MEASURING THE NATURAL ENVIRONMENT

IAN STRANGEWAYS

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK http://www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011-4211, USA http://www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain

First published 2000

Printed in the United Kingdom at the University Press, Cambridge

Typeface 11/14 pt Times

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication data

Strangeways, Ian, 1932–
Measuring the natural environment / Ian Strangeways.
p. cm.
Includes index.
ISBN 0 521 57310 6
1. Earth sciences – Measurement. 2. Environmental monitoring.
I. Title.
QE33.S79 2000
363.7′063 – dc21 99-18381 CIP

ISBN 0 521 57310 6 hardback

Contents

1

Basics

The need for measurements

Whether it be for meteorological, hydrological, oceanographic or climatological studies or for any other activity relating to the natural environment, measurements are vital. A knowledge of what has happened in the past and of the present situation, and an understanding of the processes involved, can only be arrived at if measurements are made. Such knowledge is also a prerequisite of any attempt to predict what might happen in the future and subsequently to check whether the predictions are correct. Without data, none of these activities is possible. Measurements are the cornerstone of them all. This book is an investigation into how the natural world is measured.

The things that need to be measured are best described as *variables*. Sometimes the word 'parameters' is used but 'variables' describes them more succinctly. The most commonly measured variables of the natural environment include the following: solar and terrestrial radiation, air and ground temperature, humidity, evaporation and transpiration, wind speed and direction, rainfall, snowfall, and snow depth, barometric pressure, soil moisture and soil tension, groundwater, river level and flow, water quality (pH, conductivity, turbidity, dissolved oxygen, biochemical oxygen demand, the concentration of specific ions such as nitrates and metals), sea level, sea-surface temperature, ocean currents and waves and the ice of polar regions.

The origins of data

Early instrument development

Measurement of the natural environment did not begin in the scientific sense until around the middle of the seventeenth century; in 1643, working in Florence, Torricelli made the first mercury barometer, based on notes left by

Galileo at his death. The first thermometer is also attributable to Galileo. Castelli, also in Italy, made the first measurements of rainfall. Sir Christopher Wren in England designed what was probably the first automatic weather station, while Robert Hooke constructed a manual raingauge. In 1846 Thomas Robinson, a clergyman in Armagh, constructed the first instrument for measuring wind speed and in 1853 John Campbell developed the prototype of today's sunshine recorder. Thirteen years later, Thomas Stevenson, the father of Robert Louis Stevenson, designed the now widely used wooden temperature screen. In 1850 George Symons embarked on a lifelong mission to put rainfall measurement on a firm footing, while Captain Robert FitzRoy, who had earlier taken Charles Darwin on the voyage of the *Beagle*, spent much of his later career advancing meteorological measurements at sea. Thus the beginnings of the study of the natural environment started with the development of instruments and the taking of measurements, highlighting the great importance of hard facts in forwarding any science and of the means of obtaining these data. Instrument development continued into and through the twentieth century using similar technology until, mid-century, the invention of the transistor presented totally new possibilities.

The important point about the early designs is not their history, interesting as it is, but that the same designs, albeit perhaps refined, are still in widespread use today. Most of the national weather services (NWSs) of the world rely on them. All the data used by climatologists to study past conditions, and by anyone else for whatever purpose, are derived largely from instruments developed in the Victorian era, and the same instruments look set to continue in widespread use into the foreseeable future. The importance of appreciating their capabilities and limitations is thus of more than passing historical interest. Everyone using data from the past and from the present needs to be aware of where the data come from and of how reliable or unreliable they are likely to be.

Recent advances

In the last thirty years, owing to developments in microelectronics and the widespread availability of personal computers (PCs), new instruments have become available that greatly enhance our ability to measure the natural environment. It has been possible to design data loggers with low power consumption and large memory capacity that can operate remotely and unattended, and new sensors have been developed to supply the logging systems with precise measurements. (Sensors may be referred to in some texts as transducers.) In a balanced review of the subject, this new generation of instruments needs to be discussed along with the old, for we are at a time in the measurement of the environment when both types of instrument are equally important, although the change to the new is well under way and accelerating.

