Malaria and mosquitoes in Britain: the effect of global climate change

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Introduction

Globally, malaria is without question the most important of the insect-borne diseases. At the present time over 2000 million people in over a hundred tropical and subtropical countries of the world live under the threat of the disease. Assessments of the number of people infected vary, but the figure is probably in excess of 400 million. It is estimated that malaria causes, or contributes to, the deaths of between one and three million people each year, mostly children under five years of age (World Health Organization, 1996). The situation in Europe is that, with the exception of the Ural region of Russia and Ukraine (Nikolaeva, 1996), endemically transmitted malaria has been eliminated. In 1995 there were 50 cases of endemically transmitted malaria in Bulgaria (Nikolaeva, 1996), indicating that constant vigilance is necessary. Only female *Anopheles* mosquitoes, of which there are currently eighteen species recognised in Europe but only five in Britain, can transmit malaria.

The question that entomologists and health workers are asking at present is "with global climatic change; will malaria return to these shores as an endemically transmitted disease?" In order to begin to answer this question it is necessary to examine the magnitude of the predicted climatic warming in Britain, the environmental requirements of the malarial parasite and the ways in which mosquito populations might be affected.

Malaria in Britain: an historical perspective

Until the late nineteenth century, *vivax* malaria, also called marsh fever and ague, was endemic in lowland Britain and sporadic as far north as Inverness. The parasite was transmitted among the human population at times of the year when mosquitoes were present, and survived as dormant stages (hypnozoites) in the livers of infected persons during the colder times of the year. The Thames marshes of Essex and Kent were particularly unhealthy but, as in other parts of the country, the nineteenth century saw a steady decline in the disease (Bruce-Chwatt and de Zulueta, 1980; Dobson and Fantini, 1994). From data on the mortality caused by *vivax* malaria, it is clear that the parasite was more virulent a few centuries ago than it is now. Indeed, it may well be that the malarial parasite that historically occurred in Britain differed so markedly from the present-day *P. vivax* such that other aspects of its biology and infectivity to *Anopheles* mosquitoes may be significantly different. Hence it may be meaningless to attempt to predict future transmission bases upon historical events.

The decrease began before the role of mosquitoes in malaria transmission was understood and is attributed to the drainage of marshlands for agricultural purposes, changes in animal husbandry, housing improvements, climatic changes, improved health care and the availability of the anti-malarial drug quinine (James, 1920). Although from 1771 the Royal Navy used quinine for the prevention and treatment of malaria, it was not widely used by the civilian population until 1833 (Bruce-Chwatt and de Zulueta, 1980).

A serious outbreak of *vivax* malaria began in 1917 in the Isles of Grain and Sheppey, situated at either side of the River Medway where it meets the Thames. Sick service personnel repatriated from malarious theatres to this mosquito-infested area during the 1914-1918 war brought the disease to this country. It soon spread to the local population, causing an epidemic that lasted until well after the cessation of hostilities. According to Shute (1949), 481 confirmed cases of locally transmitted malaria occurred in Britain during the period 1917-1921. The vast majority of these were in the Medway area, and over 50% of the children in Grain, a village of 500 inhabitants, contracted the disease (Shute and Maryon, 1974). *Anopheles atroparvus*, the major vector at that time, was found to be abundant in both Grain and Sheppey. However the outbreak was eliminated by 1922 (Shute, 1949) by making malaria a notifiable disease, evacuating all cases to one of two special hospitals and instituting anti-mosquito measures in localities where transmission took place.

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A policy of excluding infected service personnel from the marshy areas of southern and eastern England prevented a similar outbreak of malaria during and after the 1939-1945 War. Out of a total of 34 indigenous cases occurring between 1941 and 1948, only nine were in Essex and Kent, the two counties bordering the Thames estuary (Shute, 1949).

Predicted climatic change

Mean temperatures in Britain, as measured in 'Central England', have risen by about 0.7°C since 1700 and by 0.5°C since 1900 (Jones and Hulme, 1997). In the present century the temperature increase has occurred in all seasons but is most pronounced in summer and autumn.

The Hadley Centre for Climate Prediction and Research at the UK Meteorological Office forecasts that the greatest warming in Britain over the next 50 to 100 years will occur due to winds from the east travelling over a warmed European land mass (Bennetts, 1995). The overall effect will be a decrease in the intensity of very cold spells in winter and an increased number of hot summers. There is also expected to be an increase in winter precipitation, but the frequency of snowfall is likely to be reduced significantly. In summer, reduced precipitation is predicted in southern Britain.

