CHAPTER 3 — MEASUREMENT OF ATMOSPHERIC PRESSURE

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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 the surface, taken horizontally, and extending to the outer limit of the atmosphere.

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 (hPa) equals one millibar (mbar), the formerly used unit.

The scales of all barometers used for meteorological purposes should be graduated in hPa. Many 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 hPa = 0.750 062 $(\text{mm Hg})_n$

1 $(\text{mm Hg})_n$ = 1.333 224 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 hPa = 0.029 530 $(\text{in Hg})_n$

1 $(\text{in Hg})_n$ = 33.863 9 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 the barometer is correctly calibrated under standard conditions.

Pressure data should preferably 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 Chapter 1, Part I. The requirements are:

Measuring range:	920–1 080 hPa for instruments at or near sea level, or an equivalent span at lower pressures for higher elevations
Required target accuracy:	0.1 hPa
Reporting resolution:	0.1 hPa
Sensor time constant:	20 s
Output averaging time:	1 minute

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, prior to their installation in an operational environment.

For barometers installed in an operational environment, practical constraints may make it difficult for a Meteorological Service to maintain this target accuracy. However, 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 following criteria:

Maximum permitted error at 1 000 hPa:	±0.3 hPa
Maximum permitted error at any other pressure for a barometer whose range	
(*a*) Does not extend below 800 hPa:	±0.5 hPa
(*b*) Extends below 800 hPa:	±0.8 hPa
Difference between errors over an interval of 100 hPa or less:	±0.3 hPa

The requirements for atmospheric pressure information vary among users of meteorological information. The aeronautical community requires QNH and/or QFE altimeter settings as described in WMO (1990) and as outlined in Chapter 2, Part II. An outline of the general requirements for atmospheric pressure measurements is contained in WMO (1981) and in United States Weather Bureau (1963).

3.1.4 *Methods of measurement and observation*

For meteorological purposes, the atmospheric pressure is generally measured with mercury barometers, electronic 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 of 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 a 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 if it is a mercury barometer.

   It is important that every meteorological observer fully understands these effects and is 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 a third of the stated absolute accuracy;

(*f*) In the event that 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 of recent design 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 seconds (and definitely no greater than 20 seconds) 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 of 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 more easily 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 the 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 now 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 piezo-resistive properties, the application of pressure alters the balance of an active Wheatstone bridge. Balancing the bridge allows for 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 to determine the atmospheric pressure.

3.2 Mercury barometers

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 — 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 have to be adjusted as the scale engraved on the barometer is contracted 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:

(*a*) Its accuracy should not vary over long periods of time. 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 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 with that of instruments for measuring temperature, humidity, and wind.

3.2.3 *Standard conditions*

As 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 read in error 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 (1973). 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 of 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, then the necessary adjustment should be made to bring the mercury in the cistern into contact with the fiducial pointer. Finally, 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 ought to be possible to see an exceedingly narrow strip of light between the vernier and the top of the mercury surface. Under no circumstance should the vernier "cut off" the top of the meniscus. The 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. Normally 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, they 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 view the following:

(*a*) The past 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 neighbouring stations on the daily synoptic chart if the change is accepted; and
(*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 of the capillary depression of the mercury surfaces due to contamination of the mercury. In areas of severe atmospheric pollution from industrial sources, contamination of the mercury may constitute a serious problem and may require relatively frequent cleaning of the mercury and the barometer cistern; and
(*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 upon the cause.

Changes in index correction are also caused by:

(*a*) Observer error caused by failure to tap the barometer before reading and improper setting of the vernier and fiducial point;
(*b*) Lack of temperature equilibrium in either the station barometer or the travelling standard; and
(*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 of 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 of 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 for the 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 made at different times and at different places into usable atmospheric pressure values, the following corrections should be made:

(*a*) Correction for index error;
(*b*) Correction for gravity; and
(*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. However, if these results are not satisfactory or if higher precision is required, then 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 of mercury barometers*

3.2.6.1 Uncertainties in the temperature of the instrument

The temperature indicated by the attached thermometer will not usually be identical with the mean temperature of the mercury, the scale, and the cistern. The resultant error can be reduced by a 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. It 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 due to 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 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, for a given tube, may change with 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 certificate of the barometer. 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, for overhaul or recalibration of 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.

