Eddy saturation in a barotropic model

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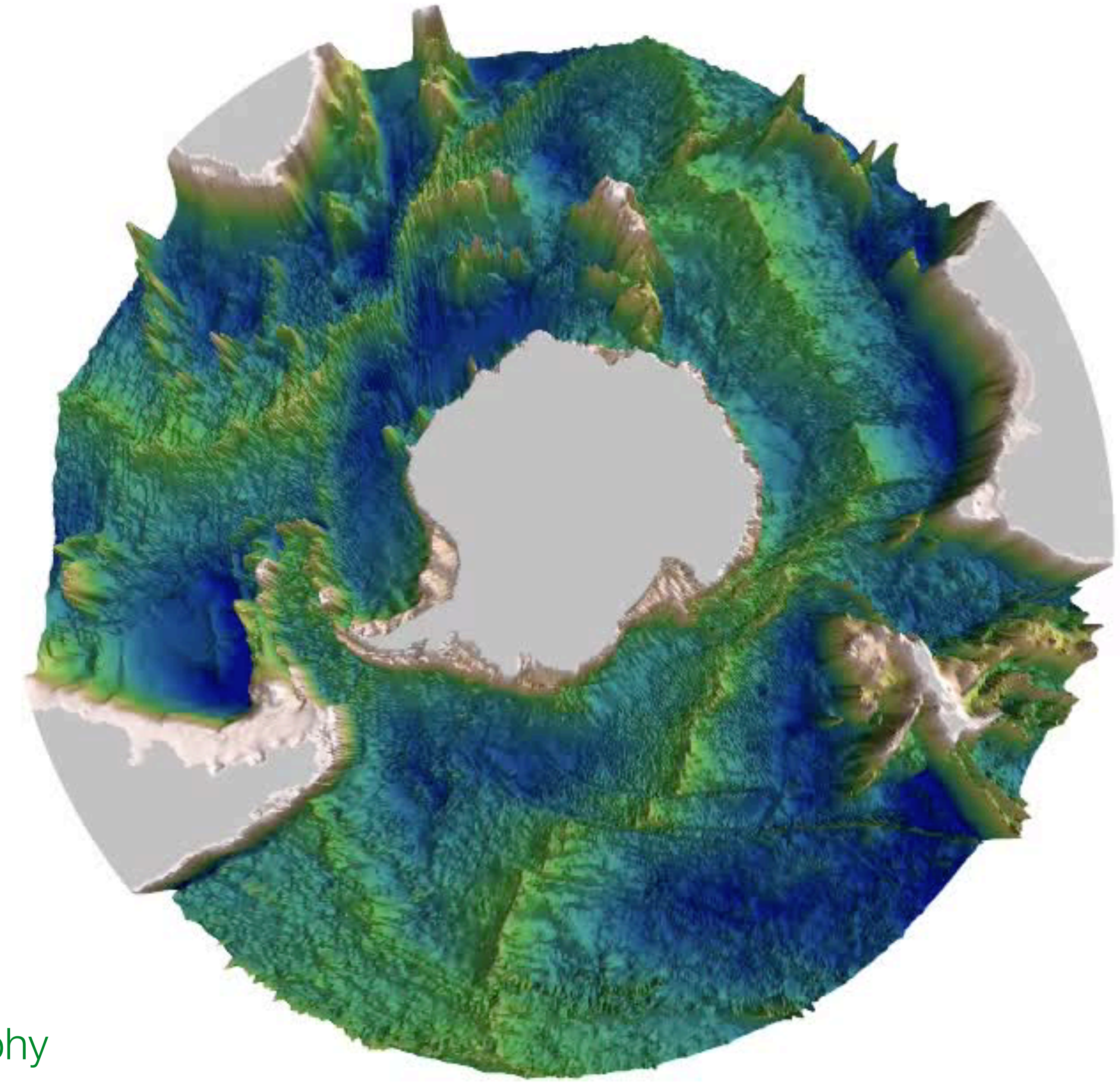

Animated view of the Southern Ocean topography by V. Tamsitt.

Can a barotropic QG model exhibit "eddy saturation"?

What is the minimum requirements for "eddy saturation"?

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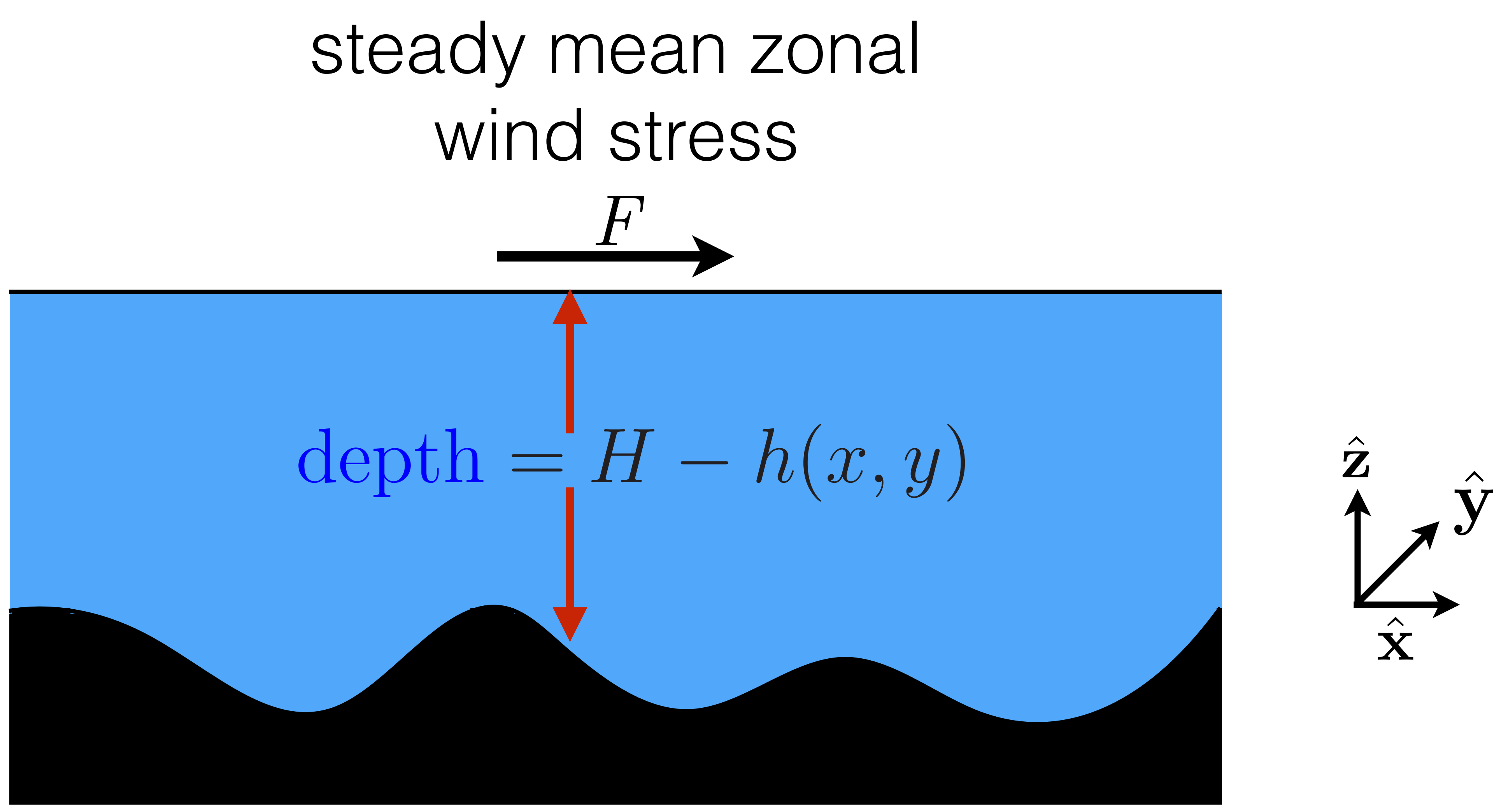
the plan

Revisit an old barotropic QG model on a β-plane.

