Eddies and Friction: Removal of Vorticity from the Wind-Driven Gyre

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0.1 Background

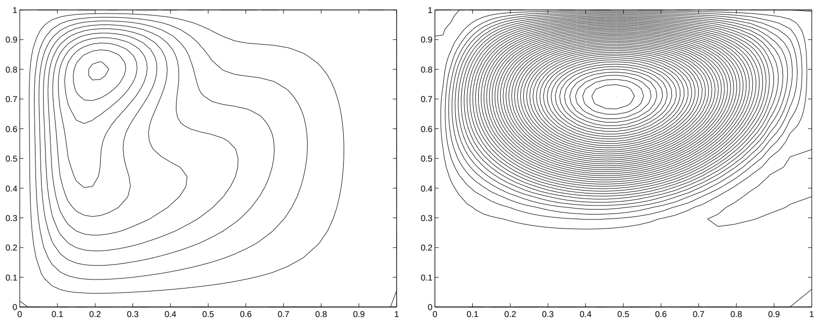
- **Inertial Domination/Vorticity Removal** (Veronis (1966)), Niiler (1966))
- **Multi-Gyre Internal Cancellation of Vorticity** (Harrison and Holland (1981), Marshall (1984))
- **Limited Intergyre Mass Flux/Dissipative Meandering** (Lozier and Riser (1989), Lozier and Riser (1990))

0.2 Major Dissertation Results

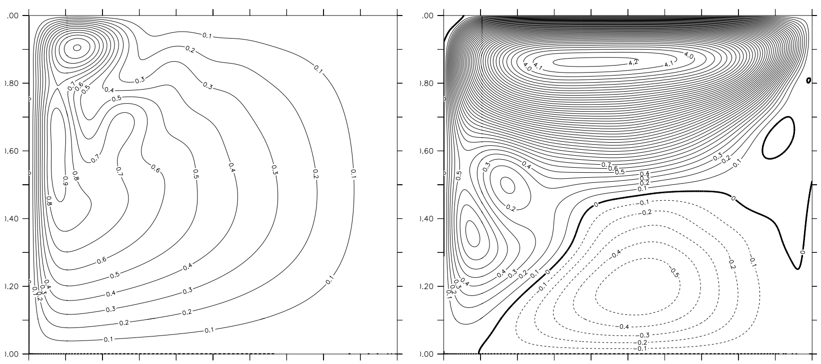
- **Control by Vorticity Flux to Enhanced Removal Region**
- **Boundary Conditions affect Intergyre Vorticity Flux**
- **Sinuous Modes affect Vorticity Flux Efficiency**

1 Inertial Domination (a.k.a Runaway)

Steady, Re=1 Steady, Re= 4.3



Eddying, Re=1 Eddying, Re=5

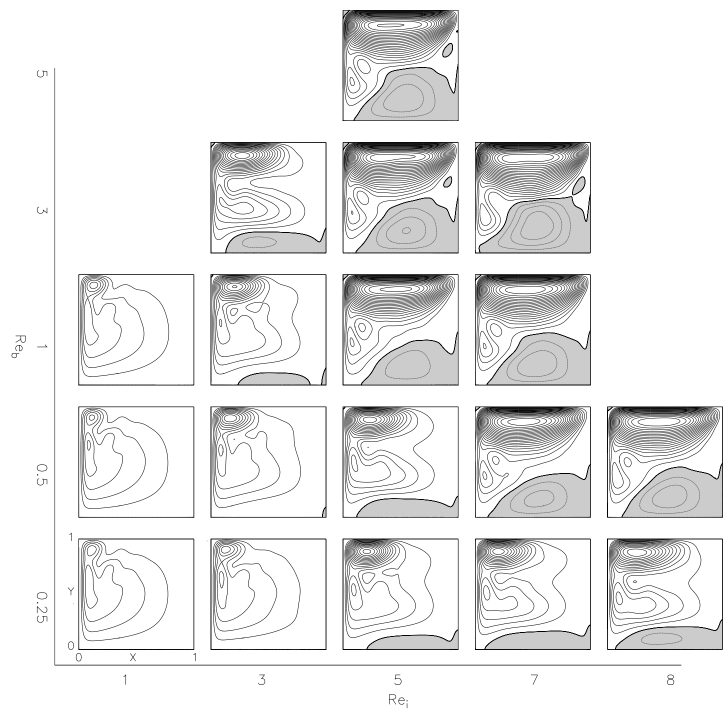


(ψ, No-slip E&W)

