The dynamics and vortex structures of the stratopause semi-annual oscillation

O'Kane, T.J., Kitsios, V., Collier, M.A.

ACCESS Science Day 2021
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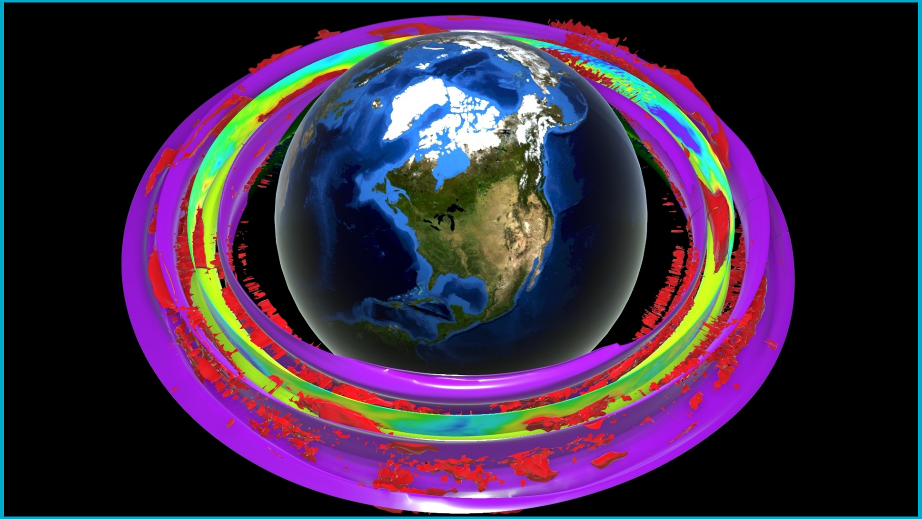

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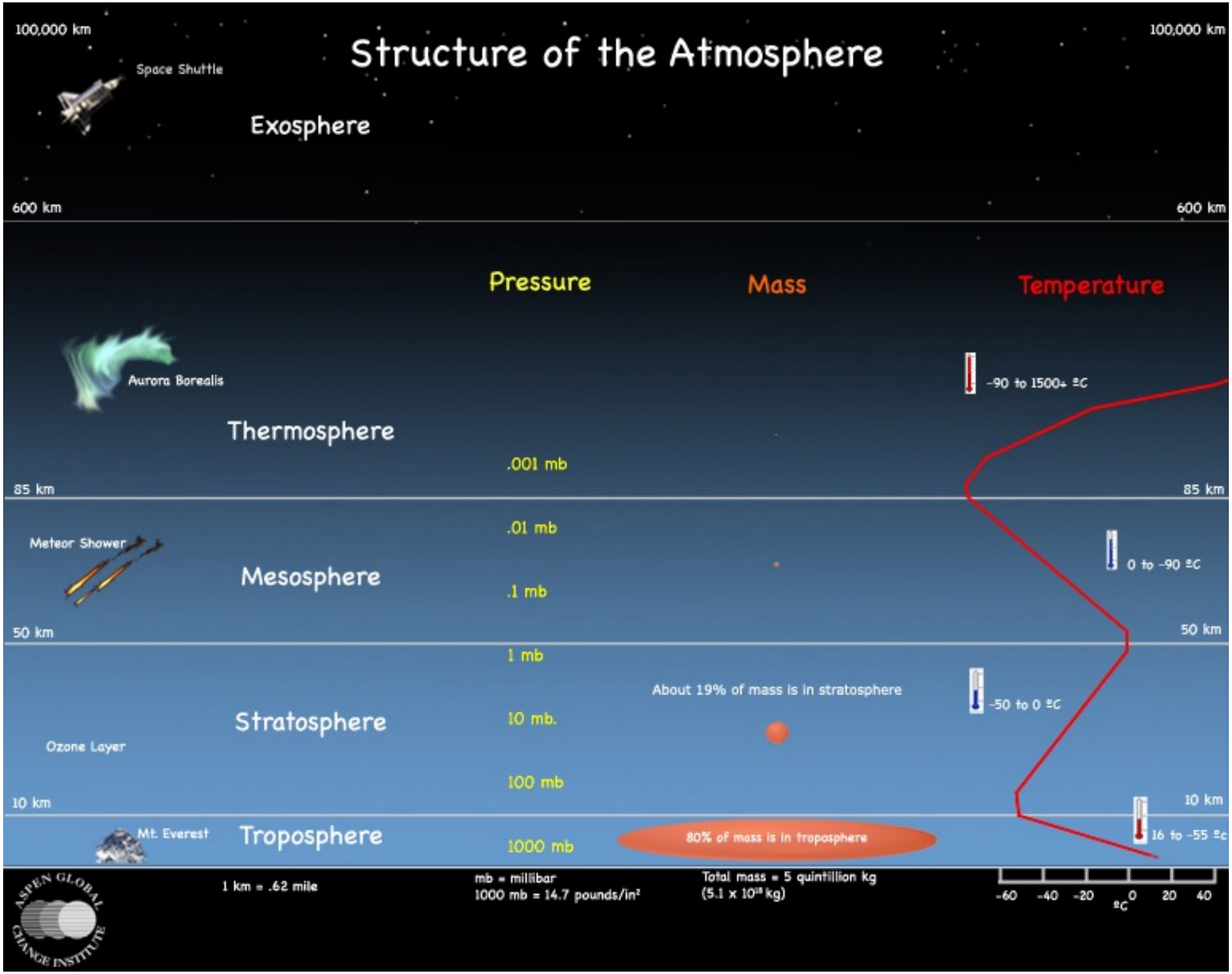
Structure of the Atmosphere
100,000 km
100,000 km
Space Shuttle
Exosphere
600 km
600 km
Pressure
Mass
Temperature
Aurora Borealis
-90 to 1500+ ºC
Thermosphere
.001 mb
85 km
85 km
Meteor Shower
.01 mb
Mesosphere
.1 mb
0 to -90 ºC
50 km
50 km
1 mb
About 19% of mass is in stratosphere
-50 to 0 ºC
Stratosphere
10 mb.
Ozone Layer
100 mb
10 km
10 km
Mt. Everest
Troposphere
1000 mb
80% of mass is in troposphere
16 to -55 ºc
1 km = .62 mile
mb = millibar
1000 mb = 14.7 pounds/in^2
Total mass = 5 quintillion kg
(5.1 x 10^{18} kg)
-60 -40 -20 0 20 40
ºC
ASPEN GLOBAL CHANGE INSTITUTE

