Quantifying Isentropic Stratosphere-Troposphere Exchange (STE) of Ozone

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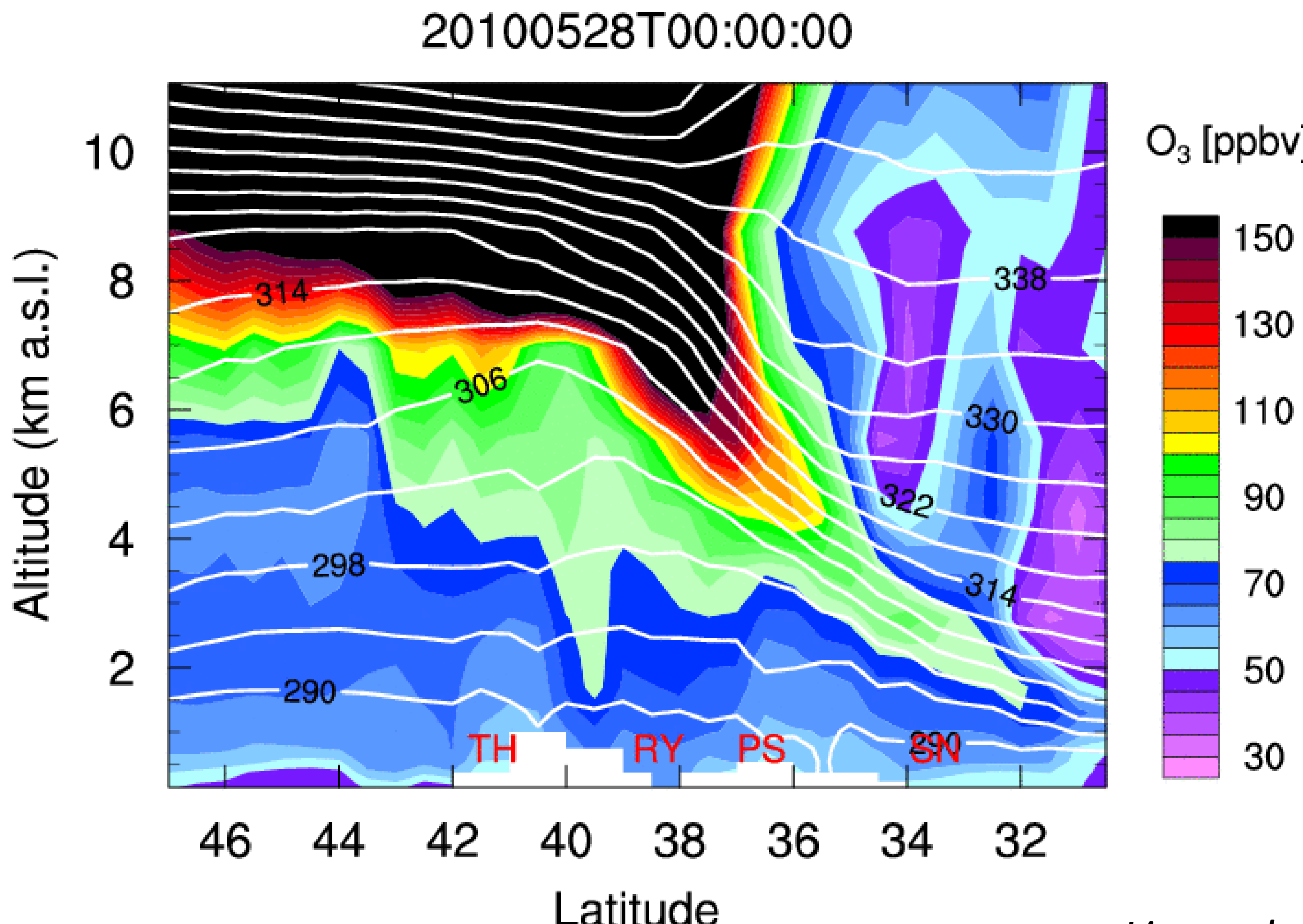
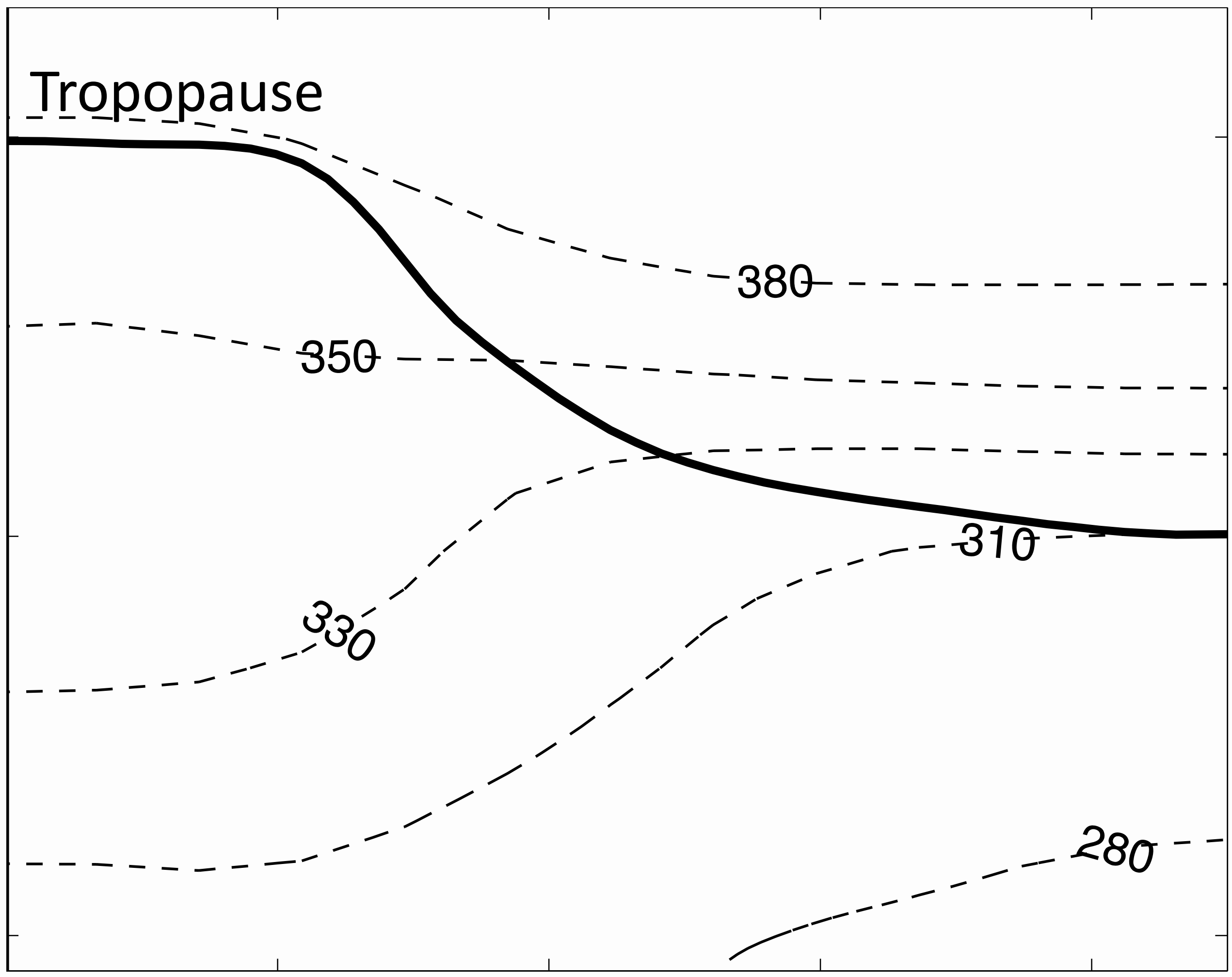
Ozone STE



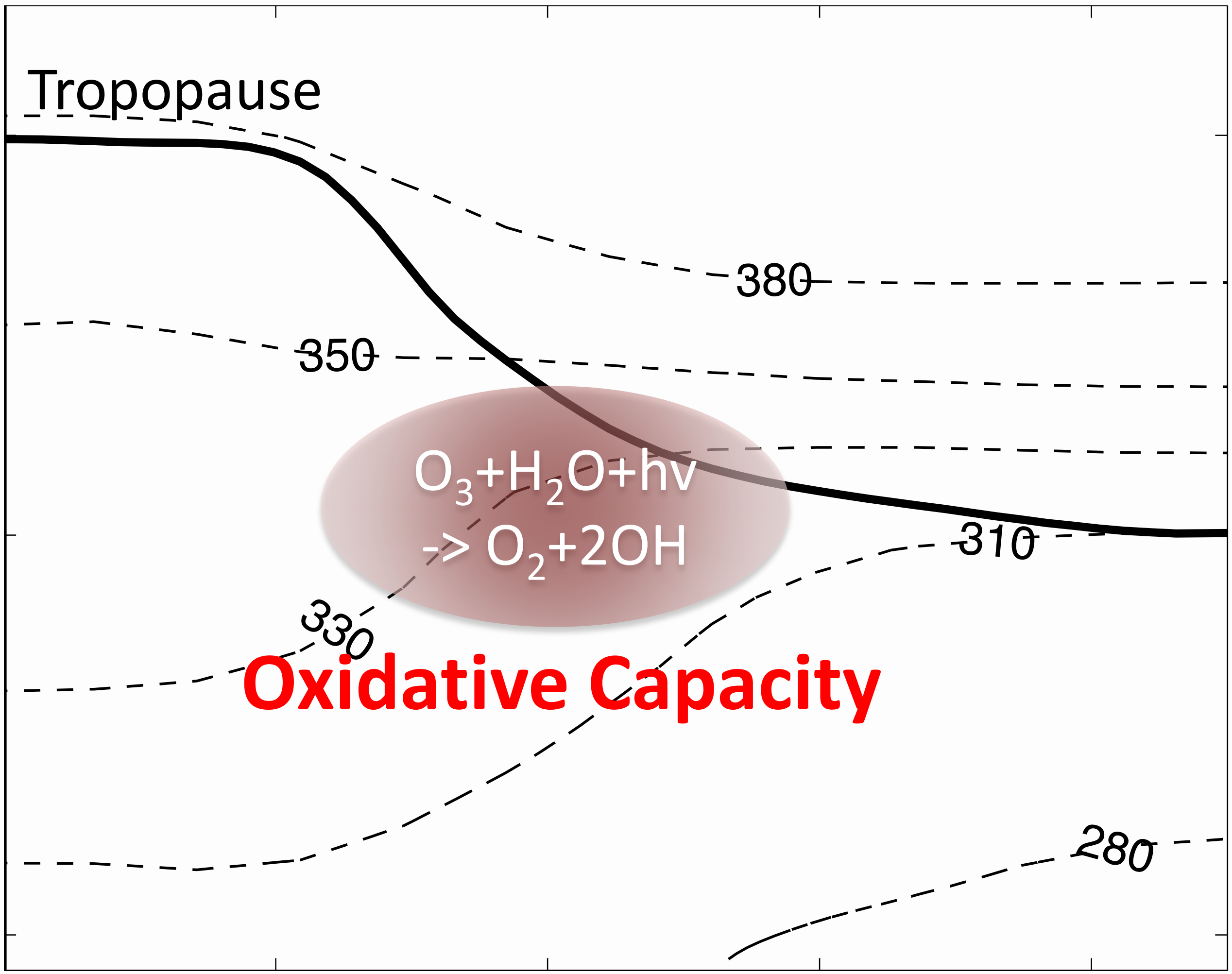
Lin et al., GFDL

http://www.gfdl.noaa.gov/news-app/story.74/title.springtime-high-surface-ozone-events-over-the-western-united-states-quantifying-the-role-of-stratospheric-intrusions

