

Foresight

Infectious Diseases: preparing for the future

OFFICE OF SCIENCE AND INNOVATION

**S10: State-of-Science Review:
Earth observation**

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Abstract:

Earth observation involves the remote observation of the Earth, usually from aircraft and satellites. These platforms allow a unique synoptic view of our planet, and allow unique observations to be made. The observations are usually combined with models to provide improved understanding of the process being studied.

Modern global communities are also enabled by space-based technology, and so allow observations to be brought together rapidly as an aid to prediction, forecasting and subsequent environmental management. Some in situ observations are also greatly enhanced by additional space-based data. For instance, global positioning systems are very useful for pinpointing sites quickly and cheaply. Although not strictly Earth observation, both novel communications and GPS will be considered in this section where they enhance the Earth observation techniques.

The use of Earth observation in all environmental management is growing rapidly in usefulness for a wide variety of environmental uses. However, it is extremely unlikely that Earth observation will be able to detect infectious diseases directly. Rather, Earth observation can be used to detect die-back of vegetation (and possibly attribute this die-back to a particular disease), and help predict the movement of the agents carrying vector-borne diseases, or of diseased animals themselves. It can also help with the mitigation and management of infectious disease outbreaks. Each of these will be discussed in turn.

Available Observations

The full chapter will review some of the relevant variables, focusing on current and ideal usage of observations as well as possible or required advances in Earth observing systems. New technology will greatly increase the prediction of several of these variables, particularly soil moisture and wind velocity, currently both poorly estimated or not measured at all. Information on observing the following variables will be included:

- Surface temperature : currently uses atmospheric sounding from space to estimate surface temperature, with some additional surface information and information from imagers, all assimilated into numerical weather prediction (NWP) models. In the future, there will be greater use of accurate space-based radiometers and far higher resolution models.
- Atmospheric humidity : currently use atmospheric sounding from space and radiosondes incorporated into NWP models. GPS offers far improved estimates of absolute humidity, with consequent model improvements.
- Precipitation : currently inferred in NWP models, with some surface information on detailed rainfall patterns, and some experimental satellite observations. Cloud-resolving models and better observations will greatly improve these estimates.
- Soil moisture : currently poorly predicted in NWP models with few surface observations. New satellites to be launched in 2007 and 2010 will greatly improve global estimates of near-surface soil moisture.
- Surface water : currently mapped by Landsat and similar satellites, but there are issues of frequency of coverage, particularly in heavily vegetated and cloudy areas.

- Run-off : poorly estimated over large areas where there are sparse observations. Lidar altimetry offers the possibility of greatly improved model initial conditions. Coupled with novel observations of precipitation and of soil moisture (see above), this variable should be much better estimated over large areas.
- Wind velocity : currently largely inferred from pressure measurements and some radiosonde data in NWP models over land. Novel backscatter lidar techniques will allow direct synoptic observation of wind vectors globally, which should greatly improve estimates; the first research satellite is launched in 2006. Scatterometry already provides ocean surface wind vector data away from coasts.
- Surface radiation budgets : estimated in NWP models using some top-of-atmosphere observations. GERB, launched in 2002, is starting greatly to improve these estimates.
- Land cover : Landsat and similar satellites are used to monitor deforestation, agriculture, urbanisation and other processes. There are still considerable issues for the organisation of the analysis of such data for purposes of monitoring precursor conditions for infectious diseases.
- Altitude (and sea-surface height) : Altitude is an important variable for studying infectious diseases. Wave height can be linked to transmission of disease from ocean sources to land.

Observation of precursor conditions

Many diseases need certain temperature and moisture conditions to breed, and occasionally other conditions. Earth observation together with numerical models is already used to predict these quantities, and new developments have particular relevance for prediction of the outbreak of infectious diseases.

The role of precursor conditions by transmission type will then be explored to synthesize the variables already discussed. The structure of this section will focus on transmission types such as vector-borne disease (including malaria as well as other mosquito-borne diseases, as well as other vector-borne diseases), water-borne diseases and air-borne diseases. Methods for forecasting precursor conditions for disease prediction will be discussed with particular reference to existing and possible early warning systems using seasonal forecasting from numerical weather models.

An important topic for infectious diseases is the role of climate change. The possible effects of climate change on the detection of disease will be discussed, particularly in the context of the need for disease identification/monitoring in currently disease free areas.

Detection

Plants: Direct detection/mapping of areas of die-back. This is usually inferential and not diagnostic of disease itself. Current technology includes Landsat, IKONOS and other mapping satellites, including of ocean colour. Novel technology includes use of hyperspectral imaging, lidar altimetry, the use of lidar to examine plants, including marine organisms, via fluorescence and “sniffer” or sentinel plants which react to disease by changing ‘colour’.

Animals and man: remote Earth observation for diagnosis from space is challenging, and not possible at present. In situ sensors (including GPS) with very low power speckled computers can be placed on animals in principle to measure their health and telemeter their data to central sites.

Transport of infectious diseases

Wind and water flow, both in rivers and in the coastal and deep ocean, can be estimated well with the use of Earth observation. New technology such as using lidar is greatly improving all of these.

Improving tagging of animals using intelligent tags incorporating GPS and telemetry would greatly assist with the monitoring and management of animal movements. The technology can in principle be applied to humans, but there are ethical concerns which need to be addressed. Speckled computing will add to the ethical concerns while making deployment of sensors far easier.

Management and mitigation of effects

Mapping techniques have been essential for the management of the spread of infectious diseases. This includes change detection, mapping of possible disposal sites so as to minimise environmental impacts, and, in developing countries, providing information on the existing infrastructure such as roads. Much of the technology is now routinely applied (such as in Darfur, Sudan, during the recent crisis), although new methods such as lidar altimetry to give detailed topography information are being developed. The delivery of the information in the field in a timely fashion is far less developed, and the use of modern technology such as GRID computing will be essential for effective use of the new technology.

Giving confidence to the observations

In all these observations, they need to be combined with models to infer quantities of interest for the prediction and prevention of infectious diseases. These quantities are not necessarily being produced at present for these purposes. It is important to estimate the errors of the fields being produced in order to give reliable forecasts of risk to practitioners. This will involve statisticians in the work to allow formal confidence levels to be given. There are risks in either predicting an infectious disease outbreak where none occurs, or not predicting an outbreak where one occurs. These risks need to be minimised through formal involvement of statisticians to review the methodology being used.