DATA: : Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2)

- MERRA-2 provides a multi-decadal reanalysis whereby aerosol and meteorological (satellite radiances, microwave temperature, ATOVs etc) observations are jointly assimilated
- MERRA-2 also includes several improvements to the representation of the stratosphere including ozone (total column, profiles from EOS Aura OMI)
- MERRA-2 makes possible an observationaly constrained examination of the stratosphere-stratopause - mesosphere. That said the stratopause remains only partially observed.

The MERRA-2 Aerosol Reanalysis, 1980 Onward. Part I: System Description and Data Assimilation Evaluation
In Special Collection: Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2)
C. A. Randles; A. M. da Silva; V. Buchard; P. R. Colarco; A. Darmenov; R. Govindaraju; A. Smirnov; B. Holben; R. Ferrare; J. Hair ...
J. Climate (2017) 30 (17): 6823–6850.
https://doi.org/10.1175/JCLI-D-16-0609.1

The MERRA-2 Aerosol Reanalysis, 1980 Onward. Part II: Evaluation and Case Studies
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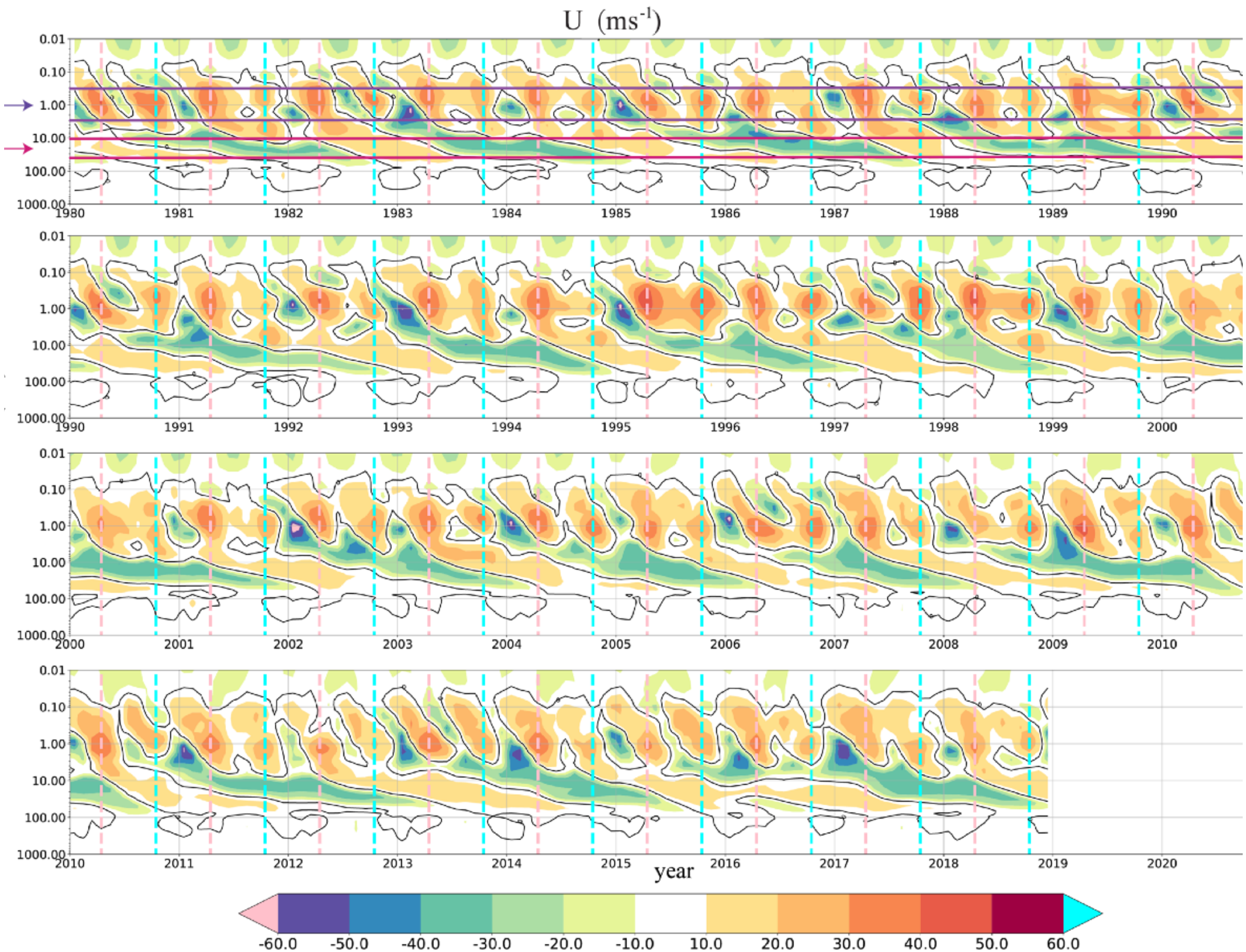
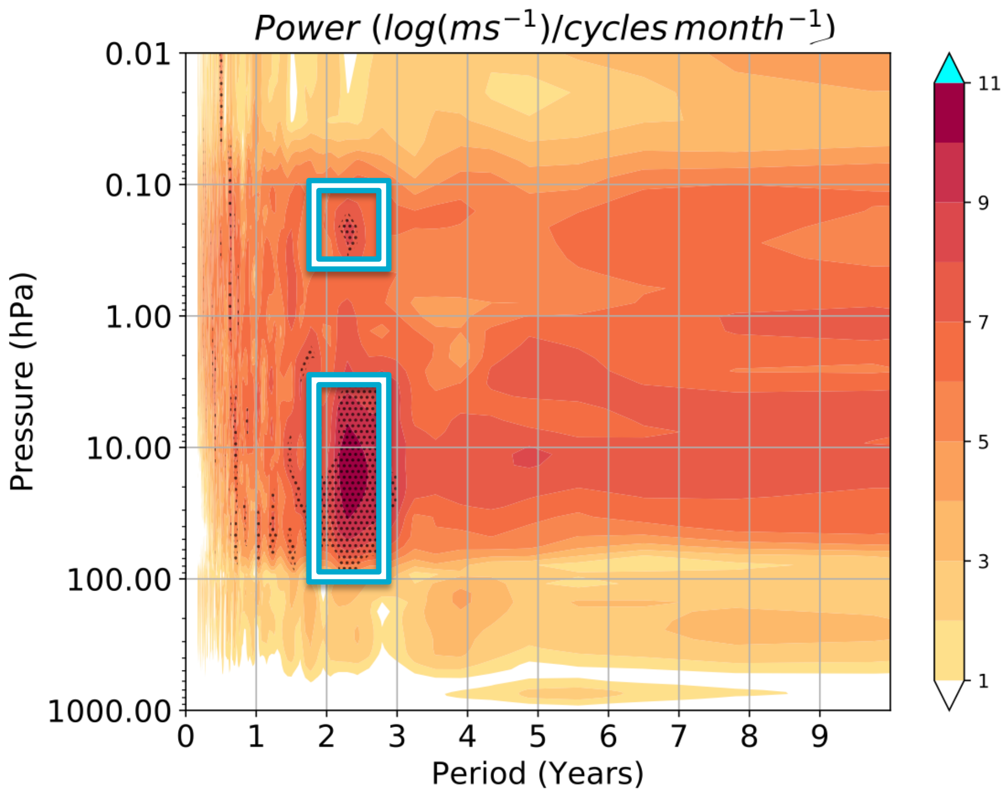
J. Climate (2017) 30 (17): 6851–6872.
https://doi.org/10.1175/JCLI-D-16-0613.1

