Figure 1

\[ p \]

\[ \text{continuum} \]

\[ y \]

density \( p = \frac{\text{mass}}{\text{Volume}} \)
**Figure 2**

(a) \[ \text{isotropic} + \text{deviatoric (results in anisotropic deformation)} \]

(b) Non-isotropic normal and shear forces are equivalent.
Figure 3.

$F(x,t)$ is a sinusoid moving to the right.

(a) An observer who moves with $F$ and looks at one point will see a constant.

(b) An observer fixed in space who observes $F$ through a slit which is also fixed will see a value that oscillates up and down.
Figure 4

(a) $t = 0$

(b) $t = \delta t$

Side is stretched

Side is rotated
Figure 5

Non-uniform normal forces acting on a small volume of fluid.

\[ \text{normal force/}\text{unit area} = -p\hat{n} \]
Figure 6

\[ \tau_{xz} = \mu \frac{\partial u}{\partial z} \]

Coulomb Flow
Figure 7
Figure 8

(a)

\[ \mathbf{\Omega}_R = \mathbf{\Omega} \times \mathbf{r} \]

observer on Earth

(b)

\[ \mathbf{\Omega} \times \mathbf{r} \times \mathbf{r} = -\mathbf{\Omega}^2 \mathbf{r} \]
FIGURE 9
Figure 10

\[ P = P_{\text{atm}} \]

[Diagram: A cycle with arrows indicating movement between two points labeled as 'surface' and 'bottom'.]
(a) Rotating "Couette" Flow (Top View)

(b) Cone-Plate "Couette" Flow (Side View)

\[ u(R) = \Omega R \]
\[ \delta(R) = R \tan \Theta \approx R \Theta \]
\[ \frac{\partial u}{\partial z} = \frac{u}{\delta} = \frac{\Omega}{\Theta} = \text{constant} \]
(a) Plane Poiseuille Flow

(b) Cylindrical Poiseuille Flow (Pipe Flow)
(a) Porous medium

Flux \( F \rightarrow \)

- total area \( A \)

\[ u_{\text{avg}} = \frac{F}{A} \]

(b) Hele-Shaw Cell

\[
\begin{align*}
\text{fluid} \\
\end{align*}
\]
FIGURE 14

T 0°C

Z (m e k n)

1000

2000

Tropics or Seasonal mid-latitude
Polar Winter
$u = U \cos(wt)$
Figure 16

\[ u = u_x \]
also see figure 2.5 in Tritton
There is a baroclinic geostrophic current (northward in N. hemi) in lower layer.

The pressure gradient force $Pp'$ is independent of depth. There is a barotropic geostrophic current at all depths.
Block moves very slowly relative to rotating tank.
**Figure 21**

(a) \[ |r_1| = |r_2| \]

Twisting (or tilting)

(b) \[ |r_{11}| < |r_{12}| \]

Stretching
\begin{equation}
\mathbf{u}_2 - \mathbf{u}_1 \Rightarrow L_2 > L_1
\end{equation}
\begin{equation}
\mathbf{u}_2 > \mathbf{u}_1 \Rightarrow \Theta > 0
\end{equation}
$\text{at small, } L_1 \approx L_2$
FIGURE 23

Bernoulli's Theorem \( \Rightarrow P \) inversely proportional to \( \nu \).

(a) Airfoil

![Diagram of airfoil]

Velocity above airfoil higher due to longer path.

(b) Venturi

![Diagram of venturi]

Velocity in constriction is high due to small cross section.

(c) Corrugated
Flow separation can occur in the B1 when $\Delta p$ reverses local flow.
FIGURE 25

\[ f_c = \text{centrifugal force due to rotation (decreases in boundary layer)} \]

\[ f_p = \text{pressure gradient force due to tilt of surface (increases linearly with } R \Rightarrow \text{slope increase with } R) \]
(a) Ekman Spiral (side view)

(b) Ekman layer on top of stationary fluid

(c) Ekman layer on fixed lower boundary
**Figure 27**

(a) Hadley Cell

(b) Polar Easterlies
   Westernlies
   Trade Winds
Northward displacement creates clockwise rotation [shortens vortex tube]

Southward displacement creates counter clockwise rotation [stretches vortex tube]
No stretching of vortex tubes

Stretching linearly proportional to latitude

--- wind ---

More realistic picture
Figure 30(a)

Schematic cross section of South Atlantic
Fig. 30(b)

Schematic flow lines for abyssal circulation. The cross-hatched areas indicate regions of production of bottom water. [Adapted from Stommel, H., Deep Sea Research (1958).]