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1 Introduction

Earth observation not only involves observing the Earth remotely from satellites, but also includes surface, airborne or submarine observations, which can be collected on a regional or global basis. Satellite observations allow a unique synoptic view of our planet, enabling us to realise many of the interactions in our Earth system.

However, on their own, these observations are of limited value. One important development in recent years has been to couple observations with computer models of how our planet works. These models, some of the most challenging and complicated used today, simulate the interacting global atmospheric, ocean, land and cryosphere system, including its physical changes, biology and chemistry. Such models are necessarily simplified, and so need to be checked carefully against observations and the differences diagnosed and understood. The Earth is naturally varying. Any changes observed need, therefore, the understanding provided by the models so that we know whether the variations we observe are due to natural variability or whether they can be attributed to a secular change, and whether this change is due to human intervention. This coupled system of observation and computer analysis is the system of Earth observation discussed in this section.

Earth observation is evolving rapidly because of technological innovation. Although satellite observations of the Earth have been made since 1960, primarily as an aid for weather forecasting, it is only since the advent of large computer data stores, good digital communications and large computers on which to run ever more complex global models, that the observations have been of most use. Since 1960, the range of space-based observations and their accuracy and precision have been transformed. The ability to make comparisons between ground-based observations regionally and globally has also greatly increased the accuracy and precision, and thus the worth, of these observations. In modelling diseases, we will often use a blend of satellite and ground-based observations and model calculations, carefully integrated to minimise errors and biases. This blending is usually called 'data assimilation'. It started to be applied primarily in weather forecasting, but is now being used increasingly in studies of the ocean circulation, and is also beginning to be used to model the land surface and in understanding land surface and ocean biology. One of the grand challenges of the next 20 years will be to extend these powerful techniques fully to encompass not just the physical and chemical changes on our planet, but also its biology.

This section has several parts. First, there is a brief description of some of the observations which are now, or soon will be, available to observe the Earth system. It is extremely unlikely that such Earth observation will be able to detect infectious diseases directly. Rather, Earth observation can be used to detect (for instance) die-back of vegetation and possibly attribute this die-back to a particular disease. It can also be used to predict the movement of agents carrying vector-borne diseases, or of diseased animals themselves. It can also help with the mitigation and management of infectious disease outbreaks. Each of these will be discussed in turn.

2 Available observations

Although there are many quantities that can be measured by an Earth observing system, not all of these are likely to be of relevance to the detection and identification of infectious diseases. What follows is a discussion of some of the relevant variables, how well they can be observed, and what likely advances will be made in the next few years.

Surface and air temperature

Near-surface air temperature has been observed systematically in some areas for about 150 years, mainly over the land and along shipping routes. These observations have been supplemented since the early days of satellite deployment by data on infrared radiances, both to observe atmospheric temperature profiles and the temperature of the land and ocean surface. The observations of surface temperature are, of course, what can be seen from space, so they usually represent the top of vegetation rather than lower down through a vegetation canopy (although areas of frozen ground may be seen directly in areas of sparse, or no, vegetation). Nevertheless, the near-surface air temperature is often close to that in the canopy air space. The near-surface air temperature in land areas is usually estimated within a range of less than 2km, while over the ocean the range is less than 1km, with some observations considerably better than that. These observations, blended from satellite and surface observations into models, are effectively already available continuously and globally, in near-real-time, as part of the global weather forecasting system. Many models of the geographical limits of diseases in plants, animals and humans include controls dependent on temperature, and the accurate predictions available from the global Earth observing system could already improve current disease models. It may be expected that, over the next 15 years, the spatial resolution of the temperature fields will increase as better computers become available and as the accuracy of the observations improves. Any error in the temperature estimates will also improve as model error handling techniques become more sophisticated.

Atmospheric humidity

As with air temperature, estimates of atmospheric humidity are made routinely as part of weather forecasts by blending surface and satellite observations with numerical models. Such observations are used in some insect-borne disease models and in some models of plant diseases. All existing observations of atmospheric humidity are biased. Accurate global positioning systems (GPS) can be used to improve the absolute estimates of water vapour in a whole atmospheric column. With the great proliferation of such systems, it is to be expected that the errors and biases on estimates will both reduce considerably, giving far better information than at present.

Precipitation

Rainfall and snowfall are closely related to the estimates of atmospheric humidity. The spread of many diseases is limited by available water, while, for human diseases, a lack of water can lead to increases in susceptibility, either

directly or by leading people to drink polluted water, or by leading to mass migration or starvation. Although weather forecast models estimate precipitation, the detailed distribution of rainfall is not well estimated because of the sparsity of observations and by the spatial resolution of the numerical models. Richer parts of the world supplement the sparse data available from rain gauges by the use of ground-based weather radars, but such data are rarely available in poorer areas such as Africa.

There have been direct observations of rainfall over the oceans from satellites, and some observations from experimental satellites over land, most effectively taken by the US/Japanese Tropical Rainfall Measurement Mission. Numerical models that resolve cloud systems will be needed to take full advantage of these experimental observations. Higher resolution models should be available in the next 15 years.

Snow accumulation and snow area are observed directly by satellites, although snow lying on the ground is as yet poorly represented in global models, even though it shows great regional, seasonal and inter-annual variability. Snow is particularly important in the spring, during snow melt, leading both to large floods and to plentiful supplies of fresh water that can be important particularly for insect-borne diseases. The global snow estimates available are currently under-used in identifying precursor conditions for diseases, even though such data have been available routinely since 1979.

Soil moisture

Soil moisture is currently poorly estimated globally, with very few surface observations, despite its importance in regional agronomy and in famine prediction. In 2007, the European Space Agency will launch the experimental Soil Moisture Ocean Salinity satellite, which will give practically global observations of near-surface soil moisture for the first time. Combining these with models will be challenging, but should lead to considerable improvements in this field, which, in turn, should flow through to disease detection, identification and monitoring models.