(Hart 1979, Davey 1980, Bretherton & Haidvogel 1976, Holloway 1987, Carnevale & Fredericksen 1987)



A distinctive feature of this model is a "large-scale barotropic zonal flow" $U(t)$.

this is the "ACC"

topographic PV $\quad \eta = \dfrac{f_0 h}{H}$

total streamfunction $\quad -U(t)y + \psi(x,y,t)$

QGPV $\quad \nabla^2\psi + \eta + \beta y$

Study how momentum is balanced by topographic form stress and investigate the requirements for eddy saturation.

a barotropic QG model for mid-ocean region

total streamfunction $-U(t)y + \psi(x, y, t)$

QGPV $\nabla^2\psi + \eta + \beta y$

Material conservation of QGPV

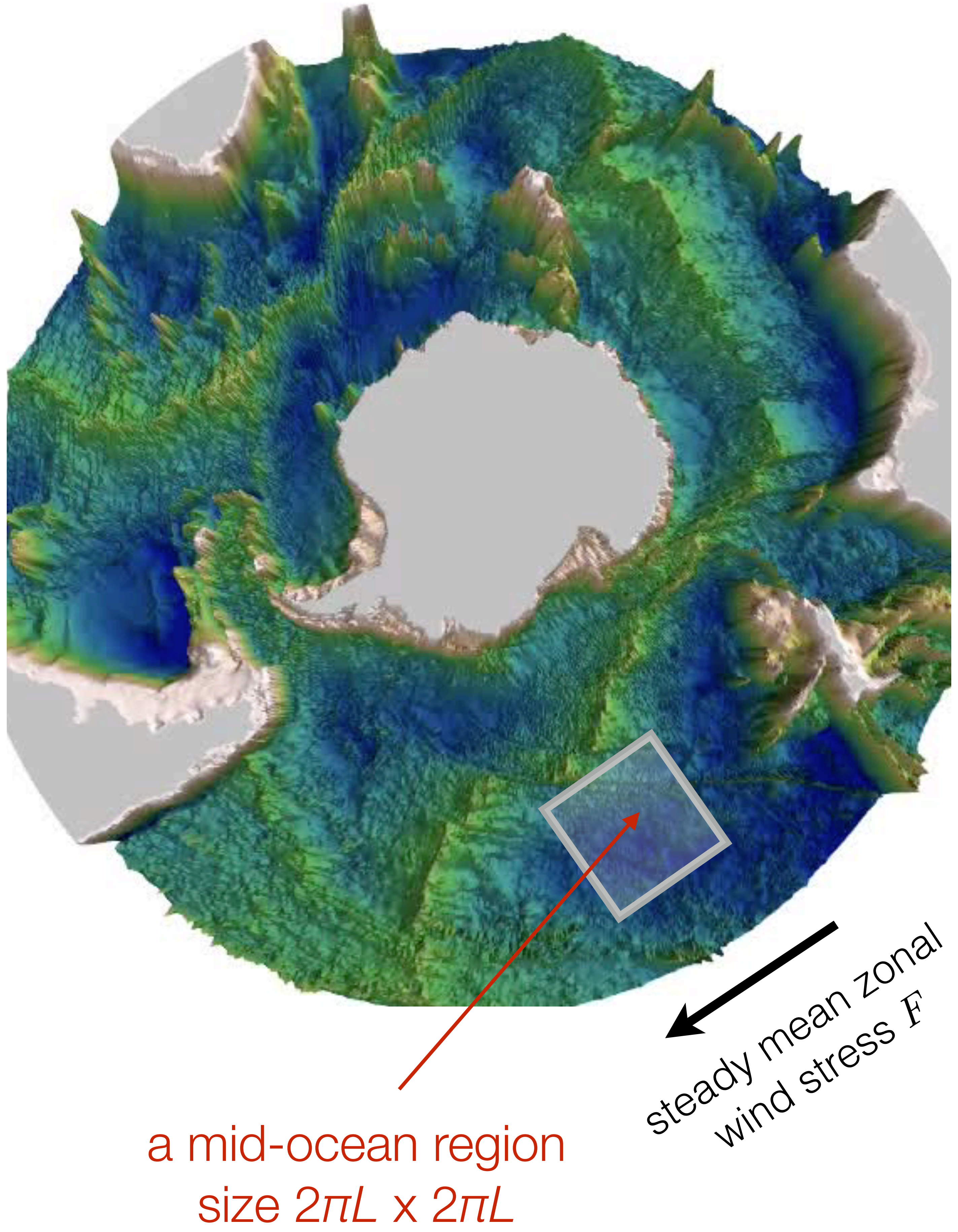
$$\nabla^2\psi_t + U(\nabla^2\psi + \eta)_x + \mathsf{J}(\psi, \nabla^2\psi + \eta) + \beta\psi_x = -\mu\,\nabla^2\psi + \text{hyper visc.}$$

Large-scale zonal momentum

$$U_t = F - \mu U - \langle \psi \eta_x \rangle$$

topographic
form stress

vertically integrated and horizontally averaged zonal angular momentum equation



$\langle\ \rangle$ is domain average

$F = \dfrac{\tau_s}{\rho_0 H}$: wind stress forcing

periodic boundary conditions

(Hart 1979, Davey 1980, Bretherton & Haidvogel 1976, Holloway 1987, Carnevale & Fredericksen 1987)

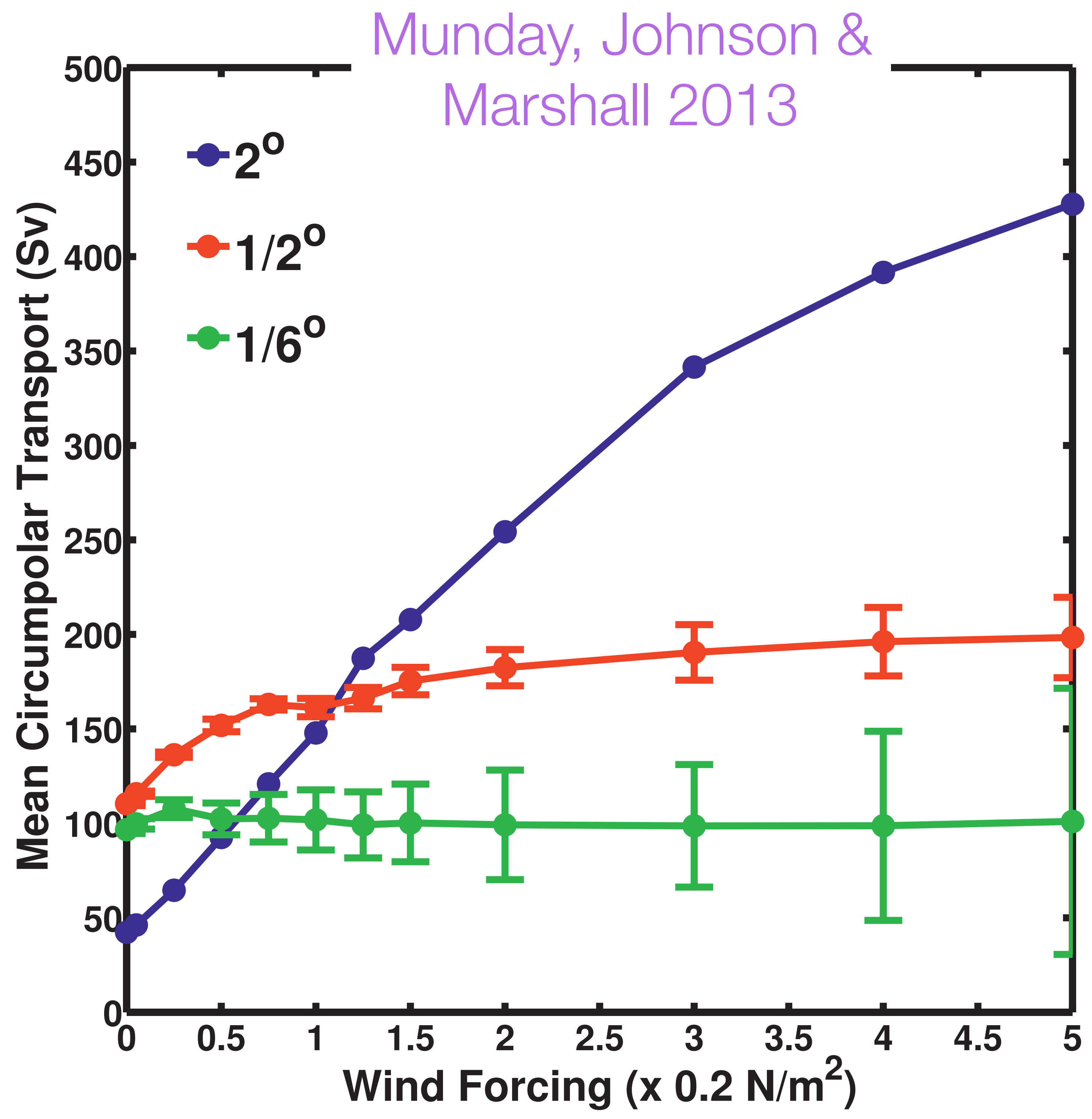
Question:

Does this barotropic QG model show "eddy saturation"?

Do we need baroclinicity?
Do we even need channel walls?

what is "eddy saturation"?

The *insensitivity* of the total ACC volume transport to wind stress increase.



Eddy saturation is seen in eddy-resolving ocean models.