The global climate model, HADCM2 SUL, predicts that, from the 1961-1990 period to the year centred on 2050, there will be a temperature increase of 1.2°C-1.6°C and to the year 2100 between 2.5°C and 3.0°C (Raper *et al.*, 1997). This will give summer mean temperatures in 2050 ranging from 10-14°C in Scotland through 12-16°C in northern England, Wales and Ireland to 16-18°C in southern and central England. Winter mean temperatures will be 2-6°C in most areas, less than 2°C in some central areas of Scotland, and 6-8°C in the south of Ireland and parts of Wales and the West of England (Raper *et al.*, 1997). Although temperature levels are important, the length of the season when temperatures are favourable for transmission is also a major factor (Ramsdale and Haas, 1978). This is discussed below in the context of the time required for malarial parasites to develop within mosquitoes.

The malarial parasites

Human malaria is caused by four different, but related, parasites: *Plasmodium falciparum*, *P. vivax*, *P. malariae* and *P. ovale*. Of these, the last two are less common, with *P. ovale* restricted to West Africa. All of these are transmitted by female *Anopheles* mosquitoes that become infected when they feed on people with the gametocyte stages of the malaria parasites in their blood. Inside the insect the parasite continues its development and after an interval, the length of which varies with temperature levels experienced by the mosquito host, the salivary glands are invaded by the infective sporozoites. These are injected together with saliva into a human host when the mosquito feeds. As mosquitoes are not infective until the sporozoites are in their salivary ducts, they may take several bloodmeals between acquiring and transmitting the infection. Once infective the mosquito will normally remain so for the rest of its life; only during overwintering do mosquitoes gradually lose their infectivity.

In considering the possible reintroduction of malaria to Britain, with the advent of global climatic change, it is important to take into account the minimum temperature required to complete the cycle in the mosquito. For *P. vivax* this is varyingly reported as 6°C (James, 1931), 15°C (MacDonald, 1957), 16°C (Garnham, 1988) and 17.5°C (Grassi, 1901); for *P. malariae* as 16.5°C (Grassi, 1901) and for *P. falciparum* 18°C (Grassi, 1901; Garnham, 1988) and 19°C (MacDonald, 1957). There appears to be no corresponding data for *P. ovale*. The current world distribution of *P. falciparum* shows it to be limited by a summer isotherm of 20°C while both *P. vivax* and *P. malariae* are restricted by the 16°C summer isotherm (Kettle, 1984).

In general, the time required to complete the life cycle of the malarial parasite in the mosquito is reduced with increased ambient temperature (Figure 1) and ends with death of the parasite at an upper limit of about 45°C (Garnham, 1988). For *P. vivax* this ranges from 9 days at 25°C to 44 days at 6°C (James, 1931); for *P. falciparum* 14-15 days at 23-25°C to 20 days at 19°C (Cambournac, 1942; Roubaud, 1918 in Jetten and Takken, 1994); for *P. ovale* it is 14 days at 27°C (Garnham, 1988) and for *P. malariae* 25 days at 24°C and 40 days at 19°C (Cambournac, 1942).

It therefore follows that mosquitoes do not have to live as long and the temperatures do not have to be as high for them to transmit *P. vivax* compared with the other species of malarial parasites, and that with global warming this species has the highest chance of making a return to Britain. Equally it is unlikely that *falciparum* malaria could occur at the predicted temperatures. In the year 2050, at the expected mean summer temperature of 16-18°C in southern and central England, it is calculated that *P. vivax* would require around 25 days to complete its cycle in the mosquito. The length of the season during which temperatures are high enough for development in the mosquito together with mosquito density, longevity and susceptibility to infection are the principle factors which will ultimately influence malaria incidence (Ramsdale and Haas, 1978).

***Anopheles* mosquitoes in Britain**

In Britain there are currently five species of *Anopheles* mosquitoes, all of which are potential malaria transmitters. They are *Anopheles algeriensis, An. atroparvus, An. claviger, An. messeae* and *An. plumbeus*. A sixth species, *An. maculipennis*, was suspected in Britain, but its presence has never been substantiated (Cranston *et al*., 1987).

