7

Atmospheric Pressure

7.1 Introduction

Atmospheric pressure is a fundamental atmospheric quantity in providing synoptic information and because of its close relationship with height and atmospheric thickness. Accurate measurement of pressure altitude using sensors carried by radiosondes, in combination with temperature and wind, serve to define the dynamical state of the atmosphere.

The SI unit of pressure is the pascal, which is the pressure exerted by a force of 1 Newton acting on a perpendicular area of 1 m^2. Atmospheric pressure at mean sea level is approximately 10^5 Pa, or 1000 hPa, which is conveniently equal to 1000 mbar, an older unit of measurement. The desirable accuracy in pressure measurement at the surface or aloft is about ±0.1 hPa, equivalent to 1 part in 10^4, which is a very demanding requirement for a routine scientific measurement. The radiosonde application (Chapter 11) is even more challenging, as the operating range of a radiosonde pressure sensor required may extend across roughly three orders of magnitude, during substantial changes in temperature.

Against this background of a demanding but routine measurement, surface pressure measurements are also conventionally corrected for the variation in pressure with height, which shows a reduction of about 1 hPa per 10 m of altitude near the surface. The pressure as observed without correction for altitude is known as the *station pressure*, whereas the *mean sea level pressure* is that corrected to the universally agreed sea level datum. In order that the correction itself does not degrade the measurement accuracy, the full sea level correction also allows for temperature effects (Section 7.3.1).

A measuring instrument for atmospheric pressure is known as a *barometer*, and one able to produce a chart record is known as a *barograph*.

7.2 Barometers

Instruments to measure atmospheric pressure have been used for over three centuries, and have been traditionally divided into two broad categories, depending on whether they use a liquid (usually mercury) as the sensing element, or not (*aneroid* barometers).[1] Mercury barometers measure pressure by determining the height of a liquid column, which is related to pressure by the hydrostatic equation. Aneroid barometers use a thin metal chamber or diaphragm, having a membrane which deforms under pressure differences which can be measured mechanically or electronically. These are now discussed in turn, with the various techniques for measuring atmospheric pressure summarised in Table 7.1.

Table 7.1 Sensing methods used in barometry

Pressure sensor	Barometric parameter	Measurement method	Typical accuracy
Mercury column	Column length	Mechanical scale, sometimes with a vernier system	±0.1 hPa
Aneroid capsule	Capsule dimension	Mechanical dial; change in frequency of resonant circuit coupled inductively	±1 hPa
Precision aneroid device – dimension change of bellows	Micrometer	±0.1 hPa	
Hypsometer	Boiling point of a liquid	Temperature	
Vibrating cylinder	Resonant frequency of cylinder	Frequency	±0.05 hPa
Electronic diaphragm	Capacitance between diaphragm and reference plate	Capacitance (via resonant frequency)	±0.5 hPa
Resistance of strain gauge bonded to diaphragm	Resistance		

7.2.1 Liquid barometers

The position of a liquid in a tube is sensitive to the pressure difference to which the liquid is exposed. This means that pressure differences can be measured[2] by the change in position of a liquid in a tube. If the tube is made symmetric, such as in a 'U' shaped tube, the difference in height of the fluid between one side and the other depends directly on the pressure difference applied (Figure 7.1) and the density of the liquid concerned.

