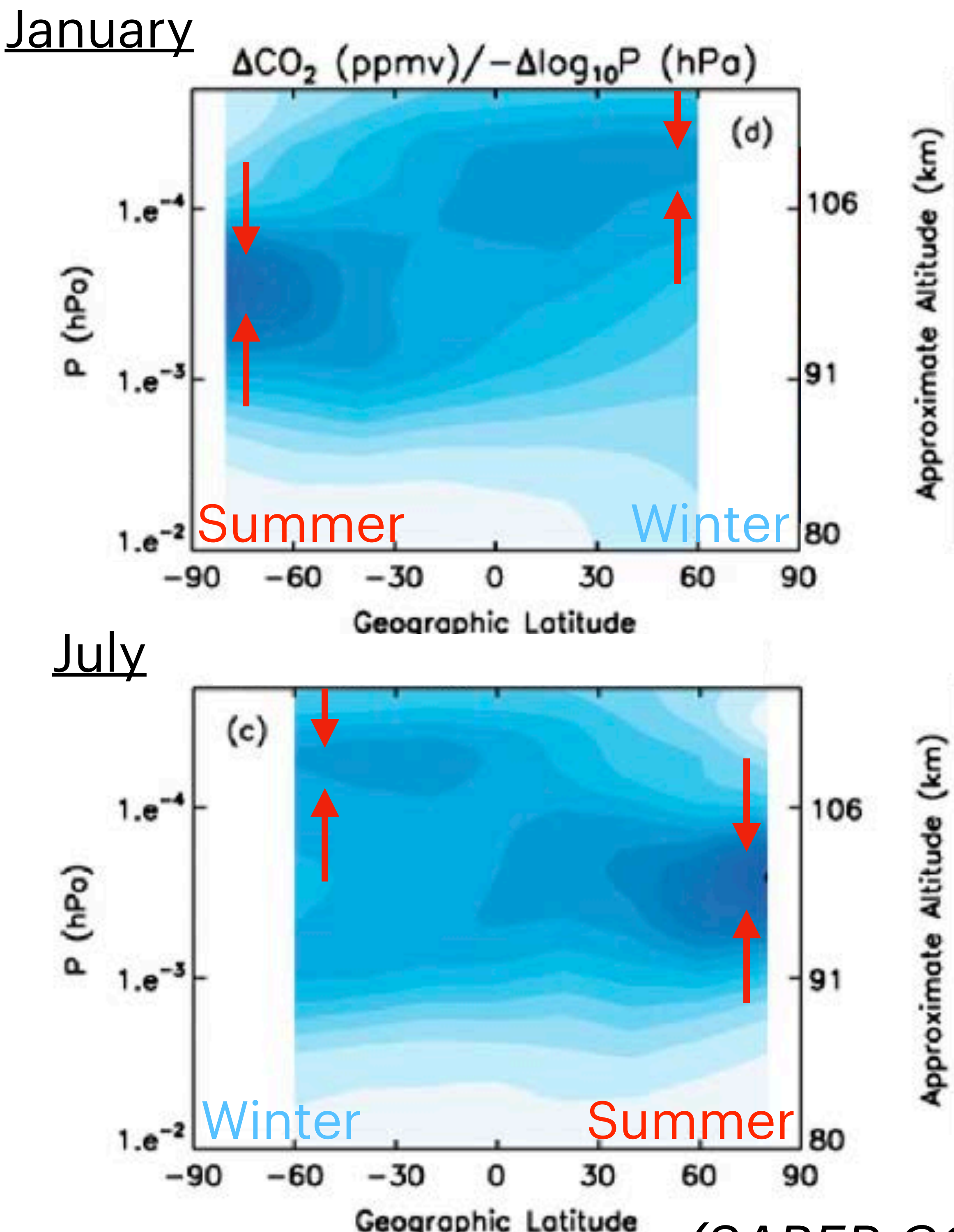
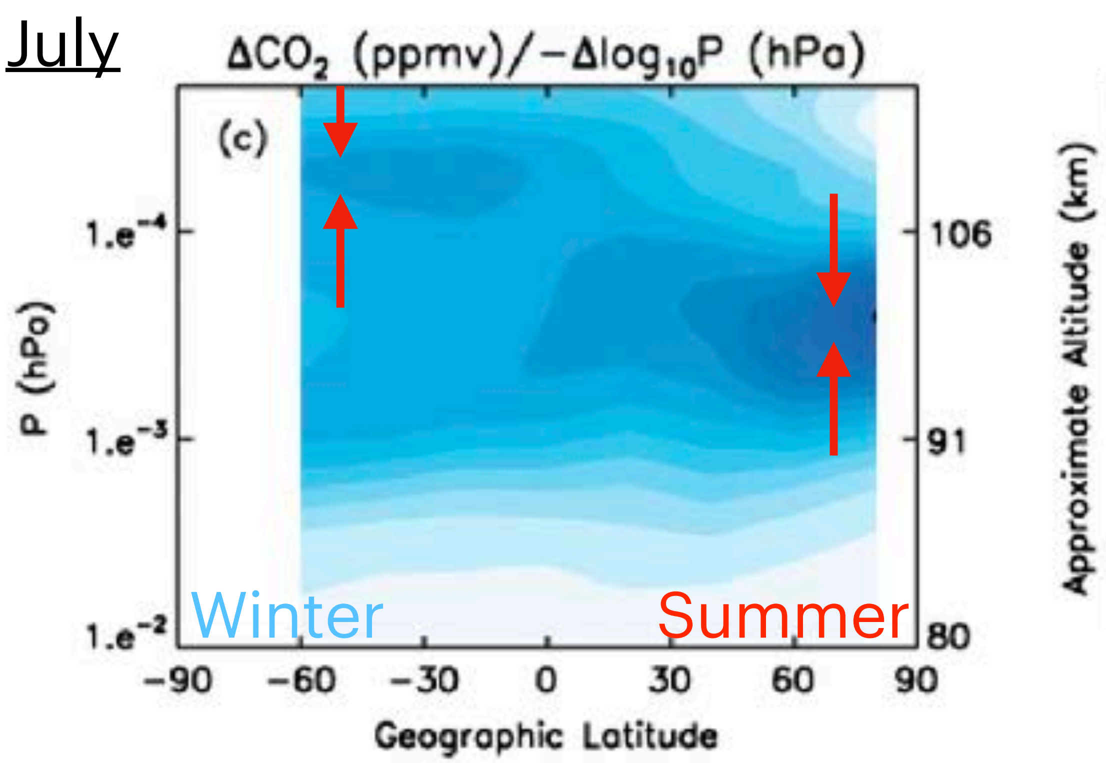


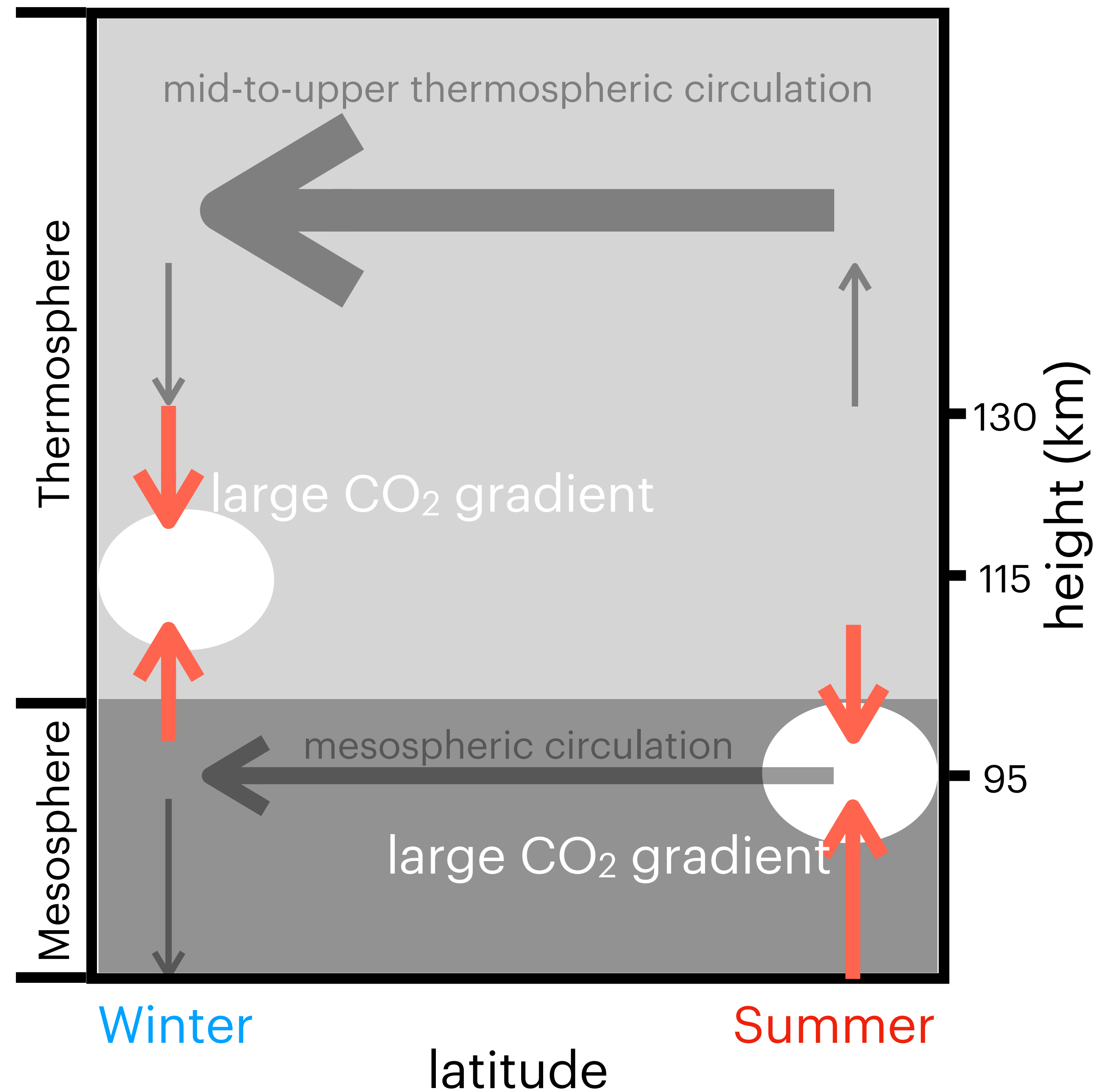
The location of the max. vertical gradient indicates there is a convergence which is created by upwelling below and downwelling above.

(SABER CO_2; Qian+, 2017)

CO_2 and H_2O vertical gradient suggests a reversed layer above the mesospheric circulation

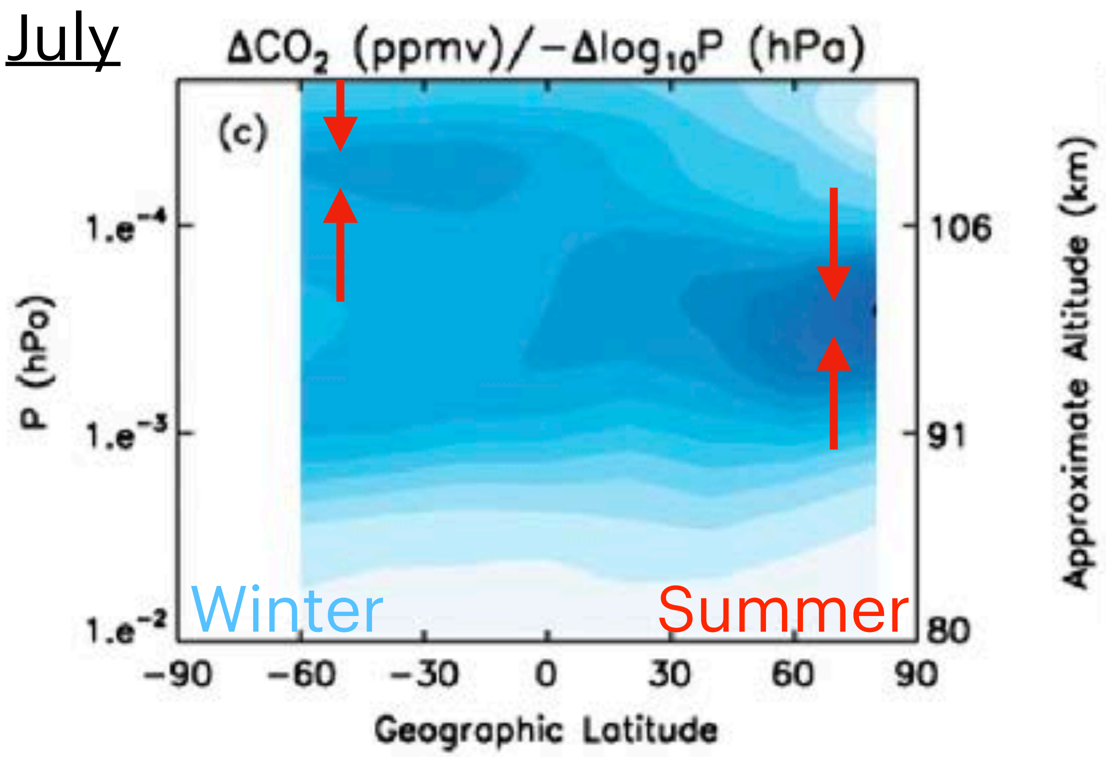


(SABER CO_2; Qian+, 2017)

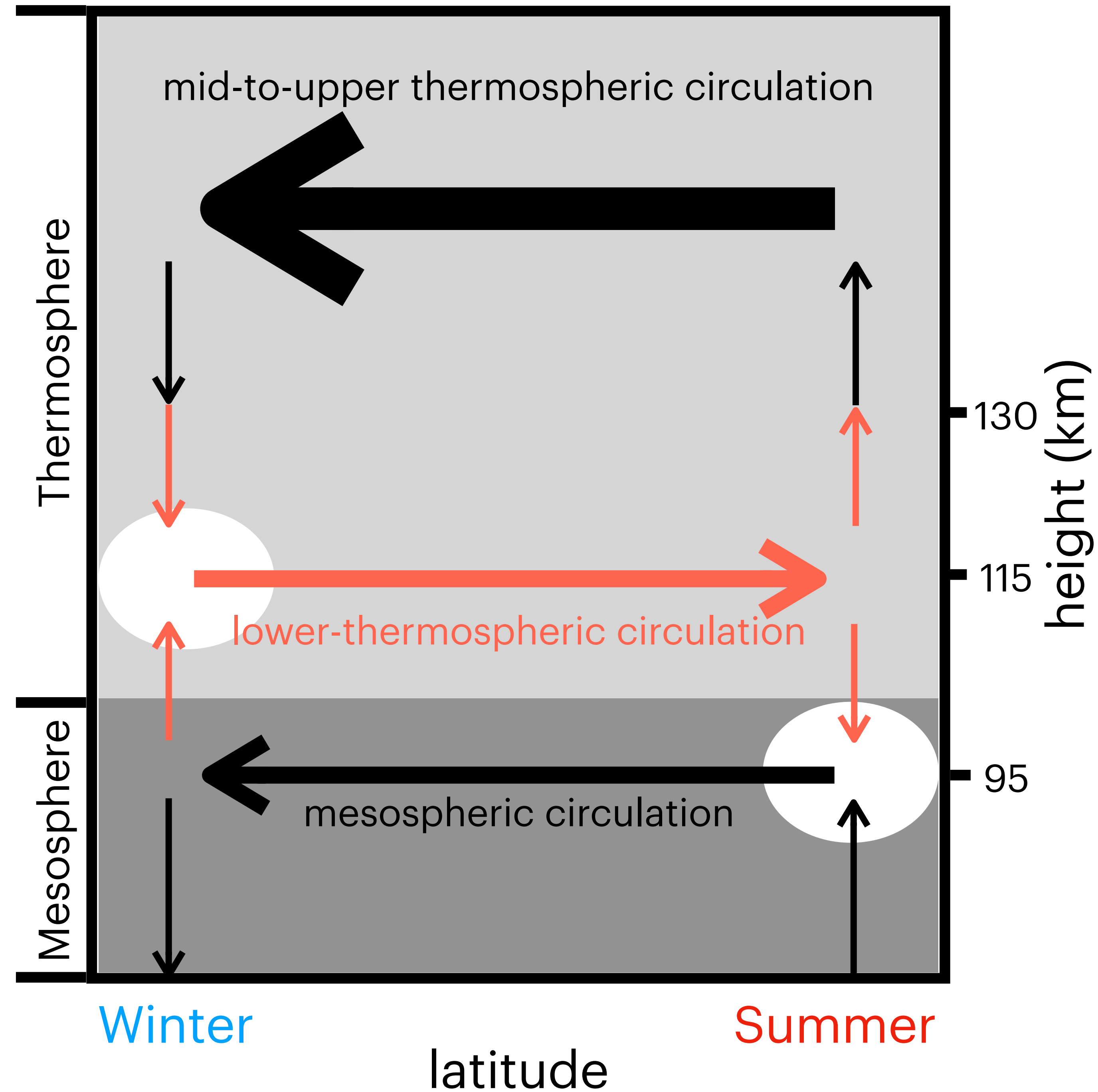


CO_2 and H_2O vertical gradient suggests a reversed layer above the mesospheric circulation

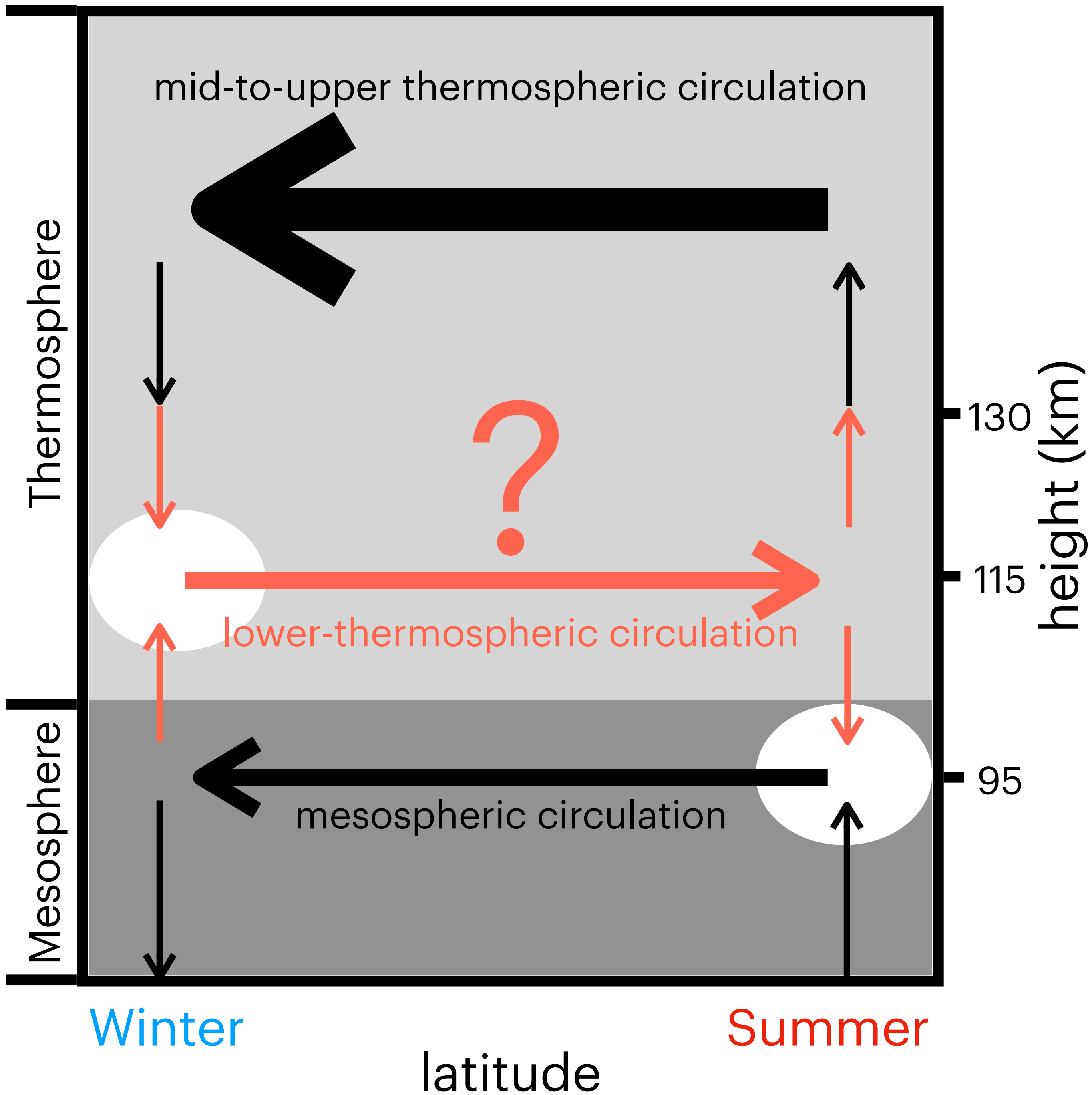
July



(SABER CO_2; Qian+, 2017)

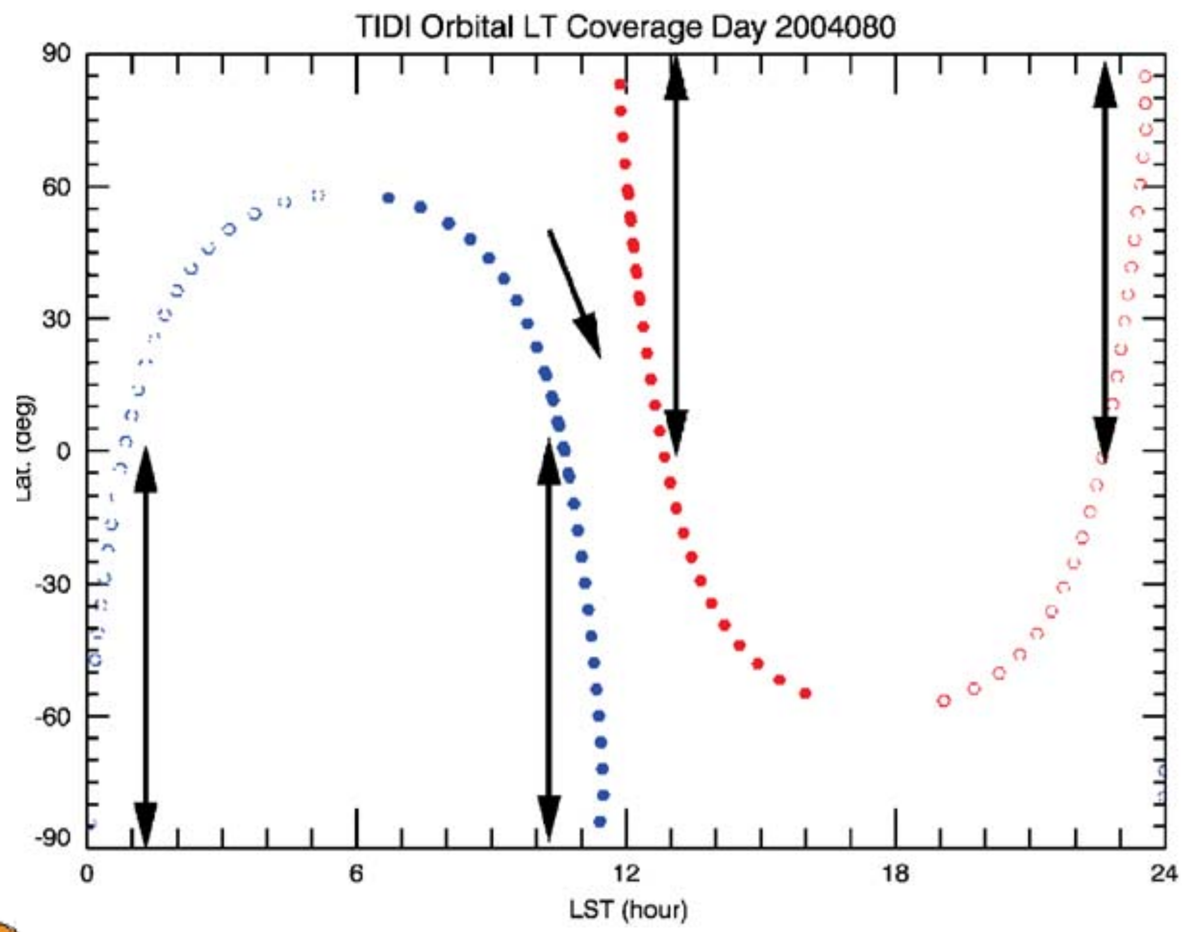


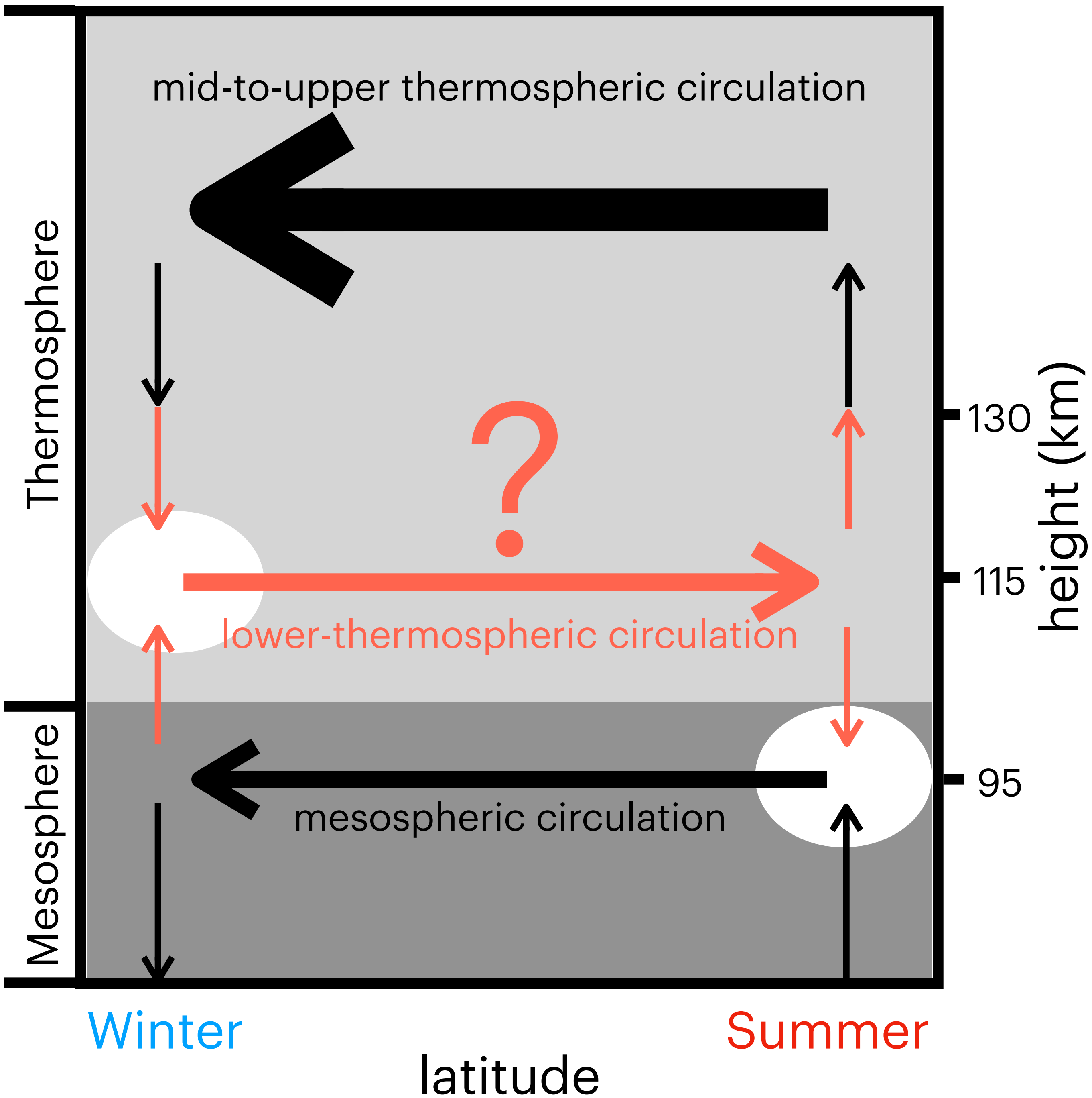
Can we directly observe the lower-thermospheric circulation?



