Energetic dynamics of a rotating horizontal convection model with wind forcing

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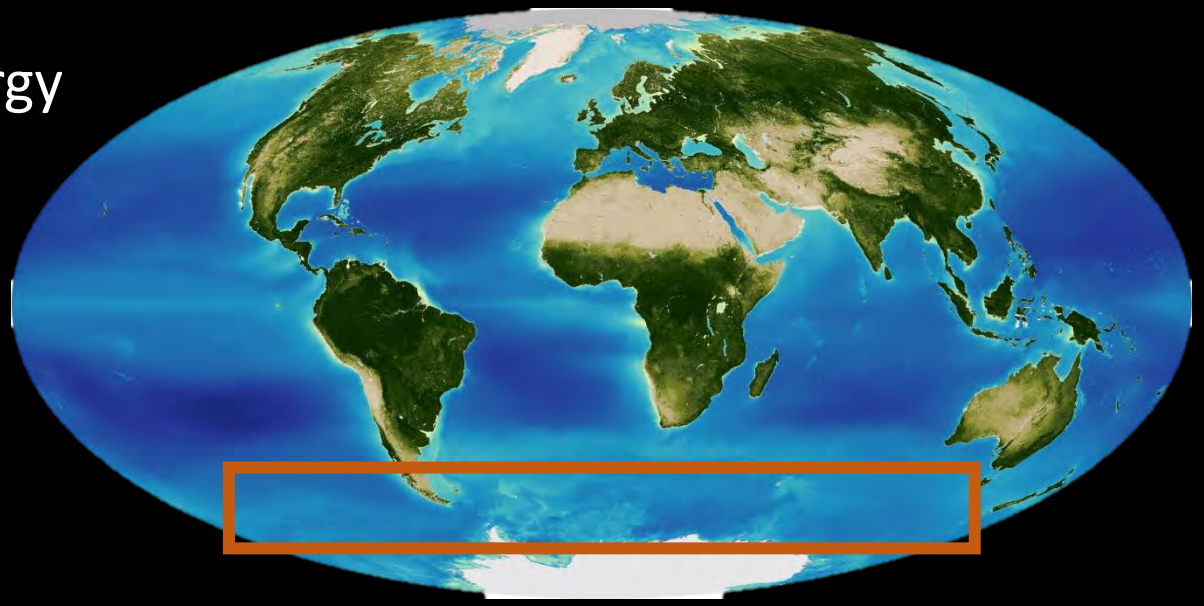
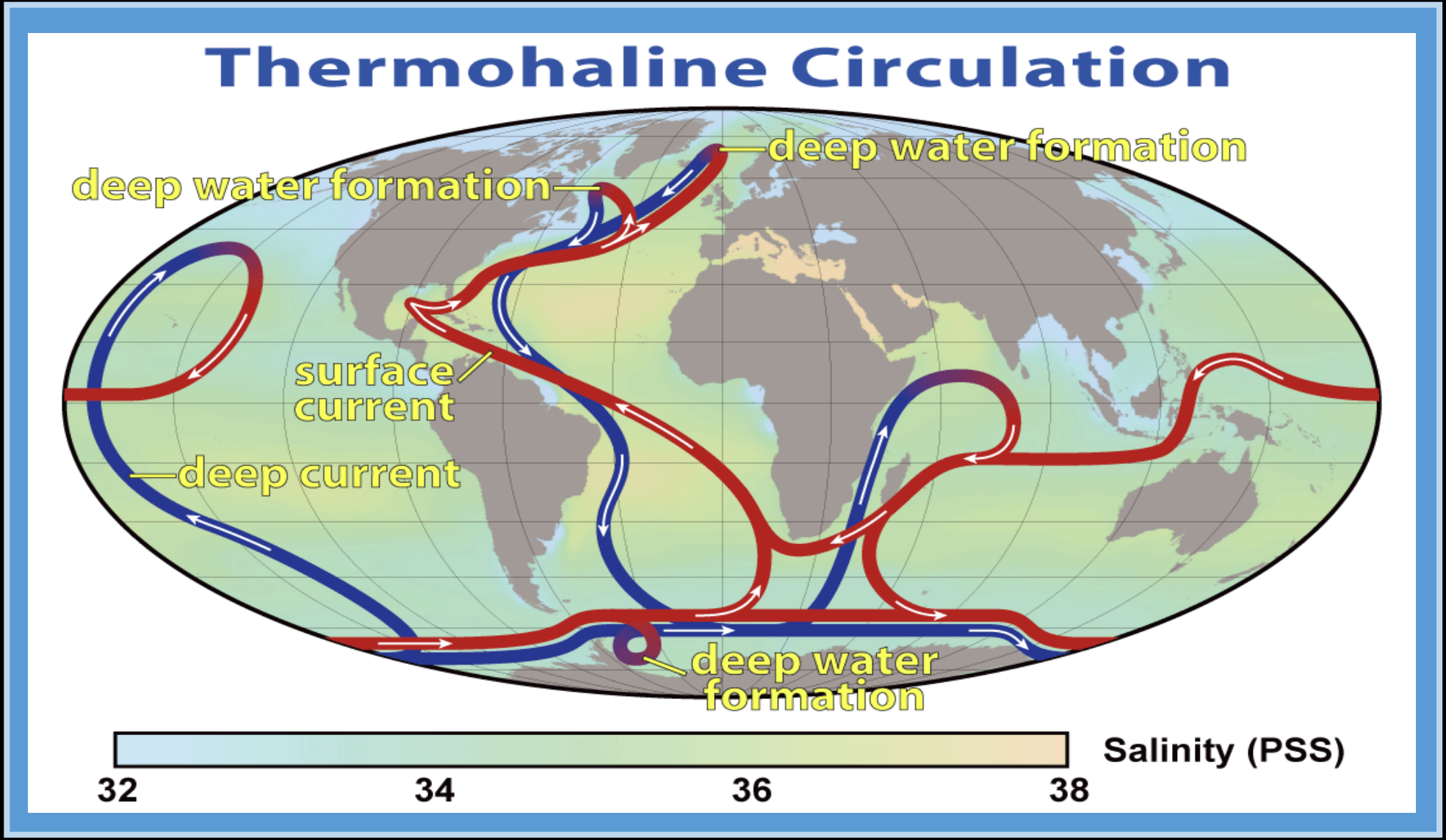
OUTLINE

1. Motivation
   - Overview of ocean circulation
   - Prior assumptions about energy sources in the ocean
2. Energy terms in the ocean
   - Kinetic energy, Available potential energy
   - Exchange between KE and APE
3. Simulation set-up
   - Surface forcing
   - Importance of Blue Waters resources
4. Results
5. Summary and further work