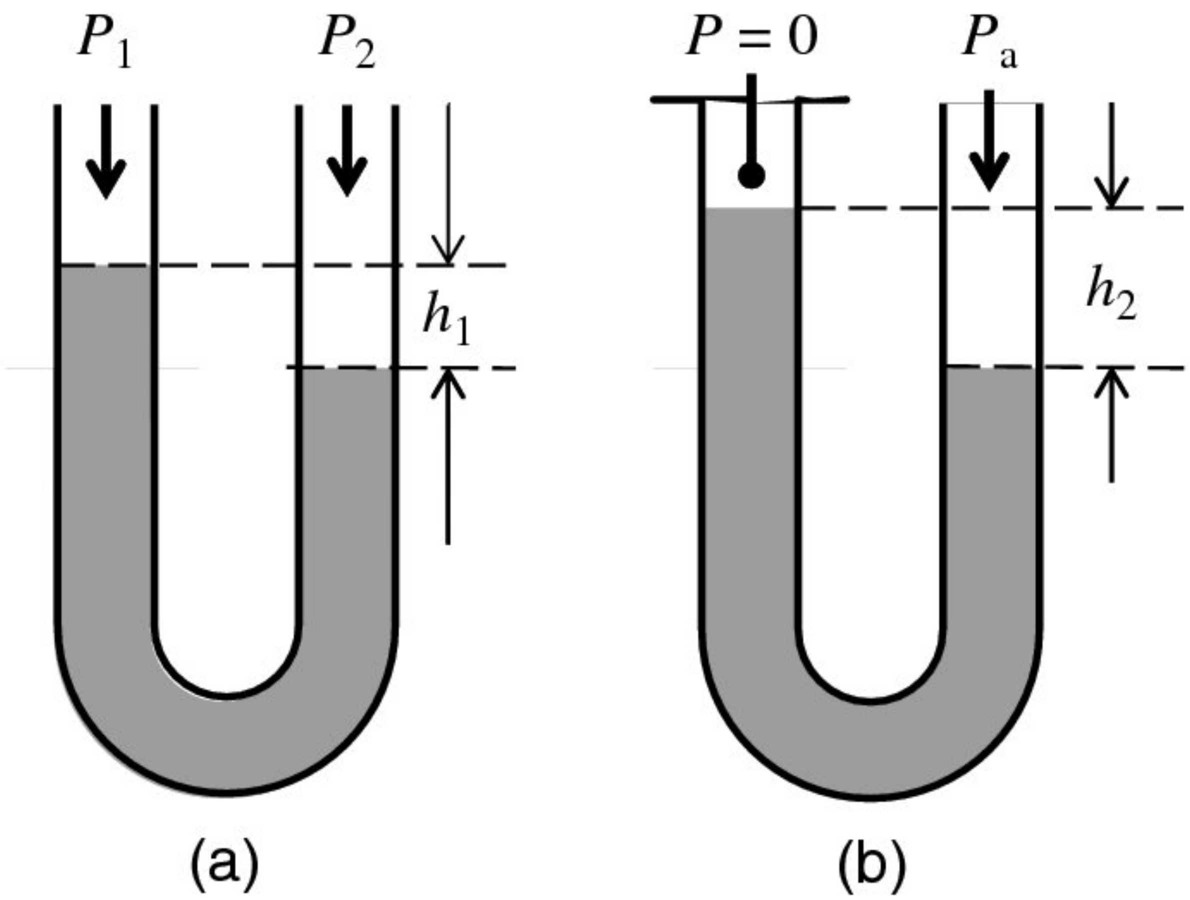

Figure 7.1 Pressure differences measured with a liquid manometer (a) for two finite pressures P_1 and P_2 ($P_2 > P_1$), giving a height difference h_1 and (b) between a vacuum ($P = 0$) and atmospheric pressure P_a giving a height difference h_2.

The difference in height Δh is related to the pressure difference ΔP by the hydrostatic equation

$$\Delta P = \Delta h \rho g \,, \tag{7.1}$$

where ρ is the liquid's density and g the local gravitational force per unit mass (acceleration due to gravity). In the case illustrated by Figure 7.1a, the pressure difference and height difference are related by

$$P_2 - P_1 = h_1 \rho g, \tag{7.2}$$

but, if the tube is sealed and evacuated, to establish a vacuum[3] (Figure 7.1b), the atmospheric pressure and height vary directly together as

$$P_a = h_2 \rho g, \tag{7.3}$$

and hence the device measures absolute atmospheric pressure. This configuration is adapted to provide the operating principle of the liquid barometer, Figure 7.2.

