# Inter-annual Variation of the Antarctic Ozone Hole and Its Implication for Seasonal Prediction

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with

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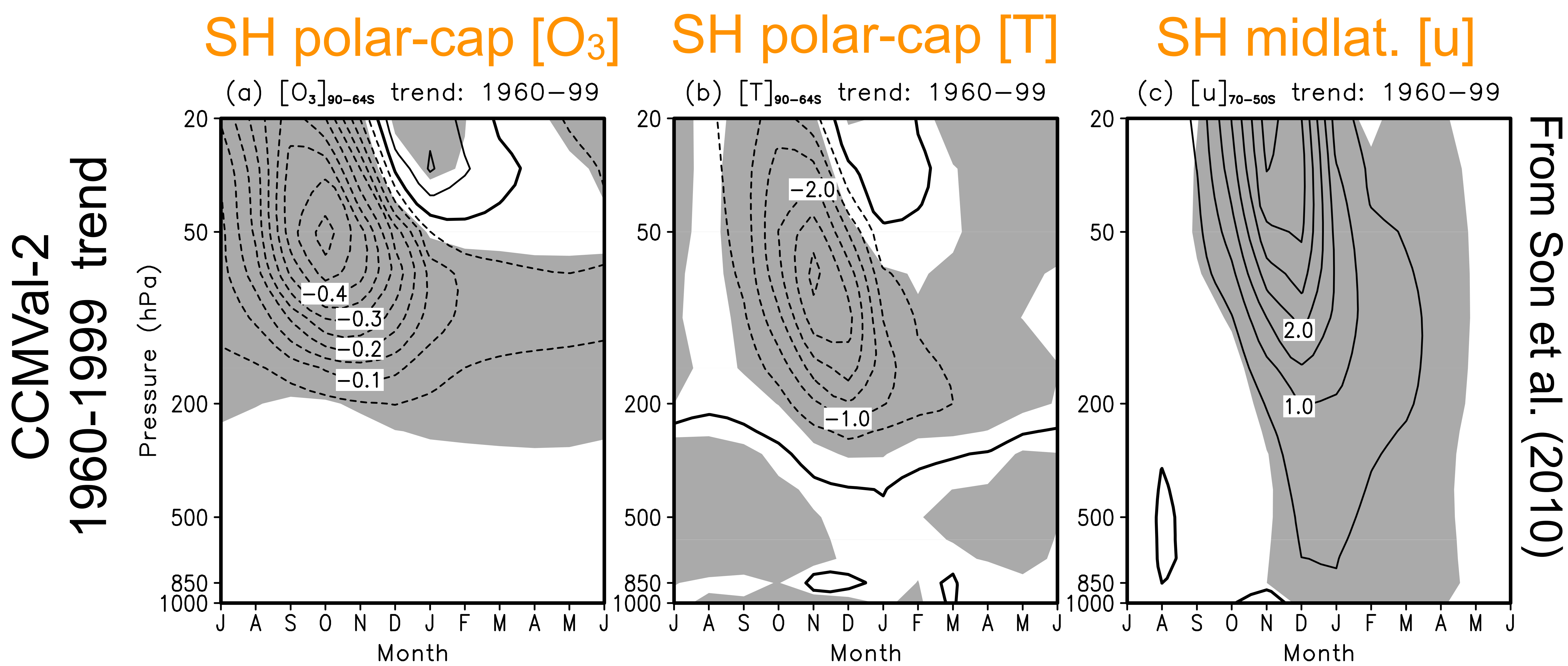
# SH circulation change associated w/ $O_3$ depletion




- SH-summer circulation change in the late 20th century is caused by combined effects of ozone depletion and greenhouse gas increase. The former plays at least a comparable role to the latter.

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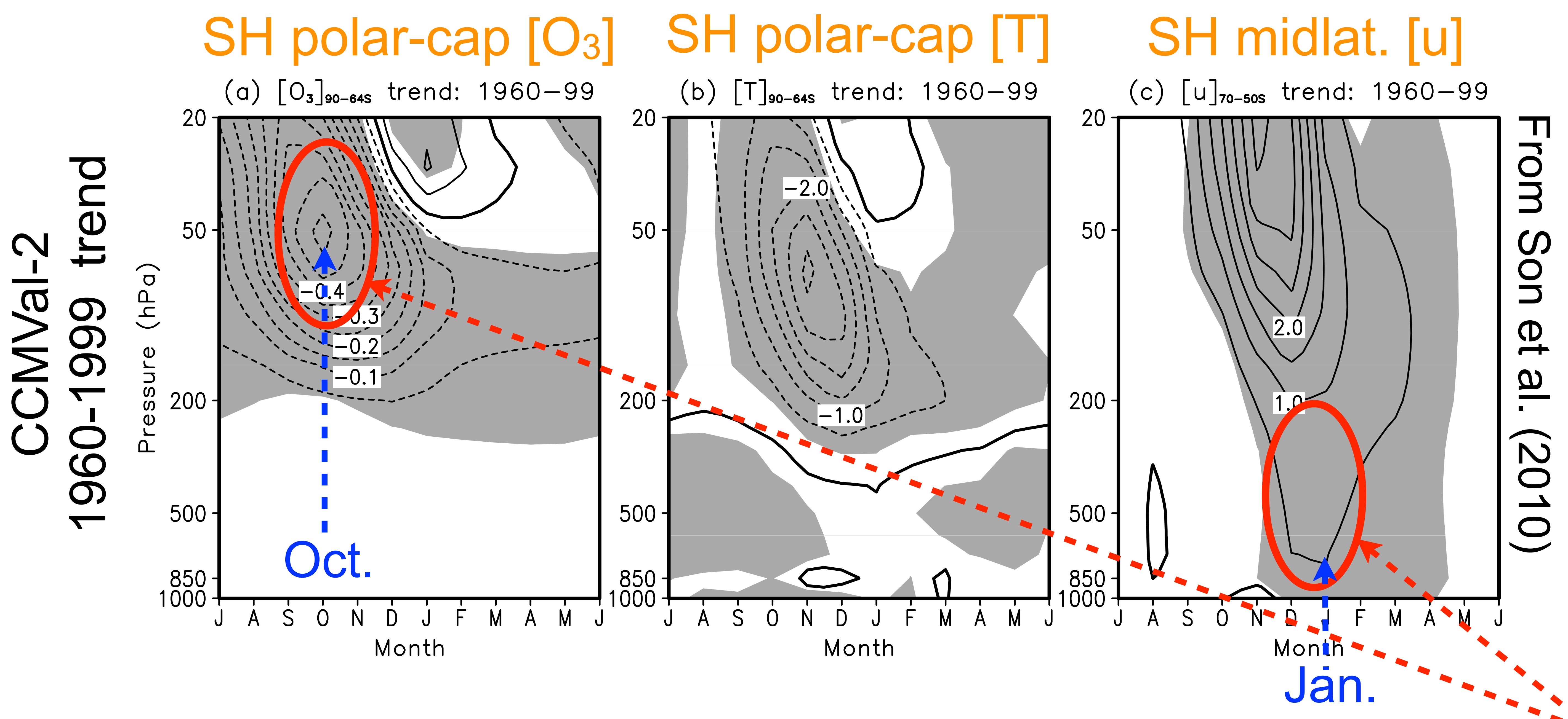


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- The ozone hole in spring significantly influences tropospheric circulation in summer.

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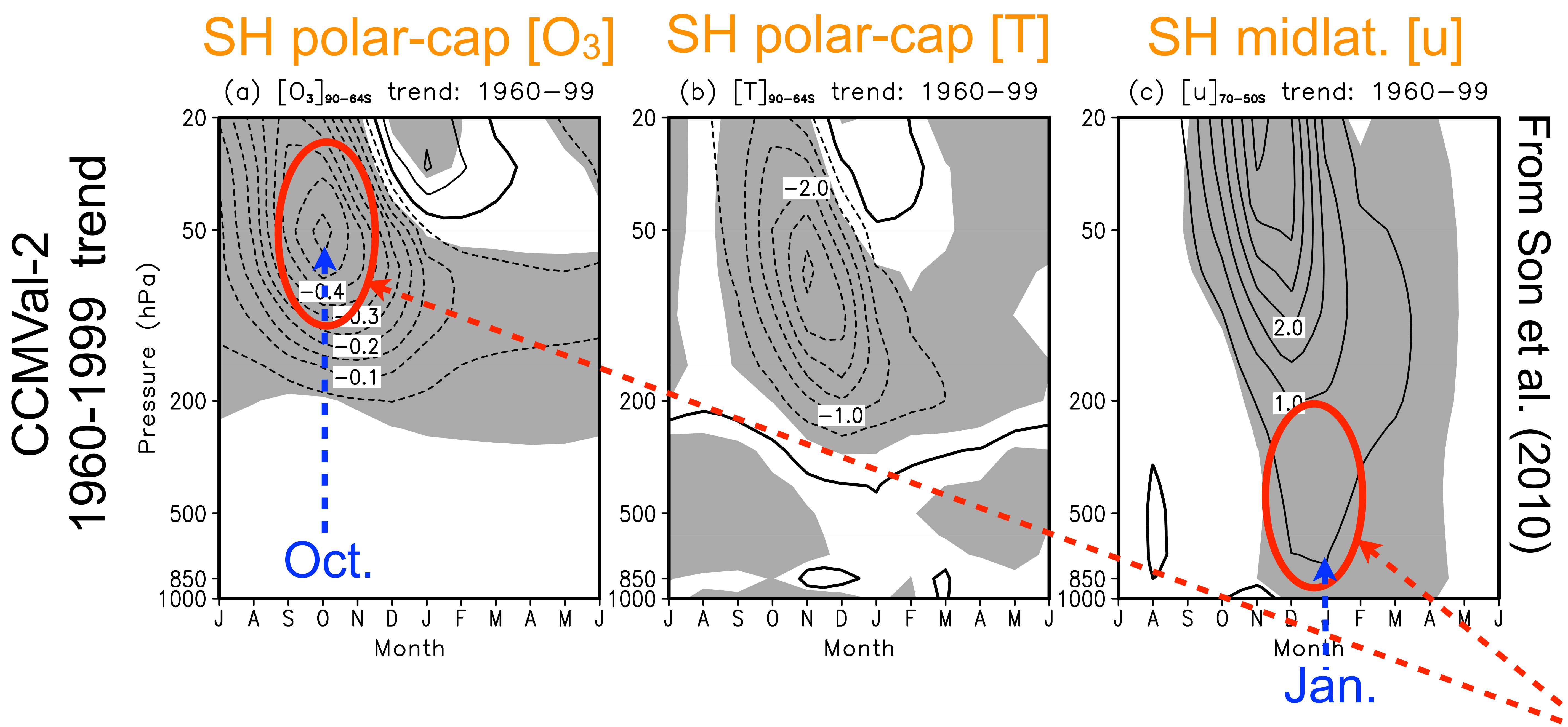
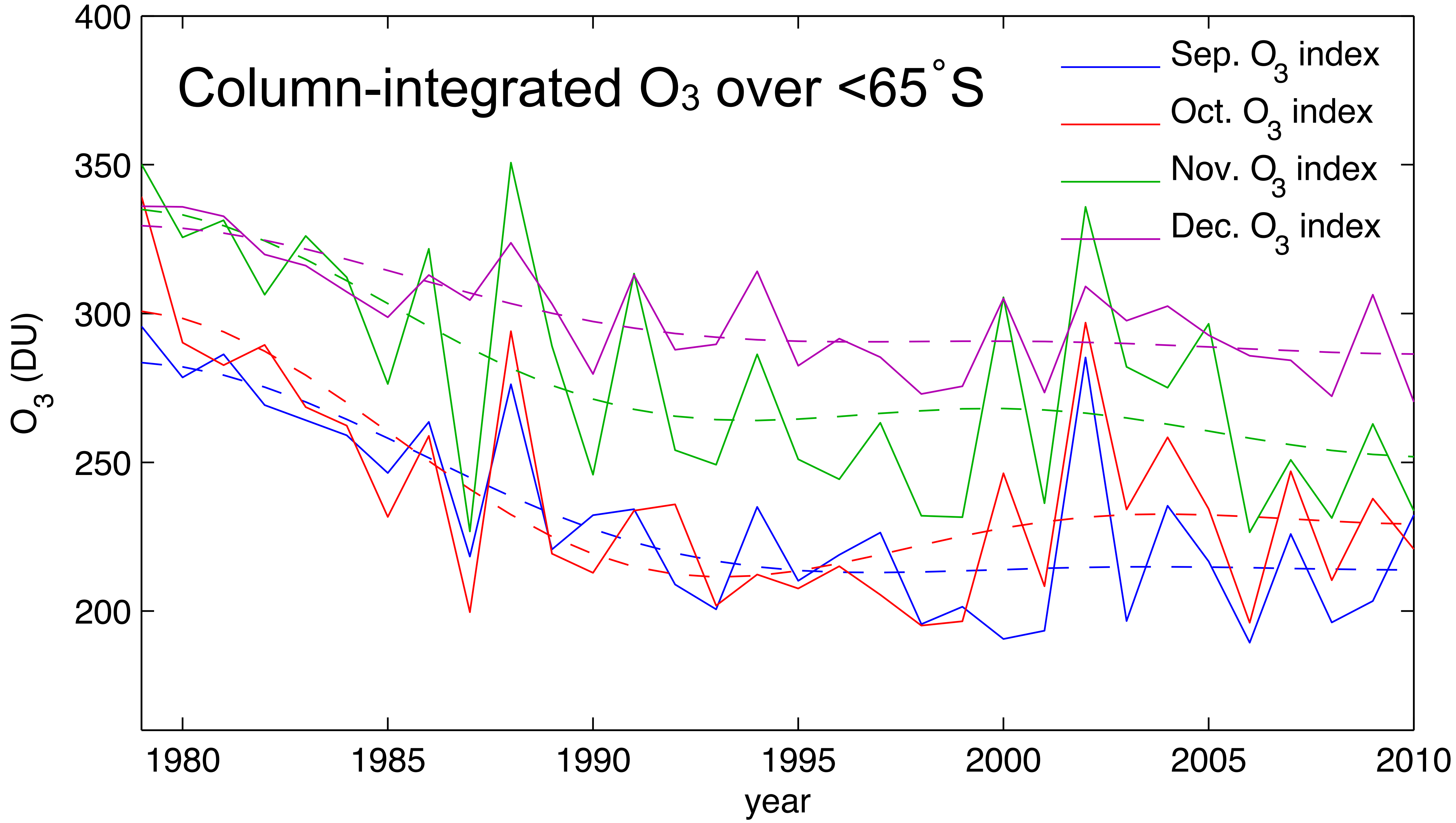



- SH-summer circulation change in the late 20th century is caused by combined effects of ozone depletion and greenhouse gas increase. The former plays at least a comparable role to the latter.

