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CHAPTER 3. MEASUREMENT OF ATMOSPHERIC PRESSURE

3.1 GENERAL

3.1.1 Definition

The atmospheric pressure on a given surface is the force per unit area exerted by virtue of the weight of the atmosphere above. The pressure is thus equal to the weight of a vertical column of air above a horizontal projection of the surface, extending to the outer limit of the atmosphere.

Apart from the actual pressure, pressure trend or tendency has to be determined as well. Pressure tendency is the character and amount of atmospheric pressure change for a 3 h or other specified period ending at the time of observation. Pressure tendency is composed of two parts, namely the pressure change and the pressure characteristic. The pressure change is the net difference between pressure readings at the beginning and end of a specified interval of time. The pressure characteristic is an indication of how the pressure has changed during that period of time, for example, decreasing then increasing, or increasing and then increasing more rapidly.

3.1.2 Units and scales

The basic unit for atmospheric pressure measurements is the pascal (Pa) (or newton per square metre). It is accepted practice to add the prefix "hecto" to this unit when reporting pressure for meteorological purposes, making the hectopascal (hPa), equal to 100 Pa, the preferred terminology. This is largely because one hectopascal equals one millibar (mbar), the formerly used unit.

The scales of all barometers used for meteorological purposes should be graduated in hPa. Some barometers are graduated in "millimetres or inches of mercury under standard conditions", $(\text{mm Hg})_n$ and $(\text{in Hg})_n$, respectively. When it is clear from the context that standard conditions are implied, the briefer terms "millimetre of mercury" or "inch of mercury" may be used. Under these standard conditions, a column of mercury having a true scale height of 760 $(\text{mm Hg})_n$ exerts a pressure of 1 013.250 hPa.

The following conversion factors will then apply:

$$1\ \text{hPa} = 0.750\,062\ (\text{mm Hg})_n$$
$$1\ (\text{mm Hg})_n = 1.333\,224\ \text{hPa}$$

In the case where the conventional engineering relationship between the inch and the millimetre is assumed, namely 1 in = 25.4 mm, the following conversion factors are obtained:

$$1\ \text{hPa} = 0.029\,530\ (\text{in Hg})_n$$
$$1\ (\text{in Hg})_n = 33.863\,9\ \text{hPa}$$
$$1\ (\text{mm Hg})_n = 0.039\,370\,08\ (\text{in Hg})_n$$

Scales on mercury barometers for meteorological purposes should be so graduated that they yield true pressure readings directly in standard units when the entire instrument is maintained at a standard temperature of 0 °C and the standard value of gravity is 9.806 65 m s^{-2}.

Barometers may have more than one scale engraved on them, for example, hPa and mm Hg, or hPa and in Hg, provided that the barometer is correctly calibrated under standard conditions.

Pressure data should be expressed in hectopascals. Hereafter in this chapter only the unit hectopascal will be used.

3.1.3 Meteorological requirements

Analysed pressure fields are a fundamental requirement of the science of meteorology. It is imperative that these pressure fields be accurately defined as they form the basis for all subsequent predictions of the state of the atmosphere. Pressure measurements must be as accurate as technology will allow, within realistic financial constraints, and there must be uniformity in the measurement and calibration procedures across national boundaries.

The level of accuracy needed for pressure measurements to satisfy the requirements of various meteorological applications has been identified by the respective WMO commissions and is outlined in Part I, Chapter 1, Annex 1.E, which is the primary reference for measurement specifications in this Guide. The requirements are as follows:

Measuring range: 500 – 1 080 hPa (both station pressure and mean sea-level pressure)
Required target uncertainty: 0.1 hPa
Reporting resolution: 0.1 hPa
Sensor time-constant: 20 s (for most modern barometers, 2 s is achievable – see Part I, Chapter 1, Annex 1.E)
Output averaging time: 1 min

The above requirements should be considered achievable for new barometers in a strictly controlled environment, such as those available in a properly equipped laboratory. They provide an appropriate target accuracy for barometers to meet before their installation in an operational environment.

For barometers installed in an operational environment, practical constraints will require well-designed equipment for a National Meteorological Service to maintain this target accuracy. Not only the barometer itself, but the exposure also requires special attention. Nevertheless, the performance of the operational network station barometer, when calibrated against a standard barometer whose index errors are known and allowed for, should not be below the stated criteria.

3.1.4 Methods of measurement and observation

For meteorological purposes, atmospheric pressure is generally measured with electronic barometers, mercury barometers, aneroid barometers or hypsometers. The latter class of instruments, which depends on the relationship between the boiling point of a liquid and the atmospheric pressure, has so far seen only limited application and will not be discussed in depth in this publication. A very useful discussion of the performance of digital barometers (which mostly have electronic read-out) is found in WMO (1992).

Meteorological pressure instruments (barometers) are suitable for use as operational instruments for measuring atmospheric pressure if they meet the following requirements:

(a) The instruments must be calibrated or controlled regularly against a (working) standard barometer using approved procedures. The period between two calibrations must be short enough to ensure that the total absolute measurement error will meet the accuracy requirements defined in this chapter;

(b) Any variations in the accuracy (long-term and short-term) must be much smaller than the tolerances outlined in section 3.1.3. If some instruments have a history of a drift in calibration, they will be suitable operationally only if the period between calibrations is short enough to ensure the required measurement accuracy at all times;

(c) Instrument readings should not be affected by temperature variations. Instruments are suitable only if:

    (i) Procedures for correcting the readings for temperature effects will ensure the required accuracy; and/or

(ii) The pressure sensor is placed in an environment where the temperature is stabilized so that the required accuracy will be met.

Some instruments measure the temperature of the pressure sensor in order to compensate for temperature effects. It is necessary to control and calibrate these temperature-compensating functions as part of the standard calibration activity;

(d) The instrument must be placed in an environment where external effects will not lead to measurement errors. These effects include wind, radiation/temperature, shocks and vibrations, fluctuations in the electrical power supply and pressure shocks. Great care must be taken when selecting a position for the instrument, particularly for mercury barometers.

It is important that every meteorological observer should fully understand these effects and be able to assess whether any of them are affecting the accuracy of the readings of the barometer in use;

(e) The instrument should be quick and easy to read. Instruments must be designed so that the standard deviation of their readings is less than one third of the stated absolute accuracy;

(f) If the instrument has to be calibrated away from its operational location, the method of transportation employed must not affect the stability or accuracy of the barometer. Effects which may alter the calibration of the barometer include mechanical shocks and vibrations, and displacement from the vertical and large pressure variations such as may be encountered during transportation by air.

Most barometers with recent designs make use of transducers which transform the sensor response into pressure-related quantities. These are subsequently processed by using appropriate electrical integration circuits or data-acquisition systems with appropriate smoothing algorithms. A time constant of about 10 s (and definitely no greater than 20 s) is desirable for most synoptic barometer applications. For mercury barometers, the time constant is generally not important.

There are several general methods for measuring atmospheric pressure which will be outlined in the following paragraphs.

Historically, the most extensively used method for measuring the pressure of the atmosphere involves balancing it against the weight of a column of liquid. For various reasons, the required accuracy can be conveniently attained only if the liquid used is mercury. Mercury barometers are, in general, regarded as having good long-term stability and accuracy, but are now losing favour to equally accurate electronic barometers, which are easier to read.

A membrane of elastic substance, held at the edges, will be deformed if the pressure on one side is greater than on the other. In practice, this is achieved by using a completely or partially evacuated closed metal capsule containing a strong metal spring to prevent the capsule from collapsing due to external atmospheric pressure. Mechanical or electrical means are used to measure the deformation caused by the pressure differential between the inside and outside of the capsule. This is the principle of the well-known aneroid barometer.

Pressure sensor elements comprising thin-walled nickel alloy cylinders, surrounded by a vacuum, have been developed. The natural resonant frequency of these cylinders varies as a function of the difference in pressure between the inside of the cylinder, which is at ambient atmospheric pressure, and the outside of the cylinder, which is maintained as a vacuum.

Absolute pressure transducers, which use a crystalline quartz element, are becoming more commonly used. Pressure exerted via flexible bellows on the crystal face causes a compressive force on the crystal. On account of the crystal’s piezoresistive properties, the application of pressure alters the balance of an active Wheatstone bridge. Balancing the bridge enables accurate determination of the pressure. These types of pressure transducers are virtually free of hysteresis effects.

The boiling point of a liquid is a function of the pressure under which it boils. Once this function has been determined, the temperature at which the liquid boils may be used in a hypsometer to determine the atmospheric pressure.

3.2 MERCURY BAROMETERS

There is an increasing move away from the use of mercury barometers because mercury vapour is highly toxic; free mercury is corrosive to the aluminium alloys used in air frames (for these reasons there are regulations proscribing the handling or carriage of mercury barometers in some countries); special lead glass is required for the tube; the barometer is very delicate and difficult to transport; it is difficult to maintain the instrument and to clean the mercury; the instrument must be read and corrections applied manually; and other pressure sensors of equivalent accuracy and stability with electronic read-out are now commonly available.

3.2.1 Construction requirements

The basic principle of a mercury barometer is that the pressure of the atmosphere is balanced against the weight of a column of mercury. In some barometers, the mercury column is weighed on a balance, but, for normal meteorological purposes, the length of the mercury column is measured against a scale graduated in units of pressure.

There are several types of mercury barometers in use at meteorological stations, with the fixed cistern and the Fortin types being the most common. The length to be measured is the distance between the top of the mercury column and the upper surface of the mercury in the cistern. Any change in the length of the mercury column is, of course, accompanied by a change in the level of the mercury in the cistern. In the Fortin barometer, the level of the mercury in the cistern can be adjusted to bring it into contact with an ivory pointer, the tip of which is at the zero of the barometer scale. In the fixed-cistern barometer, often called the Kew-pattern barometer, the mercury in the cistern does not need to be adjusted as the scale engraved on the barometer is constructed to allow for changes in the level of the mercury in the cistern.