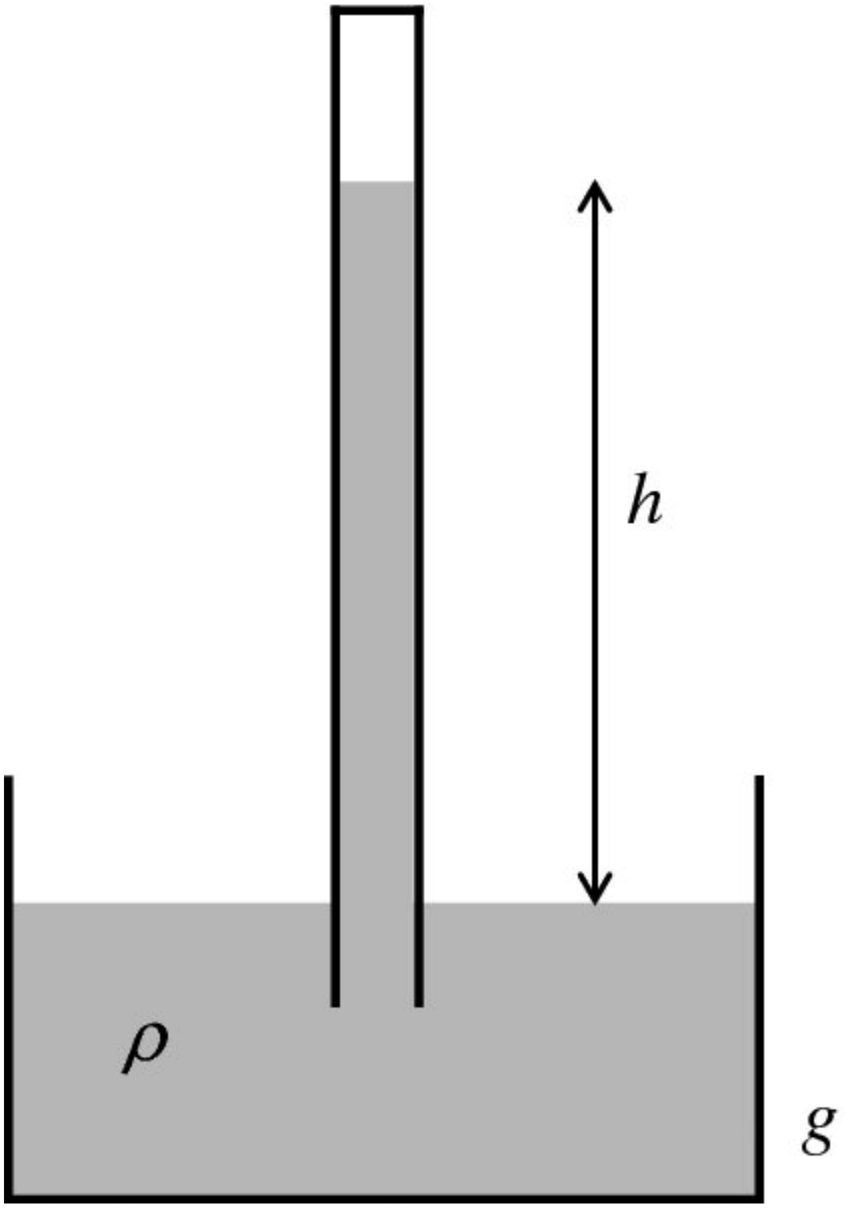

Figure 7.2 Principle of the liquid barometer. Accurate knowledge of the column height *h*, the liquid's density *ρ*, and the local acceleration due to gravity *g* are all required to determine the atmospheric pressure.

As the measurement of atmospheric pressure using a liquid barometer requires knowledge of three other quantities, obtaining an accurate measurement of atmospheric pressure requires an accurate measurement of the column height h, the local acceleration due to gravity g and the liquid's density ρ. The fractional uncertainty in the calculated pressure ($\delta P/P$) can be found by combining the individual fractional uncertainties as

$$\left(\frac{\delta P}{P}\right)^2 = \left(\frac{\delta h}{h}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2 + \left(\frac{\delta g}{g}\right)^2, \tag{7.4}$$

(see also Section 2.2.2). This means that, to achieve ($\delta P/P$) < 10^{-4}, or 0.1 hPa in 1000 hPa as indicated in Section 7.1, each of the measurements of h, ρ and g must also be accurate to better than 1 part in 10^4.

7.2.2 Mercury barometers

Mercury is chosen for use in barometers because, as Equation 7.1 indicates, for ΔP of the order of surface atmospheric pressure, conveniently measurable values of Δh (<1 m) will require a dense liquid. In addition, mercury has a low vapour pressure at the temperatures required, and is easily cleaned. It does not wet the glass walls of tubes, which leads to formation of a convex meniscus, providing a well-defined measurement datum. A disadvantage is that mercury does show appreciable thermal expansion, and also mercury barometers are not very portable so are unsuitable for remote automatic data logging. They are usually used as free standing devices for station barometers, commonly arranged to hang vertically from a hook, or mounted on gimbals. A further notable difficulty is the considerable volume of liquid needed, which presents a hazard under failure conditions, as mercury is a cumulative poison, absorbed through the skin.

One commonly used practical mercury instrument for synoptic and climatological measurements is the Kew pattern barometer (Figure 7.3). This uses a mercury storage cistern and a vernier scale to find the height accurately. Air temperature T is measured with a thermometer attached to the barometer, to allow corrections to be applied.