Ocean Circulation



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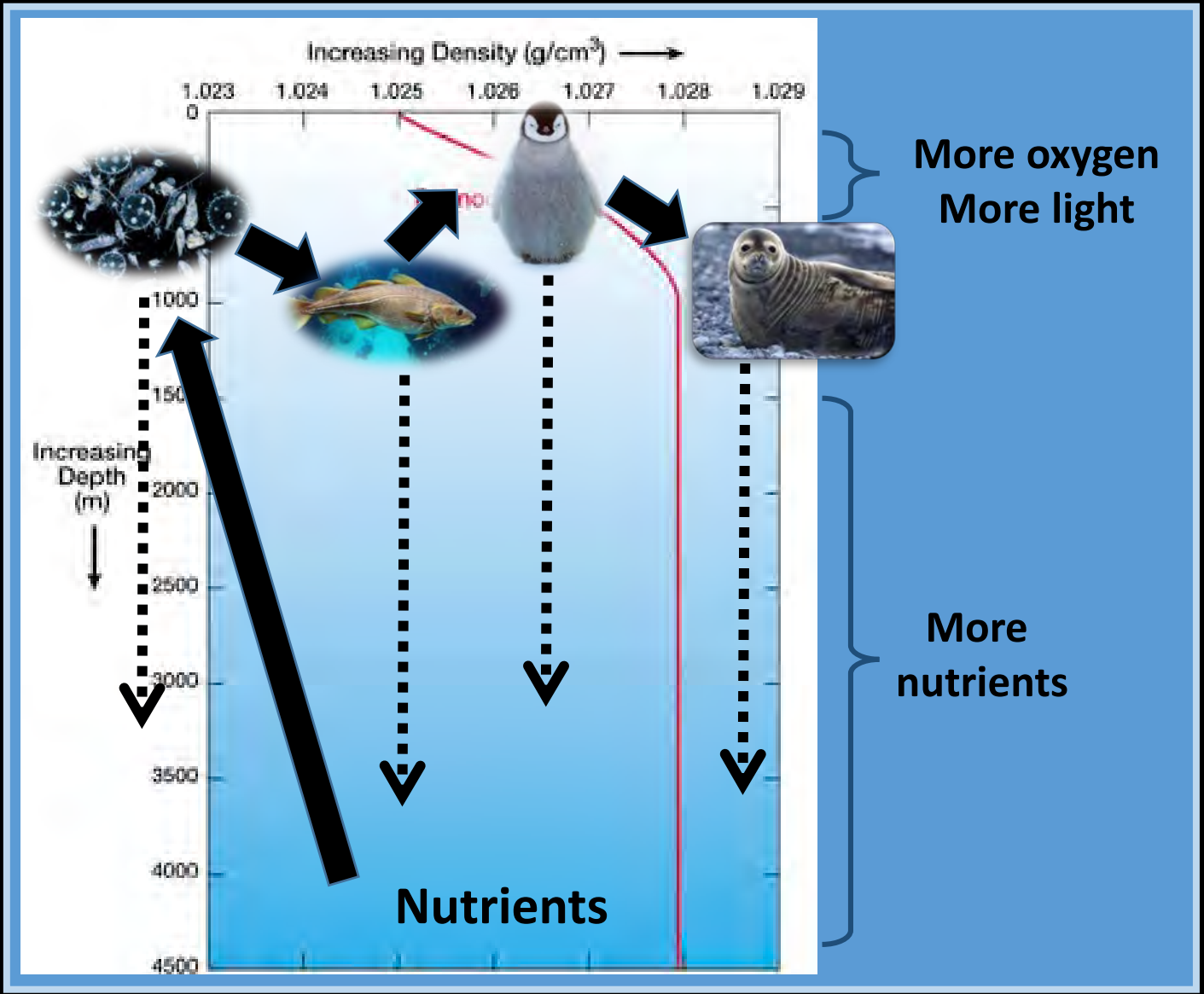
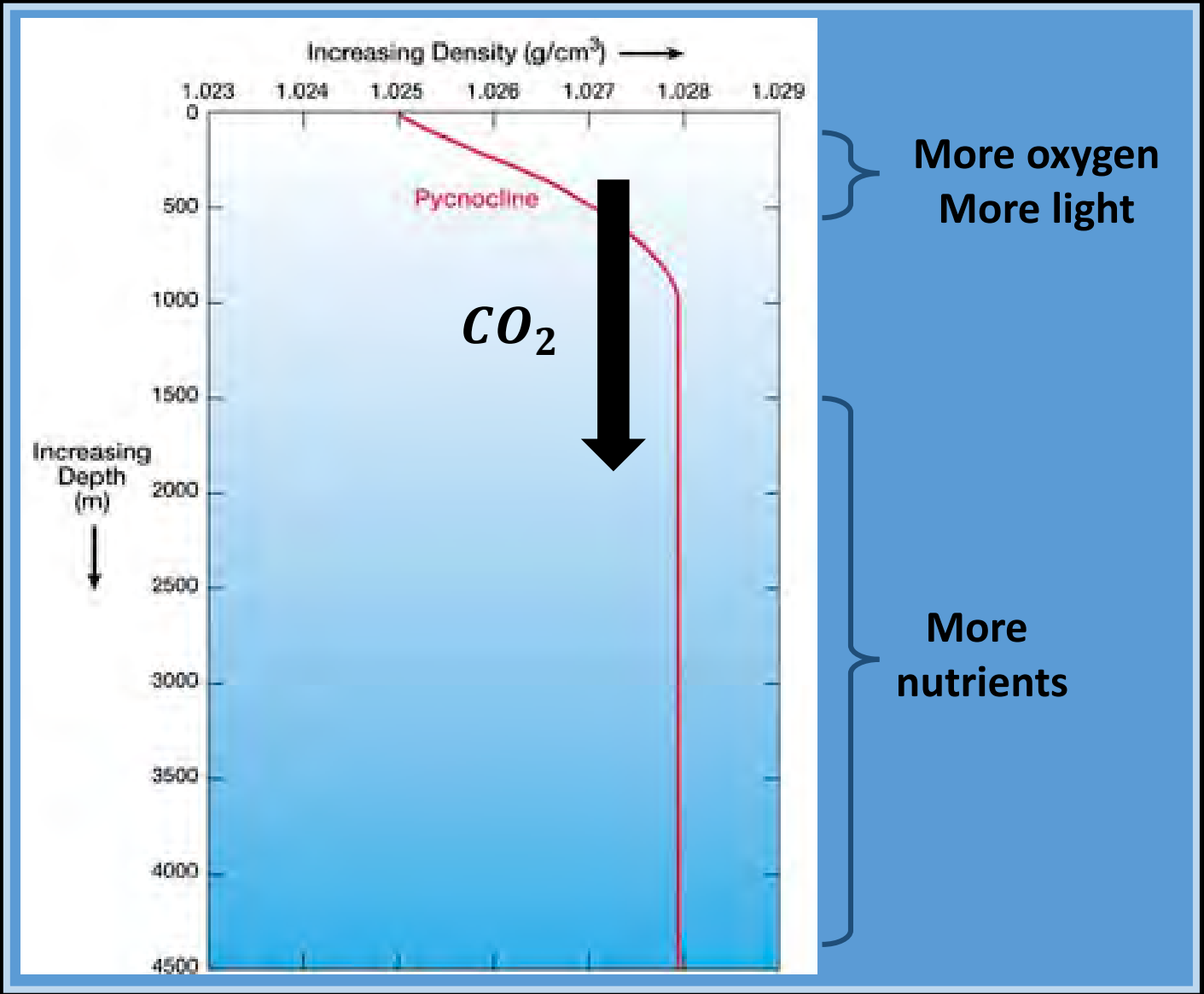


- Ocean is vertically stratified
- Most of the flow is along surfaces of constant density
- Exchange across surfaces of constant density is important

Ocean Circulation



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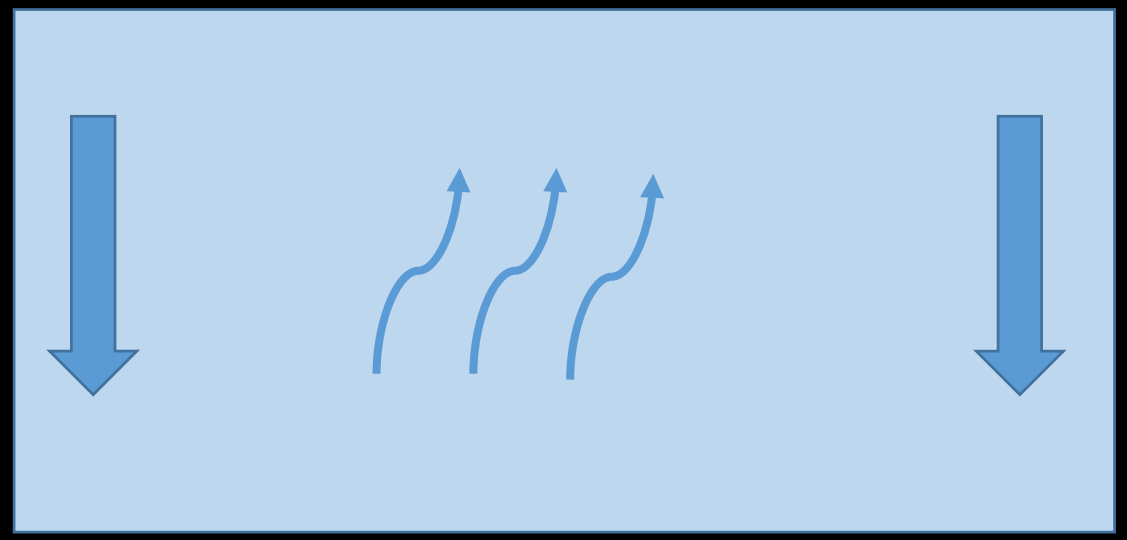
Two Mixing Models

"ABYSSAL RECIPES"

- Sinking of dense water at high latitudes
- Balancing upwelling at mid-latitudes