Attention is drawn to the fact 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 about 6 mm from the vertical position, the indicated pressure will be about 0.02 hPa too high. Such barometers generally hang more 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 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 ought to 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 due to the pumping effect on the mercury surface.

3.2.7 *Safety precautions in the use of mercury*

Mercury is used in relatively large quantities in barometers and, being poisonous, must be handled with care. Elemental mercury is liquid at temperatures and pressures experienced at the Earth's surface. Mercury vapour forms in the air whenever liquid mercury is present. It can be absorbed through the skin in both liquid and gaseous states and it can be inhaled as a vapour. Its properties are described by Sax (1975). In many countries, precautions for its use are prescribed by regulations governing the handling of hazardous goods.

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

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.

The danger exists 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 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 in contact with any other metallic object;

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

(*e*) Mercury in large quantities 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 it 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.

3.2.7.1 Spillages and disposal

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

Spillages of 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 spill 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 spill, dozens of small droplets 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, 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, flowers of sulphur, 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 on to 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 (IATA). Transportation by rail or road is usually governed by hazardous material regulations in each country.

In general, metallic mercury must be packed in glass or plastic containers of less than 2.5-kg capacity. 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 of recent design make use of transducers which transform the sensor response into a pressure-related electrical quantity in the form of either analogue signals, e.g. voltage (DC or AC with a frequency related to the actual pressure), or digital signals, e.g. pulse frequency or with standard data communication protocols such as RS232, RS422 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 recommendation exist to ensure good practice (see Annex VII of the *Abridged Final Report of the Eleventh Session of the Commission for Instruments and Methods of Observation*, 1994, WMO-No. 807). Meteorological organizations should:

(*a*) Control or re-adjust the calibration setting of digital barometers upon receipt and repeat these operations regularly;
(*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;
(*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 great range of DC voltages (eg. 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 has to be completely prevented. An effective technique is to put a hygroscopic agent, such as silica-gel crystals, into the die-cast housing and then prevent water vapour diffusion into the housing by connecting a long plastic tube (approximately 25 m) with a bore of 2 mm or less.

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

3.3.2 *Digital piezo-resistive barometers*

Measurements of atmospheric pressure have become possible by utilizing the piezo-electric (piezo-resistive) 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 piezo-resistive barometers and are a type of absolute pressure transducer. Crystalline quartz has been chosen because of its piezo-electric 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 piezo-resistive 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 it, the resistors are submitted to compressive and tensile stresses. By the piezo-electric 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 direct-current supplied, is transduced into a standard signal by an appropriate magnifier. A light-emitting or liquid crystal display usually presents the measured pressure values.

In a modern version of the pressure transducer using a piezo-electric transducer, two resonance frequencies of the piezo-electric 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 use of dry air is recommended.

3.3.4 *Reading of electronic barometers*

An electronic barometer measures the atmospheric pressure of the surrounding space or any space which 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 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 adapted 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 nonlinearities 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 time intervals in order to allow early detection and replacement of defective sensors.

The need to check frequently the calibration of electronic barometers imposes an additional burden on 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 when the temperature changes reasonably quickly, this can result in short-term hysteresis errors in the measured pressure.

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

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, etc. This is not often a problem but 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 the barometer is operated during calibration, as compared with its operational use. A pressure read on a barometer which is run continuously and is, 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 which prevents the chamber from collapsing due to the external atmospheric pressure. At any given pressure, there will be an equilibrium between the force due to the spring and that of the external pressure.

The aneroid chamber may be made of materials (steel or beryllium copper) which 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 that occur. This may be a system of levers which 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:

(*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 a 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 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 of 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 it is 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 for reducing the errors due to mechanical levers.

3.4.3.2 Corrections applied to aneroid barometers

In general, the aneroid barometer 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 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 of aneroid barometers*

3.4.4.1 Incomplete compensation for temperature

In an aneroid barometer, the weakening of the spring by increasing temperature will result in an indication of too high a pressure by the instrument. 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 modern read-out systems suitable for automation, such complete corrections can be supplied as a part of the system.

