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SCIENTIFIC REPORT

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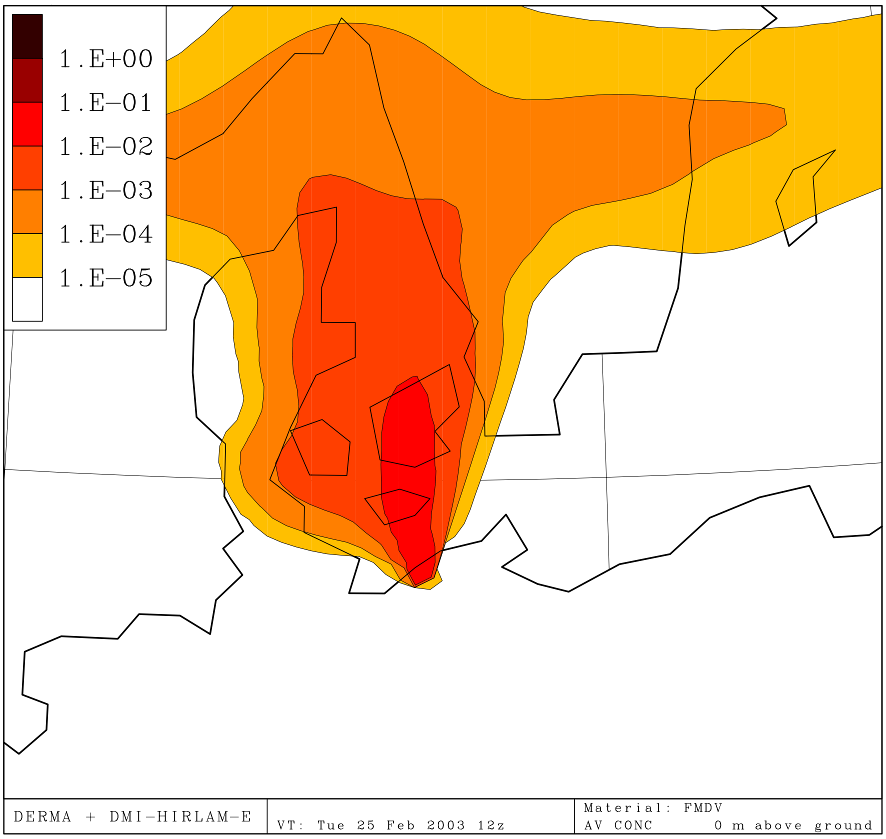
Modelling the Atmospheric Spread of Foot-and-Mouth Disease

Jens Havskov Sørensen



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PREFACE

This report is prepared on request by EUMETNET's Working Group on the Environment (WG-ENV). At a working group meeting I gave a lecture entitled "Modelling atmospheric spread of foot-and-mouth disease – a new subject for operational emergency preparedness at NMSs?" In the discussion which followed I was asked to prepare a description of the present knowledge on atmospheric dispersion modelling of the airborne spread of Foot-and-Mouth Disease (FMD) aiming at emergency preparedness and management.

To some extent this report is based on work which has been carried out in close collaboration with colleagues in atmospheric and veterinary sciences. Parts of the text and some of the figures and tables are taken from joint papers published in atmospheric and veterinary scientific journals. I am very grateful to Alex I. Donaldson, Soren Alexandersen and David Mackay (Pirbright Laboratory, Institute for Animal Health, UK), Torben Mikkelsen, Poul Astrup and Søren Thykier-Nielsen (Risø National Laboratory, Denmark), and John Gloster, Helen Champion and Derrick Ryall (Met Office, UK) for comments and corrections to this report – not to mention our enjoyable collaboration throughout the years!

Jens Havskov Sørensen

INTRODUCTION

Foot-and-mouth disease (FMD) is a highly contagious viral disease in cloven-hoofed domesticated and wild animals. The highly contagious nature of FMD is a reflection of the wide range of species which are susceptible, the enormous quantities of virus liberated by infected animals, the range of excretions and secretions which can be infectious, the stability of the virus in the environment, the multiplicity of routes of infection and the very small doses of virus that can initiate infection in susceptible hosts. One of the routes for the spread of the disease is the atmospheric dispersion of virus exhaled by infected animals.

Animals infected with foot-and-mouth disease (FMD) excrete virus into the atmosphere as a function of virus strain, disease stage, and animal species. Atmospheric spread of infectious virus can be rapid and extensive, and it is known in certain circumstances to have occurred over a distance of several hundred kilometres. The corresponding air concentrations downwind can vary by several orders of magnitude depending on the atmospheric conditions. The highest concentrations can be expected in low-wind stable conditions, which result in low levels of turbulence and hence minimal mixing.

The operational value of atmospheric dispersion modelling is primarily to identify premises which may have been exposed to infectious doses of FMD virus so that the human resources for surveillance and disease control purposes are employed most effectively by the veterinary emergency management authorities. Thus the veterinary surveillance activities can be reduced to those farms which are considered at risk of being infected. The results of the dispersion models may be integrated with geographical and demographic data and can be presented using e.g. a Geographical Information System (GIS).

This report addresses the modelling techniques and presents results related with recent outbreaks in Europe.

ATMOSPHERIC DISPERSION OF FMD VIRUS

The objective of model simulations of the atmospheric spread of infectious FMD virus is to calculate FMD virus concentrations at ground level and at distances in general up to few hundred kilometres from the sources. Those values can be directly compared with experimentally determined threshold values of minimum infection doses.

Excretion of Airborne Virus

Animals infected with foot-and-mouth disease exhale virus in their breath as droplets and droplet nuclei at various levels depending on the virus strain, disease stage, and animal species. Based on experimental data (Sellers and Parker, 1969; Donaldson *et al.,* 1970, 1982) on virus excretion by different species of animals during the incubation period and the early clinical phase of FMD, a virus production model (VPM) has been developed (Sørensen *et al.,* 2000). The amount of airborne virus released by infected animals on a holding is calculated by the VPM using the number of affected animals, their species and the age of the oldest lesion detected during the clinical inspection.

There are large variations in the excretion rates for different animal species and for different strains of FMD virus. For certain strains of virus, notably C Noville, infected pigs excrete on a daily basis more than three orders of magnitude greater amounts of virus than cattle and sheep, while for most strains the difference is probably in the 50–100 fold range. In Fig. 1 the excretion of airborne virus from different animal species is shown as a function of time for the type C Noville strain of FMD virus, which is known to be excreted in large quantities from infected animals. For details see Sørensen *et al.* (2000).

There is a potential for errors in the estimate of virus excretion. For instance, if the estimated age of lesions of an infected pig is wrong by a day, the error in the excretion estimate may amount to more than four orders of magnitude for that animal. However, one should expect that such errors to some extent average out for an infected holding.

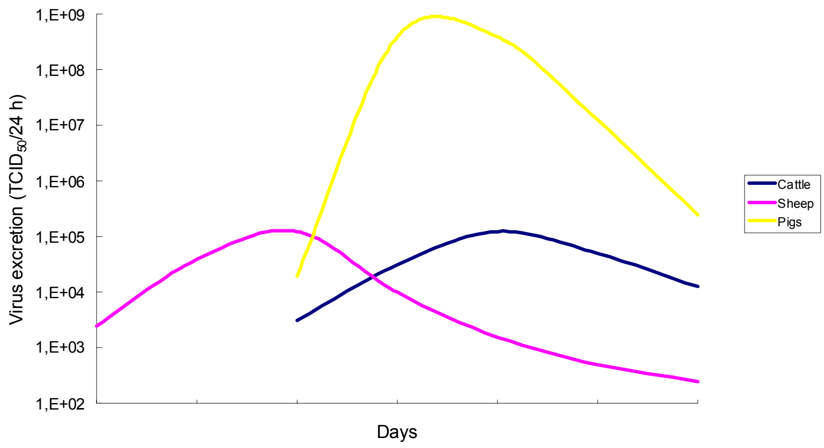

Figure 1 Excretion of airborne virus from different animal species shown as a function of time for the strain of FMD virus known to be excreted in the largest amounts.

