MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

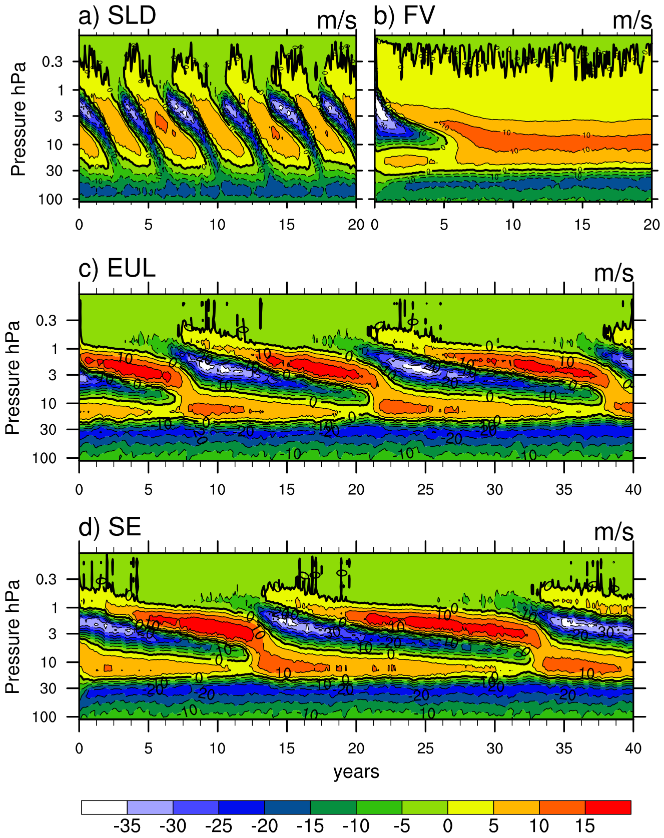
A Stratospheric Perspective of a GCM Dynamical Core Intercomparison

Weiye Yao and Christiane Jablonowski
University of Michigan

- **NCAR's Community Atmosphere Model (CAM), Version 5**
- **CAM5 dynamical cores** （*Neale et al. 2010*）
    - SLD spectral transform semi-Lagrangian
    - EUL spectral transform Eulerian
    - FV Finite Volume
    - SE Spectral Element, cubed-sphere grid

Dycore	Dynamical Δt	Resolution	Diffusion	Diffusion Coefficient
SLD	2700 s	T63	Implicit	–
FV	360 s	2°×2°	Implicit and explicit 2nd-order divergence damping	see (Whitehead et al. 2011)
EUL	720 s	T63	4th-order hyper-diffusion	$K_4 = 5 \times 10^{15}$ m^4 s^{-1}
SE	540 s	ne16np4	4th-order hyper-diffusion	$K_4 = 5 \times 10^{15}$ m^4 s^{-1}

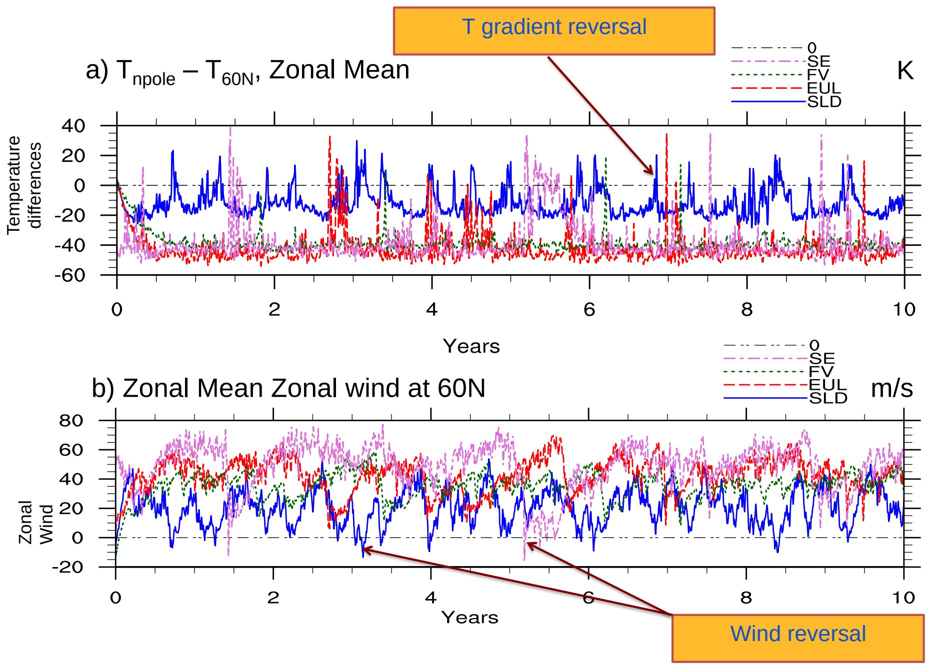
- **Held-Suarez Forcing** （*Held and Suarez, 1994*）
- **Resolution**
    - 2x2 degrees ~220 km
    - 55 vertical levels
        - 1.2 km in the stratosphere and increase to 2 km
    - Model top 0.1 hPa ~ 64 km



