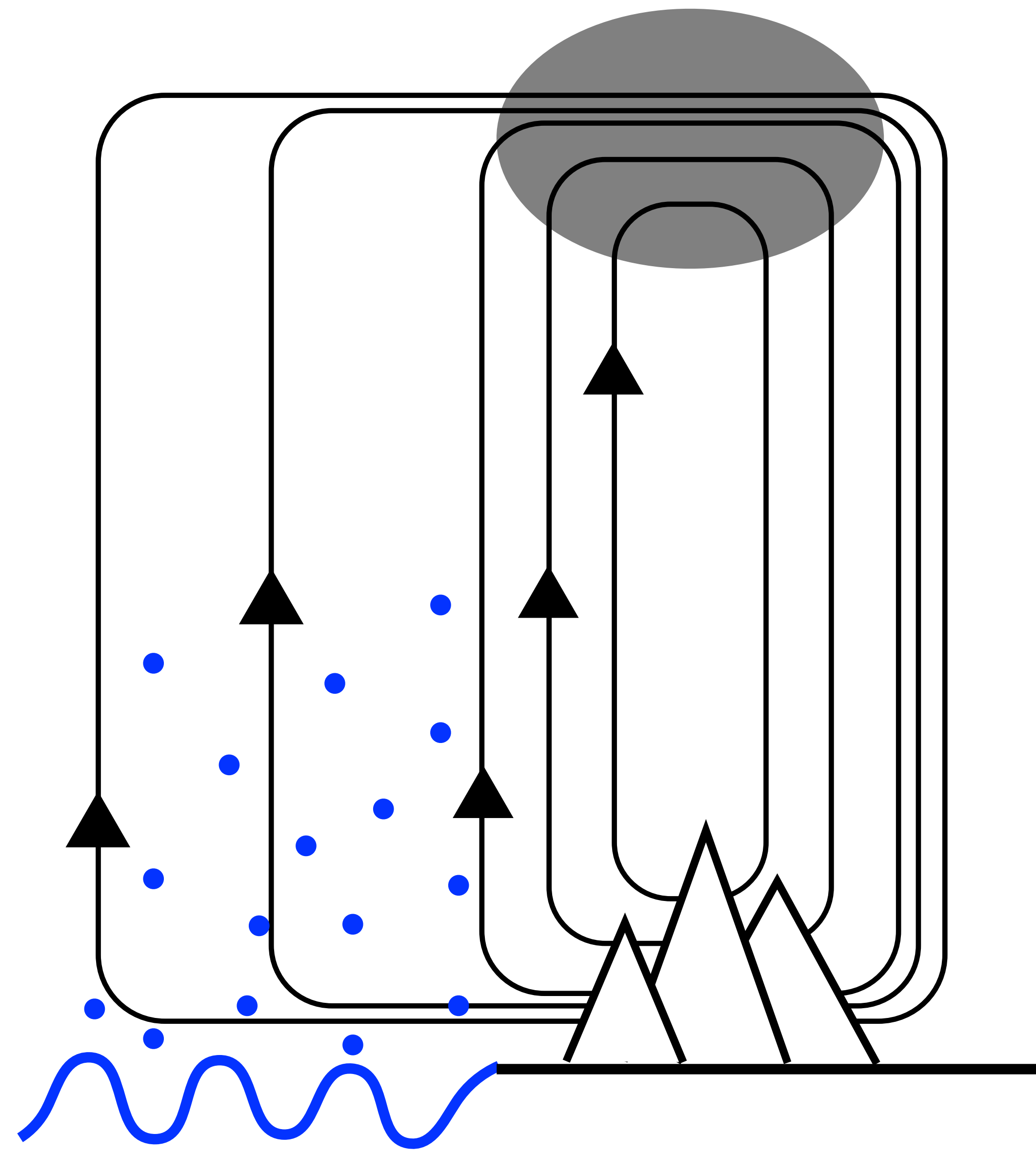
The impact of gravity waves on the large-scale circulation

Naftali Cohen

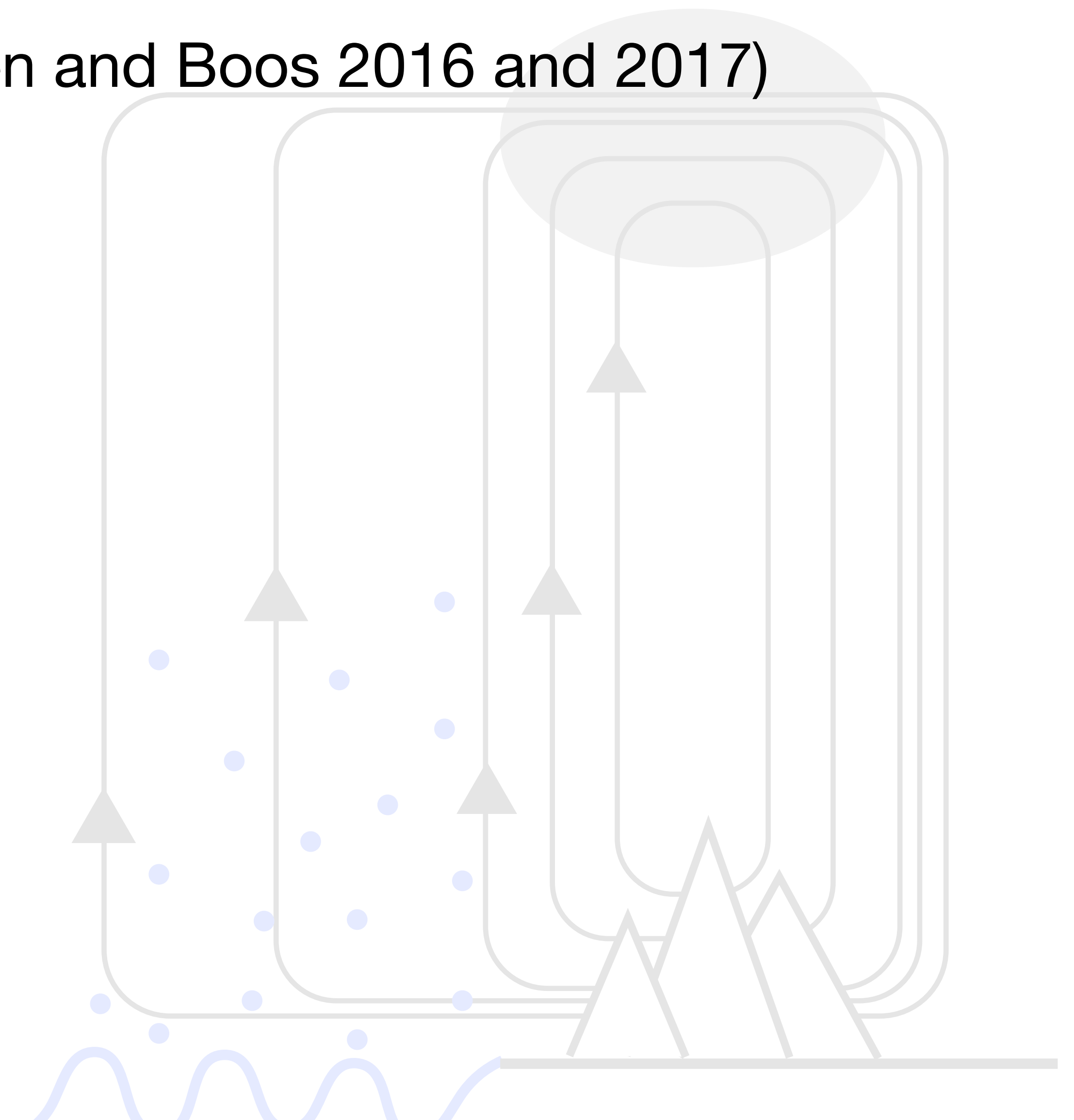
Columbia University

2017 DEEPWAVE Workshop



Outline

- Global-scale: how do gravity waves interact with the stratospheric zonal-mean flow? (Cohen, Gerber and Buhler 2013 and 2014)
- Regional scale: how do gravity waves interact with the large-scale precipitation field? (Cohen and Boos 2016 and 2017)



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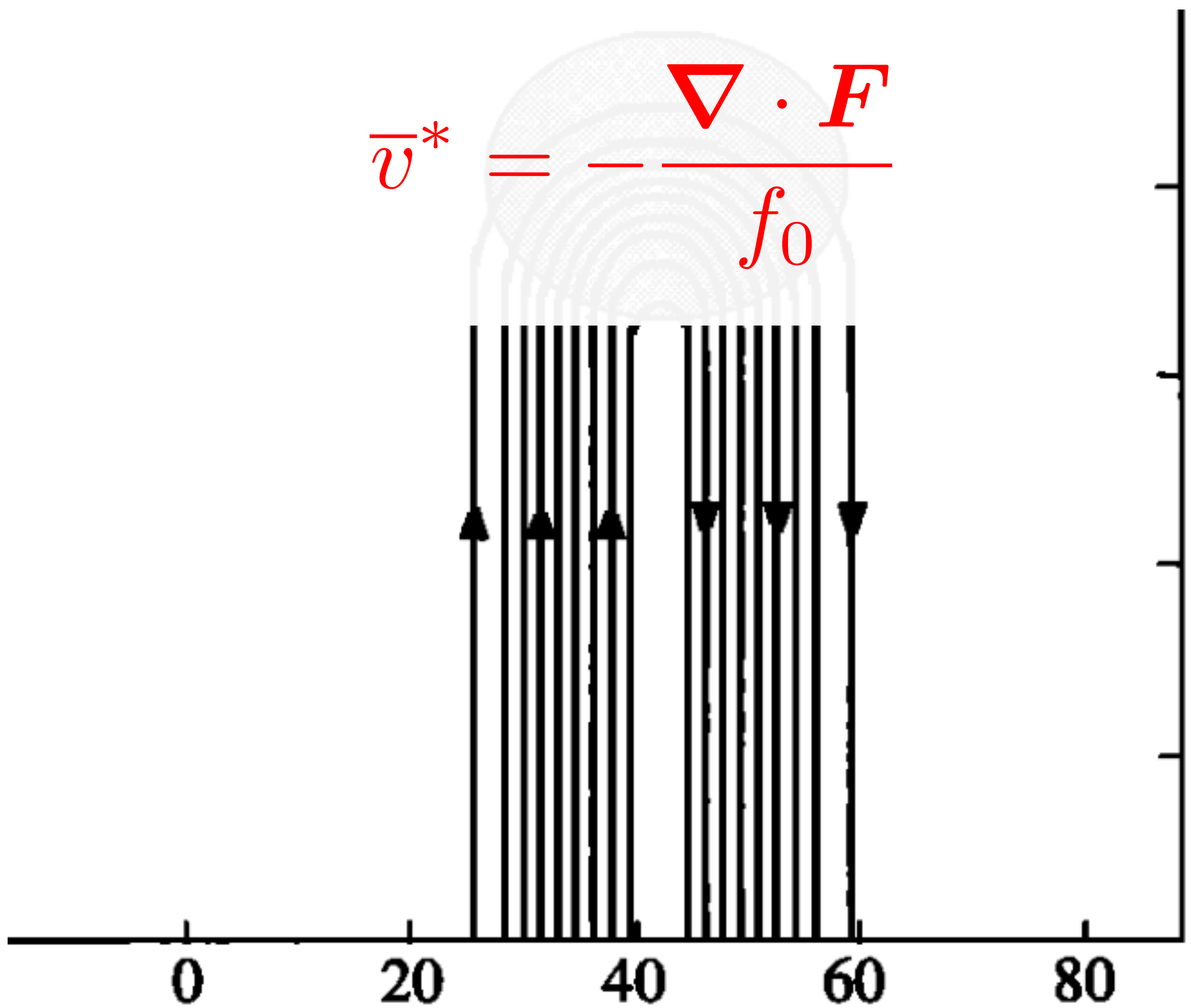
Two approaches to investigate the BDC dynamics

wave forcing
(downward control)

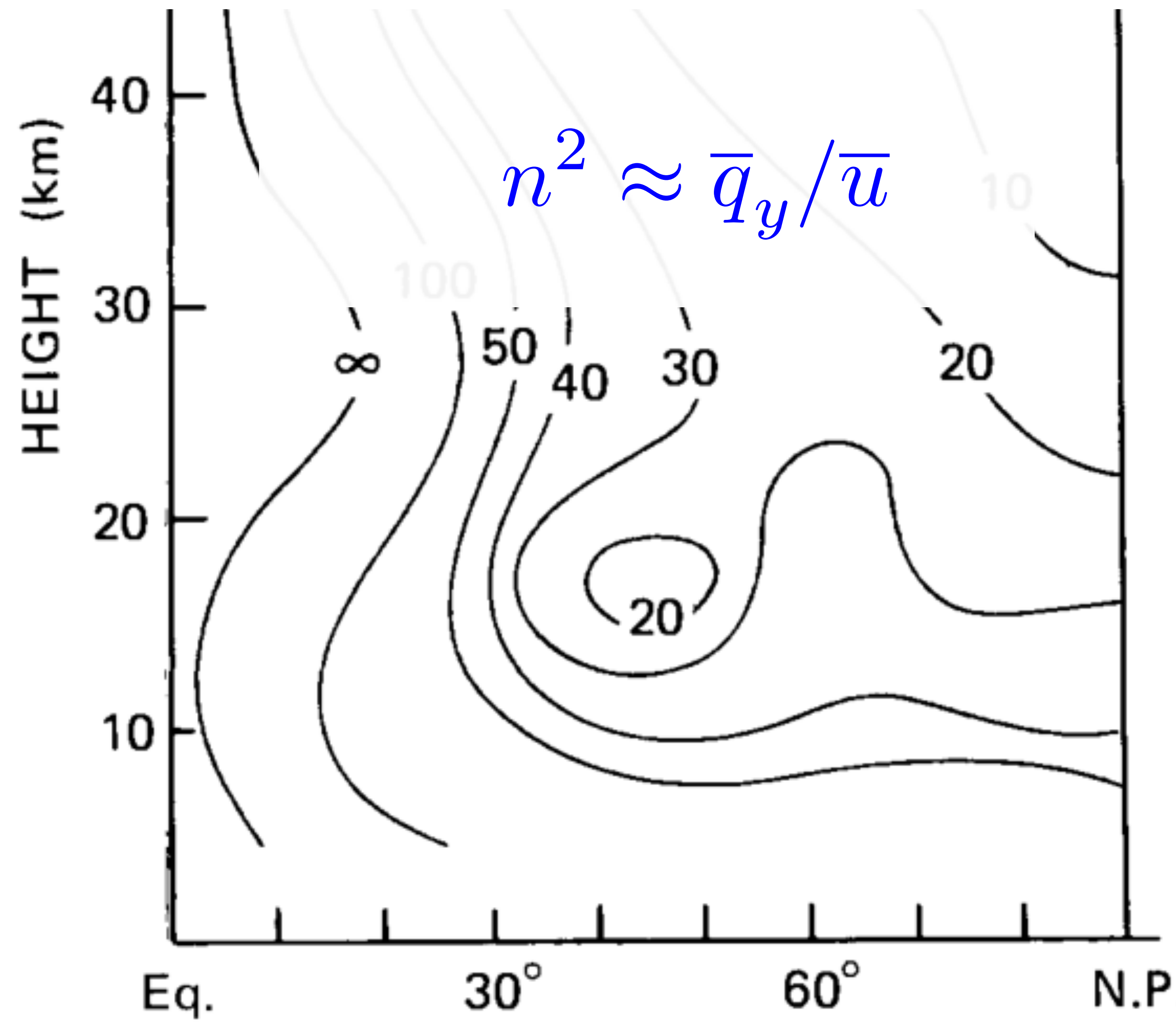
$$\overline{v}^* = -\frac{\boldsymbol{\nabla} \cdot \boldsymbol{F}}{f_0}$$



Eliassen and Palm 1961
Andrews and McIntyre 1976
Haynes el al 1991

mean flow
(refractive index)

$$n^2 \approx \overline{q}_y / \overline{u}$$



Charney and Drazin 1961
Matsuno 1970
Karoly and Hoskins 1982

Two approaches to investigate the BDC dynamics

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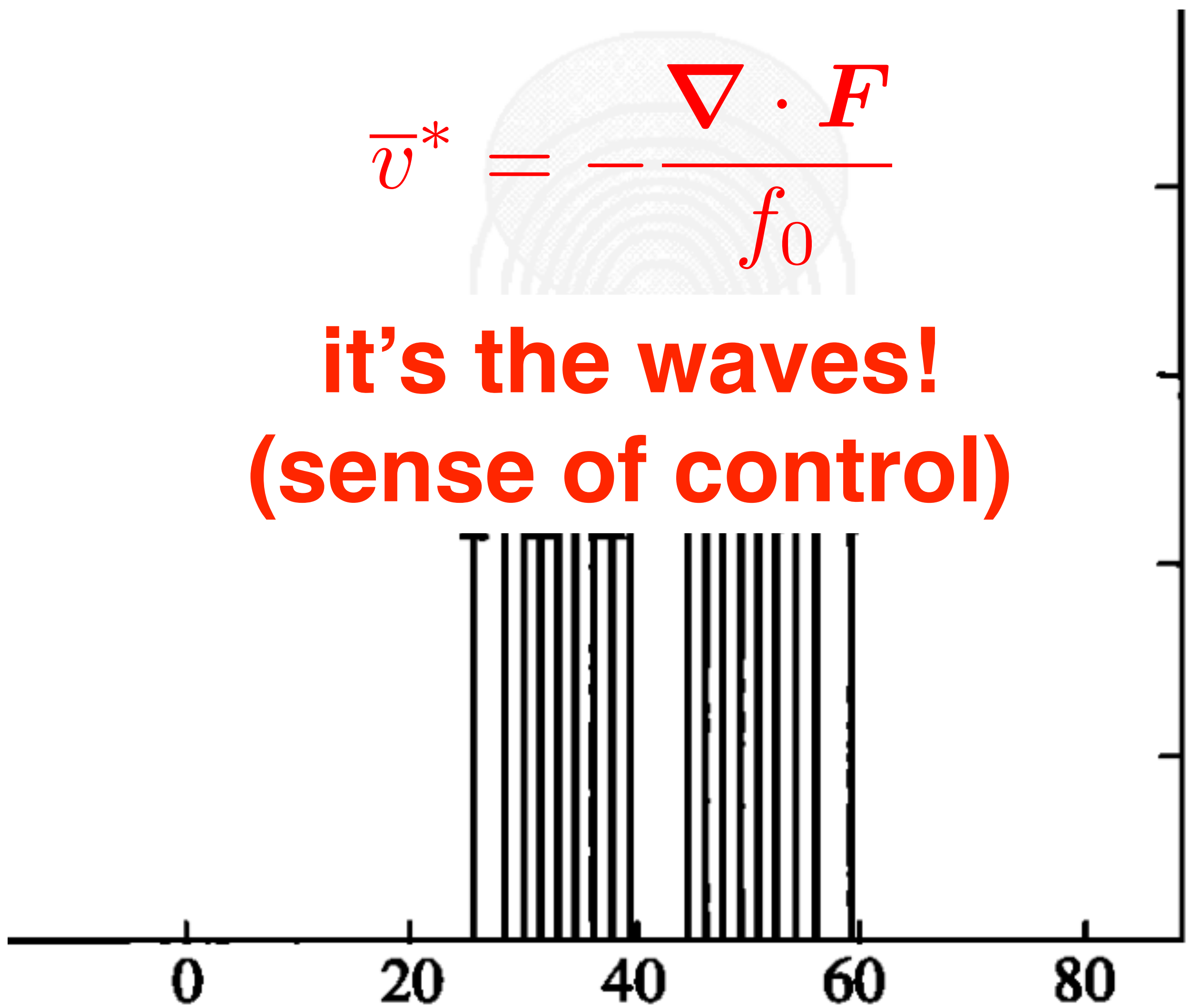
$$\overline{v}^* = -\frac{\boldsymbol{\nabla} \cdot \boldsymbol{F}}{f_0}$$

it's the waves!
(sense of control)



Eliassen and Palm 1961
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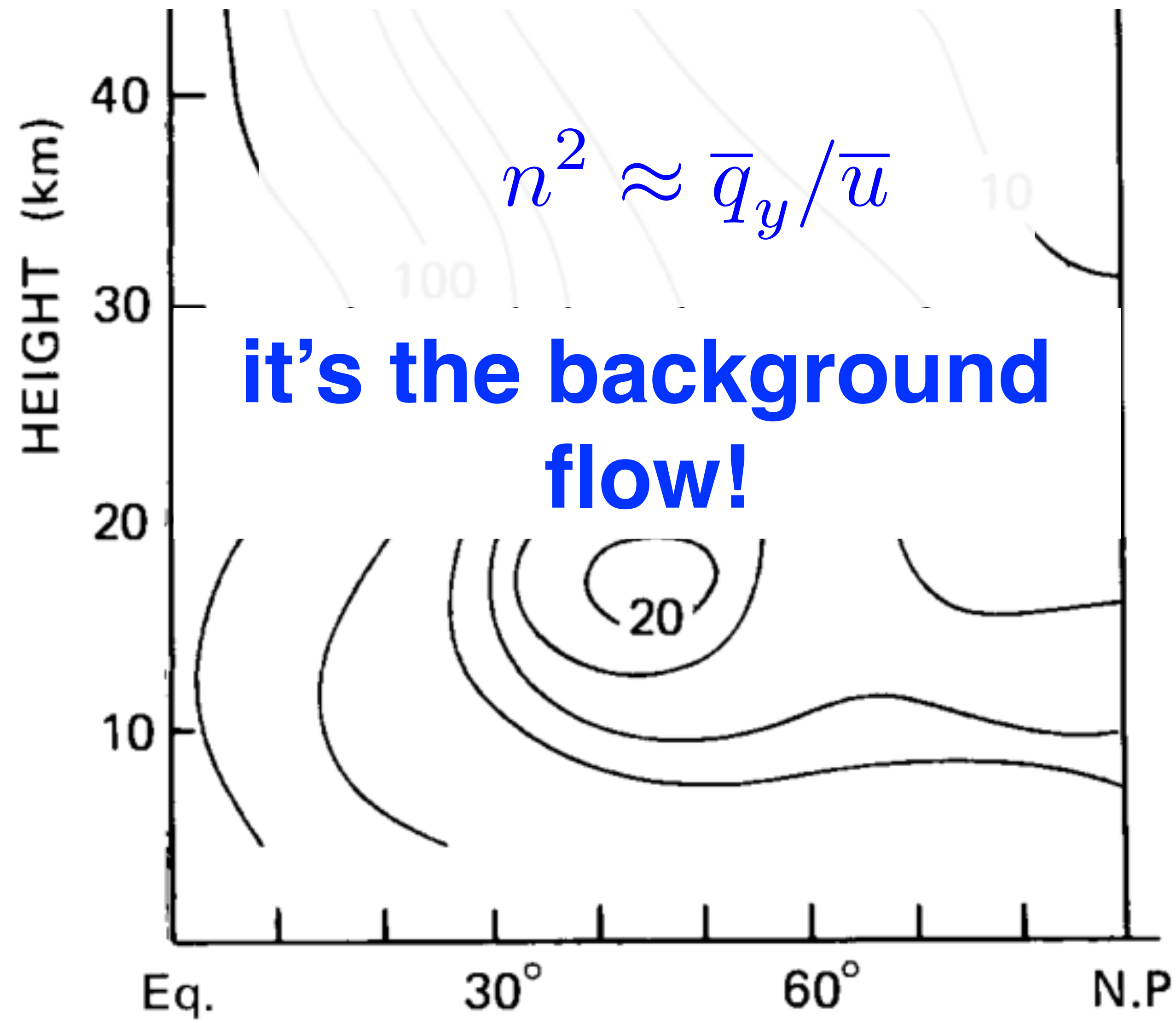
mean flow
(refractive index)

$$n^2 \approx \overline{q}_y / \overline{u}$$

it's the background flow!