Inactivation of Airborne Virus

The inactivation of airborne FMD virus, or the physical loss of viability, in aerosols sampled 1 second after generation is mainly due to the effect of atmospheric relative humidity. This dependence is very strong: at a relative humidity greater than 55–60% airborne virus is relatively stable, but at lower values virus becomes inactivated very rapidly (Donaldson, 1972, 1973). In order to model the dependence on relative humidity, the value of 55% was taken as an “on/off” switch with virus being considered viable above this value but not below.

Assuming that the probability of a single virus being inactivated does not depend on time, i.e. there is no effect of ageing, the decay of the virus population is exponential, as is the case for radioactivity. The decay is weak and is known to depend on the strain of virus (Barlow and Donaldson, 1973). However, the experimental data are not sufficient to make quantitative estimates of exponential decay parameters.

UV radiation has previously been thought to inactivate FMD virus. However, there is no experimental evidence that radiation has any measurable direct effect on the viability of FMD virus (Alexandersen *et al.,* 2003b). Likewise, temperatures below 30°C have minimal effects on virus survival.

Deposition of Airborne Virus

Exhaled viruses are contained in aerosols, which deposit on the ground by wet and dry deposition mechanisms. Thus well-known parameterisations used e.g. for radioactive particles can be applied, cf. e.g. Baklanov and Sørensen (2001). The distribution of sizes of exhaled aerosols is given by e.g. Alexandersen *et al.* (2003b).

Infection by ingestion is much less likely to occur in comparison with infection by inhalation since it requires doses, which are about five orders of magnitude larger (Alex Donaldson and Soren Alexandersen, personal communication). Thus deposition is included in the modelling as a sink reducing air concentrations – the deposition pattern is in itself not useful to the disease management. This is contrary to nuclear emergency management, where the deposition patterns play an important role.

Atmospheric Flow and Dispersion Models

For the model results presented in this report, the Danish Emergency Response Model of the Atmosphere (DERMA) (Sørensen, 1998), which is developed at the Danish Meteorological Institute (DMI), has been used for long-range predictions of atmospheric dispersion of FMD virus making use of high-resolution data from the DMI-HIRLAM numerical weather prediction model (Sass *et al.,* 2002). For the local-scale predictions, the Local Scale Model Chain (LSMC) (Astrup *et al.,* 2001) was employed. It should be noted that in certain situations local topography and effects of urbanisation can influence the atmospheric flow. LSMC involves the RIMPUFF atmospheric dispersion model (Mikkelsen *et al.,* 1997) and the LINCOM flow models (Dunkerley *et al.,* 2001). All of these models are in use mainly for nuclear emergency preparedness purposes.

The basic quantities involved in mathematical modelling of airborne spread of FMD include minimum infectious doses (MIDs) for the different cloven-hoofed animal species, their inhalation rates and the virus concentration in the inhaled air. The latter depends on the rate of virus excretion and the meteorological conditions.

Inhalation Dose

The amount of virus, $\mathrm{d}N$, in units of tissue culture infectious doses ($TCID_{50}$) inhaled in an infinitesimal time interval, $\mathrm{d}t$, by an animal at geographic location $\mathbf{r}$ at time t may be expressed

$$\mathrm{d}N = c(\mathbf{r},t)\, I\, \mathrm{d}t\,,$$

where $c(\mathbf{r},t)$ is the concentration and I the inhalation rate. Whereas the concentration varies in time and space, we assume that the inhalation rate is constant. Introducing the average rate of virus inhalation, n, within the considered time interval, we thus obtain

$$n = I\,\bar{c}\,,$$

where $\bar{c}$ is the corresponding average ground-level concentration of virus in air inhaled by the animal.

Minimum Infectious Doses

Minimum doses of airborne FMD virus required to infect different species (MIDs) were compiled by Sørensen *et al.* (2000), see Table 1 below. From these data and from average inhalation rates for the different species (Green, 1979), corresponding threshold values of, e.g. 24-hour, average concentrations of airborne FMD virus sufficient to constitute a risk for the animals have been obtained. The figures suggest that cattle are twenty times more susceptible to airborne FMD virus than sheep, and a hundred times more susceptible than pigs. Recently, however, the MID for pigs has been re-evaluated with the result that it is for sure more than 800 $TCID_{50}$ (Soren Alexandersen, personal communication). Furthermore, studies on accumulated doses in pigs suggest that the 24-hour threshold concentration is very high, probably around 1000 $TCID_{50}/m^3$ or more.

Table 1 Minimum infectious doses, inhalation rates and corresponding threshold values for 24-hour average concentration and time-integrated concentration. Values obtained from Sørensen *et al.* (2000).

Animal species	Minimum infectious dose ($TCID_{50}$)	Inhalation rate (m^3/24 h)	Threshold for 24-hour average concentration ($TCID_{50}/m^3$)	Threshold for time-integrated concentration ($TCID_{50}/m^3 \times h$)
Cattle	10	173	0.058	1.4
Pigs	400	52	7.7	185
Sheep	10	9	1.1	27

The minimum infectious doses in the table are obtained experimentally by exposing a limited number of healthy animals to different atmospheric doses at short exposure periods (1–10 minutes). Unfortunately, present knowledge on the dependence of infectivity on the period of exposure and the strain of virus is very limited. Presumably, a short-time exposure to a large virus concentration is more infectious than the opposite although both cases may give rise to the same accumulated dose. However, it is assumed for modelling purposes that the MID is unaffected for exposure periods less than 24 hours, while increased values apply to larger periods.

Instead of calculating threshold values for average concentration, one might calculate thresholds for the total accumulated virus dose corresponding to the total time-integrated concentration, a concept which, however, is probably less comprehensible and suffers from the above-mentioned dependence of infectivity on the period of exposure. The threshold value for the time integral is given by $\int_0^\infty c\,\mathrm{d}t = \mathrm{MID}/I$, cf. the last column of table 1. These threshold values should probably not be used for exposure periods longer than about 24 hours. In fact, it is not known what period is relevant. However, it is likely that the probability of infection is increased by increased concentration but probably also by extended exposure, i.e. total accumulated exposure.

Little is known about MIDs for younger animals. Weak animals possibly with damaged epithelia of the mouth and respiratory tract are likely to be more susceptible to infection than those that are healthy. Note that a single hyper-susceptible animal under the virus plume may be sufficient to initiate a new outbreak.

The process of infecting an animal is to some extent stochastic and ought perhaps to be described in terms of a probability distribution depending on the dose. This would imply the integration of the output from dispersion models with animal density databases, e.g. using a GIS, thereby providing statistical parameters such as the average number of infected animals on individual premises under the plume. The MIDs are accordingly probably not absolute quantities but represent very low probabilities of infection. Unfortunately, however, the experimental data are not sufficient to describe such probability distributions. It is important to realise that low infection probabilities can be statistically compensated by a correspondingly larger population under the plume leaving the average number of infected animals unaffected. Thus in view of the potentially large number of animals under a virus plume from a holding of infected pigs, one should worry also about very low probabilities.