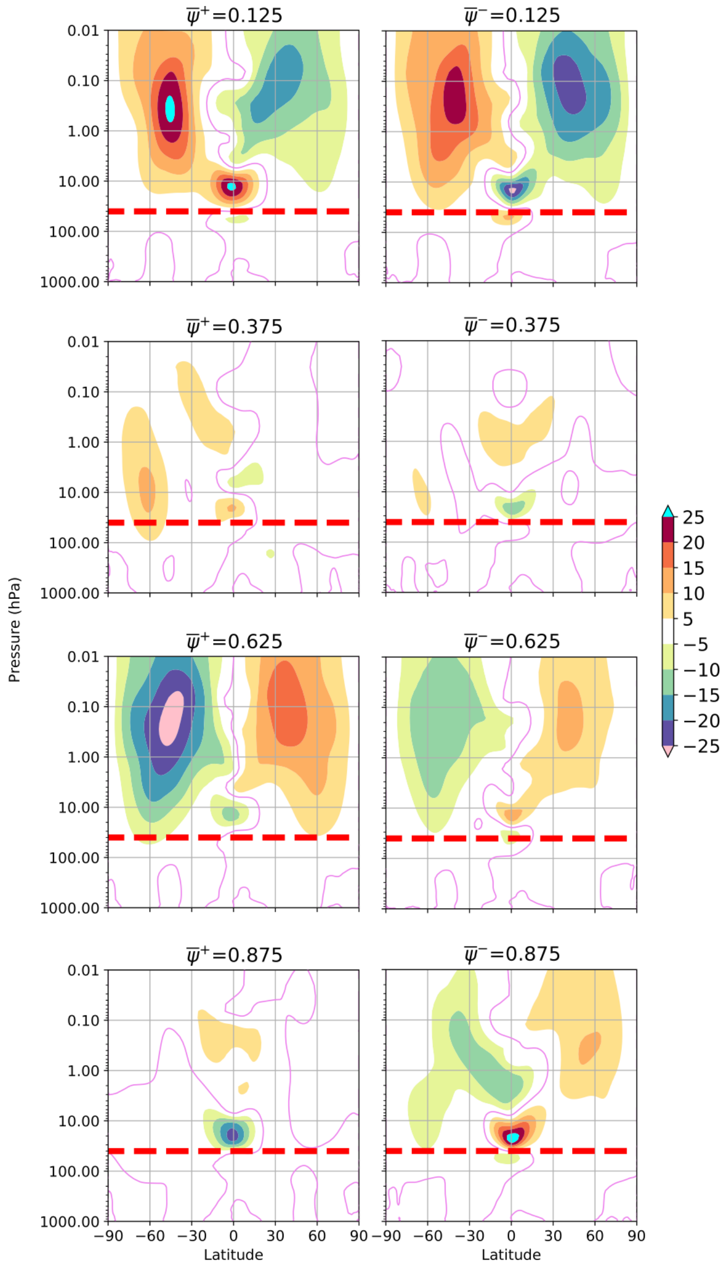
Quasi-Biennial & Semi-Annual Oscillations



Monthly averages of the U zonal winds averaged between 0-360 longitude and 5N-5S latitude. Black contour shows zero average of winds. April and October are indicated by the pink and cyan vertical lines respectively.