Charney and Drazin 1961
Matsuno 1970
Karoly and Hoskins 1982

Two approaches to investigate the BDC dynamics

It's a coupled system!

downward control

$$-f_0\overline{v}^* = \nabla \cdot \mathbf{F}$$

$$\overline{v}^*_y + \overline{\omega}^*_p = 0$$

$$\overline{\omega}^*\overline{\theta}_p + \frac{\overline{\theta} - \theta_r}{\tau_r} = 0$$

$$f_0\overline{u}_p - \frac{p^{\kappa-1}R\overline{\theta}_y}{p_0^{\kappa}} = 0$$

refractive index

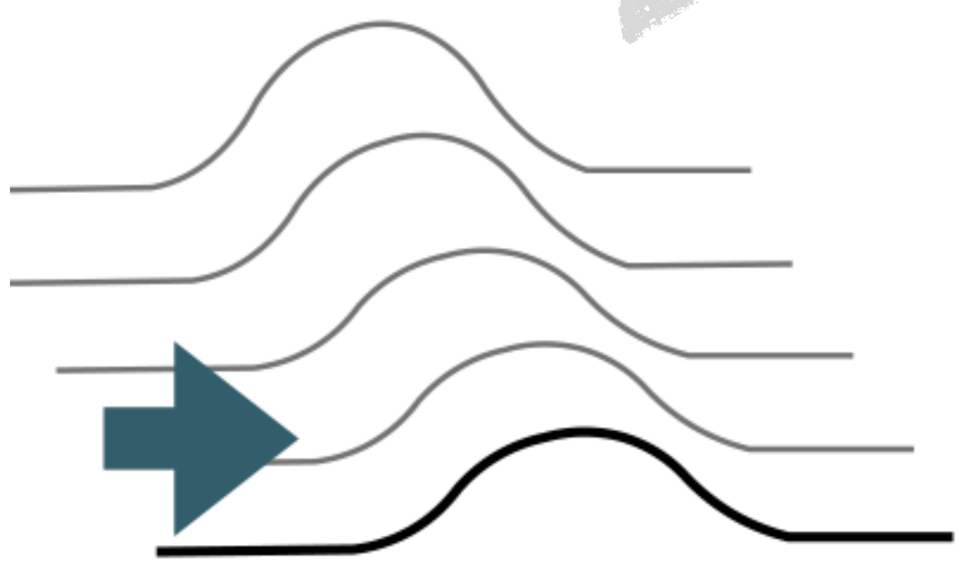
(unresolved) gravity waves are important too!

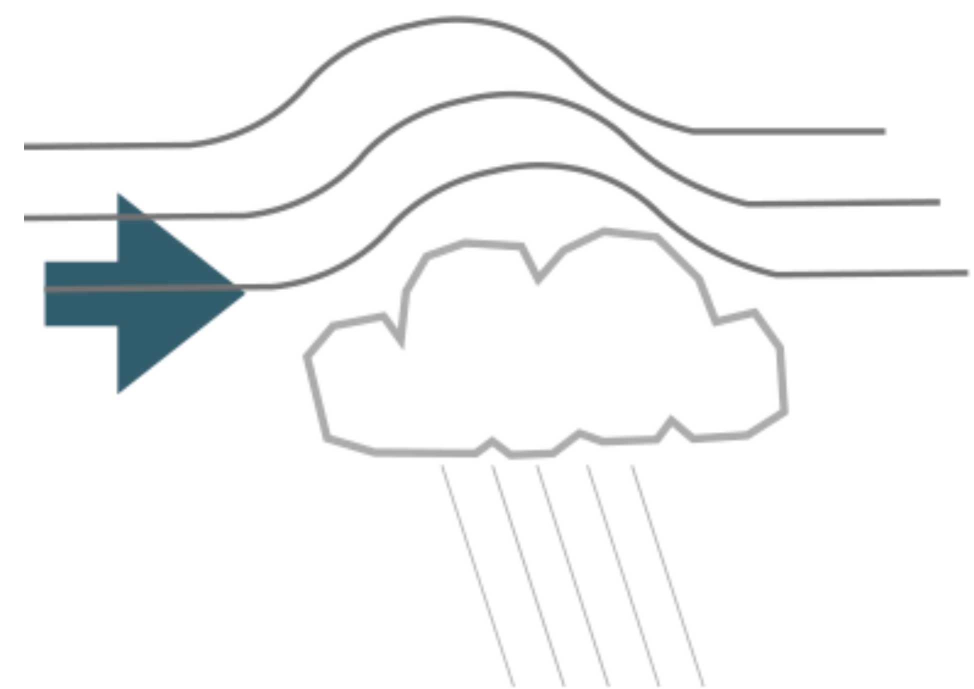
Rossby Waves (resolved)

Orographic Gravity Waves (parameterized)

Non-orographic Gravity Waves (parameterized)

$$\overline{v}^* = -\frac{\boldsymbol{\nabla} \cdot \boldsymbol{F} + \overline{X}_{OGW} + \overline{X}_{NOGW}}{f_0}$$





Standard practice: linearly additive downward control

Rossby Waves (resolved)

Orographic Gravity Waves (parameterized)

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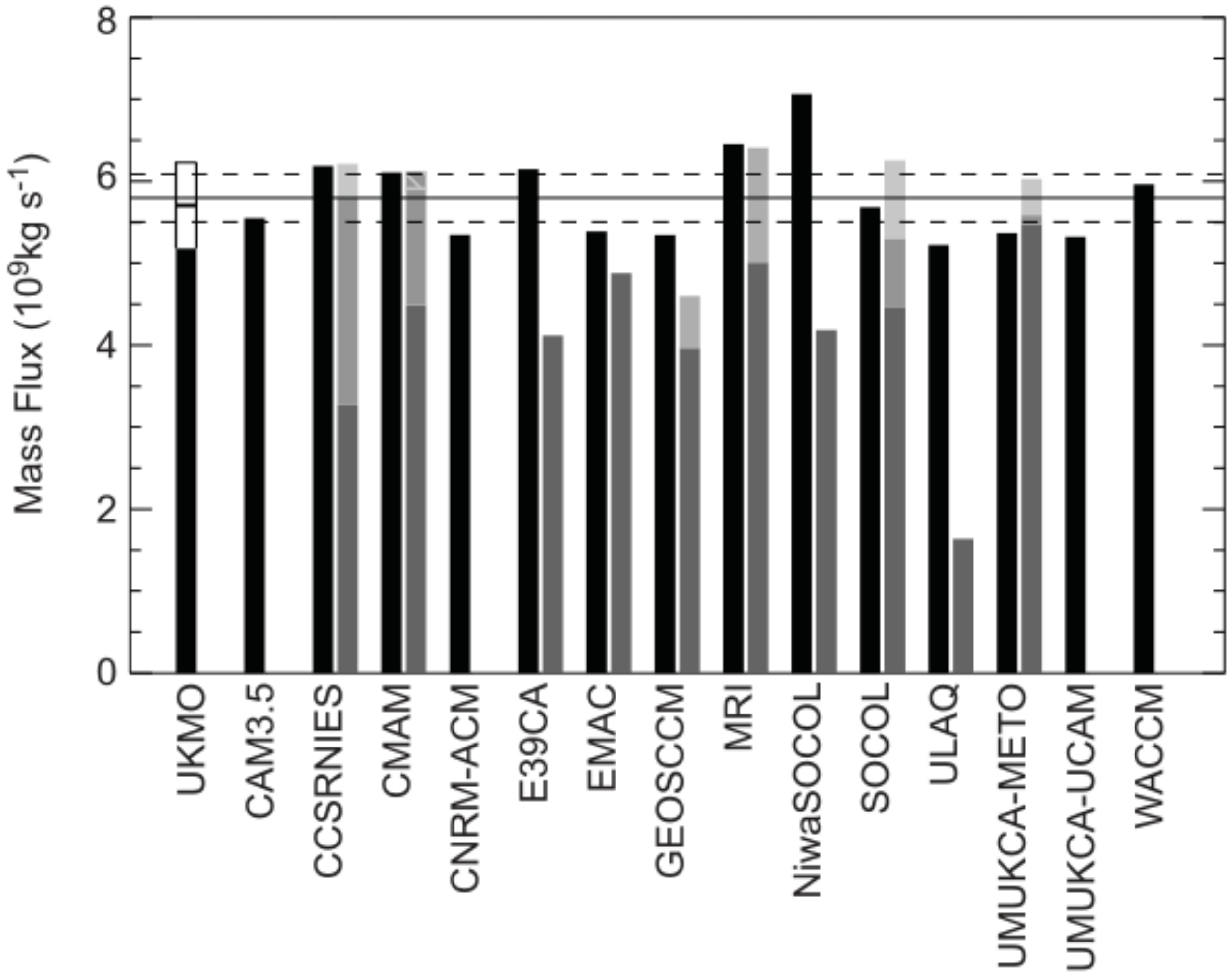
$$\overline{v}^* = -\frac{\boldsymbol{\nabla} \cdot \boldsymbol{F} + \overline{X}_{OGW} + \overline{X}_{NOGW}}{f_0}$$

$$\overline{v}^*_{RW} + \overline{v}^*_{OGW} + \overline{v}^*_{NOGW} = -\frac{\boldsymbol{\nabla} \cdot \boldsymbol{F} + \overline{X}_{OGW} + \overline{X}_{NOGW}}{f_0}$$

Standard practice: linearly additive downward control

Current climate, CCMVal2 report



total

Rossby waves

orographic GW

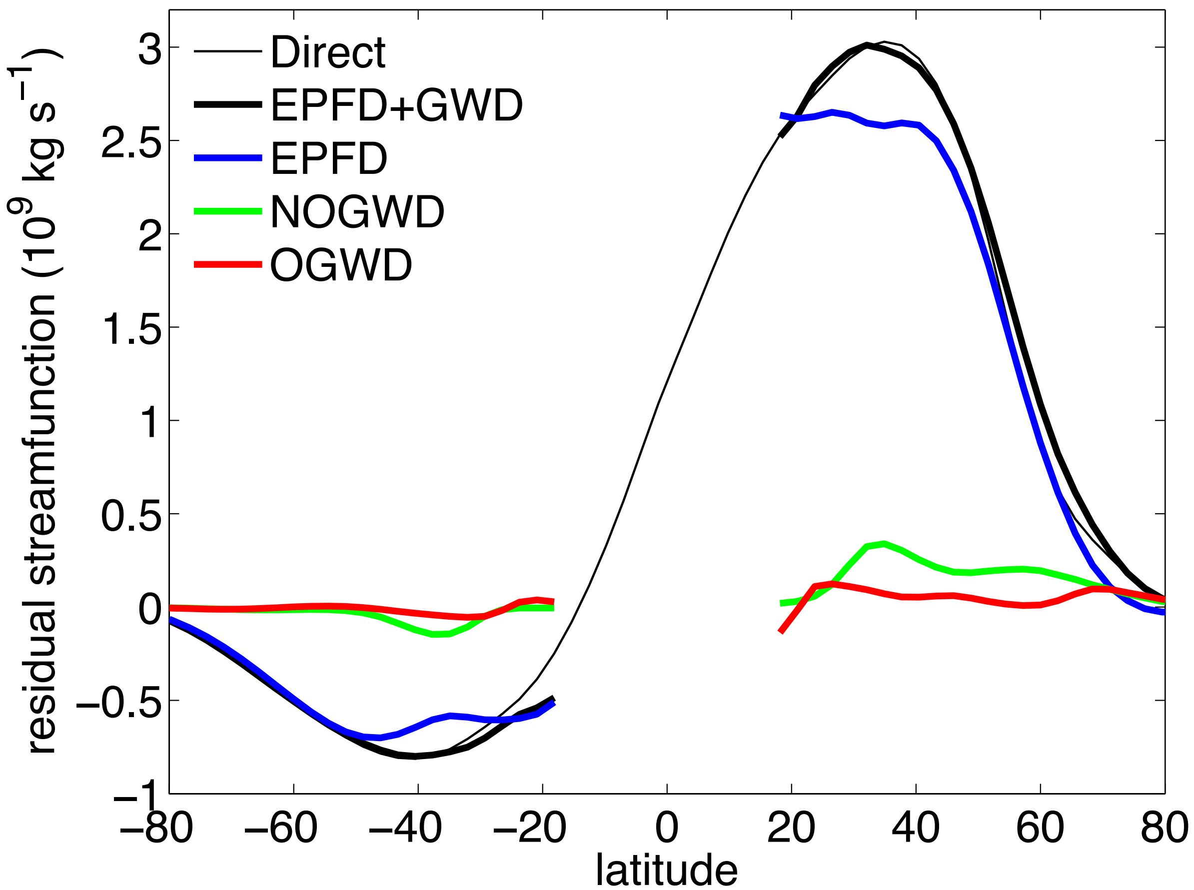
non-orographic GW

70hPa

$$\overline{v}^*_{RW} + \overline{v}^*_{OGW} + \overline{v}^*_{NOGW} = -\frac{\boldsymbol{\nabla} \cdot \boldsymbol{F} + \overline{X}_{OGW} + \overline{X}_{NOGW}}{f_0}$$

The illusion of (downward) control

model A



$$\overline{v}^*_{RW} + \overline{v}^*_{OGW} + \overline{v}^*_{NOGW} = -\frac{\boldsymbol{\nabla} \cdot \boldsymbol{F} + \overline{X}_{OGW} + \overline{X}_{NOGW}}{f_0}$$

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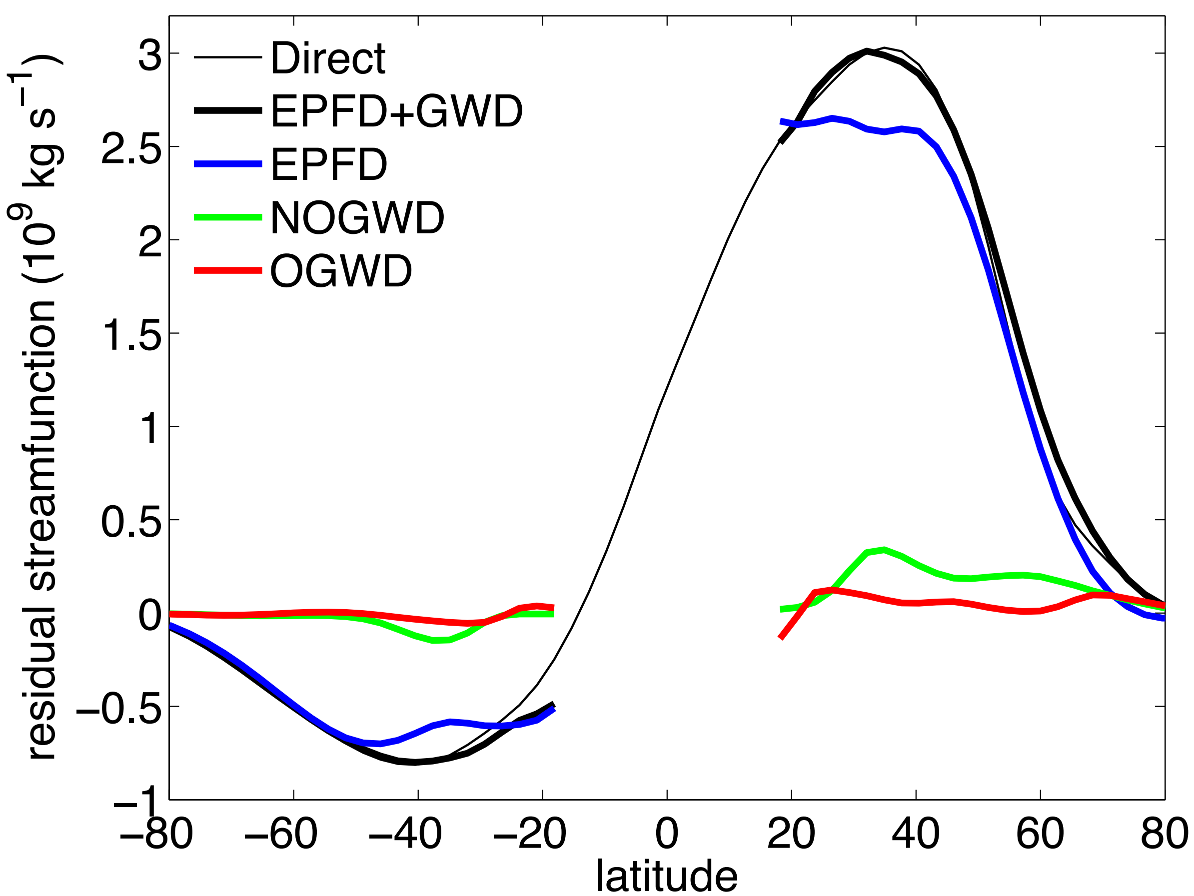
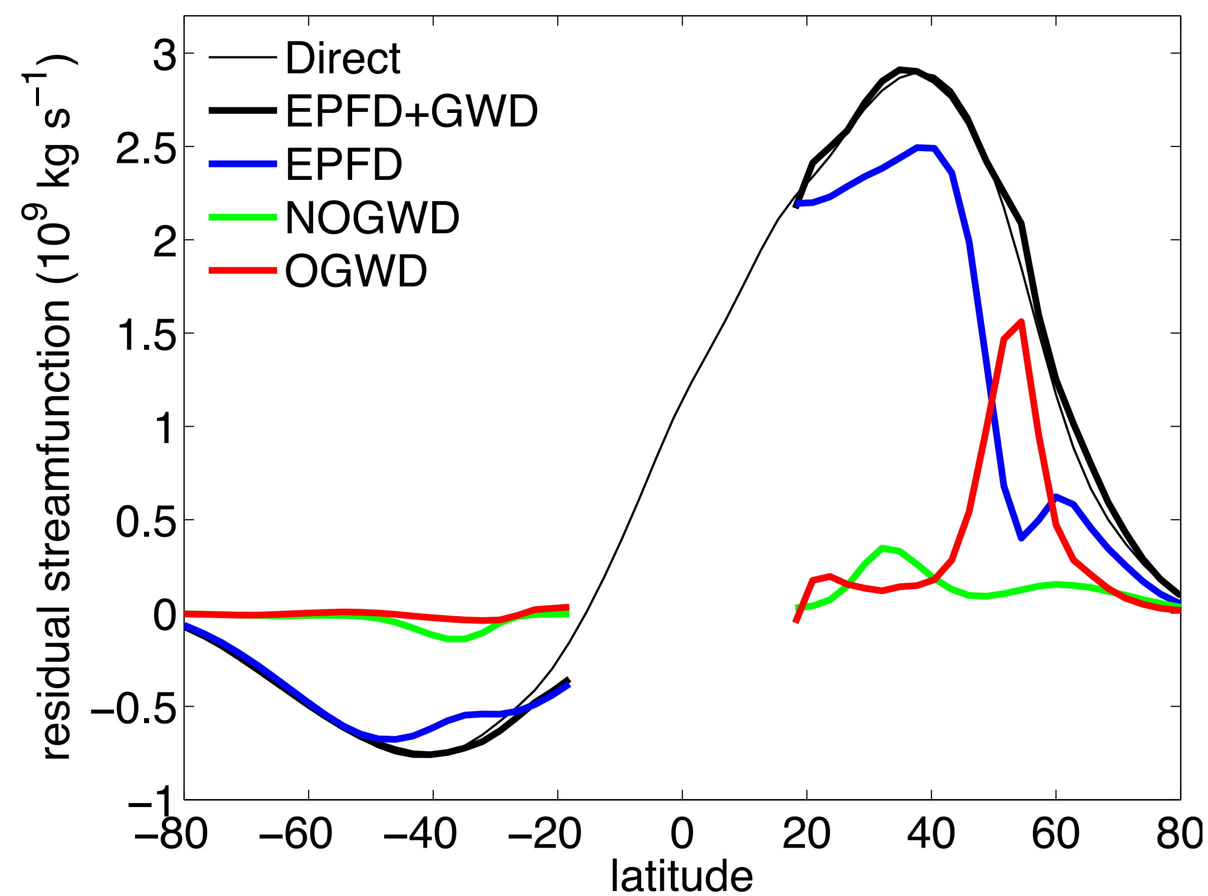


model B

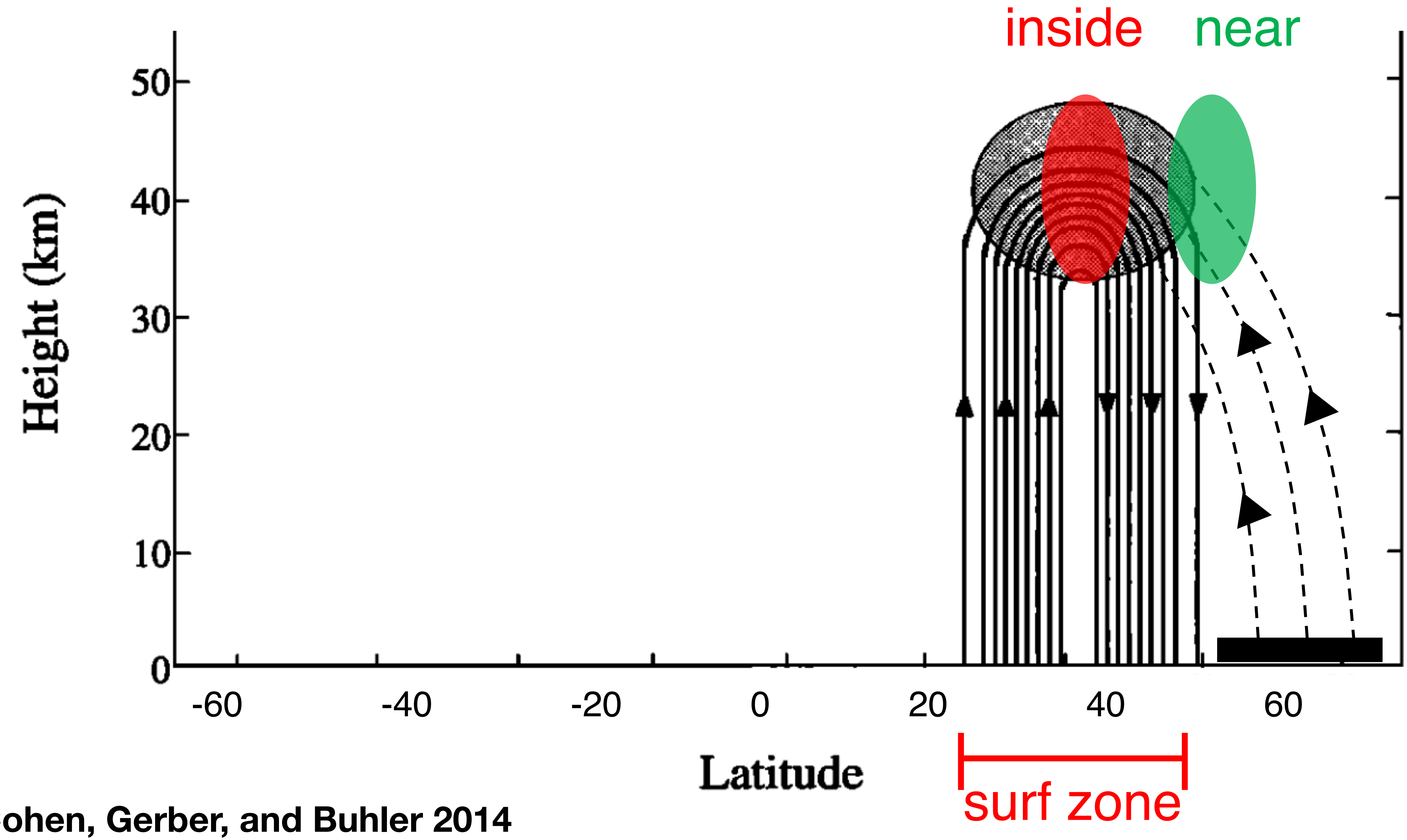


$$\overline{v}^*_{RW} + \overline{v}^*_{OGW} + \overline{v}^*_{NOGW} = -\frac{\nabla \cdot \boldsymbol{F} + \overline{X}_{OGW} + \overline{X}_{NOGW}}{f_0}$$

?

