Maintenance of the mean kinetic energy in the global ocean by the barotropic and baroclinic energy routes

Nori Aiki (JAMSTEC) and K. J. Richards (Univ of Hawaii)

Output of 0.1-deg global MOM is diagnosed ….

Classical Debate:

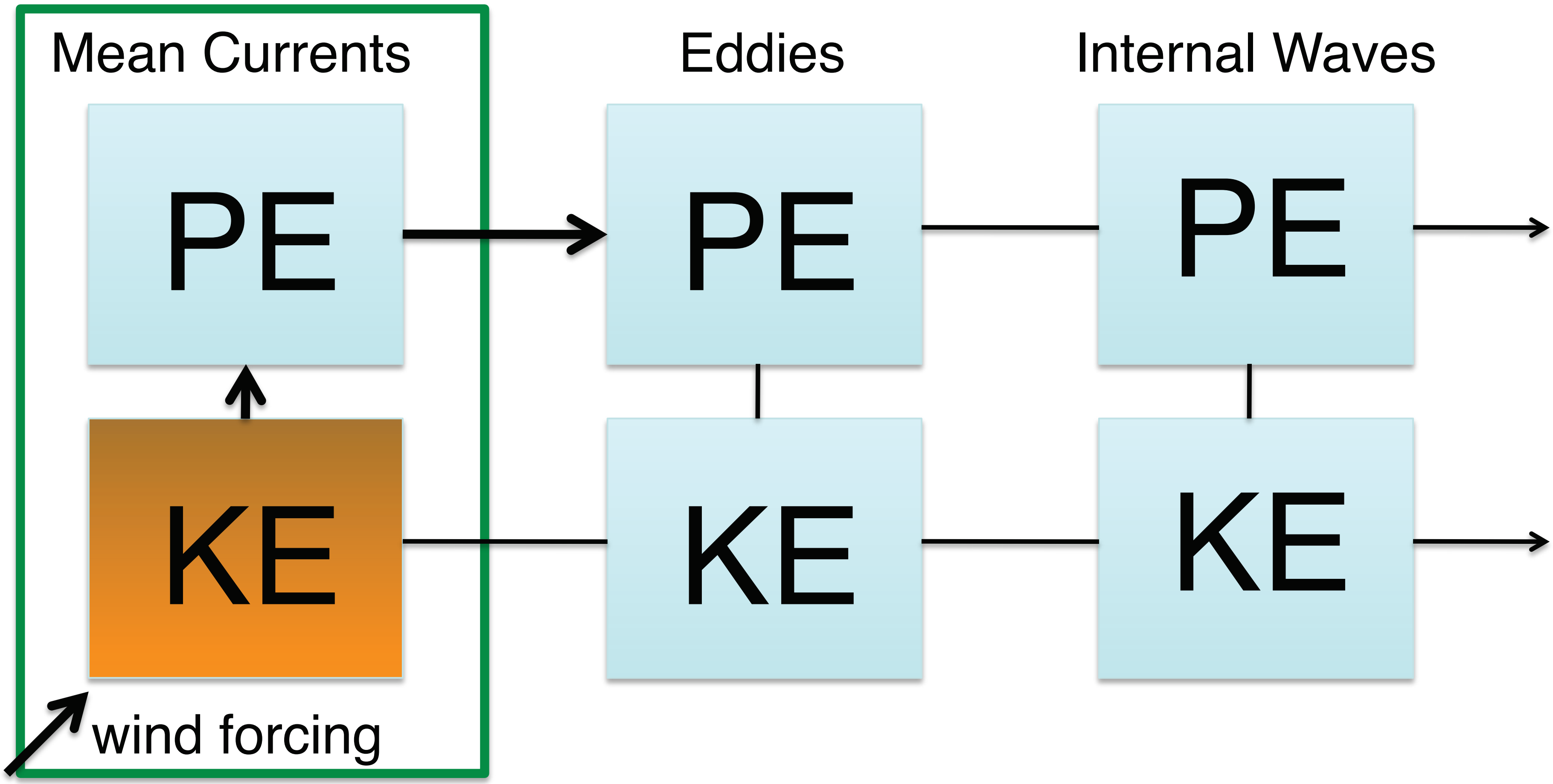
Dynamics of the Antarctic Circumpolar Current:
Munk and Palmen (1951, inviscid theory)
Stommel (1957, viscid theory)

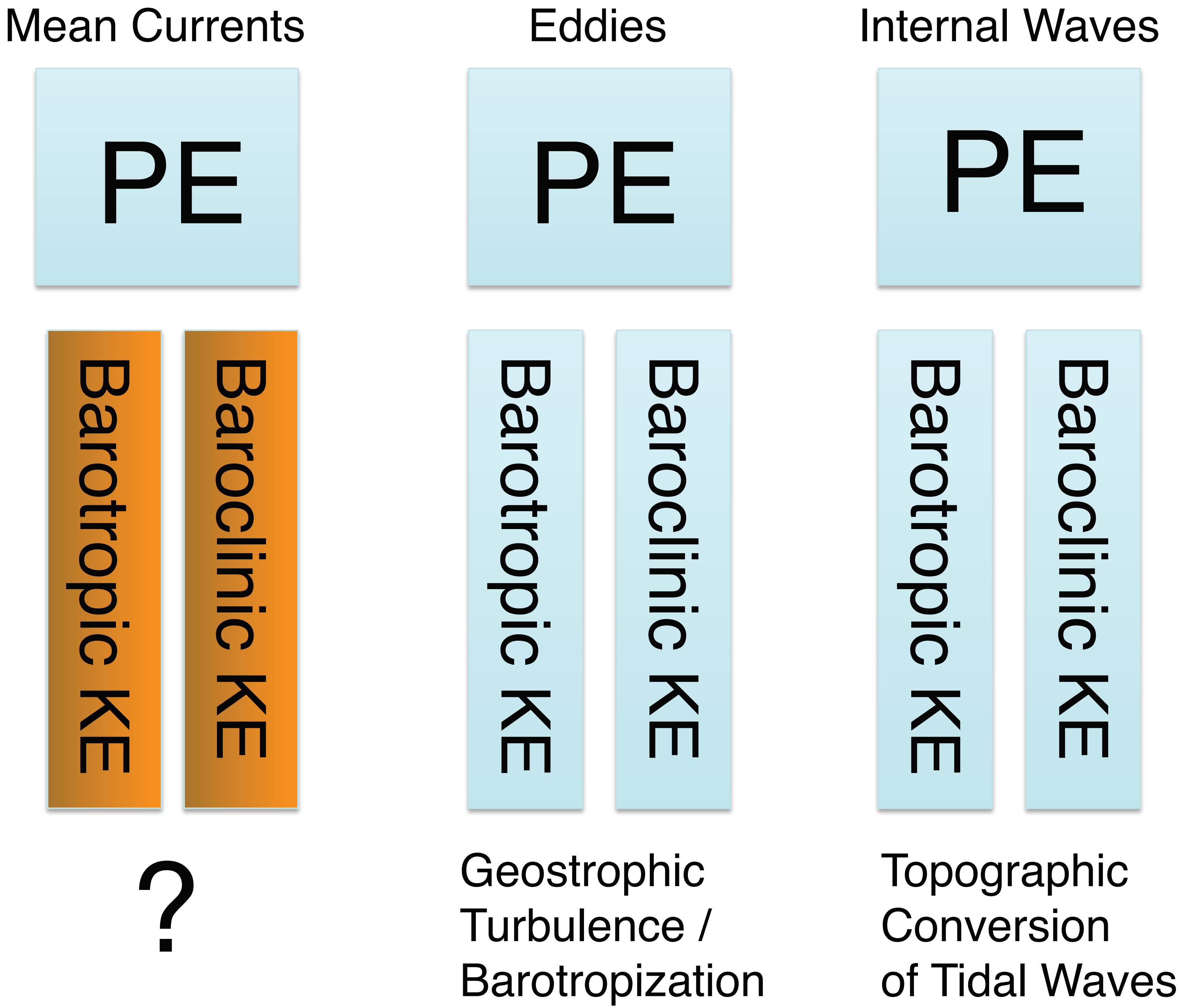
Future Direction:

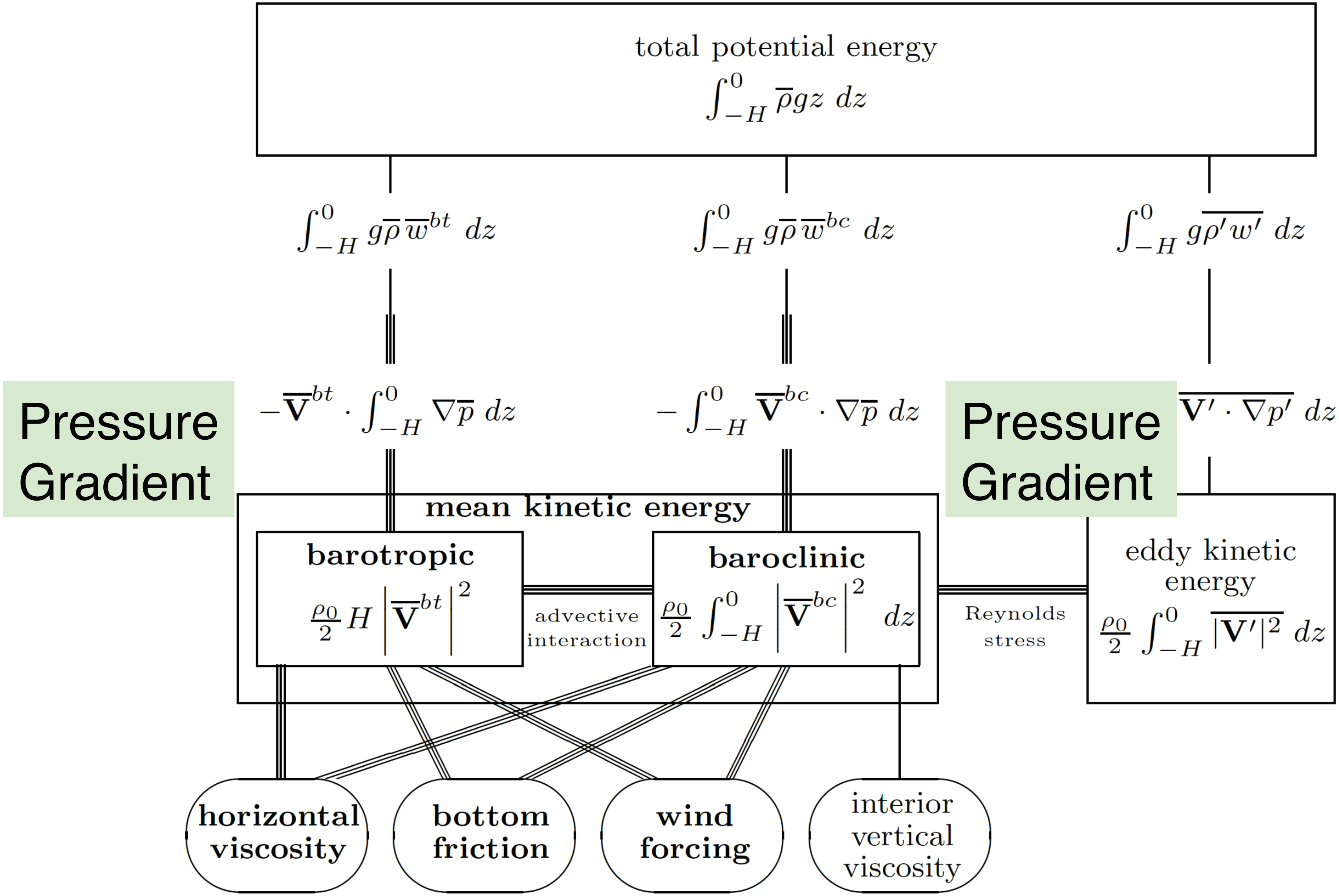
Separation of Gulf Stream / Kuroshio
Horizontal Viscosity in OGCMs:
Biharmonic (cosmetic) or Laplacian (physical)

z-coordinate models (friction at subsurface side walls)

General Circulation Theories /
Climate Models



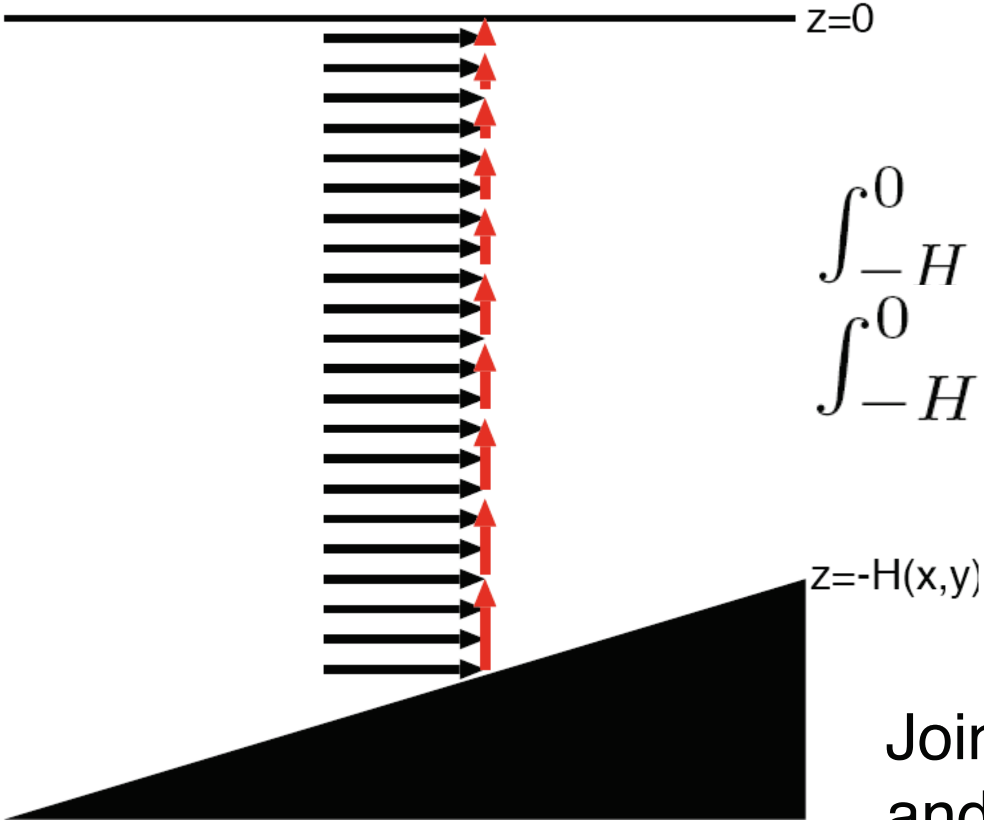

Mean Currents
Eddies
Internal Waves
PE
PE
PE
Barotropic KE
Baroclinic KE
Barotropic KE
Baroclinic KE
Barotropic KE
Baroclinic KE
?
Geostrophic Turbulence / Barotropization
Topographic Conversion of Tidal Waves



Modification of the energy diagram of Holland (1975) and Ivchenko et al. (1997)