Higher resolution ⟶ eddy saturation "occurs"

Eddy saturation was theoretically predicted by Straub (1993) but with an *entirely* **baroclinic** argument.
(vertical momentum transfer interfacial eddy form stress)

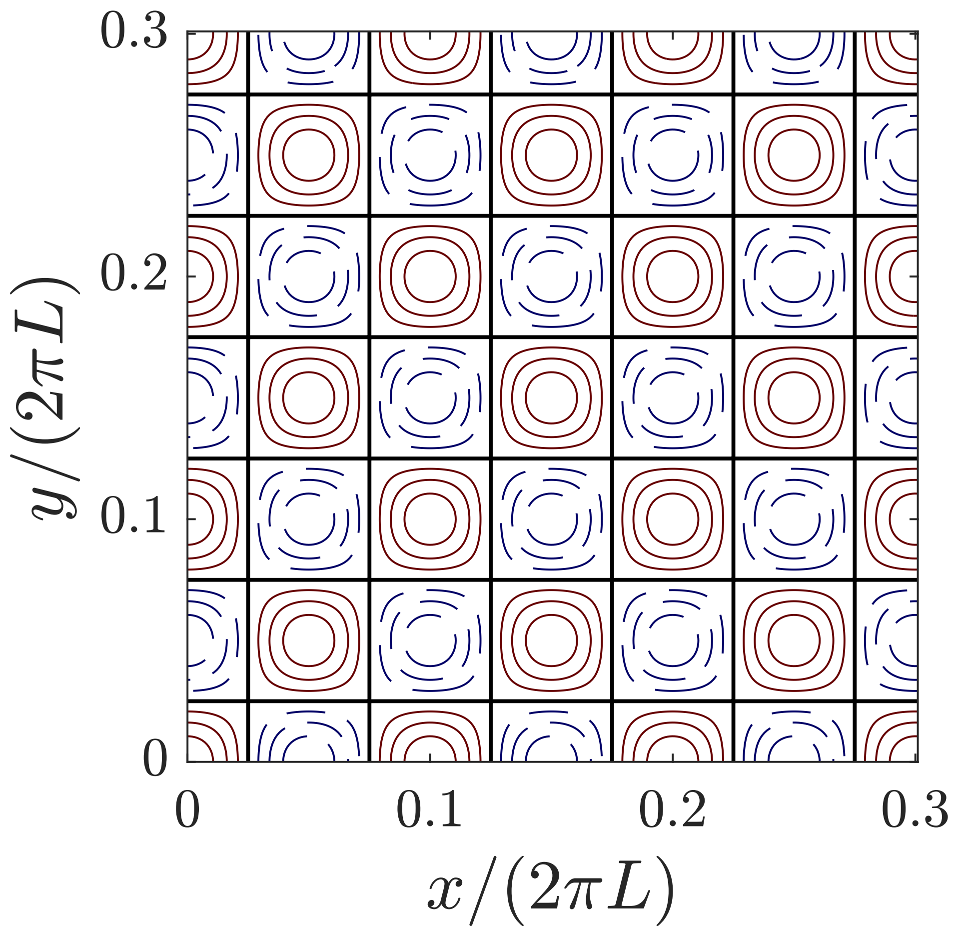
[There are many other examples: Hallberg & Gnanadesikan 2001, Tansley & Marshall 2001, Hallberg & Gnanadesikan 2006, Hogg et al. 2008, Nadeau & Straub 2009, Farneti et al. 2010, Nadeau & Straub 2012, Meredith et al. 2012, Morisson & Hogg 2013, Abernathey & Cessi 2014, Farneti et al. 2015, Nadeau & Ferrari 2015, Marshall et al. 2016.]

Question:

So, does this barotropic QG model show eddy saturation or not?

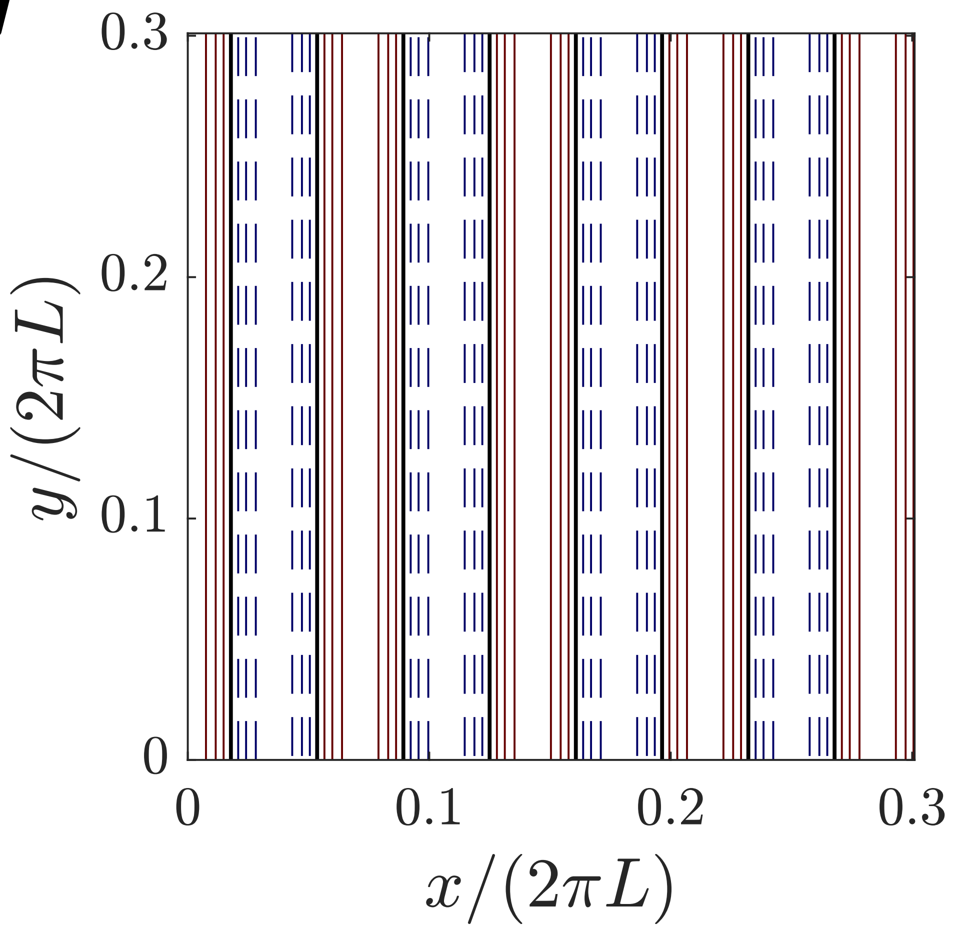
let’s use these two topographies

$\eta^{\times}$ $2\eta_{\mathrm{rms}}\cos(10x/L)\cos(10y/L)$



$^1/_9$ of the periodic domain

$\eta^{\parallel}$ $\sqrt{2}\eta_{\mathrm{rms}}\cos(14x/L)$



(both topographies imply the same length-scale: $\ell_\eta = \sqrt{\dfrac{\langle \eta^2 \rangle}{\langle |\boldsymbol{\nabla}\eta|^2 \rangle}} = 0.07L$)

put some “quasi-realistic” numbers

$$L = 775\ \mathrm{km} \quad H = 4\,\mathrm{km} \quad \rho_0 = 1035\ \mathrm{kg\ m^{-3}}$$

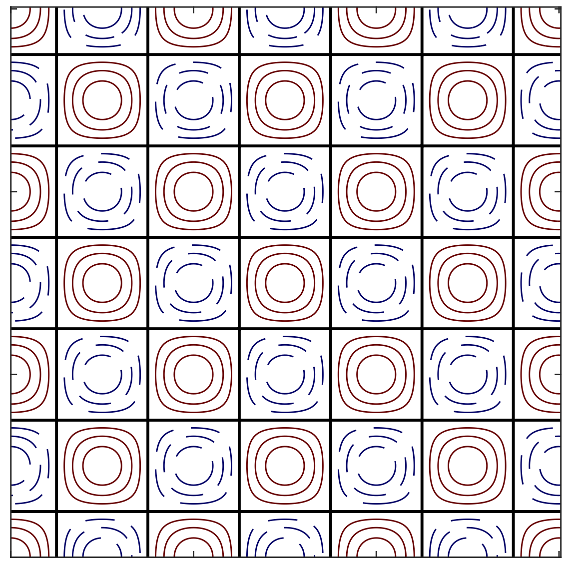
$$f_0 \quad \& \quad \beta \quad \text{for } 60^\circ\mathrm{S}$$

