AGU Fall Meeting, 8 December 2011

On jet dynamics and the **DIMBO** effect

Michael E. McIntyre,
Dept of Applied Mathematics & Theoretical Physics,
University of Cambridge, UK

– some glimpses into the multiplicity & subtlety of fluid-dynamical mechanisms.

(Will I be burnt at the stake? – more on my **home page at the string "jets".**)
Also salutary, e.g. Thompson & Young (2007, *JAS*)
Esler (2008, *JFM*)
Scott & Dritschel (2011)

Two main points in this talk:

(1) there's more than one mechanism for atmosphere-ocean jet formation;

(2) oceanic strong jets induce diapycnal mixing **beneath** the mixed layer.
(**DIMBO** = **DI**apycnal **M**ixing by **B**aroclinic **O**verturning.)

Reprints, preprints & corrigenda: websearch **"lucidity principles"**
then back to my home page at the string "jets".

The literature on jets – a complex conceptual landscape.

Zoology:

1. Classic tropopause/polar-night/major-oceanic (Gulf-stream-like)
2. Mid-oceanic “striations” or “ghost jets”, e.g.Maximenko et al (2008 *GRL*)
3. Jovian jets (**straight!**)
4. Tokamak jets (Marshall Rosenbluth Lecture, available on my home page)

Reprints, preprints & corrigenda: websearch **”lucidity principles”**
then back to my home page at the string “jets”.

The literature on jets – a complex conceptual landscape.

Zoology:

1. Classic tropopause/polar-night/major-oceanic (Gulf-stream-like)
2. Mid-oceanic "striations" or "ghost jets", e.g.Maximenko et al (2008 *GRL*)
3. Jovian jets (**straight!**)
4. Tokamak jets (Marshall Rosenbluth Lecture, available on my home page)

Physiology (starting point only):

Assume free or forced-dissipative **balanced vortex dynamics** ↔ PV invertibility principle holds. (So, e.g. **anything** that makes a background PV gradient even slightly step-like ,or staircase-like, must give rise to jets – e.g. via **"PV Phillips effect"**, Dritschel & M (2008, *JAS*)

Reprints, preprints & corrigenda: websearch **"lucidity principles"** then back to my home page at the string "jets".

The literature on jets – a complex conceptual landscape.

Zoology:

1. Classic tropopause/polar-night/major-oceanic (Gulf-stream-like)
2. Mid-oceanic "striations" or "ghost jets", e.g.Maximenko et al (2008 *GRL*)
3. Jovian jets (**straight!**)
4. Tokamak jets (Marshall Rosenbluth Lecture, available on my home page)

Physiology (starting point only):

Assume free or forced-dissipative **balanced vortex dynamics** ↔ PV invertibility principle holds. (So, e.g. **anything** that makes a background PV gradient even slightly step-like ,or staircase-like, must give rise to jets – e.g. via **"PV Phillips effect"**, Dritschel & M (2008, *JAS*)

Anatomy (2 clear extremes):

Strong jets (PV-staircase-like,
Rossby waves **guided**)

Weak jets (PV close to large-scale
background beta, Rossby waves
unguided, quasi-plane)

"lucidity principles"
"jets".

The literature on jets – a complex conceptual landscape.

Zoology:

1. Classic tropopause/polar-night/major-oceanic (Gulf-stream-like)
2. Mid-oceanic “striations” or “ghost jets”, e.g.Maximenko et al (2008 *GRL*)
3. Jovian jets (**straight!**)
4. Tokamak jets (Marshall Rosenbluth Lecture, available on my home page)

Physiology (starting point only):

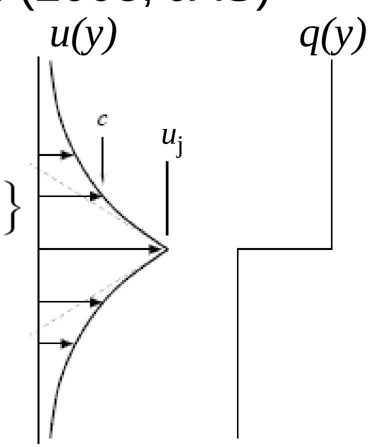
Assume free or forced-dissipative **balanced vortex dynamics** ↔ PV invertibility principle holds. (So, e.g. **anything** that makes a background PV gradient even slightly step-like ,or staircase-like, must give rise to jets – e.g. via **“PV Phillips effect”**, Dritschel & M (2008, *JAS*)

Anatomy (2 clear extremes):

Strong jets (PV-staircase-like, Rossby waves **guided)**

Simplest waveguide model (Rosenbluth Lecture):

$$c = u_{\rm j}\left\{1 - \left(1 + L_{\rm D}^2 k^2\right)^{-1/2}\right\}$$



Weak jets (PV close to large-scale background beta, Rossby waves **unguided**, quasi-plane)

The literature on jets – a complex conceptual landscape.

Zoology:

1. Classic tropopause/polar-night/major-oceanic (Gulf-stream-like)
2. Mid-oceanic “striations” or “ghost jets”, e.g.Maximenko et al (2008 *GRL*)
3. Jovian jets (**straight!**)
4. Tokamak jets (Marshall Rosenbluth Lecture, available on my home page)

Physiology (starting point only):

Assume free or forced-dissipative **balanced vortex dynamics** ↔ PV invertibility principle holds. (So, e.g. **anything** that makes a background PV gradient even slightly step-like ,or staircase-like, must give rise to jets – e.g. via **“PV Phillips effect”**, Dritschel & M (2008, *JAS*)

Anatomy (2 clear extremes):

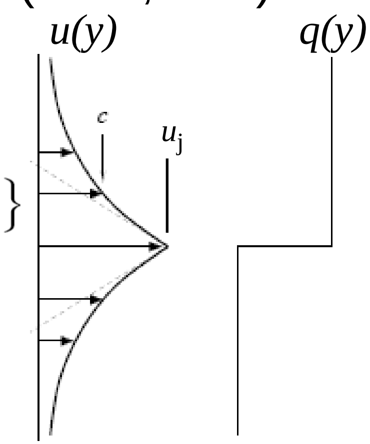
Strong jets (PV-staircase-like, Rossby waves **guided)**

Weak jets (PV close to large-scale background beta, Rossby waves **unguided**, quasi-plane)

Simplest waveguide model (Rosenbluth Lecture):

$$c = u_{\mathrm{j}}\left\{1 - \left(1 + L_{\mathrm{D}}^2 k^2\right)^{-1/2}\right\}$$

$$\omega = \frac{-\beta k}{k^2 + l^2 + L_{\mathrm{D}}^{-2}}$$



The literature on jets – a complex conceptual landscape.

Zoology:

1. Classic tropopause/polar-night/major-oceanic (Gulf-stream-like)
2. Mid-oceanic “striations” or “ghost jets”, e.g.Maximenko et al (2008 *GRL*)
3. Jovian jets (**straight!**)
4. Tokamak jets (Marshall Rosenbluth Lecture, available on my home page)

Physiology (starting point only):

Assume free or forced-dissipative **balanced vortex dynamics** ↔ PV invertibility principle holds. (So, e.g. **anything** that makes a background PV gradient even slightly step-like ,or staircase-like, must give rise to jets – e.g. via **“PV Phillips effect”**, Dritschel & M (2008, *JAS*)

Anatomy (2 clear extremes):

Strong jets (PV-staircase-like, Rossby waves **guided)**

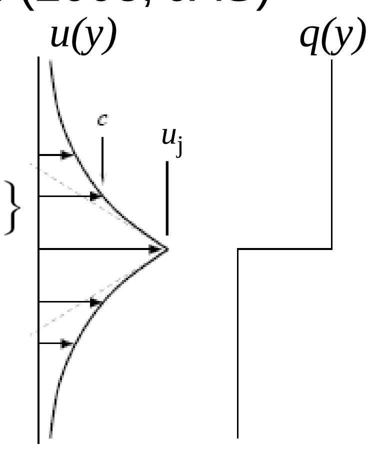
Simplest waveguide model (Rosenbluth Lecture):

$$c = u_{\rm j}\{1 - (1 + L_{\rm D}^2 k^2)^{-1/2}\}$$

Weak jets (PV close to large-scale background beta, Rossby waves **unguided**, quasi-plane)

$$\omega = \frac{-\beta k}{k^2 + l^2 + \cancel{L_{\rm D}^{-2}}}$$

→ Rhines scale



The literature on jets – a complex conceptual landscape.

Zoology:

1. Classic tropopause/polar-night/major-oceanic (Gulf-stream-like)
2. Mid-oceanic "striations" or "ghost jets", e.g.Maximenko et al (2008 *GRL*)
3. Jovian jets (**straight!**)
4. Tokamak jets (Marshall Rosenbluth Lecture, available on my home page)

Physiology (starting point only):

Assume free or forced-dissipative **balanced vortex dynamics** ↔ PV invertibility principle holds. (So, e.g. **anything** that makes a background PV gradient even slightly step-like ,or staircase-like, must give rise to jets – e.g. via **"PV Phillips effect"**, Dritschel & M (2008, *JAS*)

Anatomy (2 **clear** extremes):

Strong jets (PV-staircase-like, Rossby waves **guided)**

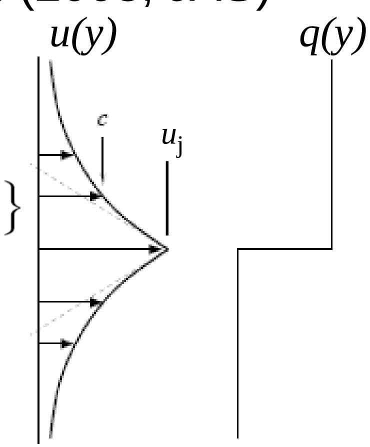
Weak jets (PV close to large-scale background beta, Rossby waves **unguided**, quasi-plane)

Simplest waveguide model (Rosenbluth Lecture):

$$c = u_{\mathrm{j}}\{1 - (1 + L_{\mathrm{D}}^2 k^2)^{-1/2}\}$$

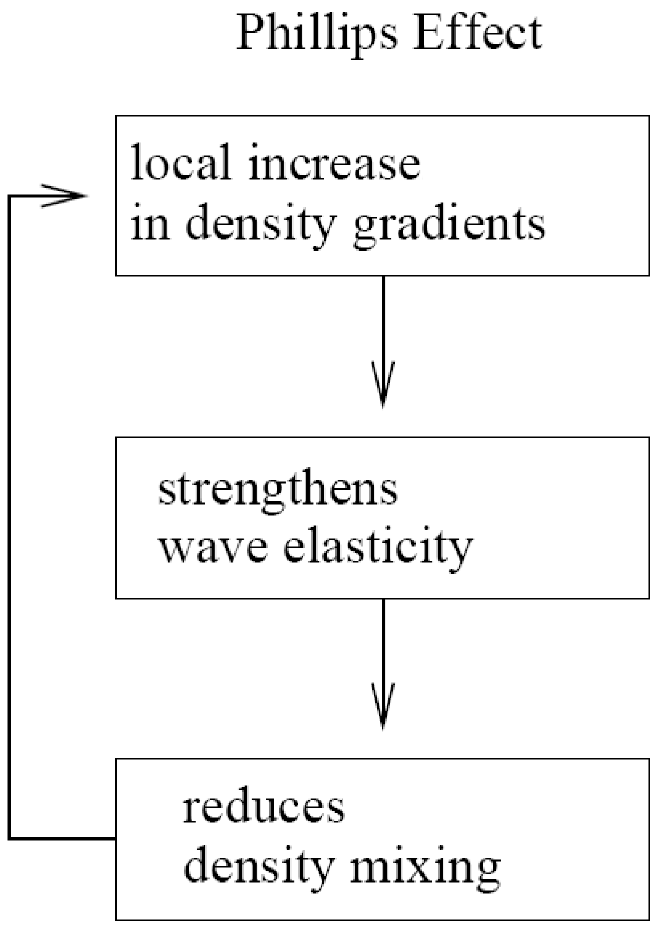
$$\omega = \frac{-\beta k}{k^2 + l^2 + L_{\mathrm{D}}^{-2}}$$

