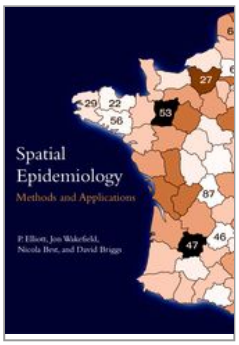


Spatial Epidemiology: Methods and Applications
Paul Elliott, Jon Wakefield, Nicola Best, and David Briggs

Print publication date: 2001
Print ISBN-13: 9780198515326
Published to Oxford Scholarship Online: September 2009
DOI: 10.1093/acprof:oso/9780198515326.001.0001

Disease mapping: a historical perspective

S. D. Walter

DOI:10.1093/acprof:oso/9780198515326.003.0012

Abstract and Keywords

This chapter reviews the history of disease mapping over the past two hundred years. Topics discussed include the early development of cartography, disease maps in the 19th century, disease maps from 1900–90, developments since 1990, and mapping in the 21st century.

Keywords: disease maps, spatial epidemiology, epidemiological studies, geographical analysis

12.1 Introduction

This chapter reviews the history of disease mapping over the past two hundred years. Medical geography is by now a substantial discipline, and space will permit only a sampling of the relevant literature; only selected examples of disease maps will be discussed, particularly those that illustrate points of methodology. There will be some emphasis on developments over the past ten years, and how they might suggest future directions in this field.

12.2 Early development of cartography

The creation of maps is an activity almost as old as recorded history. The earliest examples of maps from ancient civilisations in Mesopotamia and Egypt are as much as 5000 years old, and typically show important features of physical geography (such as mountains and bodies of water). Aspects of human activity were also mapped, for example to re-establish property lines after the annual floods of the Nile (Robinson *et al*. 1978).

In contrast to so-called *general* maps, which simultaneously represent several geographical phenomena, *thematic* maps display the spatial pattern of a single phenomenon, or sometimes the spatial relationships between several phenomena. Thematic cartography began around 1800, and was often stimulated by available data on the environment or society, for example on the weather or crime rates. Disease mapping began at about this time, motivated by a desire to evaluate geographical patterns in disease, and to identify risk factors that might explain those patterns.

12.3 Disease maps in the nineteenth century

Early disease maps often concerned infectious diseases, particularly yellow fever in the United States and cholera in Europe. Stevenson (1965) reports examples by Seaman just before 1800, spot maps that show the street locations of individual cases of yellow fever **(p.224)** in New York. Similar maps in the early nineteenth century were used in the miasma-contagion debate. Areas with a suitable environment (warm temperatures and poor drainage) were supposed to suffer from a ‘pathogenic mist’ causing the disease, rather than the disease being spread by person-to-person transmission.

The cholera maps in Europe followed the same approach, sometimes showing mortality on a national scale, such as in Britain (Peterman 1852, cited by Howe 1989). A more recent example shows risks in parts of the Ganges Delta (Fig. 12.1); note that in addition to the case locations, it indicates areas of slow water flow below a certain height contour, a possible risk factor for the disease. At a local street level, the spot map approach was used most famously by John Snow (1855) in London, to demonstrate the spread of cholera through contaminated water.

(p.225) It should be noted that spot maps show only the case numerators, and do not take underlying population denominators into account. They therefore fail to provide disease rates, as would be expected by the contemporary epidemiologist. Interpretation of a spot map has to be supplemented by knowledge of the population residential density; or the distribution of potential risk factors. In examples, such as the Ganges cholera map, one cannot infer much about geographical differences in risk without also knowing about the population distribution in the area. In Snow's investigation interpretation was aided by information on the water distribution system.

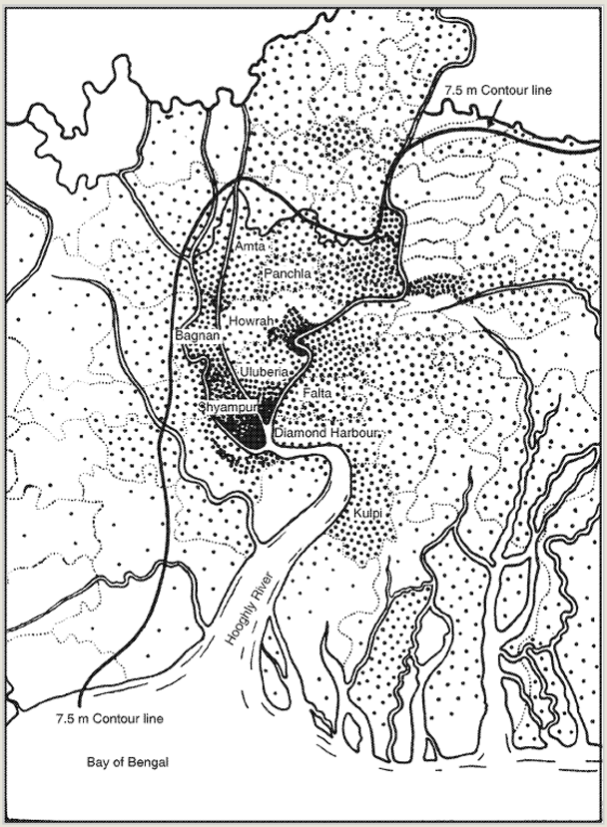


Fig. 12.1 Spot map of cholera in the Ganges Delta, 1936 (Jusatz 1977). Note that data reflect the case numerators only.

Since the nineteenth century, interest in mapping infectious disease has continued, including the use of 'diffusion' maps to examine the spread of disease on a wider scale. Examples include the spread of cholera (see Fig. 12.2), influenza (Hunter and Young 1971), measles (Cliff *et al*. 1981), and a reconstruction of the spread of plague in the fourteenth century (Carpentier 1962). Other examples are considered in Chapter 14.

In a notable exception to the preoccupation at the time with the threat of infectious diseases, Haviland (1875) pioneered mapping of chronic disease, including heart disease and cancer in England and Wales. Haviland used mortality data from 1851–60: centralised, vital registration had been in existence since 1839. Combining mortality numerators

(p.226) with populations from the census, he computed crude death rates, thus becoming one of the first epidemiologists systematically to take denominators into account in a geographical analysis. Haviland recognised a problem that persists in disease maps even today, that of possible instability in the rates. He stated;

> … the numbers … that I use are proportional, not absolute: and being so, it is all the more necessary that the gross sum from which they are deduced should be as large as possible.

