Dynamical connections between stratosphere and troposphere

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Aim: set out basic dynamical mechanisms that link stratosphere and troposphere (with emphasis on stratosphere affecting troposphere)

Outline

- Non-local dynamics
- Zonal-mean circulations
- Wave mean-flow interaction
- Wave propagation
- The stratosphere as a 'flywheel'?

Key (concrete) questions?

How do stratospheric changes affect tropospheric climate?

How do shortcomings in model representation of stratosphere affect predictions of tropospheric weather and climate?

Stratosphere as indicator of tropospheric change?

Theoretical approach

Decomposition into zonal mean flow and waves/eddies is useful.

(Less controversial for stratosphere,
more controversial for troposphere.)

Then consider:

- Wave propagation on given mean state.
- Mean flow response to given wave forcing.
- Two-way interaction between waves and mean flow.

Example (Hartmann et al 2000)

Deep NAM signal in mean flow, with corresponding signal in wave fluxes.

Are waves essential? [surely yes]

Troposphere drives? (Tropospheric anomaly implies different wave propagation out of troposphere implies stratospheric anomaly.)

Stratosphere drives? (Variation in stratospheric wave driving implies anomaly in stratosphere which penetrates to troposphere.)

Non-local balanced dynamics

Local change to PV field implies instantaneous non-local change to velocity, temperature etc.

Given horizontal scale L, vertical penetration scale for velocity is

$$\max\left(\frac{2\Omega L \sin\phi}{N}, \frac{4\Omega^2 L^2 \sin^2\phi}{N^2 H}\right) \quad \text{(above)}$$

$$\min\left(\frac{2\Omega L \sin\phi}{N}, H\right) \quad \text{(below)}$$

Changes to PV field in lower stratosphere (i.e. wave driving) inevitably imply changes to velocity field in upper troposphere (e.g. Hartley et al 1998).

[Features separated by less than the penetration scale cannot be regarded as independent!]

Dynamics of zonal mean circulation (I)

Response to given force Re$(\hat{F}(\phi,z)e^{i\omega t})$, radiative damping rate α.

$$\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sin\phi}\hat{u}\right)\right)+$$

$$\frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0\left(1+\frac{\alpha}{i\omega}\right)\frac{4\Omega^2a^2}{N^2}\frac{\sin\phi}{\cos\phi}\frac{\partial\hat{u}}{\partial z}\right)$$

$$=\frac{1}{i\omega}\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sin\phi}\hat{F}\right)\right).$$

$\alpha/\omega \to 0$ gives PV inversion limit.

As α/ω increases response deepens.