Old and new compared

A serious limitation of the old instruments is that, being manual and mechanical, they need operators and this restricts their use to those parts of the world that are inhabited. Most mountainous, desert, polar and forested areas and most of the oceans are, in consequence, almost completely blank on the data map. Thus far, our knowledge of the natural environment comes from a rather limited range of the planet's surface.

In contrast the new instruments need the attendance of an operator only once every few months, or even less frequently, and so can be deployed at remoter sites. The same electronic developments have also made it possible to telemeter measurements from remote automatic stations via satellites, making it possible to operate instruments in almost any region of the world, however remote. To this capability has also been added the new technique of remote sensing – its images being generated by the same satellites as those that relay data.

The old instruments also lack the accuracy of the new. Compare for instance the data from a sunshine recorder giving simple 'sun in or out' information with those from a photodiode giving an exact measure of the intensity of solar energy second by second. Ironically, these improvements are often a hindrance to change, for although changing to a better instrument improves the data the continuity of old records is lost. This deters many long-established organisations from changing their methods and so the old ways persist. While it is possible to operate a new instrument alongside the old to establish a relationship between them, this is usually only partly successful, the complexity of the natural environment and of an instrument's behaviour meaning that a simple relationship between the two rarely exists.

The new instruments record their measurements directly in computer-compatible form, in solid state memory, allowing their measurements to be transferred to a portable PC or retrieved by removing a memory unit. In the case of telemetry the transmission, reception, processing and storage of the measurements is fully automatic. There is none of the labour-intensive work involved with handwritten records or with reading manually values from paper charts.

Because automatic instruments do not require the regular attendance of an operator and because their data can be processed with the minimum of manual intervention, staff costs are also reduced.

Both old and new instruments are thus important at this stage in the evolution of environmental monitoring and both are covered in the chapters that follow.

General points concerning all instruments

Definitions of terms

For any instrument, the *range* of values over which it will give measurements must be specified. For example a sensor may measure river level from 0 to 5 metres. (In old terms, 5 metres would have been called the instrument's full-scale deflection, meaning that the pointer on an analogue meter has been deflected to the end of its scale.)

The *span* is the difference between the upper and lower limits. If the lower end is zero, the span is the same as the range, but if the range of a thermometer is, say, $-10\,^{\circ}\mathrm{C}$ to $+40\,^{\circ}\mathrm{C}$ its span is $50\,^{\circ}\mathrm{C}$.

The *accuracy* is usually expressed in the form of limits of uncertainty, for example a particular instrument might measure temperature to within $\pm 0.3\,^{\circ}\mathrm{C}$ of the actual temperature. Accuracy may differ across the range covered, such that in the case of a relative humidity (RH) sensor, the accuracy may be $\pm 2\%$ RH from 0–80% RH while from 80%–100% RH it may be $\pm 3\%$.

The *error* is the difference between an instrument's reading and the true value. It is thus another way of stating accuracy. A systematic error is a permanent bias of the reading in one direction, away from the correct value, as opposed to a random error, which may be plus or minus and might, therefore, cancel out over a series of readings.

Instruments often respond to more than just the variable they are meant to measure. Temperature dependence is, for example, a common problem. In such a case a *temperature coefficient* will be quoted to allow a correction to be made. The coefficient is given as the percentage change in reading per degree Celsius change of temperature. Not only may the sensitivity change with temperature, but so also may the zero point.

The *resolution* of an instrument indicates the smallest change to which it responds; for example, a meter might respond to river level changes of as little as 1 mm. This is also sometimes known as sensitivity or discrimination. But just because an instrument can respond to changes of 1 mm, it does not necessarily mean that it measures them to that accuracy; the instrument might only have an accuracy of ± 2.0 mm.

