ESCI 485 – Air/sea Interaction
Lesson 7 – Deep Ocean Circulation and Air-sea Interaction
Dr. DeCaria

References: ***Introductory Dynamical Oceanography*, Pond and Pickard**
***Principles of Ocean Physics*, Apel**

SVERDRUP TRANSPORT

- **The vorticity equation below the Ekman layer (so we can ignore the direct effects of wind stress) is**

$$\frac{\partial \zeta}{\partial t} + \vec{V} \bullet \nabla \zeta = -\beta v - f \nabla \bullet \vec{V} . \qquad (1)$$

- **This equation states that the relative vorticity of a fluid parcel following the flow will increase due to southward flow, or due to convergence.**
- **In steady state we can ignore the time derivative on the LHS of the equation. If we further restrict ourselves to slow flows with low gradients, we can ignore the advection term on the LHS as well, so we have balance between advection of planetary vorticity and divergence,**

$$\beta v = -f \nabla \bullet \vec{V} . \qquad (2)$$

- **From the continuity equation**

$$\nabla \bullet \vec{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -\frac{\partial w}{\partial z} \qquad (3)$$

so we have

$$v = \frac{f}{\beta} \frac{\partial w}{\partial z} . \qquad (4)$$

- **Multiplying by density and integrating from the bottom of the ocean upward to the bottom of the Ekman layer we get (treating density as constant)**

$$\int_{-H}^{-D_E} \rho v dz = \frac{f}{\beta} \int_{-H}^{-D_E} \rho \frac{\partial w}{\partial z} dz$$

which becomes

$$M_y = \frac{f\rho}{\beta} w_E \qquad (5)$$

where w_E is the vertical velocity at the bottom of the Ekman layer.

- **We've previously established that**

$$w_E = \frac{1}{\rho f} \nabla \times \vec{\tau} \tag{6}$$

so combining the above two equations gives

$$M_y = \frac{1}{\beta} \nabla \times \vec{\tau} \tag{7}$$

- **Equation (7) tells us that the interior transport in the ocean (the transport below the Ekman layer) is also driven by the surface wind stress.**
  - ***Anticyclonic wind stress will induce southward flow in the deep (benthic) layer, so within the sub-tropical gyres there should be southward flow, even on their northern extremities!***
  - **This is known as *Sverdrup* transport.**
- **The physical explanation of why the benthic flow should be southerly uses the conservation of potential vorticity (technically, *Ertel's potential vorticity*)**

$$P \equiv -g\left(\zeta_\theta + f\right)\frac{\partial \theta}{\partial p}, \tag{8}$$

  which is conserved in adiabatic motion.
  - **As the fluid descends the spacing between potential temperature surfaces (*isentropes*) decreases so that $\partial\theta/\partial p$ has greater magnitude. This means that either the relative vorticity or the planetary vorticity must decrease.**
  - **A change in relative vorticity would require a change in the depth of the fluid. Therefore, the planetary vorticity must decrease instead, which requires a southward flow.**
- **Key point: Even the interior flow of the ocean, though isolated from the surface by a very stable layer (the thermocline) is still driven by air-sea interaction via the Ekman layer!**
- **Equation (7) is only valid away from the western boundary current. This is because near a strong current we can no longer ignore the advective terms in the vorticity equation.**

DEEP CONVECTION IN THE OCEAN

- **Another manifestation of air-sea interaction is oceanic deep convection.**

- **The ocean contains a very stable layer (the thermocline). Oceanic convection is therefore difficult to achieve, and occurs only in relatively few locations.**
- **The primarily spots for oceanic deep convection are:**
    - **Mostly in high latitudes (where the stability of the ocean is less than in the lower latitudes).**
    - **Near the boundaries with continents, so that very cold continental air masses can move out over the water.**
- **Examples of areas with deep convection are the Gulf of Lions in the Mediterranean Sea, and the Labrador Sea.**
- **Oceanic deep convection occurs when the surface waters are quickly cooled, which causes them to become denser and sink.**
- **Oceanic convection vertical velocities are two orders of magnitude less than in the atmosphere (~ cm/s).**