3.4.4.2 Elasticity errors

An aneroid barometer may be subjected to a large and rapid change of pressure. For example, in a strong gust of wind, an aneroid barometer would 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 due to slow changes in the metal of the aneroid capsule. This effect can be allowed for only by comparison at regular intervals with a standard barometer. A good aneroid barometer should retain an accuracy of ±0.2 hPa over a period of a month or more; in order to detect departures from this accuracy by individual barometers, a regular checking procedure should be instituted.

3.5 Barographs

3.5.1 *General requirements*

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

(*a*) Graduated in hPa;
(*b*) Readable to 0.1 hPa; and
(*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*) It 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 of pressure of 50 hPa and after return to the original value does not exceed 1 hPa;
(*e*) There should be a time-marking arrangement which allows the marks to be made without lifting the cover; and
(*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 by gravity. An adjustment should be provided for setting the position of the pen.

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

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 which is 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 $100 \cdot A$ Newtons, where A is the effective cross-sectional area of the capsule in square metres. If the magnification is X, then 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 errors due to this cause, e.g. by having the aneroid capsule sufficiently large.

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

3.5.4 *Modern developments*

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 a record 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 of a barograph*

The barograph should be read without touching the instrument. The time mark and any inspection of the instrument involving lifting the cover, etc., 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, then the corrections are not usually applied to the readings. In this case, the accurate setting of the position of the pen 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 hours and the desired values should be found by interpolation.

3.6 Bourdon tube barometers

The Bourdon tube barometers usually consist of a sensor element which, as for an aneroid capsule, changes its shape under the influence of pressure changes (pressure transducers), and a transducer which transforms the changes into a form directly usable by the observer. The display may be remote from the sensor.

3.7 Barometric change

Two methods are available to stations making observations at least every three hours:

(*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, then the latter should be selected for the reasons outlined below.

The error of a single barometric reading is mainly random, assuming perfect functioning of the barometer. Therefore, when two independent readings are subtracted to find the amount of change, the errors may be cumulative. The errors of a barograph are partly systematic in nature, so that in the relatively short period of three hours, 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 necessity for correcting 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, away from draughts, 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. It 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 barometer. 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, the magnitude and sign of the fluctuations depending also on the nature of the openings of the room 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.

The 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 the use of a static head. Details concerning the principles of operation of static heads can be found in several publications (Miksad, 1976; United States Weather Bureau, 1963). For a mercury barometer, the cistern of the barometer 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. The design of such a head requires careful attention.

3.8.2 *The effect of air conditioning*

Air conditioning may create a 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.

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, then care should be taken that the meniscus and the fiducial point are provided 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 of the barometer by 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 vertical. 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 provision 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 it must always be turned over very slowly. Special precautions have to be taken for some individual types of barometer before the instrument is turned over.

3.9.2 *Exposure of electronic barometers*

Electronic barometers require a clean, dry atmosphere which 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 or, where this is not possible, the wires and casing should be shielded.

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

3.9.3 *Exposure of aneroid barometers*

The exposure requirements for an aneroid barometer are similar to those for a mercury barometer (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 be preferably one which has a fairly uniform temperature throughout the day. Therefore, it should be a location where it is shielded from 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, from vibration and from 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 on a sponge rubber cushion is a convenient means of reducing the effects of vibration. The site selected should be dry and clean. It should also be relatively free of substances in the air which would cause corrosion, fouling of the mechanism, etc.

It is important to mount the instrument so that its face will be at a convenient height for reading 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 sent by air or if it must be 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 in view of the various possible errors to which mercury 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 frequently checked (at least once every week) against a mercury barometer and a permanent record of all such checks should be kept on a suitable card or in a special log-book.

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 accuracy of at least ±0.05 hPa;

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 a 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 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

There are different opinions over the best type of primary standard barometer. Two types are outlined in the following paragraphs.