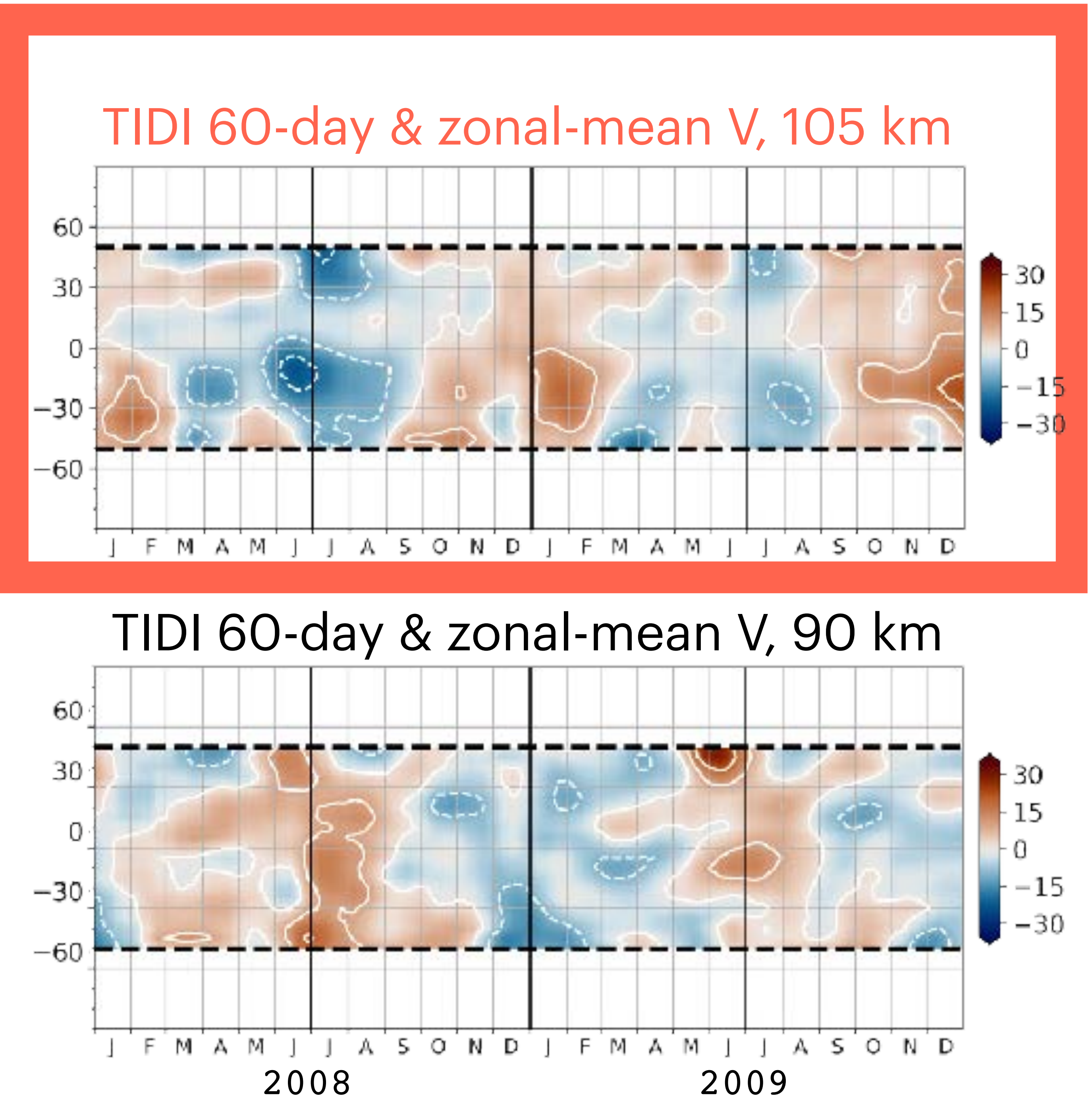
Let's see if TIDI can reveal the reversed circulation

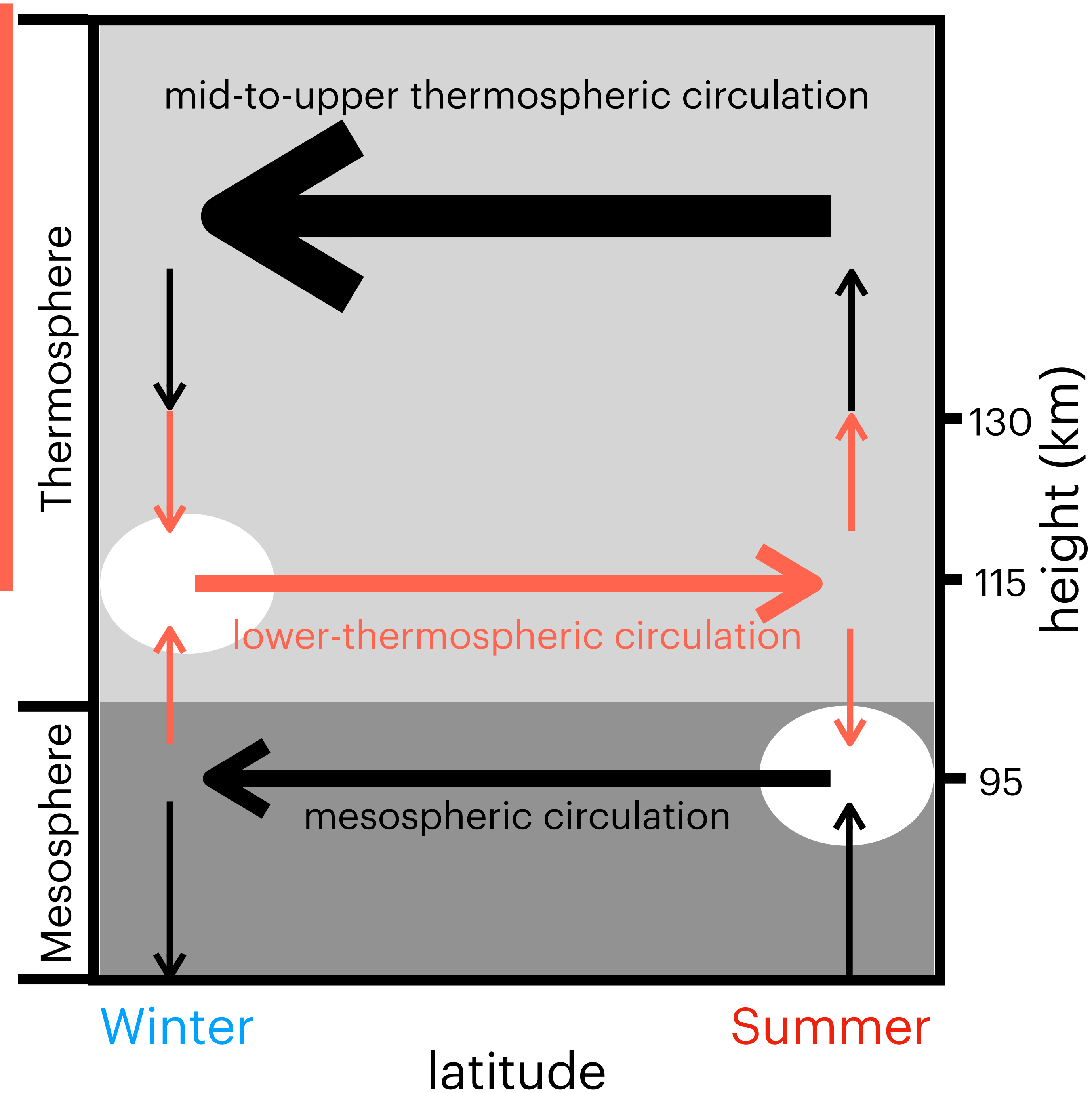
TIMED-TIDI





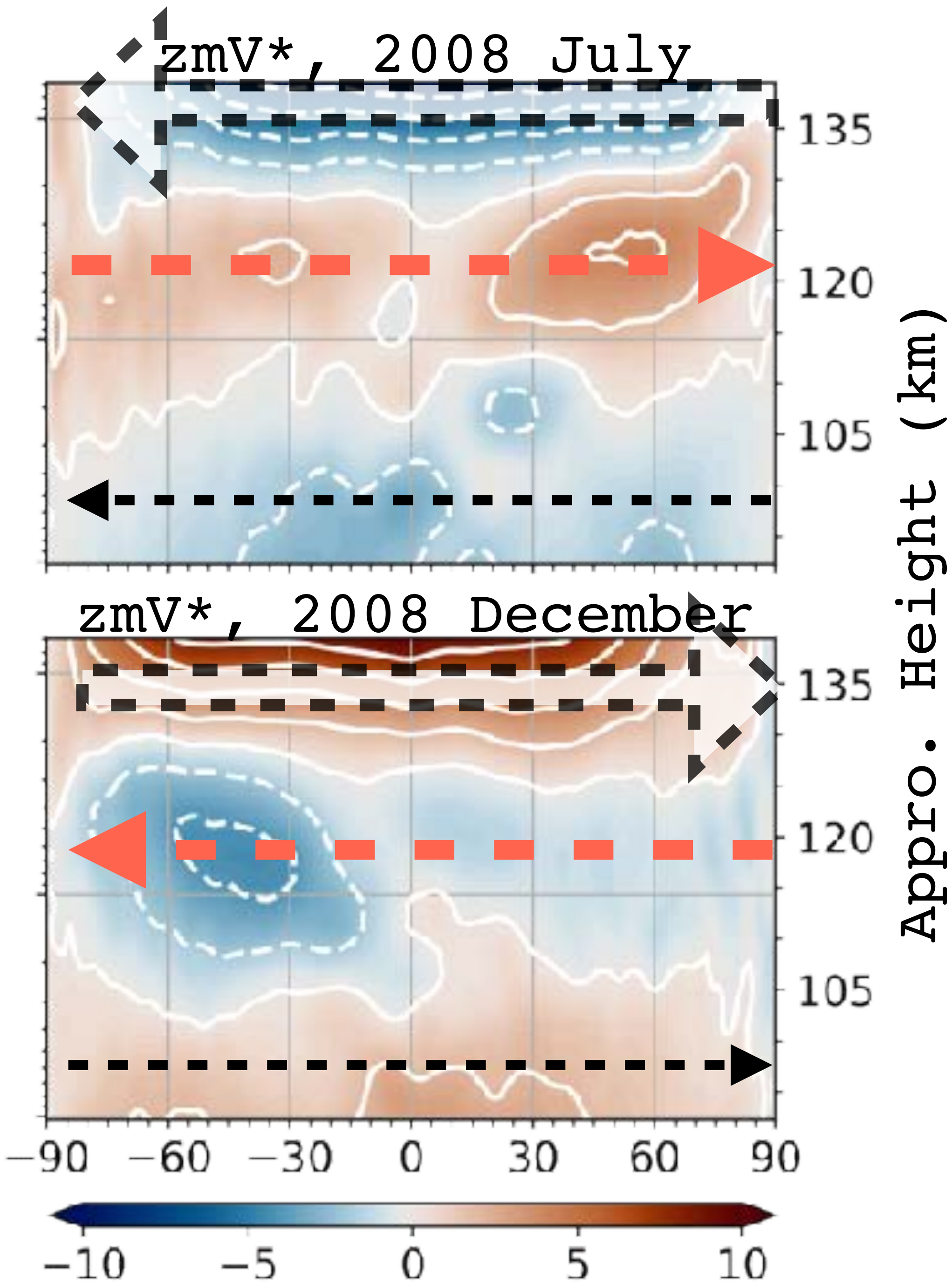
Confirmed with TIDI observations
a winter-to-summer circulation exists at ~105 km

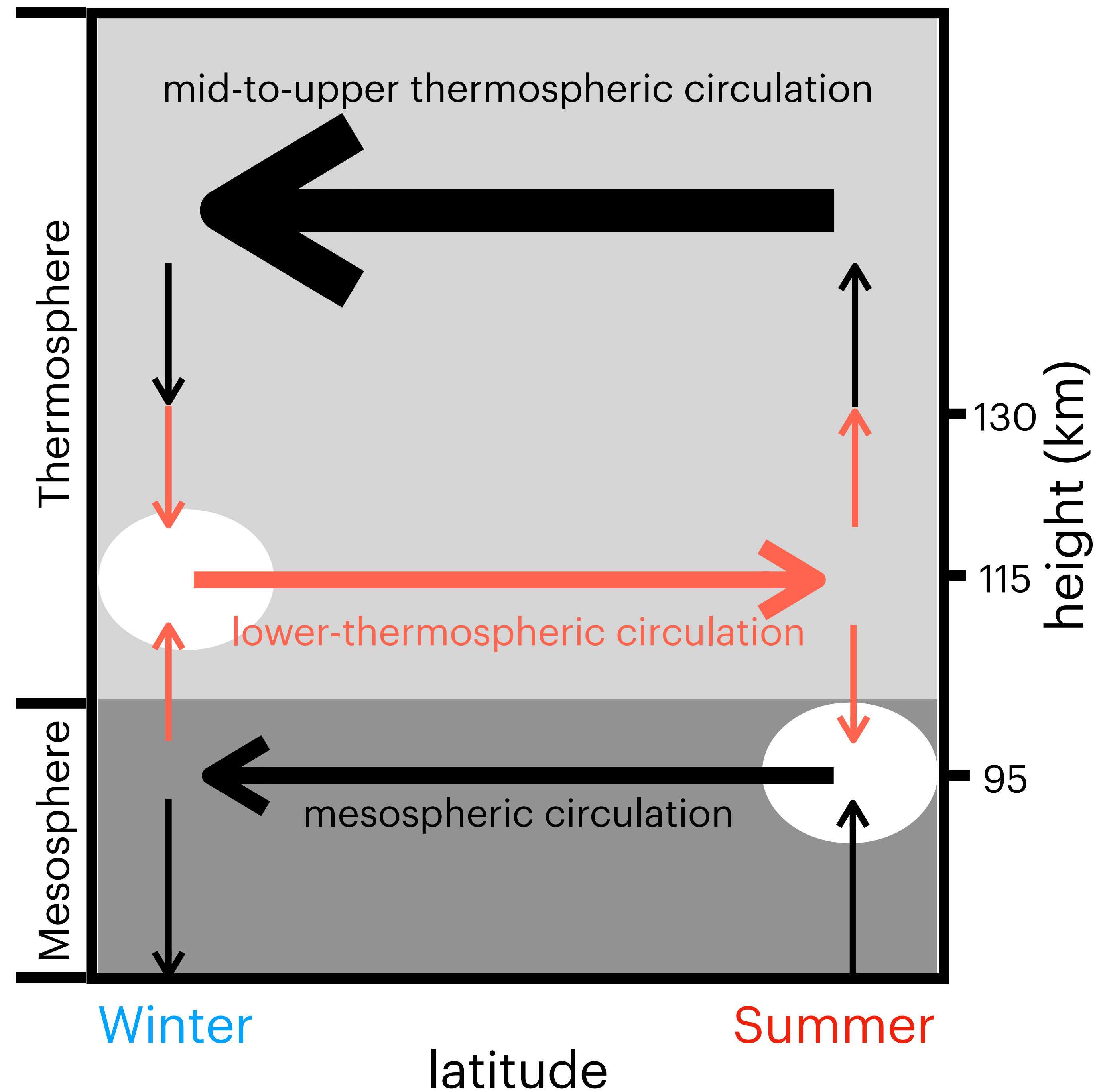




Reproduced by SD-WACCMX

a narrow circulation exists between 105-125 km





Key takeaways

<u>Can we observe the lower-thermospheric circulation?</u>

- TIDI reveals a robust lower-thermospheric circulation
- WACCM-X reproduces the observed circulation pattern
- Seasonal discrepancies in circulation strength

Our Scientific Journey Over the Past 5 Years

Discovery

Can we observe the lower-thermospheric circulation?

Mechanism

What drives the lower-thermospheric circulation?

Impacts

Why does it matter for the whole thermosphere?

To understand the driving mechanism, we turn to the zonal-mean zonal momentum budget

$$\frac{\partial \bar{u}}{\partial t} + \left[\frac{1}{a\cos\phi}\frac{\partial}{\partial \phi}(\bar{u}\cos\phi) - f\right]\bar{v}^* + \frac{\partial \bar{u}}{\partial z}\bar{w}^* = \frac{1}{\rho_0 a\cos\phi}\nabla\cdot\mathbf{F} + \mathbf{GWF}$$

local tendency

meridional advection + Coriolis force

vertical advection

resolved wave forcing

parameterized GW forcing

Don’t panic! Let’s break it down

$$\frac{\partial \bar{u}}{\partial t} + \left[\frac{1}{a\cos\phi}\frac{\partial}{\partial \phi}(\bar{u}\cos\phi) - f\right]\bar{v}^* + \frac{\partial \bar{u}}{\partial z}\bar{w}^* = \frac{1}{\rho_0 a\cos\phi}\nabla\cdot\mathbf{F} + \mathbf{GWF}$$

local tendency

meridional advection + Coriolis force

vertical advection

resolved wave forcing

parameterized GW forcing

Local time tendency is small on seasonal time scale, it can be neglected

$$\cancel{\frac{\partial \bar{u}}{\partial t}} + \left[\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(\bar{u}\cos\phi) - f\right]\bar{v}^* + \frac{\partial\bar{u}}{\partial z}\bar{w}^* = \frac{1}{\rho_0 a\cos\phi}\nabla\cdot\mathbf{F} + \mathbf{GWF}$$

~~local tendency~~

meridional advection + Coriolis force

vertical advection

resolved wave forcing

parameterized GW forcing

Scale analysis suggests vertical advection plays a minor role in zonal-mean zonal momentum budget

$$\cancel{\frac{\partial \bar{u}}{\partial t}} + \left[\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(\bar{u}\cos\phi) - f\right]\bar{v}^* + \cancel{\frac{\partial \bar{u}}{\partial z}}\bar{w}^* = \frac{1}{\rho_0 a\cos\phi}\nabla\cdot\mathbf{F} + \mathbf{GWF}$$

~~local tendency~~

meridional advection
+ Coriolis force

~~vertical advection~~

resolved
wave forcing

parameterized
GW forcing

Now the equation is much friendlier (and still contains the important physics!)

$$\left[\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(\bar{u}\cos\phi) - f\right]\bar{v}^* = \frac{1}{\rho_0 a\cos\phi}\nabla\cdot\mathbf{F} + \mathbf{GWF}$$

response of the mean meridional circulation

= resolved wave forcing + parameterized GW forcing

Which wave forcing term is responsible for driving the lower-thermospheric circulation?

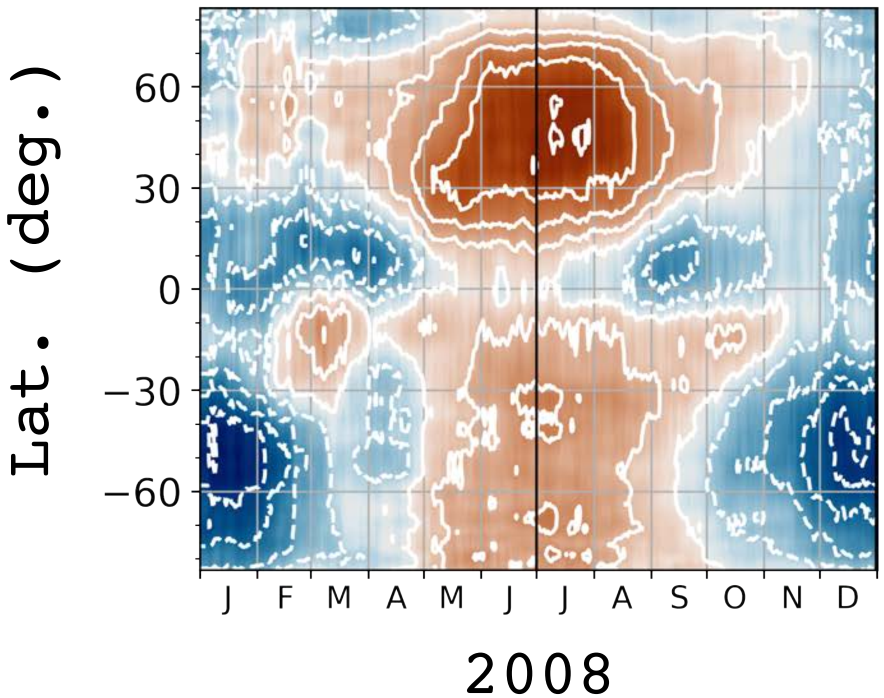
$$\left[\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(\bar{u}\cos\phi) - f\right]\bar{v}^* = \frac{1}{\rho_0 a\cos\phi}\nabla\cdot\mathbf{F} + \mathbf{GWF}$$

response of the mean meridional circulation

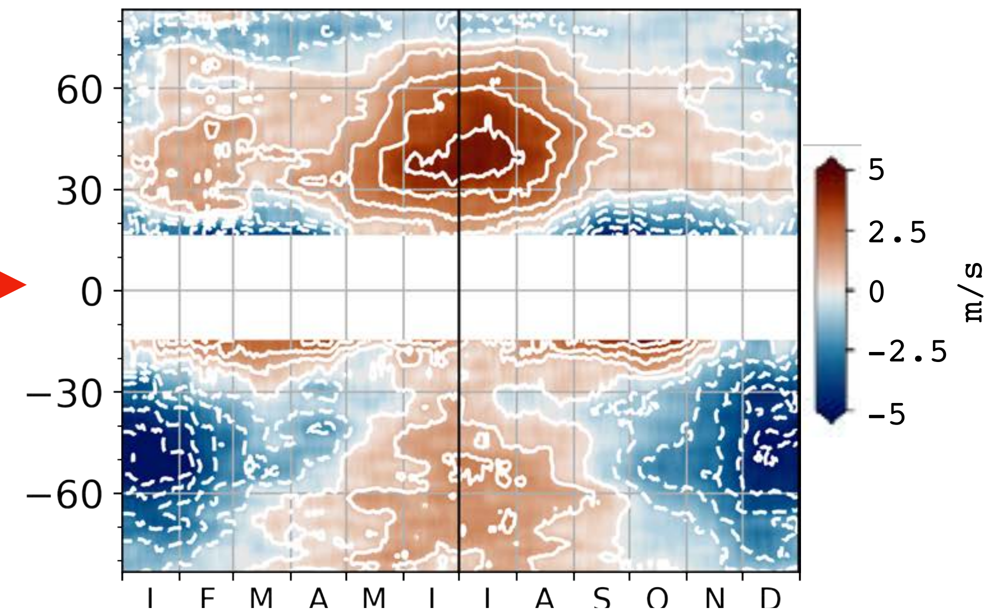
= resolved wave forcing + parameterized GW forcing

Lower-thermospheric circulation is driven by resolved wave forcing

V*, model direct output, ~115km



V* estimation, resolved waves

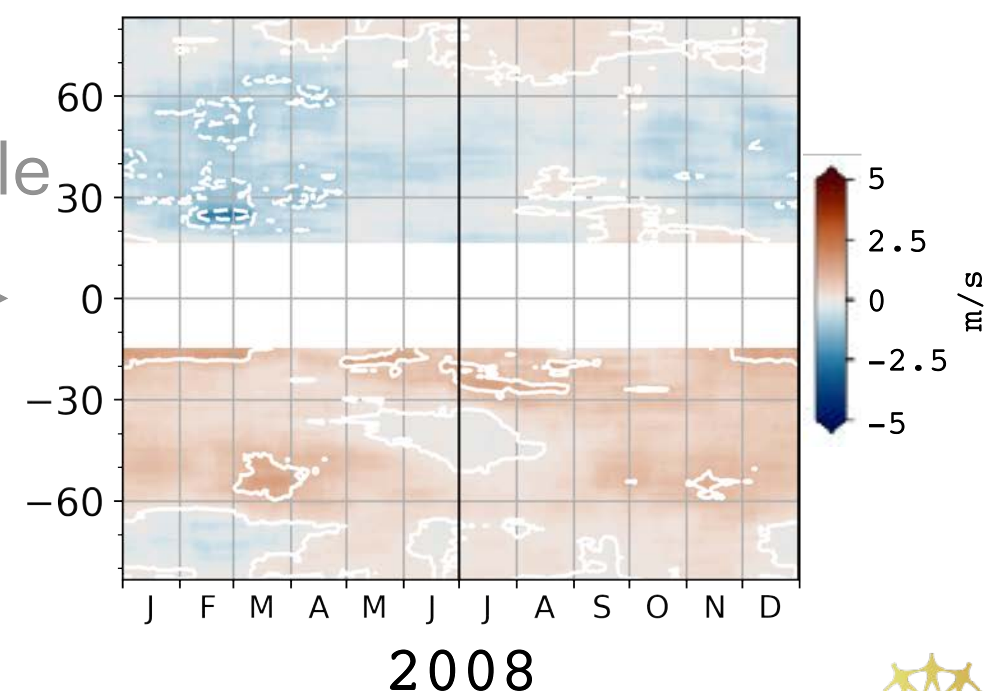


dominant

negligible

$$\bar{v}^* = \frac{\boxed{\frac{1}{\rho_0 a \cos\phi}\nabla\cdot\mathbf{F}} + \boxed{\mathbf{GWF}}}{\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(\bar{u}\cos\phi) - f}$$

V* estimation, parameterized GW



Key takeaway

<u>What drives the lower-thermospheric circulation?</u>

- Lower-thermospheric circulation is mainly driven by the resolved wave forcing, including tides and IGWs.

Our Scientific Journey Over the Past 5 Years

<u>Discovery</u>

Can we observe the lower-thermospheric circulation?

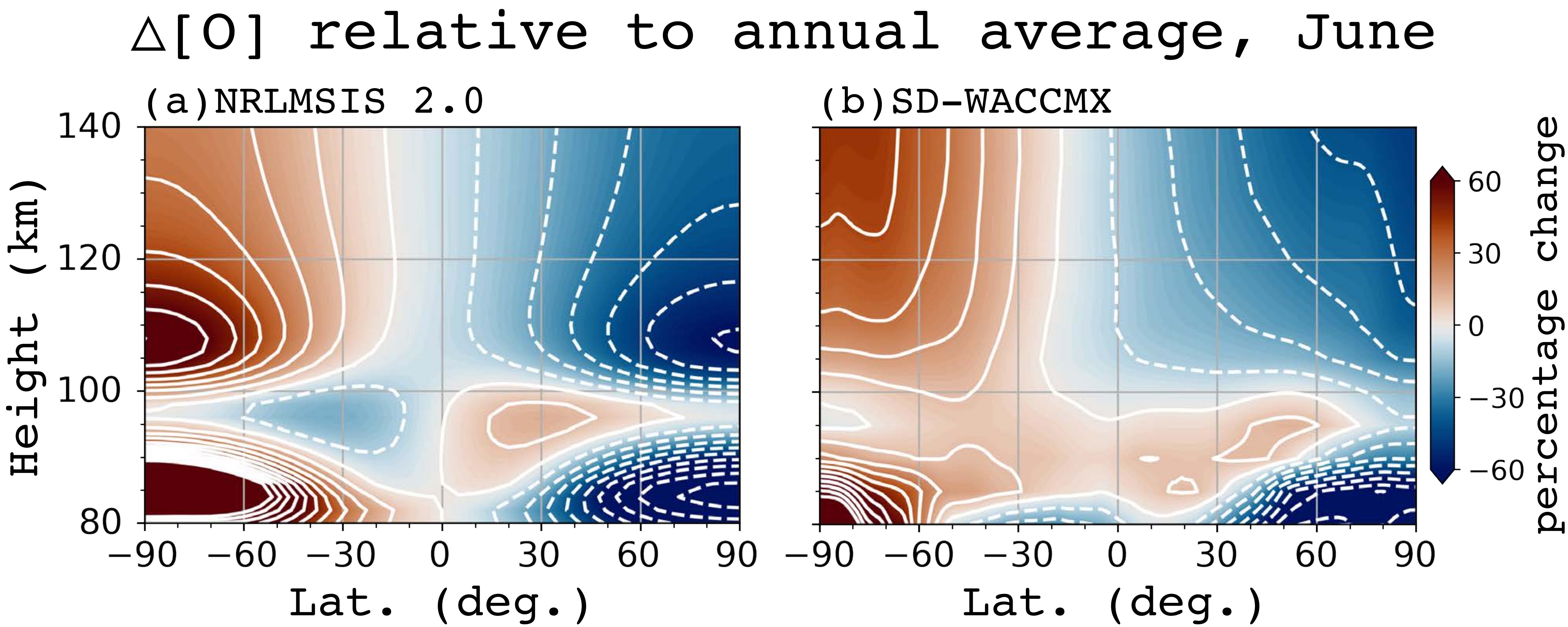
<u>Mechanism</u>

What drives the lower-thermospheric circulation?

<u>**Impacts**</u>

Why does it matter for the whole thermosphere?