Surface water

Many diseases propagate in open water. Large areas of permanent open water are observed routinely by mapping satellites such as Landsat. However, ephemeral flooded areas, or areas under trees, or areas covered by cloud, are not observed by many such systems. Imaging radars can see through clouds and through some vegetation, except dense tropical forest. There are still problems with observing ephemeral surface water because most mapping satellites have an orbit that does not repeat over an area very quickly. An observing system to detect ephemeral surface water is technically possible today, but it remains to be seen whether a system will be implemented over the next 15 or 20 years that can make sufficiently frequent observations anywhere.

Runoff

Runoff is poorly estimated over many large areas, particularly in poor or sparsely inhabited regions. The levels of very large rivers such as the Amazon can be observed with satellite altimetry, though infrequently in time. Poor estimates of detailed topography, soil moisture and precipitation mean that model estimates, for instance, of floods, are often inadequate. This is in spite of the economic importance of runoff data, the dependence of much of the world's population on river runoff for its water supply, the potential for economic and social disruption by large floods, and the transport of water-borne diseases downriver in runoff. Similar poor estimates of likely areas of flooding are also found in coastal regions. Technically, observations can be made of river discharge that are of considerable importance in the detection, identification and mitigation of infectious diseases, but there is often little will to make these observations in poor and sparsely populated areas and even less willingness to share the information across national boundaries.

Land cover

Land cover has been monitored routinely since 1972 by Landsat and similar satellites, and, with higher temporal but poorer spatial resolution, by sensors mounted on weather satellites. These generally observe solar reflectance at a set of narrow visible and near infrared wavebands, and these reflectances can be used to infer the land cover types in broad classes. It would be unusual to infer individual species types, but areas of deforestation or die-back are observable, as are areas of man-made cover such as houses or other infrastructure.

More recently, imaging radars have been used to supplement the earlier optical sensors. It is again hard to infer other than general land cover classes from these data as they relate mainly to vegetation structure or to the shape of man-made structures. The advantage of radar is that it can see through clouds and at night.

Land cover observations have been used very effectively in the mitigation of disasters by providing quick mapping data of population movements and of informal settlements. This can then be used to direct aid and other relief operations, including the mitigation of diseases that are often inherent in such informal settlements. However, there are currently some unresolved issues around the fast access to and effective management and use of such data. It is to be expected that this is an area where rapid progress is likely to be made over the next 15 years. Disasters such as earthquakes or volcanic eruptions, because of the regions in the Earth's crust within which they occur, often take place in remote regions. Interferometric radar can easily be used to catalogue such areas and pinpoint local deformation in the Earth's crust, which occurs before and after such events.

Wind velocity

Wind velocity is important for predicting the spread of airborne diseases and of diseases carried by insects. Wind fields are currently largely inferred from

pressure measurements and some radiosonde balloon observations over land. Novel backscatter lidar techniques to be deployed on a new European Space Agency satellite, ADM Aeolus, to be launched in 2008, will allow these fields to be checked directly against observations on a regional and global basis and should quickly lead to considerable improvements in regional wind fields.

Ocean circulation and biology

Data assimilation systems that routinely take in observations of sea-surface height, sea-surface temperature and sea-surface state, which is related to wind speed, are leading to great advances in our knowledge of global and regional ocean circulation. Information on ocean colour, related to ocean biology, is also rapidly being included. This knowledge of the global ocean circulation will greatly inform our modelling of the spread of ocean-borne diseases over the next 15 years.

A general issue

This section has described very briefly what is currently possible in the area of Earth observation from satellites to feed into models for the detection, identification and mitigation of infectious diseases. However, such data need to be tailored for and delivered to users in a timely fashion. These users also need to know what is available, and what the limitations are on use. The population of such users is currently small, and it is important that this number is increased if full advantage is to be taken of the new observations that are now becoming available.

3 Observations of precursor conditions

Climatic conditions play an important role in the spread of many diseases. In general, the largest climate effect can be seen in vector-borne diseases such as malaria where the vector requires particular climatic conditions in which to prosper. This section explores the relationship between disease and meteorological variables, focusing on several examples. This relationship is, at first, useful in understanding the pattern of disease, but can also be of practical use in the production of disease risk maps. Seasonal forecasts can then be used to predict disease hotspots based on the observed relationships, and such information can be used to target vaccination or pest-control programmes, thus providing cost-effective mitigation using existing technology. Furthermore, changes in disease risk areas are an important and likely impact of climate change. This section will review some of the possible effects of climate change on infectious disease.

Probably the most important disease vector is the mosquito. Mosquitoes are sensitive to temperature, precipitation and humidity, and the diseases they carry may also be sensitive to temperature, as is the case with malaria. Another important vector-borne disease is dengue which is often endemic in urban areas across the tropics and is also spread by the mosquito. Minimum temperature is recognised as the most important factor for the mosquito, as it

has an effect on both the survival and development rates of adults and larvae. Additionally, precipitation rates are important in the larval stages of development because precipitation provides the puddles and open water which are the breeding sites for mosquitoes. Precipitation, however, can also have a detrimental effect: extreme rainfall can, for instance, wash away breeding sites. Precipitation from the previous month has been shown to be a good indicator of disease incidence, thus providing some predictive power, despite the fact that precipitation is one of the most challenging meteorological variables to predict. Additionally, atmospheric humidity is also an important factor, affecting the survival rate of the adult mosquito.

Hopp and Foley (2001) used a simple global model for *Aedes aegypti* as a vector for dengue fever driven by temperature, precipitation and humidity. They found a relatively close agreement with observed populations, although they (and other authors: see WHO 2004) note that socio-economic factors are likely to be just as important. An example of this was the incorrect prediction of absence of *Aedes aegypti* over deserts in the results of Hopp and Foley (2001), because precipitation is scarce but water is stored for human settlements. However, remote sensing still has an important role to play in combating dengue. Social and economic reform is unlikely to be achieved in the short term, and climate variability (and perhaps climate change) is therefore an important factor in the prediction of disease risk.

Another mosquito-borne disease that has received much recent attention is West Nile virus. Several, high-profile epidemics have occurred in the USA in the past few years, although these have resulted in relatively few deaths. Epstein (2001) reported that warm winters and spring droughts lead to increased infections in animals and humans, presumably via mosquitoes. The relatively low prevalence of West Nile virus in humans in the USA is most likely due to the higher standard of living in developed nations. This highlights the fact that the relationship between climatic variables and human infectious diseases is of greater use in less-developed countries, where humans are more at risk due to their lower standard of living. Remote sensing also plays a critically useful role in monitoring the climate of these countries, because ground-based observations are often sparse.