→ Rhines scale

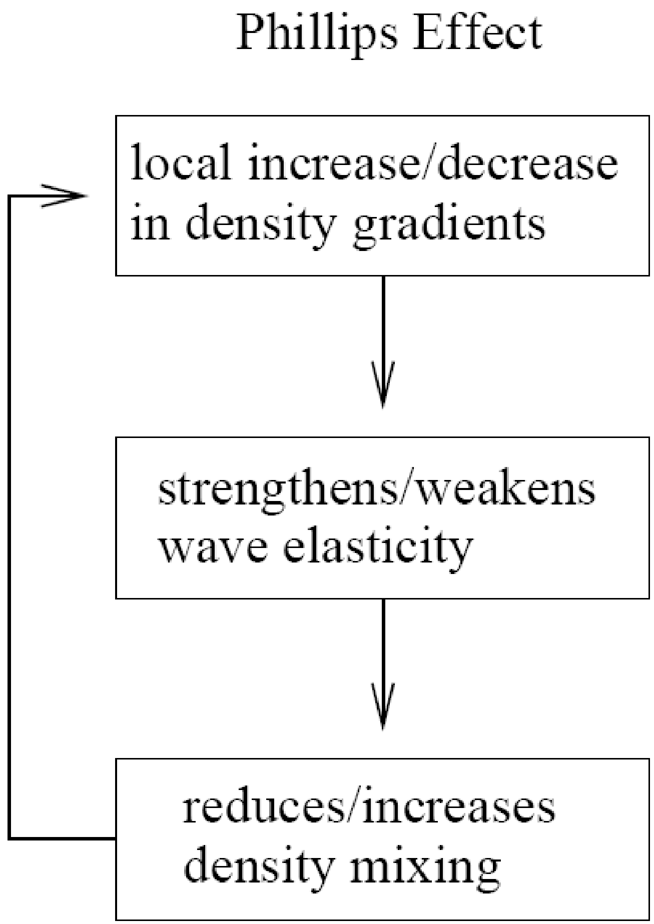


Not so clear: hyper-strong, hyper-staircase-like? **Jupiter?** (Dowling 1993, *JAS*)

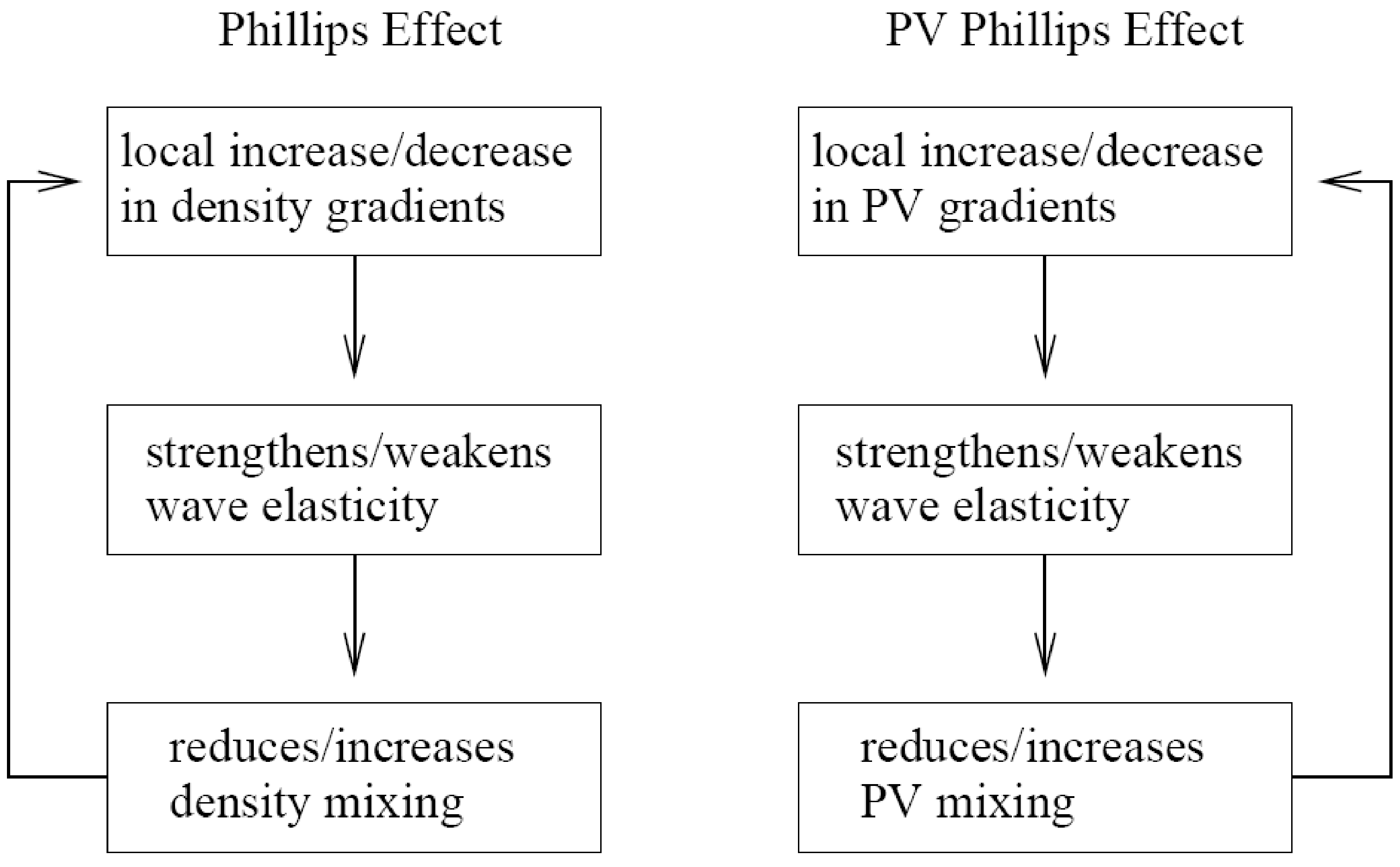
O. M. Phillips (1972 *Deep Sea Res*). **NB: Don't** need to assume Fickian diffusion.



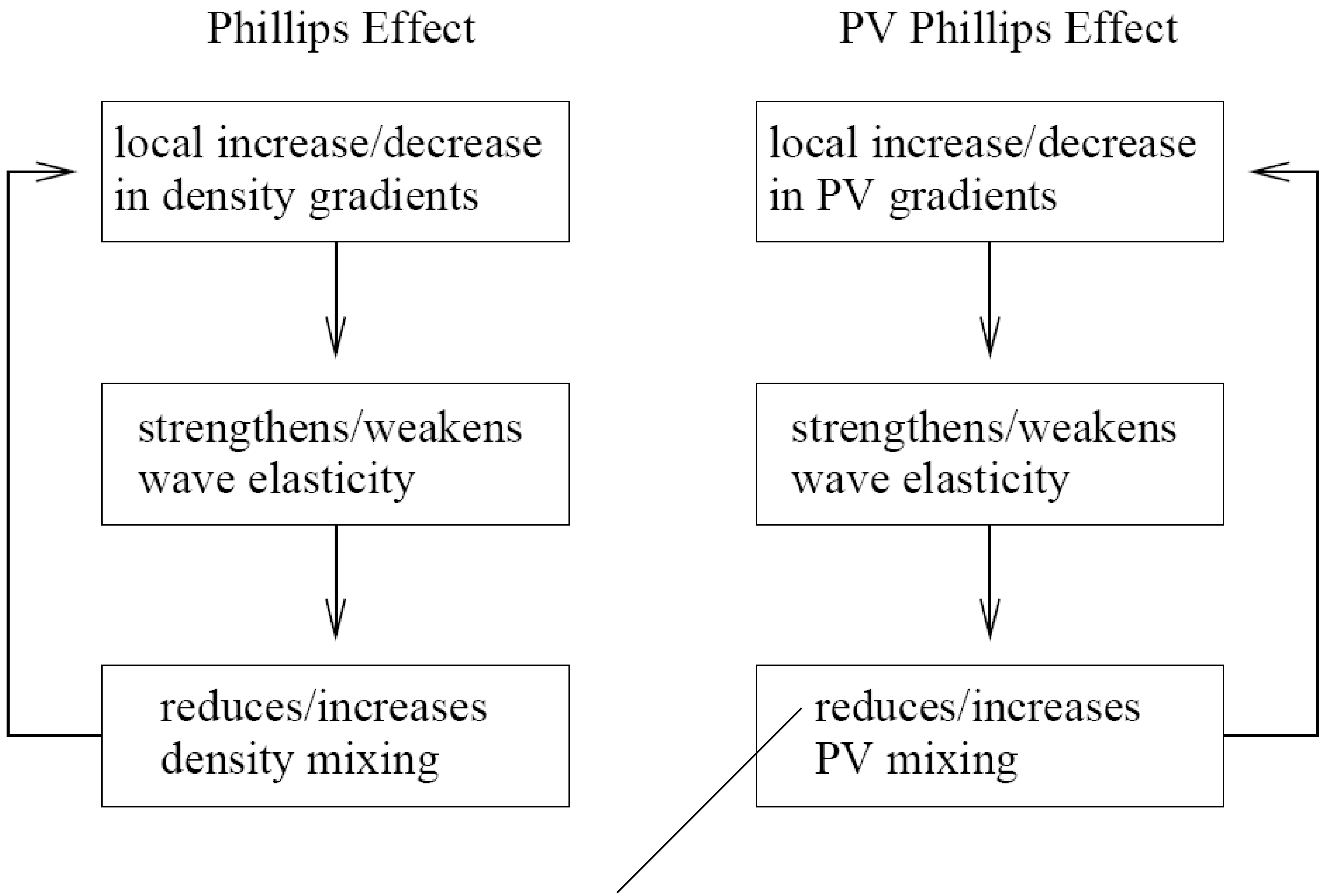
O. M. Phillips (1972 *Deep Sea Res*). **NB: Don't** need to assume Fickian diffusion.