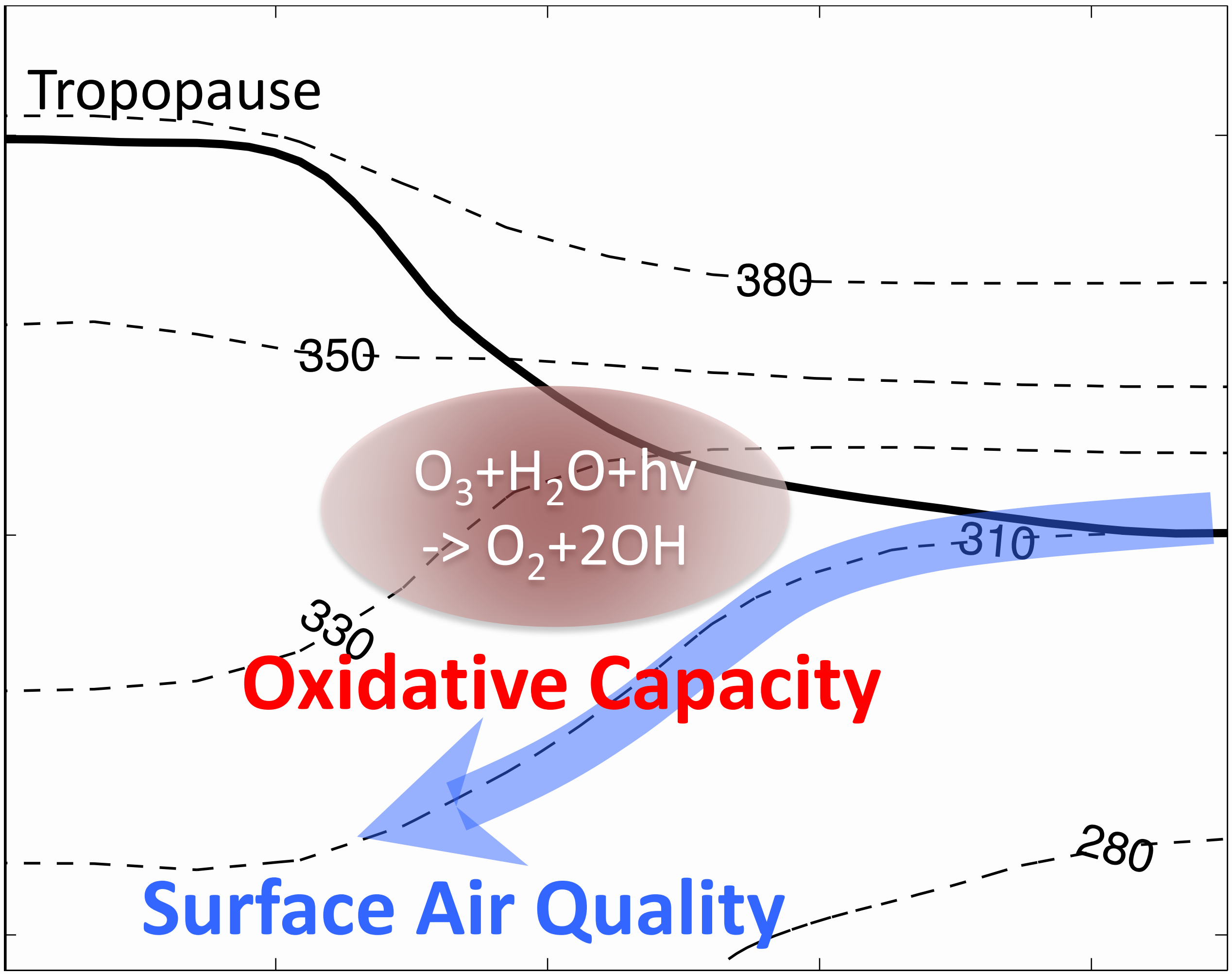
Impacts of ozone STE



Impacts of ozone STE

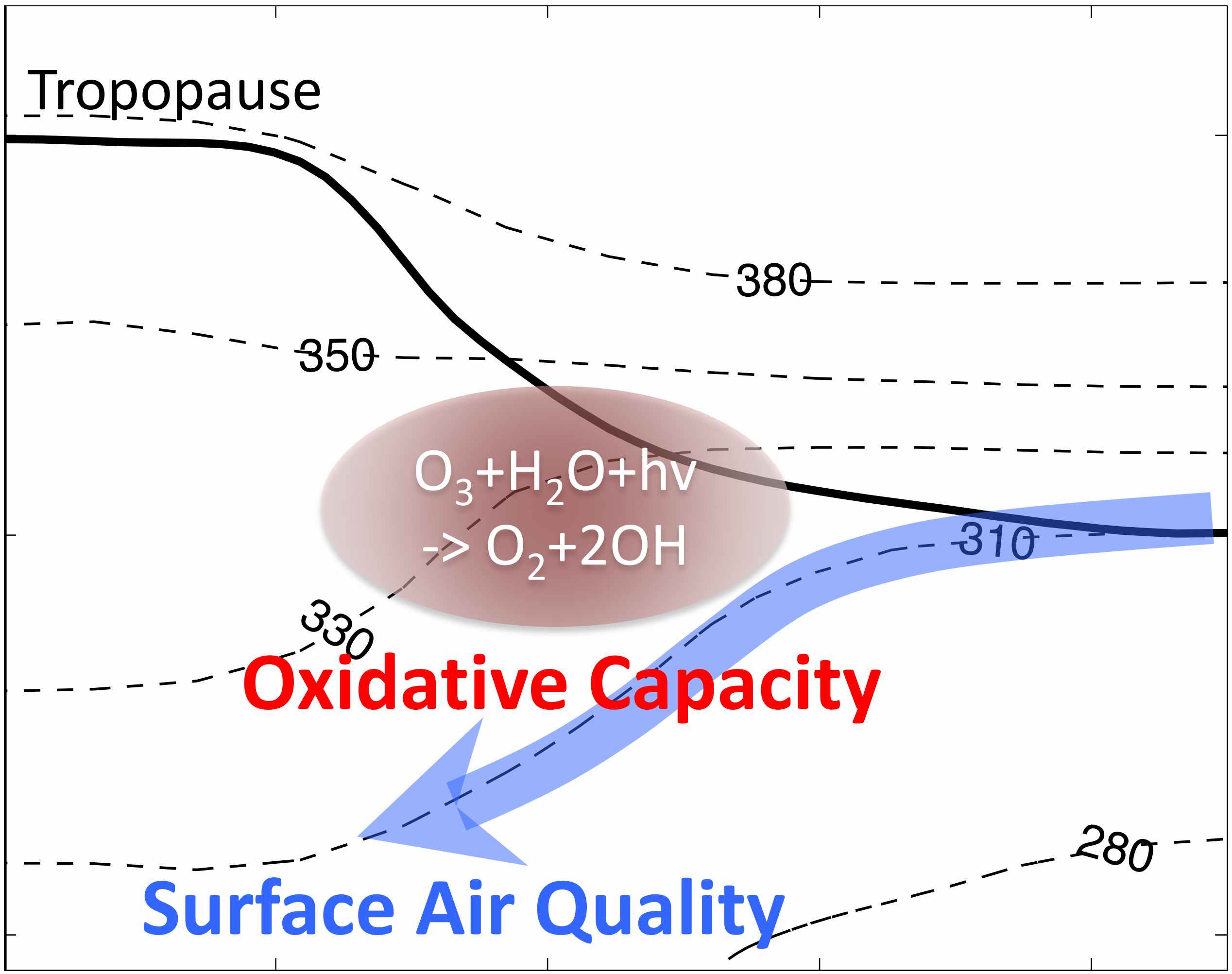


Impacts of ozone STE



Impacts of ozone STE

Spatially NOT uniform

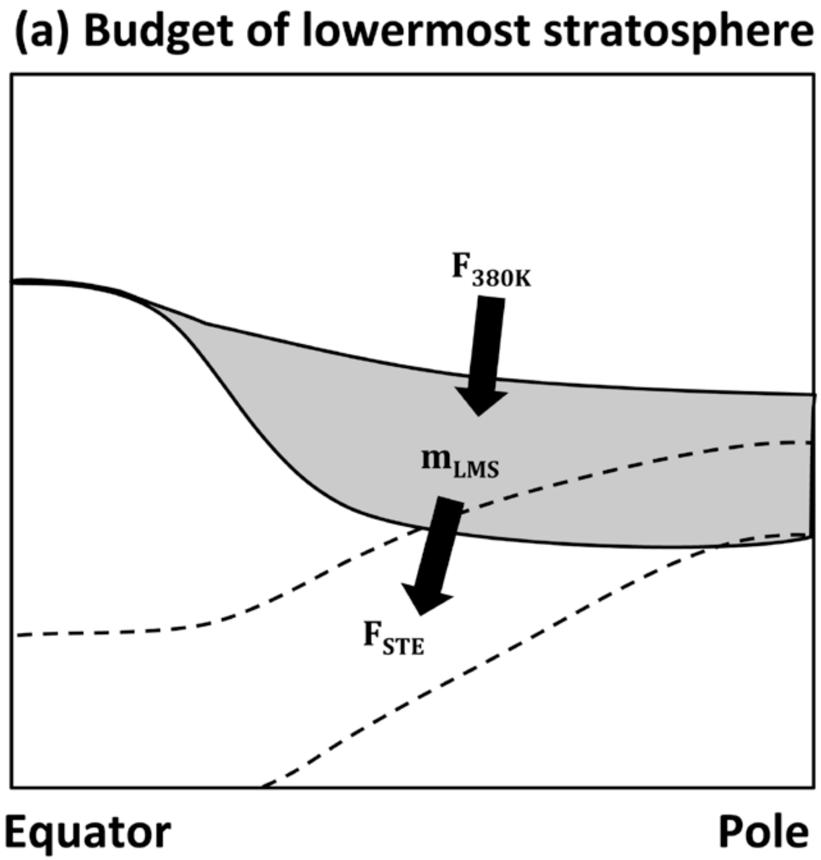


It is important to quantify the **spatial distribution** of ozone STE

- What does the spatial distribution of ozone STE look like?
- What causes such a spatial distribution of ozone STE?