According to Soren Alexandersen (personal communication), the interpretation of the risks associated with FMD virus plume concentrations is highly complex. A detailed opinion on a given exposure will have to be given on the basis of specific knowledge about FMD virus as well as knowledge of diseases in animals in general. A significant amount of data exists but the veterinary science is still short of knowledge, which will allow a purely statistical approach to the problem. It may be worthwhile to mention that 1 $TCID_{50}$ is approximately 100 copies of FMD virus RNA, and thus one is very close to the lower theoretical limit for infection in any system.

Another reason for extending the plotting of plumes to lower values of 24-hour average concentration of course is a more general precaution attempting to take account of the inherent large uncertainties and fluctuations.

Length Scale

For a given strain of FMD virus and a given holding of infected animals of different species, it can be valuable to estimate the potentially largest range of an infectious FMD virus plume for recipient animals of different species. The atmospheric conditions, which are favourable for atmospheric transport, involve a persistent wind, a high degree of atmospheric stability, no precipitation and a relative humidity above 55%. Sørensen *et al.* (2001) have performed such estimations based on numerical modelling as well as obtained approximate analytical expressions. The length scale depends on the virus excretion rate, the minimum infectious dose and the atmospheric conditions. Results are presented in Fig. 2. Note that according to the most recent estimate of the MID for pigs (cf. section Minimum Infectious Doses), the estimate for pigs being infected is almost for sure an overestimate.

These results are obtained by using the MIDs of Table 1 without invoking more cautious considerations of the possibilities for infection also at lower doses, cf. the discussion in Section “Minimum Infectious Doses”.

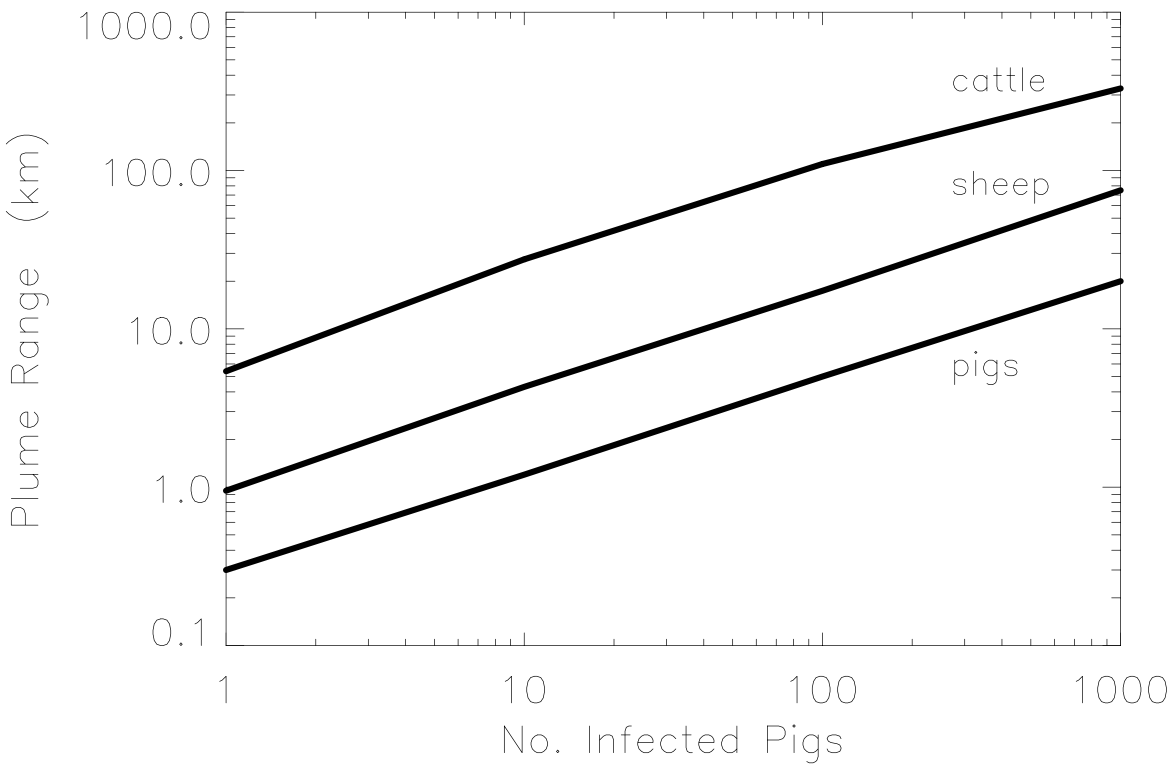

Figure 2 Range of an infectious FMD virus plume as a function of the number of pigs at source and recipient animals of different species downwind (pigs excrete by far the largest quantities of airborne FMD virus). Numerical simulations were made under optimum meteorological conditions for airborne virus transport. The plume range shown is the maximum distance travelled by virus particles in a plume at sufficient concentration to infect. Use has been made of the MIDs given in Table 1. Figure obtained from Sørensen *et al.* (2001). According to a recent estimate of the MID for pigs, the plume range for pigs being infected is an overestimate.

Long-range transport of infectious virus is mainly an issue for infected pigs as a source, and cattle and potentially sheep as recipients of virus. According to Fig. 2, airborne virus from 1000 infected pigs (with lesions of the same age) can infect cattle up to about 300 km downwind. For the airborne transmission across the English Channel in 1981, the distance between the outbreaks in Brittany and the recipient farm on the Isle of Wight was around 250 km, cf. Sørensen *et al.* (2000) and the chapter below. Note that the results presented in Fig. 2 address length scales calculated on the basis of the *actual* values of the MIDs. A more cautious use of lower values (see discussion in the above section "Minimum Infectious Doses") will imply correspondingly increased length scales.

HYPOTHETICAL SCENARIOS

Summer Situation

In order to address the dependence of airborne spread of FMD virus on the meteorological conditions and on the size of infected premises, a number of hypothetical scenarios are presented below. In every case, the DERMA model has been applied making use of DMI-HIRLAM data, and for the virus excretion the maximum values have been used (cf. Fig. 1).

When applying atmospheric dispersion models in real time to FMD outbreaks, one should envisage using meteorological forecast data in addition to the more accurate analysed data. As soon as the veterinary inspection of an infected premise is completed and sufficient veterinary data are prepared, the VPM can be run providing input data on the virus source to atmospheric dispersion models. One should, however, expect that it will take some time to organise the slaughter of animals on the infected premise, e.g. a day or so. Thus, in case the veterinary report is received before the virus source is terminated by slaughter, the first atmospheric dispersion model run for an infected premise may involve the use of forecasted meteorological data. Therefore the calculation should be repeated later using analysed meteorological data as they become available.