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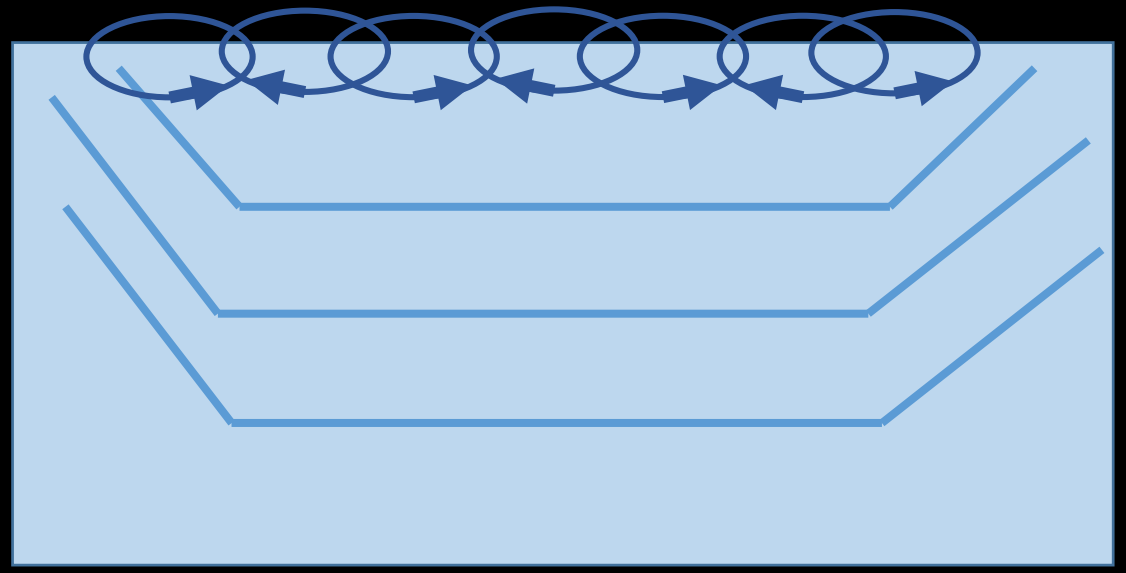
"EDDY COMPENSATION"

- Flow follows isopycnals (lines of constant density) created by surface wind stress
- Transient eddies balance the mean flow



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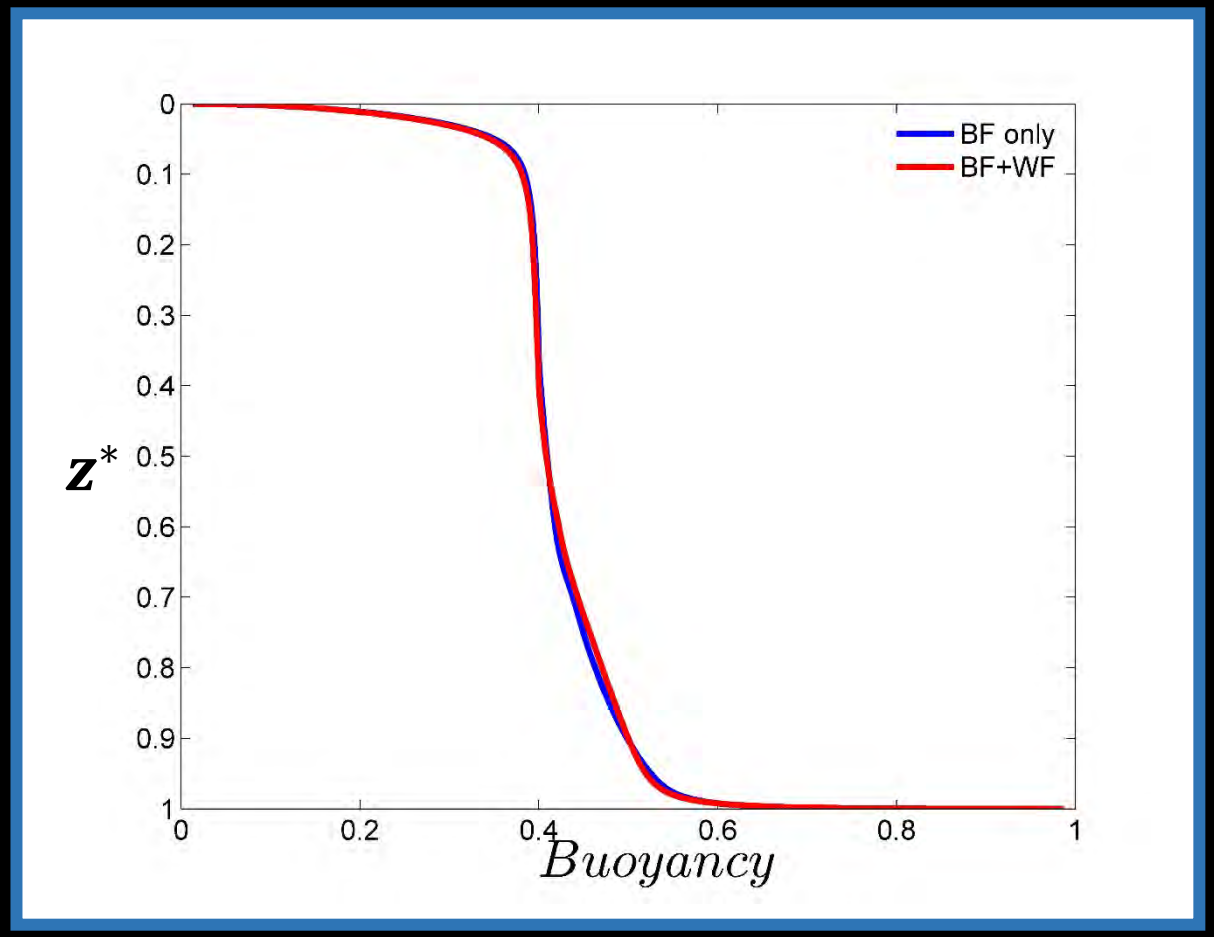
IMPORTANT ENERGY TERMS IN THE OCEAN

- Kinetic Energy (KE) – generated by winds and tides
- Available Potential Energy (APE) – generated by buoyancy flux through differential heating/cooling and evaporation/precipitation at the surface
- Vertical Buoyancy Flux – exchange between KE and APE
  - Positive if raising of dense fluid or lowering of light fluid (more APE)
  - Negative if lowering of dense fluid or raising of light fluid (less APE)

AVAILABLE POTENTIAL ENERGY



- Obtain minimal potential energy state by resorting fluid parcels and stacking them from the bottom in decreasing order by density
- For a given density b, can find $z^*(b)$
- Background potential energy:

$$BPE = \int_V bz^* dV$$

- Available potential energy:

$$APE = \int_V b(z - z^*) dV$$

Scotti and White (JFM, 2015)

PROBLEM FORMULATION

Solve Navier-Stokes Equations with Boussinesq approximation and rotation:

$$\frac{\partial \mathbf{u}}{\partial t} = -\mathbf{u}\cdot\nabla\mathbf{u} - \nabla p + \nu\nabla^2\mathbf{u} - b\hat{z} + f_{ext}$$

