Energetic dynamics of a rotating horizontal convection model with wind forcing

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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

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

More oxygen
More light
More nutrients

Motivation KE&APE Set-up Results Summary
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Two Mixing Models

"ABYSSAL RECIPES"
- Sinking of dense water at high latitudes
- Balancing upwelling at mid-latitudes

"EDDY COMPENSATION"
- Flow follows isopycnals (lines of constant density) created by surface wind stress
- Transient eddies balance the mean flow
• **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:
  
  $$ BPE = \int_V b z^* dV $$

- Available potential energy:
  
  $$ APE = \int_V b(z - z^*) dV $$

Scotti and White (JFM, 2015)
Solve Navier-Stokes Equations with Boussinesq approximation and rotation:

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

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

\[ b = g \left( \frac{\rho - \rho_0}{\rho_0} \right) \quad \nabla \cdot \mathbf{u} = 0 \]

SOMAR: Stratified Ocean Model with Adaptive Refinement

Santilli and Scotti (JCP, 2015)
**SIMULATION SET-UP**

Left BCs: no buoyancy flux, free slip

Right BCs: no buoyancy flux, free slip

Bottom BCs: no buoyancy flux, solid wall

Periodic in x-direction

Top BCs: Dirichlet buoyancy, solid wall OR Wind forcing
COMPARISON OF FORCING TO OCEAN DATA

Motivation
KE&APE
Set-up
Results
Summary

1) Wind stress magnitude
2) Shape of wind stress
• 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 mimic realistic ocean
  - Large aspect ratio: $10^4$ km in horizontal
  - Large Rayleigh number: depends on viscosity and horizontal scales

• Computational capabilities on Blue Waters allow:
  - Fine resolution (512x1024x128 grid points base grid + AMR)
  - Long run time
    - Small time step due to high velocities resulting from wind stress and rotation
    - Many time steps required to reach steady state (100,000+)

DIRECT NUMERICAL SIMULATIONS ON BLUE WATERS
EVOLUTION OF BUOYANCY FIELD

Buoyancy and Wind Forcing

Instantaneous

Temporal and zonal average
Latitude-depth residual overturning streamfunctions

- 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

\[ \Psi_{y\rho} = -\frac{1}{\Delta t} \int_t \int \int_{\rho'} v(x, y, z, t) dz dx dt \]
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TERMS OF THE ENERGY BUDGET

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