1.1 Single Gyre

- Mean flow fluxes vorticity to IWBC
- Eddies flux from IWBC to FSL
- Friction removes vorticity
- If bdy. visc. too small, inertia takes over basin
- Only eddies & fric. flux across mean streamlines

1.1.1 Circulation Control by Eddy Vorticity Flux to a Region of Enhanced Removal



Circulation Control

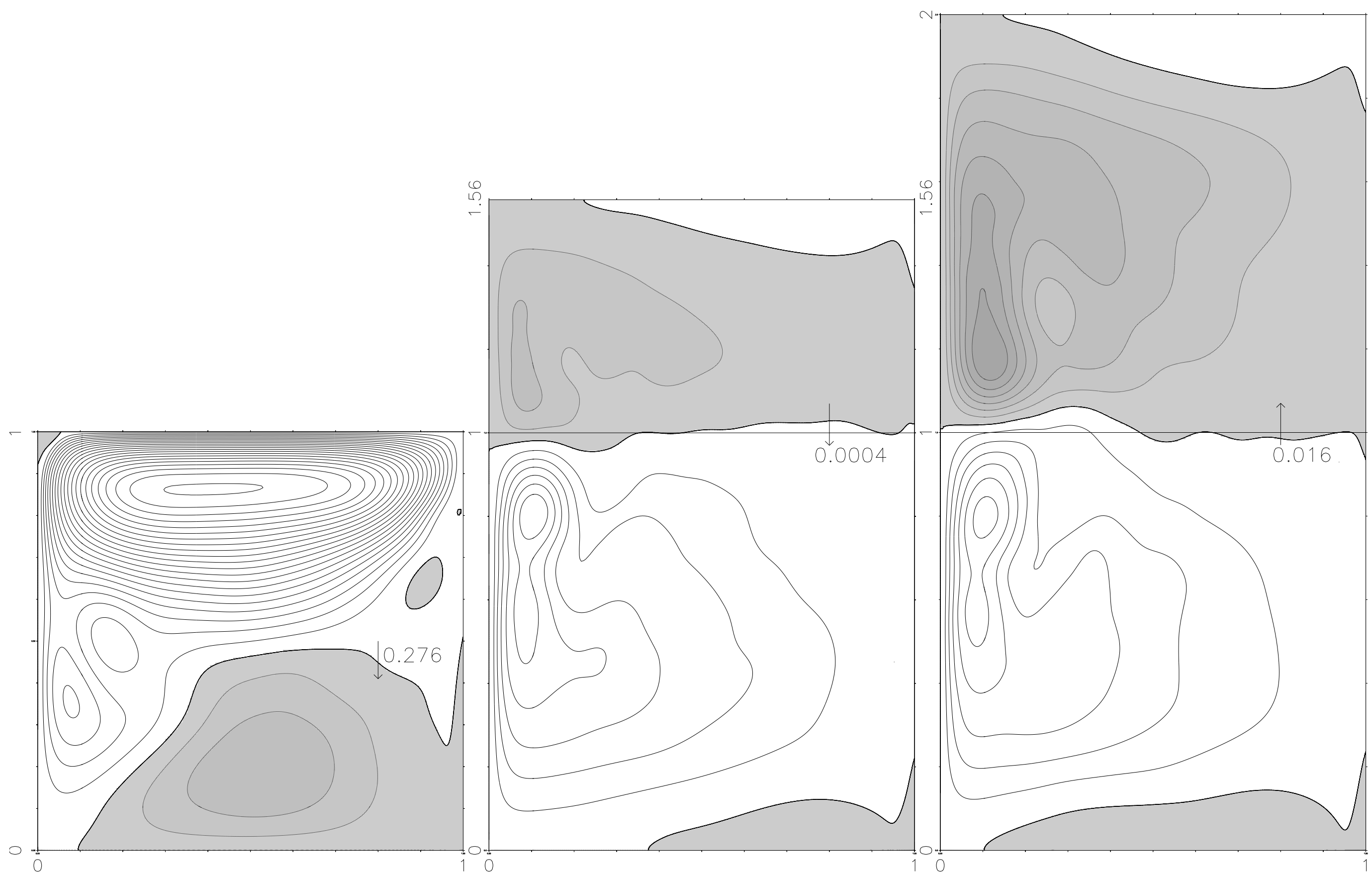
- Eddies cannot ultimately remove vorticity
- Increased viscosity in a narrow region near bdy. helps remove it
- IBL wider than FBL, even in western-intensified solns!
- Eddies *can* replace friction, but only in interior, not at bdy.

