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A Computer System for the Management of Epidemiological Data and Prediction of Risk and Economic Consequences During Outbreaks of Foot-and-Mouth Disease.

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DMI

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FINAL REPORT

A COMPUTER SYSTEM FOR THE MANAGEMENT OF EPIDEMIOLOGICAL DATA AND PREDICTION OF RISK AND ECONOMIC CONSEQUENCES DURING OUTBREAKS OF FOOT-AND-MOUTH DISEASE

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Contents

Summary

The relations between the fundamental quantities involved in mathematical modelling of airborne spread of foot-and-mouth disease (FMD), i.e. minimum infectious dose, inhalation rate and virus concentration in the inhaled air, have been described.

A review of existing atmospheric meso-scale flow and dispersion models suitable for use within real-time decision-support systems such as EpiMAN (EU) has been made. For practical and operational use, Lagrangian-type models are the most appropriate, and, among these, Gaussian puff models are the fastest. Correspondingly, the LINCOM/RIMPUFF atmospheric meso-scale flow and dispersion model complex was selected for the EpiMAN (EU) system.

The atmospheric flow and dispersion models LINCOM and RIMPUFF have been implemented on a number of workstations. The input and output requirements have been specified, and a detailed description of a quasi-automatic set-up providing a realistic set of input parameters for LINCOM and RIMPUFF have been prepared in a separate document.

Decay of virus, as well as viability as a function of relative humidity, has been described and included in the atmospheric modelling.

An interface (Rimpuff2ArcInfo) between the RIMPUFF dispersion model and the Arc/Info Geographical Information System used in EpiMAN (EU) has been developed. This interface converts the RIMPUFF output, and calculates 24-hour average concentration fields to be compared with threshold values for infection.

The workstation implementations of the atmospheric models have been thoroughly tested and optimised. With the objective to compare different implementations of the RIMPUFF code with respect to output and execution time, the EpiMAN (EU) implementation of RIMPUFF took part in a benchmark of the model.

The meteorological data required by the LINCOM/RIMPUFF flow and dispersion model complex have been specified. These data may be obtained either from appropriately positioned meteorological stations or from a numerical weather-prediction (NWP) model with high resolution. The availability of meteorological data have been described, and advantages and disadvantages of the two sources of data have been discussed. In conclusion, it is recommended to base the real-time decision-support system EpiMAN (EU) on data derived from an operational high-resolution NWP model.

In 1994 the European Tracer Experiment (ETEX) took place. ETEX is organised and financed by WMO, IAEA and EU. The experiment addresses long-range atmospheric transport as well as validation of atmospheric dispersion models based on NWP data. Following the experiment, the Danish Meteorological Institute (DMI) participated in a model evaluation utilising an atmospheric dispersion model developed by Dr. Jens Havskov Sørensen. The model is based on data from the NWP model DMI-HIRLAM, which is operational at DMI, and the dispersion model obtained high scores in the evaluation. This result justifies the use of high-quality high-resolution NWP data for atmospheric dispersion modelling.

The Institute for Animal Health, Pirbright Laboratory, U.K., Wageningen Agricultural University, the Netherlands, and Massey University, New Zealand, have been assisted in the implementation of the LINCOM and RIMPUFF models as well as the Rimpuff2ArcInfo interface. Assistance was provided in the integration of these models in the EpiMAN system. Meteorological (NWP) data, derived from the DMI-HIRLAM model output, have been provided for the Dutch pilot area.

Based on given threshold values of 24-hour average concentrations in comparison with RIMPUFF model output, estimates of maximum ranges of infectious FMD virus plumes under optimum meteorological conditions have been made for different combinations of excreting and recipient species.

Case studies of historic FMD outbreaks in Brittany/U.K. in 1981, and in East Germany and Denmark in 1982 have been performed. Simulations based on available meteorological observations, as well as on NWP model data (DMI-HIRLAM), have been utilised in the analyses. Possible internal atmospheric spread in Brittany, France, and on Funen, Denmark, have been reported. Long-range atmospheric transport across the English Channel from Brittany to the Isle of Wight have been analysed, and favourable periods identified. An airborne link between the East German and Danish outbreaks in 1982 have been sought, and potential periods and locations have been established by performing back-trajectory calculations and corresponding RIMPUFF dispersion simulations.

Chapter 1

Introduction

Foot-and-mouth disease (FMD) is the most contagious disease of cloven-hoofed livestock, and can be quickly spread by a variety of means. Among these, airborne spread is uncontrollable but predictable. In general, outbreaks of FMD have very serious economic consequences. The eradication of foot-and-mouth disease requires prompt disease recognition and reporting, accurate diagnosis, and application of disease-control measures without delay. A quick response is essential if further spread is to be minimised. A crucial component of the control measures is a thorough epidemiological investigation of the disease situation on the infected premises. This includes an attempt to establish the origin and the mechanism of the introduction of infection.