Vertical component of Barotropic velocity

$$\overline{w}^{bt} \equiv (z/H)\overline{\mathbf{V}}^{bt} \cdot \nabla H$$

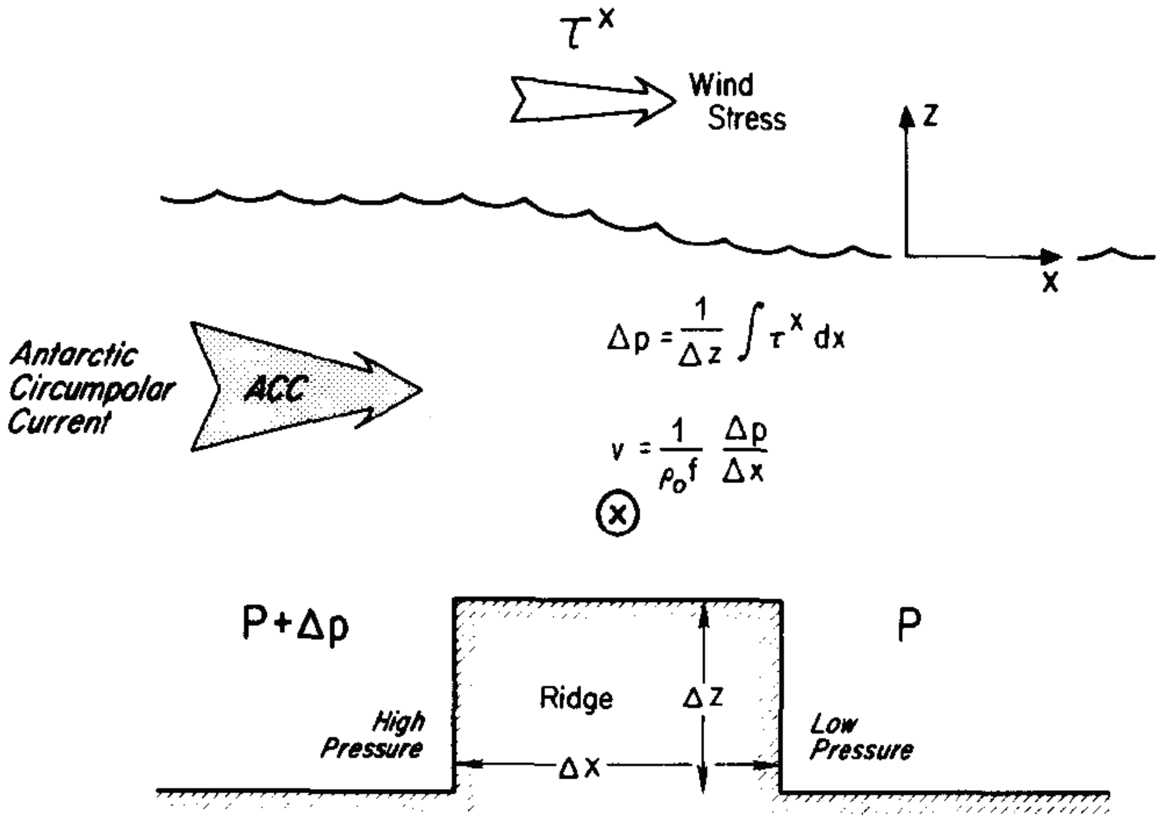


$$\int_{-H}^{0} g\bar{\rho}\,\overline{w}^{bt}\ dz =$$
$$\int_{-H}^{0} g\bar{\rho} z dz\ (1/H)\overline{\mathbf{V}}^{bt} \cdot \nabla H$$

could be called
the work of JEBAR:

Joint Effect Baroclinicity
and Bottom Relief (Sarkisian and Ivanov, 1971)

Momentum balance of Antarctic Circumpolar Current



Johnson and Bryden (1989)
Munk and Palmen (1951)

Barotropic Momentum

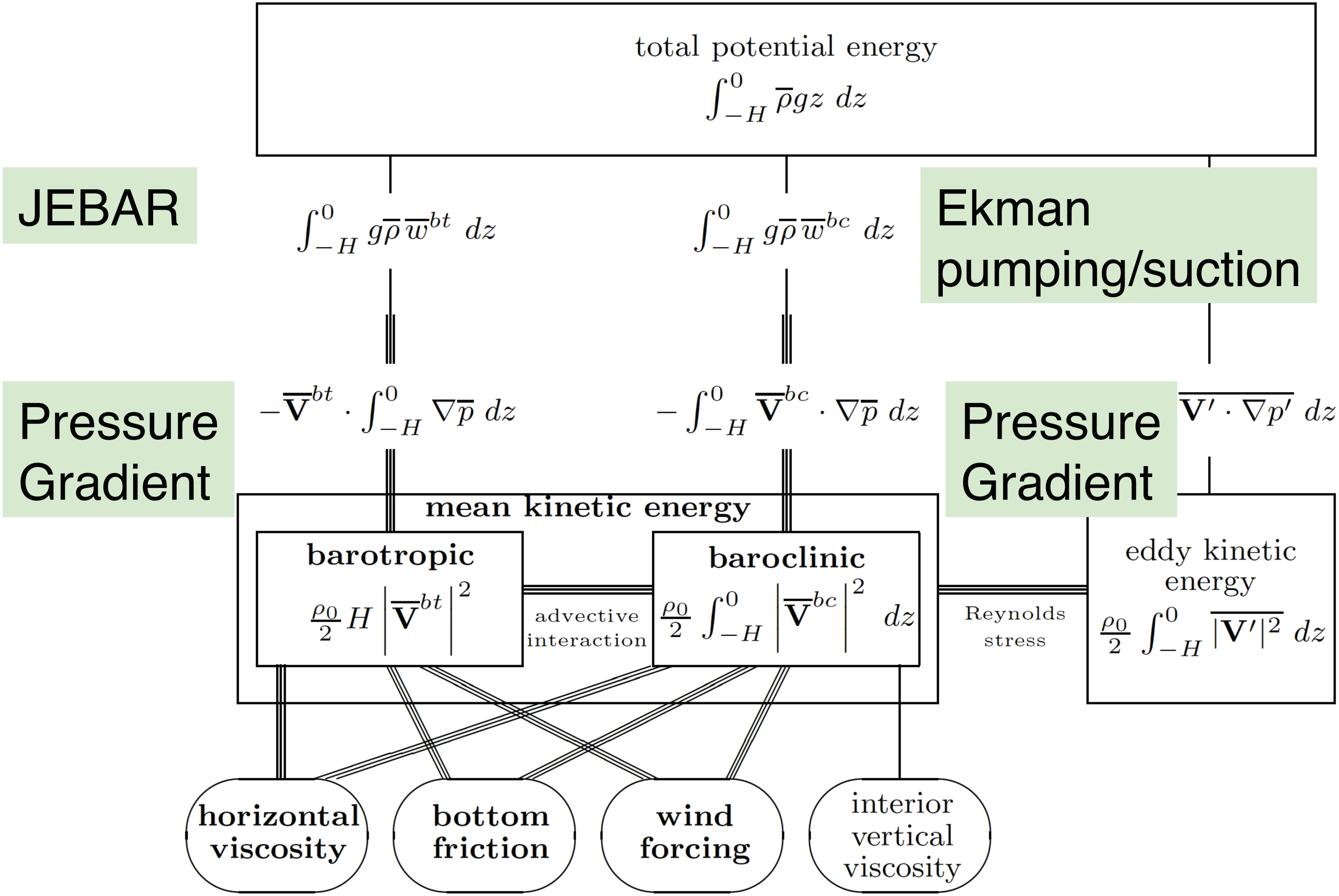
$$\rho_0 \mathbf{f} \times \int_{-H}^{0} \overline{\mathbf{V}}\, dz \simeq \boxed{-\int_{-H}^{0} \nabla \overline{p}\, dz} + \overline{\boldsymbol{\tau}}^{\mathbf{wind}}$$

Barotropic Vorticity $\Psi:$ barotropic streamfunction

$$\rho_0 J\left(\Psi, f/H\right) \simeq \boxed{J\left(\int_{-H}^{0} g\overline{\rho} z\, dz, 1/H\right)} + \nabla \times \frac{\overline{\boldsymbol{\tau}}^{\mathbf{wind}}}{H}$$

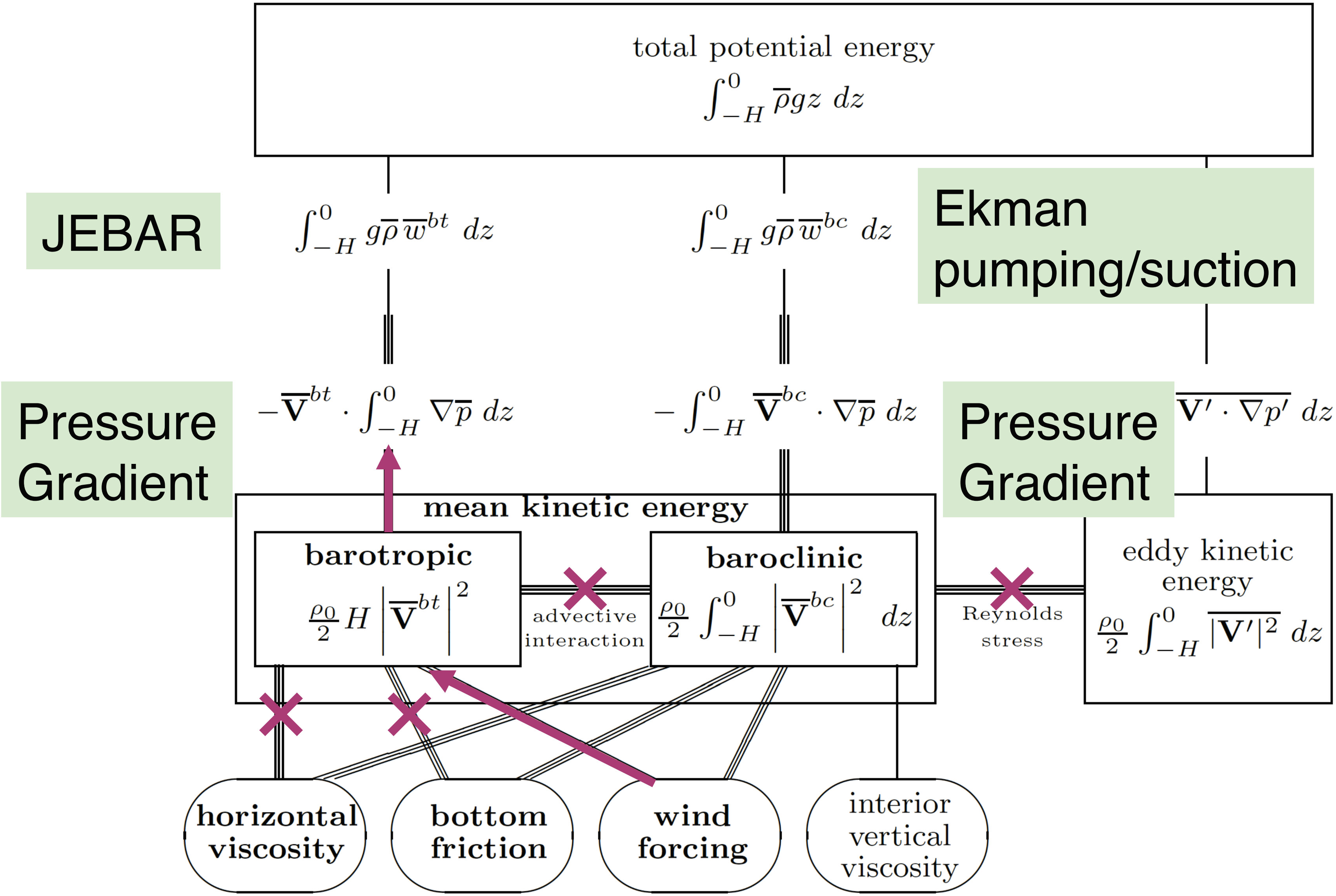
Joint Effect Baroclinicity
and Bottom Relief (JEBAR)

(Sarkisian and Ivanov, 1971)

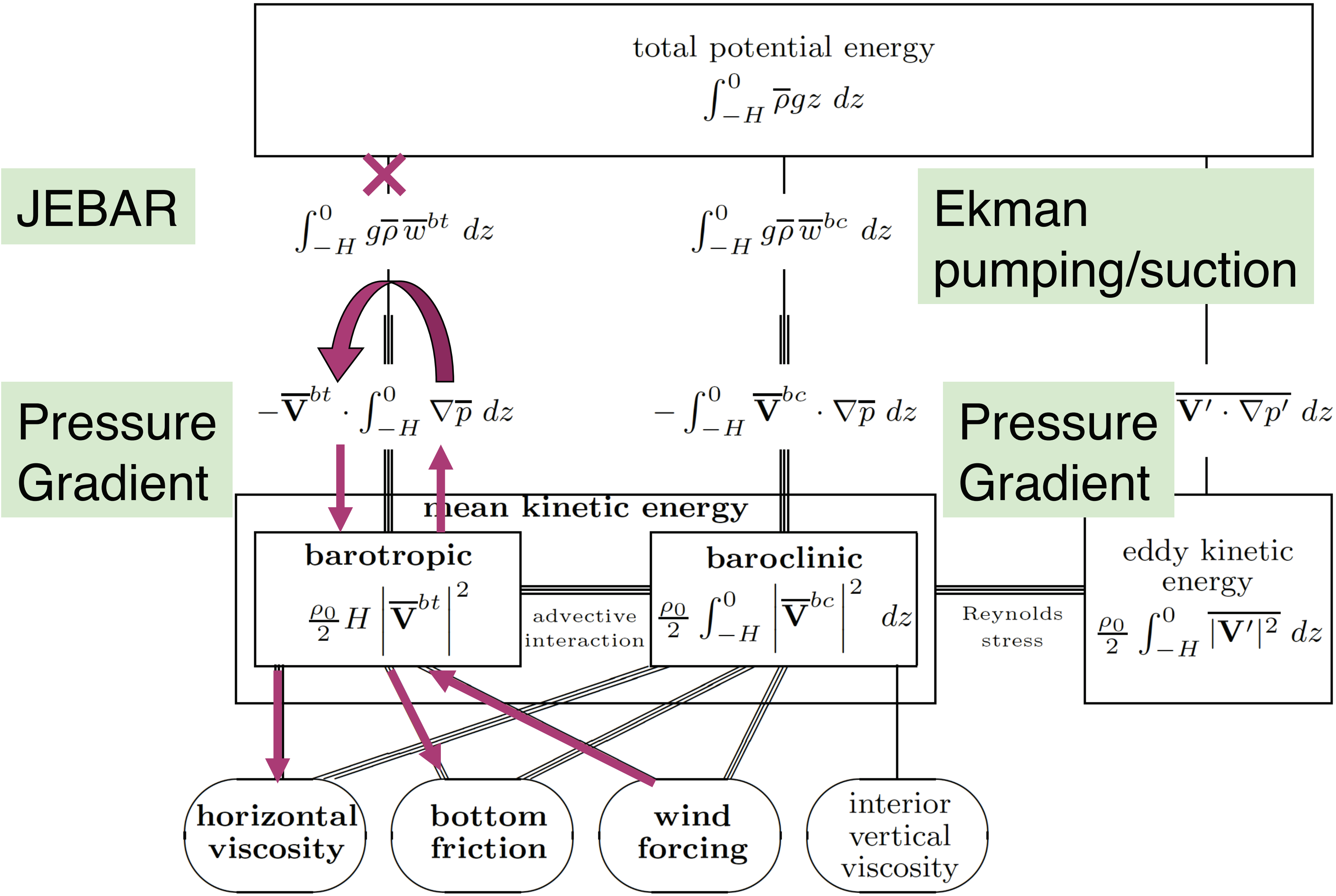


Modification of the energy diagram of Holland (1975) and Ivchenko et al. (1997)

ACC as an inviscid sloped-bottom model (Munk & Palmen, 1951)



ACC as a viscid flat-bottom model (Stommel, 1957)



Purpose

- Compare JEBAR and the frictional effects
- Compare the barotropic and baroclinic energy routes