3.2.2 General requirements

The main requirements of a good mercury station barometer include the following:

(a) Its accuracy should not vary over long periods. In particular, its hysteresis effects should remain small;

(b) It should be quick and easy to read, and readings should be corrected for all known effects. The observers employing these corrections must understand their significance to ensure that the corrections applied are correct and not, in fact, causing a deterioration in the accuracy of the readings;

(c) It should be transportable without a loss of accuracy;

(d) The bore of the tube should not be less than 7 mm and should preferably be 9 mm;

(e) The tube should be prepared and filled under vacuum. The purity of the mercury is of considerable significance. It should be double-distilled, degreased, repeatedly washed, and filtered;

(f) The actual temperature for which the scale is assumed to give correct readings, at standard gravity, should be engraved upon the barometer. The scale should preferably be calibrated to give correct readings at 0 °C;

(g) The meniscus should not be flat unless the bore of the tube is large (greater than 20 mm);

(h) For a marine barometer, the error at any point should not exceed 0.5 hPa.

The response time for mercury barometers at land stations is usually very small compared with that of marine barometers and instruments for measuring temperature, humidity and wind.

3.2.3 **Standard conditions**

Given that the length of the mercury column of a barometer depends on other factors, especially on temperature and gravity, in addition to the atmospheric pressure, it is necessary to specify the standard conditions under which the barometer should theoretically yield true pressure readings. The following standards are laid down in the international barometer conventions.

3.2.3.1 ***Standard temperature and density of mercury***

The standard temperature to which mercury barometer readings are reduced to remove errors associated with the temperature-induced change in the density of mercury is 0 °C.

The standard density of mercury at 0 °C is taken to be $1.359\ 51 \cdot 10^4$ kg m^{-3} and, for the purpose of calculating absolute pressure using the hydrostatic equation, the mercury in the column of a barometer is treated as an incompressible fluid.

The density of impure mercury is different from that of pure mercury. Hence, a barometer containing impure mercury will produce reading errors as the indicated pressure is proportional to the density of mercury.

3.2.3.2 ***Standard gravity***

Barometric readings have to be reduced from the local acceleration of gravity to standard (normal) gravity. The value of standard gravity (g_n) is regarded as a conventional constant, $g_n = 9.806\ 65$ m s^{-2}.

Note: The need to adopt an arbitrary reference value for the acceleration of gravity is explained in WMO (1966). This value cannot be precisely related to the measured or theoretical value of the acceleration of gravity in specified conditions, for example, sea level at latitude 45°, because such values are likely to change as new experimental data become available.

3.2.4 **Reading mercury barometers**

When making an observation with a mercury barometer, the attached thermometer should be read first. This reading should be taken as quickly as possible, as the temperature of the thermometer may rise owing to the presence of the observer. The barometer should be tapped a few times with the finger in two places, one adjacent to the meniscus and the other near the cistern, so as to stabilize the mercury surfaces. If the barometer is not of a fixed-cistern type, the necessary adjustment should be made to bring the mercury in the cistern into contact with the fiducial pointer. Lastly, the vernier should be set to the meniscus and the reading taken. The vernier is correctly adjusted when its horizontal lower edge appears to be touching the highest part of the meniscus; with a magnifying glass it should be possible to see an exceedingly narrow strip of light between the vernier and the top of the mercury surface. Under no circumstances should the vernier “cut off” the top of the meniscus. The observer’s eye should be in such a position that both front and back lower edges of the vernier are in the line of vision.

3.2.4.1 ***Accuracy of readings***

The reading should be taken to the nearest 0.1 hPa. Usually it is not possible to read the vernier to any greater accuracy.

Optical and digital systems have been developed to improve the reading of mercury barometers. Although they normally ease the observations, such systems may also introduce new sources of error, unless they have been carefully designed and calibrated.

3.2.4.2 *Changes in index correction*

Any change in the index correction shown during an inspection should be considered on its merits, keeping in mind the following:

(a) The history of the barometer;

(b) The experience of the inspector in comparison work;

(c) The magnitude of the observed change;

(d) The standard deviation of the differences;

(e) The availability of a spare barometer at the station, the correction of which is known with accuracy;

(f) The behaviour of travelling standards during the tour;

(g) The agreement, or otherwise, of the pressure readings of the station with those of neighbouring stations on the daily synoptic chart if the change is accepted;

(h) Whether or not the instrument was cleaned before comparison.

Changes in index errors of station barometers, referred to as drift, are caused by:

(a) Variations in the capillary depression of the mercury surfaces due to contamination of the mercury. In areas of severe atmospheric pollution from industrial sources, mercury contamination may constitute a serious problem and may require relatively frequent cleaning of the mercury and the barometer cistern;

(b) The rise of air bubbles through the mercury column to the space above.

These changes may be erratic, or consistently positive or negative, depending on the cause.

Changes in index correction are also caused by:

(a) Observer error resulting from failure to tap the barometer before taking the reading and improper setting of the vernier and fiducial point;

(b) Lack of temperature equilibrium in either the station barometer or the travelling standard;

(c) Non-simultaneity of readings when the pressure is changing rapidly.

Such changes can be caused by accidental displacement of the adjustable scale and the shrinkage or loosening of fiducial points in Fortin-type barometers.

3.2.4.3 *Permissible changes in index correction*

Changes in index correction should be treated as follows:

(a) A change in correction within 0.1 hPa may be neglected unless persistent;

(b) A change in correction exceeding 0.1 hPa but not exceeding 0.3 hPa may be provisionally accepted unless confirmed by at least one subsequent inspection;

(c) A change in correction exceeding 0.3 hPa may be accepted provisionally only if the barometer is cleaned and a spare barometer with known correction is not available. This barometer should be replaced as soon as a correctly calibrated barometer becomes available.

Barometers with changes in index correction identified in (b) and (c) above warrant close attention. They should be recalibrated or replaced as soon as practicable.

The same criteria apply to changes in the index corrections of the travelling standards as those applied as to station barometers. A change in correction of less than 0.1 hPa may be neglected unless persistent. A larger change in correction should be confirmed and accepted only after repeated comparisons. The "before" and "after" tour index corrections of the travelling standard should not differ by more than 0.1 hPa. Only barometers with a long history of consistent corrections should, therefore, be used as travelling standards.

3.2.5 Correction of barometer readings to standard conditions

In order to transform barometer readings taken at different times and different places into usable atmospheric pressure values, the following corrections should be made:

(a) Correction for index error;

(b) Correction for gravity;

(c) Correction for temperature.

For a large number of operational meteorological applications, it is possible to obtain acceptable results by following the barometer manufacturer's instructions, provided that it is clear that these procedures give pressure readings of the required uncertainty. However, if these results are not satisfactory or if higher precision is required, detailed procedures should be followed to correct for the above factors; these procedures are described in Annex 3.A.

3.2.6 Errors and faults with mercury barometers

3.2.6.1 *Uncertainties as to the temperature of the instrument*

The temperature indicated by the attached thermometer will not usually be identical to the mean temperature of the mercury, the scale and the cistern. The resultant error can be reduced by favourable exposure and by using a suitable observation procedure. Attention is drawn to the frequent existence of a large, stable vertical temperature gradient in a room, which may cause a considerable difference between the temperature of the upper and lower parts of the barometer. An electric fan can prevent such a temperature distribution but may cause local pressure variations and should be switched off before an observation is made. Under normal conditions, the error associated with the temperature reduction will not exceed 0.1 hPa if such precautions are taken.

3.2.6.2 *Defective vacuum space*

It is usually assumed that there is a perfect vacuum, or only a negligible amount of gas, above the mercury column when the instrument is calibrated. Any change in this respect will cause an error in pressure readings. A rough test for the presence of gas in the barometer tube can be made by tilting the tube and listening for the click when the mercury reaches the top, or by examining the closed end for the presence of a bubble, which should not exceed 1.5 mm in diameter when the barometer is inclined. The existence of water vapour cannot be detected in this way, as it is condensed when the volume decreases. According to Boyle's Law, the error caused by air and unsaturated water vapour in the space will be inversely proportional to the volume above the mercury. The only satisfactory way to overcome this error is by conducting a recalibration over the entire scale; if the error is large, the barometer tube should be refilled or replaced.

3.2.6.3 *The capillary depression of the mercury surfaces*

The height of the meniscus and the capillary depression,[1] for a given tube, may change with the ageing of the glass tube, mercury contamination, pressure tendency, and the position of the mercury in the tube. As far as is practicable, the mean height of the meniscus should be observed during the original calibration and noted on the barometer certificate. No corrections should be made for departures from the original meniscus height, and the information should be used only as an indication of the need, or otherwise, to overhaul or recalibrate the barometer. A 1 mm change in the height of the meniscus (from 1.8 to 0.8 mm) for an 8 mm tube may cause an error of about 0.5 hPa in the pressure readings.

It should be noted that large variations in the angle of contact between the mercury and the wall of the cistern in a fixed-cistern barometer may cause small but appreciable errors in the observed pressure.

3.2.6.4 *Lack of verticality*

If the bottom of a symmetrical barometer of normal length (about 90 cm), which hangs freely, is displaced by about 6 mm from the vertical position, the indicated pressure will be about 0.02 hPa too high. Such barometers generally hang more truly vertical than this.

In the case of an asymmetrical barometer, however, this source of error is more critical. For example, if the fiducial pointer in the cistern is about 12 mm from the axis, the cistern needs to be displaced by only about 1 mm from the vertical to cause an error of 0.02 hPa.

3.2.6.5 *General accuracy of the corrected pressure readings*

The standard deviation of a single, corrected barometer reading at an ordinary meteorological station should be within 0.1 hPa. This error will mainly be the result of the unavoidable uncertainty in the instrument correction, the uncertainty concerning the temperature of the instrument, and the error caused by the pumping effect of wind gusts on the mercury surface.

3.2.7 Safety precautions for the use of mercury

Mercury is used in relatively large quantities in barometers and, because it is poisonous, must be handled with care. Elemental mercury is a liquid at temperatures and pressures experienced at the Earth's surface. Mercury vapour forms in the air whenever liquid mercury is present. Mercury can be absorbed through the skin in both liquid and gaseous states and can be inhaled as a vapour. The properties of mercury are described by Sax (1975). In many countries, precautions for its use are prescribed by regulations governing the handling of hazardous goods. The Minamata Convention on Mercury of the United Nations Environment Programme (UNEP) entered into force in October 2013 and will have a significant impact on the use of mercury for meteorological applications.