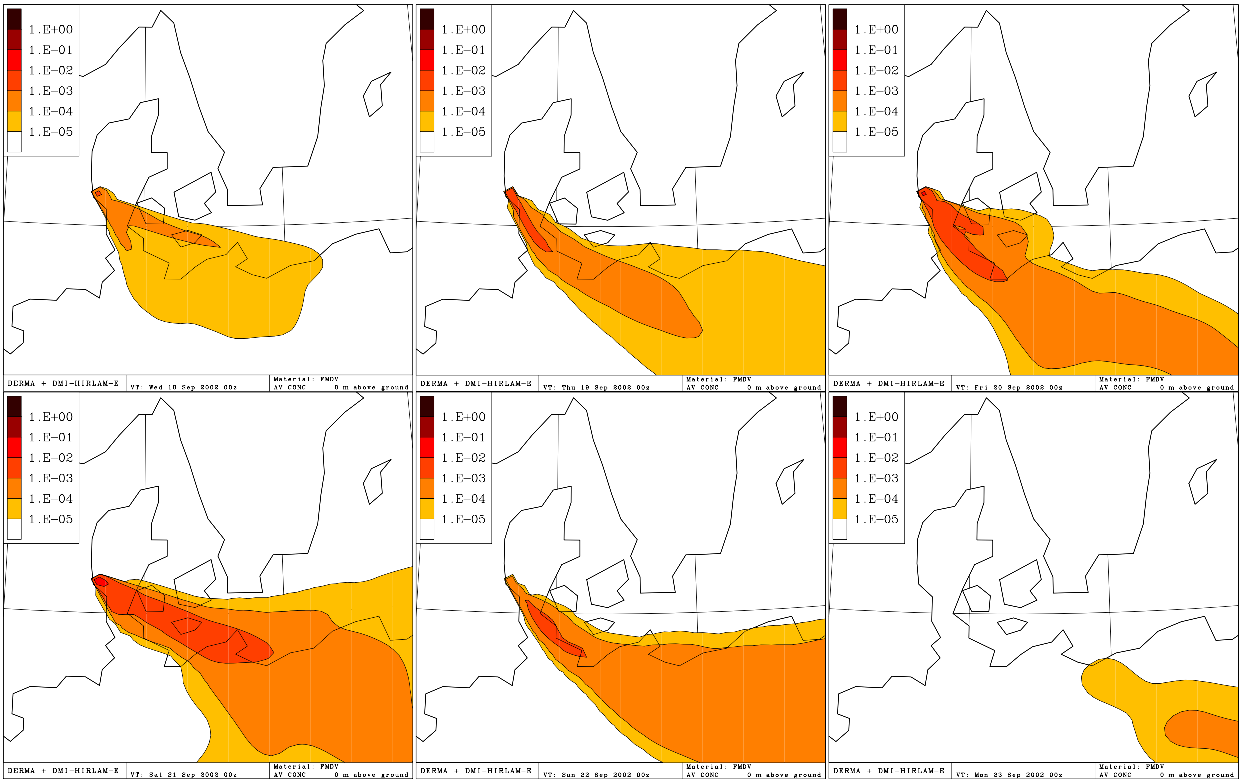

Figure 3 FMD virus plume from a hypothetical infected premise. The plume is simulated by DERMA using DMI-HIRLAM data. The time series of plots covers six days. The contours indicate 24-hour average FMD virus concentrations in units of $TCID_{50}/m^3$.

In Fig. 3, the infection is assumed to take place in a typical Danish pig farm holding 1.500 pigs in south-west Jutland. It is assumed that 15% of the pigs are infected at the veterinary inspection – this should be a realistic scenario. For details see Nielsen, Oldrup and Sørensen (2003).

Taking the MIDs literally, the figure indicates that only cattle within a local area downwind from the infected premise are at risk. However, taking into account the cautionary remarks in section “Minimum Infectious Doses”, and thus considering also regions exposed to one or two orders of magnitude lower 24-hour average concentrations, northern Germany, southern Jutland and the islands of Funen and Lolland-Falster are seen to be at a low risk of infection. As discussed in section “Minimum Infectious Doses”, unfortunately we cannot assign infection probabilities to the risk zones.

In Fig. 4 similar results are shown from a calculation involving a hypothetical outbreak of FMD in a very large pig farm holding 24.000 pigs. For such a large farm a realistic scenario involves probably only up to 10% infected pigs at the veterinary inspection. In comparison with the scenario described in relation with Fig. 3, this corresponds to about ten-fold increased virus excretion from the infected premise, and thereby a similar increase in the concentration values.

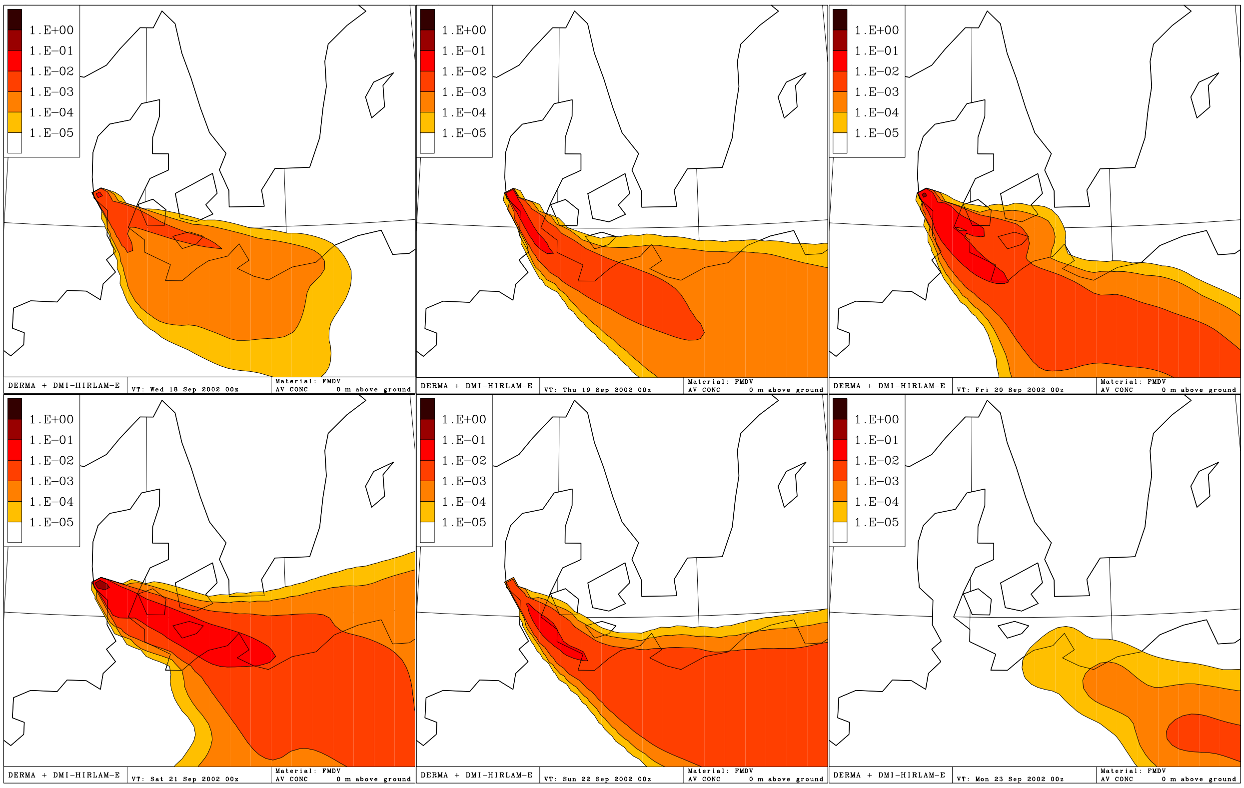

Figure 4 FMD virus plume from a hypothetical infected premise, cf. Fig. 3 for details.

According to the MIDs, Fig. 4 shows that cattle in northern Germany, southern Jutland and the islands of Funen and Lolland-Falster are at risk. However, considering also regions exposed to one or two orders of magnitude lower concentrations, large parts of Germany and Poland are seen to be at a low risk of infection. Indeed the potential for disease spread seems to be very large.

Winter Situation

In Fig. 5, the infection is again assumed to take place in a typical pig farm holding 1.500 pigs, this time located in northern Germany. And again it is assumed that 15% of the pigs are infected at the veterinary inspection. However, in this case the scenario is assumed to take place at winter time under stable atmospheric conditions implying increased virus concentrations.