While mosquitoes are a common route of several serious diseases, the mosquito is by no means the only vector that is sensitive to climatic conditions. African trypanosomiasis (also known as sleeping sickness in humans and nagana in cattle), spread by the tsetse fly, has caused recent human and cattle epidemics. Rogers (2000) reviewed the use of satellite remote sensing for monitoring and predicting outbreaks of trypanosomiasis. Rogers (2000) outlined how vegetation indices, elevation data, temperature and a precipitation proxy (all four remotely sensed) have been used in several studies to predict tsetse fly distribution.

Rogers (2000) also notes that the best predictions of tsetse fly distribution are obtained using a mixture of remotely sensed variables and non-climatic variables such as herd or population movement. This suggests that an integrated GIS (geographical information systems) approach is required, such as that outlined by Hendricx et al. (2001) for Togo. The major stumbling block

for an integrated system being applied across Africa is likely to come from government reluctance to share sensitive disease information. In contrast to ground-based data sources, measurements are already routinely obtained from space across the world and therefore transcend political boundaries.

Lyme disease is a widely distributed, endemic infectious disease in North America and Europe, primarily spread by ticks (see Randolph 2000 for a full review of monitoring tick-borne disease from space). Transmission of Lyme disease is seasonal, with its peak in June/July. This is the most common vector-borne disease in the USA. Some studies have looked at a possible link with climate variables (e.g. Brownstein et al. 2003). In fact, it seems more likely that these climatic effects are indirect, and that the direct effect on tick population is in fact vegetation. Normalised derived vegetation indices (NDVIs) have been used in several studies (Estrada-Peña 2002; Eisen et al. 2005). Future advances will allow for more accurate classification of vegetation types, vitality and quantity, which can be used to improve estimates of ticks.

Schistosomiasis is a disease with various forms found in Africa and China. The disease is transmitted by blood flukes which develop in snails, so snail abundance is an important factor in predicting disease risk. Several studies have examined the link between remotely sensed observations and snail abundance. Important variables are temperature, precipitation and altitude, as well as other surface characteristics which affect the abundance of snail populations, such as water-body type and river-flow speed. Brooker and Michael (2000) give a thorough overview of the application of remote sensing to helminth control programmes in Africa, with particular emphasis on the use of GIS. This example shows how remotely sensed observations can be used to track the disease reservoirs (containing the snails) rather than the disease vectors alone.

For an overview of the use of remote sensing techniques for monitoring disease vectors, see Hay et al. (1997) and Beck et al. (2000). See also Randolph (2000) for an overview of tick-borne disease monitoring.

Cholera outbreaks are initiated by ingestion of water with high concentrations of the bacterium *Vibrio cholerae*. While concentrations of *Vibrio cholerae* cannot be directly measured using remote sensing, some of the natural reservoirs of the organism can be detected. Lobitz et al. (2000) used remote sensing to detect plankton concentrations by linking them to sea-surface temperature and height. Remote sensing can also be used to identify large blooms of dinoflagellate phytoplankton (red tides), which, when accumulated by shellfish and eaten by humans, causes paralytic (PSP) or diarrhoeic (DSP) shellfish poisoning.

Rodó et al. (2002) looked at the link between El Niño southern oscillation (ENSO) and cholera prevalence in Bangladesh. They found that there was a correlation between the two in more recent times (after 1980) which is most likely the result of ENSO-induced changes in the hydrological cycle, which in turn affect cholera prevalence. However, since ENSO reflects a range of climatic conditions, the precise cause of this link is not obvious. Hunter (2003)

reviewed some of the links between climate and water-borne diseases in the UK, particularly concentrating on the effect of heavy rainfall events, flooding and increased temperature. Heavy rainfall, for instance, has been observed to precede *Escherichia coli* outbreaks. However, forecasting precipitation is challenging due to its small spatial scale and inhomogeneous spatial distribution, such that current forecasts can be relatively crude, particularly those of extreme events. The accuracy of hydrological parameter predictions is likely to improve in the future as model resolution increases and modelling techniques move to higher levels of sophistication.

The application of climate–disease relationships

The examples discussed above illustrate the sometimes strong relationships between infectious diseases and environmental factors. These relationships are the focus of a great many publications, but they have been utilised in an operational framework in a surprisingly small number of cases. These relationships can be effectively used, along with other information, to support decisions of policy makers about where to direct possible treatments or precautions. Furthermore, modern seasonal forecasting can also be used to predict potential disease outbreak in a particular region if there is a strong link to meteorological conditions.

One of the major drawbacks of applying these relationships to support policy decisions is the need for synthesised information. Robinson et al. (2002) developed a GIS to provide decision support for the application of limited aid resources for trypanosomiasis in Zambia, in conjunction with satellite remote sensing data. Booman et al. (2000) give an example of a similar GIS decision support tool for malaria in South Africa, and Brooker et al. (2002) outline a similar GIS for a helminth control programme in Chad. Thomson and Connor (2000) give further examples of a range of other GIS for disease risk monitoring and decision support, which use a host of variables, including climatic data.

Decision support tools are based on creating maps of disease risk, which can be used to predict the current risk of infection in a given location, including the variables which are generally fixed in time or vary slowly, such as population densities and land cover type. One useful application of the weather–disease relationships already discussed is to use predictions of meteorological conditions to provide disease early warning systems. This is of particular use if seasonal predictions indicate non-standard conditions such as, for example, a long mild summer that might lead to a longer mosquito lifespan and increased disease prevalence.

Meteorological forecasts can be split into three main types: short-range, medium-range and long-range or seasonal forecasts. Short-range forecasts are the most accurate and extend to around five days, while medium-range forecasts extend to 10–20 days, such as that supplied by the European Centre for Medium-range Weather Forecasts (ECMWF). Short-range and medium-range forecasts may be of little use for most diseases, although they have clear potential for predicting the airborne spread of foot-and-mouth

disease in the UK, where wind fields and atmospheric stability both play an important role in airborne transmission (Gloster and Alexandersen 2003).