MSIS shows a [O] phase reversal on seasonal time scale, which qualitatively agrees with SD-WACCMX simulation



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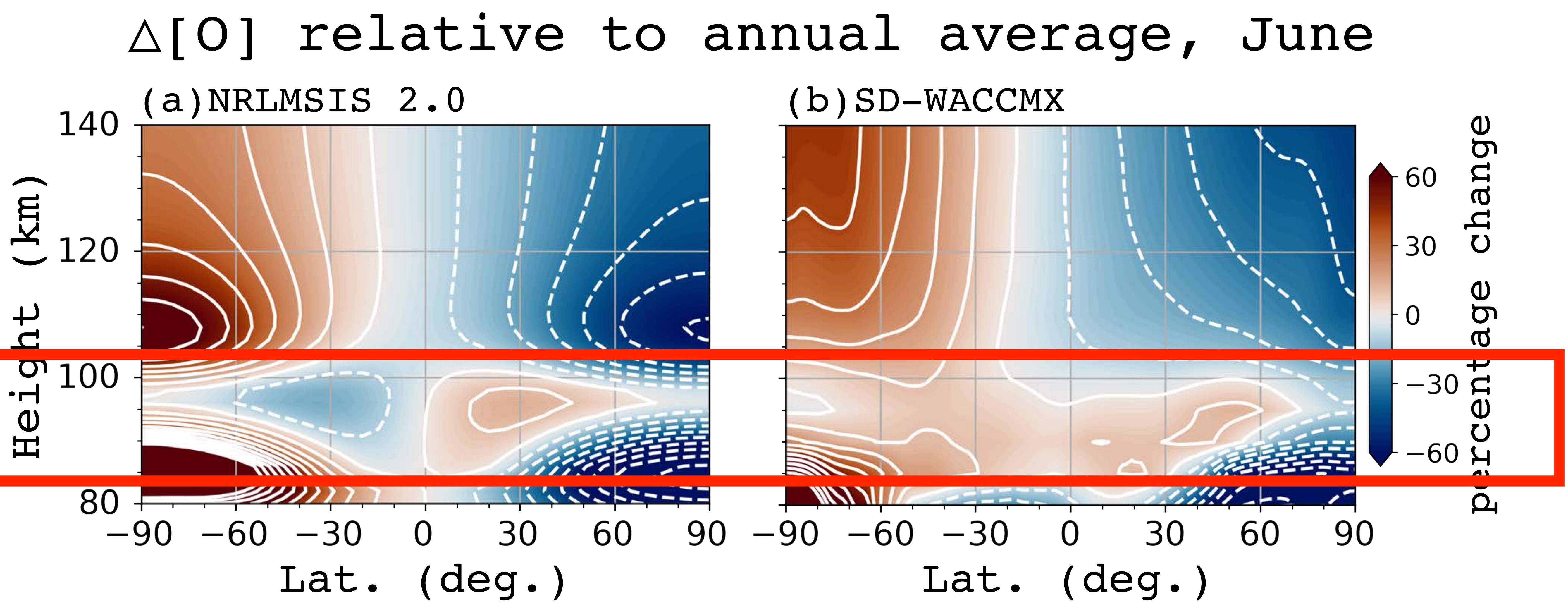
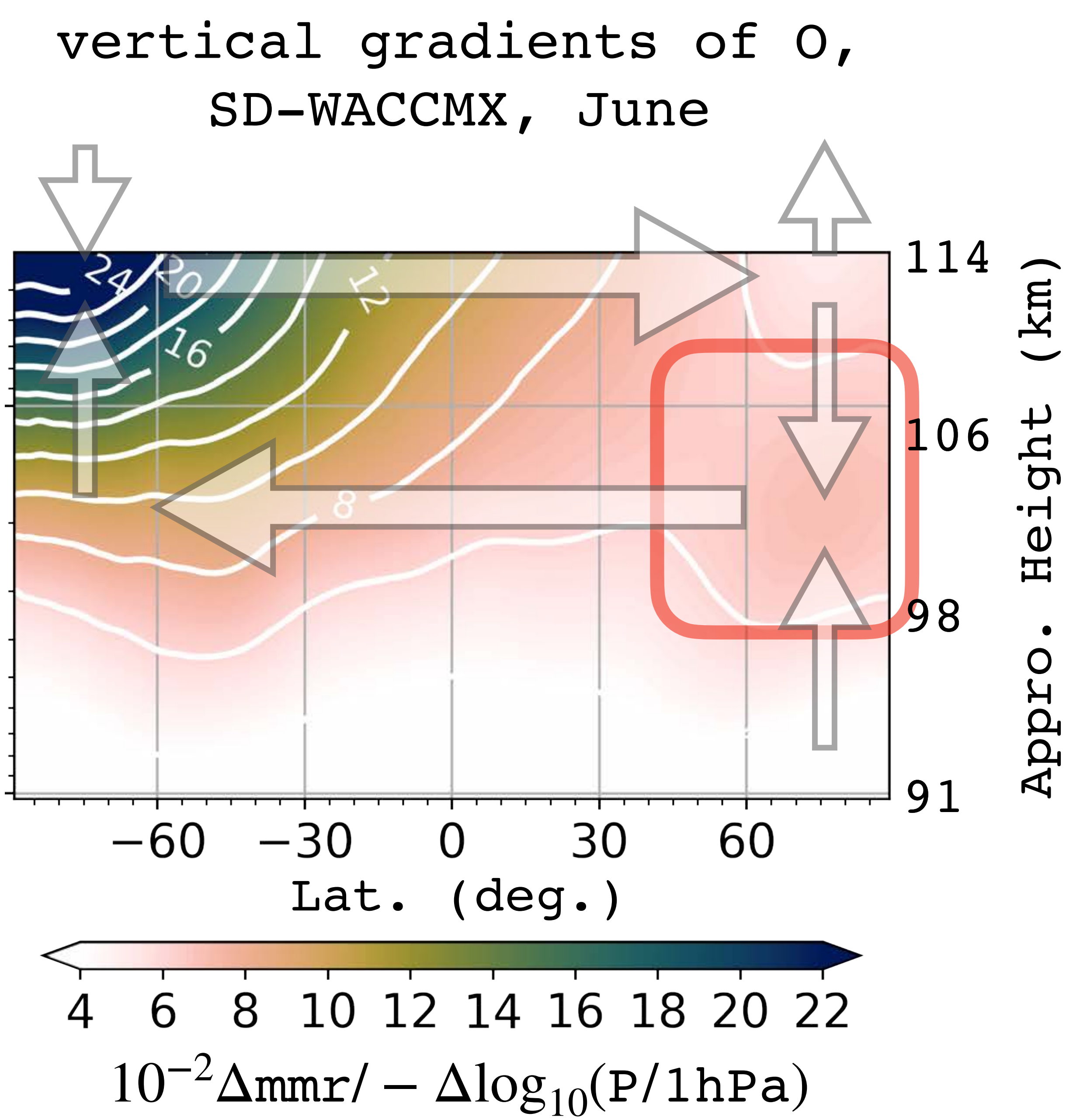
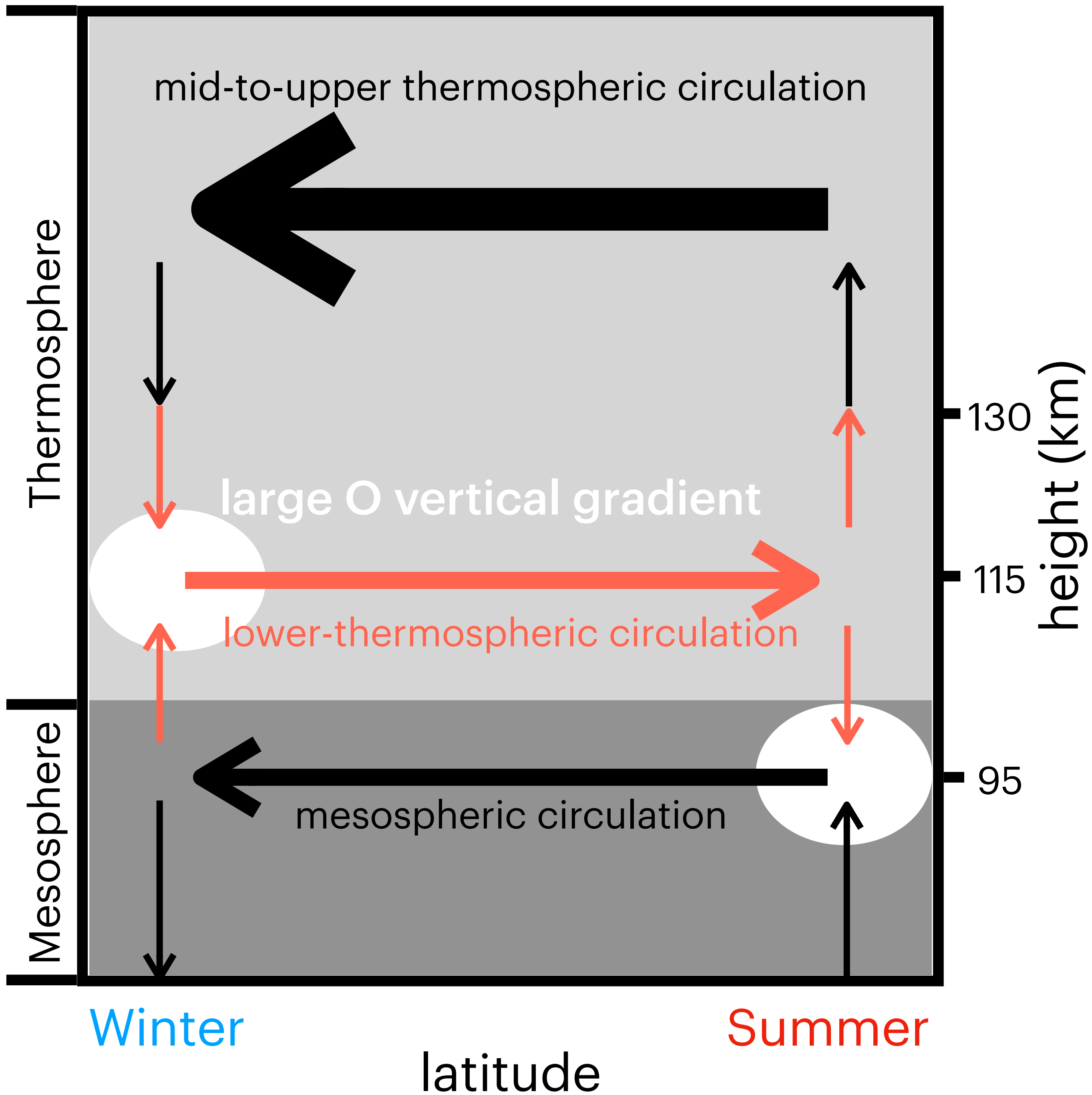


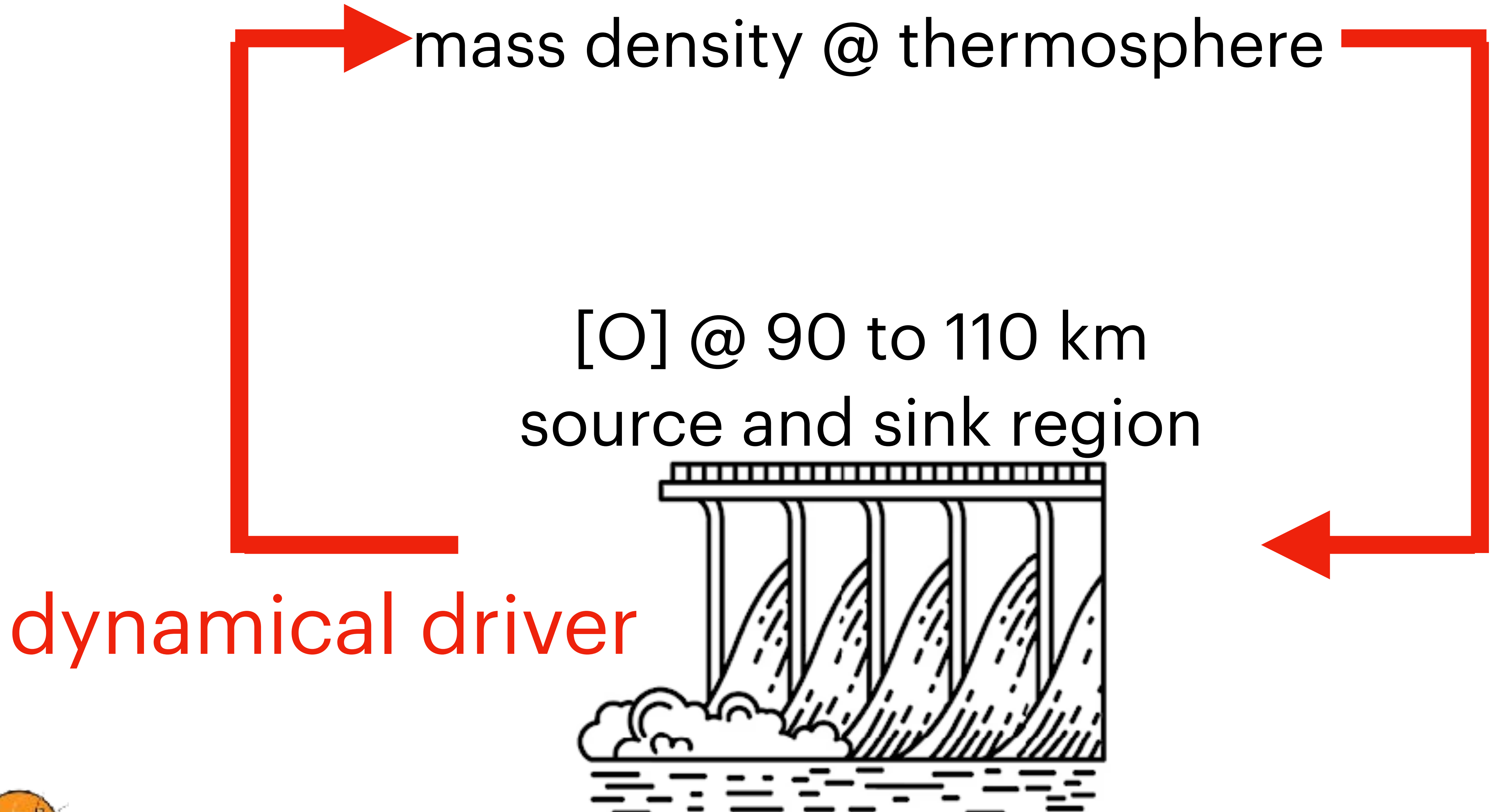
The seasonal phase reversal of O is linked to the lower-thermospheric circulation





[O] in the lower thermosphere acts as a reservoir for neutral density in upper atmosphere

Define the absolute value of mass density (precondition)



Traditional turbopause paradigm

The turbopause marks the altitude where molecular diffusion becomes dominant

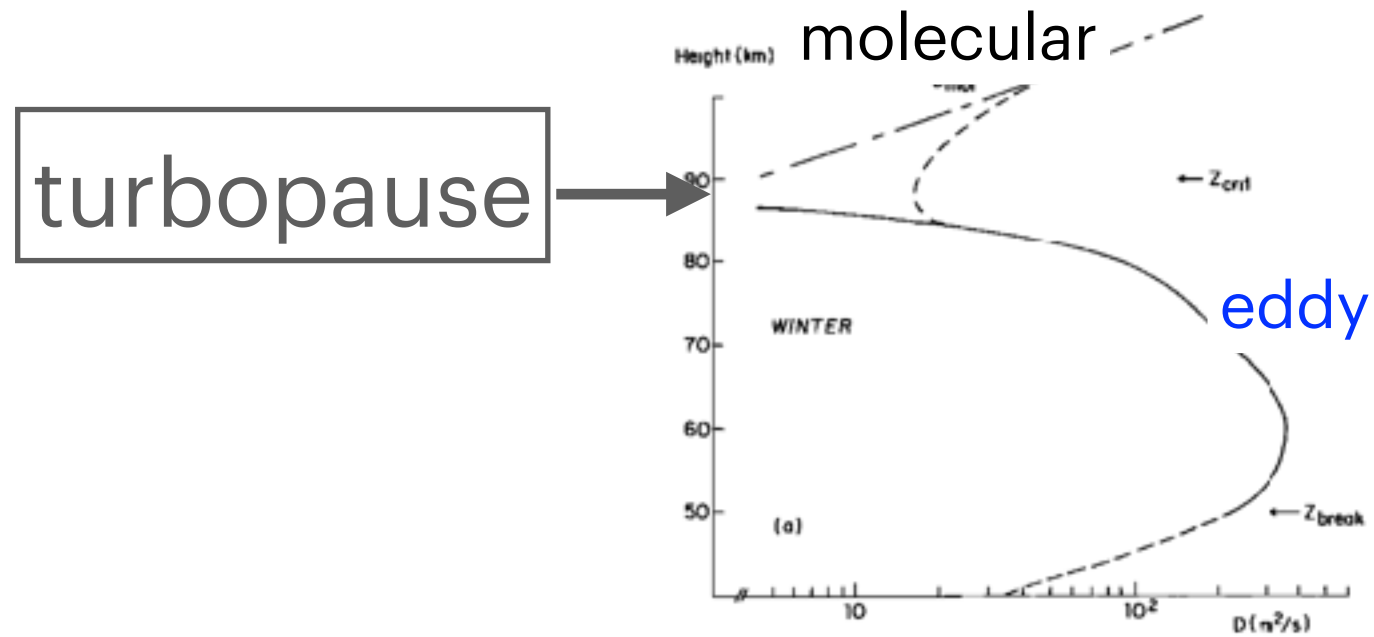
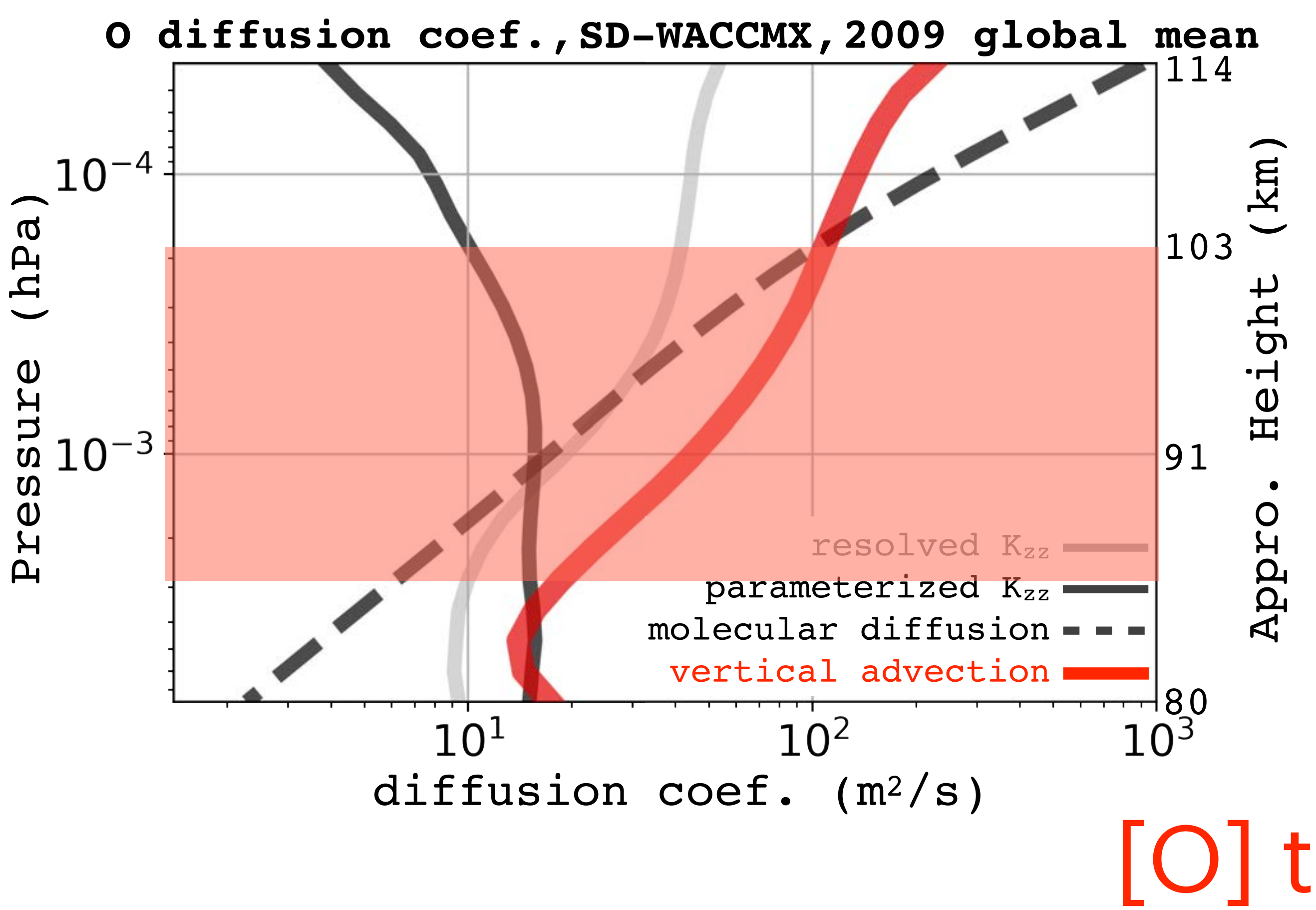


Fig. 5a

Fig. 5. Solid line shows predicted eddy diffusion coefficient based on breaking gravity waves. Simple dashed lines show schematic extrapolations as discussed in the text. The line consisting of alternating short and long dashes shows the molecular diffusion coefficient. (*a*) results for winter; (*b*) results for summer.

(Lindzen, 1981)

Vertical advection can dominate over eddy diffusion, defining the altitude range of the turbopause layer.



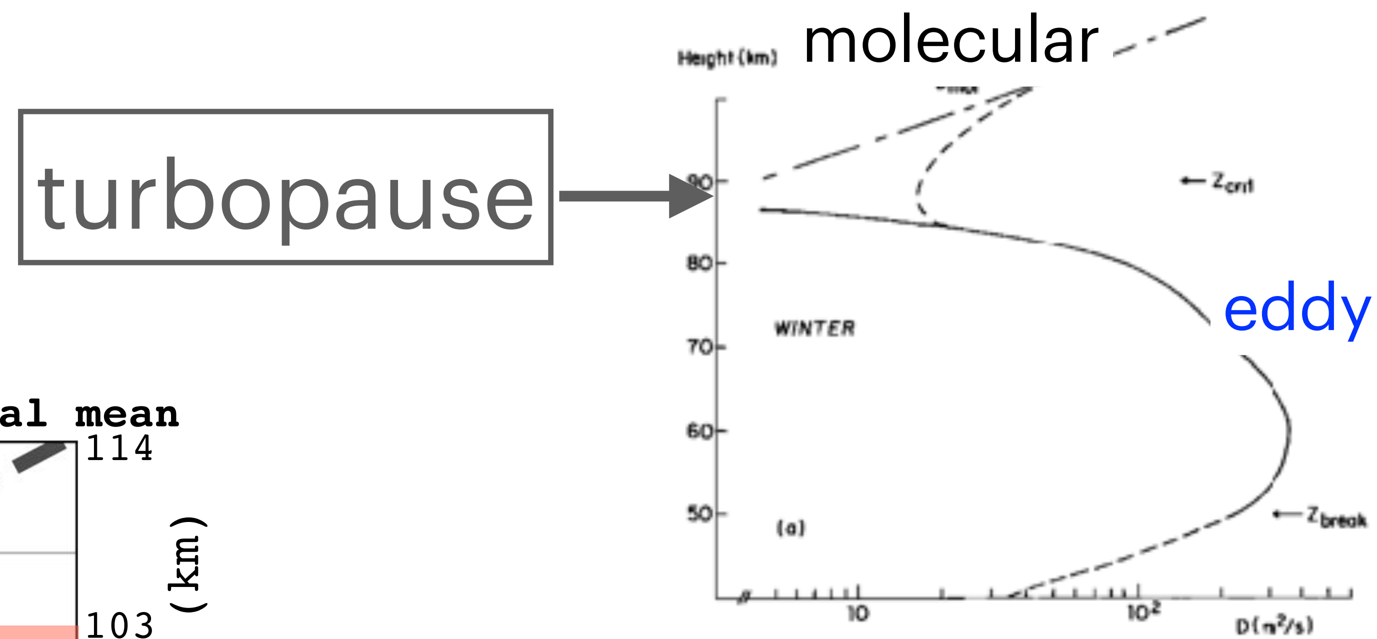


Fig. 5. Solid line shows predicted eddy diffusion coefficient based on breaking gravity waves. Simple dashed lines show schematic extrapolations as discussed in the text. The line consisting of alternating short and long dashes shows the molecular diffusion coefficient. (*a*) results for winter; (*b*) results for summer.

(Lindzen, 1981)

Key takeaways

<u>Why does it matter for the whole thermosphere?</u>

- Vertical advection associated with the circulation can efficiently transport O between its source and sink region within the vertical column in the lower thermosphere.
- Vertical advection appears to play a dominant role in seasonal [O] variability.
- The turbopause is likely a “turbolayer”: a broad transition region where molecular diffusion overtakes eddy diffusion and vertical advection.

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TIDI reveals a robust lower-thermospheric circulation,
and SD-WACCMX reproduces the observed circulation pattern.

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Mechanism

Lower thermospheric circulation is driven by
model-resolved waves (tides + gravity waves).

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Impacts

Vertical advection can efficiently transport O between its source and sink region within the vertical column in the lower thermosphere.

Recent advances in the topics

JGR Atmospheres

RESEARCH ARTICLE
10.1029/2025JD044600

Contribution of Gravity Waves to the Lower Thermospheric Winter-To-Summer Meridional Circulation in High-Resolution WACCM-X

D. Koshin[1,2], N. M. Pedatella[2], A. K. Smith[3], and H.-L. Liu[2]

Key Points:

- The global distribution of the small-scale wave forcing in the middle at-

Geophysical Research Letters

RESEARCH LETTER
10.1029/2024GL113414

Modulation of Thermospheric Circulation by Lower-Thermospheric Winter-to-Summer Circulation: The Atmosphere Gear Effect

Jack C. Wang[1,2], Jia Yue[1,2], Wenbin Wang[3], and Liying Qian[3]

Key Points:

- The lower-thermospheric circulation enhances the circulation in the summer thermosphere and strengthens upwell-

Related and Complementary Studies

JGR Space Physics

RESEARCH ARTICLE

10.1029/2018JA026424

Special Section:
Equatorial Aeronomy: New Results From the 15th Interna-

Interhemispheric Meridional Circulation During Sudden Stratospheric Warming

Fazlul I. Laskar[1,2], John P. McCormack[3], Jorge L. Chau[1], Duggirala Pallamraju[4], Peter Hoffmann[1], and Ravindra P. Singh[4]

Geophysical Research Letters

RESEARCH LETTER

10.1029/2019GL086313

Key Points:
- A global O/N_2 column density depletion is observed by GOLD

Thermospheric Composition O/N_2 Response to an Altered Meridional Mean Circulation During Sudden Stratospheric Warmings Observed by GOLD

J. Oberheide[1], N. M. Pedatella[2], Q. Gan[3], K. Kumari[1], A. G. Burns[2], and R. W. Eastes[3]

JGR Atmospheres

RESEARCH ARTICLE

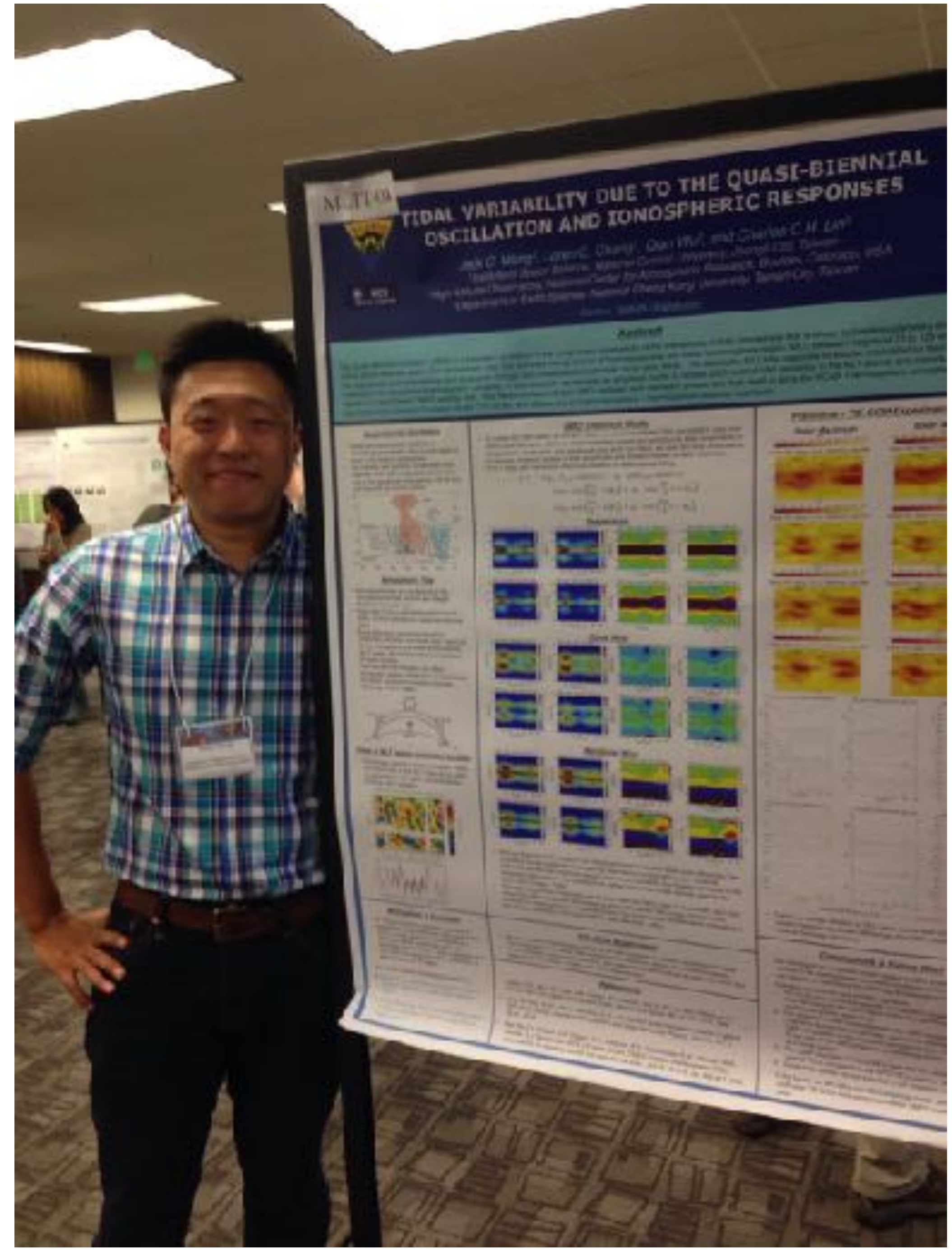
10.1029/2022JD037050

Key Points:
- The lower thermospheric mean meridional circulation (MMC)

Abrupt Change in the Lower Thermospheric Mean Meridional Circulation During Sudden Stratospheric Warmings and Its Impact on Trace Species

Yvan J. Orsolini[1,2], Jiarong Zhang[3], and Varavut Limpasuvan[3]

- 2014 CEDAR workshop @ Seattle
- My first CEDAR workshop.
- My first visit to the US…



Thank you, CEDAR, for opening the door to my career,
to the NSF for the support along the way,
and to my advisors, Loren Chang, Scott Palo, Jia Yue,
whose mentorship has shaped my path from the beginning.