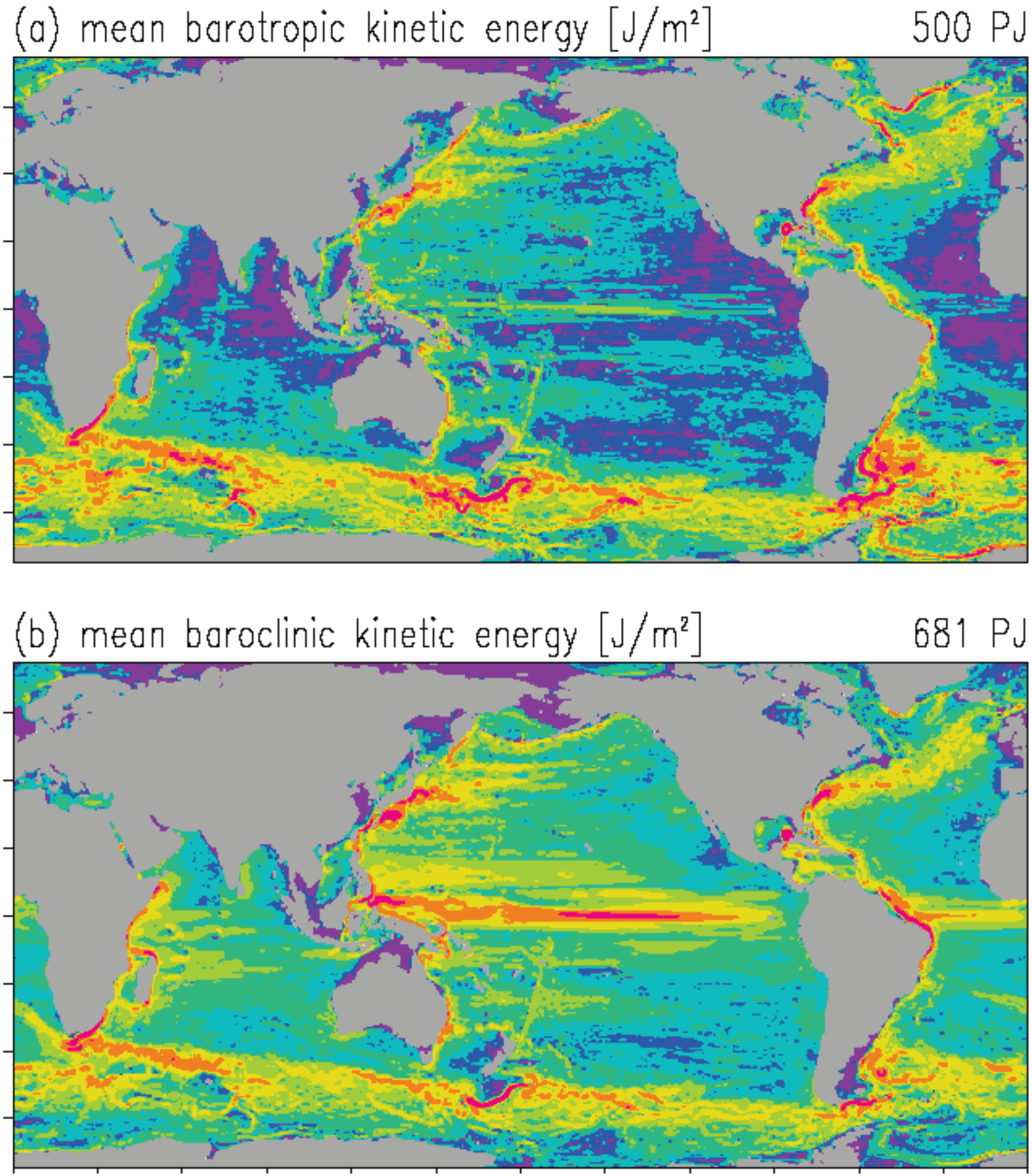
An OGCM for the Earth Simulator (MOM3)

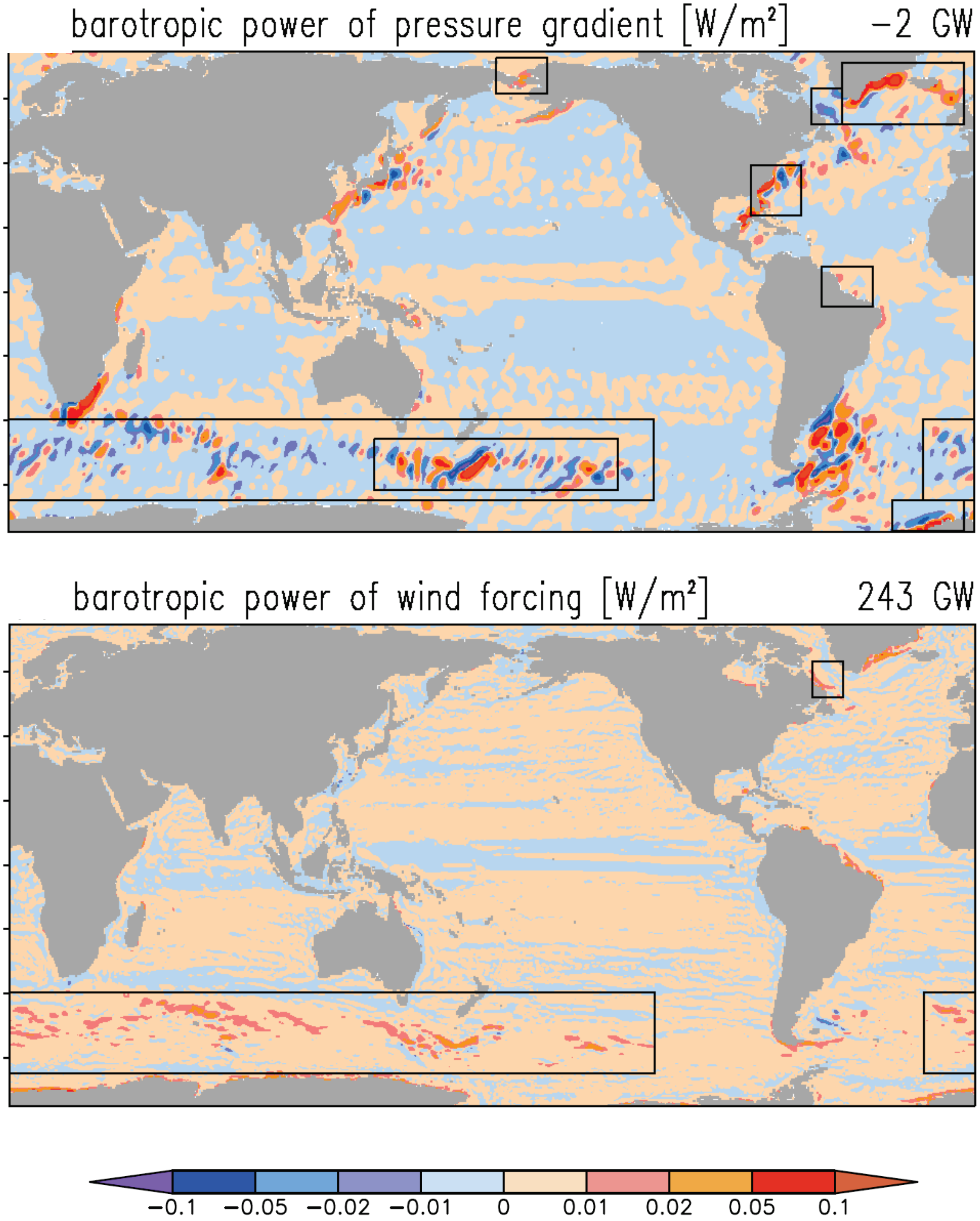
Masumoto et al. (2004)
Sasai et al. (2004)

•Horizontal resolution of 0.1 x 0.1 deg in a semi-global domain
•Climatological atmospheric forcing from NCEP/NCAR reanalysis
•Horizontal Friction is biharmonic

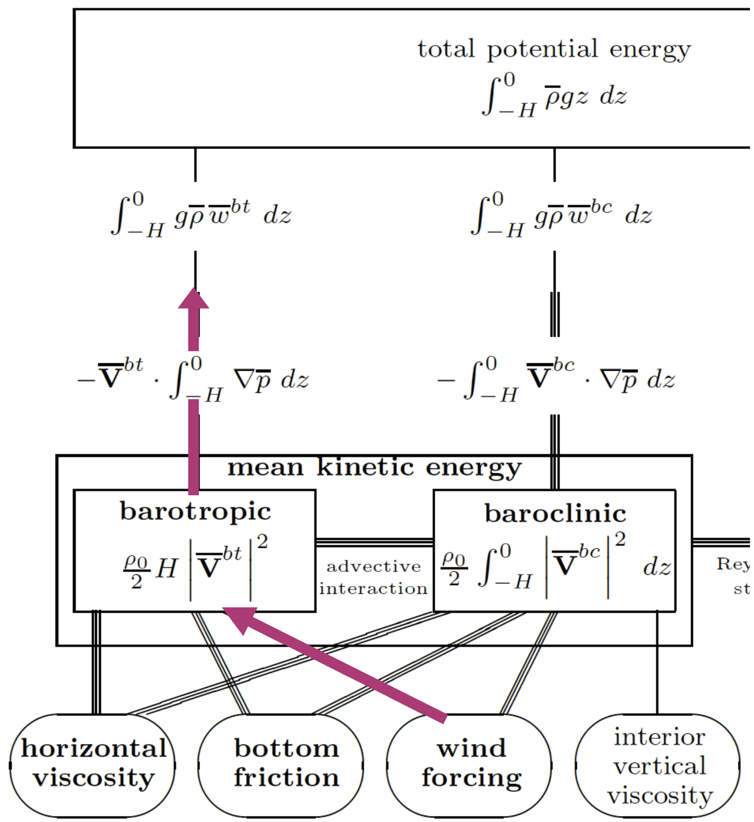
Analysis

1. Annual mean fields for 6 years (46th-51th)
2. 3-day snapshots used to calculate the Reynolds stress

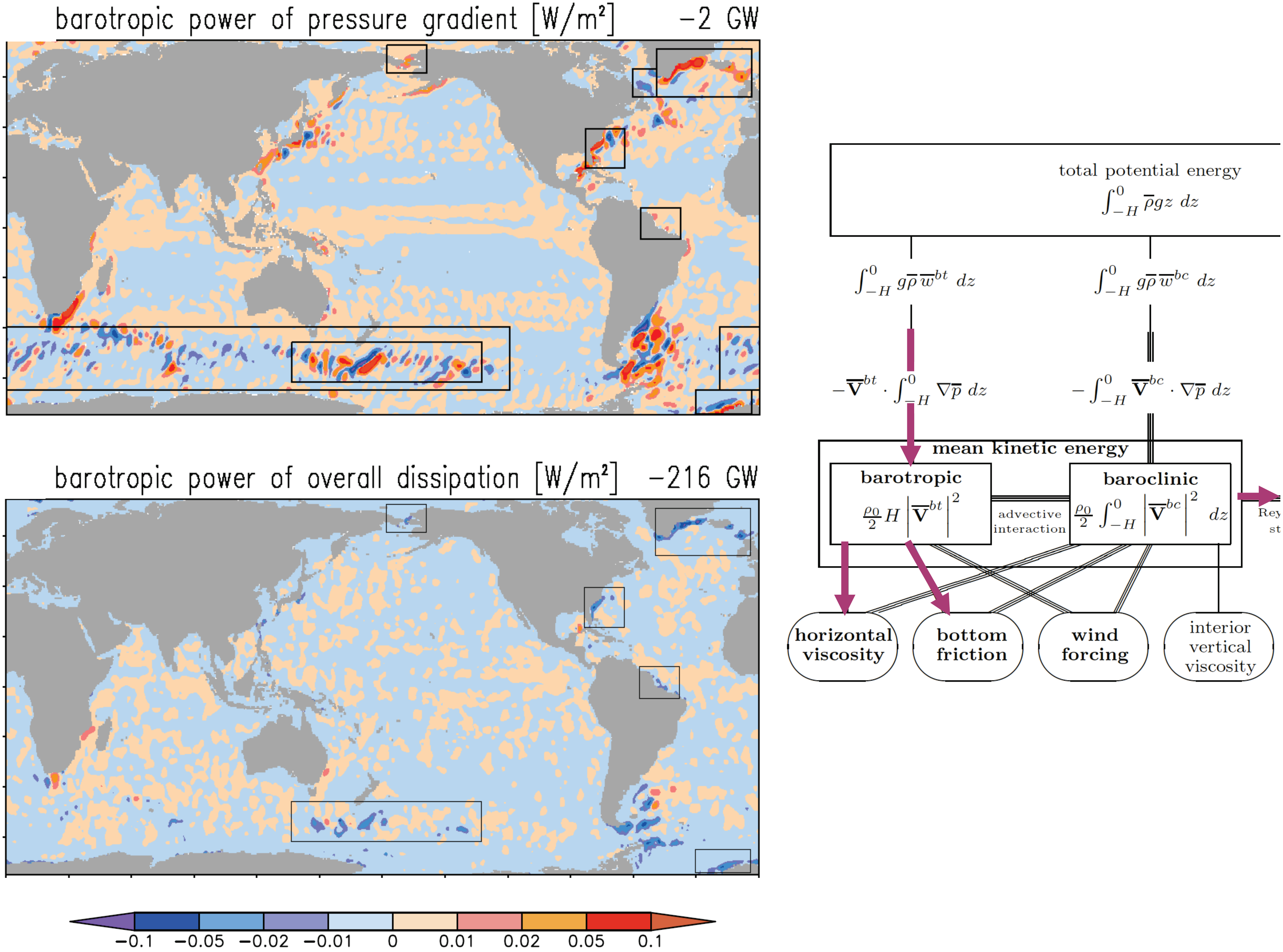

(a) mean barotropic kinetic energy [J/m²]
500 PJ
(b) mean baroclinic kinetic energy [J/m²]
681 PJ



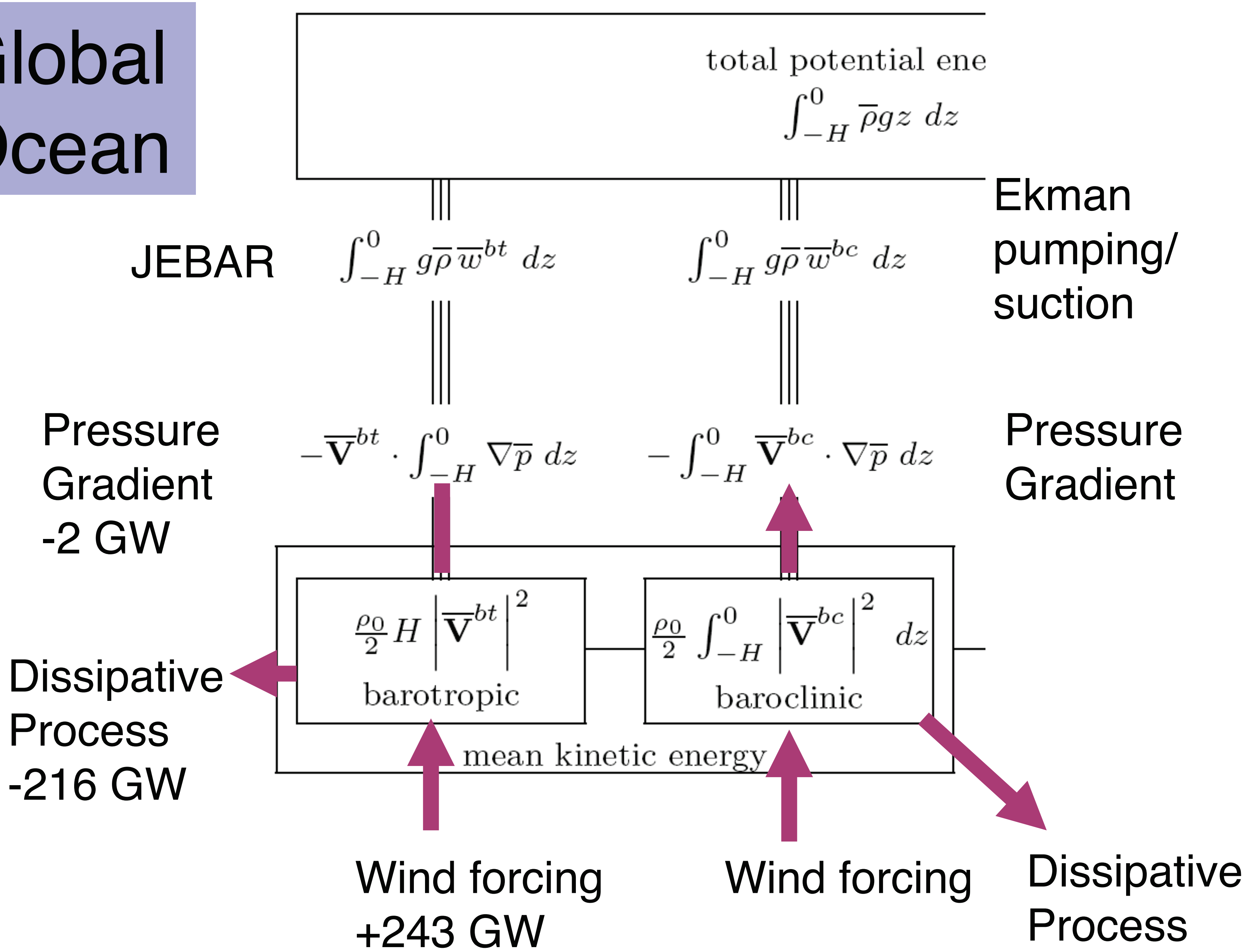
barotropic power of pressure gradient [W/m²]
−2 GW
barotropic power of wind forcing [W/m²]
243 GW
−0.1 −0.05 −0.02 −0.01 0 0.01 0.02 0.05 0.1