Both short- and medium-range weather forecasts are produced using complex numerical integrations based on the underlying dynamics of the atmosphere and oceans, which are run on supercomputers. The forecast range of these models is constantly being improved and is likely to increase in the future, although it is highly unlikely that such complex models will be able to predict much further than 20 days into the future in the next 25 years, not least of all due to errors in the initial observations. Furthermore, predictions of precipitation and other hydrological variables are still a challenge for current dynamical models.

Long-range forecasts are generally based on simplified versions of the medium-range forecast models or are made using statistical models. Long-range forecasts are usually applicable for large areas and, for most predicted variables, are rather general in their nature. For instance, seasonal precipitation forecasts for India might give a prediction of the percentage of average rainfall expected for the monsoon season over the whole of India rather than a breakdown of expected precipitation in each district. Nevertheless, long-range forecasts are likely to improve in accuracy and resolution and have the capacity to provide indications of possible disease outbreaks some months in advance.

Teklehaimanot et al. (2004) used a statistical model to predict the number of cases of malaria in Ethiopia from lagged weather variables. Their model was able to predict malaria outbreaks four weeks in advance, and they concluded that the model did indeed have some usefulness for targeting treatment. Morse et al. (2003) described an early warning system for malaria based on the ECMWF seasonal forecast model and a biological model for the disease vector (see Hoshen and Morse 2004 for a full description of the model). This model was calibrated using climate data, although the main aim was to develop a mathematical–biological model for predicting epidemics. The lead time of these predictions has the potential to increase using currently existing technology. The link between ENSO and malaria (Bouma and van der Kaay 1994, 1996; Bouma et al. 1997a, 1997b), for example, could provide scope for weather-driven, early warning systems with the ECMWF (among others) providing a seasonal forecast with a lead time of up to nine months, as shown in Figure 1. See also Kovats et al. (2003) for a review of ENSO and health.

The studies described by Teklehaimanot et al. (2004) and Morse et al. (2003) show that the incorporation of forecast weather data into malaria outbreak models can enhance capability to predict major outbreaks. Future developments will focus on improving these models and packaging the final outputs into a form that can readily be used by governments and aid agencies at ground level. Additionally, see Myers et al. (2000) for a general review of disease early warning systems, and WHO (2004) for examples of early warning systems.

The effect of climate change

Given the relationships discussed above, it is likely that climate change will have a high impact on infectious diseases. Current diseases that have a relationship with climatic variables, such as temperature, precipitation and humidity, will be affected in a number of ways. Of prime concern is the possibility that disease vectors might spread to higher latitudes as meteorological conditions become more favourable here due to climate change. Others may die out because their temperature maximum is exceeded. These changes could also increase prevalence in current risk areas as higher altitudes become viable environments for disease vectors and favourable conditions extend the transmission season. Furthermore, zoonotic diseases might also increase as population dynamics in humans or animals lead to changes in natural habitat and the encroachment of human dwellings into previously unpopulated wildlife areas.

A less obvious impact of climate change is how it will indirectly affect disease. For instance, climate change might alter people's preference for where and how they live, which might have a large effect that is difficult to predict. It is also likely that extremes will increase under climate change, leading to increased flooding and drought, both of which can provide suitable conditions for the outbreak of epidemics. Rapid climate change might also drive the emergence of new disease (Harvell et al. 1999; McMichael 2004). However, the detection and identification of infectious diseases through Earth observation is less applicable to the indirect effects of climate change, as is the detection of emerging diseases, since known disease characteristics are generally required to link large-scale observable variables with small-scale disease transmission.

Changes in the future risk of known diseases can be forecast if adequate predictions of future climate can be made. IPCC (2001a) showed that the global mean temperature is likely to increase by about 3°C over the next 100 years (see Figure 2). But the regional characteristics of this temperature change are still not clear: the exact change might be higher or lower at the individual country level. A further complication is the effect of this change on the hydrological cycle, which is still relatively poorly modelled and is likely to be a major feedback for local temperature changes. For instance, although IPCC (2001a) showed that global precipitation would increase, the magnitude and even whether regional precipitation will increase or decrease are still unclear.

Despite these uncertainties, it is now apparent that climate change will have a major effect on infectious diseases. Particular attention has been paid to the role of climate change and malaria, with many studies hypothesising on the likely extent of the effect of a future warmer climate (see, for example, Hay et al. 2004; Tanser et al. 2003; Rogers and Randolph 2000). Controversy still remains, however, as to whether climate change is the cause of recent changes in malaria prevalence (see, for example, Zhou et al. 2004; Crabb 2002; Hay et al. 2002a, 2002b; Patz et al. 2002). There is also little evidence of climate-induced changes for other diseases up to the end of the 20th century (Kovats et al. 1999; WHO 2003). IPCC (2001b) reported on the likely

impacts of climate change and included synthesis information on the likely effect on infectious diseases. They list the potential impacts of climate change on vector- and rodent-borne diseases, which include positive and negative effects from increased temperature, increased/decreased/extreme precipitation and sea-level rise. They also stress that public health systems will play an important role in controlling future infectious disease prevalence, citing the example of dengue transmission on the border of Mexico and the USA (Reiter et al. 2003), where the number of cases is substantially lower in the USA, probably due to the higher standard of living (e.g. the use of air conditioning).

Despite all the research on malaria transmission, it is still uncertain whether the potential for increased transmission into new areas as a direct result of climate change will be transformed into an increase in actual cases (WHO 2003). Further work is required to combine global and regional climate general circulation models (GCMs) with biological models for disease vectors. Patz et al. (1998) used a simple biological model in conjunction with climate GCM predictions to produce maps of potential dengue transmission (see also Martens et al. 1997, and Hales et al. 2002). Clearly, these kinds of models represent a step in the right direction, but the inclusion of socio-economic factors in such models is an essential step in understanding the true impact of climate change on infectious diseases. To achieve this will require greater interdisciplinary interaction between climate modellers, biologists and social scientists.