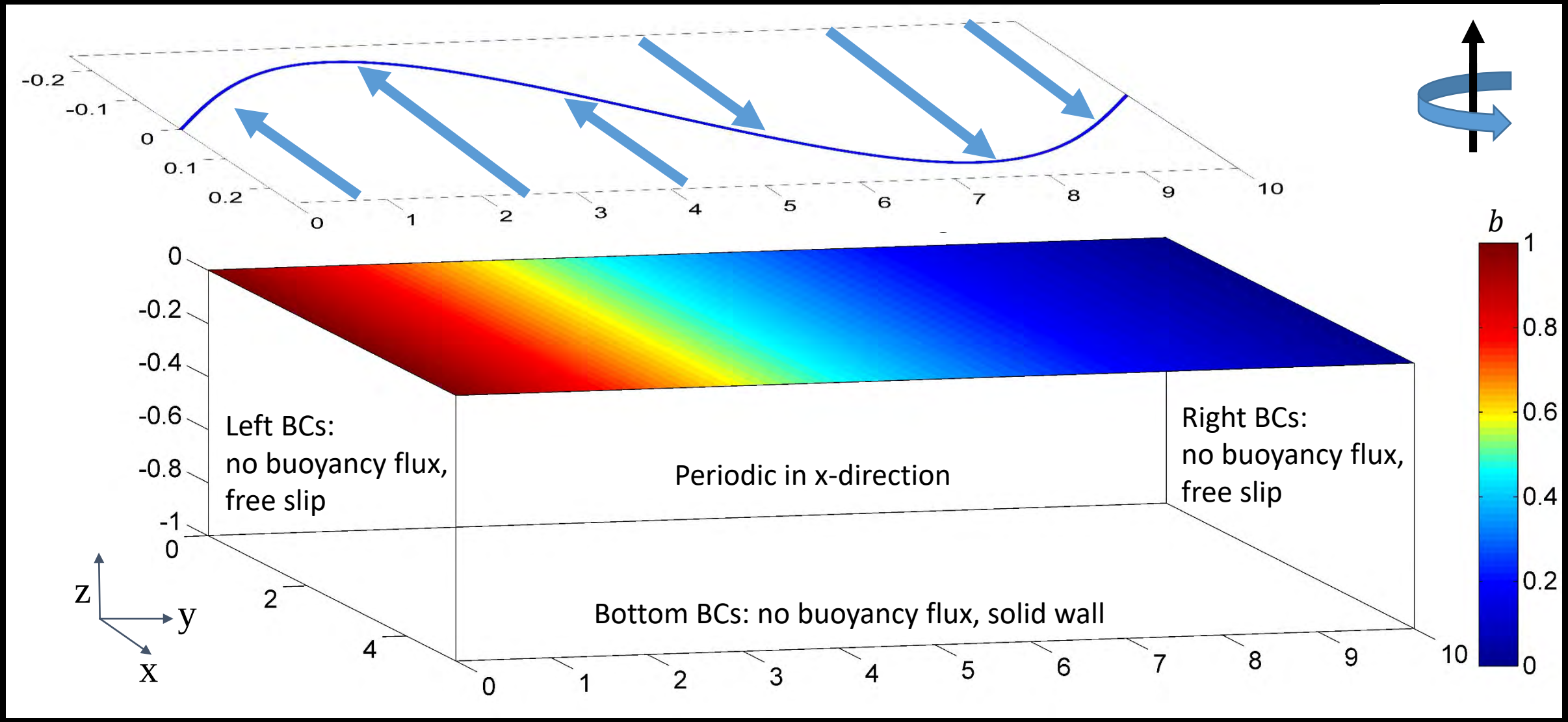
$$\frac{\partial b}{\partial t} = -\nabla\cdot(\mathbf{u}b) + \kappa\nabla^2 b$$

$$b = g\left(\frac{\rho-\rho_0}{\rho_0}\right) \qquad \nabla\cdot\mathbf{u} = 0$$

SOMAR: Stratified Ocean Model with Adaptive Refinement

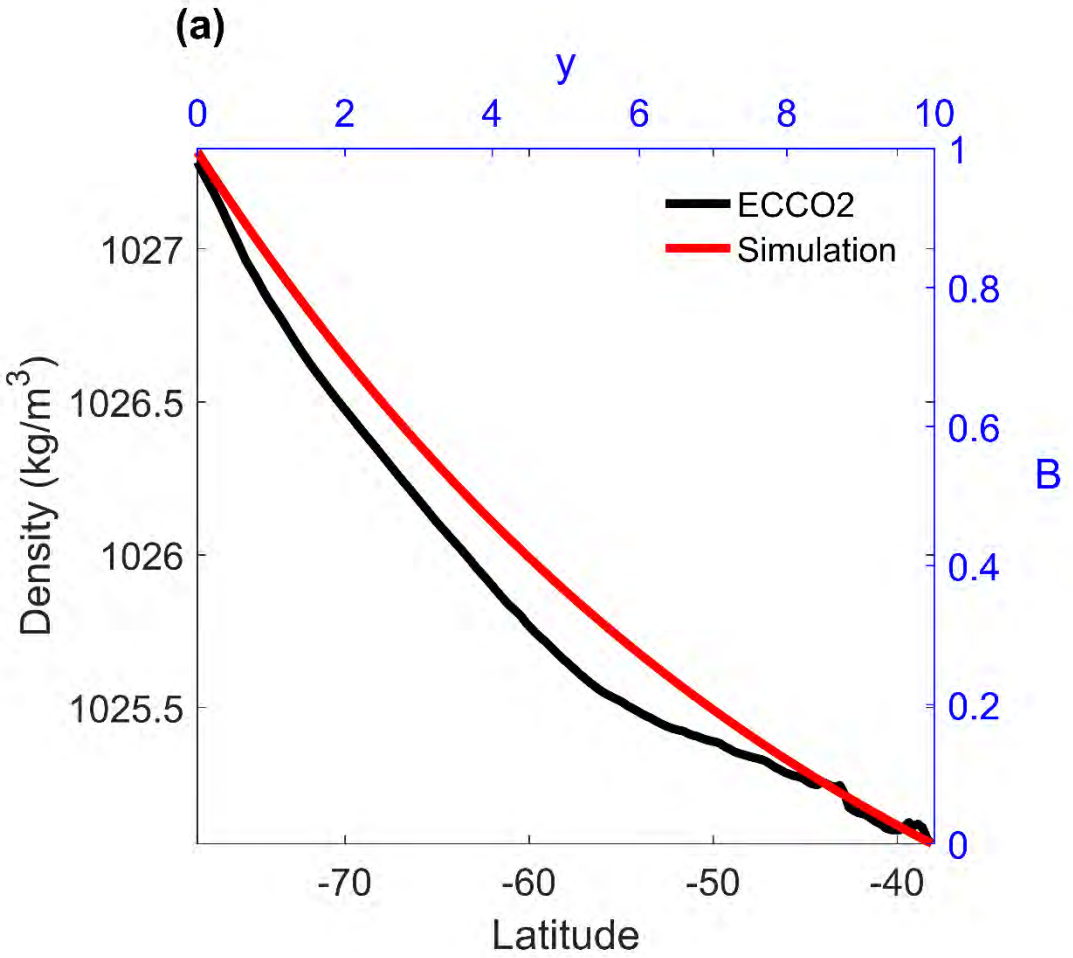
Santilli and Scotti (JCP, 2015)