Sometimes an instrument does not respond equally across its full working range, so that its response deviates from a straight line. The extent of the deviation is expressed as its *linearity*, this usually being specified as the maximum deviation (as a percentage of the full scale reading) of any point from a best-fit straight line through the calibration points. The term is used only for instruments that have a close-to-linear response. Some sensors have characteristics that are far from approaching a straight line and may not even have a smooth-curve response. In the case of mechanical instruments, non-linearity may be compensated for in the design of the mechanical links between the sensor and the recording pen; in the case of electrical instruments, a non-linear response may either be compensated electronically, or by recourse to a look-up table or an equation when processing the records in a computer.

Hysteresis is the characteristic of a sensor whereby it responds differently to an increasing reading and to a falling one, the upward curve following a different path to that downward. This might be due to 'stiction' in the mechanical links between sensor and pen; there are equivalent processes in electronic systems. Again the deviation is expressed as the percentage difference (of full scale) between increasing and falling readings.

With the passage of time, a change in instrument performance often occurs, and settings *drift*. This may be due to the aging of components, which results in a change in sensitivity or a change in the zero point, or both. Stability is the converse of drift and is usually expressed as the change which occurs in a sensor's sensitivity, or zero point, over a year. Because of drift, it is usually necessary to readjust, or *calibrate*, an instrument periodically.

Sensors take time to respond to a change in the variable which they are measuring. Some respond in milliseconds, others take minutes. A *time constant* is given to quantify this. This is the time for a reading to increase to $1 - 1/e$ (about 63%) of its final value, or to fall to $1/e$ (about 37%) of its initial value, following a step change in the variable (Fig. 1.1). It takes about three to four times longer than the time constant to reach 95% of the final reading. Thus a constantly changing variable with a slow-response sensor can result in considerable error. To complicate matters further, the response in one direction can be different to the reverse, owing to hysteresis, as mentioned above. These various terms are illustrated in Fig. 1.2.

The *repeatability* is the degree of agreement between an instrument's readings when presented more than once with the same input signal. Different readings may result each time through a combination of all the various sources of error.

There is also the question of the number of decimal points shown. As mentioned above, just because, for example, a temperature is quoted as being 25.03°C it does not necessarily mean that it is accurate to hundredths of a degree. The instrument may only be good to ± 0.1 degrees or less. Extra

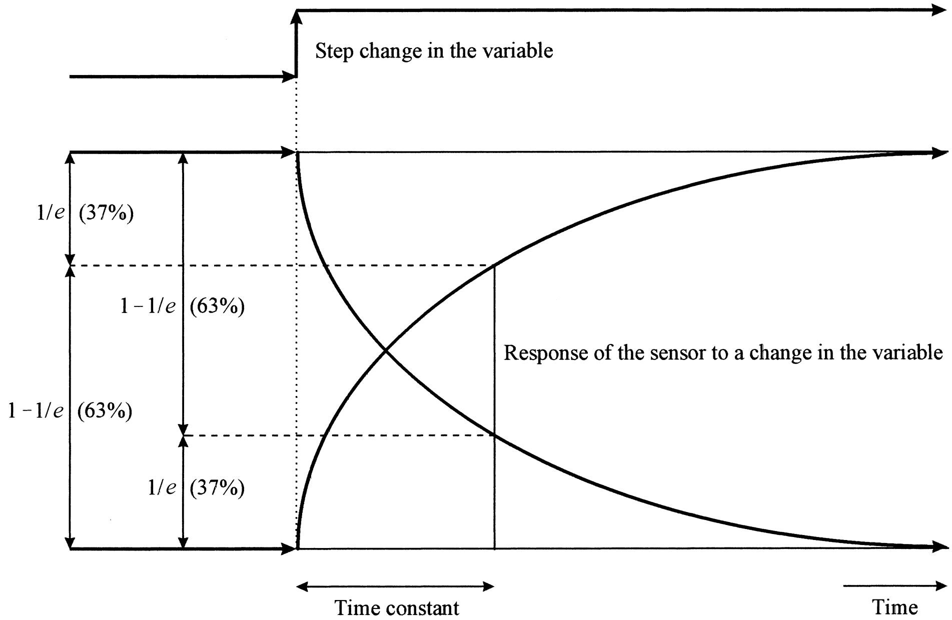


Figure 1.1. The meaning of time constant for response of a sensor to a variable.

decimal points can be introduced into data in many ways, for example during processing to fit a standard format. Decimal points can also be lost in the same way. Users of data should always beware of such possibilities.

