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An integrated model to predict the atmospheric spread of foot-and-mouth disease virus

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SUMMARY

The application of a computer model called Rimpuff for simulating the airborne spread of foot-and-mouth disease (FMD) is described. Rimpuff is more sophisticated and accurate than other FMD simulation models previously described. It can be run on a desktop computer and performs analyses very quickly. It can be linked to a geographical information system and so the information generated can be integrated with geographical and demographical data for display in a format that can be easily assimilated and transmitted electronically. The system was validated using historical data from outbreaks of FMD in France and the UK in 1981, and from Denmark and the former German Democratic Republic (GDR) in 1982. A very good fit was obtained between the direction of the plumes of virus simulated by the model and the spread of disease from France to the UK in 1981. Although cattle in the UK were infected during the episode, the concentrations of airborne virus in the plumes simulated by the model were beneath the infectivity threshold for cattle. It was concluded from the analysis that the number of pigs infected in France, and therefore the source concentration of airborne virus, was probably much higher than was recorded at the time of the outbreaks. Analysis of the Denmark/GDR episode pointed to the possibility that the source of virus for the 1982 epidemic in Denmark could have been one or more unreported outbreaks involving pigs in the former GDR.

INTRODUCTION

Foot-and-mouth disease (FMD) is a highly contagious disease of cloven-hoofed animals which has the potential to spread rapidly in susceptible populations and cause devastating losses. In the event of an outbreak the prevention of extensive spread requires rapid reporting, accurate diagnosis and the implementation of control and eradication procedures without delay. FMD is a difficult disease to control and eradicate because of its contagiousness and the variety of mechanisms by which the virus can be transmitted. Those mechanisms include the carriage of virus by the wind. Spread by this means is not a common event as it requires the simultaneous occurrence of certain climatic and epidemiological conditions. However, when those events coincide the extent and speed of spread can be spectacular and disease control programmes may be compromised [1–5].

Computer systems have been developed for predicting the airborne spread of a number of viral diseases, including FMD [6–12], Aujeszky's disease [13, 14] and Newcastle Disease [15]. The primary purpose of these models is to provide an objective assessment during an outbreak of disease of whether there is a risk of airborne spread and, if so, which premises downwind are at risk. The information obtained can be used to direct disease surveillance

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efforts both geographically and temporally. Geographically, the extent of the region exposed to an infectious 'plume' can be quickly defined and the farms at risk under the plume identified. Temporally, an estimate can be made of the periods during which infection was most likely, the resulting period of incubation and when the earliest clinical signs can be expected. Based on this information, the timing and frequency of clinical inspections of livestock on farms at risk can be optimized so that control and eradication measures are implemented without delay.

Models for simulating the spread of FMD have been developed in England [7, 9, 10] and France [12]. These computer-based systems use the classical Gaussian plume dispersion model or modifications thereof. More recently the feasibility of using the Aerial Location of Hazardous Atmospheres (ALOHA) system, a Spanish model, to simulate the airborne spread of FMD was proposed [6]. However, this system offers no significant advances over earlier models as no account is taken of the influence of topography (terrain) on plume dispersion or the influence of relative humidity (RH) and other factors on virus survival.

Concern about the consequences of nuclear accidents has maintained support for the continued development of computer models to simulate the atmospheric dispersion of particles and gases. One such model called Rimpuff has been extensively validated using tracer gas experiments [16]. This model can simulate the spread of airborne particles and gases on a horizontal scale for several hundred kilometres under changing meteorological conditions. This paper describes the validation of a system in which Rimpuff was combined with a virus production model to simulate the long-distance spread of airborne FMD virus. Validation was performed using historical data from FMD outbreaks in France and the UK in 1981 and in Denmark and the former GDR in 1982.

MATERIAL AND METHODS

Parameters for modelling the airborne spread of FMD

Excretion of airborne virus

A series of workers have investigated the quantity of airborne FMD virus excreted by different species of infected livestock before and during the early stages of clinical disease following infection by different strains of the virus [17, 18]. A virus production model (VPM) was developed by collating data from these reports to derive values for the amount of airborne virus excreted by the different species of livestock during the late stages of incubation and the early clinical phase of vesicular disease. The period of excretion was taken as 5 days for cattle and pigs and 7 days for sheep (Table 1). Where experimental data for the time points were missing, extrapolations were made from the derived data. The model was written in Borland C$^{++®}$ compiled to run on a Sun Unix Workstation. The VPM used as input the number of animals with vesicular lesions, the species affected and the age of their lesions. The output of the VPM was expressed as the total amount of virus, in terms of tissue culture infectious doses ($TCID_{50}$) per 24 h, for each day that excretion was considered to have occurred on an infected premises. The output from the VPM was transferred to the Rimpuff model to perform atmospheric simulations (see later).

Table 1. *Quantities and duration of excretion of airborne FMD virus by different species*

Day of clinical disease*	Log_{10} $TCID_{50}$ virus/24 h		
	Cattle	Sheep	Pigs
−2		3·4	
−1		4·6	
0	3·5	5·1	4·3
1	4·5	4·0	8·6
2	5·1	3·2	8·6
3	4·7	2·7	7·1
4	4·1	2·4	5·4

* Vesicular lesions present.

Survival of airborne virus

The survival of airborne virus depends on its resistance to physical and biological decay factors. The consequence of biological decay is the loss of viability. The biological decay of airborne FMD virus depends principally on the atmospheric relative humidity (RH); above 55% RH airborne virus is stable but below 55% RH it is rapidly inactivated [19, 20]. The value of 55% RH was incorporated in the model as an 'on/off' switch. Above 55% RH the decay of virus can be modelled as an exponential function of time, exp $(-\lambda t)$, assuming no effect of ageing on the rate of biological decay and that inactivation is a random event. The half-life, $T_{\frac{1}{2}}$ is given in terms of the exponential decay constant, λ (s^{-1}), by $T_{\frac{1}{2}} = \ln 2/\lambda$. The decay constant can be calculated from the decay rate, s (h^{-1}), i.e. log viability per h [19, 20] by using the formula:

$$\lambda = \frac{s \cdot \ln 2}{60^2 \cdot \log_{10} 2} = 6{\cdot}4 \times 10^{-4} s.$$

The biological decay rate, s, depends on the strain of virus and the nature of the fluid in which the virus was suspended for aerosol generation [21]. The decay rates for FMD virus in aerosols originating from the respiratory tract of infected animals have not been determined but studies on the decay rate of virus from bovine fluids indicate that a typical value is of the order of 0·5 h^{-1} or less [22]. The capacity to estimate virus decay was built into the system so that the model could have worldwide application. The effect of RH was not used in the simulations described in this paper.

