Atmospheric Motions

Chapter 8
Part 1
Atmospheric Motion

• Atmospheric motion in the form of wind is determined by the balance of various forces

• Forces include the
  – pressure gradient force
  – the coriolis force due to earth’s rotation
  – the centripetal force for curved motion
  – the frictional force, strongest near the earth’s surface
Atmospheric Motion

• Equations of motion expressed as force per unit mass of air - from Newton’s second law of motion, $F=ma$, so force/unit mass = acceleration $\rightarrow F/m=a$

• We are usually interested in wind speed (velocity) instead of acceleration
Acceleration

- Acceleration is speeding up, slowing down, or changing direction of motion (it takes force to change the direction, and from Newton’s 2nd law, F/m =a)

- Velocity is rate of change of position- e.g miles travelled per hour, or meters per second V=dS/dt or ΔS/Δt

- In a, position changes 10 m in one second, velocity 10 m/sec to the right. For the next second, position changes 15 m in 1 sec, velocity =15 m/sec

  a
  
  10 meters
  
  b
  
  15 meters

  Time=1 second  Time=1 second

Acceleration= rate of change of velocity= dV/dt or ΔV/Δt

Acceleration= (15 m/s - 10 m/s)/1 s = 5m/s² to the right
• Alternatively, consider that the air is moving 10 m/s (as in point a) and a force per unit mass (acceleration) of 5 m/s$^2$ is applied to it for one second. It’s new velocity is $10\text{m/s} + (5\text{m/s}^2)\times1\text{s} = 15 \text{ m/s}$

$$a = \frac{dV}{dt}, \quad \int_{t_1}^{t_2} a\,dt = \int_{v_1}^{v_2} dV, \quad a(t_2-t_1) = V_2 - V_1$$

$$V_2 = V_1 + a(t_2 - t_1) = V_1 + a \Delta t = 10 + 5(1) = 15 \text{ m/s}$$

Most calculations for atmospheric motions apply an acceleration to an initial velocity to calculate velocity at next time period
Pressure gradient force

TANK A

Higher pressure

Net force

TANK B

Lower pressure

H

L
Pressure gradient force in x direction: \( \frac{dp}{dx} = \frac{\Delta p}{\Delta x} \)

Pressure gradient force per unit mass: \( \frac{1}{\rho} \frac{dp}{dx} = \frac{1}{\rho} \frac{\Delta p}{\Delta x} \)
Pressure gradient force

• Pressure gradient force directed from higher to lower pressure at right angle to isobars
• Magnitude of pressure gradient force directly proportional to pressure gradient
• Pressure gradient force is what causes the wind to blow
• Closely spaced isobars – strong winds; widely spaced – light winds
• As air starts to move in response to the pressure gradient force, it is deflected by the coriolis force
Pressure Gradient Force
Coriolis force - apparent force due to the rotation of the earth - (rotating coordinate system)
Coriolis force

- Coriolis force deflects wind to the right in the northern hemisphere and to the left in the southern hemisphere.
- Coriolis force has effects on circulations that persist over a significant fraction of a day—sea-breeze start out directly on-shore, then gradually turns to the right and is nearly parallel to shore by sunset.
- Coriolis force affects wind direction but not speed.
- Coriolis force depends upon latitude, greatest at poles, zero at equator.
Coriolis Force

- Coriolis force per unit mass = $2\Omega V \sin \phi$
  where
  \[ \phi = \text{latitude in degrees} \]
  \[ V = \text{velocity} \]
  \[ \Omega \text{ is the rotation rate of the earth in radians per day (} 2\pi \text{ radians} = 360^\circ) = 7.292 \times 10^{-5} \text{sec}^{-1} \]
- $2\Omega \sin \phi$ is called coriolis parameter denoted as $f$
- Note that $f=0$ at equator, since $\sin(0^\circ)=0$
- $f$ approaches $2\Omega V$ near the poles
Geostrophic Flow

Balance of PGF and CF

Result is geostrophic flow
Wind and Pressure Gradient

- Weak (slow) flow
- Strong (fast) flow

Diagram: Left shows uneven land with weak and strong flow, right shows pressure gradients with L and H regions.
The Geostrophic Wind

• In upper levels of the atmosphere, isobars are often nearly parallel to each other (at the surface, isobars are curved around high and low pressure systems)

• The geostrophic wind is defined as wind where the pressure gradient force and coriolis force are in balance

• $2\Omega V_g \sin\phi = fV_g = (1/\rho) \Delta p/\Delta s$

• $V_g = (1/\rho f) \Delta p/\Delta s$, where $g$ stands for geostrophic
Geostrophic Flow

• Decrease of density with height causes $V_g$ to increase with height
• Can also write geostrophic wind in terms of height gradient of constant pressure surface - e.g. 500 mb
• $V_g = (g/f) \Delta z/\Delta s$
(a) Isobar or contour pattern

(b) Wind pattern
Calculate Geostrophic wind: Detroit to Topeka

$$\Delta z/\Delta s = 430 \text{ m}/1120 \text{ km} = 3.83 \times 10^{-4}$$

$$f = 10^{-4} \text{s}^{-1}, \ g = 9.8 \text{ ms}^{-2}$$

$$V_g = (g/f) \Delta z/\Delta s = (9.8 \text{ ms}^{-2})(3.83 \text{s}^{-1}) = 38 \text{ ms}^{-1} = 75 \text{ knots}$$
Gradient winds

• Flow parallel to curved isobars is called gradient flow – the wind is the gradient wind

• From Newton’s second law, change in speed or direction is acceleration. Curved flow is change in direction → acceleration

• The force causing this acceleration is the centripetal force = $V^2/r$, where $r$ is the radius of curvature
Gradient Winds

- Pressure gradient force, coriolis force, and centripetal force in balance is the gradient wind equation
  \[ \frac{V^2}{R} + \frac{1}{\rho} \frac{\Delta p}{\Delta s} + fV = 0 \]
- Solve for V
- Gradient winds are less than geostrophic winds for cyclonic flow, greater for anticyclonic flow, but usually within 20%
Frictional force

- Frictional drag of the ground slows the wind down within the lowest 1000 m or so of the atmosphere (stops at the surface)
- Frictional force causes surface wind to blow at angle to isobars, toward lower pressure angle typically about 30°, depending upon roughness of surface
- Frictional force causes winds to converge in center of low-pressure system and slowly rises- divergence aloft balances surface convergence or surface pressure changes- vertical motions typically <0.1 m/s
- Similarly for high, friction causes flow outward from high-convergence and subsidence above high to replace air
- Show example weather map with obvious frictional force
Winds Associated with Highs and Lows