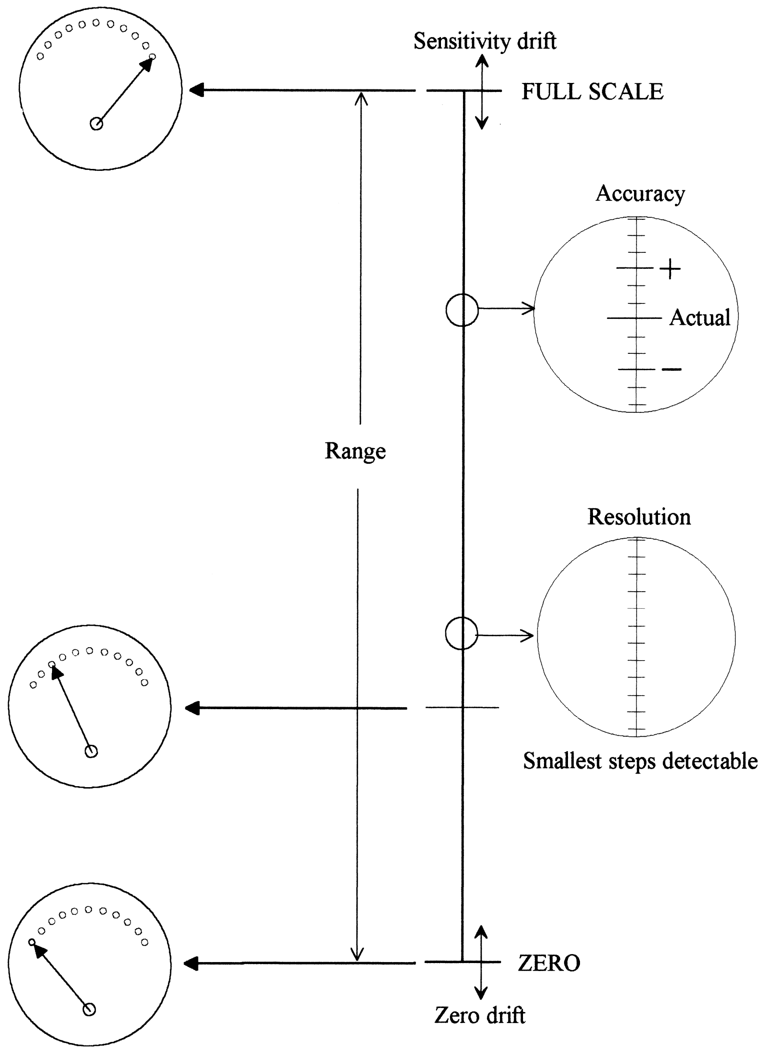
Choice of site

Where, and how, an instrument is placed in the field (finding a representative site and positioning the instrument on the site) affects how good its readings are, often having as great an influence on overall accuracy as the instrument's own characteristics. Comments are made on this throughout the book. Changes at a site after an instrument has been installed, perhaps slowly over years such as the growth of trees or suddenly such as the erection of buildings, also need consideration.

Maintenance

The maintenance of an instrument, such as its periodic readjustment against a standard, the regular painting of a temperature screen or the levelling of a raingauge, is as important as any other aspect of accuracy and data quality. Neglect of this is widespread and results in unreliable data.