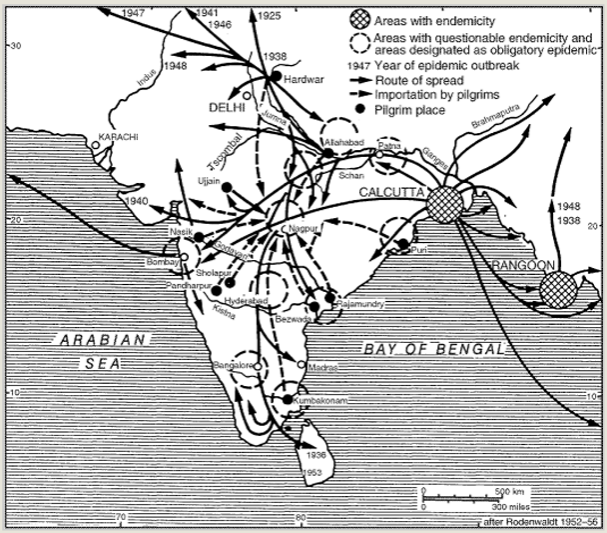


Fig. 12.2 Diffusion of cholera in Asia, 1931–55 (Learmonth 1972). Note postulated routes of transmission between endemic areas, dates of diffusion and postulated high risk groups (pilgrims).

Haviland claimed to detect distinct regional patterns in mortality throughout the country; areas of high risk were coloured in blue (possibly by analogy with cyantotic blood) and low risk in red (healthy, oxygenated blood)—the opposite of the common modern convention to show *high* risk in red.

12.4 Disease maps 1900–90

Disease mapping in this century has been dominated by the production of numerous national and regional atlases of chronic diseases, particularly cancer. The United Kingdom and the United States were prominent early participants, and atlases published in those countries demonstrate some evolution in methodology.

12.4.1 The United Kingdom

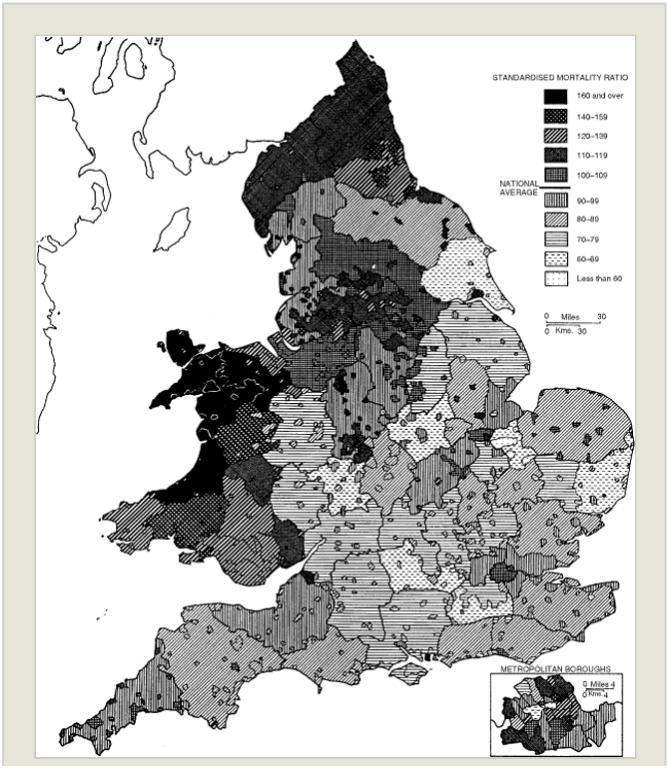
In the 1920s and 1930s, Stocks produced a series of cancer mortality maps for England and Wales (Stocks 1928, 1936, 1937, 1939). An important methodological advance was an adjustment for regional differences in age and sex, thus avoiding possibly biased comparisons of crude rates, as in Haviland’s work more than fifty years earlier. These maps also stimulated a formal statistical assessment of the spatial pattern in the data (Cruickshank 1947).

Stocks' work was updated by Howe (1963) in a national atlas for 13 major causes of death in 1954–8. A typical map is shown in Fig. 12.3; the standardised mortality ratio (SMR) is the function plotted, using the choropleth method in which each geographical area of analysis is shaded according to its data value. In a later revision (Howe 1970), a plotting symbol was used for each area, with size representing the base population. Modifications to the plotting symbols also indicated urban versus rural areas and statistical significance. Further updates in the 1980s (Gardner *et al*. 1983, 1984; Howe 1989) have followed essentially the same methods, with the addition of colour.

Use of plotting symbols was prompted in part by a desire to reduce the visual impact of large areas with small populations; these areas may dominate choropleth maps. Another option is the cartogram (Dorling 1995). This distorts the area (and shape) of the spatial units to make them proportional to the denominator variable. One example is the iso-demographic map, which distorts the base geographical map to have approximately equal population density. Figure 12.4 shows an iso-demographic map for influenza in England and Wales.

In Scotland, data from five regional registries were combined to show national maps of cancer incidence (Kemp *et al*. 1985). Geographical clustering of high risk areas was also examined using a rank adjacency statistic.

(p.227)



12.4.2 The United States

Disease mapping at the national level in the US began somewhat later than in Britain. Early work (Burbank 1971) had suggested some geographical variation in mortality rates, **(p.228)**

Fig. 12.3 Choropleth map showing cancer mortality of the stomach (males) in England and Wales (from Howe 1963: 33). Note the use of classed choropleths, and the inset for densely populated area. Mapped function is the standardised mortality ratio.

although not as great as international differences. National atlases were produced showing approximately 3000 area-specific cancer mortality rates in whites (Mason *et al*. 1975) and non-whites (Mason *et al*. 1976), plus non-cancer mortality (Mason *et al*. 1981). Later updates showed trends in risk during 1950–80 (Pickle *et al*. 1987, 1990).