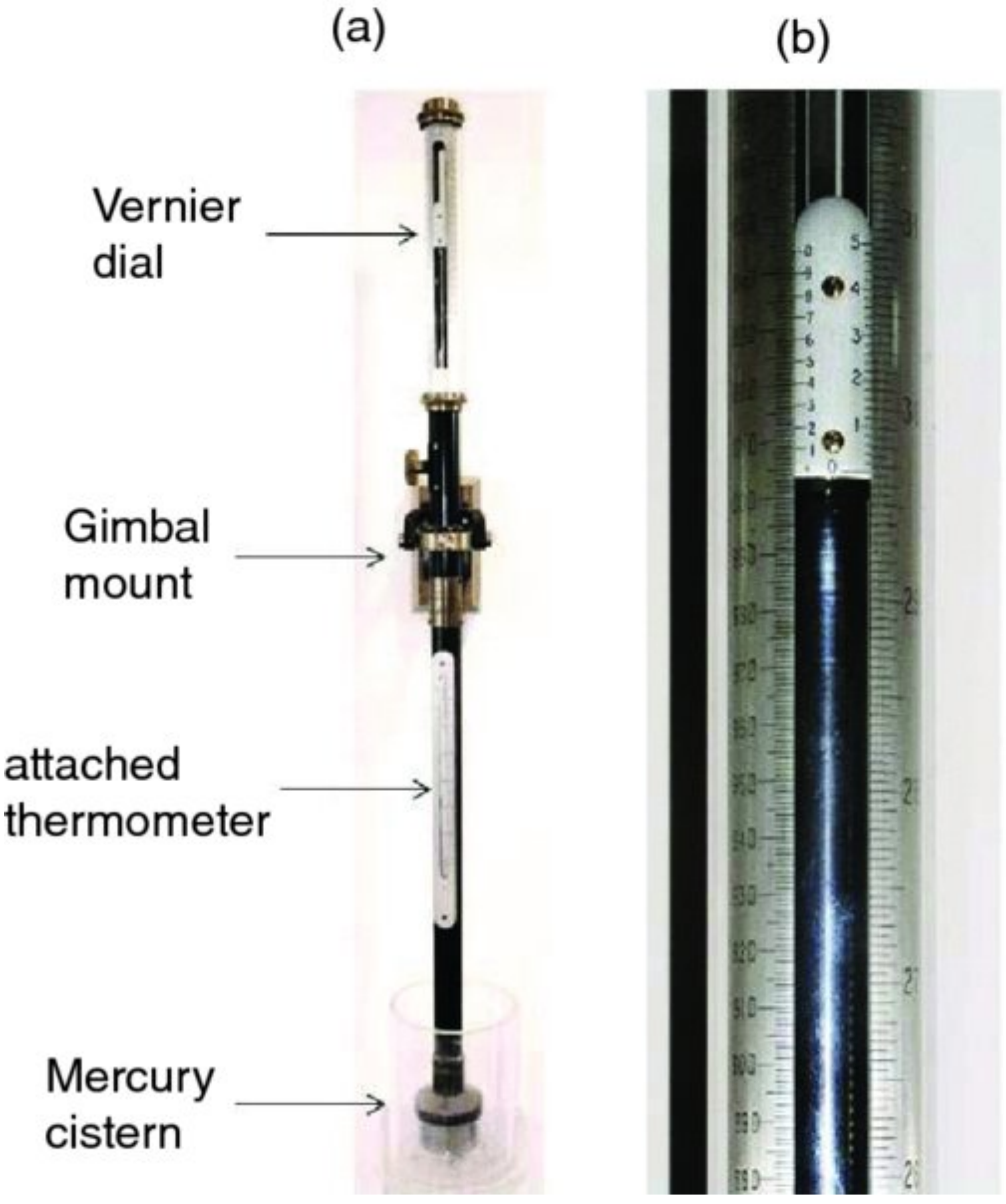

Figure 7.3 A Kew barometer, showing (a) the layout of the instrument and (b) the vernier dial used to determine the height accurately.

There are some detailed practical considerations specific to mercury barometers. Surface tension changes occur in mercury barometers due to contamination of mercury and/or the barometer's tube which can be corrected by cleaning the barometer and mercury. A vacuum defect such as from mishandling is more serious, generally requiring refilling of the barometer and recalibration.