2 What about Multi-Gyres? Internal Cancellation?

Will eddies dispose of vorticity by an intergyre eddy flux or by a flux to the frictional sublayer?

Does internal cancellation control the circulation strength at high Re?

2.1 Very Little intergyre Flux with No-slip

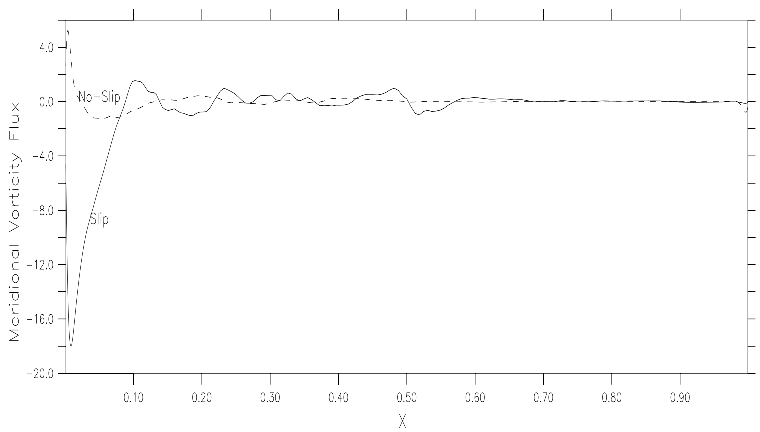


Re(bdy)=5, Re(int)=5, and no-slip boundary conditions.