Cohen, Gerber, and Buhler 2013

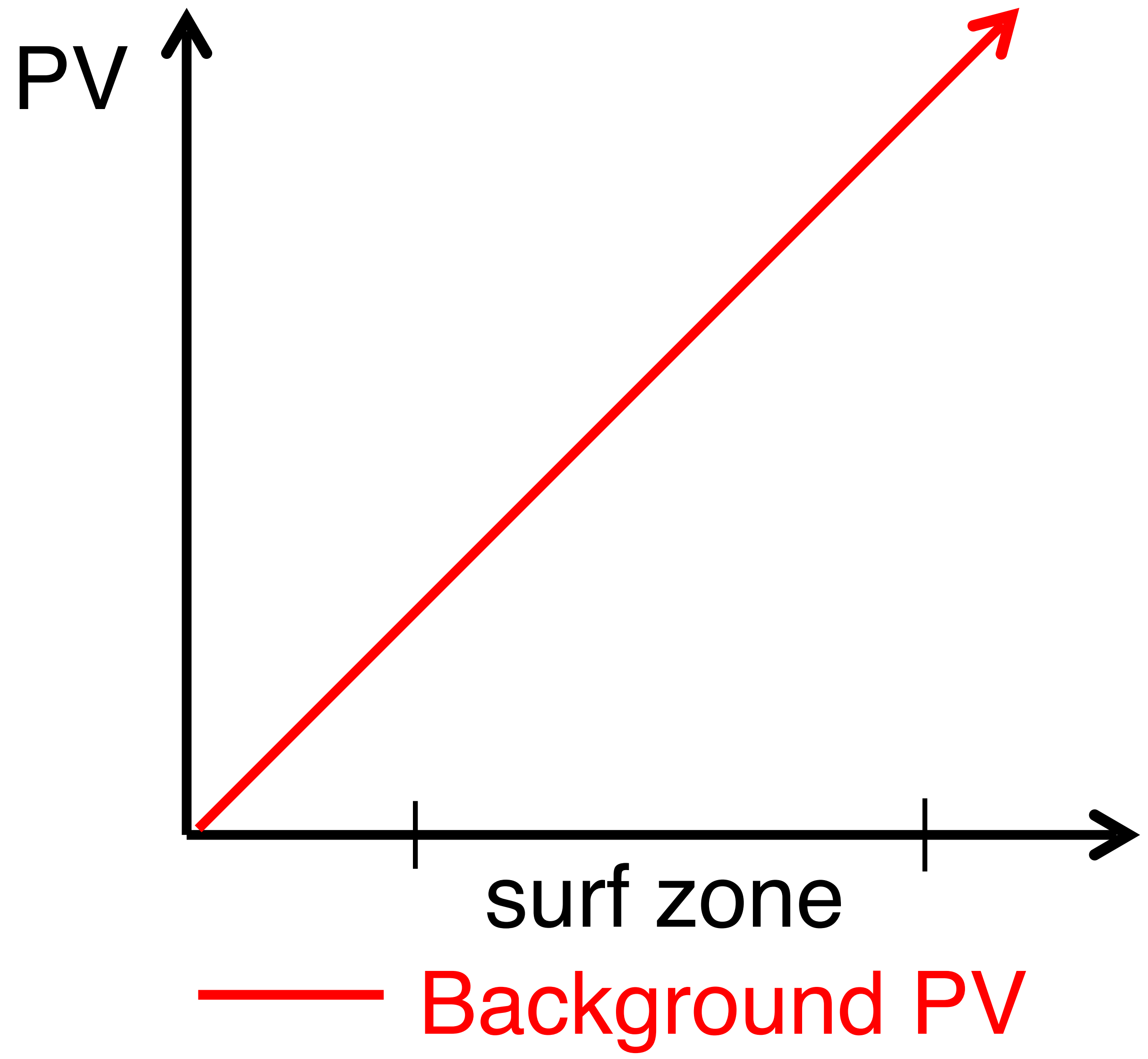
Two key regions: inside and near

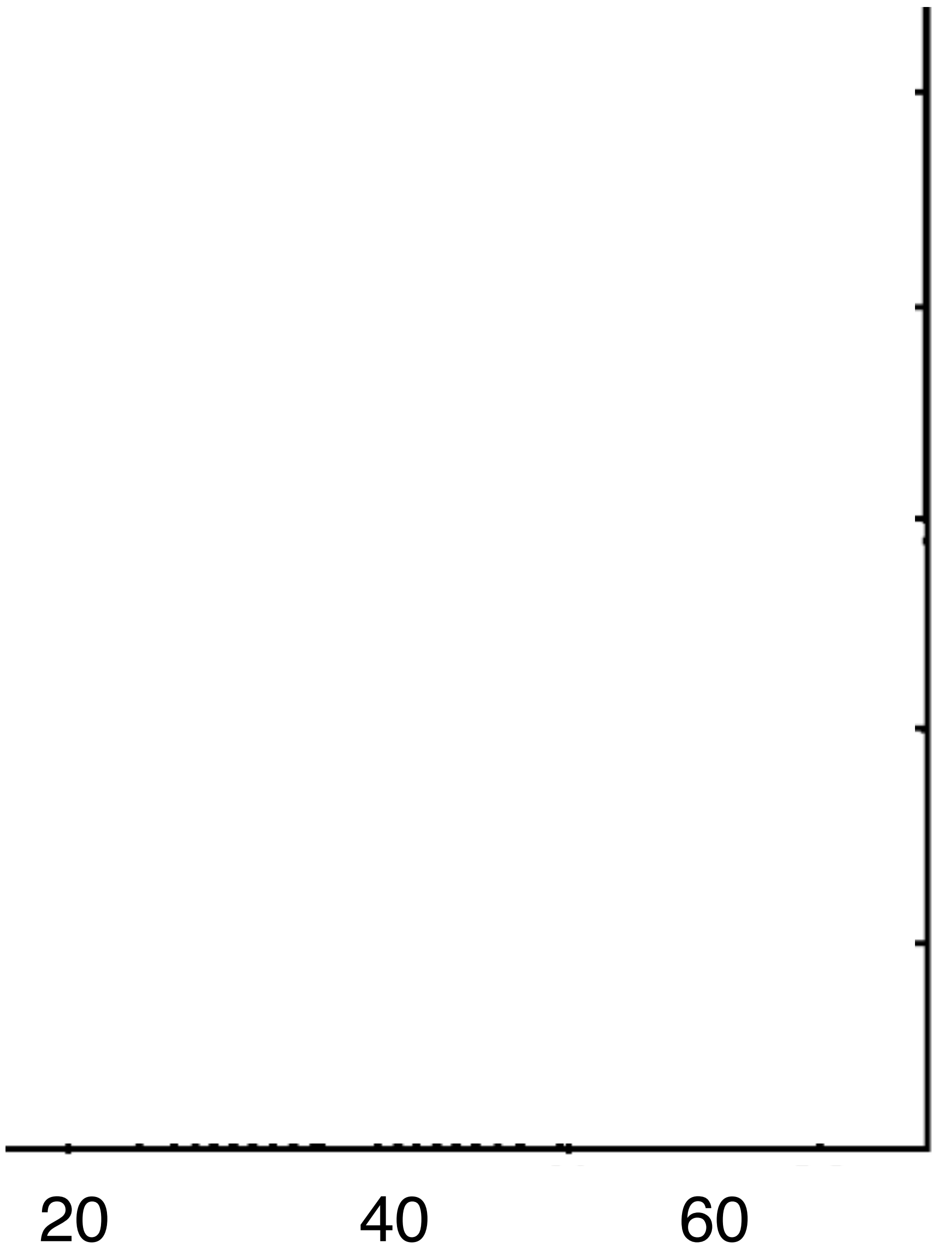


Cohen, Gerber, and Buhler 2014

Surf-zone interactions

1D PV Staircase model





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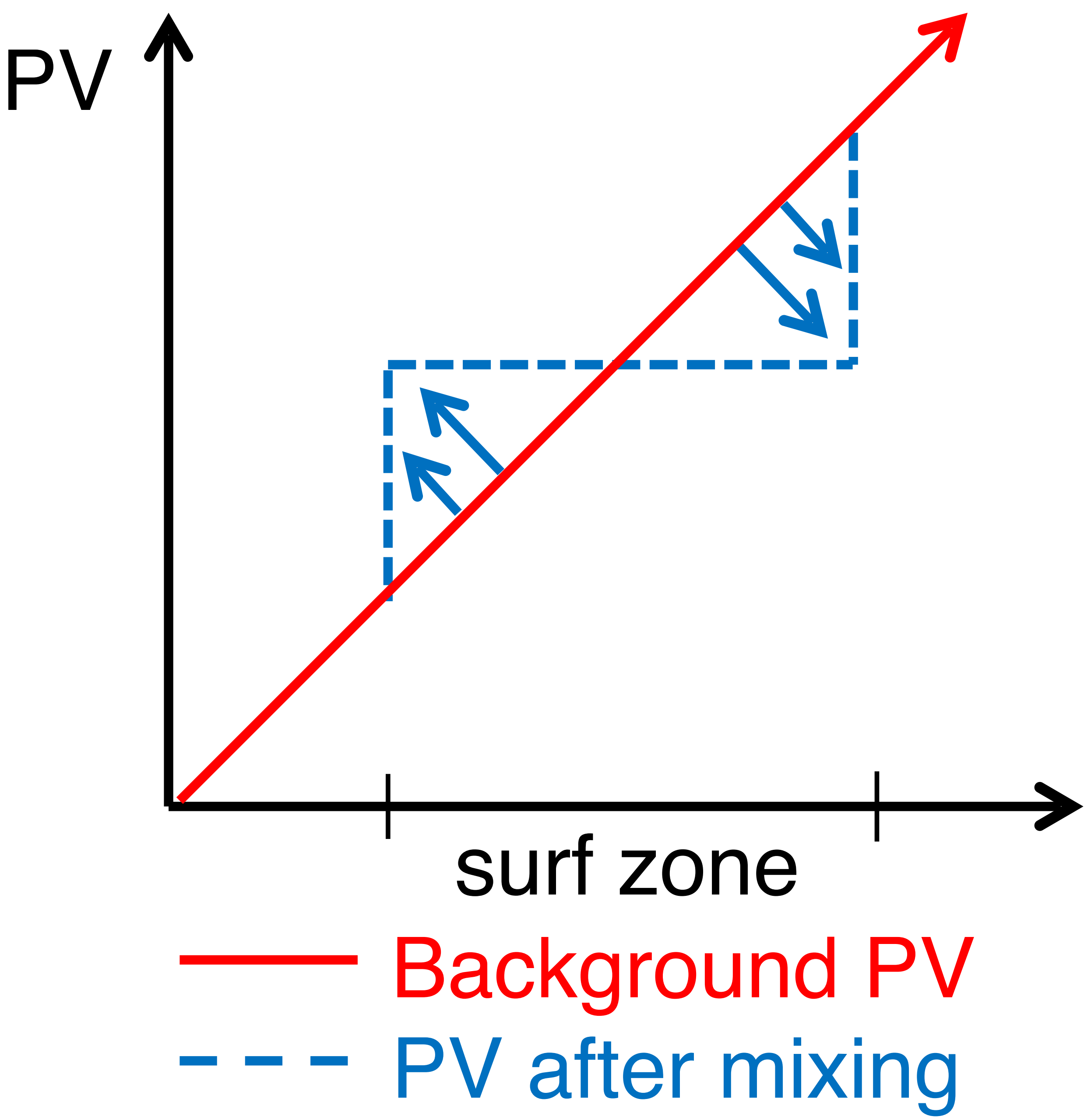
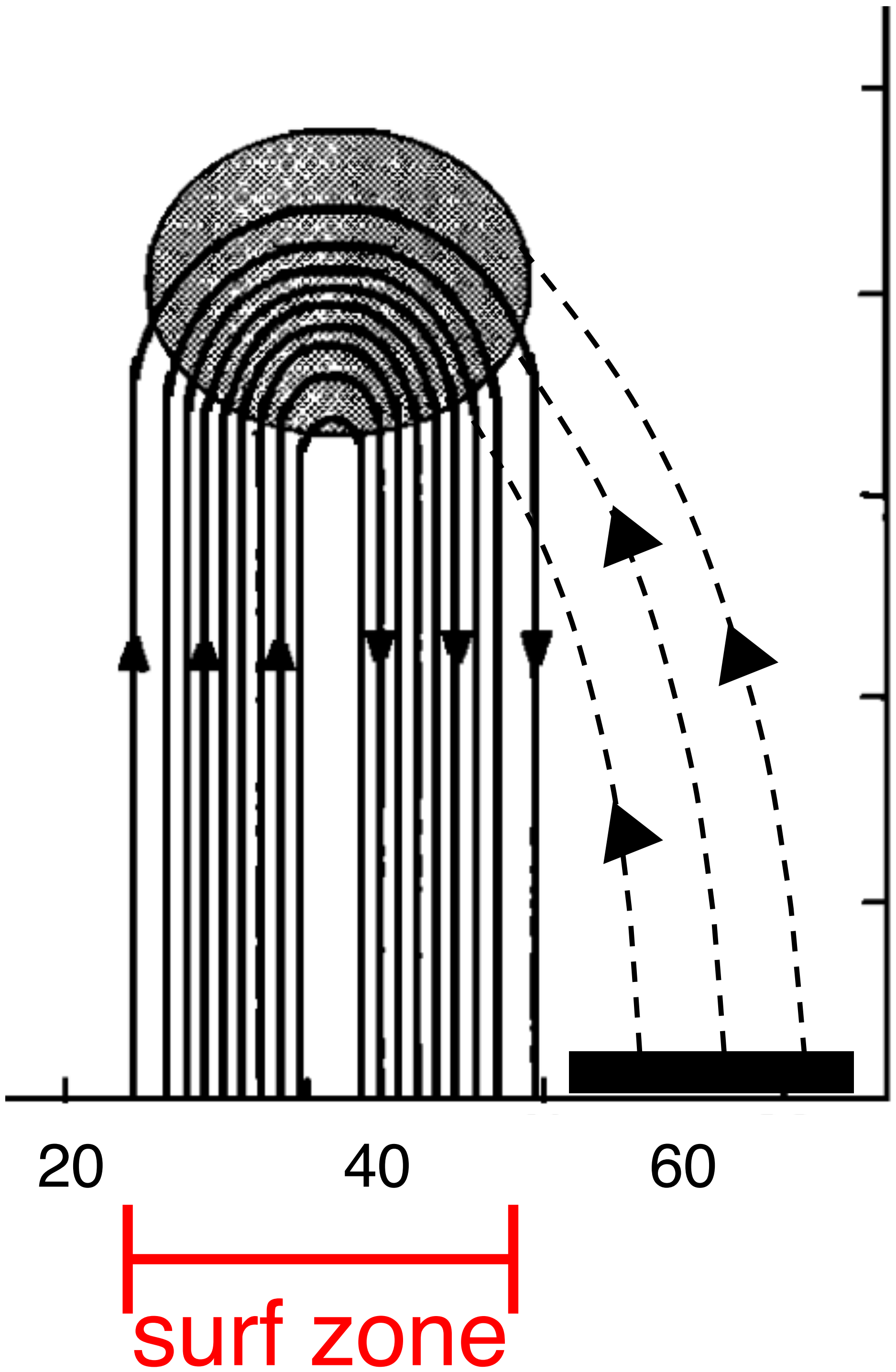


$\bar{q}_y = 0$



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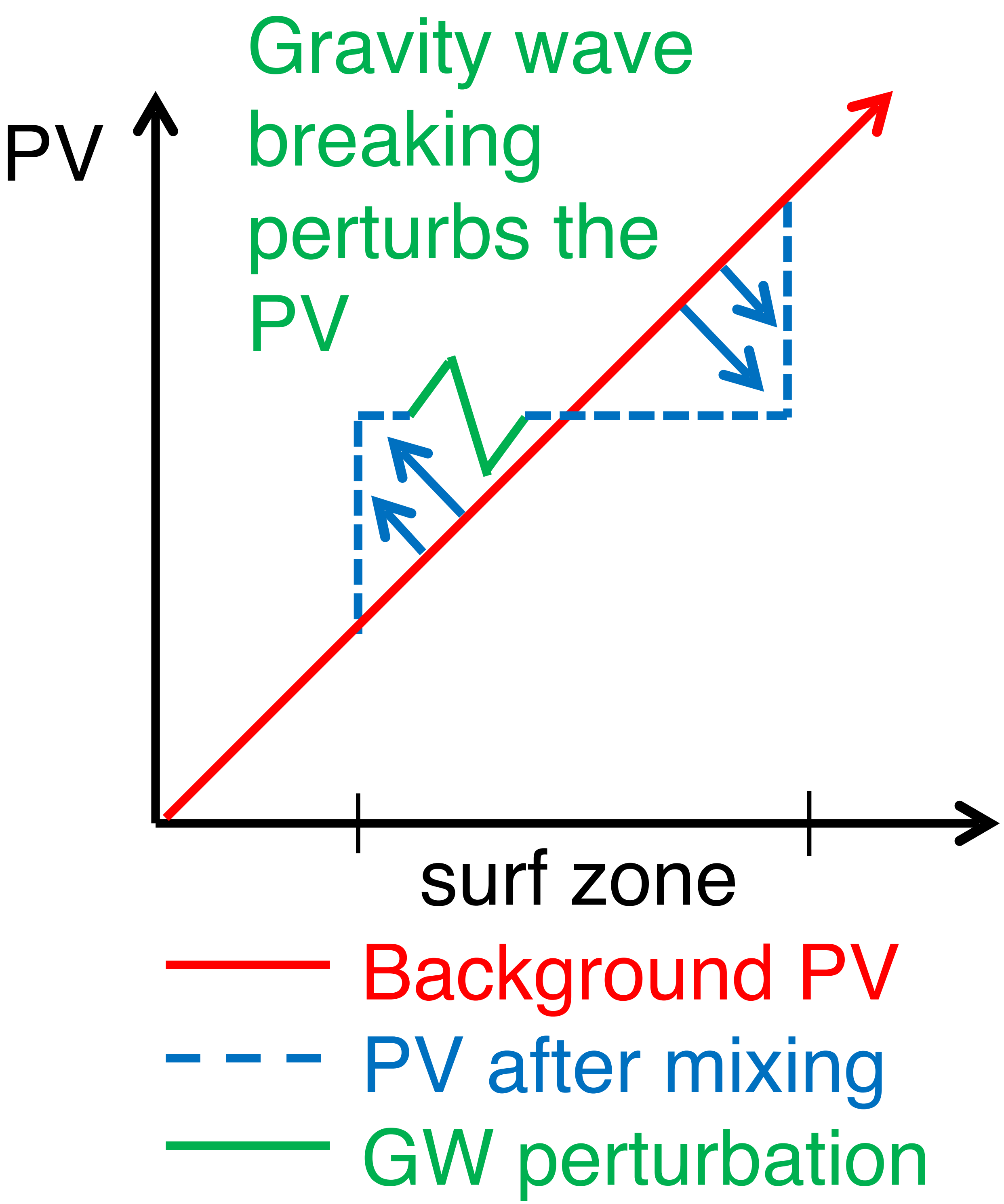

