ESCI 344 – Tropical Meteorology
Lesson 9 – The Tropical Oceans

References: *Climate Dynamics of the Tropics*, Hastenrath
Descriptive Physical Oceanography, Pickard and Emery
Ocean Circulation, Brown and Colling
"On the wind-driven ocean circulation", W.H. Munk, *J. Meteor.*, **7**, 79-93, 1950
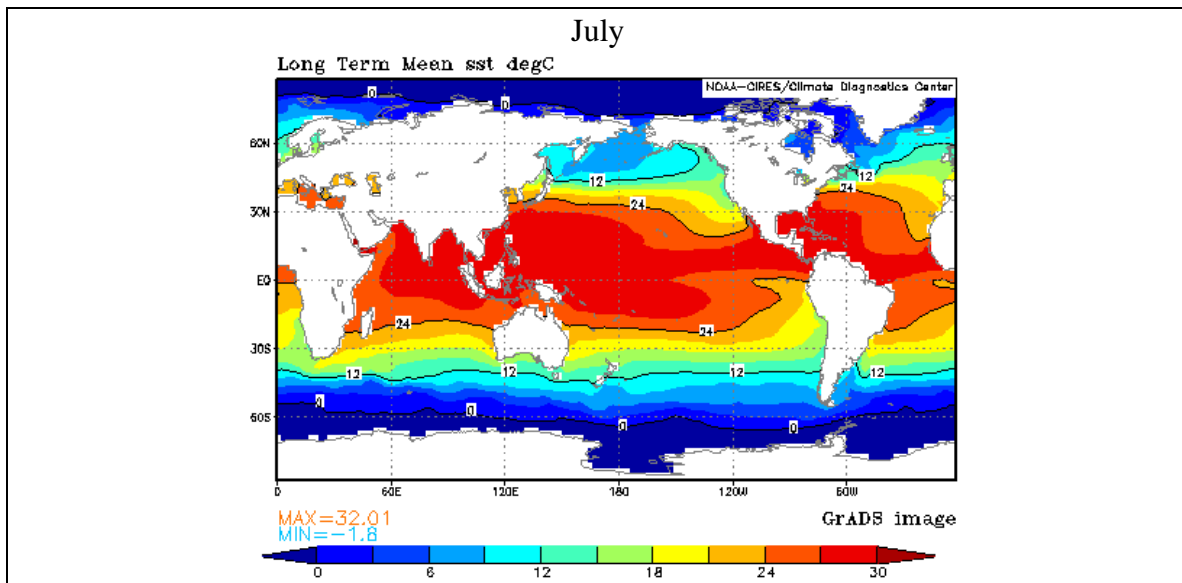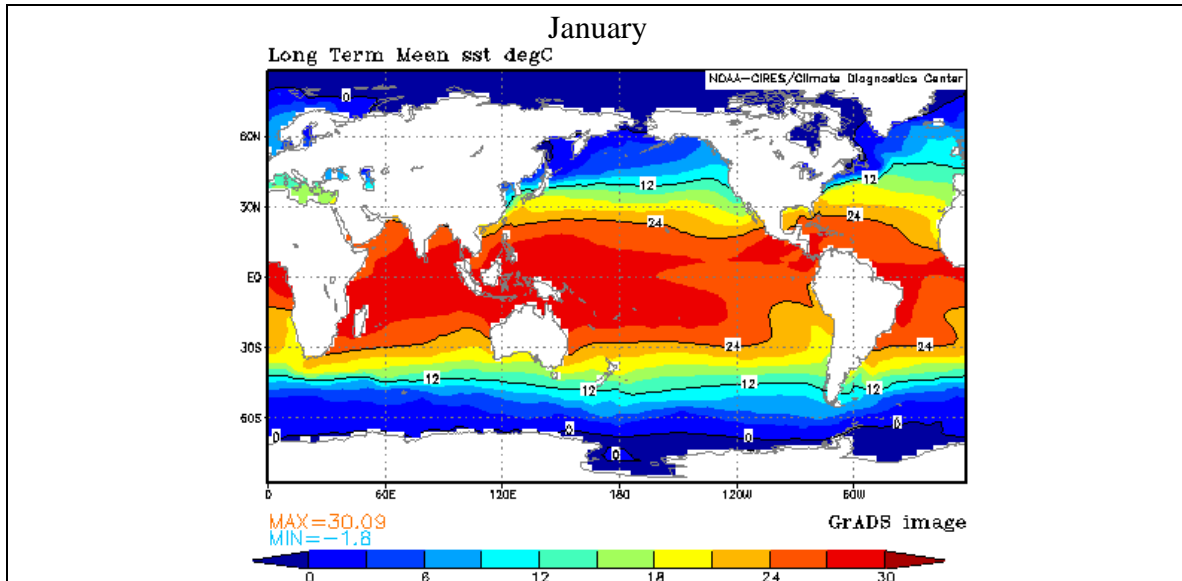
Reading: 'Equatorial Currents'