- The ozone hole in spring significantly influences tropospheric circulation in summer.

- Seasonally-delayed impact of the Antarctic ozone depletion on the long-term circulation change in the Southern Hemisphere has been widely documented. (Thompson and Solomon, 2002; Gillett and Thompson, 2003; Shindell and Schmidt, 2004; Arblaster and Meehl, 2006; Miller et al. 2006; Cai and Cowan, 2007; Perlwitz et al. 2008; Son et al. 2010; Polvani et al. 2011; McLandress et al. 2011, Lee and Feldstein 2013).

# Long-term trend vs. variability of $O_3$




- Antarctic ozone concentration has been changing with a significant inter-annual variation. Its 1std is comparable to the long-term trend.
- The impact of inter-annual variability of the Antarctic ozone concentration on the surface climate has not well been examined.

# Key questions

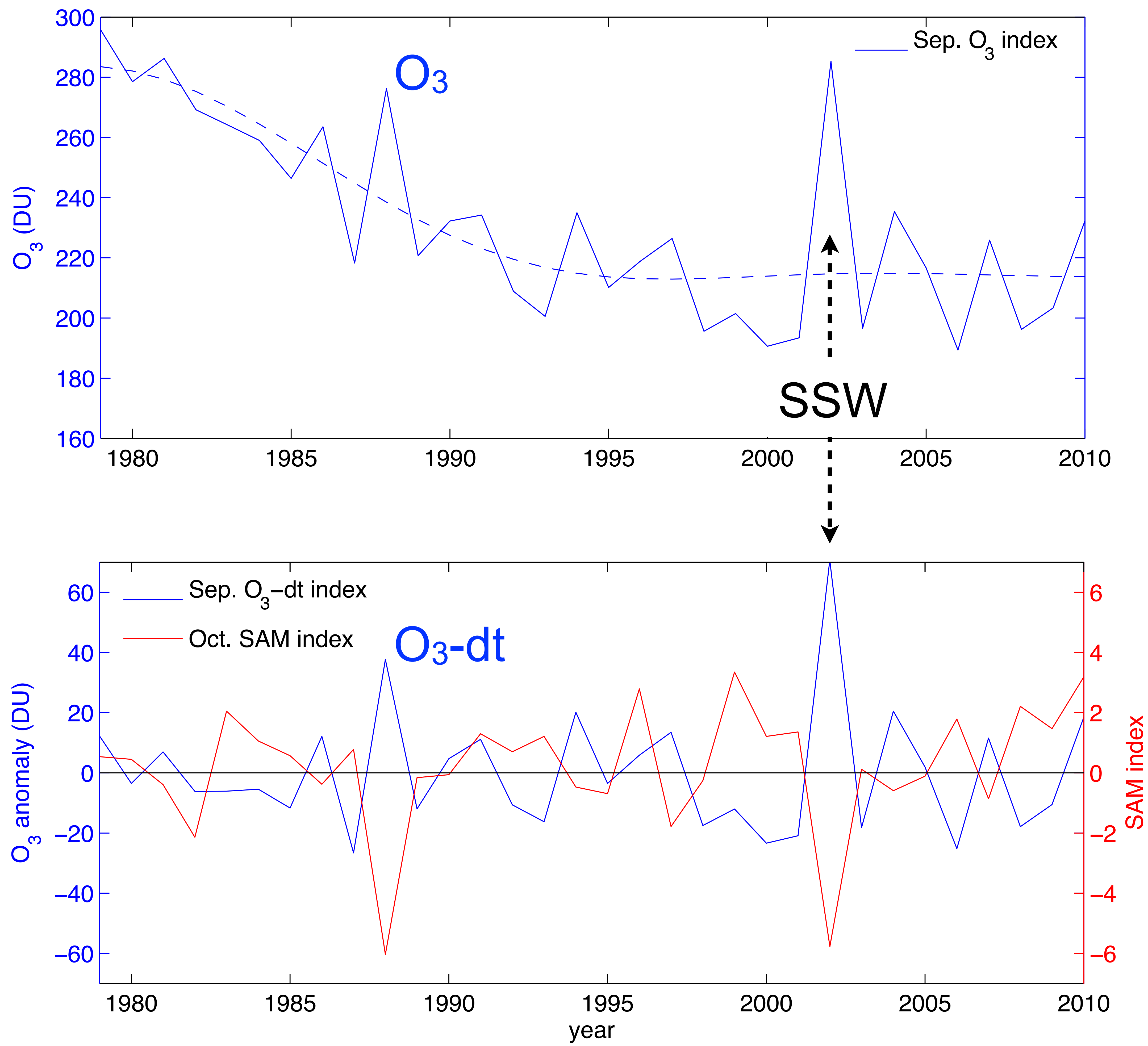
***Does inter-annual variability of the Antarctic ozone hole affect Southern Hemisphere (SH) surface climate?***

***If it does, how much is it important in comparison to ENSO and IOD?***

# Data

- Total column $O_3$ concentration from NIWA merged satellite ozone data for time period of 1979-2010.
- Tropospheric fields from ERA-Interim
- Station-based SAM index from Marshall (2003)
- The Nino3.4 index from NOAA & Indian Ocean Dipole Mode Index (DMI) from JAMSTEC.
- Station-based precipitation and surface temperature from CRU station data of University of East Anglia.
- High-resolution regional data from Bureau of Meteorology analysis.

# Inter-annual component ($O_3$-dt)




- $O_3$ index is defined by polar-cap total column ozone, integrated poleward of 65˚S.
- Slowly-varying component is derived using Fourier filter.
- Inter-annual variation, $O_3$-dt, is defined by the deviation from the slowly-varying component.

# What controls $O_3$-dt?

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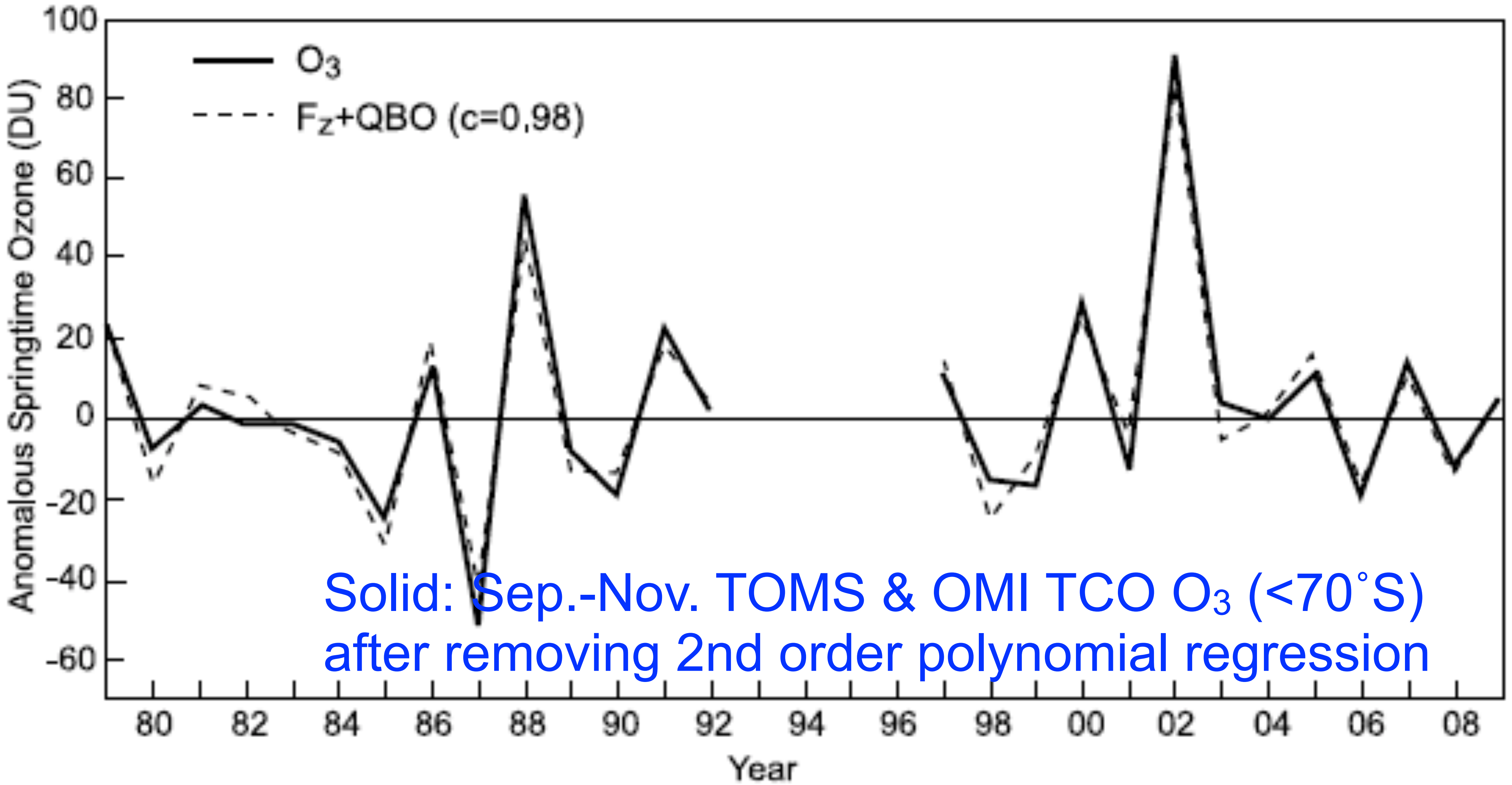
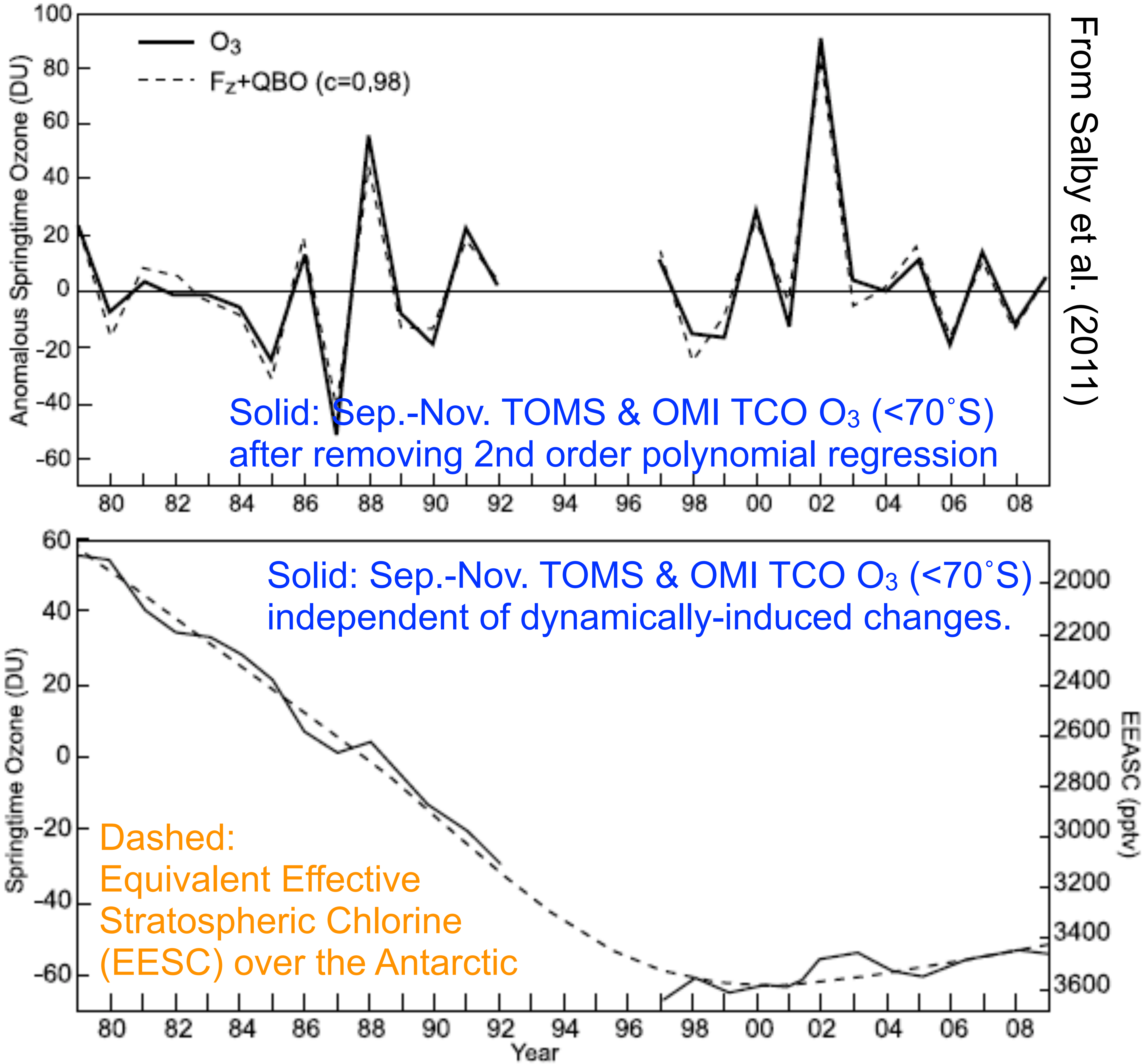



Dashed: $O_3$ regressed against LS Fz and QBO

From Salby et al. (2011)

- $O_3$-dt is mainly controlled by wave forcing: Higher ozone concentration is associated with stronger wave forcing in the extratropical lower stratosphere.