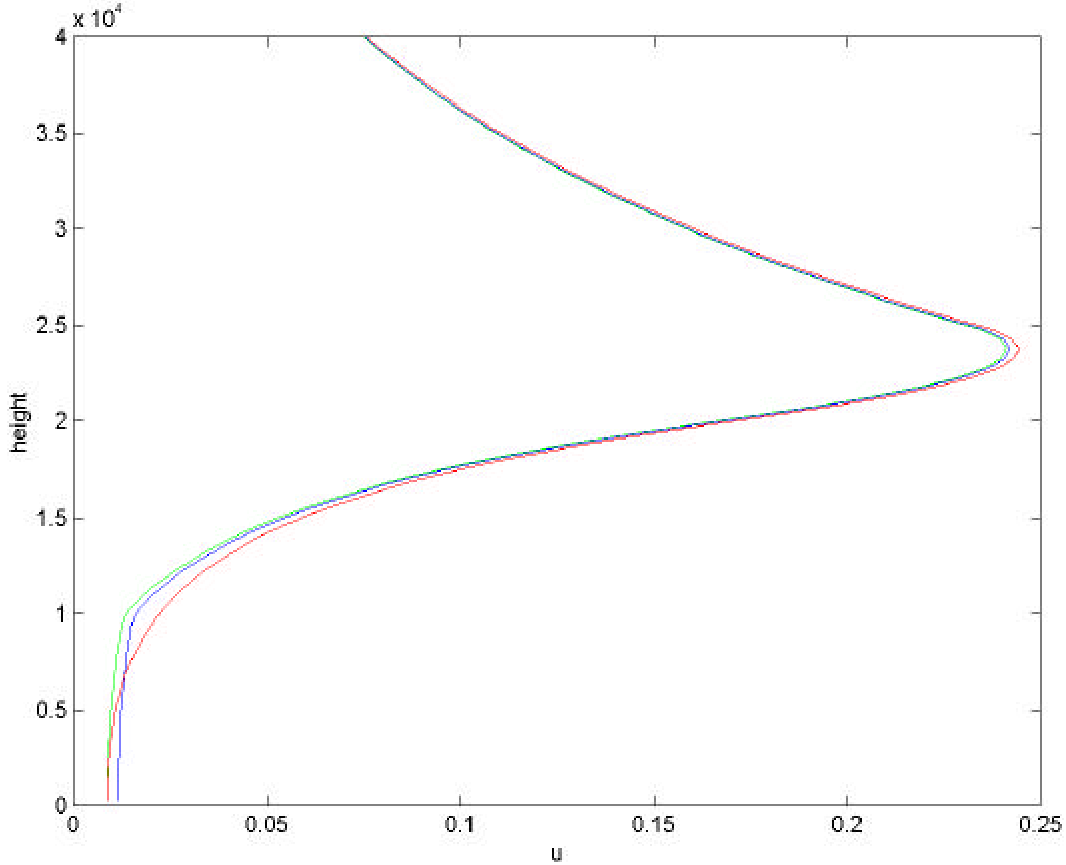
'Downward control' limit is $\alpha/\omega \to \infty$.

Instantaneous response to force

Force confined to 20km < z < 25km, horizontal structure Hough mode 3 (scale 1000km)

Uniform N^2 , N^2 reduced in troposphere,

N^2 reduced in troposphere plus correct lower boundary condition



Dynamics of zonal mean circulation (II)