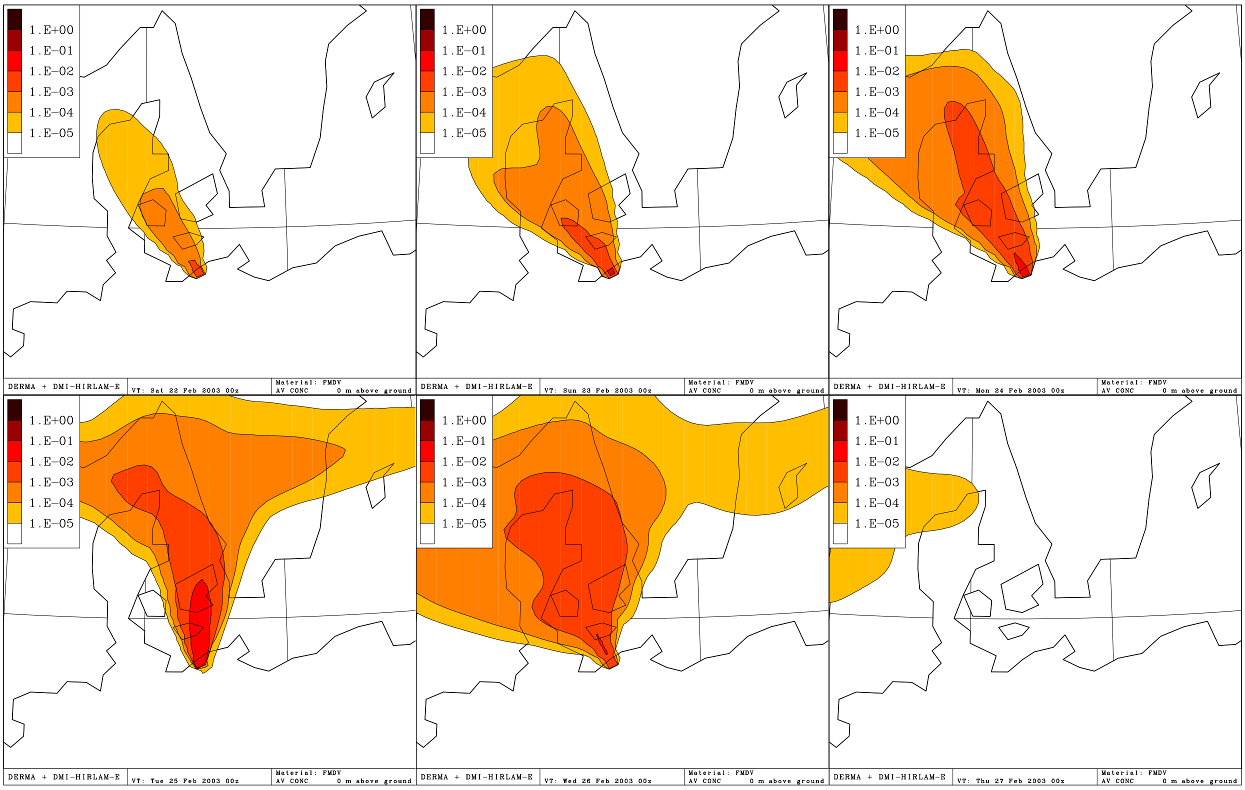

Figure 5 FMD virus plume from a hypothetical infected premise, cf. Fig. 3 for details.

Taking the MIDs literally, the figure indicates that cattle on Lolland-Falster and a part of Zealand are at risk. With a more cautious use of the MIDs, large parts of Denmark are seen to be at a low risk of infection.

Assuming instead a corresponding outbreak of FMD in a very large pig farm holding 24.000 pigs and involving around 10% infected pigs at the veterinary inspection under otherwise similar conditions, cattle will be at risk in large parts of Denmark while south-west Sweden and southern Norway will be at a low risk of infection.

The effect of a Front Passage

Typically, a scenario of airborne spread of FMD has duration of a number of days. However, in such a time span much may happen from a meteorological point of view. In the example below (cf. Fig. 6) a cold front is passing Denmark on 7 March, 2003, while airborne FMD virus is being spread northward from a hypothetical infected premise in northern Germany. The cold front that is associated with a low pressure centre located north of the map shown in Fig. 6 is accompanied by a sudden jump in wind direction.

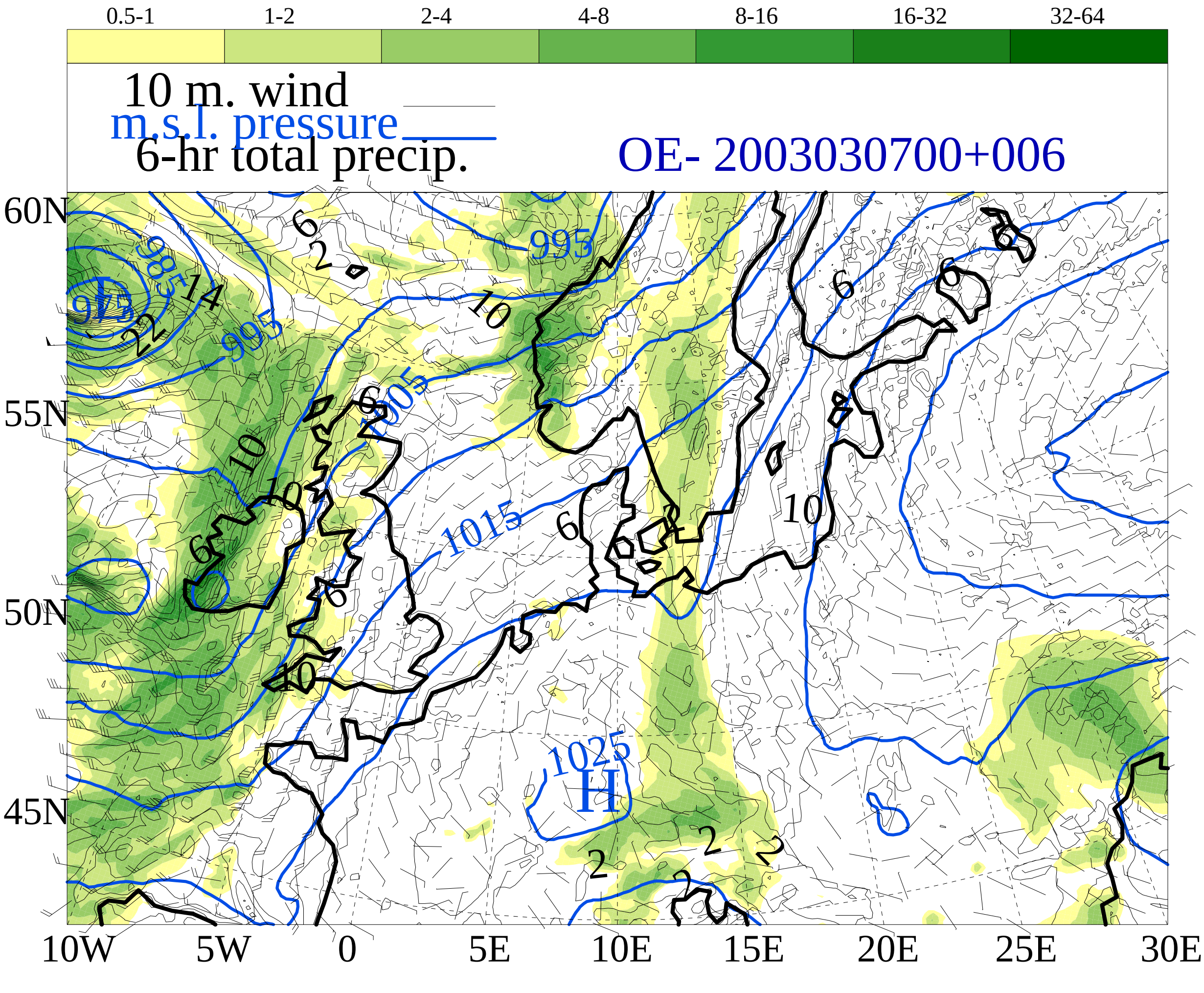

Figure 6 Six-hour forecast of accumulated precipitation (colour coded), 10-m wind (WMO wind arrows) and mean-sea-level pressure (blue iso-curves) on 7 March, 2003, at 6 UTC according to DMI-HIRLAM-E.

