Interpreting downward influence from the stratospheric ozone depletion-like cooling to the tropospheric circulation in an idealized model

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1. Introduction

•Observation and models suggest that the stratospheric ozone depletion is the main driver of the Southern Hemisphere (SH) atmospheric circulation changes during the second half of the twentieth century (Polvani et al. 2011). The atmospheric circulation changes are marked by a springtime polar cooling in the stratosphere and resultant poleward shift of eddy-driven jet in the troposphere (Thompson et al. 2011).

•There are three mechanisms that tend to interpret the downward influence from the stratospheric ozone depletion-induced cooling to the tropospheric circulation changes via impacting the tropospheric synoptic eddies (see Fig. 1):

(a) the direct influences on the lower stratospheric synoptic eddies;

(b) the planetary wave-induced residual circulation, a.k.a the downward control with eddy feedback (**DCWEF**);

(c) the planetary eddy-synoptic eddy nonlinear interaction.

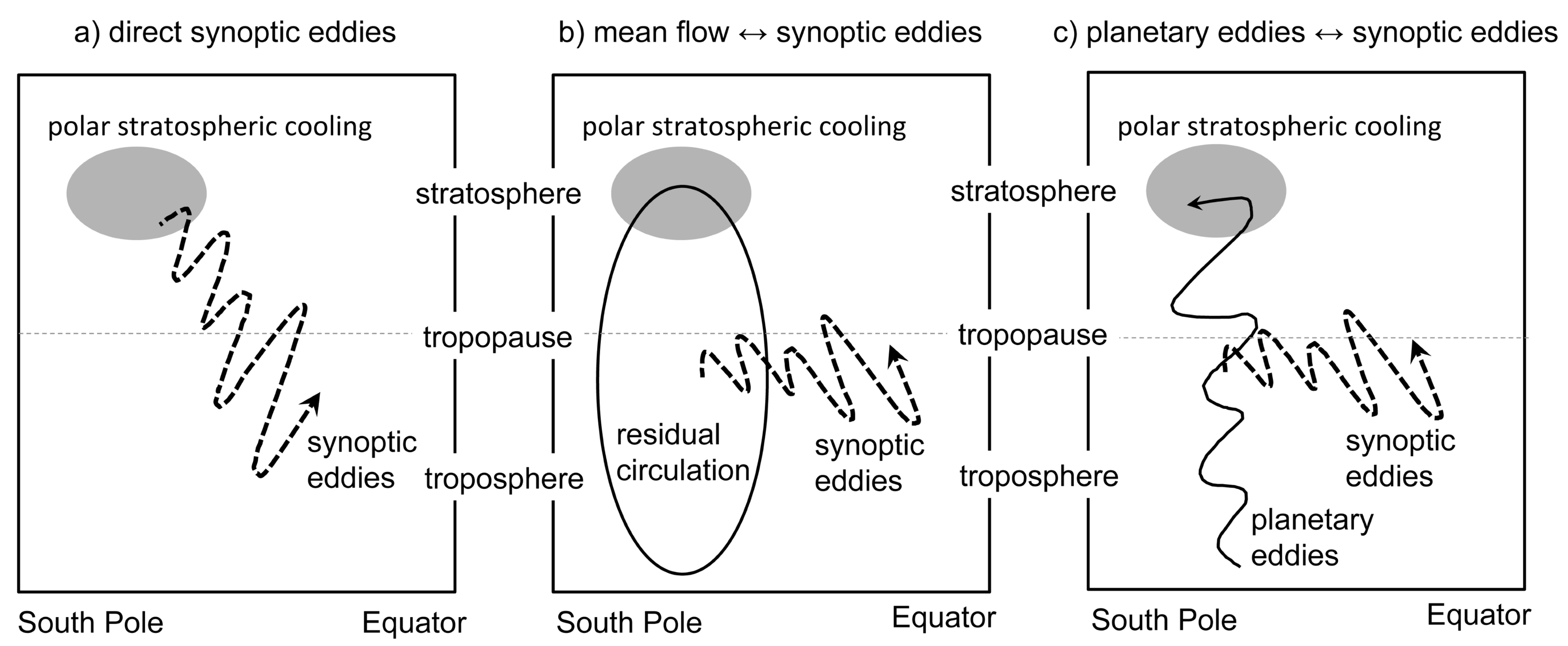