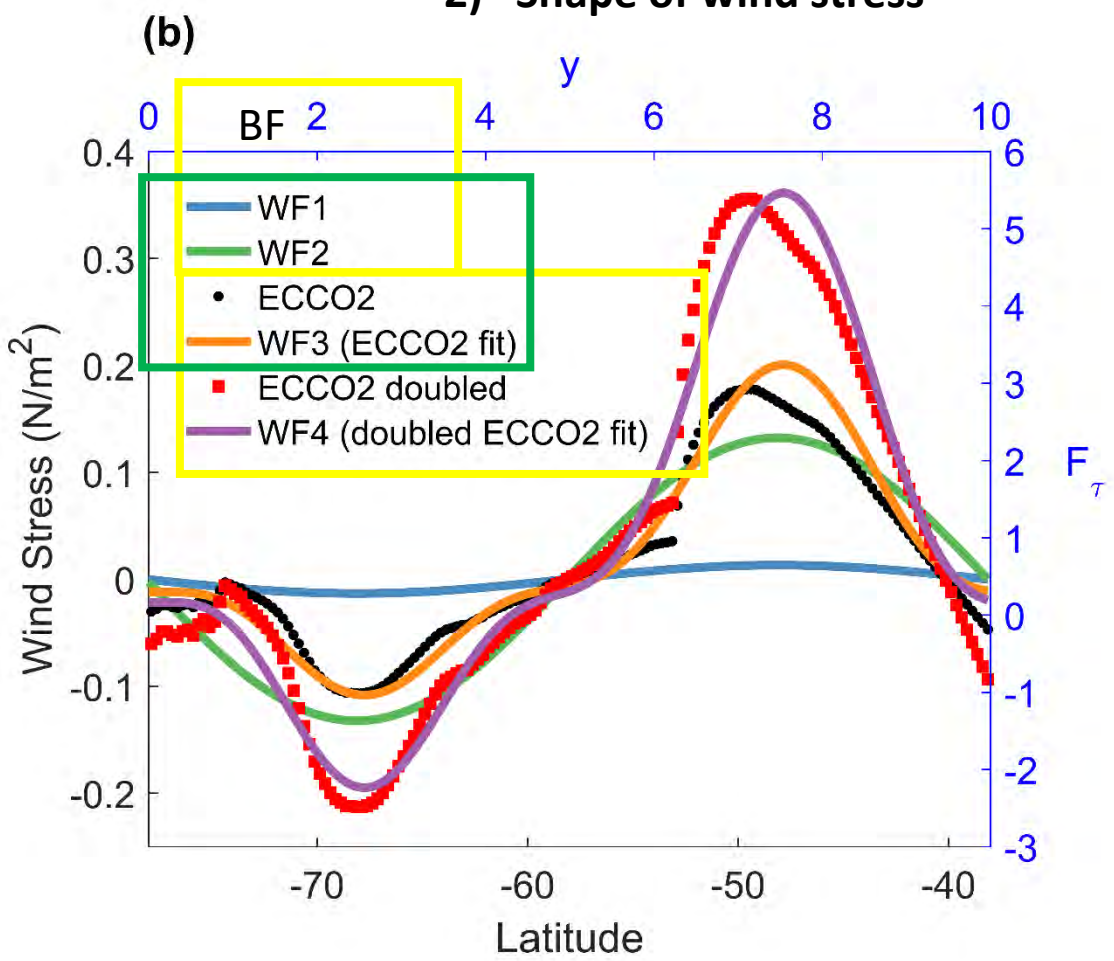
SIMULATION SET-UP



COMPARISON OF FORCING TO OCEAN DATA

1) **Wind stress magnitude**
2) **Shape of wind stress**



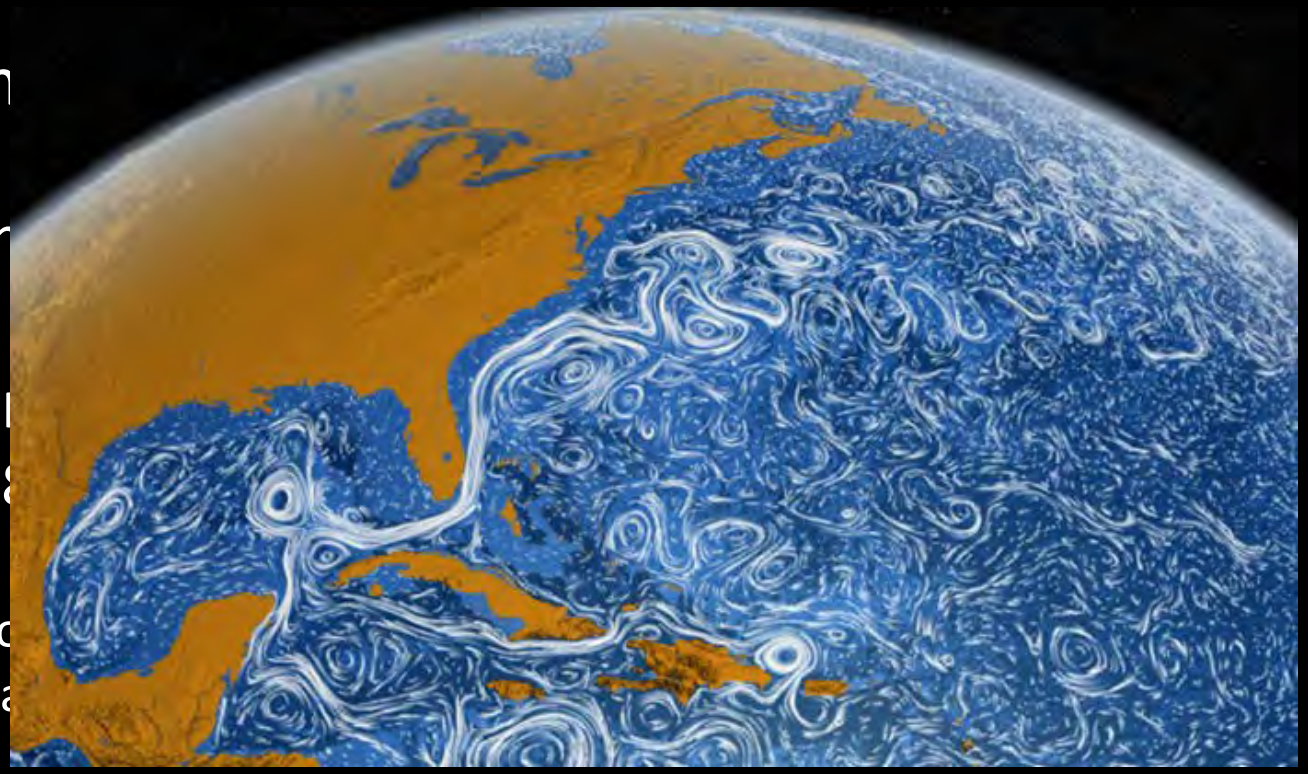


DIRECT NUMERICAL SIMULATIONS ON BLUE WATERS

- Large scale ocean models do not resolve mixing
  - MITgcm ECCO2 ocean-state estimate model: 18km x 18 km resolution
  - Irreversible mixing is computed as a residual from steady state

- Difficult for DNS models to m
  - Large aspect ratio: $10^4\ km$ in
  - Large Rayleigh number: deper

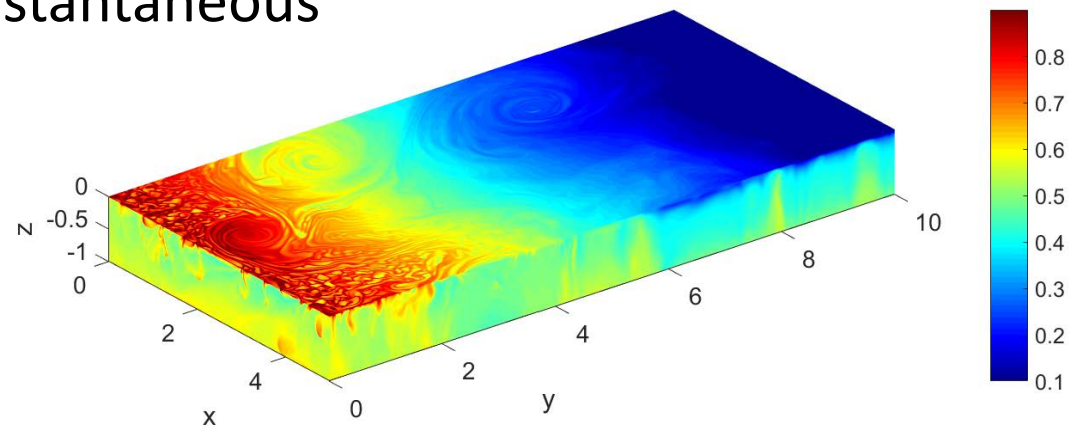
- Computational capabilities o
  - Fine resolution (512x1024x12
  - Long run time
    - Small time step due to high velo
    - Many time steps required to rea