Lowermost Stratosphere (LMS) STE vs. Isentropic STE

Appenzeller et al., 1996

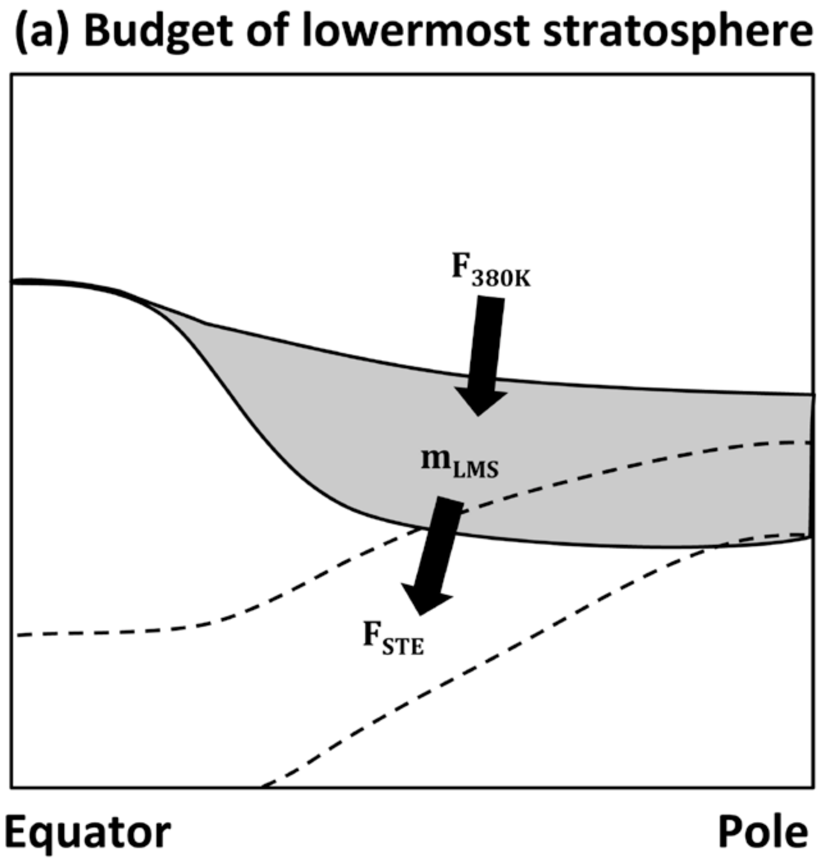


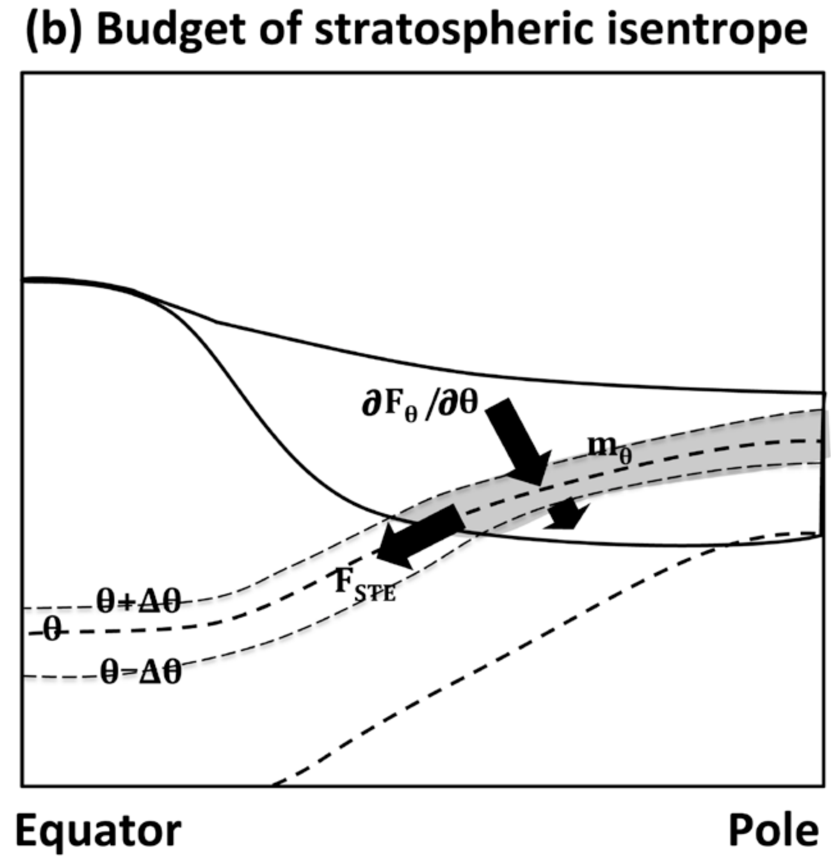
$$\frac{\partial m_{LMS}}{\partial t} = F_{STE} - F_{380K}$$

NO spatial distribution

Lowermost Stratosphere (LMS) STE vs. Isentropic STE

Appenzeller et al., 1996 *Nakamura, 2007*





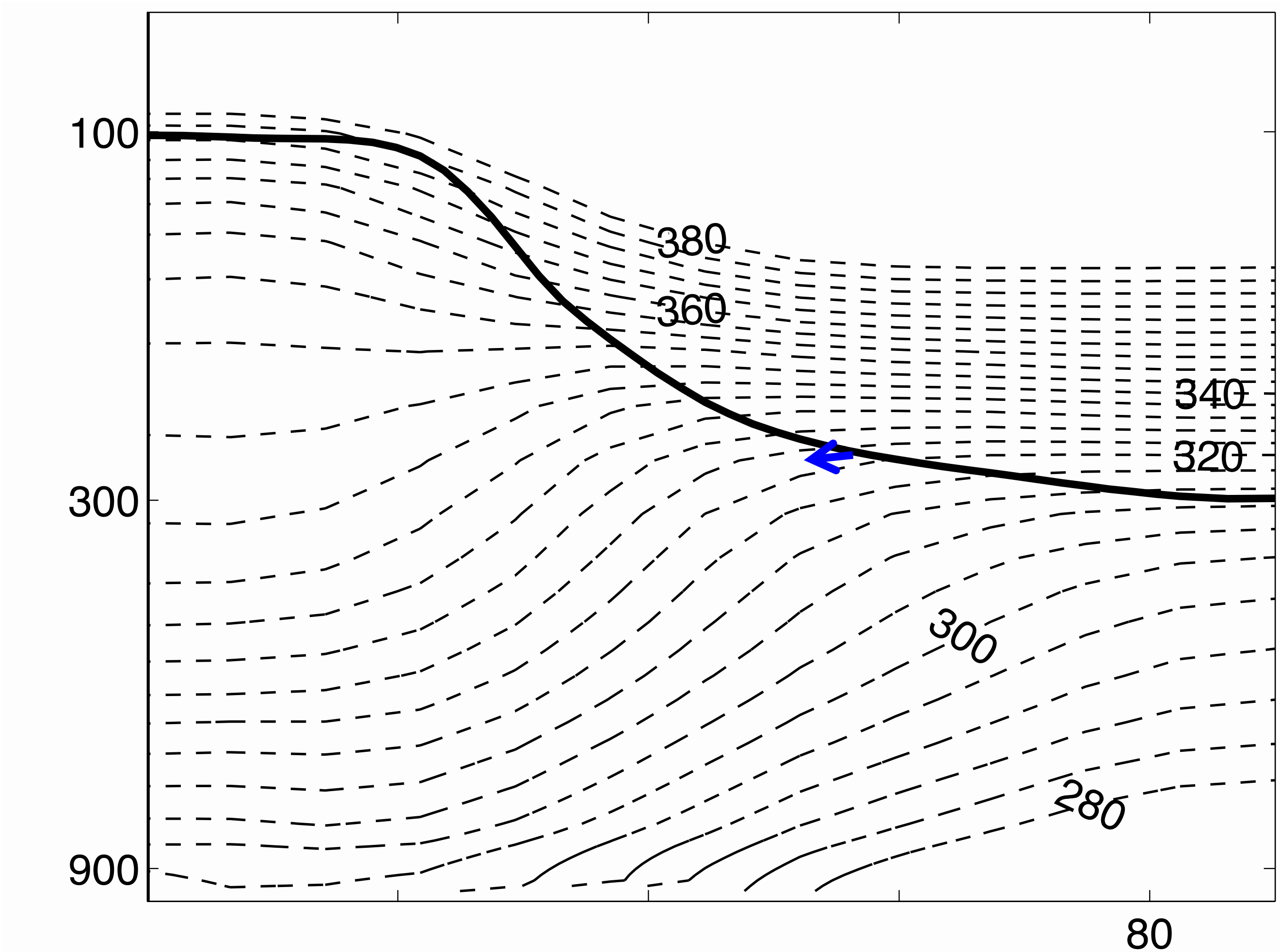
$$\frac{\partial m_{LMS}}{\partial t} = F_{STE} - F_{380K}$$