Airborne spread of virus for contagious diseases, e.g. FMD, may be described by mathematical modelling on computers. Recent studies of outbreaks of Aujeszky's disease [1] have justified the use of atmospheric models for predicting airborne spread of virus. The virus is contained in airborne aerosols exhaled by infected animals. Today it is possible to estimate the amount of virus excreted on a daily basis. Such estimates are based on inspection of the infected animals. The minimum infectious inhalation doses are known with reasonable accuracy for a number of species. Based on adequate meteorological data, local- and meso-scale atmospheric flow and dispersion models may be used to predict the virus-dose patterns from infected herds. Such predictions will play a vital role in computer based real-time decision-support systems. The EpiMAN system, which utilises a geographical information system (GIS) for graphical display, is an example of such a decision-support system.

For the EpiMAN (EU) system, the LINCOM [2] and RIMPUFF [3, 4] atmospheric flow and dispersion models were selected. These models are developed at the Risø National Laboratory, Denmark. In case of flat terrain or moderate topography, the RIMPUFF local- and meso-scale atmospheric dispersion model may be run without the use of a flow model. In this case, there is no need for digitised topographical data. Such a calculation is merely based either upon meteorological recordings from a number of meteorological stations or upon output from a numerical weather-prediction model. In case of more complex terrain, the LINCOM local- and meso-scale atmospheric flow model may be utilised providing a terrain dependent wind field for the dispersion calculation. For very complex terrain, however, it is of great significance to have access to appropriately positioned weather-recording stations. For each meteorological station, a time series of weather recordings should be provided with the same time intervals. To run the LINCOM model, the terrain heights in the grid points for the grid used for the flow and dispersion calculation should first be provided by the Digital Elevation Module (DEM) of the Geographical Information System (GIS).

The future user of the EpiMAN (EU) system cannot be expected to be an expert on local and meso-scale flow and dispersion modelling. Therefore, a quasi-automatic set-up has been described [5] which provides a realistic set of input parameters for LINCOM and RIMPUFF. These input parameters are based upon knowledge on the chosen grid and the available weather recordings. An expert user should, however, have the possibility of changing any of the many input parameters.

Chapter 2

Materials and Methods

Extensive use has been made of computer resources. The computers used were the following workstations: Silicon Graphics Indigo, Silicon Graphics Indy, Silicon Graphics Challenge, Sun Sparc IPX and Sun Sparc 10.

The methods used were computer programming based on mathematical physics principles (theory of atmospheric meso-scale flow and dispersion).

Based upon recorded information regarding historical FMD epidemics, case studies were performed. These studies involved the outbreaks of FMD in Brittany, France, in 1981, and the East German and Danish outbreaks in 1982.

2.1 Virus Dose by Inhalation

The fundamental quantities involved in mathematical modelling of airborne spread of FMD are the minimum infectious doses for cloven-hoofed animal species, the inhalation rates and the virus concentration in the inhaled air. The latter depends on the rate of virus excretion and the meteorological conditions. In order to utilise mathematical modelling of airborne spread of FMD virus in a risk assesing decision-support system as e.g. EpiMAN, it is necessary to establish the relations between these basic quantities.

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

$$\mathrm{d}N = c(\mathbf{r}, t)\, I\, \mathrm{d}t, \tag{2.1.1}$$

where $c(\mathbf{r}, t)$ is the concentration, in units of $\mathrm{TCID}_{50}/\mathrm{m}^3$, and I is the inhalation rate of the animal, in units of $\mathrm{m}^3/24$ hr. Thus, the amount $N(\mathbf{r}, T, \Delta T)$ of virus inhaled in the period from time $T - \Delta T$ to T (e.g. $\Delta T = 24$ hr) is obtained by integration,

$$N(\mathbf{r}, T, \Delta T) = \int_{T-\Delta T}^{T} c(\mathbf{r}, t)\, I\, \mathrm{d}t. \tag{2.1.2}$$

Whereas the concentration c may vary in time and space, we assume that the inhalation rate I is fixed, i.e. within the period considered, the animal is assumed to move around on a scale much smaller than the characteristic length scale of the dose plume, and the rate of inhalation is assumed constant in time. Under these assumptions, we may put I outside the integration and write

$$N = I \int_{T-\Delta T}^{T} c \,\mathrm{d}t = I \,\overline{c}\, \Delta T. \tag{2.1.3}$$