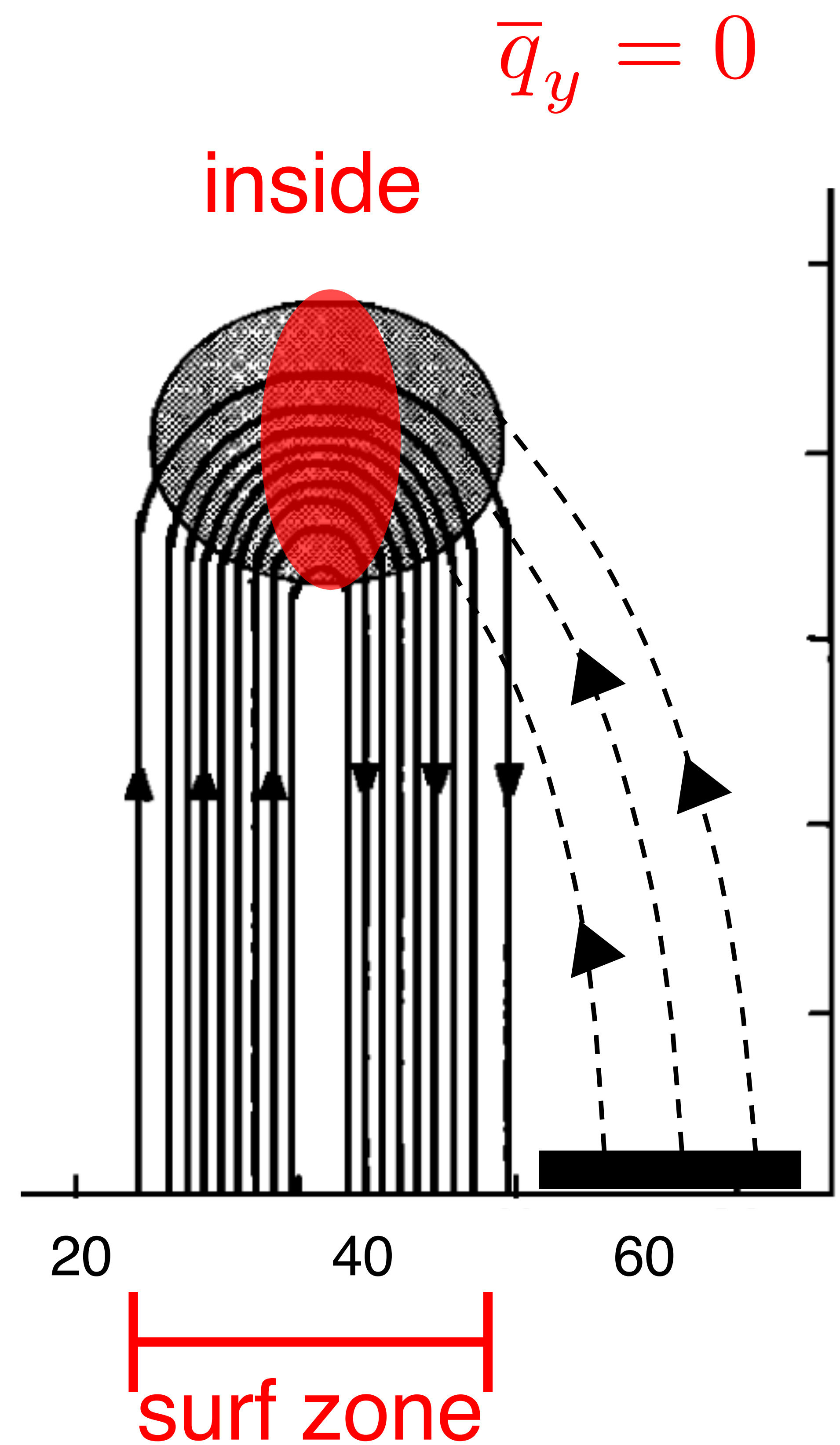

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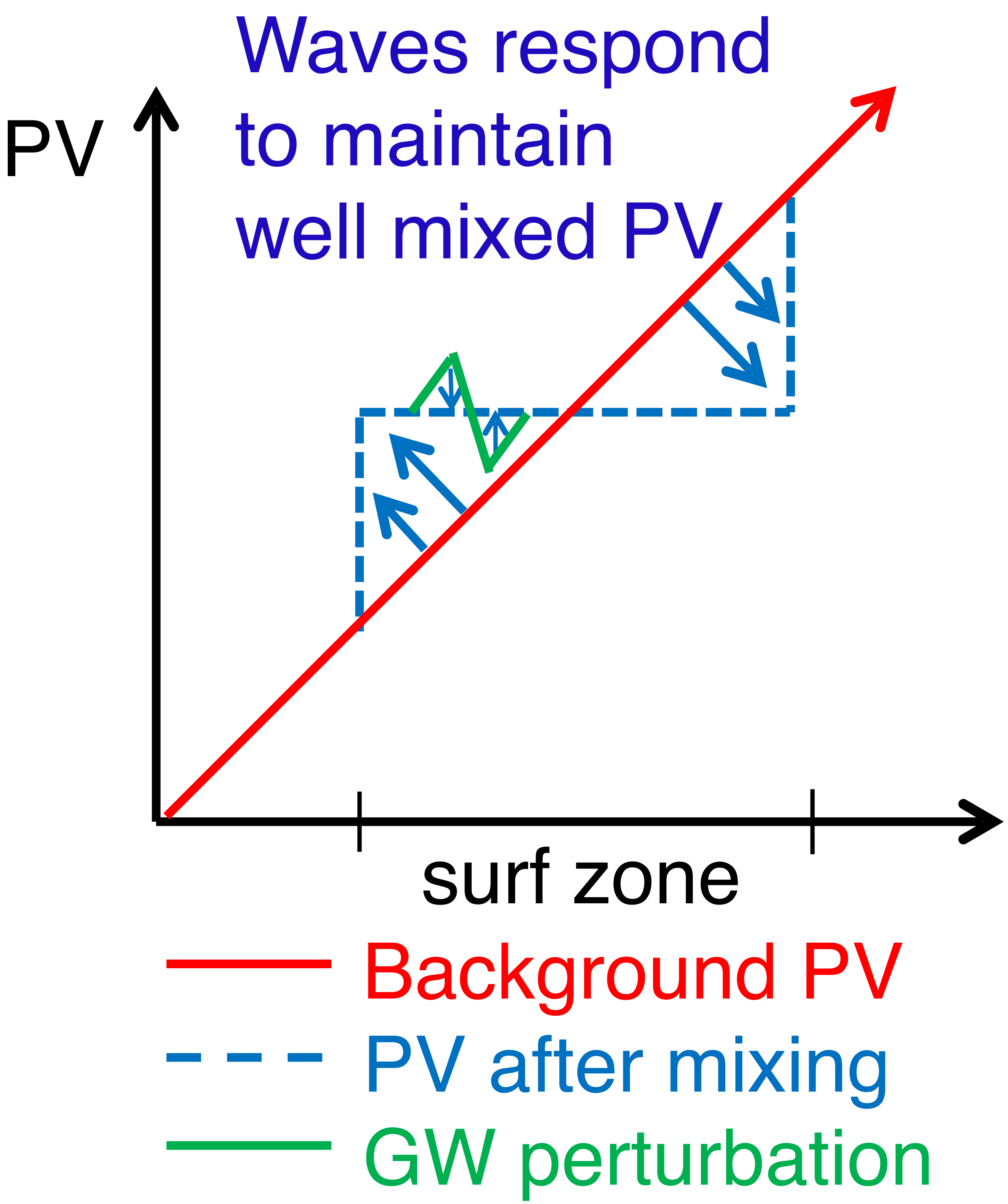
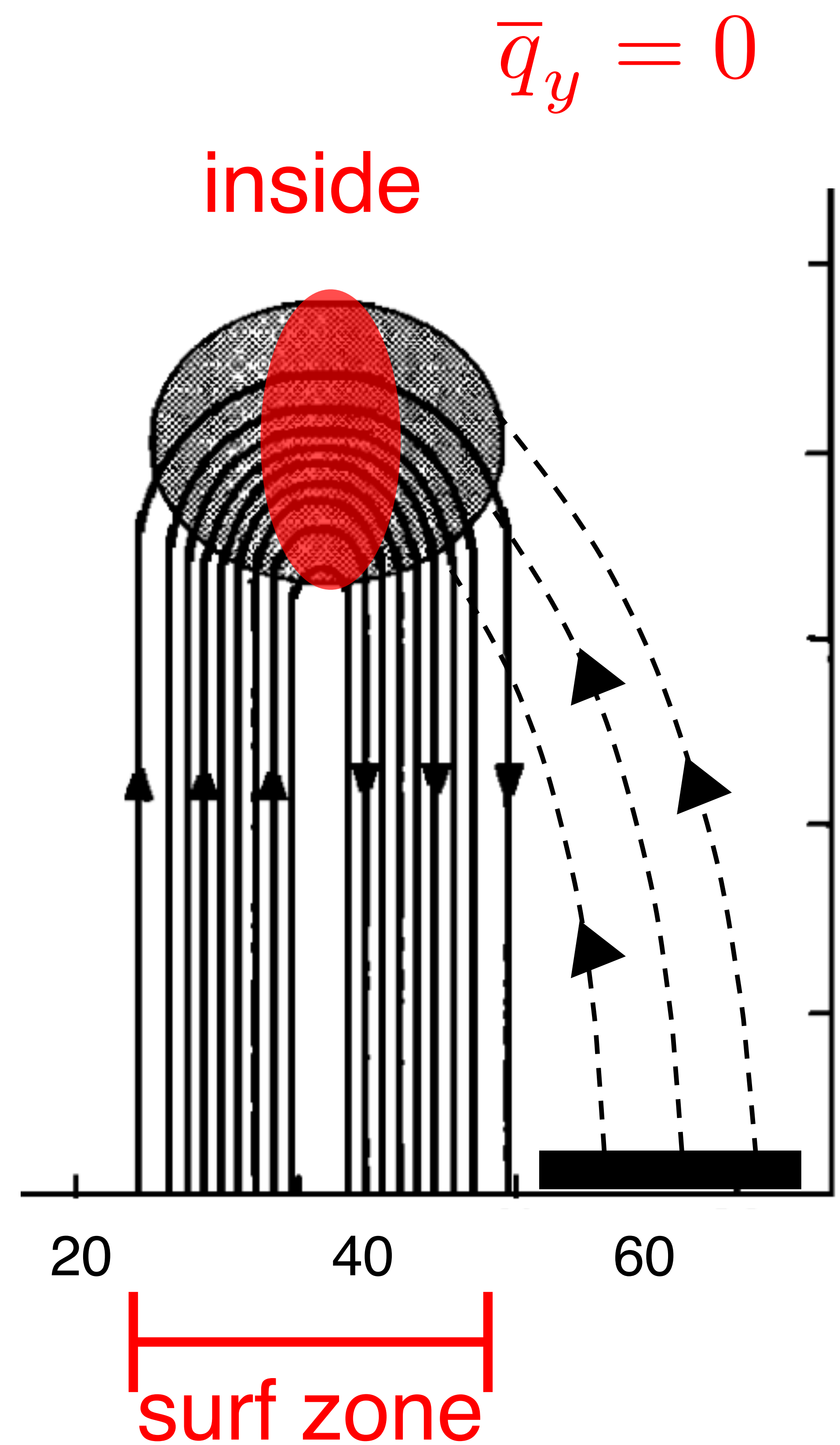
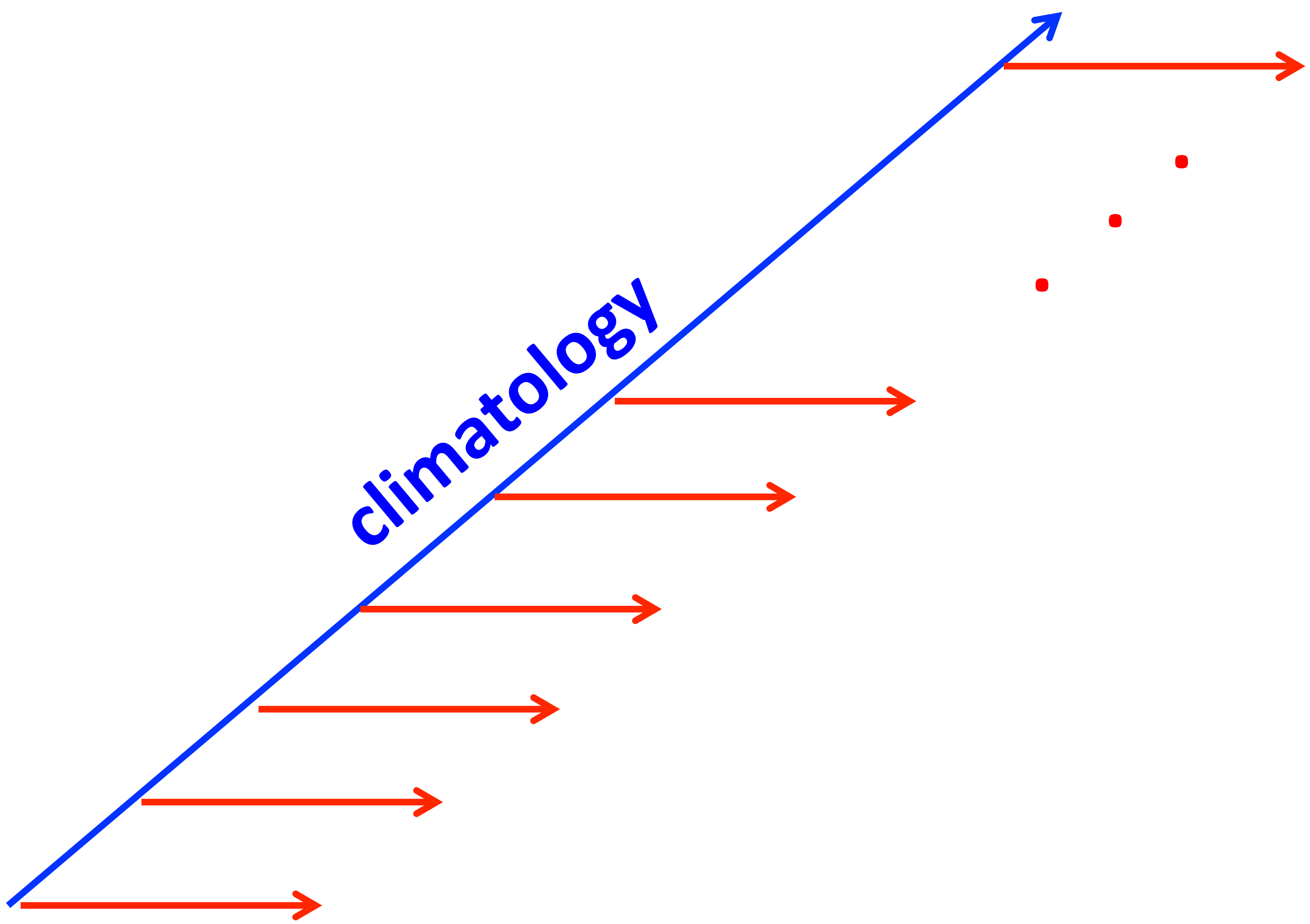
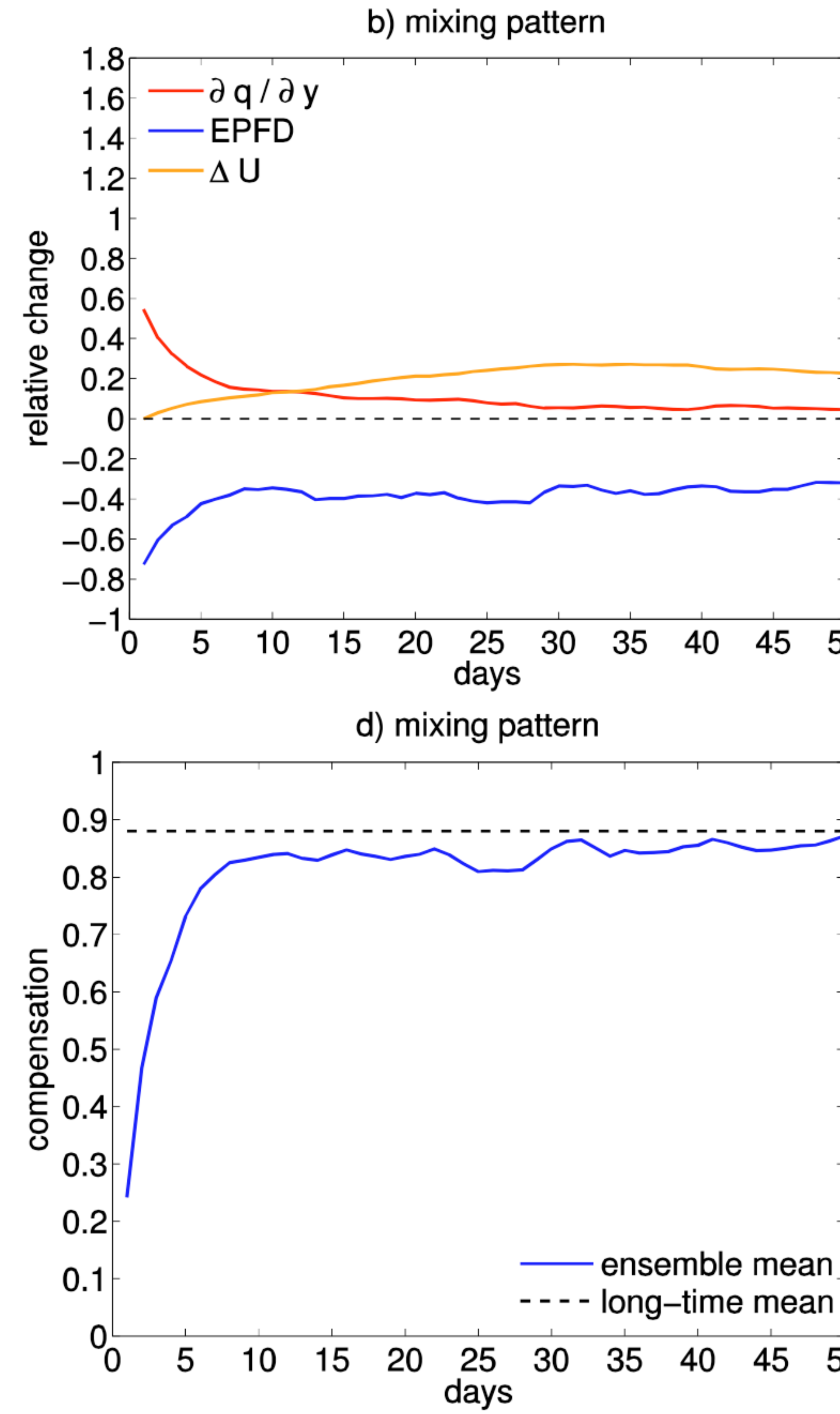




Surf-zone interactions

Switch-on torque experiments



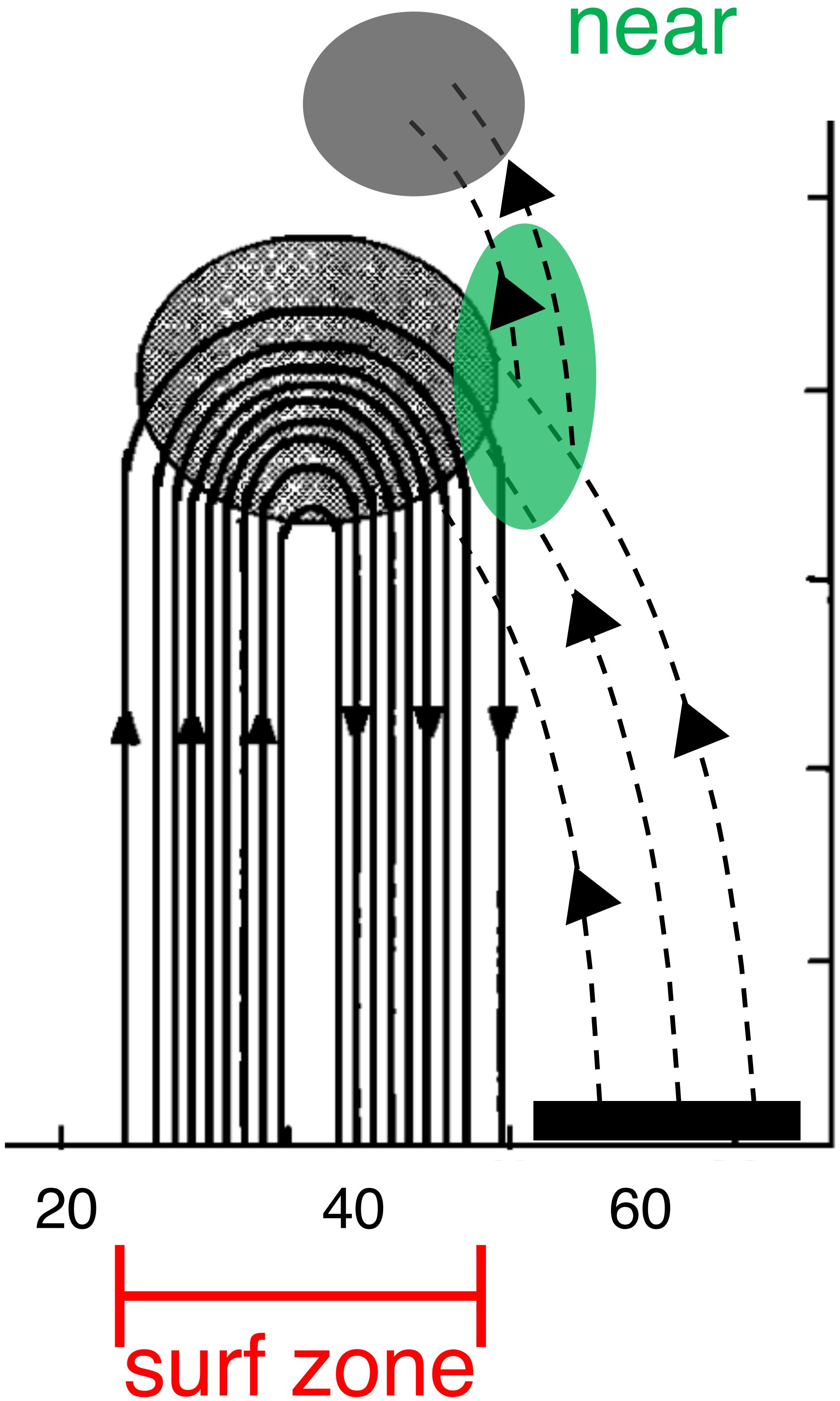


Cohen, Gerber, and Buhler 2013 $A = 2 \times 10^{-5} \mathrm{m\ s}^{-2}, h = 10°, y_0 = 35°\mathrm{N}$

Near surf zone interaction

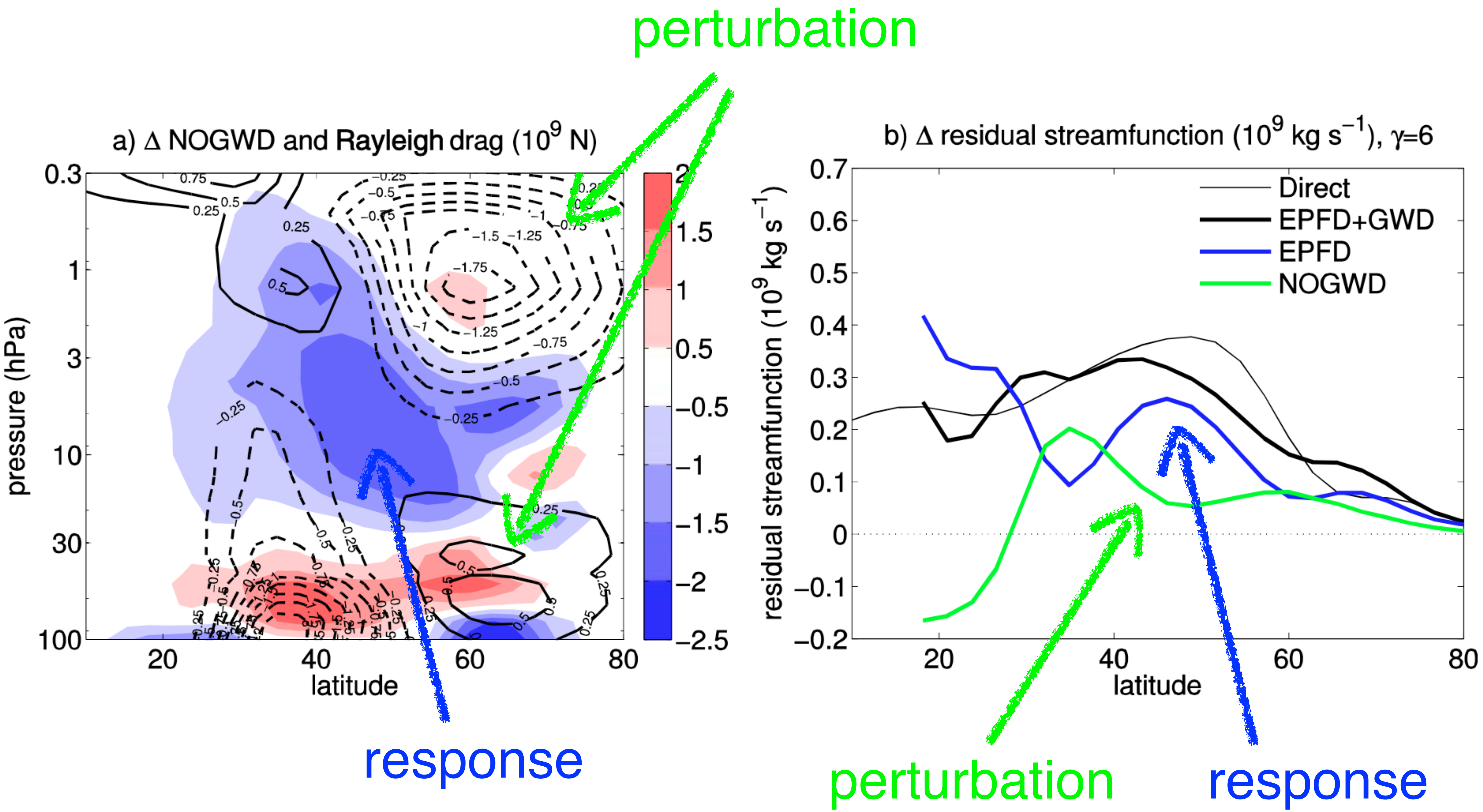
$$\delta n^2 \approx \delta \overline{q}_y / \overline{u} - \overline{q}_y \delta \overline{u} / \overline{u}^2$$