NO spatial distribution

$$\frac{\partial m_{\theta}}{\partial t} = F_{STE} - \frac{\partial F_{\theta}}{\partial \theta}$$

spatial distribution **YES**

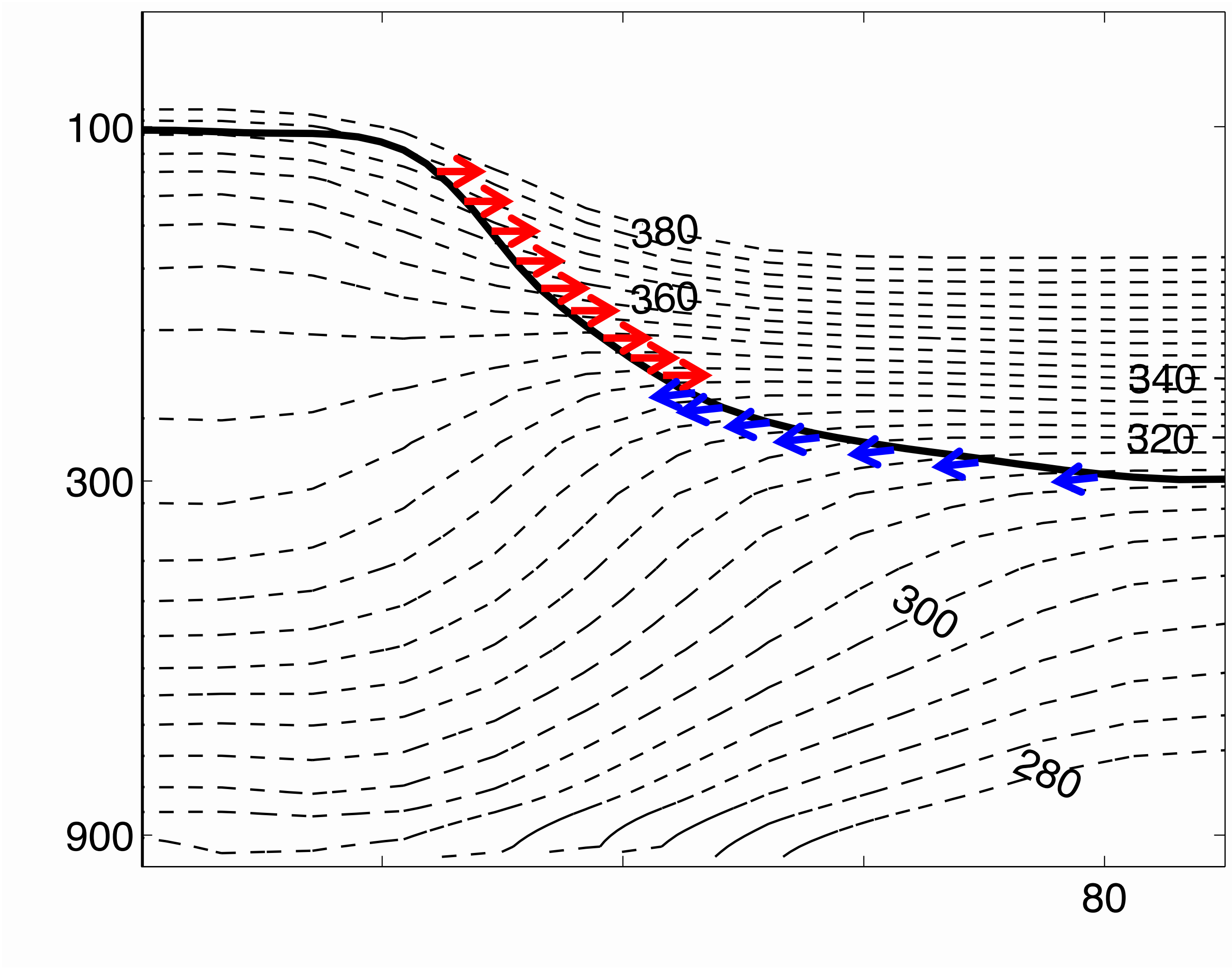
Isentropic STE <-> Meridional distribution of STE



Bold – tropopause

Dashed – isentropes

Isentropic STE <-> Meridional distribution of STE



High isentropes <-> **Low latitudes**   Low isentropes <-> **High latitudes**

Air mass STE

$$\frac{\partial m_\theta}{\partial t} = F_{STE} - \frac{\partial F_\theta}{\partial \theta}$$

isentropic air mass tendency

air mass STE

air mass diabatic flux div

Isentropic ozone tendency

ozone STE

ozone diabatic flux div

ozone chemical tendency

Ozone STE

$$\frac{\partial (\chi m_\theta)}{\partial t} = F^{\chi}_{STE} - \frac{\partial F^{\chi}_\theta}{\partial \theta} + S^{\chi}_\theta$$

χ – ozone mixing ratio

Budget diagnostics: net STE flux

unlike Langrangian **Trajectory** diagnostics: one-way STE flux

Models

- **WACCM** – Whole Atmosphere Community Climate Model at NCAR
- **CMAM** – Canadian Middle Atmosphere Model at Environment Canada

Models	Hor. Res.	Vert. Res.	Top	Duration	Nudging
SD-WACCM	1.5°×2°	88	0.0006Pa	1991-2009	MERRA
SD-CMAM	3.75°×4°	63	0.07Pa	1981-2010	ERA-interim

Tropopauses

- **O3S –** stratospheric ozone
- **e90 –** idealized tracer
- **WMO –** lapse rate
- **3PVU –** potential vorticity

LMS STE

LMS STE

The global ozone STE is **410 ~ 450 Tg/yr** from stratosphere to troposphere (in both models and for all tropopauses).

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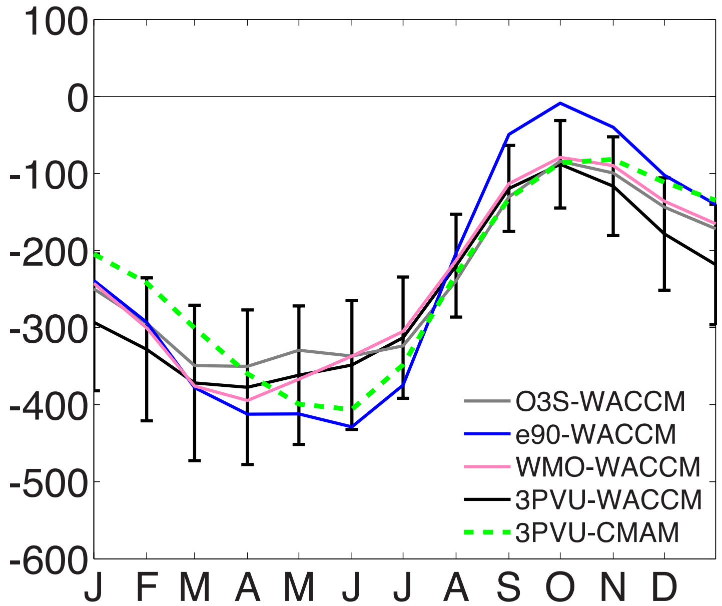

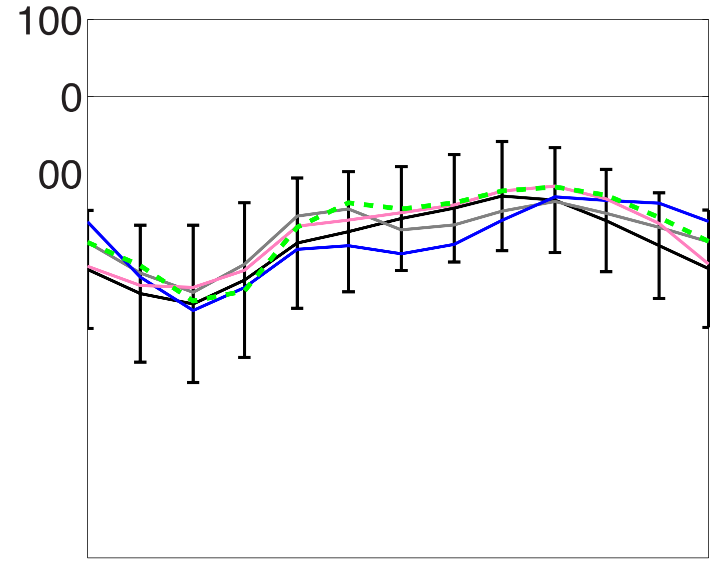

Positive – troposphere to stratosphere Negative – stratosphere to troposphere

LMS STE

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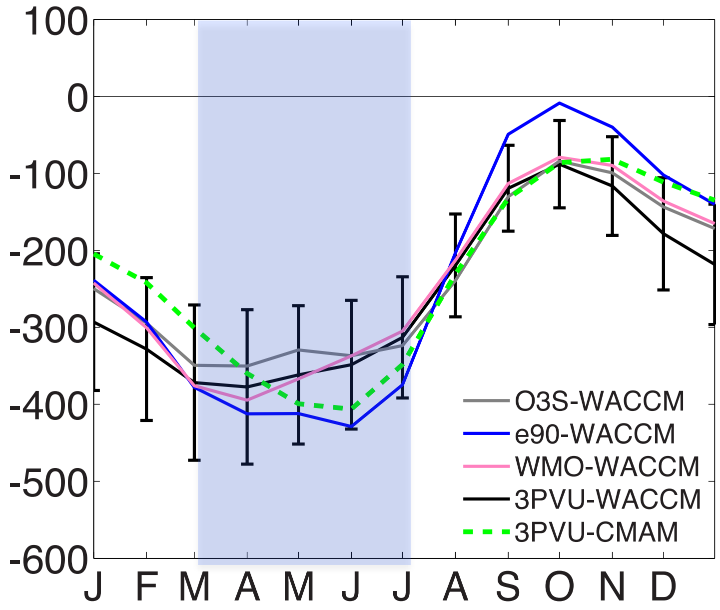
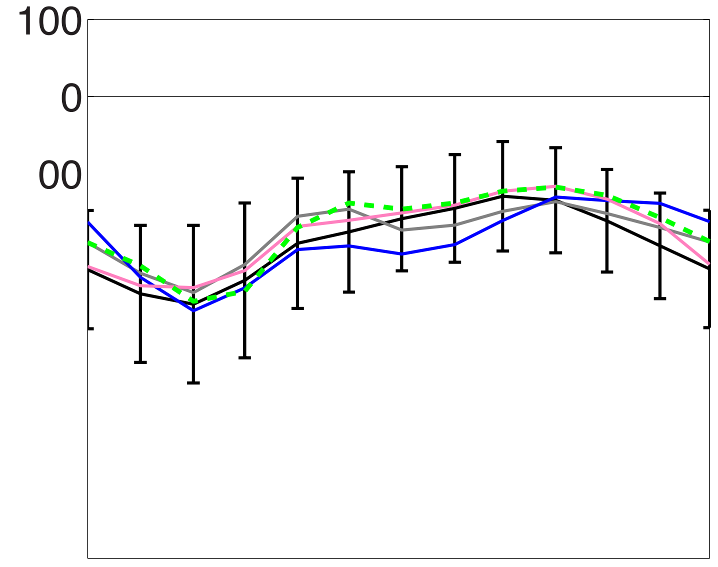