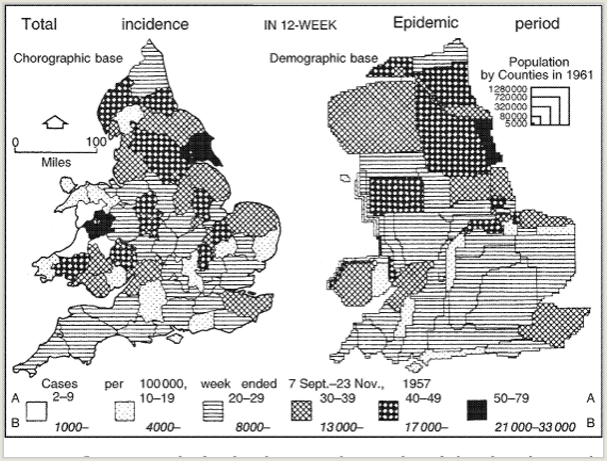


Fig. 12.4 Influenza in England and Wales, 1957, showing choropleth and iso-demographic maps (from Learmonth 1978). The left panel represents notified cases of acute pneumonia; the right panel represents estimated cases of influenza based on pneumonia rates. Note the increased impact of densely populated southeastern areas and reduced impact of areas such as North Wales in the iso-demographic projection.

The American atlases used choropleths, with areas such as counties. The plotted data function has usually been the age-adjusted rate; areas in the highest decile of risk relative to the national rate are shown, together with an indication of statistical significance. Values significantly lower than the national rate are also differentiated, but without regard to their decile group. Some of the trend analyses (Pickle *et al*. 1987, 1990) have plotted only those areas in which mortality was increasing or decreasing at a statistically significant rate.

12.4.3 Other countries

Many other countries have initiated disease mapping over the last forty years. A survey of disease atlases and their methods in 1991 (Walter and Birnie 1991) showed that most concerned cancer in developed countries. The majority involved mortality data from the **(p.229)** 1960s and later, although a few were able to use incidence figures, or data from earlier years (e.g. Finland accessed cancer incidence starting in 1953, Pukkala *et al*. 1987). Only a few examples existed of international collaboration, from the European Community and the Nordic countries. The 1991 survey revealed the following points:

1. ***Data selection*** There was considerable variation in the diseases selected, and in the diagnostic categories used. For example, cancer was variously grouped into as few as 4 or as many as 36 categories by different countries.
2. ***Numerators and denominators*** Information was often lacking on case numerators or population denominators, making it impossible to assess the precision of the mapped values of disease risk.
3. ***Units of analysis*** The regional units of analysis also varied considerably in size. Many regions had such small expected frequencies that random variation would dominate the data. Interestingly, the smaller regions tended to occur in atlases that covered larger total populations.
4. ***Criteria for mapping*** Criteria for selecting a diagnostic group for mapping, or for plotting regional values on a map, were frequently not stated. A few atlases offered criteria based on min imum case frequencies, population sizes, or population density.
5. ***Data function to be mapped*** The most commonly plotted data function was the relative risk (or equivalent), possibly in conjunction with statistical significance. Other functions included case frequencies or statistical significance alone. The choice of function makes an enormous difference to the appearance of the map, but the rationale for the choice adopted was rarely discussed.
6. ***Mapping method*** Most atlases used choropleth shading, but a few used plotting symbol to indicate the levels of other variables. Data smoothing was used only rarely.
7. ***Age-standardisation*** Age-standardisation was used by almost all atlases, most often with the indirect method. Contrary to expectation, atlases using the direct method tended to have smaller regional populations and case frequencies than those using the indirect method. Age groups used in the standardisation were often not reported.
8. ***Colour*** About half the atlases used colour. Red usually indicated high risk, but there were many exceptions. Colour schemes to represent average risk, low risk, and missing values were highly variable.
9. ***Trend and spatial analysis*** Time trend analysis was included in about half of the atlases, but only a few statistically assessed the spatial pattern. Some atlases provided informal verbal summaries of the patterns, but few attempted any substantive aetiologic interpretation. Few provided supplemental data or maps on important covariates (e.g. Socio-economic status, smoking, occupation, climate).

In summary, the position in the early 1990s was that the methodology of disease mapping varied considerably between countries. Many atlases failed to provide the basic information needed for a rigorous appraisal of the geographical disease patterns they displayed. Comparisons between atlases, especially internationally, was made difficult by numerous differences in their methods, particularly concerning disease definitions, data summarisation and mapping techniques. The Walter and Birnie (1991) survey concluded with a set of proposed guidelines to alleviate these problems in the future.

A few maps published before 1990 illustrate specific points of interest. The Finnish cancer atlas (Pukkala *et al*. 1987) was one of the earliest to use data smoothing, with a geometric centroid approach. Although this alleviates the difficulty of unstable rates, it has the disadvantage of 'smearing out' the rates in regions with sparse populations. The impact of excess risks in isolated towns can then be magnified as the rates are smoothed out into surrounding rural areas. Finland also provides a rare example of mapping *prevalence* by region (Hakulinen *et al*. 1989). This work is also unique in offering projections **(p.230)** of incidence and prevalence into the future, by modelling the incidence rates by region, age, period, and cohort.

Vershasselt and Timmermans (1987) have proposed a three-dimensional plot for cancer mortality, but this idea has not been widely adopted. The study by Martinez *et al*. (1998) of heat-related deaths is an example of mapping acute events in small geographical areas, using dot and choropleth methods. Some maps have used risk contours instead of choropleths, for example in Australia (Fig. 12.5), but this idea has not been adopted often.

In addition to the proliferation of disease atlases, the 1970s and 1980s saw the publication of a number of texts in the growing discipline of medical geography. They dealt with various diseases, often on a global scale, and associated methods (Howe 1977; McGlashen 1972; Learmonth 1978; McGlashen and Blunden 1983; Hutt and Burkitt 1986; Cliff and Haggett 1988; Boyle *et al*. 1989). Learmonth (1972) provided more details of mapping in the period 1950–70.

The existence of disease maps had the effect of stimulating epidemiologic studies to investigate areas of high risk. In the USA, for example, several studies of potential hazards from occupational exposures, lifestyle factors, or the environment were initiated (National Cancer Institute 1987).