A large dose of mercury may cause acute poisoning. It can also accumulate in the body's hard and soft tissues and prolonged exposure to even a low dose can cause long-term damage to organs, or even death. Mercury mainly affects the central nervous system, and the mouth and gums, with symptoms that include pain, loosening of teeth, allergic reactions, tremors and psychological disturbance.

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1 Capillary depression is a reduction in height of the meniscus of a liquid contained in a tube where the liquid (such as mercury) does not wet the walls of the tube. The meniscus is shaped convex upward.

For barometric applications, the main risks occur in laboratories where barometers are frequently emptied or filled. There may also be problems in meteorological stations if quantities of mercury, for example from a broken barometer, are allowed to remain in places where it may continuously vaporize into an enclosed room where people work.

A danger exists even if the mercury is properly contained and if it is cleaned up after an accident. The following points must be considered when using mercury:

(a) Vessels containing mercury must be well sealed and not likely to leak or easily break, and must be regularly inspected;

(b) The floor of a room where mercury is stored or used in large quantities should have a sealed, impervious and crack-free floor covering, such as PVC. Small cracks in the floor, such as those between floor tiles, will trap mercury droplets. It is preferable to have the flooring material curving up the walls by approximately 10 cm, leaving no joint between the floor and the walls at floor level;

(c) Mercury must not be stored in a metal container as it reacts with almost all metals, except iron, forming an amalgam which may also be hazardous. Mercury should not come into contact with any other metallic object;

(d) Mercury must not be stored with other chemicals, especially amines, ammonia or acetylene;

(e) Large quantities of mercury should always be stored and handled in a well-ventilated room. The raw material should be handled in a good-quality fume cupboard;

(f) Mercury should never be stored near a heat source of any kind as it has a relatively low boiling point (357 °C) and may produce hazardous concentrations of toxic vapour, especially during a fire;

(g) If mercury is handled, the room where it is used and the personnel using it should be regularly tested to determine if hazardous quantities of mercury are being encountered.

Under the Minamata Convention, imports and exports of mercury will no longer be allowed. In this context, the production, import and export of mercury-added products such as thermometers will be stopped by 2020. The Convention states that "[e]ach party shall not allow, by taking appropriate measures, the manufacture, import or export of mercury-added products listed in Part I of Annex A [of the Convention] after the phase-out date specified for those products" (UNEP, 2013). More specifically, this list includes:

> The following non-electronic measuring devices except non-electronic measuring devices installed in large-scale equipment or those used for high precision measurement, where no suitable mercury-free alternative is available:
>
> (a) barometers;
>
> (b) hygrometers;
>
> (c) manometers;
>
> (d) thermometers;
>
> (e) sphygmomanometers.

3.2.7.1 ***Spillages and disposal***

The two common methods of cleaning up mercury spillages are either with a suitable aspirated pick-up system, as outlined below, or by adsorption/amalgamation of the mercury onto a powder.

Mercury should be cleaned up immediately. The operator should wear PVC gloves or gauntlets, safety goggles and, for significant spills, a respirator fitted with a mercury vapour cartridge.

Depending upon how large the spillage is, the mercury will be picked up by using a vacuum system; an adsorption kit should then be used to clean up the small droplets. The use of an adsorption kit is imperative because, during a spillage, dozens of small droplets of less than 0.02 mm in diameter will adhere to surfaces and cannot be efficiently removed with a vacuum system.

In an aspirated pick-up system, the mercury is drawn through a small-diameter plastic tube into a glass flask with approximately 3 cm of water in the bottom, with the tube opening being below the water line in the flask. One end of a larger diameter plastic tube is connected to the air space above the water in the flask, and the other end is connected to a vacuum cleaner or vacuum pump. The water prevents the mercury vapour or droplets from being drawn into the vacuum cleaner or pump. The slurry is then placed in a clearly labelled plastic container for disposal.

By using adsorption material, a variety of compounds can be used to adsorb or amalgamate mercury. These include zinc powder, sulphur flour or activated carbon. Commercial kits are available for cleaning up mercury spills. The powder is sprinkled on the spill and allowed to adsorb or amalgamate the mercury. The resulting powder is swept up and placed in a clearly labelled plastic container for disposal.

The collected mercury can be either disposed of or recovered. Details on how to dispose of mercury can be obtained from local authorities and/or the supplier. The supplier can also advise on recovery and purification.

3.2.7.2 *Fire*

Mercury will not burn but does give off significant concentrations of toxic fumes. After a fire, the mercury vapour will condense on the nearest cool surfaces, contaminating large areas and being adsorbed onto open surfaces, such as carbonized timber. During a fire, evacuate the area and remain upwind of any fumes. Advise the fire authorities of the location and quantity of mercury involved.

3.2.7.3 *Transportation*

The transportation by air of mercury or instruments containing mercury is regulated by the International Air Transport Association. Airlines will provide the specific conditions for such transport upon request. Transportation by rail or road is usually governed by the hazardous material regulations in each country.

In general, metallic mercury must be packed in glass or plastic containers. The containers should be packed with sufficient cushioning to prevent breakage and should be clearly labelled. Mercury-containing instruments should be packed in a strong cushioned case which is leak-proof and impervious to mercury.

3.3 ELECTRONIC BAROMETERS

Most barometers with recent designs make use of transducers which transform the sensor response into a pressure-related electrical quantity in the form of either analogue signals, for example, voltage (DC or AC with a frequency related to the actual pressure), or digital signals, for example, pulse frequency or with standard data communication protocols such as RS232, RS422, RS485 or IEEE488. Analogue signals can be displayed on a variety of electronic meters. Monitors and data-acquisition systems, such as those used in automatic weather stations, are frequently used to display digital outputs or digitized analogue outputs.

Current digital barometer technology employs various levels of redundancy to improve the long-term stability and accuracy of the measurements. One technique is to use three independently operating sensors under centralized microprocessor control. Even higher stability and reliability can be achieved by using three completely independent barometers, incorporating three sets of pressure transducers and microprocessors. Each configuration has automatic temperature compensation from internally mounted temperature sensors. Triple redundancy ensures excellent long-term stability and measurement accuracy, even in the most demanding applications. These approaches allow for continuous monitoring and verification of the individual sensor performances.

The use of digital barometers introduces some particular operational requirements, especially when they are used with automatic weather stations, and formal recommendations exist to ensure good practice (see the *Abridged Final Report of the Eleventh Session of the Commission for Instruments and Methods of Observation* (WMO-No. 807), Annex VII). Meteorological organizations should:

(a) Control or re-adjust the calibration setting of digital barometers upon receipt and repeat these operations regularly (annually, until the rate of drift is determined);

(b) Ensure regular calibration of digital barometers and investigate the possibility of using calibration facilities available nationally for this purpose;

(c) Consider that certain types of digital barometers may be used as travelling standards because of their portability and good short-term stability;

(d) Consider that the selection of a specific type of digital barometer should not only be based on stated instrument specifications but also on environmental conditions and maintenance facilities.

Manufacturers should:

(a) Improve the temperature independence and the long-term stability of digital barometers;

(b) Use standardized communication interfaces and protocols for data transmission;

(c) Enable the power supply of a digital barometer to function over a large range of DC voltages (for example, 5 to 28 VDC).

3.3.1 **Aneroid displacement transducers**

Contact-free measurement of the displacement of the aneroid capsule is a virtual necessity as regards precision pressure-measuring instruments for meteorological applications. A wide variety of such transducers are in use, including capacitive displacement detectors, potentiometric displacement detectors, strain gauges placed at strategic points on the sensor, and force-balanced servo-systems which keep the sensor dimensions constant regardless of pressure.

All sensitive components must be encased in a die-cast housing. This housing must be kept at a constant temperature by an electronically controlled heater. Condensation of water must be completely prevented. An effective technique is to put a hygroscopic agent, such as silica gel crystals, into the die-cast housing and to prevent water vapour diffusion into the housing by connecting a long plastic tube (approximately 25 m) with a bore of 2 mm or less between the pressure port and a static head (see section 3.8.1).

The pressure-sensor housing must be airtight, allowing external connection to the compartment where the pressure is to be measured.

3.3.2 Digital piezoresistive barometers

Measurements of atmospheric pressure have become possible by utilizing the piezoelectric (piezoresistive) effect. A common configuration features four measuring resistors placed onto the flexible surface of a monolithic silicon substratum interconnected to form a Wheatstone bridge circuit.

Axially loaded crystalline quartz elements are used in digital piezoresistive barometers and are a type of absolute pressure transducer. Crystalline quartz has been chosen because of its piezoelectric properties, stable frequency characteristics, small temperature effects and precisely reproducible frequency characteristics. Pressure applied to an inlet port causes an upward axial force by means of flexible bellows, thus resulting in a compressive force on the quartz crystal element. Since the crystal element is a substantially rigid membrane, the entire mechanical structure is constrained to minute deflections, thereby virtually eliminating mechanical hysteresis.

The fully active Wheatstone bridge mentioned above may consist either of semiconductor strain gauges or piezoresistive gauges. The strain gauges are either bonded to a thin circular diaphragm, which is clamped along its circumference, or atomically diffused into a silicon diaphragm configuration. In the case of diffused devices, the silicon integrated chip itself is the diaphragm. Applied pressure presents a distributed load to the diaphragm which, in turn, provides bending stress and resultant strains to which the strain gauges react. This stress creates a strain that is proportional to the applied pressure and which results in a bridge imbalance. The bridge output is then proportional to the net difference in pressure acting upon the diaphragm.

This mode of operation is based on the fact that the atmospheric pressure acts on the sensor element covering a small evacuated cell, through which the resistors are submitted to compressive and tensile stresses. By the piezoelectric effect, the values of resistance change proportionally with atmospheric pressure. To eliminate temperature errors, the sensor often incorporates a built-in thermostat.

The output from the Wheatstone bridge, which is fed from a direct-current source, is transduced into a standard signal by an appropriate amplifier. A light-emitting diode or liquid crystal display usually presents the measured pressure values.

In a modern version of the pressure transducer using a piezoelectric transducer, two resonance frequencies of the piezoelectric element are determined. By calculating a linear function of these frequencies and with an appropriate set of variables obtained after calibration, a pressure is calculated by a microprocessor which is independent of the temperature of the sensor.

