6

CLIMATE DATA

The past and present

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> I'll show you how t' observe a strange event.
>
> Timon of Athens *by William Shakespeare*

6.1 Introduction

Historical and current weather and climate observations and monitoring products are essential for health risk assessment, planning and for the development of climate-informed early warning systems (see § 3.4). They are also important in assessing the efficacy of climate-sensitive interventions.[1] Historical climate data are also needed as a baseline for assessing any changes in climate, for developing and evaluating climate models used in predictions and projections, and for providing the initial conditions for climate predictions[2] (see §§ 8.2.2 and 9.4). However, only a few weather observations can be used for climate work because the objectives in taking the observations differ from those for climate observations. For weather forecasts, the best possible observations are required to make accurate predictions; if the observations can be improved in any way – perhaps by moving the station, or using more accurate instruments – then such improvements offer an immediate advantage. In contrast, consistency of observation is a key consideration for climate work. Climate scientists want to compare observations (is this year hotter than last year?). If an instrument is changed or moved to a different location, then it makes it difficult to make comparisons.

In this chapter we describe how climate variables are measured (e.g., ground observation, remote sensing or modelled data), how the data are collected and how they are shared. We discuss the advantages and disadvantages of different data sources and highlight the potential advantages of climate data made available through National Meteorological and Hydrological Services. The use of observed climate monitoring products in the development of early warning systems is highlighted.

6.2 How are global weather and climate data produced and shared?

Accurate weather and climate monitoring and forecasting requires a massive international coordination of data collection and sharing (see, for example, §7.4). In 1963, the World Meteorological Organization (WMO) implemented the World Weather Watch as a system for facilitating this coordination.[3] The Watch involves three components, one to take the observations (the *Global Observing System*), another to share the observations and resulting information products (the *Global Telecommunication System*) and a third to generate those information products from the data (the *Global Data Processing and Forecasting System*).

6.2.1 Global Observing System

The Global Observing System (GOS) provides observations of the air and the ocean surface from surface weather stations and ships, ocean buoys, weather balloons, satellites and other sources. The observations are collected by National Meteorological and Hydrological Services (NMHSs) and various satellite agencies and consortia, all of which collect the observations according to specified standards. Some of the observations (the 'synoptic' observations) are collected at coordinated times so that these can be used to initialize weather prediction models (see §7.4).

Although most of the observations are used for weather prediction, a few observations are specifically for climate work. These observations form part of the *Global Climate Observing System* (GCOS),[4–6] which provides the long-term observations required for monitoring, research and prediction of climate change and variability and their impacts, such as for the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports[7] (see § 9.2). Countries are supposed to report monthly statistics from these stations to global climate monitoring centres in Germany and Japan. Although the frequency of on-time reporting has been historically poor from many areas outside of the northern mid-latitudes, it has improved dramatically since 2012 with the formation of the Global Framework for Climate Services (GFCS)[8] (see Box 1.3). These GCOS observations form the basis for some of the freely available and most commonly used global climate datasets (§ 6.4). However, there are many additional observations that are not routinely shared with regional and global data centres. These additional observations may be available only from NMHSs and other national centres. Because there are much more data available at the national level than at the global level, countries have the possibility of producing datasets that are of higher quality than global products (Case Study 6.1).

CASE STUDY 6.1 ENHANCING NATIONAL CLIMATE SERVICES (ENACTS) DATA PRODUCTS

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The recently developed Enhancing National Climate Services (ENACTS) merged station-proxy temperature and rainfall data products[9] have been found to be of high value for climate analysis, especially in regions with sharp climatic contrasts over a small geographic domain. ENACTS products use all available meteorological station data from participating countries. For rainfall, the station data are blended with the most appropriate global satellite rainfall products (such as CHIRPS[i] or TAMSAT[ii]) using an interpolation algorithm to construct a temporally and spatially complete gridded product. For temperature, the station network is blended with reanalysis (such as the Japanese 55-year Reanalysis[10]) and digital elevation model data.

One country that has sharp spatial climatic contrasts that has benefited from ENACTS is Rwanda. Situated in the East African highlands, Rwanda is a small, densely populated country, whose citizens depend largely on rain-fed agriculture. Despite its small size (~26,000 km^2) the landscape ranges from relatively lush savannah grassland to cloud rainforests. Elevation ranges from just under 1000 m to almost 4500 m above sea-level.

Within the last several years, high resolution ENACTS data products (with national coverage and ~4 km spatial resolution) and services have been established by Meteo Rwanda with the support of the International Research Institute for Climate and Society. The rainfall products are available from the early 1980s to the present, and are particularly valuable as there was a precipitous decline in meteorological observations from the early/mid 1990s until almost 2010 because of the Rwandan genocide, civil war and aftermath (See Figure 6.1). The ENACTS products fill the data gaps with satellite data adjusted using historical and more recent stations observations. The resurgence in the number of meteorological stations in ENACTS data post-2009 is not reflected in global datasets such as the Global Precipitation Climatology Centre (GPCC) (see Figure 6.1) re-iterating the point that more data are available locally than ever make their way into the global archives.

Because Rwanda sits just a few degrees off the equator, temperature variability in time is quite low and temperature variability in space is controlled largely by elevation (§ 5.2.1). Rwanda experiences a bimodal pattern of rainfall with rainy seasons in March–May and September–December, a partially dry period in January–February and very dry period from June–August. For rainfall, the higher elevations, which are the wettest regions of this small country in the northwest and southwest, can receive in excess of 2 m of rainfall per year on average, while the driest regions in the lowland east and south may receive less than 700 mm of average annual rainfall.