Atmospheric dispersion of virus

Atmospheric dispersion simulations were performed using the Rimpuff model [23–25] developed at the Risø National Laboratory, Denmark. The model is written in Fortran and compiled to run on PCs or Unix Workstations. Rimpuff uses as inputs: (i) recordings of weather conditions from meteorological stations; (ii) the quantity of airborne virus excreted from infected premises estimated using the VPM; and (iii) the geographical co-ordinates of all virus sources. Rimpuff simulates plumes on a horizontal scale up to a few hundred kilometres and responds to changing meteorological conditions. Puff models, like Rimpuff, simulate plumes under non-stationary and non-homogeneous conditions by breaking the plume into independent three-dimensional concentration fields, 'puffs'. The individual puffs are transported by the local wind. The turbulent diffusion of the individual puffs is described in terms of parameters, which depend on atmospheric stability. The puffs are reflected from the ground as well as from inversion layers. The amount of a pollutant, e.g. virus particles, associated with a given puff is determined by the emission rate, which may change with time. The concentration field associated with a puff is reduced continuously by deposition of airborne particles to the ground (dry deposition) and by removal due to precipitation (wet deposition). In addition Rimpuff is capable of treating plume bifurcation which is likely to occur over hilly and mountainous terrain, by using a puff-splitting technique. The model is also capable of managing several simultaneous emission sites.

Table 2. *Minimum doses of airborne FMD virus required to infect different species during a 24-h exposure period*

Species	Min. dose ($TCID_{50}$)	Inhalation rate (m^3/24 h)*	Threshold conc. ($TCID_{50}/m^3$)
Cattle	10	173	0·06
Pigs	400	52	7·70
Sheep	10	9	1·11

* Average inhalation rate of a full-grown adult animal [37].

For each meteorological station a series of weather recordings is required at equally spaced time intervals. The data collected consists of wind speed and direction, rain intensity, lateral and vertical atmospheric stability. The stability can be obtained from the Pasquill–Turner index [26], or by standard deviations of the lateral and vertical wind directions. The meteorological parameters can also be derived [27] from numerical weather prediction (NWP) models, such as the High Resolution Limited Area Model (HIRLAM) [28–30]. Rimpuff can also be linked to the atmospheric flow model LINCOM [31–33] that simulates airflow over hills and terrain with different atmospheric roughness e.g. fields, forests and sea. This is useful when modelling airborne dispersion over land but is not required when transmission occurs over water, as was the case in both of the episodes described here.

Risk of infection for animals downwind

The minimum doses of FMD virus for different livestock species were compiled from the published data [34–36]. From the average respiratory exchange rates for the different species [37] the minimum doses were extrapolated to 24-h exposure periods (Table 2). In analyses to predict whether the plume of airborne virus released from an infected premises contained a concentration of virus sufficient to constitute a risk for animals downwind the concentrations calculated by Rimpuff were averaged over 24-h periods.

Effect of species on airborne transmission

Simulations were performed to determine the effect that varying the species and number of animals at the source would have on the distance that a plume would be infectious for different species downwind. The parameters chosen were: the virus output of 1 to 1000 animals, in 10-fold increments from each species, meteorological conditions favourable for long-range

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Table 3. *Estimated amount of airborne virus excreted each day from clinically affected animals during the 1981 FMD epidemic in Brittany, France*

		Number of animals/duration of airborne virus excretion																	
		Feb	March																
Farm no.	Clinical cohort*	28	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	(i)	2																	
	(ii)		6																
2	(i)					4													
	(ii)						8												
	(iii)							3											
3	(i)							1				†							
	(ii)								7										
4	(i)							3											
	(ii)									11									
5	(i)										1								
6	(i)											4							
7	(i)														1				
8	(i)											3							
	(ii)													22					
9	(i)													2					
10	(i)														4				
	(ii)															4			
Total virus ($\log_{10}$ $TCID_{50}$)		4·6	8·9	9·5	9·4	7·9	9·2	9·7	9·8	9·75	9·85	9·7	9·2	9·1	10·0	10·0	9·5	9·2	7·7

Pigs, ═══; Sheep, ▬▬▬; cattle, ---------.
* A group of animals in close proximity with the same age of lesions.
† Animals slaughtered during the excretion phase, so < 5 days.