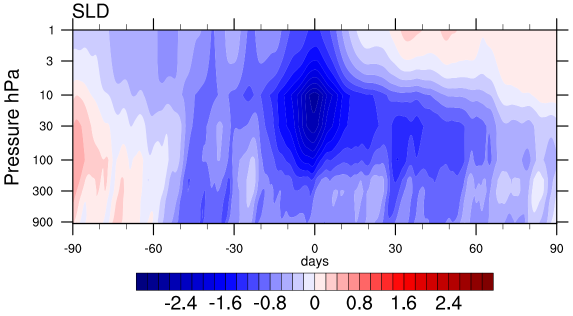
Sudden Stratospheric Warming

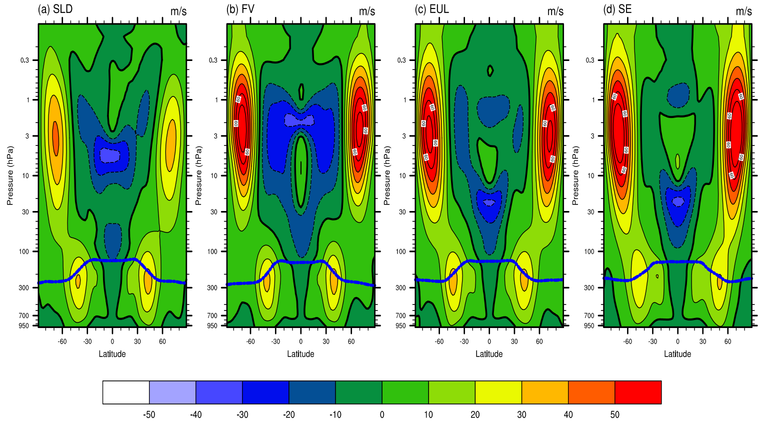
Held-Suarez Williamson Forcing *Williamson et al. (1998)*

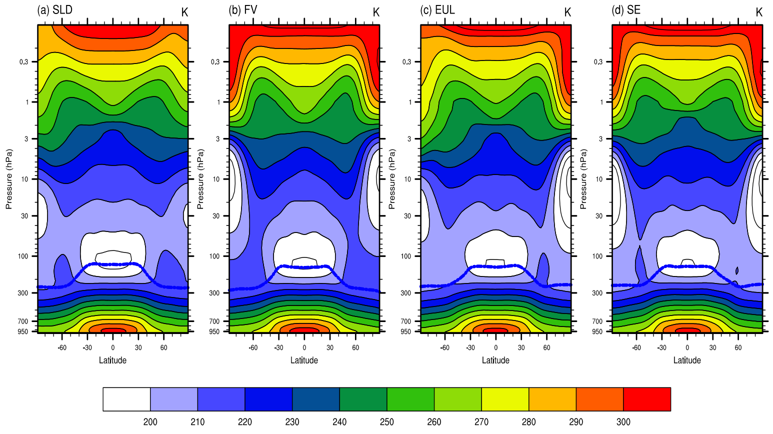
Modified stratosphere


T gradient reversal

Wind reversal







A Stratospheric Perspective of a GCM Dynamical Core Intercomparison

Weiye Yao, Christiane Jablonowski

Atmospheric Oceanic and Space Sciences, University of Michigan; weiyeyao@umich.edu

The Workshop on Partial Differential Equations on the Sphere

1. Introduction

The Quasi-Biennial Oscillation (QBO) in the tropics and Sudden Stratospheric Warmings (SSWs) in the polar regions are the two major dynamic phenomena in the stratosphere. The QBO is mainly generated and influenced by tropical waves, which consist of large-scale equatorially-trapped Kelvin waves, mixed Rossby-gravity waves, inertio-gravity waves and small- scale gravity waves. SSWs are generated by large-scale planetary waves. These waves are generated in the troposphere, propagate upwards and deposit their momentum in the upper atmosphere once they break. The ability of a General Circulation Model (GCM), and in particular their dynamical cores, to simulate the waves and the corresponding wave-mean flow interactions is very important in simulating the QBO and SSWs. This ability varies with the chosen vertical and horizontal resolutions, but it is also dependent on the details of the numerical schemes, the strengths of explicit vertical or horizontal diffusion, and the characteristics of the sponge layer near the model top. We discuss the curious result that both QBO-like oscillations and SSWs can already be simulated without moisture or topographic effects which are generally believed to be the main wave triggering mechanisms.

2. Idealized Simulation

The QBO and SSWs are simulated with version 5 of the NCAR/DOE Community Atmosphere Model (CAM 5) with a high model top at 0.1 hPa and 55 levels. The QBO and SSWs are modeled with four dynamical cores.

