Predicting the risk of bluetongue through time: climate models of temporal patterns of outbreaks in Israel

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Summary
Determining the temporal relationship between climate and epidemics of *Culicoides*-borne viral disease may allow control and surveillance measures to be implemented earlier and more efficiently. In Israel, outbreaks of bluetongue (BT) have occurred almost annually since at least 1950, with severe episodes occurring periodically.

In this paper, the authors model a twenty-year time-series of BT outbreaks in relation to climate. Satellite-derived correlates of low temperatures and high moisture levels increased the number of outbreaks per year. This is the first study to find a temporal relationship between the risk of *Culicoides*-borne disease and satellite-derived climate variables.

Climatic conditions in the year preceding a BT episode, between October and December, coincident with the seasonal peak of vector abundance and outbreak numbers, appeared to be more important than spring or early summer conditions in the same year as the episode. Since Israel is an arid country, higher-than-average moisture levels during this period may increase the availability of breeding sites and refuges for adult *Culicoides imicola* vectors, while cooler-than-average temperatures will increase fecundity, offspring size and survival through adulthood in winter, which, in turn, increases the size of the initial vector population the following year.

The proportion of variance in the annual BT outbreak time-series resulting from climate factors was relatively low, at around 20%. This was possibly due to temporal variation in other factors, such as viral incursions from surrounding countries and levels of herd immunity. Alternatively, since most BT virus (BTV) circulation in this region occurs silently, in resistant breeds of local sheep, the level of transmission is poorly correlated with outbreak notification so that strong relationships between BTV circulation and climate, if they exist, are obscured.

Keywords
Bluetongue virus – Climate – Culicoides imicola – Israel – Remote-sensing – Satellite imagery – Time-series analysis.

Introduction

Bluetongue (BT) virus, a double-stranded ribonucleic acid orbivirus (*Reoviridae*), causes an infectious, non-contagious disease called bluetongue (44). The BT virus (BTV) replicates in all ruminants but severe disease is restricted mainly to certain breeds of sheep and some deer (64). In view of its potential for rapid spread and its serious consequences for trade in animals and animal products, BT is classified as a List A disease by the World Organisation for Animal Health (OIE).

The BTV is transmitted between its vertebrate hosts by the bites of vector species of *Culicoides* (Diptera: Ceratopogonidae) (45) and the distribution and intensity of infection are thus dependent on the distribution and abundance of these vectors in space and time.

Since 1998, an unprecedented epidemic of BT has occurred in the Mediterranean Basin, affecting many countries in both the East and West Mediterranean (most for the first time) and spreading as far as 44ºN (6, 46). In response, recent studies have investigated the spatial distribution of vectors and the virus in this region to aid in predicting areas at risk from BT (7, 19, 21, 24, 63). However, few studies have focused on the distribution of *Culicoides* and BT (or BTV) through time (67, 69), even though identifying the factors that favour the occurrence of BT in particular months or years could allow control measures to be implemented much earlier and more efficiently. It is important to conduct such investigations in both endemic as well as epidemic BT zones for several reasons. First, this division (between endemic and epidemic) is blurred and dynamic for BTV, in which most transmission worldwide occurs silently in disease-resistant hosts. Furthermore, even in susceptible hosts, the expression of the disease may depend upon the particular viral strain in circulation. Consequently, in some areas defined as 'endemic', BT outbreaks can occur suddenly after long periods of silent transmission.

One such example is the outbreak produced by BTV serotype 16 in 2003 in Cyprus (49) (over twenty years after the last recorded outbreaks in 1977), whilst in certain 'epidemic' zones, such as Italy, BT outbreaks have occurred annually since 2000. However, to be effective, control measures such as vaccination and vector abatement must be implemented as early as possible during an outbreak in both 'endemic' and 'epidemic' zones: a task that has thus far proved difficult to achieve in conditions of such variability. The timing of outbreaks in epidemic BT areas may also be related to those in endemic BT areas because endemic BT areas often act as source regions for incursions into epidemic BT areas.

Although Israel has remained relatively unaffected by the recent Mediterranean epidemic (with sporadic outbreaks of BT in 1998, 2000 and 2003), outbreaks have occurred almost annually since the disease was first confirmed there in 1950 (32). Severe episodes of BT (with more than 30 outbreaks per year) have occurred periodically: in 1975, 1987, 1988 and 1994 (17). Five BTV serotypes (types 2, 4, 6, 10 and 16) are involved. Israel is located in the Southeast Mediterranean Basin and has an intensive agriculture system, including farming of BT-susceptible, European breeds of sheep (61). Although Israel is traditionally considered to fall within an endemic zone for BT, control measures such as vaccination are routinely implemented and need to be well timed. Despite its arid climate, Israel and its surrounding countries with similar climates probably act as a source of incursion for BTV strains into the 'fringes' of European epidemic zones (37, 57, 66). Thus, determining the relationships between time-series of vector, virus and host information in Israel over long (annual/inter-annual) time scales may assist with prediction of the timing of transmission in Israel and of epidemics elsewhere in this region.

Climatic factors may affect the temporal distribution of BT outbreaks indirectly, through their effects on the life-history parameters and breeding sites of *Culicoides* vectors (45). The main vector species in Europe and Africa is *Culicoides imicola* (Kieffer). A strong association has been identified between the timing of epidemics of African horse sickness (also a *Culicoides*-borne disease) since 1800 and the warm phase of the El Niño/Southern Oscillation in South Africa, possibly due to the combination of rainfall and drought caused by this phase (5). Such long-term temporal associations between outbreaks and climatic events have been widely observed across vector-borne diseases (23, 25, 27, 28, 38, 39, 59, 60). In addition to climatic factors, other factors that could influence the temporal distribution of BT outbreaks include the following:

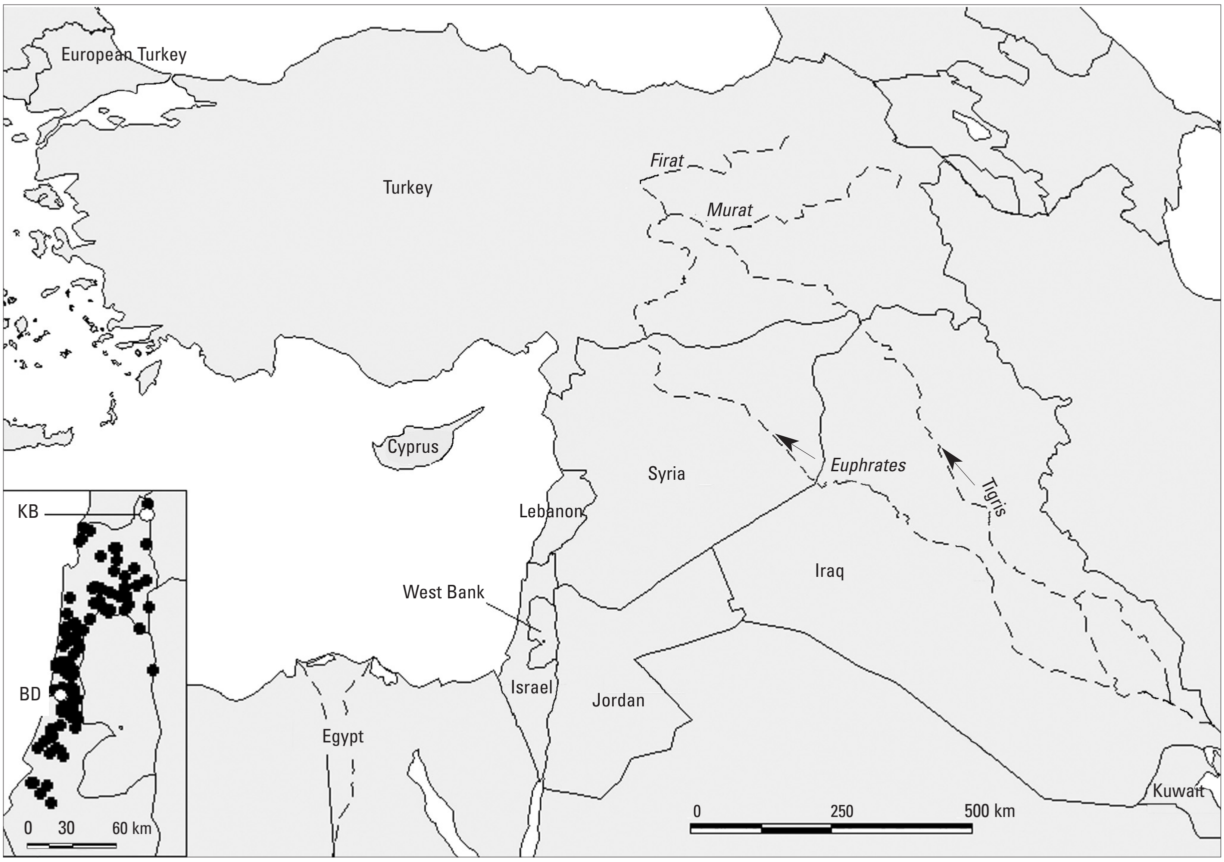
– the occurrence of viral incursions from surrounding countries (Fig. 1)

– the introduction of new viral strains (29)

– the variation in the susceptibility of the hosts (levels of herd immunity)

– changes in the location and timing of the samples taken in any surveillance system.

In this paper, to determine whether the timing of severe BT episodes is attributable to climatic factors in Israel as opposed to other potential host or virus factors, the authors analyse the relationships between a continuous twenty-year monthly BT incidence data set accumulated by the Israeli Ministry of Agriculture and monthly climatic variables derived from remotely sensed, Advanced Very



BD: Bet Dagan
KB: Kefar Blum
Closed circles: bluetongue outbreaks

Fig. 1
Countries of the South-eastern Mediterranean Basin
Inset: location of bluetongue outbreaks in recent severe episodes in Israel (1987, 1993, 1994, 1996)

High Resolution Radiometer (AVHRR) data (8 km^2 grid resolution). These climatic variables include the normalised difference vegetation index (NDVI), which has been shown to be a significant determinant of the spatial distributions of *C. imicola* (3, 4). The authors interpret these relationships in light of the available information on BTV activity and vaccination policies in surrounding Middle Eastern countries over the same time period.

Methods

Study area and bluetongue incidence, vaccination and seroconversion data

Israel includes areas of relatively moist temperate climate in the north (coastal plains), cool central mountain ranges (e.g. Mount Hermon) and an arid desert area in the south (Negev). The annual climate can be divided into a rainy season between October and April, with peak rainfall and minimum temperatures in December and February, and a completely dry season from May to August (usually to October).

The livestock population of Israel comprises the following (22):

– approximately 320,000 bovines (ranging between 229,000 and 395,000 since 1960)

– approximately 300,000 ovines (ranging between 189,000 and 389,000 since 1960), at least one quarter of which are exotic breeds and their crosses (61)

– 100,000 goats (ranging between 62,000 and 165,000 since 1960).

A ewe spends four to five years, on average, in the flock and the rate of replacement is approximately 25% a year in dairy flocks but slightly slower in mutton (E. Gootwine, personal communication). Vaccination of exotic sheep breeds and their crosses has been conducted annually since 1964. A polyvalent vaccine from Onderstepoort Veterinary Institute (containing live, attenuated BTV types 2, 4, 6, 10 and 16) was used in the period from 1964 to 1973 and from 1995 (following outbreaks in Israel due to BTV-16 in 1993 and 1994) to the present. In the intervening period (1974 to 1994), a quadrivalent vaccine (types 2, 4, 6, 10) was used. The annual usage of vaccine (number of doses) has been recorded since 1989.

Few livestock, apart from cattle in some dairies, are kept in the part of Israel which receives less than 200 mm annual rainfall (61), and this area is not covered by any of the sixteen veterinary regions for which case data were obtained. Monthly numbers of BT outbreaks in sheep flocks across the whole of Israel, from 1968 to 2002, were obtained from the Israeli Veterinary Services. These numbers were not converted to monthly incidence values using data on the total numbers of sheep (22), since these totals were decadal and were not accompanied by the proportion of the totals represented by susceptible exotic breeds or their crosses. The following was calculated for each year:
– the total number of outbreaks
– the duration of the outbreaks (in months)
– the proportion of the annual total number of outbreaks contained in each month.