Again, the infection is assumed to take place in a typical pig farm holding 1.500 pigs in northern Germany. And again it is assumed that 15% of the pigs have become infected at the veterinary inspection.

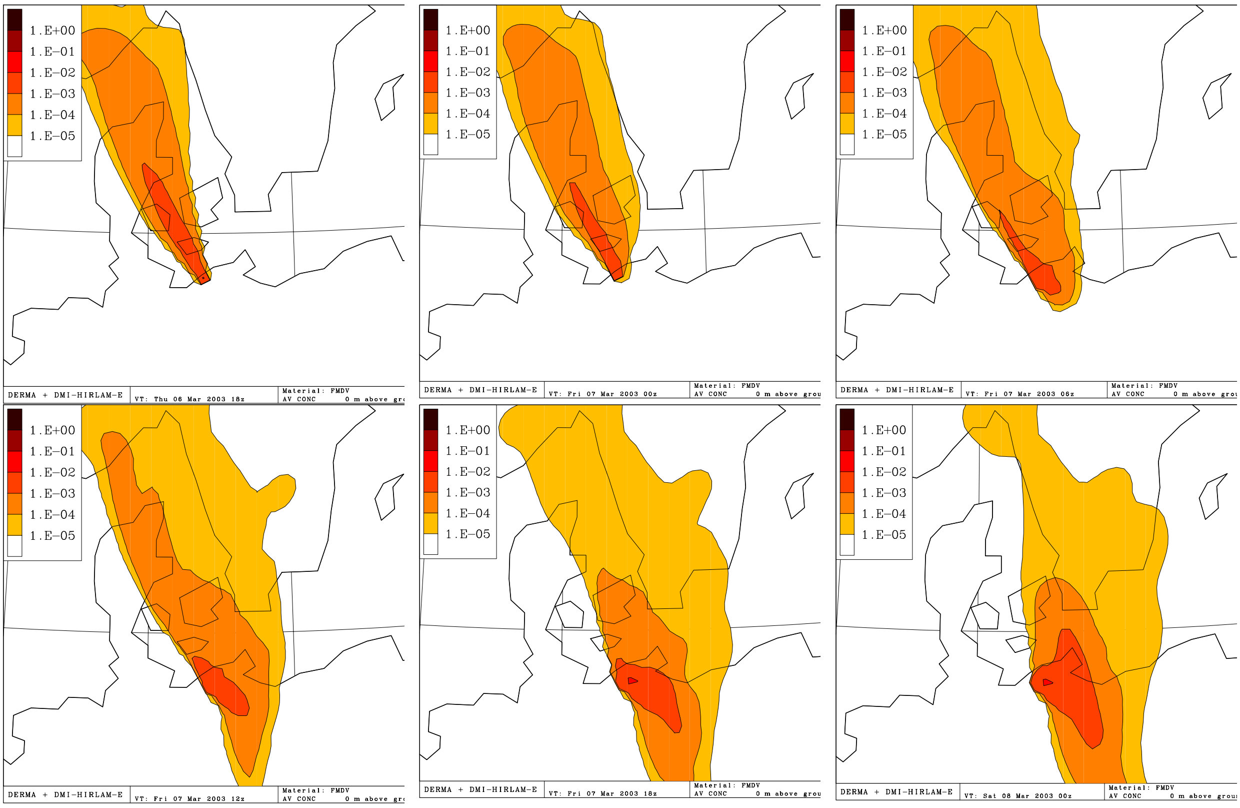

Figure 7 FMD virus plume from a hypothetical infected premise, cf. Fig. 3 for details.

As can be seen from Fig. 7, the noticeable change in wind direction has serious consequences for the airborne virus spread pattern. To some extent, however, this effect is smoothed by the 24-hour averaging of concentrations. In such a situation correct timing of the virus excretion is of great importance, and it will be adequate to perform a related, possibly simple, sensitivity study taking into account the uncertainties in the time profile of the virus excretion. Accordingly, in such situations it is of great value for the veterinary disease management to obtain advice from duty meteorologists.

CASE STUDIES

The model system has been applied to a number of historical FMD epidemics. A few validation results are presented below relating to outbreaks (i) in Brittany, France, and on the Isle of Wight, in 1981, (ii) in the former German Democratic Republic (GDR) and in Denmark in 1982, and (iii) in the UK in 2001.

Brittany–Isle of Wight 1981

In the present section, two examples of airborne transmission of FMD virus are shown from outbreaks in Brittany, France, in 1981. Additional model validation results and detailed epidemiological data are presented by Sørensen *et al.* (2000) as well as further discussions.

RIMPUFF simulations of transmissions of virus from Brittany to the UK, as well as from the former German Democratic Republic (GDR) to Denmark in 1982, have been compared with predictions by the DERMA model (Sørensen, 1998). In both cases similar results were obtained.

Using epidemiological data from the 1981 epidemic of FMD in Brittany, France, estimates of the amounts of virus released to the atmosphere were produced by the virus production model for March 1981. The DMI-HIRLAM model was run with high resolution for this period, and the output data used by the RIMPUFF local-scale atmospheric dispersion model.

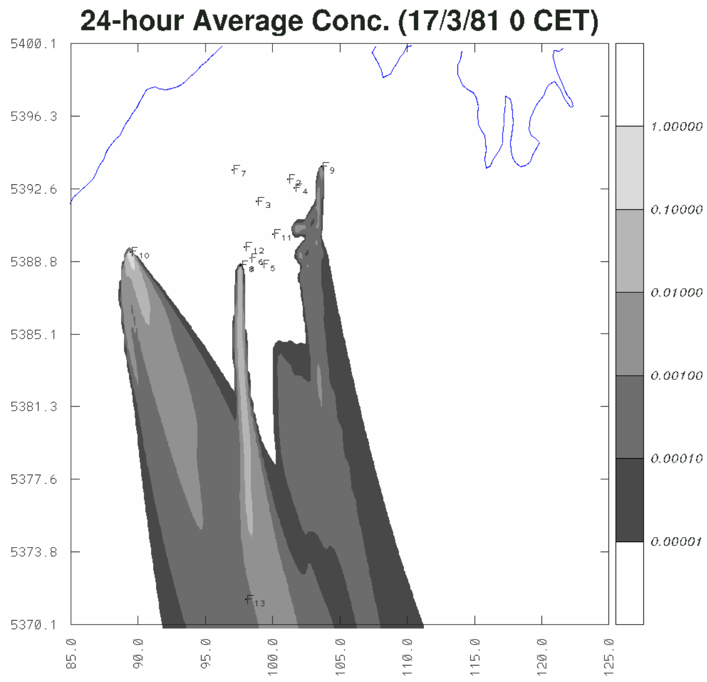

Figure 8 Virus plume from simultaneously infected premises in Brittany, France. The contours indicate 24-hour average FMD virus concentrations for the preceding 24 hours in units of $TCID_{50}/m^3$ on 17 March, 1981, at 0 CET. The F symbols denote farms. The axis units (km) are UTM coordinates, zone 31. Figure obtained from Sørensen *et al.* (2001).