Relationship between SAO & QBO





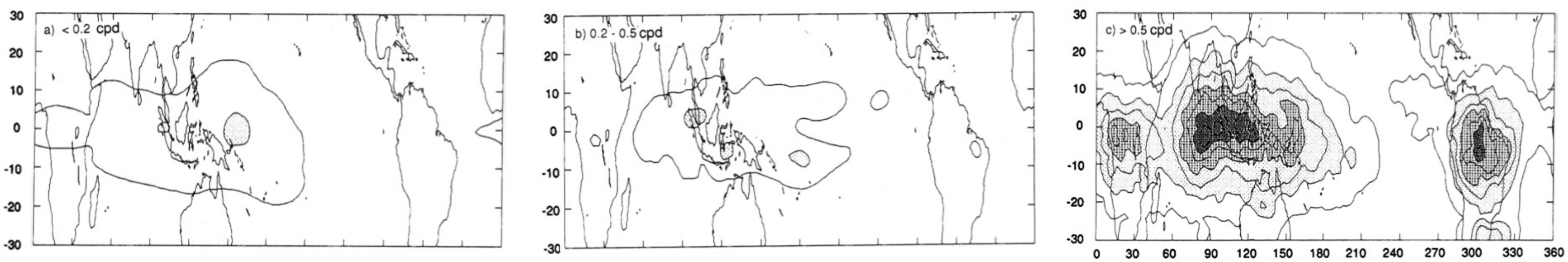
Semi-Annual Oscillation

- Holton (AMS 1975) proposed that:
- The westerly SAO results from the combined effects of a steady background source of westerly momentum due to Kelvin waves excited in the tropical troposphere with the downward propagation of the jet indicative of dissipation of vertically propagating waves near critical layers.
- In contrast, the easterly phase was hypothesised to arise from an oscillating source of easterly momentum due to vertically and equatorward propagating planetary waves of the winter hemisphere stratosphere being absorbed near the critical line in the tropics.

Sources of momentum

Dunkerton (JAS 1979), showed that a Kelvin wave with sufficiently fast phase speed could propagate through the stratosphere with only modest attenuation and then be strongly absorbed in the region of very fast radiative damping near the stratopause.

Bergman & Salby (JAS 1994) analysed observed tropical convection to map the spatial and temporal distributions of equatorial heating where sufficiently fast Kelvin waves might be generated.



> 5 days (<0.2 cpd) | 2-5 days (0.2-0.5 cpd) | < 2 days (>0.5 cpd)

Global convective pattern based on the vertical component of frequency integrated absolute value of the E-P flux for equatorial waves with periods from satellite data

E-P flux and zonal winds

Vortices only form in equinoctial seasons!

When the E-P flux vector

: points upward, the meridional heat flux dominates;

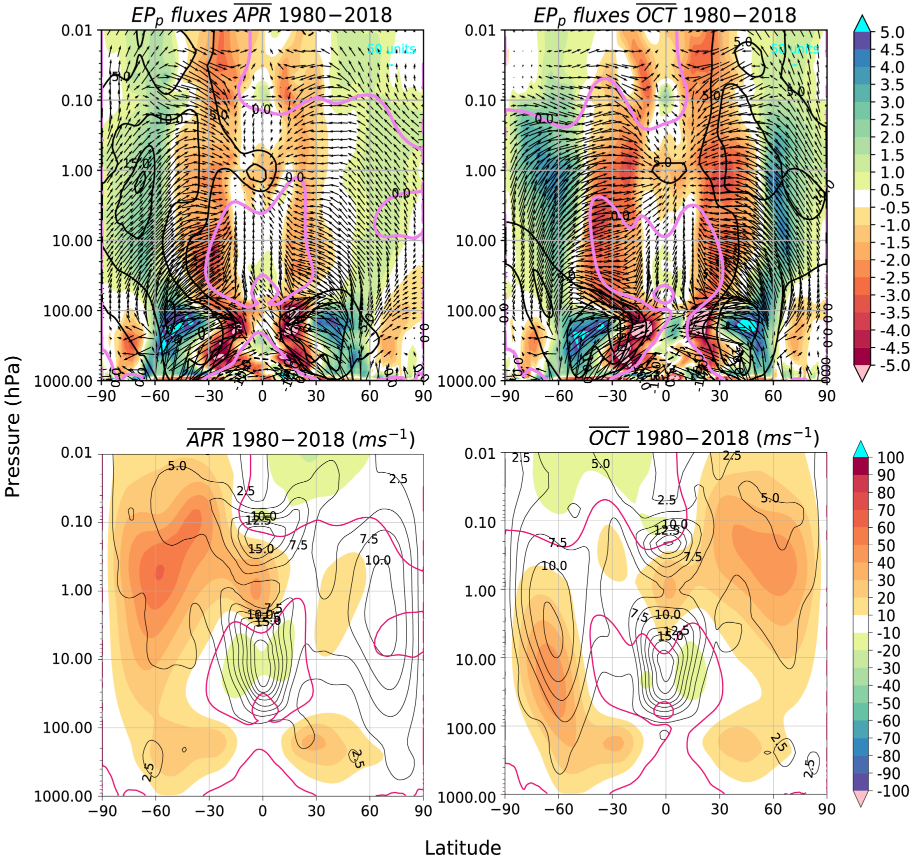
:points in the meridional direction, the meridional flux of zonal momentum dominates.

$$\mathbf{F}^P = \{F_\phi, F_z\}$$

$$F_\phi = a\cos\phi\left(\overline{U}_z \frac{\overline{V'\theta'}}{\overline{\theta}_z} - \overline{U'V'}\right),$$

$$F_z = a\cos\phi\{\left[f - (a\cos\phi)^{-1}(\overline{U}\cos\phi)_\phi\right]\frac{\overline{V'\theta'}}{\overline{\theta}_z} - \overline{U'\omega'}\}$$

The divergence of the E-P flux is proportional to the eddy potential vorticity flux and when zero i.e. $\nabla \cdot F = 0$, thermal wind balance is maintained



Equinoctal flux normalized by climatological (1980-2018) standard deviation at each latitude and level (vectors). Flux divergence (shading). Contours indicate climatological winds (black) and critical line (magenta).

