On the analysis of mean vertical velocities around the Antarctic polar vortex

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1. Introduction

Downward motion plays an important role in the constituent distribution and heat balance around the polar vortex. As a result of a radiative-dynamical interaction, the downward motion may be influenced significantly by climate change. However, because there isn't a network making direct measurements of vertical velocities, it is difficult to investigate the variability on a long-term basis. Several methods have been developed to approximate the Lagrangian-mean motion and evaluate the mean vertical velocity (e.g., GLM, TEM, Isentropic coordinate). Nevertheless, limitations of analysis methods may hinder accurate analysis of the mean vertical velocity especially around the Antarctic polar vortex because of nonlinearity in the strong polar night jet. The present study characterizes the various methods of analyzing the Lagrangian mean vertical velocity around the Antarctic polar vortex.

2. Analysis methods for the mean vertical velocities

Mean-meridional circulation and meridional transport process are discussed on the basis of the mass weighted isentropic zonal means (Miyazaki and Iwasaki, 2005). Mass weighted zonal means are

$$\overline{A(\phi,\theta,t)^*} \equiv \frac{1}{2\pi}\int A(\lambda,\phi,\theta,t)\left(\frac{\partial p}{\partial\theta}\Big/\frac{\partial\overline{p}}{\partial\theta}\right)d\lambda.$$

where the overbar and asterisk indicate isentropic zonal mean and mass weight, respectively. Eddies are departures from them.

This analysis method has following conceptual advantages;

1. Meridional transport is accurately separated into mean transport due to Lagrangian motion and eddy transport due to wave mixing.
2. Nonacceleration theorem is formulated in a nongeostrophic/finite-amplitude sense.

List of analysis methods for mean vertical velocities.

Meridional transport equation

$$\frac{\partial\overline{r^*}}{\partial t} = -\frac{\overline{v^*}}{a}\frac{\partial\overline{r^*}}{\partial\phi} - \overline{w_\dagger^*}\frac{\partial\overline{r^*}}{\partial z_\dagger} - \frac{1}{a\cos\phi}\frac{\partial\overline{(r'v')^*\cos\phi}}{\partial\phi} - \frac{1}{\rho}\frac{\partial\rho\overline{(r'w_\dagger')^*}}{\partial z_\dagger} + \overline{X^*}$$

Tracer analysis on geographical and equivalent latitude coordinates
(input: N2O as a passive tracer)

$$\overline{w_\dagger^*} \simeq -\left(\frac{\partial\overline{r^*}}{\partial t}\right)\Big/\left(\frac{\partial\overline{r^*}}{\partial z_\dagger}\right) = -\left(\frac{\partial z_\dagger}{\partial t}\right)_{\overline{r^*}},$$

Zonal mean continuity equation
Dynamical analysis
(input: meridional wind)

$$\overline{w_\dagger^*} = -\frac{1}{\rho}\int_{z_\dagger}^{\infty}\frac{1}{a\cos\phi}\frac{\partial\overline{v^*}\cos\phi}{\partial\phi}\rho dz_\dagger.$$

Zonal mean thermodynamic equation
Thermoynamic analysis
(input: diabatic heating rate)

$$\overline{w_\dagger^*} = \left(\frac{\overline{Q^*}}{\pi} - \frac{\partial\theta}{\partial t} - \frac{\overline{v^*}}{a}\frac{\partial\theta}{\partial\phi}\right)\Big/\left(\frac{\partial\theta}{\partial z_\dagger}\right)$$

Zonal mean momentum equation
Downward control calculation
(input: EP-flux divergence)

$$\overline{w_\dagger^*} = -\frac{1}{a\rho\cos\phi}\frac{\partial}{\partial\phi}\left(\int_{z_\dagger}^{\infty}\left(\frac{\frac{\partial\overline{u^*}}{\partial t} - \frac{1}{a\rho\cos\phi}\nabla\cdot\mathbf{F}}{f - \frac{1}{a\cos\phi}\frac{\partial\overline{u^*}\cos\phi}{\partial\phi}}\right)\rho\cos\phi dz_\dagger\right),$$