Fig. 1. Mechanisms by which ozone depletion-like stratospheric cooling impacts synoptic eddies: a) the stratospheric radiative cooling induces a direct impact on synoptic eddies; b) the stratospheric radiative cooling generates planetary wave drag anomalies, and a planetary wave-induced residual circulation impacts synoptic eddies by the anomalous zonal flow associated with the residual circulation; c) the stratospheric radiative cooling impacts the planetary waves in the stratosphere and troposphere via changes in reflection and propagation, which altered planetary waves then interact with the synoptic eddies by nonlinear eddy-eddy interactions.

Three mechanisms, which one is DOMINANT?

•In this study, we aim to examine these three mechanisms in an idealized model, and to determine which mechanism is more dominant. Details are referred to Yang et al. (2015, JAS with copyright to the AMS).

2. Model description and experiment setup

Full Model (FM)

•GFDL dynamic core (Kushner and Polvani 2006)

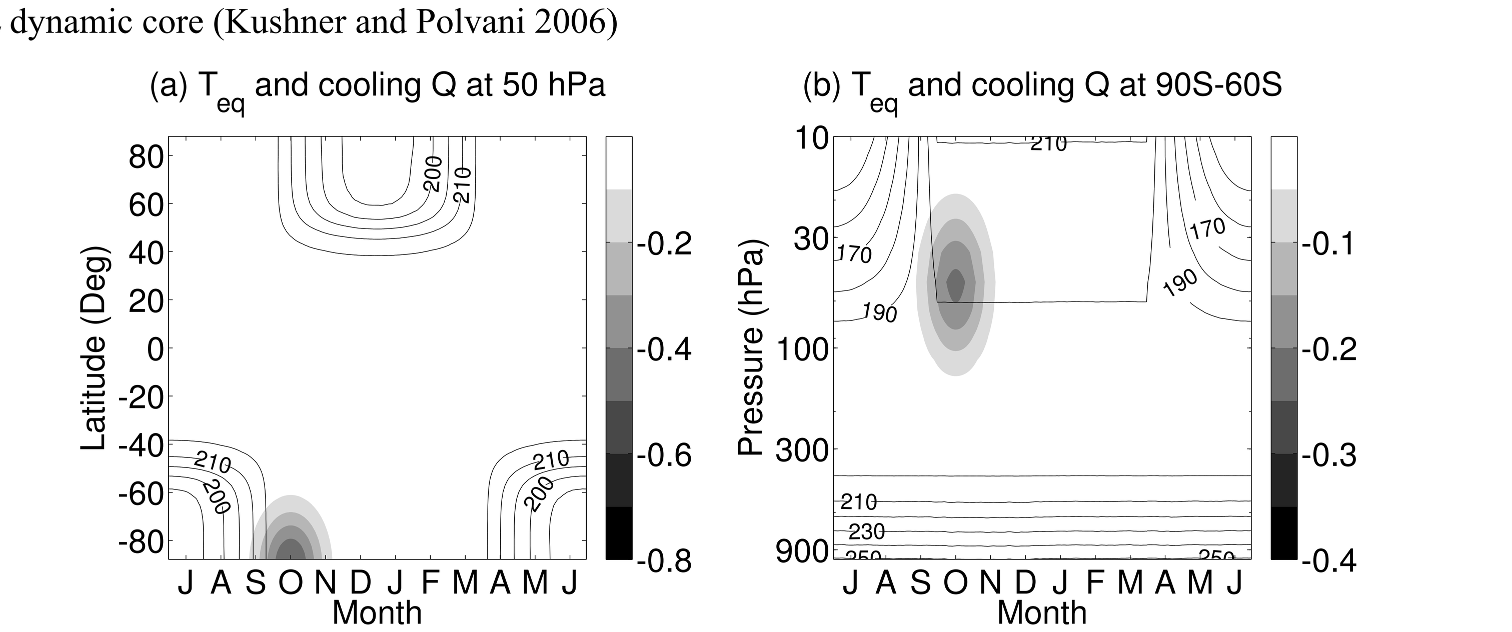

Fig. 2 The annual cycle of the equilibrium temperature profile (contours, unit: K, interval: 5 K) in the control run and additional ozone depletion-like radiative cooling in the perturbation run (shadings, unit: K day^{-1}). The figure shows (a) the meridional distribution at 50 hPa and (b) vertical distribution averaged over polar cap (90°S − 60°S).