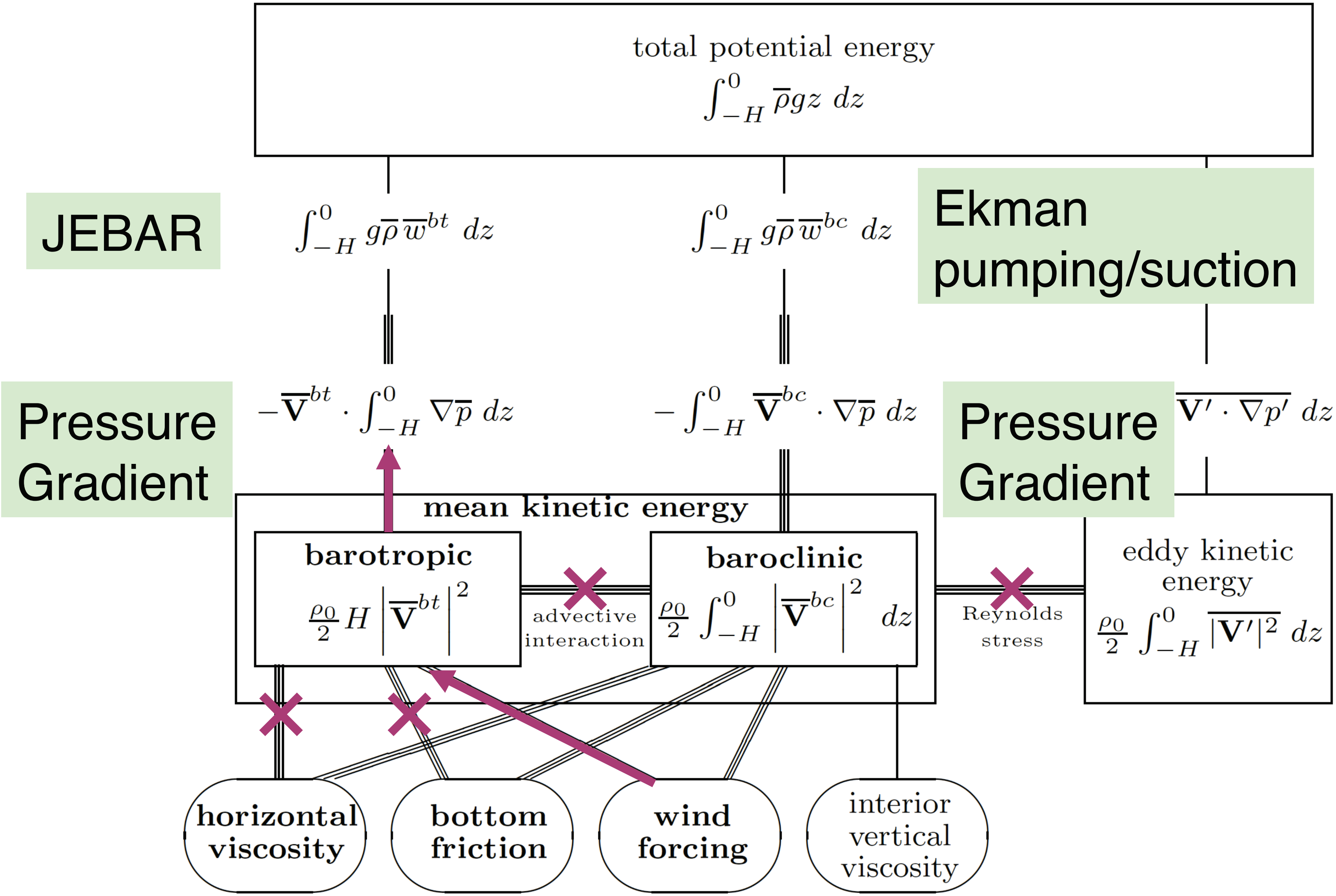
total potential energy
$\int_{-H}^{0} \overline{\rho} g z \, dz$
$\int_{-H}^{0} g\overline{\rho}\,\overline{w}^{bt} \, dz$
$\int_{-H}^{0} g\overline{\rho}\,\overline{w}^{bc} \, dz$
$-\overline{\mathbf{V}}^{bt} \cdot \int_{-H}^{0} \nabla \overline{p} \, dz$
$-\int_{-H}^{0} \overline{\mathbf{V}}^{bc} \cdot \nabla \overline{p} \, dz$
mean kinetic energy
barotropic
$\frac{\rho_0}{2} H \left|\overline{\mathbf{V}}^{bt}\right|^2$
advective interaction
baroclinic
$\frac{\rho_0}{2} \int_{-H}^{0} \left|\overline{\mathbf{V}}^{bc}\right|^2 dz$
horizontal viscosity
bottom friction
wind forcing
interior vertical viscosity


barotropic power of pressure gradient [W/m²] −2 GW
barotropic power of overall dissipation [W/m²] −216 GW
−0.1 −0.05 −0.02 −0.01 0 0.01 0.02 0.05 0.1
total potential energy
$\int_{-H}^{0} \overline{\rho} g z \, dz$
$\int_{-H}^{0} g\overline{\rho}\,\overline{w}^{bt} \, dz$
$\int_{-H}^{0} g\overline{\rho}\,\overline{w}^{bc} \, dz$
$-\overline{\mathbf{V}}^{bt} \cdot \int_{-H}^{0} \nabla\overline{p} \, dz$
$-\int_{-H}^{0} \overline{\mathbf{V}}^{bc} \cdot \nabla\overline{p} \, dz$
mean kinetic energy
barotropic
$\frac{\rho_0}{2} H \left|\overline{\mathbf{V}}^{bt}\right|^2$
advective interaction
baroclinic
$\frac{\rho_0}{2} \int_{-H}^{0} \left|\overline{\mathbf{V}}^{bc}\right|^2 dz$
horizontal viscosity
bottom friction
wind forcing
interior vertical viscosity

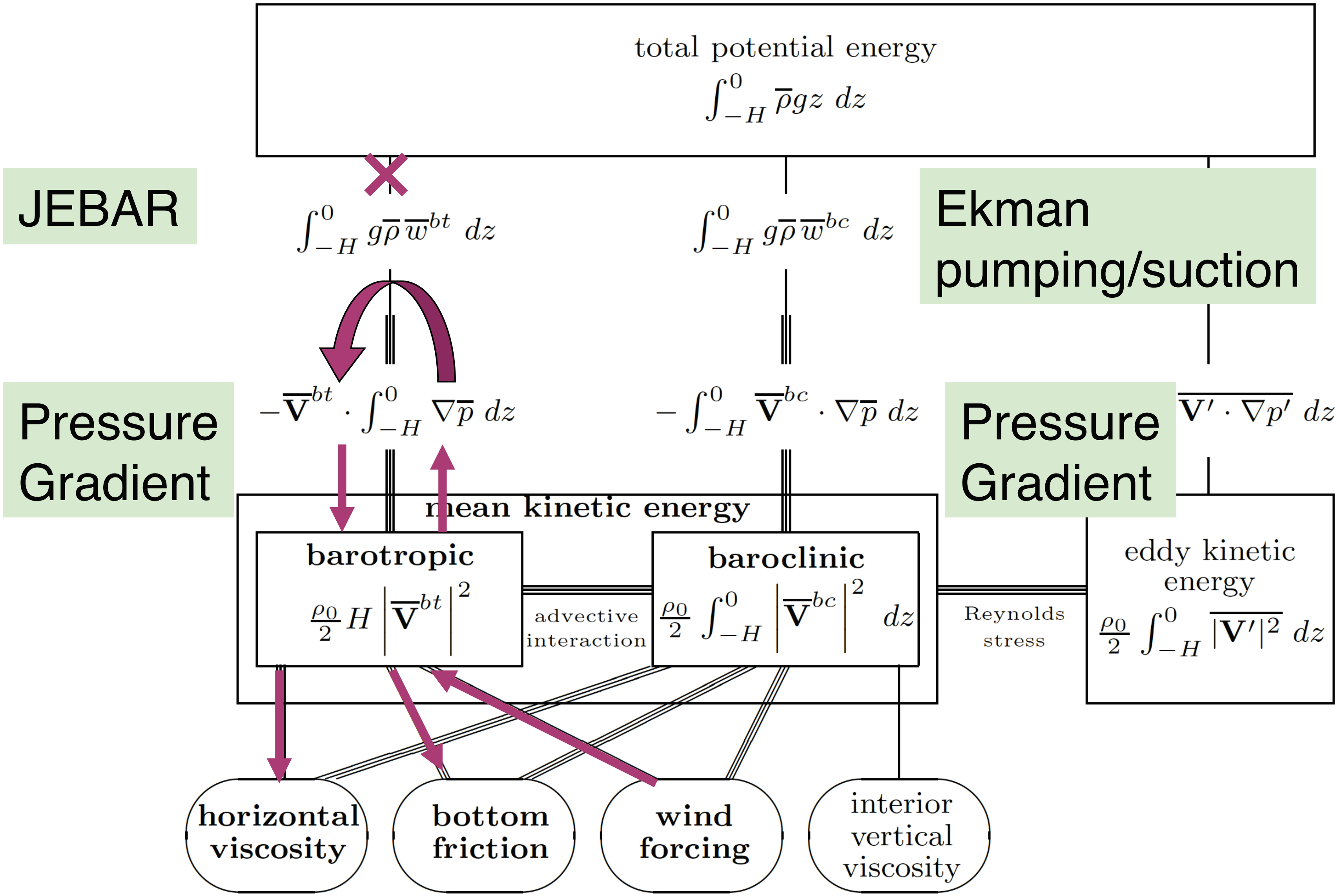
Global Ocean



ACC as an inviscid sloped-bottom model (Munk & Palmen, 1951)



ACC as a viscid flat-bottom model (Stommel, 1957)