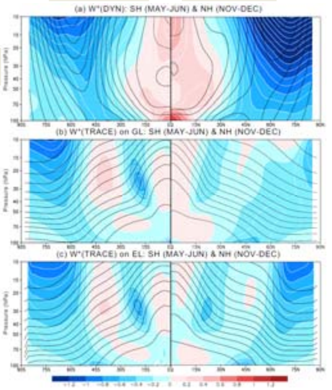
TEM residual circulation
(input: Temperature and wind)

$$\overline{w^*} = \overline{w} + \frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\cos\phi\overline{v'\theta'}\Big/\left(\frac{\partial\overline{\theta}}{\partial z}\right)\right)$$

Input data: MRI-JMA 98 GCM-CTM (Shibata et al. 2005)

3. Accuracy of the tracer analysis

SH (May-June) **NH (Nov-Dec)**



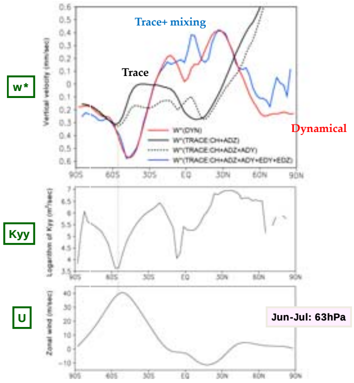
Dynamical analysis (contour: zonal wind)

Trace analysis on GL (contour: N2O)

Trace analysis on EL (contour: N2O

Latitude-pressure cross-section of w* calculated from the dynamic and trace analyses for the GL and EL coordinates

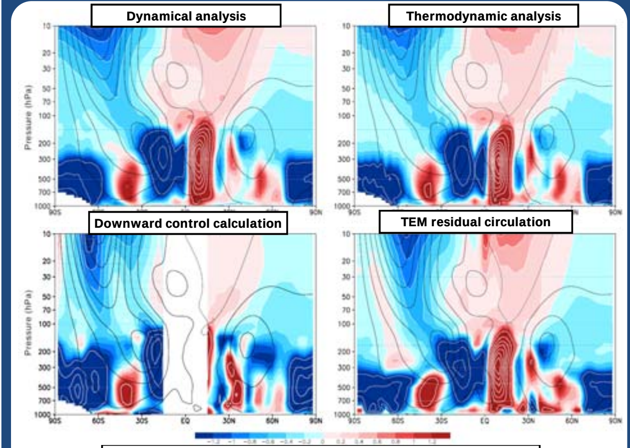
$$\overline{w_\dagger^*} = -\left(\frac{\partial\overline{r^*}}{\partial t} + \boxed{\frac{\overline{v^*}}{a}\frac{\partial\overline{r^*}}{\partial\phi} + \frac{1}{a\cos\phi}\frac{\partial\overline{(r'v')^*\cos\phi}}{\partial\phi} + \frac{1}{\rho}\frac{\partial\rho\overline{(r'w_\dagger')^*}}{\partial z_\dagger} - \overline{X^*}}\right)\Big/\left(\frac{\partial\overline{r^*}}{\partial z_\dagger}\right)$$



Latitudinal distributions of the mean vertical velocities calculated from the dynamical and trace analyses, the logarithm of the adiabatic diffusion coefficient, and zonal mean zonal wind.

- Around the Antarctic polar vortex, the vertical velocity estimated from the trace analysis differs little between the geographical and equivalent latitude (GL and EL) coordinates, confirming that the mean meridional circulation in isentropic coordinate is capable of representing the Lagrangian characteristic of mean motions even on the GL.
- The dynamical downward velocity outside the Antarctic vortex is three times larger than that inside the vortex in the lower stratosphere during winter. Trace analyses using either the two coordinates cannot capture it.
- The simple trace analysis does not consider mean horizontal advection or eddy mixing. These factors can be very significant outside the vortex, degrading the assumption of the trace analysis. When the meridional eddy mixing is included, trace analysis shows strong downward velocity consistent with the dynamical estimate.

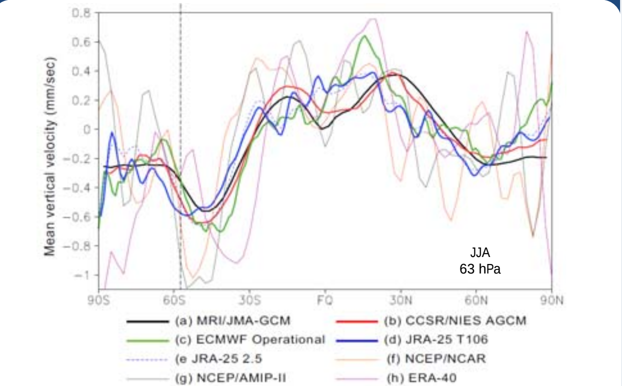
4. Comparison between the dynamical and thermodynamic analyses