References

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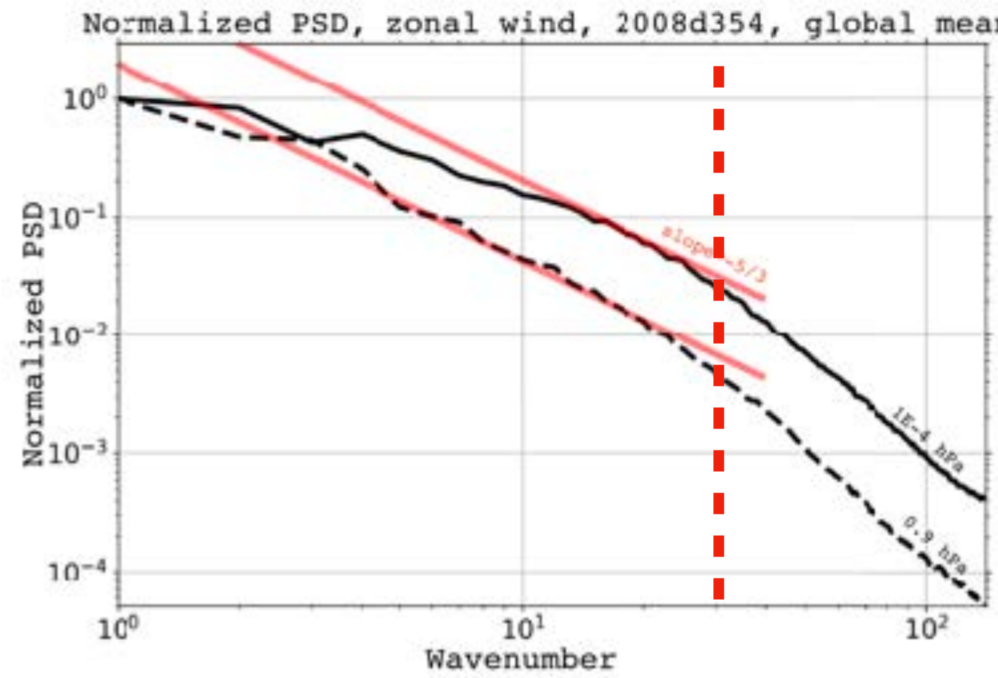
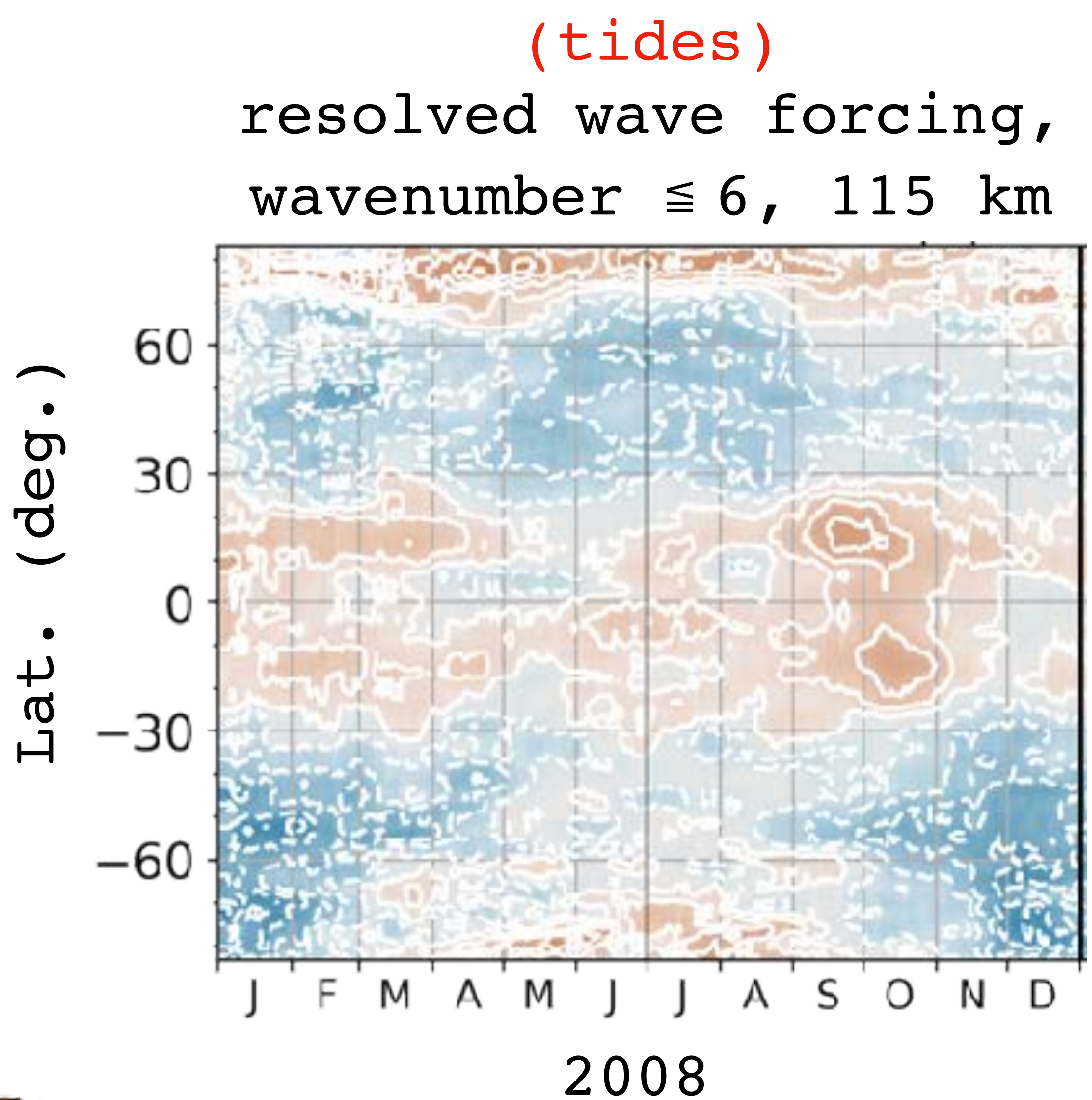
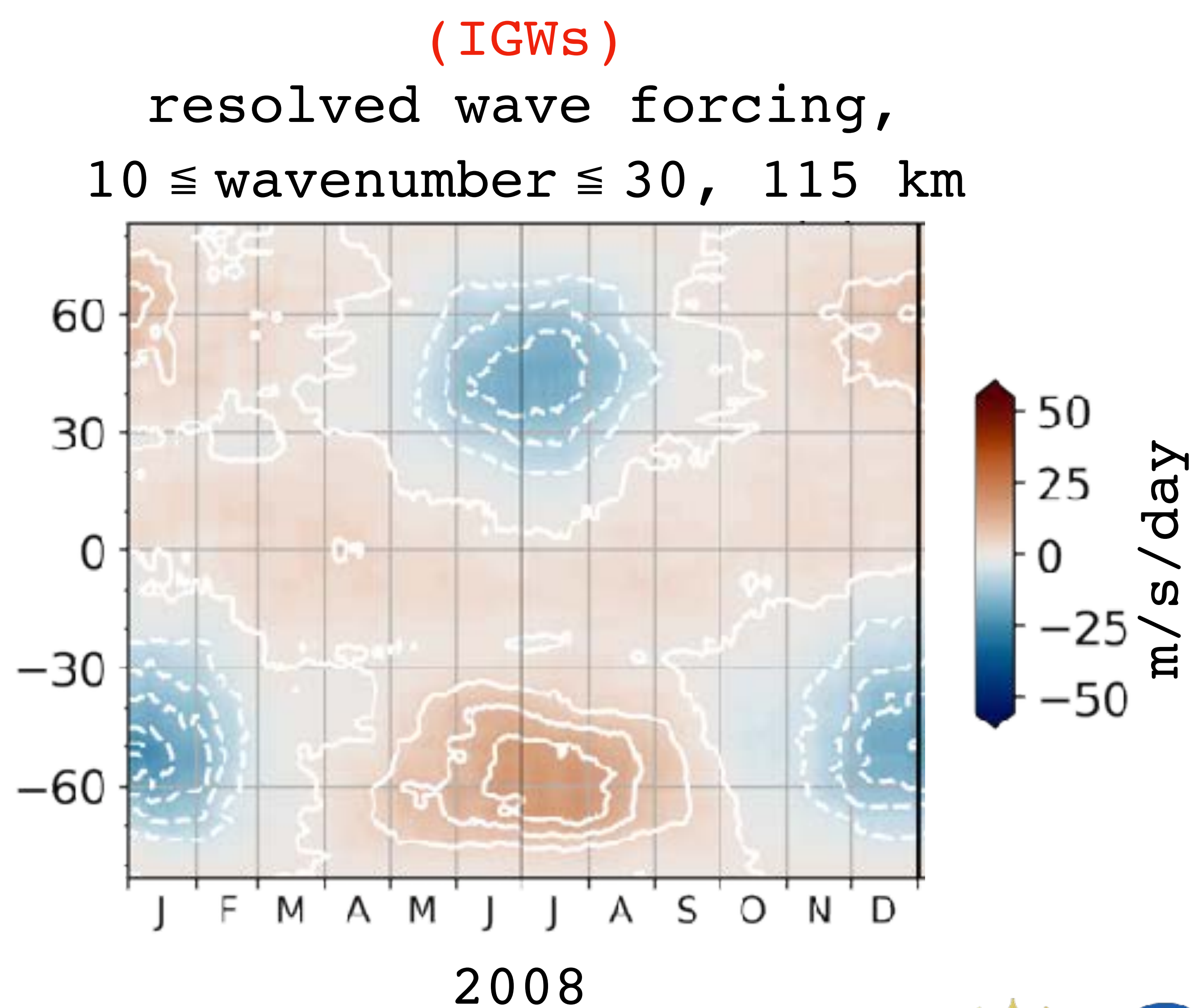
- Lindzen, R. S. (1981). Turbulence and stress owing to gravity wave and tidal breakdown. Journal of Geophysical Research: Oceans, 86(C10), 9707-9714.

Backup

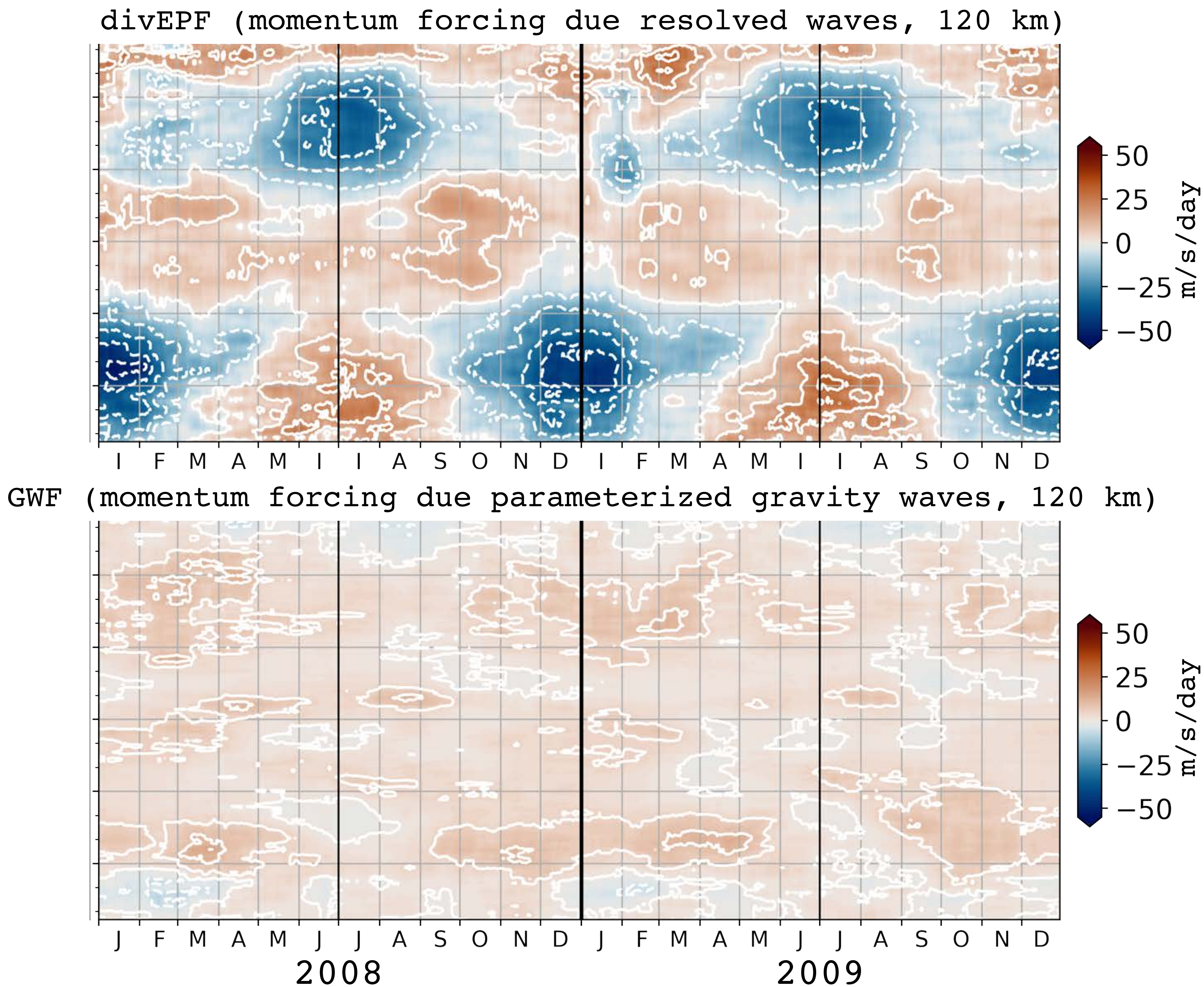
Lower-thermospheric circulation is driven by tides and resolved inertia gravity waves

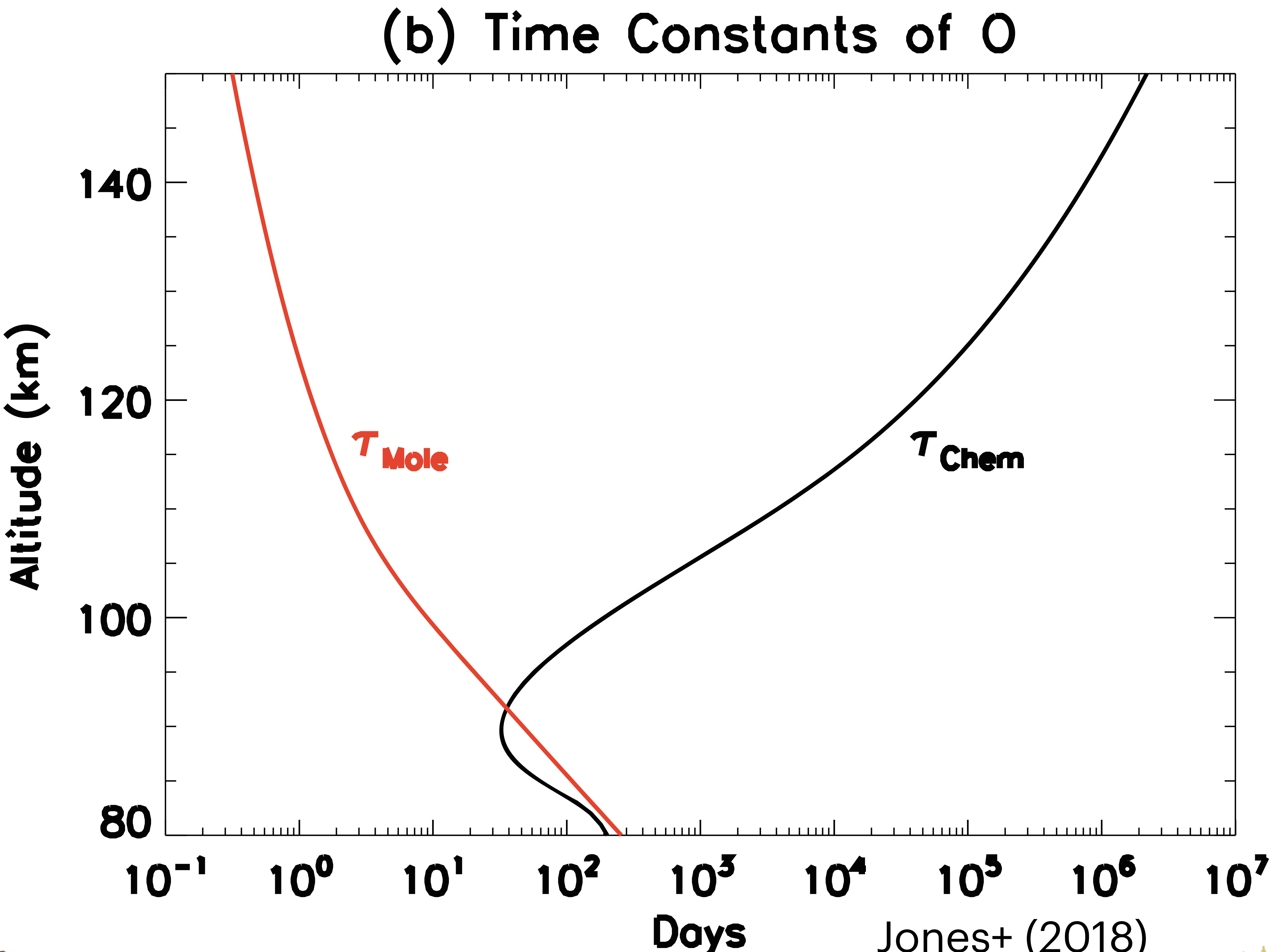






Divergence of momentum flux (model resolved wave forcing) exhibits semi-annual variation



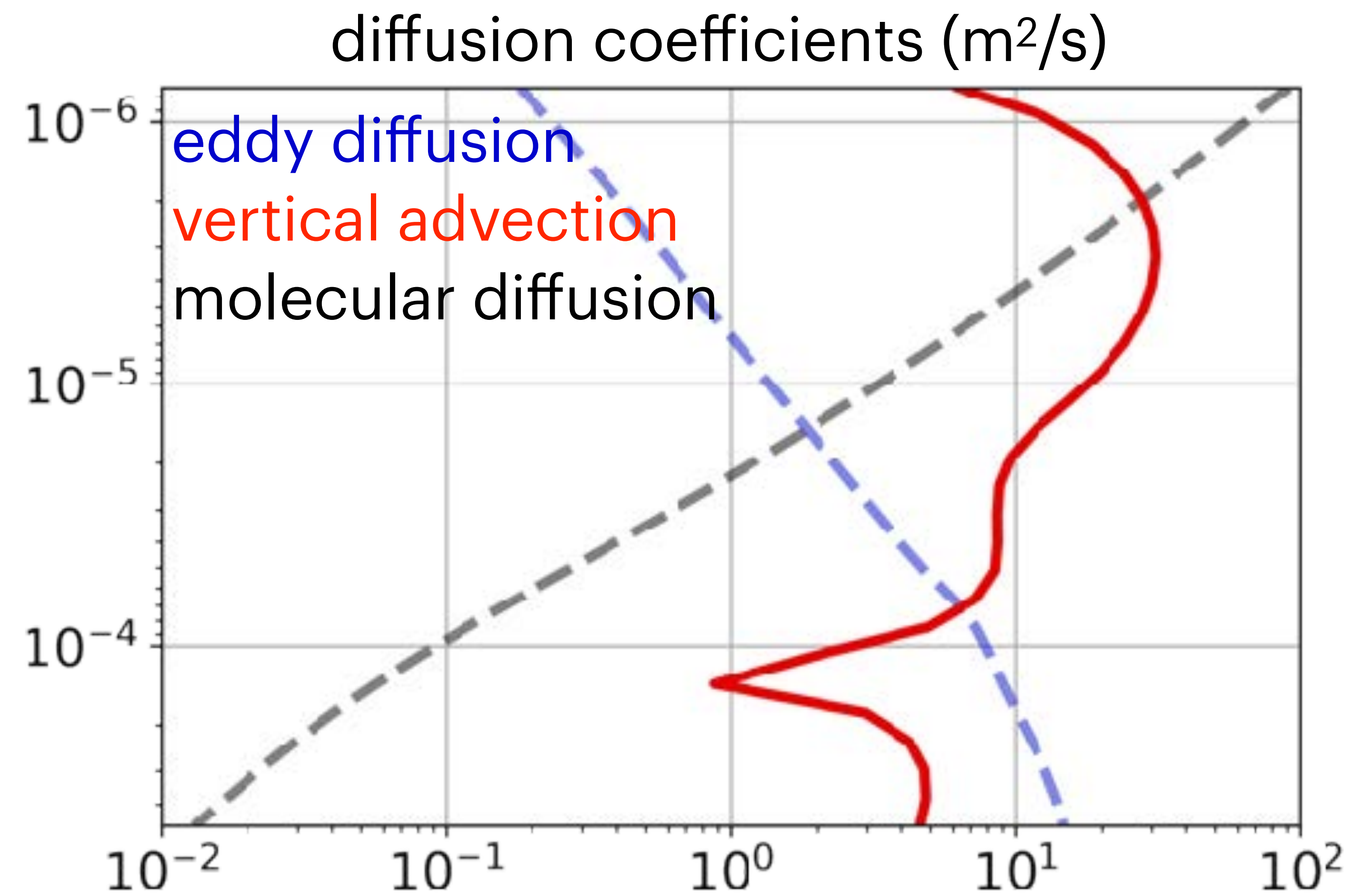

(b) Time Constants of O
Altitude (km)
140
120
100
80
τ_{Mole}
τ_{Chem}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Days

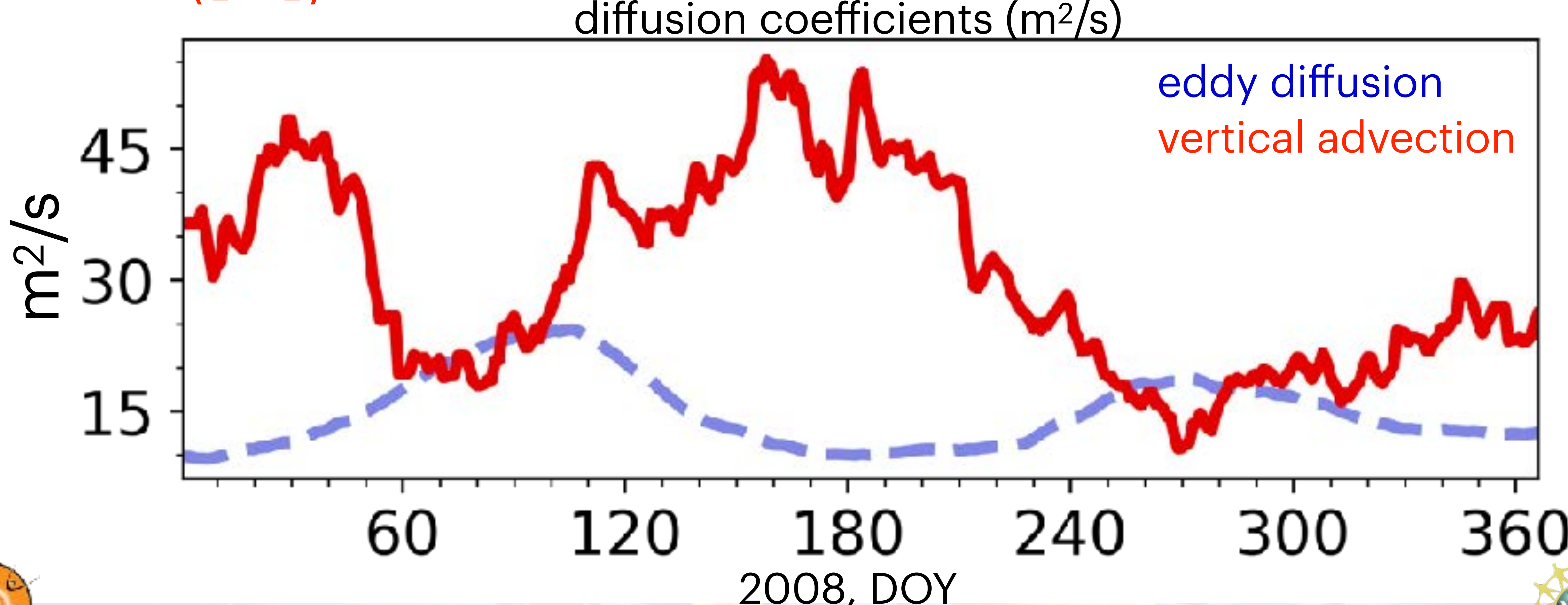
Jones+ (2018)

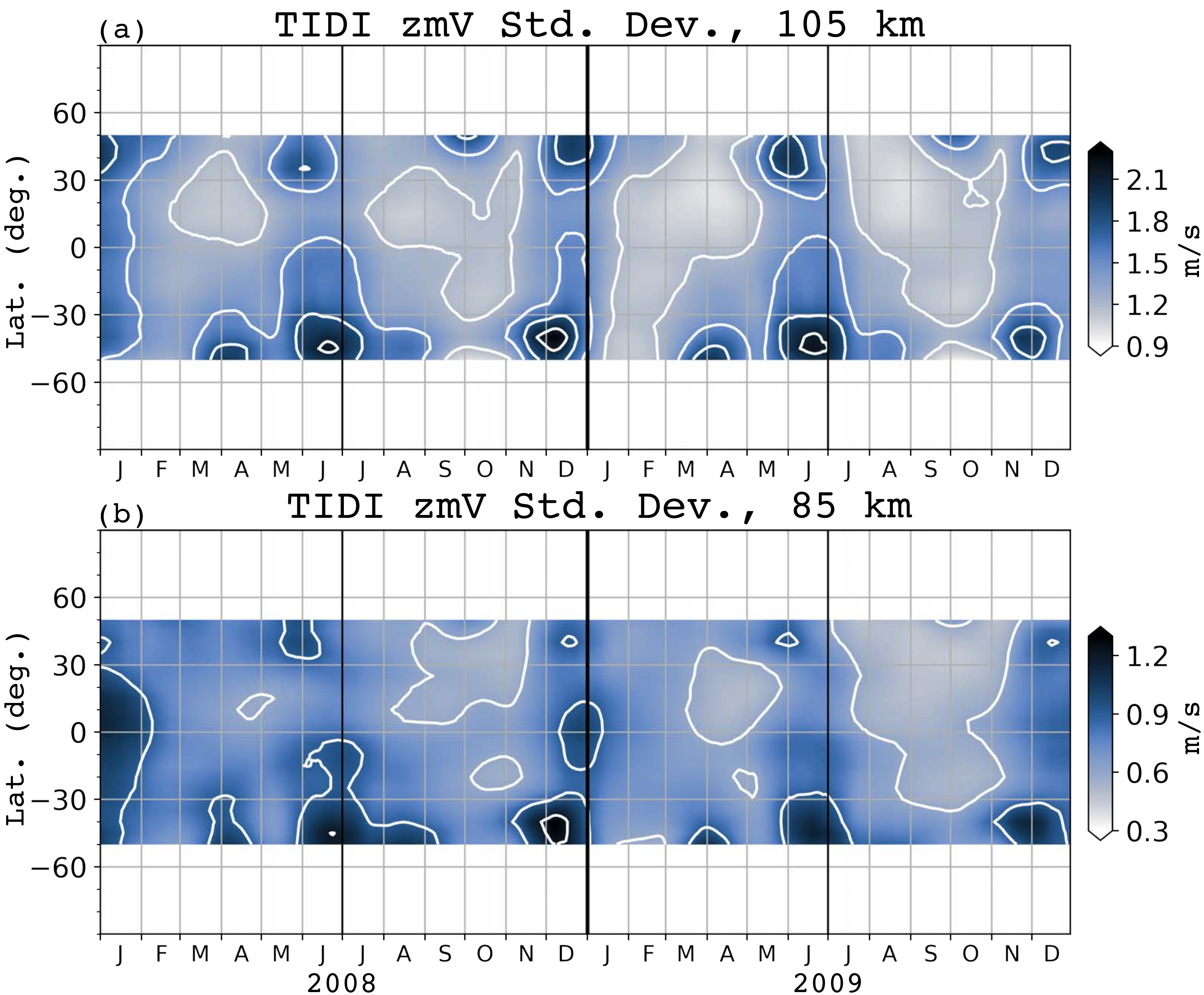
Vertical advection is more effective in transporting O from its source to sink than Kzz(small-scale turbulence)

effective vertical advection coef.