In Fig. 8 model simulation results are presented corresponding to overlapping FMD virus plumes from a number of simultaneously infected premises in Brittany, France. The contour plot shows 24-hour average concentration in units of $TCID_{50}/m^3$.

A period of several days was found with highly stable and persistent meteorological conditions over the English Channel. The high degree of atmospheric stability was in part due to the stabilising effect of the cold water surface on the atmosphere. In this period, three large holdings of pigs in Brittany near the coast of the English Channel were infected by FMD, and thus excreting large amounts of virus to the atmosphere. Sørensen *et al.* (2000) have shown that the disease could have been spread by airborne transmission from outbreaks in Brittany to recipient farms on Jersey, Channel Islands, and on the Isle of Wight. Results are shown in Fig. 9.

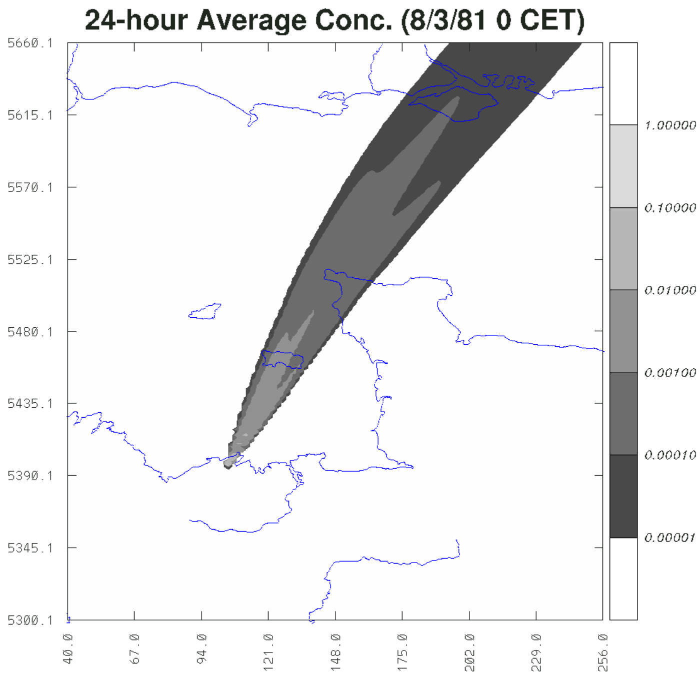

Figure 9 Virus plume from an outbreak on a pig-holding farm in Brittany, France. The plume reaches Jersey and the Isle of Wight. The contours indicate 24-hour average FMD virus concentrations in units of $TCID_{50}/m^3$ on March 8, 1981, at 0 CET. The axis units are UTM coordinates, zone 31. Figure obtained from Sørensen *et al.* (2000).

GDR–Funen 1982

Below, an example of airborne transmission of FMD virus is given from a hypothetical outbreak in the former German Democratic Republic (GDR) to the island of Funen, Denmark, in 1982, cf. Sørensen *et al.* (2000) for details. The first officially recorded suspicions of FMD in both Denmark and the former GDR were on the same date, 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 whether an earlier outbreak, or outbreaks, either unreported or unrecognized, had occurred in the former GDR.

Atmospheric dispersion simulations have been carried out to determine whether the meteorological conditions in early March would have been suitable for a realistic virus plume originating in the former GDR to have reached Denmark at sufficient concentration to infect. Also in this case the DMI-HIRLAM model was run with high resolution for the relevant area and period. Using these data 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 applying to air parcels arriving inside the turbulent atmospheric boundary layer (the mixing layer) above the first infected premise (Fig. 10). Due to the turbulent nature of the boundary layer, any back-trajectory arriving within the layer above the receptor point is a valid representative of large-scale transport of air masses reaching that location. On March 7–8, 1982, this layer was very thin (less than a few hundred meters) over the northern part of GDR and the southern part of Denmark. From the back-trajectory calculations it is evident that the northern part of the former GDR was a potential source of airborne FMD virus reaching Denmark on March 7–8, 1982.

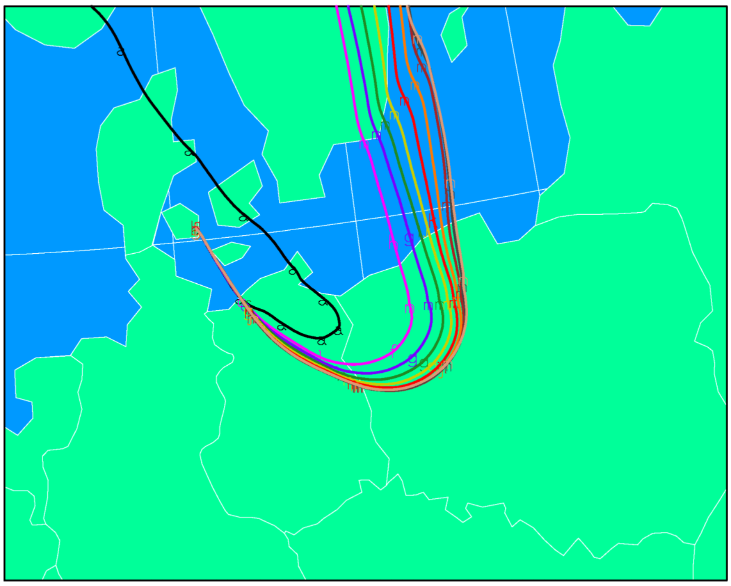

Figure 10 Back-trajectories corresponding to 10 arrival heights inside the atmospheric boundary layer above the first infected premise of the Danish 1982 epidemic. The arrival time is 12 UTC on March 7, 1982. Figure obtained from Sørensen *et al.* (2000).

A simulation was then made using the RIMPUFF model of a hypothetical outbreak involving 1000 pigs in the former GDR south-west of Rostock, cf. Fig. 11. The virus plume passed directly over the site of the first reported outbreak on the island of Funen, Denmark, and the amount of virus present over the farm was sufficient to initiate infection in cattle. With an incubation period of seven days, transmission at this time would be consistent with the first appearance of lesions seven days later on 14 March, 1982. Model simulations showed that plumes corresponding to hypothetical outbreaks some days before or after did not reach Funen. The simulations shown in Fig. 11 indicate that airborne FMD virus originating from the former GDR might have been the source of virus for the epidemic on Funen.