The very high resolution ENACTS data products are able to capture many of the nuances of Rwanda's climate in ways that coarser datasets fail to do and can thus provide valuable information for farmers and decision-makers in multiple sectors. Furthermore, in some preliminary studies, ENACTS products are shown to be a more skilful tool for calibration of seasonal forecasts than other comparably high-resolution global rainfall datasets (e.g., CHIRPS). However, users should not automatically assume that higher resolution data gives a clearer picture of the real spatial and temporal climate variability without careful evaluation and verification.

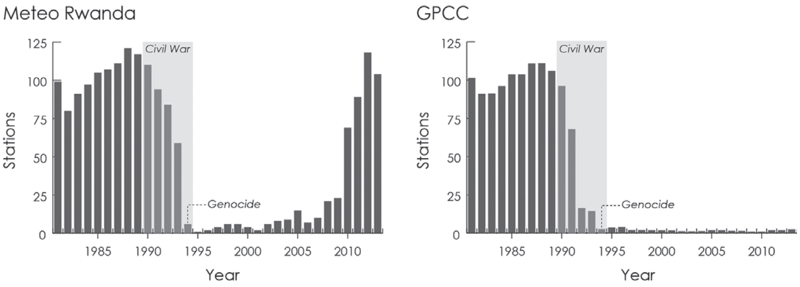

FIGURE 6.1 Number of functioning meteorological stations by year in Rwanda that provide data in a) ENACTS and b) GPCC rainfall products

6.2.2 Global Telecommunication System

The Global Telecommunication System (GTS) enables the communication of the observations to a network of centres that produce global or regional weather analyses and forecasts (§§ 6.3.3 and 7.4.2). This coordinated exchange of observations and model data is critical for the timely and accurate generation of warnings, and is promoted through a set of international agreements on data exchange (Box 6.1). Those forecasts are then transmitted back to the NMHSs for further downscaling and interpretation. Since 2003, the WMO has begun to upgrade the GTS to take advantage of new technologies (see Box 10.1) and to facilitate exchange of information beyond the network of Meteorological Services.

6.2.3 Global Data Processing and Forecasting System

The Global Data Processing and Forecasting System (GDPFS) performs quality control on the collected observed data, and uses the observations to produce analyses (§§ 6.3.3 and 7.4.2), monitoring products, and forecasts, which are then made available to the NMHSs. This system involves a network of national, regional and international centres that not only makes weather forecasting possible, but which

BOX 6.1 DATA-SHARING POLICIES

Agreements for the exchange of essential weather information have been in place since 1947 when the Convention of the WMO was signed. Promotion of the collection and exchange of meteorological data is effectively listed as the primary role of the WMO.[11] In practice, international data exchange has been sub-optimal, in part because of lack of clarity about what 'essential' means, and what the rules for non-essential data are. To address these issues, WMO has passed a series of Resolutions to clarify definitions and the rules over the exchange of non-essential data.[12] There have been three important such Resolutions[iii]:

- WMO Resolution 40 (1995; *WMO policy and practice for the exchange of meteorological and related data and products including guidelines on relationships in commercial meteorological activities*) reaffirmed the commitment to worldwide co-operation in the establishment of observing networks and the free and unrestricted exchange of meteorological and related information for non-commercial purposes.[13] Although the data are supposed to be 'freely' available, provision is made for costs incurred in distributing the data.
- WMO Resolution 25 (1999; *Exchange of hydrological data and products*) extended the provisions of Resolution 40 to include hydrological data.
- WMO Resolution 60 (2015; *WMO policy for the international exchange of climate data and products to support the implementation of the GFCS*) extends the definition of climate data given in Resolution 40 to include all 'GFCS relevant data and products' and reaffirms the commitment to their free and unrestricted exchange.

What do all these Resolutions mean for people working in public health? In theory, it should be possible to access relevant global, regional and national data and information products that are essential for serving the public good[8] at no more than the cost of redistribution. In practice, however, the required data may: a) not exist; b) be difficult to use and interpret because of missing values and other quality issues; c) still come at a significant cost because many NMHSs are provided with insufficient funds to collect and manage the data in the first place; and d) be provided with reluctance or not at all because of concerns over how the data may be used (or mis-used).

has enabled sustainable provision of information products and services for hazardous conditions, such as tropical cyclones, storm surges and the provision of operational meteorological services in the case of nuclear and other technological accidents, wild fires and volcanic eruptions.

6.2.4 Global Atmospheric Watch

In addition to the World Weather Watch, the WMO also coordinates the Global Atmosphere Watch (GAW) Programme,[14] which collects information on air quality and composition (§§ 4.2.6 and 4.2.7.3). The primary foci of the GAW include greenhouses gases, the ozone layer, reactive gases[15] and other air pollutants, and ultraviolet radiation. The GAW programme has played a key role in providing data in support of initiatives such as the Montreal Protocol on Substances that Deplete the Ozone Layer (Box 4.4) and the IPCC (§ 9.2).