For a more detailed exploration of the effects of climate change on infectious diseases, see IPCC (2001b) and WHO (2003), as well as reviews by Githeko et al. (2000), Haines et al. (2000), Gubler et al. (2001), Hunter (2003), Haines and Patz (2004), and Sutherst (2004). Additionally, for more specific reviews, see: Reiter et al. (2001) for mosquito-borne diseases; Lindgren (2000) and Randolph (2001) for tick-borne disease; Rose et al. (2001) for water- and food-borne diseases; and Patz et al. (2000) and Kolivras and Comrie (2004) for infectious diseases in the USA.

Figures

Figure 1: Areas of increased risk of infectious diseases in 2050 with a doubling of pre-industrial levels of carbon dioxide (Hales et al. 2002)

Figure 2: Growth in uncertainty of predictions in a seasonal forecast, as shown by predictions in sea-surface temperatures. Observations and model are blended until 1 March, thereafter only model predictions are used (ECMWF)

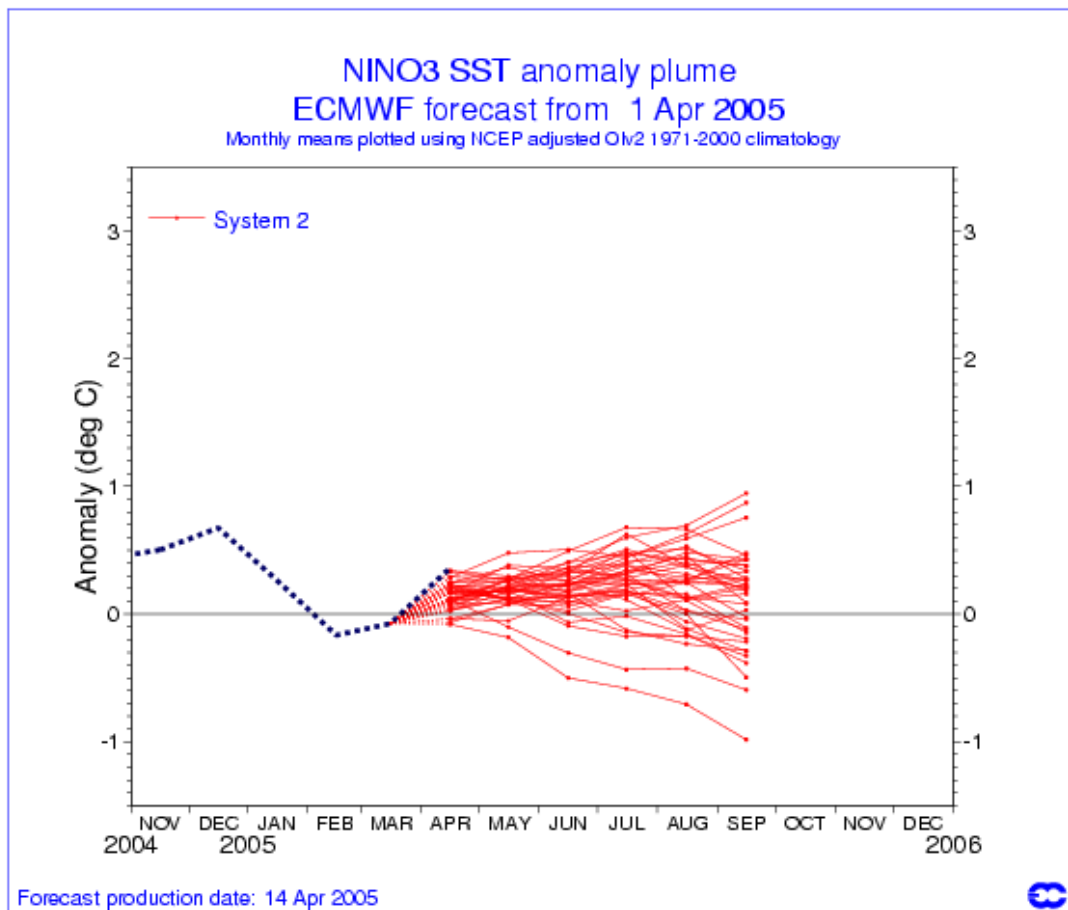


Figure 3: Predictions of increase in air temperature following an increase in CO₂ concentrations, from a series of different models (IPCC 2001a)