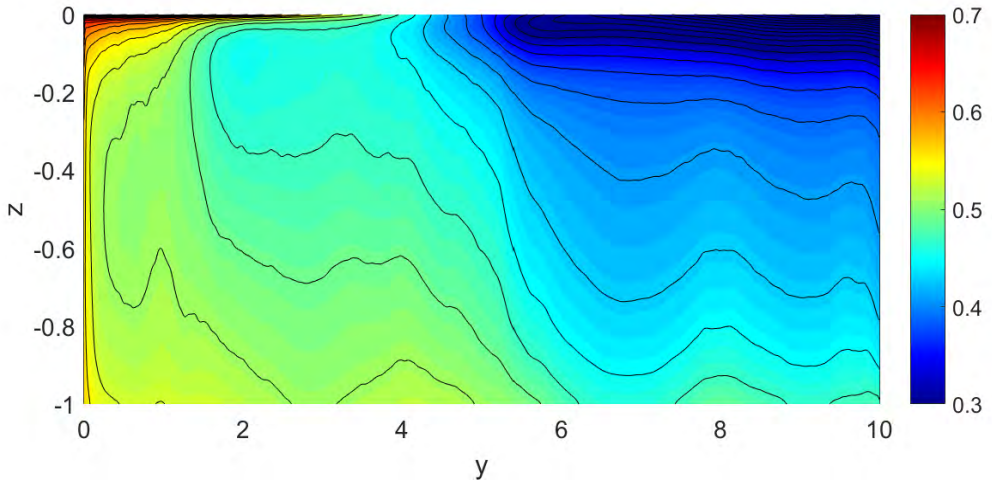
EVOLUTION OF BUOYANCY FIELD

Buoyancy and Wind Forcing

Instantaneous



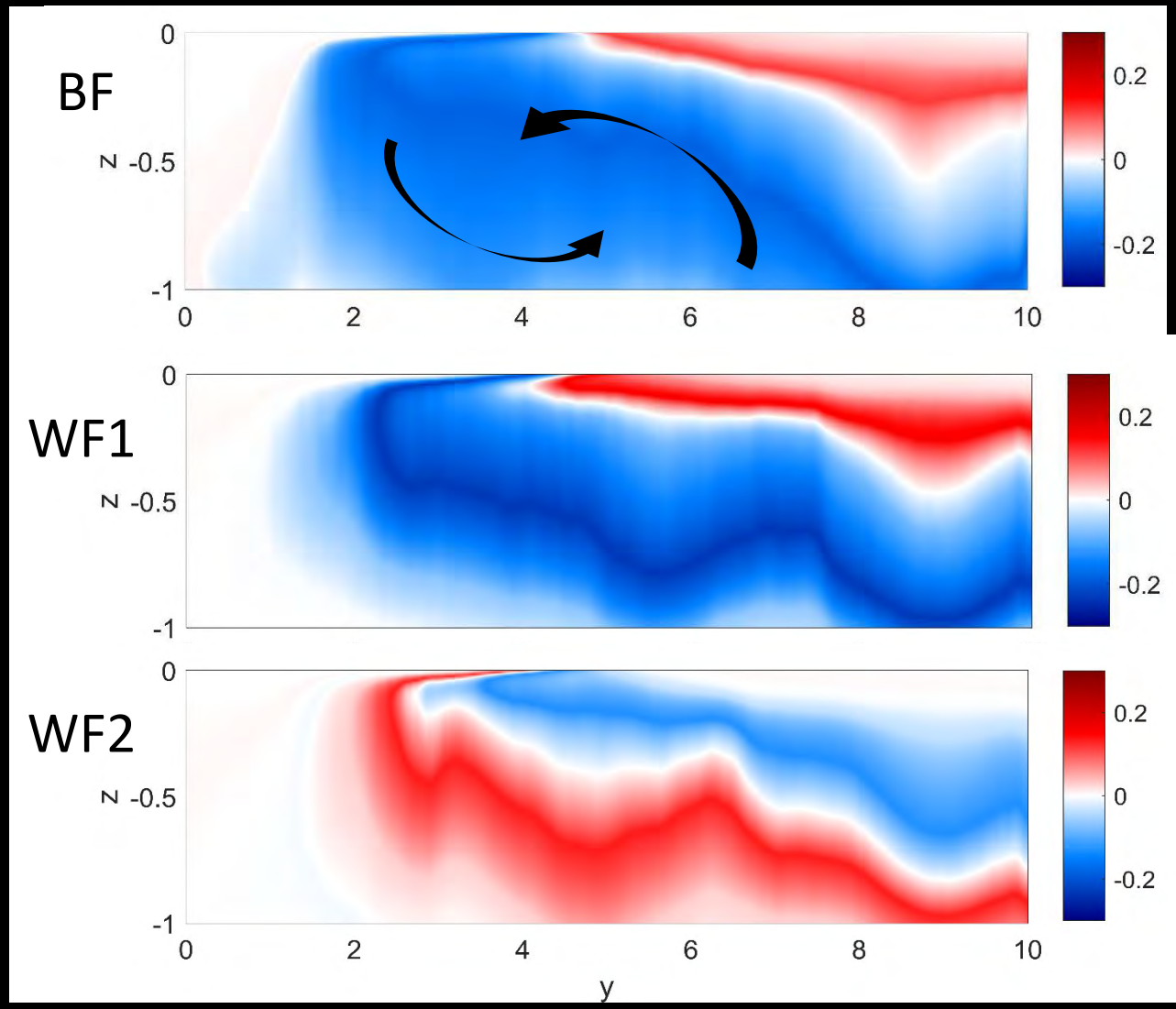
Temporal and zonal average

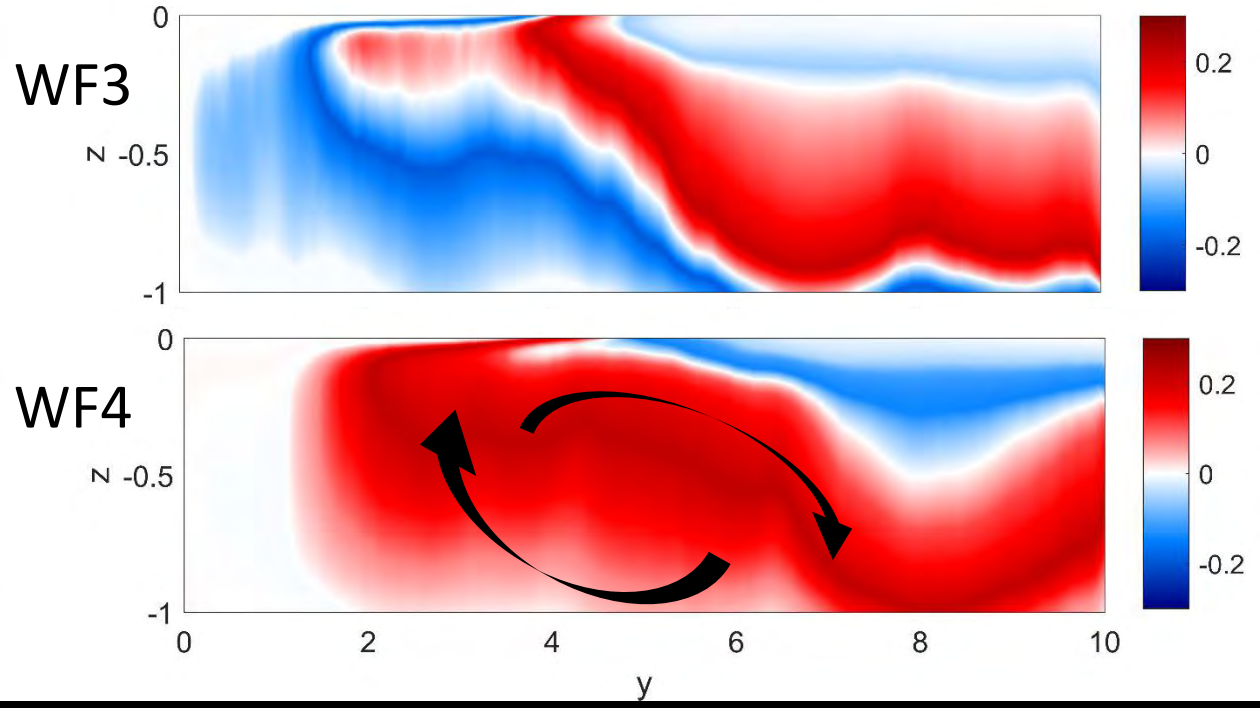


Latitude-depth residual overturning streamfunctions

$$\Psi_{y\rho} = -\frac{1}{\Delta t}\int_t \int \int_{\rho' \leq \rho} v(x,y,z,t)\,dz\,dx\,dt$$

- Positive: clockwise; negative: counterclockwise
- Different circulation depending on symmetry (WF2) or asymmetry (WF3) of wind stress profile
- WF3: 3 cells similar to the Southern Ocean