Sentinel surveillance systems of unvaccinated bovines for detecting BTV have been employed in Israel since 1980. Between 1980 and 1984, 180 sera were screened for antibodies against BT across six sites in five districts (the Jordan Valley; Yizreel; the coastal plain: Akko and Hadera; the Judean foothills and Ashkelon-Beersheeva) in December. Between 1987 and 1995, twenty sera were screened in June and December in between nine and eleven districts, depending on the year. The proportion of sera testing positive for antibodies against BT, and the number of districts from which samples tested positive per year, were calculated.

Seasonal vector data

Long-term entomological surveillance of *C. imicola*, using Du Toit light traps, has been conducted at Bet Dagan, Ramle (32°05'N, 34°50'E; see the inset on Figure 1 for location) since 1987 (12, 14, 15). In 2000 and 2001, trapping was conducted every three to four days, throughout the year, and four traps were set on each trapping occasion. To examine the seasonal distribution of *C. imicola*, the mean (± standard error or s.e.) proportion of the annual total of *C. imicola* individuals contained in each month was calculated across 2000 and 2001.

Climate time-series data

The study area above the 200 mm rainfall line was divided into pixels of 8 km^2. Most villages (116 out of 125) affected by BT outbreaks in the years of major outbreaks (M. Van Ham, unpublished data) were geo-referenced using Microsoft® Encarta® World Atlas and the Alexandria online digital library (1). This layer of point data was then overlaid on the 8 km^2 pixel centroids to identify pixels in Israel within 4 km of an outbreak. For each pixel, the maximum composited monthly values of four environmental variables were obtained from the pathfinder AVHRR data set (56), from 1 km^2 spatial resolution imagery (30), for the months between July 1981 and September 2001. These four environmental variables were as follows:
– NDVI
– middle infra-red reflectance (MIR)
– land surface temperature (LST)
– air temperature (TAIR).

The NDVI specifically measures chlorophyll abundance, but is correlated with soil moisture, rainfall and vegetation biomass, coverage and productivity (20). Middle infra-red reflectance is correlated with the water content, surface temperature and structure of vegetation canopies (9). Land surface temperature is a general index of the apparent environmental surface temperature (whether of the soil or vegetation) and TAIR is an estimate of the air temperature a few metres above the land surface (31).

Unfortunately, a long-term instrumental bias in these time-series is caused by changes in the satellite equatorial crossing time (42), producing a data gap between September 1994 and December 1994 and leading to a fall in the mean values of all variables from the beginning of the year 2000. Thus, the following analysis is restricted to monthly values from two time-series: the first between January 1981 and August 1994 and the second between January 1995 and December 1999.

Monthly minimum and maximum temperatures, average daily minimum and maximum temperatures (for all months) and monthly rainfall amounts were obtained (for September to May) from a weather station at Kefar Blum (33°09'N, 35°38'E, see the inset of Figure 1), for comparison with the satellite-derived climate variables.

Data analysis

Strong seasonal variation, generally annual in period, was observed in both epidemiological and climate monthly time-series (see 'Results', below). The authors wanted to test hypotheses of the form: are outbreaks more pronounced in years where the NDVI reached unusually high values in early months of the year?

Thus, the authors decided to remove the seasonal variation from the monthly climate time-series and model the variation in the deseasonalised variable, rather than using a moving average process in which information about the specific months in which unusually high values occurred would be lost. Seasonal decomposition (26) of the time-series of climatic variables was performed in MINITAB® release 12.21. An additive model of the type $X_t = mt + S_t + \epsilon_t$ was used for seasonal decomposition (where m_t is the deseasonalised mean level at time t, S_t is the seasonal effect at time *t*, and ϵ_t is the random error) to make the seasonal effect constant from year to year. The

goodness-of-fit of the model was assessed using two measures (based on prediction errors): the mean absolute deviation and the predictive mean squared error.

Relationship between bluetongue outbreaks and climate variables

To evaluate the relationship between climate and BT outbreaks, cross-correlation functions (CCF) were calculated between the monthly totals of BT outbreaks and the deseasonalised climate variables (one CCF was calculated from 1981 to 1994 and one from 1995 to 1999), lagged by up to 100 months. The approximate standard error of the cross-correlation coefficients at particular monthly lags (lag k) was calculated according to the assumption that the series are not cross-correlated and that one of the series is white noise (8). Correlations between time-series at lag k are considered to be significant if the cross-correlation coefficient exceeds twice this approximate standard error. Given the large number of such coefficients generated by a cross-correlation function analysis (one per lag), only significant cross-correlations are reported here. These analyses were interpreted with caution, due to the short duration of the satellite-derived time-series, the large number of zero values for outbreaks per month and the seasonal incidence of BT outbreaks.

Thus, this relationship was also investigated at an annual time scale (as opposed to the monthly time scale of the above analysis) by calculating a linear regression between the annual total of BT outbreaks (log-transformed), the year (to consider the linear temporal trend) and forty independent climatic variables. The year was divided into four quarters:

– January to March
– April to June
– July to September
– October to December.

The following ten independent variables were calculated from monthly values across outbreak pixels for each of the deseasonalised TAIR, NDVI, LST and MIR:

– annual mean
– annual minimum
– annual maximum
– annual amplitude
– mean of the variable across months within each quarter of the same year (thus giving four values)
– mean of the variable within the last two quarters of the previous year (thus giving two values).

Variables significant in univariate regressions were then included in a global model and the best one- or two-variable model was chosen by 'best subsets' regression. This process was repeated with the duration of outbreaks as the dependent variable. Since no satellite-derived climate variables were available for 1994, this produced missing values at 1994 for annual variables and for the means from the third and fourth quarter of the same year, but produced missing values at 1995 for the means from the last two quarters of the previous year. Since 1994 was one of the severe outbreak years, and the sample size of years was small, these two years were not omitted from regression analyses but included wherever possible. F statistics (F), adjusted R^2 values (the proportion of variance in the dependent variable that is explained by the model) and p-values (p) are presented.

The relationship between monthly time-series of satellite-derived climate variables and weather station-derived climate variables was evaluated for Kefar Blum by CCF between deseasonalised variables. Since monthly rainfall amounts were only available for September to May for each year, this variable could not be deseasonalised and Spearman's rank correlation between this weather station variable and deseasonalised satellite-derived variables was calculated instead.