Positive – troposphere to stratosphere Negative – stratosphere to troposphere

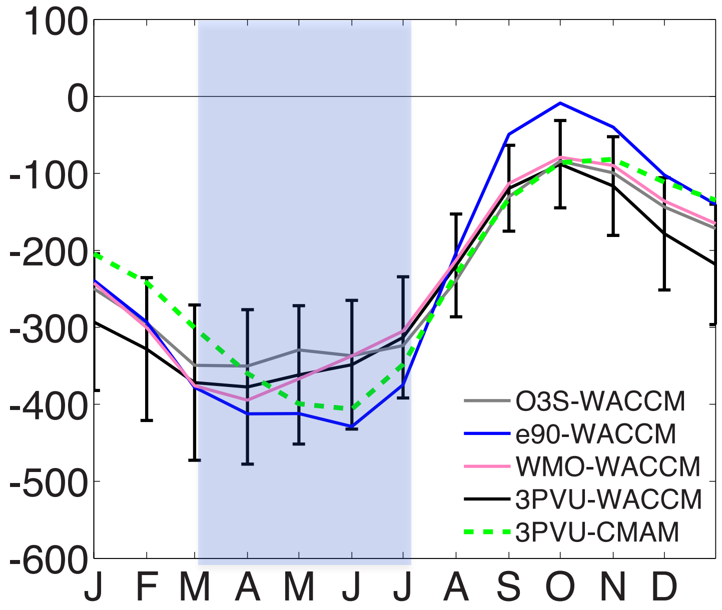
NH - maximum in late spring and early summer

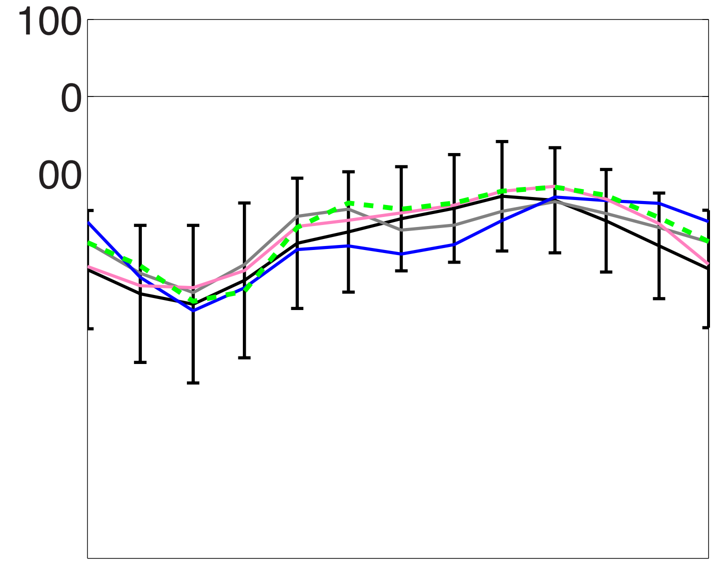
SH – much less seasonality, **focus on NH hereafter**

LMS STE

Consistent with previous works

The global ozone STE is **410 ~ 450 Tg/yr** from stratosphere to troposphere (in both models and for all tropopauses).





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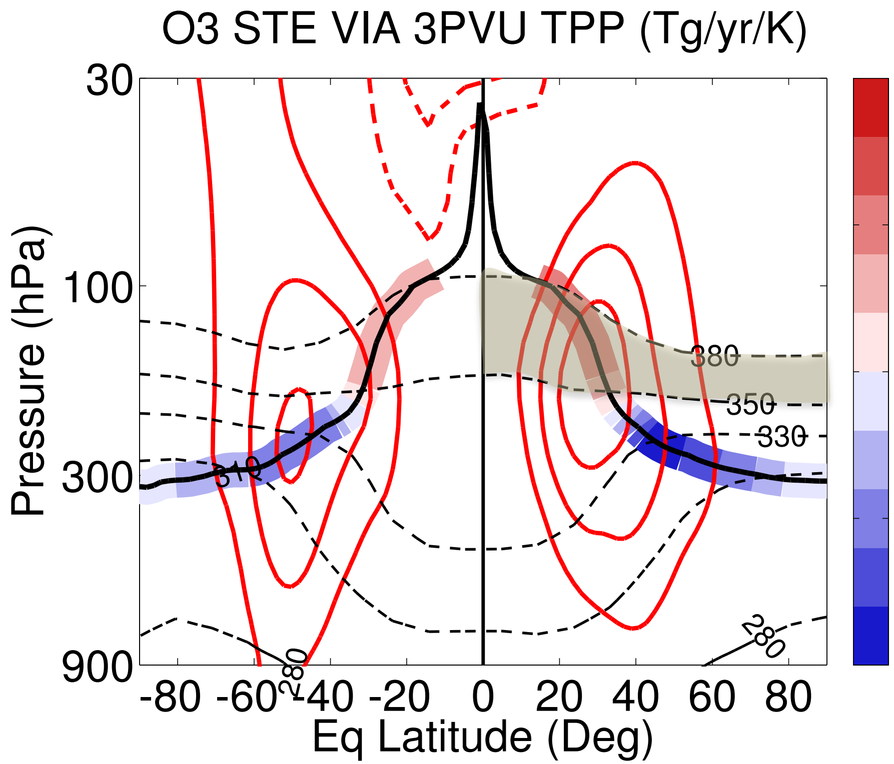
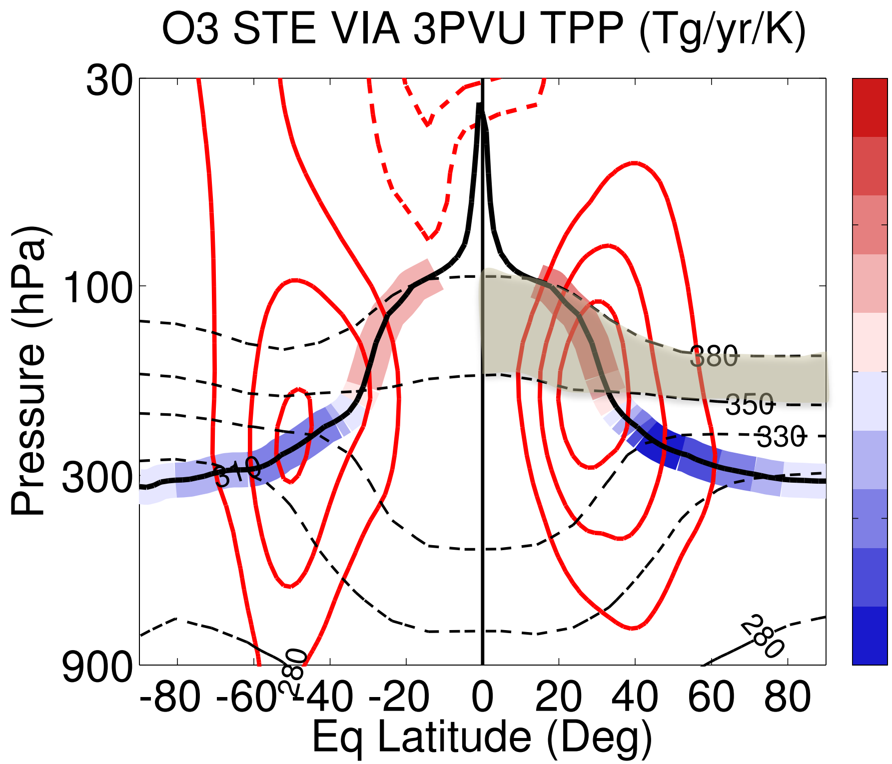
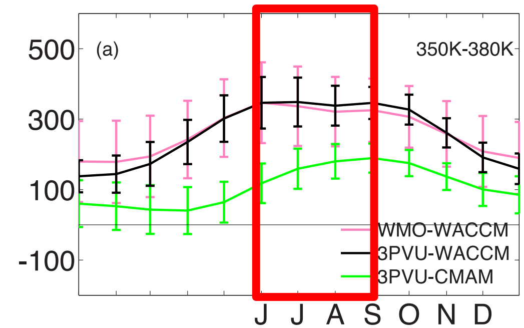
Meridional Structure of Ozone STE



Subtropical region (350K-380K):