Monthly climatological (1980-2018) U winds zonally averaged (shading). Negative (positive) wind values indicate easterly (westerly) flow. Black contours are the corresponding standard-deviations in m/s.

Vortex identification at the stratopause

4.1 Calculation of Q

Following (Chong et al., 1990; Soria et al., 1994; Chakraborty et al., 2005) we define the velocity gradient tensor A_{ij} in terms of symmetric $S_{ij} = S_{ji}$ and anti-symmetric $W_{ij} = -W_{ji}$ parts where,

$$A_{ij} = \partial u_i/\partial x_j = S_{ij} + W_{ij} \tag{2a}$$

and

$$S_{ij} = (\partial U_i/\partial x_j + \partial U_j/\partial x_i)/2 \tag{2b}$$

$$W_{ij} = (\partial U_i/\partial x_j - \partial U_j/\partial x_i)/2 \tag{2c}$$

are the rate of strain and the rate of rotation tensors respectively. The $U_{i=1,2,3}$ indices are the zonal and meridional velocities (U, V) in meters per second (ms^{-1}) and ω the Lagrangian rate of change of pressure with time in units of pascals per second $(Pa\ s^{-1})$. The $x_{i=1,2,3}$ indices are latitude and longitude (ϕ, λ) in meters (m) and isobaric pressure level p in Pa respectively. The eigenvalues γ of A_{ij} satisfy the characteristic equation

$$\gamma^3 + P\gamma^2 + Q\gamma + R = 0, \tag{2d}$$

where the matrix invariants are

$$P = -\operatorname{Tr}[A] = -S_{ii} \tag{2e}$$

$$\begin{aligned} Q &= \frac{1}{2}(P^2 - \operatorname{Tr}[A^2]) = \frac{1}{2}(P^2 - S_{ij}S_{ji} - W_{ij}W_{ji}) \\ &= \begin{vmatrix} \frac{\partial U}{\partial \phi} & \frac{\partial U}{\partial \lambda} \\ \frac{\partial V}{\partial \phi} & \frac{\partial V}{\partial \lambda} \end{vmatrix} + \begin{vmatrix} \frac{\partial U}{\partial \phi} & \frac{\partial U}{\partial p} \\ \frac{\partial \omega}{\partial \phi} & \frac{\partial \omega}{\partial p} \end{vmatrix} + \begin{vmatrix} \frac{\partial V}{\partial \lambda} & \frac{\partial V}{\partial p} \\ \frac{\partial \omega}{\partial \lambda} & \frac{\partial \omega}{\partial p} \end{vmatrix} \end{aligned} \tag{2f}$$

Tr is the trace, Q has units of s^{-2}, and

$$R = -|A| \tag{2g}$$

where || defines the determinant.