O. M. Phillips (1972 *Deep Sea Res*). **NB: Don't** need to assume Fickian diffusion.

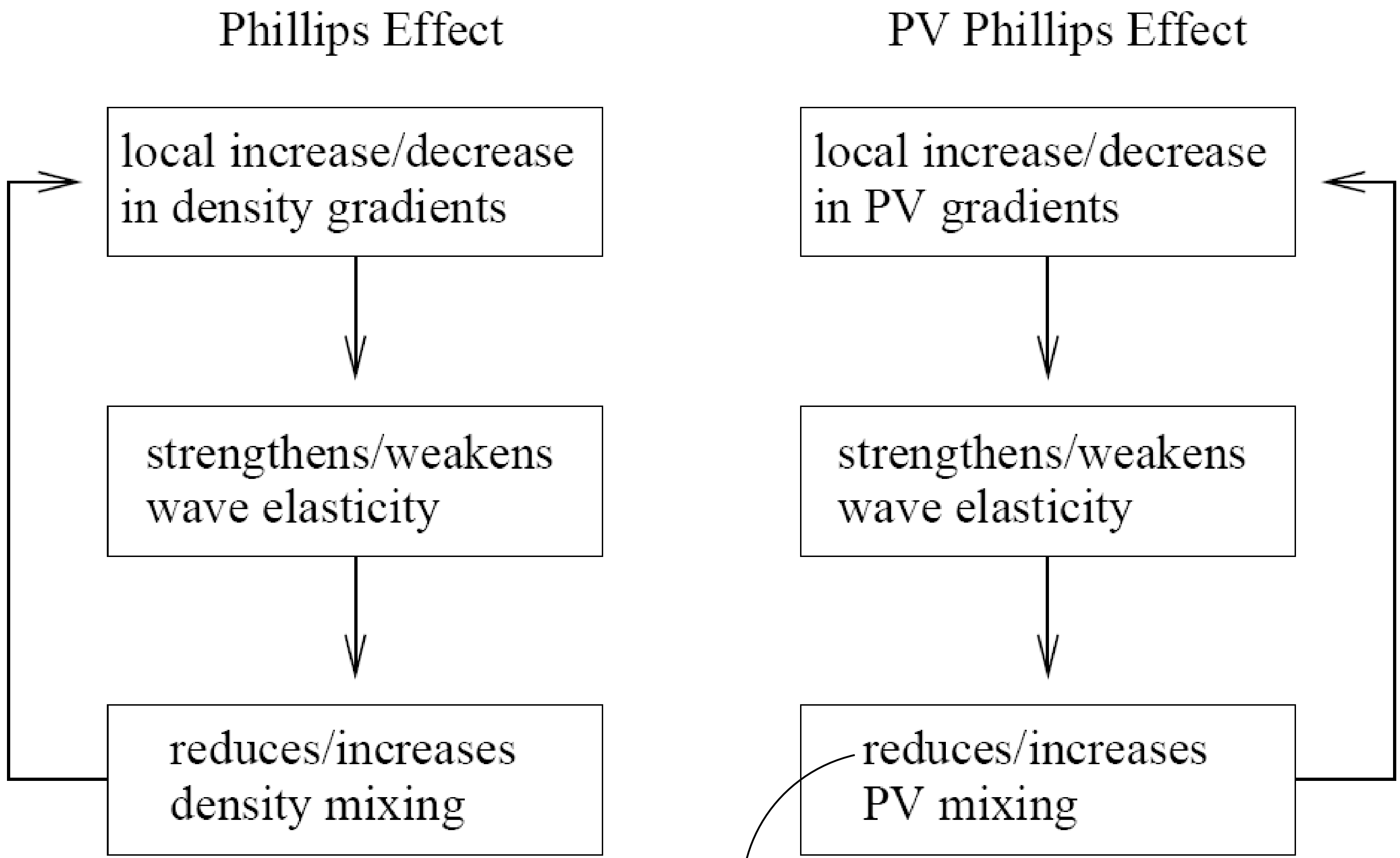


O. M. Phillips (1972 *Deep Sea Res*). **NB: Don't** need to assume Fickian diffusion.



So if PV mixing occurs, it tends to be spatially **inhomogeneous**. (PV inversion then gives jets.)

O. M. Phillips (1972 *Deep Sea Res*). **NB: Don't** need to assume Fickian diffusion.

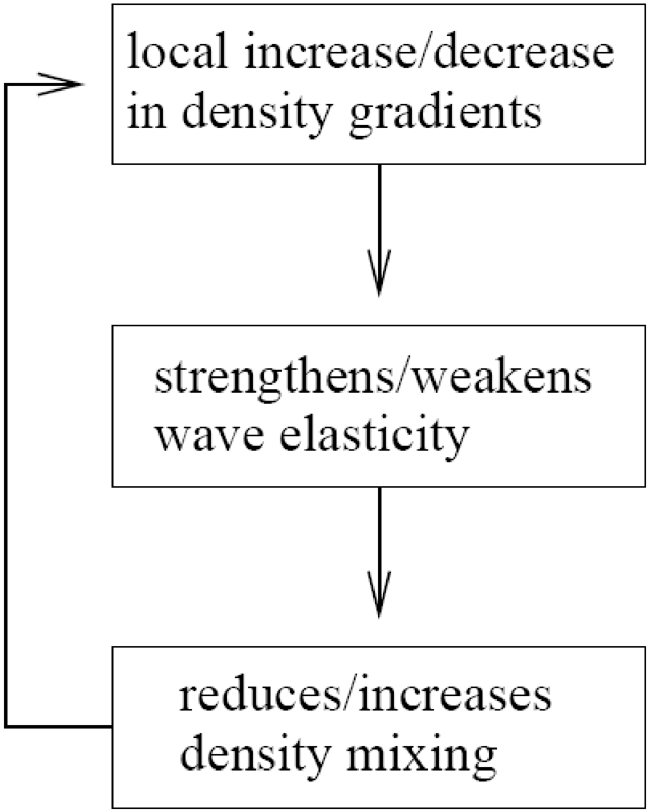


So if PV mixing occurs, it tends to be spatially **inhomogeneous**. (PV inversion then gives jets.)

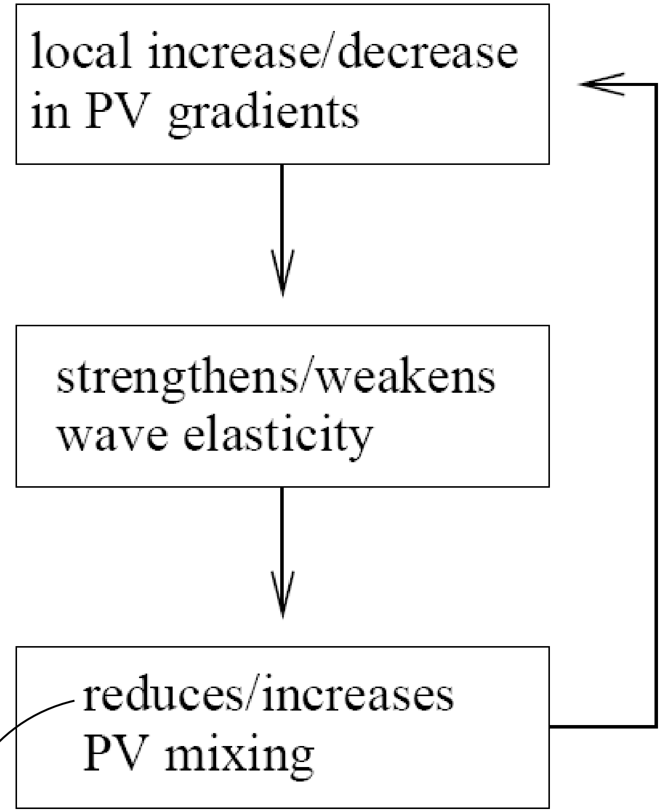
Feedback stronger in strong-jet cases: PV inversion implies **reinforcement by shear** to form a classical **eddy-transport barrier** (Juckes & M, *Nature* 1987).

O. M. Phillips (1972 *Deep Sea Res*). **NB: Don't** need to assume Fickian diffusion.

Phillips Effect



PV Phillips Effect



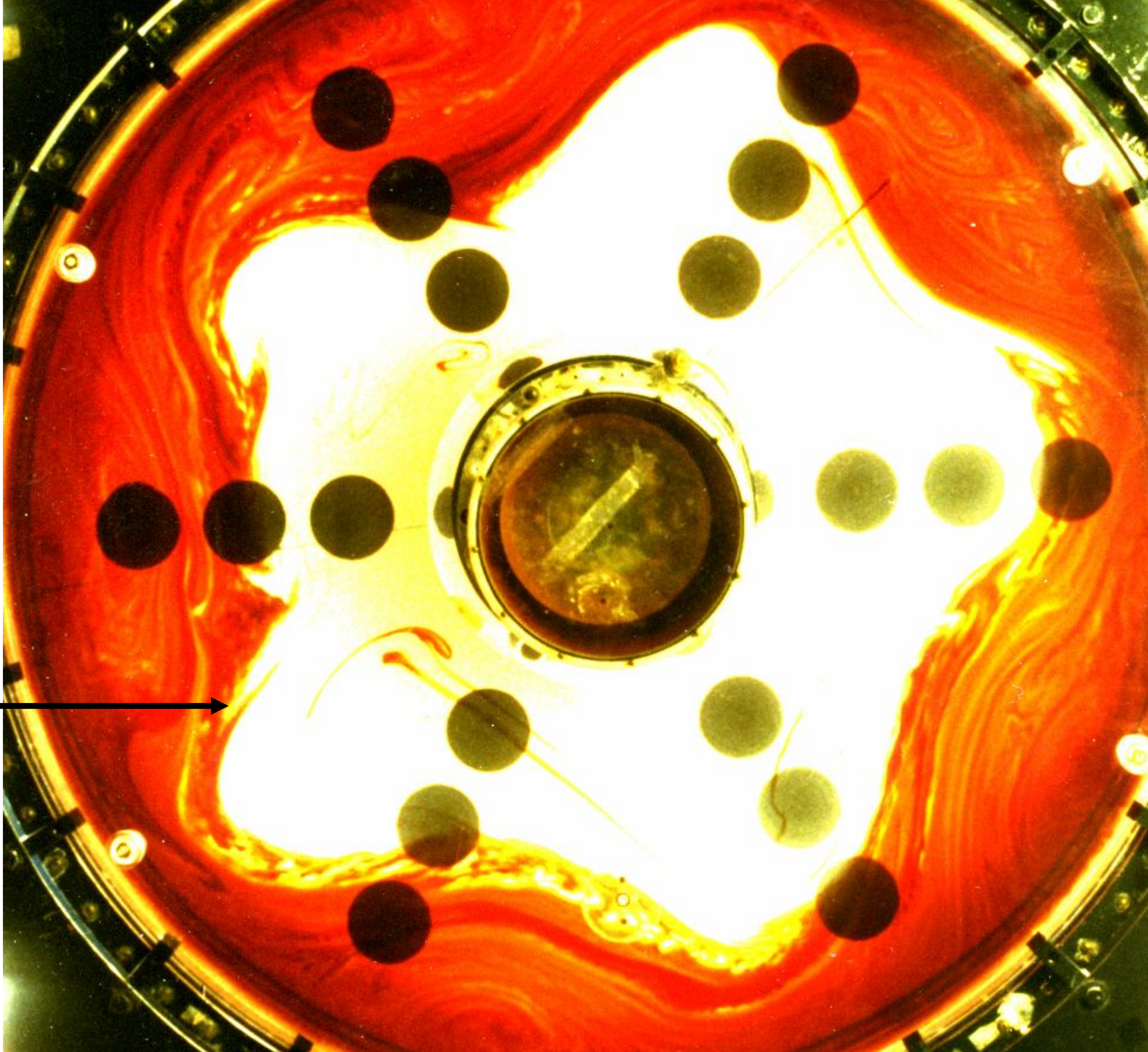
So if PV mixing occurs, it tends to be spatially **inhomogeneous**. (PV inversion then gives jets.)