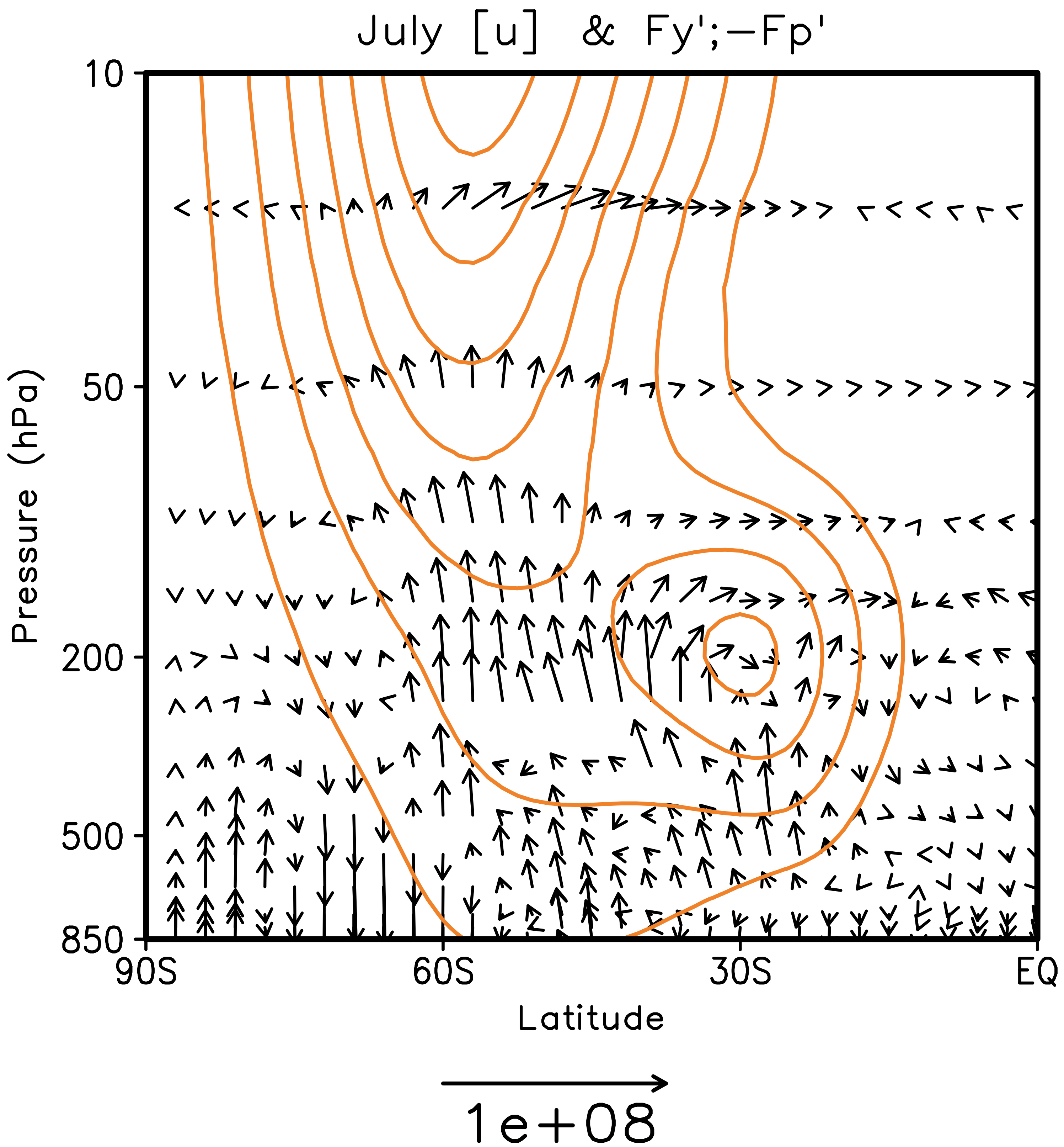
# What controls $O_3$-dt?




- $O_3$-dt is mainly controlled by wave forcing: Higher ozone concentration is associated with stronger wave forcing in the extratropical lower stratosphere.
- Slowly-varying component of $O_3$ is largely controlled by ozone depleting species.

# What controls $O_3$-dt?

July EP flux anomaly
regressed against Sep. $O_3$-dt




(1) Enhanced vertical wave propagation in winter.

(2) Enhanced wave breaking in the stratosphere strengthens a large-scale stratospheric circulation, causing adiabatic warming in the polar stratosphere.

(3) Polar warming then reduces the formation of PSC (type II) in winter, resulting in less ozone destruction in spring. Enhanced stratospheric circulation is also likely to transport more ozone from the extratropical upper stratosphere to the polar lower stratosphere. The net result is anomalously high Antarctic ozone concentration in spring.

# Vertical coupling

# Vertical coupling: r($O_3$/$O_3$-dt, SAMI)

| $O_3$ \ SAM | *Sep.* | *Oct.* | *Nov.* | *Dec.* | *Jan.* | *Feb.* | *Mar.* |
|---|---|---|---|---|---|---|---|
| *Sep* | -0.17 | -0.48** | -0.09 | -0.13 | -0.50** | -0.15 | -0.03 |
| *Oct.* | -0.27 | -0.46** | -0.18 | -0.29 | -0.50** | -0.21 | -0.07 |
| *Nov.* | -0.33 | -0.51** | -0.20 | -0.31 | -0.49** | -0.33 | 0.01 |

- Sep.-Oct.-Nov. $O_3$ is correlated with Oct. & Jan. SAM indices at the 99% confidence level.

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| *Sep* | -0.23 | **-0.66**** | -0.19 | 0.04 | -0.09 | -0.06 | 0.12 |
| *Oct.* | -0.32 | **-0.64**** | -0.28 | -0.19 | -0.23 | -0.18 | 0.06 |
| *Nov.* | -0.40* | **-0.58**** | -0.25 | -0.23 | -0.22 | -0.32 | 0.14 |

- Sep.-Oct.-Nov. $O_3$ is correlated with Oct. & Jan. SAM indices at the 99% confidence level.
- Sep.-Oct.-Nov. $O_3$-dt is correlated only with Oct. SAM index at the 99.9% confidence level. No correlation with Jan. SAM index is observed.

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By inter-annual variation of $O_3$.

By long-term trend of $O_3$; Consistent with previous findings that show time-lagged response of tropospheric circulation to springtime $O_3$ depletion.

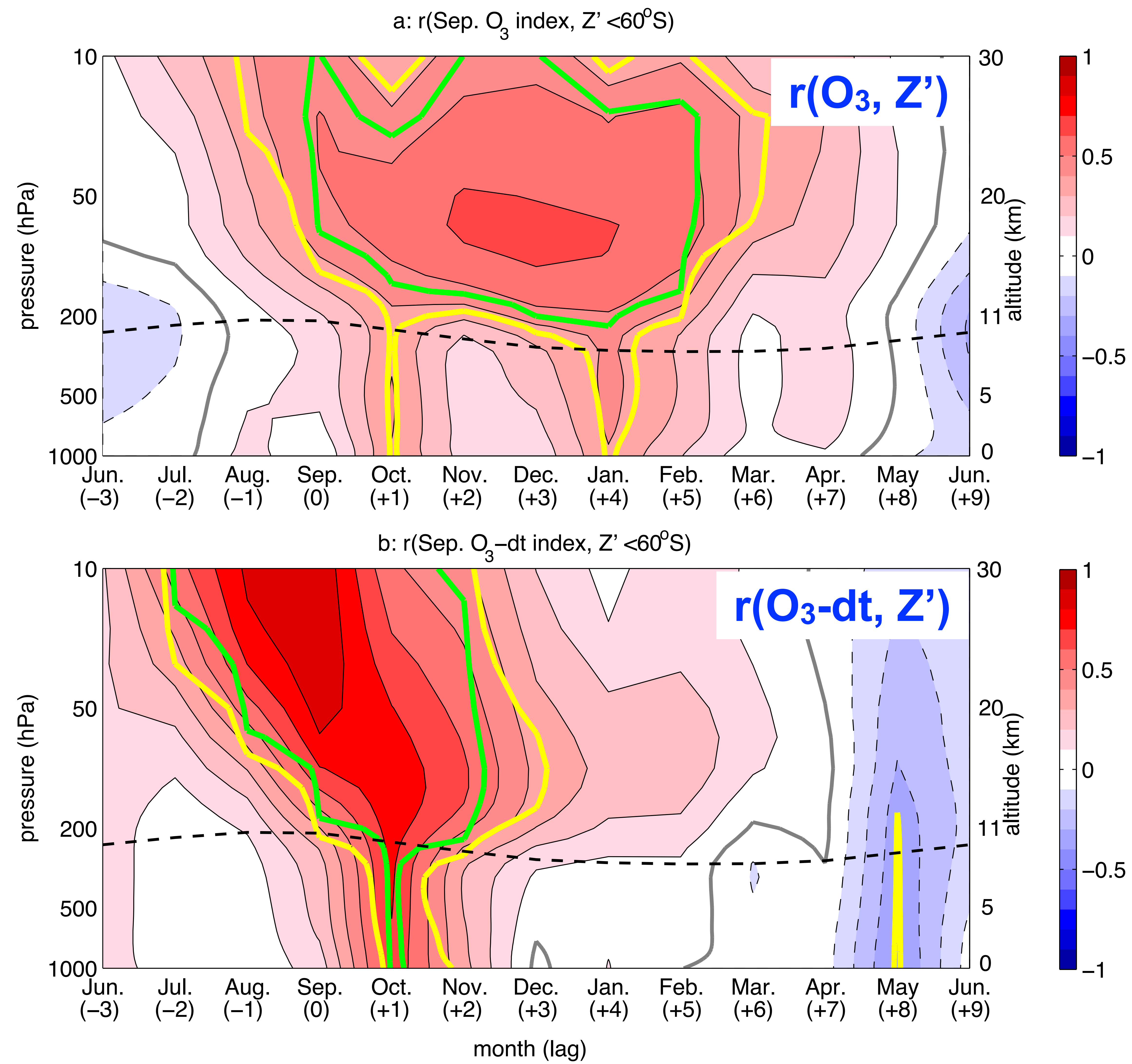
# Vertical coupling: r($O_3$-dt, SAMI)

| ALL $O_3$-dt \ SAM | *Sep.* | *Oct.* | *Nov.* | *Dec.* |
|---|---|---|---|---|
| *Sep* | -0.23 | **-0.66**** | -0.19 | 0.04 |
| *Oct.* | -0.32 | **-0.64**** | -0.28 | -0.19 |
| *Nov.* | -0.40* | **-0.58**** | -0.25 | -0.23 |

| No 2002 $O_3$-dt \ SAM | *Sep.* | *Oct.* | *Nov.* | *Dec.* |
|---|---|---|---|---|
| *Sep* | -0.13 | -0.50** | -0.21 | -0.02 |
| *Oct.* | -0.25 | -0.51** | -0.30 | -0.27 |
| *Nov.* | -0.35 | -0.46** | -0.26 | -0.30 |

- Strongest correlation between Sep. $O_3$-dt and Oct. SAM index : Higher $O_3$ concentration is followed by negative SAM with a month lag.
- Without 2002 SSW event, correlation coeff. is still about -0.5.
- Quantitatively similar results are also found when $O_3$ is replaced by 10-hPa polar-cap geopotential height anomaly.