6.3 What types of meteorological data are available?

Unfortunately, there is no single climate dataset that is likely to address all public health purposes. All the datasets have some drawbacks, and choices need to be made between length of record, availability in near-real time, numbers of missing values, accuracy, consistency, temporal and spatial resolution, etc. Strengths and weaknesses of the different datasets are best described by classifying the data based on how they are generated. Some data are obtained by direct measurement at a weather or climate station (e.g., temperature by thermometer), others by proxy measurement (e.g., tree ring width, isotope analyses or by remote sensing estimations), while others are generated theoretically using models (e.g., analyses and predictions[16]).

6.3.1 Direct measurements from climate stations

6.3.1.1 In situ station data

Some climate stations have records extending back more than 100 years, although most have less than 50 years. Monthly accumulations or averages are by far the most widely available resolution, but daily and sub-daily data may be obtainable. Although extensive use can be made of the monthly data, information about individual severe weather events may get lost or severely dampened, and so some significant events of relevance to public health may not be well-represented at this resolution. In many countries, much of the daily and sub-daily data remain as hand-written or graphical records. There are ongoing data rescue programmes to digitize these data to make them available for product generation and analysis (Box 6.2).

There are challenges when using historical weather records because the observations may not have been collected consistently. The weather station may have been moved or the instruments on it may have been replaced or upgraded so that some of the measured changes over time have nothing to do with climate change or variability. It may be possible to correct for these inhomogeneities, especially if information about changes in how the data were collected (so-called meta-data) is available.

Even when the data are consistent, there are likely to be some missing values, especially at daily and finer resolutions, and so some degree of quality control

BOX 6.2 DATA RESCUE

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In many places modern technology automates rain gauge observations to record rainfall continuously and saves the information directly onto an electronic medium for archival and analysis purposes. However, in the absence of modern technology, automated rainfall observations are recorded directly onto paper by hand and are not automatically archived in a digital format. Data rescue projects are designed to transfer archived paper-based meteorological observations onto an electronic medium so that the information is readily available for scientific analysis using computational software programs.[17] Because analysing long-term meteorological observations from paper records is a very inefficient and time consuming task, electronic digitization software has been developed to automatically convert scanned paper records into a computer ready electronic format. Digitization software reads strip chart paper data, which is a common recording medium for automated weather stations that measure rainfall, temperature, wind speed, wind direction and atmospheric surface pressure. Data rescue projects still exist for non-automated observations, which are taken by hand, but they require an arduous task of manually typing the written observations onto a computer. The Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative undertakes and facilitates most global data rescue projects with the aim of converting historic paper-based data into modern gridded datasets commonly used for climate models. Results from ACRE-led projects provide usable meteorological data that were at one time locked in a paper format.

is almost always required before using station data in health analyses.[18] It may be possible to estimate these missing values from neighbouring stations or from remotely sensed data, but for some analyses it may be sufficient to know only whether an extreme event occurred without details of its magnitude. Unfortunately, missing values disproportionately occur during severe weather and climate events when instrumental failures and breaks in communication are most likely to happen. Consequently, lower quality data are also most likely to occur in developing countries where climate impacts on the population may be particularly severe.

6.3.1.2 Gridded station data

Meteorological stations are not always representative of a location where data are needed by health specialists. What is to be done if there is no station in the location of interest? One option is to use interpolated station data. Some of the most commonly used climate datasets are constructed from station data interpolated to a regular grid (§ 6.4). These gridded datasets are ideal for large-scale (sub-continental) analyses, and for some country-scale analyses. However, although some quality control checks and corrections have been performed on the station data, serious inhomogeneities may remain in data-poor regions and periods. In most areas, the number of stations used in these datasets peaks in the 1950s–1970s, and drops off considerably before and after then. The changes in the locations and numbers of available stations can have serious implications for the quality of the interpolations (Case Study 6.1). In most cases, information about the number of stations in the vicinity of each gridpoint should be available, and this information needs to be checked before using the data, particularly for rainfall because of its localized nature (§ 5.2.5.2). The number of stations used in the global and regional gridded datasets are generally far fewer than are available nationally, and so more detailed and more accurate data may be available for national and sub-national analyses.

6.3.1.3 Index datasets

Some station data are used to measure specific climate phenomena rather than local climate at a distinct location. Data from a set of carefully selected stations may be combined into an index to represent such phenomena. Examples include the Southern Oscillation (Boxes 5.1 and 6.3) and the All-India Monsoon Index. Because of the broader interest of such indices, particular care is taken to control the data quality, and so it is worth considering whether any of these datasets might be usable in public health contexts.

BOX 6.3 HOW DO WE MEASURE ENSO?

As discussed in Box 5.1, the Southern Oscillation is measured using an index of air pressure at Darwin and Tahiti. This Index is an indication of whether El Niño or La Niña are affecting the weather and climate. An advantage of the Index is that high-quality meteorological observations are available from 1866 and other observations can be used to estimate the Index back to 1829. However, a disadvantage of the Index is that it includes short-term weather variability, and so averaging over long periods (scientists use a five-month period) is required for a reliable indication of whether El Niño or La Niña is occurring.