The Kew barometer is calibrated for use at an air temperature of 0°C and for standard value of g (9.80665 m s^{-2}). In practice, however, measurements will be made in circumstances which differ from these conditions and several elaborate corrections are necessary for the target accuracy required. These corrections allow for the influence of temperature on the density of mercury, the local value of g and imperfections in the barometer tube and scale, as tabulated by the manufacturer. For the Kew barometer [68], the corrections required are: (1) for expansion of the mercury and the scale,

$$P = \frac{g}{9.80665}\left\{B + i - B\left[\frac{(\alpha - \beta)T}{1 + \alpha T}\right] - f\frac{V}{A}(\alpha - 3\times 10^{-5})T\right\}, \tag{7.5}$$

where P is the corrected barometer and B the uncorrected reading, i the ‘index’ error due to errors in capillary, scales and vacuum), α the coefficient of expansion for mercury, β the linear expansion of the scale, T the instrument temperature, V the volume of mercury contained, A the effective area of the cistern, and f a unit conversion factor,[4] and (2) for the local gravitational acceleration g, as

$$g = [9.80616\times(1 - 2.6373\times 10^{-3}\cos 2\varphi + 5.9\times 10^{-6}\cos^2 2\varphi)] - 3.086\times 10^{-4}h, \tag{7.6}$$

where g is the acceleration due to gravity (m s^{-2}) for a station which is at a latitude φ and a height h (metres) [69].

7.2.3 Hypsometer

A hypsometer is an instrument which primarily measures height, by determining the temperature at which a liquid boils. This can provide an indirect determination of pressure, as boiling occurs when the saturation vapour pressure of the liquid equals the local atmospheric pressure. Hence, by knowing the relationship between the saturation vapour pressure and temperature (such as Equation 6.4), and recording the liquid's boiling temperature, pressure can be found. The water hypsometer is important historically, as it provided one of the first techniques for an indirect measurement of altitude. Such an approach has also been used for pressure measurement in radiosondes (see Section 11.2.1), particularly as the sensitivity to pressure improves at lower pressures aloft, using liquids such as carbon disulphide or chlorofluorocarbons.

7.2.4 Aneroid barometers

Aneroid barometers are more convenient to use than mercury barometers and avoid the hazard associated with use of mercury. The sensor in an aneroid is a small metal capsule or diaphragm which is substantially evacuated, and of an elastic modulus to allow it to be distorted by atmospheric pressure changes. This change in dimension can be monitored mechanically or electrically (Figure 7.4), through changes in capacitance or inductance. Aneroid sensors can be made cheaply, and hence are widely used in domestic wall barometers, pressure altimeters and barographs. In these instruments, the displacement of the aneroid capsule is usually converted to a pointer's displacement by a mechanism of levers or pulleys. The properties of the mechanism limits accuracy of the dial reading, as it may stick or exhibit hysteresis.

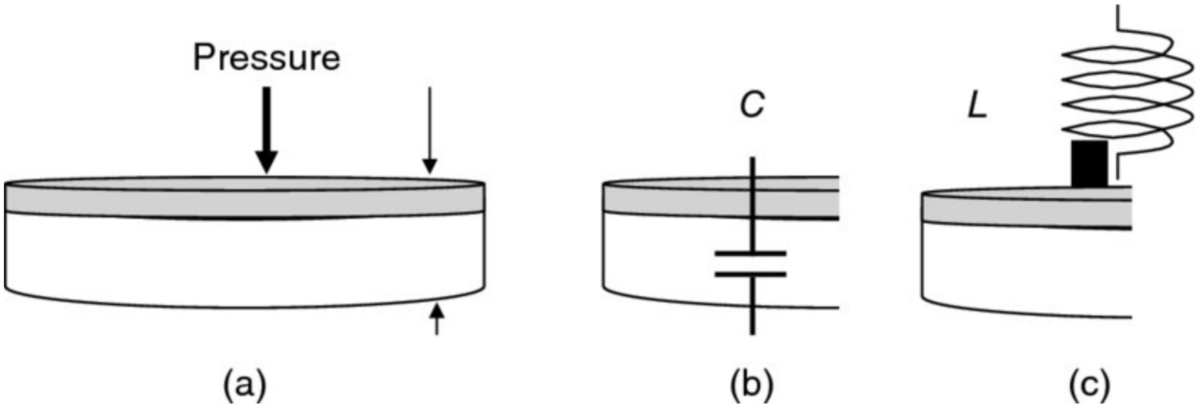

Figure 7.4 (a) Aneroid capsule concept in which vertical deformation occurs due to pressure changes. Electrical sensing methods can use the deformation change by (b) modifying the dimensions defining a capacitance *C* or (c) by displacing a permeable core within a coil of wire forming an inductance *L*.