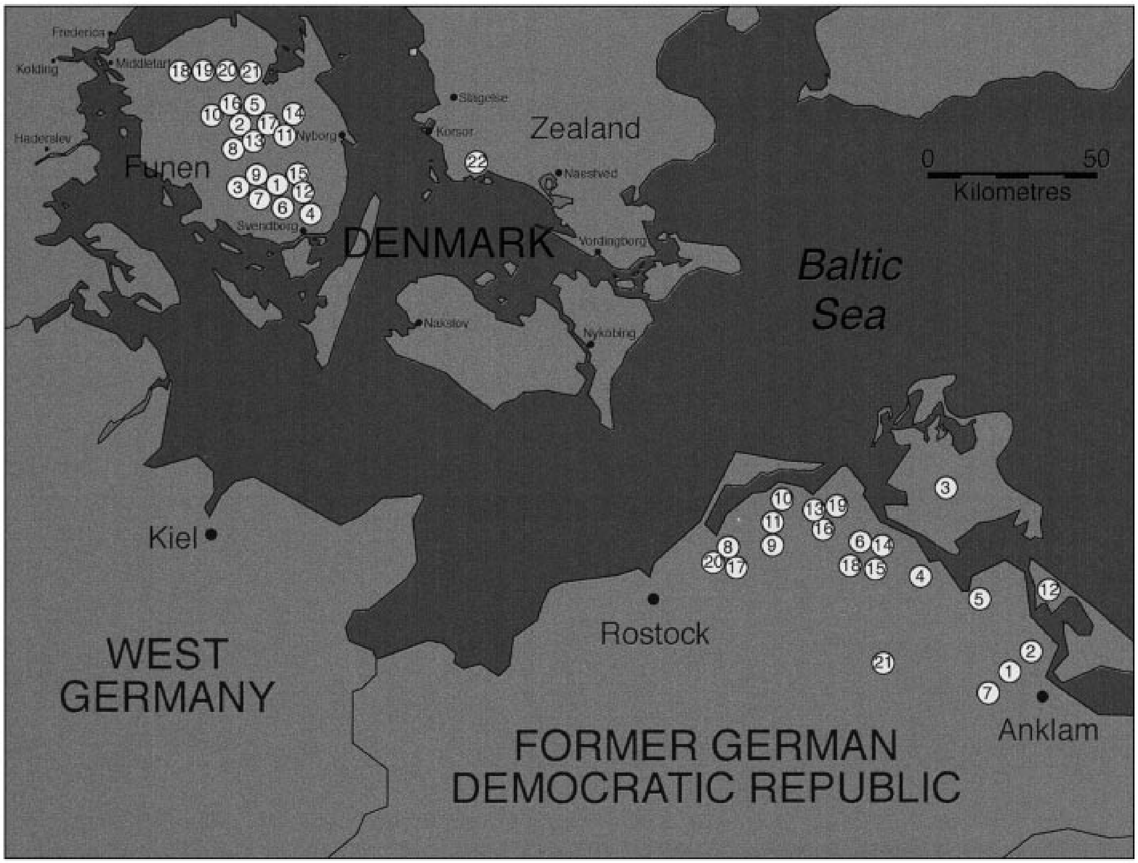

Fig. 1. Location of reported outbreaks of FMD in Denmark and the former German Democratic Republic GDR during the type O FMD epidemic of 1982. The numbers refer to the order that outbreaks were reported in the GDR (1–21) and in Denmark (1–22).

airborne dispersion, i.e. a constant wind direction, a wind speed of 5 m/s, a high degree of atmospheric stability, no precipitation and an RH > 55%.

Validation of the model

The predictive capability of the model was determined by using as input for the VPM estimates of airborne virus excretion from outbreaks during two epidemics: the 1981 epidemic in France and the UK; and the 1982 epidemic in Denmark and the former GDR.

FMD in France and the UK in 1981

An account of the outbreaks on Jersey, Channel Islands and on the Isle of Wight and their likely origin from outbreaks in Brittany, France has been published [8]. In brief, FMD type O was confirmed in pigs in the Henansal municipality, Brittany on 4 March 1981. Epidemiological investigations suggested that clinical signs of disease had been present from 28 February. Control measures, including vaccination, were implemented immediately but a further three outbreaks occurred, all in pigs, on 7 and 8 March. During the next 3 weeks 10 more outbreaks were reported, making a total of 14 (13 in Côtes-du-Nord, Brittany and 1 in Le Mesnil, Manche, Normandy). On Jersey, Channel Islands, a single outbreak in 2 cows in a group of 6 non-milking cattle was suspected on 18 March and confirmed as FMD virus type O on 19 March 1981. Later a single outbreak of type O FMD also occurred on the Isle of Wight. Clinical signs were reported by the farmer on the 21 March and confirmed on 22 March. In total, 16 of 19 non-milking cows were clinically affected. Ageing of their lesions by an epidemiology team indicated that clinical disease had been present from at least 17 or 18 March [8].

Molecular analysis of isolates of virus from Brittany, Jersey and the Isle of Wight showed that they were closely related to each other and to the vaccine strain O_1 Lausanne. It was concluded that the outbreaks in Brittany arose from the use of incompletely inactivated vaccine which then became the source of the virus which spread to the UK [38].