BASIC OCEAN STRUCTURE

- **The ocean can be divided into three layers**
  - *Mixed* (or *surface*) **layer**
  - *Thermocline*
  - *Deep layer*
- **The mixed layer is akin to the atmosphere's planetary boundary layer.**
- **The mixed layer gets its name from the fact that it tends to be well mixed, with the temperature being nearly isothermal with depth.**
- **The depth of the mixed layer varies with location and season. Typical ranges are from 25 to 500 meters.**
- **The depth is determined primarily by how rough the seas are. The rougher the seas, the deeper the mixing.**
  - **Since seas are generally rougher in winter, the mixed layer depth is usually deeper in winter than in summer.**
- **At the bottom of the mixed layer is the beginning of the *thermocline*.**
- **The thermocline is characterized by a decrease in temperature with depth.**
- **The thermocline is a very stable layer. Because of this, vertical mixing in the ocean at depths below the mixed layer is very slow.**
- **Because the ocean typically has a strong thermocline that inhibits mixing between the mixed layer and the deep layer, it is sometimes conceptually and mathematically convenient to model the ocean as a two-layer fluid.**

SEA-SURFACE TEMPERATURE

● **The images below show the monthly mean sea-surface temperature (SST) for January and July. (***Images provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at* http://www.cdc.noaa.gov/*.**

January

Long Term Mean sst degC

MAX=30.09
MIN=-1.8

GrADS image

July

Long Term Mean sst degC

MAX=32.01
MIN=-1.8

GrADS image

● **Things to note about the SST distribution**
  ○ **Tongue of cold SST along Equator in Atlantic and Pacific Oceans.**
  ○ **Relatively colder SST along west coasts of continents (except Australia) as compared to the east coasts.**

WIND STRESS AND THE EKMAN SPIRAL

- **The horizontal momentum equations for the ocean are**

$$\frac{Du}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv + \frac{1}{\rho}\frac{\partial \tau_x}{\partial z}$$

$$\frac{Dv}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu + \frac{1}{\rho}\frac{\partial \tau_y}{\partial z}$$

  where the stress terms (those involving τ) are due to vertical turbulent momentum fluxes (Reynolds stress).

- **For steady flow the equations are**

$$-fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{1}{\rho}\frac{\partial \tau_x}{\partial z}$$

$$fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{1}{\rho}\frac{\partial \tau_y}{\partial z}$$

- **The flow can be broken up into a part driven by the pressure gradient and that driven by the stresses. The part driven by the stresses is governed by the equations**

$$v = -\frac{1}{f\rho}\frac{\partial \tau_x}{\partial z}$$

$$u = \frac{1}{f\rho}\frac{\partial \tau_y}{\partial z}$$

- **In the early 1900's an oceanography students named Ekman solved the above two equations to find the vertical structure of flow driven by the wind stress. His result is**

$$u(z) = \exp(\gamma z)[U_0 \cos(\gamma z) - V_0 \sin(\gamma z)]$$
$$v(z) = \exp(\gamma z)[V_0 \cos(\gamma z) + U_0 \sin(\gamma z)] \quad .$$

  where *U_0 and V_0* are the zonal and meridional components of the surface current, and

$$\gamma \equiv \sqrt{f/2K}$$

  where *K* is the eddy viscosity.

- **If the solution above is plotted on a hodograph it traces a decaying clockwise spiral with depth (in the Northern Hemisphere). This is known as the *Ekman spiral*.**

- **The depth of the Ekman layer is taken to be that point at which the spiral has made one complete rotation (or the *e*-folding scale of the decay). Therefore, the depth of the Ekman layer is**

$$D_E = \frac{1}{\gamma} = \sqrt{\frac{2K}{f}} \ .$$

- **Two interesting and important facts about the Ekman spiral:**
  - o **#1 – *The surface current flows at exactly 45° to the right of the surface wind* (in the NH).**
    - ■ **Objects such as icebergs, life rafts, etc. will actually drift to the right of the prevailing wind.**
  - o **#2 - *The vertically-integrated mass transport in the Ekman layer is directed at 90° to the right of the surface wind*.**


EKMAN TRANSPORT AND UPWELLING/DOWNWELLING
- **The fact that the vertically-integrated mass transport in the Ekman layer is directed at 90° to the right of the surface wind is important in the distribution of ocean surface temperature.**
- **Off of the east coast of North America, the winds from the Pacific High in spring and summer blow nearly parallel down the coast.**
  - o **The resultant Ekman transport is to the west, away from the coast.**
  - o **The surface divergence along the coast results in the *upwelling* of cooler water from below, explaining the cooler SST observed off of the west coast of North America.**
  - o **This cool water helps keep the summertime climate of the coast cool and often foggy.**
  - o **The Ekman transport forced by the South Pacific high also explains cool water off of west coast of South America.**
- **Along the Equator, the trade winds result in Ekman transport away from the Equator in both hemispheres.**
  - o **The resultant surface divergence along the Equator results in upwelling of cooler water from below, and explains the tongue of cold water observed in the SST distribution in the Atlantic and Pacific Oceans.**

