Vorticity describes the rotation of air (Fig. 10.29b). The relative vorticity, ζ_r , about a locally vertical axis is given by:

$$\zeta_r = \frac{\Delta V}{\Delta x} - \frac{\Delta U}{\Delta y} \tag{10.73}$$

The sign is positive for counterclockwise rotation (i.e., cyclonic rotation in the N. Hemisphere), and negative for clockwise rotation. Vorticity is discussed in greater detail in the General Circulation chapter. Neither divergence nor vorticity vary with rotation of the axes — they are **rotationally invariant**.

Two types of **deformation** are stretching deformation and shearing deformation (Figs. 10.29c & d). **Stretching deformation**, F_1, is given by:

$$F_1 = \frac{\Delta U}{\Delta x} - \frac{\Delta V}{\Delta y} \tag{10.74}$$

The axis along which air is being stretched (Fig. 10.29c) is called the **axis of dilation** (x axis in this example), while the axis along which air is compressed is called the **axis of contraction** (y axis in this example).

Shearing deformation, F_2, is given by:

$$F_2 = \frac{\Delta V}{\Delta x} + \frac{\Delta U}{\Delta y} \tag{10.75}$$

As you can see in Fig. 10.29d, shearing deformation is just a rotated version of stretching deformation. The **total deformation**, F, is:

$$F = \left[F_1{}^2 + F_2{}^2 \right]^{1/2} \tag{10.76}$$

Deformation often occurs along fronts. Most real flows exhibit combinations of divergence, vorticity, and deformation.

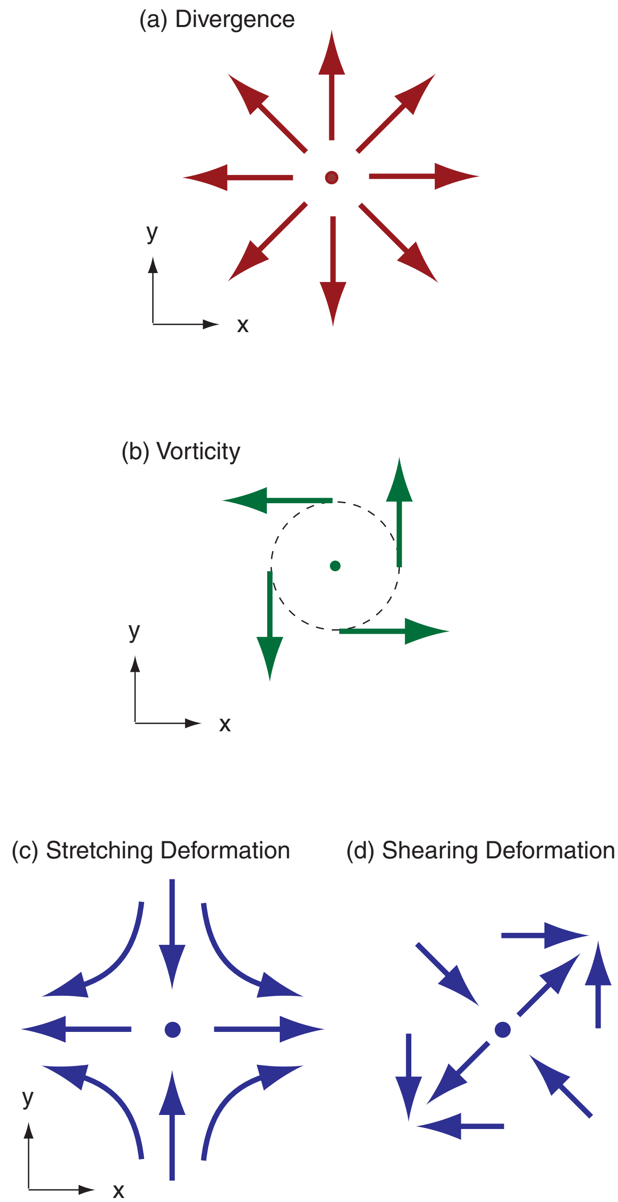

Figure 10.29
Kinematic flow-field definitions. Black arrows represent wind velocity.