Meridional Structure of Ozone STE



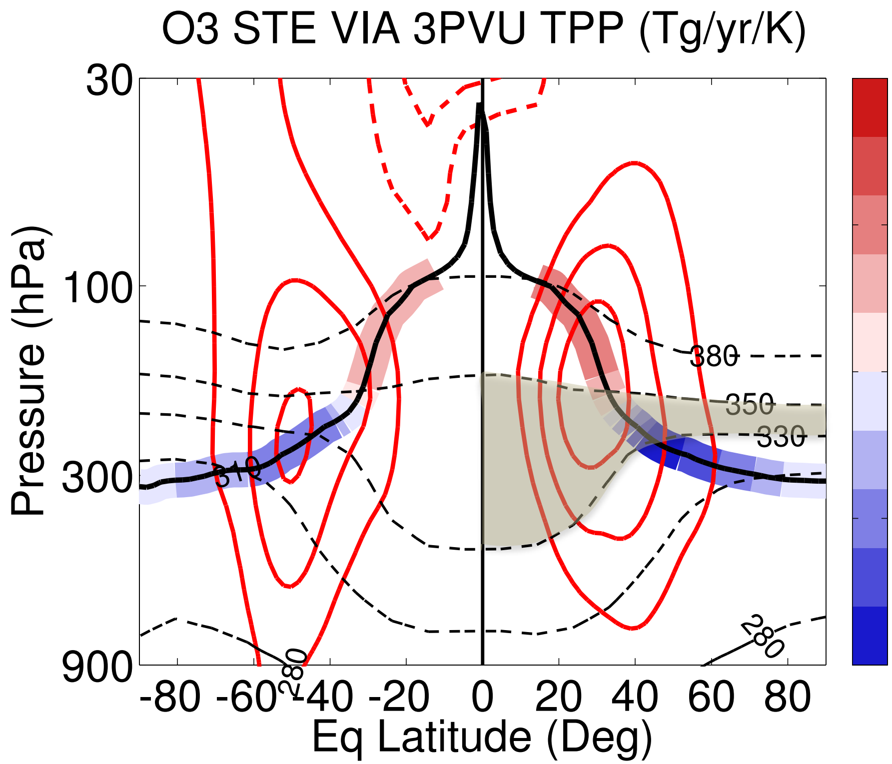


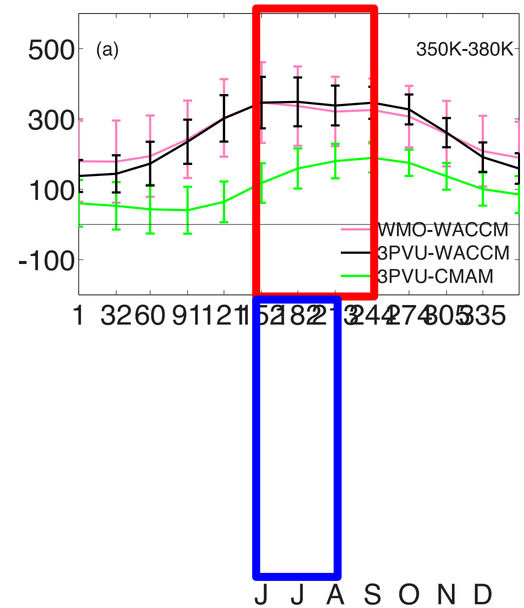
Summer

Subtropical region (350K-380K):

Troposphere-to-stratosphere ozone STE, with maximum in summer.

Meridional Structure of Ozone STE





Summer

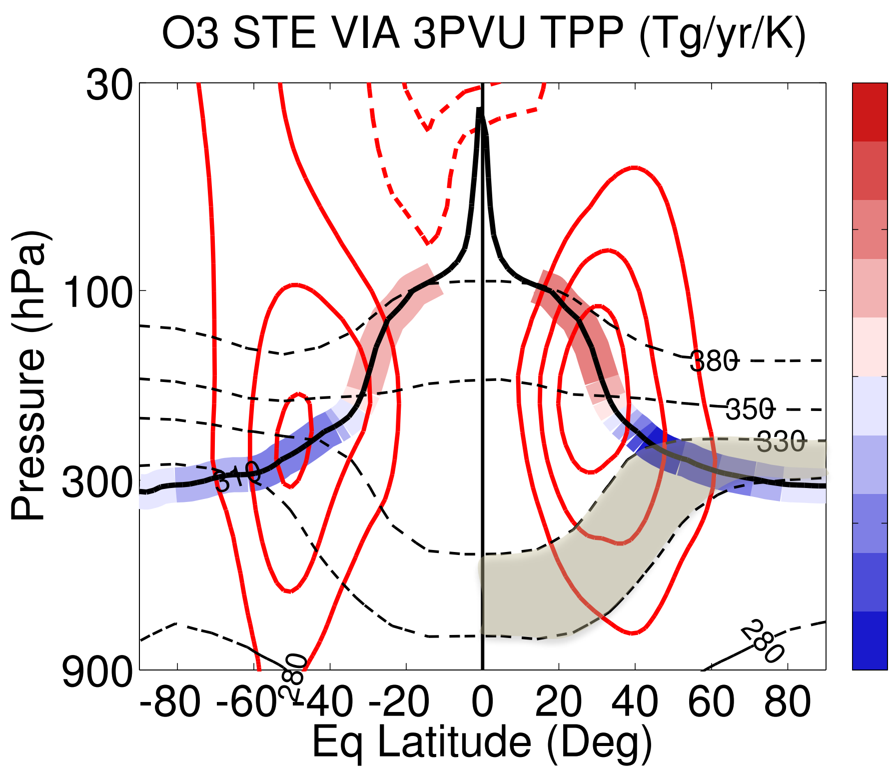
Summer

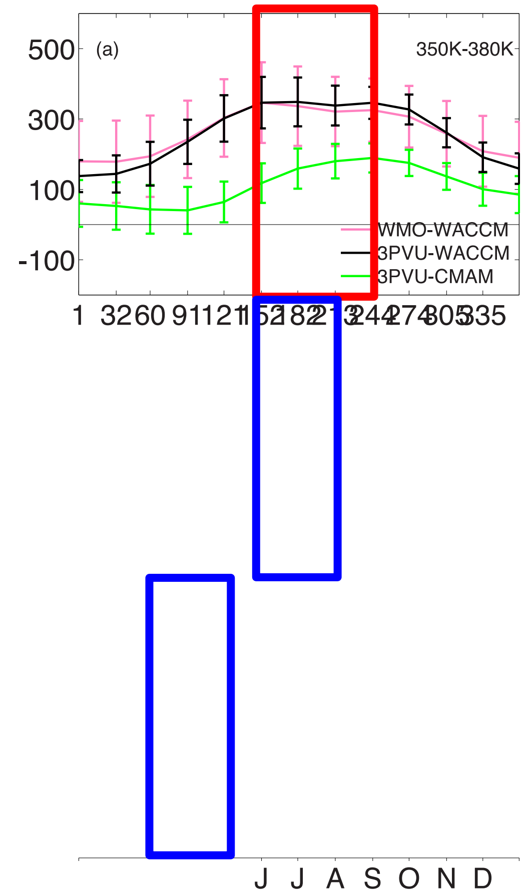
Core of jet (330K-350K):

Stratosphere-to-troposphere ozone STE, with maximum in summer;

Cancel greatly with the subtropical troposphere-to-stratosphere ozone STE.

Meridional Structure of Ozone STE





Summer

Summer

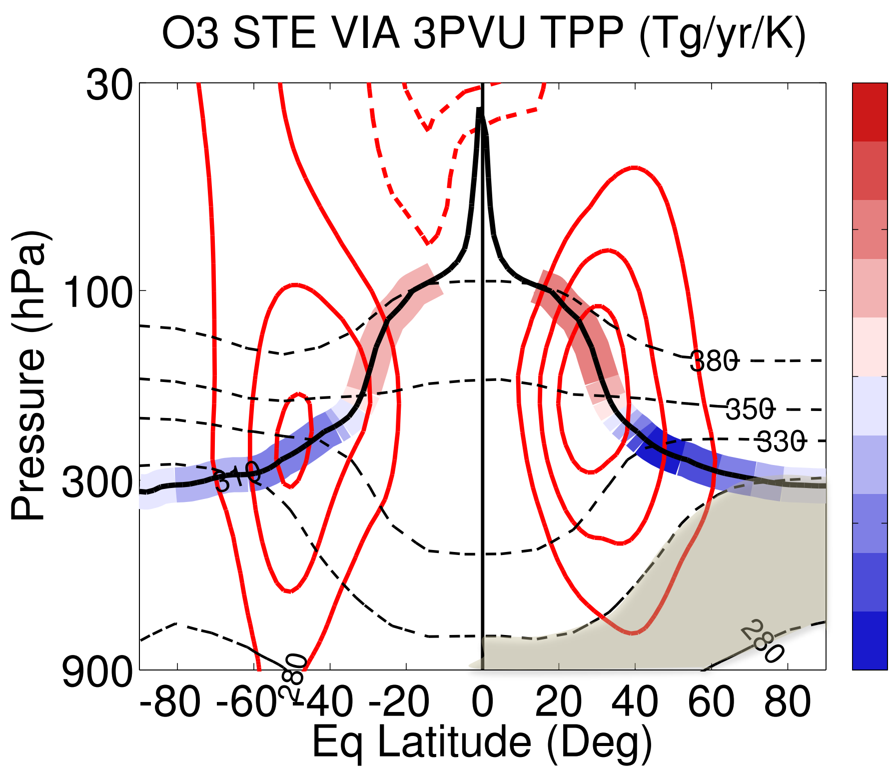
Spring

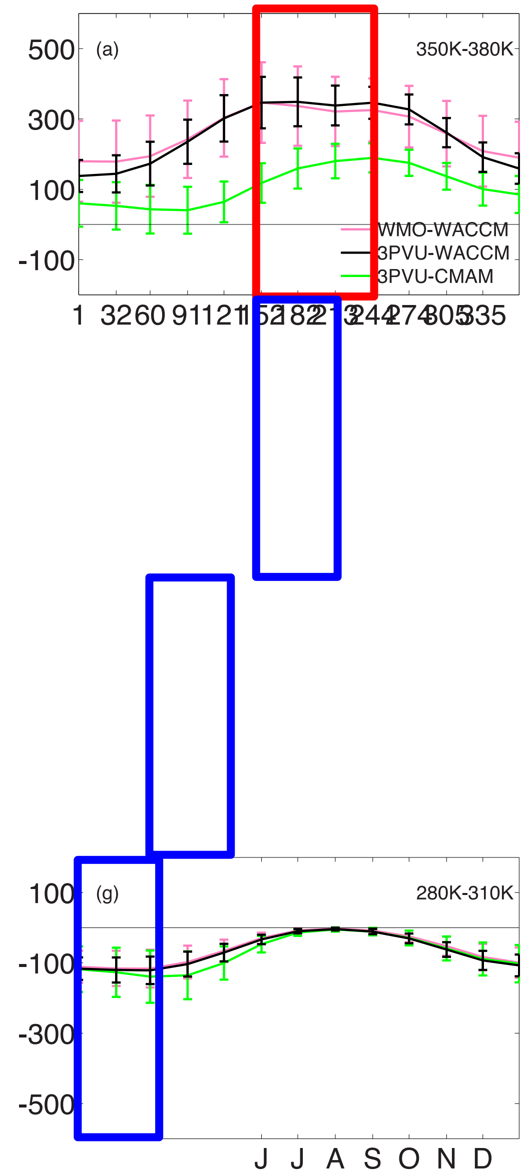
Poleward edge of jet (310K-330K):

Stratosphere-to-troposphere ozone STE, with maximum in spring;

Largest contribution to the NH ozone STE budget.