Results

Temporal patterns in bluetongue outbreaks and seroconversions, vector and climatic time-series

A total of 386 outbreaks of BT were recorded between 1968 and 2001 in Israel. Of these outbreaks, 101 occurred before 1981; 230 outbreaks were recorded during the period coincident with the satellite data (1981 to 1999), but 55 outbreaks were recorded between September 1994 and December 1994, a period for which the satellite data were missing. Outbreaks occurred almost annually (Fig. 2) (range in annual total number of outbreaks per year: 0 to 60) and only six of these 34 years (18%) contained no outbreaks (annual mean outbreaks ± s.e. for years with outbreaks = 13.8 ± 2.8, n = 28). However, 50% of these years had five outbreaks or fewer and 82% had 20 outbreaks or fewer. More than twenty outbreaks occurred in 1969, 1975, 1987 and 1988, 1991 and 1994. Within the year of a BT episode, the duration of the outbreaks in months ranged from one to six months (annual mean duration ± s.e. for years with outbreaks = 3.14 ± 2.84) and it took between zero and four months for case numbers to reach a peak. There was a significant positive correlation between the annual total number of outbreaks and their duration (Spearman's rank correlation $r_s = 0.76$, $p < 0.001$, $n = 28$). Outbreaks only occurred between July and January within the year but were concentrated in October and November. Considering the six years which had more than twenty outbreaks, 71% of all outbreaks were detected in October and November, with 21% detected in August and September (Fig. 3).

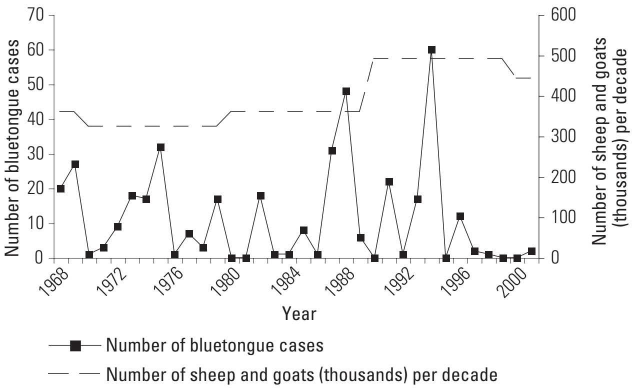


Fig. 2
Annual time-series of bluetongue outbreaks from 1968 to 2001 and livestock numbers (in thousands per decade) in Israel

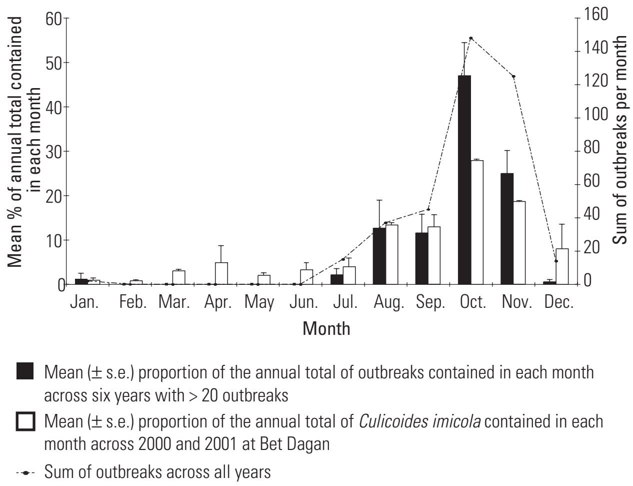


Fig. 3
Seasonal distribution of bluetongue outbreaks and vector *Culicoides imicola* populations in Israel

This seasonal distribution of outbreaks was mirrored by that of adults of the vector species *C. imicola*, the highest numbers of which are also concentrated in September to November, as shown for the years 2000 and 2001, and peak in October and November. The LST, MIR and TAIR all show a similar pattern of seasonal variation, with the annual minimum occurring between December and March, most commonly in January. Their annual maxima occur between June and August (September for the TAIR) and most commonly in July. In contrast, the NDVI peaks between February and April, with a second, smaller peak in July and August, and is lowest between September and November (Fig. 4).

At least 20% of animals in sentinel herds seroconverted to BT in every year of testing except 1993 (Fig. 5a). Seroconversions were geographically widespread, being detected yearly in at least five out of six sites sampled between 1981 and 1984, and six out of nine to eleven districts sampled between 1987 and 1995 (Fig. 5b). Although the annual time-series of the percentage of seroconversion in sentinel animals broadly shows the same dynamics as those of the outbreaks, exhibiting peaks and troughs in the same years, years with high percentages of seroconversion in the sentinels (such as 1987 to 1989, 1991 and 1994) were not always mirrored by high numbers of outbreaks. In fact, 46% of the sentinel animals in 1981 seroconverted to BT, and 38% seroconverted in 1995 but no outbreaks were reported in these years. It is significant that, in 1994, when seroconversions were occurring in eleven districts across Israel, only 60 outbreaks were reported: the maximum number recorded during the study period (Fig. 5a).

Vaccination usage ranged from 30,000 to 40,000 doses in the early to mid-1980s. It peaked at 77,000 doses per year in the late 1980s and declined to 10,000 doses in the late 1990s. Vaccination usage does not appear to be correlated with outbreaks or the percentage of seroconversions to BT (Fig. 5b).