- Nonlinear
- Nonlocal
- Highly dependent on the current state
- Hard to predict



Cohen, Gerber, and Buhler 2014

Near surf zone interaction



Cohen, Gerber, and Buhler 2014

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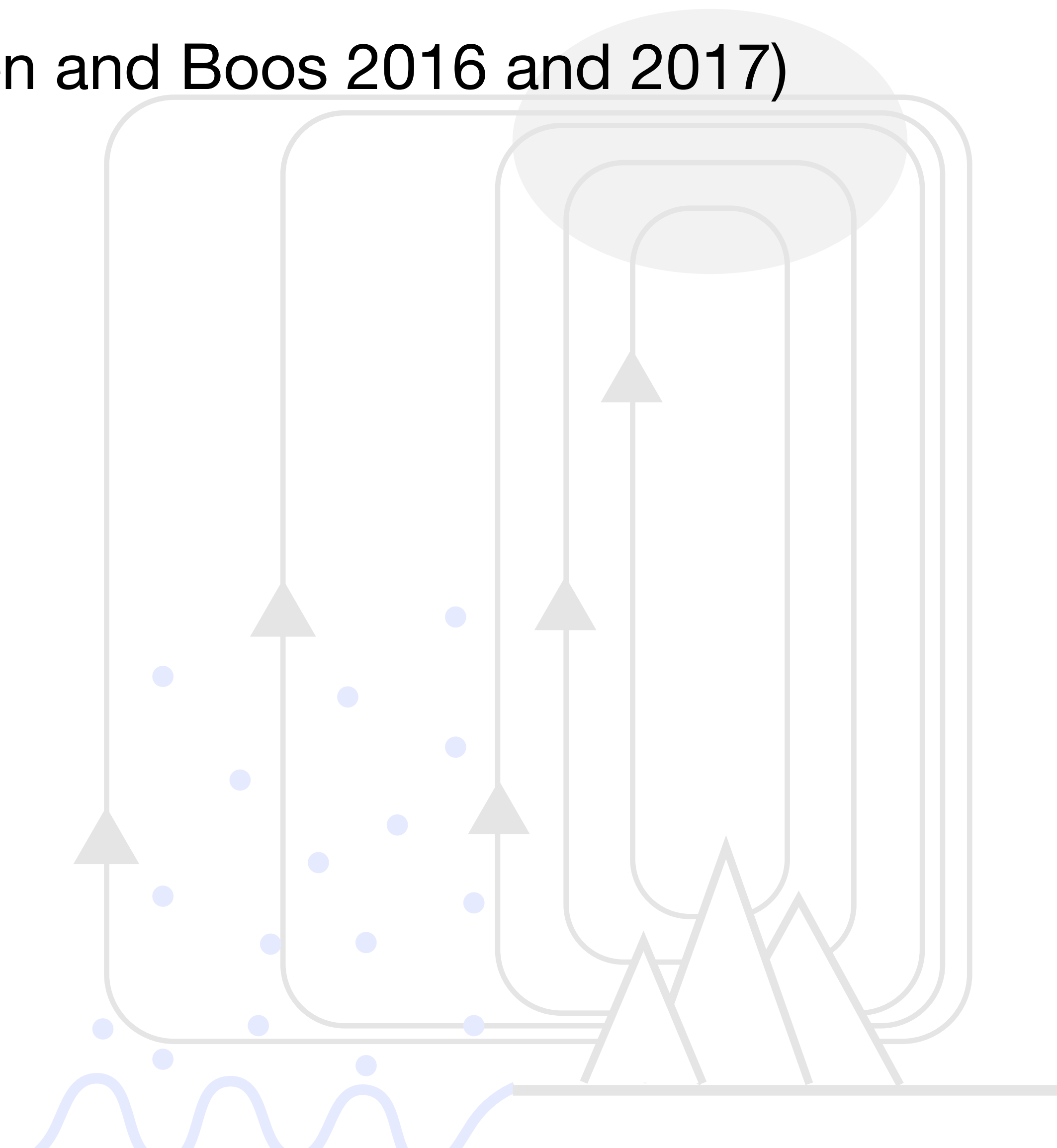
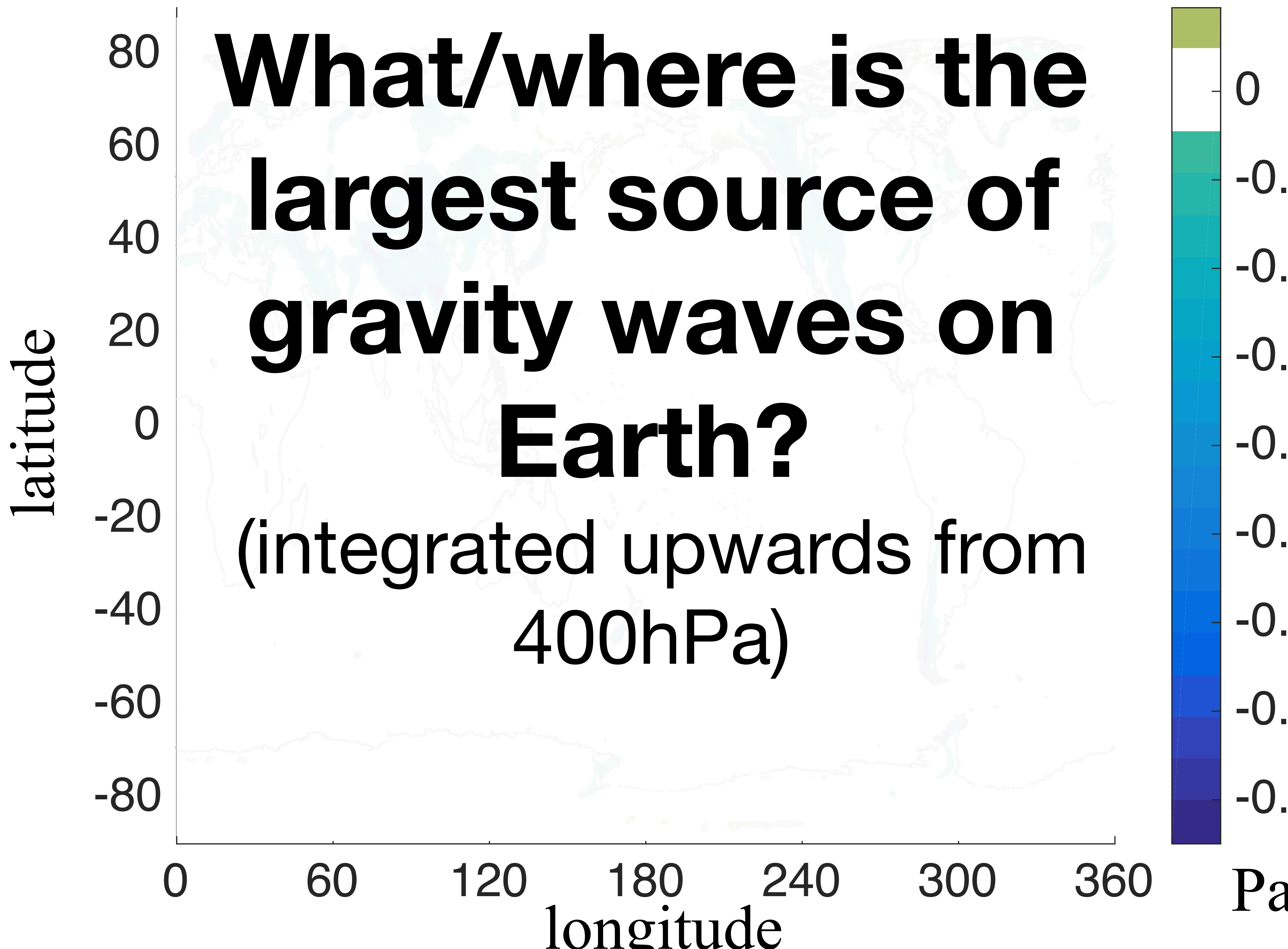


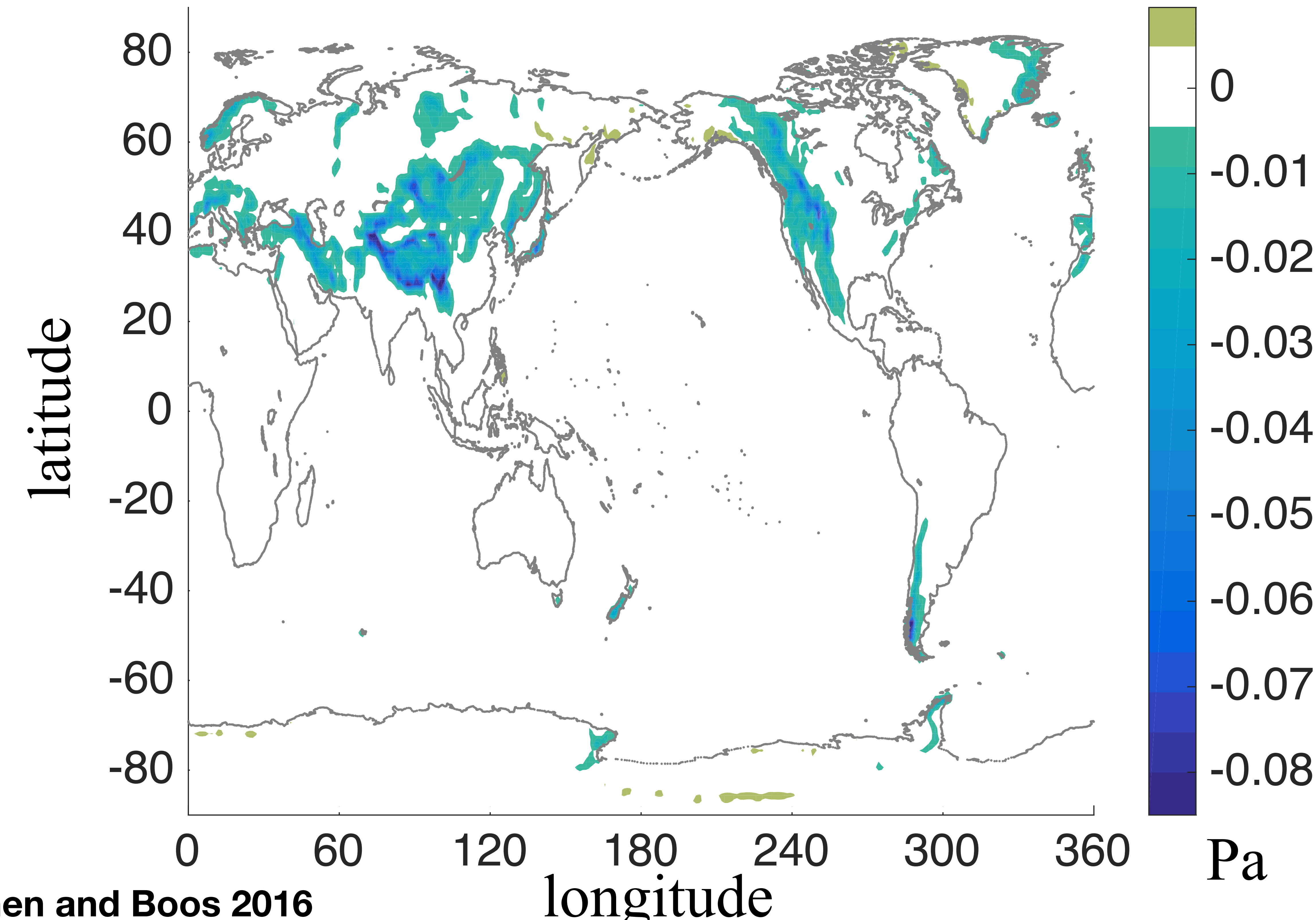
Regional scale: part 1



What/where is the largest source of gravity waves on Earth?

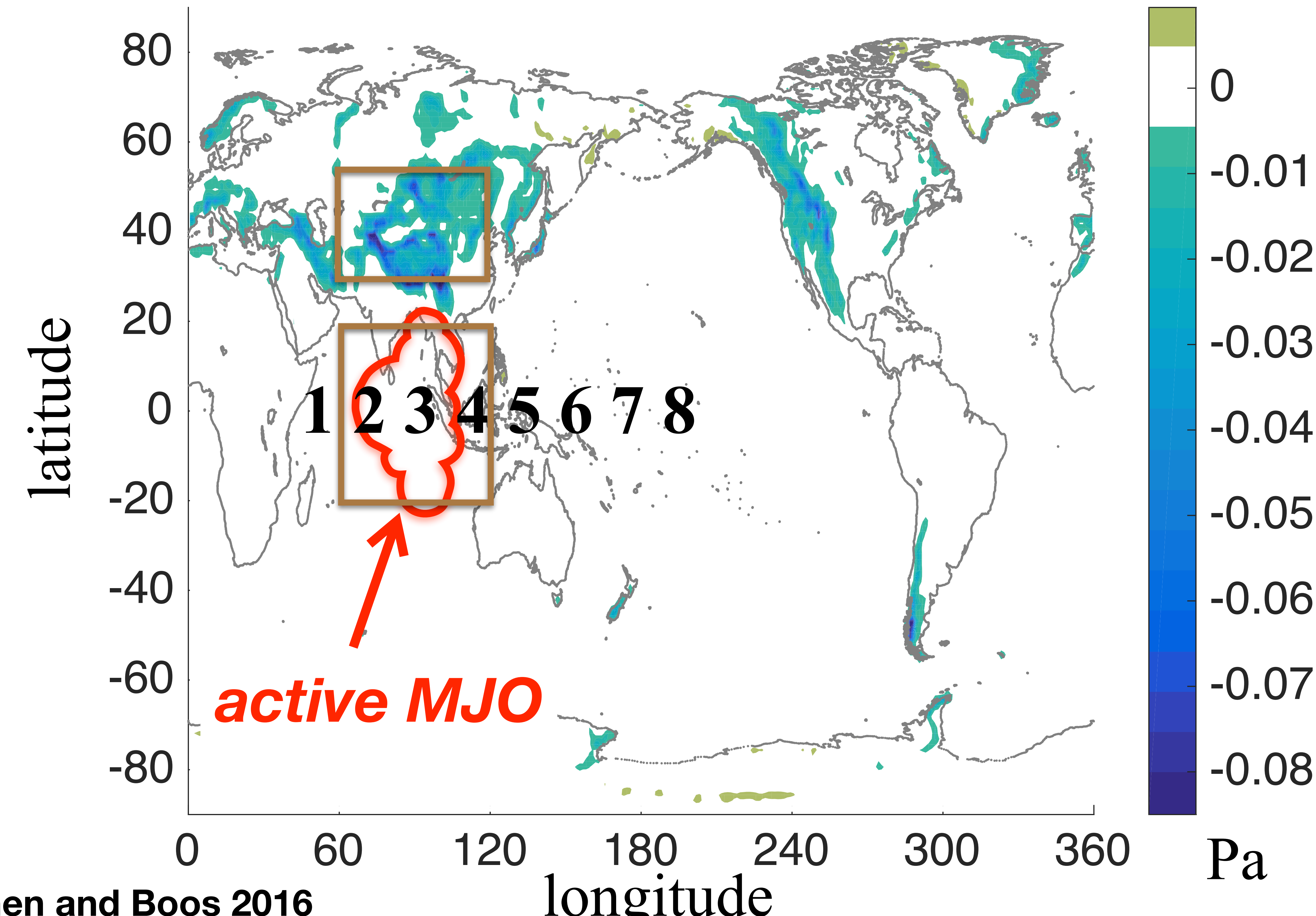
(integrated upwards from 400hPa)

Integrated GWD (MERRA, DJF 1979-2012)



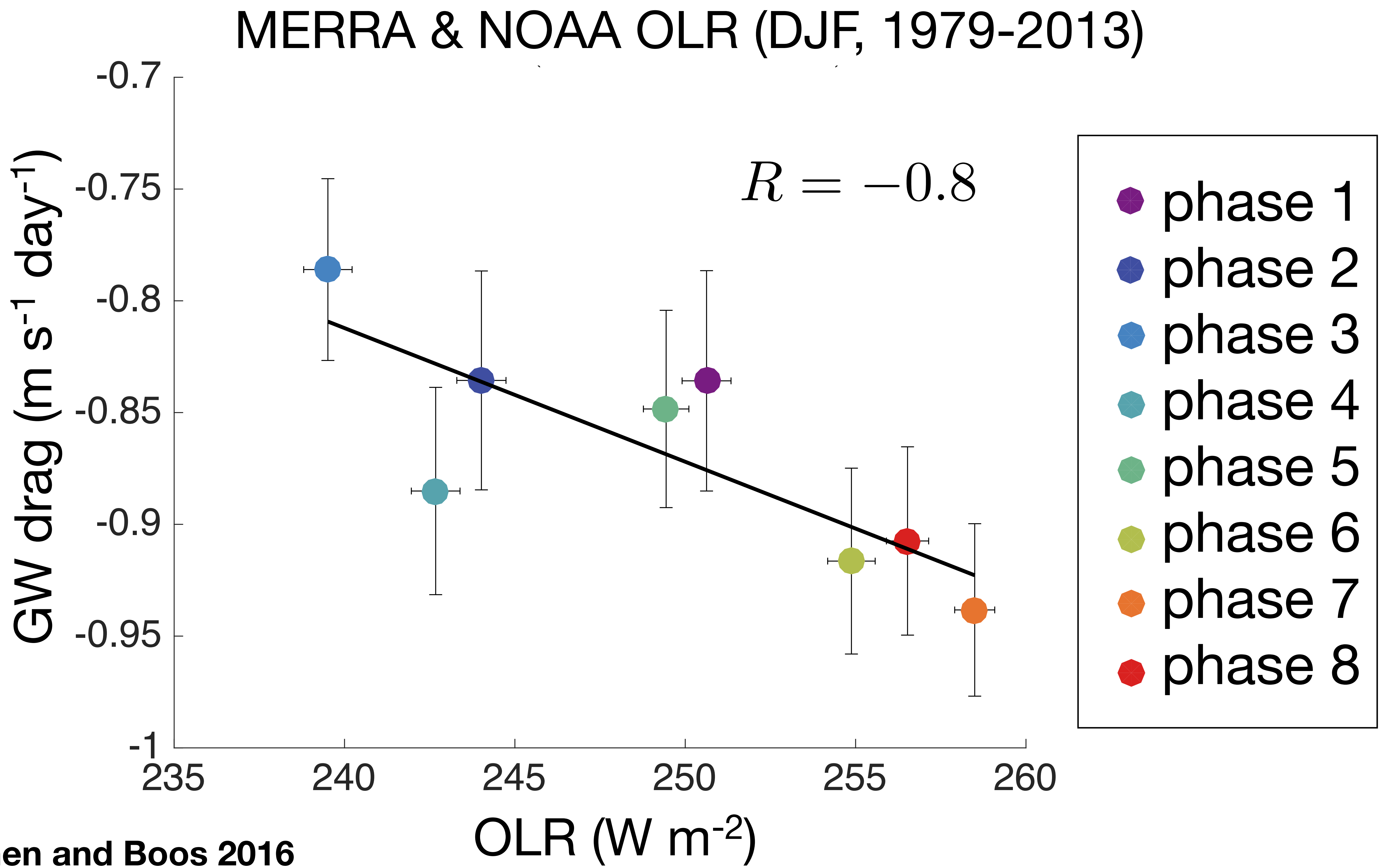
Cohen and Boos 2016

Tropical rainfall and the extratropical waves



Cohen and Boos 2016

The statistical association between the MJO and GW drag over Tibet



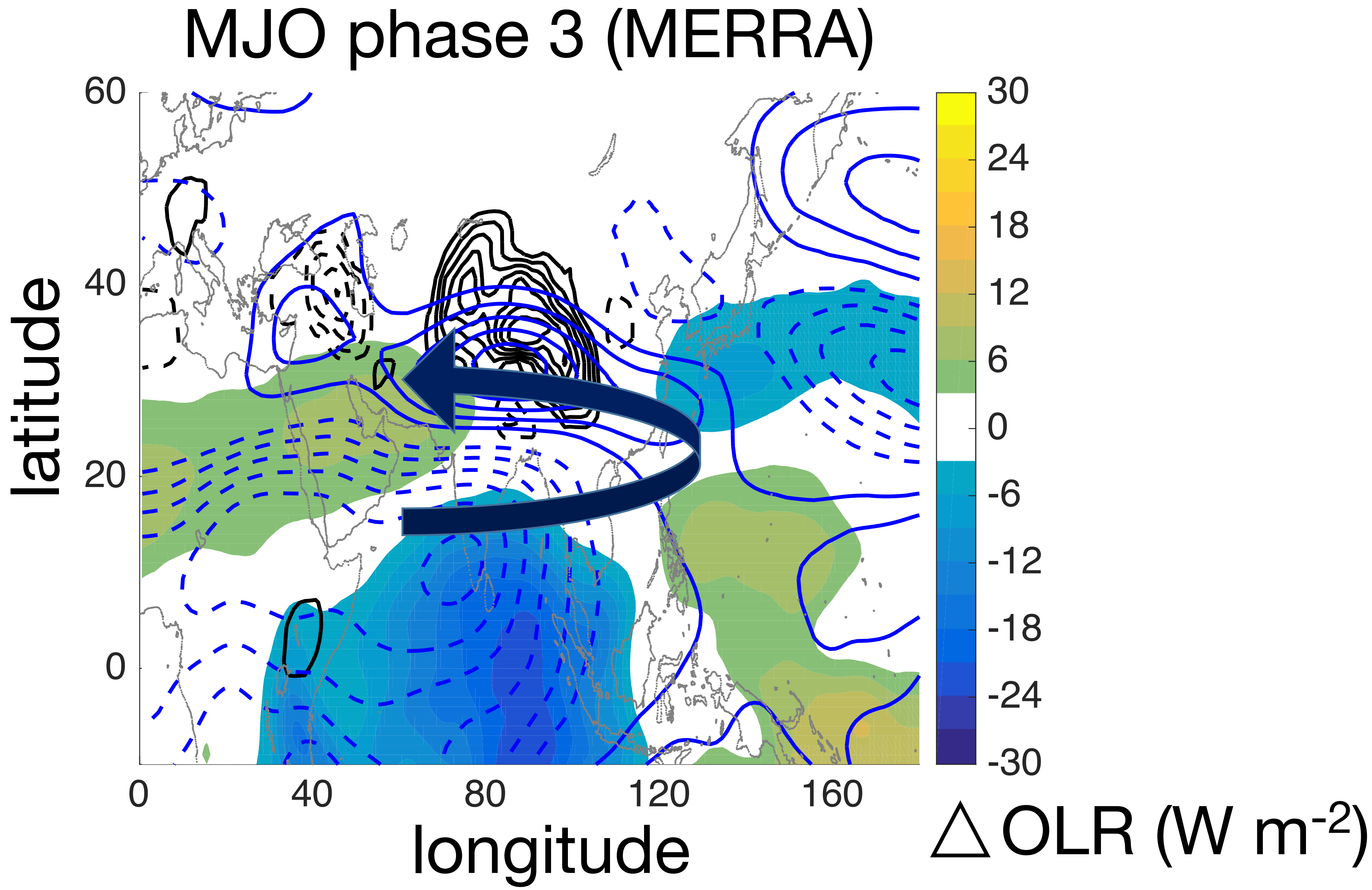
Cohen and Boos 2016

The statistical association between the MJO and GW drag over Tibet

GWD / OLR data source	Correlation
MERRA / NOAA OLR	-0.81
MERRA* / NOAA OLR	-0.78
MERRA / MERRA	-0.84
JRA55 / NOAA OLR	-0.82
JRA55* / NOAA OLR	-0.71
JRA55 / JRA55	-0.94

