1. **(Total 20%) Bow Echo**
   
   (a) (10%) Discuss the key features that can be identified in the radial velocity and reflectivity fields of the low-elevation scans of a Doppler radar located near a strong bow echo.

   (b) (10%) Briefly discuss the origin of strong surface winds in severe bow echoes.

2. **(Total 30%) Squall line**
   
   (a) (15%) Discuss, with sketches, the perturbation pressure patterns associated with a mature squall line, in both the vertical cross-section and the horizontal cross section at the surface. Explain the cause of such perturbation patterns.

   (b) (15%) Describe the RKW theory of long-lived squall lines.

3. **(Total 15%) Supercell Storm**
   
   (a) (5%) Why do supercells require large environmental shear?

   (b) (10%) Describe the key process by which vertical shear contributes to the establishment of supercell storms.

4. **(Total 15%) Supercell Storm Dynamics**

   The equation for the vertical vorticity $\zeta$ is
   
   $$\frac{\partial \zeta}{\partial t} = -\vec{\nu} \cdot \nabla \zeta + \frac{\partial w}{\partial z} + \left[ \xi \frac{\partial w}{\partial x} + \eta \frac{\partial w}{\partial y} \right],$$

   where $\xi$, $\eta$ are the $x$ and $y$ components of vorticity, respectively.

   Give the definition of each of the terms on the right hand side, and discuss in physical terms how these terms cause the change in the vertical vorticity.
5. (Total 20 %) Supercell Storm Dynamics

The pressure perturbation in a thunderstorm due to vertical rotation is approximately given by equation

\[ \nabla^2 p' \equiv \frac{\partial^2 p'}{\partial x^2} + \frac{\partial^2 p'}{\partial y^2} = \frac{\rho_o}{2} \xi^2, \]

where \( \xi \) is the vertical vorticity.

Assume that within a rotating updraft, \( \xi \) increases linearly from zero at the ground level to \( 10^{-2} \) s\(^{-1} \) at 5 km level.

We further assume that perturbation pressure \( p' \) has the following functional form within the updraft region:

\[ p' = P(z) \cos \left[ \frac{2\pi x}{L_x} + \frac{2\pi y}{L_y} \right] \]

where \( L_x \) and \( L_y \) are the wavelengths in \( x \) and \( y \) directions, and \( L_x = L_y = 20 \) km. The origin of the \( x-y \) coordinate is located at the center of the updraft. For simplicity, we assume that \( \rho_0 = 0.75 \) kg m\(^{-3} \) and remains constant with height.

a) (10%) Determine the perturbation pressure induced by the vertical rotation at the center of updraft at the 5 km level.

b) (5%) Determine the vertical pressure gradient force below 5 km level due to this pressure perturbation.

c) (5%) Determine the extra vertical velocity this updraft attains at 5 km level due to the effect of rotation. Assume the updraft speed increases linearly from 0 at the ground level to 50 m/s at 5 km AGL therefore the mean vertical velocity is 25 m/s in the 0-5km layer.

Hint: \( \frac{\partial^2 \cos(kx)}{\partial x^2} = -k^2 \cos(kx) \).