(*a*)



(*b*)

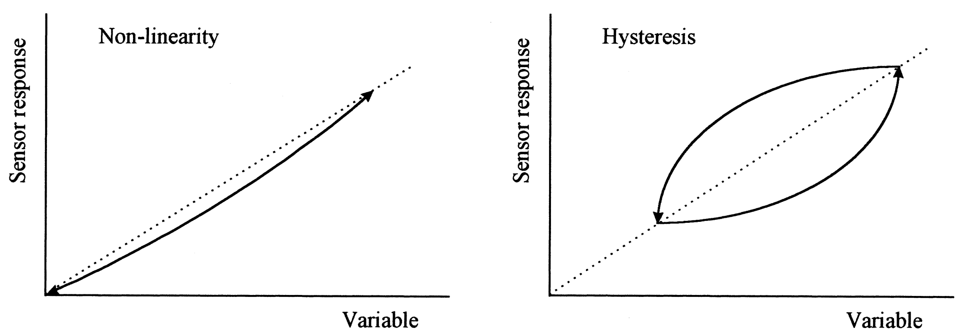


Figure 1.2. Illustration of terms.

Spatial variability

Most environmental variables vary not just with time but also across space, for example across a local thunderstorm. Faced with this problem, it can be tempting to conclude that it is pointless to improve instrument performance because instrument error is swamped by spatial variability as well as by the difficulty of selecting the perfect site. But this is a philosophy of defeat. Better, instead, to improve the instrument, choose the site more carefully, take measurements at several points and so get an estimate of variability. Spatial variability cannot be measured unless we have good instruments, for what might be assumed to be spatial variability may instead be instrument error.

Using data of unknown quality

It is difficult to know how good data are if there is no record, along with the data, of what type of sensor was used, how it was exposed or its maintenance schedule (metadata). Often there is no sure way of checking on these matters. In general, our data sets are a mix of measurements collected by a variety of instruments, installed in different ways and operated at different levels of competence, all of which may have changed with time and with the operator. Discontinuities and different levels of error are invariably present.

Plan of the book

The aim of this book is to show how measurements of the natural environment are made and to point out the pitfalls. Each variable, or group of variables, is given a chapter to itself, working through from the early instruments, most of which are still in use, to the latest developments, only a few of which may yet be in use. How the measurements from the new electronic sensors are processed and stored automatically in data loggers or are telemetered to a distant base are the topics of two later chapters. While remote sensing is a specialised topic, already well covered in other publications, a chapter on it is included for completeness, comprising how measurements are made remotely, how good or bad they are and how they relate to measurements made *in situ* on the ground.

Mathematical analysis is used sparingly, and where equations are used a line-by-line derivation from first principles is not always given. The SI (Système International d'Unites, NPL 1963, BSI 1969) is used throughout, unless otherwise stated. The method of defining units is, for example, to abbreviate metres per second to $m\ s^{-1}$ and cubic metres to m^3.

This is not an operator's handbook, for the technician, but an outline for the users of data who would like (or need) to know how the data they use were collected and how good or bad they are likely to be. It is also intended for instrument designers who need background information, or for those about to collect field data and instal instruments, or for students of meteorology, hydrology and environmental sciences, who should know how measurements are made. Useful additional information on the basic meteorological instruments can be found in three UK Meteorological Office handbooks (1982a, b and 1995) while the World Meteorological Organisation (WMO 1994) periodically issues and updates technical reports on how meteorological instruments should be installed and operated.

References

British Standards Institute (1969) The use of SI units. Report PD 5686. HMSO, London.

Meteorological Office (1982a) The handbook of meteorological instruments. HMSO, London.

Met. Office (1982b) The observer's handbook. HMSO, London.

Met. Office (1995) The marine observer's handbook. HMSO, London.

National Physical Laboratory (1963) The inclusion of metric values in scientific papers. HMSO, London.

World Meteorological Organisation (1994) Guide to meteorological instruments and methods of observation. WMO No. 8 (generally known as the CIMO Guide).