3.3.3 Cylindrical resonator barometers

Cylindrical resonator barometers use a sensing element which is a thin-walled cylinder of nickel alloy. This is electromagnetically maintained in a "hoop" mode of vibration. The input pressure is sensed by the variation it produces in the natural resonant frequency of the vibrating mechanical system. Cylinder wall movement is sensed by a pick-up coil whose signal is amplified and fed back to a drive coil. The air pressure to be measured is admitted to the inside of the cylinder, with a vacuum reference maintained on the outside. The natural resonant frequency of vibration then varies precisely with the stress set up in the wall due to the pressure difference across it. An increase in pressure gives rise to an increase in frequency.

The thin cylinder has sufficient rigidity and mass to cater for the pressure ranges over which it is designed to operate, and is mounted on a solid base. The cylinder is placed in a vacuum chamber and its inlet is connected to the free atmosphere for meteorological applications. Since there is a unique relationship between the natural resonant frequency of the cylinder and the pressure, the atmospheric pressure can be calculated from the measured resonant frequency. However, this relationship, determined during calibration, depends on the temperature and the density of the gas. Temperature compensation is therefore required and the air should be dried before it enters the inlet.

3.3.4 Reading electronic barometers

An electronic barometer measures the atmospheric pressure of the surrounding space or any space that is connected to it via a tube. In general, the barometer should be set to read the pressure at the level of the instrument. On board a ship or at low-level land stations, however, the instrument may be set to indicate the pressure at mean sea level, provided that the difference between the station pressure and the sea-level pressure can be regarded as constant.

Electronic barometers give accurate readings on a digital read-out, normally scaled in hPa but readily adaptable to other units, if required. Provision can usually be made for digital recording. Trend in pressure changes can be presented if the unit is microprocessor-controlled.

The accuracy of electronic barometers depends on the accuracy of the barometer's calibration, the effectiveness of the barometer's temperature compensation (residual air method, temperature measurement and correction, use of a thermostat) and the drift with time of the barometer's calibration.

Circuits may be attached to primary transducers which correct the primary output for sensor non-linearities and temperature effects and which convert output to standard units. Standard modern barometer versions comprise the barometer sensor, the microcomputer unit (including the display) and an interface circuit to communicate with any data logger or automatic weather station.

Electronic barometers which have more than one transducer or sensing element generally calculate a weighted mean of the outputs from each of the sensors and establish the resultant pressure with a resolution of 0.1 hPa. During calibration, each of the sensing elements can be checked with a resolution of 0.01 hPa. This should not lead operators to believe that the sensor accuracy is better than 0.1 hPa (see section 3.10.3.4).

3.3.5 Errors and faults with electronic barometers

3.3.5.1 *Calibration drift*

Calibration drift is one of the key sources of error with electronic barometers. It is often greater when the barometer is new and decreases with the passage of time. Step jumps in calibration may occur.

In order to maintain the acceptable performance of a barometer, the calibration corrections applied to the readings must be checked at relatively frequent intervals, for example, annually, for early detection and replacement of defective sensors.

The need to check frequently the calibration of electronic barometers imposes an additional burden on National Meteorological Services, particularly on those with extensive barometer networks. The ongoing cost of calibration must be taken into consideration when planning to replace mercury barometers with electronic barometers.

3.3.5.2 *Temperature*

Electronic barometers must be kept at a constant temperature if the calibration is to be maintained. It is also preferable that the temperature be near the calibration temperature. However, many commercially available electronic barometers are not temperature-controlled and are prone to greater error. Most depend on accurate temperature measurement of the sensing element and electronic correction of the pressure. This assumes that there are no thermal gradients within the sensing element of the barometer. In situations where the temperature changes reasonably quickly, this can result in short-term hysteresis errors in the measured pressure.

The change in calibration is also highly dependent on the thermal history of the barometer. Prolonged exposure to temperatures that differ from the calibration temperature can result in medium to long-term calibration shifts.

The electronics of the barometer can also introduce errors if it is not held at the same temperature as the sensor element. Electronic barometers are very often used in extreme climatic conditions, especially in automatic weather stations. In these situations, the barometer can be exposed to temperatures well in excess of its manufacturer's design and calibration specifications.

3.3.5.3 *Electrical interference*

As with all sensitive electronic measurement devices, electronic barometers should be shielded and kept away from sources of strong magnetic fields, such as transformers, computers, radar, and so forth. Although this is not often a problem, it can cause an increase in noise, with a resultant decrease in the precision of the device.

3.3.5.4 *Nature of operation*

Apparent changes in the calibration of an electronic barometer can be caused by differences in the way in which the barometer is operated during calibration, as compared with its operational use. A pressure read on a barometer that is run continuously and, therefore, warmed up will read differently from that read in a pulsed fashion every few seconds.

3.4 ANEROID BAROMETERS

3.4.1 Construction requirements

The greatest advantages of conventional aneroid barometers over mercury barometers are their compactness and portability, which make them particularly convenient for use at sea or in the field. The principal components are a closed metal chamber, completely or partly evacuated, and a strong spring system that prevents the chamber from collapsing under the external atmospheric pressure. At any given pressure, there will be an equilibrium between the force caused by the spring and that of the external pressure.

The aneroid chamber may be made of materials (steel or beryllium copper) that have elastic properties such that the chamber itself can act as a spring.

A means is required to detect and display the changes in deflection which occur. This may be a system of levers that amplify the deflections and drive a pointer over a scale graduated to indicate the pressure. Alternatively, a ray of light may be deviated over the scale. Instead of these mechanical analogue techniques, certain barometers are provided with a manually operated micrometer whose counter indicates the pressure directly in tenths of a hectopascal. A reading is taken when a luminous indicator signals that the micrometer has just made contact with the aneroid. This type of aneroid is portable and robust.

3.4.2 Accuracy requirements

The chief requirements of a good aneroid barometer are as follows:

(a) It should be compensated for temperature so that the reading does not change by more than 0.3 hPa for a change in temperature of 30 K;

(b) The scale errors at any point should not exceed 0.3 hPa and should remain within this tolerance over periods of at least one year, when in normal use;

(c) The hysteresis should be sufficiently small to ensure that the difference in reading before a change in pressure of 50 hPa and after a return to the original value does not exceed 0.3 hPa;

(d) It should be capable of withstanding ordinary transit risks without introducing inaccuracies beyond the limits specified above.

3.4.3 Reading aneroid barometers

3.4.3.1 *Accuracy of readings*

An aneroid barometer should always be read in the same orientation (vertical or horizontal) as during calibration. It should be tapped lightly before being read. As far as possible, it should be read to the nearest 0.1 hPa. Optical and digital devices are available for improving the reading accuracy and reducing the errors caused by mechanical levers.

3.4.3.2 *Corrections applied to aneroid barometers*

In general, aneroid barometers should be set to read the pressure at the level of the instrument. On board a ship or at low-lying land stations, however, the instrument may be set to indicate the pressure at mean sea level, provided that the difference between the station pressure and the sea-level pressure can be regarded as constant. The readings should be corrected for instrumental errors, but the instrument is usually assumed to be sufficiently compensated for temperature, and it needs no correction for gravity.

3.4.4 Errors and faults with aneroid barometers

3.4.4.1 *Incomplete compensation for temperature*

In an aneroid barometer, if the spring is weakened by an increase in temperature, the pressure indicated by the instrument will be too high. This effect is generally compensated for in one of the following ways:

(a) By means of a bimetallic link in the lever system; or

(b) By leaving a certain amount of gas inside the aneroid chamber.

In most ordinary aneroid barometers, the compensation obtained by these methods is complete only at one particular compensation pressure. It is desirable that all aneroid barometers and barographs used at meteorological stations should be properly compensated for temperatures over the full range of pressure. In digital read-out systems suitable for automation, such complete corrections can be applied as part of the electronic system.

3.4.4.2 *Elasticity errors*

An aneroid barometer may be subjected to a large and rapid change in pressure. For example, a strong gust of wind would cause an aneroid barometer to experience a rapid increase in pressure followed by a more gradual return to the original value. In such circumstances, the instrument will, owing to hysteresis, indicate a slightly different reading from the true pressure; a considerable time may elapse before this difference becomes negligible. However, since aneroids and barographs at surface stations are not usually directly exposed to such pressure changes, their hysteresis errors are not excessive.

There is also a secular error caused by slow changes in the metal of the aneroid capsule. This effect can be allowed for only by comparison at regular intervals, for example, annually, with a standard barometer. A good aneroid barometer should retain an accuracy of 0.1 hPa over a period of one year or more. In order to detect departures from this accuracy by individual barometers, a regular inspection procedure with calibration and adjustment as necessary should be instituted.

3.5 BAROGRAPHS

3.5.1 General requirements

Of the various types of barographs, only the aneroid barograph will be dealt with in detail here. For synoptic purposes, it is recommended that charts for barographs:

(a) Be graduated in hPa;

(b) Be readable to 0.1 hPa;

(c) Have a scale factor of 10 hPa to 1.5 cm on the chart.

In addition, the following requirements are desirable:

(a) The barograph should employ a first-class aneroid unit (see section 3.5.2);

(b) The barograph should be compensated for temperature, so that the reading does not change by more than 1 hPa for a 20 K change in temperature;

(c) Scale errors should not exceed 1.5 hPa at any point;

(d) Hysteresis should be sufficiently small to ensure that the difference in reading before a change in pressure of 50 hPa and after a return to the original value does not exceed 1 hPa;

(e) There should be a time-marking arrangement that allows the marks to be made without lifting the cover;

(f) The pen arm should be pivoted in a "gate", the axis of which should be inclined in such a way that the pen rests on the chart through the effects of gravity. A means of adjustment should be provided for setting the position of the pen.

Marine barographs are subject to special requirements, which are considered in Part II, Chapter 4.

3.5.2 Construction of barographs

The principle of the aneroid barograph is similar to that of the aneroid barometer, except that a recording pen is used instead of a pointer. This involves some change in the design of the capsule stack, and usually means a decrease in the overall magnification and an increase in the number and size of the capsules used.

The "control" of the barograph may be expressed as the force required to move the pointer over one unit of the scale (1 hPa) and is, thus, equal to the force required to prevent the pen from moving when the pressure changes by 1 hPa. It is a measure of the effect that friction is likely to have on the details of the record.