# Vertical coupling: r(Sep. $O_3$/$O_3$-dt, polar-cap Z')



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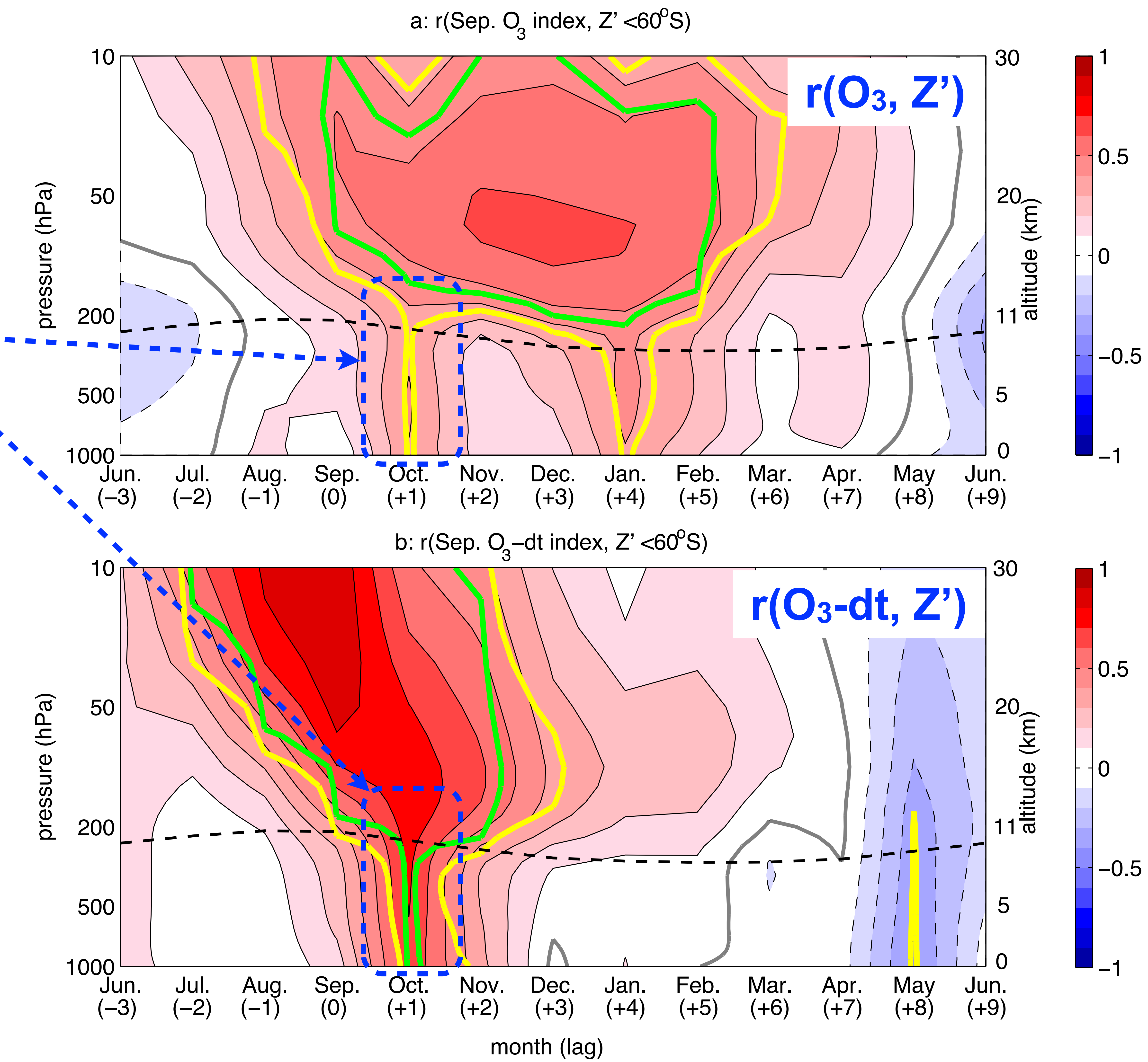
By inter-annual variation of $O_3$.



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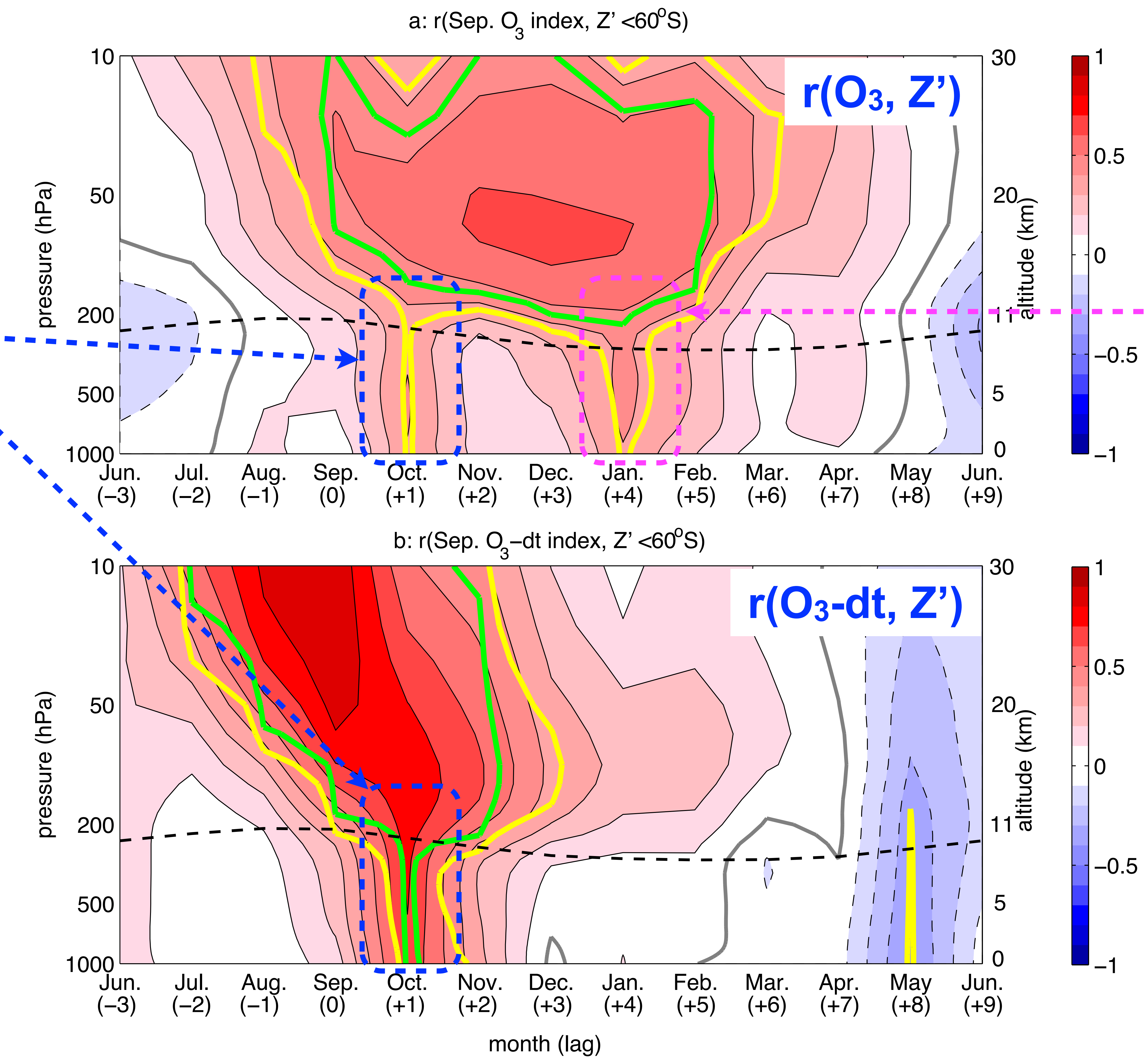
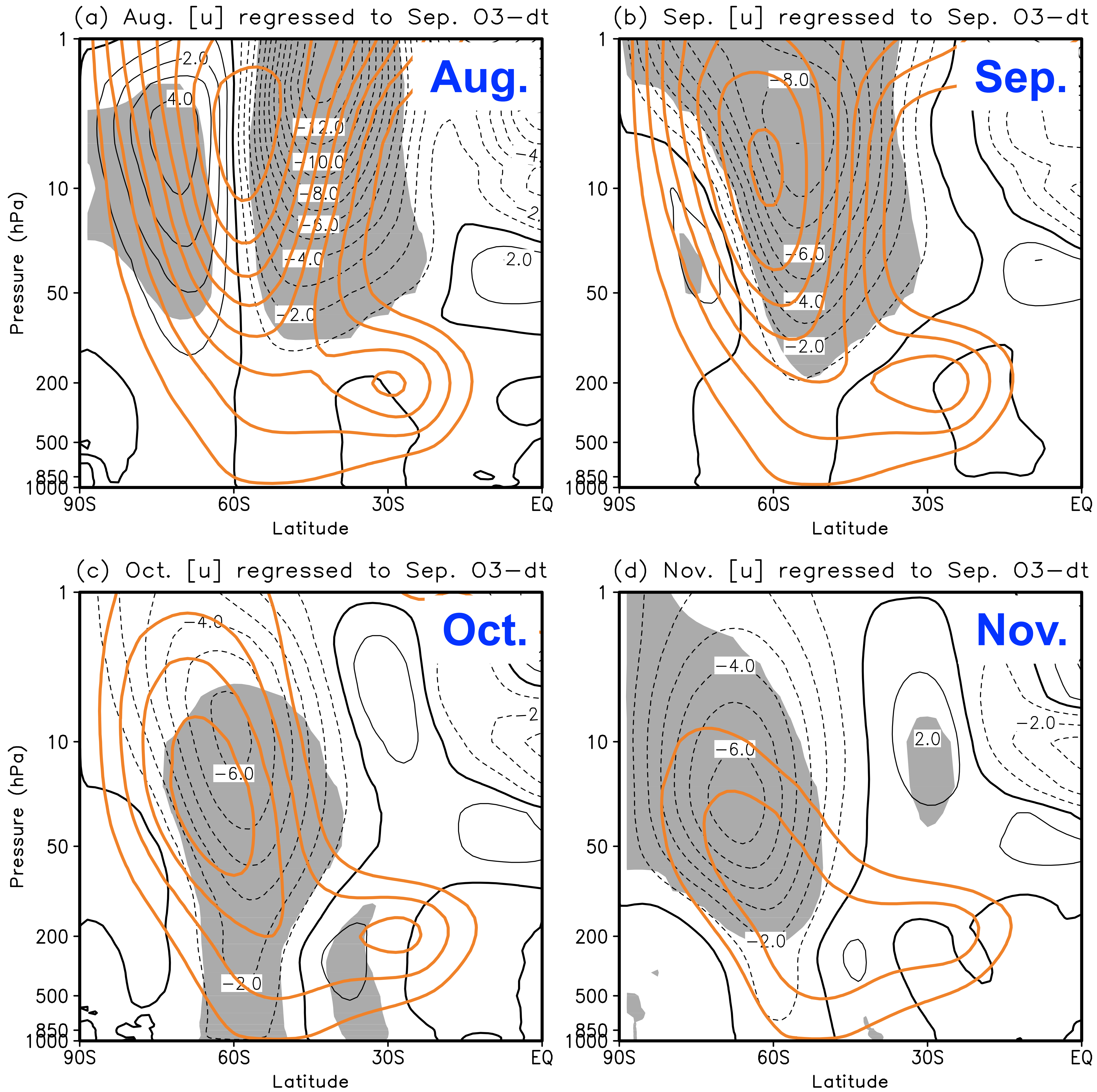



By long-term trend of $O_3$

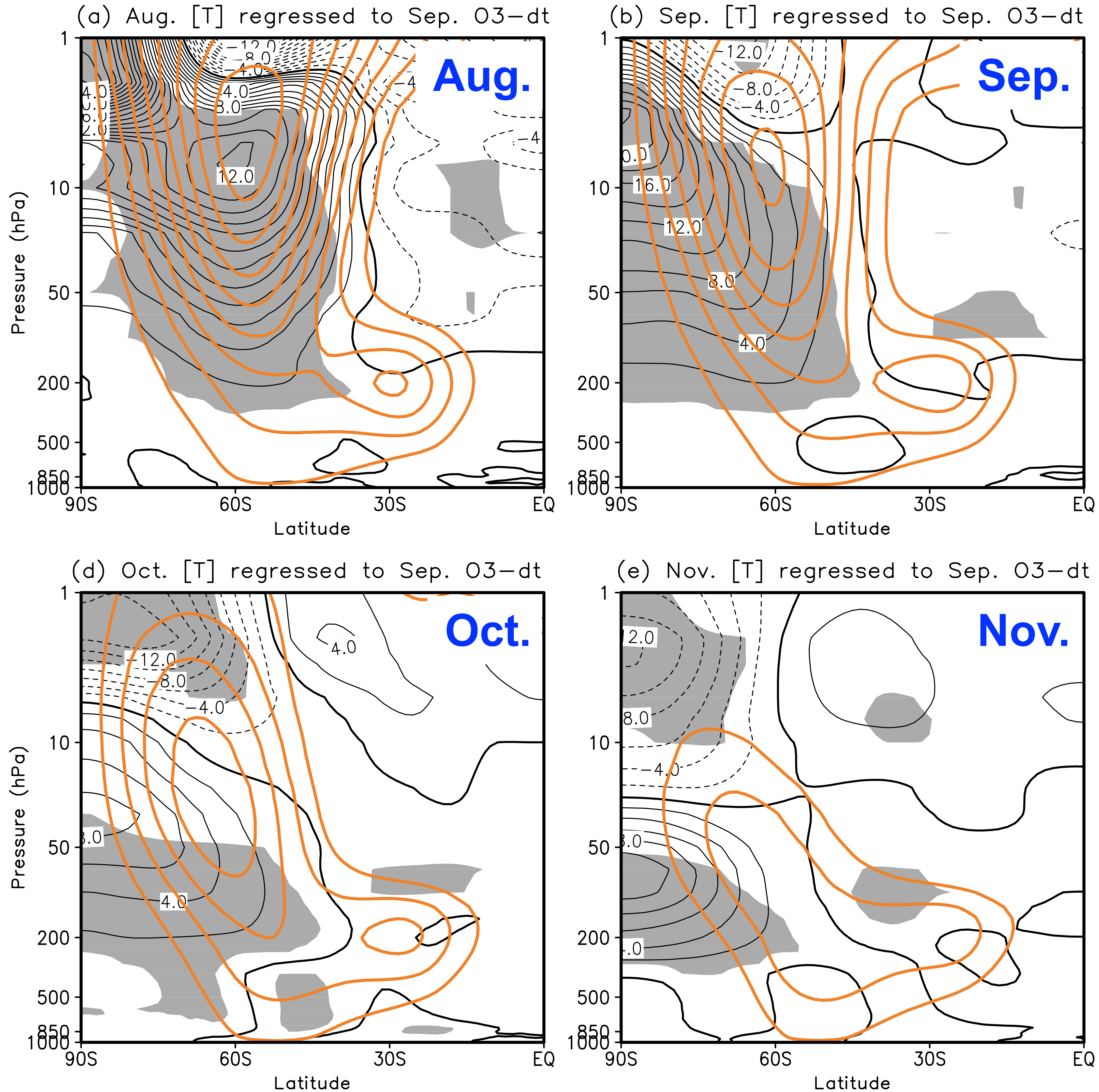
# [u] anomaly regressed against Sep. $O_3$-dt




- 2002 SSW is excluded.
- Deceleration begins in July and August in response to extratropical wave driving, and shifts poleward and downward in time.