Fig. 30(c)

Schematic cross section of surface and subsurface currents in the North and South Atlantic. [Adapted from Wüst, G., Kieler Meeresforschungen (1950).]
Figure 31

\[ p = \rho gh \quad \Rightarrow \quad f_p = \rho g \frac{\partial h}{\partial x} \]

\[ W = 0 \quad \Rightarrow \quad \frac{\partial p}{\partial x} = 0 \]
Figure 32

(a) 

$\sin(kx)$

$\cos(kx)$

$\lambda = \frac{2\pi}{k}$

(b)

envelope
Figure 33

\[ t_{\sim 0} \]

\[ t_{1 > 0} \]

\[ t_{2 > t_{1}} \]
Fig. 34. Wave energy spectra on successive days at a coastal site.
Figure 35

Fluid motion in surface gravity waves

(a) Deep water

(b) Shallow water
Figure 36 – Deep and shallow water waves; period = 10 s

- Shallow water
- Deep water
Wave crest convergence (focussing) and divergence (de-focussing) due to bottom contours. Wave energy is focussed on a ridge (which would erode the ridge).
Figure 38

Linear wave

Weakly non-linear wave

Strongly non-linear wave

Bore (shock wave)

\[ \sqrt{gH_1} < c < \sqrt{gH_2} \]
Figure 39

Kelvin Wave

\[ \uparrow \Omega \]

\[ \rightarrow C_P \]
Fig. 40(a) Schematic of rise and fall of tides in an embayment in the Northern Hemisphere. Tidal elevations appear to rotate counterclockwise about the amphidromic point. [Adapted from von Arx, W. S., An Introduction to Physical Oceanography (1962).]

Fig. 40(b) Transition of tidal amplitude from New York harbor across the continental shelf to the shelf break. [Adapted from Schwiderski, E. W., Rev. Geophys. and Space Phys. (1980).]
Figure 40(c). Positions of crests as a function of time for the M2 (Lunar Diurnal) tide. This is the largest tide. The next largest is the S2 (Solar Diurnal). Note that the time is labeled in units of the period/12 and is not exactly hours, because the lunar day (time from moon overhead to moon overhead) is not 24 hours. Note that the wave circulates around single nodes (amphidromes) in the North and South Atlantic, but that there are four amphidromes in the Pacific south of the equator.
Figure 41 – Deep water capillary and gravity waves
To keep the constant observer at speed, \( \phi \) must move to cancel (11 to \( k \)).

\[
\text{Phase } \phi = k \cdot x - \phi
\]

\[
\dot{\phi} = k^2 \cdot \dot{x} + \frac{1}{2} m \cdot \dot{y}^2
\]

\[
\text{Surface (i.e. to const)} + \text{towards (i.e. to)}
\]

Figure 42
All the acoustic rays between a source (at 1200 m) and a receiver (at 1000 m) though a realistic ocean that includes a mesoscale warm eddy centered at 200 km downrange. From Mercer and Booker (1983).
Sound speed profile from a station near Bermuda as averaged over nine years. (Adapted from Jones, L. M., and W. A. Von Winkle, USN Underwater Sound Laboratory Report 632 (1965).)

All the acoustic rays between a source (at 1200 m) and a receiver (at 1000 m) though a realistic ocean that includes a mesoscale warm eddy centered at 200 km downrange. From Mercer and Booker (1983).
Fig. 4.35  (a) Positions of the 15°C isotherm at depths between 100 and 700 m, showing the Gulf Stream, nine cyclonic, and three anticyclonic eddies. Data were taken by subsurface drifting floats and other means. (b) Subsurface profile along a line segment A–A′–A″ in Fig. 6.42a, showing the Gulf Stream boundary at left, and cold-core rings at 650 and 850 km. [From Richardson, P., et al., J. Geophys. Res. (1978)].
Phase progression, September 1965 – May 1966
Figure 47

(a) 

(b) 

Restoring force in $z$ direction $\propto g \sin \theta$

Restoring force directed towards original position $\propto g \sin^2 \theta$
\[
\sin \theta = \frac{k}{|k|}, \quad \cos \theta = \frac{m}{|k|}
\]
Fig. 15.11 Waves produced by vibrating cylinder in a stratified fluid (dark vertical line is cylinder support). (a) $\omega/N = 0.90$; (b) $\omega/N = 1.11$. Ref. [282].
Generation of vorticity by lateral density variation
Figure 51

Fluid

$T_1 - z = d$

$T_1 + 0 \quad \frac{z}{2} = 0$

$T \rightarrow$

$p_o$

$p_{oo} \rightarrow$
Figure 52

(a)

(b)

unstable

stable

$k_c$
FIGURE 53

(a) \[\uparrow \quad T\]

const. density line

(b) heat diffus. →

warm fresh + unstable salt finger

warm salty

cold fresh