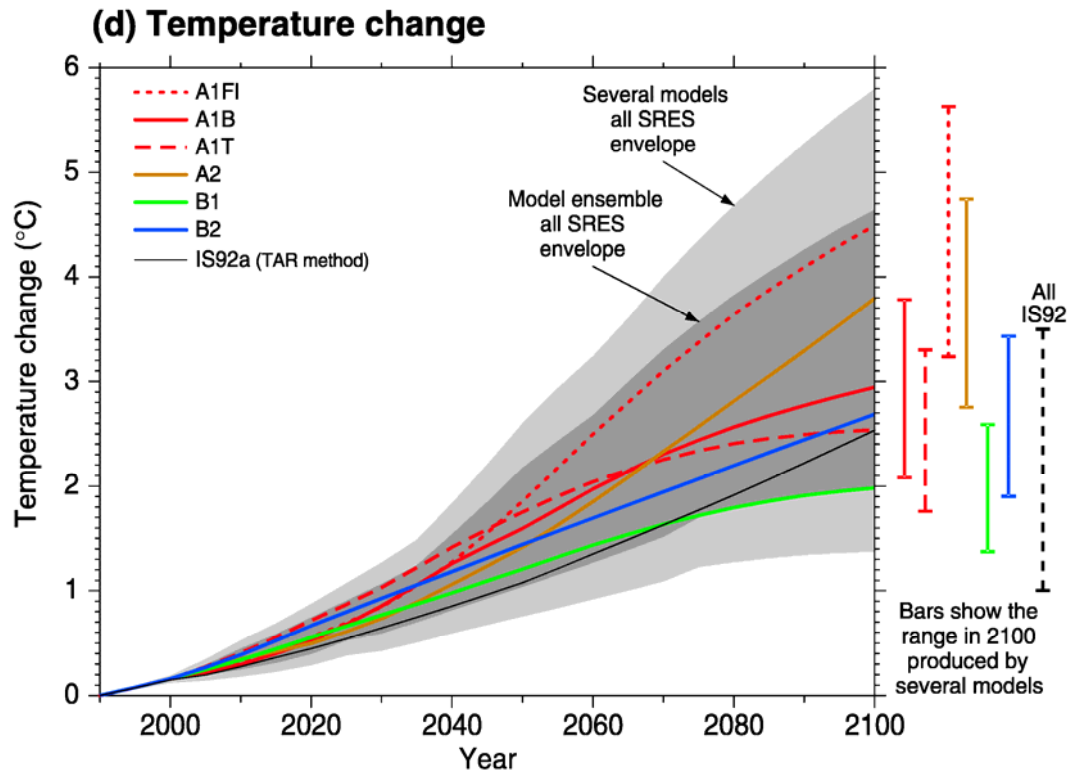
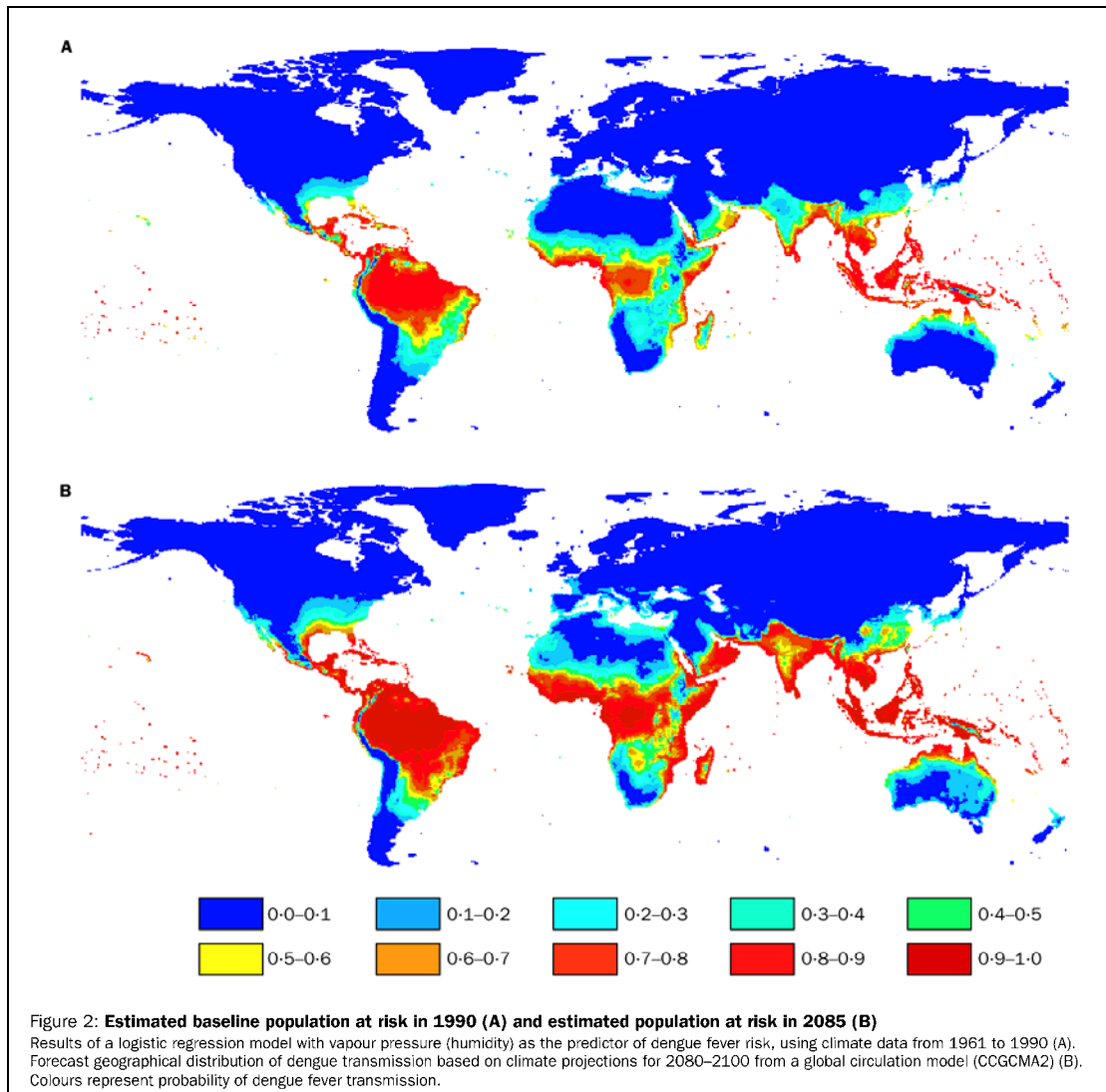


Figure 4: Predicted risk of dengue fever in 1990, and following a climate change in 2085 (Kovats et al. (2003, Lancet, 362)



4 Detection of infectious diseases

Direct detection of infectious diseases is, at present, hardly possible using Earth observation. Swarms of insects such as locusts have been tracked using ground-based radars, and die-back of vegetation due to disease has been observed from spacecraft and attributed to particular plant diseases, but the information is usually secondary and an aid to obtaining a synoptic view.

There are a few specific plant diseases that do give distinctive signatures. *Striga* is a plant in east Africa – locally called witchweed – that is parasitic on maize, sorghum and other cereals, and greatly reduces yields and plant health. It has very distinctive purple flowers that are very different from all other similar plants in east Africa (see Figure 5). These parasites infect stands that are potentially visible from spacecraft and aircraft. The shape of the heads is such that a spacecraft that can view an area obliquely will be best able to see the parasite, and so it has not yet actually been detected. However, the technique has been demonstrated on *striga* in the laboratory, and field trials will be undertaken soon.

Figure 5: *Striga* – overhead view *Striga* – side view

An extension to this technique may be possible during the next 20 years. Genetic modification techniques could be used to attach a gene to plants that would have a specific response if a disease is detected, for instance, by making the plant fluoresce at a particular wavelength. Such fluorescence could be detected from aircraft or spacecraft. Sentinel plants could even be modified to change reflectance or fluorescence at particular wavelengths with different diseases, and so act directly to detect and identify a range of diseases in plants, animals or humans. While considerable progress would be needed to deploy such techniques operationally, much of the technology required can be demonstrated now in the laboratory.