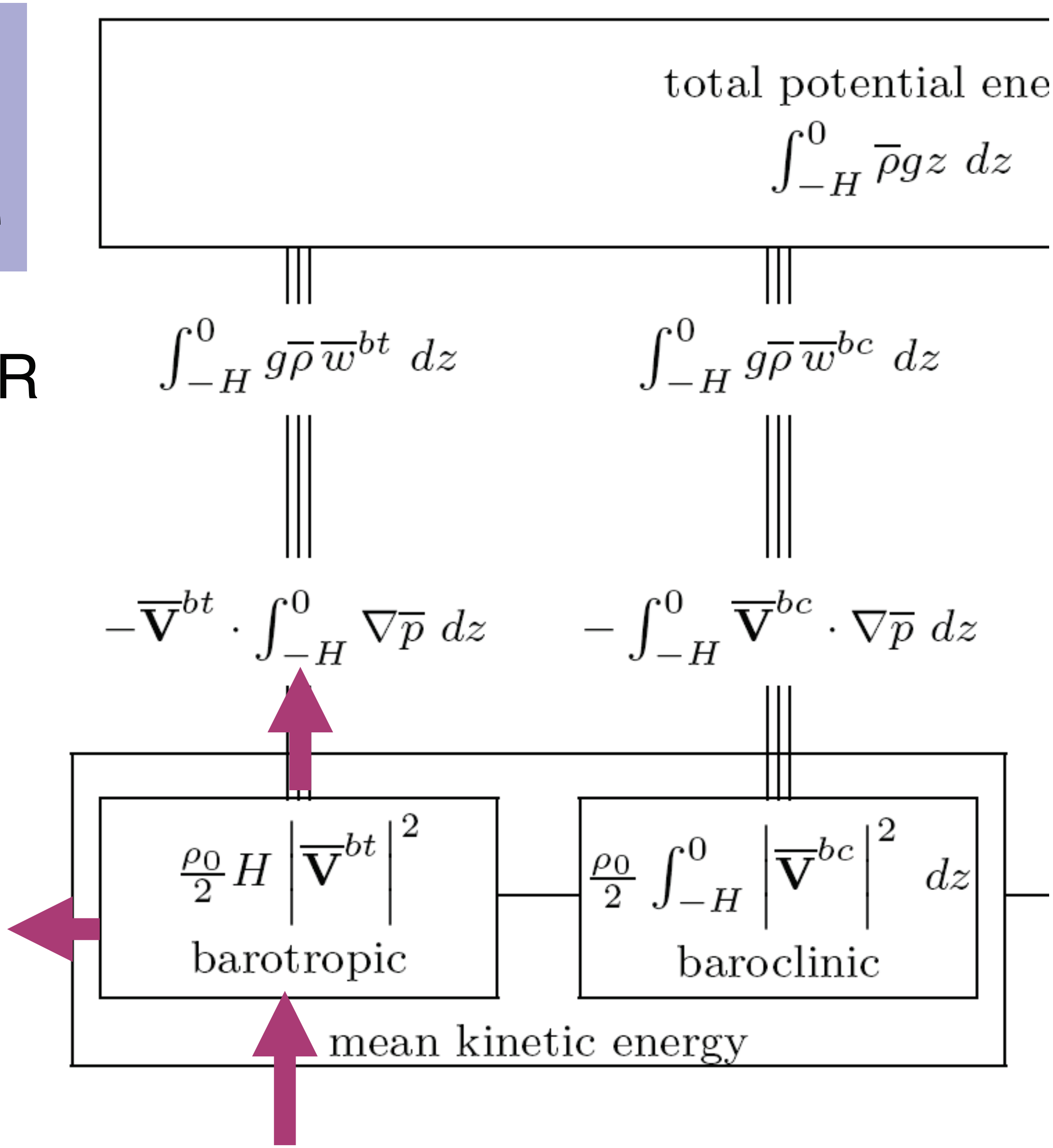


ACC
streamline

JEBAR

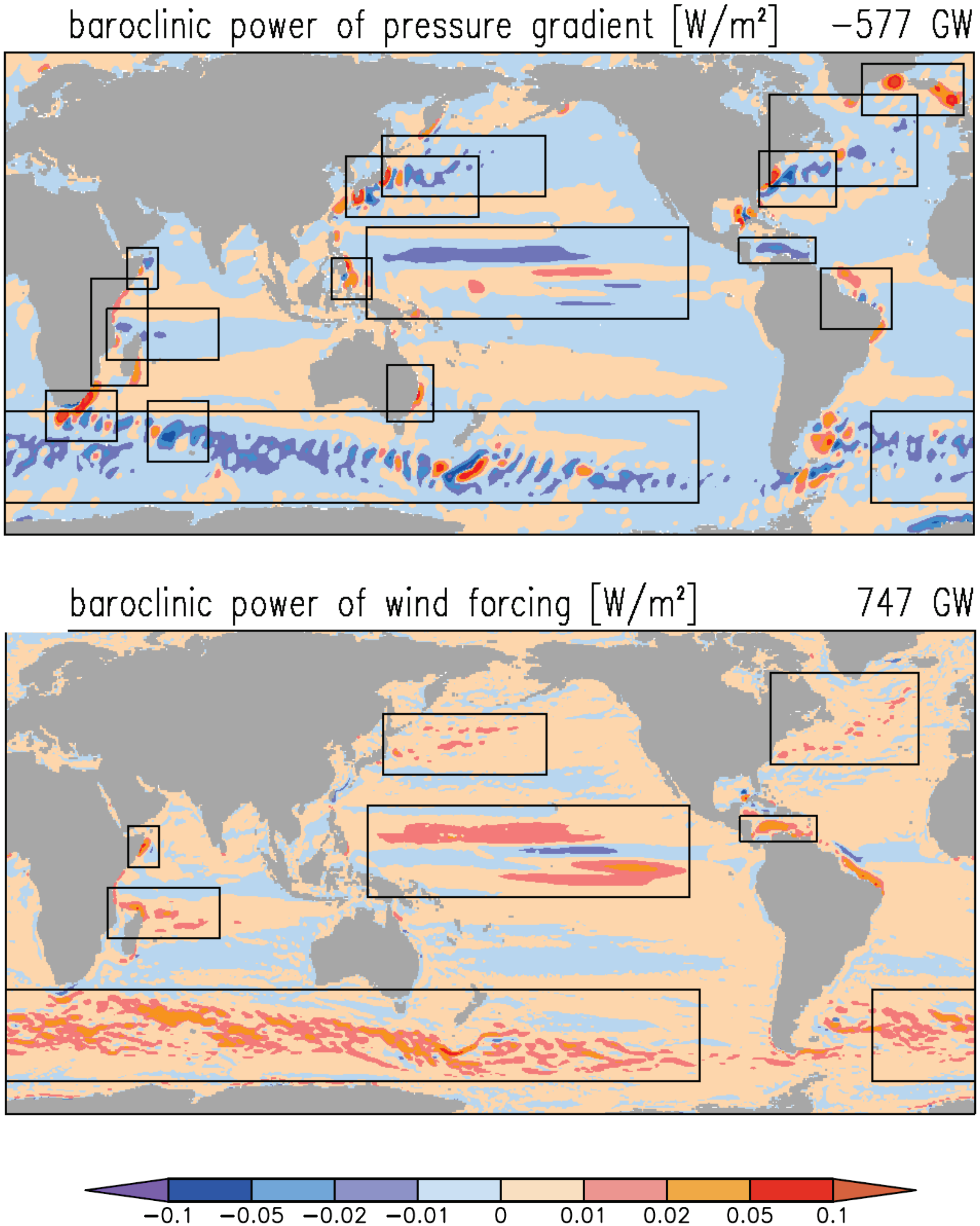
Pressure
Gradient
-42 GW

Dissipative
Process
-38 GW

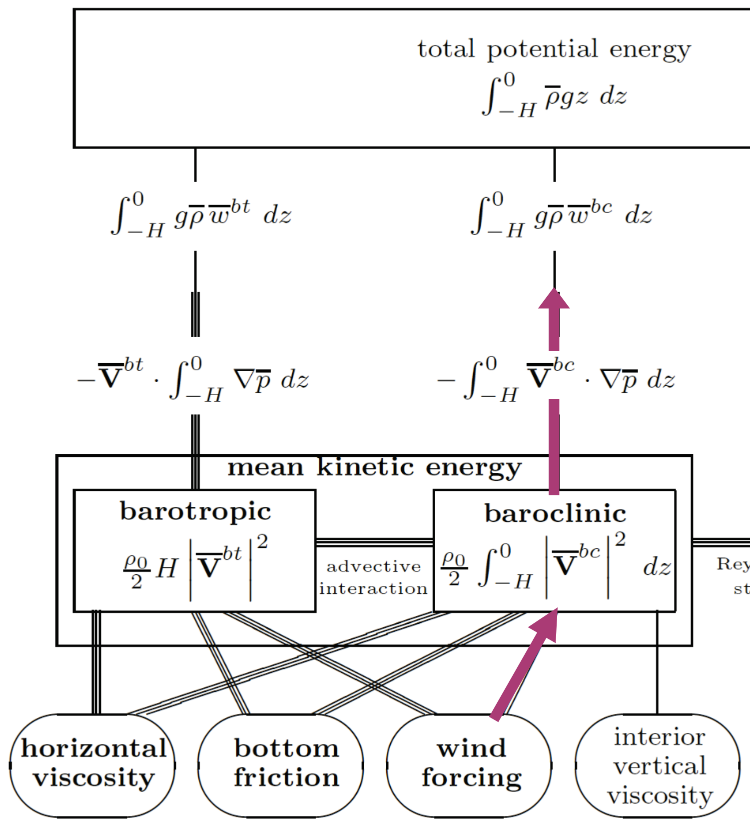


Wind forcing
+81 GW

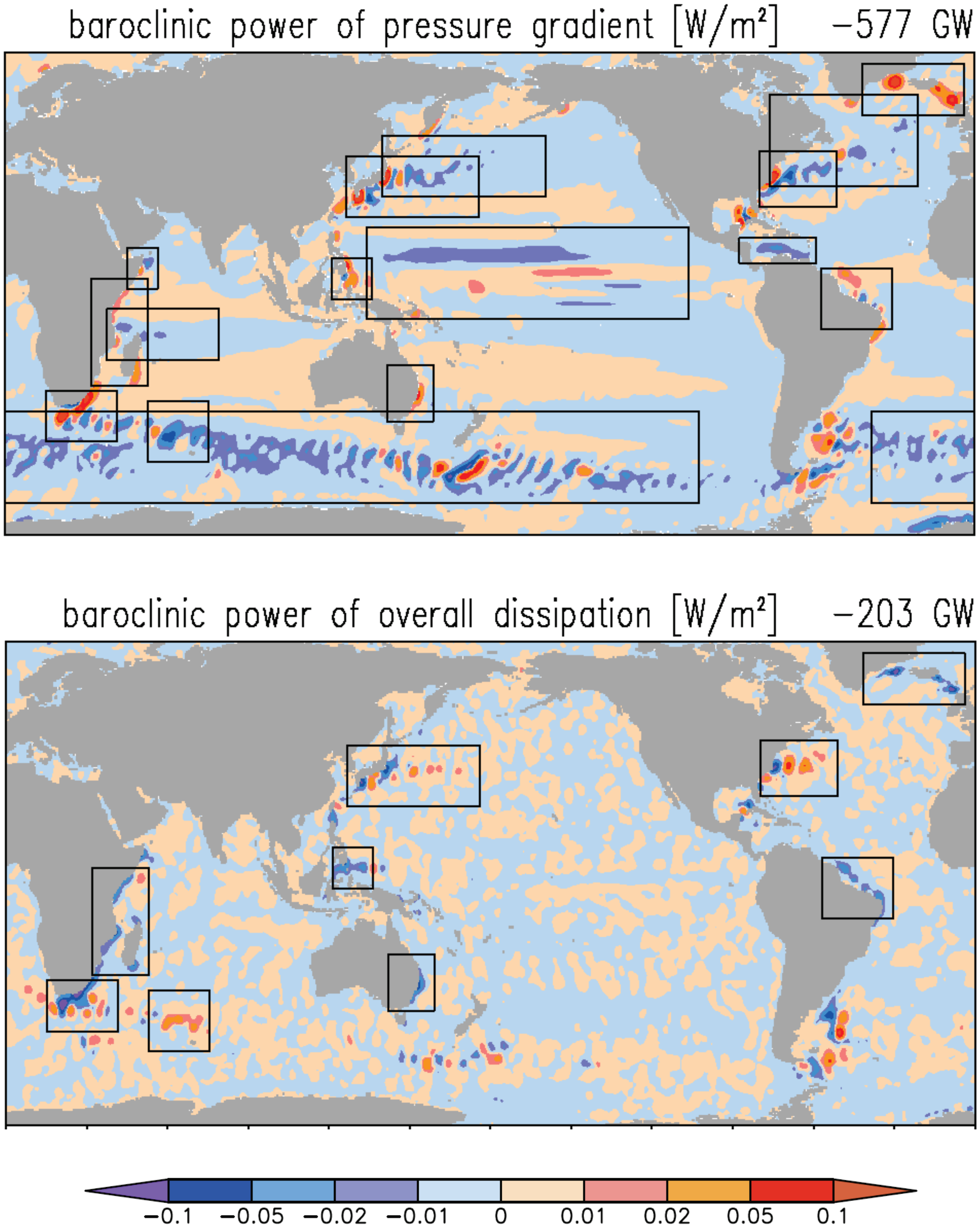
Munk vs. Stommel
draw

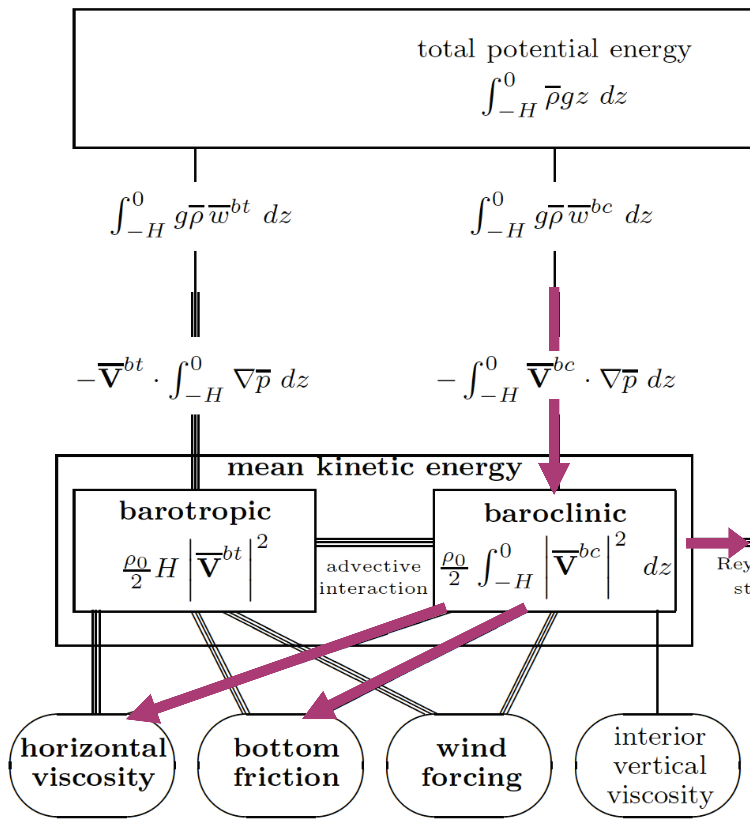


baroclinic power of pressure gradient [W/m²] −577 GW
baroclinic power of wind forcing [W/m²] 747 GW
−0.1 −0.05 −0.02 −0.01 0 0.01 0.02 0.05 0.1



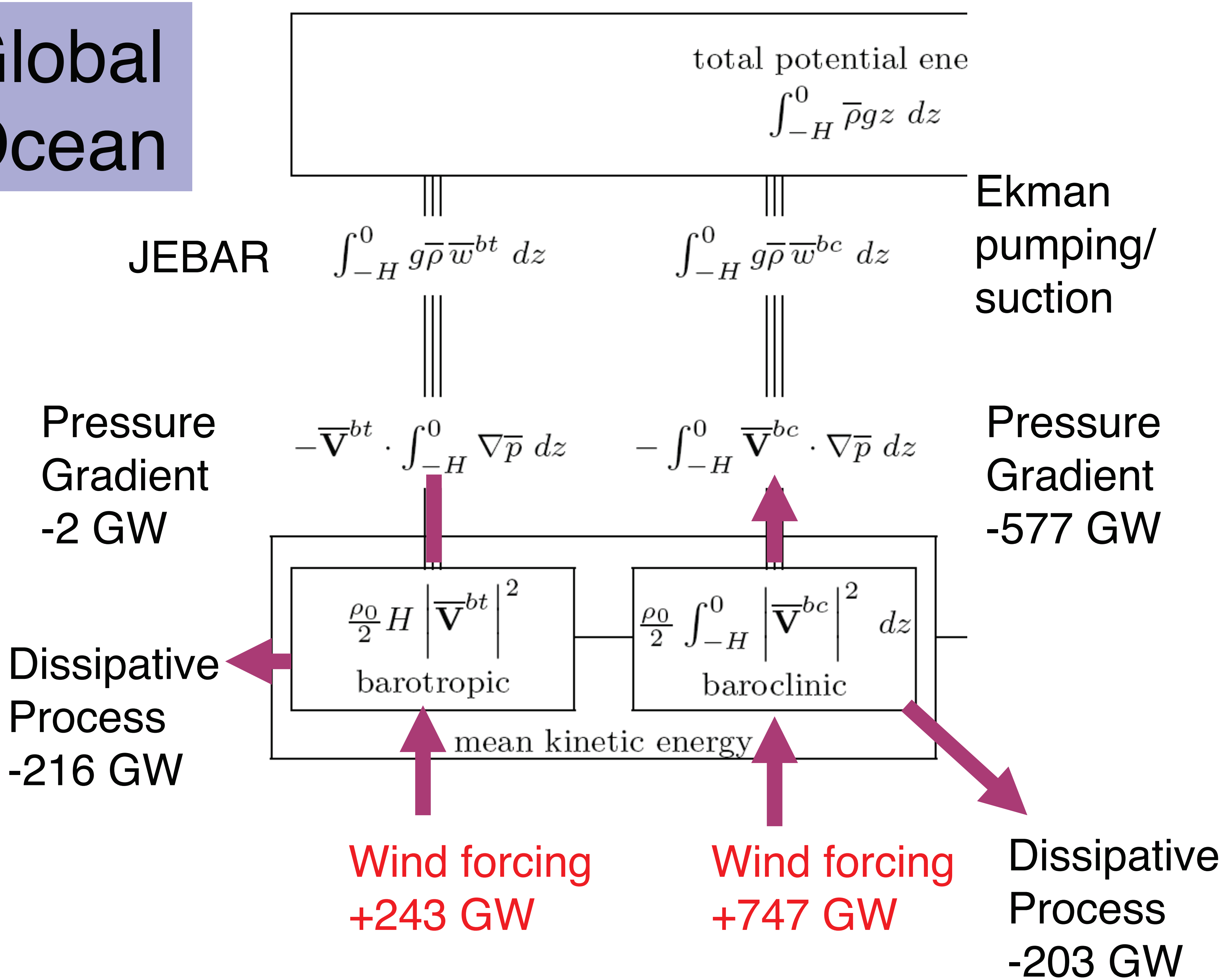
total potential energy
$\int_{-H}^{0} \overline{\rho} g z \; dz$
$\int_{-H}^{0} g\overline{\rho}\,\overline{w}^{bt} \; dz$
$\int_{-H}^{0} g\overline{\rho}\,\overline{w}^{bc} \; dz$
$-\overline{\mathbf{V}}^{bt} \cdot \int_{-H}^{0} \nabla\overline{p} \; dz$
$-\int_{-H}^{0} \overline{\mathbf{V}}^{bc} \cdot \nabla\overline{p} \; dz$
mean kinetic energy
barotropic
$\frac{\rho_0}{2} H \left|\overline{\mathbf{V}}^{bt}\right|^2$
advective interaction
baroclinic
$\frac{\rho_0}{2} \int_{-H}^{0} \left|\overline{\mathbf{V}}^{bc}\right|^2 dz$
horizontal viscosity
bottom friction
wind forcing
interior vertical viscosity


baroclinic power of pressure gradient [W/m²] −577 GW
baroclinic power of overall dissipation [W/m²] −203 GW
−0.1 −0.05 −0.02 −0.01 0 0.01 0.02 0.05 0.1

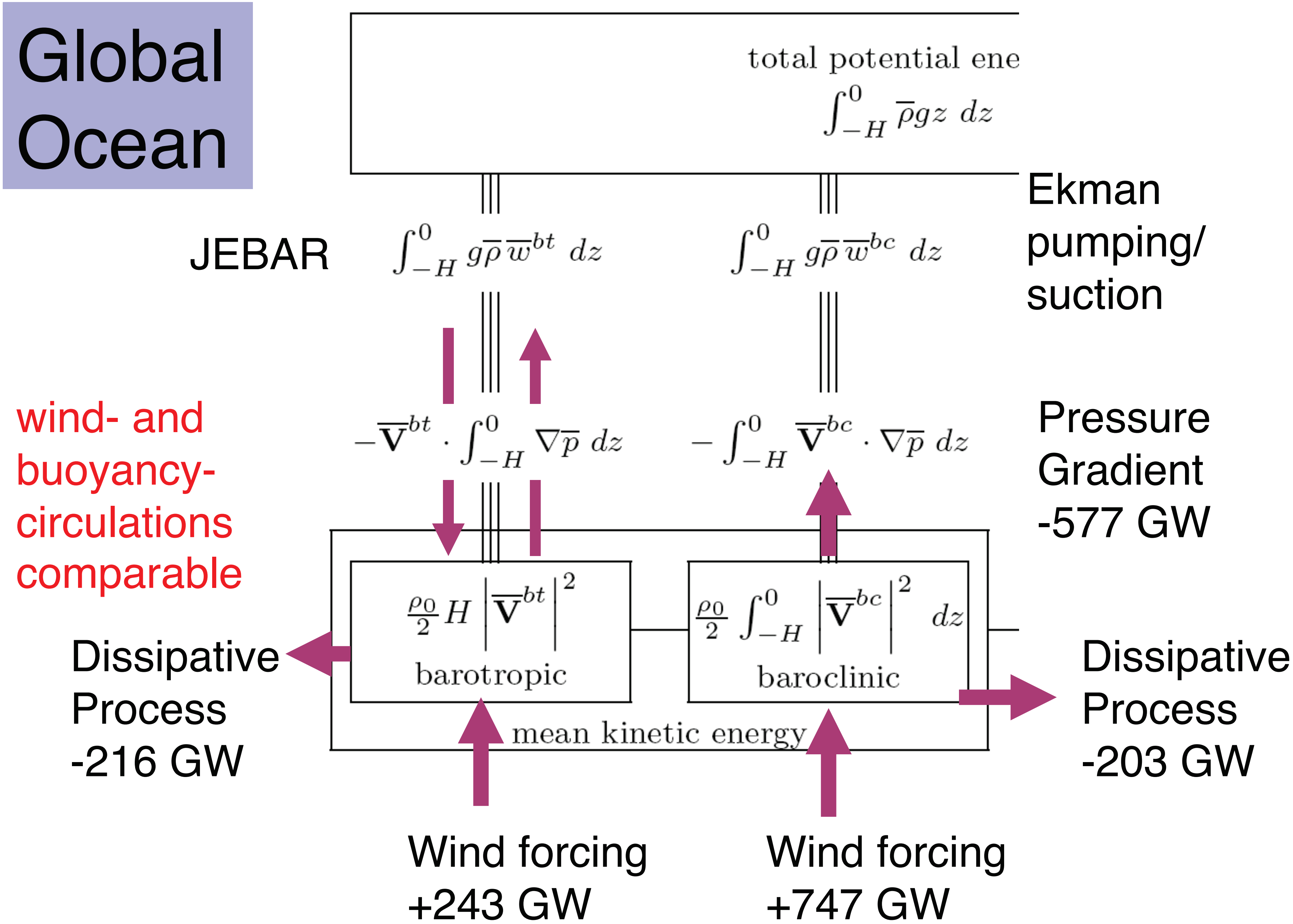

total potential energy
$\int_{-H}^{0} \overline{\rho} g z \; dz$
$\int_{-H}^{0} g \overline{\rho}\, \overline{w}^{bt} \; dz$
$\int_{-H}^{0} g \overline{\rho}\, \overline{w}^{bc} \; dz$
$-\overline{\mathbf{V}}^{bt} \cdot \int_{-H}^{0} \nabla \overline{p} \; dz$
$-\int_{-H}^{0} \overline{\mathbf{V}}^{bc} \cdot \nabla \overline{p} \; dz$
mean kinetic energy
barotropic
$\frac{\rho_0}{2} H \left| \overline{\mathbf{V}}^{bt} \right|^2$
advective interaction
baroclinic
$\frac{\rho_0}{2} \int_{-H}^{0} \left| \overline{\mathbf{V}}^{bc} \right|^2 \; dz$
horizontal viscosity
bottom friction
wind forcing
interior vertical viscosity