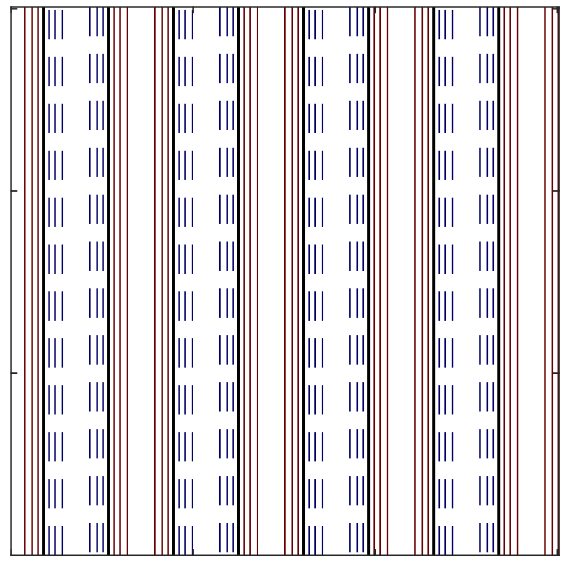
$$\mu = (180\ \text{days})^{-1}$$

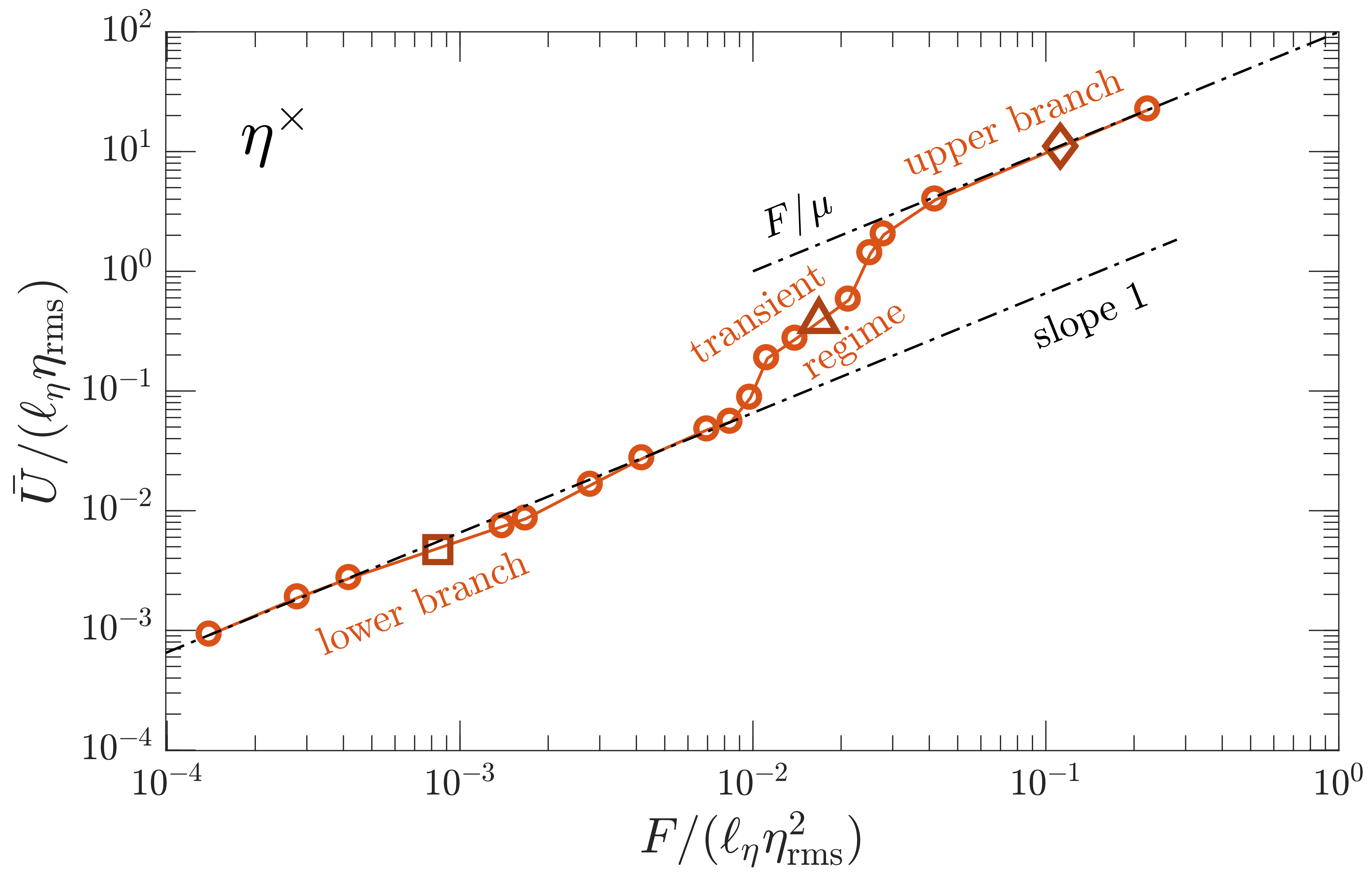
$$h_{\mathrm{rms}} = 200\ \mathrm{m} \Rightarrow \eta_{\mathrm{rms}} = (1.8\ \text{days})^{-1}$$

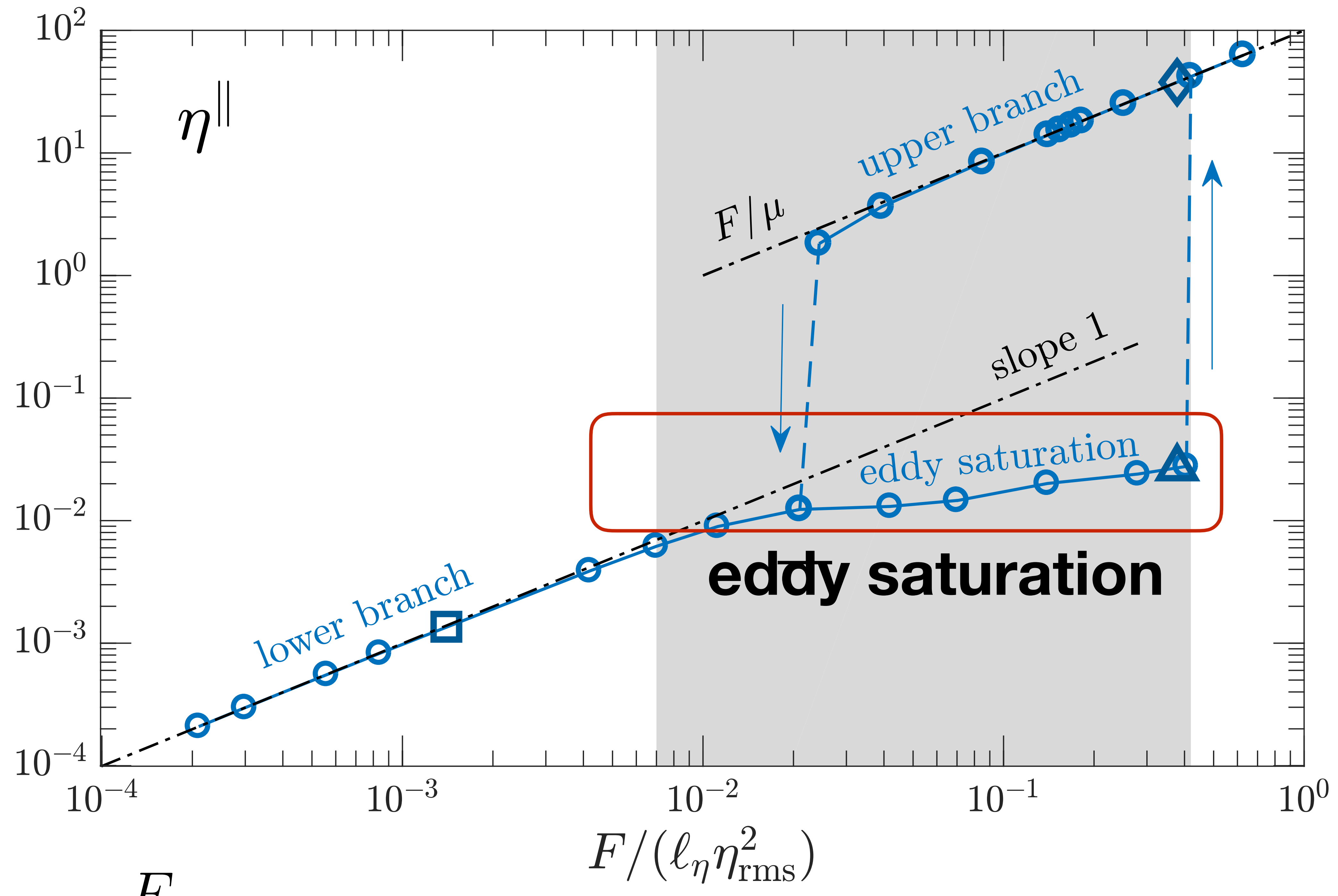
and vary the wind stress…

how does the transport $\bar{U}$ vary with wind stress?









$$\tau = 0.2\,\mathrm{N\,m^{-2}} \Leftrightarrow \frac{F}{\ell_\eta \eta_{\rm rms}^2} \approx 0.02$$

U increases 4 times
over a 60-fold wind stress increase

do we understand why?