All linear regression slopes are negative and statistically significant.   * for “highly defined” MJO event

Horizontal structures of MJO and GW drag anomalies

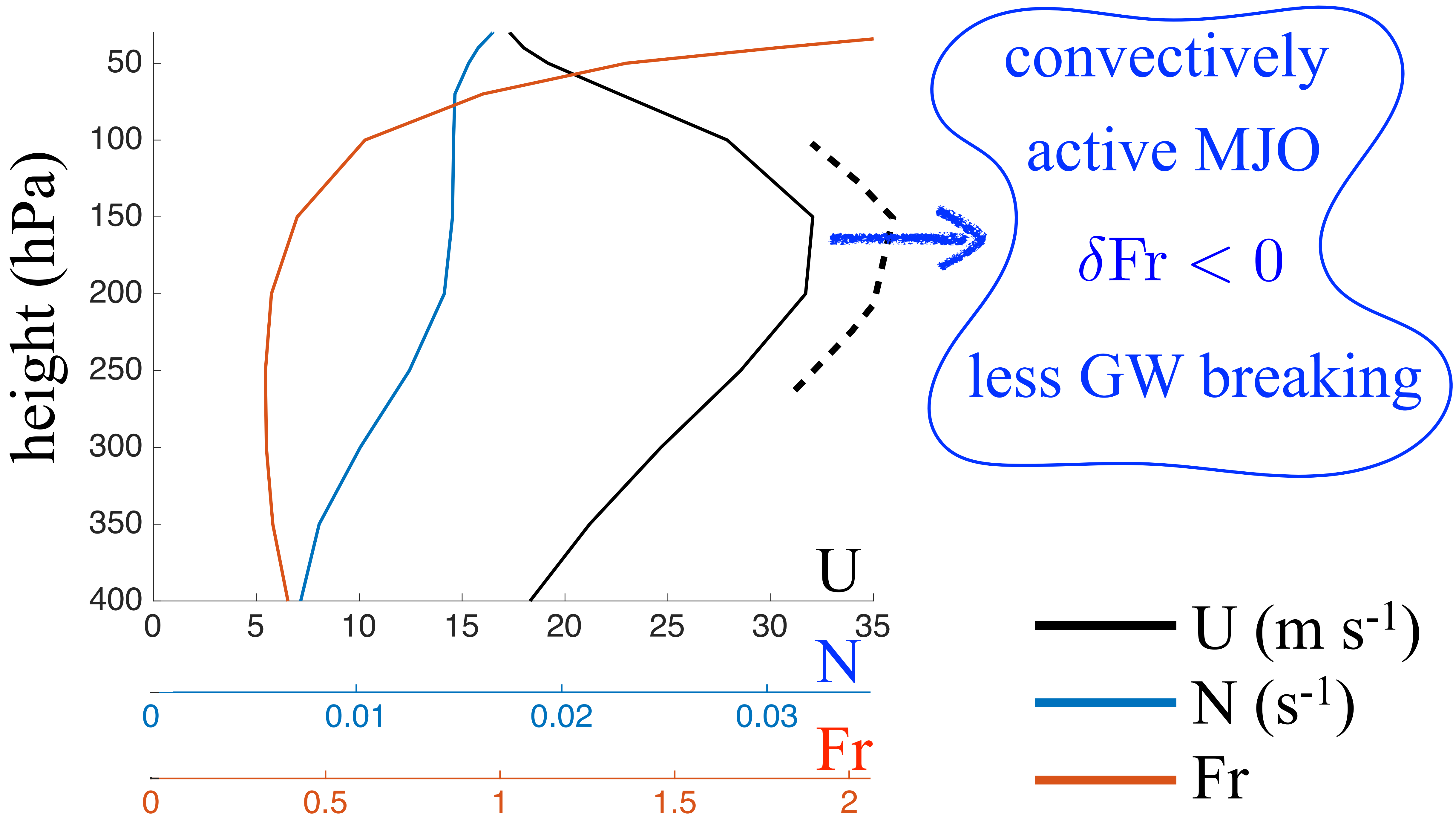


△GWD (100hPa, interval of 0.05 m s^{-1} d^{-1})

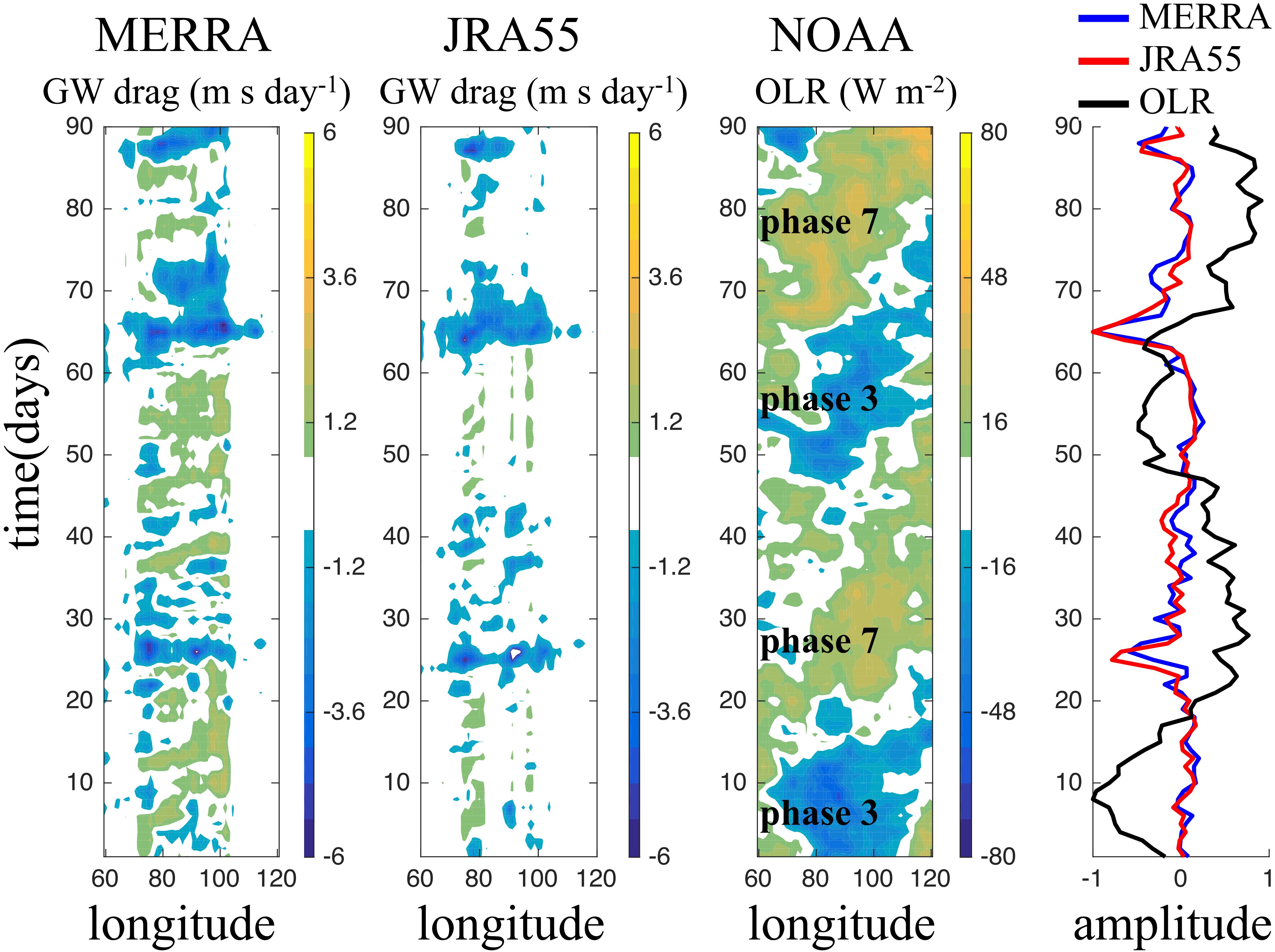
△zonal wind (200hPa, interval of 1 m s^{-1})

Simple mechanism for the interaction

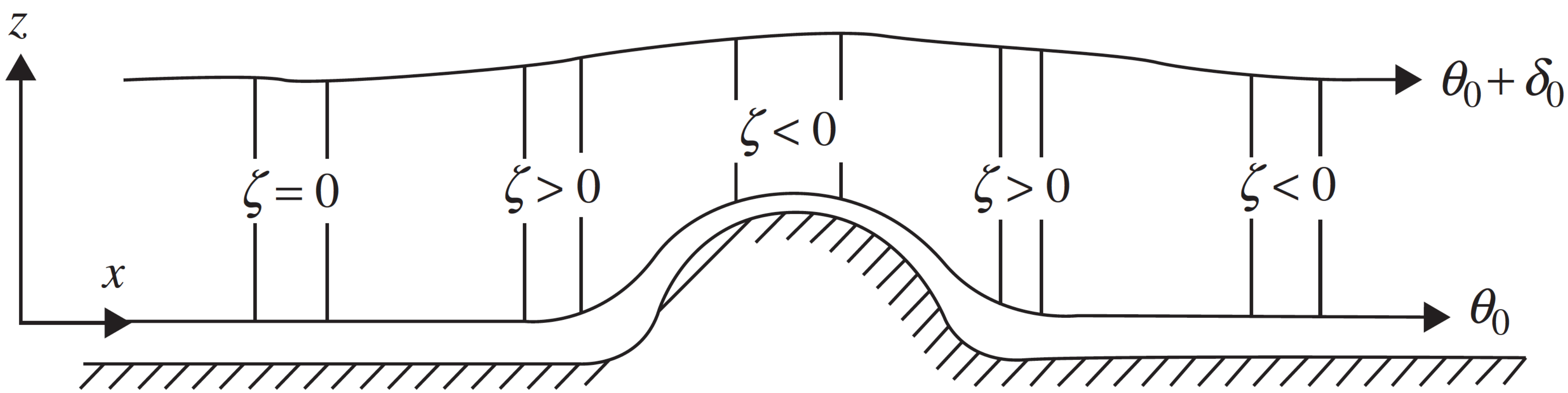
$$\text{Stability criterion: } \text{“}Fr\text{”} = \left(\frac{Nh}{U}\right)\sqrt{\frac{\rho_0 N_0 U_0}{\rho N U}} \le 1$$



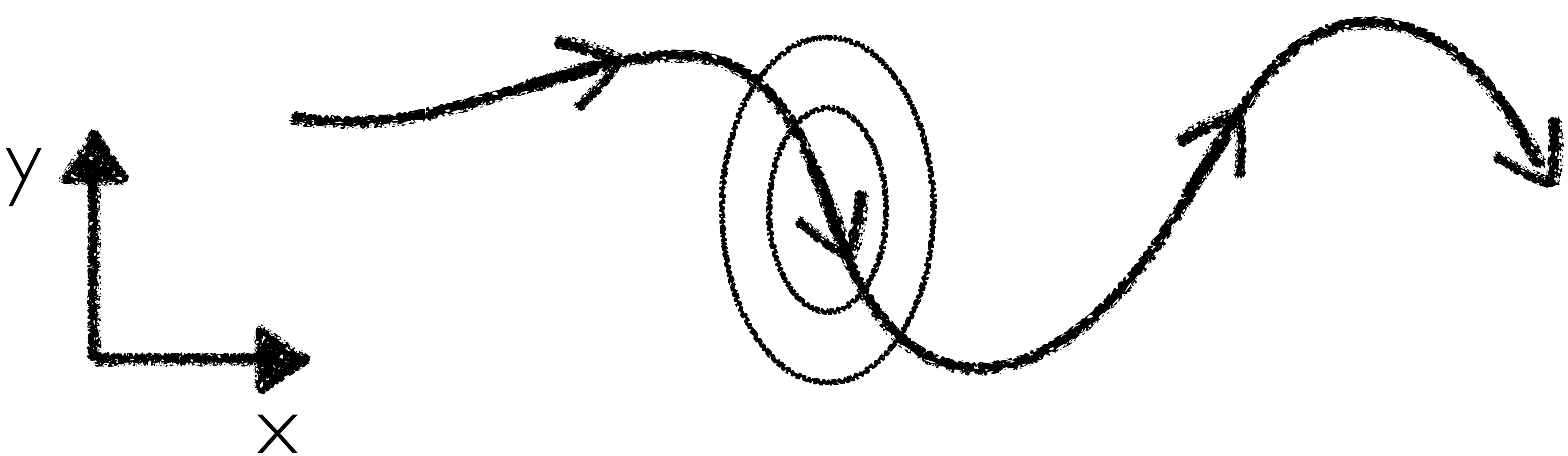
Daily GW drag and OLR anomalies during the winter of 1987-88



Regional scale: part 2

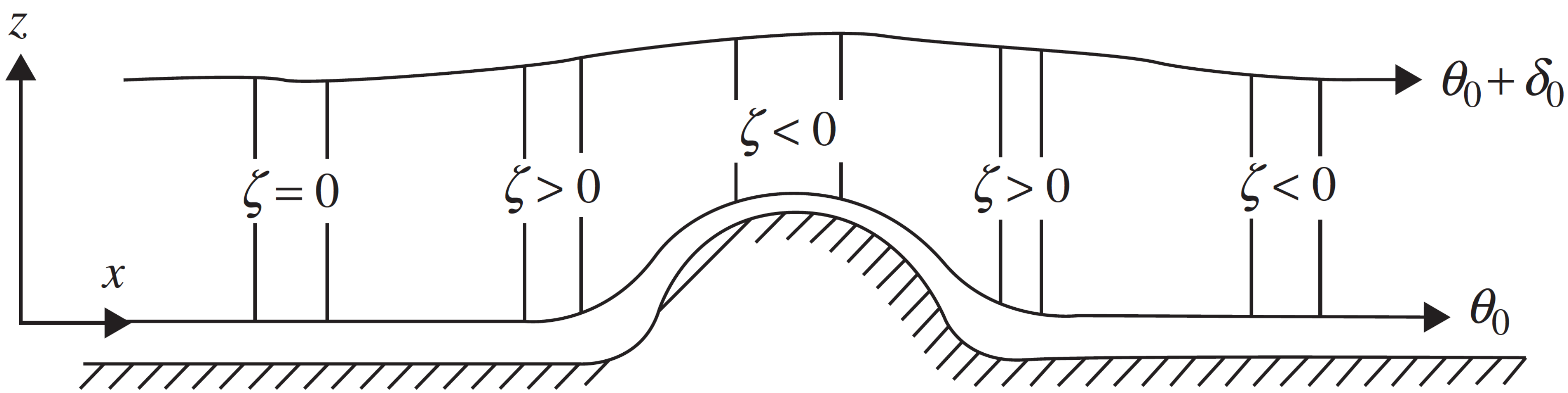


$$\frac{D}{Dt}\frac{\zeta + f}{h} = 0$$



Holton and Hakim 2013

Regional scale: part 2



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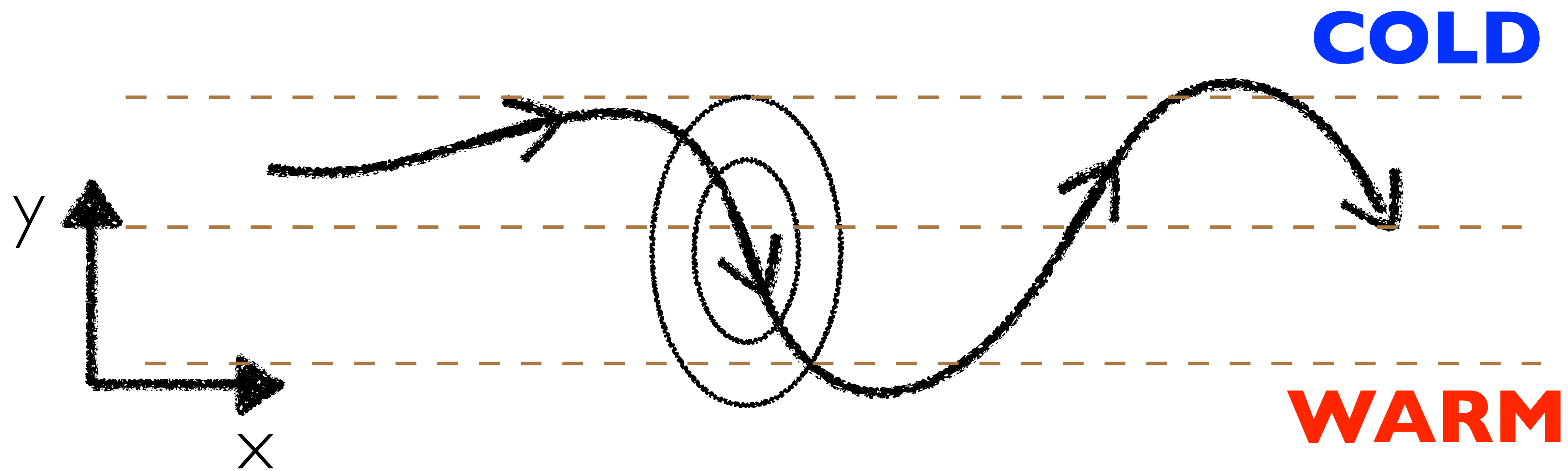

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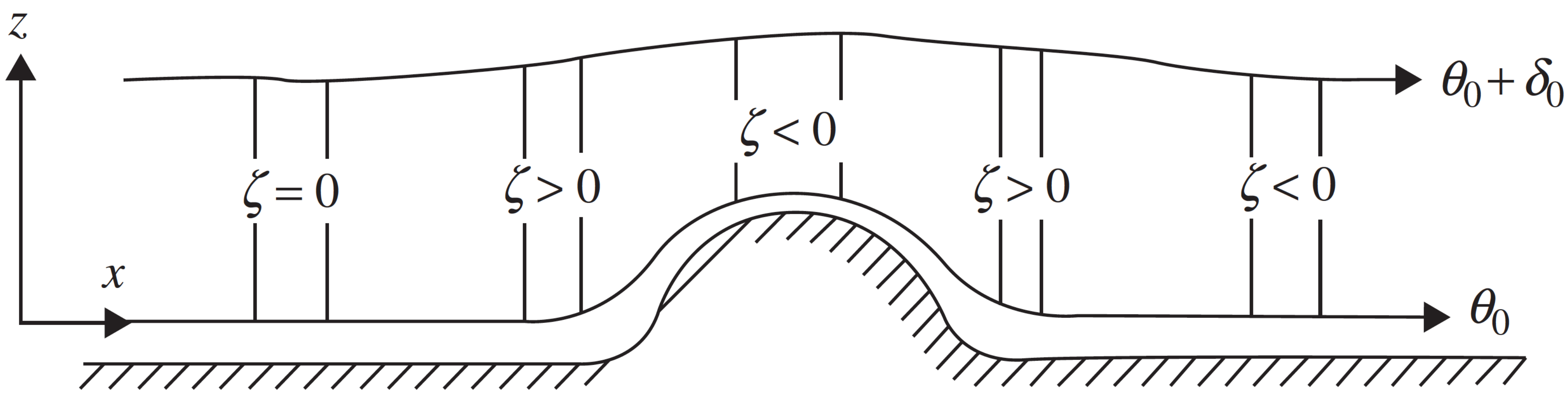

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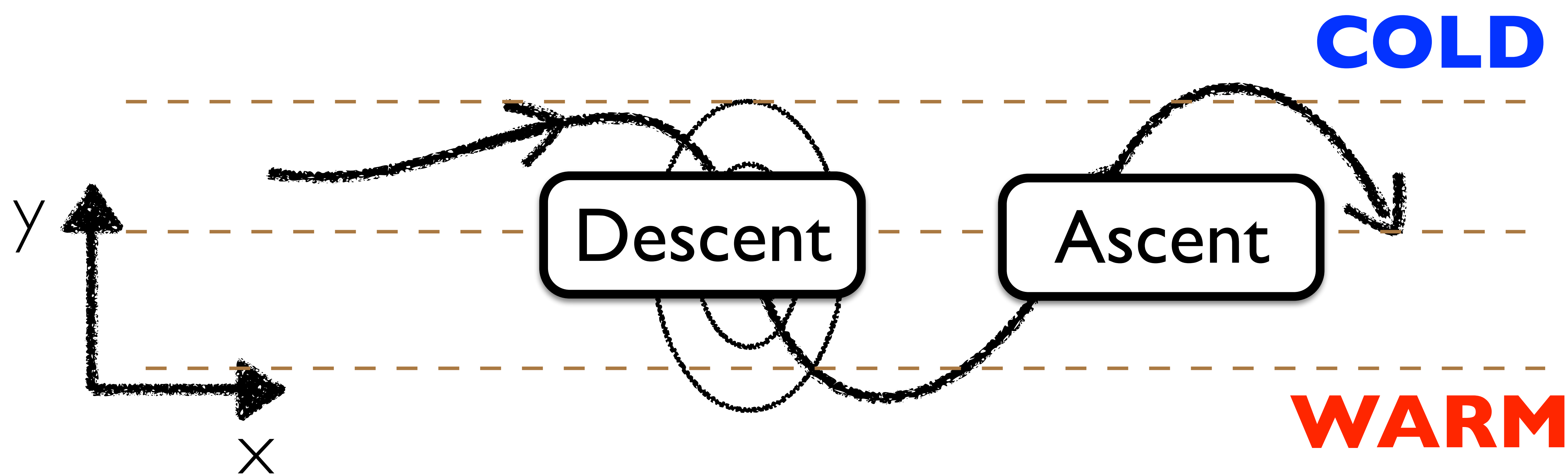