$$\frac{\left|\frac{\partial}{\partial z}\langle\overline{w}\overline{[O]}\rangle\right|}{\langle\overline{[O]}\rangle}\times \mathrm{H}^2$$



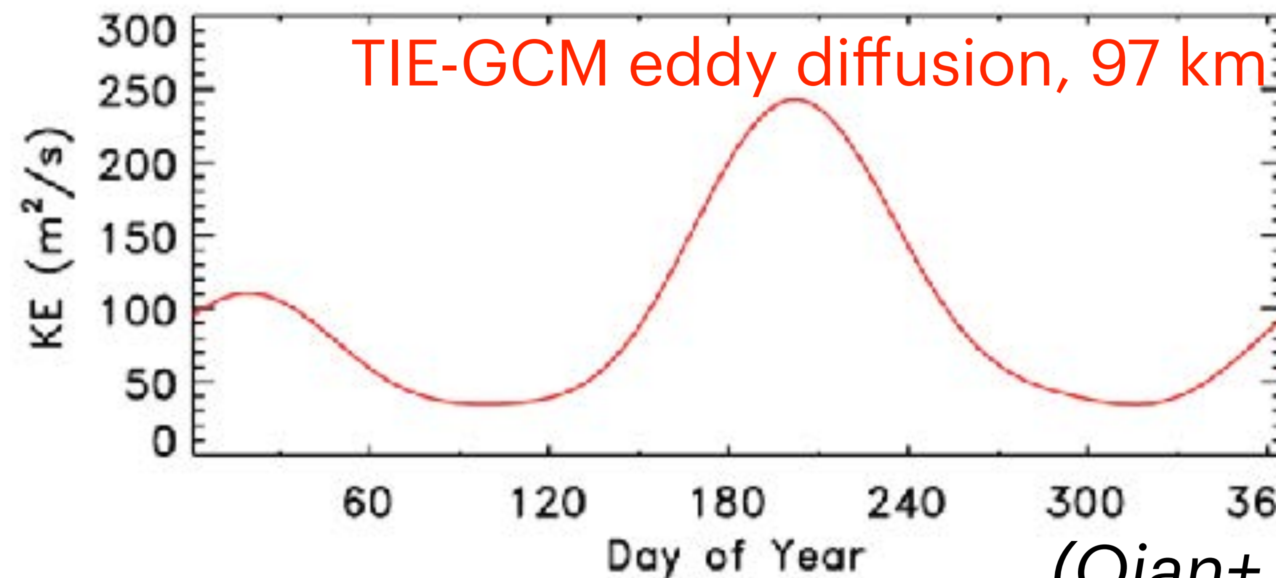



(a)
TIDI zmV Std. Dev., 105 km
Lat. (deg.)
60
30
0
−30
−60
J F M A M J J A S O N D J F M A M J J A S O N D
2.1
1.8
1.5
1.2
0.9
m/s
(b)
TIDI zmV Std. Dev., 85 km
Lat. (deg.)
60
30
0
−30
−60
J F M A M J J A S O N D J F M A M J J A S O N D
2008
2009
1.2
0.9
0.6
0.3
m/s

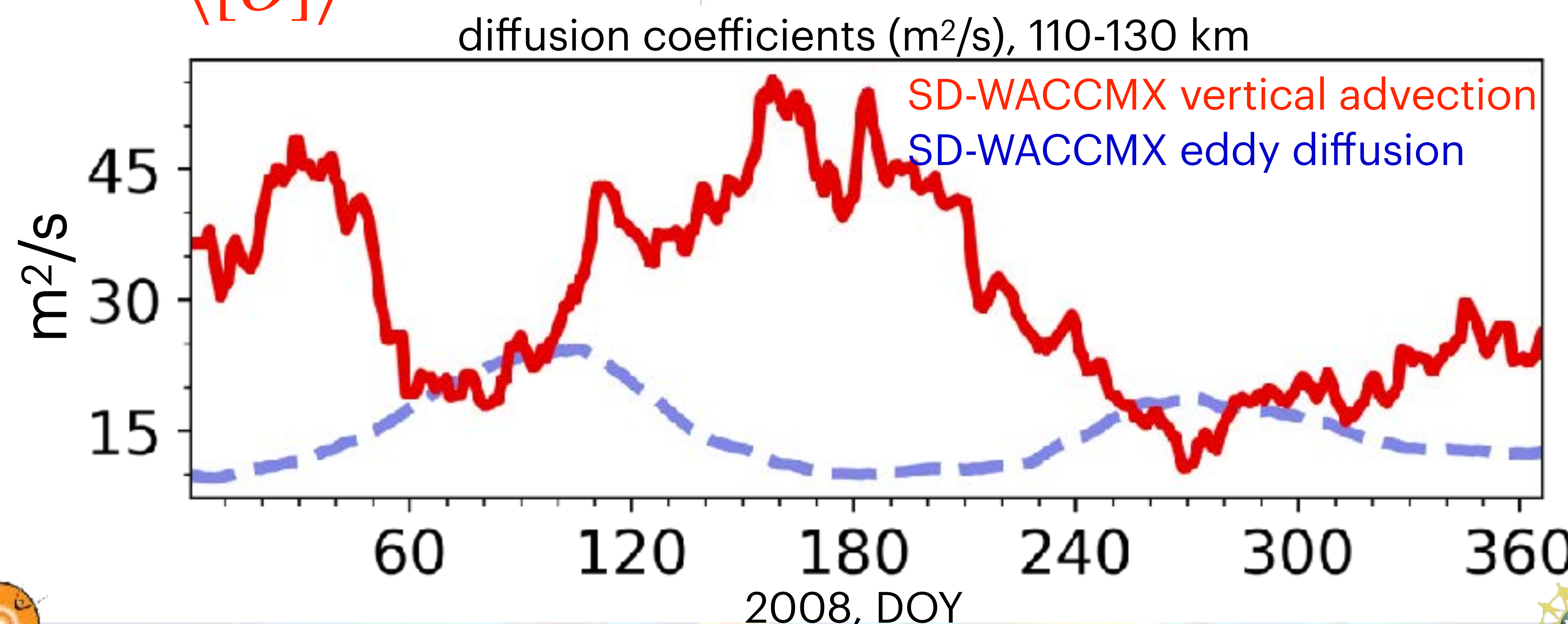
Vertical advection is effective in driving the intra-annual variation of O in the lower thermosphere

effective vertical advection coef.

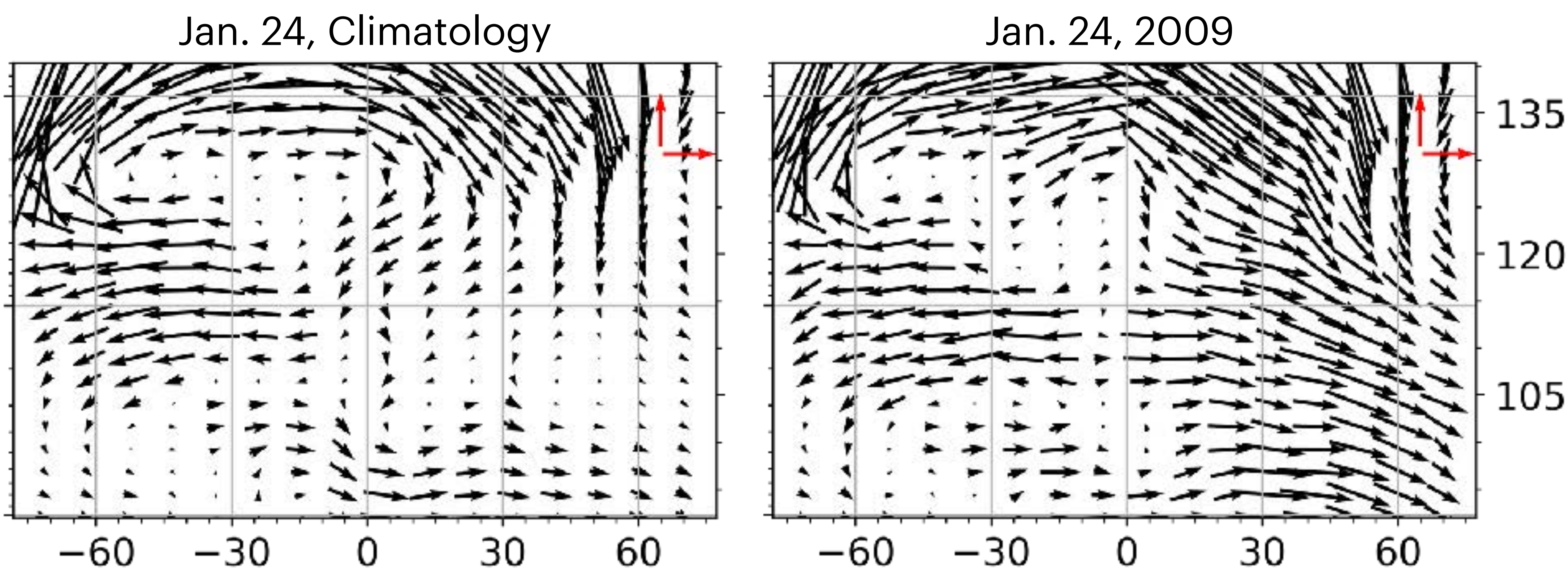
$$\frac{\left|\frac{\partial}{\partial z}\langle \overline{w}\,\overline{[O]}\rangle\right|}{\langle\overline{[O]}\rangle} \times \mathrm{H}^2$$



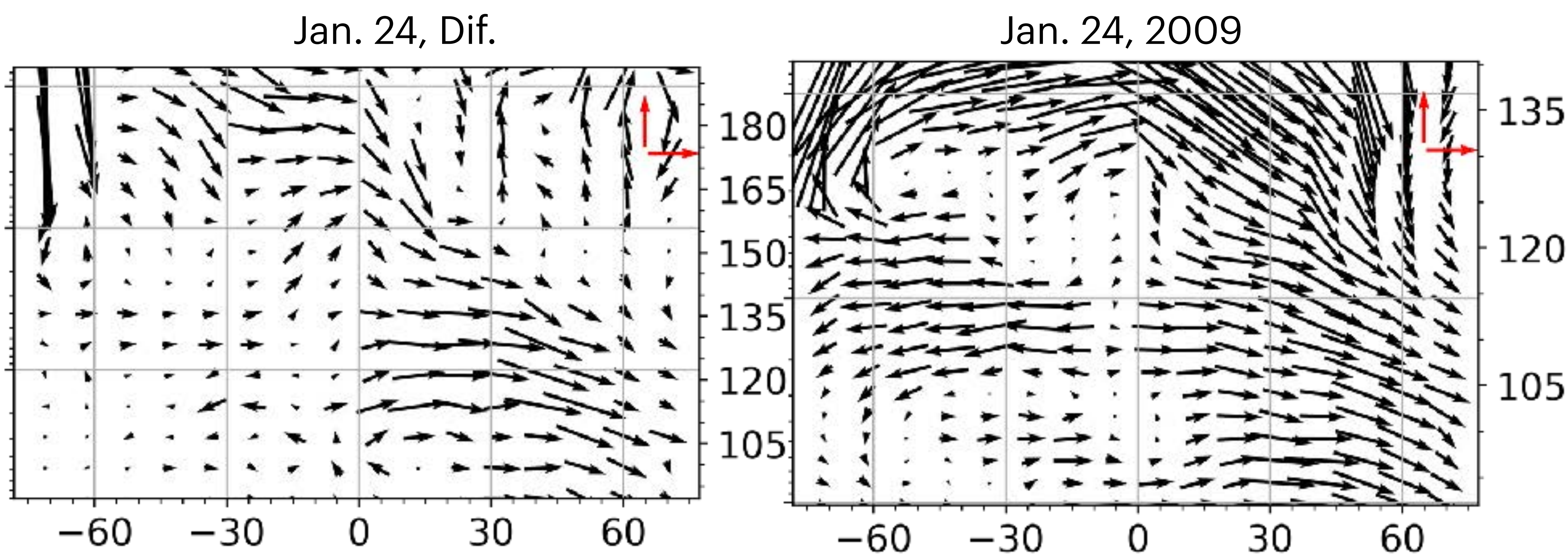
(Qian+, 2009)



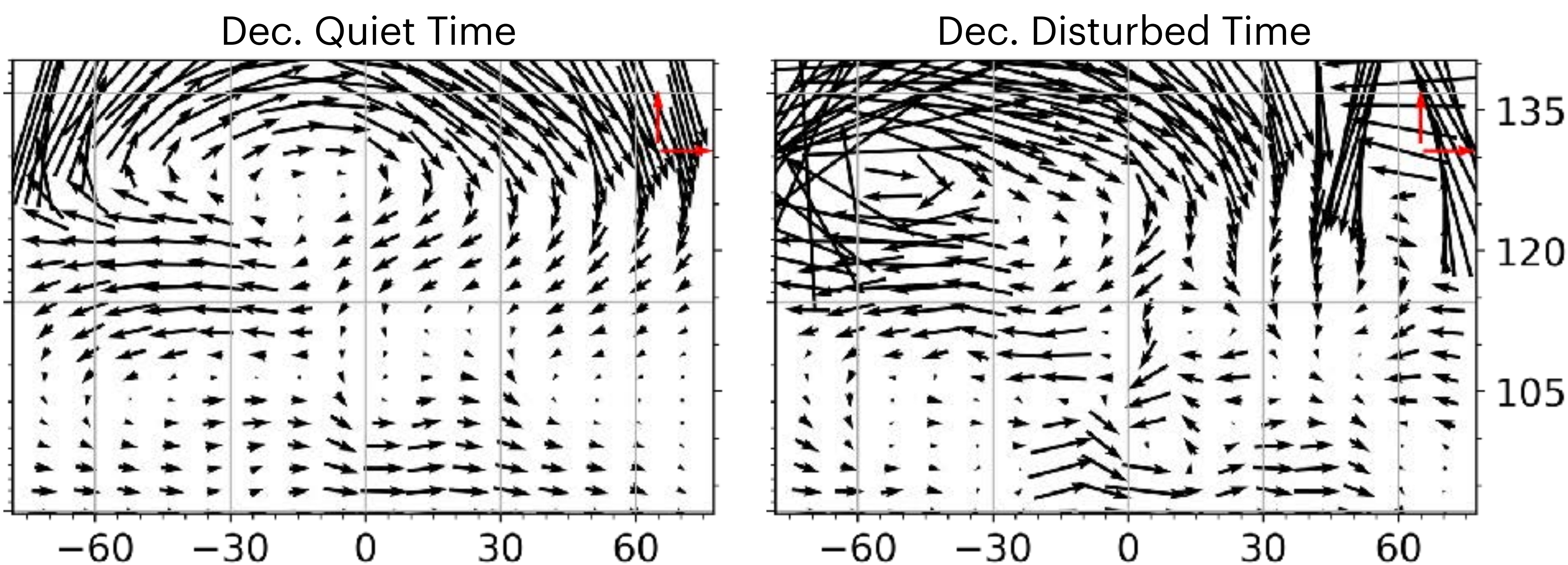
Lower thermospheric circulation during stratospheric sudden warming

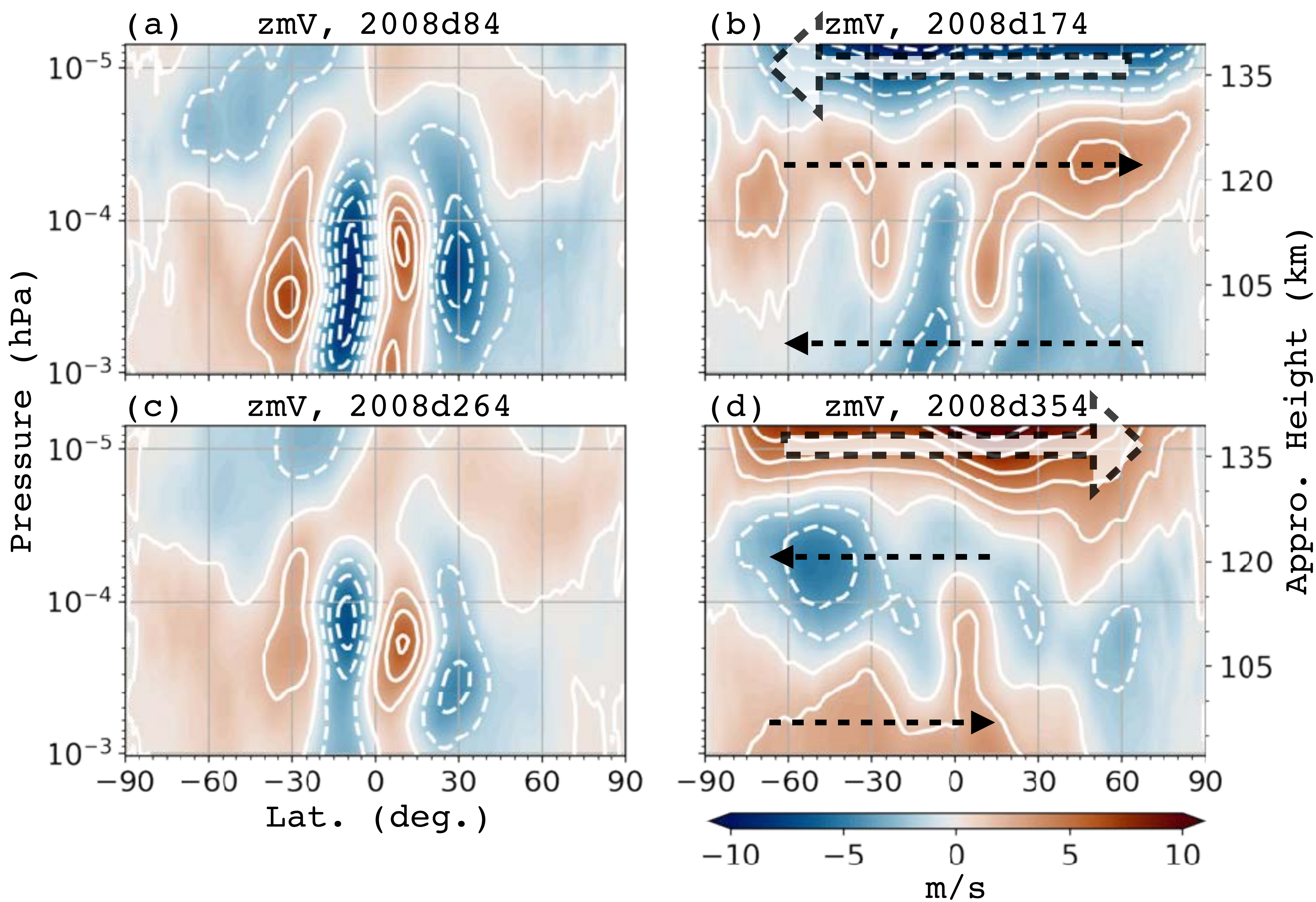


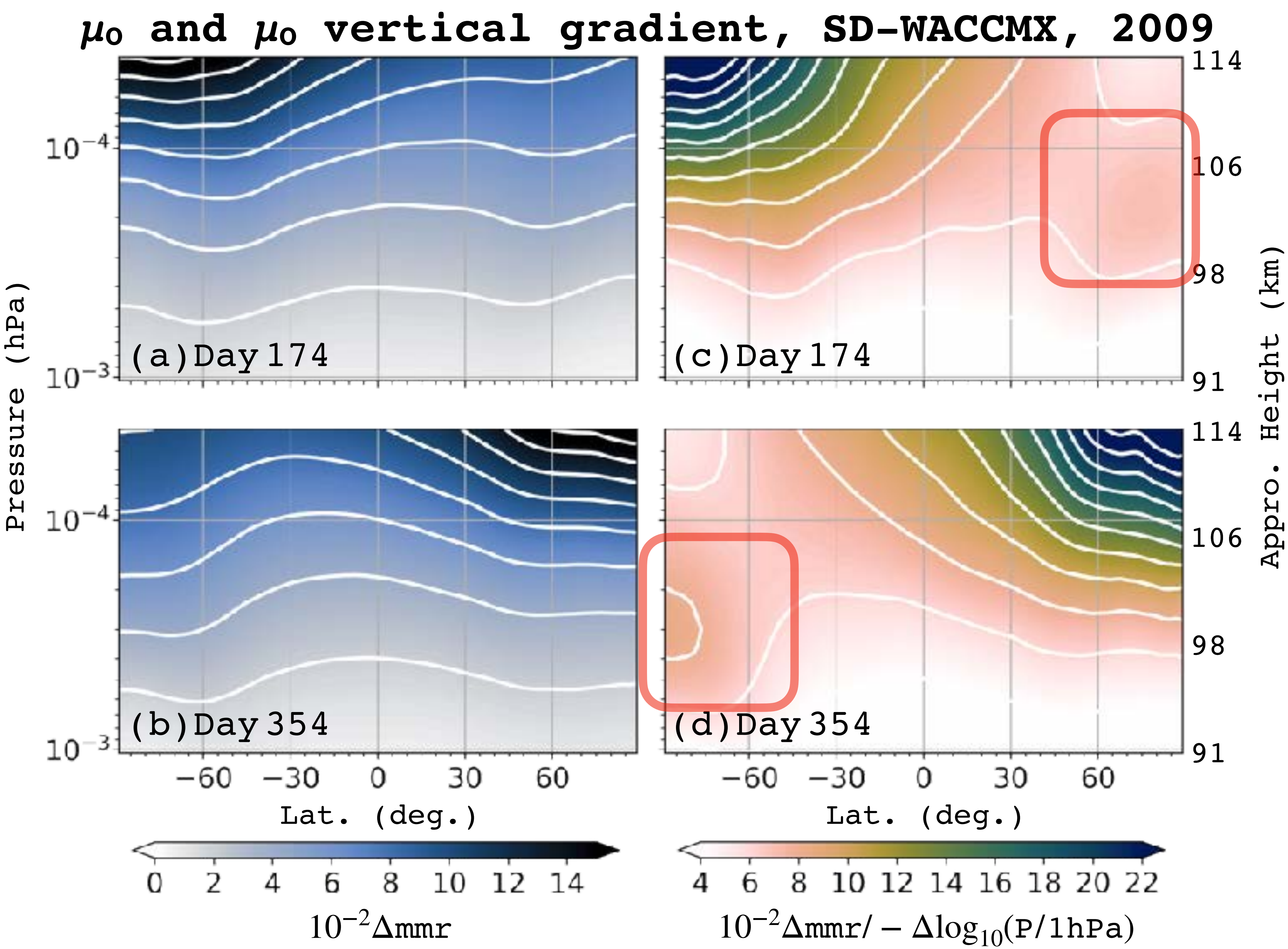
Lower thermospheric circulation during stratospheric sudden warming



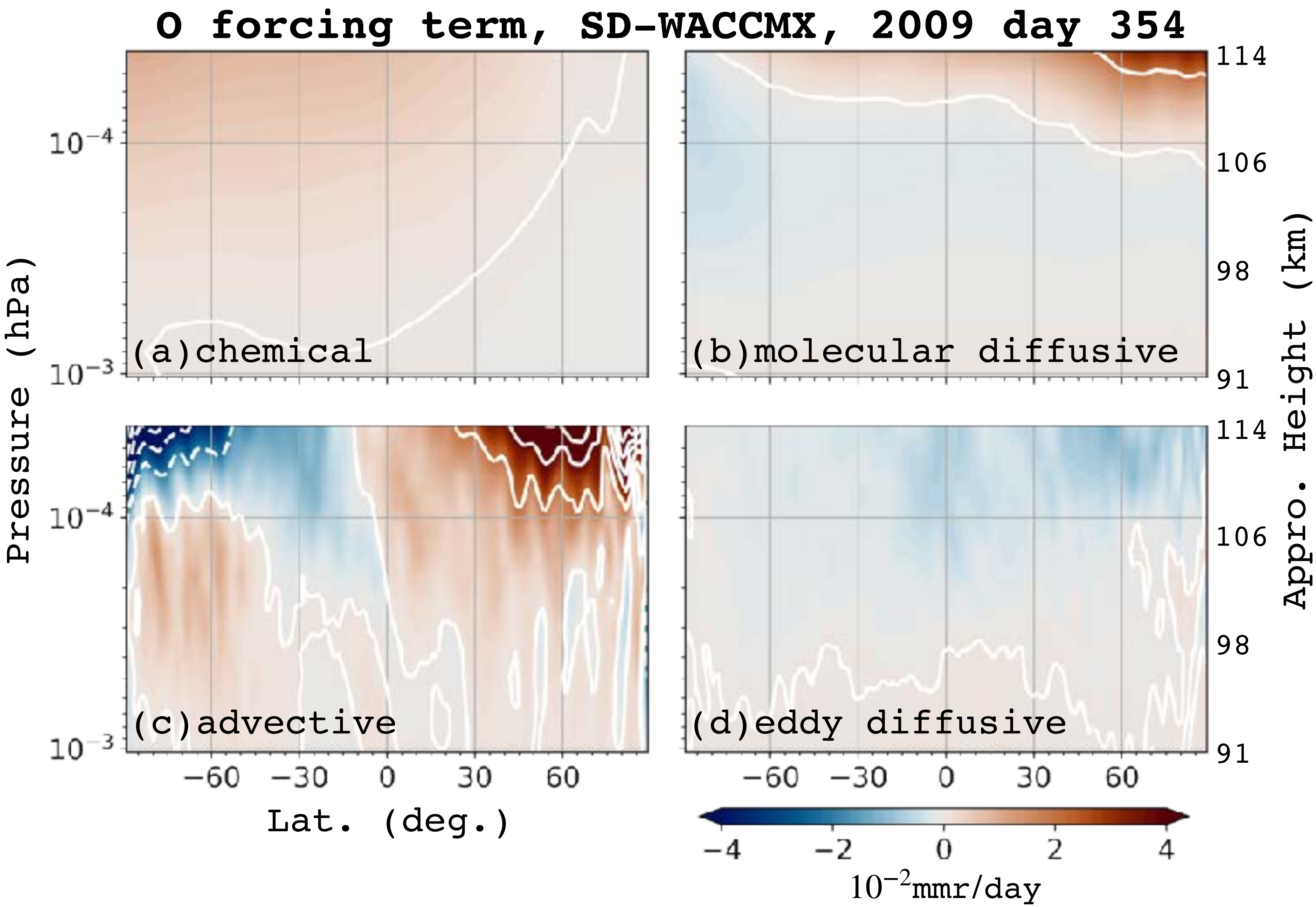
Lower thermospheric circulation during geomagnetically disturbed time



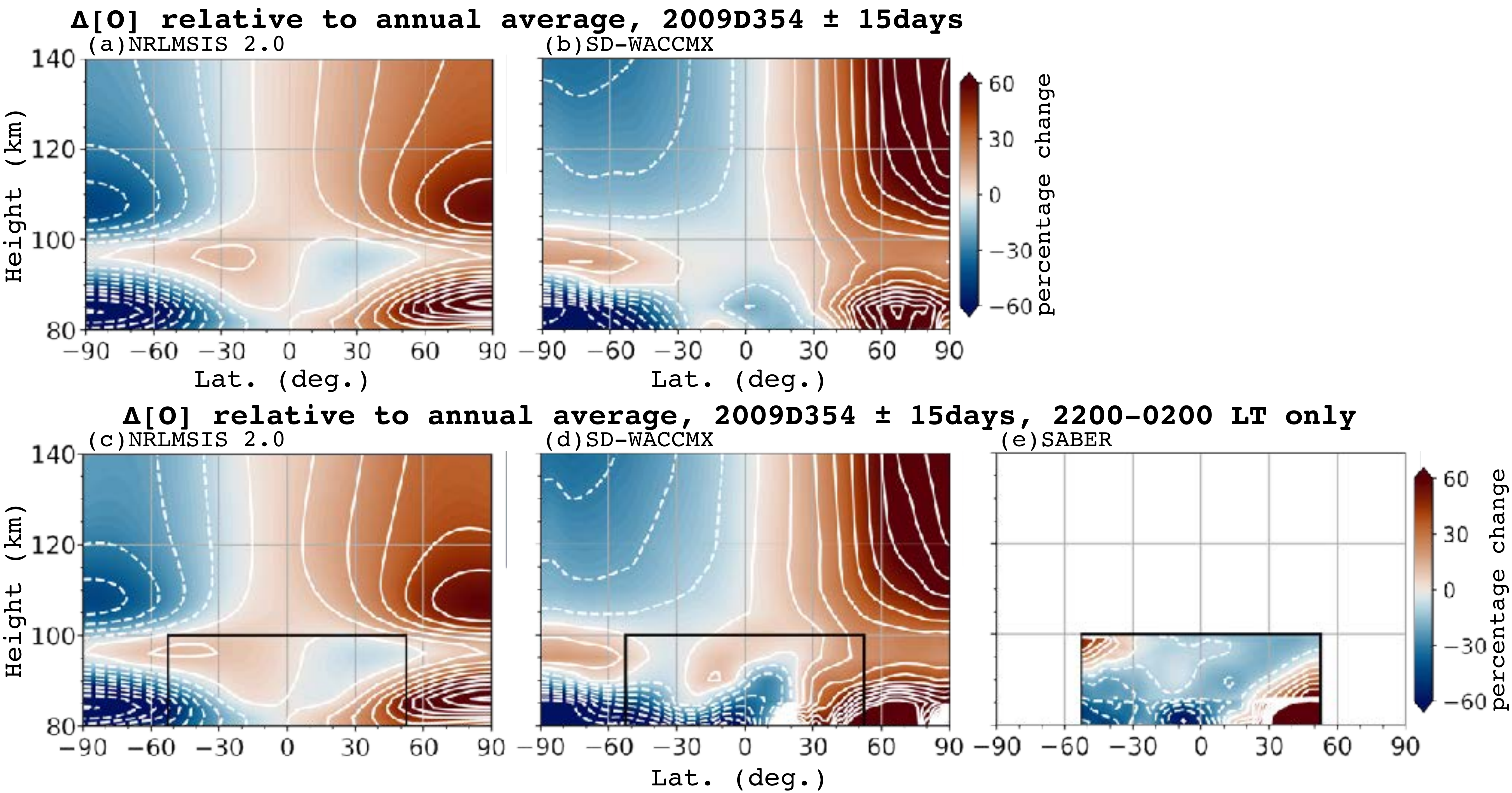

(a) zmV, 2008d84
(b) zmV, 2008d174
(c) zmV, 2008d264
(d) zmV, 2008d354
Pressure (hPa)
10^{-5}
10^{-4}
10^{-3}
Appro. Height (km)
135
120
105
−90 −60 −30 0 30 60 90
Lat. (deg.)
−10 −5 0 5 10
m/s