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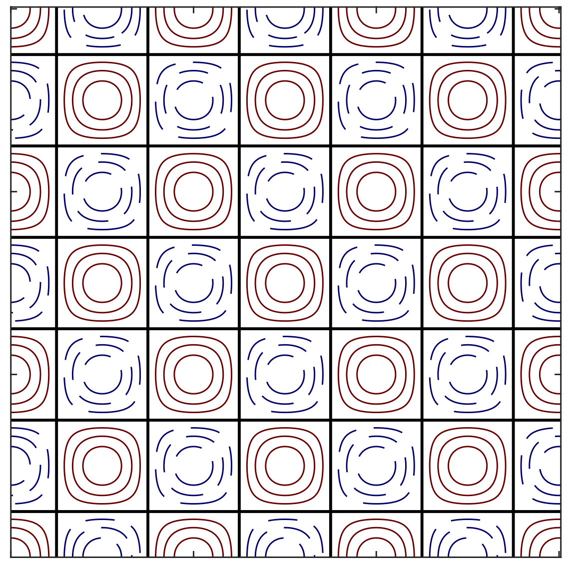

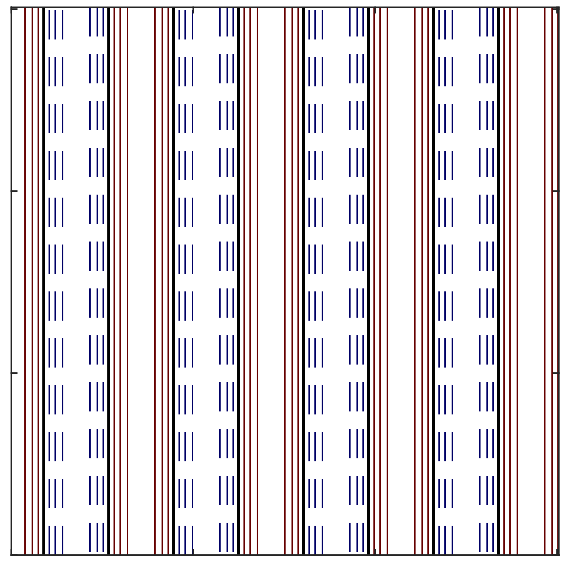

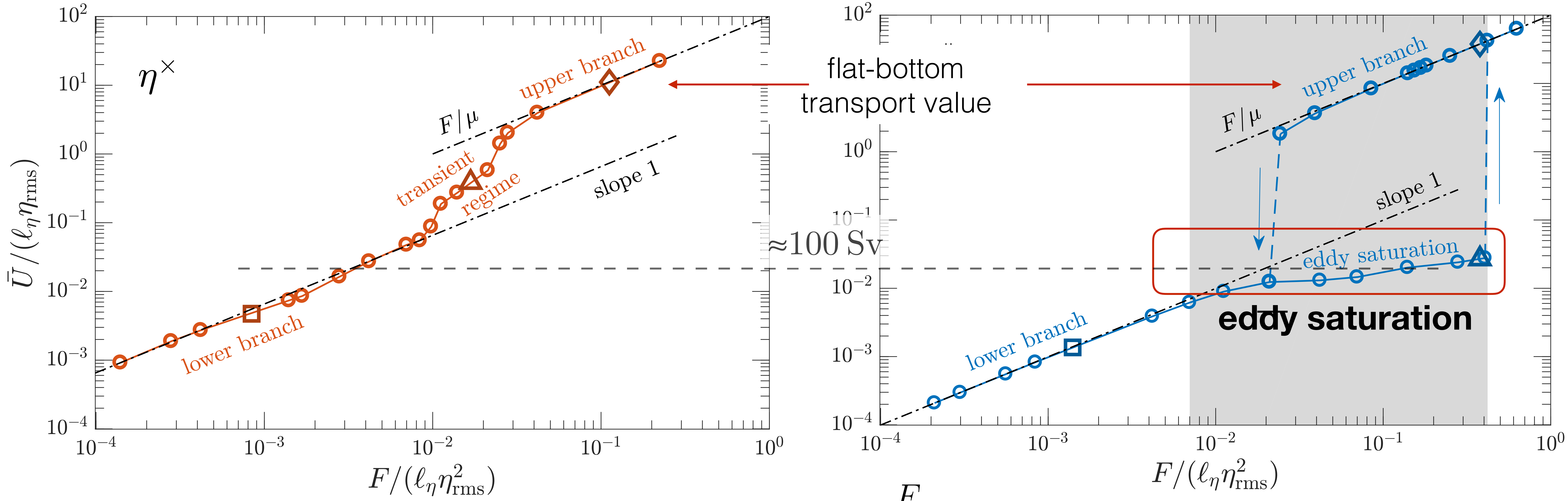

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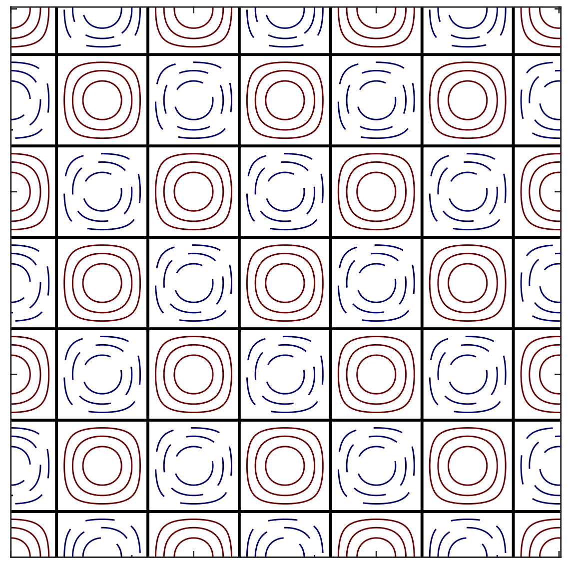
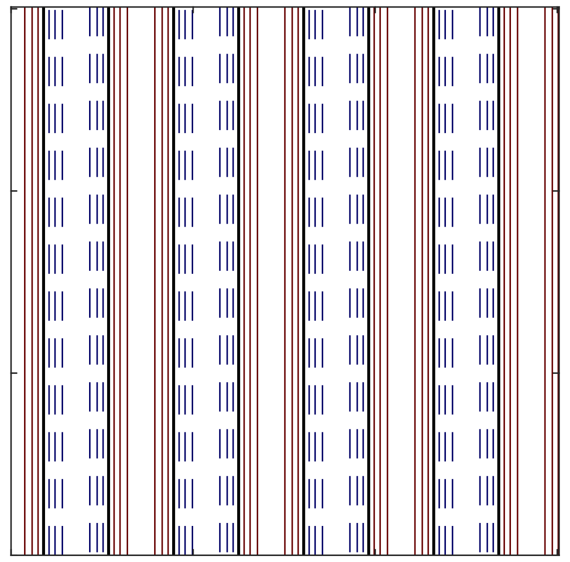
geostrophic contours $\beta y + \eta(x, y)$