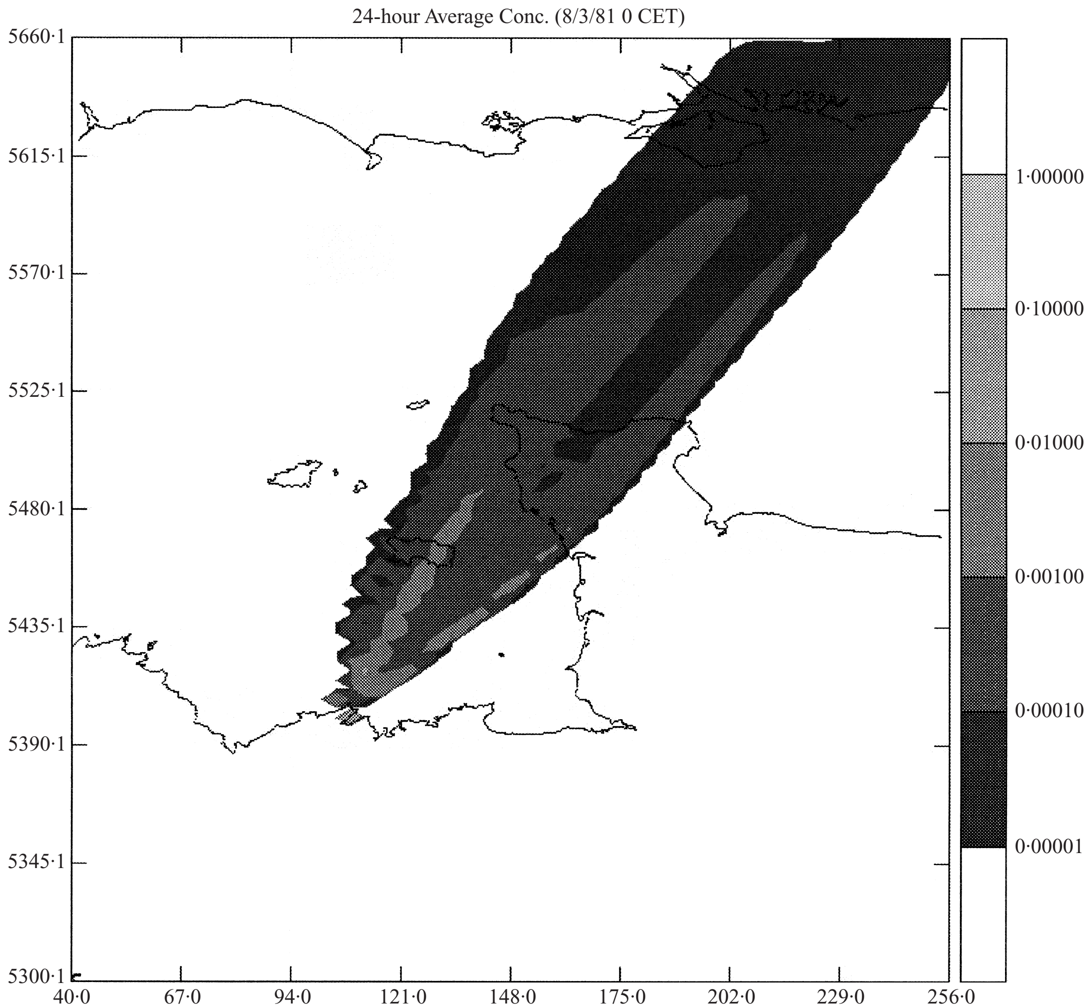

Fig. 2. Simulated virus plume produced by infected pigs on farms 2–4 (Table 4) in Brittany, France, as derived by Rimpuff using data from weather stations. The contours indicate 24-h average FMD virus concentrations for the preceding 24 h in units of $TCID_{50}/m^3$ on 8 March 1981, at 0 CET. The axis units are UTM co-ordinates, zone 31. The plume is seen to extend over the island of Jersey and the Isle of Wight.

Epidemiological data for the outbreaks in Brittany were obtained from Dr J. Christophe, Chief, Veterinary Service, Côtes-du-Nord and Dr P. Vannier, Director, Laboratoire de Pathologie Porcine, Plufragon. Using this information an estimation was made of the quantity of airborne virus produced each day during the period 28 February to 17 March by reference to the epidemiological information for each farm, taking into consideration the number of different species of animals on each farm reported to have been clinically affected from the time when disease was first suspected until they were slaughtered. An estimate was made of the quantity and duration of airborne virus excretion by each clinical cohort of affected animals on the infected farms (Table 3) from the epidemiological data and by reference to the species/lesion age data shown in Table 1. Clinical cohorts were defined as groups of animals in close proximity which had clinical lesions of the same age. The duration of excretion for each cohort was taken as 5–7 days, depending on the species (Table 1), or up to the time of slaughter. These values were used as input for the VPM.

Meteorological data were obtained from weather stations in the area. Two sets of simulations were performed. In the first, weather station data were used directly as input for the Rimpuff model. In the second, simulations were made using numerical weather-prediction model data generated by the DMI-HIRLAM model [31], the operational NWP model at the Danish Meteorological Institute (DMI), for the area and period of interest using the information from the weather stations as input among other sources of input data.

FMD in Denmark and the former GDR in 1982

A full report of the 1982 Danish epidemic of FMD has been published [39]. Cattle with vesicular lesions were observed on 14 March by the owner of the first farm on which FMD was reported. A veterinarian who visited the farm on 14 March made a diagnosis of mucosal disease. When he visited again on 16 March he revised his clinical diagnosis to FMD. Confirmation was obtained on 18 March. A total of 22 outbreaks occurred during the period 18 March to 4 May. The first 17 outbreaks between 18 March and 14 April were in the eastern part of Funen and the next four in the north of that island between 16 and 21 April. There was then a respite of approx. 2 weeks until 4 May when the final outbreak occurred on the neighbouring island of Zealand.

The first international announcement of FMD in the former GDR in 1982 was on 18 March when the veterinary authorities informed l'Office International des Épizooties, Paris by telex that two outbreaks of FMD, first suspected on 14 and 15 March, had been confirmed as type O. The infected premises were located in Murchin commune, Neubrandenburg district and in neighbouring Lassan commune. Another 19 outbreaks were reported between mid-March and early May. The sequence and location of the epidemics in Denmark and the former GDR are summarized in Figure 1.

The viruses responsible for the German and the Danish epidemics were subsequently shown by molecular analysis to have nucleotide sequences which were almost identical to each other and to the vaccine strain O_1 Lausanne [40]. Vaccination against FMD was routine in the former GDR around the time of the outbreaks, however, it had not been used in Denmark for many years. It was concluded at the time that faulty vaccine was the origin of the outbreaks in the former GDR and that by some unknown mechanism the virus was transported to Denmark where it initiated further spread.

The first officially recorded suspicions of FMD in both Denmark and the former GDR were on 14 March. The earliest reported outbreaks in the former GDR could not, therefore, have been the source of virus for the Danish epidemic. However, the question arises as to whether an earlier outbreak, or outbreaks, either unreported or unrecognized, had occurred in the former GDR or perhaps in a neighbouring country. Simulations were carried out with the Rimpuff model to determine whether the climatic conditions in early March would have been suitable for a virus plume originating in the former GDR to have reached Denmark.

Table 4. *Effect of species and number of animals excreting virus on the risk for different species downwind*

Species excreting	Species at risk downwind: Cattle	Sheep	Pigs
1000 infected animals			
Pigs	300 km	90 km	20 km
Cattle	3 km	0·5 km	< 0·1 km
Sheep	3 km	0·5 km	< 0·1 km
100 infected animals			
Pigs	120 km	15 km	5 km
Cattle	0·7 km	< 0·1 km	< 0·1 km
Sheep	0·7 km	< 0·1 km	< 0·1 km
10 infected animals			
Pigs	30 km	4 km	1 km
Cattle	< 0·1 km	< 0·1 km	< 0·1 km
Sheep	< 0·1 km	< 0·1 km	< 0·1 km
1 infected animal			
Pigs	5 km	1 km	0·3 km
Cattle	< 0·1 km	< 0·1 km	< 0·1 km
Sheep	< 0·1 km	< 0·1 km	< 0·1 km

Rimpuff simulations were run using as input the amount of airborne virus excreted by 1–1000 animals of each species and optimal meteorological conditions for airborne virus transport. The distance shown is the maximum distance travelled by virus particles in a plume at sufficient concentration to infect each of the species shown, based on the MID's given in Table 2.

Meteorological data was obtained from weather stations in the area. As above, these data were either used directly, or the DMI-HIRLAM NWP model was run to produce predicted weather data for the area and period of investigation.