El Niño and La Niña themselves are measured by averaging sea-surface temperatures over areas of the Equatorial Pacific Ocean and comparing these to long-term averages. The long-term average is updated, so that decades-long records are effectively detrended. Different areas have been defined for calculating the averages, and each region is labelled by a number; the most commonly used being the Niño3.4 region, which extends from close to the date-line towards South America (Figure 5.14).[19] Using measurements from ships, this index can be calculated back to 1949, and less reliably back to 1856. Since the 1980s, satellite measurements and data transmitted from a series of moored buoys have supplemented the ship observations to provide more accurate estimates. The Oceanic Niño Index (ONI) is the Niño3.4 index averaged over a three-month period, and is used operationally by some countries, including the USA, to define El Niño and La Niña events.

Numerous other indices exist,[20] but these are used more in research than in operational work. For most purposes, the Southern Oscillation Index (SOI), Niño3.4 or ONI are likely to be suitable. Similarly, and somewhat confusingly, different criteria are used to define whether El Niño or La Niña is happening, and so there is no universal agreement on when ENSO episodes have occurred, or agreement on when to declare a developing event. Nevertheless, the various classifications are similar.

6.3.2 Indirect measurements of climate by proxy, including by remote sensing

6.3.2.1 Historical proxy datasets

Climate scientists make extensive use of proxy measurements to infer changes in climate, primarily to reconstruct climate histories for times before the period of instrumental records. Examples include chemical and isotope analyses of ice cores, tree-ring data, coral growth and sedimentary deposits. Such datasets have been important for comparing recent global warming with previous warm epochs, for example. However, they are unlikely to be of direct interest for health analyses, and so are not discussed further here.

6.3.2.2 Satellite data

There are hundreds of satellites now in space, some of which have revolutionized developments in weather forecasting and climate work. Those of broad interest to meteorologists can be classified into two types according to their orbit, namely *polar-orbiting* and *geosynchronous* (also called *geostationary*). Polar-orbiting satellites, as the name implies, have an orbit which passes close to the North and South Poles. One advantage of such an orbit is that it is sun-synchronous – the satellite takes measurements for a given location at the same time of day (or 12 hours different) each overpass. Geostationary satellites, in contrast, remain vertically above a fixed point on the Earth's surface. Thus a geostationary satellite sees the same view of Earth all the time, and scans each point within that field of view every 15 minutes.

There are some important advantages of satellite data for climate work:

- *Cost*: some of the data are available free of charge.
- *Availability in real-time*: data from geostationary satellites are generally available in near real-time – often downloadable from the internet within 15 to 30 minutes.

- *Availability of historical data*: some datasets commence around the start of the satellite era, in the late 1970s, but high temporal and spatial resolution products are more recent.
- *Spatial coverage*: satellite imagery provides a spatially complete perspective for most of the world, including information for places with no *in situ* observations. This coverage is particularly important for countries whose environmental conditions, e.g., flooding, are determined by factors in neighbouring countries or where pests migrate over long distances.[21]

For many countries, satellite imagery provides the only affordable way of monitoring climate and environmental conditions in real-time. Satellite data are commonly used to map populations at risk of various environmentally sensitive diseases and to develop early warning systems.[22] However, because many of the environmental parameters are sensed indirectly, estimates may not be always reliable or usable in all circumstances and may require the interpretation of a skilled operator. The satellite estimates therefore need calibration and validation against ground-based data,[23] and so the use of satellite imagery does not negate the need for field measurements. As a result, many of the highest quality climate datasets are based upon a blend of satellite and station observations.[9]

Remote-sensing products are widely used by researchers studying infectious diseases that are influenced by climate and environmental factors. While a wide range of climate and environmental proxies are available for use in health studies[24] satellite data are most commonly used for estimating rainfall and temperature and for monitoring vegetation and water bodies. The accuracy and limitations of these remote-sensing products are discussed in turn.

6.3.2.2.1 Satellite monitoring of rainfall

No satellite yet exists that can reliably identify rainfall and accurately estimate the rainfall rate in all circumstances. Using a standard camera, a satellite can see the clouds from above that we see from below, but cloud presence by itself is not a good indicator of rainfall. Not all clouds produce rain, and rainfall intensity varies from place to place beneath those clouds that are generating rain. However, satellites carry sensors that can 'see' the Earth in a variety of ways (Box 6.4). Using a selection of sensors, in some situations it is possible to distinguish raining cloud from non-raining cloud by estimating:

- *Cloud-top temperatures*: deep convective clouds have cold, high tops, and so show up as low temperatures. This method of identification works best in the tropics and in the mid-latitude summer months when convective rainfall may predominate (§ 5.2.5.2). However, other types of rainfall (§ 4.2.2) may go unidentified because they do not form from cold clouds, and there may be false detection of rainfall from non-raining cold clouds (Box 6.4). Such errors may

BOX 6.4 REMOTE SENSORS

Sensors are instruments that are sensitive to different wavelength bands in the electromagnetic spectrum. The wavelengths in common use for rainfall, vegetation, soil properties, dust and land-surface temperature are summarized below.

Visible (wavelengths between 0.4 and 0.7 μm)

A sensor in the visible region of the spectrum acts like an ordinary camera and sees what your eyes would see if you were on the satellite. As visible radiation is just reflected sunlight, no information is obtained when the satellite is on the night-time side of the Earth. Visible radiation is used in cloud and vegetation monitoring.