● **A persistent anticyclone over the ocean will result in a net transport of ocean water toward the center of the anticyclone, with down-welling pushing the cooler deep water even deeper.**

● **A persistent cyclone over the ocean will result in a net transport of ocean water away from the center of the cyclone, with up-welling pulling the cooler deep water toward the surface.**

WIND-DRIVEN SURFACE CURRENTS IN A RECTANGULAR OCEAN

● **In 1950, Walter Munk used a realistic latitudinal wind profile to derive what the steady-state surface circulation would be in a rectangular ocean.**
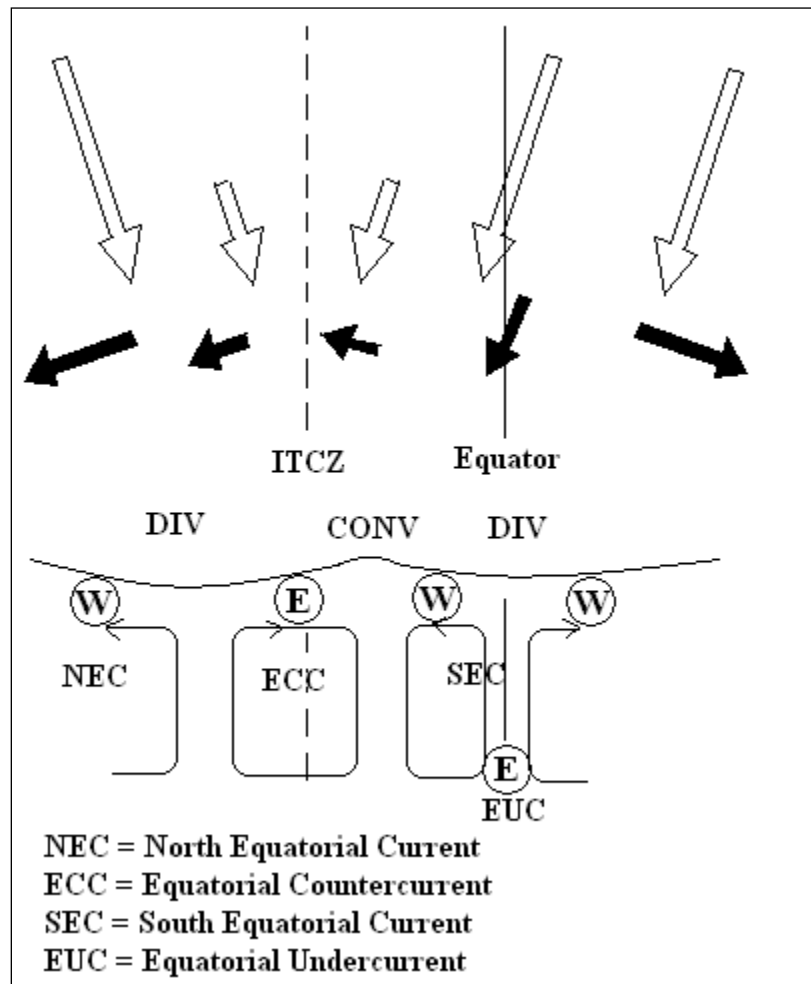
    ○ **His results are recreated in the figure below.**