Arrows=Eddy Vort. Flux, Subtrop. input=0.637. Movie

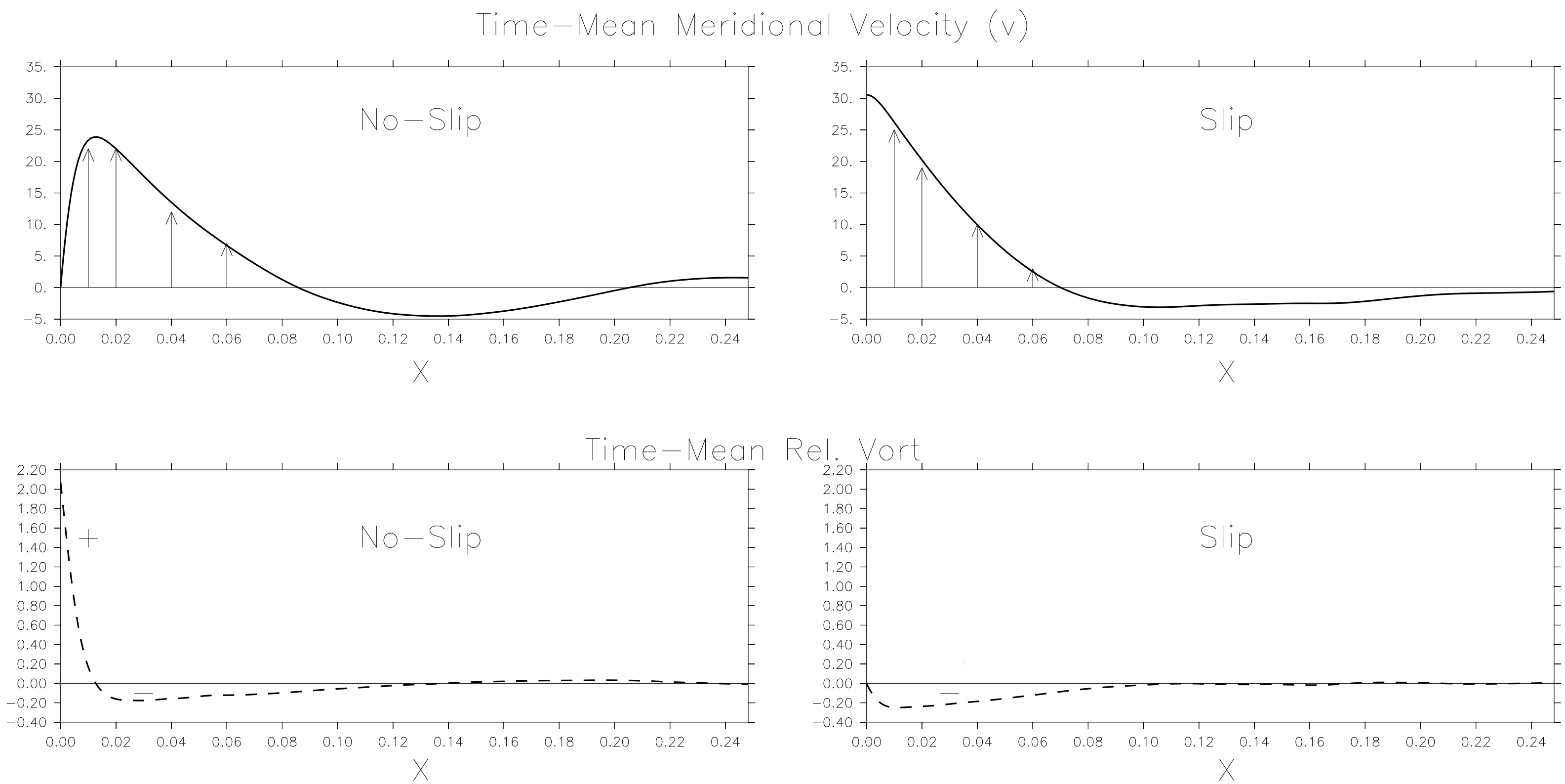
2.2 Conflict with Slippery BC results

Eddy flux across y=1



- Different from Harrison and Holland (1981), Marshall (1984), Lozier and Riser (1990) who use slippery bcs.
- Most intergyre eddy flux in slippery models is dissipative meandering, not by parcel exchange Lozier and Riser (1989), Berloff et al. (2002).