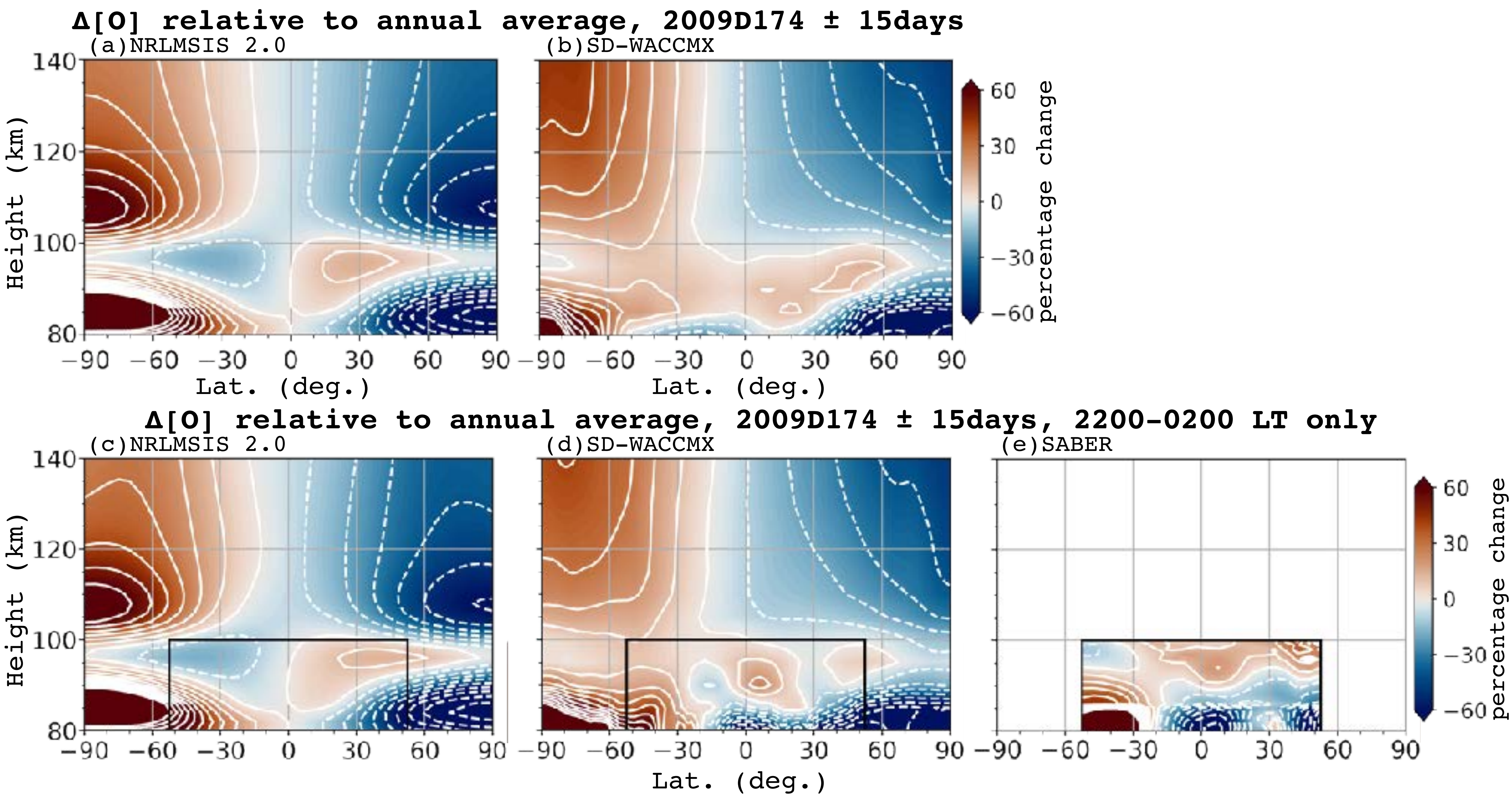
contour level is 0.02 mmr



contour level is 1



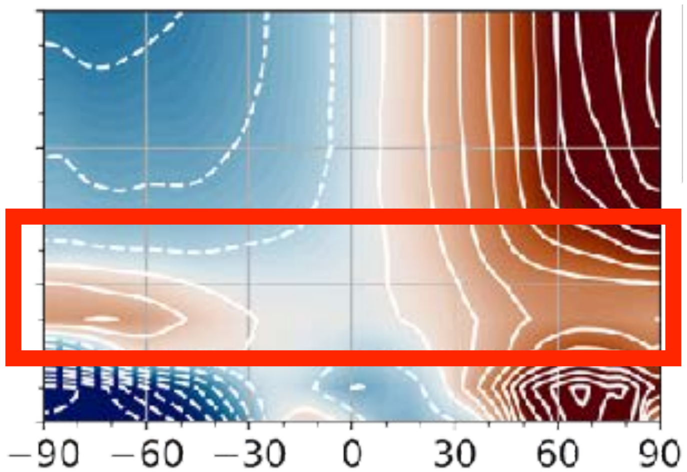
contour level is 10%



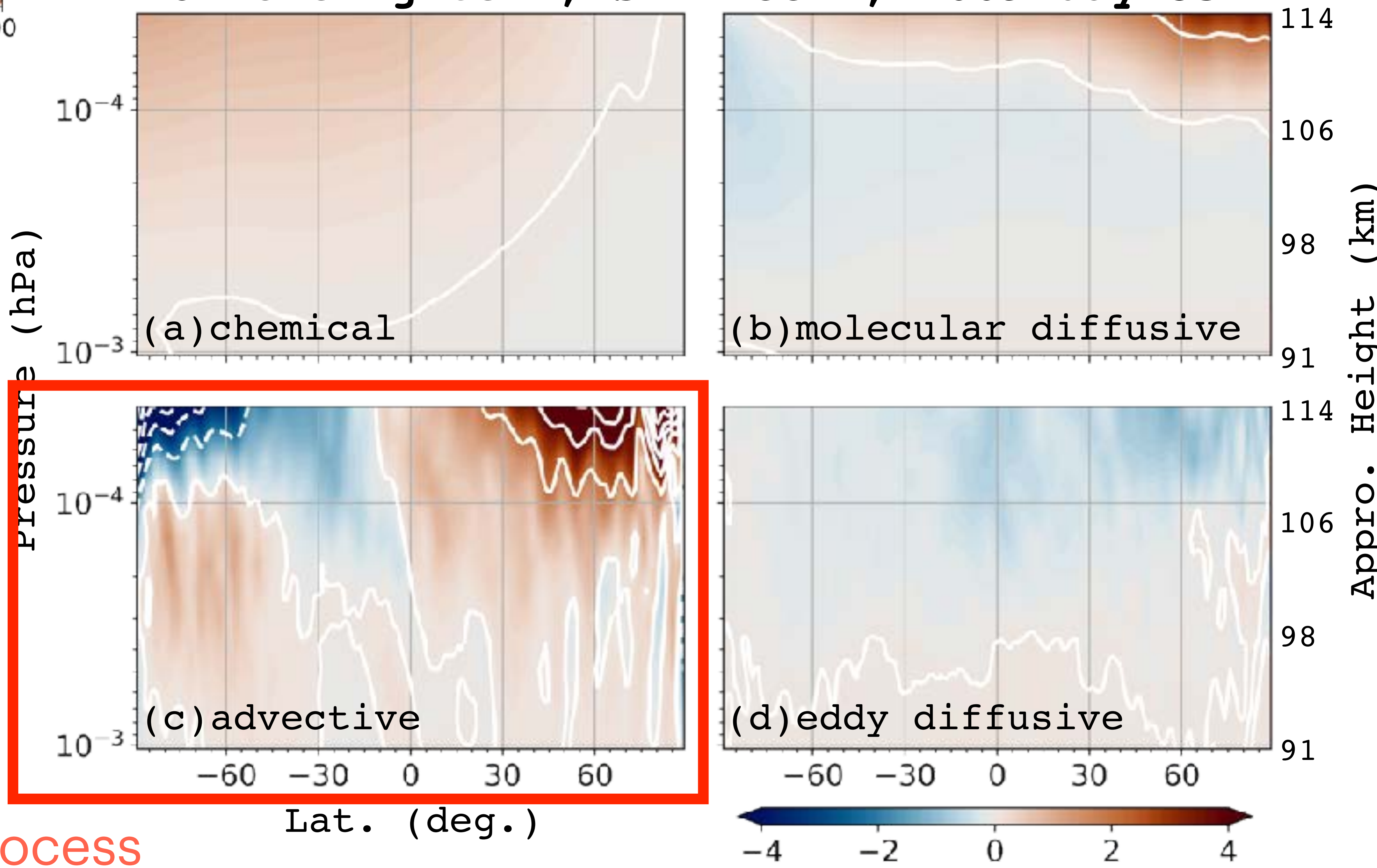
contour level is 10%

[O] seasonal variation is dominated by advection

[O] relative change

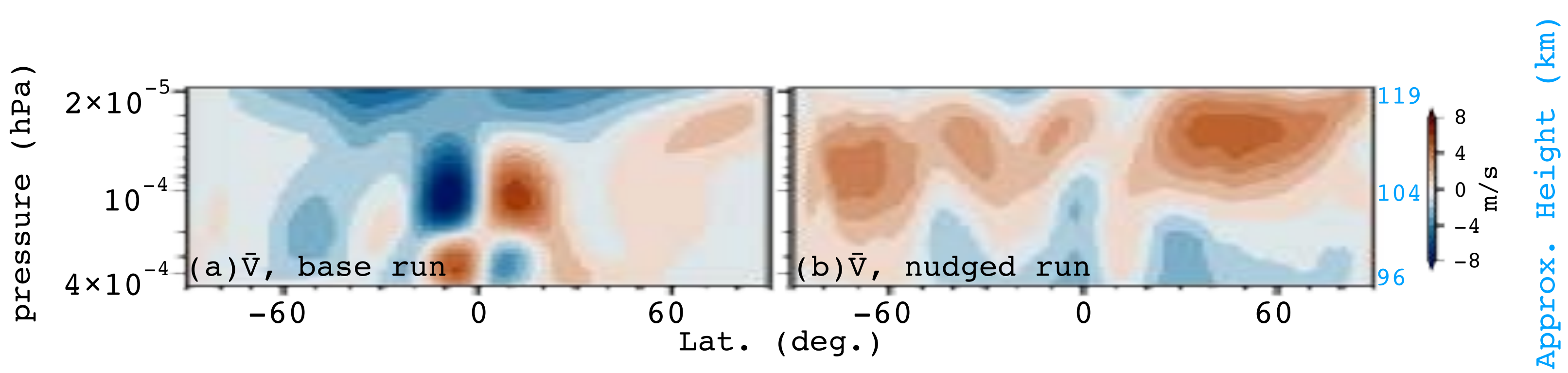


O forcing term, SD-WACCMX, 2009 day 354

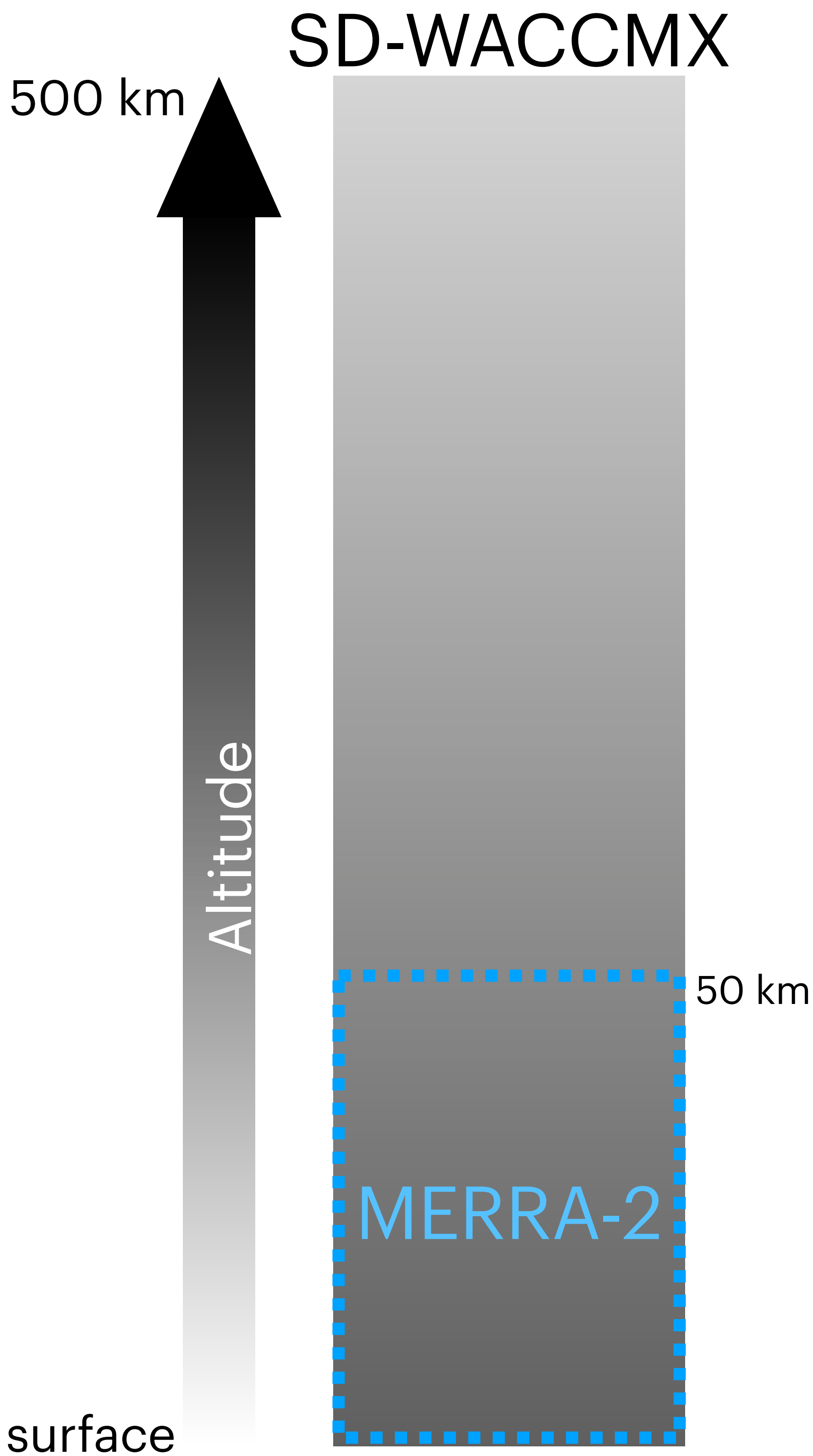


advective process

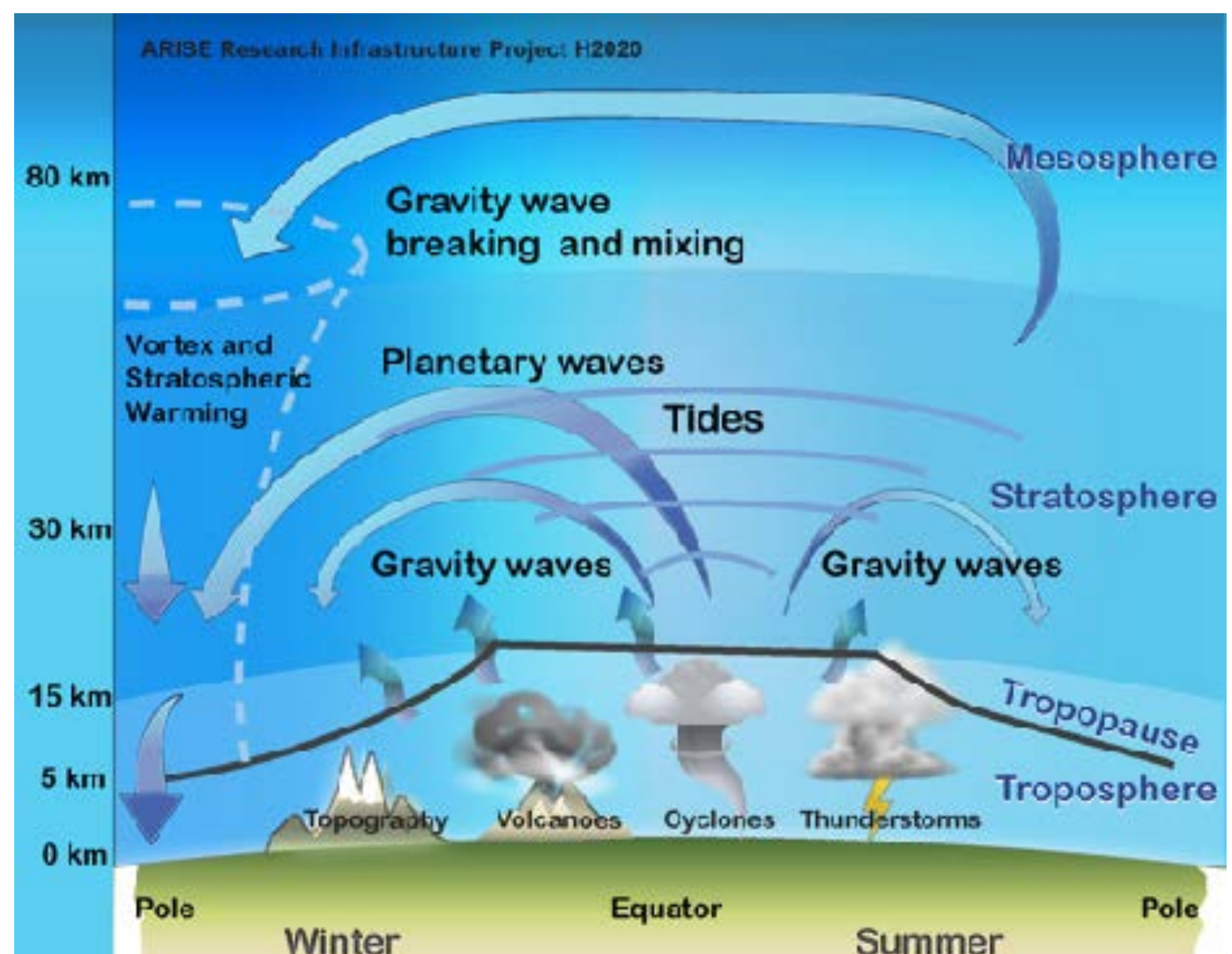
Lower-thermospheric circulation can modulate upper part of the thermospheric circulation as well



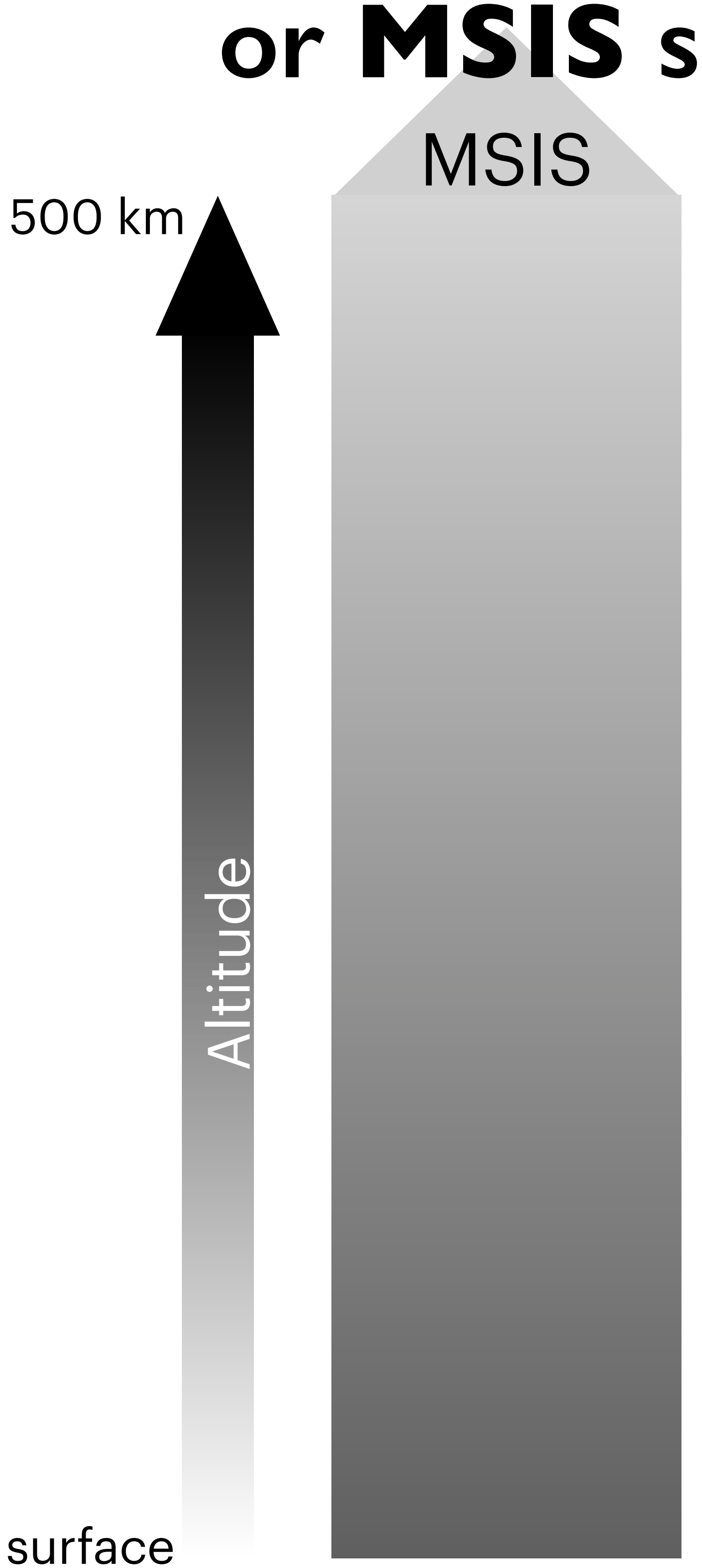
Specified Dynamics configuration runs of the Whole Atmosphere Community Climate Model eXtended

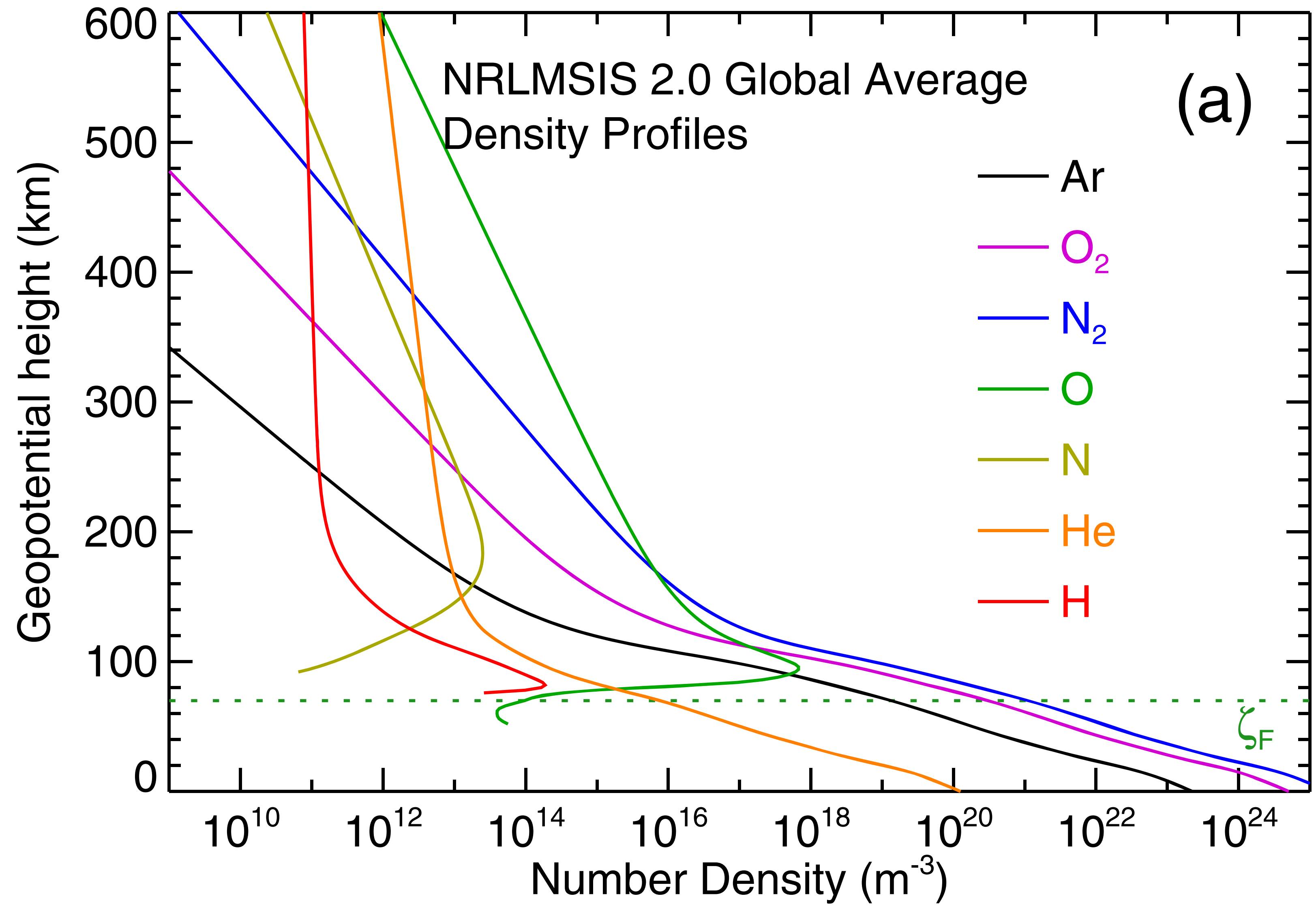


- three-dimensional, time-dependent
- surface-500km
- resolution:0.9°x 1.25°, 0.25 scale height above ~50km (one scale height = ~25 km in thermosphere)
- explicit gravity wave parameterization (sub-grid waves)