RESULTS

Effect of species on airborne transmission

Simulation of airborne FMD dispersion using Rimpuff and assuming optimal climatic and topographical conditions showed that airborne virus from 1000 infected pigs could infect cattle located up to 300 km downwind (Table 4). Transmission from infected cattle or sheep could not be shown to occur over distances of more than about 3 km. A pig, when excreting maximally, can liberate the equivalent amount of airborne virus as 3000 cattle [41] and in outbreaks where there has been circumstantial evi-

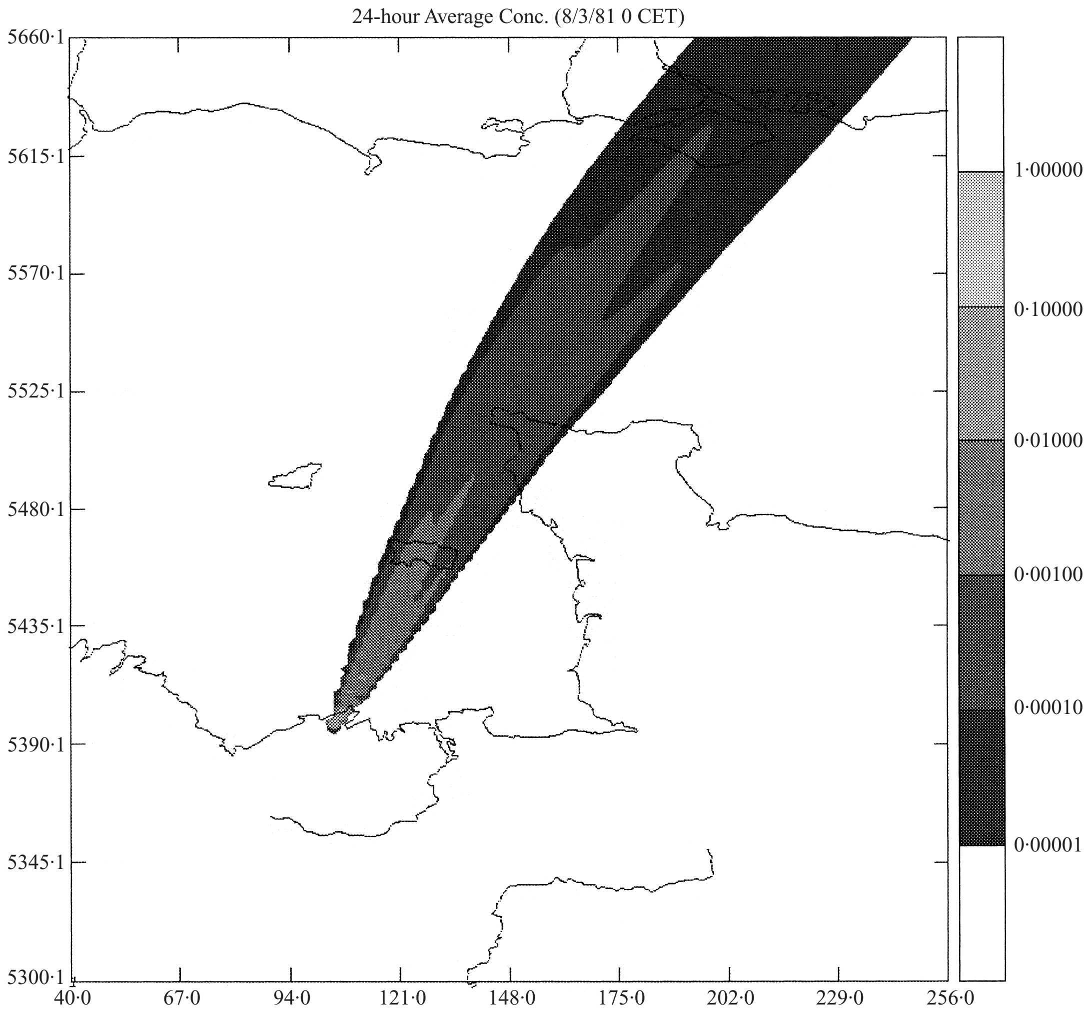

Fig. 3. Simulated virus plume produced by infected pigs on farms 2–4 (Table 3) in Brittany, France, as derived by Rimpuff using output from the DMI-HIRLAM NWP model. All other details as for Figure 2. The plume is narrower and more concentrated than that predicted using actual weather recordings.

dence of airborne spread it has been concluded that pigs were the source [8–10]. The distance between where the outbreaks occurred in Brittany and on the Isle of Wight was approx. 250 km.

FMD in France and the UK in 1981

Using data from weather stations in the study area, highly stable and constant meteorological conditions were found during the period 7–8 March 1981. This was considered the period most likely to have been favourable for transmission of airborne infection. At that time virus excretion was taking place from the infected pigs on farms 2–4 (Table 3). The Rimpuff model was run using for the VPM the estimated output from 26 and 37 pigs, respectively, on those 2 days (Table 3). The number of pigs excreting maximally on 7 and 8 March totalled 19 and 26; the clinical cohorts of 7 pigs on 7 March and 11 pigs on 8 March would have excreted relatively much less virus (Table 3). Thirty-four piglets were found dead on the three farms on those days but they were not included in the VPM since no information is available about the quantities of airborne FMD virus excreted by piglets.