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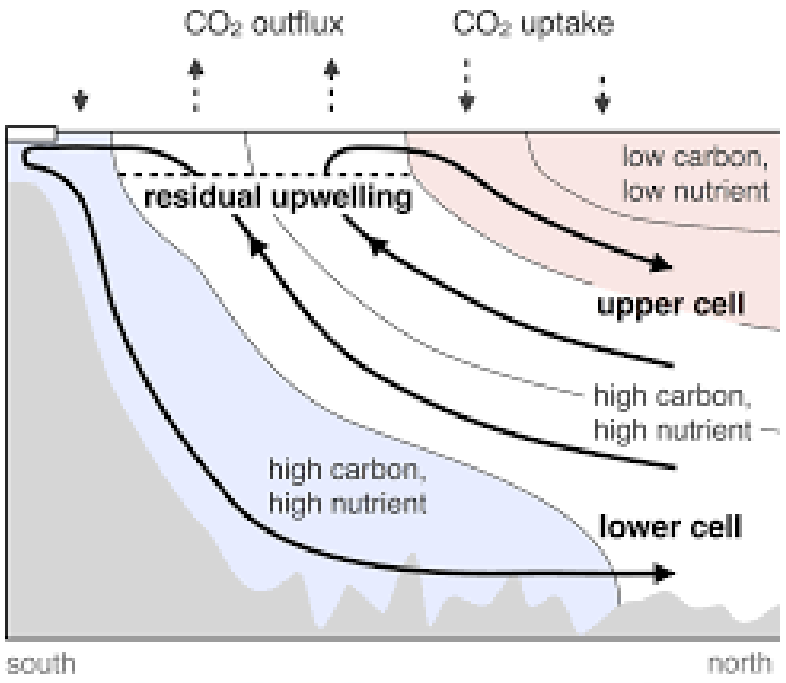
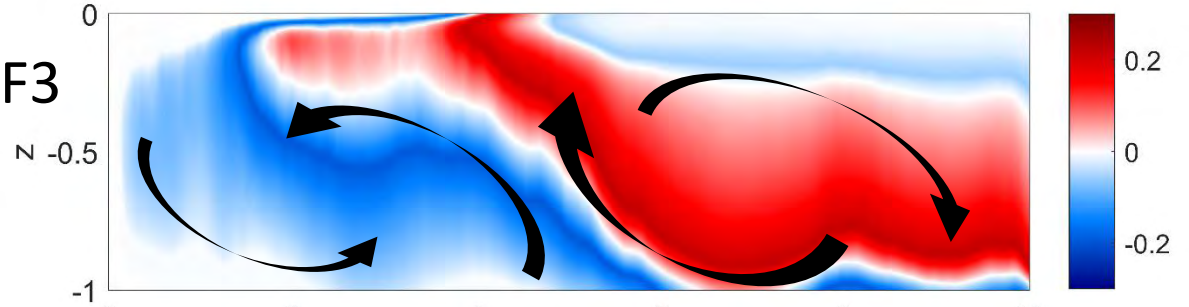
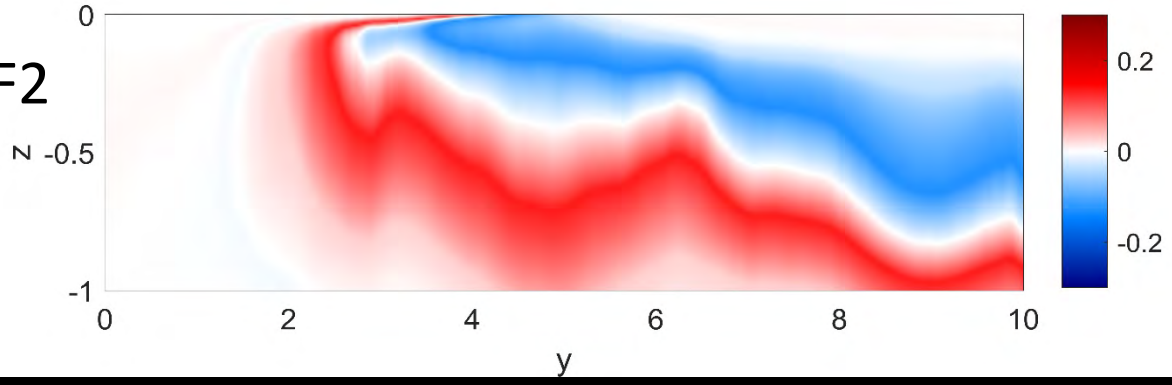
Real Ocean



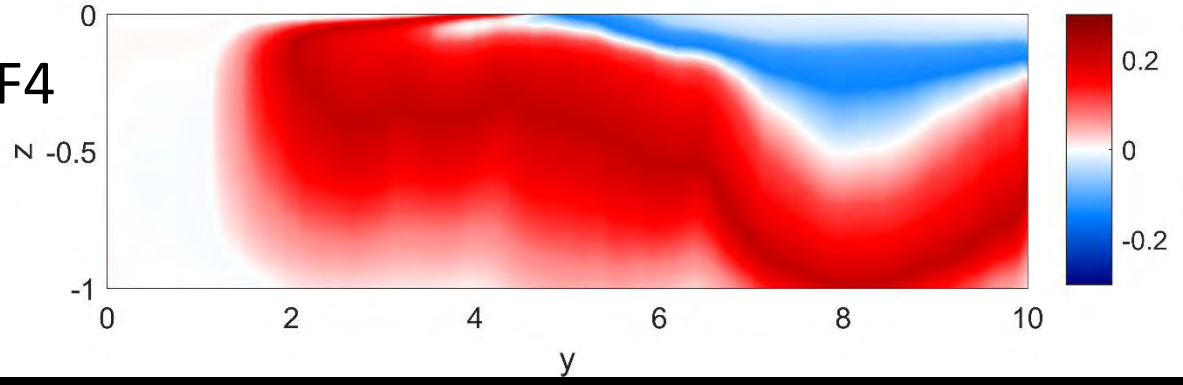
WF3



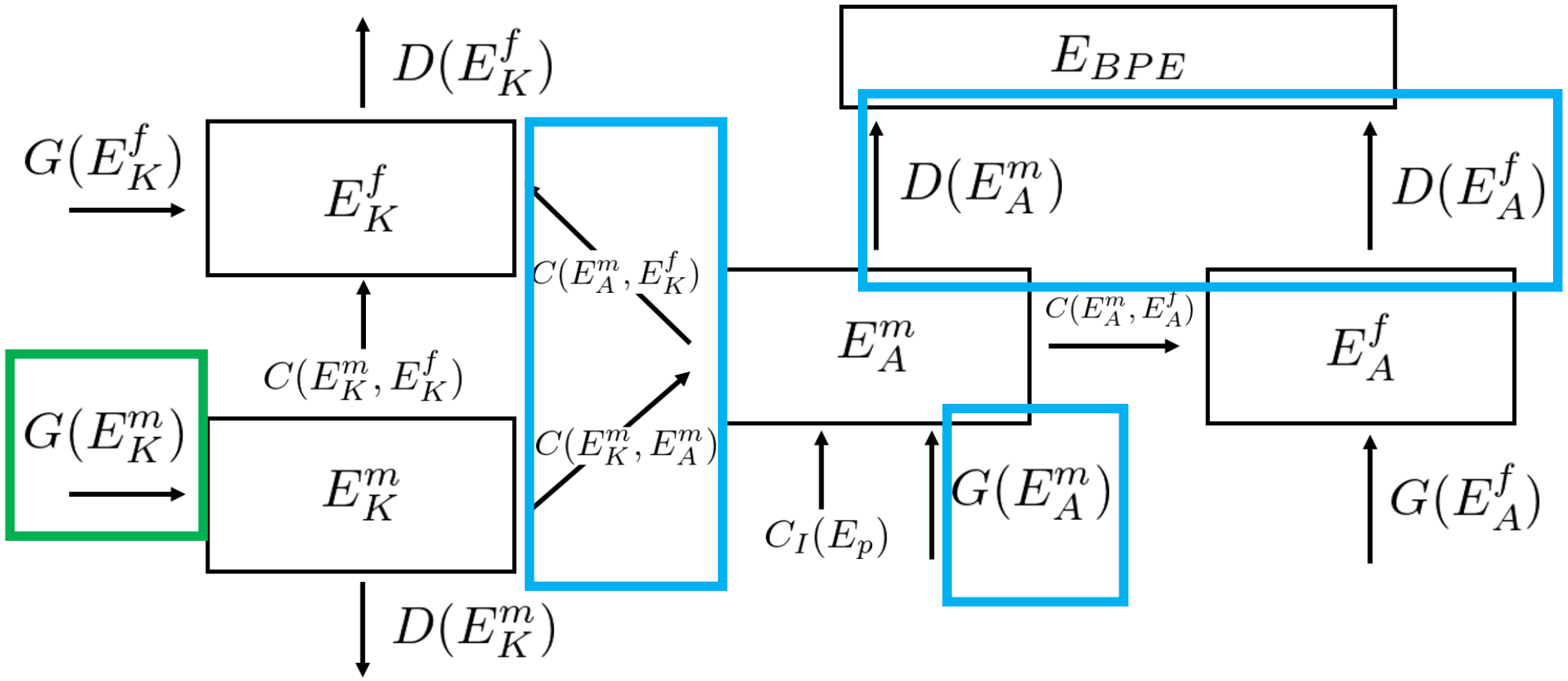
WF2



WF4



TERMS OF THE ENERGY BUDGET



Scotti and White (JFM, 2015), Zemskova et al (JPO, 2015)