Orange: Climatological [u]
Contour: [u]' regressed against Sep. $O_3$-dt
Shading: Significant at 99% confidence level.

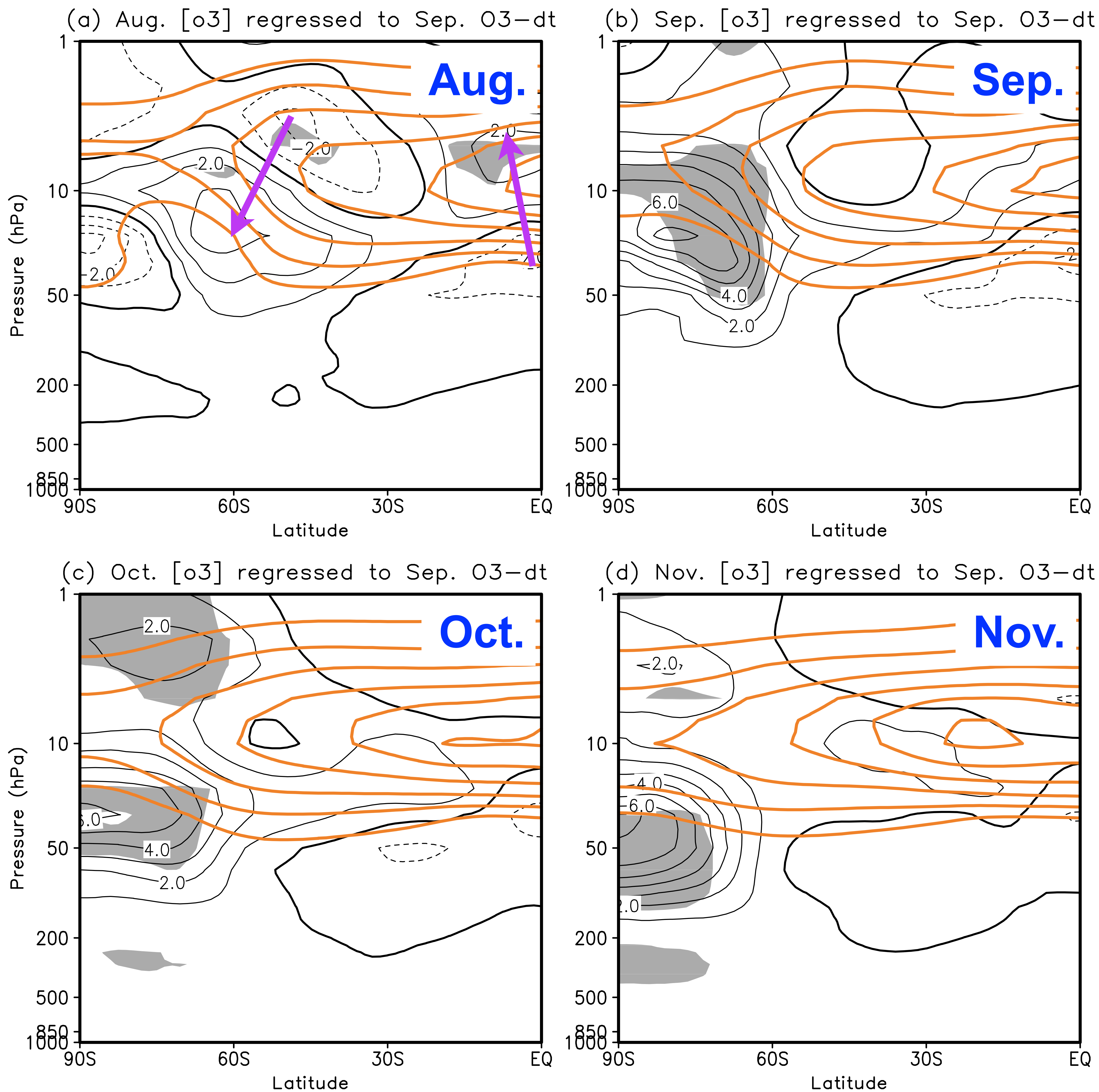
# [T] anomaly regressed against Sep. $O_3$-dt




- Mid- to upper-stratospheric warming is largely due to adiabatic warming.
- Lower stratospheric warming in Oct. and Nov. is likely caused by both dynamic and radiative warming due to anomalous ozone concentration.

Orange: Climatological [u]
Contour: [T]' regressed against Sep. $O_3$-dt
Shading: Significant at 99% confidence level.

# [$O_3$] anomaly regressed against Sep. $O_3$-dt

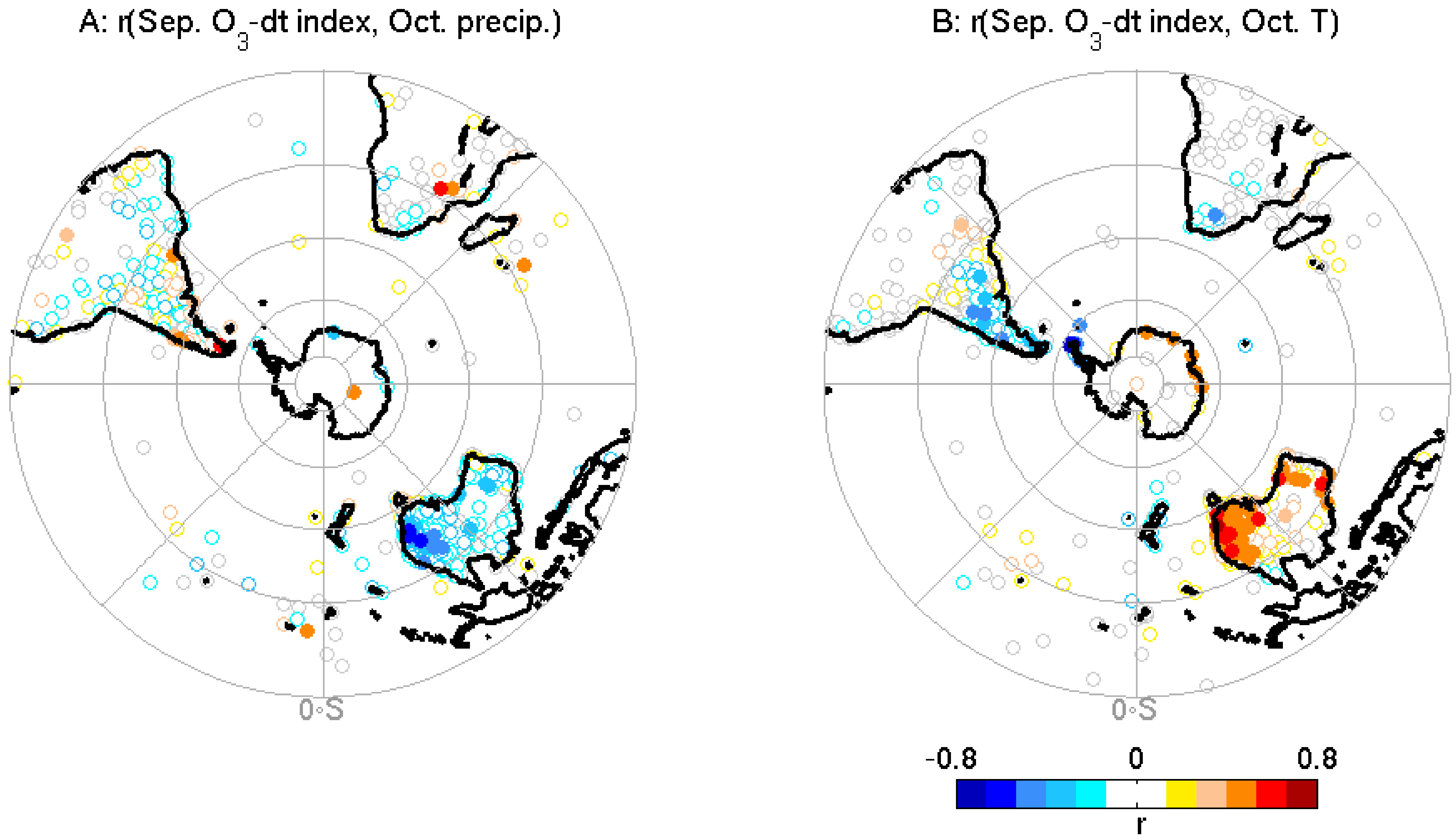



- Antarctic LS $O_3$ increase in Oct. and Nov. => Warming in the polar LS likely => Likely helps stratosphere-troposphere dynamical coupling.
- More detailed analyses are needed.

Orange: Climatological [$O_3$]
Contour: [$O_3$]' regressed against Sep. $O_3$-dt
Shading: Significant at 99% confidence level.

# Surface response

# Surface response: r(Sep. $O_3$-dt, Oct. Precip./SAT)



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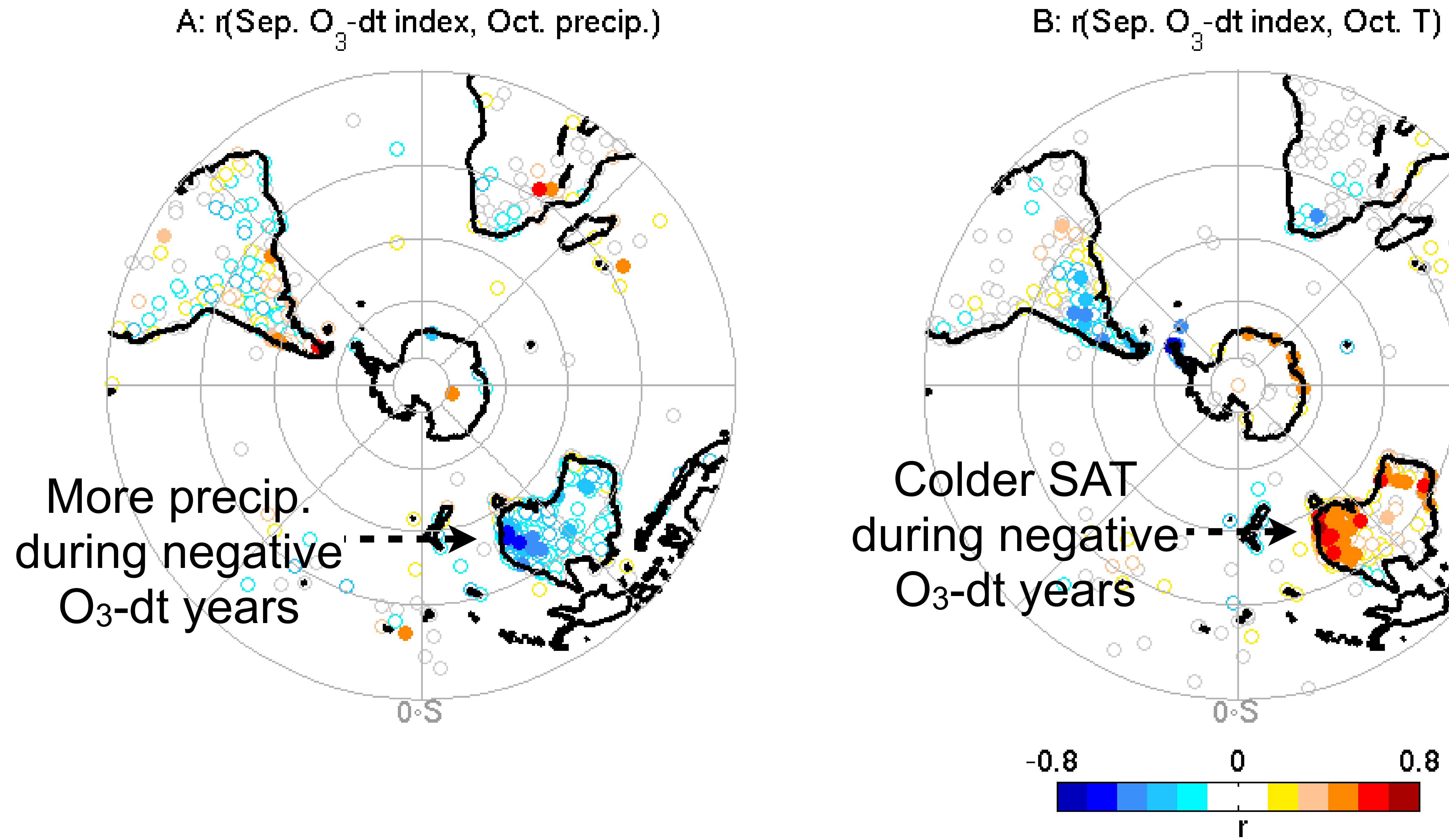
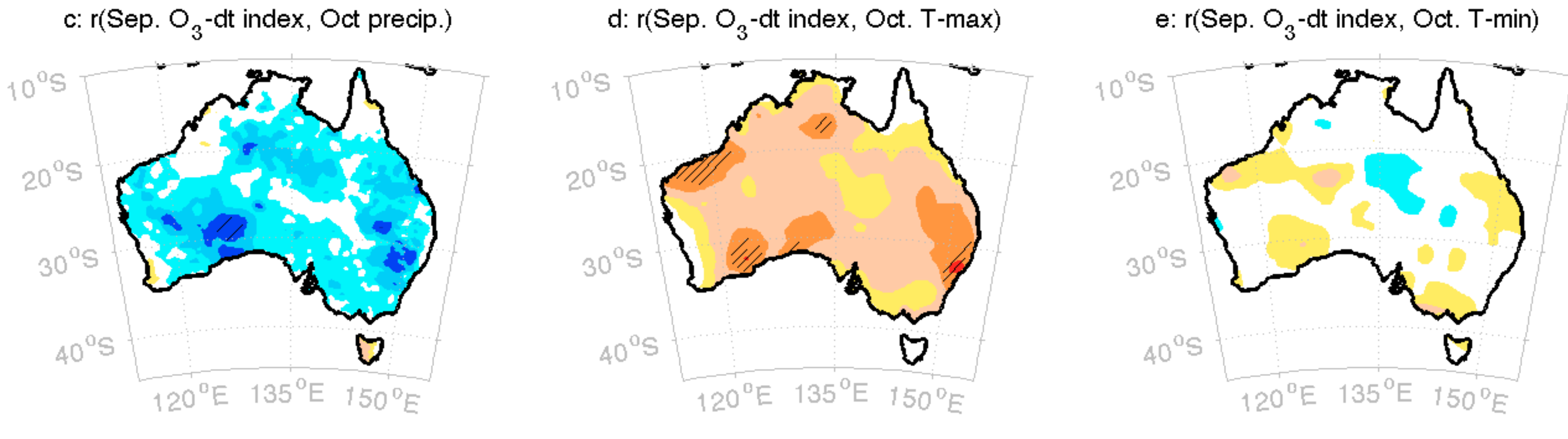