- ❖ Control (contours): seasonal variation in the stratosphere, but perpetual austral summer in the troposphere. 80-year consecutive run.
- ❖ Forced (shades): prescribed perturbed cooling mimics the **polar stratosphere cooling** due to ozone depletion in the SH peaking in the austral spring (Sun et al. 2014). 80 1-year ensemble runs with the forced cooling being prescribed at the onset of spring (Sep. 1st) in each year of individual run.

Zonally Symmetric Model (ZM)

•Only zonal mean quantities are resolved (Kushner and Polvani 2004)

•Contribution of eddies and radiation are extracted from the full model (*FM*) and specified as external forcings in an annual cycle (Domeisen et al. 2013)

$$\frac{\partial q}{\partial t} = -u \bullet \nabla q - k(q - q_{eq}) \equiv F(u,q) \qquad \overline{u^e \bullet \nabla q^e} = \overline{F(\overline{u},\overline{q})} - \overline{F(\overline{u}+u^e,\overline{q}+q^e)}$$

Tracer advection equation

Specified eddies: overbar – zonal mean, e - eddies

$$\delta\overline{u} = \delta\overline{u}^Q + \delta\overline{u}^p + \delta\overline{u}^s$$

Wind tendency in the full model; Radiation; Planetary eddies; Synoptic eddies

2. Model description and experiment setup (continued)

Model	Exps	Description	Zonal Mean	Planetary eddies	Synoptic eddies	Ozone loss
Full Model	FM_C	Control	Resolved	Resolved	Resolved	No
	FM_F	Forced ozone depletion	Resolved	Resolved	Resolved	Yes
Zonally Symmetric Model	ZM_C	Control	Resolved	Specified (FM_C)	Specified (FM_C)	No
	ZM_F	Total forcing	Resolved	Specified (FM_F)	Specified (FM_F)	Yes
	ZM_Q	Radiative cooling	Resolved	Specified (FM_C)	Specified (FM_C)	Yes
	ZM_P	Planetary eddy	Resolved	Specified (FM_F)	Specified (FM_C)	No
	ZM_S	Synoptic eddy	Resolved	Specified (FM_C)	Specified (FM_F)	No

Table. 1. Summary of numerical experiments. 'Resolved' denotes the component is resolved in the model. 'Specified' denotes the component is specified and the simulation indicated in the bracket.