(p.231) 12.5 Developments since 1990

The 1990s have seen a widening of scope of disease maps. Many countries have expanded or updated their national atlases, while others have published them for the first time. Some local authorities have begun to map health data in smaller administrative areas. Several major international atlases have appeared, showing disease patterns on a wide scale. Some new causes of morbidity and mortality have been examined. Selected examples of these new publications will now be given.

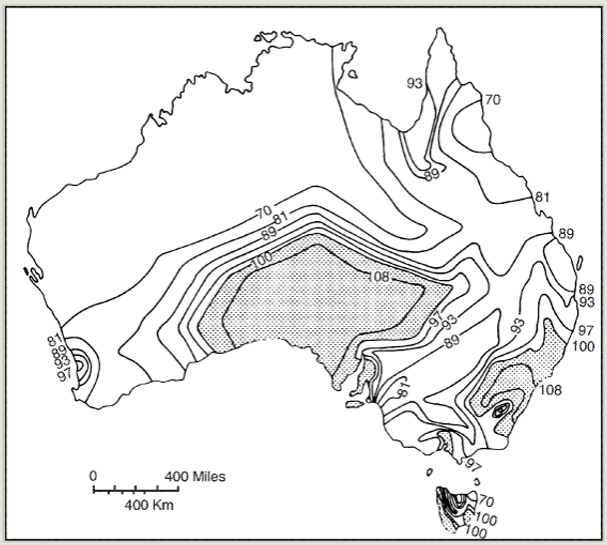


Fig. 12.5 Contour map of heart disease mortality in Australia, males, 1965–66 (from Howe *et al*. 1977). Map function if the standardised mortality ratio. Note use of inter-contour shading for areas of excess risk.

The Canadian federal government has extended its series of atlases, to examine general mortality and time trends. Particular interest in the spatial pattern is evinced by the fact that causes of death were selected for mapping in part because of their ‘quality and/or uniqueness of the spatial distribution’. In other words, regional differences themselves were used as a data selection criterion (Health and Welfare Canada 1991).

More recently, a Canadian atlas of cancer incidence has appeared (Le *et al*. 1996; see Plate 1). Cancer is registered provincially, so considerable attention was paid to the quality and comparability of the data from contributing registries. Geographical patterns may arise artefactually from differences in nosology, data completeness, and accuracy. Further points to note include: the stated criteria for the selection of cancer sites; a stated rationale for the choice of cut-points on the map’s colour scale; and an assessment of the spatial pattern through Moran’s I-statistic (see Chapter 8), with a new bootstrap estimate of its confidence interval. Relative to the large area of the country, Canada’s population is highly concentrated; the base map projection is intended to reduce the impact of sparsely populated areas, and a neutral colour is used to indicate the substantial areas of the country with essentially no data.

In the Ontario cancer incidence atlas (Marrett *et al*. 1995; see Fig. 12.6), an unclassed choropleth method is used; this avoids subjective bias associated with the arbitrary choice of the number and width of class intervals. The atlas also allows for discrepancies between perceived and actual intensity of shading. Statistical significance in census districts is indicated by '+' and '−' overlays, and Moran's I-statistic is used to assess the spatial pattern. The base map uses an inset to show the sparsely populated northern areas on a larger scale.

Much smaller geographical areas (census sub-divisions) were examined in the Great Lakes Health Effects Program, which produced atlases of cancer, birth defects, and hospital morbidity in Ontario (Mills and Semenciw 1992; Johnson *et al*. 1992; Health Canada 1993).

The 1996 US mortality atlas (Pickle *et al*. 1996) shows age-adjusted rates by sex and race. As in previous US publications, the data are also shown as risks relative to the national average, with categories defined by a combination of percentiles and statistical significance. Smoothed regional rates are computed. Data on a given cause of death are presented in five different forms, with different colours for each. The style of presentation was guided by associated research on cognition; this indicated a preference for classed choropleths, and that plotting symbols were not feasible for the US map because of its large number of areas (see Chapter 13 and Plate 3).

An earlier US publication (Devine *et al*. 1991) investigated injury mortality, covering deaths such as homicide, falls, and drowning. Empirical Bayes smoothing (Chapters 7 and 15) was used on age–specific rates by county, which were subsequently **(p.232)**

age–standardised. National and state maps include an estimate of the excess deaths, relative to the national mean.

Several European countries have recently published disease maps, and some present new methodological points. The cancer mortality atlas of Poland (Zatoński *et al*. 1993) used a geographical centroid smoothing method, with weights inversely proportional to the distance from the point being smoothed, and directly proportional to the population denominator. Special plotting symbols show the rates in large cities.

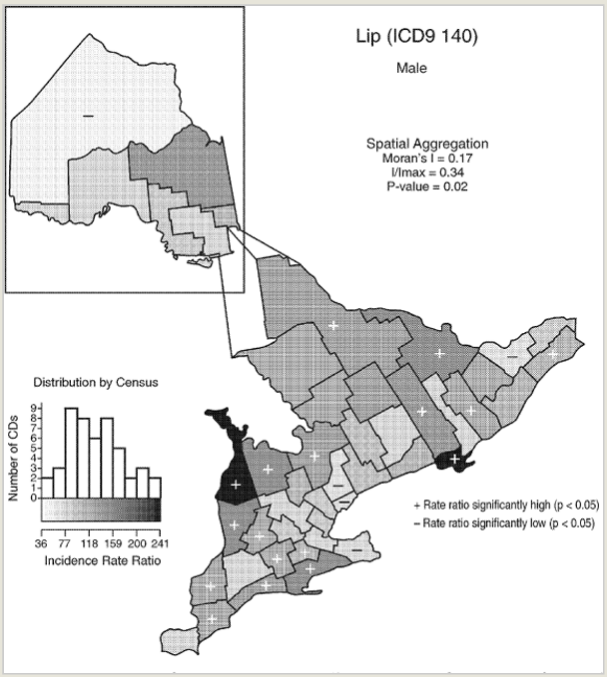


Fig. 12.6 Lip cancer incidence, Ontario 1980–91 (from Marrett *et al*. 1995). Note the use of unclassed choropleths, inset for sparsely populated areas, map overlays to indicate statistical significance, rate histogram, and summary index of spatial aggregation.