The main distribution of *An. algeriensis* is in Mediterranean countries, but it was recorded in Norfolk in the early 1930s and for a further 20 years (Cranston *et al*., 1987). The present status of this mosquito in Norfolk in uncertain. More recently it has been discovered in Anglesey (Rees and Rees, 1989) and Clare in the west of Ireland (Ashe *et al*., 1991). All of the specimens from England, Wales and Ireland occurred in lime-rich waters which may explain the disparate distribution of this species. The fact that a predominantly Mediterranean species can exist in this country at present is significant. It is presumed that such introductions will be more common if mean temperatures increased although, as seen with *An. algeriensis*, the habitat requirements are often very specific and such conditions may not be readily available in this country.

All of the other four species are widespread and common in places. Each develops in a distinct type of water: *An. atroparvus* in brackish pools and ditches, and hence has a mainly coastal distribution; *An. claviger* in pools, ponds, ditches, streams, canals, and artificial collections of water in troughs and rain butts; *An. messeae* in freshwater pools, ditches and slowly-moving waters and *An. plumbeus* in water-filled tree holes (Cranston *et al*., 1987).

To predict how these and other quite varied aquatic habitats will change when subjected to global climatic change is difficult, if not impossible. What is certain is that they will not all alter in either the same way or to the same extent. Reduced summer precipitation together with increased temperature could lead to ditches and pools drying more quickly and hence being less available to species such as *An. claviger, An. atroparvus* and *An. messeae* to complete their life cycles. It may well have a similar impact on water-filled tree holes and hence *An. plumbeus*. However, reduced summer precipitation, accompanied by increased water abstraction, may lead to the slowing of streams and rivers making them more suitable for *An. claviger* and *An. messeae*. It will almost certainly have the effect of making people more water conscious and lead to an increase in the provision of water butts and other rain storing devices to aid gardening and horticulture. These are suitable development sites for *An. claviger* and may well be colonised more intensely. However Postiglione *et al.* (1972) and other authors have noted that *An. claviger* shows a marked preference for water below 20°C. Other species may also adopt these newly provided sites.

The recent spread of the Asian mosquito, *Aedes albopictus*, discussed below, serves to demonstrate not only the speed with which a species can extend its range but also the rapidity with which mosquitoes can adapt. Car tyres are a relatively new item and yet *Ae. albopictus* has adapted to lay its eggs in these and await their flooding with rain water, instead of utilising natural water masses. This speed of evolution may be vital in determining the adaptation of mosquitoes to climatic change.

Do all British *Anopheles* feed on humans?

All of our native *Anopheles* mosquitoes will feed on humans. *An. atroparvus* and *An. messeae* are domestic mosquitoes in the sense that they tend to rest in buildings, feeding on the occupants. They enter both houses and animal shelters and prefer domestic animals to humans when there is a choice. *An. plumbeus* and *An. claviger* may also enter buildings, although both normally rest and feed outdoors. *An. algeriensis* rarely enters houses; adults rest in dense vegetation and will feed on people in the open.

Can all British *Anopheles* transmit malaria?

The case for *An. atroparvus* and *vivax* malaria is well established, beginning with the study by James (1917), but the questions remain." can any other British species act as a vector of this form of malaria and can any of them transmit the more acute *falciparum* malaria?" Blacklock (1921) reported a case of *P. falciparum* infection in an 18-year-old girl who had not travelled outside Britain. He concluded that the infection had been acquired at "a northern health resort" where *Anopheles* mosquitoes were plentiful. However the possibility exists that the girl was infected in her hometown of Liverpool, not by a native mosquito but by an exotic anopheline arriving at the port. Indeed many studies have shown that native *An. atroparvus* are incapable of transmitting this species of malarial parasite (Shute, 1940). More recently Ramsdale and Coluzzi (1975) found no infectivity in *An. atroparvus* from southern Europe and Ribeiro *et al.* (1989) showed that Portuguese *An. atroparvus* were not susceptible to strains of *P. falciparum* from East Africa. However Marchant *et al.* (1998) found that of 43 *An. atroparvus* which fed on infected blood, one developed a single oocyst. It is most likely that this refractoriness will continue to be a limiting factor for *falciparum* transmission.