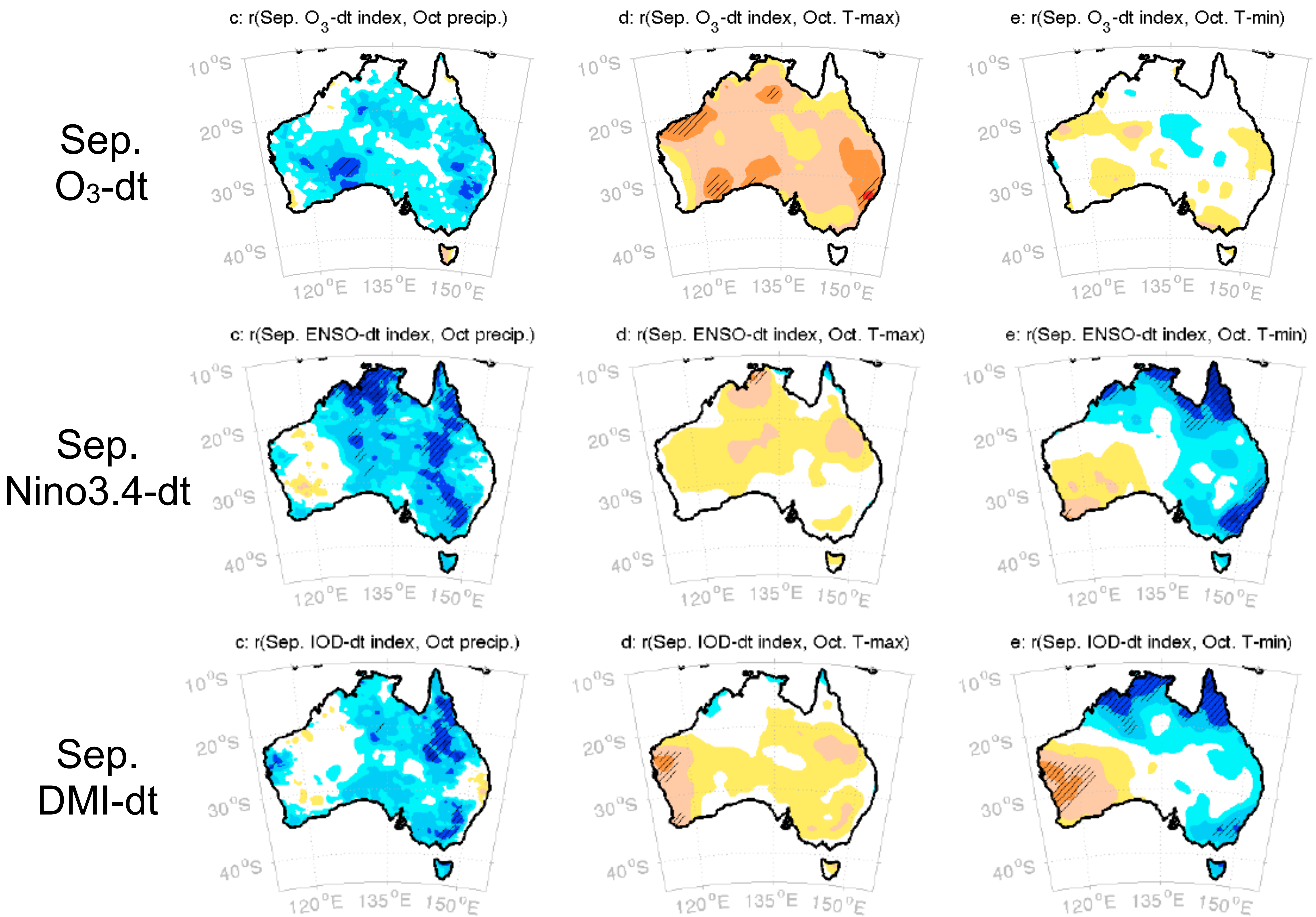

- Surface climate variations: negative Sep. $O_3$-dt anomaly (due to weaker LS wave driving in winter) => positive Oct. SAM index anomaly => anomalous surface easterlies in midlatitudes => more precipitation by moisture advection => less daytime insolation and colder surface temperature.

# Surface response to Sep. $O_3$-dt, ENSO-dt, DMI-dt

Sep. $O_3$-dt



# Surface response to Sep. $O_3$-dt, ENSO-dt, DMI-dt




- Sep. $O_3$-dt related surface climate variation is different from that associated with ENSO and Indian Ocean Dipole Mode.

# Conclusions

***Do inter-annual variability of the Antarctic ozone hole affect Southern Hemisphere (SH) surface climate?***

***If it does, how much is it important in comparison to ENSO and IOD?***

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***If it does, how much is it important in comparison to ENSO and IOD?***

- A significant time-lagged negative correlation between the Sep. $O_3$ and Oct. SAM index is observed in an inter-annual timescale.
- The resulting surface climate variations are largely comparable to but independent of those associated with ENSO and Indian Ocean Dipole (IOD) mode.
- Seasonal prediction in the SH Oct. could be improved by considering stratospheric variability in Sep. (more precisely lower-stratospheric dynamical and chemical variations).

# Open questions

- Why does downward coupling occur in Sep. instead of Nov. when inter-annual variation of $O_3$-dt is maximum?

| std($O_3$-dt) | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Jan. | Feb. | Mar. | Apr. | May. | Jun. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $O_3$ index (DU) | - | - | 32.00 | 36.37 | 39.59 | 18.92 | 8.05 | 7.52 | 7.73 | 7.62 | - | - |
| $O_3$-dt index (DU) | - | - | 20.27 | 24.70 | 30.33 | 12.44 | 5.28 | 5.86 | 6.65 | 6.71 | - | - |
| SAM index | 1.73 | 1.58 | 1.70 | 2.06 | 1.84 | 1.67 | 1.67 | 1.93 | 1.56 | 1.74 | 1.70 | 1.80 |

- denotes insufficient satellite observations due to polar darkness.

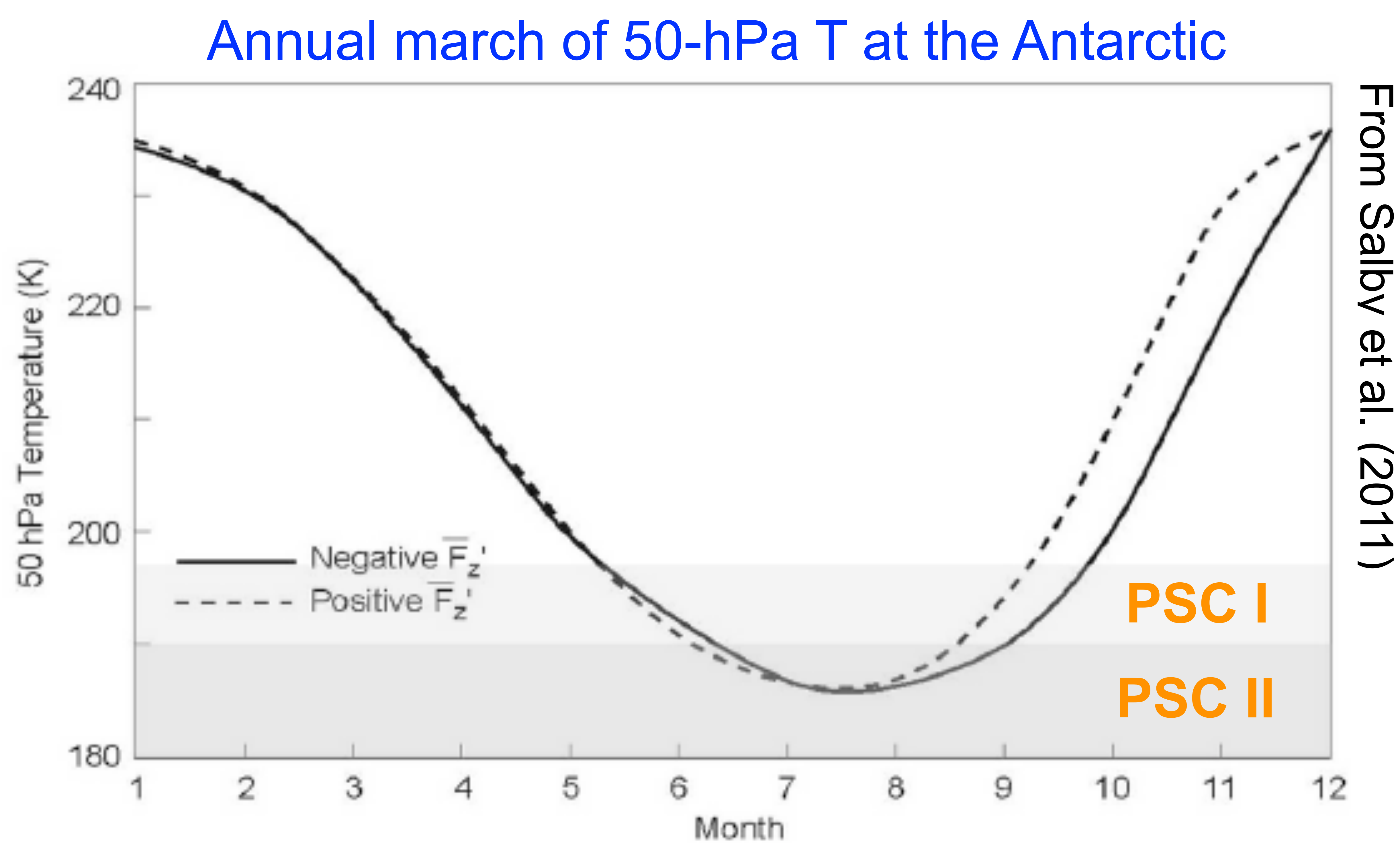
- What drives downward coupling?

# Thanks! Any suggestions or comments are welcome.

- Son, S.-W., A. Purich, H. H. Hendon, B.-M. Kim, and L. M. Polvani, 2014: Improved seasonal forecast using ozone hole variability? Geophysical Research Letters, published online

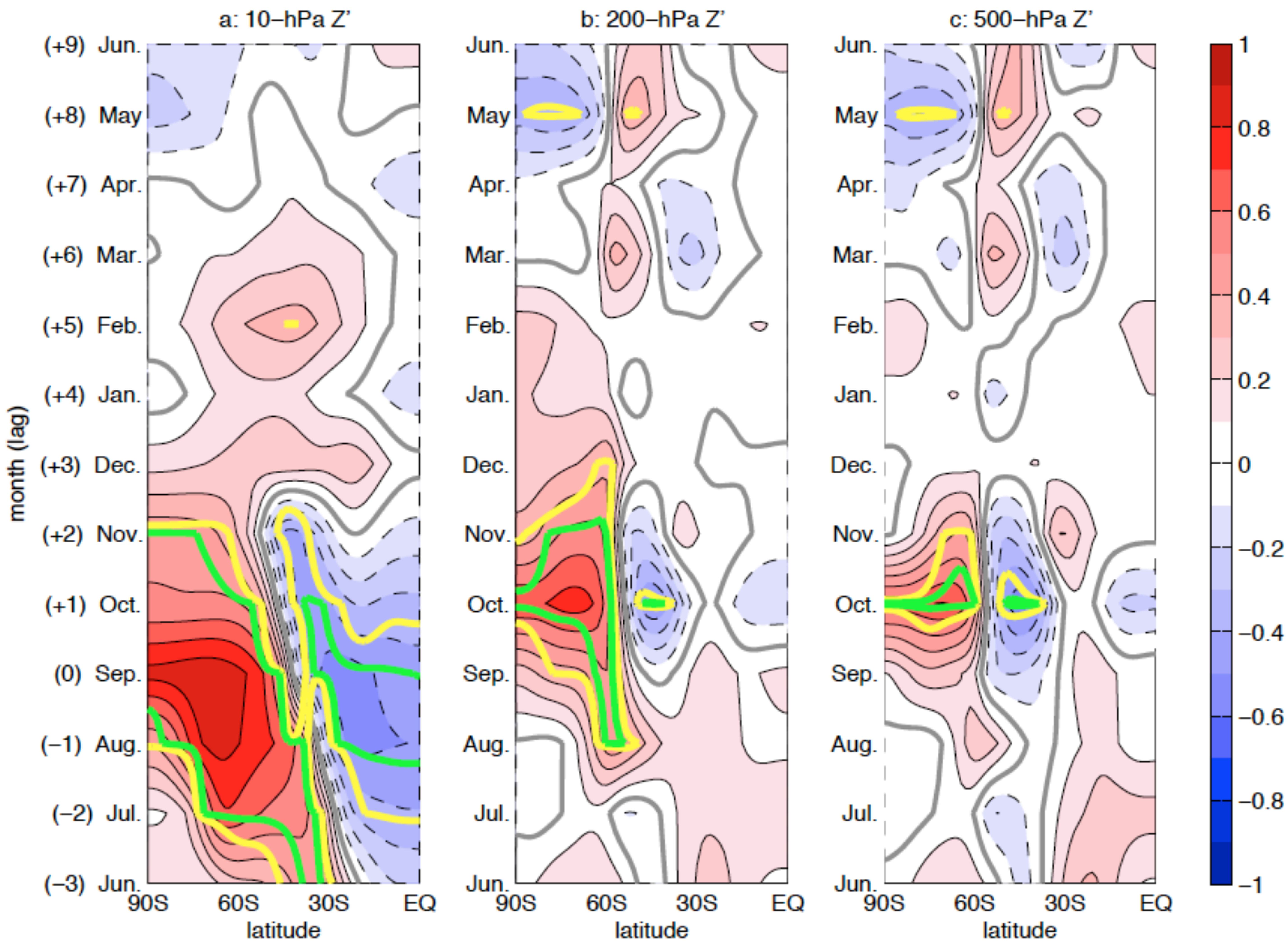
seokwooson@snu.ac.kr

# What determine $O_3$-dt?




- Strong wave driving in JAS enhances stratospheric mean meridional circulation. The resulting adiabatic warming causes anomalously warm polar stratosphere which does not support PSC formation (type II) in September, possibly resulting in less ozone destruction in spring.