Meridional Structure of Ozone STE





Summer

Summer

Spring

Winter

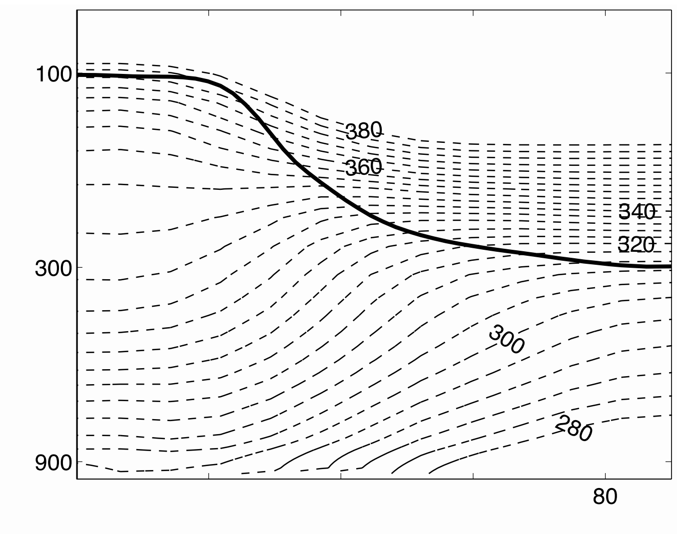
Polar region (280K-310K):

Stratosphere-to-troposphere ozone STE, with maximum in winter;

Much smaller in magnitude -> few stratospheric ozone can reach the surface.

Meridional Structure of Ozone STE

(subtropics)



(pole)

Bold – tropopause
Dashed – isentropes

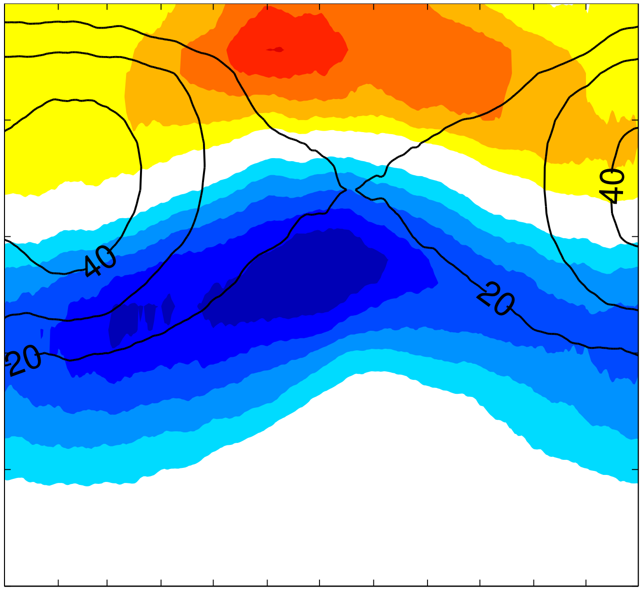
Colors – isentropic ozone STE
Contours – zonal wind

- Troposphere-to-stratosphere (upward) ozone transport in subtropics, stratosphere-to-troposphere (downward) ozone transport in extratropics.
- Maximum of downward ozone STE situates at the poleward edge of the jet, and moves seasonally with the jet.

Insensitive to choice of tropopause

WACCM-3PVU

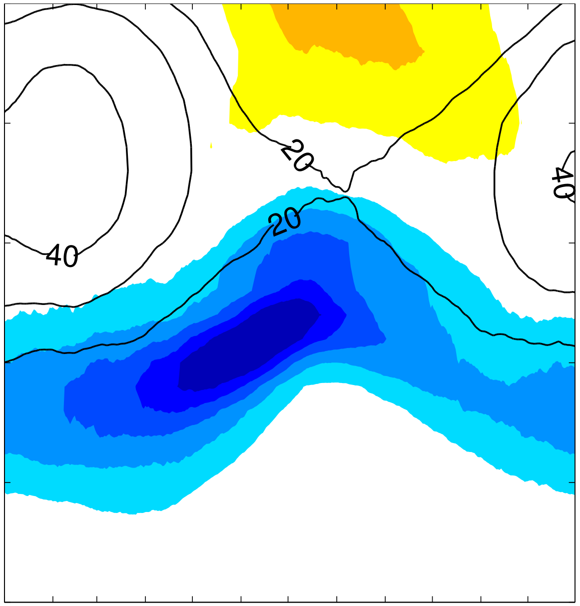
WACCM-WMO



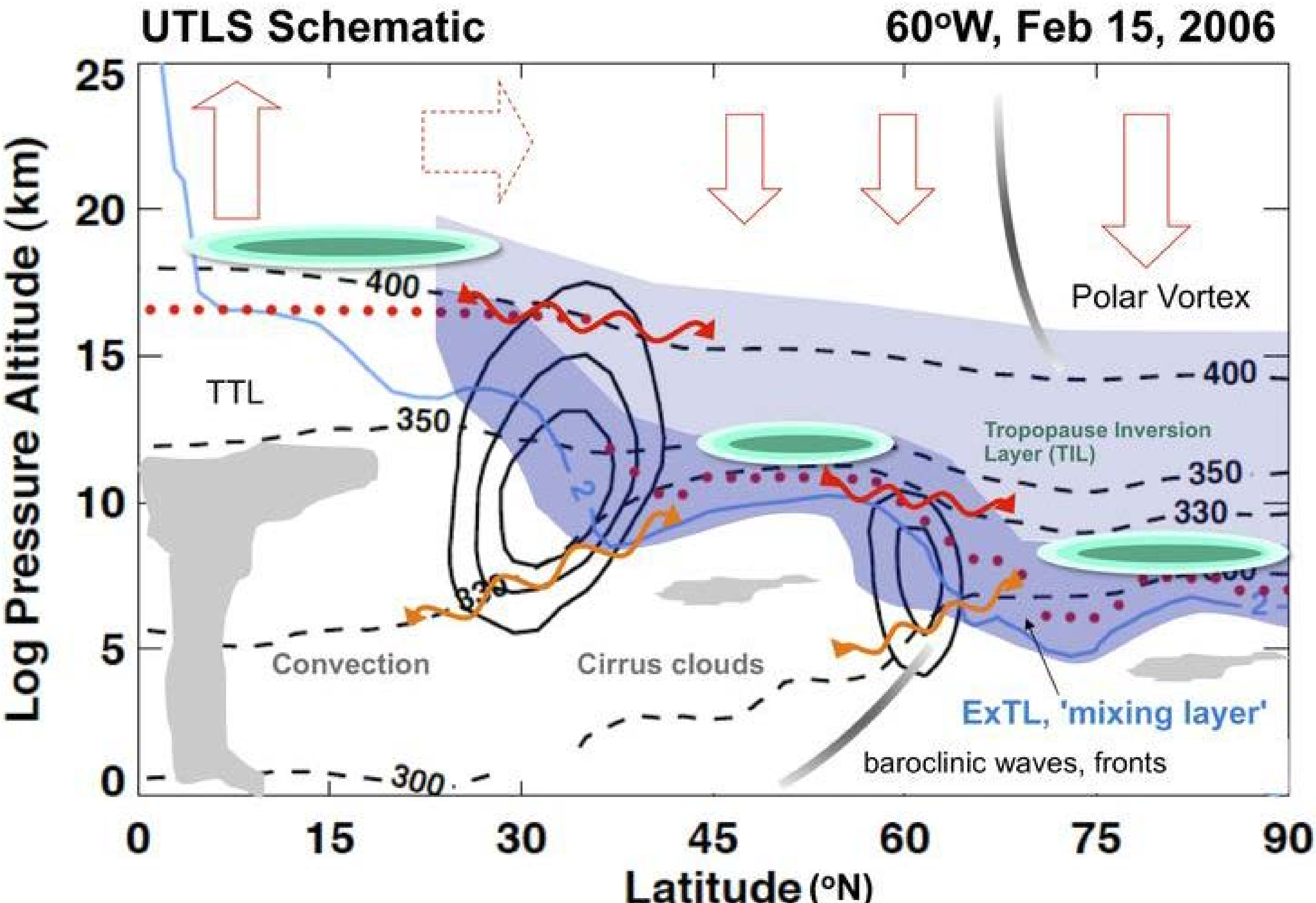
Insensitive to choice of model

WACCM-3PVU

CMAM-3PVU



Processes affecting STE



Dynamic Partition

For PV tropopause Q,

$$F_{STE} = -\frac{\partial M\left(\dot{q}\right)}{\partial Q} \approx -\dot{Q}\frac{\partial m}{\partial Q}$$

Nakamura, 2007

Dynamic Partition

For PV tropopause Q,

PV tendency

mass gradient

$$F_{STE} = -\frac{\partial M(\dot{q})}{\partial Q} \approx -\dot{Q}\frac{\partial m}{\partial Q}$$

Nakamura, 2007

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Nakamura, 2007

Similar to the advective Eulerian meridional air mass flux

$$F_y = v\frac{\partial m}{\partial y} = \dot{y}\frac{\partial m}{\partial y}$$

by replacing the Eulerian coordinate into PV coordinate

Dynamic Partition

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by replacing the Eulerian coordinate into PV coordinate

$$F_{STE} = -\frac{\partial M(\dot{q})}{\partial Q}$$

Air mass flux across the PV tropopause is caused by the changes in the tropopause itself (PV tendency)

Dynamic Partition

$$F_{STE} = -\frac{\partial M(\dot{q})}{\partial Q}$$

For PV tropopause tendency,

$$\dot{q} = \dot{q}_{\kappa} + \dot{q}_{S}$$

Isentropic PV Mixing (→ $\dot{q}_{\kappa}$)

Diabatic PV Source (→ $\dot{q}_{S}$)