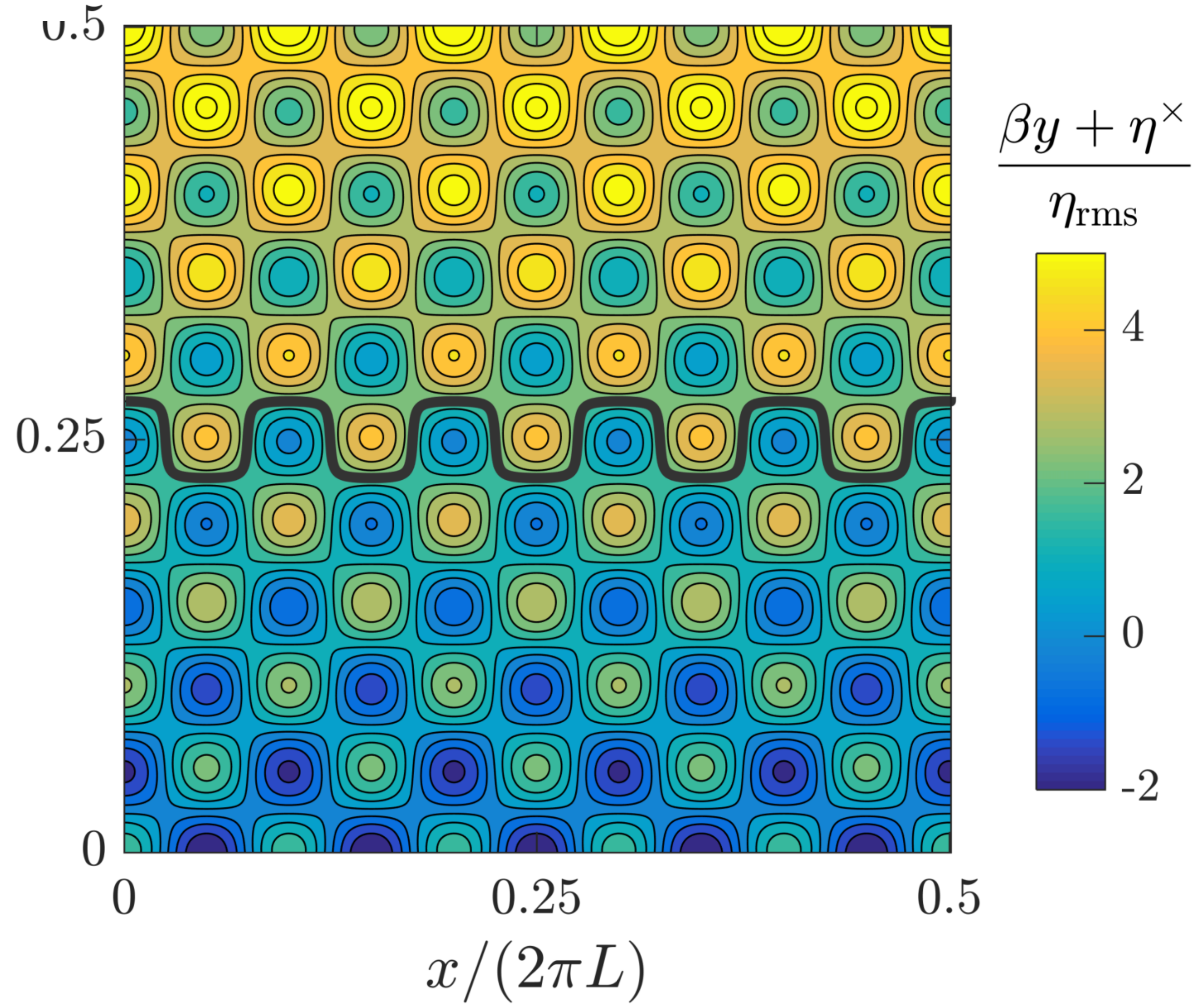
this is small-Rossby number expansion of $f/(H+h)$





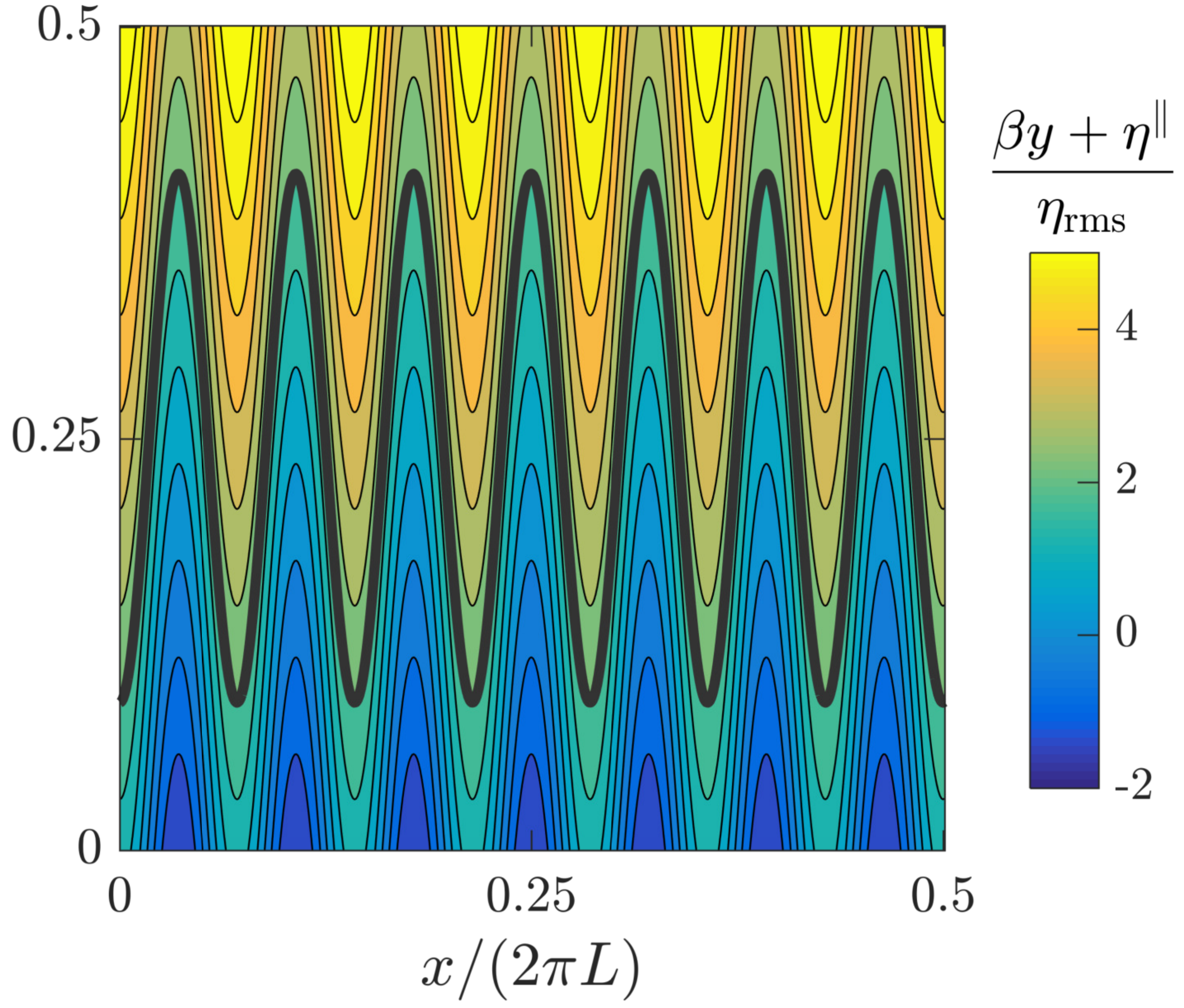
The *main control* parameter for whether eddy saturation occurs is the structure of the geostrophic contours.

$\eta^{\times}$ closed geostrophic contours



most geostrophic contours are **closed**

$\eta^{\parallel}$ open geostrophic contours



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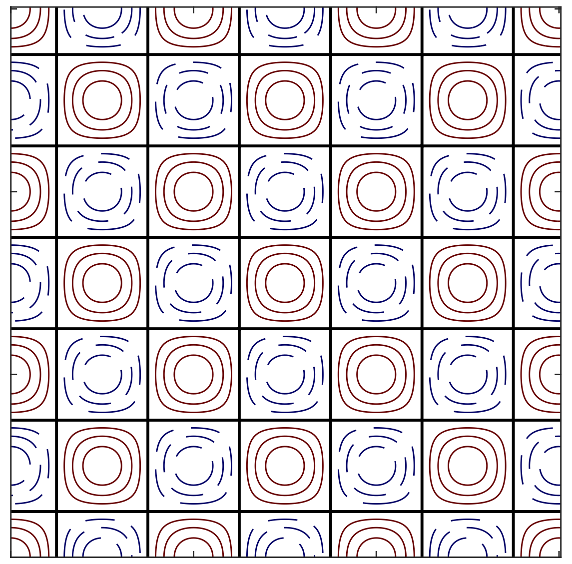