(p.233) Special plotting symbols are also used in the mortality atlas for Estonia (Baburin *et al*. 1997), which discussed the difficulty of converting the several Russian versions of the ICD that had been in use during the data collection period (1968–92). Some jurisdictions, for example, Norway (Cancer Registry 1998) and Sweden (Regional Oncologic Centres 1996), have continued to exploit their high quality disease registration systems to issue atlases of cancer incidence, thus also avoiding interpretational problems associated with mortality data (Boyle 1989).

An atlas of cancer mortality in Switzerland (Schüler and Bopp 1997) stabilises the mapped rates with a new method based on mean ranks over time. Continuous shading with overlays to indicate statistical significance is used, similar to the Ontario cancer incidence atlas. Other features include the display of data by language regions of the country and by size of community; and the detailed attempt at aetiological explanation of the geographical patterns observed.

In its mortality atlas, Spain (Ortega *et al*. 1996) joins the small group that have included a statistical examination of the spatial pattern, using the rank adjacency statistic pioneered in atlases in Scotland (Kemp *et al*. 1985) and Italy (Cislaghi *et al*. 1986). Maps of southern Sweden (Southern Swedish Regional Tumour Registry 1994) use plotting symbol overlays to show the number of cancer cases in each region.

The Europeans have also made considerable progress in the field of international disease mapping, with the recent publication of three major atlases. The European Community (EC) atlas of cancer mortality (Smans *et al*. 1992) assembled data from nine countries, with 355 regions. International mortality comparisons involve additional questions of data comparability and accuracy. Although previous literature suggests substantial international differences in how deaths are coded (Percy *et al*. 1981; Boyle 1989), no study of this question had been carried out in all the countries contributing to the EC atlas. Some indirect markers of data quality were available, such as the proportion of deaths occurring in hospital, but the potential for systematic between-country bias is strong. Indeed, several maps in this atlas show evidence of changes in risk at international boundaries. It is not clear if these effects are related to true differences in risk, or to cultural differences in how deaths are classified.

The EC authors discuss some other issues of methodology that arise when considering such a large and diverse geographical area. The role of chance in labelling particular regions as having extreme risk is prominent. They also consider potential biases associated with inaccurate denominators and migration effects, especially with respect to the surprisingly low risk seen in Southern Italy for many causes of death.

The atlas of cancer mortality in Central Europe (Zatoñski *et al*. 1996) used mortality and trend data from nine other countries. Major issues of data quality and comparability arose here also. The authors discussed the process of death coding in the various countries, and considered measures of quality such as the proportion of autopsies, ill-defined causes of death, and ‘vague site’ classifications. Substantial international variation existed in these indices, with the implication that some of the geographical patterns found could be artefactual. While these potential problems in the mortality data should be recognised, the preferred incidence data are not yet available in these countries.

Lastly, the atlas of mortality in Europe (WHO 1997) is perhaps the most ambitious collaborative project of this type to date. It covers 50 countries in the European Region of the WHO, with a total population of approximately 850 million people. Mortality data are shown as rates and histograms for 1980/91 and 1990/91. Numerous discrepancies and **(p.234)** idiosyncracies occurred in the assembly of data. Compilation required elimination of non–comparable data groupings, and 'plausibility checking' to eliminate clerical and programming errors. Despite these attempts to improve data quality, apparent risk differences are still observed at national boundaries, as occurred in the EC atlas. For example (Plate 2), international boundaries can be discerned quite easily in the map of mortality from ischaemic heart disease. The European atlas has the progressive feature of allowing Internet access via its website (http://www.euromort.rivm.nl). Users can access maps of their own choosing, with control over data time period, cause of death, and sex. Some details of contributing nations and local area data are also available.

The worldwide distribution of AIDS has been examined recently (Smallman–Raynor *et al*. 1992). This atlas uses conventional mapping techniques, but also includes maps of the disease diffusion based on stochastic modelling. A considerable amount of data at the national and regional levels is also provided. This atlas represents an interesting return to mapping infectious diseases, but with modern techniques.

As in earlier years, the existence of disease maps has stimulated the execution of targeted epidemiological studies, and the development of new mapping methods. There has been some interest in trend surface analysis, to identify local deviations in risk after adjustment for regional effects or relevant covariates (e.g. Cislaghi *et al*. 1990; Jones *et al*. 1992; Sturgeon *et al*. 1995; Sinha and Benedict 1996). Smoothing, in conjunction with covariate adjustment, has also been proposed (Kafadar 1997). Some studies attempt to use geographical patterns to demonstrate the effect of preventive interventions, such as cervical cancer screening (Lazcano–Ponce *et al*. 1996).

A small amount of work has taken place concerning the perceptual psychology of maps. Experimental evidence has shown that the impact of a map can be substantially affected by 'incidental' features such as the type of shading used, and that there may be differences between the statistical and visual impressions of the data. Perception may also depend on the inherent complexity of the base map (Walter 1993). Map features, such as plotting symbols, have been used very successfully in some circumstances, but they may not be feasible for maps with large numbers of areas (Pickle *et al*. 1996). Use of colour, while having aesthetic appeal, may nevertheless be confusing to the map reader (Wainer and Francolini 1980); and makes accurate photo–reproduction more difficult. The choices of data collection periods and mapping categories can also be debated (Hole and Lamont 1992; Cromley and Cromley 1996).

Interpretation of the spatial relationships of diseases to risk factors are complicated by the so–called ecological fallacy (Walter 1991; Greenland and Robins 1994; Chapter 11). Even greater analytic complexity occurs when risk factors are measured at several levels of geographical scale (e.g. Duncan *et al*. 1993; Langford *et al*. 1998).

12.6 Mapping in the twenty-first century

Recent years have seen a rapid growth in the availability of data suitable for geographical analysis, and in the methods for producing disease maps. The 1991 survey (Walter and Birnie 1991) highlighted the diversity in approaches used in various countries, and this diversification has continued in the past decade. Accordingly, it seems dangerous to make detailed prognostication about future directions. There are, however, a few broad trends, which might be conjectured to persist.