10.10. MEASURING WINDS

For weather stations at the Earth's surface, wind direction can be measured with a **wind vane** mounted on a vertical axle. **Fixed vanes** and other shapes can be used to measure wind speed, by using strain gauges to measure the minute deformations of the object when the wind hits it.

The generic name for a wind-speed measuring device is an **anemometer**. A **cup anemometer** has conic- or hemispheric-shaped cups mounted on spokes that rotate about a vertical axle. A **pro-**

peller anemometer has a propeller mounted on a horizontal axle that is attached to a wind vane so it always points into the wind. For these anemometers, the rotation speed of the axle can be calibrated as a wind speed.

Other ways to measure wind speed include a **hot-wire** or **hot-film anemometer**, where a fine metal wire is heated electrically, and the power needed to maintain the hot temperature against the cooling effect of the wind is a measure of wind speed. A **pitot tube** that points into the wind measures the dynamic pressure as the moving air stagnates in a dead-end tube. By comparing this dynamic pressure with the static pressure measured by a different sensor, the pressure difference can be related to wind speed.

Sonic anemometers send pulses of sound back and forth across a short open path between two opposing transmitters and receivers (transceivers) of sound. The speed of sound depends on both temperature and wind speed, so this sensor can measure both by comparing sound travel times in opposite directions. Tracers such as smoke, humidity fluctuations, or clouds can be **tracked** photogrammetrically from the ground or from remote sensors such as laser radars (**lidars**) or satellites, and the wind speed then estimated from the change of position of the tracer between successive images.

Measurements of wind vs. height can be made with **rawinsonde balloons** (using a GPS receiver in the sonde payload to track horizontal drift of the balloons with time), **dropsondes** (like rawinsondes, only descending by parachute after being dropped from aircraft), **pilot balloons** (carrying no payload, but being tracked instead from the ground using radar or theodolites), **wind profilers**, **Doppler weather radar** (see the Satellites & Radar chapter), and via anemometers mounted on aircraft.

10.11. REVIEW

According to Newton's second law, winds are driven by forces. The pressure-gradient creates a force, even in initially calm (windless) conditions. This force points from high to low pressure on a constant altitude chart (such as at sea-level), or points from high to low heights on an isobaric chart (such as the 50 kPa chart). Pressure-gradient force is the main force that drives the winds.

Other forces exist only when there is already a wind. One example is turbulent drag against the ground, which pushes opposite to the atmospheric boundary-layer wind direction. Another example is Coriolis force, which is related to centrifugal force of winds relative to a rotating Earth.

If all the forces vector-sum to zero, then there is no net force and winds blow at constant speed. Theoretical winds based on only a small number of forces are given special names. The geostrophic wind occurs when pressure-gradient and Coriolis forces balance, causing a wind that blows parallel to straight isobars. For curved isobars around lows and highs, the imbalance between these two forces turns the wind in a circle, with the result called the gradient wind. Similar winds can exist in the atmospheric boundary layer, where turbulent drag of the air against the Earth's surface slows the wind and causes it to turn slightly to cross the isobars toward low pressure.

Waterspouts and tornadoes can have such strong winds that pressure-gradient force is balanced by centrifugal force, with the resulting wind speed known as the cyclostrophic wind. In oceans, currents can inertially flow in a circle.

The two most important force balances at mid-latitudes are hydrostatic balance in the vertical, and geostrophic balance in the horizontal.

Conservation of air mass gives the continuity equation, for which an incompressible approximation can be used in most places except in thunderstorms. Mechanisms that cause motion in one direction (horizontal or vertical) will also indirectly cause motions in the other direction as the air tries to maintain continuity, resulting in a circulation.

Kinematics is the word that describes the behavior and effect of winds (such as given by the continuity equation) without regard to the forces that cause them. The word **dynamics** describes how forces cause winds (as given by Newton's 2nd law).

10.12. HOMEWORK EXERCISES

Some of these questions are inspired by exercises in Stull, 2000: *Meteorology for Sci. & Engr. 2nd Ed.*, Brooks/Cole, 528 pp.

10.12.1. Broaden Knowledge & Comprehension

For all the exercises in this section, collect information off the internet. Don't forget to cite the web sites you use.

B1. a. Find a weather map showing today's sea-level pressure isobars near your location. Calculate pressure-gradient force (N) based on your latitude and the isobar spacing (km/kPa).