The output from the model for the period from 0 Central European time (CET) on the 7 March 1981 to 0 CET on the 8 March 1981 showed a narrow and intense plume of virus which passed over the Island of Jersey and reached the Isle of Wight (Fig. 2). Similar results were obtained using as input weather data generated using the DMI-HIRLAM NWP model. In this case, the plume was narrower and more concentrated (Fig. 3). However, using either set of weather data, the predicted 24-h average concentration of virus arriving at the Isle of Wight was some 500-fold

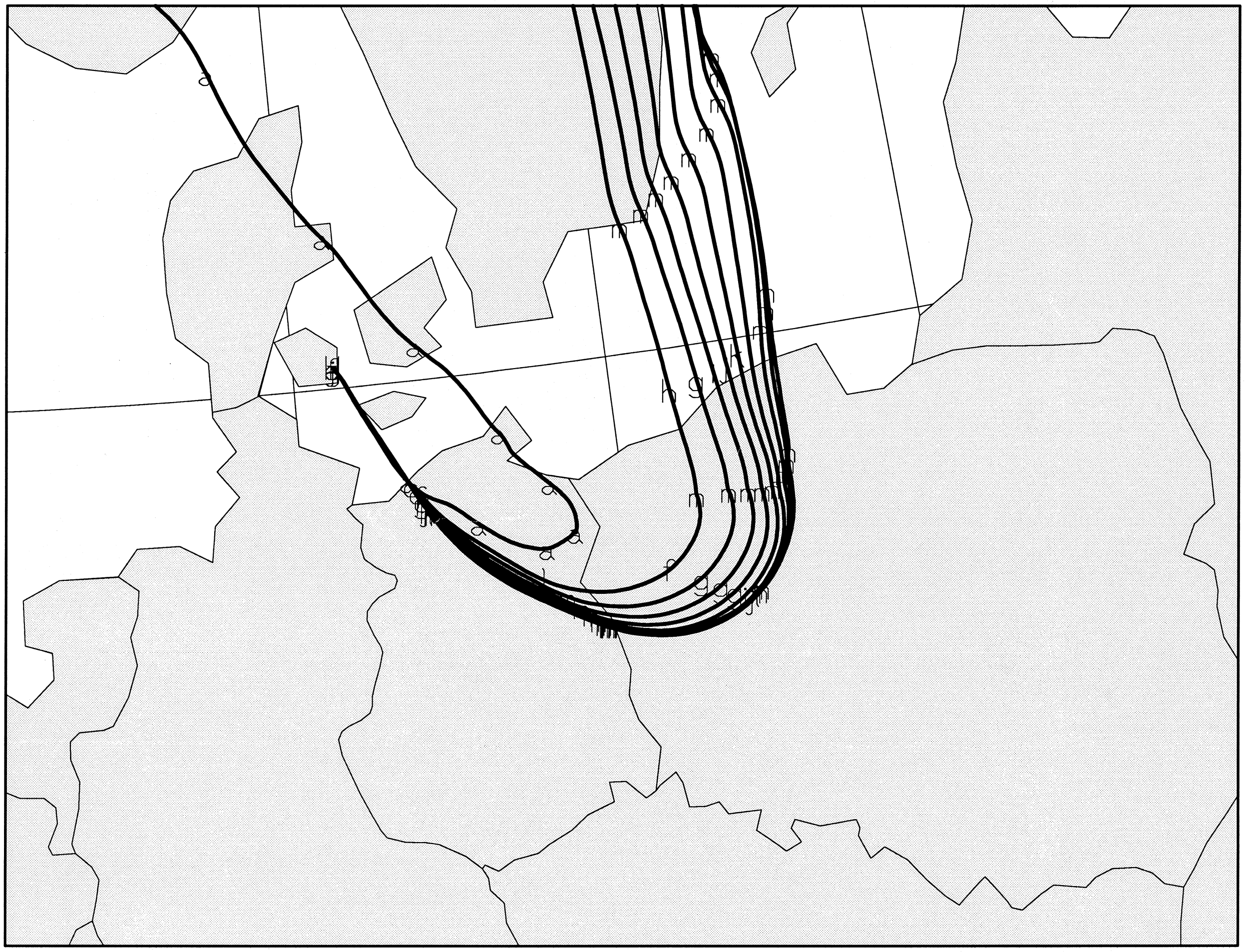

Fig. 4. Back-trajectories of plumes at 10 arrival heights inside the turbulent atmospheric boundary layer above the first infected premise of the Danish 1982 epidemic. The arrival time is 12 Universal Time Coordinated (UTC), also known as Greenwich Mean Time (GMT) on 7 March 1982. Along the trajectories the ratio of the height above ground to the atmospheric boundary-layer height is indicated by letters for every 6 h (i.e. a $< 0{\cdot}1$, $0{\cdot}1 <$ b $< 0{\cdot}2$ etc.).

lower than the threshold value of 0·06 $TCID_{50}/m^3$ required to initiate infection in cattle, the only species infected on the island. Model plumes applying to the days before and after 7–8 March extended into the English Channel but not as far as the Isle of Wight (data not shown). This was mainly due to changing wind directions.

FMD in Denmark and the former GDR in 1982

Before attempting to model the airborne spread of FMD virus from the former GDR, it was necessary to demonstrate that meteorological conditions at the time were consistent with the possibility of the GDR being the source of virus for the Danish outbreaks. The DMI-HIRLAM NWP model was run at high resolution for the relevant area and period. Using the data thus generated, an attempt was made to locate potential sources of airborne FMD virus for the first infected premises in Denmark. A period of 7–10 days before the first appearance of clinical signs in Denmark was chosen as being the most probable for transmission to have occurred. A calculation was made of three-dimensional back-trajectories of air parcels which would have transported airborne particles over the first infected premises within the turbulent atmospheric boundary (mixing) layer (Fig. 4). To a large extent atmospheric dispersion of material released from the ground takes place inside the mixing layer, which is often limited by a temperature inversion acting as a lid. Trajectory calculations do not take into account the effect of turbulent diffusion, and thus the average large-scale transport of air parcels reaching the premise may be represented by trajectories arriving within the mixing layer above the infected premises. On 7–8 March 1982