Feedback stronger in strong-jet cases:
PV inversion implies **reinforcement by shear** to form a classical **eddy-transport barrier** (Juckes & M, *Nature* 1987).
Here's a classic lab. demo. of a strong jet:

Sommeria, Myers, and Swinney, *Nature* 1989
86.4 cm dia.; rotation ~ 20 rad/s **(!)**

PV map and **dye map** near-identical.

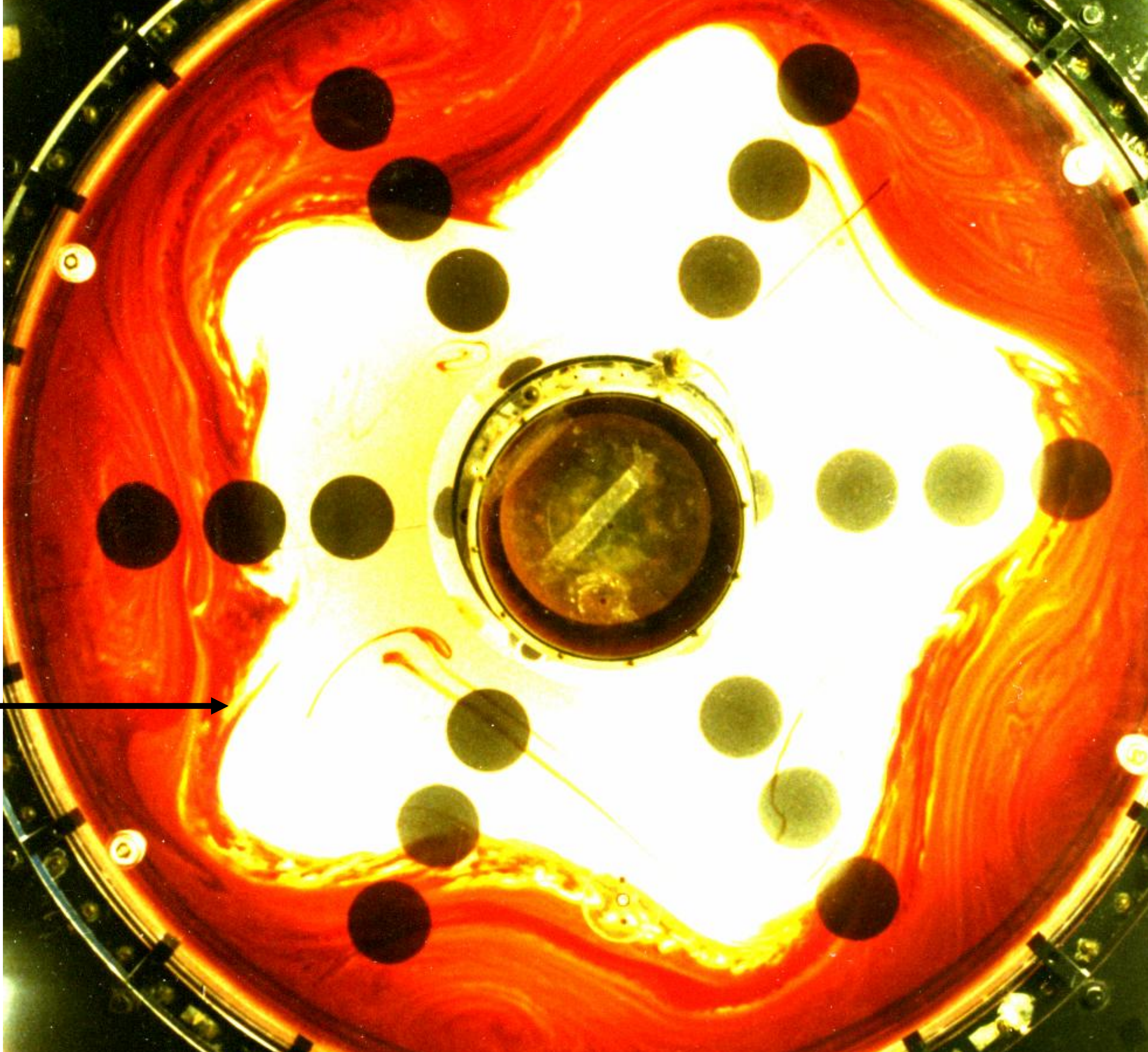
This is clearly a **strong jet:** staircase-like; eddy-transport barrier.



Sommeria, Myers, and Swinney, *Nature* 1989
86.4 cm dia.; rotation ~ 20 rad/s **(!)**

PV map and **dye map** near-identical.

This is clearly a **strong jet:** staircase-like; eddy-transport barrier.



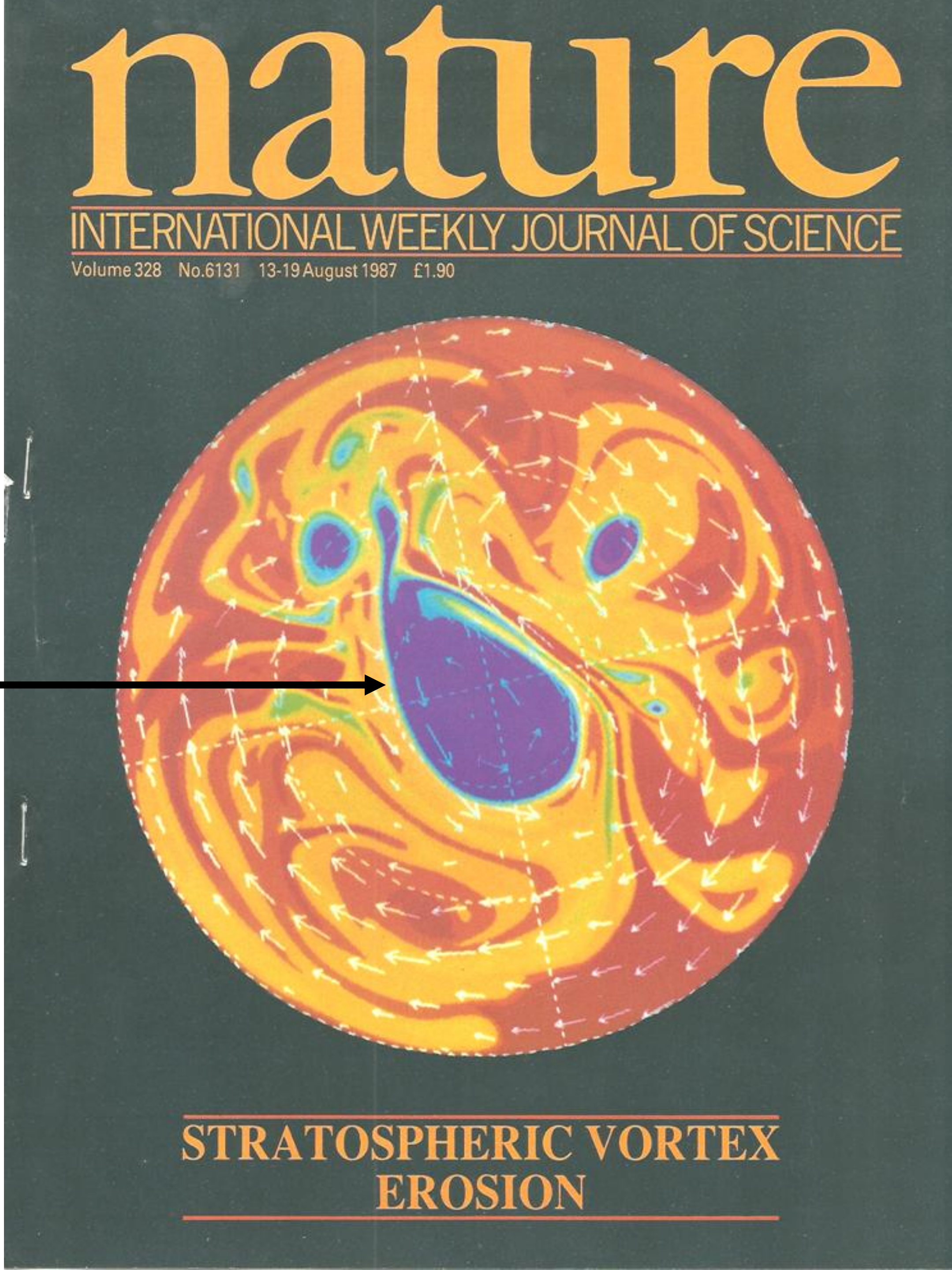
By the way: **no inverse cascade** is involved. (Surprise??)

Model stratospheres are similar (Juckes & M 1987):

Polar-night jet strengthened and sharpened by PV mixing mainly on its equatorward flank, forming a **strong jet** and **eddy-transport barrier**

(This is a well-studied problem!)

Again, no inverse cascade.



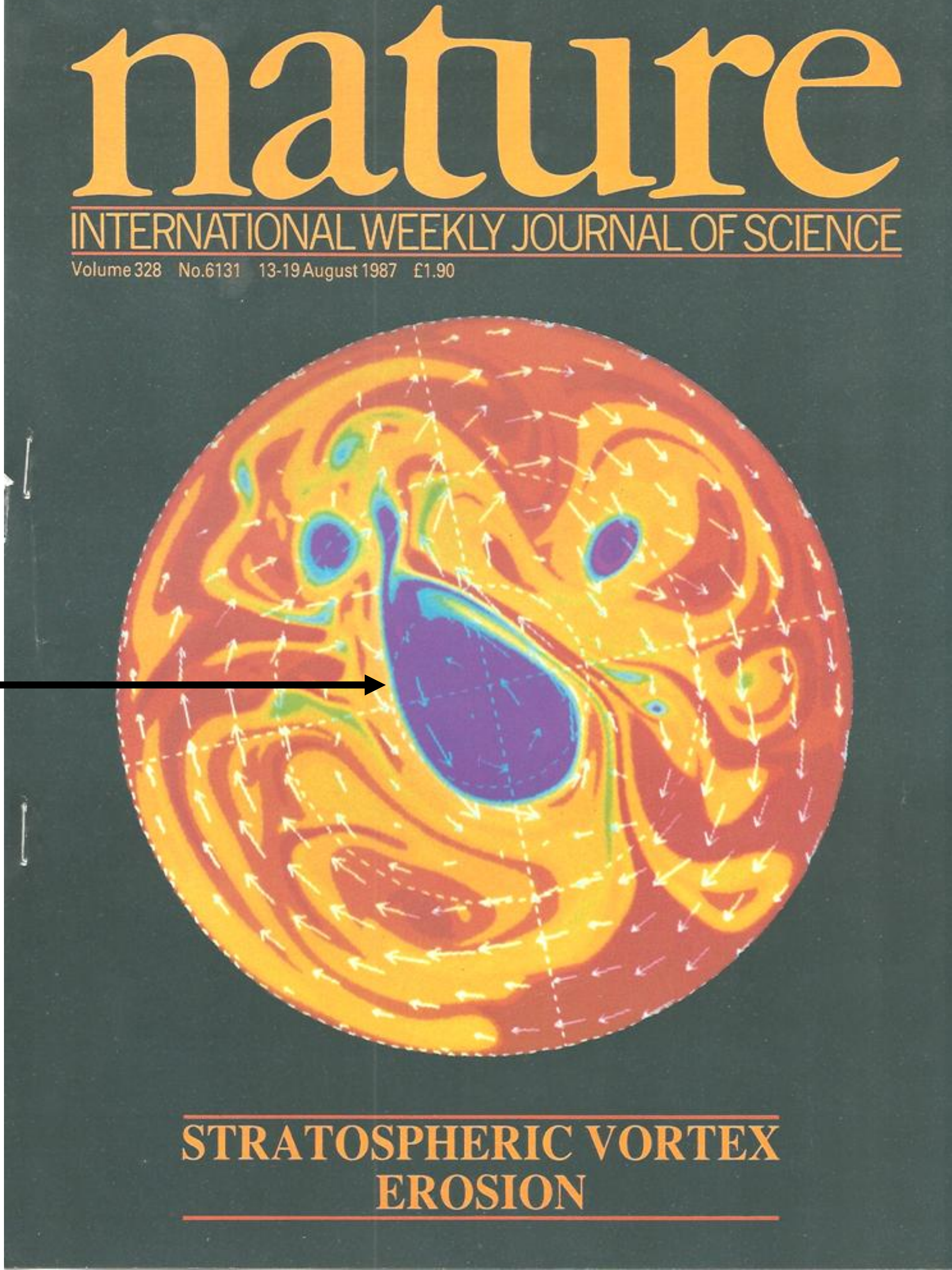
Model stratospheres are similar (Juckes & M 1987):