The force required to overcome the movement of the capsule when the pressure changes by 1 hPa is 100 A newtons, where A is the effective cross-sectional area of the capsule in square metres. If the magnification is X, the force necessary to keep the pen from moving is 100 A/X newtons and varies as A/X. For a given type of capsule and scale value, the value of X will be largely independent of A, so that the control of a barograph pen may be considered to vary approximately with the effective cross-sectional area of the capsule.

3.5.3 Sources of error and inaccuracy

In addition to the sources of error mentioned for the aneroid (see section 3.4.4), the friction between the pen and the paper is important. The control of the pen depends largely on the effective cross-section of the aneroid. In a well-made barograph, the friction of the pen is appreciably greater than the total friction at all the pivots and bearings of the instrument; special attention should, therefore, be given to reduce such errors, for example, by having a sufficiently large aneroid capsule.

A first-class barograph should be capable of an uncertainty of about 0.2 hPa after corrections have been applied and should not alter for a period of one or two months. The barometric change read from such a barograph should usually be obtained within the same limits.

3.5.4 Instruments with data-processing capability

A barometer suitable for automated reading can be linked to a computer, typically a microprocessor, which can be programmed to provide suitably sampled data. These data, in turn, can be presented graphically to provide records similar to those supplied by a barograph. Models are available that print their own scales, thereby eliminating one source of error.

3.5.5 Reading a barograph

The barograph should be read without touching the instrument. The time mark and any inspection of the instrument involving lifting the cover, and so on, should always be made after the reading is completed.

3.5.5.1 *Accuracy of readings*

The chart should be read to the nearest 0.1 hPa. The barometric change should be obtained within the same resolution limits.

3.5.5.2 *Corrections to be applied to barograph readings*

The temperature compensation of each individual instrument should be tested before the instrument is used, and the scale factor should be adjusted by testing in a vacuum chamber. If the barograph is used only to find the barometric change, the corrections are not usually applied to the readings. In this case, the accurate setting of the pen position is not important. When absolute pressure values are required from the barograph, the record should be compared with the corrected readings of a mercury barometer or a good aneroid barometer at least once every 24 h and the desired values found by interpolation.

3.6 BOURDON-TUBE BAROMETERS

Bourdon-tube barometers usually consist of a sensor element that, as for an aneroid capsule, changes its shape under the influence of pressure changes (pressure transducers) and a transducer that transforms the changes into a form directly usable by the observer. The display may be remote from the sensor. Precise and stable digital instruments with quartz Bourdon tubes are used as working reference barometers in calibration laboratories.

3.7 BAROMETRIC CHANGE

Two methods are available to stations making observations at least every 3 h as follows:

(a) The change can be read from the barograph; or

(b) The change can be obtained from appropriate readings of the barometer, corrected to station level. If the choice is between an ordinary mercury barometer and a first-class open-scale barograph, the latter should be selected for the reasons outlined below.

The error of a single barometric reading is mainly random, assuming that the barometer functions perfectly. Therefore, when two independent readings are subtracted to find the amount of change, the errors may be cumulative. Barograph errors are partly systematic in nature, so that in the relatively short period of 3 h, the errors are likely to have the same sign and would, therefore, be diminished by subtraction.

A further reason for using the barograph is the convenience of avoiding the need to correct barometric readings to station level. In any case, the barograph must be used to ascertain the characteristic of the barometric change.

Barometers with digital displays are also very suitable for determining the magnitude and character of a pressure change.

3.8 GENERAL EXPOSURE REQUIREMENTS

It is important that the location of barometers at observation stations be selected with great care. The main requirements of the place of exposure are uniform temperature, good light, a draught-free environment, a solid and vertical mounting, and protection against rough handling. The instrument should, therefore, be hung or placed in a room in which the temperature is constant, or changes only slowly, and in which gradients of temperature do not occur. The barometer should be shielded from direct sunshine at all times and should not be placed near any heating apparatus or where there is a draught.

3.8.1 The effect of wind

It should be noted that the effects of wind apply to all types of barometers. More information on wind effects is found in Liu and Darkow (1989).

A barometer will not give a true reading of the static pressure if it is influenced by gusty wind. Its reading will fluctuate with the wind speed and direction and with the magnitude and sign of the fluctuations, depending also on the nature of the room's openings and their position in relation to the direction of the wind. At sea, error is always present due to the ship's motion. A similar problem will arise if the barometer is installed in an air-conditioned room.

Wind can often cause dynamic changes of pressure in the room where the barometer is placed. These fluctuations are superimposed on the static pressure and, with strong and gusty wind, may amount to 2 or 3 hPa. It is usually impractical to correct for such fluctuations because the "pumping" effect on the mercury surface is dependent on both the direction and the force of the wind, as well as on the local circumstances of the barometer's location. Thus, the "mean value" does not only represent the true static pressure. When comparing barometers in different buildings, the possibility of a difference in readings due to the wind effect should be borne in mind.

It is possible to overcome this effect to a very large extent by using a static head between the exterior atmosphere and the inlet port of the sensor. Details concerning the operating principles of static heads can be found in several publications (Miksad, 1976; United States Weather Bureau, 1963). For a mercury barometer, the barometer cistern must be made airtight except for a lead to a special head exposed to the atmosphere and designed to ensure that the pressure inside is true static pressure. Aneroid and electronic barometers usually have simple connections to allow for the use of a static head, which should be located in an open environment not affected by the proximity of buildings. The design of such a head requires careful attention. Static pressure heads are commercially available, but there is no published literature on intercomparisons to demonstrate their performance.

3.8.2 The effects of air conditioning

Air conditioning may create a significant pressure differential between the inside and outside of a room. Therefore, if a barometer is to be installed in an air-conditioned room, it is advisable to use a static head with the barometer which will couple it to the air outside the building.

3.9 BAROMETER EXPOSURE

3.9.1 Exposure of mercury barometers

The general exposure requirements of mercury barometers have been outlined in the preceding sections. Mercury barometers have additional exposure requirements above those already mentioned. It is always preferable to hang the mercury barometer on an inside wall. For very accurate work, the best position would be in an unheated basement room with no windows and with a small electric fan to prevent any stratification of temperature.

In order to obtain uniform lighting conditions for reading the barometer, it is advisable to use artificial lighting for all observations. For this purpose, some sort of illuminator – which can provide a white and slightly luminous background for the mercury meniscus and, if necessary, for the fiducial point – may be provided. If no illuminator is used, care should be taken to provide the meniscus and the fiducial point with a light background, by such means as pieces of milk glass, white celluloid, or a sheet of white paper. Artificial light should also be provided for reading the barometer scale and the attached thermometer. Care should, however, be taken to guard against heating the barometer with artificial light during a barometer reading.

The barometer should be mounted in a place where it is not subject to vibration, preferably on a solid wall. The instrument must be mounted with the mercury column in a vertical position. Errors due to departure from verticality are more critical for asymmetric barometers. Such barometers should be mounted with their longest axis vertical in order that a true setting of the mercury surface to the fiducial point remains correct even when the instruments are tilted from the vertical.

To protect the barometer from rough handling, dust and air currents, it is recommended that the instrument be placed in a box furnished with a hinged door with provisions for sufficient ventilation to prevent stratification of the air inside.

Great care should be taken when transporting a mercury barometer. The safest method is to carry the barometer upside down in a wooden case furnished with a sling. If the barometer cannot be accompanied by a responsible person, it ought to be transported in a suitable sprung crate with the cistern uppermost. The barometer should not be subject to violent movements and must always be turned over very slowly. Special precautions must be taken for some individual types of barometers before the instrument is turned over.

3.9.2 Exposure of electronic barometers

Electronic barometers require a clean, dry atmosphere that is free of corrosive substances. The barometer should also be kept at a constant temperature (see section 3.3.5.2). The instrument should be mounted in such a manner as to avoid mechanical shock and vibration. It should also be mounted away from electromagnetic sources, where this is not possible, the wires and casing should be shielded.

Barometers with digital read-outs should be mounted where there is good general lighting, but should not face a window or other strong light sources.

3.9.3 Exposure of aneroid barometers

The exposure requirements for aneroid barometers are similar to those for mercury barometers (see section 3.9.1) owing to the fact that such instruments may not be perfectly compensated for the effects of temperature. The place selected for mounting the device should preferably have a fairly uniform temperature throughout the day. Therefore, a location is required where the barometer is shielded from the direct rays of the sun and from other sources of either heat or cold, which can cause abrupt and marked changes in its temperature.

At land stations, it is an advantage to have the aneroid barometer installed in the vicinity of a mercury barometer for cross-checking and standardization purposes (see section 3.10).

3.9.4 Exposure of barographs

The barograph should be installed where it is protected from sudden changes in temperature and from vibration and dust. It should not be exposed to direct sunshine. The barograph should also be placed at a location where it is unlikely to be tampered with by unauthorized persons. Mounting the barograph on a sponge rubber cushion is a convenient means of reducing the effects of vibration. The site selected should be clean and dry. The air should also be relatively free of substances which would cause corrosion, fouling of the mechanism, and the like.

It is important to mount the instrument so that its face will be at a convenient height to be read at eye-level under normal operating conditions with a view to minimizing the effects of parallax. The exposure ought to be such that the barometer is uniformly illuminated, with artificial lighting being provided if necessary.

If a barograph has to be transported by air or transported at a high altitude, the pen arm should be disconnected and precautions should be taken to ensure that the mechanism is able to withstand the overload caused by exceeding the normal measuring range of the instrument.

3.10 COMPARISON, CALIBRATION AND MAINTENANCE

3.10.1 General requirements of a barometer comparison

In view of the importance of accurate pressure observations, especially for aeronautical and synoptic purposes, and of the various possible errors to which barometers are subject, all station barometers should be checked regularly by an inspector. Some guidance is given in the following sections regarding the equipment to be used for checks, the frequency with which these should be carried out, and other related topics. Where precision aneroid barometers are used as station barometers, they should be checked frequently (at least once every week) against a mercury or digital barometer, and a permanent record of all such checks should be kept on a suitable card or in a special logbook.

Alternatively, mercury barometers can be dispensed with if a daily comparison, both with a second aneroid barometer kept at the station and with analysed pressures in the vicinity, is undertaken. This should be supported by six monthly checks with a travelling standard.