In a barograph (Figure 7.5), multiple aneroid capsules are connected together to increase the sensitivity to pressure changes. The barograph is usually set up to measure the mean sea level pressure without correction, as, although not very accurate (±1 hPa), its importance is in providing a continuous record of pressure tendency.

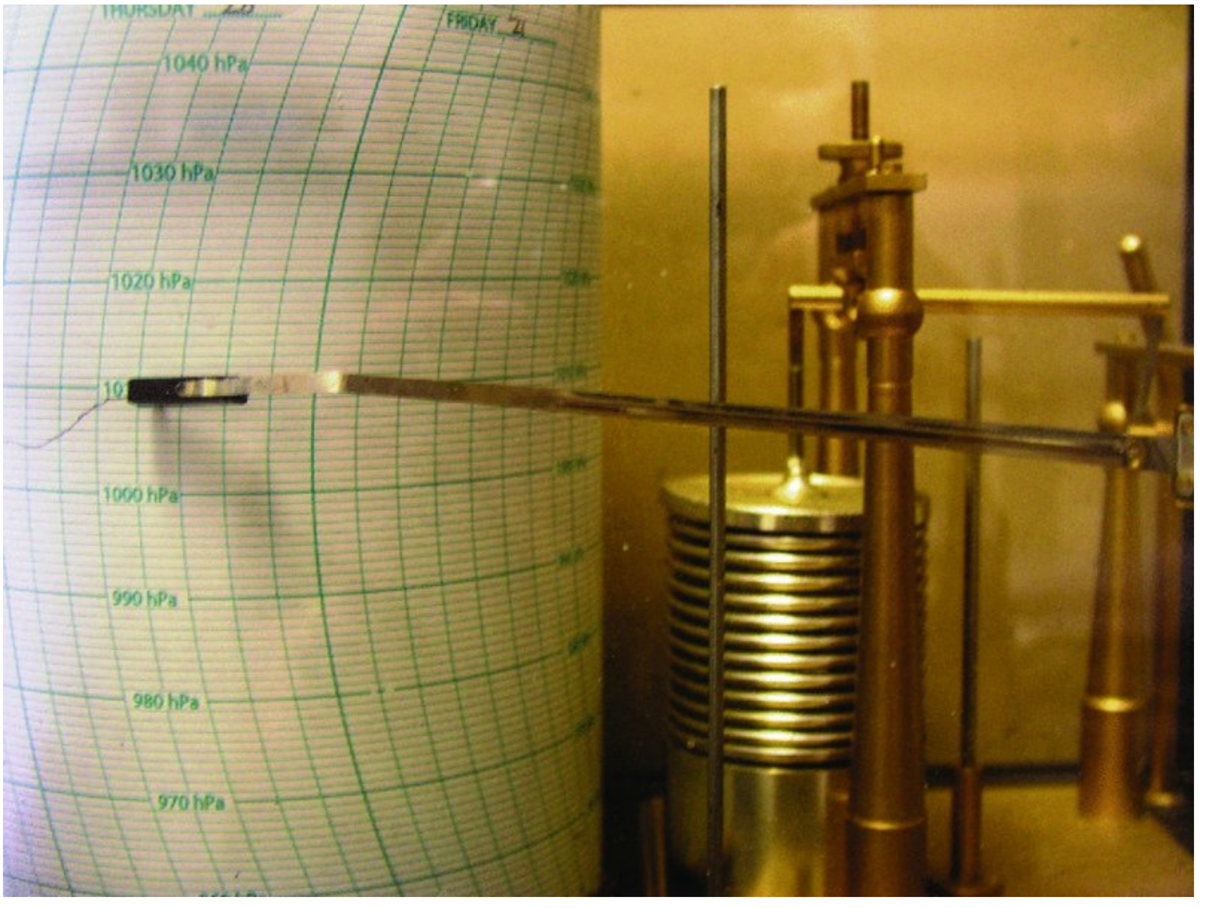

Figure 7.5 A mechanically recording barometer (or barograph). The set of aneroid capsules connected together amplifies, with connecting levers, the change in response to pressure to cause an observable mechanical deflection on the recording chart drum.