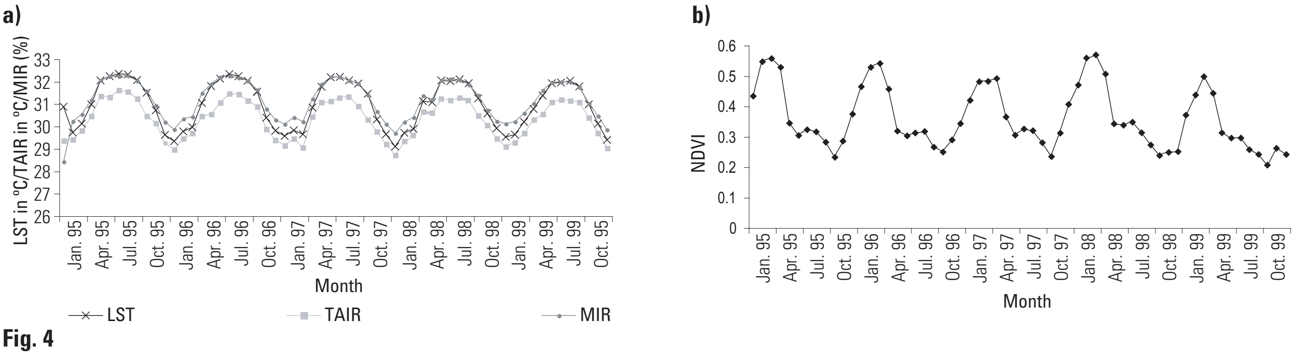
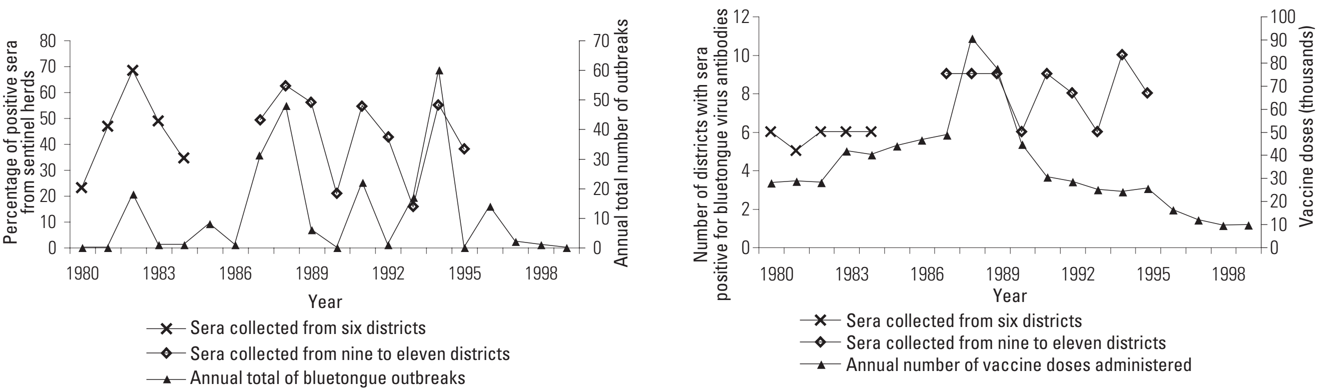


Fig. 4
Seasonal variation in land surface temperature (LST), air temperature (TAIR), middle infra-red reflectance (MIR) (a) and normalised difference vegetation index (NDVI) (b) in Israel from 1995 to 1999

a) **b)**



a) Annual time-series of bluetongue outbreaks from 1981 to 1999 and the percentage of positive sera in sentinel herds

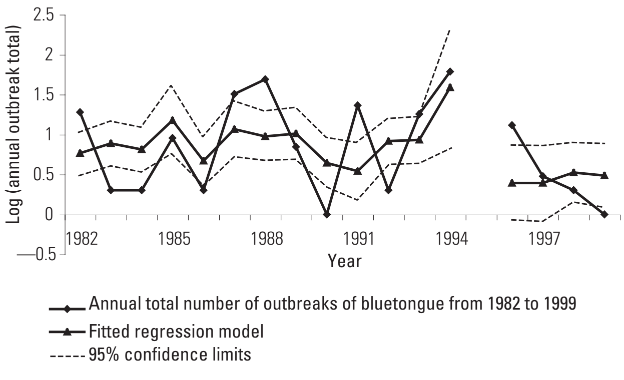
b) Annual vaccine usage (in thousands of doses) and number of districts from which sera tested positive for antibodies against bluetongue virus

Fig. 5
Seroconversion to bluetongue in sentinel herds in Israel between 1981 and 1999

Relationship between bluetongue outbreaks and climatic variables

Between 1981 and 1994, monthly BT outbreak numbers were negatively correlated with MIR ($r = -0.26$), TAIR ($r = -0.26$) and LST ($r = -0.28$), at a lag of one month. Between 1995 and 1999, monthly BT outbreak numbers were negatively correlated with MIR ($r = -0.13$), TAIR ($r = -0.35$) and LST ($r = -0.23$) at a lag of five months, and positively correlated with NDVI in the same month ($r = 0.31$), at a lag of four months ($r = 0.26$). These results suggest that outbreaks are more likely in a month which is preceded by periods of low temperature and high moisture levels. There was no significant relationship between the annual total number of outbreaks and year ($F_{1, 17} = 0.05$, $p = 0.82$, adjusted $R^2 = 0.0$) or the duration of the outbreaks and year ($F_{1, 17} = 0.03$, $p = 0.88$, adjusted $R^2 = 0.0$), indicating that there was no linear temporal trend in either variable. The annual total number of outbreaks was negatively related to the mean LST (equation: $y = 28.8 - 0.09 \times$ mean LST; $F_{1, 17} = 4.7$, $p < 0.05$, adjusted $R^2 = 18.7$) and mean MIR (equation: $y = 24.2 - 0.08 \times$ mean MIR; $F_{1, 17} = 5.6$, $p = 0.03$, adjusted $R^2 = 22.2$) in the last quarter of the previous year (October to December) by univariate regression but was unrelated to all other independent variables. A regression model including both variables did not sufficiently increase the amount of variance explained by the predictor variables to justify the inclusion of LST (equation: $y = 22.7 - 0.09 \times$ mean MIR $+ 0.02 \times$ mean LST; $F_{1, 17} = 2.6$, $p = 0.11$, adjusted $R^2 = 16.8$). Thus, a model based on the mean MIR in the last quarter of the previous year alone was considered the most parsimonious model and the fit of the model predictions to the observed data is shown in Figure 6. The average across the time-series of the annual mean LST in the last quarter of the year was 30.8ºC (± 0.06ºC) but ranged from 30.3ºC to 31.3ºC, whilst the average across the time-series of the annual mean MIR in the same period was 30.8 (± 0.1ºC) and ranged from 29.7 to 31.3.