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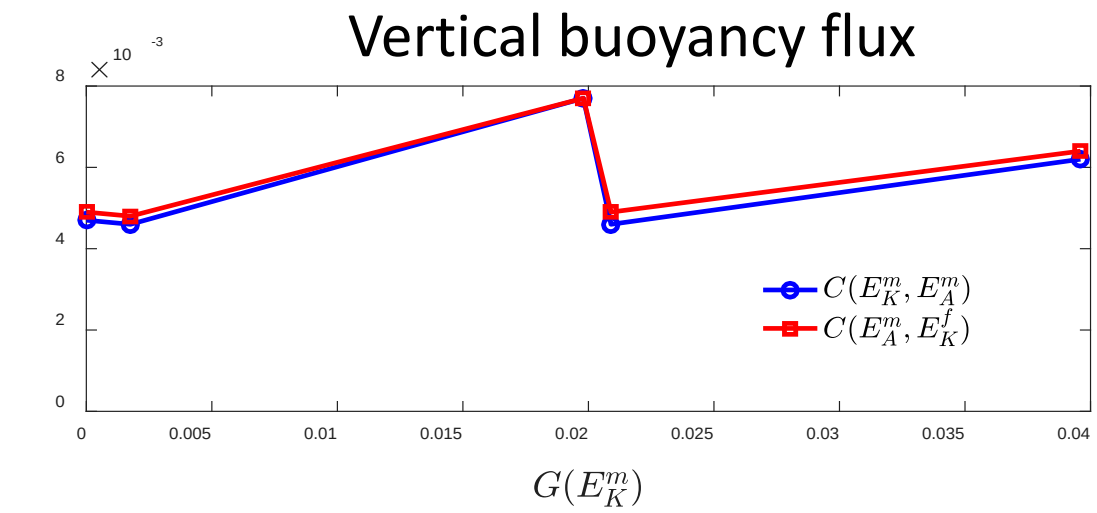

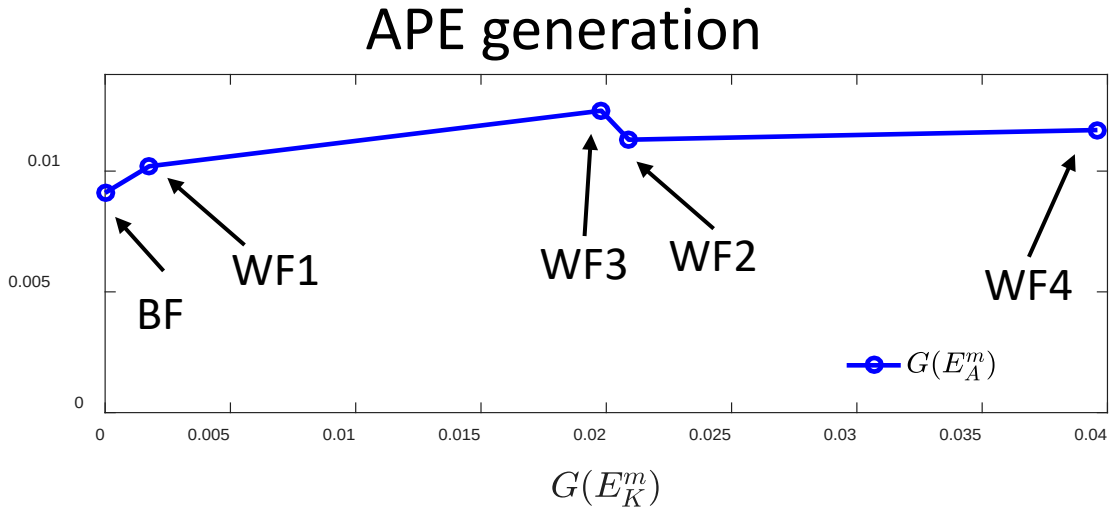

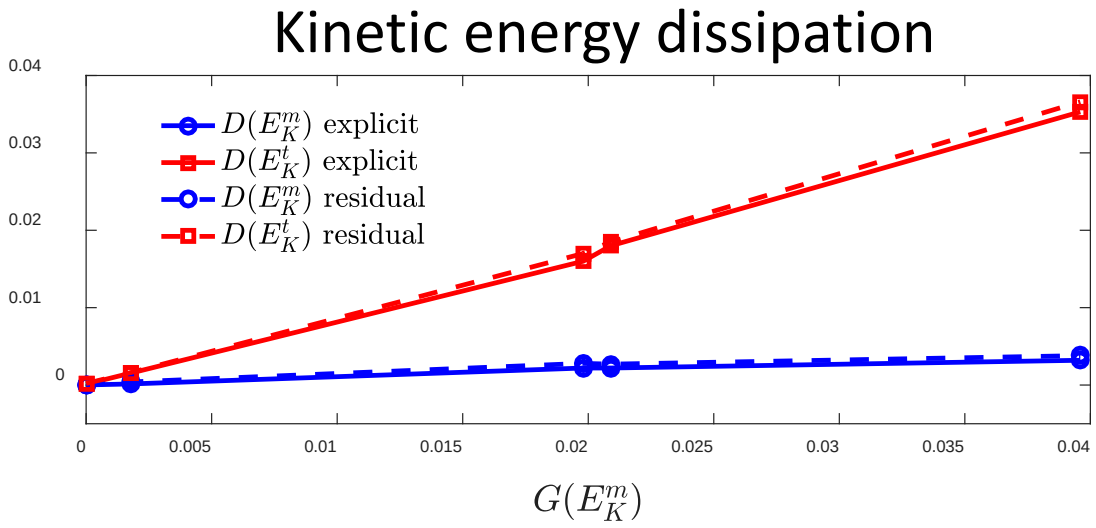

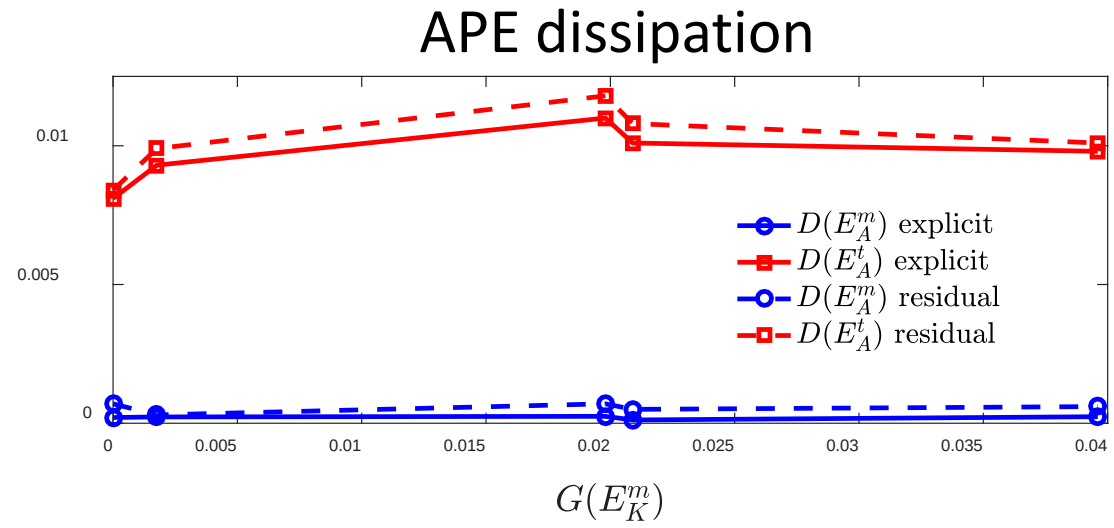

Conclusions

- Increase in wind stress magnitude does not significantly change the net APE energy budget terms
  - Balance between KE and APE conversion is maintained through mean and eddy vertical buoyancy flux fields
  - No significant increase in surface APE generation or dissipation

- Wind stress magnitude/shape plays a significant role in circulation
  - As G(KE) increases, progression from 2 cell-circulation (dominated by dense water formation) to 3 distinct circulation cells similar to the ocean
  - Strong wind forcing (WF4): more dominant downwelling of lighter water at the northern end and the dense water formation cell more confined and insignificant
  - The current wind stress profile is “the sweet spot”

Acknowledgements

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