(p.235)

1. ***International cooperation*** As noted earlier, international comparisons between national disease atlases have previously been hampered by their substantial differences in methodology. Continued collaboration between the European countries is therefore an encouraging sign. With the new European atlases, one can make broad–scale geographical comparisons, based on methods that are nominally consistent. There remain concerns about data quality, and some of the apparent regional trends may be due in part to methodological artefacts, rather than true environmental effects. The same may also be true within countries, such as between the provinces of Canada. *We may anticipate further efforts at inter-jurisdictional cooperation in the future*.
2. ***Use of incidence data*** There have been an increasing number of cancer atlases based on incidence data. As noted earlier, incidence data are much preferable, avoiding many biases associated with mortality data. Many countries, however, still do not possess population–based cancer registries to estimate incidence. *One may hope for an expansion of cancer incidence registration to the many places that currently have to rely on mortality data*.
3. ***Maps of non-cancer diseases*** Incidence data for non–cancer disorders is at a primitive stage, and only isolated examples of maps for problems, such as birth defects exist currently. *There may be greater emphasis in future disease maps on causes of morbidity such as injuries, mental disease, and non-cancer chronic disease, which have received little attention to date*.

4. ***Adoption of statistical methods*** *As shown elsewhere in this book, there has been a dramatic increase in the scope and complexity of statistical techniques for the analysis of geographical health data, but so far this has had relatively little impact on how disease maps are produced in practice*. For example, while a few atlases show smoothed rates (using geographical smoothers or empirical Bayes methods), the vast majority continue to show only unsmoothed data. It seems that this is partly because of some distrust of statistical manipulation of any kind by local heath authorities; administrators and medical officers of health want to see their rates, uncontaminated (as they see it) by statistical adjustments of any kind.

A case in point arose during the production of the Ontario cancer atlas (Marrett *et al*. 1995). It was discovered that Bayesian smoothed rates in many smaller regions were substantially affected by the dominant effects of one or two locations that had much larger populations. Future users of the atlas had a strong preference to see the data in ‘raw’ form in the first place; showing smoothed data as well would have meant approximately doubling the size of the atlas, which then became infeasible. It may be assumed that this experience is not an isolated one. Smoothing was employed, however, in the most recent US mortality atlas (Pickle *et al*. 1996); smoothing may be more feasible here, given the relatively large number of units of analysis.

A similar picture emerges with respect to the analysis of spatial pattern. Despite the wide range of statistical techniques available, to date only a few atlases have included statistical measures of geographical clustering in the data. Most present merely a subjective verbal description of the data patterns.

5. ***Trend analysis*** *There have been an increasing number of atlases that consider changes in the pattern of risk over time*. This may reflect the increasing data collection periods provided by centralised disease and death registration systems. Analysis of space–time interaction is an appealing way to obtain greater insight into disease aetiology, but as the time–span of the analysis increases, one must be cautious about possible artefactual changes in the data. These would include issues, such as changes in disease coding, and completeness and accuracy over time, especially if such changes might have a geographical component.

6. ***Choice of data function to be mapped*** The earlier survey (Walter and Birnie 1991) revealed substantial inconsistencies between countries in the methods used, including the choice of function to be mapped. *Inconsistency persists in more recent atlases, with a mixture of rate values and statistical significance being plotted simultaneously or separately*. Recently, there has perhaps **(p.236)** been greater recognition of the potential misinterpretation of statistical *p*–values, in particular that significant deviations in risk are more likely to occur in large populations, even if the actual deviations are small. Nevertheless, one continues to see maps where this problem is not acknowledged. The reluctance of map publishers to used smoothed data probably reflects lack of familiarity on the part of users and a continuing desire by consumers to inspect their basic data at the local level.
7. ***Increasing access to mapping technology*** The development of powerful computers has been a major force in the potential for disease mapping. It is likely that this trend will continue, so that larger databases and more rigorous analytical methods will become accessible to a wide circle of consumers. The availability of the European mortality atlas on the Internet is probably only the first such venture. *In the future we will likely see capability for on-line manipulation of data to create maps to the user's specifications, and an interface with other databases containing information on relevant covariables*.
8. ***Reduction of publication times*** To date the interval between data collection and map publication has typically been measured in years. *We may expect the greater availability of rapid computing to reduce publication times, and make disease maps more useful as a tool for ongoing health surveillance*.
9. ***Integration of risk factor information*** Atlases to date have focused primarily on the disease data, with little attention to possible risk factors. *It is likely that we will see improved integration of disease and risk factor databases, enhanced capability to map such data simultaneously, and to understand their relationships*. Multi–level analysis is emerging as an important statistical technique for risk factor analysis in epidemiology, but limited methodology exists for effectively mapping this type of data. *A particular challenge will be to develop suitable cartographic methods to display covariates measured at several levels of scale*.

10. ***Geographical scope of future maps*** In the early development of disease maps, there was much concern with the worldwide spread of infectious diseases, including the interplay between the developed and the developing world. *Most of the activity in this century has nonetheless been dominated by work in the developed countries*. Large parts of the world's population live in territory still uncharted by the medical geographer. *One may hope that this situation will improve with increasing globalisation of science, the growing importance of the developing countries, and the recognition that disease does not respect political boundaries*.

Acknowledgements

This work was supported in part through a National Health Scientist award from Health Canada

References

Bibliography references:

Baburin, A., Gornoi, K., Leinsalu, M., and Rahu, M. (1997). *Atlas of mortality in Estonia*. Institute of Experimental and Clinical Medicine, Tallinn.

Boyle, P. (1989). Relative value of incidence and mortality data in cancer research. In *Cancer mapping* (P. Boyle, C. S. Muir, and E. Grundmann ed.). Springer, Berlin.

Boyle, P., Muir, C., and Grundmann, E. (ed.) (1989). *Cancer mapping*. Springer, Berlin.

Burbank, F. (1971) Patterns in cancer mortality in the United States: 1950–70. *National Cancer Institute Monograph*, **33**, 1–594.

(p.237) Cancer Registry (1998). *Cancer in Norway 1995*. Cancer Registry of Norway, Oslo.

Carpentier, E. (1962). Autour de la peste noire: famines et epidemies dans l'histoire du xiv eme siécle. *Annals of Economic and Social Civilisations*, **17**, 1062–92.