7.2.5 Precision aneroid barometers

Precision aneroid barometers can be made robust enough for routine pressure measurements, and show little drift with time with no temperature correction required. The sensor in a precision aneroid barometer is a metal capsule, consisting of two thin diaphragms, separated by a flexible cylindrical metal bellows from which almost all the air has been removed. Pressure changes cause a relative movement between the diaphragms, which is measured by as a change in distance using an adjustable electrical contact moved on a fine micrometer screw thread. This is calibrated directly in terms of pressure.

In use, the screw thread is adjusted until the electrical contact is just broken, as shown by a visual indicator. Temperature compensation is achieved by leaving a small amount of gas in the capsule, and by the use of compensating metal linkages. Since the total relative movement of the diaphragms is only about 1.5 mm for the whole range of surface pressure (∼900 to 1050 hPa), the measurement mechanism has to be very precisely engineered. In practice, several bellows connected in series may be used to increase sensitivity.

7.2.6 Flexible diaphragm sensors

These are based on a similar principle to that of an aneroid capsule, but rely either on detecting the flexing of a thin silicon diaphragm with changes in pressure, or changes in capacitance associated with changes in the separation between the diaphragm and a fixed plate. The latter type of sensor can be very small and light, and is used in radiosondes for measuring the pressure at the altitude reached by the instrument package.

An alternative approach is to couple the diaphragm to a resistive strain gauge, for a direct electrical output related to pressure. Such sensors are suitable for remote and automatic pressure measurements, but suffer from substantial temperature errors. Compensation systems, temperature characterisation or temperature stabilisation are therefore required [70].

7.2.7 Vibrating cylinder barometer

A vibrating cylinder barometer is capable of very high accuracy and stability. The operating principle is based on detecting the natural frequency of oscillation in the 'hoop' vibrating mode of a thin-walled cylinder (open to the atmosphere), which is surrounded by a near vacuum. The oscillations are excited by magnetic forces from electromagnetic coils placed around the cylinder and detected by the induced current in detector coils (Figure 7.6). A feedback signal processing system is used to 'tune' the forcing to the natural frequency of the cylinder to sustain the oscillations. The natural frequency obtained is measured using a frequency counter.