- Semi-Lagrangian (SLD): two-time-level, semi-implicit semi-Lagrangian spectral transform model, Gaussian grid, T63 triangular truncation (about 200 km grid spacing), no explicit diffusion is used.
- Finite-Volume (FV): default dycore in CAM 5 - 5.2 , grid-point-based finite-volume discretization, explicit time-stepping scheme, latitude-longitude grid, 2°x2°
- Eulerian (EUL): three-time-level, semi-implicit Eulerian spectral transform dycore, Gaussian grid, T63 triangular truncation, uses 4th-order hyper-diffusion $K_4 = 5 \times 10^{15}$ m^4 s^{-1}.
- Spectral Element (SE): new default dycore (CAM 5.3), based on continuous Galerkin spectral finite element method, designed for fully unstructured quadrilateral meshes (cubed-sphere grid), locally energy- and mass-conserving, explicit time-stepping scheme, ne16 resolution (about 2°x2° or 200 x 200 km grid spacing), uses 4th-order hyper-diffusion $K_4 = 5 \times 10^{15}$ m^4 s^{-1}.

Idealized Physics The simulations are driven by the Held and Suarez (1994) forcing (HS)(with modifications by Williamson et al. (1998) (HSW)) The HS is isothermal in the stratosphere, therefore has no typical stratospheric structures. The HSW forcing has the same set up as the HS forcing, only with a different equilibrium temperature profile in the stratosphere.

- Dry flat earth without moisture
- Rayleigh damping near the surface and model top (1-0.1 hPa)
- Prescribed Newtonian temperature relaxation

These mimic the effects of radiation, boundary-layer friction, and additional sponge layer dissipation at the model top.

3. QBO simulation with HS forcing

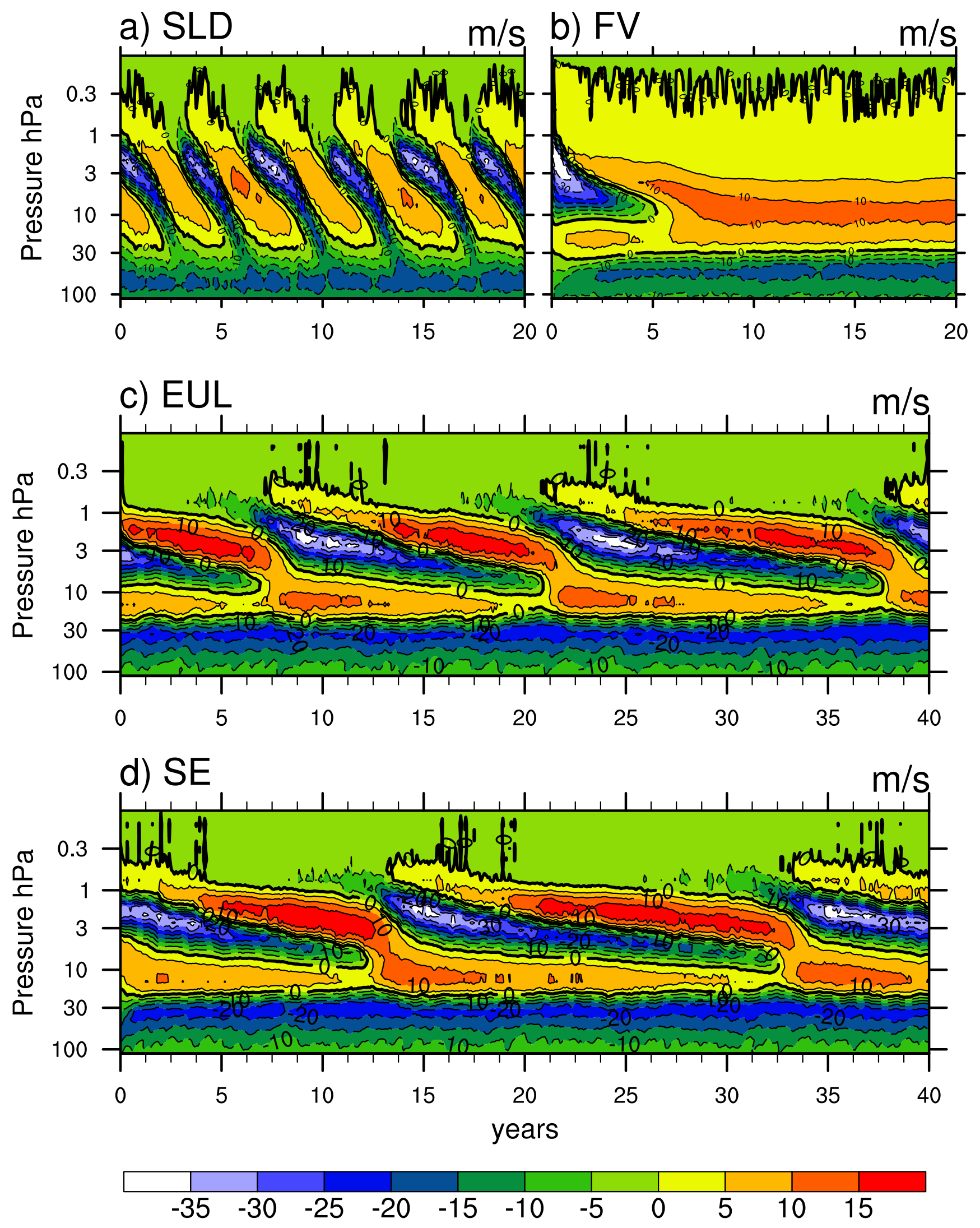


Figure 1: *Monthly-mean zonal-mean zonal wind at the equator from different dynamical cores, averaged between $\pm 2^{\circ}$, in m s^{-1}. a) SLD, b) FV, c) EUL and d) SE.*