Cislaghi, C., DeCarli, A., LaVecchia, C., Laverda, N., Mezzanotte, G., and Smans, M. (1986). *Data, statistics and maps on cancer mortality, Italy 1975/77*. Pitagora Editrice, Bologna.

Cislaghi, C., DeCarli, A., LaVecchia, C., Mezzanotte, G., and Vigotti, M.A. (1990). Trend surface models applied to the analysis of geographical variations in cancer mortality. *Revue d'Epidemiologie et de Santé Publique*, **38**, 57–69.

Cliff, A. D. and Haggett, P. (1988). *Atlas of disease distributions: analytic approaches to epidemiologic data*. Blackwell, Oxford.

Cliff, A. D., Haggett, P, Ord, J. K., and Versey, G. R. (1981). *Spatial diffusion*. Cambridge University Press.

Cromley, E. K. and Cromley, R. G. (1996). An analysis of alternative classification schemes for medical atlas mapping. *European Journal of Cancer*, **32A**, 1551–9.

Cruickshank, D. B. (1947). Regional influences in cancer. *British Journal of Cancer*, **1**, 109–28.

Devine, O. J., Annest, J. L., Kirk, M. L., Holmgreen, P., Emrich, S. S., Rosenberg, M. L. *et al*. (1991). *Injury mortality atlas of the United States, 1979–87*. US Department of Health and Human Services, Atlanta.

Dorling, D. (1995). *A new social atlas of Britain*. Wiley, Chichester.

Duncan, C., Jones, K., and Moon, G. (1993). Do places matter? A multi–level analysis of regional variations in health–related behaviour in Britain. *Social Science and Medicine*, **37**, 725–33.

Gardner, M. J., Winter, P. D., Taylor, C. P., and Acheson, E. D. (1983). *Atlas of cancer mortality in England and Wales 1968–78*. Wiley, Chichester.

Gardner, M. J., Winter, P. D., and Barker, D. J. P. (1984). *Atlas of mortality from selected diseases in England and Wales 1968–78*. Wiley, Chichester.

Greenland, S. and Robins, J. (1994). Ecologic studies—biases, misconceptions and counter examples. *American Journal of Epidemiology*, **139**, 747–60.

Hakulinen, T., Kenward, M., Luostarinen, T., Oskanen, H., Pukkala, E, Söderman, B. *et al*. (1989). *Cancer in Finland in 1954–2008*. Finnish Cancer Registry, Helsinki.

Haviland, A. (1875). *The geographical distribution of diseases in Great Britain*. Smith Elder, London.

Health and Welfare Canada (1991). *Mortality atlas of Canada*. Vol. 4: *General mortality patterns and recent trends*. Government of Canada, Ottawa.

Health Canada (1993). *Hospital morbidity atlas, Ontario: 1985–88*. Government of Canada, Ottawa.

Hole, D. J and Lamont, D. W. (1992). Problems in the interpretation of small area analysis of epidemiologic data. *Journal of Epidemiology and Community Health*, **46**, 305–10.

Howe, G. M. (1963). *National atlas of disease mortality in the United Kingdom*. Nelson, London.

Howe, G. M. (1970). *National atlas of disease mortality in the United Kingdom*, (2nd edn). Nelson, London.

Howe, G. M. (ed) (1977). *A world geography of human diseases*. Academic Press, London.

Howe, G. M. (1989). Historical evolution of disease mapping in general and specifically of cancer mapping. In *Cancer mapping* (P. Boyle, C. S. Muir, and E. Grundmann ed.), 1–21. Springer, Berlin.

Howe, G. M., Burgess, L., and Gatenby, P. (1977). Cardiovascular disease. In *A world geography of human diseases* (G. M. Howe, ed.). Academic Press, London.

Hunter, J. M. and Young, J. C. (1971). Diffusion of influenza in England and Wales. *Annals of the Association of American Geographers*, **61**, 627–31.

Hutt, M. S. R. and Burkitt, D. P. (1986). *The geography of non-infectious diseases*. Oxford University Press.

Johnson, K., Rouleau, J., and Stweart, C. (1992). *Birth defects atlas of Ontario 1978–88*. Health Canada, Ottawa.

Jones, M. E., Shugg, D., Dwyer, T., Young, B., and Bonett, A. (1992). Interstate differences in incidence and mortality from melanoma. *Medical Journal of Australia*, **157**, 373–8.

Jusatz, H. (1977). Cholera. In *A world geography of human diseases* (G. M. Howe ed.). Academic Press, London.

Kafadar, K. (1997). Geographical trends in prostate cancer mortality: an application of spatial smoothers and the need for adjustment. *Annals of Epidemiology*, **7**, 35–45.

(p.238) Kemp, L, Boyle, P., Smans, M., and Muir, C. (1985). *Atlas of cancer in Scotland, 1975–80*. International Agency for Research on Cancer, Scientific Publication 72. IARC, Lyon.

Langford, I. H, Bentham, G., and McDonald, A. (1998). Multi–level modelling of geographically aggregated data. *Statistics in Medicine*, **17**, 41–57.

Lazcano–Ponce, E. C., Rascon–Pacheco, R. A., Lozano–Ascencio, R., and Velasco–Mondragon, H. E. (1996). Mortality from cervical carcinoma in Mexico: impact of screening, 1980–90. *Acta Cytologica*, **40**, 506–12.

Le, N. D., Marrett, L. D., Robson, D. L., Semenciw, R. M., Turner, D., and Walter, S.D. (1996). *Canadian cancer incidence atlas*. Government of Canada, Ottawa.

Learmonth, A. (1972). Atlases in medical geography 1950–70: a review. In *Medical geography: techniques and field studies* (N. D. McGlashen ed.). Methuen, London.

Learmonth, A. (1978). *Patterns of disease and hunger*. David & Charles, London.

Marrett, L. D., Nishri, E. D., Swift, M. B., Walter, S. D., and Holowaty, E. J. (1995). *Geographical distribution of cancer in Ontario*. Vol. II: *Atlas of cancer incidence 1980–91*. Ontario Cancer Treatment and Research Foundation, Toronto.

Martinez, B F., Annest, J. L, Kilbourne, E. M., Kirk, M. L., Lui, K–J., and Smith, S. M. (1989). Geographical distribution of heat–related deaths among elderly persons. *Journal of American Medical Association*, **262**, 2246–50.