Polar-night jet strengthened and sharpened by PV mixing mainly on its equatorward flank, forming a **strong jet** and **eddy-transport barrier**

(This is a well-studied problem!)

Again, no inverse cascade.

The **real** stratosphere is similar too:



Courtesy Dr A J Simmons,
European Centre for Medium
Range Weather Forecasts:

McIntyre and Palmer (1983), revisited

Breaking planetary waves in the stratosphere

M. E. McIntyre* & T. N. Palmer†

* Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, UK
† Meteorological Office, Bracknell, Berks RG12 2SZ, UK

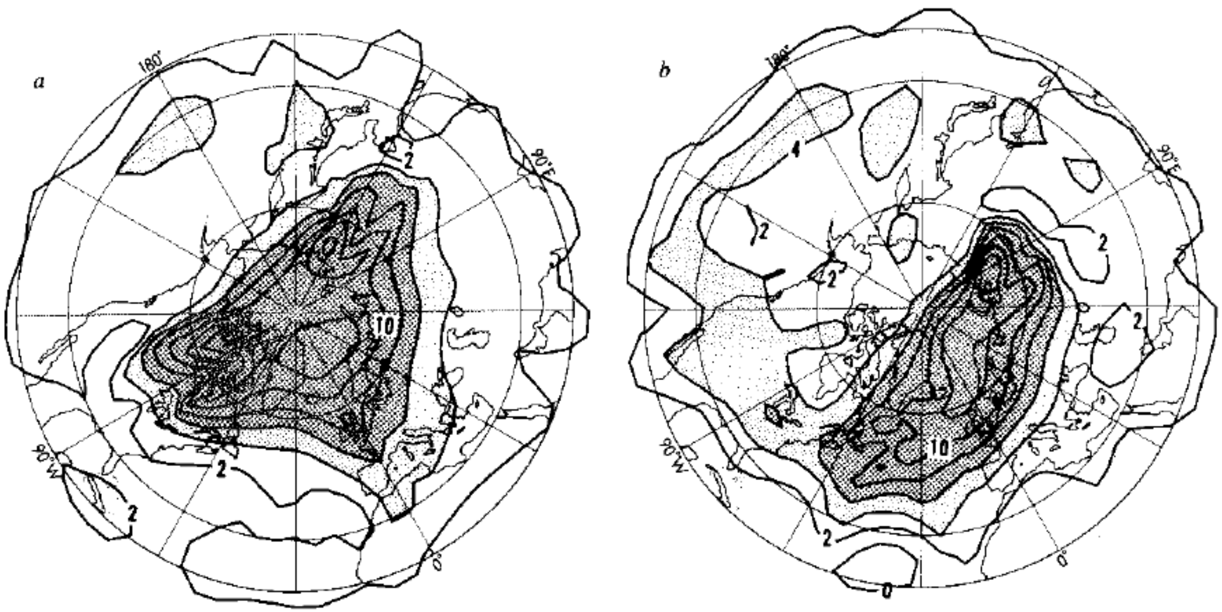
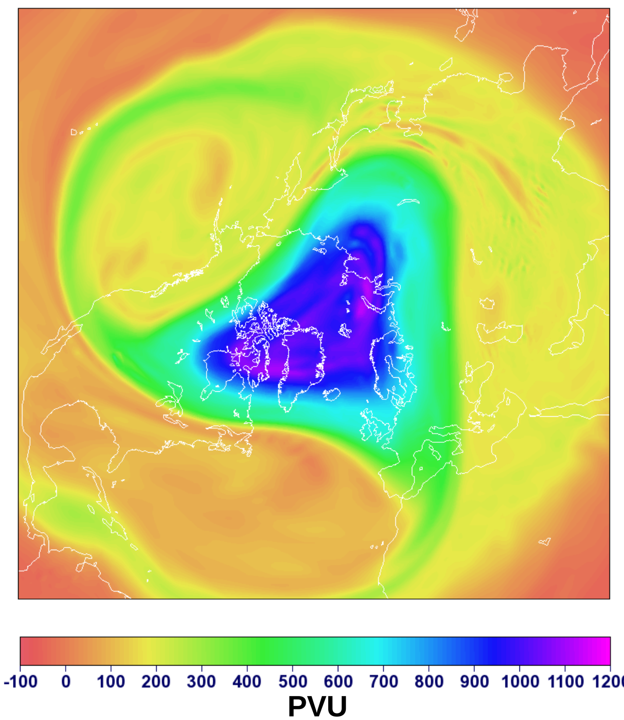


Fig. 2 Coarse-grain estimates of Ertel's potential vorticity Q on the 850 K isentropic surface (near the 10-mbar isobaric surface) on 17 (a) and 27 (b) January 1979, at 00 h GMT. The southernmost latitude circle shown is 20° N; the others are 30° N and 60° N. Map projection is polar stereographic. For units see equation (5) onwards. Contour interval is 2 units. Values greater than 4 units are lightly shaded, and greater than 6 units heavily shaded.

Initial state

Potential vorticity at 850K   00UTC 1979/01/17



Courtesy Dr A J Simmons,
European Centre for Medium
Range Weather Forecasts:

McIntyre and Palmer (1983), revisited

Breaking planetary waves in the stratosphere

M. E. McIntyre* & T. N. Palmer†

* Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, UK
† Meteorological Office, Bracknell, Berks RG12 2SZ, UK

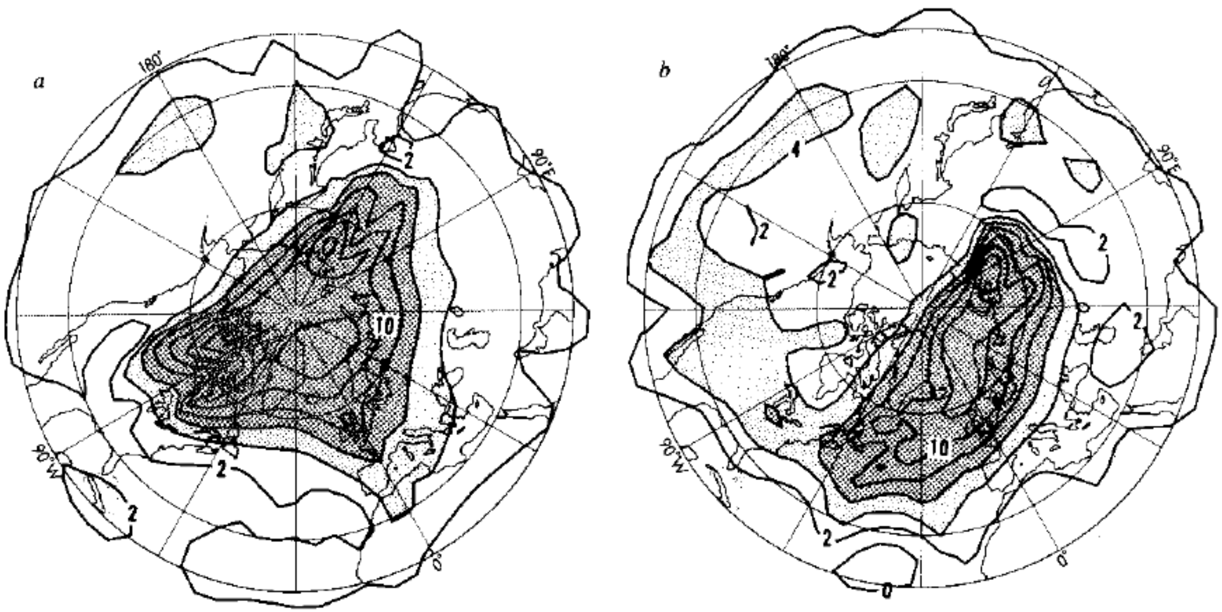
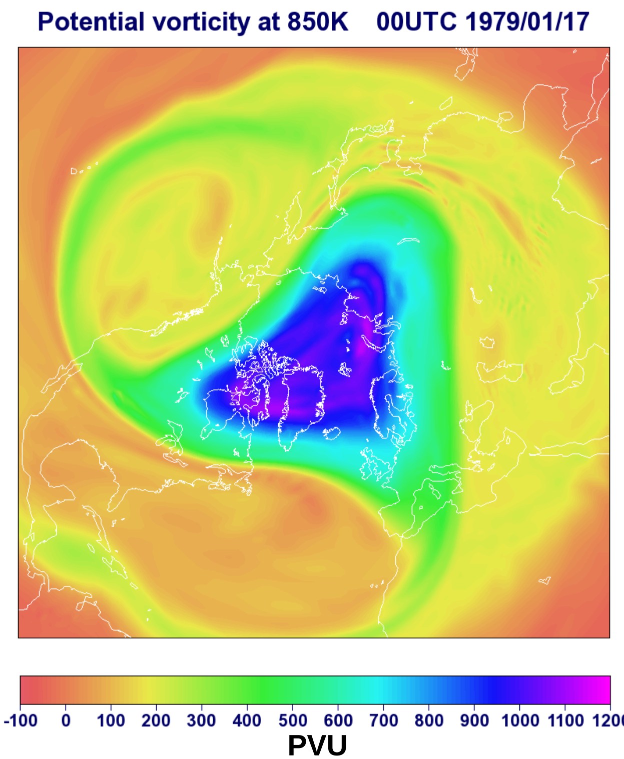


Fig. 2 Coarse-grain estimates of Ertel's potential vorticity Q on the 850 K isentropic surface (near the 10-mbar isobaric surface) on 17 (*a*) and 27 (*b*) January 1979, at 00 h GMT. The southernmost latitude circle shown is 20° N; the others are 30° N and 60° N. Map projection is polar stereographic. For units see equation (5) onwards. Contour interval is 2 units. Values greater than 4 units are lightly shaded, and greater than 6 units heavily shaded.