The SLD dycore shows an oscillation that is closest to observation. However, the period of the QBO-like oscillation is on average 43.5 months, which is longer than observation. The simulation with the EUL and SE dycore both show QBO-like oscillations with periods longer than 13 years. The oscillation regimes are higher in altitude compared to observations, which has been a common issue in most QBO simulations . The FV dycore does not sustain the oscillation. (Yao and Jablonowski, 2013, 2014 (in preparation))

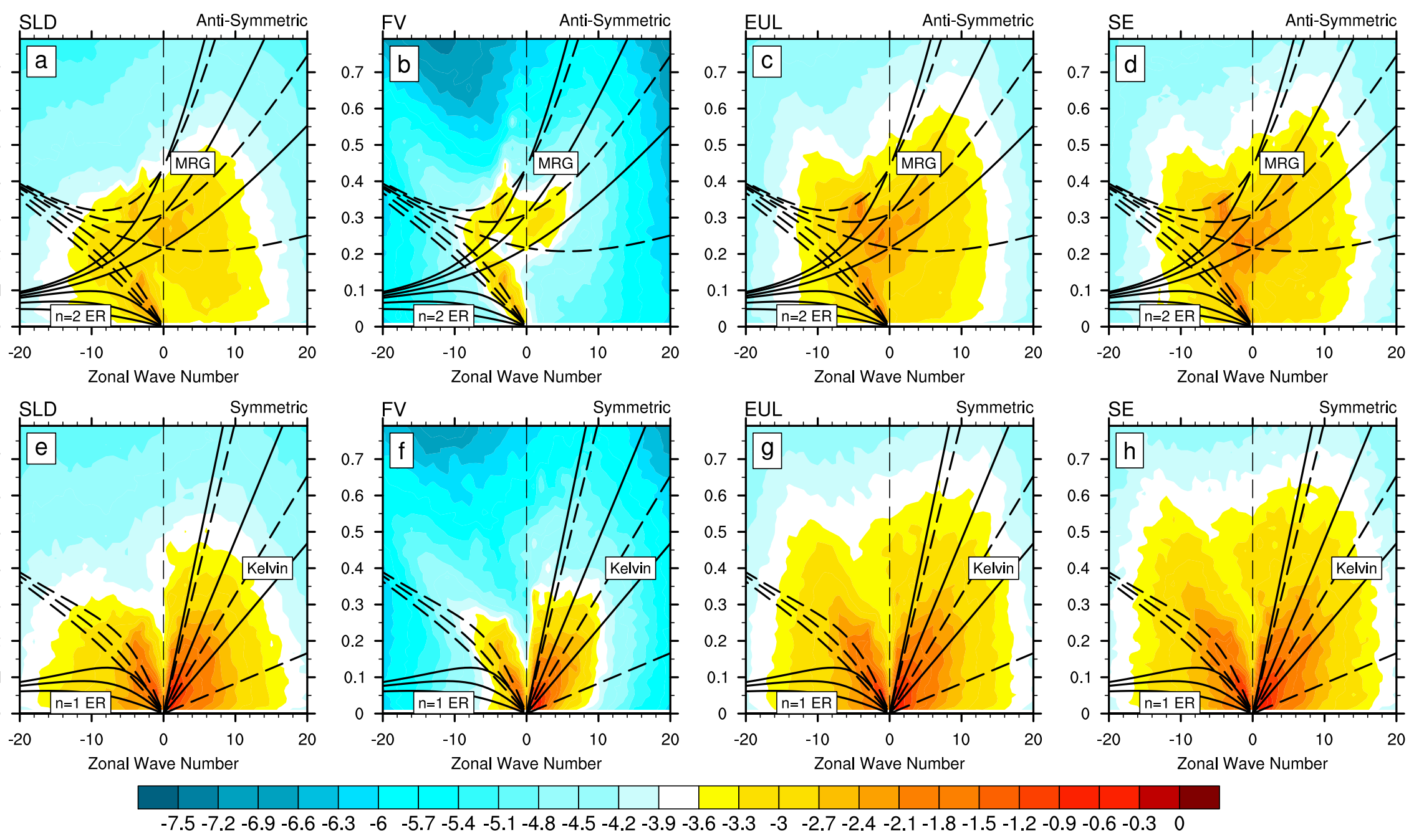


Figure 2: *Wavenumber-frequency analysis of the 22 hPa temperature field (raw power spectrum, log-scale) for different dycores between 10S-10N. Left to right are SLD, FV, EUL and SE. The top row is the anti-symmetric, the bottom row is the symmetric component. Solid lines are dispersion curves with 0 m/s background wind and equivalent depths of 12, 50, and 200 m (increasing towards higher frequency). Dashed lines are Doppler-shifted dispersion curves with the same equivalent depths, using a background wind of -7 m s^{-1}.*