Here, the quantity $\overline{c}$ denotes the average concentration over the time interval from $T-\Delta T$ to T, which may be extracted from the RIMPUFF dose output. In the literature concerning atmospheric dispersion, the term dose is often used for time integrated concentrations. Introducing the average rate of virus inhalation within this time interval, $\overline{n} = N/\Delta T$, in units of $\mathrm{TCID}_{50}/24$ hr, we may write

$$\overline{n} = I \,\overline{c}. \tag{2.1.4}$$

Species	Min. infectious dose N_i (TCID_{50})	Inhalation rate I ($\mathrm{m}^3/24$ hr)	Threshold conc. c_i ($\mathrm{TCID}_{50}/\mathrm{m}^3$)
Cattle	10	173	0.06
Pigs	15	52	0.3
Sheep	10	9	1

TABLE 2.1. Minimum infectious doses for 24-hour virus exposure [6, 7], inhalation rates and threshold values of 24-hour average concentrations, cf. Eq. (2.1.5).

Let N_i denote the minimum dose, in units of TCID_{50}, to infect by the respiratory route for an animal of a given species exposed to virus for the period ΔT (e.g. 24 hours), cf. Table 2.1. For especially pigs, the minimum infectious dose is not known with great accuracy. Corresponding to the minimum infectious dose N_i, we may introduce a threshold value $n_i = N_i/\Delta T$, in units of $\mathrm{TCID}_{50}/24$ hr, for the average rate of virus inhalation. By using Eq. (2.1.4), we may further introduce a threshold value c_i, in units of $\mathrm{TCID}_{50}/\mathrm{m}^3$, for the average concentration,

$$c_i = n_i/I. \tag{2.1.5}$$

The cause of the period of 24 hours for the dose accumulation is that the minimum infectious doses are measured for such a period. Today, the correlation between minimum infectious dose and accumulation time is not known. Besides, the virus production is estimated on a daily basis.

Chapter 3

Results

Atmospheric dispersion models, usable for a decision-support system for the management of epidemiological data and prediction of risk and economic consequences during outbreaks of foot-and-mouth disease (FMD), should simulate the transport, deposition and decay of the air-borne virus. The models should use as much information as possible about the release of virus to the atmosphere, and adequate meteorological data obtained for the area of concern and at frequent intervals.

3.1 Selection of Atmospheric Flow and Dispersion Models

Atmospheric dispersion models suitable for describing point sources may be of different nature. To exemplify, three models will be described here:

- The NAME model, which is developed at the U.K. Meteorological Office by Dr. R.H. Maryon *et al.* [8], is a *long-range* transport model of *stochastic Lagrangian* type, i.e. the plume spread is simulated by releasing large numbers of 'particles' into the model atmosphere. The particles are advected passively by the model wind, and spread by small-scale diffusion which is effected by 'random walk'. An equally important influence on the spread of particles is the interaction of the vertical mixing with the wind shear in the vertical which fans out the plume. Air concentrations are calculated taking into account the loss of material to the surface by deposition processes. Wet deposition due to precipitation effectively reduces the air concentration, dry deposition due to absorption, impaction and sedimentation is often less effective. Also the possible decay of the air-borne material may be simulated. The wind and other meteorological variables are not taken directly from observations but from an operational meteorological database available at a national meteorological institute. The various numerical weather-prediction (NWP) models assimilate great numbers of observations from around the world, and produce complete fields of the three-dimensional wind components, temperature, etc., several times each day. These analysed fields are the starting point of the integrations made by the NWP models to produce weather forecasts for the ensuing few days. The length and time scales for the plume spread, as described by this stochastic Lagrangian dispersion model, are thus given by the NWP model used.

- The *meso-scale* dispersion model RIMPUFF [3, 4], developed at the Department of Meteorology and Wind Energy, Risø National Laboratory, Denmark, by Dr. T. Mikkelsen *et al.,* is a fast *Lagrangian puff* model. RIMPUFF may be linked to a fast diagnostic flow model (LINCOM). The combined model complex applies to homogeneous as well as non-homogeneous terrain on a horizontal scale of 0 to 300 km, and responds to changing meteorological conditions. In complex terrain, atmospheric dispersion is influenced not only by turbulent mixing and diffusion of the plume itself, but also by topographically induced wind shear, channeling, local slope flows etc. The puff model simulates time-changing continuous releases of material into the atmosphere by sequentially releasing a series of Gaussian-shaped puffs. RIMPUFF is equipped with features for stability-dependent dispersion parametrisation, inversion and ground-level reflection capabilities, and wet and dry deposition. In addition, RIMPUFF is capable of treating plume bifurcation in complex terrain by using a puff-splitting technique, and RIMPUFF may handle multiple simultaneous emission sources. It should be mentioned that the RIMPUFF model received the highest score in competition with five other dispersion models in a recent evaluation [9]. RIMPUFF accepts meteorological data from either weather-recording stations or from an operational meteorological database.