Movie



Courtesy Dr A J Simmons, European Centre for Medium Range Weather Forecasts:

McIntyre and Palmer (1983), revisited

Breaking planetary waves in the stratosphere

M. E. McIntyre* & T. N. Palmer†

* Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, UK
† Meteorological Office, Bracknell, Berks RG12 2SZ, UK

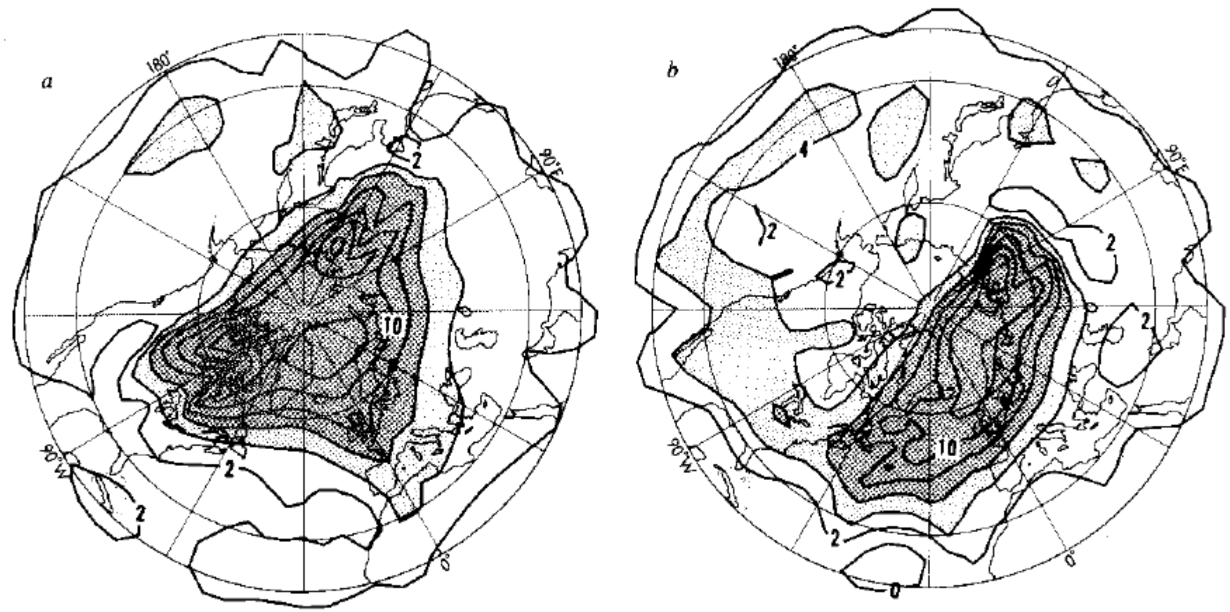
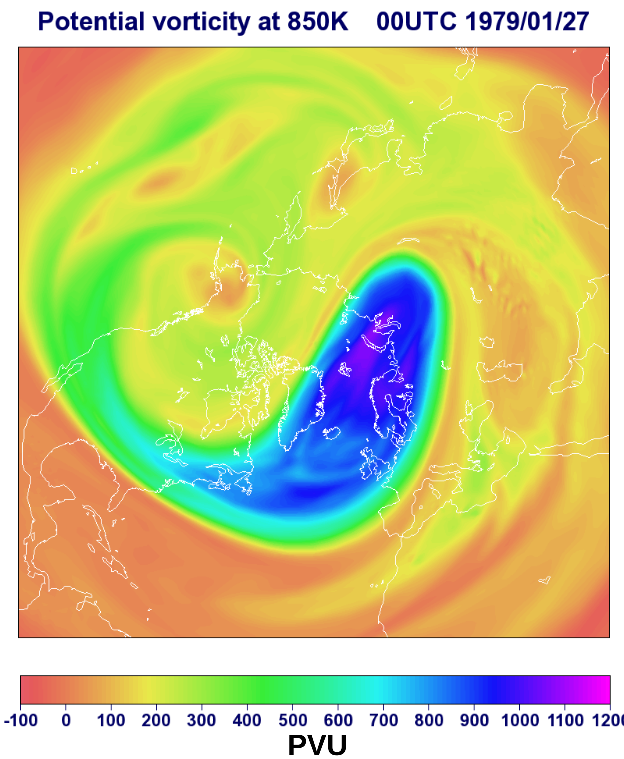


Fig. 2 Coarse-grain estimates of Ertel's potential vorticity *Q* on the 850 K isentropic surface (near the 10-mbar isobaric surface) on 17 (*a*) and 27 (*b*) January 1979, at 00 h GMT. The southernmost latitude circle shown is 20° N; the others are 30° N and 60° N. Map projection is polar stereographic. For units see equation (5) onwards. Contour interval is 2 units. Values greater than 4 units are lightly shaded, and greater than 6 units heavily shaded.

Final state



Courtesy Dr A J Simmons,
European Centre for Medium
Range Weather Forecasts:

McIntyre and Palmer (1983), revisited

Breaking planetary waves in the stratosphere

M. E. McIntyre* & T. N. Palmer†

* Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, UK
† Meteorological Office, Bracknell, Berks RG12 2SZ, UK

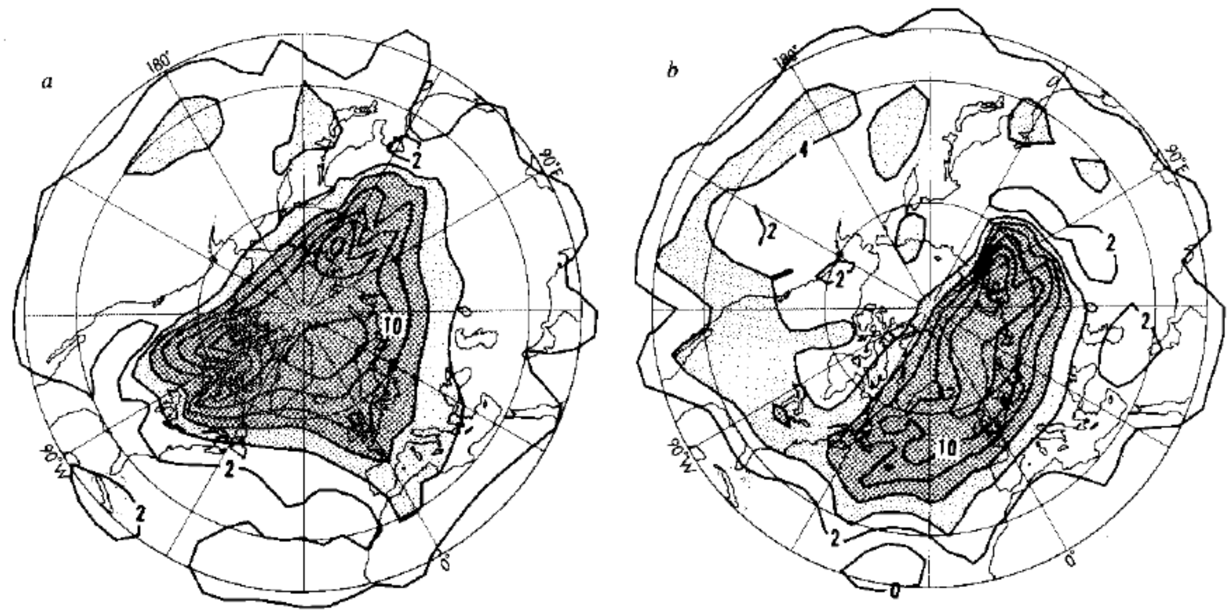
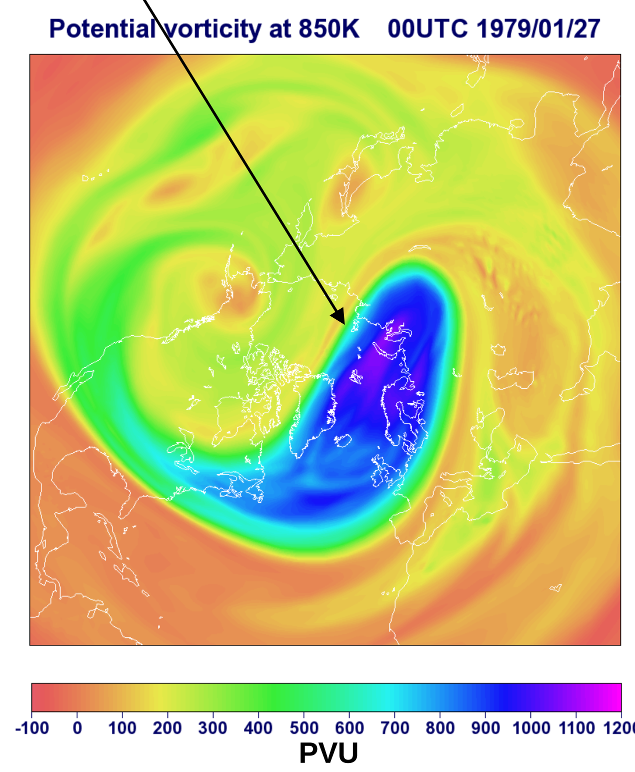


Fig. 2 Coarse-grain estimates of Ertel's potential vorticity Q on the 850 K isentropic surface (near the 10-mbar isobaric surface) on 17 (*a*) and 27 (*b*) January 1979, at 00 h GMT. The southernmost latitude circle shown is 20° N; the others are 30° N and 60° N. Map projection is polar stereographic. For units see equation (5) onwards. Contour interval is 2 units. Values greater than 4 units are lightly shaded, and greater than 6 units heavily shaded.