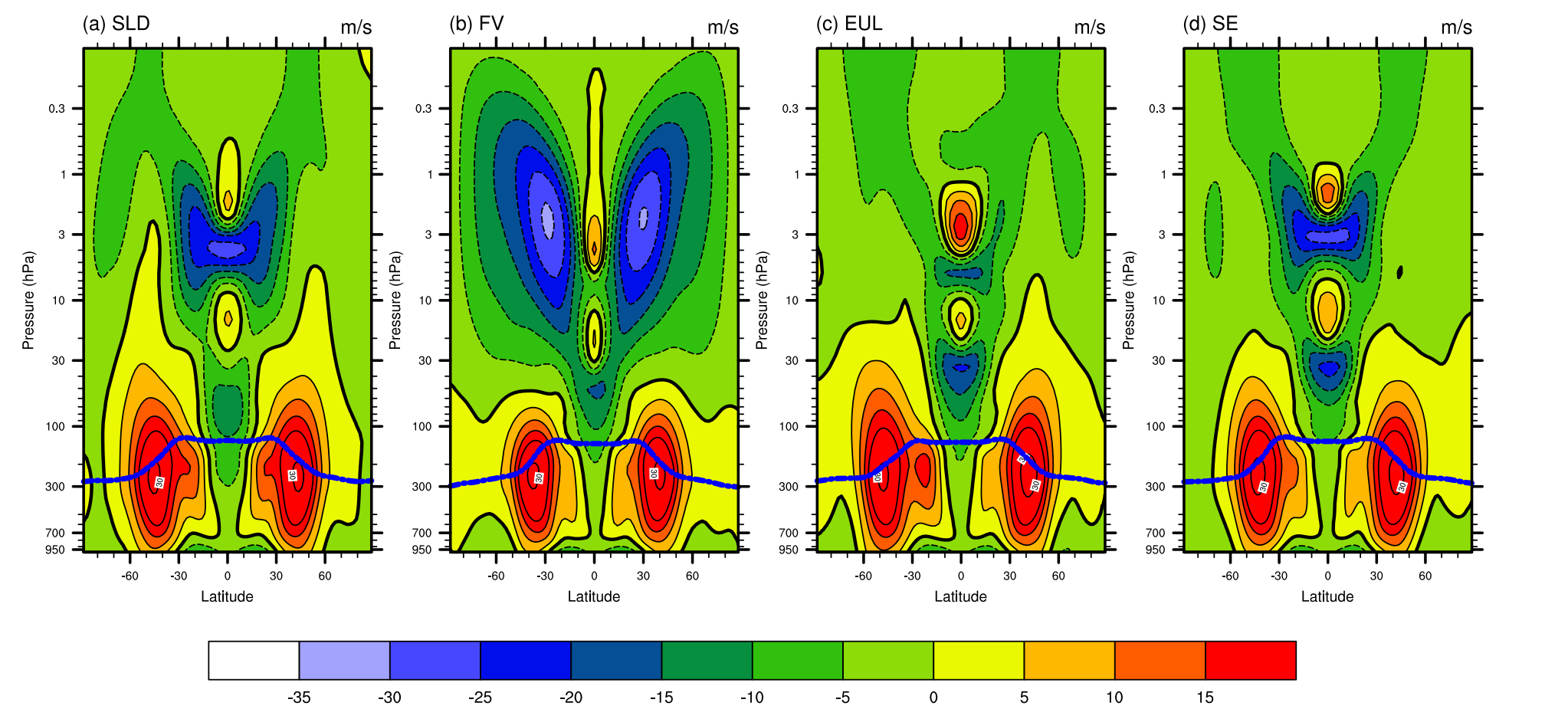


Figure 3: *Pressure-latitude cross section of monthly-mean zonal-mean zonal wind from different dynamical cores with HS forcing. a) SLD, b) FV, c) EUL and d) SE. Blue lines indicates the tropopause position of each simulation. FV develops very strong easterly jests near 30S/N which are not present in other dycores.*