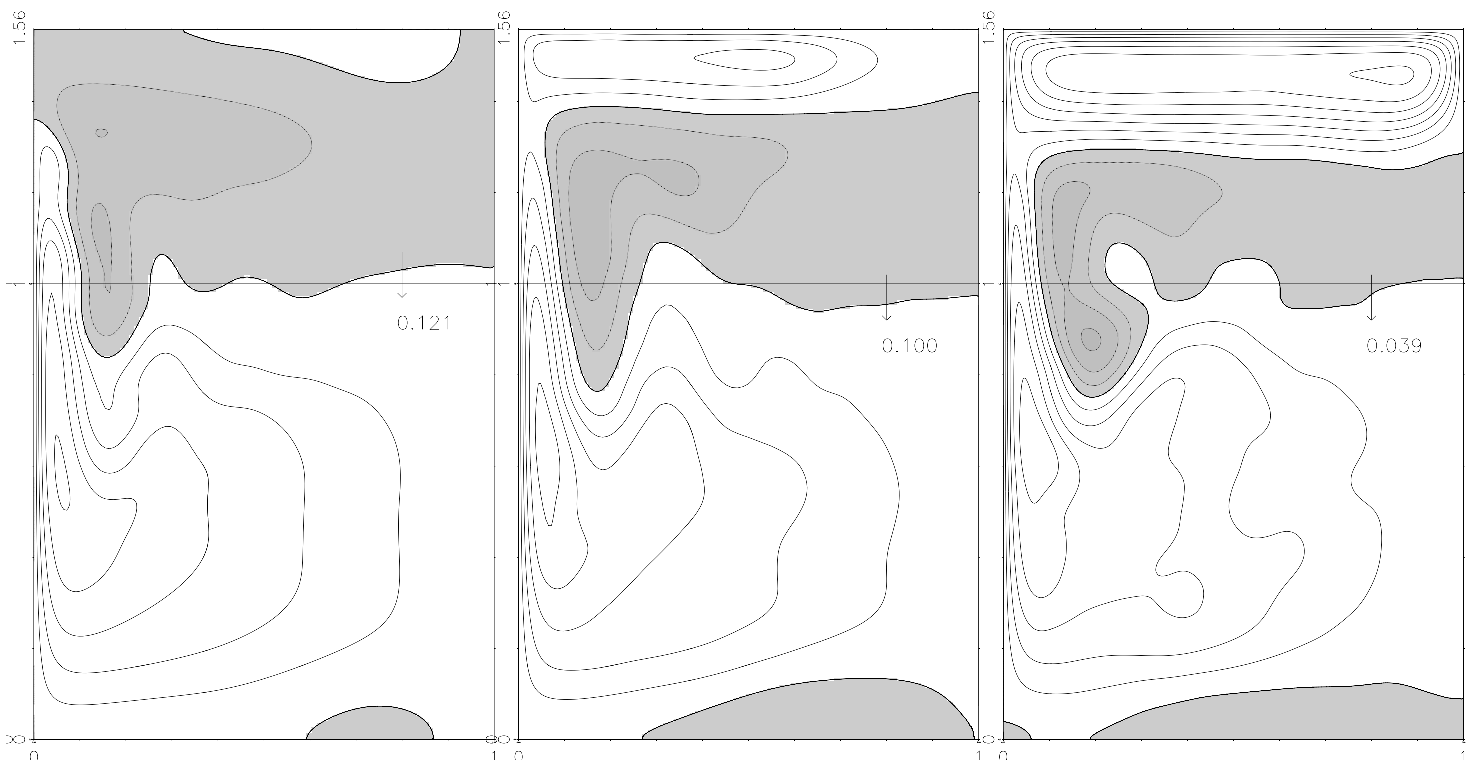
2.3 Intergyre Flux due to Rel. Vort. in BL



No dissipative meandering with no-slip because 1) separation point doesn't meander easily and 2) rel. vorticity in BL is different. Movie

2.4 So why not Slip BCs & Eddy Fluxes?

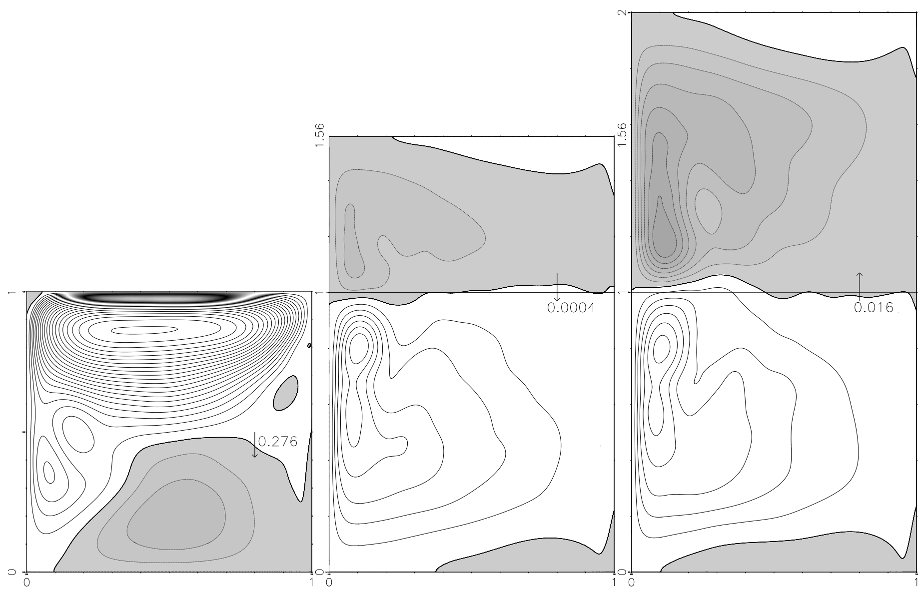
Slip Two-Gyre: w/o *antisymmetric* wind, intergyre *eddy flux* not preferred, instead it's *mean flux*. Cessi (1991): stronger WBC no-slip/slip under/overshoots.