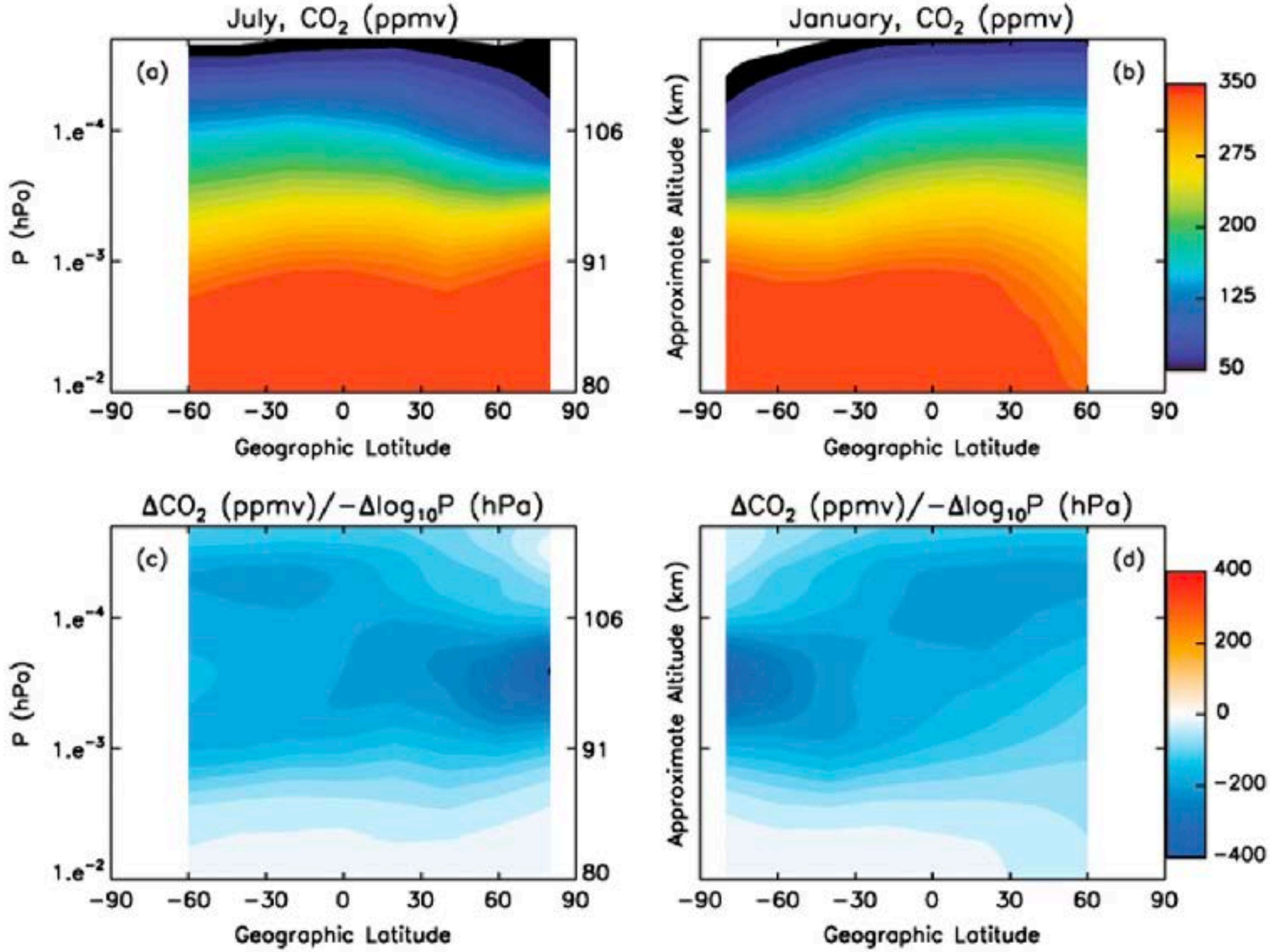
The **M**ass **S**pectrometer **I**ncoherent **S**catter radar or **MSIS** series of empirical model

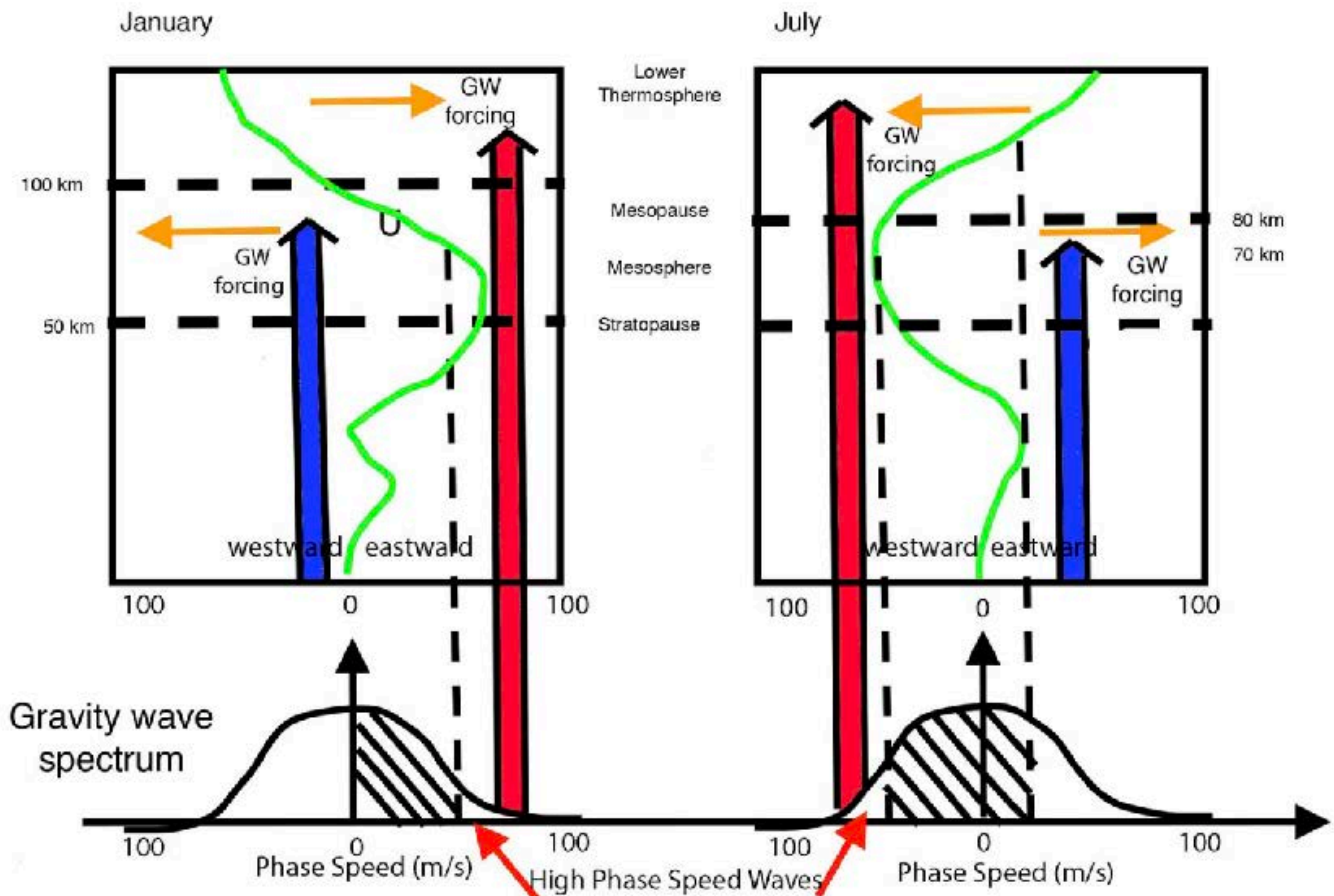




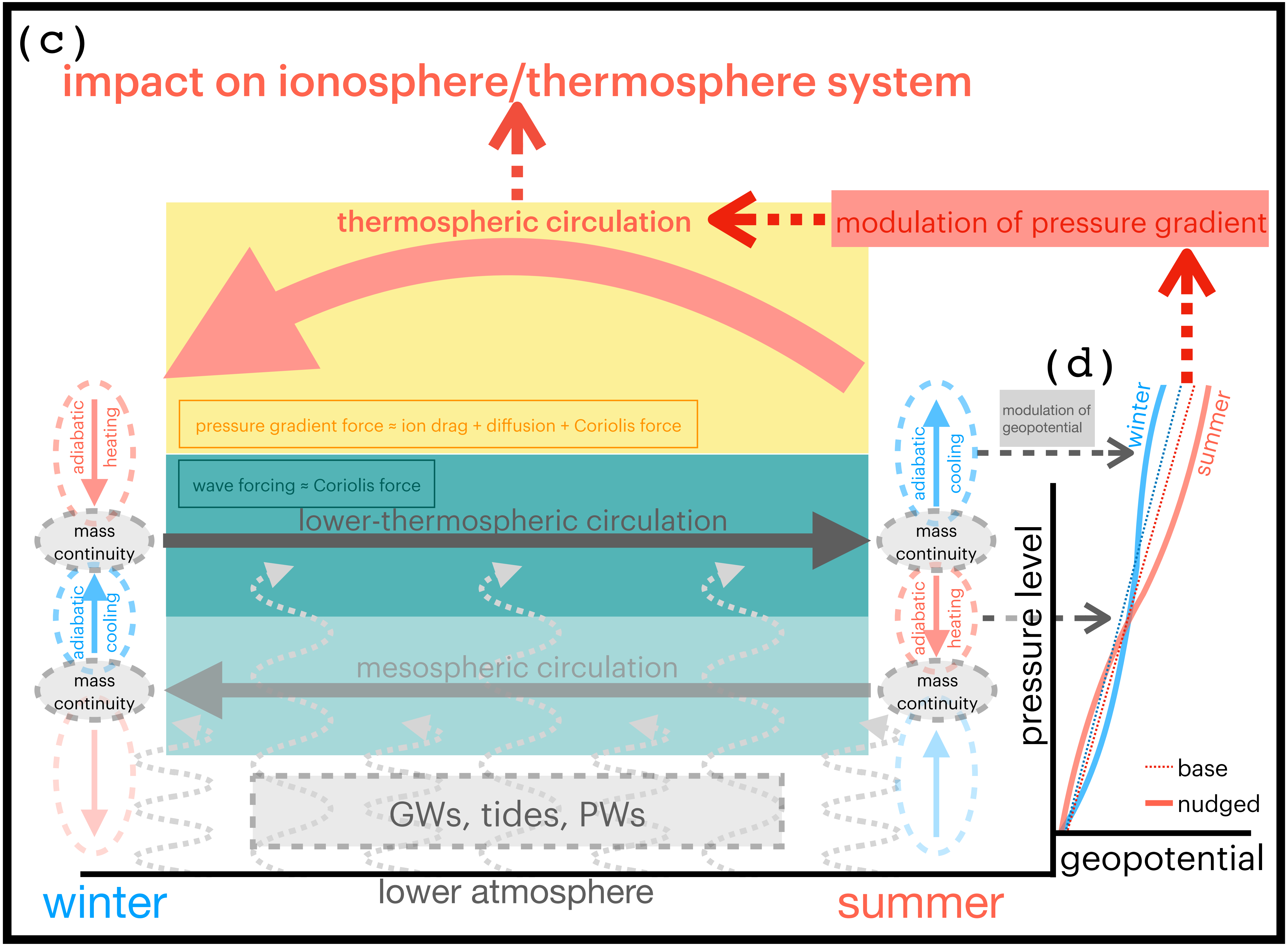
(Emmert+, 2020)

H_2O, CO_2 observations suggested an existence of this reversed layer above the mesospheric circulation

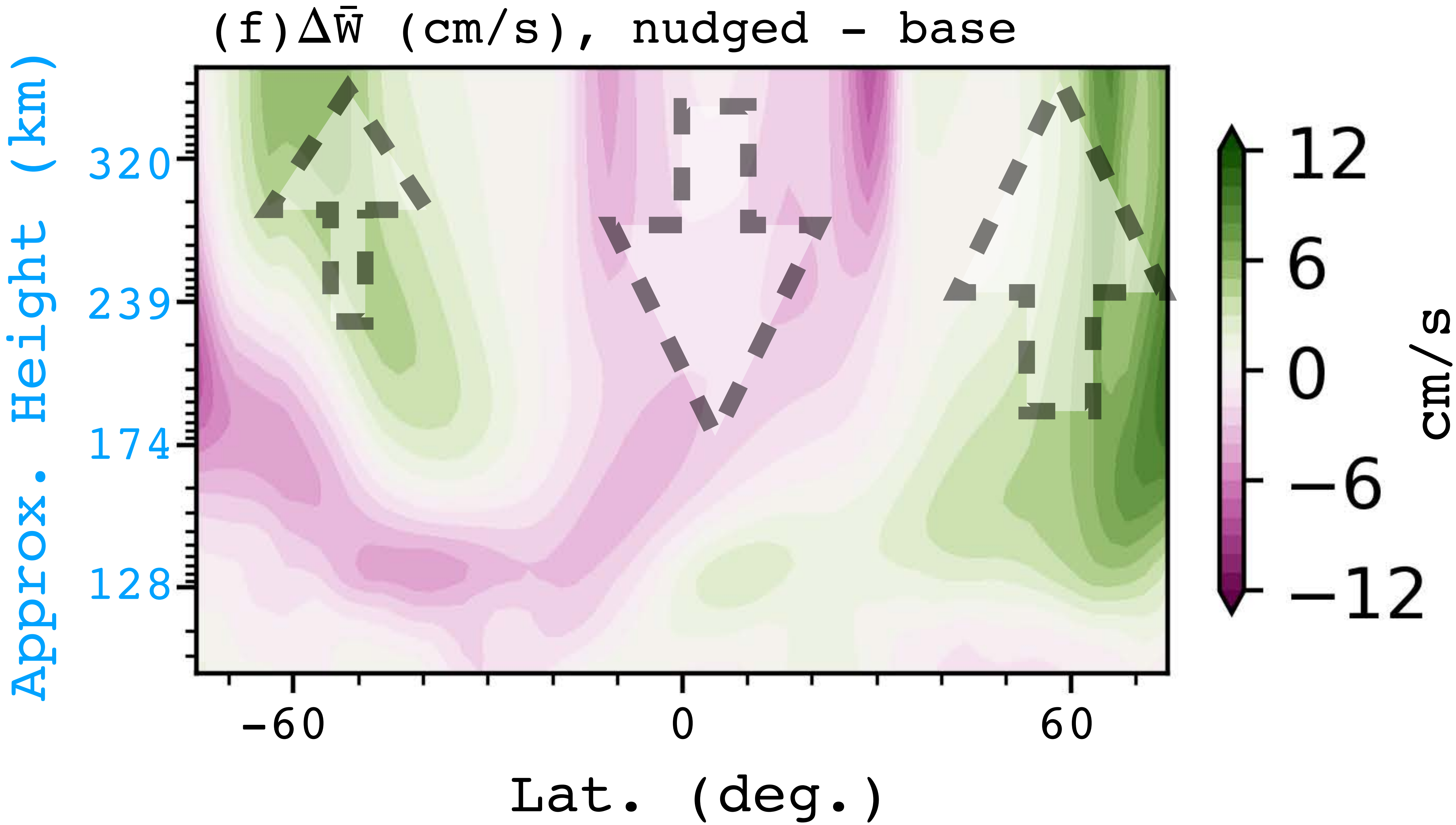




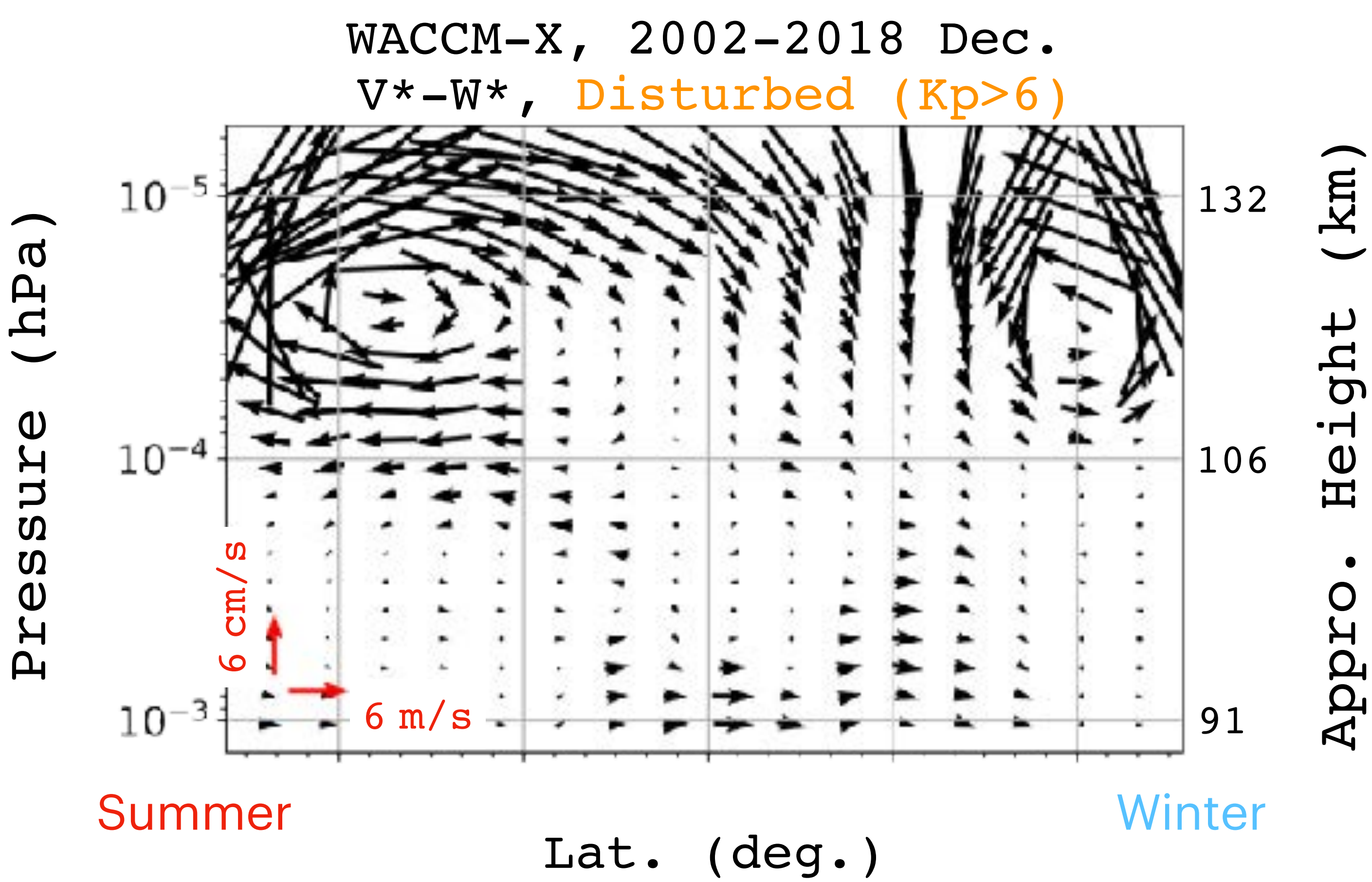
Qian et al., (2017)

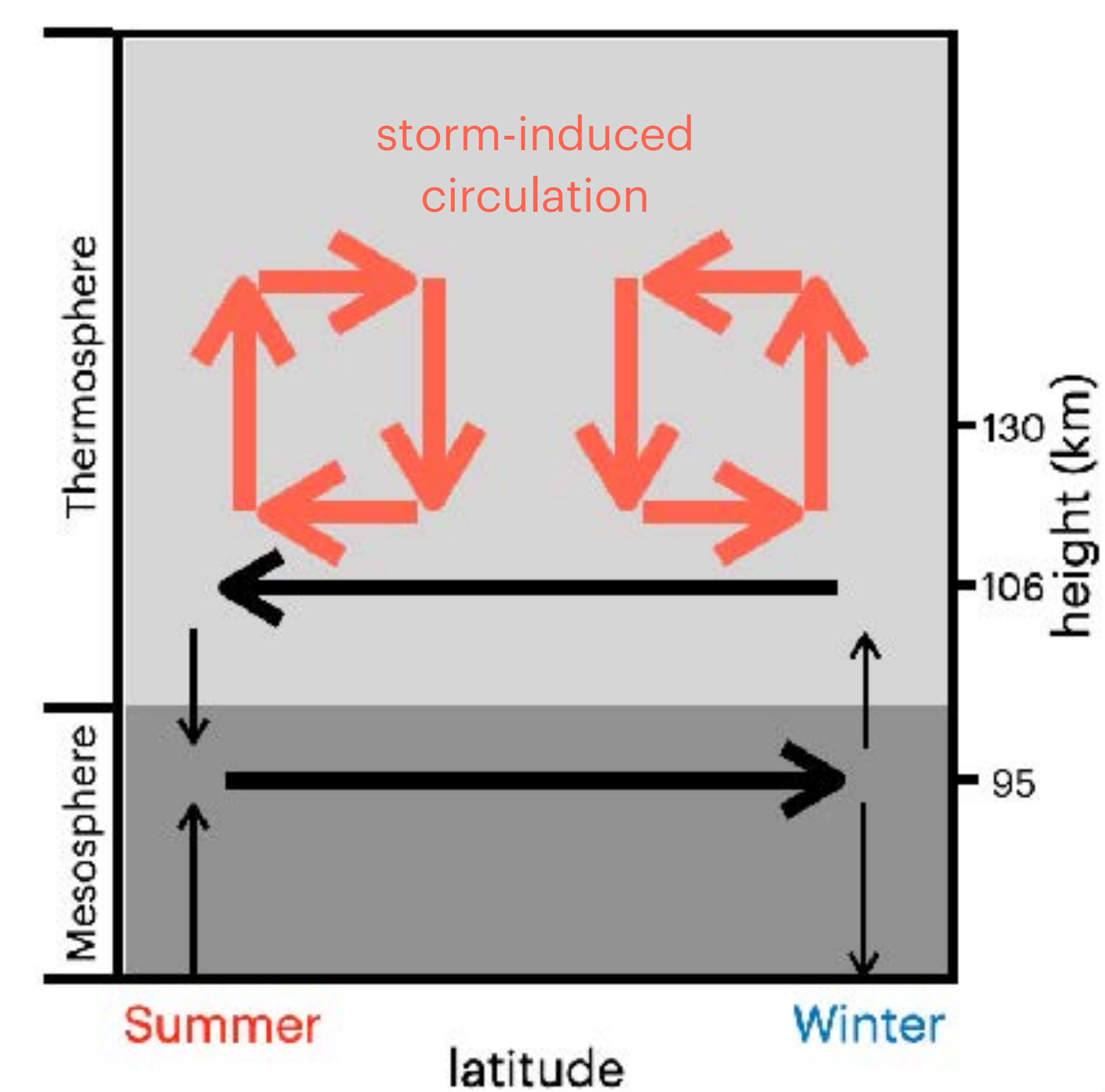

(c)
impact on ionosphere/thermosphere system
thermospheric circulation
modulation of pressure gradient
pressure gradient force ≈ ion drag + diffusion + Coriolis force
wave forcing ≈ Coriolis force
lower-thermospheric circulation
mesospheric circulation
adiabatic heating
adiabatic cooling
mass continuity
GWs, tides, PWs
lower atmosphere
winter
summer
(d)
modulation of geopotential
pressure level
geopotential
base
nudged

The lower-thermospheric circulation enhances thermospheric upwelling at high latitudes



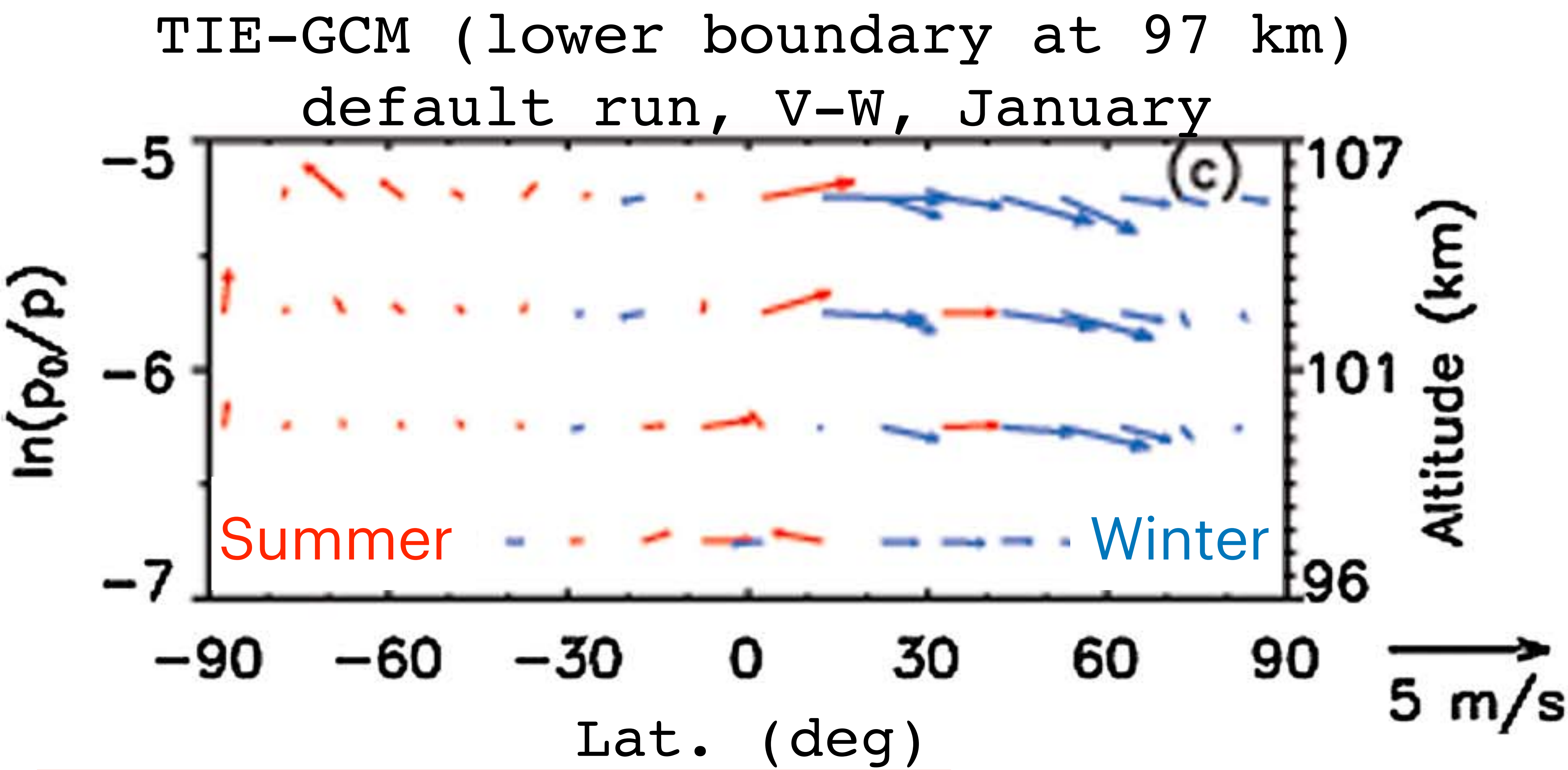
Lower-thermospheric circulation during storm times





Enhancement of ion drag and Joule heating induce
additional circulations in the lower thermosphere during storm times.