The following symbols may be used to denote various categories of barometers in a National Meteorological Service:

A: A primary or secondary standard barometer capable of independent determination of pressure to an uncertainty of 0.05 hPa or less;

B: A working standard barometer of a design suitable for routine pressure comparisons and with known errors, which have been established by comparison with a primary or secondary standard;

C: A reference standard barometer used for comparisons of travelling standard and station barometers at field supervising stations of a National Meteorological Service;

S: A barometer (mercury, aneroid, electronic) located at an ordinary meteorological station;

P: A mercury barometer of good quality and accuracy, which may be carried from one station to another and still retain calibration;

N: A portable precision aneroid barometer of first quality;

Q: A portable precision digital barometer of first quality, to be used as a travelling standard (Q stands for quality);

M: A portable microbarograph of good quality and accuracy.

In order that barometer correction programmes be conducted on the same basis by all National Meteorological Services, it is desirable that uniform practices be followed in the quality of the equipment used, the frequency of comparisons, the procedures to be followed, the permissible changes in index correction, and the criteria for remedial action.

3.10.2 Equipment used for barometer comparisons

3.10.2.1 *Primary standard barometer (A)*

There are different opinions regarding the best type of primary standard barometer (WMO, 2010*c*). Two types are outlined in the following paragraphs.

One possible primary standard for atmospheric pressure consists of a precision dead weight tester that produces a calibrated pressure related to the precision weights used and the local gravity field. This type of barometer is relatively simple and does not suffer from the problem of excessive drift experienced by mercury barometers in a polluted environment.

The primary standard barometer may well be a high-quality mercury barometer specially designed for that purpose. The primary standard mercury barometer must have a high vacuum, contain very pure mercury with a well-known density maintained at a constant temperature, and be located in an environment where pollution effects are prevented. The barometer also needs a calibrated measure (scale) and an optical read-out facility. These types of barometers measure absolute pressure with high absolute accuracy, while dead weight testers are gauge pressure measuring instruments.

Considering the cost of such primary standards and the constraints on their use and maintenance, these barometers are most frequently used in high-level calibration laboratories.

3.10.2.2 *Working standard barometer (B)*

The working and reference standards, and the travelling standards used to compare barometers, should have high stability over long periods. These standards may be either mercury or electronic barometers. In the case of mercury barometers, they should have a tube with at least a 12 mm bore. It is also desirable that barometers be instruments in which the vacuum can be checked. They should be fully and carefully corrected for all known errors, which should have been established by two or more recent comparisons with barometers of a higher category.

3.10.2.3 ***Travelling standard barometer (C)***

A reliable travelling standard barometer must retain its index correction during transit to within 0.1 hPa. It should be standardized with reference to the working or reference standard before and after each tour. Once standardized, it should on no account be opened or adjusted in any fashion until after the final comparison at the station of origin of the tour. A travelling standard barometer needs to be carried in a high-quality, cushioned travelling case to protect it during transit.

Considering the restrictions on mercury transportation and the ongoing development of digital barometers, National Meteorological Services may use an appropriate high-precision digital barometer as a travelling standard barometer. In this case, the National Meteorological Service should regularly control the drift of such instruments by conducting regular comparisons with working or reference standards.

If a mercury travelling standard is used, before the beginning of a tour it should be examined carefully and checked to ensure that the mercury in the tube and cistern is clean, that there are no bubbles in the tube, and that the vacuum above the mercury in the tube is good. Every care should be taken in handling, packing and transporting travelling standards so that there is the least possible cause for any change, however slight, in their index correction. Quick, jerky movements which might cause air bubbles from the tube cistern to rise in the tube should be avoided. Mercury travelling standards should be carried in a suitably cushioned leather or metal case, with the cistern end always higher than the tube.

3.10.2.4 ***Specifications of portable mercury barometers (P)***

If a mercury barometer is to be used as a category P barometer, it must be designed so that the vacuum can be checked or so that a good degree of vacuum can be established at the top of the tube with a vacuum pump. A check valve for sealing the tube is essential. It should also have the property of high stability over long periods and have a tube with at least a 12 mm bore. Another desirable feature is a means of determining whether the quantity of mercury in the fixed cistern has remained constant since the original filling.

Also, a well-built Fortin-type barometer with a tube bore of at least 9 mm, but preferably 12 mm, can be used as a travelling standard. The degree of accuracy (as regards repeatability) considered necessary for a travelling standard is about 0.1 hPa. Category P barometers should be calibrated over a wide pressure and temperature range, covering all possible values likely to be encountered.

3.10.2.5 ***Specifications of portable electronic barometers (Q)***

Portable electronic barometers have now reached the level of development and reliability to allow them to be used as a category Q barometer. The barometer must have a history of reliability with low drift corrections, as determined by several comparisons with a standard barometer both over a period of one year or more and over the maximum pressure range in which the barometer must be expected to operate.

Electronic barometers with multiple pressure transducers under independent microprocessor control are preferred. The temperature-compensation mechanism for the barometer must be proven to be accurate. The method for taking measurements from the pressure transducer must be contact-free and the barometer itself sufficiently robust to withstand the type of shock that may be encountered during transportation.

3.10.3 **Barometer comparison**

3.10.3.1 ***International barometer comparison***

Great importance is attached to international barometer comparisons. The WMO Automatic Digital Barometer Intercomparison was carried out in De Bilt (Netherlands) from 1989 to 1991. Only by such comparisons is it possible to ensure consistency in the national standards of pressure-measuring instruments and thus prevent discontinuities in pressure data across international boundaries. The recommended procedure for such comparisons is given in section 3.10.4.

The programme of comparisons includes the following:

(a) Comparison of national working standard B with primary or secondary standard barometer A, at least once every two years. If barometers A and B are located at the same centre, no travelling standards are required;

(b) Comparison of reference standard C with national working standard B, at least once every two years by means of travelling standards;

(c) Comparison of station barometer S with reference standard C, at least once every year, by means of travelling standards, or by comparison with the working standard B, every one to two years, depending upon the known characteristics of the barometers being used. It is a matter of policy whether the comparison occurs at the station or at a central calibration facility. In the latter case, travelling standards are not required.

It should be understood that the error of each barometer at the end of any link in a chain of comparison is determined with respect to the primary or secondary standard barometer A, so that the results of corrected barometric pressure readings are on an absolute basis at each stage.

3.10.3.2 ***Inspection of station barometers***

For the inspection of station barometers, Fortin barometers with a tube bore of 9 mm are suitable; however, note section 3.2.7.3 on restrictions on the carriage of mercury instruments. Electronic barometers may also be used as travelling standards, provided that they have the necessary stability and accuracy.

3.10.3.3 ***Procedure for the comparison of mercury barometers***

The instructions given in previous sections should be generally followed. All normal precautions necessary while setting and reading barometers should be enforced with great care. Investigations show that readings averaging within 0.05 hPa can normally be achieved in a barometer comparison if adequate precautions are taken.

Comparative readings of the barometers should be entered in appropriate forms. A permanent record of all checks should be attached to the instrument and should include such information as the date of the check, the temperature and pressure at which the comparison was made, and the correction obtained.

Reports of barometer comparisons should be forwarded to the National Meteorological Service for evaluating errors, computing and issuing corrections, and determining the need for remedial action. Continuous records of the comparison data should be kept for each station barometer for a study of its performance over a period of years and for the detection of defects. Tabular and/or graphical records are useful visual tools for a barometer quality control programme.

3.10.3.4 *Checking electronic barometers*

At the current state of development, it is important to calibrate electronic barometers at intervals of about one year. It is standard procedure to calibrate an electronic barometer at a calibration facility immediately before its dispatch to a meteorological observation station. At the station, a number of comparison readings of pressure between the electronic barometer and the travelling standard should be taken at different pressures (either over an adequate period of time or using a pressure generator). The readings should be taken with all barometers at the same height, when the wind speed is less than 12 m s^{-1} and when the pressure is either steady or changing by less than 1 hPa h^{-1}. Any electronic barometer whose mean difference from the travelling standard exceeds 0.25 hPa should be regarded as unserviceable and returned to the calibration facility for recalibration.

If at all possible, it is advisable to install two independent electronic barometers at a meteorological observing station, with one barometer preferably having a history of low drift. This barometer is identified by the calibration facility staff from its calibration history and is identified as a low-drift barometer. With the arrival of each new barometer at a station, a set of comparison readings are taken, as described above, and the mean difference between the low-drift barometer and the new barometer is established. Once this is accomplished, daily readings from both barometers should be taken and a running sum of 25 differences calculated. If the new barometer and the low-drift barometer exhibit different rates of drift, the sums of the 25 differences will change. If a station has one mercury barometer and one electronic barometer, it would be normal for the mercury barometer to be the low-drift barometer. The low drift of the mercury barometer should still be verified by regular calibration checks.

These checks do not represent an inspection or a new calibration of the electronic barometer. Every National Meteorological Service should establish detailed inspection and calibration procedures for its electronic barometers, with the above method being used as a practical guide.

3.10.4 General procedure recommended for the comparison of barometers at different locations

The comparison of barometers is essential and should be undertaken in the following ways:

(a) If barometer “1” is to be compared with barometer “2”, a qualified person should carry the travelling standard(s), preferably of the P or Q category, from barometer “1” to barometer “2”, and then return to “1”, thus closing the circuit. This procedure is applicable both between and within countries. Barometer “1” is usually at the central laboratory of a national standards organization or at the laboratory of a National Meteorological Service. Barometer “2” is at some other location. The carrying of category N and M standards is optional, and M may be omitted if microbarographs of good quality are installed at the two locations;

(b) For standardization purposes, the travelling standards should be placed next to the barometer to be compared and all the instruments given equal exposure for at least 24 h before official comparative readings are begun. An air current from an electric fan played on the instruments will aid in equalizing their temperature. The temperature of the room should be kept as uniform as practicable;

Note: The fan should be turned off before comparisons are made.