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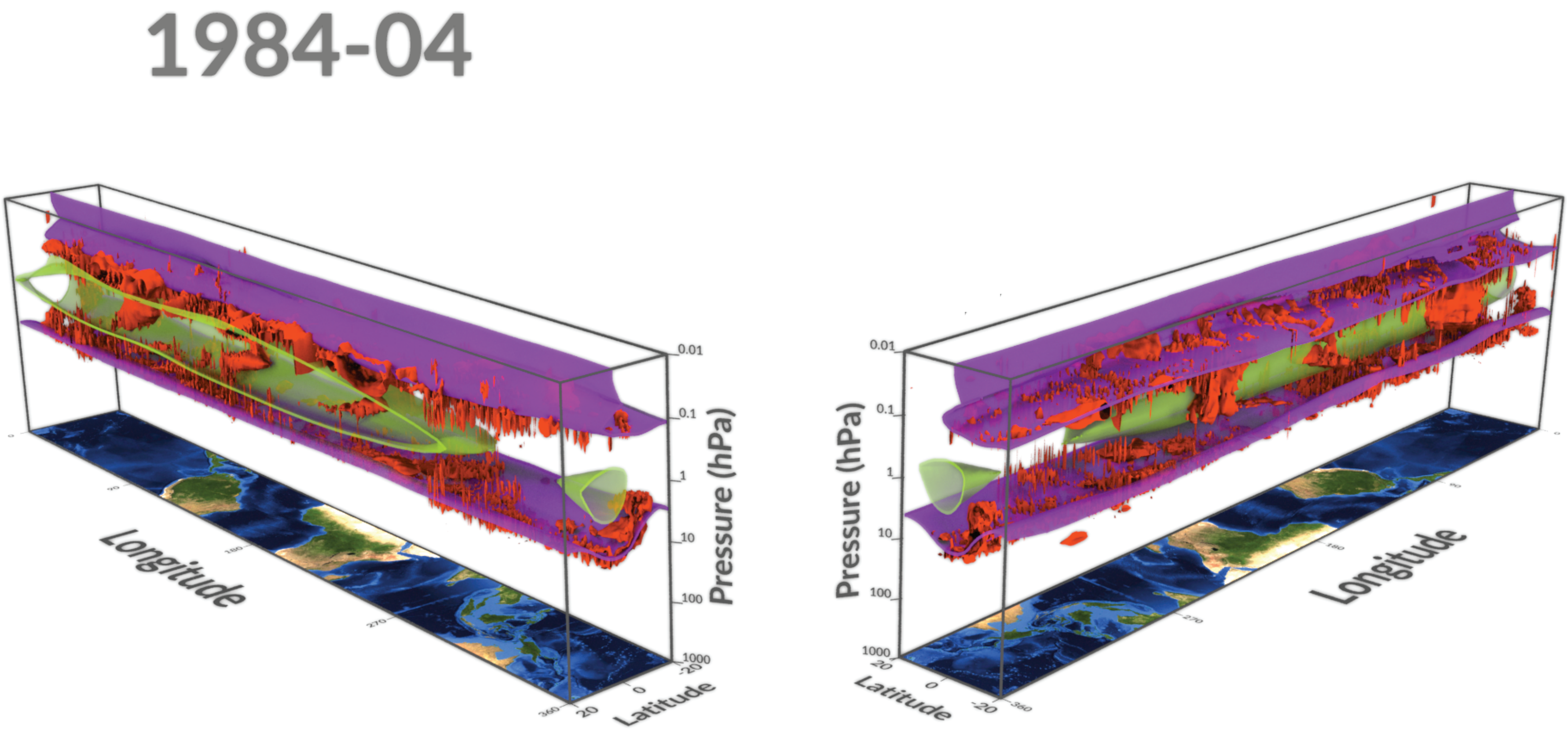
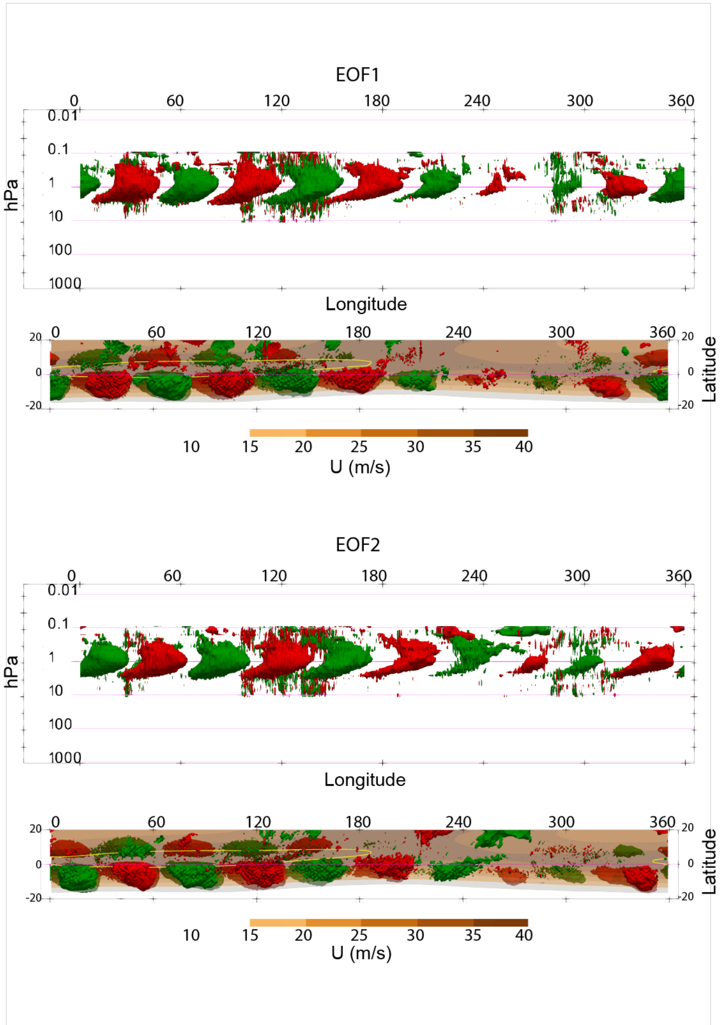
For incompressible flows $P = -S_{ii} = 0$ and then large negative values of Q are indicative of regions where the strain dominates the rotation whereas for large positive values indicate rotation dominates strain.