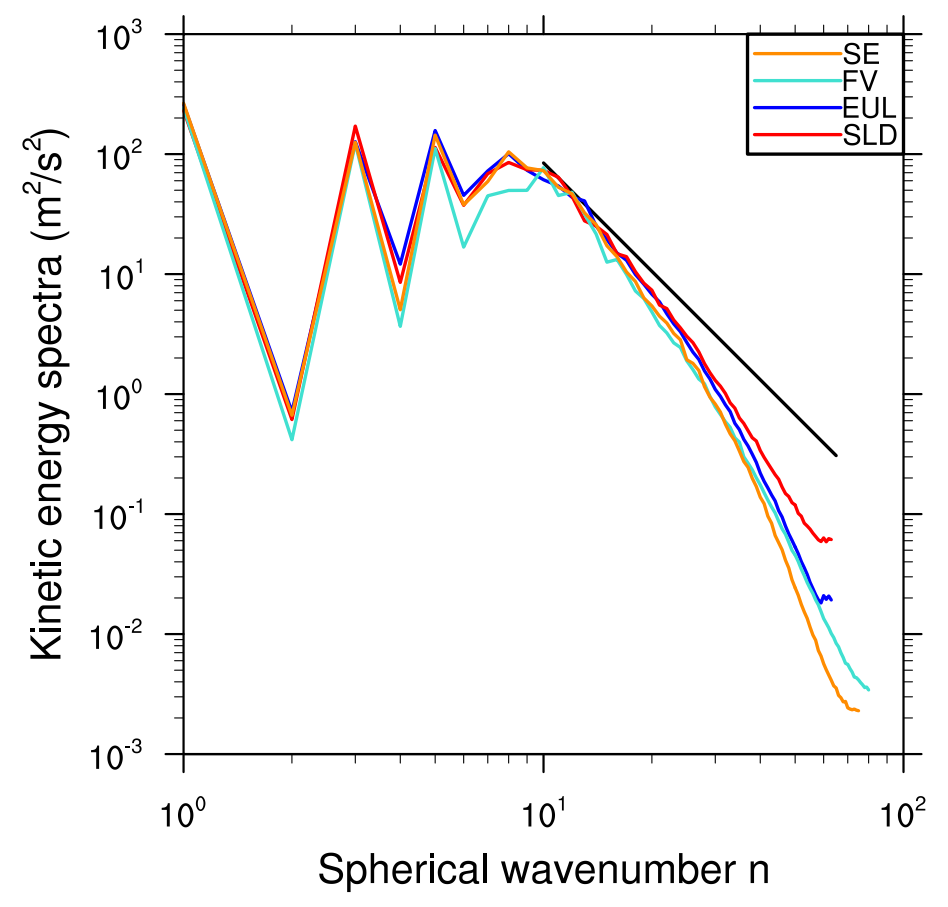


Figure 4: *30 day mean kinetic energy spectra for four dycores at 250 hPa, the black line shows theoretical n^{-3} kinetic energy decaying rate with wave numbers. SE has the steepest slope and is the most diffusive*