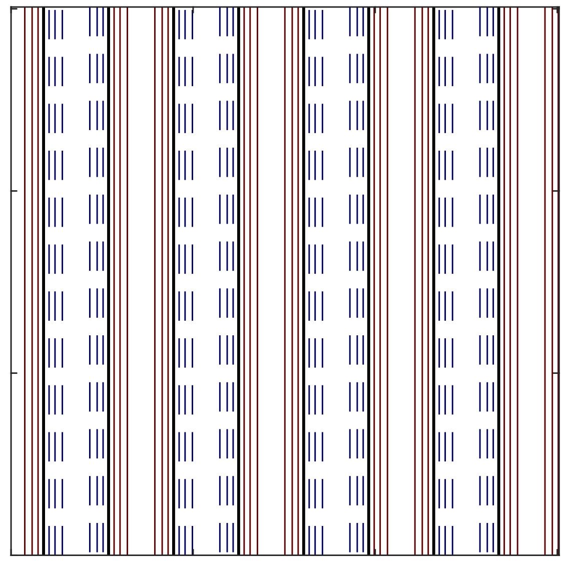

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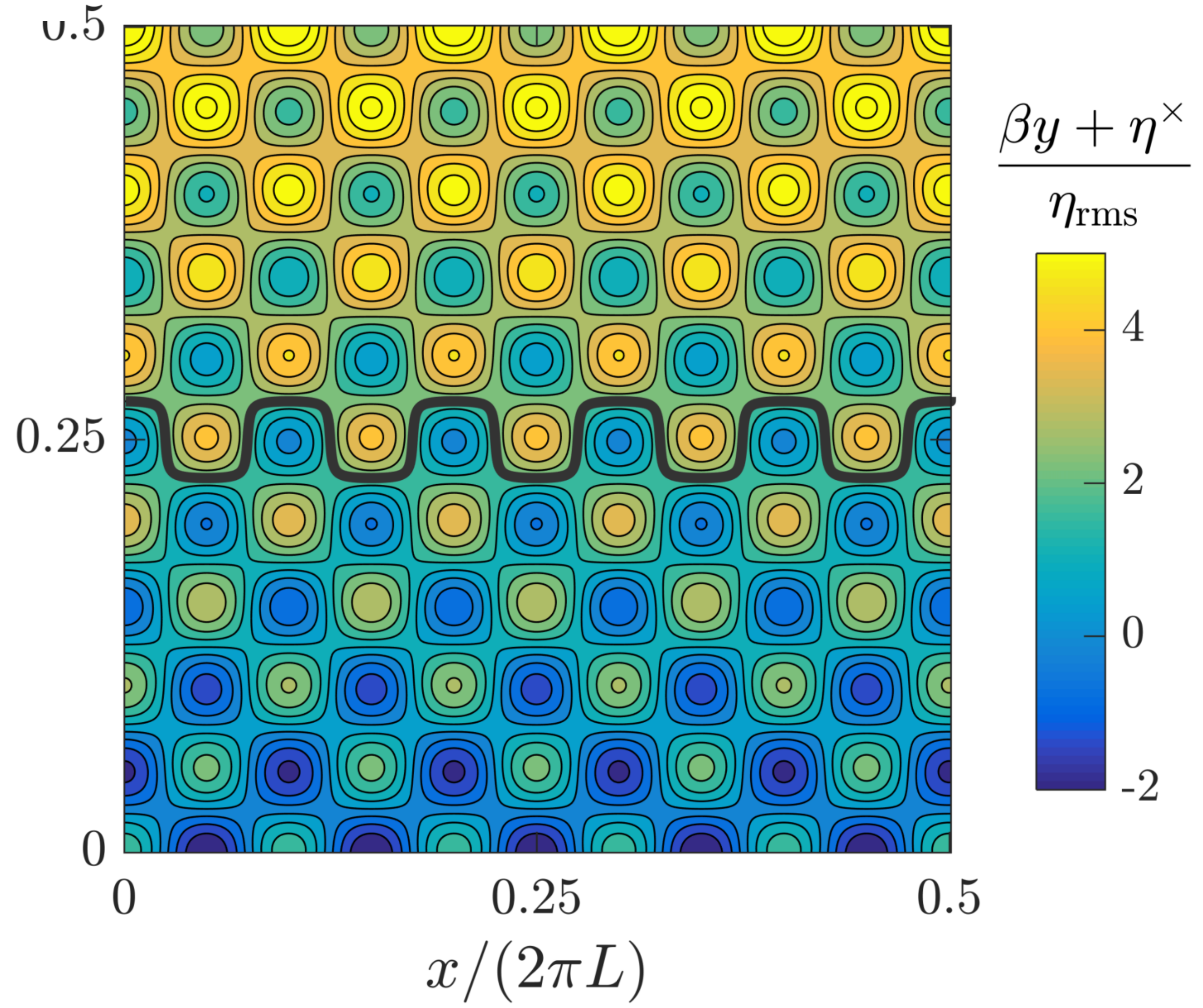

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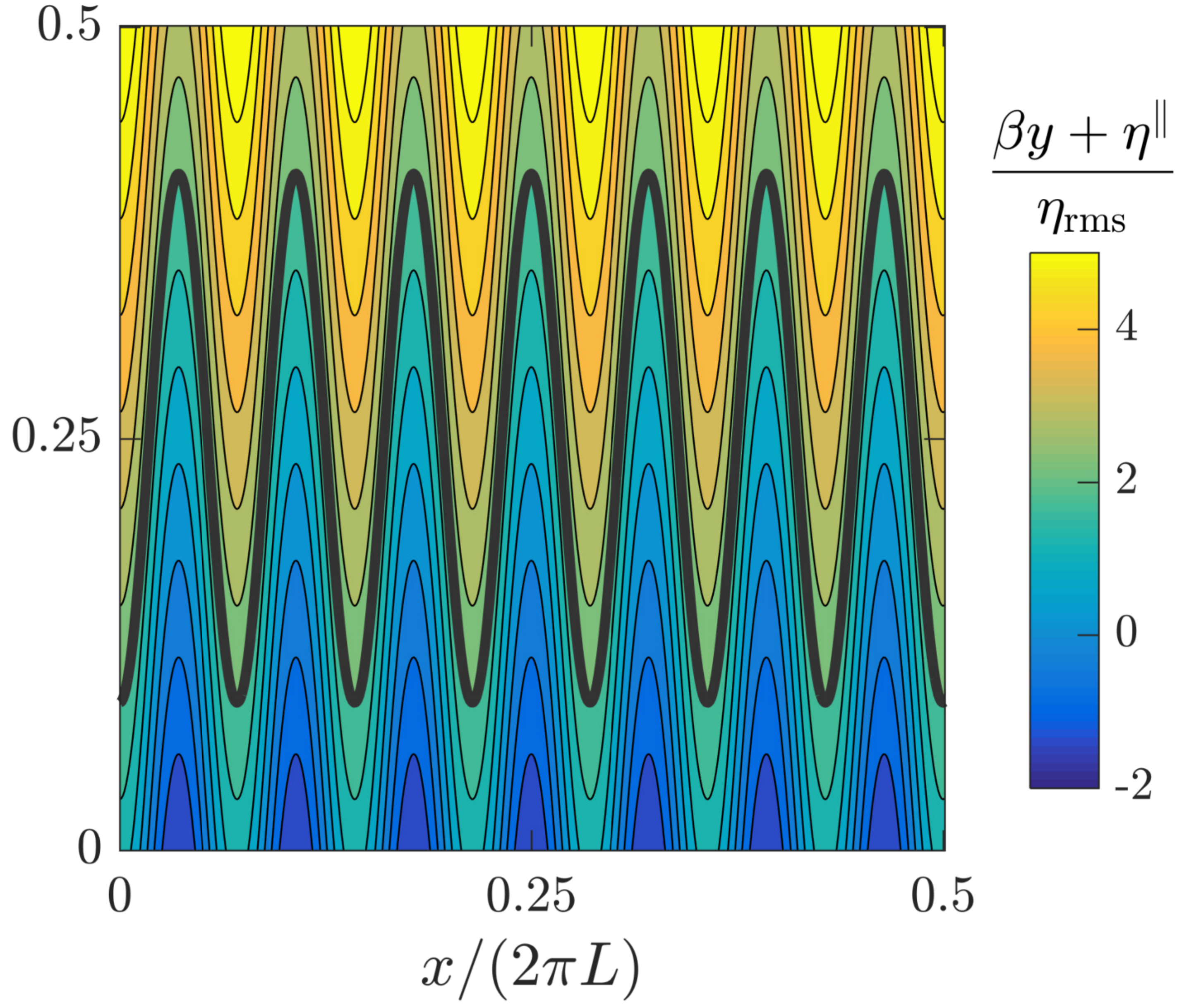