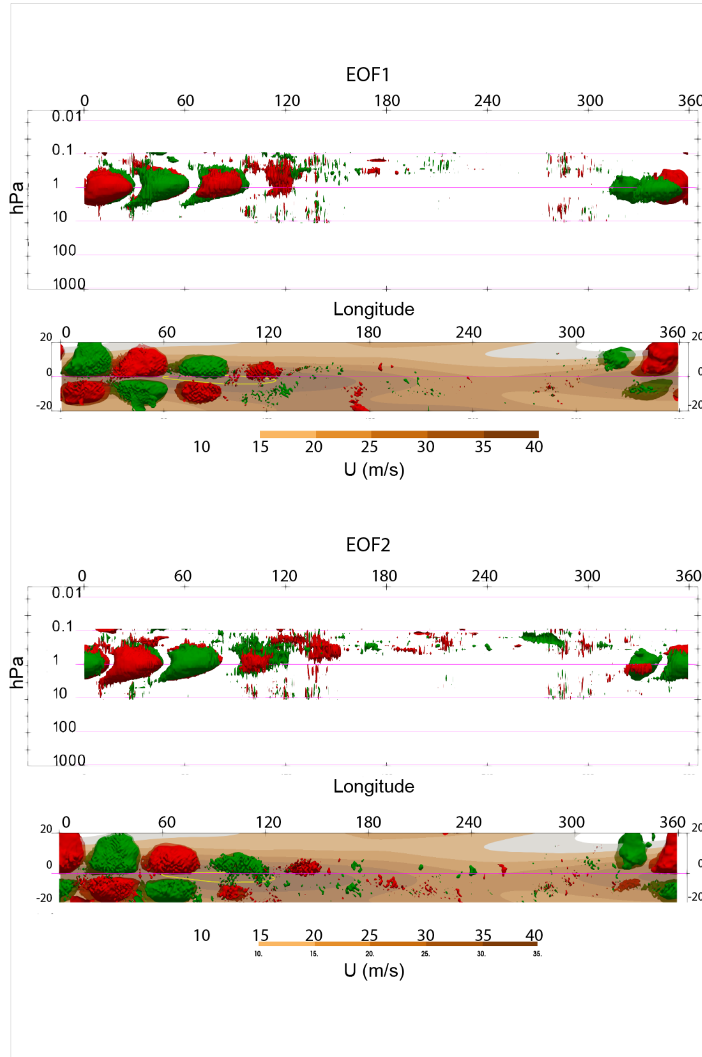


4.2 EOFs of Q

In calculating EOFs of Q, we first construct daily anomalies w.r.t. the climatological month i.e. $Q'(\phi, \lambda, p, t) = Q(\phi, \lambda, p, t) - \overline{Q}(\phi, \lambda, p)$. We then construct spatial anomalies from the zonal average as $Q''(\phi, \lambda, p, t) = Q'(\phi, \lambda, p, t) - Q'(\lambda, p, t)$. These anomalies are then normalized by the spatial and temporal standard deviation σ of Q'' at each pressure level i.e. $\hat{Q}(\phi, \lambda, p, t) = Q''(\phi, \lambda, p, t)/\sigma(p)$. In the current study, vortex structures will be represented by isosurfaces of EOFs of Q. Normalizing by the spatio-temporal standard deviation allows us to then rescale the EOF patterns before calculating the isosurfaces of interest i.e. $Q_i^{eof}(\phi, \lambda, p) = \hat{Q}_i^{eof}(\phi, \lambda, p) \times \sigma(p)$.

EOFs of Q (April, October)





These structures are approx 3200km long (30 deg lon), span 1500km across (15 deg lat) and 40km in vertical (10 - 0.1 hPa).

Vortex structures of the stratopause

- Vortex structures manifest only during the SAO westerly phase and only where the westerly jet reaches speeds in excess of $35 ms^{-1}$. Similar wind velocities are necessary to form the shear zones at the jets upper and lower boundary.
- The vortices are most coherent during March-April and less evident during October.
- Vortex structures manifest on particular dates with wave numbers between 4-7 but are typically wave 5, resembling the leading statistically stationary 3D-EOF Q patterns.
- Our analysis indicates that the vortices are maintained by a combination of local (shear zones) and remote (vertically propagating tropical) sources of momentum.
- The phase relationship between the QBO and SAO directly influences the strength of the shear zone at the lower boundary of the stratopause SAO during its westerly phase with consequences for the resulting Q vortices.
- The vortex structures appear to be unique to the stratopause and the SAO.

Thank you

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