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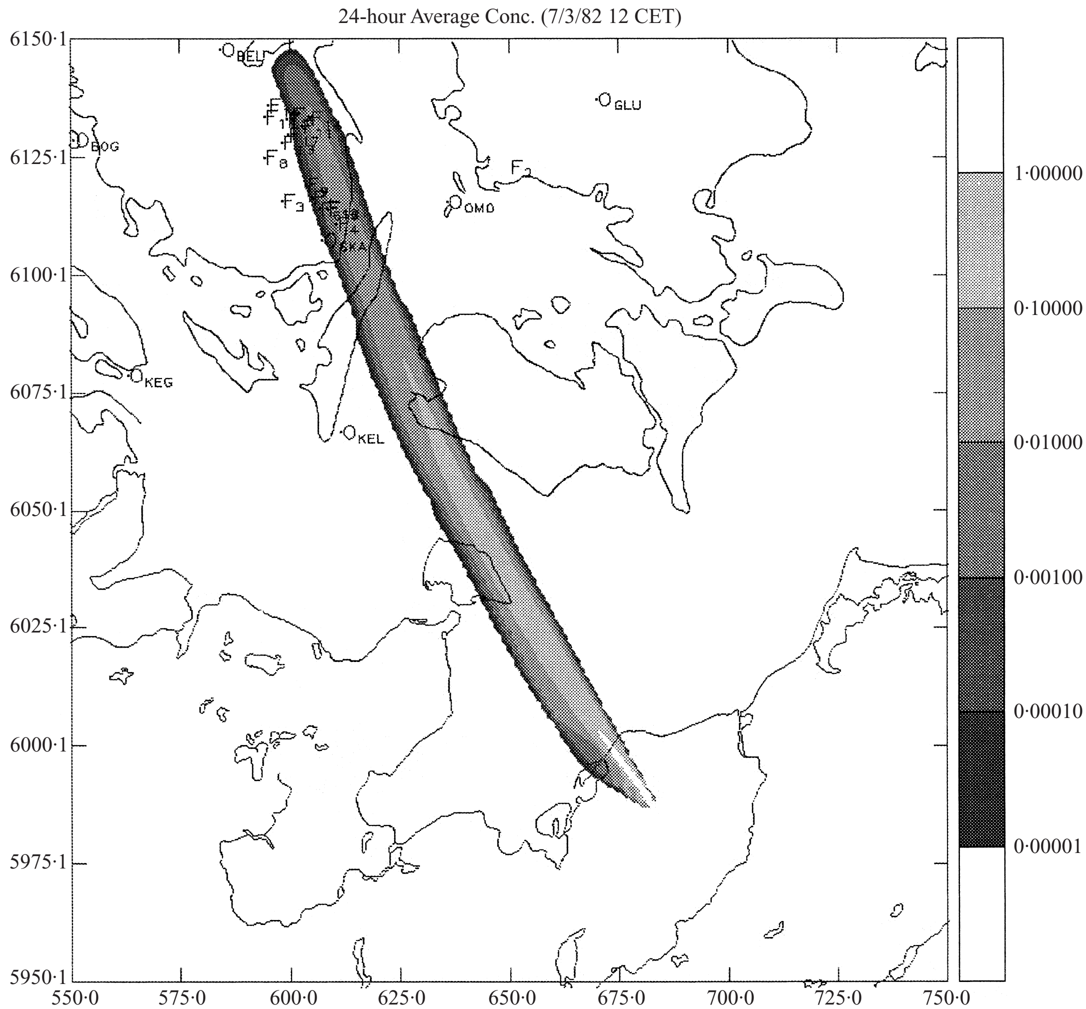

Fig. 5. Simulated virus plume from a hypothetical infected premise in the former GDR as derived by Rimpuff using data output from the DMI-HIRLAM NWP model. The plume reaches the first infected premise on Funen, Denmark. The contours indicate 24-h average FMD virus concentrations in units of $TCID_{50}/m^3$ on 7 March 1982 at 12 CET. The axis units are UTM co-ordinates, zone 32.

the mixing layer was very thin (less than a few hundred metres) over the northern part of the former GDR and the southern part of Denmark. From the back-trajectory calculations it is evident that the northeastern part of the former GDR was a potential source of airborne FMD virus reaching Denmark on 7–8 March 1982.

A simulation was then made using the Rimpuff model of a hypothetical outbreak involving 1000 pigs in the GDR southwest of Rostock. The virus plume passed directly over the site of the first reported outbreak on the island of Funen, Denmark (Fig. 5), and the amount of virus present over the farm was sufficient (more than 0·06 $TCID_{50}/m^3$) to initiate infection in cattle. With an incubation period of 7 days, transmission at this time would be consistent with the first appearance of lesions 7 days later on the 14 March 1982. This plume could also have been the source of virus for the early outbreaks in the GDR (Fig. 1). Model simulations showed that plumes corresponding to hypothetical outbreaks some days before or after did not reach the island of Funen. The simulations shown in Fig. 5 indicate that airborne FMD virus originating from the former GDR might have been the source of virus for the epidemic on Funen.

DISCUSSION

In the work described in this paper the atmospheric dispersion model Rimpuff was linked to a VPM that used as input the epidemiological data from infected premises. The system described is more sophisticated, therefore, than those designed previously in terms of both the modelling techniques used and in that transmission on any scale up to a few hundred kilometres can be modelled in a single system. Additionally, epidemiological expertise is not required to estimate the amount of virus being produced from infected premises. Unlike previous models, Rimpuff can simulate simultaneous emission from several sources, a situation which is not unusual during epidemics.

Sensitivity analysis of the model confirmed the findings of Sellers & Parker [42] that pigs act as the amplifier species for airborne FMD and cattle as the indicator species. The single most important factor in airborne transmission was shown to be the species of origin of airborne virus. In this study only when pigs were affected did transmission of airborne virus occur over distances of more than 3 kilometres. The stability of the boundary layer and the extent of variation in wind direction are also critical factors in long distance transmission. Stable conditions with a constant wind direction favour the production of a narrow plume of high virus concentration. For short-range transmission, local topographical features such as buildings or trees may well affect virus concentration by disturbing the airflow [1]. However, it is not possible to include those detailed factors in a computerized prediction system.

One constraint on the accurate prediction of the airborne spread of FMD virus is the availability of good quality meteorological data. Weather stations can be used as the source but the data may not completely reflect the actual conditions at the location of the infected premises. Rimpuff has the advantage that it can use input data generated by NWP models such as DMI-HIRLAM. Meteorological databases containing the output of NWP models are a source of historical meteorological data as well as forecasts. Benefits can be gained by using such a database in real time. Limited-area NWP models are applied to large areas such as Europe. Currently the horizontal resolution of operational limited-area NWP model is typically 15–50 km with 20–30 layers in the vertical. From the output of NWP models, parameters can be obtained such as wind speed and direction at different heights, precipitation intensity, cloud cover, relative humidity, atmospheric stability and the height of the atmospheric boundary layer (the mixing layer). The latter parameters, which may be used as additional inputs to the Rimpuff model, are not recorded by standard weather-recording stations. Arrangements can be put in place so that, in the event of an outbreak, these data can be downloaded quickly from a national weather service.