this topography exhibits eddy saturation

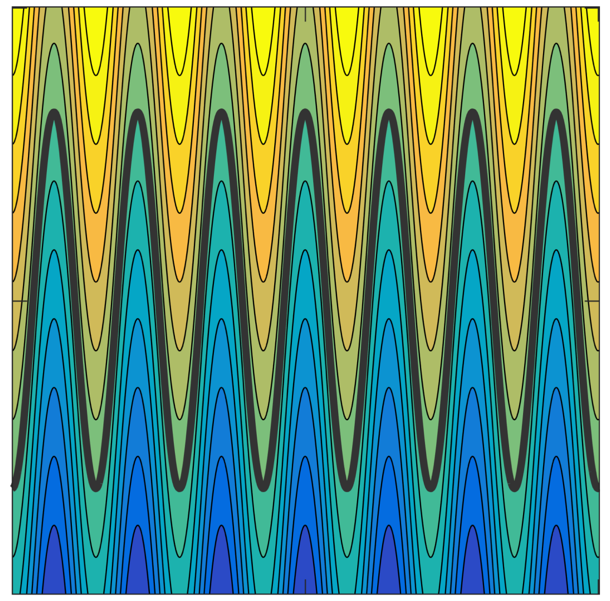
all geostrophic contours are **open**

geostrophic contours $\beta y + \eta(x, y)$

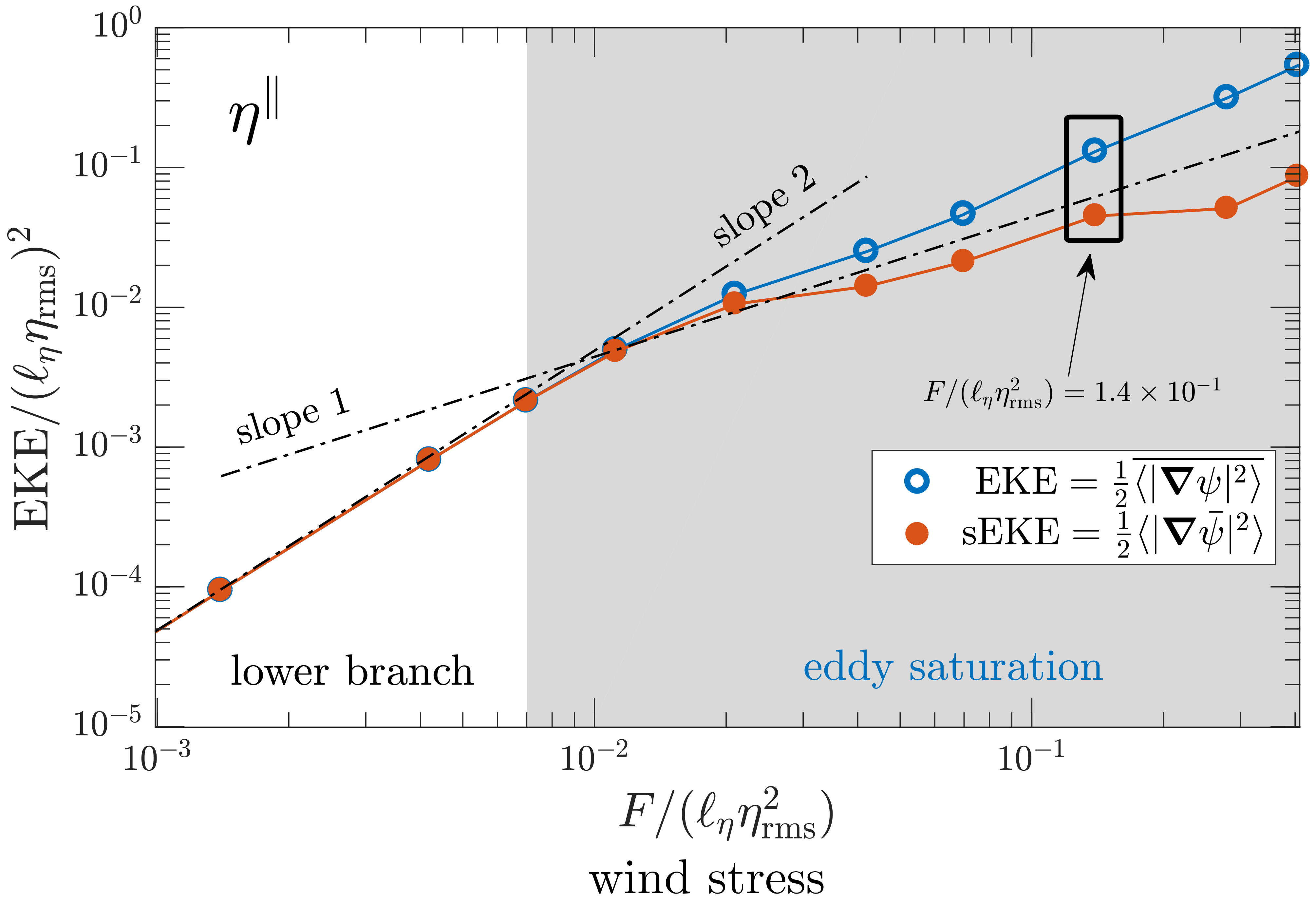
this is small-Rossby number
expansion of $f/(H+h)$

Eddy saturation occurs when
the geostrophic contours are "open",
that is, when the geostrophic contours
span the domain in the zonal direction.

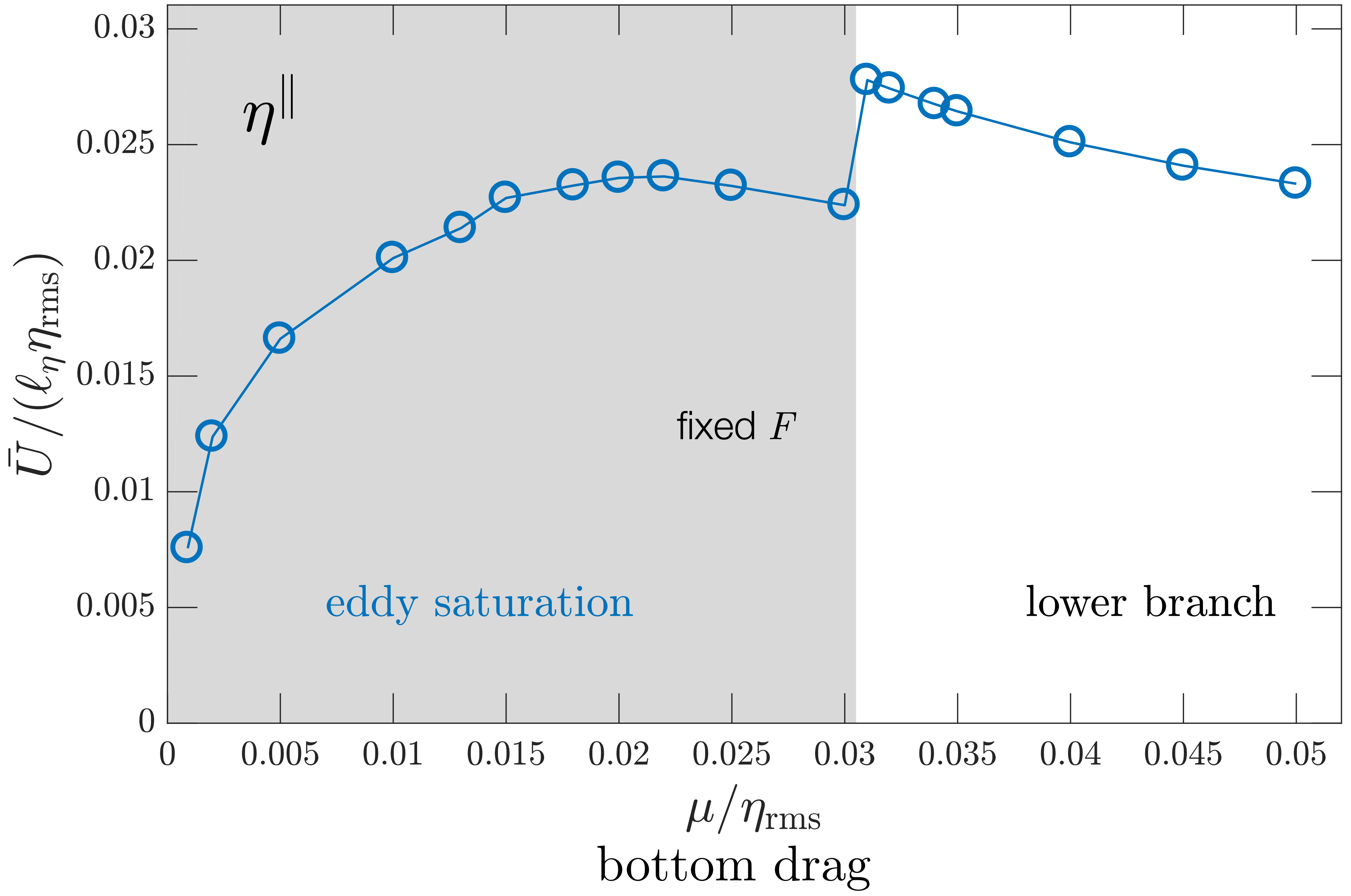
this is a general result
we've seen it in various cases
whatever the topography



further "symptoms" of eddy saturation



EKE grows roughly linearly with wind stress



transport grows with increasing bottom drag

[Hogg & Blundell 2006, Nadeau & Straub 2012, Nadeau & Ferrari 2015, Marshall et al. 2016]

take home messages

Eddy saturation *can* occur *without* baroclinicity!

The barotropic QG model shows eddy saturation
when geostrophic contours are open.
This is surprising! All previous arguments were based on baroclinicity.

This, does not preclude the role of baroclinic processes in the ACC equilibration.
But it *does* argues that barotropic processes do contribute.

We need new process models of baroclinic turbulence in which
the mean flow is wind-driven and topography exerts form stress.

(In progress)

thank you

Constantinou (2017). A barotropic model of eddy saturation. *JPO* (submitted, arXiv:1703.06594)

Constantinou and Young (2017). Beta-plane turbulence above monoscale topography. *JFM* (in revision, arXiv:1612.03374)