3. Full model performance

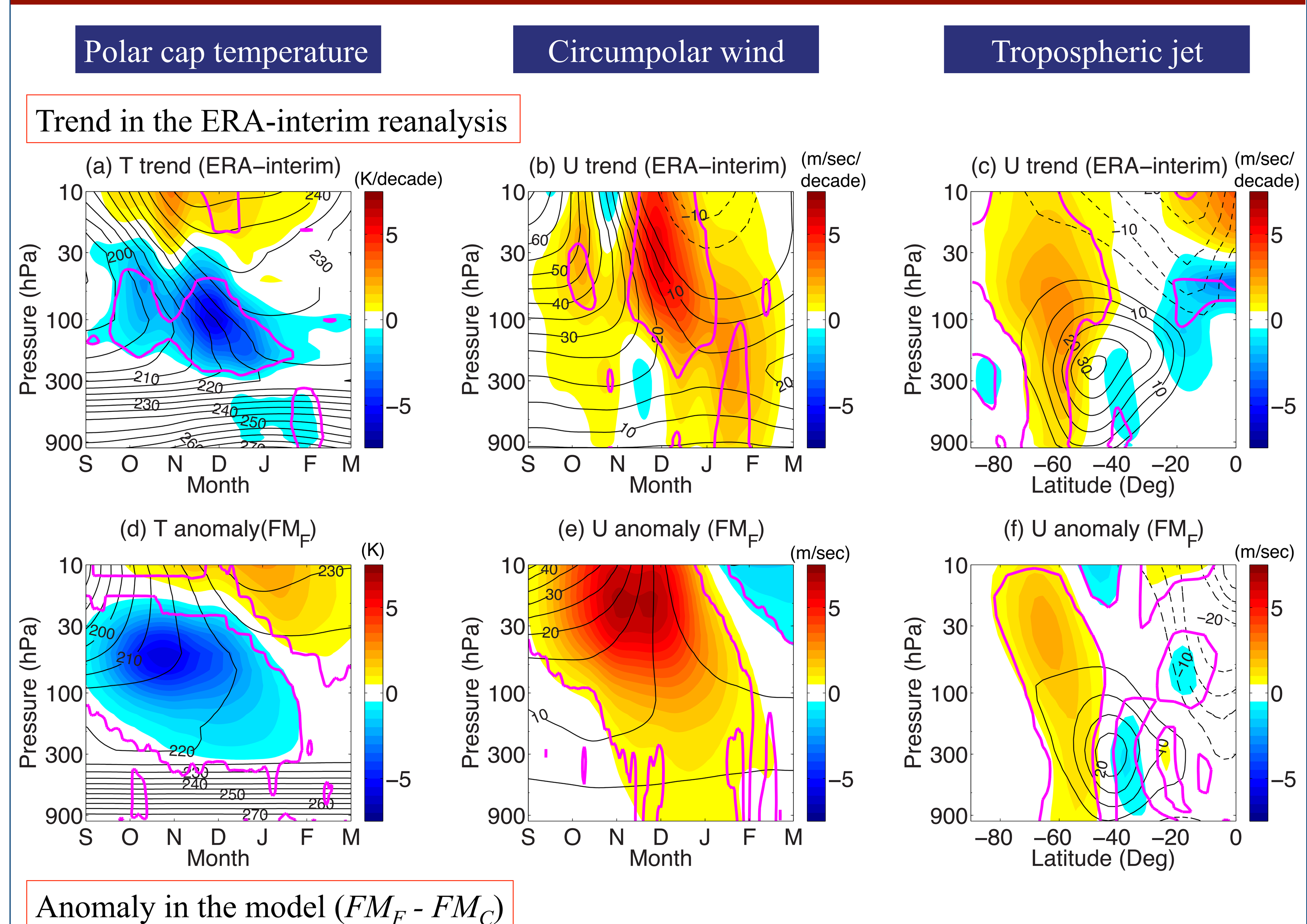

Fig. 3. Comparison between the ERA-interim reanalysis (top) and the idealized full model with ozone depletion-like cooling (bottom). The figure shows: (a)(d) the temporal variation of zonal mean temperature within the polar cap (averaged over 90°S − 60°S), (b)(e) the temporal variation of zonal mean zonal winds at the edge of the polar cap (averaged over 70°S−50°S), and (c)(f) latitude-altitude cross section of zonal mean zonal winds during the austral summer (DJF). Climatologies are shown as contours (solid for positive values and dashed for negative). Shades denote the trends over 1979-2002 (K dec^{-1} for temperature or m sec^{-1} dec^{-1} for zonal wind) in the ERA-interim reanalysis and the anomalies (K for temperature or m sec−1 for zonal wind) in the idealized model simulation, respectively. The signals in regions enclosed by purple contours are significant above the 95% confidence level using a two-sided student's t-test.

- ❖ Downward propagation of temperature and zonal wind perturbations are seen in the observation, as well as a poleward shift of the tropospheric jet.
- ❖ The full model successfully reproduces the general pattern of the downward influence from the polar stratospheric ozone depletion on the tropospheric thermal profile and circulations.