Blacklock and Carter (1920b) were able to infect *An. plumbeus* with *P. falciparum*, observing oocysts, an intermediate stage of the parasite, in the mid-gut of one mosquito after 8 days at 28°C. A similar study (Marchant, 1997; Marchant *et al.*, 1998) also indicated that *An. plumbeus*, collected from southern England, may be capable of transmitting *P. falciparum*. Of five mosquitoes that fed successfully on blood containing the malarial parasite, three revealed oocysts in their mid-guts. Whether the parasite is capable of completing its life cycle and being transmitted to produce infection remains to be proven.

In 1953 two cases of *vivax* malaria occurred in London (Shute, 1954). *An. plumbeus* was suspected to be the vector as it was found breeding in a collection of water in the hollow of a plane tree close to the house where the cases of malaria occurred. Attempts by Blacklock and Carter (1920a) to infect *An. plumbeus* with *P. vivax* in the laboratory were successful; they recorded sporozoites in the salivary glands at 28°C but only mid-gut stages at room temperature (17-26°C). Shute (1954) believes that *An. plumbeus* was the main vector of *vivax* malaria in Britain when the country was covered in forest.

Blacklock and Carter (1920a) also attempted to infect *An. claviger* maintained at 28°C with *P. vivax* and observed mid-gut stages. *An. claviger* was shown to be a vector of malaria in south-eastern Italy and probably played a role in other parts of Europe (MacDonald, 1957) and in the Middle East (Horsfall, 1955).

An. algeriensis has been implicated as a malaria vector in Algeria (Horsfall, 1955). An epidemic of malaria, of unspecified type, was reported when *An. algeriensis* was the only *Anopheles* present. Two females caught at the time were found to have oocysts in their mid-guts. It is of interest that *An. messeae* was formerly reported as being the main vector of malaria over a large part of European Russia (Detinova, 1953).

Effect of temperature on British *Anopheles*

Longevity

The longevity of adult mosquitoes is temperature dependent and, in general, they survive for longer periods at lower temperatures. Therefore, although elevated temperature will increase the chances of the malarial parasite successfully completing its cycle in the mosquito, the enhanced temperature will also reduce the life span of the mosquito. An optimum temperature for transmission therefore exists.

Temperature is, of course, not the only factor affecting longevity: activity, nutrition, pathogens, predators, control measures and other climatic factors, especially humidity, all play their part.

Detinova (1953) studied *An. messeae* in a village in the northern Russian plain where the summers are warm but highly variable and the winters moderately severe. In June the first adults of the summer generation appeared but individuals which had overwintered as fertilised females were still present; the oldest were still alive 8-10 weeks after emergence from hibernation. This is a remarkable age, especially considering that they became adult the previous August-September. However most mosquitoes survived far less time than this: 10% living 6-7 weeks and 50% only 3 weeks.

Shute and Ungureanu (1939) recorded 50% of *An. messeae* surviving after 11 days at 24°C and 80% relative humidity. These same authors recorded 60% survival of *An. atroparvus* females after 21 days when kept at temperatures between 15-27°C and 70% relative humidity. Hill (1937) found that at the height of summer (conditions not stated) *An. atroparvus* survived for about six weeks. There is little information on *An. algeriensis*, but Rees and Rees (1989) reared two females in captivity and noted that they lived for 40 and 63 days.

As stated above, at the expected mean summer temperature of 16-18 °C in southern England in the year 2050, *P. vivax* will require around 25 days to complete its cycle in a mosquito. It is well documented that female mosquitoes are not attracted to a host until some 12-24 hours after emerging and that they normally require to mate before searching for a blood meal. Mating usually occurs within a day or so of emergence and so, assuming that a host is located almost immediately, a mosquito must survive 26-27 days before becoming infective at this temperature.

From the limited information available, it would appear that many native *Anopheles* would survive the four-week period required to transmit *P. vivax*. At present-day mean summer temperatures in southern England *P. vivax* will develop in mosquitoes in about 33 days, which although significantly longer is still feasible. The increased speed of development of the parasite within the mosquito vector is unlikely to be a significant factor as the future temperatures will still be less than those in southern Europe at present where anopheline vectors exist without transmitting malaria.

Rate of development

The rate of development of mosquito eggs, larvae and pupae is also influenced by temperature. Within the viable range, an increase in temperature will result in a decrease in the development time. Horsfall (1955) reports that *An. claviger* takes 76 days to mature from egg-hatch to adult emergence at 10.5°C but only 34 days at 19.5 °C. Other studies on a range of species show a similar pattern (Clements, 1992).