- *Cloud monitoring*: thicker cloud is more opaque – i.e., less sunlight passes through it than through thin cloud and more is reflected back into space. Seen from below, the base of a thick cloud is dark, but seen from the satellite's point of view, the reflected light makes the cloud appear bright. Thinner clouds (whether at a low or a high altitude) allow through more light and reflect less. Therefore, thin clouds appear less bright to the visible sensor on the satellite.
- *Vegetation monitoring*: chlorophyll absorbs the red and blue electromagnetic wave and reflects the green. By measuring the reflectance at the sensor level in the red channel, it is possible to retrieve some information on the chlorophyll activity in the vegetation.

Near- and shortwave infrared (wavelengths between 0.7 and 3.0 μm)

Near-infrared wavelengths are sensitive to leaves while the shortwave infrared wavelengths are sensitive to water. Using combinations of the visible and infrared wavelengths it is possible to derive vegetation indices that provide specific information on the vegetation status. Some simple vegetation indices (such as the Normalized Difference Vegetation Index [NDVI]) have been developed to monitor vegetation greenness and quantity of biomass. A vegetation index is a simple mathematical formula used to estimate the presence of vegetation.

Thermal infrared (wavelengths between 8.0 and 15.0 μm)

The thermal infrared sensor registers radiation at wavelengths that are a good indicator of the temperature of the surface observed. The infrared image can be viewed during the day and during the night. The emission of infrared radiation is less at lower temperatures and greater at higher temperatures. The infrared sensor therefore acts as a remote thermometer which can estimate the temperature. However, their use in estimating air temperature is limited; instead, the temperatures are used to infer the presence of rain clouds. Because temperature decreases with height in a regular way depending on weather conditions and the amount of moisture present (§ 5.2.4), storm clouds show up as very cold with temperatures typically less than –40 °C and sometimes as low as –80 °C. Cirrus is also identified as very cold, and its presence is a problem when identifying rainfall using infrared sensors. Low-level coastal rain-producing and orographic clouds (§ 4.2.2) may show up at higher temperatures of between 0 °C and –20 °C, and so may also be problematic for rainfall estimation using infrared sensors.

Microwave (wavelengths between 1.0 and 300.0 mm)

Radiation emitted at microwave wavelengths is influenced strongly by the nature of the emitting surface (whether rough or smooth, wet or dry) and the size of particles through which it passes. Microwaves are scattered by water drops and ice crystals in cloud, and so, unlike the other forms of radiation already mentioned, microwaves can identify whether clouds have droplets big enough to produce rain. Thus, in general, microwave frequencies are better suited for rainfall detection than infrared frequencies. However, although rainy areas show up well over the oceans as bright against a dark background it is more complicated over the land because the background emission from the surface is very variable. The wetness of the surface as well as its roughness and the kind of vegetation all cause variations in the emitted radiation. Making quantitative estimates of rainfall against this continually changing background is a challenge. However, there are promising algorithms for overland rainfall estimation from microwave sensors that may provide a basis for the development of accurate rainfall datasets in the future.

be substantial in regions near the coast or in mountainous areas. Although estimates of rainfall from cloud-top temperatures have good spatial coverage, high temporal resolution and frequent updates (every 15–30 minutes), the accuracy is often poor

- *Cloud thickness*: the amount of water and ice in the cloud can be estimated by measuring the amount of scattered microwave radiation (Box 6.4). These methods offer a more accurate rainfall estimate, but have coarse spatial resolution and are updated only twice per day. Currently, the estimates are least accurate over the land, where, unfortunately, the information is needed most

CASE STUDY 6.2 SEASONAL MALARIA CHEMOPREVENTION IN THE AFRICAN SAHEL

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The intense seasonality of the Sahelian rainy season, which runs from June–September, governs the lives and livelihoods of the region's diverse populations, many of whom are small-holder farmers and pastoralists (see Box 2.2). It also determines the short, but deadly, malaria season. These seasonal characteristics make the region an ideal choice for the use of presumptive seasonal malaria chemoprevention (SMC) with a combination of anti-malarial drugs as the key intervention.[25] When the transmission season is short (three to four months), anti-malarials administered monthly through the transmission season have the potential to protect children throughout the period of exposure to malaria infection – both at the individual level and through a population level 'mass effect'.

Compelling evidence from numerous studies as to the efficacy of SMC[26] prompted its rapid promotion to a regional programme for the Sahel. The target region for the SMC initiative was chosen on the basis that, on average, 60% of rainfall fell within three months.[27] Monthly Africa rainfall estimates (RFE 2.0) data for 2002–2009 at 10 km^2 spatial resolution were used to generate average long-term monthly rainfall, which were then used to define the average seasonality of each pixel in the region. Children under 5 who lived in areas that met the 60% criteria were then identified to be included in the implementation programme. The malaria season substantially follows the rains with peak malaria incidence lagging peak rainfall by about one to two months.[28]

Within a year, and with the support of the World Health Organization's (WHO) Technical Expert Group on Preventive Chemotherapy,[29] 3.2 million children under 5 years were protected from malaria by SMC in seven Sahelian countries – from Senegal to Chad.[27] Cost-effectiveness analysis for wide-scale implementation indicated that drug costs were marginal relative to distributional costs. Further studies revealed the significant benefits of the approach to children aged 6–10 years and that the extra budgets needed to include the additional children, while variable, were low relative to overall programme costs.[30] This was because older children resided in households where younger children were benefiting from the programme; substantially reducing the need for additional budgets for distribution.

In this example, freely available rainfall estimates for the entire Sahelian region are a pivotal aid in establishing where and when SMC should be implemented. Whether or not improvements in the quality of the rainfall data used would significantly improve programme efficacy is an open question.