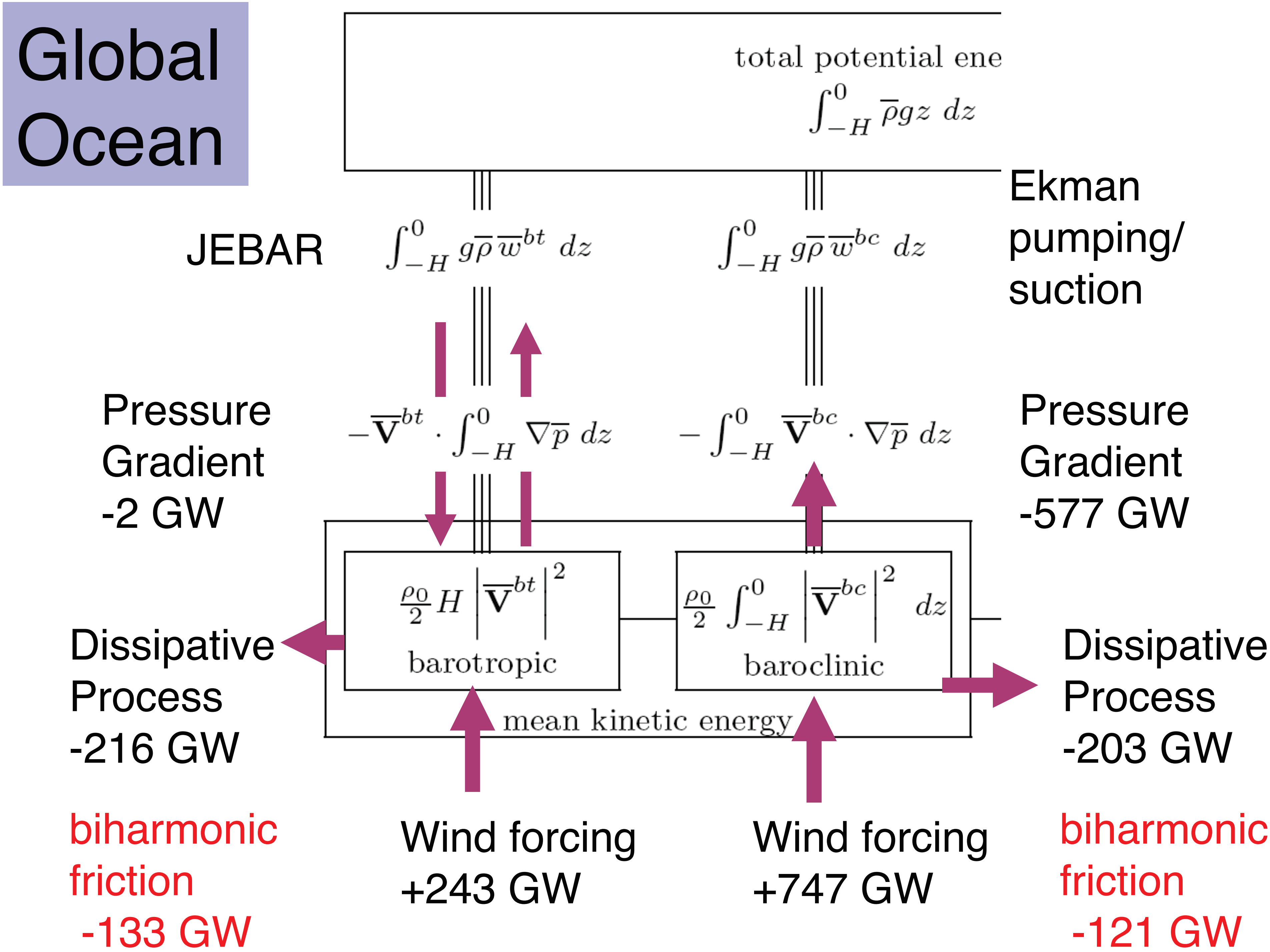
Summary

Global Ocean



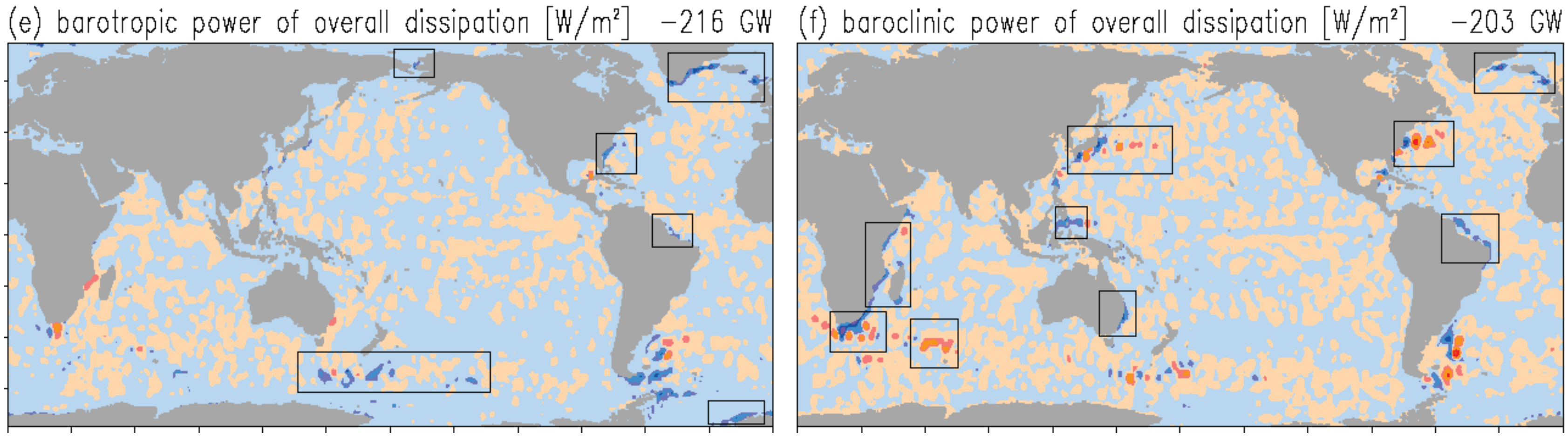
Global Ocean



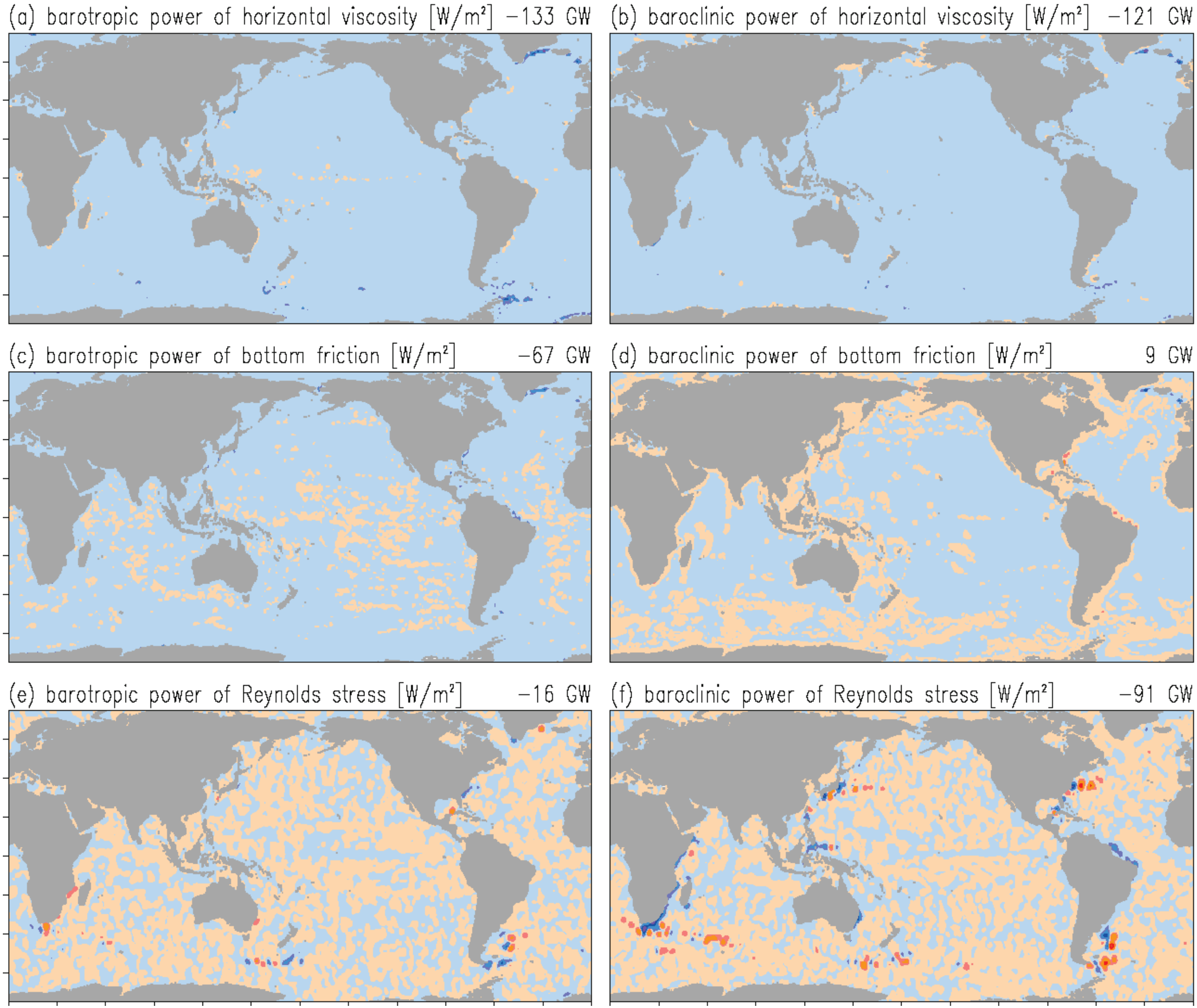


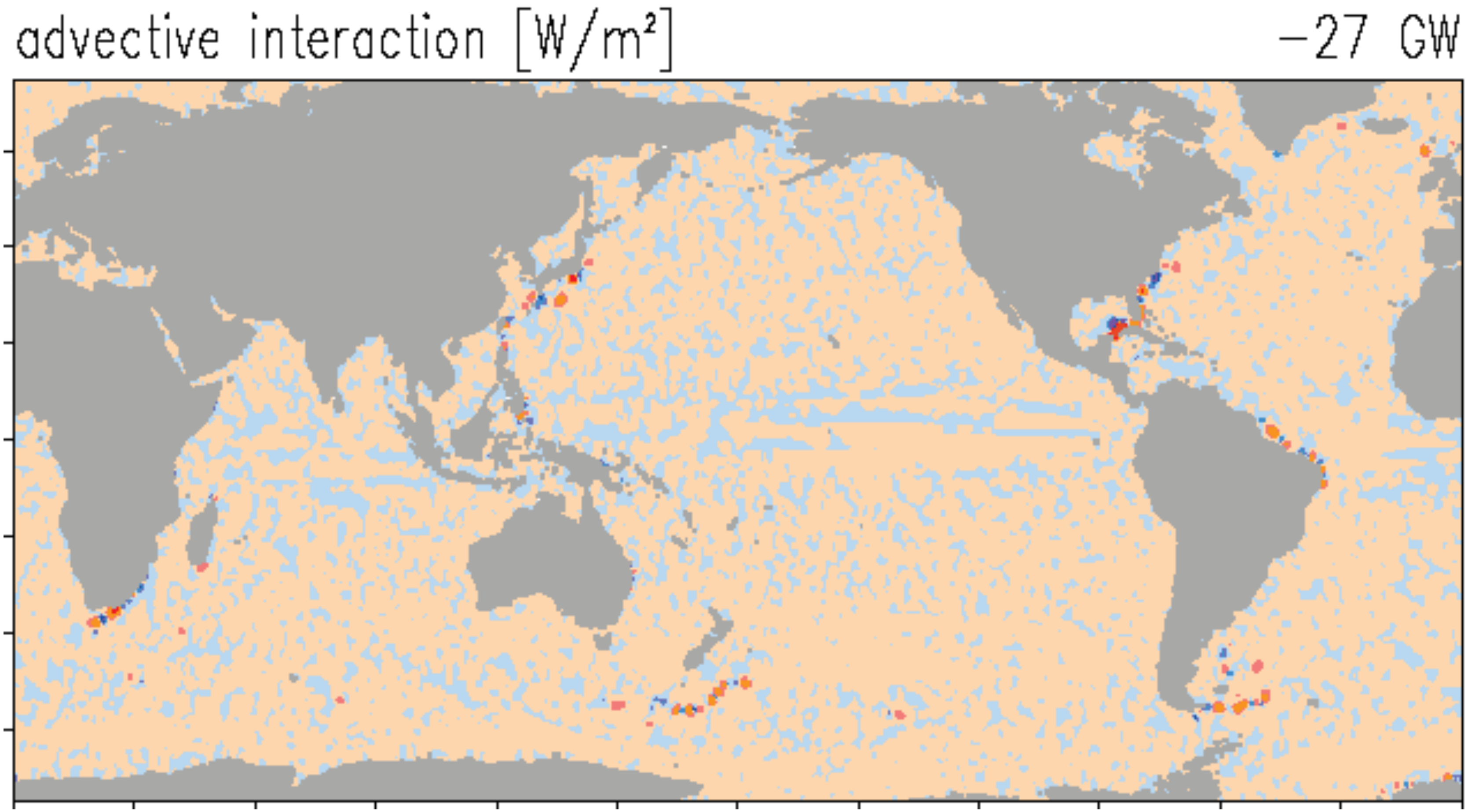
Global Ocean
total potential ene
$\int_{-H}^{0} \overline{\rho} g z \, dz$
JEBAR
$\int_{-H}^{0} g\overline{\rho}\,\overline{w}^{bt} \, dz$
$\int_{-H}^{0} g\overline{\rho}\,\overline{w}^{bc} \, dz$
Ekman pumping/ suction
Pressure Gradient -2 GW
$-\overline{\mathbf{V}}^{bt} \cdot \int_{-H}^{0} \nabla \overline{p} \, dz$
$-\int_{-H}^{0} \overline{\mathbf{V}}^{bc} \cdot \nabla \overline{p} \, dz$
Pressure Gradient -577 GW
$\frac{\rho_0}{2} H \left| \overline{\mathbf{V}}^{bt} \right|^2$
barotropic
$\frac{\rho_0}{2} \int_{-H}^{0} \left| \overline{\mathbf{V}}^{bc} \right|^2 dz$
baroclinic
mean kinetic energy
Dissipative Process -216 GW
Dissipative Process -203 GW
biharmonic friction -133 GW
Wind forcing +243 GW
Wind forcing +747 GW
biharmonic friction -121 GW