For the simulations of virus transmission across the English Channel in 1981 the outputs from Rimpuff based on actual recordings from weather stations in the area was compared with those using NWP data from DMI-HIRLAM. The plumes generated using the data from the NWP model were in every case narrower and of higher concentration than the plumes generated using data from the weather stations. This was probably due to the fact that the recordings at the weather stations, which were situated at the coast, did not accurately reflect the air-flow over the Channel due to bias from land–sea contrasts and the effects of local topography. Using the DMI-HIRLAM NWP model it was possible to model airflow (also at higher altitudes) more accurately, and it is likely that the predictions produced with these data were more accurate. To compare the results of Rimpuff with another verified dispersion model, the long-range transmissions of virus from Brittany to the UK, and from GDR to Denmark were simulated using the Danish Emergency Response Model of the Atmosphere (DERMA) [43, 44]. In both cases similar predictions of transmission were obtained (data not shown).

The possibility of airborne transmission from Brittany to the island of Jersey and to the Isle of Wight was proposed by Donaldson and colleagues [8] using a long-range model. This model estimated the period and amount of virus excretion and then established the days on which suitable conditions existed for airborne transmission in terms of the wind direction and the stability of the air over the Channel. Conditions were considered favourable on 7 and 10 March 1981 which was consistent with the first development of clinical disease on 17 March after an incubation period of 7–10 days. The Rimpuff model described here also predicted that conditions were favourable for transmission on 7 March. Estimation of the concentration of virus transferred suggested that it was 500-fold less than the minimum concentration of 0·06 $TCID_{50}/m^3$ required to infect cattle. The most likely explanation for this discrepancy is that the number of clinically affected pigs on farms 2–4 was much higher than recorded. It is probable that when the veterinarians involved had examined a few animals and were satisfied with their clinical diagnosis that they ceased their investigations. The number of pigs on premises 2–4 was 3595 in total and, considering the high mortality among the piglets, it is very probable that infection had been present on those farms for several days before a clinical diagnosis was made. Many more pigs were probably affected than was recorded. Thus the input value used for the VPM was probably a considerable under-estimation of the real situation. In order to simulate an infectious plume of sufficient virus concentration over the Isle of Wight, an input for the VPM corresponding to at least 1500 infected pigs on premises 2–4 was required. Another reason why virus output was considerably under-estimated was because no calculation could be made for the quantity of airborne virus excreted by piglets since there is no experimental data for that age of pig. (A total of 34 piglets were recorded as being found dead on 7/8 March.) Considering both of these factors, it is very probable that the output of airborne virus was under-estimated by a factor of at least 10-fold. In addition, from the experience gained from model validation against tracer gas dispersion experiments inaccuracies in the modelling procedure could account for a further factor of 10 [cf. 16, 24, 25, 32]. Finally, the factor that is least clear in modelling the airborne spread of FMD is the probability of infection of animals under a plume. Many animals on farms on the Isle of Wight and Jersey were undoubtedly exposed to airborne FMD virus but did not subsequently develop disease. Likewise in the Danish epidemic of 1982 several farms escaped infection although the animals on them were presumably exposed to airborne virus. Sellers & Forman [42] recorded that during the UK, Hampshire 1967 epidemic that the largest cattle herds downwind were those most frequently affected. The determinants of variation in the susceptibility of individual animals are not known neither is it known whether animals exposed repeatedly to sub-threshold doses of virus can accumulate an infectious dose over time.

These considerations do not detract from the usefulness of Rimpuff for assisting decision making in an FMD emergency. By identifying the geographical and temporal distribution of virus plumes surveillance activities can be focused on the farms at risk and thereby ensure the most rapid detection of disease and the fastest possible implementation of control measures. However, care will be necessary not to 'overinterpret' the results as there are still several uncertainties, in particular the probability of whether or not the animals on a particular premises considered at risk will be infected. In practice, many of the parameters used as inputs for the model will be estimates. For example, the number of animals excreting virus on the source farm or farms may not be exact, especially if a large livestock unit is affected as a balance has to be struck between the time permitted for careful clinical examination and the need to implement control measures. It is probable, therefore, that it will be necessary to use the model to simulate a variety of possibilities, based on the best, worst and mid-case scenarios. Operational decisions, in terms of surveillance and possible pre-emptive slaughter, can then be based on knowledge of the probable outcomes.

It was concluded from an analysis of the meteorological conditions that the weather conditions during the period 1–10 March 1982 were ideal for the long distance transport of airborne FMD virus from the former GDR to the Island of Funen. Although there was no official information of a virus source in the former GDR at that time, the geographical location and the meteorological conditions strongly supported an hypothesis for the carriage of virus to Denmark by the wind (J. Gloster, unpublished results, 1982). In the present study the same conclusions were reached following simulations of airborne spread using Rimpuff. The results showed that had infection been present in a large pig unit in the northeast of the former GDR then windborne virus transmission could have occurred to Denmark and might also have been the source of infection for the first cattle to be affected on the farms near Rostock. In the hypothetical case of virus production by 1000 pigs the concentration of virus estimated to have reached the first infected premises in Denmark exceeded the threshold value for the infection of cattle.

In both the 1981 and 1982 episodes the long-distance transmission of airborne virus over sea ways is proposed. Conditions for transmission are more likely to be favourable over water than over land due to the reduced surface turbulence over the former. Furthermore the stability of the air over the sea will be greater when the temperature of the sea is lower than that of the air, as occurred over the English Channel in 1981 [8] and over the Femern Belt in 1982.

Therefore, the Rimpuff model is useful for predicting the airborne spread of FMD and is ideally suited for operational purposes. The Rimpuff model has been incorporated into the decision support system of EpiMAN-FMD [45] and software has been written to analyse and display the output with the ARC/INFO® GIS [27, 46]. Currently such models are generally used as stand-alone tools. Worldwide the size of the infrastructure of state veterinary services is being reduced. To maintain efficiency the increased use of information technology is required. Models such as Rimpuff, and their integration within operational decision support systems such as EpiMAN-FMD, will play an increasingly important role in future developments.

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