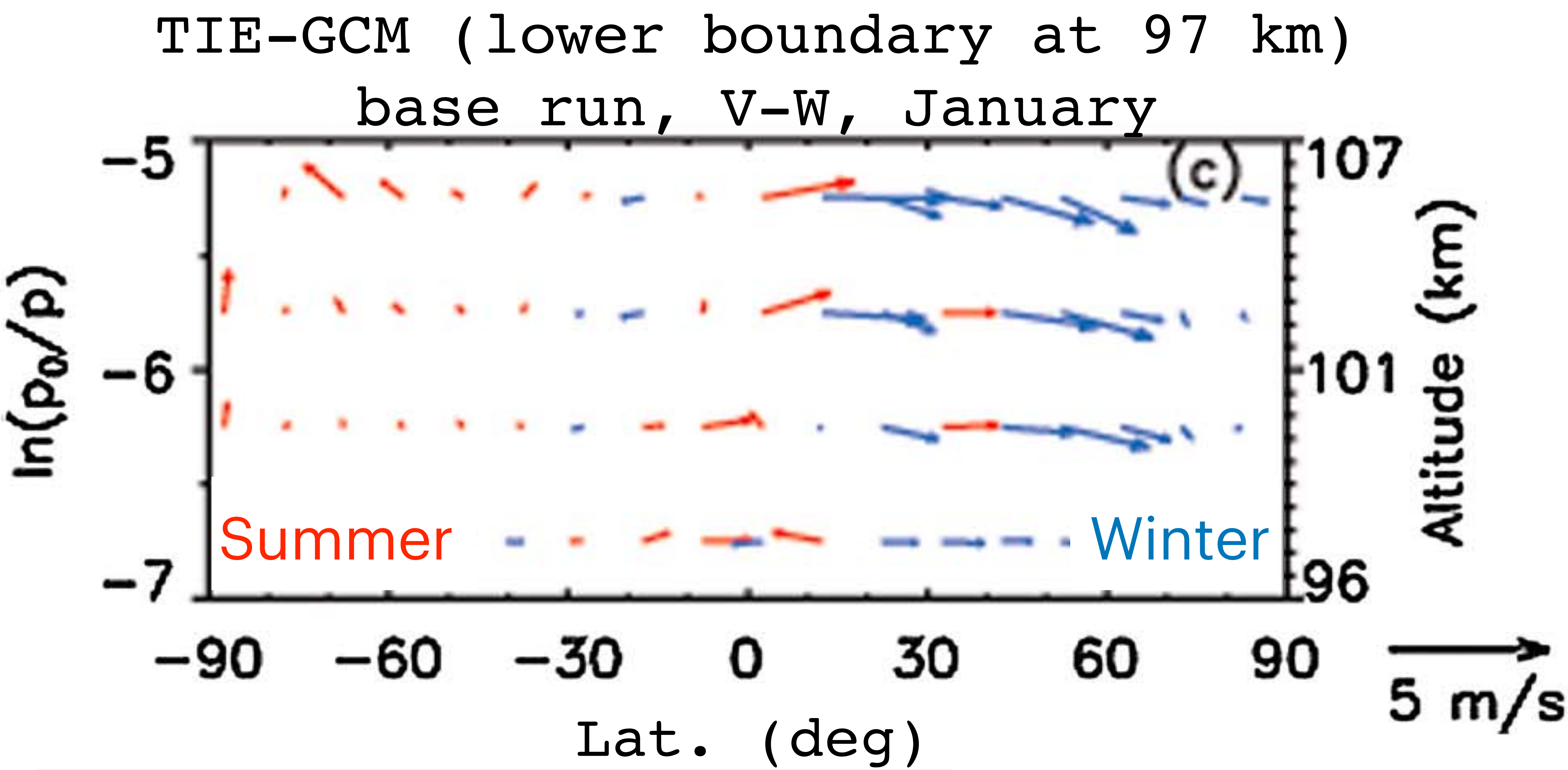
Not all models can reproduce lower-thermospheric circulation…



only models "with lower atmospheric components" can reproduce

(Qian & Yue, 2017)

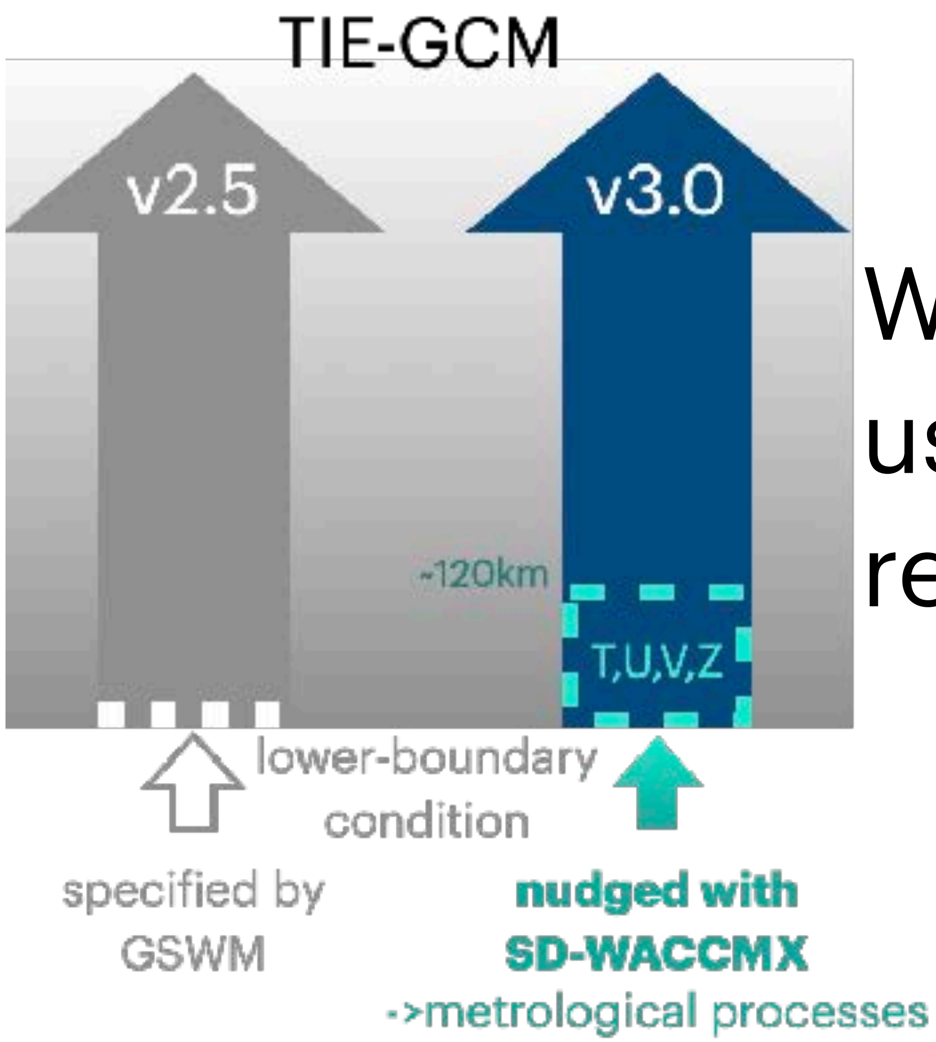
What if we constrain the TIE-GCM lower thermosphere by prescribing the observed circulation?



(Qian & Yue, 2017)

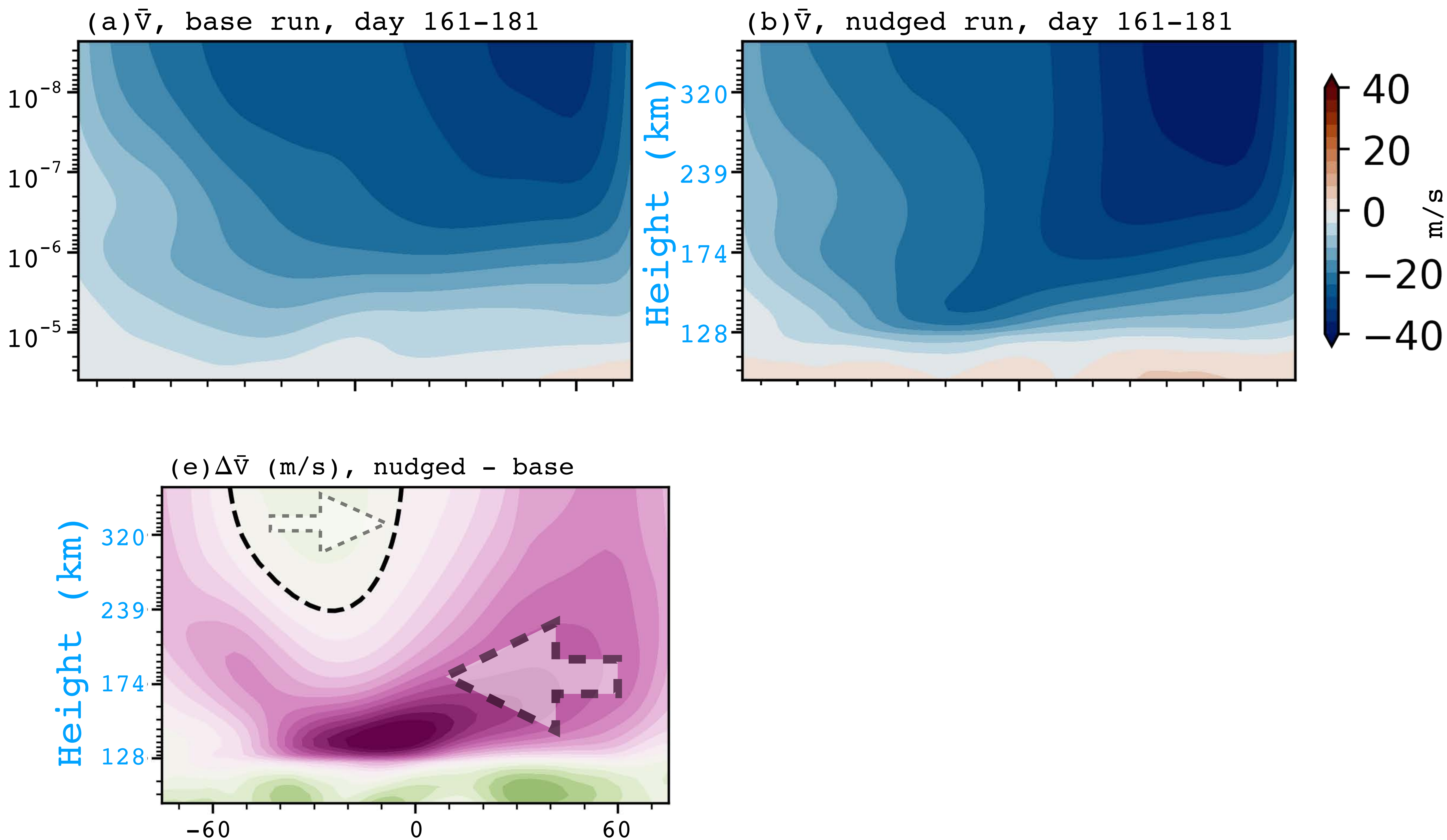
only models "with lower atmospheric components" can reproduce

Model: TIE-GCM v3.0

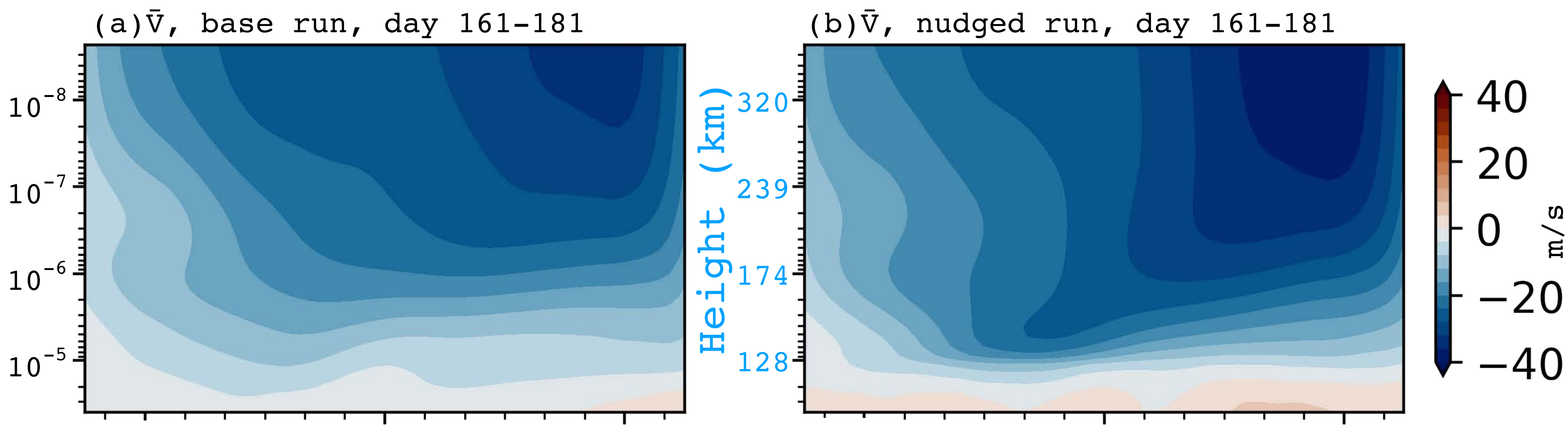


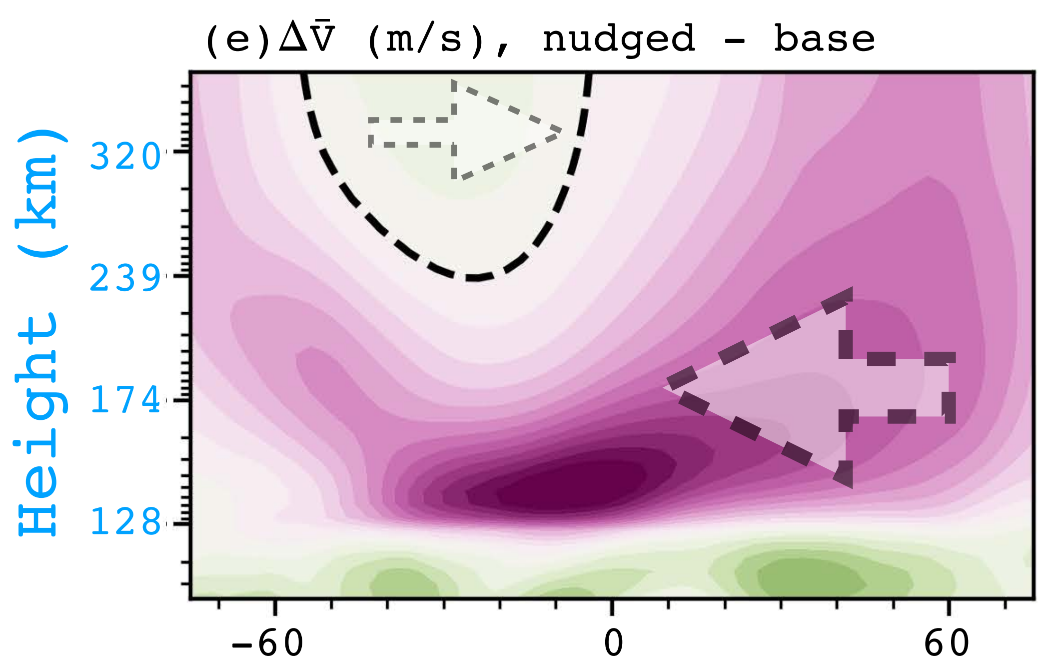
We constrain the lower thermosphere using SD-WACCMX and compare the results with a base run.

Lower-thermospheric circulation modulates thermospheric circulation

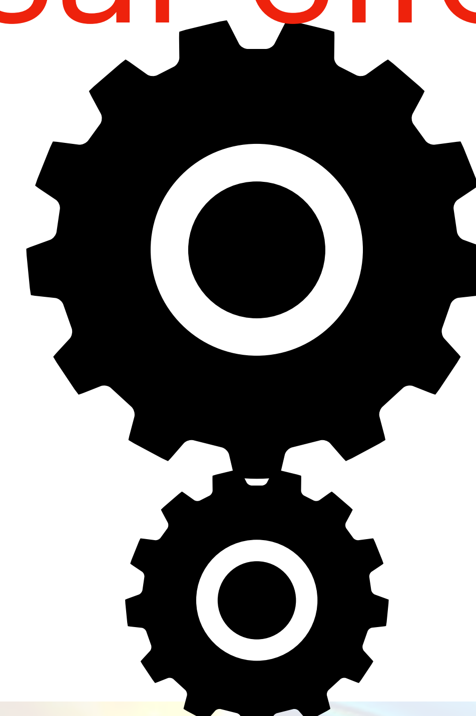


Lower-thermospheric circulation modulates thermospheric circulation





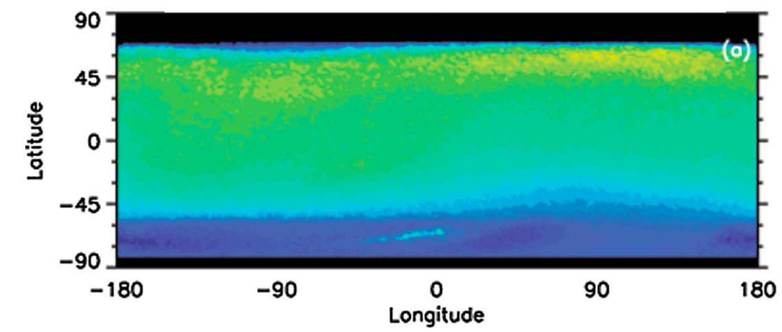
Gear effect



Model with lower-thermospheric circulation could reproduce more realistic O/N_2 values

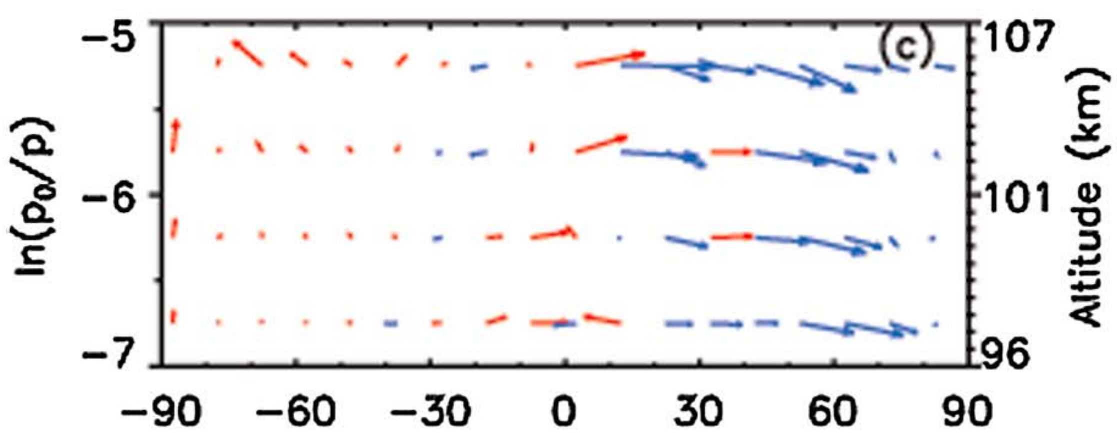
TIMED/GUVI

observed O/N_2

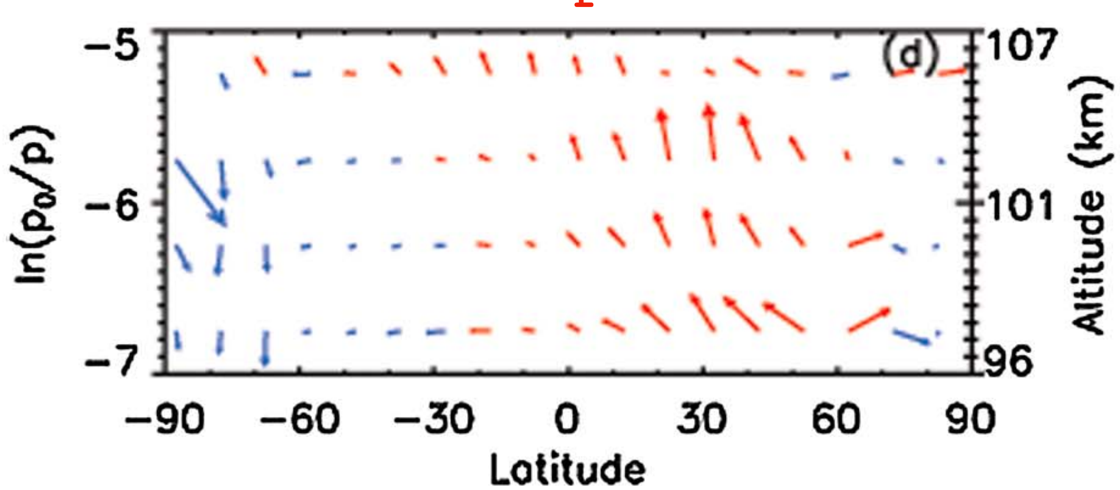


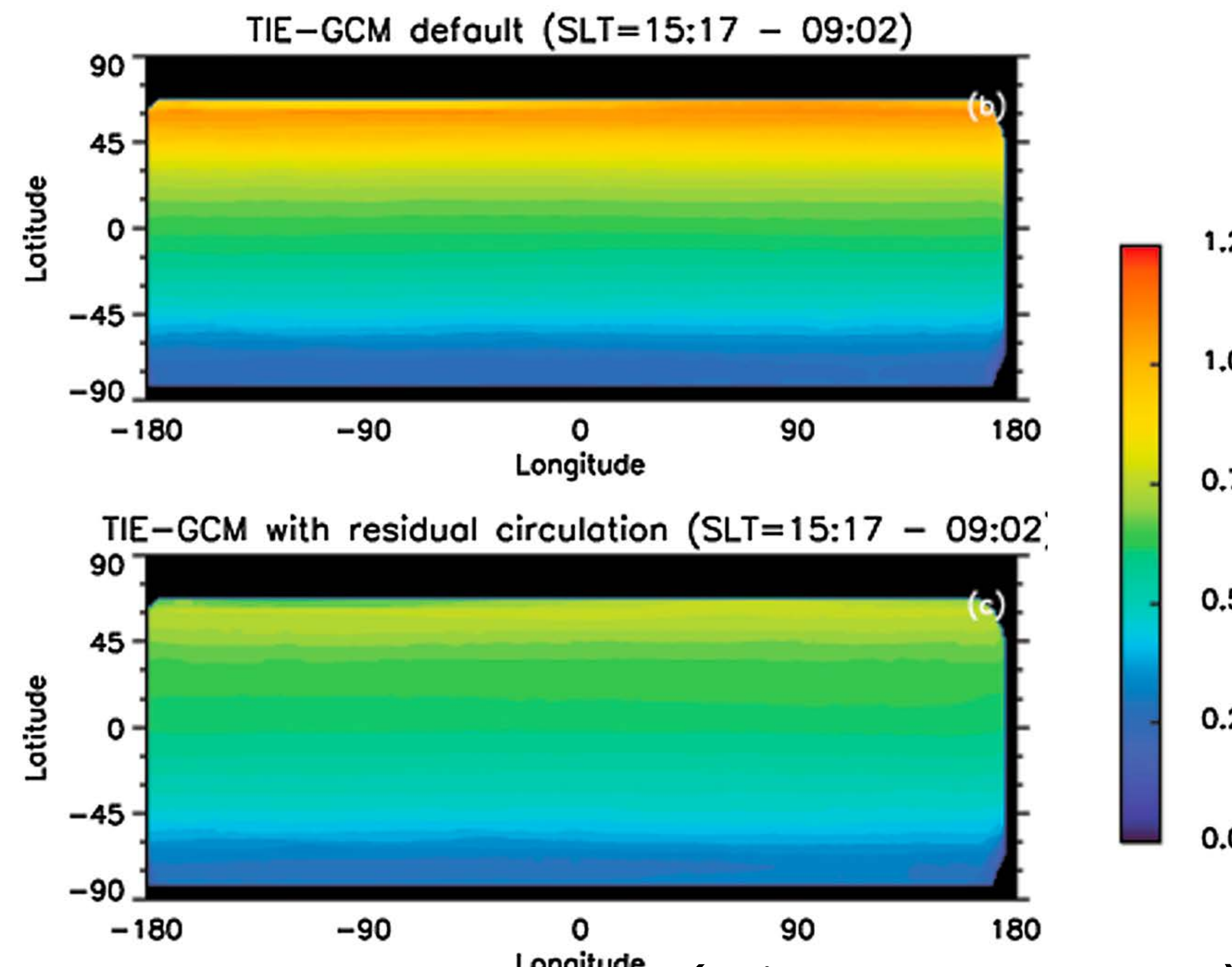
5 m/s

TIE-GCM, default run, V-W, Jan.



with lower-thermospheric circulation





(Qian & Yue, 2017)

Summer Winter

The [O] continuity equation provides insight into the seasonal variability of atomic oxygen

$$\frac{d\langle[O]\rangle}{dt} = \boxed{-\frac{\partial}{\partial z}\langle\overline{w}\,\overline{[O]}\rangle}\;\boxed{-\frac{\partial}{\partial z}\langle\overline{\Gamma}_z\rangle} + \cancel{\langle\overline{P}\rangle - \langle\overline{L}\,\overline{[O]}\rangle}\;\cancel{-\frac{\partial}{\partial z}\langle\overline{w'[O]'}\rangle}$$

vertical advection (due to lower-thermospheric circulation)

eddy and molecular diffusion (due to small-scale turbulence)

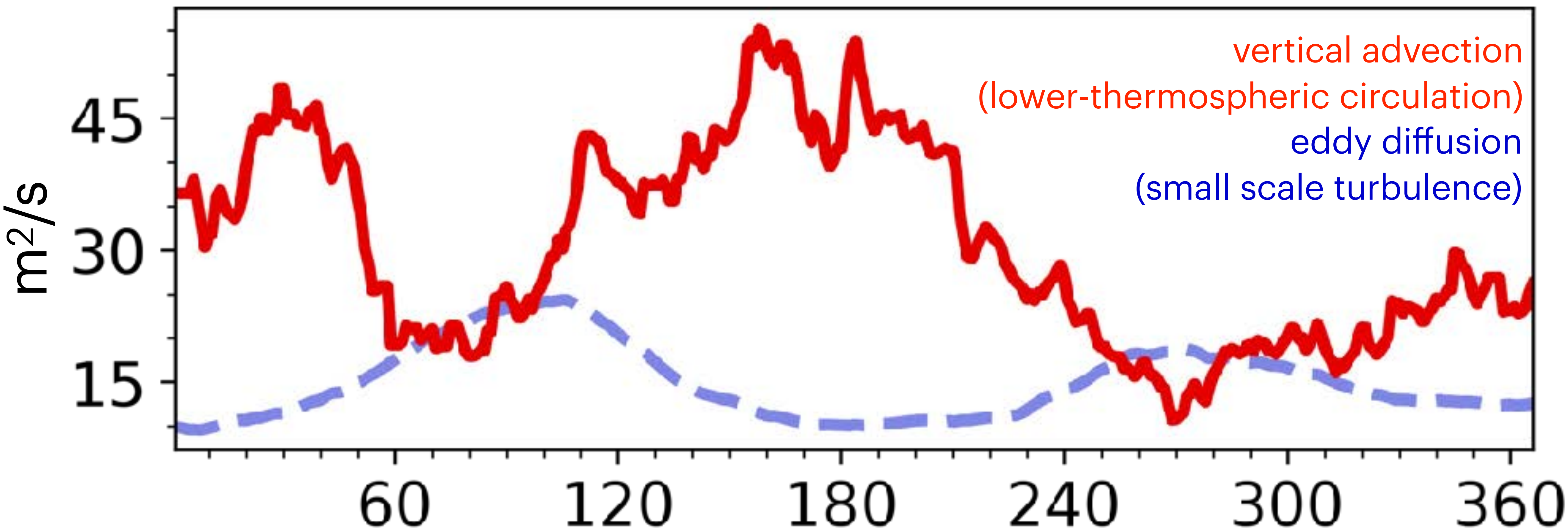
chemical production and loss

tidal and planetary wave transport

$\langle\ \rangle$: global mean

Vertical advection appears to play a dominant role in seasonal [O] variability

SD-WACCMX diffusion coefficients (m^2/s), ~100km

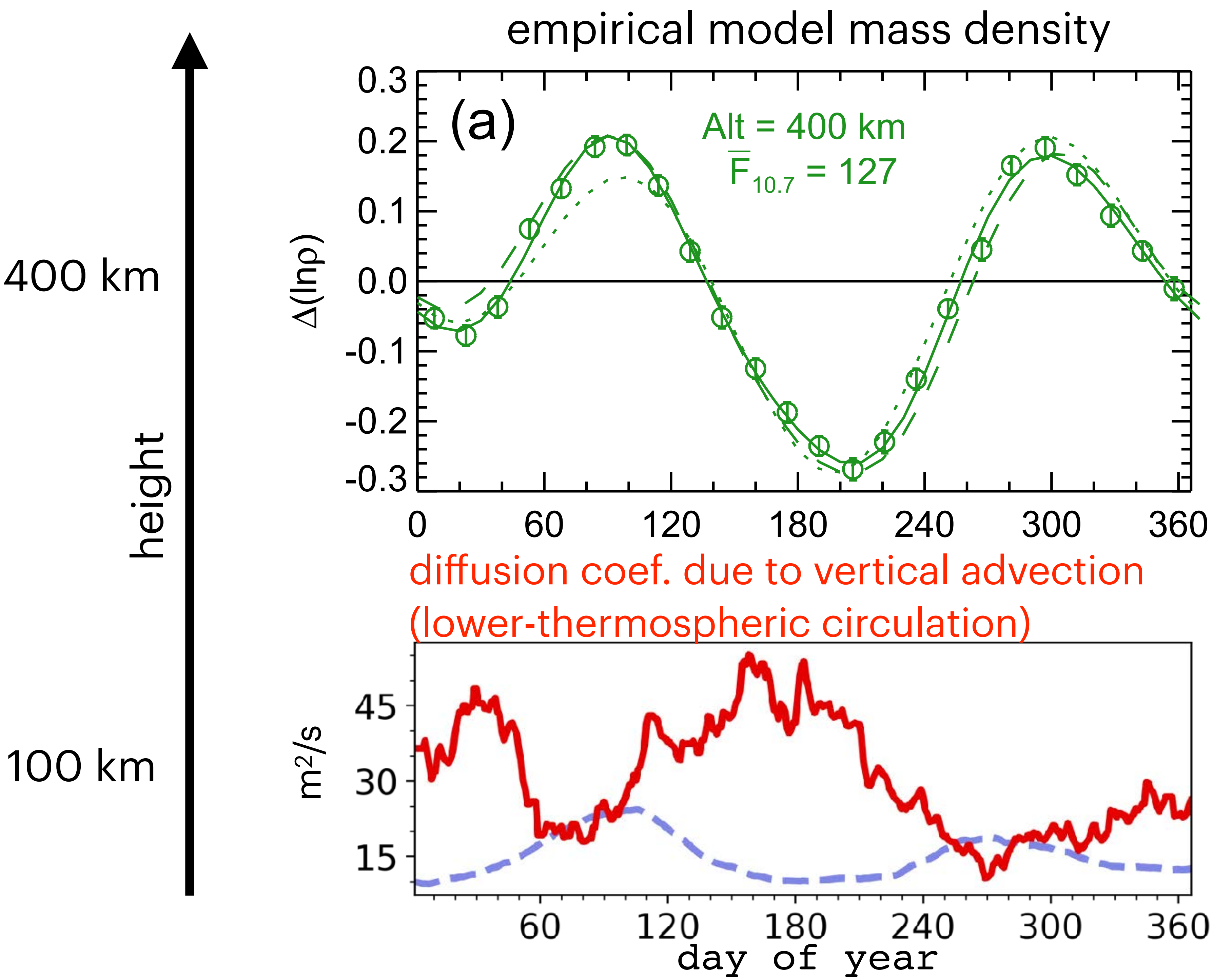


2008, DOY

diffusion coef. = efficiency to transport [O] from high to low density region

<u>larger value</u>
<u>-> stronger mixing</u>
<u>-> lower mass density</u>

Vertical advection appears to play a dominant role in seasonal [O] variability



(Emmert, 2015)