The observation for the 1994 outbreak year had a large influence in these regressions (equation omitting 1994: $y = 20.0 - 0.06 \times$ mean MIR; $F_{1, 15} = 2.1$, $p = 0.17$, adjusted $R^2 = 6.5$). Owing to the gap in the climatic time-series (from September 1994 to December 1994), mean climatic variables from the third and fourth quarters in the same year had missing values at 1994. Thus, the lack of significant relationships between the annual total number of outbreaks and the annual climate variables, and from the third and fourth quarters in the same year, may be attributable to the omission of 1994 in these analyses, rather than to the lack of a biological relationship.



No data was available for 1995

Fig. 6
Results of the regression model (year [*y*] = 24.2 – 0.076 × mean middle infra-red reflectance), representing the annual total number of outbreaks of bluetongue from 1982 to 1999 and the fitted regression model with the corresponding 95% confidence limits

The duration of outbreaks was negatively related to the mean LST in the last quarter of the previous year (equation: $y = 93.4 - 0.3 \times$ mean LST; $F_{1, 15} = 6.5$, $p = 0.02$, adjusted $R^2 = 25.4$). Once more, 1994 had a large influence on this relationship (equation omitting 1994: $y = 88.3 - 0.28 \times$ mean LST; $F_{1, 14} = 3.1$, $p = 0.10$, adjusted $R^2 = 12.3$).

Relationship between satellite-derived climate variables and those derived from weather stations for Kefar Blum

Monthly minimum temperatures were uncorrelated with satellite-derived variables, whereas monthly maximum temperatures were positively correlated with the TAIR ($r = 0.32$), LST ($r = 0.26$) and MIR ($r = 0.30$) in the same month. Average daily minimum temperatures were negatively correlated with the NDVI in the same month ($r = -0.26$) and positively correlated with the MIR ($r = 0.29$) and LST ($r = 0.28$) in the same month. Average daily maximum temperatures were negatively correlated with the NDVI one month later ($r = -0.24$), and positively correlated with the TAIR ($r = 0.39$), MIR ($r = 0.33$) and LST ($r = 0.36$) in the same month. The monthly amount of rainfall was correlated with the MIR (Spearman's rank $r_s = -0.17$, $p = 0.03$, $n = 162$) and LST (Spearman's rank $r_s = -0.18$, $p = 0.02$, $n = 162$) in the same month.

Discussion

The transmission of BTV in Israel, indicated by the rate of seroconversion in sentinel herds, is geographically widespread and occurs in a substantial proportion of sentinel animals on an annual basis. In contrast, reported BT outbreaks are usually few in number, reaching a maximum of only sixty in 1994, and are geographically restricted to the northern coastal plain. Thus, the rate of outbreak notification does not reflect the actual extent of BTV circulation. Indeed, in surrounding countries, seroconversions to BTV are also reported much more frequently than outbreaks (Table I).

The circulation of BTV often occurs without any detectable clinical signs either because up to 75% of the sheep population consists of relatively resistant breeds (35, 57, 61, 65) or because the virus strains that are now circulating are avirulent, even in historically susceptible breeds. Whilst the annual variation in the level of BTV transmission may depend largely on the suitability of climatic conditions for vector populations, the annual variation in reported BT outbreaks will also depend on the variation in the susceptible proportion of the livestock population (i.e. on the importation, movement and vaccination of exotic sheep) and on the incursion of virulent strains from surrounding countries.

Despite these additional factors, BT outbreaks were significantly related to satellite-derived climate variables in Israel over time, with some degree of delay. This indicates at least some potential for the development of a climate-based early warning system for BT. This is the first study to find a temporal relationship between the risk of *Culicoides*-borne disease and satellite-derived climate variables. Throughout this discussion, references to low or high values of the climatic variables refer not to low or high absolute values but to lower or higher values than the seasonal average. On a monthly basis, BT outbreak numbers decreased when the temperatures (TAIR and LST) and MIR were high in the preceding months (one to five months before) and increased when the NDVI was high in the same and preceding months (four months before). Although correlations were significant at slightly different lags between the two time periods examined (1981 to 1994 and 1995 to 1999), probably due to the differing duration and data quality over these periods, the significant lags were all less than six months. This suggests that there is a strong intra-annual relationship, as opposed to an inter-annual one, between BT and climate.

On an annual basis, the total number of outbreaks decreased when there was a high MIR in the final quarter of the preceding year (October to December). The duration of outbreaks in the following year was reduced by high temperatures (LST) in that same final quarter.

Thus, cooler-than-average temperatures (indicated by low LST, TAIR and MIR) and higher-than-average moisture levels (indicated by low MIR and high NDVI) have a positive effect on BTV outbreaks in Israel, increasing both the number of outbreaks per episode and their duration. Conditions in the preceding year, between October and December, appear to be more important than spring or early summer conditions in the year of the outbreak. Previous studies have found that high moisture levels have a positive effect on the abundance of the vector, *C. imicola*. Spatial climatic models found higher mean NDVIs (3, 4) or earlier peaks of the NDVI to occur in high abundance sites (7, 63). Short-term temporal studies have found increases in the abundance of *C. imicola* in seasons that follow rainfall (48, 67). In addition, severe BT outbreaks have been observed to be preceded by higher-than-average rainfall in the previous autumn or winter (52, 53, 61, 62).

Owing to its location in the Southeastern Mediterranean Basin, Israel has a mixture of warm, temperate and arid desert climates. Temperature conditions will generally be far from the lower limits required for the development of *C. imicola* vectors whilst moisture conditions may generally be close to the lower limits of the requirements of this species. When considering the mechanism for the relationship between high outbreak numbers and lower-than-average temperatures with higher-than-average moisture in late autumn and winter in Israel, it is notable

Table I
Bluetongue virus serotypes in Middle Eastern countries between 1963 and 2001, including both those serotypes confirmed as causing outbreaks and those detected only by sero-surveillance with no clinical signs