Re=2.5 Re= 5 Re= 10

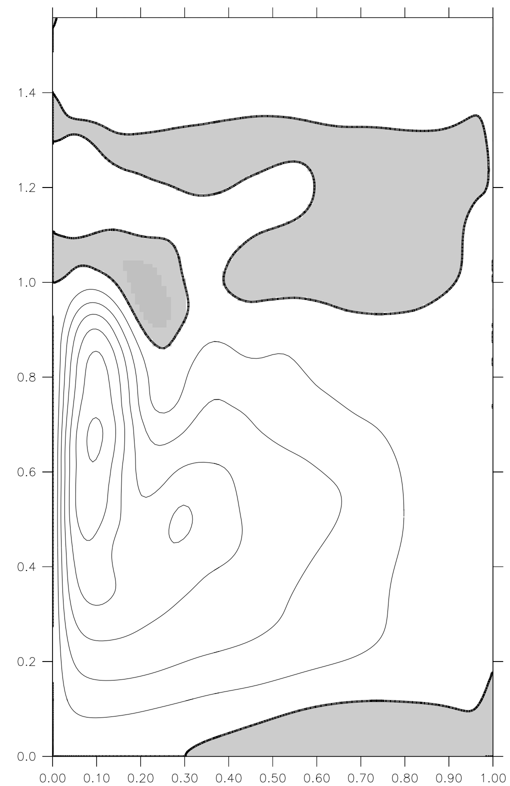
3 Why is No-Slip Multi-gyre Circ. Controlled?

Negligible intergyre eddy flux of vorticity, yet circ. is reduced with addition of a second gyre.



Re(bdy)=5, Re(int)=5, and no-slip boundary conditions.

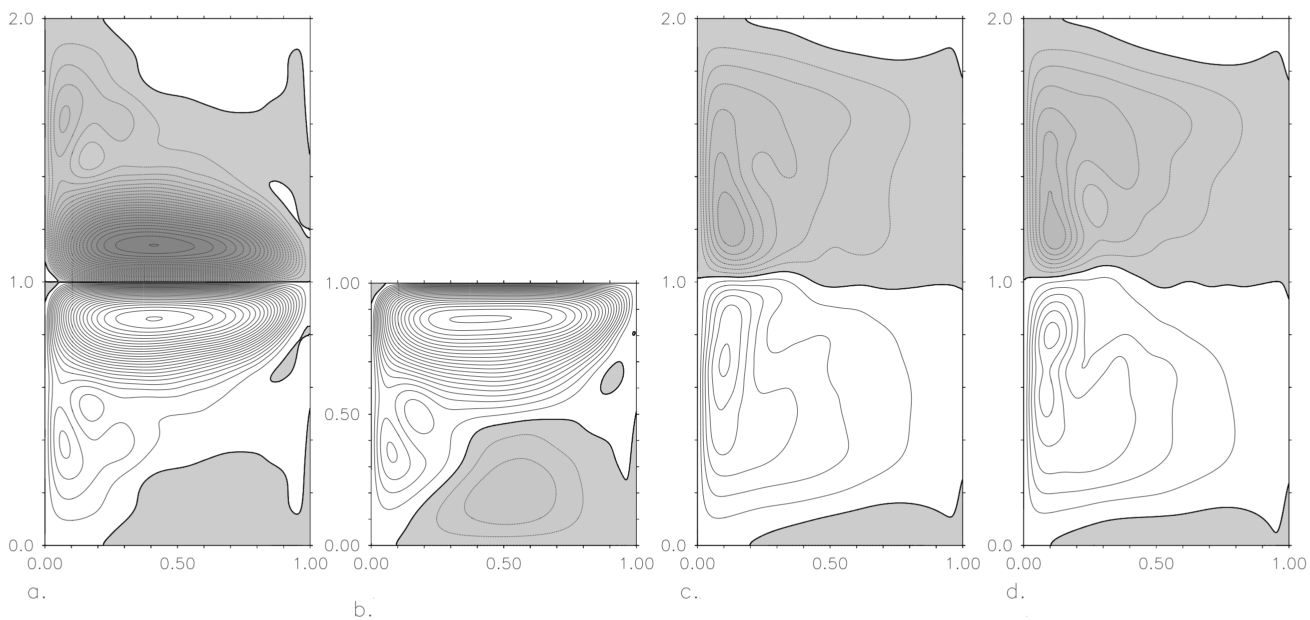
Circulation reduced even *without subpolar wind forcing*!