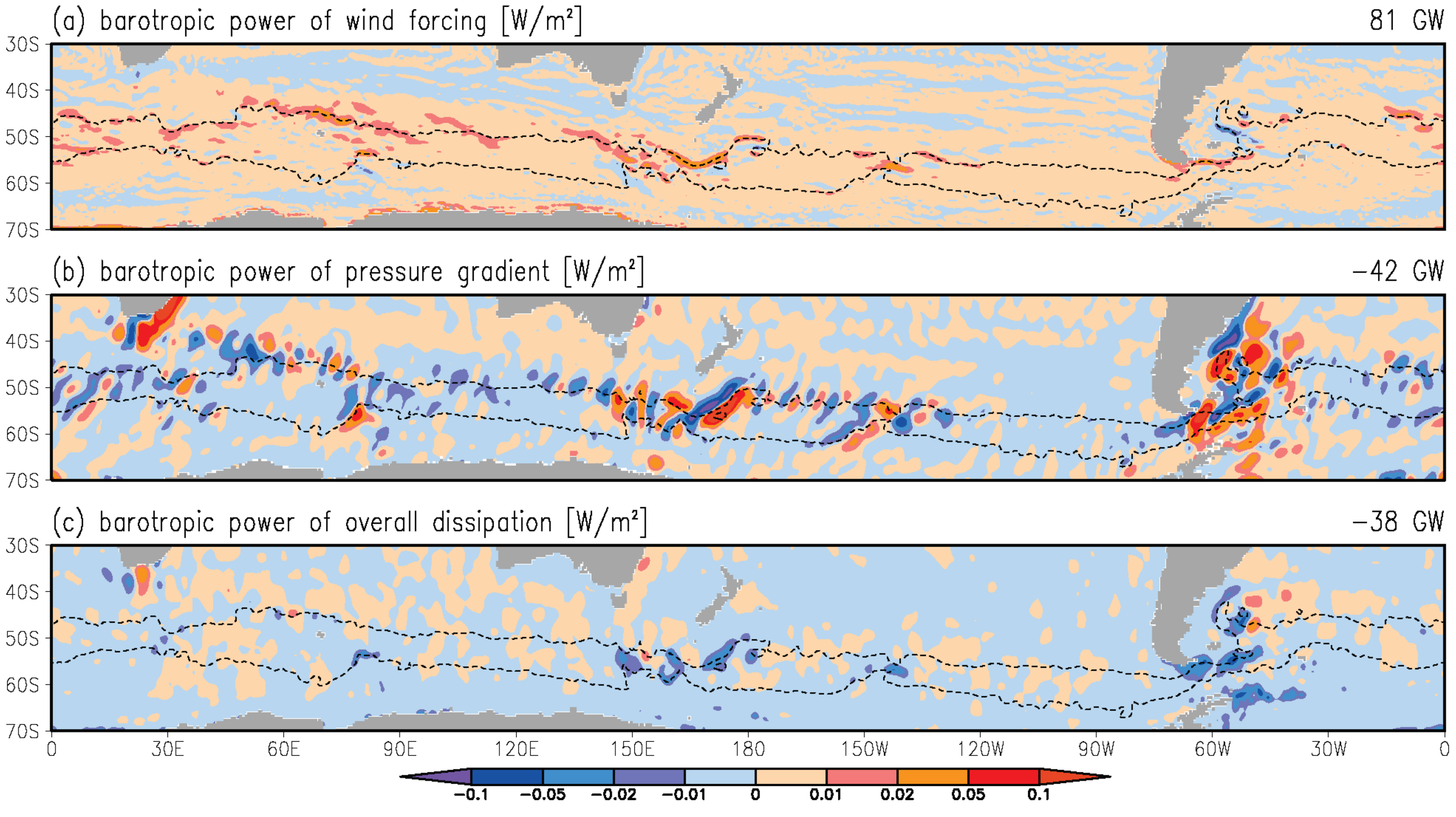
Thank you

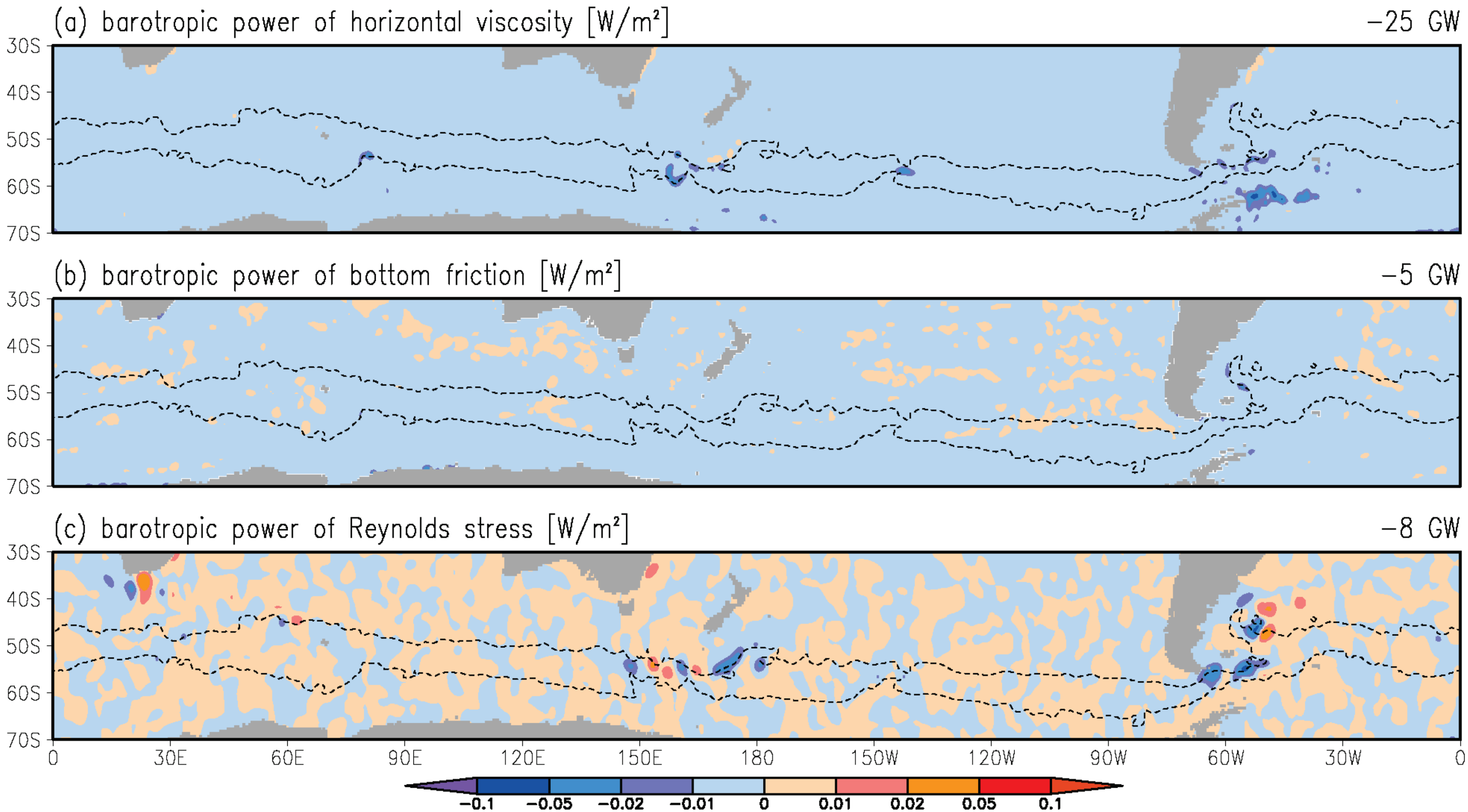


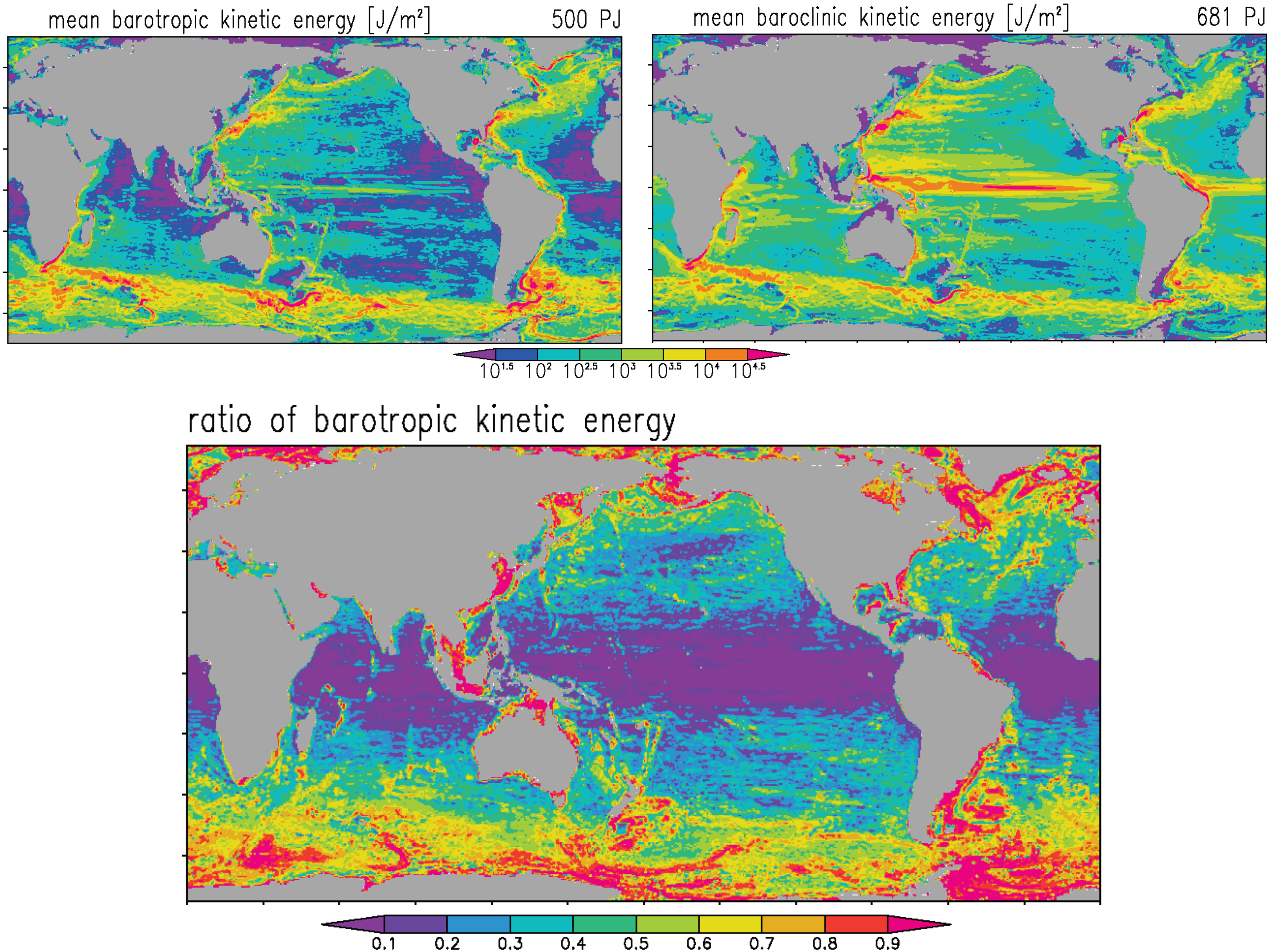
(e) barotropic power of overall dissipation [W/m²] −216 GW
(f) baroclinic power of overall dissipation [W/m²] −203 GW


(a) barotropic power of horizontal viscosity [W/m²] −133 GW
(b) baroclinic power of horizontal viscosity [W/m²] −121 GW
(c) barotropic power of bottom friction [W/m²] −67 GW
(d) baroclinic power of bottom friction [W/m²] 9 GW
(e) barotropic power of Reynolds stress [W/m²] −16 GW
(f) baroclinic power of Reynolds stress [W/m²] −91 GW


advective interaction [W/m²]
−27 GW


(a) barotropic power of wind forcing [W/m²]
81 GW
(b) barotropic power of pressure gradient [W/m²]
−42 GW
(c) barotropic power of overall dissipation [W/m²]
−38 GW
30S
40S
50S
60S
70S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
−0.1
−0.05
−0.02
−0.01
0
0.01
0.02
0.05
0.1

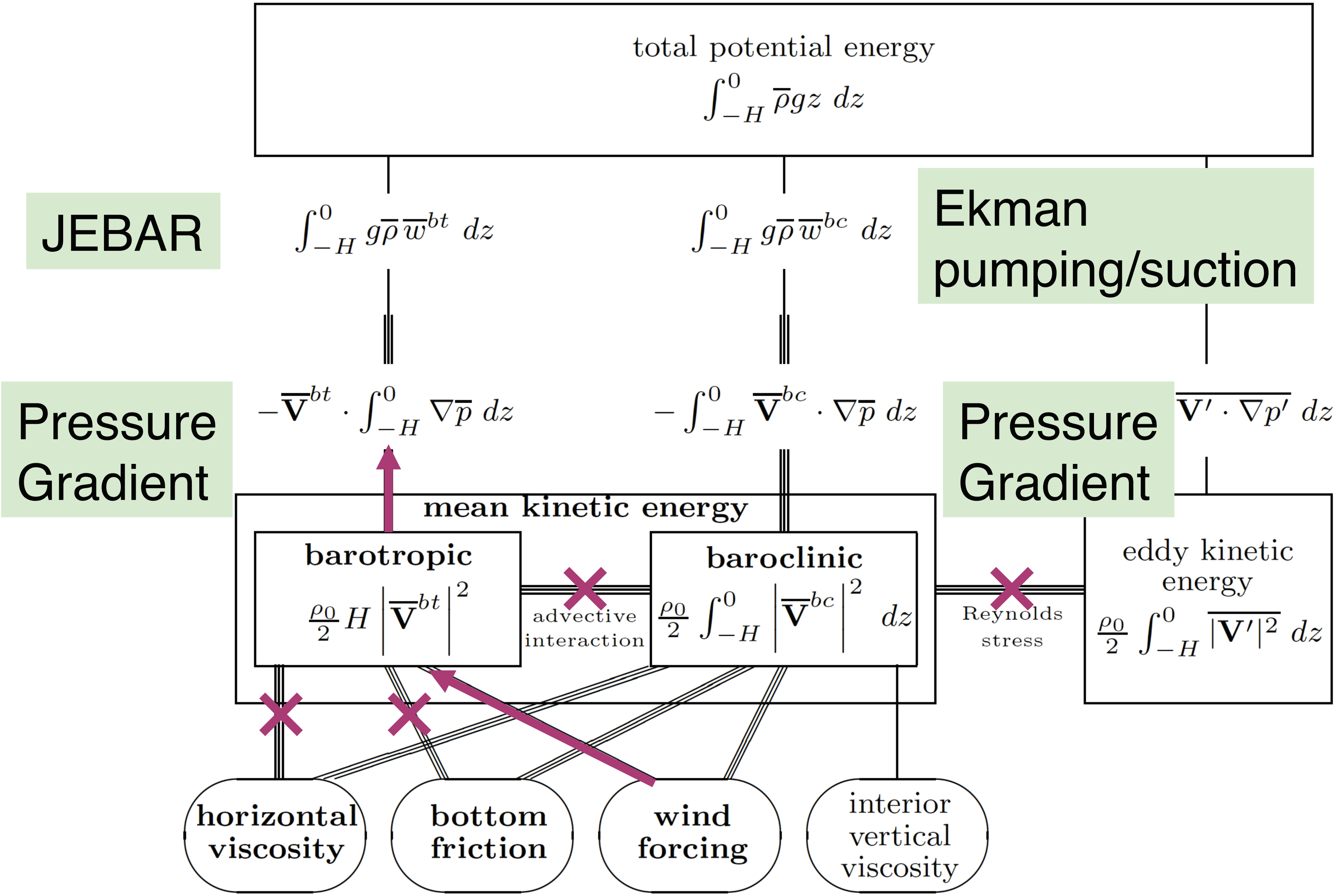

(a) barotropic power of horizontal viscosity [W/m²]
−25 GW
(b) barotropic power of bottom friction [W/m²]
−5 GW
(c) barotropic power of Reynolds stress [W/m²]
−8 GW
30S
40S
50S
60S
70S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
−0.1
−0.05
−0.02
−0.01
0
0.01
0.02
0.05
0.1


mean barotropic kinetic energy [J/m²]
500 PJ
mean baroclinic kinetic energy [J/m²]
681 PJ
10^1.5 10^2 10^2.5 10^3 10^3.5 10^4 10^4.5
ratio of barotropic kinetic energy
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