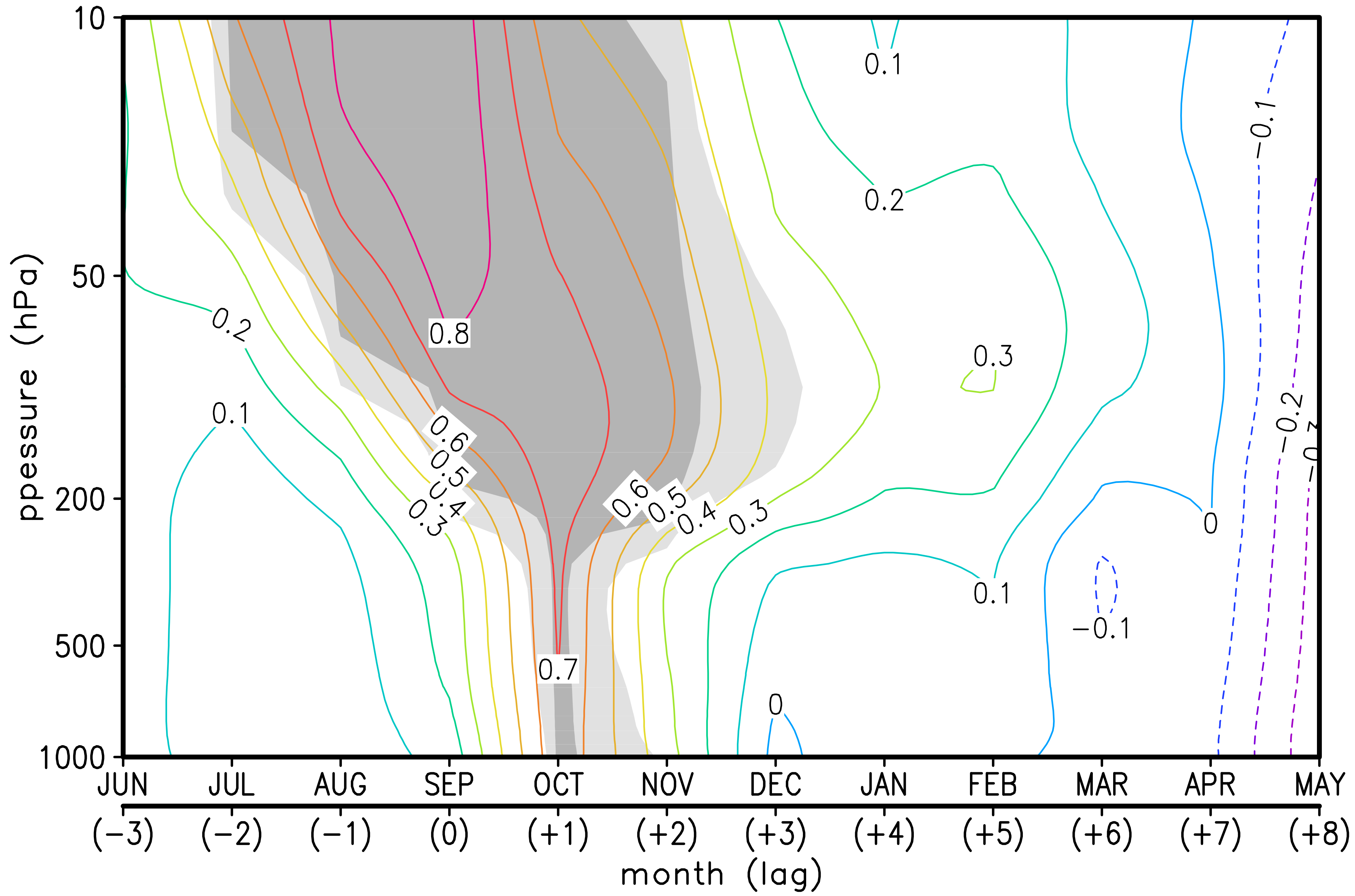
# Vertical coupling: r(Sep. $O_3$-dt, Z10, Z200, Z500)



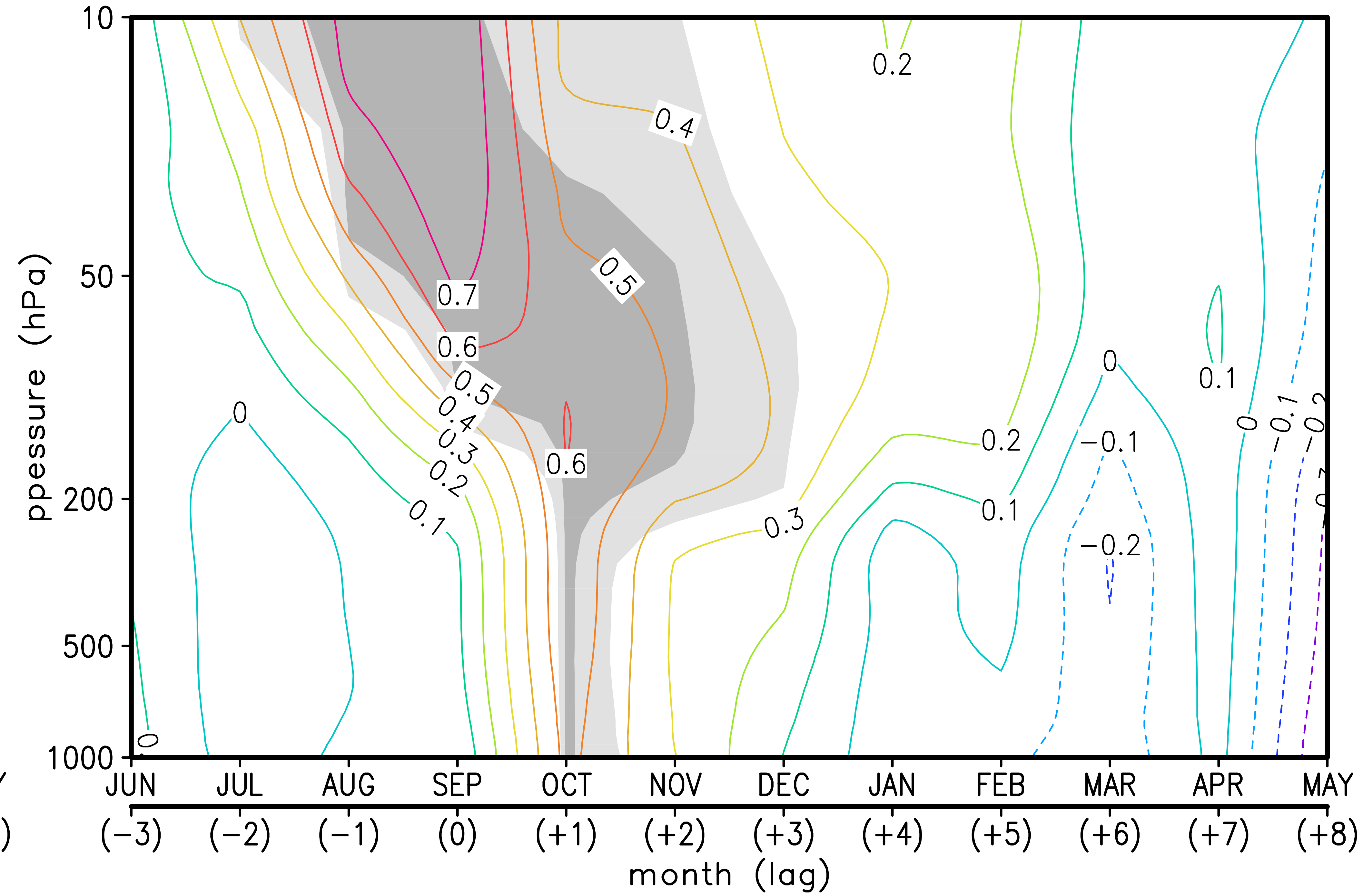

- Time-lagged poleward and downward coupling is evident.
- Over two-month long lagged correlation is observed at 10 hPa! Wave-driven warm anomalies in the polar stratoshere is associated with higher-than-normal $O_3$ in spring.

# Robustness of downward coupling

r(Sep. $O_3$-dt, Z')




r(Sep. $O_3$-dt, Z') w/o 2002 SSW



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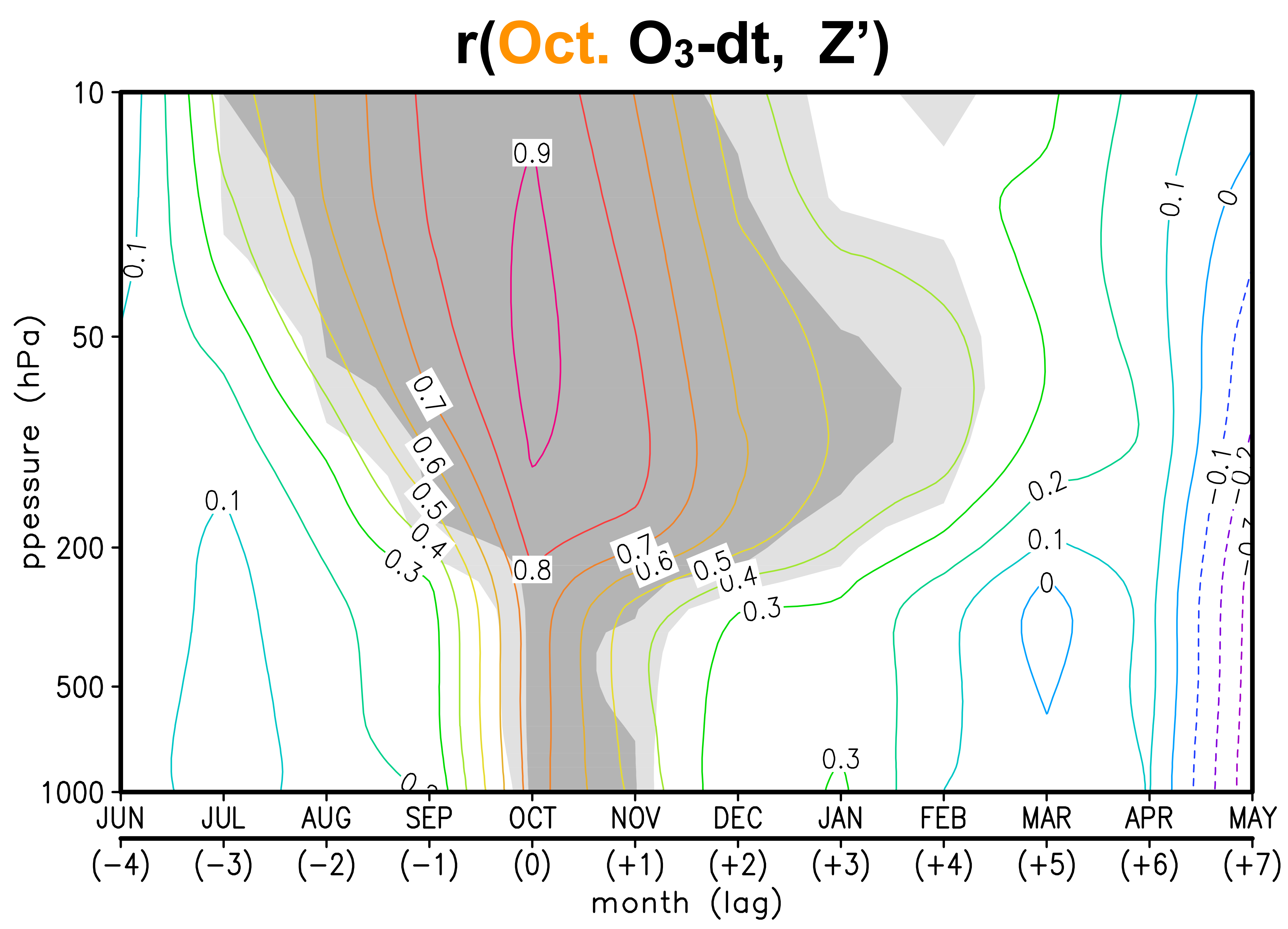
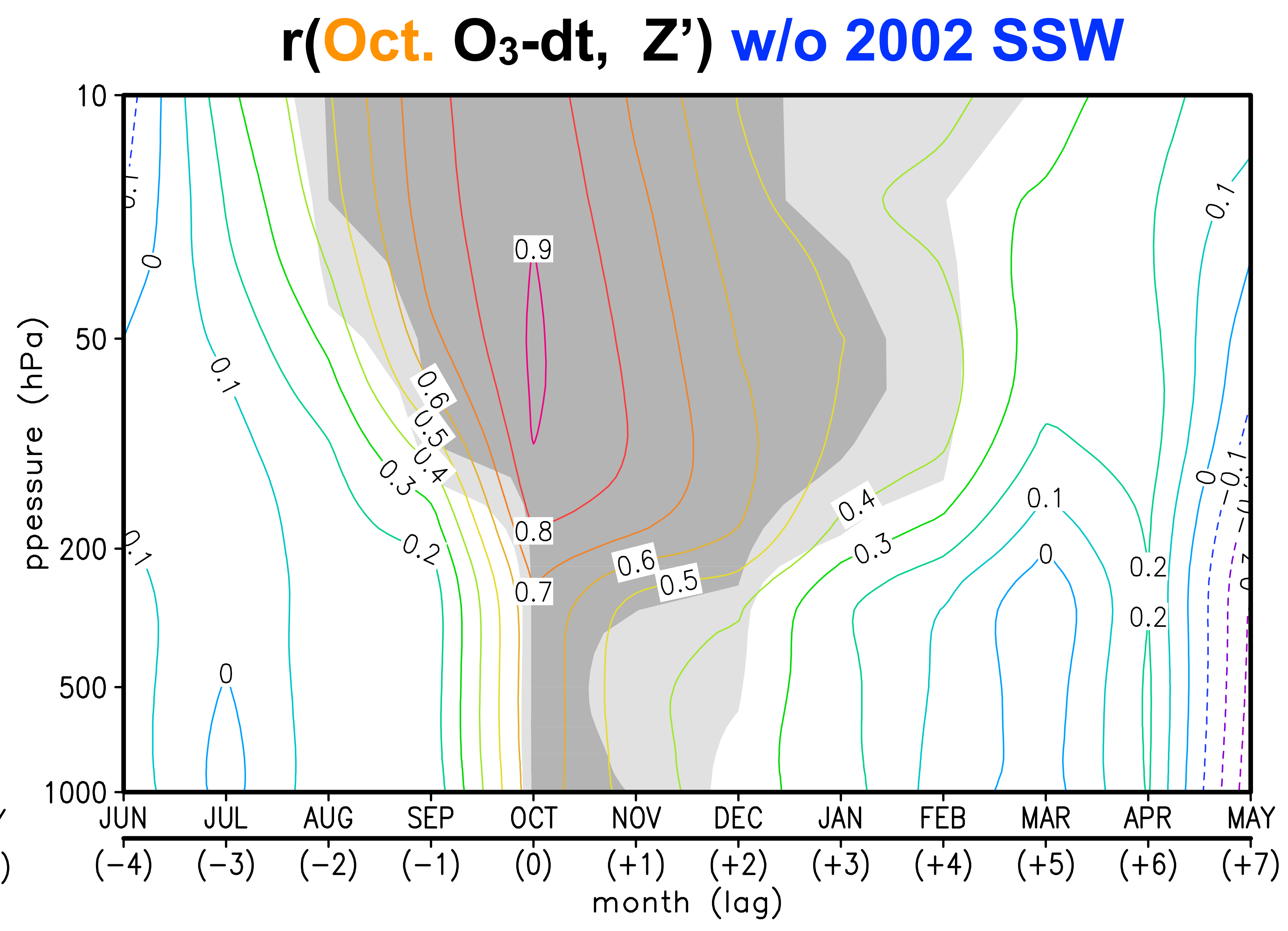