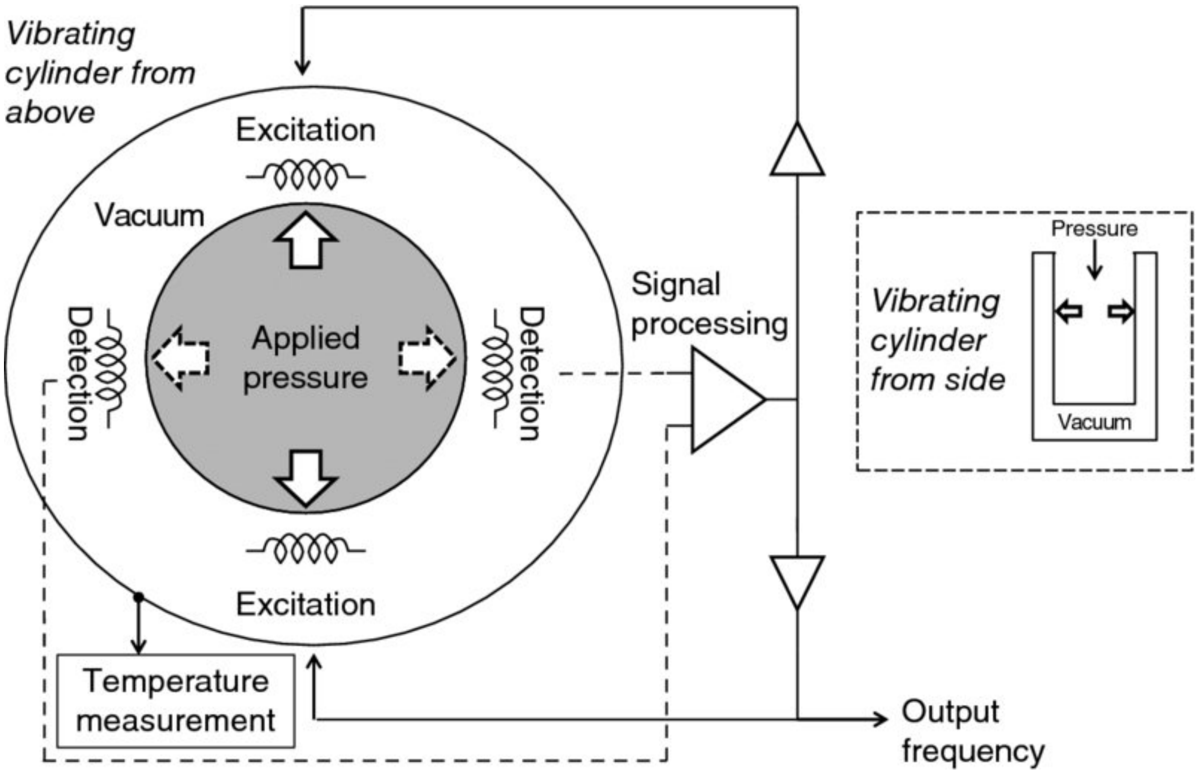

Figure 7.6 Outline schematic of a vibrating cylinder barometer system. Pressure is applied to a thin-walled open-ended central cylinder, which is surrounded by a vacuum. The cylinder is encouraged to oscillate by magnetic excitation applied using coils spaced around the cylinder, with its oscillatory motion detected by other coils. Signal processing circuitry adjusts the frequency of excitation to allow the cylinder to oscillate at its natural frequency. The oscillation is in the hoop mode of the cylinder as viewed from above, alternately across the cylinder in one direction (solid arrows) and then at right angles (dashed arrows).

The natural frequency of the cylinder depends on both the pressure and density of the air inside the cylinder, but shows a complicated non-linear response which has to be obtained empirically by calibration. (The influence of density is also allowed for by measuring the temperature of the sensor.) Precision versions of this instrument are able to measure atmospheric pressure to an accuracy of better than ±0.05 hPa, and with a resolution of 0.01 hPa.

A summary of the different methods used in determining atmospheric pressure is given in Table 7.1.

7.3 Corrections to barometers

For routine use, the pressure measured by a barometer will usually be corrected to sea level. In addition, the effect of flow around a building will cause local pressure differences which can occasionally compromise the measurement from an accurate barometer.

7.3.1 Sea level correction

Mean sea level is the standard reference height used for pressure measurements at sites below about 1000 m altitude. Hence, for a barometer operated at a site above sea level, a correction due to the additional weight of the air column between sea level and the station height must be added to the barometer reading. If an isothermal atmosphere is assumed (usually a good approximation), the variation in pressure with height z follows an exponential relationship,

$$P_z = P_0 \exp\left(\frac{-z}{H}\right), \quad (7.7)$$

where P_z is the pressure at a height z, P_0 is the sea level pressure and H is the scale height. The scale height is found from $H = R^* T/M_a g$ where T is the assumed isothermal temperature, R^* the universal gas constant, M_a the relative molecular mass of air and g the acceleration due to gravity. A pressure measurement made at a height z can be converted to its equivalent value at sea level by finding

$$P_0 = P_z \exp\left(\frac{z}{H}\right). \quad (7.8)$$

The difficulty in general is deciding on an appropriate isothermal temperature value T to use, and hence there are standard guidelines applied for observing stations. In practice, a value for T can be estimated as the mean temperature between the station and sea level, for example by assuming a typical lapse rate from the station temperature.

7.3.2 Wind speed corrections

Air flow around a building housing the barometer causes pressure changes of order $\rho u^2/2$ (see Equation 8.1), which yields appreciable pressure fluctuations compared with the target accuracy of 0.1 hPa, for example 0.4 hPa for $u = 8$ m s^{-1}, although this varies with building geometry and wind direction. For better accuracy under these conditions, barometers can be connected to a static head sampling outside the building, where the flow effect is minimised.

Notes

1 A further liquid-based indirect method of pressure measurement is that of the hypsometer, which determines height by determining the liquid's boiling point, when the variation of boiling point with atmospheric pressure is known (Section 7.2.3).

2 An instrument to measure pressure or pressure difference is a *manometer*. If one of the two pressures is the ambient pressure, the result is known as the *gauge pressure*, that is the difference from ambient pressure.

3 The evacuated region in a mercury barometer is known as the Torricellian vacuum after the inventor of the barometer Evangelista Torricelli (1608–1647); the *Torr* remains used as a non-SI unit of pressure (1 hPa = 0.75 Torr). *Fortin* barometers include a reference setting for the mercury reservoir, originated by the instrument maker Jean Nicolas Fortin (1750–1831).

4 These quantities are usually provided in a calibration certificate.