Eddy-transport barrier

Final state



Layerwise-2D mixing in the real stratosphere:

CRISTA

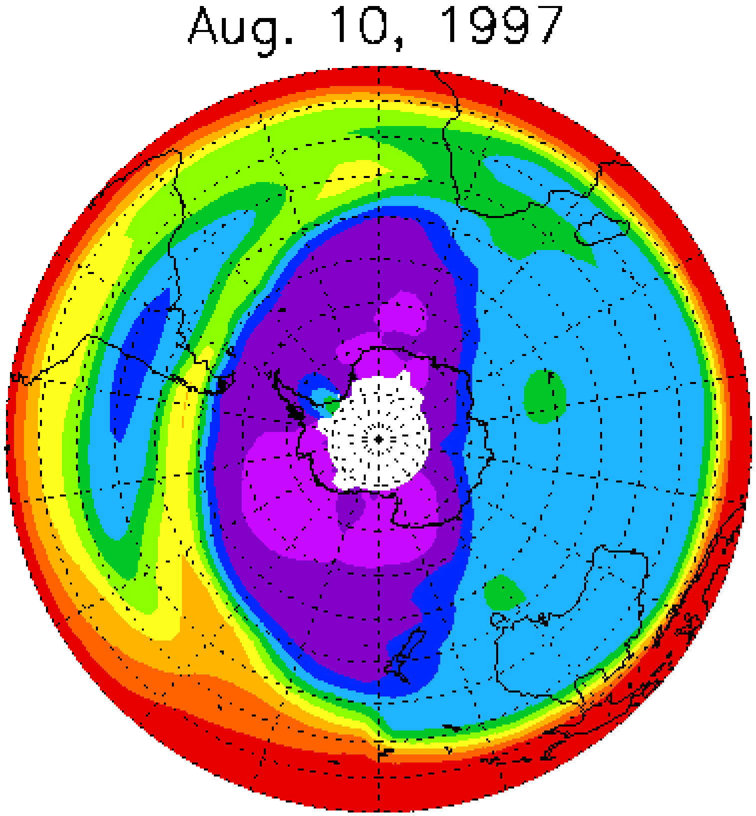
N_2O in upper

stratosphere,

courtesy

Martin

Riese



websearch “gyroscopic pump in action”

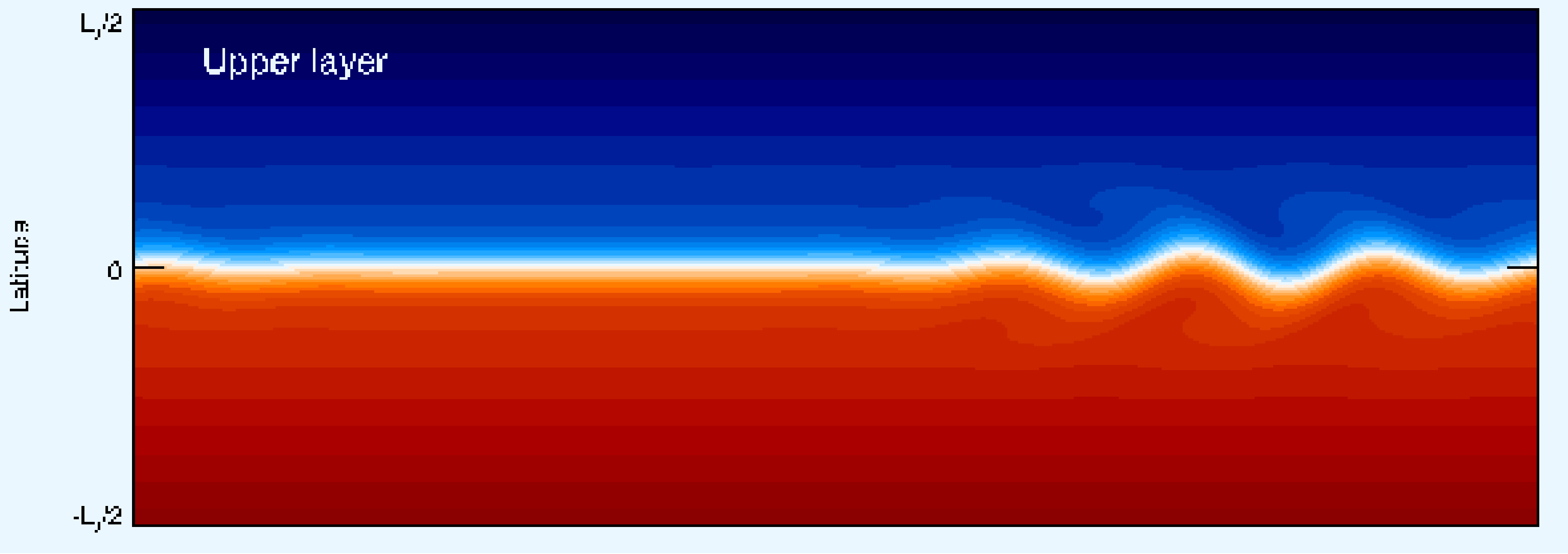
2-layer channel. PV animation showing the typical **self-sharpening** of a jet (**antifrictional!**). Rossby waves

(a) undulate the jet core elastically, and

(b) **break** on both sides, mixing PV and sharpening the jet's velocity profile (consequence of **PV inversion**)

The core acts as a fairly effective "eddy-transport barrier" against mixing.
Note resemblance to tropopause jets and ocean jets – "veins & arteries"

Esler, G., 2008, *J. Fluid Mech*. **599**, 241



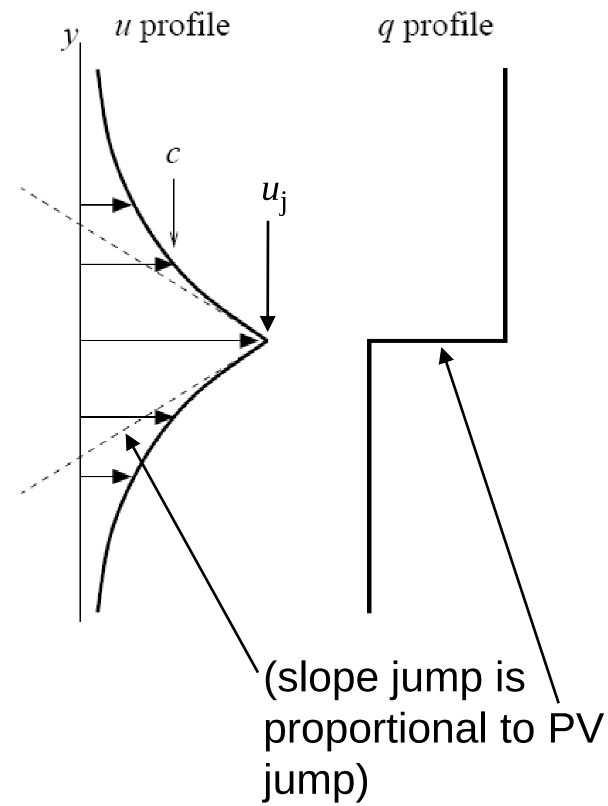
So strong jets, when disturbed naturally, tend to sharpen themselves.

Consider the simplest strong-jet model again:

In this simplest model, the dispersion relation

$$c = u_{\mathrm{j}}\left\{1 - \left(1 + L_{\mathrm{D}}^2 k^2\right)^{-1/2}\right\}$$

implies that the phase speed c
lies within the range of jet velocity profile.



So strong jets, when disturbed naturally, tend to sharpen themselves.

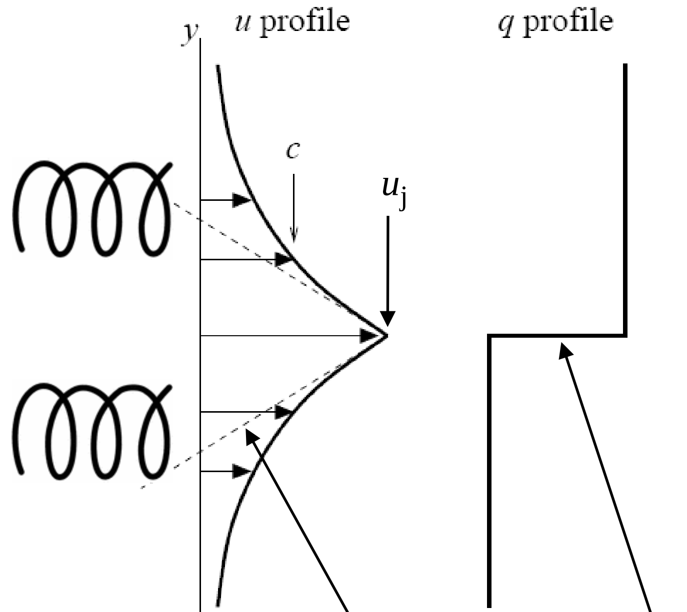
Consider the simplest strong-jet model again:

In this simplest model, the dispersion relation

$$c = u_{\mathrm{j}}\left\{1 - \left(1 + L_{\mathrm{D}}^2 k^2\right)^{-1/2}\right\}$$

implies that the phase speed c
lies within the range of jet velocity profile.

Simple kinematics strongly favours Rossby-wave breaking on the jet flanks. (This is the key message from Rossby-wave critical-layer theory – another way of seeing the **feedback from shear**.



(slope jump is proportional to PV jump)

So strong jets, when disturbed naturally, tend to sharpen themselves.

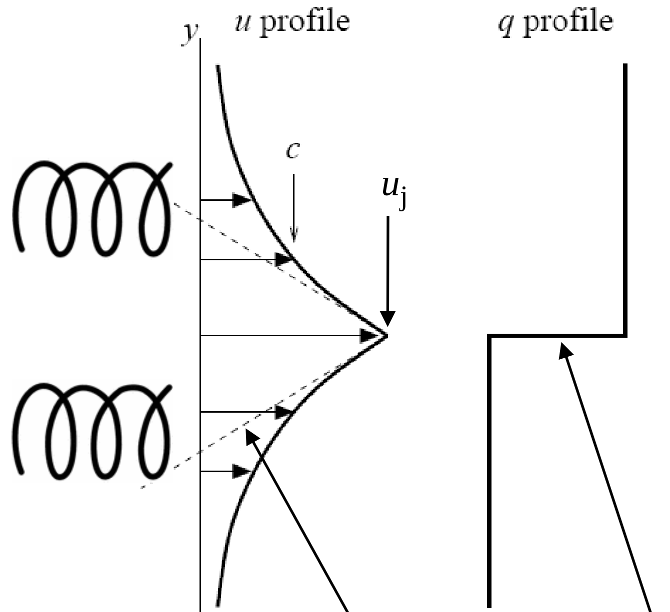
Consider the simplest strong-jet model again:

In this simplest model, the dispersion relation

$$c = u_{\mathrm{j}}\left\{1 - \left(1 + L_{\mathrm{D}}^2 k^2\right)^{-1/2}\right\}$$

implies that the phase speed c
lies within the range of jet velocity profile.

Simple kinematics strongly favours Rossby-wave breaking on the jet flanks. (This is the key message from Rossby-wave critical-layer theory – another way of seeing the **feedback from shear**.



The stratospheric examples are similar
except that the polar-night jet self-sharpens
mainly by PV mixing on its **equatorward** flank (McI 1982, *J Met Soc Japan*).

So strong jets, when disturbed naturally, tend to sharpen themselves.

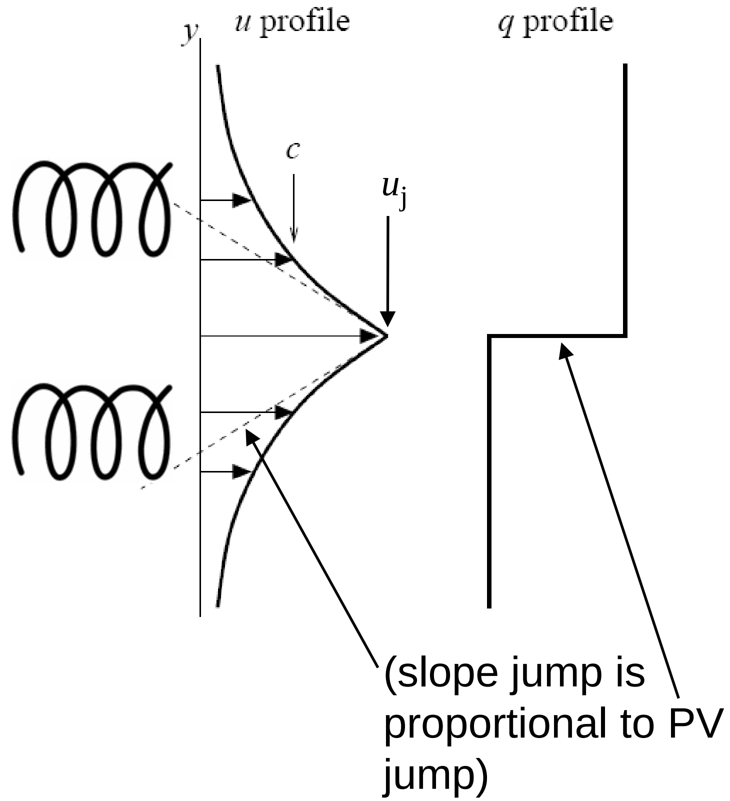
Consider the simplest strong-jet model again:

In this simplest model, the dispersion relation

$$c = u_{\mathrm{j}} \left\{ 1 - \left(1 + L_{\mathrm{D}}^2 k^2 \right)^{-1/2} \right\}$$

implies that the phase speed c
lies within the range of jet velocity profile.