6. Summary

- ➢ Separation of the transient responses to a prescribed polar ozone depletion-like cooling shows the radiative cooling itself does NOT contribute to the downward influence, but the planetary eddies and synoptic eddies do.
- ➢ Downward control with eddy feedback (DCWEF) is NOT the dominant mechanism at play. Our results suggest the importance of planetary eddy – synoptic eddy nonlinear interaction in the troposphere, while the downward influence is carried by the downward propagation and refraction of planetary eddies.

4. Separation of the transient response in the zonally symmetric model

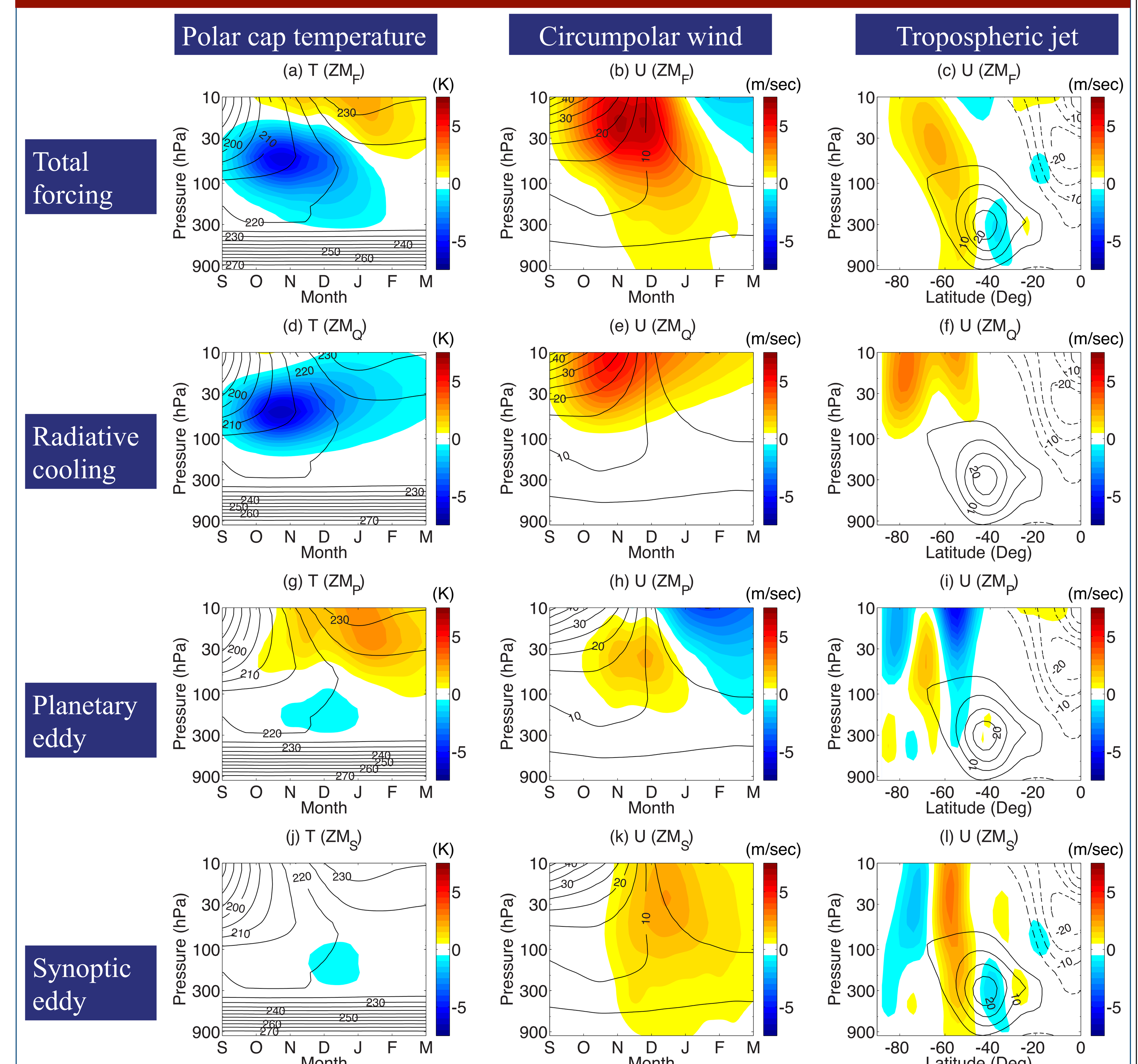

Fig. 4. As the bottom row of Fig. 3, but for the anomalies in the zonally symmetric model separated by individual forcings: (a)(b)(c) with total forcing; (d)(e)(f) with spring cooling forcing only; (g)(h)(i) with planetary eddy forcing only; (j)(k)(l) with synoptic eddy forcing only.