- The *local-scale* OML model, developed at the National Environmental Research Institute in Denmark by Dr. R. Berkowics *et al.* [10], is a *Gaussian plume* model usable up to about 30 km from the source. The OML model is developed for regulatory purposes with the principal intention of estimating the impact on the environment of emissions from power plants. The model is capable of treating several simultaneous emission sites. It requires information on emission and meteorology on an hourly basis. It is characteristic for the model that it does not use traditional discrete stability categories but instead describes dispersion processes in terms of basic scaling parameters such as the friction velocity, the Monin-Ubukhov length and the convective velocity scale. Thus, before using the model, meteorological measurements must be processed by a preprocessor. The dispersion parameters are regarded as the result of contributions from several mechanisms: convective turbulence, mechanical turbulence and building down-wash.

The shortcoming of any Gaussian plume model is its poor treatment of non-stationary and non-homogeneous flow and turbulence – the model merely represents a statistical time-averaged concentration pattern, which may be a gross simplification of reality. Lagrangian models, on the other hand, have the advantage of accounting for the instantaneous spread of material in the atmosphere.

The Federation of Danish Pig Producers and Slaughterhouses, National Committee for Pig Breeding, Health and Production, has initiated a project concerning air-borne dispersion of virus for Aujeszky's disease. In this ongoing project, the above-mentioned RIMPUFF model is utilised. The person responsible for this project is Mr. Sten Mortensen who is a Ph.D. student under the guidance of Dr. Torben Mikkelsen (key-modeller of RIMPUFF), Risø National Laboratory, and Dr. Mats Rudemo, Department of Mathematics and Physics, Agricultural University, Denmark.

Recently, Dr. Mikkelsen has reviewed and ranked existing local- and meso-scale dispersion models for a CEC project entitled "Nuclear Fission Program 1990–1994, Decision Support System: Phase II, Coordination of Atmospheric Dispersion Activities for the Real-Time Decision Support System under development at KfK (RODOS)" in which the Danish Meteorological Institute (DMI) is also participating. This project is a collaboration between the European Atomic Energy Community, Denmark, Greece, Italy, Sweden and U.K. Dr. Mikkelsen is project coordinator for the atmospheric-dispersion sub-project of RODOS. The review and ranking of models is work is described in a report: "Guidance and Support in the Selection of Atmospheric Dispersion Models suitable for use with Real-time Decision Support and Training Systems for Nuclear Accidents". The recommendations from this report were useful in the selection of the atmospheric dispersion model to be used in the EpiMAN (EU) project. These recommendations may be summarised as follows: for practical and operational use, Lagrangian-type models are the most appropriate for real-time local- and meso-scale atmospheric diffusion problems, and, among these models, the Gaussian puff models are the fastest (least CPU-time consuming). The simple Gaussian plume models are too simplistic to apply in cases with time- and space-changing dispersion scenarios. Furthermore, it is recommended that the dispersion models can incorporate forecast meteorological fields from NWP models.

Based on the above-mentioned considerations, it was decided to use the LINCOM/RIMPUFF atmospheric meso-scale flow and dispersion model complex in the EpiMAN (EU) system. The source code of the models were obtained from the Risø National Laboratory, Denmark. Also user manuals as well as scientific articles and reports concerning the RIMPUFF/LINCOM model system were provided by Risø.

3.2 Implementation of LINCOM and RIMPUFF

The LINCOM and RIMPUFF atmospheric flow and dispersion models have been implemented on a Sun IPX workstation at the Danish Meteorological Institute (DMI), as well as on a number of Silicon Graphics workstations, and on the Sun Sparc 10 workstation at the Institute for Animal Health, Pirbright Laboratory. The source code obtained was written in non-standard Fortran

(Lahey Fortran). Thus, in order to compile the code with the Sun Fortran 77 compiler, modifications had to be made. Following the modifications, testing of the code was performed. User manuals for the RIMPUFF/LINCOM model complex have been provided for the Pirbright Laboratory. The models have furthermore been optimised.