Thus the images produced by the satellite are not much use for giving a precise estimate of rainfall for a particular spot on the ground at a particular time. The usefulness of satellites lies in their ability to give (literally) an overview, and the fact that they can be easy to access (see Case Study 6.2).

Techniques are being developed to take advantage of the better accuracy of microwave sensors and the better spatial and temporal coverage of infrared sensors by optimally combining the two products. Various monitoring products are becoming available using different ways of combining the sensor data, but it is not yet possible to generate a consistent historical set of rainfall estimates because some of the important sensors have been installed only on recent satellites.

Another approach towards generating better rainfall datasets is to blend the satellite rainfall estimates with available gauge measurements. The quality of the blended product depends on the quality, number, and distribution of the rain gauges used.[31,32] The ENACTS products (Case Study 6.1) are examples of blended data that are generated at the national level using a much larger set of station observations than are used in the generation of regional and global products. Currently, ENACTS products are available only for selected African countries.[33]

6.3.2.2.2 Satellite monitoring of temperature

The derivation of near-surface air temperature (typically measured at 2 m [§ 4.2.1]) from satellite sensors is far from straightforward. Clouds block the radiation from Earth's surface that the satellites measure to estimate temperature. Even in cloudless conditions when the satellites can measure the temperature of Earth's surface, the surface temperature is not necessarily a good indication of the air temperature (§ 5.2). Although night-time satellite products provide reasonable estimates of minimum temperatures, maximum temperature estimates are problematic.[34]

6.3.2.3 Data from drones

Unmanned aerial vehicles (UAVs), more commonly known as drones, are a new and significant technology with a wide range of potential uses at the environment-health interface. Their relatively low cost, small size and ease of use mean they can provide high resolution, rapidly updated information on very specific targets that service to fill a gap between ground-based stations and satellite-based sensors (see Box 6.5).

6.3.3 Modelled data

A key step in making weather forecasts is to use a weather prediction model to estimate the current conditions (§ 7.4.2). This estimate is known as an *analysis*, and represents our best estimate of the full state of the air in all three dimensions. Because of the motivation to be always improving the accuracy of weather forecasts, new and higher quality observations and upgraded models are frequently introduced in

BOX 6.5 DRONES

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Drones come in many shapes and sizes. Whilst they are perhaps more notoriously connected to military applications, their potential to benefit other industries and domains are increasingly being realized. For example, drones are being used as transportation devices, which, within the public health context, enable medical supplies to be delivered to remote health facilities and inaccessible disaster areas. More ambitiously, solar-powered drones are also being considered by companies such as Facebook as a method of delivering high-speed broadband internet to remote areas across the globe. Microsoft has been working on drones that are able to capture and discriminate between different mosquito species.

Within the context of climate and health, drones are starting to fill both the literal and figurative gap between climate and environment information obtained from ground-based stations and earth observation satellites. With the ability to fly close to the ground, access otherwise inaccessible areas, and carry multiple sensors, they bring access to real-time information on the climate and environment at the micro-scale at a much lower cost and greater accuracy than could be achieved using more conventional approaches. For example, cameras attached to a drone can collect contemporary images of the ground at a spatial resolution of a few centimetres, allowing vector control programmes to identify mosquito breeding sites, which can subsequently be targeted for larval source management.[35] Visual information collected by drones is also being used to explore the impact of a changing climate on biodiversity and agriculture, which also impact human health.

Whilst imagery of similar spatial resolution can be obtained from commercial satellites, its quality is often impeded by cloud cover and comes at a financial cost, making it a less attractive and affordable option for control programmes in resource poor settings. Publicly available data sources tend to be at a coarse spatial resolution and suffer the same limitations with respect to cloud cover, and subsequently temporal availability. The caveat to the use of drones for image capturing is that the image collection process is time consuming due to limitations in drone battery capacity and flight speed. However, as long as these images are being captured for local rather than large-scale operations the quality versus efficiency trade-off is often worth it.

Provided the carrying capacity of the drone is sufficient, it is, of course, not limited to capturing visual information. Sensors aboard drones are able to capture a wealth of climate information such as temperature, relative humidity, dust and even odours at altitudes and spatial scales of much greater relevance to human health than can be captured via satellites. This information can subsequently be integrated into early warning systems providing the ability to target health interventions spatially.

the process of producing the analysis (§ 6.1) The effect is that more recent analyses cannot be compared with older ones, and so it is problematic to use a history of analyses for climate work.

A few centres produce *reanalyses*, which are historical sets of analyses made using a fixed version of a weather prediction model, and a reasonably consistent set of observational data. Most reanalysis products have high temporal resolution (6-hourly), and reasonably high spatial resolution (< 2° latitude and longitude) and global coverage. There are some higher resolution regional reanalyses. Reanalyses provide excellent sources of information about the three-dimensional circulation of the air, and may be useful in studies such as the dispersion of dust and pollutants. For example, reanalysis data were used in a study of environmental drivers of meningococcal meningitis in the Sahel (Case Study 7.2).

Only a few surface observations are used in generating analyses and reanalyses, and so their estimates of the most commonly considered surface and near-surface parameters, such as rainfall and humidity, are problematic. Surface air temperature estimates from reanalyses are somewhat less problematic than rainfall because of the relatively large scale of temperature anomalies (§ 5.2.5), but should still be used with caution, and are no substitute for station-based observations.