4. SSW simulation with HSW forcing

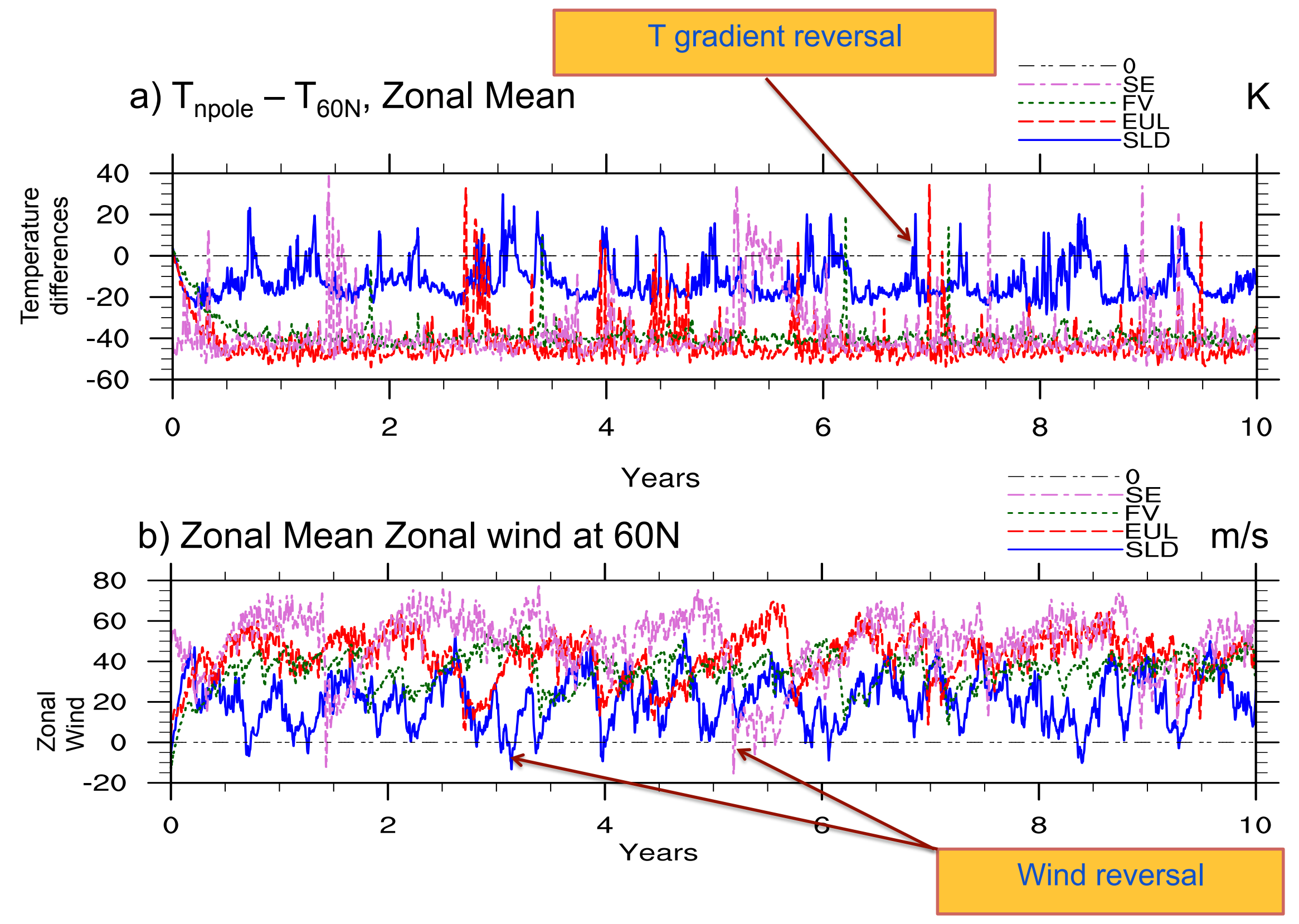


Figure 5: *10 years of 6-hourly simulation data for the SE, FV, EUL and SLD dycore. a) zonal-mean temperature gradient from North Pole to the 60°N at 10 hPa. b) zonal-mean zonal wind at 60°N 10 hPa. Although the temperature reversal is frequent for all dycores, only selected events are accompanied by a wind reversal. Events with wind reversals are defined as major warmings, events with only temperature reversal are defined as minor warmings. SLD exhibits the most SSW events among the four dycores.*