- ❖ Responses associated with the radiative cooling propagate upward, NOT responsible for the downward influence;
- ❖ The downward influence of the polar stratospheric ozone depletion-like cooling and resultant tropospheric responses are due to the planetary eddies and synoptic eddies. In particular, synoptic eddies contributes dominantly to the tropospheric responses.

$$\delta\overline{u} = \delta\overline{u}^Q + \delta\overline{u}^p + \delta\overline{u}^s$$

- ❖ For DCWEF, effects of downward control (DC) is displayed as the responses from $\delta u^Q + \delta u^P$, and this response should be amplified by the synoptic eddies as in δu^S. However, the former shows a slight equatorward shift of the tropospheric jet while the latter shows a poleward shift of the jet, suggesting the DCWEF may **NOT** be dominantly at play.

5. Examination of DCWEF

Model	Exps	Description	Zonal Mean	Planetary eddies	Synoptic eddies	Ozone loss
Full Model	FM_P	Planetary eddy	Resolved	Resolved plus specified (FM_F-FM_C)	Resolved	No

The planetary eddy-synoptic eddy nonlinear interaction is largely missing!

Downward Control

Eddy Feedback

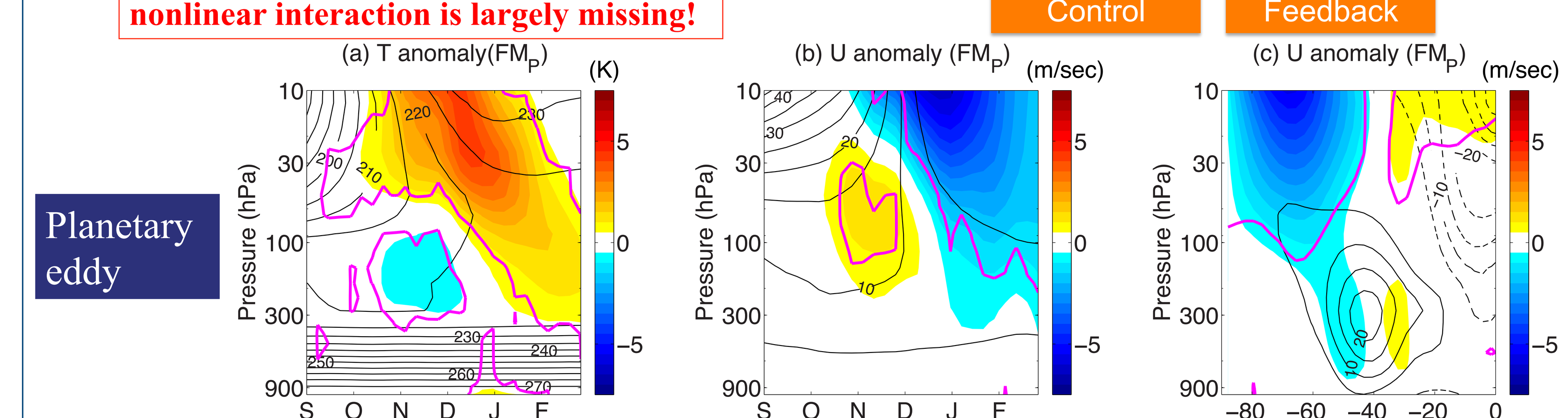

Fig. 5. As the bottom row of Fig. 3, but for specified anomalous zonal mean planetary wave forcing extracted as the difference between the perturbed run (with ozone depletion-like cooling) and the control run in the full model (i.e. $FM_F - FM_C$).

- ❖ DCWEF yields an equatorward shift of the jet, unlike the poleward shift in the observation