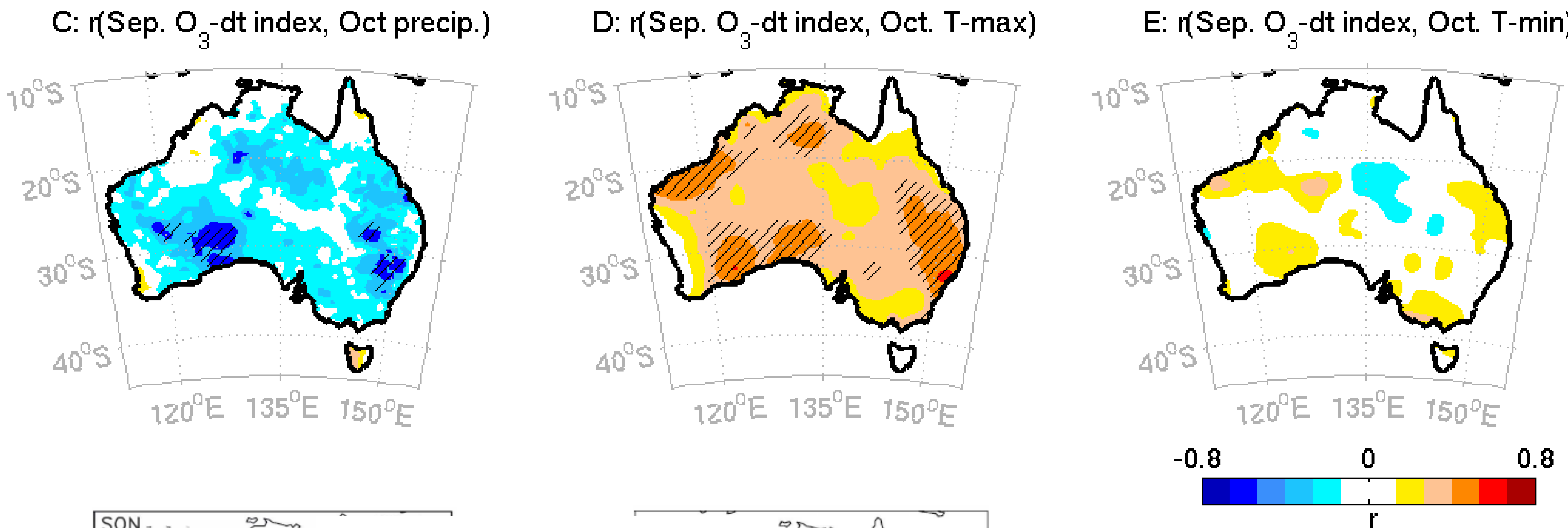
# Robustness of downward coupling

## r(10-hPa Z’, SAMI)

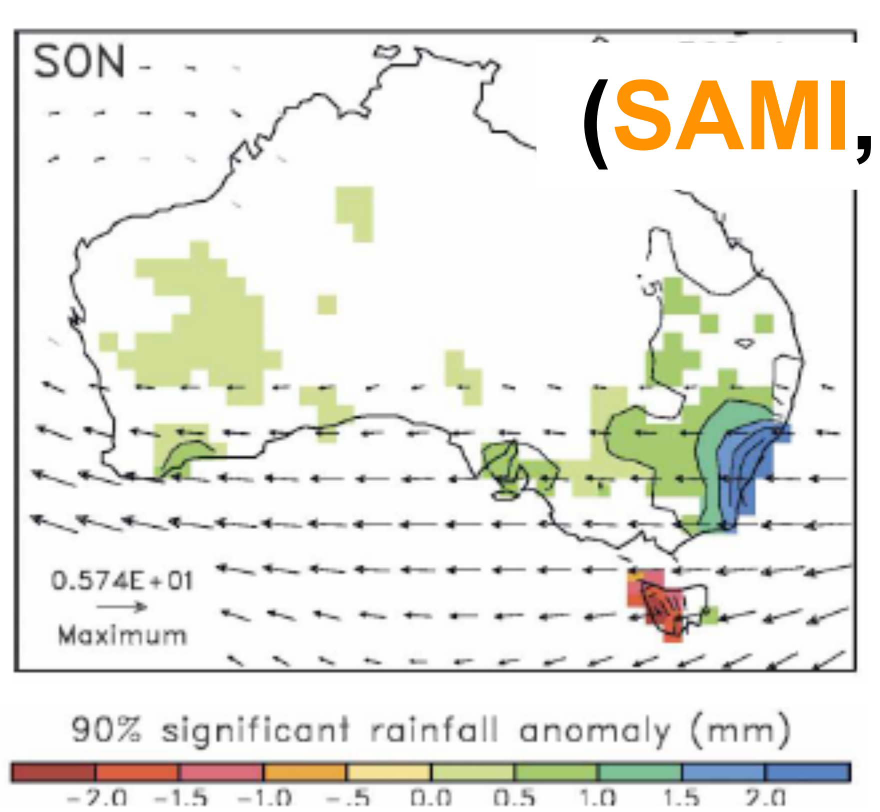
| *Z′\SAM* | *Jun.* | *Jul.* | *Aug.* | *Sep.* | *Oct.* | *Nov.* | *Dec.* | *Jan.* | *Feb.* | *Mar.* | *Apr.* | *May* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Jul.* | -0.09 | -0.69** | -0.35* | -0.10 | -0.38* | -0.19 | 0.13 | -0.13 | 0.04 | 0.08 | -0.02 | 0.05 |
| *Aug.* | -0.15 | -0.01 | -0.23 | -0.22 | -0.56** | -0.10 | 0.08 | -0.19 | 0.06 | 0.19 | 0.16 | 0.20 |
| *Sep.* | -0.27 | -0.22 | -0.13 | -0.33 | -0.67** | -0.09 | -0.05 | -0.25 | -0.17 | 0.20 | 0.18 | 0.26 |
| *Oct.* | -0.26 | -0.12 | -0.06 | -0.23 | -0.60** | -0.30 | -0.32 | -0.31 | -0.24 | 0.02 | 0.07 | 0.16 |
| *Nov.* | -0.15 | -0.04 | -0.13 | -0.32 | -0.51** | -0.36* | -0.36* | -0.26 | -0.32 | 0.05 | -0.04 | 0.04 |
| *Dec.* | -0.04 | -0.12 | -0.26 | -0.44* | -0.33 | -0.66** | -0.41* | -0.11 | -0.19 | -0.01 | -0.07 | -0.09 |
| *Jan.* | 0.11 | -0.14 | -0.42* | -0.41* | -0.07 | -0.42* | -0.31 | -0.17 | 0.13 | -0.21 | 0.00 | -0.10 |
| *Feb.* | 0.02 | -0.01 | -0.09 | -0.17 | -0.12 | -0.38* | -0.12 | 0.04 | -0.18 | -0.26 | -0.23 | 0.02 |
| *Mar.* | 0.07 | 0.02 | -0.07 | -0.28 | 0.13 | -0.11 | -0.20 | -0.03 | 0.08 | -0.28 | -0.38* | 0.03 |
| *Apr.* | 0.16 | 0.00 | -0.08 | -0.28 | 0.08 | -0.30 | -0.31 | 0.16 | 0.13 | -0.23 | -0.49** | -0.09 |
| *May* | 0.15 | 0.18 | 0.12 | -0.23 | 0.14 | 0.01 | -0.15 | 0.27 | -0.03 | -0.22 | -0.24 | -0.44* |
| *Jun.* | 0.17 | 0.29 | -0.08 | -0.10 | 0.29 | -0.16 | -0.43* | 0.09 | -0.08 | -0.22 | -0.14 | -0.35 |

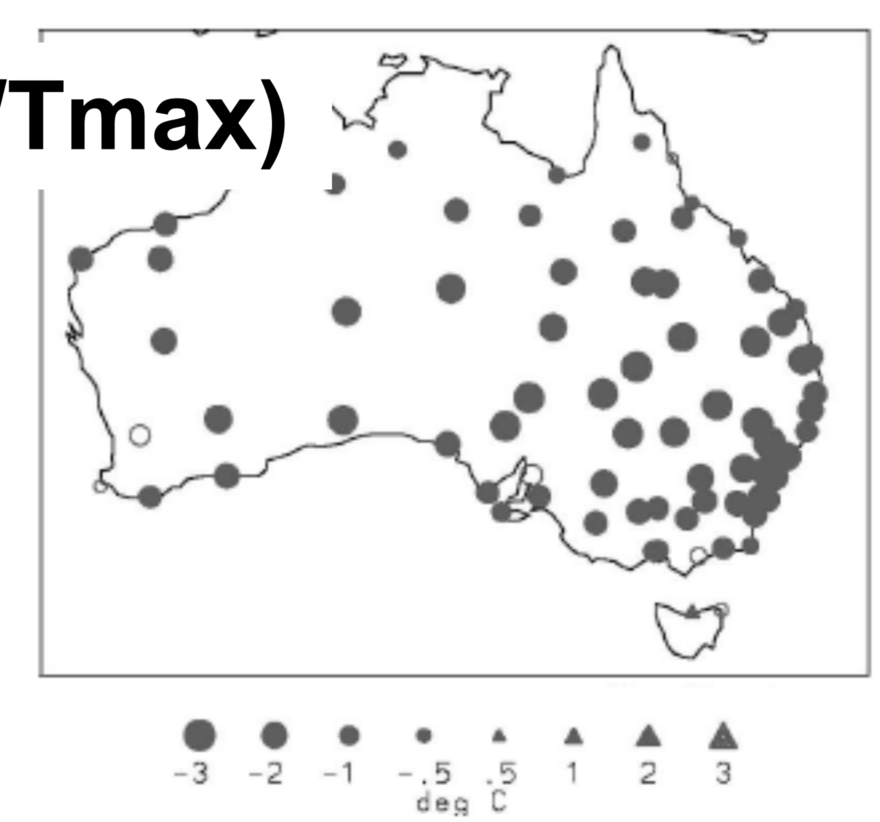
- Strong correlation between Aug.-Sep.-Oct. 10-hPa polar-cap Z’ and Oct. SAM index. Strongest correlation is again found between Sep. 10-hPa polar-cap Z’ and Oct. SAM index with a month lag.

# Surface response: r(Sep. $O_3$-dt, Oct. SAT/Precip.)




(**SAMI**, **Precip./Tmax**)




From Hendon et al. (2007)

# Ozone forcing is not zonally symmetic