One possible primary standard for atmospheric pressure consists of a precision dead weight tester which 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 of 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 readout facility. These types of barometers measure absolute pressure with high absolute accuracy, while dead weight testers are gauge pressure measuring instruments.

3.10.2.2 Working standard barometer

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 higher category.

3.10.2.3 Travelling standard barometer

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.

Before the beginning of a tour, a mercury travelling standard 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 so designed that the vacuum can be checked or 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 with a tube bore of at least 9 mm, but preferably 12 mm, can be used as a travelling standard. The necessary 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 range of pressure and temperature, covering all possible values that are likely to be encountered.

3.10.2.5 Specifications of portable electronic barometers (P)

Portable electronic barometers have now reached the level of development and reliability to allow them to be used as a category P 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 a 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 of measurement 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:

(*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. Precision aneroid barometers and electronic barometers may also be used as travelling standards, provided they have the necessary stability and accuracy. It is recommended that three or more such instruments be used at a time, so that any change in any one can be detected immediately. An aneroid barometer used for this purpose must not suffer from hysteresis effects. Furthermore, it should have a negligible temperature coefficient. These features can be obtained only by the use of special materials and designs. An essential feature of a suitable instrument is that the aneroid capsule should not be loaded by the indicating mechanism. Barometers with digital read-outs are very convenient as travelling standards provided that their stability is good enough.

3.10.3.3 PROCEDURE FOR THE COMPARISON OF MERCURY BAROMETERS

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 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, for computing and issuing corrections, and for 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 check the accuracy of electronic barometers at frequent intervals. It is standard procedure to calibrate an electronic barometer at a calibration facility immediately prior to 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 made over a period of several days. The readings should be made 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 made, as described above, and the mean difference between the low-drift and the new barometer is established. Once this is accomplished, daily readings from both barometers should be made 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

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 three or more travelling standards, preferably of the P 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 are 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 hours 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 made 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 made at uniform intervals of time not less than 15 minutes 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, C for standardization purposes;

(*f*) If meteorological conditions permit, the comparative readings in the latter cases should be made 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 the 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", namely:

- (i) Before the travelling standards are hand carried from where barometer "1" is located to the place where barometer "2" is located; and
- (ii) Following 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, then 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 it is known that a mishap has occurred which might have affected the instruments, or if the validity of the comparison data is in question for any reason, then 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 barometer of category A. 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 elimination of residual barometric errors is adopted, there will exist 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 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 barometer of category A 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 have to 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 barometer of category B will be designated jointly as the regional standard barometer for that Region, 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 in accordance with the method outlined in section 3.10.3;

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 records of the comparison should be transmitted to each of the central stations equipped with a barometer of category A and to the station where the barometer B or B_r compared is located. Summaries of the results of the comparison should be forwarded to all 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 have to be considered when planning international comparisons:

(*a*) Each national Meteorological Service will compare its category B barometer with 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 Meteorological Services of the Region will be compared with the category B_r barometer for the Region, accomplishing this 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, whilst 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 section 3.10.5.2 (*c*).

3.11 Adjustment of barometer readings to other levels

In order to enable barometer readings made at stations at different altitudes to be compared, 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.

Some of the methods used are described in WMO (1964; 1968). WMO (1973) contains a comprehensive set of formulae which may be used for calculations involving pressure.

3.11.1 *Standard levels*

The observed atmospheric pressure should be reduced to mean sea level 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.

3.11.2 *Low-level stations*

At low-level stations, pressure readings should be reduced to mean sea level by adding to the station pressure a reduction constant C given by the following expression, which has been developed from that already given in the fourth edition of this *Guide* so as to be usable over a greater range of conditions:

$$C = p \cdot H_p / 29.27\ T_v$$

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 (1973) contains virtual temperature increments of saturated moist air for various pressure and temperature.

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) are negligible in comparison.

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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, to capillarity, and to 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, e.g. 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 with 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 mercury barometer, B_t be 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, $g_{\phi H}$ be the local acceleration of gravity (in m s^{-2}) at a station at latitude ϕ and elevation H above sea level, and g_n be the standard acceleration of gravity, 9.806 65 m s^{-2}.