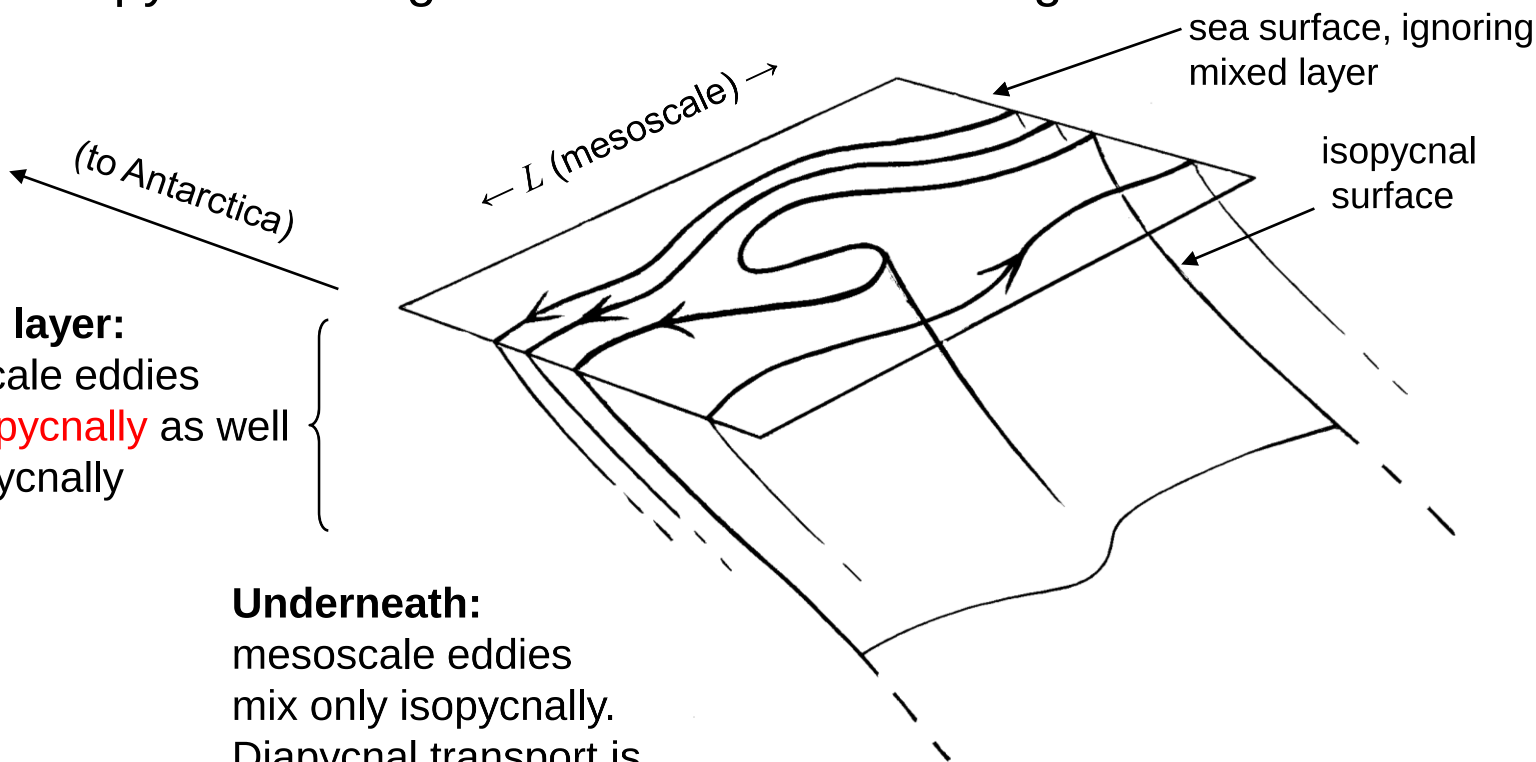
Simple kinematics strongly favours Rossby-wave breaking on the jet flanks. (This is the key message from Rossby-wave critical-layer theory – another way of seeing the **feedback from shear**.



The stratospheric examples are similar
except that the polar-night jet self-sharpens
mainly by PV mixing on its **equatorward** flank (McI 1982, *J Met Soc Japan*).

Oceanic counterparts: consider strong-jet models whose PV gradients are mainly in surface temperature (PV delta function, ignoring mixed layer):

DIMBO = DIapycnal Mixing via Baroclinic Overturning



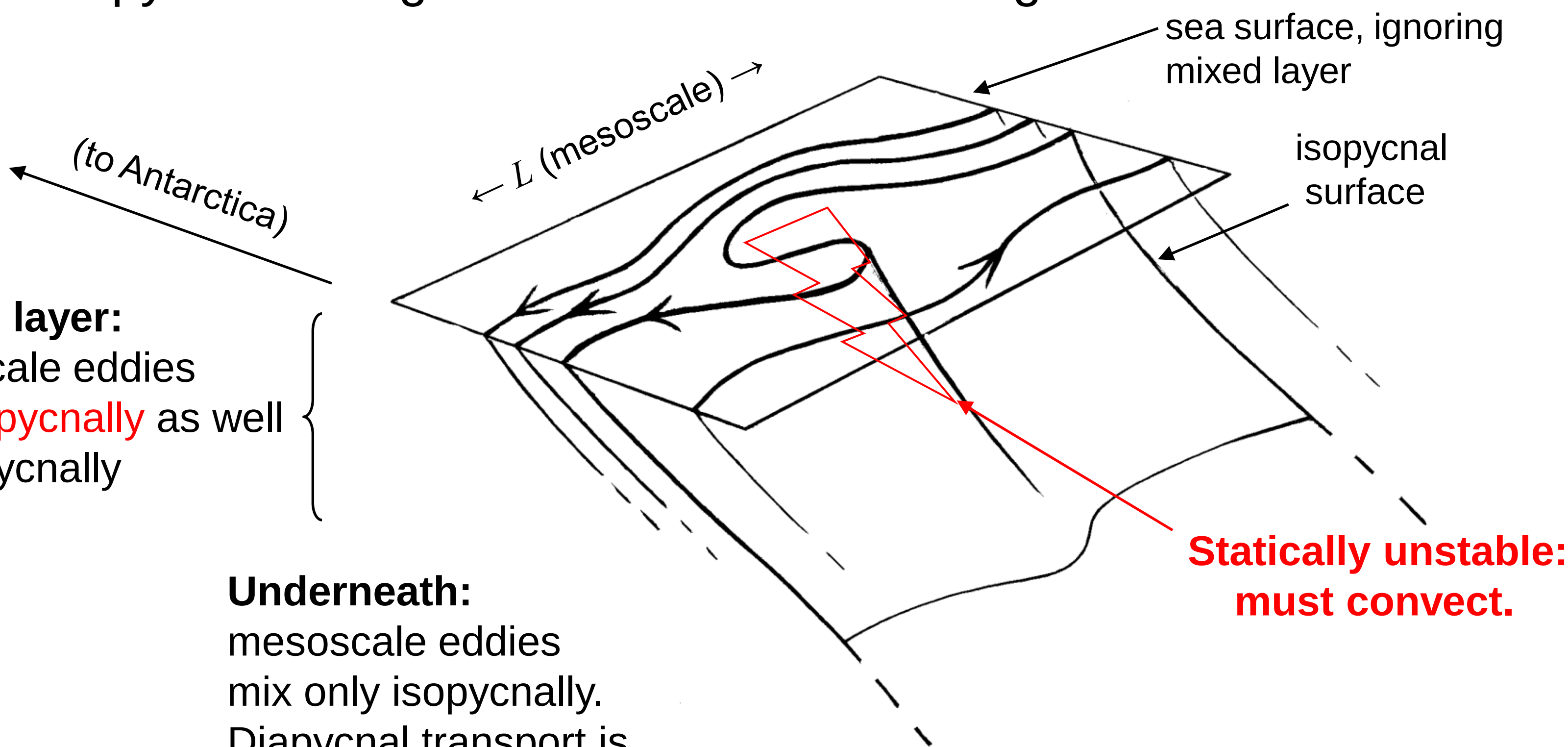
DIMBO layer:
mesoscale eddies
mix diapycnally as well
as isopycnally

Underneath:
mesoscale eddies
mix only isopycnally.
Diapycnal transport is
solely by inertia-gravity-wave
breaking, cabbeling, DD, spiralling

How deep is the DIMBO layer? Scale analysis and semigeostrophic PV inversion suggest the "obvious" answer fL/N. Could ~ kilometre or two. Must often exceed mixed-layer depth.

Numerical experiments underway (John Taylor, Raff Ferrari, personal communication)
– watch this space!

DIMBO = DIapycnal Mixing via Baroclinic Overturning



DIMBO layer:
mesoscale eddies
mix diapycnally as well
as isopycnally

Underneath:
mesoscale eddies
mix only isopycnally.
Diapycnal transport is
solely by inertia-gravity-wave
breaking, cabbeling, DD, spiralling

How deep is the DIMBO layer? Scale analysis and semigeostrophic PV inversion suggest the "obvious" answer fL/N. Could ~ kilometre or two. Must often exceed mixed-layer depth.

Numerical experiments underway (John Taylor, Raff Ferrari, personal communication) – watch this space!

Summary: 2-level hierarchy of ideas for understanding the fluid dynamics of jets

1. Generic ideas:

PV Phillips effect

Taylor-Bretherton identity
$\overline{v'q'}$ = – div (eddy momentum flux)
Nonlinear, forced/free/self-excited

2. Particular mechanisms:

(i) Rhines effect. Re **weak** jets generated by strong small-scale forcing – strong enough to create **active** small-scale vortices that merge or cluster, producing an **inverse cascade** that is arrested or slowed when eddy velocities ~ **plane** Rossby-wave phase speeds. Wave-turbulence interaction is spatially **homogeneous**.

(ii) Jet self-sharpening by Rossby-wave breaking. Re jets **strong** enough to be Rossby waveguides. Wave-turbulence interaction spatially **inhomogeneous**.

(iii) Repeated excitation of **Kelvin sheared disturbances** by small-scale forcing weaker than in (i). (Kelvin 1887, Farrell and Ioannou 2007 & refs.).

(iv) Downstream wind stress reinforcing strong ocean jets (e.g.Thomas & Lee'05 *JPO*)

3. Additional point (new?): **DIMBO** a significant addition to the list of diapycnal mixing mechanisms (internal-wave breaking, cabbeling, near-topographic etc)?

Reprints, preprints & corrigenda: websearch **"lucidity principles"**
then back to my home page at the string "jets".