Mason, T. J., McKay, F. W., Hoover, R., Blot, W. J., and Fraumeni, J. F. (1975). *Atlas of cancer mortality for U.S. counties: 1950–69*. US Government Printing Office, Washington, DC.

Mason, T. J., McKay, F. W., Hoover, R., Blot, W. J., and Fraumeni, J. F. (1976). *Atlas of cancer mortality among U.S. nonwhites: 1950–69*. US Government Printing Office, Washington, DC.

Mason, T. J., Fraumeni, J. F., Hoover, R., and Blot, W. J. (1981). *An atlas of mortality from selected diseases*. US Government Printing Office, Washington, DC.

McGlashen, N. D. (ed.) (1972). *Medical geography: techniques and field studies*. Methuen, London.

McGlashen N. D. and Blunden, J. R. (ed.) (1983). *Geographical aspects of health*. Academic Press, London.

Mills, C. and Semenciw, R. (1992). *Cancer incidence in the Great Lakes region, Ontario: 1984–88*. Health Canada, Ottawa.

National Cancer Institute (1987). *Backgrounder: research contributions made possible by the NCI cancer atlases published in the 1970s*. Office of Cancer Communications. NCI, Bethesda, MD.

Ortega, G. L–A., Santamaría, M. P., Pujolar, A. E., Saizar, M. E., and Santos, V. A. (1996). *Atlas of cancer mortality and other causes of death in Spain 1978–92*. Fundación Científica de la Asociación Española contra el Cáncer, Madrid.

Percy, C., Stanek, E., and Gloeckler, L. (1981). Accuracy of death certificates and its effect on cancer mortality statistics. *American Journal of Public Health*, **71**, 242–50.

Petermann, A. H. (1852). *Cholera map of the British Isles showing the districts attacked in 1831, 1832 and 1833. Constructed from official documents*. Betts, London.

Pickle, L. W., Mason, T. J., Howard, N., Hoover, R., and Fraumeni, J. F. (1987). *Atlas of U.S. mortality among whites: 1950–80*. US Government Printing Office, Washington, DC.

Pickle, L. W., Mason, T. J., Howard, N., Hoover, R., and Fraumeni, J. F. (1990). *Atlas of US mortality among nonwhites: 1950–80*. US Government Printing Office, Washington, DC.

Pickle, L. W., Mungiole, M., Jones, G. K., and White, A. A. (1996). *Atlas of United States mortality*. National Centre for Health Statistics, Hyattsville, MD.

Pukkala, E., Gustavsson, N., and Teppo, L. (1987). *Atlas of cancer incidence in Finland 1953–82*, publication 37. Cancer Society of Finland, Helsinki.

Regional Oncologic Centres (1996). *Atlas of cancer incidence in Sweden*. Karolinska Hospital, Stockholm.

Robinson, A., Sale, R., and Morrison, J. (1978). *Elements of cartography* (4th edn). Wiley, New York.

Schüler, G. and Bopp, M. (1997). *Atlas der Krebsmortalität in der Schweiz 1970–90*. Birkhäuser, Basel.

Sinha, T. and Benedict, R. (1996). Relationship between latitude and melanoma incidence: inter national evidence. *Cancer Letters*, **99**, 225–31.

Smallman–Raynor, M., Cliff, A. D., and Haggett, P. (1992). *International atlas of AIDS*. Blackwell, Oxford.

(p.239) Smans, M., Muir, C. S., and Boyle, P. (1992). *Atlas of cancer mortality in the European Economic Community*. International Agency for Research on Cancer, Scientific Publication 107. IARC, Lyon.

Snow, J. (1855). *On the mode of communication of cholera* (2nd edn). Churchill, London.

Southern Swedish Regional Tumour Registry (1994). *Cancer incidence in southern Sweden 1988–92*. Lund.

Stevenson, L. G. (1965). Putting disease on the map: the early use of spot maps in the study of yellow fever. *Journal of History of Medicine and Allied Sciences*, **20**, 226–61.

Stocks, P. (1928). On the evidence for a regional distribution of cancer prevalence in England and Wales. *Report of the International Conference on Cancer*, 508–19. British Empire Cancer Campaign, London.

Stocks, P. (1936). *Distribution in England and Wales of cancer of various organs*, 239–80. Annual Report. British Empire Cancer Campaign, London.

Stocks, P. (1937). *Distribution in England and Wales of cancer of various organs*, 198–223. Annual Report. British Empire Cancer Campaign, London.

Stocks, P. (1939). *Distribution in England and Wales of cancer of various organs*, 308–43. Annual Report. British Empire Cancer Campaign, London.

Sturgeon, R., Schairer, C., Gail, M., McAdams, M., Brinton, L. A., and Hoover, R. N. (1995). Geographical variation in mortality from breast cancer among white women in the United States. *Journal of the National Cancer Institute*, **87**, 1846–53.

Verhasselt, Y. and Timmermans, A. (1987). *World maps of cancer mortality*. Geografisch Instituut VUB, Brussels.

Wainer, H. and Francolini, C. M. (1980). An empirical inquiry concerning human understanding of two–variable colour maps. *American Statistician*, **34**, 81–93.

Walter, S. D. (1991). The ecologic method in the study of environmental health. *Environmental Health Perspectives*, **94**, 61–65.

Walter, S. D. (1993). Visual and statistical assessment of spatial clustering in mapped data. *Statistics in Medicine*, **12**, 1275–91.

Walter, S. D. and Birnie, S. E. (1991). Mapping mortality and morbidity patterns: an international comparison. *International of Journal of Epidemiology*, **20**, 678–89.

WHO (World Health Organisation) (1997). *Atlas of mortality in Europe*. WHO Regional Publications, European series. 75. WHO, Copenhagen.

Zatoński, W., Pukkala, E., Didkowska, J., Tyczyński, J., and Gustavsson, N. (1993). *Atlas of cancer mortality in Poland, 1986–90*. Cancer Center, Warsaw.

Zatoński, W., Smans, M., Tyczyński, J., and Boyle, P. (ed.) (1996). *Atlas of cancer mortality in central Europe*. International Agency for Research on Cancer, Scientific Publication 134. IARC, Lyon.