Year	Israel		Egypt		Jordan		Syria		Turkey		Cyprus		Iraq		Lebanon	
	No. OB	OB	OB	SR	OB	SR	OB	SR	OB	SR	OB	SR	OB	SR	OB	SR
1963	+		1, 12	+												
1964	40	4		+												
1965	8	10		4, 10, 12								+				
1966	63	16	1, 12													
1967	15	4, 16									4					
1968	20	4,16	16		4, 6, 9			2, 4, 9								
1969	27	4, 16	+													
1970	1	4	1, 12													
1971	3	5	+													
1972	9	4, 6														
1973	18	2, 4, 6, 10, 16														
1974	17	2, 6, 10, 16														
1975	32	4, 16						+					+			
1976	1	4						+						+		
1977	7	4						+	4		4	2, 3, 4, 10, 12		+		
1978	3	2						+	4			+				
1979	17	2				2, 6, 9, 13		9,?	4	4, 9,?		+				
1980	0					2, 6, 13		4, 9, 13		4,?		4				
1981	0					6, 9, 13		2, 6, 9, 13		2,?		+				
1982	18	4						2, 6				+				
1983	1	6										+				
1984	1	4														
1985	8	+				+					+	+				
1986	1	+			+							+				
1987	31	4, 6			+							+				
1988	48	+		10, 12								+				
1989	6	+		10, 12				+				+			+	
1990	0											+				
1991	22	+										+				
1992	1	+										+				
1993	17	4, 10, 16										+				
1994	60	16										+				
1995	0															
1996	12	2, 4, 16														
1997	2	+										+				
1998	1	+														
1999	0								9			+				
2000	0											+				
2001	2	+							9			+				
Vaccination policy	Poly (2, 4, 6, 10, 16) used 1964-1973; Quad (2, 4, 6, 10) used 1974-2001		Mono (1, 12) 1970 None used since 1970		No information		No information		Mono (4) used 1979-1982		None used since 1950s		No information		No information	

No. OB : number of outbreaks per year in Israel
OB : bluetongue virus serotypes confirmed as causing outbreaks
SR : bluetongue virus serotypes detected only by sero-surveillance with no clinical signs
+ in the OB column indicates the presence of outbreaks caused by a viral strain of unknown serotype
+ in the SR column indicates the detection of seroconversion to an unknown bluetongue serotype
? = presence of a new serotype

Vaccination policy:
Poly = use of polyvalent vaccine
Quad = use of quadrivalent vaccine
Mono = use of type-specific vaccine
No information = no information available on vaccination policy for this country

Sources: Israel (11, 61), Egypt (2, 36, 55,), Syria and Jordan (65), Turkey (18, 34, 66, 70, 71), Cyprus (52, 53, 57, 58, and data provided by the Cyprus Veterinary Services), Iraq (35), Middle East (37, 66)

that this period coincides with the seasonal peak and initial reduction phase of both BT outbreaks and populations of the vector, *C. imicola*. This period also coincides with the annual troughs in moisture and temperature variables, with the NDVI trough coming early in the period and those of the LST, MIR and TAIR at the end. The number of outbreaks in the following year may depend on the initial size of the vector population after the winter period and the transmission intensity, both during the previous autumn peak of the vector and virus populations and over winter. High moisture levels when vector abundance is at its highest will increase the availability and quality of breeding sites (wet soil and organic matter) (11) and provide refuges where adult vectors can resist desiccation (47). Lower-than-average temperatures during autumn and winter may increase the initial adult population size the following year, through its positive effects on fecundity, offspring size (41) and survival to adulthood (40, 68).

Further north in Europe, at the northern range limit of *C. imicola*, proximity to the lower temperature limit for development within moist climates leads instead to a positive effect of high temperature and relatively dry summer conditions on *C. imicola* abundance (50, 54). Here, the temporal relationships between temperature and moisture variables and BT outbreaks may prove to be opposite to those found in Israel.

The proportion of variance in the BT outbreak time-series accounted for by climate factors is low, at around 20% (Fig. 6). This indicates that other factors have a substantial effect on the timing of outbreaks. No qualitative relationship was detected between annual vaccine usage and the annual number of BT outbreaks, perhaps because the proportion of susceptible sheep that are vaccinated is low.

Although outbreaks in this region have been preceded historically by the importation of German Merino breeds (2, 33), exotic sheep have recently been imported to Israel for slaughter only. These sheep are not kept on farms but are held in quarantine for only forty days before slaughter, making the transmission of BTV to local midge populations from infected imported animals extremely unlikely (R. Ozari, personal communication). Data on the annual variation in serotype prevalence were not of sufficiently high quality to test whether the introduction of strains of particular serotypes was associated with severe outbreak years. The year when outbreaks peaked, 1994, was associated with the re-appearance of type 16 in Israel, after an absence of seventeen years. However, many of the seroconversions that occurred during the intervening period were not attributed to a particular serotype. If the introduction of new, more virulent viral strains was responsible for the temporal distribution of outbreaks, one might expect a strong relationship between the timing of reported outbreaks in Israel and those in adjacent countries, even considering the absence of efficient surveillance systems in these countries. Sellers (57) noted the simultaneous appearance of BT outbreaks in groups of southern Mediterranean countries (Fig. 1), in 1943 to 1944 (in Cyprus, Turkey, Syria and Israel), in 1950 to 1951 (Cyprus and Israel) and in 1964 to 1965 (Cyprus, Israel and Egypt). Hassan (37) and Taylor (66) suggested that at least two ecosystems of BT occur in this region. The first occurs around the Bekaa and Orontes river valleys linking Jordan, Israel, Lebanon and Syria, with the capacity for BT to spread to Cyprus and West Turkey. The second is around the Tigris and Euphrates valleys linking Iraq, Syria and East Turkey, with the capacity to spread to Central Turkey. However, only five (1, 2, 4, 9, 16) of the ten different BTV serotypes found in adjacent countries (1, 2, 3, 4, 6, 9, 10, 12, 13, 16) have been detected in Israel (61). This, together with the considerable temporal variation in serotype prevalence in Israel, detected during both seroconversions and outbreaks, suggests that incursions from surrounding countries, probably facilitated by wind dispersal of infected midges, play some role in the dynamics of BTV transmission. It has previously been suggested that the Persian Troughs air streams, rather than the Red Sea Troughs air streams, may play a particularly important role in bringing BTV-infected midges to Israel (16, 66). Indeed, the former synoptic weather system occurs more frequently (51) and in summer during the period of peak *Culicoides* activity, unlike the Red Sea Troughs which occur mostly in winter. However, the BTV serotypes recorded in Israel are no more similar to those identified in countries on the route of the Persian Trough air stream (Turkey, Syria, Lebanon and Iraq – types 2, 4, 9, 6, 13) than they are to those on the route of the Red Sea Trough air stream (Egypt and Jordan – types 1, 2, 4, 9, 10, 12, 13, 16). In light of this, temporal variations in wind speed and direction should be considered in future models (10, 13, 17, 43, 52, 58, 63, 65), although these factors are also inherently difficult to quantify.