Dynamic Partition

$$F_{STE} = -\frac{\partial M(\dot{q})}{\partial Q}$$

For PV tropopause tendency,

$$\dot{q} = \dot{q}_{\kappa} + \dot{q}_{S}$$

Isentropic PV Mixing

Diabatic PV Source

$$F^{\chi}_{STE} = F^{\chi}_{mix} + F^{\chi}_{dia}$$

where $F^{\chi}_{dia} = -\frac{\partial M(\chi \dot{q}_S)}{\partial Q}$

and $\dot{q}_S = \frac{q}{\sigma}\frac{\partial}{\partial \theta}(\sigma\dot{\theta})$

Dynamic Partition

$$F_{STE} = -\frac{\partial M\left(\dot{q}\right)}{\partial Q}$$

For PV tropopause tendency,

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Isentropic PV Mixing

Diabatic PV Source

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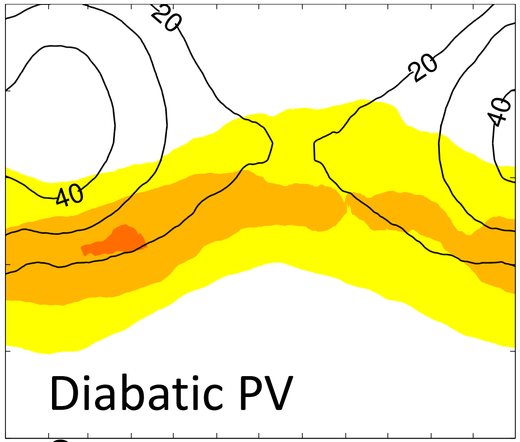
where $F^{\chi}_{dia} = -\frac{\partial M\left(\chi \dot{q}_{S}\right)}{\partial Q}$

and $\dot{q}_{S} = \frac{q}{\sigma}\frac{\partial}{\partial \theta}\left(\sigma \dot{\theta}\right)$

residual component

directly calculated

(subtropics)



(pole) Diabatic PV Source

Diabatic PV source: troposphere-to-stratosphere transport of ozone

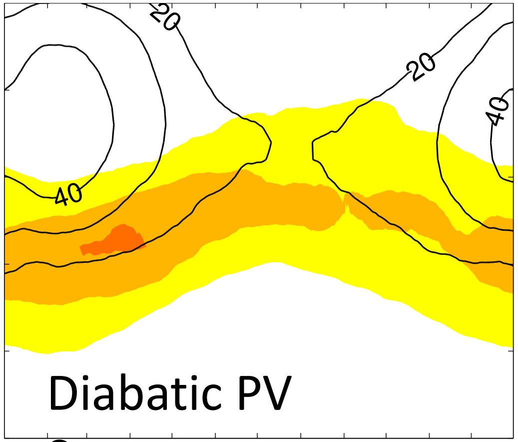
(subtropics)

(pole) Isentropic Mixing

Isentropic PV mixing: stratosphere-to-troposphere transport of ozone

Colors – ozone STE component
Contours – zonal wind

(subtropics)



(pole) Diabatic PV Source

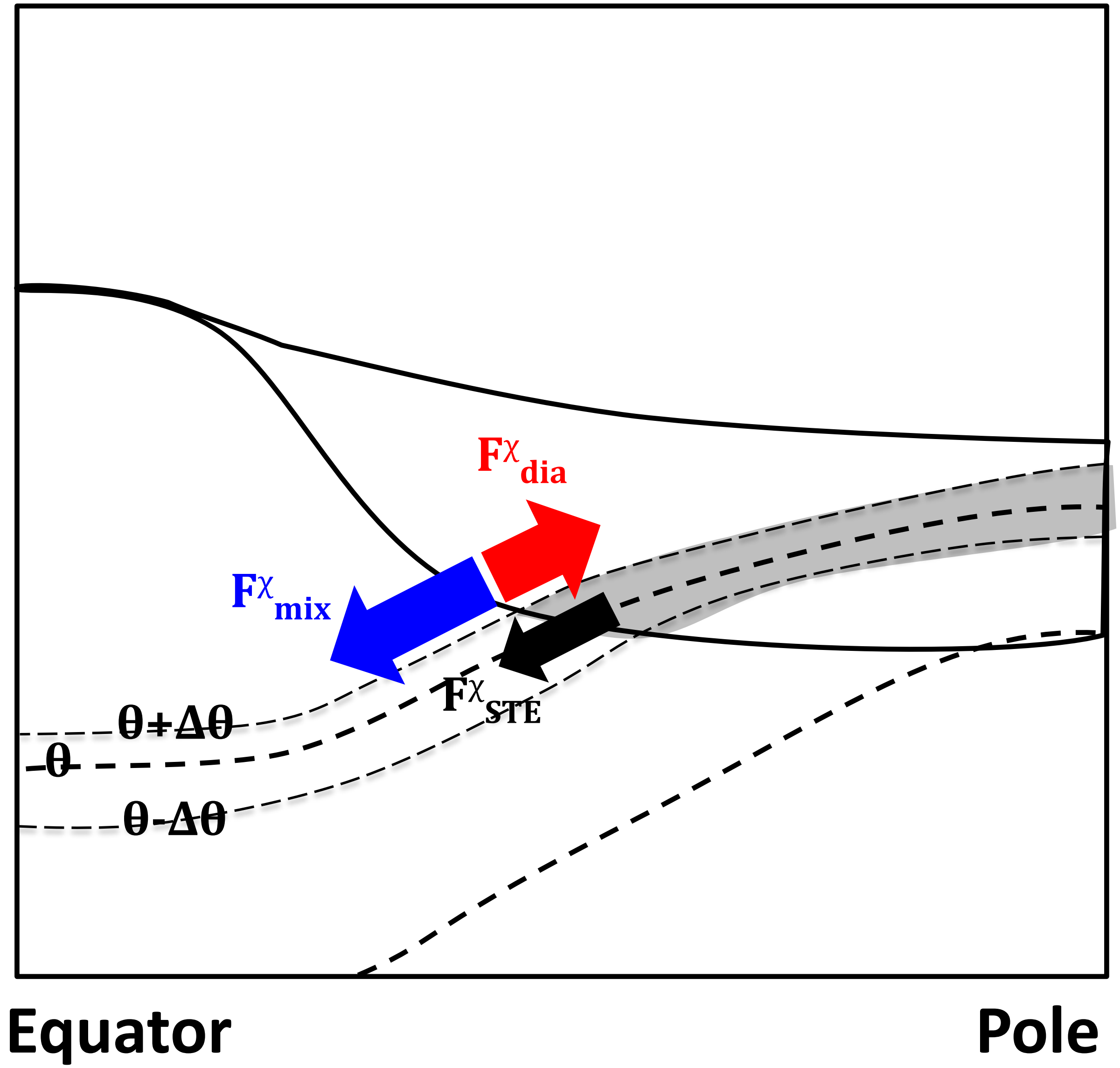
Net

(subtropics)

(pole) Isentropic Mixing

Colors – ozone STE component
Contours – zonal wind

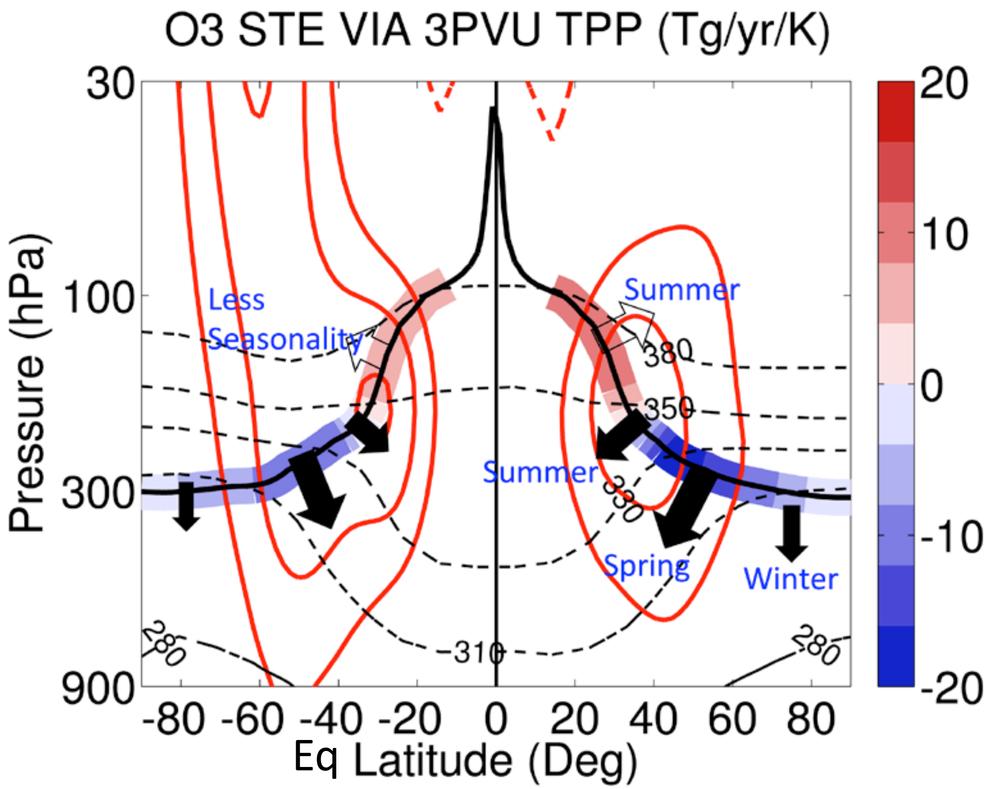
Large cancellation between ozone STE associated with isentropic mixing and ozone STE associated with diabatic PV source, but the former slightly overwhelms.



F^{χ}_{dia}
F^{χ}_{mix}
F^{χ}_{STE}
θ+Δθ
θ
θ-Δθ
Equator
Pole

Summary

- Different isentropic (meridional) regions correspond to ozone STE with different direction, magnitude, and seasonality.



Summary

- The strongest ozone STE occurs on the poleward flank of the tropospheric jet and shifts seasonally with the jet.

Summary

- Diabatic heating induces troposphere-to-stratosphere ozone STE, while isentropic mixing induces mostly stratosphere-to-troposphere ozone STE. The latter overwhelms slightly over the former.