The following relations are appropriate:

$$B_n = B_t\,(g_{\phi H}/g_n) \qquad (3.A.1)$$

or:

$$B_n = B_t + B_t\,[\,(g_{\phi H}/g_n) - 1] \qquad (3.A.2)$$

The approximate equation 3.A.3 given below 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:

$$B_n = B_t + B_{ca}[\,(g_{\phi H}/g_n) - 1] \qquad (3.A.3)$$

The local acceleration of gravity $g_{\phi H}$ 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 (IGSN) 71.

Calculating local acceleration of gravity

According to the Geodetic Reference System 1980, the theoretical value $g_{\phi 0}$ of the acceleration of gravity at mean sea level at geographic latitude, ϕ, is computed by means of equation 3.A.4:

$$g_{\phi 0} = 9.806\,20\,(1 - 0.002\,644\,2\cos 2\phi + 0.000\,005\,8\cos^2 2\phi) \qquad (3.A.4)$$

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.5:

$$g = g_{\phi 0} - 0.000\,003\,086\,H + 0.000\,001\,118\,(H - H') \qquad (3.A.5)$$

where g is the calculated local value of the acceleration of gravity, in m s^{-2}, at a given point, $g_{\phi 0}$ 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.4 above, H is the actual elevation of the given point, in metres above mean sea level, and H' is the mean elevation in metres above mean sea level of the actual surface of the terrain included within a circle whose radius is about 150 kilometres, 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.6.

$$g = g_{\phi 0} - 0.000\,003\,086\,H - 0.000\,006\,88\,(D - D') \qquad (3.A.6)$$

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 a coast, the local value of acceleration of gravity should be calculated, so far as practicable, through the use of equations 3.A.5 and 3.A.6 on a *pro rata* basis, weighting the last term of equation 3.A.5 according to the relative area of land included within the specified circle and weighting the last term of equation 3.A.6 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.7:

$$g = g_{\phi 0} - 0.000\,003\,086\,H + 0.000\,001\,118\,\alpha\,(H - H') - 0.000\,006\,88\,(1 - \alpha)\,(D - D') \qquad (3.A.7)$$

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.

Determining local acceleration of gravity

In order to determine the local value of acceleration of gravity at a station to a degree of precision greater than that obtained by means of the methods set forth above, one of two other 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.

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 IGSN-71, 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.8:

$$g = g_1 + \Delta g \qquad (3.A.8)$$

Use of Bouguer anomalies

If a gravimeter is not available, then 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 km^2 (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 advises that this method is expected to yield more reliable results than those that can be obtained by using a gravimeter.

The definition of the Bouguer anomaly (A_B) is derivable from equation 3.A.9:

$$g_s = (g_{\phi,0})s - C \cdot H + A_B \qquad (3.A.9)$$

where $(g_{\phi,0})s$ 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 system. 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.9 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.

Corrections for temperature

Barometer readings have to be corrected to the values which 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 a temperature of 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, i.e. 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.

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

Temperature corrections for mercury barometers

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

where:

C_t = temperature correction;
$C_{t,V}$ = additional correction for fixed-cistern barometers;
B = observed reading of the barometer;
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

Region	*Location*	*Category*
I	Cairo, Egypt	A_r
	Casablanca, Morocco	A_r
	Dakar, Senegal	A_r
	Douala, Cameroon	A_r
	Kinshasa/Binza, Zaire	A_r
	Nairobi, Kenya	A_r
	Oran, Algeria	A_r
II	Calcutta, India	B_r
III	Rio de Janeiro, Brazil	A_r
	Buenos Aires, Argentina	B_r
	Maracay, Venezuela	B_r
IV	Washington, D.C. (Gaithersburg, Maryland, United States)	A_r
	Toronto, Canada (subregional)	A_r
	San Juan, Puerto Rico (subregional)	A_r
	Miami, Florida, United States (subregional)	A_r
V	Melbourne, Australia	A_r
VI	London, United Kingdom	A_r
	St Petersburg, Russian Federation	A_r
	Trappes, France	A_r
	Hamburg, Germany	A_r