Rate of digestion and egg development

The rate of blood digestion and egg maturation within female mosquitoes is also temperature dependent. Females of *An. stephensi* (a tropical species) maintained at 27°C completely digested a bloodmeal after about 60 hours (Billingsley and Hecker, 1991). This is in agreement with field observations in the tropics which reveal that digestion of blood is commonly completed in 2-3 days while in temperate areas it is known to require 5-8 days (Clements, 1992). Therefore an increase in ambient temperature will permit more feeding/ egg laying cycles to be completed in a season and so both increase the number of bites from individual mosquitoes as well as augmenting the mosquito populations, which will further increase the biting potential.

The introduction of exotic mosquitoes

At all times prevailing winds and transport have an effect on mosquito distribution. Individual insects can be carried both short and long distances trapped in motor vehicles, and cabins and holds of ships and aircraft. With a warmer climate the possibilities of exotic species becoming established becomes greater.

Two decades ago *Aedes albopictus*, the Asian tiger mosquito, was unknown in Europe, mainland Africa and the Americas. However since the early to mid 1980s it has begun to extend its geographic range significantly and at an unprecedented speed. The first report of this mosquito in Europe was from Albania in 1979, followed by its introduction into Italy in 1990. Over the last 10-15 years, *Ae. albopictus* has spread around the world. It has invaded the Americas, some Pacific islands, Australia, Africa and Europe. These introductions were made primarily through the international trade in new and used tyres containing eggs and/or larvae of the mosquito. *Ae. albopictus* is clearly a very adaptable mosquito and has found suitable conditions in both tropical and temperate countries (Rodhain, 1996). Will a warmer climate allow *Ae. albopictus* and other mosquitoes, currently restricted to more southerly areas, to become established in Britain?

In this context there is also concern that other European species of *Anopheles*, which are more effective vectors of *vivax* malaria than our native species, may be introduced into Britain. These include *An. sacharovi*, which is currently recorded from Italy, Turkey, Greece and possibly neighbouring areas and *An. labranchiae*, which occurs in Corsica, Italy, Sardinia, Sicily and Croatia. Similarly the arrival of *An. superpictus* and/or *An. sergentii* would increase the risk of transmission of both *vivax* and *falciparum* malaria. Currently the former is found in Italy, Cyprus, Turkey and the Balkan Peninsula while the latter is present in North Africa. This possible introduction must be viewed in context as the presence of *An. sacharovi, An. labranchiae* and *An. superpictus* is only rarely associated with malaria in those European countries in which it is currently reported.

Airport malaria

Of real concern nowadays is the phenomenon of *airport malaria* whereby infective mosquitoes are imported on board aircraft arriving from the tropics and subsequently bite people in the vicinity of the airport. Two specific cases of airport malaria occurred in 1983; the first affected two residents living close to Gatwick Airport and the second two people who flew from London to Rome (Curtis and White, 1984; Warhurst *et al.*, 1984). More recently a small child living 100 km from the nearest international airport in northern Italy acquired *falciparum* malaria during the winter, when local *Anopheles* were in hibernation. This demonstration that imported disease-carrying mosquitoes are able to survive transportation for considerable distances through a hostile environment and still transmit the infection was labelled *baggage malaria* to distinguish it from airport malaria occurring in the close vicinity of airports (Castelli *et al.*, 1993). Clearly with a warmer climate the chances of survival of imported infected exotic mosquitoes will be enhanced and the likelihood of disease transmission increased. However it may well be that other factors, including increased aircraft movements and the failure to fumigate aircraft travelling from malarious areas of the world may be equally significant.

Global warming and human behaviour

With warmer weather there will be a greater tendency for people to spend longer periods out of doors, especially in the evenings when many mosquito species are actively seeking blood meals. People will be eating, drinking and socialising in gardens, outdoor restaurants and public houses in close contact with species such as *An. claviger* and *An. plumbeus*. When days are hot there is also the likelihood that people will start outdoor work earlier in the day and continue later in the evening to avoid the hot daytime conditions. People will wear less clothing and so expose more of their skin surface to biting insects. Clothing will also be lighter, allowing mosquitoes to penetrate through the thinner fabric. There will also be a greater inclination for people to sleep with bedroom windows open, exposing them to mosquito species, such as *An. atroparvus*, which enter buildings. It is also possible that people will sleep out of doors more frequently during warmer summers.