Temporal changes in the observations are unavoidable when generating reanalyses, and so some consistency problems remain. As a result, reanalysis data are generally unsuitable for work on climate-change detection, for example. Some reanalysis products are not updated in real-time because the model may be outdated.

6.4 What data and information are available?

6.4.1 Availability of historical and real-time data

There is a bewildering range of climate datasets available. Selecting the most appropriate one(s) to use requires careful consideration of the required characteristics. Here we provide guidance on those characteristics; for information on specific datasets see reference 16. The most important selection criteria are likely to be:

- *Length of record*: station datasets provide the longest historical records; most satellite-based datasets start in the late-1970s or later.
- *Availability in real-time*: many satellite datasets are updated in near real-time; data from automated weather stations may be available in near real-time, but many station-based datasets are updated irregularly.
- *Spatial coverage*: satellite datasets provide complete global (but possibly omitting areas near the Poles), but represent area averages rather than location-specific values; interpolated station data can give the illusion of complete spatial coverage.
- *Spatial resolution*: satellite estimates of rainfall are available at high resolution, but are only accurate when averaged over large areas; the highest resolution satellite data are available for only a few years.

- *Temporal resolution*: monthly data are most widely available, but may mask extreme weather events.
- *Data quality*: station data provide ground-truthing, but may contain missing values and inhomogeneities; some satellite estimates may be difficult to verify, and may be of poor quality at high spatial and temporal resolutions.

Provision is made for open access to 'essential' meteorological data (Box 6.1), but, in practice, the accessibility and cost of historical data varies considerably from country to country. Fees are most often levied for daily and sub-daily data, and there can be long delays in accessing the latest observations. Monthly data are more widely available and can be useful in assessing seasonality, for example, but are of limited value for risk assessment of hazardous events, with the exception of slow-onset hazards such as drought.

In general, the highest quality and most abundant datasets are for rainfall (especially in the tropics) and temperature (especially in the extratropics). When using rainfall data for public health research, care needs to be taken to avoid assuming that rainfall is a good indicator of flooding. Floods have a number of typologies, including coastal, riverine and flash floods (Box 6.6). Coastal floods may arise from sea-level rise, and riverine and flash floods may result from snowmelt or from heavy rainfall. In the case of snowmelt, the snow may have fallen far from the flooded

BOX 6.6 FLOODING

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A flood includes the notion of water being present over a land surface where and when it usually does not occur. The specific definitions of flood events are complex and depend on the source and path of the water. It is important to understand the different characteristics of flood types (see Table 2.1) because the methods of forecasting both the hazard and impact will differ.

One of the most common types of floods, *riverine flood*, results in relatively large areas of standing water over land that is usually not covered with water. For example, the Sudd is a vast swamp in South Sudan, formed by the White Nile's *Baḥr al-Jabal* section. High water levels in Lake Victoria, the source of the While Nile, in the early 1960s resulted in a tripling of the size of the swamp during 1961–1963 and the loss of extensive tracks of *Acacia-Balanities* woodland. The regrowth of the forests in the 1980s was identified as a contributing factor to the epidemics of visceral leishmaniasis that devastated the region.[36]

Most incidents of riverine flooding occur for much shorter periods of time – from days to weeks and their health impacts are more immediate. While flooding may occur as a result of extreme or persistent rainfall at the same location the source of the floodwaters may come from rainfall or snowmelt occurring hundreds of miles away. Floodwaters can lead to increased risk for water-borne diseases. Heightened risk of impacts can last for days to weeks after the initial 'flood' or inundation occurs.

Flash floods are characterized by rapid movement of water in a relatively local area leading to risk of impact from building collapse, bridges destroyed, debris flow and rapid onset disruption of sanitation systems. Drowning and crush injuries are common with flash floods.

Coastal flooding is caused by the intrusion of sea water over land and can occur without any rainfall. For example, storm surge (the rise and push of sea water over land) usually occurs to some extent during tropical cyclones, however the location of storm surge, especially the area of maximum storm surge, can occur at locations that are distant from the landfall point and can occur in areas that receive little rainfall. As a multi-hazard event, tropical cyclones can cause different types of flooding in different areas and at different times. For example, during Hurricane Harvey in the 2017 North Atlantic hurricane season, heavy rainfall caused the most severe flash flooding in inland areas in Houston. However, the landfall of the storm occurred 240 km south of Houston and led to storm surge in that region near Rockport, TX. Understanding the timing and distribution of different types of floods is important for the health sector to better pre-position medical resources before potential impact, particularly in a multi-hazard event with different types of floods.

areas weeks or even months before the flooding occurs. Some floods are entirely predictable, as when water is released from an upstream dam.

Most other data of likely interest in public health work (e.g., wind speeds and humidity) are harder to come by than for rainfall and temperature, and data quality may be problematic.

Regardless of the ease of data access, the selection, use and interpretation of climate data requires considerable expertise. Any application of climate data for public health is best accomplished in partnership between the public health and climate communities.

6.4.2 Availability of historical and real-time information

Accessing climate data may be important for many research purposes, but access to information products in practical decision-making may be more useful than access to the underlying climate data per se. As with the climate datasets, there is a large and growing selection of weather and climate monitoring products available. Most of these products are targeted at meteorologists, but only a small subset are presented in (relatively) easy-to-understand formats with broader audiences in mind, and fewer still are tailored specifically for public health specialists.