A similar technology, using intelligent *in situ* sensors, is greatly facilitated by Earth observation. Intelligent tags can be developed to sample the environment, or can be attached to animals to sample their blood supply. The use of GPS technology is essential to provide the positioning information necessary for the location of the instrument to be identified. As novel techniques described elsewhere in the report are deployed, this type of Earth observation technology becomes more necessary for providing the information needed to make sense of the *in situ* sensors.

5 Transport of infectious diseases

For the infectious diseases listed above on the detection of precursor conditions (Section 3), the link between variables that can be remotely sensed and the disease is actually related to the abundance and prosperity of the carrier/reservoir (although some of the diseases can be directly affected by temperature). In many past studies, this environmental link has been exploited rather than direct detection of the disease vector or of the disease itself. The main reason for this is the problems of spatial scale: detection of individual animals is extremely challenging from space. Indeed, this is probably impossible in the case of small insects, although insect abundance can be measured using ground-based radar over a limited area.

The box outlines the role of the UK Met Office in understanding the spread of foot-and-mouth disease in the last two major outbreaks. Improved estimates of the wind field, coupled with more sophisticated meteorological models, are key to predicting UK transmission once an outbreak is detected and could provide vital information for rapid-response measures.

<Begin Box>

Foot-and-mouth disease and the UK Met Office

John Gloster

Despite the relative difficulty, remote sensing does have some role in monitoring and predicting the transport of infectious diseases. In particular, remotely sensed observations and numerical weather prediction models can be of use in the case of airborne disease. In the 1960s, it was established that, given favourable atmospheric conditions, airborne disease spread could spread over tens of kilometres. In the 1981 UK outbreak of foot-and-mouth disease, windborne virus emitted from infected animals in Brittany (France) was believed to be the cause of the introduction of the pathogen to the Isle of Wight.

The spread of airborne disease is not controlled by introducing restrictions on the movement of livestock, personnel or vehicles. It can pass from one farm to another in the air. With knowledge of where disease is likely to spread, veterinary surveillance can be more actively targeted, thus reducing the overall duration of an outbreak. Knowledge of the extent of disease spread could also be used when considering the introduction of a vaccination programme.

A contract for operational support was set up between Defra and the Met Office around 1980. With regard to the Met Office's role during the 2001 UK epidemic, it was actively involved throughout the epidemic, supplying meteorological advice when requested by Defra or other government departments. Advice was sought on a range of topics. These included:

estimating the local spread from infected farms within the UK; the risk of spread to the Continent; and the risk of pyres spreading disease.

Virus emissions were estimated by veterinarians at the scene of an outbreak and combined with the results from experimental work at the Institute of Animal Health (IAH). These were used as input to the Met Office's atmospheric dispersion model. Downwind concentrations of virus were then estimated. These were turned into areas of risk, based on other work at the IAH concerning infection.

The following is an extract from one of our papers describing airborne spread during the outbreak: 'In the 2001 UK epidemic, airborne virus spread played a relatively minor role in spread of disease. This was primarily due to the relatively low quantities of virus released from animals infected with the 2001 UK virus strain. However, whilst overall the contribution was low, it is likely to have played a very significant role at the start of the epidemic, when airborne virus was the most likely cause for disease spread from Burnside Farm to Prestwick Hall Farm from where sheep were passed through Hexham and Longtown Markets to centres throughout the UK and caused widespread infection across the UK and abroad.'

There is much that is not known about airborne disease spread of foot-and-mouth disease. One fear is that the next outbreak will be from a much more virulent virus (from the airborne perspective), so the role of these observations would then be relatively more important.

Figure 6: *[gloster_FMD]* *Modelled risk of airborne foot-and-mouth disease transmission (courtesy of J. Gloster, Met Office)*

<End Box>

In addition to knowledge of precursor conditions which might encourage a particular disease vector to prosper, it might also be possible to monitor the movements of specific disease vectors. Satellite data can also play a role in predicting the movements of large-scale swarms of insects such as locusts (Reynolds and Riley 2002; Despland et al. 2004; Ji et al. 2004), which can have an indirect effect on human and animal health.

At a more experimental level, insects can be monitored using ground-based, vertical-looking radar, which can also be used to calculate the body mass of insects in the atmosphere (Chapman et al. 2002). One major drawback is that such systems are highly localised, so, currently, many radars would be required if the technique were to be deployed as a disease monitoring tool. At larger scales, there are still many difficulties to be overcome, such as problems with distinguishing between insects and water particles in the atmosphere (Khandwalla et al. 2003).

6 Management and mitigation of infectious diseases

Mapping techniques have been essential for managing the spread of infectious diseases. Even quite simple techniques of land cover mapping have been very useful for managing humanitarian aid. Respond is an alliance of European and international organisations working to improve access to maps, satellite imagery and geographical information in crisis situations. Map and image products of disaster events help target post-crisis healthcare responses where outbreaks of diseases such as cholera and dysentery would be expected.

Figure 7 shows a high-resolution image of the Cabinda area of Angola, which was produced in March 2005 for the WHO to aid their control of the Marburg virus. It shows an informal settlement that is not included in traditional maps, but one where knowledge of the existence of the settlement is important for the management of diseases. The delivery of such information in a timely fashion into the field is still challenging, especially in countries whose infrastructure has been damaged in a crisis. New observations, for instance, of topography using lidar altimetry, can only increase the usefulness of such observations.

Figure 7: High-resolution image of the Cabinda area of Angola, March 2005. Source: WHO.

7 Discussion

Many infectious diseases are at least partly dependent on environmental factors. Earth observation is greatly increasing our knowledge of many of these, and giving confidence in the estimates of them. Future advances in early warning systems of extreme weather events will be achieved in the coming years by using novel observations with fine-resolution models. A really important issue will be the timely availability of such environmental information in a way that it can be used effectively by agencies involved in the detection, identification and monitoring of infectious diseases. This involves both improved delivery systems and better education of users in the possibilities of such Earth observation systems.

Future climate changes will have an effect on the spread of infectious diseases and may accelerate the emergence of such infections. But the exact effect, and the relative significance of such effects, is still unknown. The challenge is to use the tools emerging from Earth observation to improve these predictions, as proposed by Chan et al. (1999), to predict disease prevalence in the next 10–100 years, and so to inform policy.

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