To improve long-term predictive models of the timing of BT outbreaks, annual estimates of BTV transmission from standardised sentinel surveillance data should be related to climatic time-series, in addition to annual outbreak totals. However, detecting relationships between the long-term, inter-annual periodicity in epidemiological time-series and that in climatic time-series will be limited by gaps in the satellite-derived time-series from instrumental bias (42). Thus, an examination of BT seroconversion data from the current epidemic in relation to a range of satellite imagery, over shorter time scales, may reveal strong relationships between climate and the timing of outbreaks that will facilitate outbreak prediction in epidemic areas. Examining concurrent vector data will reveal whether levels of BTV transmission have a direct relationship to the abundance of the main European vector, *C. imicola*, through time. Departures from a direct relationship would

be expected if other vectors were also operating or if the virus had thermal requirements for transmission which differ from those of the vector.

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La prévision du risque de fièvre catarrhale du mouton : modèles climatiques de la structure temporelle d'apparition des foyers en Israël

B.V. Purse, M. Baylis, A.J. Tatem, D.J. Rogers, P.S. Mellor, M. Van Ham, A. Chizov-Ginzburg & Y. Braverman

Résumé

La détermination de la relation temporelle entre le climat et les épidémies de maladies virales transmises par *Culicoides* peut permettre de prendre des mesures de lutte et de surveillance susceptibles d'être appliquées plus tôt et de manière plus efficace. En Israël, des foyers de fièvre catarrhale du mouton (FCM) se sont produits presque chaque année depuis au moins 1950, des flambées épidémiques apparaissant périodiquement.

Dans le présent article, les auteurs modélisent une série d'apparition de foyers de FCM sur vingt ans en relation avec le climat. Les corrélats, obtenus par satellite, de basses températures et de hauts niveaux d'humidité ont augmenté le nombre et la gravité des foyers. Il s'agit ici de la première étude à trouver une relation temporelle entre le risque de maladie transmise par *Culicoides* et des données sur des variables climatiques obtenues par satellite.

Les conditions climatiques régnant dans l'année précédant l'apparition des foyers, entre octobre et décembre, coïncidant avec le pic saisonnier d'abondance du vecteur et de nombre de foyers, semblent être plus importantes que les conditions régnant au printemps ou au début de l'été de la même année. Comme Israël est un pays aride, des niveaux d'humidité supérieurs à la moyenne pendant cette période peuvent augmenter la disponibilité des sites de reproduction et des refuges pour les vecteurs *Culicoides imicola* adultes, tandis que des températures plus fraîches que la moyenne augmentent la fécondité, la taille de la progéniture et la survie dans l'état adulte en hiver, ce qui, à son tour, augmente l'importance de la population initiale de vecteurs l'année suivante.

La proportion de la variance dans la série temporelle de foyers annuels de FCM résultant de facteurs climatiques est relativement faible, voisine de 20%. Il est possible que cela soit dû à une variation temporelle d'autres facteurs, comme des incursions virales en provenance de pays environnants et les niveaux d'immunité des troupeaux. Autre possibilité, comme la plus grande partie de la circulation du virus de la FCM (FCMV) dans cette région se fait silencieusement, chez les races locales résistantes de moutons, le niveau de transmission a une faible corrélation avec la notification des foyers, si bien que les relations fortes entre la circulation du FCMV et le climat, si elles existent, sont masquées.

Mots-clés

Analyse de série temporelle – Climat – Culicoides imicola – Détection à distance – Imagerie par satellite – Israël – Virus de la fièvre catarrhale du mouton.

Predicción del riesgo de lengua azul en el tiempo: modelos climáticos de la distribución temporal de los brotes en Israel

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Resumen

Si se determina la relación temporal entre el clima y las epidemias de la enfermedad vírica transmitida por *Culicoides*, quizá sea posible instituir con más antelación y eficacia las medidas de lucha y vigilancia. Desde 1950 como mínimo, Israel viene sufriendo casi cada año brotes de lengua azul, que periódicamente revisten cierta gravedad.

Los autores describen un modelo que recoge la secuencia temporal de brotes de lengua azul durante veinte años y la relaciona con el clima. Los datos obtenidos por satélite muestran que existe correlación entre las bajas temperaturas, los altos niveles de humedad y el aumento del número y la gravedad de los brotes. Se trata del primer estudio en que se observa una relación temporal entre el riesgo de enfermedad transmitida por *Culicoides* y variables climáticas calculadas a partir de técnicas de teledetección por satélite.

Las condiciones climáticas reinantes el año anterior al brote, entre octubre y diciembre, pico estacional del vector y el número de brotes, parecen tener más influencia que las condiciones imperantes en primavera y verano del mismo año. Dado que Israel es un país árido, es posible que un nivel de humedad más alto de lo habitual en este periodo incremente el número de sitios propicios para la reproducción y de refugios de que dispone el vector *Culicoides imicola* adulto, y que un nivel de temperaturas inferior a la media conlleve un aumento de la fecundidad, del número de descendientes y del nivel de supervivencia de adultos en invierno, lo que a su vez hará más numerosa la población de partida al año siguiente.

En la serie temporal de brotes anuales de lengua azul, la proporción de varianza debida a factores climáticos es relativamente baja (alrededor de un 20%). Ello se debe posiblemente a la variación temporal de otros factores, por ejemplo las incursiones de virus desde países vecinos o el nivel de inmunidad de los rebaños. También es posible que, como en esta región el virus de la lengua azul circula casi siempre de forma subrepticia en razas resistentes de ovejas locales, el nivel de transmisión guarde escasa correlación con la notificación de los brotes, y que ello oculte las estrechas relaciones entre la circulación del virus y el clima, suponiendo que existan.

Palabras clave

Análisis de series temporales – Clima – Culicoides imicola – Imágen por satélite – Israel – Teledetección – Virus de la lengua azul.

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