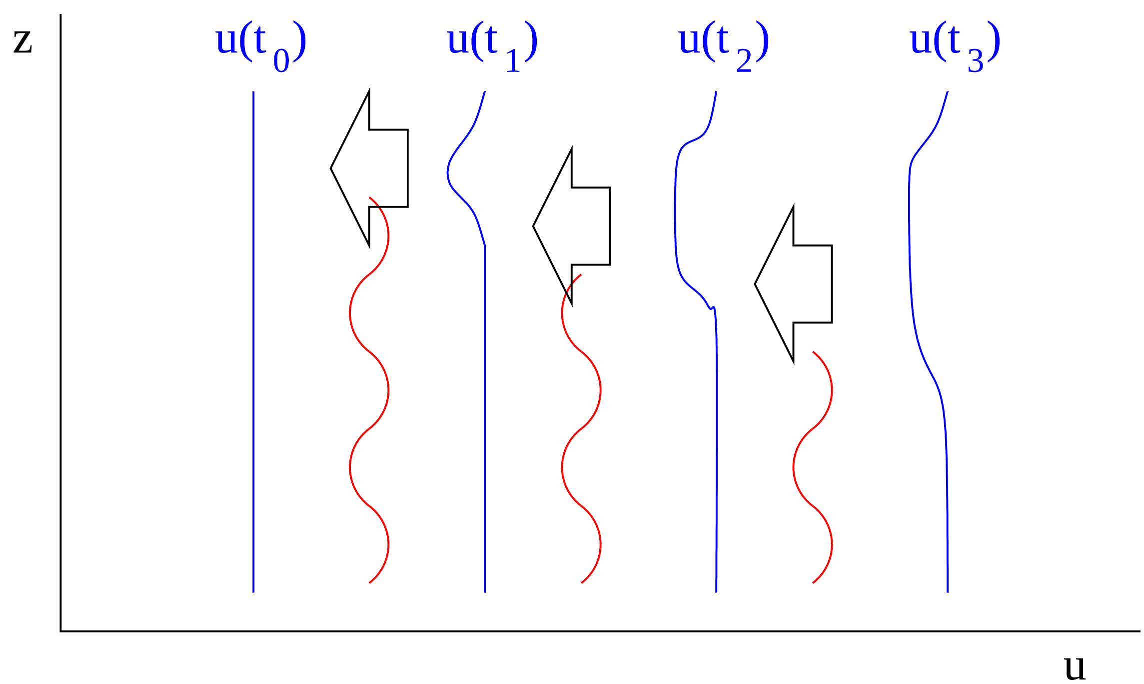
Time development of response

Balanced dynamics and radiative damping together give downward propagation at speed $w_\alpha = \alpha f^2 L^2 / N^2 H$.

Impulsive force gives downward propagating velocity anomaly that dissipates at frictional boundary layer.

Wave mean-flow interaction

Two-way interaction between wave driving and mean flow may give rise to downward propagating features.



Plumb QBO model

Equatorial dynamics, WKB assumption for waves.

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0 \overline{u'w'})$$

$$\rho_0 \overline{u'w'}(z,t) = F_+ \exp\left(-\int_0^z \frac{N\alpha}{k(u(s,t)-c)^2} ds\right) + F_- \exp\left(-\int_0^z \frac{N\alpha}{k(u(s,t)+c)^2} ds\right)$$

$\overline{u'w'}(Z,t)$ is independent of $u(z,t)$ for $z > Z$, hence evolution of flow at height Z is independent of evolution in $z > Z$.

No real downward propagation of information.

Extratropical wave mean-flow interaction

1. Acceleration response to wave driving is non-local.

2. WKB approximation for large-scale Rossby waves is questionable – no useful local relation between waves and mean state.

(1) and/or (2) may allow 'real' downward propagation of information.

Examples: effect of equatorial QBO winds on extratropics (observations and GCM), downward propagating anomalies from upper stratosphere (GCM).

Downward influence through wave propagation

Rossby waves can propagate down as well as up.

Nonlinear reflection from wave-breaking regions.

Nonlinear wave generation in wave-breaking regions.

Resonant growth in troposphere and stratosphere?

The stratosphere as a flywheel?

Mass of stratosphere is small. Stratospheric angular momentum anomalies are modest. But . . .

$$\frac{du}{dt} + \frac{u}{\tau} = F(t)$$

u low-pass filters F on time scales less than τ.

Troposphere: $\tau \sim 5 - 10$ days (Barry et al 2000)?

Stratosphere: $\tau \gtrsim 20$ days? (τ increases towards equator).

Sensitivity of stratospheric circulation

Wave mean-flow interaction in extratropical stratosphere gives sensitivity (e.g. cold pole problem).

Dynamical effects of small radiative changes may be amplified and hence have larger than expected effect on troposphere (e.g. effects may be felt in winter but not in summer).

Sensitivity of tropospheric circulation

Does internal dynamics of tropospheric circulation act to amplify small dynamical signals from the stratosphere?

Stratosphere

(S1) Response of mean flow to wave forcing is non-local and tends to be deeper on long time scales.

(S2) Waves depend non-locally on mean flow and wave propagation is not one-way.

(S3) Interaction between waves and mean flow leads to sensitivity, e.g. to wave forcing from troposphere and to radiative anomalies and in some cases to downward propagation of information.

(S4) (S1) and (S3) imply that changes in the stratosphere may be felt directly in the upper troposphere.

(S5) Damping timescales and aspects of (S3) mean that stratospheric anomalies are relatively long-lived.

Troposphere

(T1) Interactions between baroclinic eddies and mean flow in troposphere means that (S4) gives larger signal in troposphere than would be expected from zonally symmetric dynamics alone?

(T2) No particular significance of tropospheric part of observed signal for wave flux into stratosphere?

(T3) Propagation from troposphere to stratosphere may be an important part of (S3)?