Re(bdy)=5, Re(int)=5, and no-slip boundary conditions.

4 Sinuous Modes

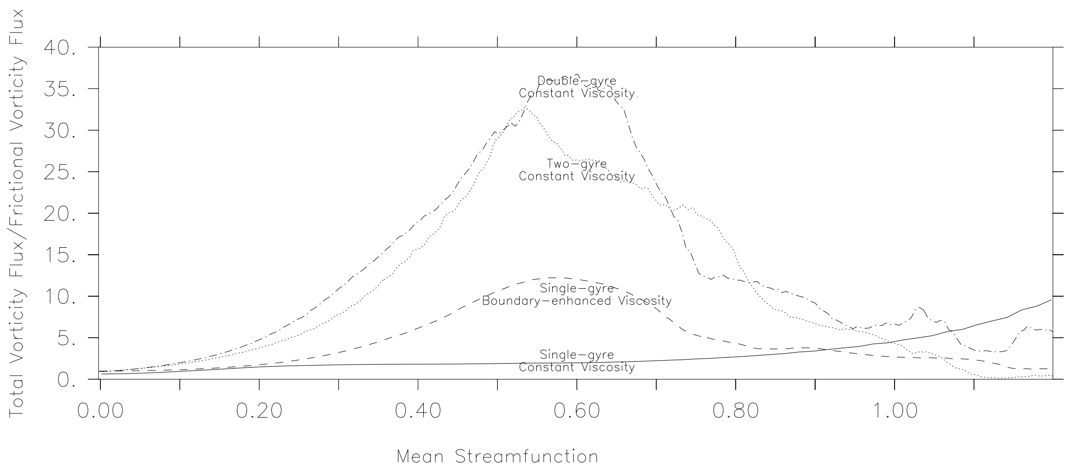
Removing northern boundary changes eddies that flux vorticity to the frictional sublayer. Rapidly-growing *sinuous modes* are then present: Movie



Rest initial | Single-gyre | Rest initial after | Asym. initial

4.1 Sinuous Efficiency (Total Flux/Fric. Flux)

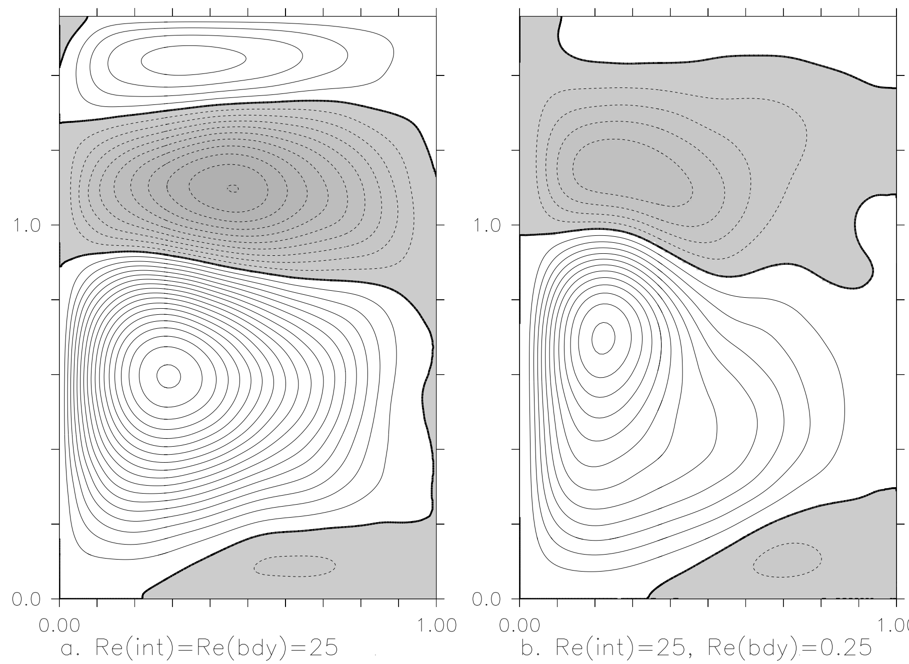
Sinuous modes known to mix strongly on either side of the jet: *e.g.*, Balmforth and Piccolo (2001), Rogerson et al. (1999).