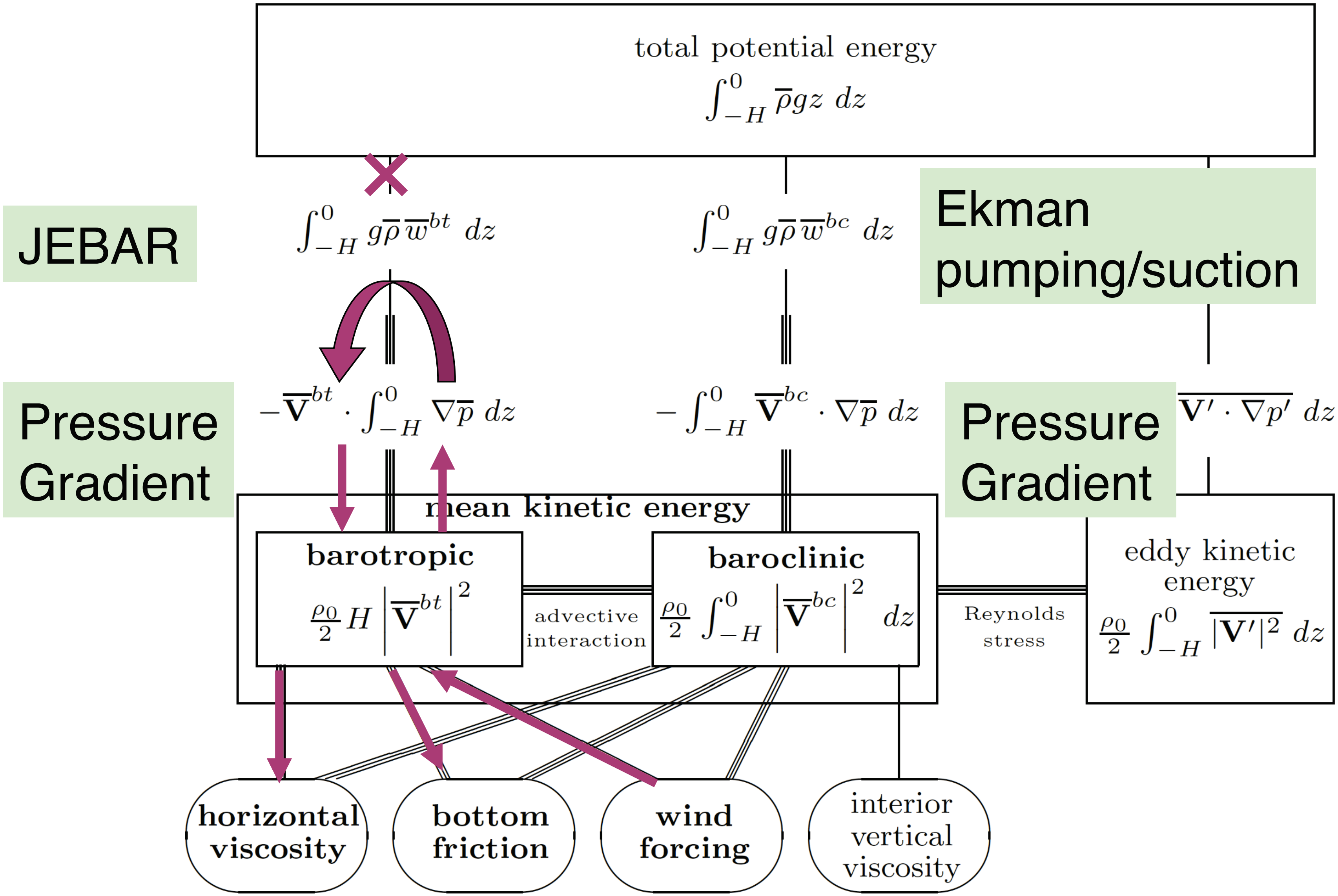
Theories for the barotropic dynamics of ACC

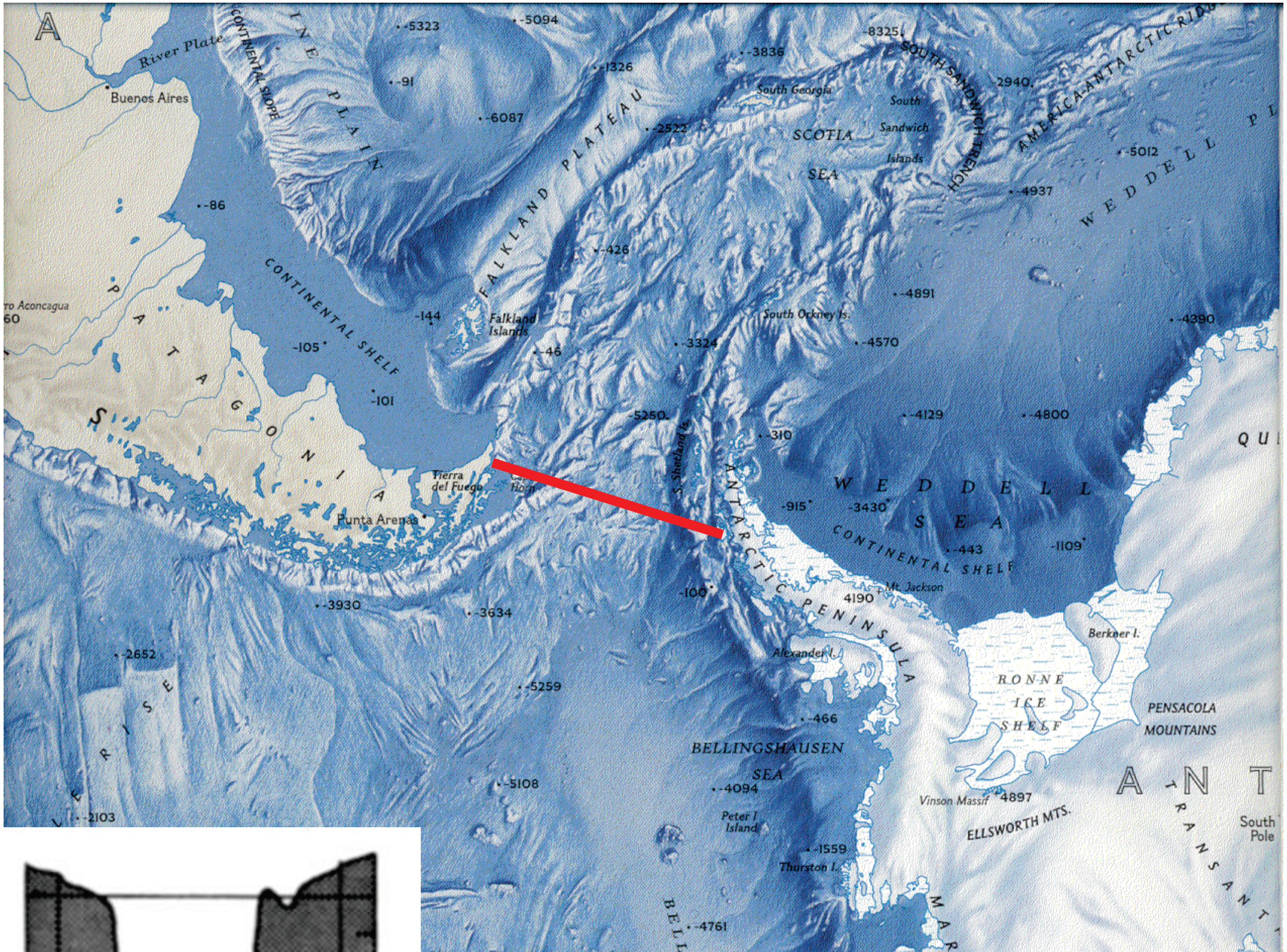
	sloping bottom	flat bottom
inhomogeneous density	Munk and Palmen (1951) Johnson and Bryden (1989) (barotropic KE is converted to potential energy)	Ishida (1994b), Cessi (2007) (barotropic KE is taken by bottom and sidewall friction and Reynolds stress)
homogeneous density	Krupitsky and Cane (1994) Wang (1994) (barotropic KE is taken by bottom and sidewall friction and Reynolds stress)	Stommel (1957) Webb (1993), Ishida (1994a) (barotropic KE is taken by bottom and sidewall friction and Reynolds stress)

ACC as an inviscid sloped-bottom model (Munk & Palmen, 1951)



ACC as a viscid flat-bottom model (Stommel, 1957)




River Plate
Buenos Aires
CONTINENTAL SLOPE
PLAIN
FALKLAND PLATEAU
SCOTIA SEA
South Georgia
South Sandwich Islands
SOUTH SANDWICH TRENCH
AMERICA-ANTARCTIC RIDGE
WEDDELL PLAIN
PATAGONIA
CONTINENTAL SHELF
Falkland Islands
South Orkney Is.
S. Shetland Is.
Tierra del Fuego
Punta Arenas
WEDDELL SEA
ANTARCTIC PENINSULA
Mt. Jackson
Berkner I.
Alexander I.
RONNE ICE SHELF
PENSACOLA MOUNTAINS
BELLINGSHAUSEN SEA
Peter I Island
Thurston I.
Vinson Massif
ELLSWORTH MTS.
ANT
South Pole
RISE
-5323
-5094
-8325
-3836
-1326
-91
-6087
-2522
-2940
-5012
-4937
-86
-426
-144
-105
-46
-3324
-4891
-4570
-4390
-101
-5250
-310
-4129
-4800
-915
-3430
-443
-1109
-100
4190
-3930
-3634
-2652
-5259
-466
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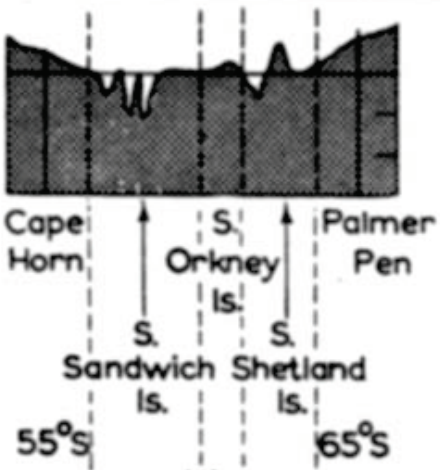
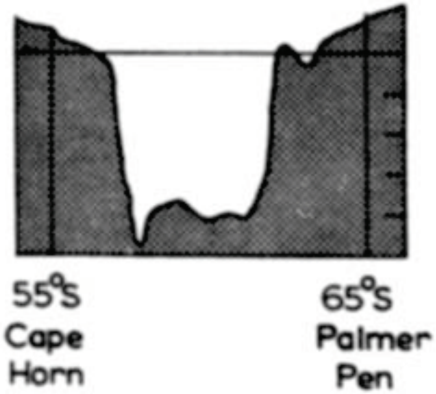
-4094
4897
-2103
-1559
-4761

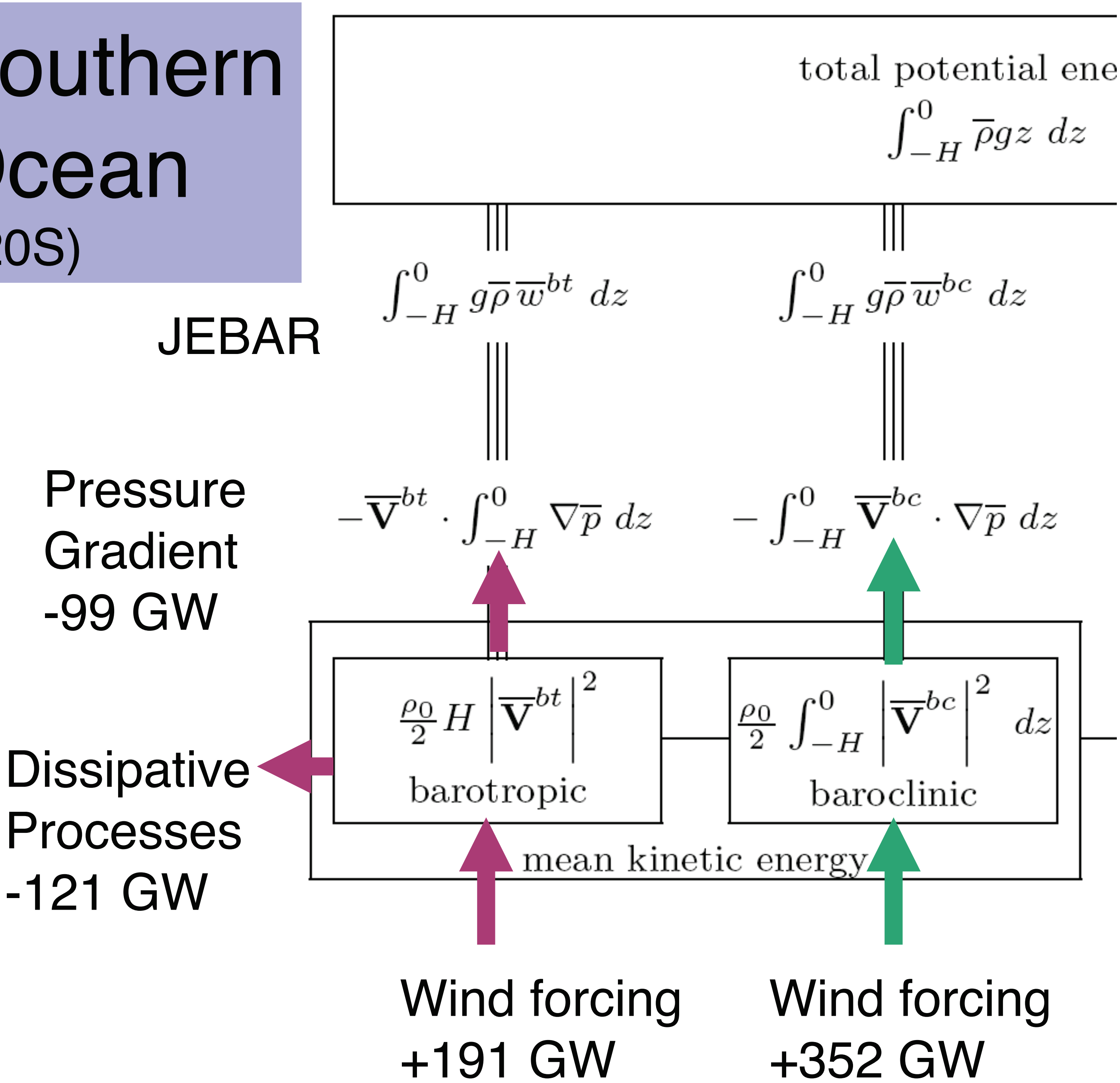

Cape Horn
S. Orkney Is.
Palmer Pen
S. Sandwich Is.
S. Shetland Is.
55°S
65°S

(b)


55°S Cape Horn
65°S Palmer Pen

(c)

Southern Ocean
(-20S)



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Barotropic Momentum

$$\rho_0 \mathbf{f} \times \int_{-H}^{0} \overline{\mathbf{V}}\, dz \simeq -\int_{-H}^{0} \nabla \overline{p}\, dz + \overline{\boldsymbol{\tau}}^{\mathbf{wind}}$$

Barotropic Vorticity Ψ: barotropic streamfunction

$$\rho_0 J(\Psi, f) \simeq J(\overline{p}|_{z=-H}, H) + \nabla \times \overline{\boldsymbol{\tau}}^{\mathbf{wind}}$$

$$\rho_0 J\left(\Psi, f/H\right) \simeq J\left(\int_{-H}^{0} g\overline{\rho} z\, dz, 1/H\right) + \nabla \times \frac{\overline{\boldsymbol{\tau}}^{\mathbf{wind}}}{H}$$

Joint Effect Baroclinicity
and Bottom Relief (JEBAR)

(Sarkisian and Ivanov, 1971)