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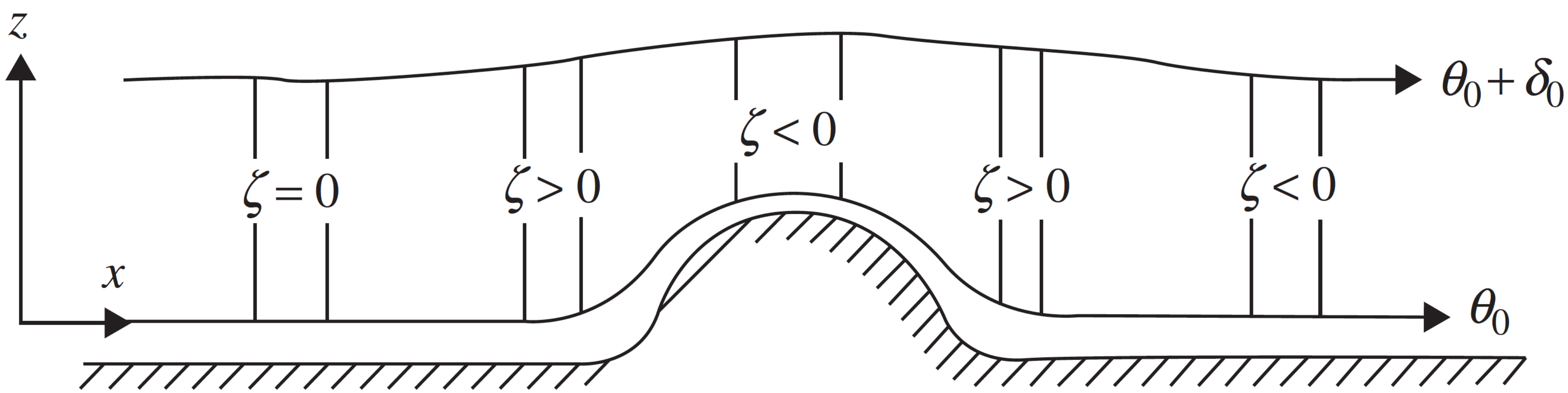

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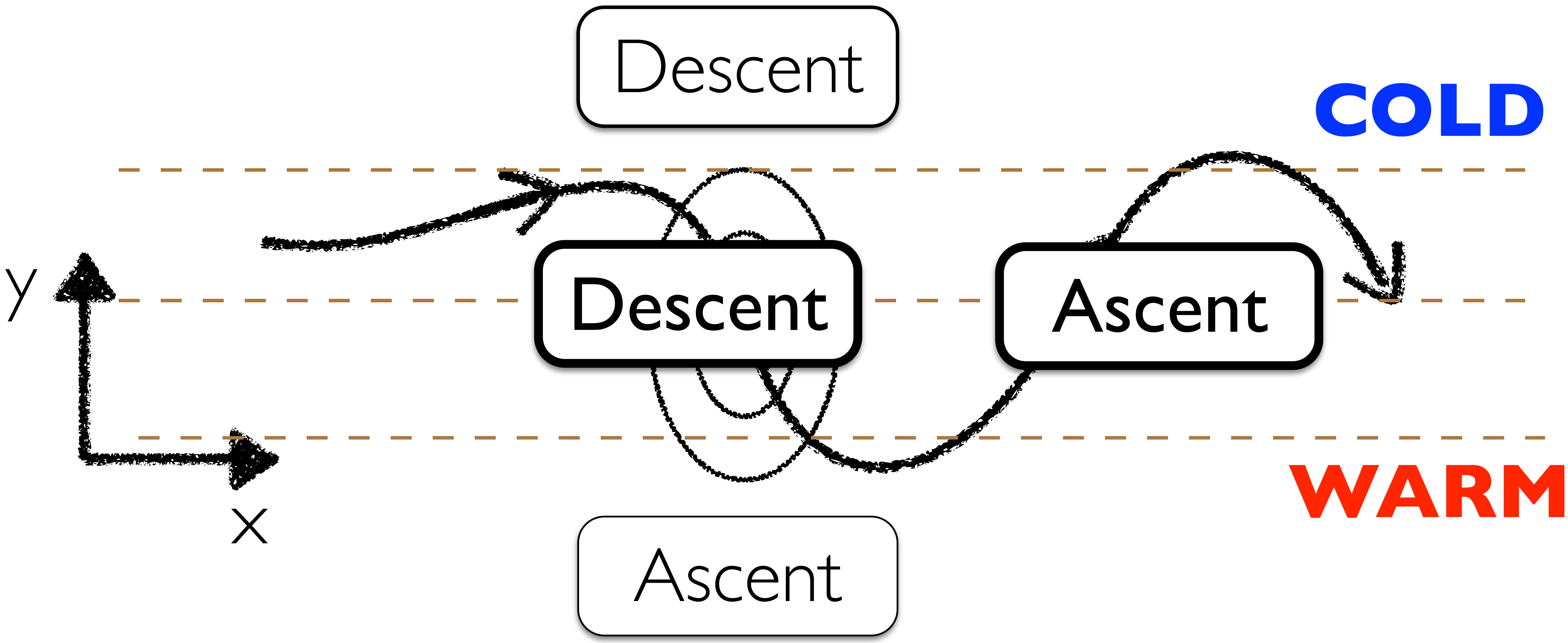

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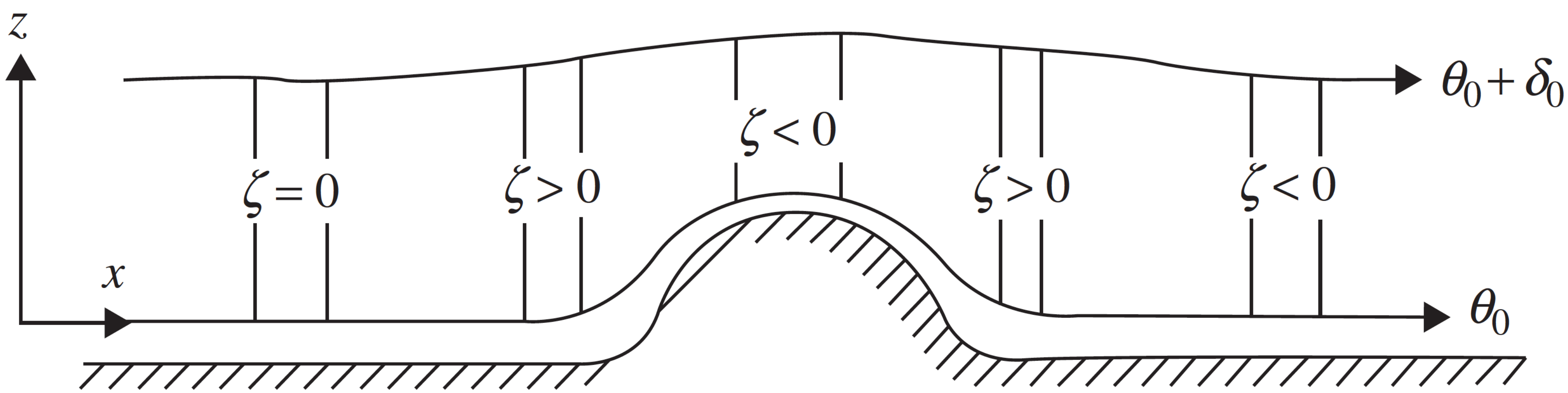

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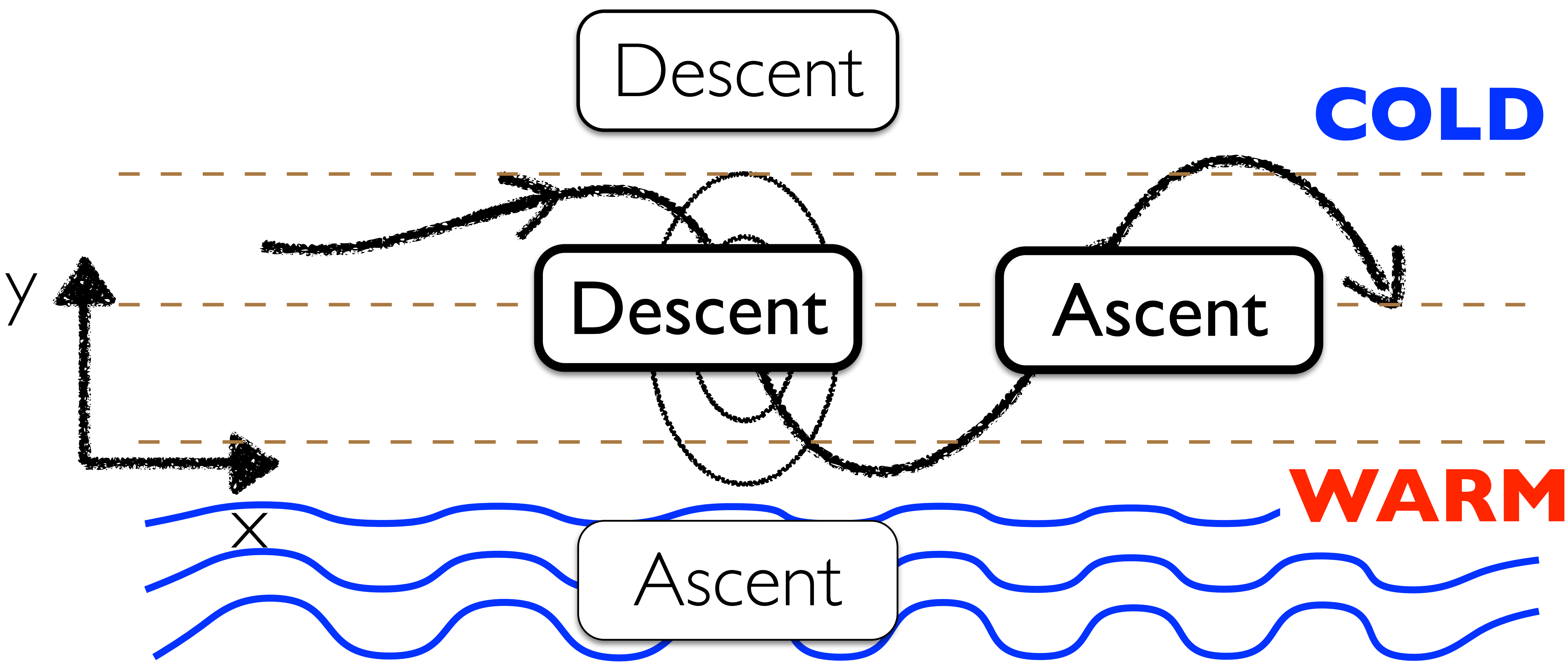

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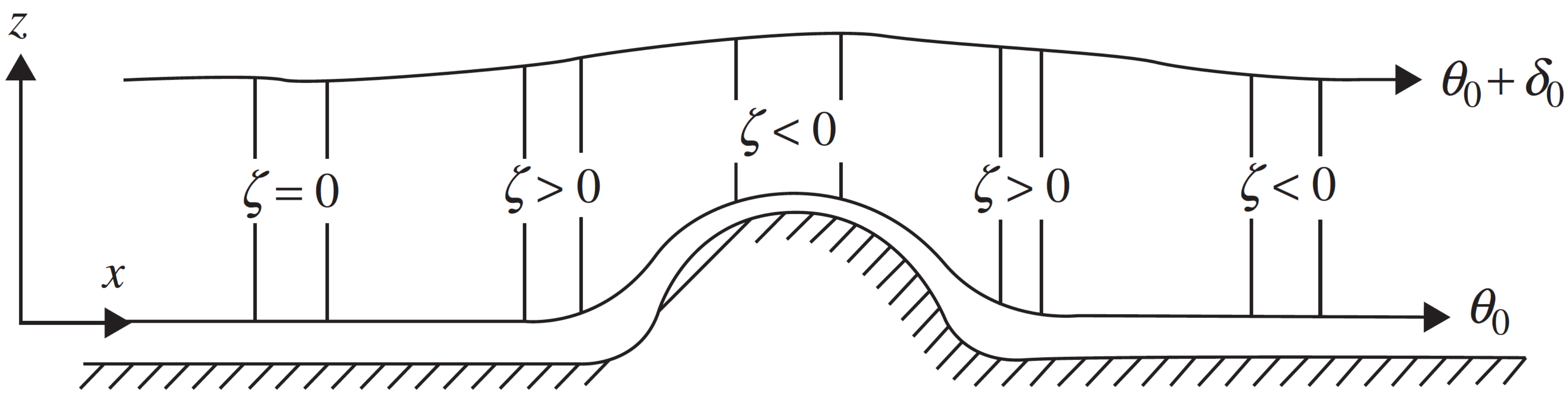

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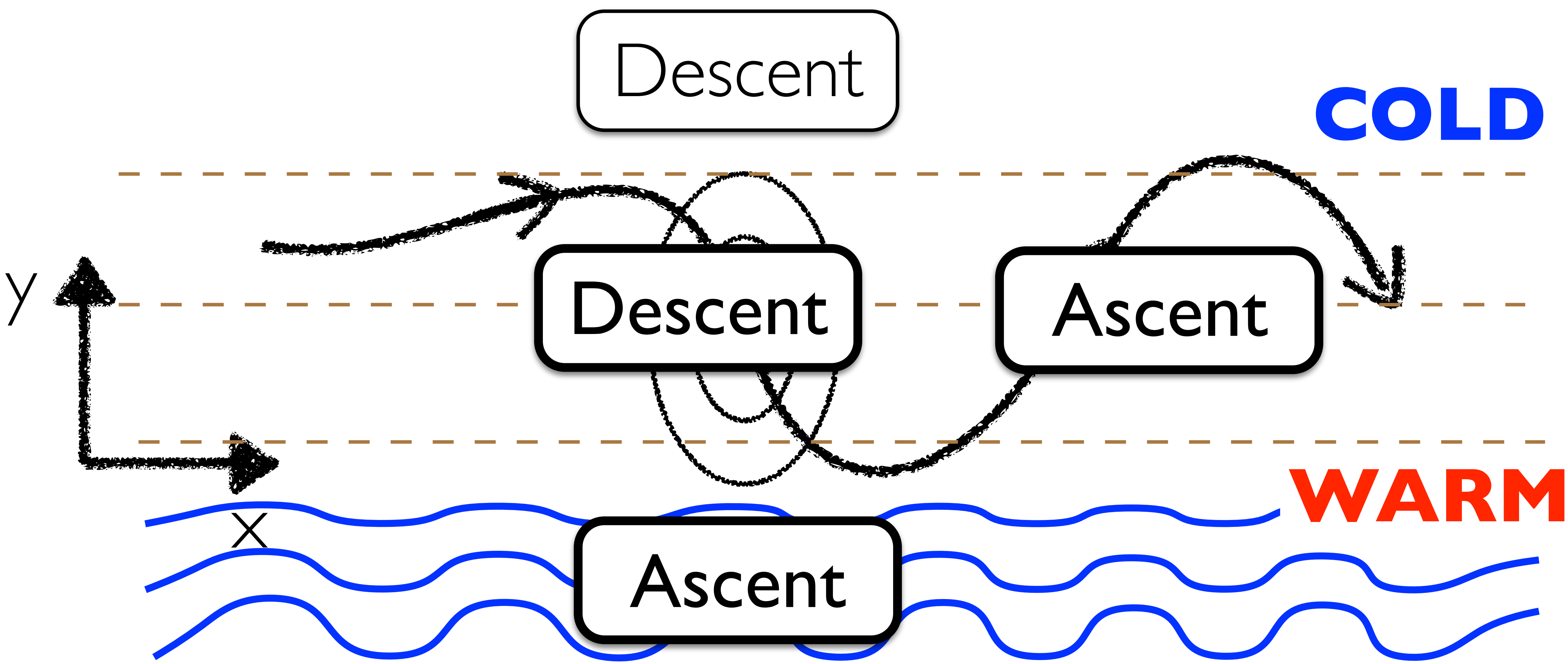
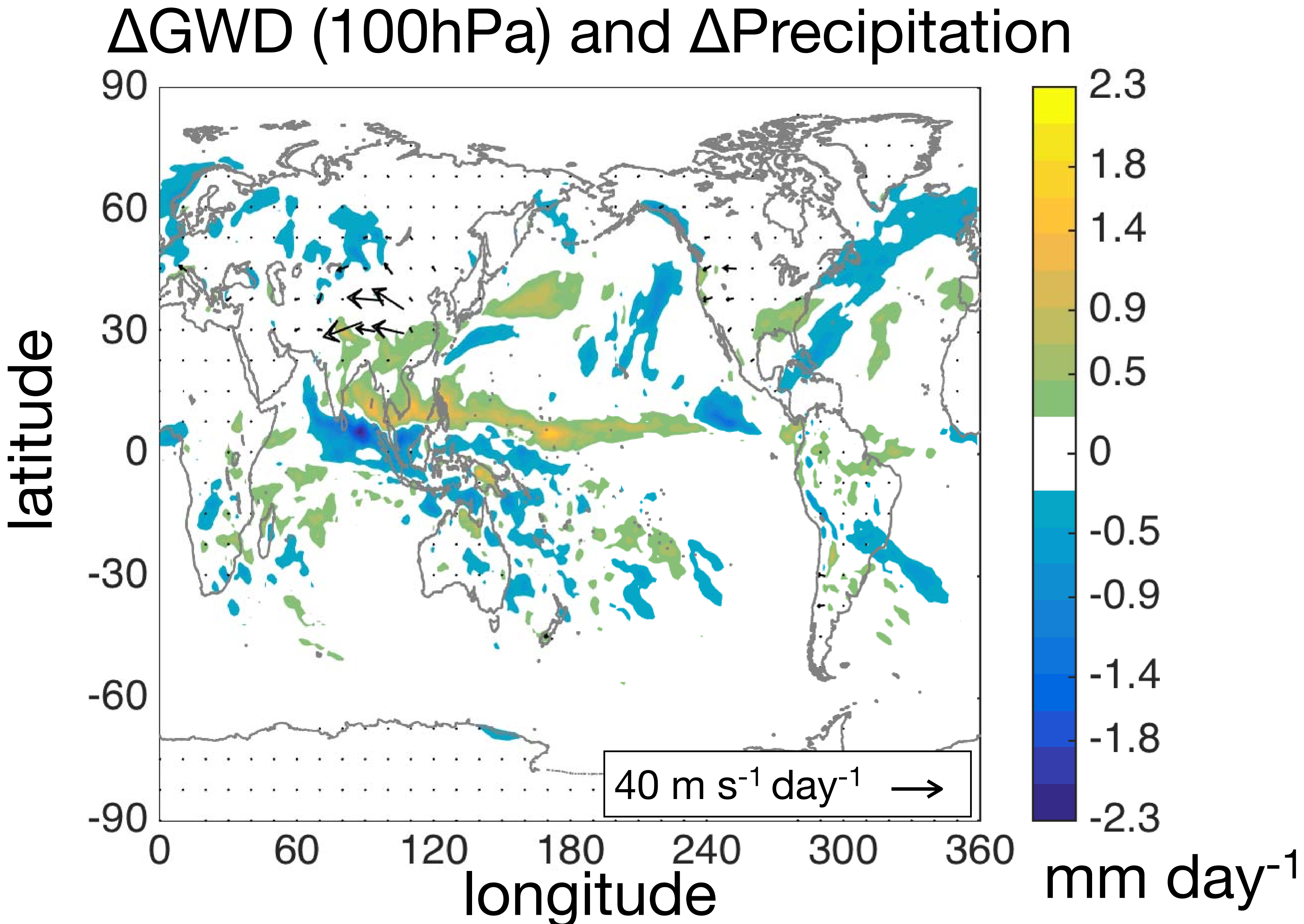


Regional scale: part 2

- Increased precipitation to the south, and decreased to the north
- Poleward shift in the precipitation pattern (ITCZ)

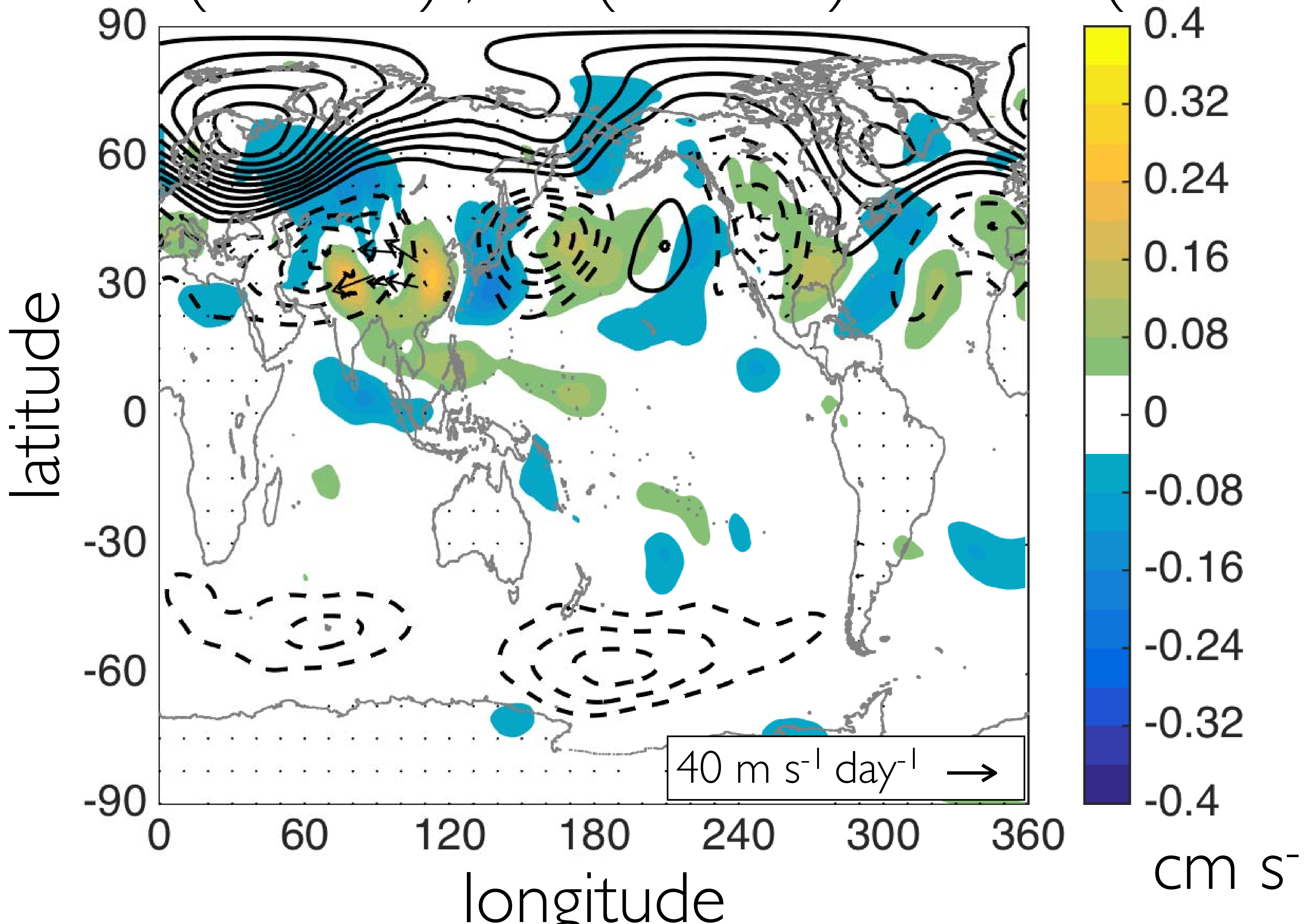


Take-home points

- Gravity waves have (sometimes surprising) zeroth-order contribution to the zonal-mean flow that must be taken into account or at least considered
- The largest source of gravity waves is the Tibetan Plateau, and this results in significant interactions with the large-scale equatorial convection