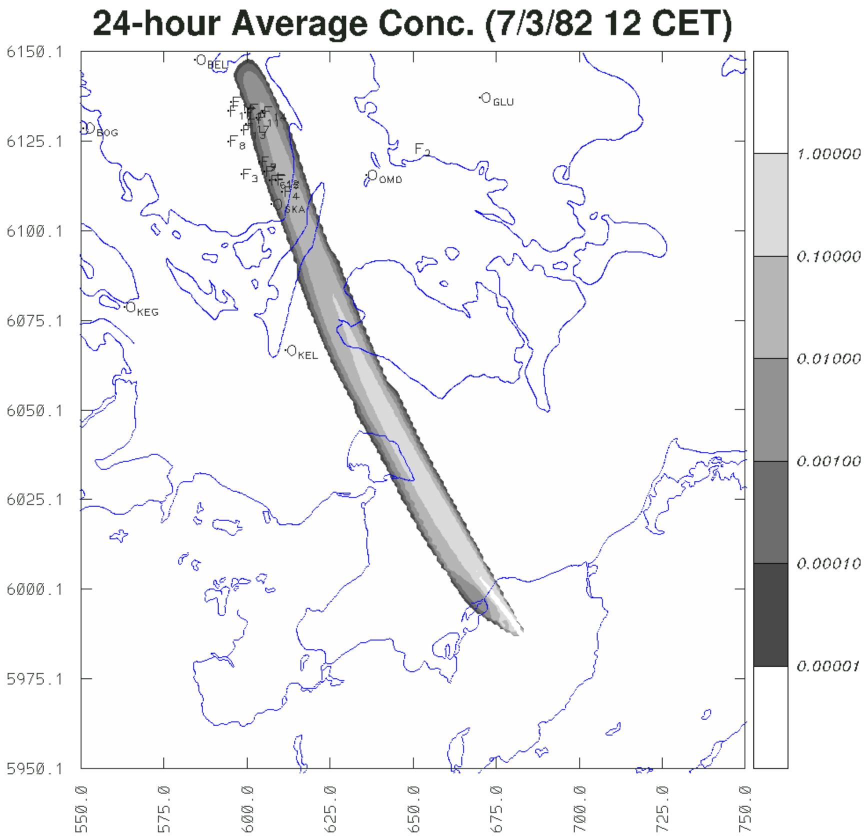

Figure 11 Virus plume from a hypothetical infected premise in the GDR south-west of Rostock. The plume reaches the first infected premise on Funen, Denmark. The contours indicate 24-hour average FMD virus concentrations in units of TCID50/m3 on March 7, 1982, at 12 CET. The axis units are UTM coordinates, zone 32. Figure obtained from Sørensen *et al.* (2000).

UK 2001

For the FMD epidemic in UK in 2001, atmospheric dispersion models were applied in real time in order to describe the atmospheric dispersion of virus for the larger outbreaks of the disease, cf. Alexandersen *et al.* (2003a), Gloster *et al.* (2003) and Mikkelsen *et al.* (2003).

In the early stage of the recent foot-and-mouth disease (FMD) epidemic in UK in 2001, DMI was asked by the British veterinary authorities to provide assistance to the epidemiological management in addition to that provided by UK Met Office. The request was to assess the risk of infection for the European Continent due to long-range transport of virus from infected premises. The task was accomplished by using DERMA applied to the disease outbreaks, which involved the largest virus excretions. At the early stage of the epidemic, the aerobiological characteristics of the virus, in particular the amount excreted by infected animals, were unknown, and correspondingly the model was used for worst-case scenarios assuming the hitherto largest known virus excretion rates, cf. Fig. 12 left. However, once the excretion parameters had been determined experimentally, it became clear that long-range atmospheric disease spread was highly unlikely, cf. Fig. 12 right. Later also the Risø National Laboratory became involved with respect to local-scale modelling of the airborne spread of FMD. Mikkelsen *et al.* (2003) have shown that in a few cases airborne spread of virus may have been the reason for the disease spread between certain premises in the range of six and perhaps ten kilometres.

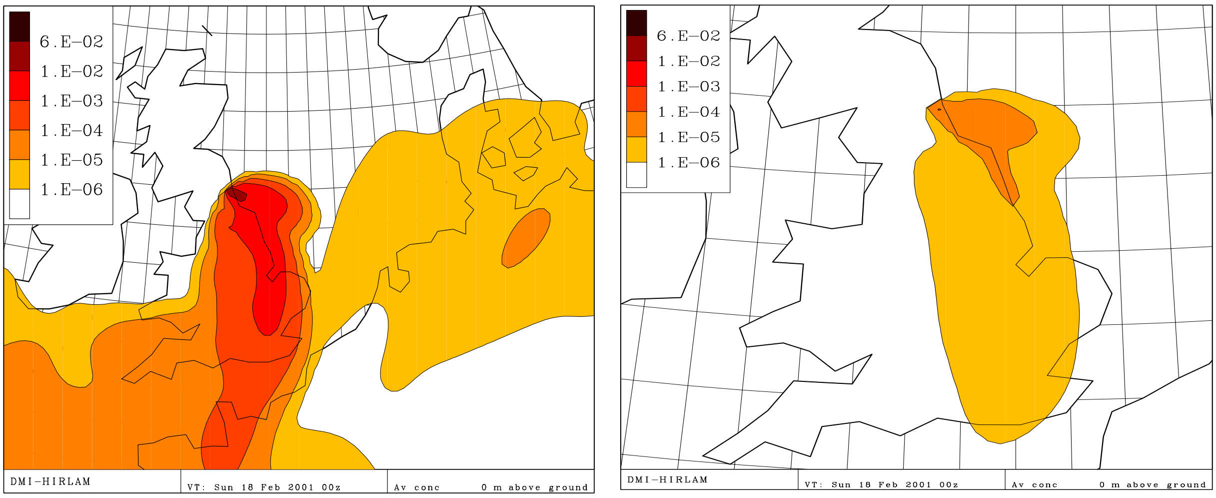

Figure 12 Virus plume from Burnside Farm, Heddon, simulated by the DERMA long-range model. The contours indicate 24-hour average FMD virus concentrations in units of $TCID_{50}/m^3$ corresponding to 17 February 2001. The left figure shows a calculation based on the virus excretion estimates corresponding to the strain of virus which as of today is known to be excreted in the largest quantities. Thus this prediction represented a first guess on a "worst case" scenario. The right figure is for the same situation but now with the virus source calculated from the experimentally determined excretion rates corresponding to the actual strain of virus. These data became available later during the outbreak (Alexandersen and Donaldson, 2002; Alexandersen *et al.,* 2003a). Figure obtained from Gloster *et al.* (2003).

SUMMARY AND CONCLUSIONS

A decision-support system for the epidemiological management of FMD outbreaks has been described. The system, which is based on detailed atmospheric dispersion models describing airborne FMD virus excreted from infected premises, is intended to be used in real time by veterinary authorities in case of outbreaks of the disease. Provided the necessary veterinary and biological parameters can be obtained, the system could quite easily be employed also for other airborne diseases.

The system used involves both a long-range dispersion model, DERMA, and a local-scale model system, LSMC, describing the airborne transmission of virus. Both systems make use of high-resolution DMI-HIRLAM numerical weather prediction model data. The LSMC system includes the LINCOM local-scale flow model and the RIMPUFF local- and meso-scale dispersion model. The LINCOM model is used to calculate the local-scale flow derived from data of the DMI-HIRLAM model. Both DERMA and RIMPUFF were originally developed to model atmospheric diffusion of radioactivity from accidental releases. The source of airborne virus is described by a virus production model, which uses as input epidemiological data from infected premises. The resulting data can be presented by e.g. a Geographical Information System (GIS) and integrated with epidemiological and demographical data.

Different species of susceptible animals produce widely varying amounts of airborne FMD virus, with pigs producing by far the greatest amounts. Only when pigs are affected at source is airborne transmission to cattle or sheep likely to occur beyond a distance of a few kilometres. The virus excretion also depends on the strain of virus.

In general, uncertainties are large for this type of modelling. These uncertainties are related with meteorological and atmospheric dispersion modelling as well as with veterinary and biological aspects.

The system described has been applied to a number of hypothetical scenarios and meteorological conditions, and it has been validated using data from historical outbreaks of FMD.

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