After Munk, 1950: "On the wind-driven ocean circulation", J. Meteor., 7, 79-93
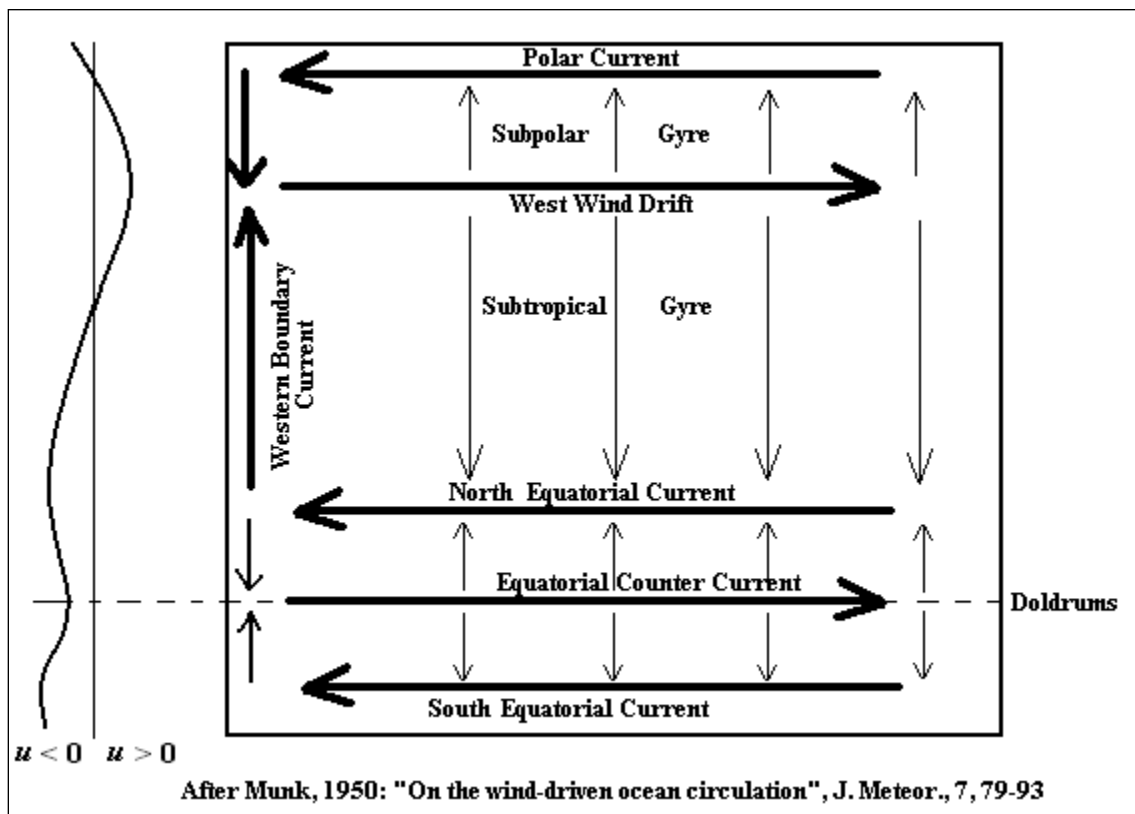
● **The major features of the circulation are:**

    ○ **A cyclonically rotating subpolar gyre**

    ○ **An anticyclonically rotating subtropical gyre**

    ○ **Two westward flowing equatorial currents symmetric with the ITCZ (not the Equator).**

- ○ **An eastward flowing equatorial counter current between the equatorial currents.**
- ○ **Strong, western boundary currents in the subtropical and subpolar gyres, contrasted with weaker return flows east of the gyre centers.**
- ● **One striking feature of this circulation pattern is the strong, well-defined *western boundary current*, as opposed to the weaker, broader flow to the east of the gyre.**
  - ○ **The western boundary currents are due to the fact that Coriolis changes with latitude. If Coriolis were constant, the western boundary currents wouldn't exist.**

EQUATORIAL CURRENTS
- ● **The surface currents in the Pacific and Atlantic have a similar structure, and can be explained at least in part by convergence and divergence associated with Ekman transport.**

ITCZ   Equator

DIV   CONV   DIV

NEC   ECC   SEC
                                      EUC

NEC = North Equatorial Current
ECC = Equatorial Countercurrent
SEC = South Equatorial Current
EUC = Equatorial Undercurrent

- **The diagram above shows the air flow (open arrows) and the resultant Ekman transport (dark arrows).**
- **The "DIV" and "CONV" denote regions of divergence and convergence in the Ekman transport.**
  - **Regions of divergence will result in a lowering of the sea-surface, while regions of convergence will raise the sea surface.**
- **Other than within a degree or so of the Equator, the ocean flow will be parallel to the sea-surface contours with low heights to the left in the Northern Hemisphere, and to the right in the Southern Hemisphere.**
  - **The ocean currents and their directions are indicated by the "W" and "E" annotations, with "W" indicating a westward current, while "E" indicates an eastward current.**
- **The resultant surface currents are the**
  - **North Equatorial Current – Westward flowing**
  - **Equatorial Counter Current – Eastward flowing, more-or-less aligned with the ITCZ.**
  - **South Equatorial Current – Westward flowing, and in both hemispheres.**
- **There is also an Eastward flowing Equatorial Undercurrent that more-or-less flows along the Equator at depth.**
- **The equatorial currents in the tropical Indian Ocean differ in that since the atmospheric flow switches directions seasonally due to the monsoon, so do the currents.**

EAST-TO-WEST STRUCTURE OF THE THERMOCLINE
- **In the tropical Pacific Ocean, the trade winds result in a net transport of surface waters toward the western part of the basin, toward Indonesia and Australia.**
- **This net transport of surface waters results in a suppressing of the thermocline toward the west, and a deep pool of warm surface water in the western part of the basin.**