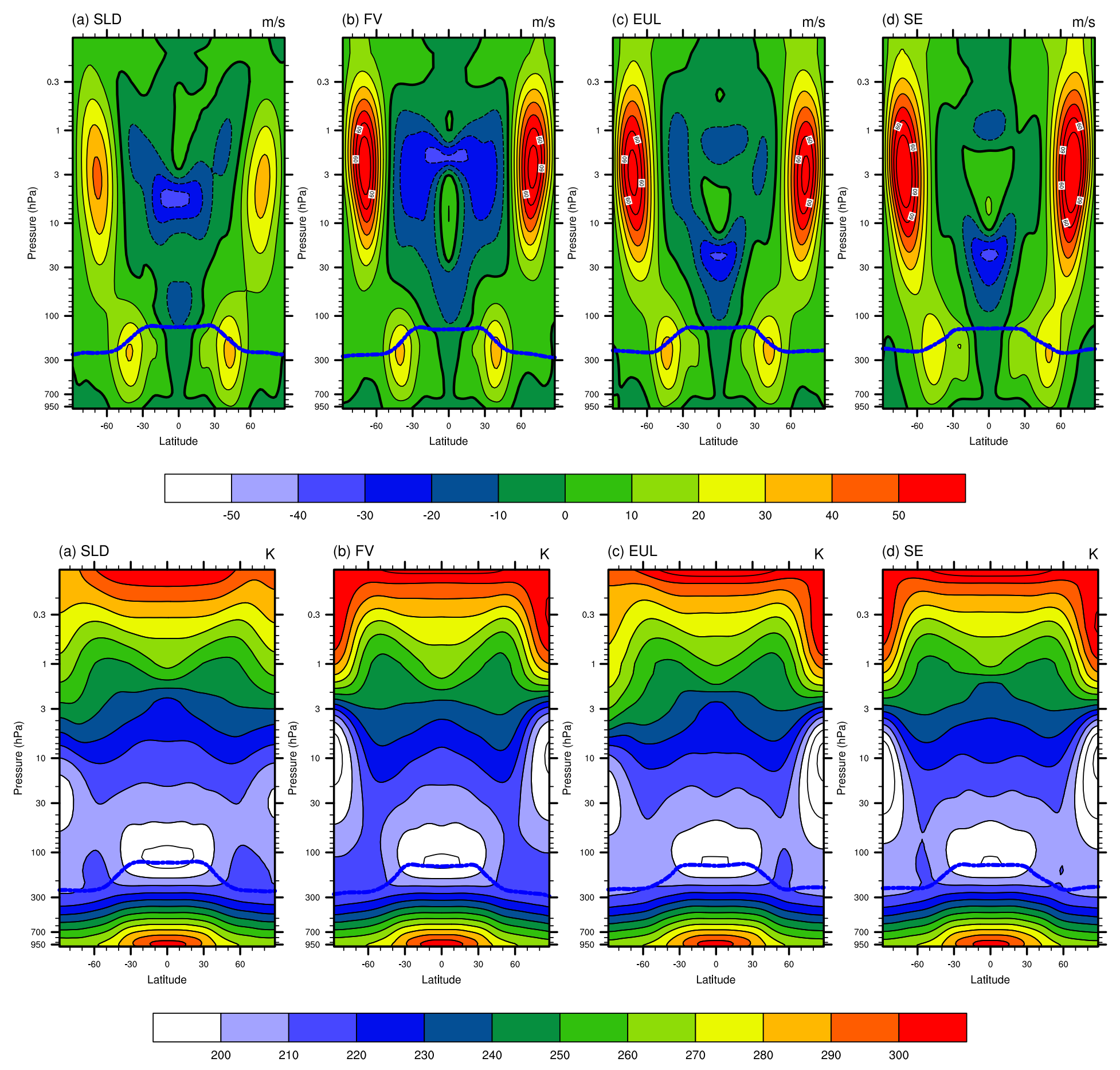


Figure 6: *Pressure-latitude cross section of monthly-mean zonal-mean zonal wind (first row) and temperature (second row) from different dynamical cores with HSW forcing. the HSW forcing leads to polar vortices, that are weakest in SLD, SSW events can more easily be triggered.*

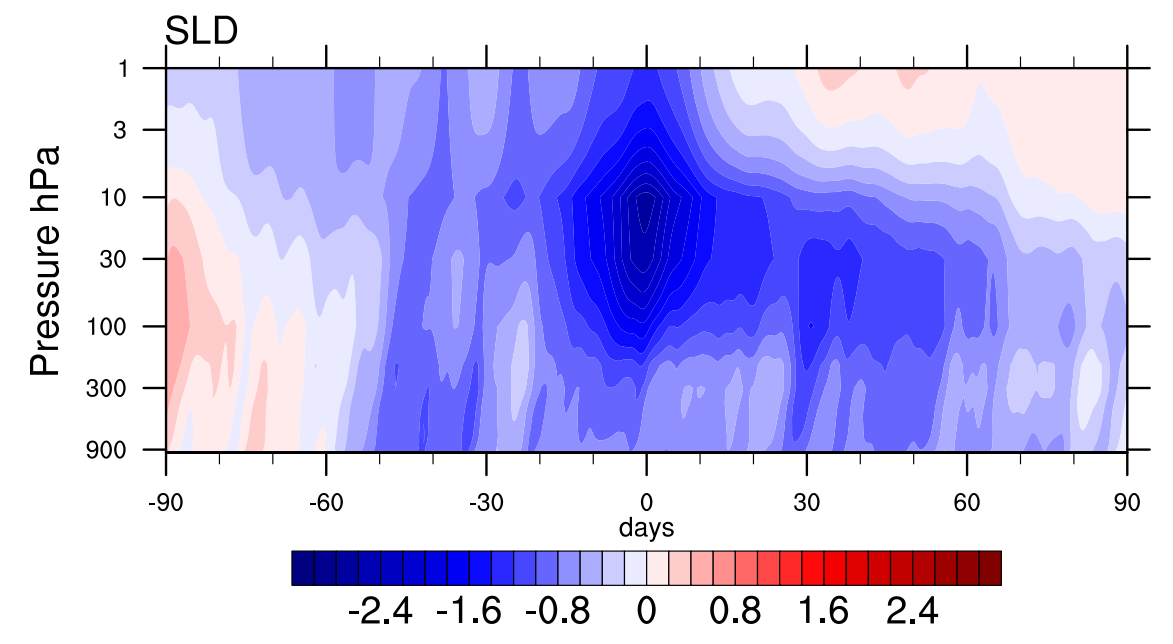


Figure 7: *SSW composites of the annular mode in SLD. Normalized time series from Empirical Orthogonal Function analysis of geopotential height. 15 events are detected from a 20-year 6-hourly data. SSWs have downward impact on the troposphere.*

5. Summary and Conclusion

- Three out of four CAM dycores show spontaneous QBO-like oscillations, with different periods.
- The wavenumber-frequency analysis for the FV dycore simulation shows much weaker wave power than the analysis of the other three dycores.
- All dynamical cores develop spontaneous minor SSW events without orographically generated planetary waves, only SLD and SE develop major SSW events.
- The frequencies of the SSW events are different for the dynamical cores, the SLD has the most SSW event. The SSW characteristics are very sensitive to the numerical design.

Held, I. M. and M. J. Suarez, 1994: A proposal for the intercomparison of the dynamical cores of atmospheric general circulation models. *Bull. Amer. Meteor. Soc.*, 75 (10), 1825–1830.

Williamson, D. L., J. G. Olson, and B. A. Boville, 1998: A comparison of semi-Lagrangian and Eulerian tropical climate simulations. *Mon. Wea. Rev.*, 126, 1001–1012.

Yao, W. and C. Jablonowski, 2013: Spontaneous qbo-like oscillations in an atmospheric model dynamical core. *Geophysical Research Letters*, 40, 3772–3776, 10.1002/grl.50723.

Yao, W. and C. Jablonowski, Idealized simulations of the Quasi-Biennial Oscillation with different GCM dynamical cores. *Journal of the Atmospheric Sciences*