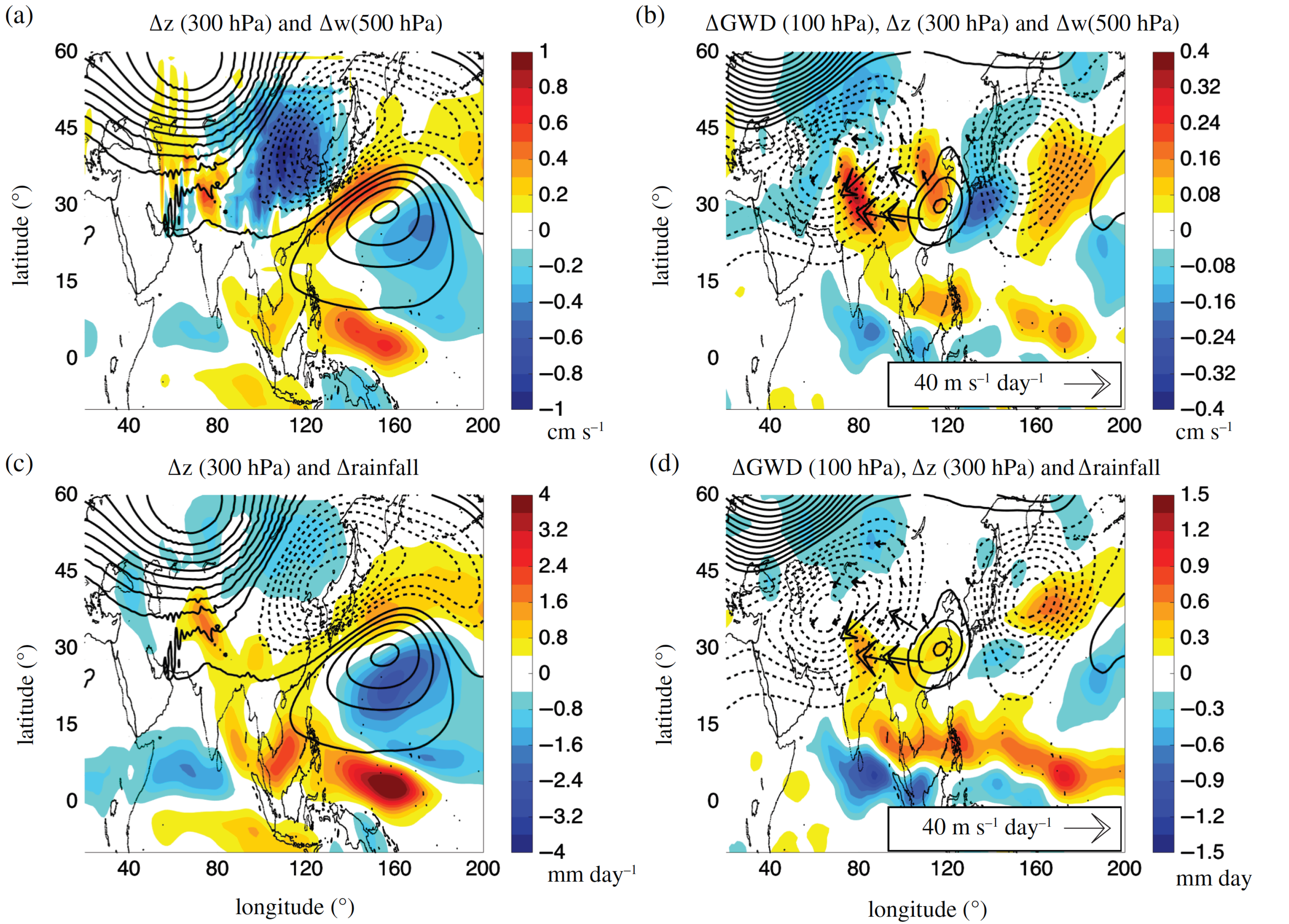
w/ minus w/o GWD over the Plateau

ΔGWD (100hPa) , Δz (500hPa) and Δw(500hPa)



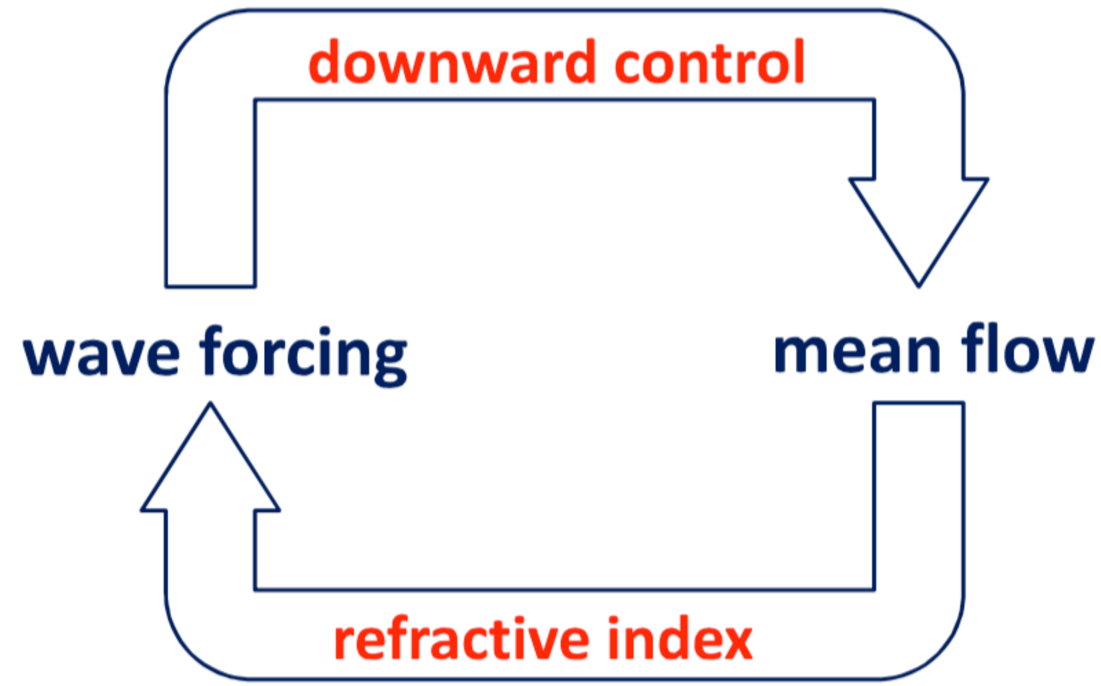
contour interval: ± 6m

Outlook

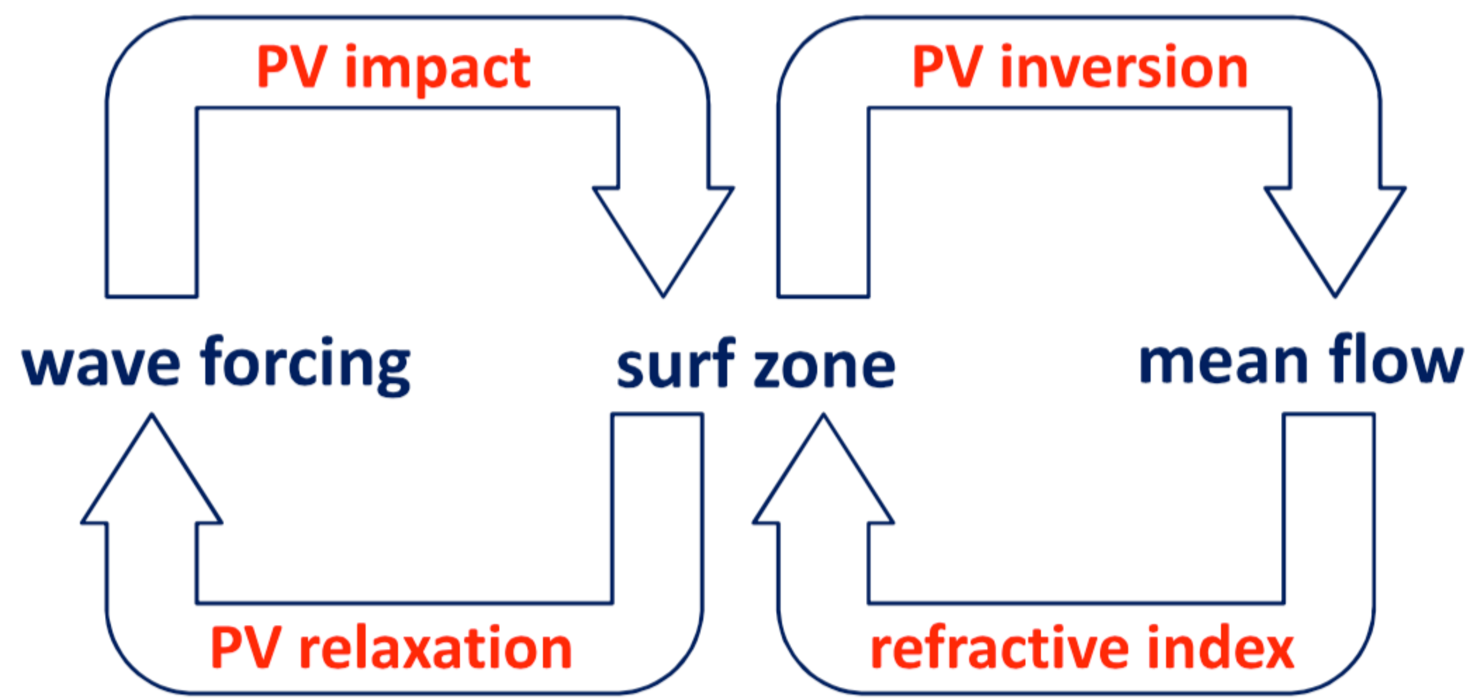

(a)
Δz (300 hPa) and Δw(500 hPa)
(b)
ΔGWD (100 hPa), Δz (300 hPa) and Δw(500 hPa)
(c)
Δz (300 hPa) and Δrainfall
(d)
ΔGWD (100 hPa), Δz (300 hPa) and Δrainfall
latitude (°)
longitude (°)
60
45
30
15
0
40
80
120
160
200
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
cm s⁻¹
0.4
0.32
0.24
0.16
0.08
0
−0.08
−0.16
−0.24
−0.32
−0.4
40 m s⁻¹ day⁻¹
4
3.2
2.4
1.6
0.8
0
−0.8
−1.6
−2.4
−3.2
−4
mm day⁻¹
1.5
1.2
0.9
0.6
0.3
0
−0.3
−0.6
−0.9
−1.2
−1.5
mm day

Two paradigms for interpreting BDC dynamics

conventional paradigm:



modified paradigm:



Stability depends critically on meridional scale

Stability constraint: $\overline{q}_y \geq 0$

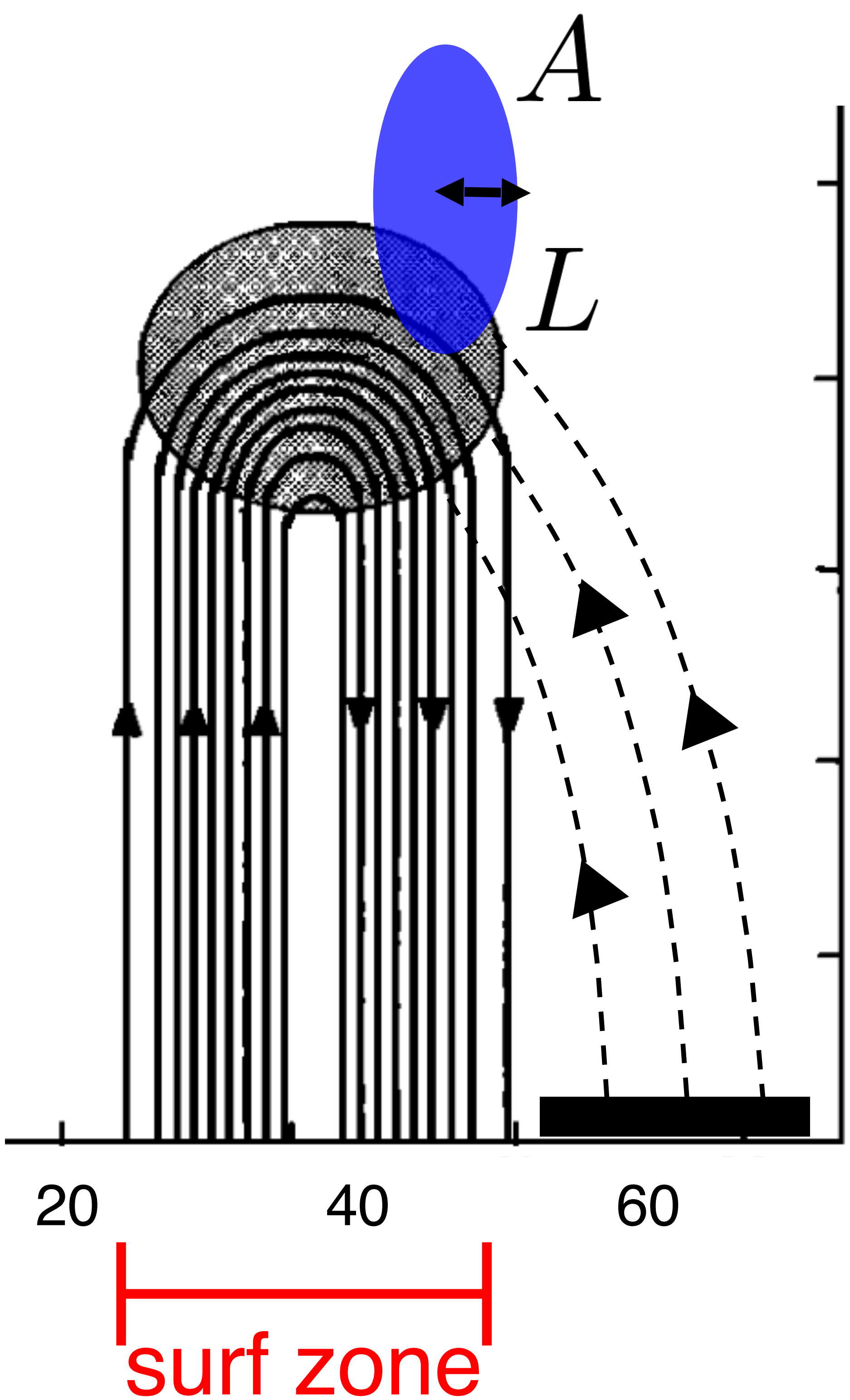
Using Quasi Geostrophic scaling

$$\delta \overline{q}_y \sim A L^{-4}$$

strong and narrow torques can initiate instability

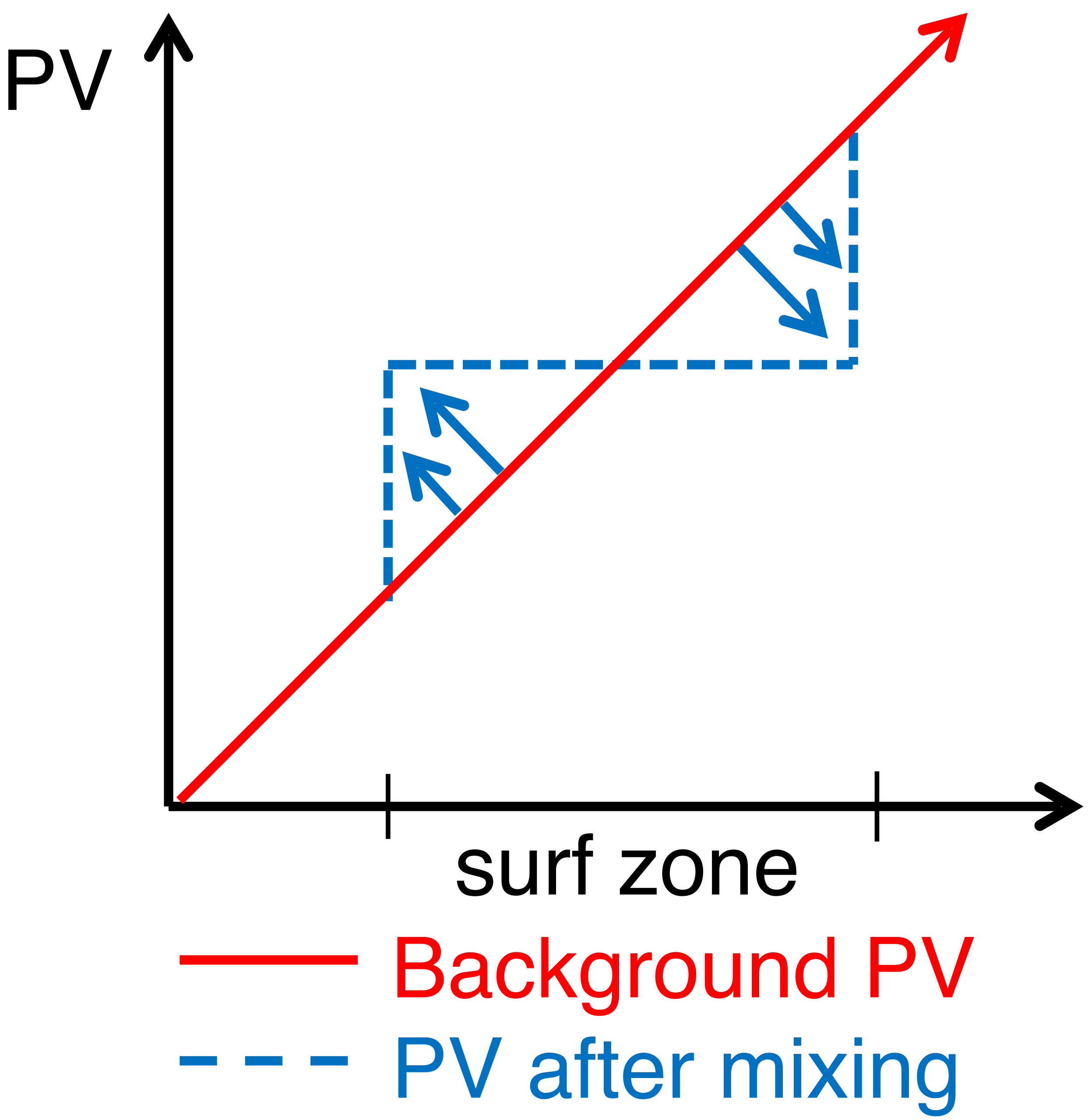
↓

the resolved flow must respond in order to maintain stability



Even more: constraint on the total wave driving

1D PV Staircase model



The zonal-mean QG PV equation

$$\bar{q}_t = -(\boldsymbol{\nabla} \cdot \boldsymbol{F} + \boldsymbol{X})_y + \overline{S}$$

$$\bar{q}_t = -(\boldsymbol{\nabla} \cdot \boldsymbol{F} + \boldsymbol{X})_y - \frac{\overline{q} - q_b}{\tau}$$

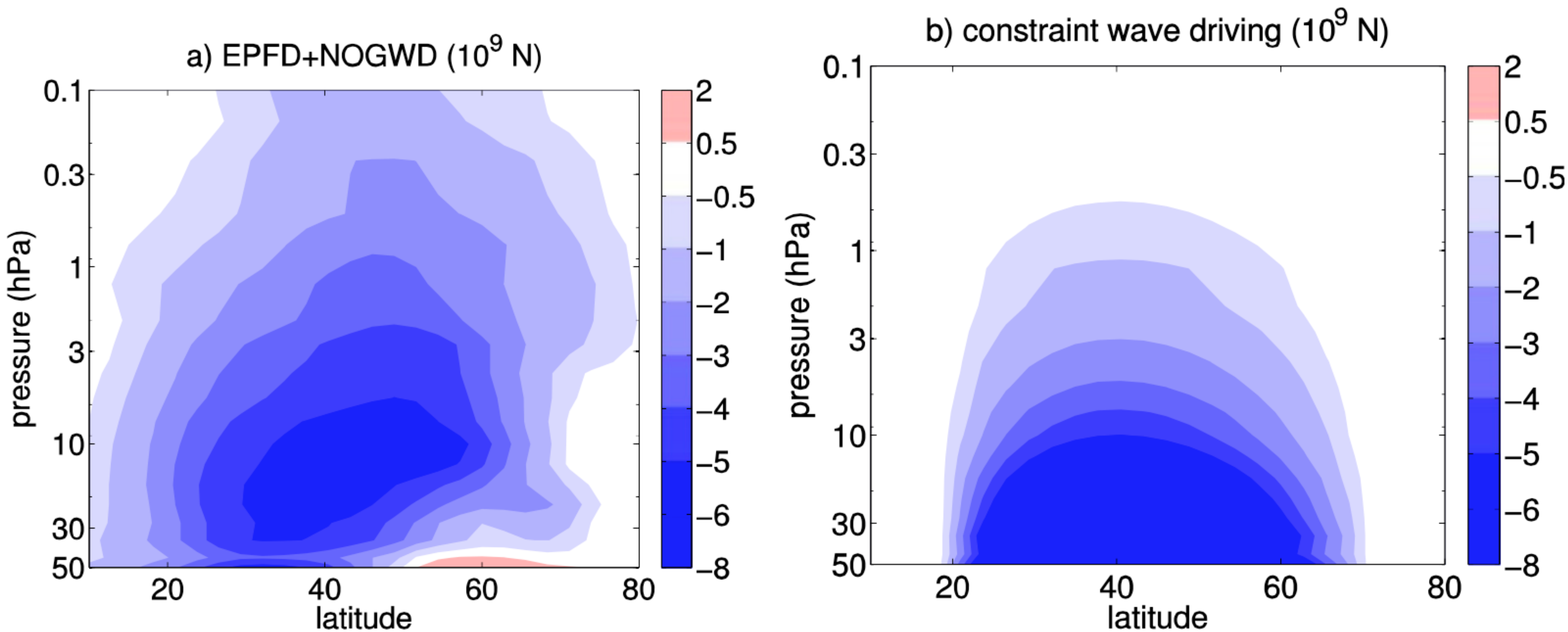
$$(\boldsymbol{\nabla} \cdot \boldsymbol{F} + \boldsymbol{X})_y = \boldsymbol{G}_y = -\frac{\overline{q} - q_b}{\tau}$$

$$\boldsymbol{G}_{yy} = -\frac{\overline{q}_y - q_{by}}{\tau} = \frac{q_{by}}{\tau}$$

$$\boldsymbol{G} = -\frac{q_{by} h^2}{2\tau} + \frac{q_{by}(y - y_0)^2}{2\tau}$$

Even more: constraint on the total wave driving

2-d structure of the 1-d model: $\boldsymbol{G} = -\frac{q_{by}h^2}{2\tau} + \frac{q_{by}(y-y_0)^2}{2\tau}$



$$q_b = f, h = 26^\circ, y_0 = 45^\circ, \tau = 40\ days$$