A change in the use and storage of water has been referred to previously and must not be underestimated. Gardeners and horticulturists will strive to store more rainwater, and uncovered or inadequately covered containers will be utilised as mosquito breeding sites.

Conclusion

The direct effect of increased temperature upon mosquitoes and the parasite developing within them, and the indirect effects on the insect and host are discussed. It is postulated that data on the past presence of *vivax* malaria in Britain is not a reliable indicator of future occurrence due to possible evolutionary changes in the parasite over the last several decades. It is also concluded that the effects of raised temperature on the cycle of the malarial parasite in the mosquito would be of little significance but that the effects on development sites, especially the slowing of watercourses, may provide additional breeding sites for anopheline mosquitoes. Perhaps most important will be the increased longevity (although not the establishment, due to our cold winters) of infected mosquitoes introduced though airports. Whatever the outcome it must be appreciated that in Britain there are well-established mechanisms for the detection, monitoring and combating of mosquitoes and the diseases which they transmit. A sophisticated health infrastructure exists ready to deal with seasonal influxes of malaria, and expertise is available within the country to devise and implement control programmes directed at specific mosquito species.

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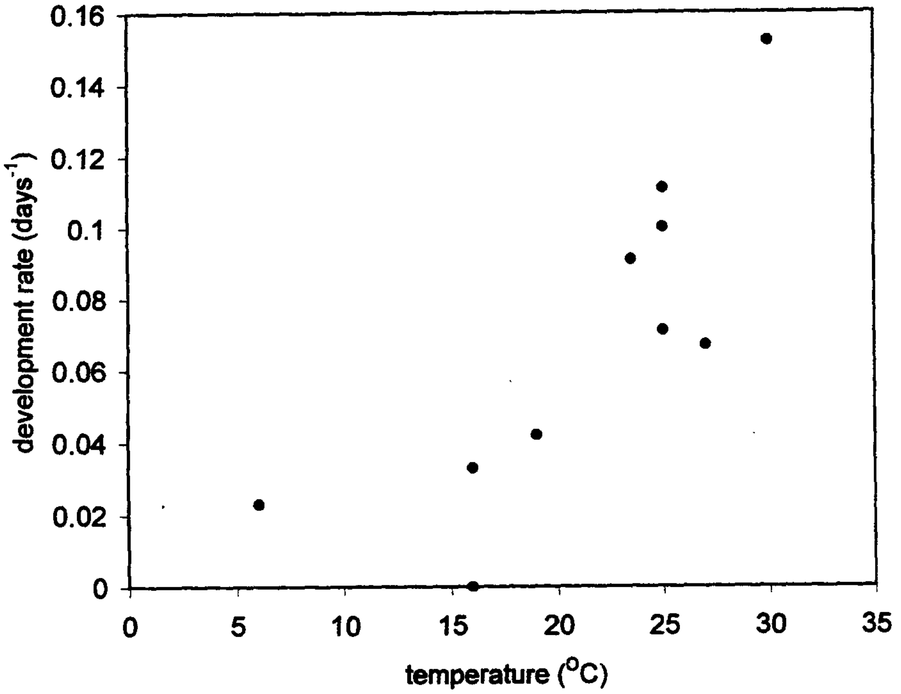

Figure 1. The duration of development of *Plasmodium vivax* in *Anopheles* species (data from various authors)

Information for Contributors

The *European Mosquito Bulletin* is intended to provide a medium for the dissemination of information and views on all aspects of the taxonomy, morphology, biology, ecology, distribution and control of European mosquitoes, and for work related to the European species. All articles and letters should be submitted as a hardcopy accompanied by a disc with the text in either Word or WordPerfect, and tables and graphs in Excel, to one of the editors:

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The following notes are for additional guidance:

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Articles may be of any length, but items exceeding ten pages may need to be serialized, depending on the space available. All articles must be accompanied by an abstract, which should not exceed 150 words. The style of articles and referencing should follow papers published in the current issue of the *Bulletin*.

Tables, graphs and line drawings should be included where appropriate. Line drawings should be submitted the same size that they are to appear in the article. Regrettably photographs, unless they are of high contrast, are unlikely to reproduce well.

2. Letters

Letters to the editors on any relevant subject, or requesting information or specimens, are welcome. The letter should include a full address for reply. Dialogues are encouraged on controversial and debatable issues.