Latitude–pressure cross-section of the mean vertical velocity (shaded) and zonal mean zonal wind (black lines)

- Dynamical analysis agrees fairly well with results of thermodynamic analysis when using GCM output. The downward control calculation disagrees with these analyses around the Antarctic polar vortex. Most of the disagreement may arise from numerical errors in the truncation and vertical integration in the downward control calculation.
- TEM analysis tends to slightly overestimate (underestimate) the mean downward velocity outside (inside) the Antarctic polar vortex, as compared with MIM analysis. This difference may arise from the limitation of TEM analysis (e.g., quasi-geostrophic approximation).

5. Analysis with reanalysis products



Latitudinal distributions of w* calculated with (a) MJ98 GCM (1999–2001), (b) CCSR/NIES AGCM (1999–2001), (c) ECMWF operational analysis (2000–2006), JRA-25 reanalysis (d) on model grid T106L40 and (e) on a regular lat–lon grid of 2.5*2.5 degree (1990–2001), (f) NCEP/NCAR reanalysis (1990–2001), (g) NCEP–DOE AMIP-II reanalysis (1990–2001), and (h) ERA-40 (1990–2001).

w* estimated from reanalysis products are very noisy compared to those from GCM forecast. Current reanalysis products cannot be used to capture the strong mean downward motion around the Antarctic polar vortex. External forcing by the assimilation process upsets the dynamic balance and causes serious noise in the mean vertical velocity field. An improvement in the mean vertical velocity field in assimilation products may be possible through better balancing of assimilated products.

Discussion: Evolution of the polar vortex

We consider whether the strong downward motion around the polar vortex affects the evolution of the polar vortex. The thermodynamic balance between radiative cooling and adiabatic heating due to the mean downward velocity controls the dynamic fields of the polar vortex through geostrophic adjustment.

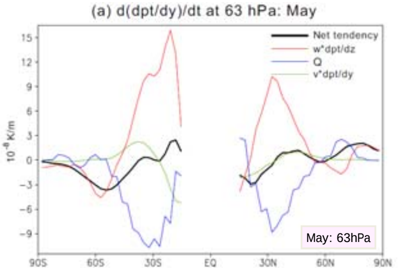
The strong downward motion in the SH mid-latitudes (45S-–55S) changes the meridional temperature gradient markedly by its adiabatic compression and enhances the polar night jet through the thermal wind balance. The result implies that the mean downward motion mainly develops the lower stratospheric Antarctic polar vortex during its formation stage, indicating the self-maintenance mechanism of the polar vortex circulation. In contrast, the radiative cooling primarily develops the Arctic polar vortex.

$$\frac{\partial}{\partial t}\frac{\partial\overline{u^*}}{\partial z} \simeq -\frac{1}{f_0}\frac{R}{H}e^{-\kappa z/H}\boxed{\frac{\partial}{\partial t}\left(\frac{\partial\theta}{a\partial\phi}\right)}$$

$$\boxed{\frac{\partial}{\partial t}\left(\frac{\partial\theta}{a\partial\phi}\right)} = \frac{\partial}{a\partial\phi}\left(\frac{\partial\theta}{\partial t}\right) = \boxed{\frac{\partial\left(\overline{Q^*}/\pi\right)}{a\partial\phi}} - \frac{\partial}{a\partial\phi}\left(\overline{v^*}\frac{\partial\theta}{a\partial\phi}\right) - \boxed{\frac{\partial}{a\partial\phi}\left(\overline{w_\dagger^*}\frac{\partial\theta}{\partial z}\right)}$$

radiative heating/cooling

adiabatic change



The time tendency of the latitudinal potential temperature gradient divided by f due to mean vertical advection, diabatic process, and mean meridional advection.

6. Conclusions

The Lagrangian characteristics of vertical motions around the Antarctic polar vortex are investigated using various analysis methods. The dynamical mean vertical velocity with GCM output shows strong downward motion outside the Antarctic polar vortex around 45S–55S in the lower stratosphere, while w* estimated from reanalysis products are very noisy. Trace analysis does not capture the strong downward velocity outside the vortex because of active horizontal mixing. The mean downward motion outside the Antarctic polar vortex causes adiabatic heating and contributes to the formation of the polar night jet in the lower stratosphere.