Sinuous modes are *extremely efficient* at tearing vorticity from the recirculation gyre. The recirculation gyre and circ. strength limited by sinuous modes. No intergyre eddy flux required.

4.2 Eventual Inertial Domination

At a sufficiently high Reynolds number inertial domination returns even with sinous modes,



Thus, vorticity removal at high Re must still be considered.

5 Conclusions

- Friction $\neq$ eddies: only friction removes vorticity; eddies have barriers to transport, nonlocal effects, upgradient regions...
- However, eddies can prevent inertial domination if vorticity removal is assured.
- Only slip double gyre shows significant intergyre eddy fluxes at high Reynolds number, due to dissipative meandering
- No-slip models have *negligible intergyre eddy flux* and slip (asymmetric) two-gyre calculations have primarily *mean* intergyre flux
- Sinuous modes increase the efficiency of vort. flux to the FSL and reduce circ. w/o requiring intergyre eddy flux. At sufficient Re, the efficiency is exhausted and boundary removal again becomes a problem.

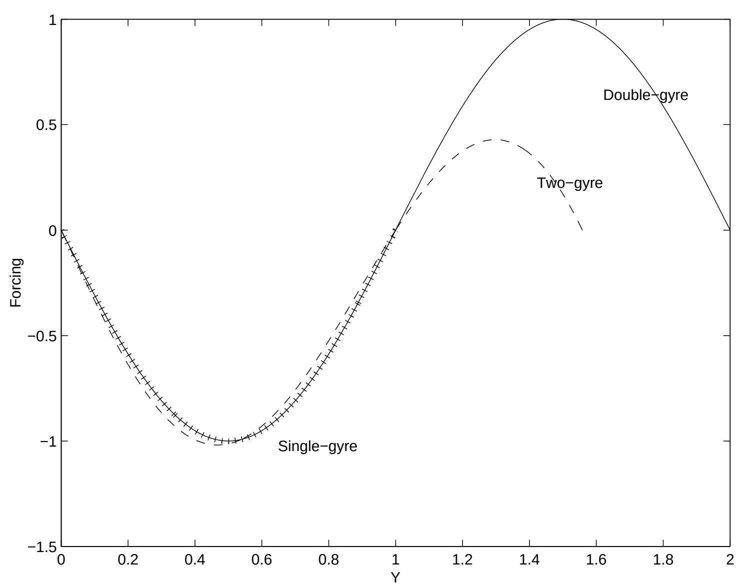
6 Implications?

- Eddy vort. flux is very important at high Re when mean streamlines are closed. True also in real ocean.
- The removal of vorticity at the boundary can be very important in determining the interior solution. *Nonlocal control.*
- If eddies are more efficient–as sinuous modes are–circulation strength can be reduced, but vorticity removal always important
- intergyre eddy vort. flux seems to be restricted to symmetric slip double-gyre, probably not a major player in real ocean.

7 Issues?

- Baroclinicity? Thickness fluxes, outcropping, buoyancy budget.
- Precisely how does boundary remove vorticity? Perhaps Hughes & De Cuevas ('02).
- What are the instabilities in the real ocean, and how efficient are they?

7.1 We Compare 3 Models: Vorticity Input



Single-gyre is in square basin.
Two-gyre is in asymmetric basin. $0 \leq y \leq 1.56$
Double-gyre is in symmetric basin. $0 \leq y \leq 2$

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