(c) Comparative readings should not be taken if category M standards show the pressure to be fluctuating rapidly. Preference should be given to barometrically quiet periods (pressure steady or changing only slowly) for making the comparisons;

(d) Comparative readings should be taken at uniform intervals of no less than 15 min in duration;

(e) Experience indicates that at least five comparative readings are required for category S barometers at ordinary stations. At least 10 comparative barometer readings are required for barometers in categories A, B or C for standardization purposes;

(f) If meteorological conditions permit, the comparative readings in the latter cases should be taken at different pressures covering both high and low pressures;

(g) Records should include the attached thermometer observations, the readings of the travelling standards and barometers being compared, the wind speed, direction and gustiness, the corrections for gravity, temperature and instrumental error, the actual elevation above sea level of the zero point of the barometers, and the latitude, longitude, place name and date and time of observations;

(h) The readings of category N barometers, if used, should include the readings of two or more precision aneroid barometers, corrected to a common reference, if standardization against instruments of category A or B shows them to differ in calibration. The correct readings of the aneroid barometers must be in agreement within tolerances appropriate to the instrument, otherwise the comparisons will be regarded as invalid;

(i) With respect to comparisons using travelling standards, barometer “1” must be the highest class of standard barometer available at the point of departure. Barometer “1” should be of category A, B or B_r (see section 3.10.5.1), with category C being the lowest acceptable quality. Two sets of comparisons of the travelling standards are necessary with barometer “1”, at the following points in time:

   (i) Before the travelling standards are carried by hand from where barometer “1” is located to the place where barometer “2” is located;

   (ii) After the return of the travelling standards to their point of origin, following transit to and from the location of barometer “2”. The “before” and “after” comparisons should be checked against each other. If agreement with barometer “1” is within satisfactory tolerances for each of the instruments involved, it can be assumed that the comparisons between the travelling standards and barometer “2” are also within the required tolerances, provided that due care has been taken during all phases of the comparison process. However, if there is a significant disagreement or if a known mishap has occurred which might have affected the instruments, or if the validity of the comparison data is in question for any reason, the comparison exercise is deemed invalid and the whole process must be repeated;

(j) As far as practical, all discrepancies should finally be expressed with respect to a primary or secondary reading of a category A barometer. This will ensure a common basis for all comparisons. In each case, the report of comparisons should indicate the standard used;

   Note: When a programme involving the elimination of residual barometric errors is adopted, there will be a homogeneous system of barometric observational data conforming to a single standard, which will permit the elimination of errors in horizontal pressure gradients from instrumental sources.

(k) Comparisons are necessary both before and after the relocation of barometers at a laboratory or a station, or the cleaning of the mercury, to ensure early detection of the development of a defect.

3.10.5 **Regional barometer comparison**

3.10.5.1 ***Nomenclature and symbols***

Symbols denoting barometer categories are as follows:

A_r: A barometer of category A which has been selected by regional agreement as a reference standard for barometers of that Region;

B_r: A barometer of category B which the National Meteorological Services of the Region agree to use as the standard barometer for that Region, in the event that the category A barometer is unavailable in the Region.

Annex 3.B contains the list of regional standard barometers.

3.10.5.2 *System of interregional comparison*

The following measures must be considered when planning interregional comparisons:

(a) Member countries in each Region will designate a primary or secondary standard barometer A to serve as A_r for the Region. If a primary or secondary barometer is not available within the Region, a category B barometer will be designated jointly as the regional standard barometer for that Region, with the barometer so chosen being denoted by the symbol B_r. Relative costs will determine whether a Region may deem it advantageous to designate more than one standard barometer;

(b) A competent person carrying travelling standard barometers will travel from a central station equipped with a barometer of category A_r to a nearby Region equipped with a barometer of at least category B or B_r. A comparison of the barometers should then be performed. When the comparison is made in ambient conditions, it should be done in accordance with the method outlined in section 3.10.3. Otherwise, in presence of a pressure generator, the comparison may be made for several pressure calibration points covering the whole range and over several cycles. This makes it possible to define the accuracy of the standards at different pressure levels and determine some metrological characteristics such as hysteresis, repeatability and reproducibility. For the purposes of verification and intercomparison, it is sometimes desirable to repeat the process by comparing the B_r barometer with a barometer of category A_r from a different Region;

(c) Copies of the comparison records should be transmitted to each of the central stations equipped with a category A barometer and to the station where the barometer B or B_r compared is located. Summaries of the comparison results should be forwarded to all National Meteorological Services in the Region where the barometer B or B_r is located.

3.10.5.3 *System of international comparison within a Region*

The following measures must be considered when planning international comparisons:

(a) Each National Meteorological Service will compare its category B barometer with the category A barometer within the Region, if available, using the system outlined in section 3.10.4. Where possible, preference should be given to the category A barometer for the Region as the standard instrument for the area;

(b) When a category A barometer is not available in the Region, the category B barometers of the respective National Meteorological Service of the Region will be compared with the category B_r barometer for the Region, in accordance with section 3.10.4;

(c) When a competent person is engaged in the execution of the programme to compare barometers of categories B with B_r, it is desirable that additional en route comparisons be made with barometers of categories B and C, while the person is travelling both to and from the station where the instrument B_r for the Region is located;

(d) Copies of records and summaries of comparisons will be prepared and forwarded to interested agencies as outlined in paragraph 3.10.5.2 (c).

3.11 ADJUSTMENT OF BAROMETER READINGS TO OTHER LEVELS

In order to compare barometer readings taken at stations at different altitudes, it is necessary to reduce them to the same level. Various methods are in use for carrying out this reduction, but WMO has not yet recommended a particular method, except in the case of low-level stations.

The recommended method is described in WMO (1954, 1964, 1968). WMO (1966) contains a comprehensive set of formulae that may be used for calculations involving pressure.

3.11.1 Standard levels

The observed atmospheric pressure should be reduced to mean sea level (see Part I, Chapter 1) for all stations where this can be done with reasonable accuracy. Where this is not possible, a station should, by regional agreement, report either the geopotential of an agreed "constant pressure level" or the pressure reduced to an agreed datum for the station. The level chosen for each station should be reported to the WMO Secretariat for promulgation.

Reduction formula for sea-level pressure feasible for stations below 750 m (from WMO, 1964, p. 22, equation 2):

$$\log_{10} \frac{p_0}{p_s} = \frac{K_p \cdot H_p}{T_{mv}} = \frac{K_p \cdot H_p}{T_s + \frac{a \cdot H_p}{2} + e_s \cdot C_h} \tag{3.1}$$

where p_0 is the pressure reduced to sea level in hPa; p_s is the station pressure in hPa; K_p is the constant = 0.014 827 5 K/gpm; H_p is the station elevation in gpm; T_{mv} is the mean virtual temperature of the fictitious air column below station level in K, ($T_{mv} = T_S + (a \cdot H_p)/2 + e_S \cdot C_h$); T_S is the station temperature in K; T_S = 273.15 + t, t is the station temperature in °C; a is the assumed lapse-rate in the fictitious air column extending from sea level to the level of the station elevation level = 0.006 5 K/gpm; e_s is the vapour pressure at the station in hPa; and C_h is the coefficient = 0.12 K/hPa.

The same formula is often used in the exponential form:

$$p_0 = p_s \cdot \exp\left(\frac{\frac{g_n}{R} \cdot H_p}{T_s + \frac{a \cdot H_p}{2} + e_s \cdot C_h} \right) \tag{3.2}$$

where g_n is the standard acceleration of gravity = 9.806 65 m s^{-2} and R is the gas constant of dry air = 287.05 J/kg/K.

3.11.2 Low-level stations

At low-level stations (namely, those at a height of less than 50 m above mean sea level), pressure readings should be reduced to mean sea level by adding to the station pressure a reduction constant C given by the following expression:

$$C = p \cdot H_p / (29.27\, T_v) \tag{3.3}$$

where p is the observed station pressure in hectopascals; H_p is the station elevation in metres; and T_v is the mean annual normal value of virtual temperature at the station in kelvins.

Note: The virtual temperature of damp air is the temperature at which dry air of the same pressure would have the same density as the damp air. WMO (1966) contains virtual temperature increments of saturated moist air for various pressures and temperatures.

This procedure should be employed only at stations of such low elevation that when the absolute extreme values of virtual temperature are substituted for T_v in the equation, the deviation of the result due to the other approximations of the equation (used for height rather than standard geopotential, and with C to be small compared with p) is negligible in comparison.

3.12 PRESSURE TENDENCY AND PRESSURE TENDENCY CHARACTERISTIC

At surface synoptic observing stations, pressure tendency and the pressure tendency characteristic should be derived from pressure observations from the last 3 h (over 24 h in tropical regions). Typically, the pressure tendency characteristic can be expressed by the shape of the curve recorded by a barograph during the 3 h period preceding an observation (WMO, 2010*b*). In the case of hourly observations, the amount and characteristic can be based on only four observations, and misinterpretations may result. Therefore, it is recommended that the characteristic should be determined on a higher frequency of observations, for example with 10 min intervals (WMO, 1985). Nine types of pressure tendency characteristics are defined (see WMO, 2010*a*, p. II-4-8).

ANNEX 3.A. CORRECTION OF BAROMETER READINGS TO STANDARD CONDITIONS

Correction for index error

The residual errors in the graduation of the scale of a barometer should be determined by comparison with a standard instrument. They may include errors due to inaccurate positioning or subdividing of the scale, capillarity and imperfect vacuum. Certificates of comparison with the standard should state the corrections to be applied for index error at no fewer than four points of the scale, for example, at every 50 hPa. In a good barometer, these corrections should not exceed a few tenths of a hectopascal.

Corrections for gravity

The reading of a mercury barometer at a given pressure and temperature depends upon the value of gravity, which in turn varies with latitude and altitude. Barometers for meteorological applications are calibrated to yield true pressure readings at the standard gravity of 9.806 65 m s^{-2} and their readings at any other value of gravity must be corrected. The following method is recommended for reducing such barometer readings to standard gravity. Let B be the observed reading of the mercury barometer, B_t the barometer reading reduced to standard temperature but not to standard gravity, and corrected for instrumental errors, B_n be the barometer reading reduced to standard gravity and standard temperature, and corrected for instrumental errors, B_{ca} be the climatological average of B_t at the station, $g_{\varphi H}$ the local acceleration of gravity (in m s^{-2}) at a station at latitude φ and elevation H above sea level, and g_n the standard acceleration of gravity, 9.806 65 m s^{-2}.