Monitoring of hazardous weather conditions is a forecasting as well as a monitoring problem, and so is discussed in Chapter 7. However, for slow on-set disasters and persistent anomalies such as drought, climate monitoring products can be useful even when it is not possible to provide accurate weather or climate forecasts. In addition, in-built lags in the transmission dynamics of many infectious diseases means that forecasts of disease incidence can be created from monitoring cumulative climate and environmental conditions (see § 3.4).

The international coordination of a climate monitoring infrastructure has received less attention than for forecasting, but addressing this oversight is a high priority of the GFCS (see Box 1.3). For example, the WMO is actively encouraging the implementation of climate watches, similar to weather alerts (§ 7.6.1), to provide official notifications of severe climate conditions.[37] Climate watches are currently implemented in only a few countries, although routine information products are more widespread. For example, ten-day and monthly bulletins, and annual reports are produced by many countries. In many cases, these bulletins are targeted at the agricultural sector, or are written for an expert meteorological readership, and few are likely to be accessible to a public health audience. The situation is beginning to improve, most notably for drought and heat (§§ 6.4.2.1 and 6.4.2.2), and a few climate monitoring products are starting to be developed specifically for health specialists. Some examples are available from the International Research Institute for Climate and Society (IRI), and from a few NMHSs. Meanwhile, the more generic bulletins may still fulfil important monitoring functions by providing information on extreme events that are ongoing or that have occurred recently and whose full impacts may yet to be experienced.

Annual climate reports are intended to serve a more retrospective purpose than the bulletins. The reports may be useful for gauging the impacts of any major climate events over the previous year, or for obtaining a sense of the severity and expected frequency of such events. The availability and usefulness to health specialists of the bulletins and reports will vary considerably from country to country depending largely on national capacity. If national level information is unavailable or inadequate, the Regional Climate Centres (§ 6.4) should be able to provide some information, since climate monitoring is one of their mandatory functions. A list of these centres is available from the WMO.[iv] Temperature and rainfall are monitored by all the centres, but additional information on extremes and climate impacts such as flooding may be available.

An important function of the annual and monthly reports is to provide regular updates to the less frequent IPCC Assessment Reports (see § 9.2) that review, inter alia, evidence for how climate is changing. Although climate-change monitoring is the dominant theme of the National Oceanic and Atmospheric Administration's (NOAA) monthly Global Climate Reports, these Reports also provide updates on major climate phenomena such as El Niño (Box 5.1). Occasional Special Reports are released after weather and climate events of particular note. All these various reports are key inputs to the WMO's Annual Statement on the Status of the Global Climate that is intended for a broad audience.

There are a few monitoring products that combine meteorological data with other environmental data to provide information that is intended to relate closely to impacts. Examples include products that target drought and air quality.

6.4.2.1 Drought monitoring

There are multiple types of drought, depending on whether the focus is on the rainfall deficit, the water deficit or the impacts of either (or both) deficits.[38] Further, there are multiple ways of measuring each particular type of drought (see §§ 2.2 and 4.3.3 on measures of rainfall deficit). Regardless of the broad array of definitions, national drought information products are available in many countries, and there are many regional and global drought monitoring products. Most of these products are based on rainfall deficits, but some include soil moisture, impacts on crops and other vegetation, fire risk, and water supply. Drought monitoring that focuses on food insecurity may be of particular interest to health specialists because of the effect of poor nutrition on health outcomes. For example, the Famine Early Warning Systems Network (FEWSNET)[39] combines data on rainfall with a range of socioeconomic data on vulnerability to map food insecurity in parts of Central America and the Caribbean, much of Africa, and part of Central Asia.

6.4.2.2 Air chemistry and air quality monitoring

The monitoring of greenhouse gases is primarily a climate-change question, and is discussed in § 9.1. Urban air pollution monitoring and information dissemination is conducted primarily at the national scale, but some regionally coordinated monitoring initiatives have been established because of transboundary pollution issues. Examples include regional smoke haze resulting from land and forest fires (monitored by the Association of Southeast Asian Nations [ASEAN] Specialized Meteorological Centre), and mineral dust in West Africa (monitored by the Sand and Dust Storm Warning Advisory and Assessment System of the Northern Africa-Middle East-Europe Regional Centre). The mineral dust in West Africa is of natural origin, but is of interest because of its links to epidemics of bacterial meningitis (see Case Study 7.1).

6.5 Conclusions

There is a bewildering array of climate datasets available, but rarely does one dataset stand out as clearly superior to all the others. To match data to decision-maker needs careful choices have to be made between duration, real-time accessibility, spatial coverage, resolution and quality. Satellite and other remotely-sensed observations have dramatically expanded the options, but do not negate the need for station observations because satellite estimates require calibration against ground-based data. Regardless of which dataset is used, ultimately, information about the past and present is used to make inferences about the future weather and climate. In many cases, predictions may be available; these are discussed in the following chapters, beginning with forecasts for the next few days.

Notes

i Climate Hazards group InfraRed Precipitation with Satellite data.
ii Tropical Applications of Meteorology using SATellite and ground based observations.
iii http://public.wmo.int/en/our-mandate/what-we-do/data-exchange-and-technology-transfer.
iv www.wmo.int/pages/prog/wcp/wcasp/rcc/rcc.php.

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