The following relations are appropriate:

$$B_n = B_t \left(g_{\varphi H} / g_n \right) \tag{3.A.1}$$

or:

$$B_n = B_t + B_t \left[\left(g_{\varphi H} / g_n \right) - 1 \right] \tag{3.A.2}$$

The approximate equation 3.A.3 may be used, provided that the results obtained do not differ by more than 0.1 hPa from the results that would be obtained with the aid of equation 3.A.2:

$$B_n = B_t + B_{ca} \left[\left(g_{\varphi H} / g_n \right) - 1 \right] \tag{3.A.3}$$

The local acceleration of gravity $g_{\varphi H}$ should be determined by the procedure outlined in the following section. The values so derived should be referred to as being on the International Gravity Standardization Net 1971 (IGSN71).

Determining local acceleration of gravity

In order to determine the local value of the acceleration of gravity at a station to a satisfactory degree of precision, one of two techniques should be used. These techniques involve, in the first case, the use of a gravimeter (an instrument for measuring the difference between the values of the acceleration of gravity at two points) and, in the second case, the use of the so-called Bouguer anomalies. Preference should be given to the gravimeter method. If neither of these methods can be applied, the local acceleration of gravity may be calculated using a simple model of the Earth.

Use of a gravimeter

Suppose g_1 represents the known local acceleration of gravity at a certain point O, usually a gravity base station established by a geodetic organization, where g_1 is on the IGSN71, and suppose further that g represents the unknown local acceleration of gravity on the meteorological gravity system at some other point X for which the value g is desired. Let Δg denote the difference in gravity acceleration at the two places, as observed by means of a gravimeter. That is, Δg is the value at point X minus the value at point O on a consistent system. Then, g is given by equation 3.A.4:

$$g = g_1 + \Delta g \tag{3.A.4}$$

Use of Bouguer anomalies

If a gravimeter is not available, interpolated Bouguer anomalies (A_B) may be used to obtain g at a given point. It is necessary that a contour chart of these anomalies be available from a geodetic organization or from a network of gravity stations spaced at a density of at least one station per 10 000 km² (no more than a 100 km distance between stations) in the vicinity of the point.

Gravity networks of somewhat less density can be used as a basis provided that a geodetic organization considers that this method is expected to yield more reliable results than those that could be obtained by using a gravimeter.

The definition of the Bouguer anomaly (A_B) is derivable from equation 3.A.5:

$$g_s = \left(g_{\varphi,0}\right)s - C \cdot H + A_B \tag{3.A.5}$$

where $(g_{\varphi,0})s$ is the theoretical value of the acceleration of gravity at latitude φ at sea level, as given by the formula actually used in computing the Bouguer anomaly. This formula expresses the value as a function of latitude in some systems. H is the elevation of the station (in metres) above sea level at which g_s is measured, g_s is the observed value of the acceleration of gravity (in m s^{-2}); A_B is the Bouguer anomaly (in m s^{-2}); and C is the elevation correction factor used in computing the Bouguer anomaly (for example, using a crustal specific gravity of 2.67, this factor is 0.000 001 968 m s^{-2}).

When g is desired for a given station and has not been measured, the value of g_s should be computed by means of equation 3.A.5, provided that the appropriate value of A_B for the locality of the station can be interpolated from the aforementioned contour charts or from data representing the Bouguer anomalies supplied by a suitable network of gravity stations, as defined.

Calculating local acceleration of gravity

If neither of the preceding methods can be applied, the local value may be calculated less accurately according to a simple model. According to the Geodetic Reference System 1980, the theoretical value ($g_{\varphi,0}$) of the acceleration of gravity at mean sea level at geographic latitude, φ, is computed by means of equation 3.A.6:

$$g_{\varphi,0} = 9.806\,20\left(1 - 0.002\,644\,2\cos 2\varphi + 0.000\,005\,8\cos^2 2\varphi\right) \tag{3.A.6}$$

The local value of the acceleration of gravity at a given point on the surface of the ground at a land station is computed by means of equation 3.A.7:

$$g = g_{\varphi,0} - 0.000\,003\,086\,H + 0.000\,001\,118\left(H - H'\right) \tag{3.A.7}$$

where g is the calculated local value of the acceleration of gravity, in m s^{-2}, at a given point; $g_{\varphi,0}$ is the theoretical value of the acceleration of gravity in m s^{-2} at mean sea level at geographic latitude φ, computed according to equation 3.A.6 above; H is the actual elevation of the given point, in metres above mean sea level; and H' is the absolute value in metres of the difference between the height of the given point and the mean height of the actual surface of the terrain included within a circle whose radius is about 150 km, centred at the given point.

The local value of the acceleration of gravity at a given point within height H above mean sea level of not more than about 10 km, and where that point lies over the sea water surface, is computed by means of equation 3.A.8:

$$g = g_{\varphi,0} - 0.000\,003\,086\,H - 0.000\,006\,88\left(D - D'\right) \quad (3.A.8)$$

where D is the depth of water in metres below the given point; and D' is the mean depth of water, in metres, included within a circle whose radius is about 150 km centred at the given point.

At stations or points on or near the coast, the local value of acceleration of gravity should be calculated, so far as practicable, through the use of equations 3.A.7 and 3.A.8 on a pro rata basis, weighting the last term of equation 3.A.7 according to the relative area of land included within the specified circle, and weighting the last term of equation 3.A.8 according to the relative area of the sea included within the circle. The values thus obtained are then combined algebraically to obtain a correction which is applied to the final term in the right-hand side of both equations, as shown in equation 3.A.9:

$$\begin{aligned} g = g_{\varphi,0} &- 0.000\,003\,086\,H + 0.000\,001\,118\,\alpha \\ &\left(H - H'\right) - 0.000\,006\,88\left(1-\alpha\right)\left(D - D'\right) \end{aligned} \quad (3.A.9)$$

where α is the fraction of land area in the specified area, and H' and D' refer to the actual land and water areas, respectively.

Corrections for temperature

Barometer readings must be corrected to the values that would have been obtained if the mercury and the scale had been at their standard temperatures. The standard temperature for mercury barometers is 0 °C. With reference to scales, some barometers have scales which read accurately at this same temperature, but some read accurately at 20 °C.

The temperature correction necessary for adjustable cistern barometers (Fortin-type barometers) is different from that required for fixed-cistern barometers, though the principle reasons leading to the necessity for temperature corrections are the same for both types, namely, the fact that the coefficient of cubic thermal expansion of mercury is different from the coefficient of linear thermal expansion of the scale. Thus, a certain correction term is required for both types of mercury barometer.

A fixed-cistern barometer requires an additional correction. The reason for this is that an increase in temperature of the instrument causes an increase both in the volume of the mercury and in the cross-sectional areas of the (iron) cistern and the (glass) tube. Owing to these area changes, the apparent rise of the mercury resulting from a temperature increase is less than would be the case if the areas remained constant. This is because some of the mercury from the barometer goes to occupy the capacity increment produced by the expansion of the cistern and tube.

The scale of a fixed-cistern barometer must, for a variety of reasons, undergo a calibration check against a primary standard barometer of the adjustable-cistern type. Some manufacturers decrease the volume of mercury by such an amount that the readings of the test barometer agree with the readings of the standard barometer at 20 °C. Correction tables can be generated for fixed-cistern barometers using the readings from a primary standard barometer whose scales are accurate when 20 °C is used as the reference temperature.

Temperature corrections for mercury barometers

Researchers have conducted exhaustive studies for temperature corrections for mercury barometers, the results of which are summarized below:

1. (a) Scale correct at 0 °C and additionally	$C_t = -B(\alpha - \beta) \cdot t$
(b) Hg volume correct at 0 °C	$C_{t,V} = -B(\alpha - \beta) \cdot t - (\alpha - 3\eta) \cdot t \cdot 4V/3A$
2. Scale correct at 0 °C and Hg volume correct at 20 °C	$C_{t,V} = -B(\alpha - \beta) \cdot t - (\alpha - 3\eta) \cdot (t - 20) \cdot 4V/3A$
3. (a) Scale correct at 20 °C	$C_t = -B[\alpha \cdot t - \beta \cdot (t - 20)]$
(b) Hg volume correct at 0 °C	$C_{t,V} = -B[\alpha \cdot t - \beta \cdot (t - 20)] - (\alpha - 3\eta) \cdot t \cdot (4V/3A)$
(c) Hg volume decreasing by an amount equivalent to 0.36 hPa	$C_{t,V} = -B(\alpha - \beta) \cdot t - (\alpha - 3\eta) \cdot t \cdot (4V/3A)$
4. Scale correct at 20 °C and (a) Hg volume correct at 20 °C	$C_{t,V} = -B[\alpha \cdot t - \beta(t - 20)] - (\alpha - 3\eta) \cdot (t - 20) \cdot (4V/3A)$
(b) Hg volume decreasing by an amount equivalent to 0.36 hPa	$C_{t,V} = -B(\alpha - \beta) \cdot t - (\alpha - 3\eta) \cdot (t - 20) \cdot (4V/3A)$

where:

C_t = temperature correction;

$C_{t,V}$ = additional correction for fixed-cistern barometers;

B = observed barometer reading;

V = total volume of mercury in the fixed-cistern barometer;

A = effective cross-sectional area of the cistern;

t = temperature;

α = cubic thermal expansion of mercury;

β = coefficient of linear thermal expansion of the scale;

η = coefficient of linear thermal expansion of the cistern.

ANNEX 3.B. REGIONAL STANDARD BAROMETERS

WMO Region	*Location*	*Category*[a]
I	Cairo, Egypt	A_r
	Casablanca, Morocco	A_r
	Dakar, Senegal	A_r
	Douala, Cameroon	A_r
	Kinshasa/Binza, Democratic Republic of the Congo	A_r
	Nairobi, Kenya	A_r
	Oran, Algeria	A_r
II	Calcutta, India	B_r
III	Buenos Aires, Argentina	B_r
	Maracay, Venezuela (Bolivarian Republic of)	B_r
	Rio de Janeiro, Brazil	A_r
IV	Miami, Florida, United States (subregional)	A_r
	San Juan, Puerto Rico (subregional)	A_r
	Toronto, Canada (subregional)	A_r
	Washington DC (Gaithersburg, Maryland), United States	A_r
V	Melbourne, Australia	A_r
VI	Hamburg, Germany	A_r
	London, United Kingdom	A_r
	St Petersburg, Russian Federation	A_r
	Toulouse, France	A_r

Note:
a For category definitions, see section 3.10.5.1.

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