The source codes are written in Fortran 77, and thus hard-coded dimensions set the maximum number allowed of e.g. virus sources and weather-recording stations. These limits may easily be changed and the codes re-compiled if need be. However, the memory allocation by RIMPUFF and LINCOM is not expected to cause any problems – for the present set-up it is about 8 Mb. Presently, the maximum number of sources is 50, the maximum number of meteorological weather-recording stations is 10, and the maximum grid resolution is 200×200. To give an example of a typical run, the run time was approximately 20 seconds for a simulation in which two sources were excreting virus for 24 hours, one meteorological station was taken into account with hourly data, and a 100×100 grid was used. The terrain was moderate (maximum height differences of 200 m), and the puff-splitting technique was utilised. The CPU time is proportional to the second power of the grid resolution, and thus one can hardly imagine a situation in which one would like to apply a flow and dispersion calculation with a higher grid resolution when using the system in case of an epidemic.

3.3 Input and Output Requirements

The RIMPUFF atmospheric dispersion model may be run by itself without using a flow model in case of flat terrain. Such a calculation is based upon weather recordings from a number of meteorological stations. In case of more complex terrain, the LINCOM flow model may be utilised in order to provide a terrain-dependent wind field for the dispersion calculation. For very complex terrain, however, it is of great significance to have access to appropriately positioned weather-recording stations.

For each meteorological station, a time series of weather recordings should be provided with the same time intervals. One such record contains the wind speed and direction, the rain intensity, and the lateral and vertical stability. Some modern wind-recording devices may provide the standard deviations for the lateral and/or vertical directions indicating the atmospheric stability. Otherwise, the stability should be indicated for each wind record by the Pasquill-Turner index [11]. In this case, the interface between the GIS and the flow and dispersion module should provide these indices based on the wind speed and the cloud cover which is communicated by the user to the interface, cf. Ref. [5].

To run the LINCOM model, a file containing the terrain heights in the grid points for the grid used for the flow and dispersion calculation should first be provided by the Digital Elevation Module (DEM) of the GIS. Roberto Lattuada, Institute for Animal Health, Pirbright Laboratory, has worked out such a filter.

The future user of the system cannot be expected to be an expert on local and meso-scale flow and dispersion modelling. Therefore, a quasi-automatic set-up has been described which provides a realistic set of input parameters for LINCOM and RIMPUFF. It is possible to ascribe realistic values to the input parameters based upon knowledge on the chosen grid and the available weather recordings. An expert user should, however, be given the opportunity to choose the many input parameters arbitrarily. This quasi-automatic provision of input parameters for LINCOM and RIMPUFF is described in a document [5] which is part of the final documentation of the EpiMAN (EU) system.

The source strengths, in units of $TCID_{50}$ per second averaged over the time interval of interest, i.e. 24 hours, for the infected farms are provided by the virus-production module developed at the Institute for Animal Health, Pirbright Laboratory.

Finally, a filter (Rimpuff2ArcInfo) transforming the output from RIMPUFF to Arc/Info format has been written, cf. Sect. 3.3.3. The result of the flow and dispersion calculation, i.e. the output of Rimpuff2ArcInfo, is the 24-hour average concentration.

3.3.1 Decay of Virus

The viability of virus as a function of the relative humidity (RH) of the atmosphere is very low at RH less than 55% [12, 13]. At RH $\approx$ 55%, the viability increases drastically to a constant value at higher values of RH. Thus the dependence of viability on RH may be modelled as an "on/off switch" turning the source on above 55% RH, and off below.

Assuming that virus have no effect of aging, and that deactivation is a random process, it follows that the decay of virus is exponential in time. The half life $T_{1/2}$ is given in terms of the exponential decay constant λ (sec^{-1}) for the virus in question by $T_{1/2} = \ln 2/\lambda$. The decay constant λ may be calculated from the (secondary) decay rate s (log. viability/hour), cf. Ref. [12, 13], by the following formula

$$\lambda = \frac{\ln 2}{\log_{10} 2} \times \frac{s}{60^2} = 0.64 \times 10^{-3} \times s. \tag{3.3.1}$$

The decay rate s (hour^{-1}) depends on the virus strain. Decay rates for naturally produced aerosols are not known with great accuracy. A typical value might be 0.5 hour^{-1} or less (Donaldson, private communication). The decay constant is input to RIMPUFF.

3.3.2 RIMPUFF Output

The RIMPUFF model outputs the time integral of the atmospheric virus concentration from the beginning of the simulation to a given time T at each grid point $\mathbf{r}$,

$$\int_0^T c(\mathbf{r}, t)\, \mathrm{d}t \tag{3.3.2}$$

(compare with the time integral appearing in Eq. (2.1.3)). This time integral is output in units of $TCID_{50} \times sec/m^3$.

In order to save CPU time, it is advisable to produce RIMPUFF simulations corresponding to more than 24 hours. Thus it is sufficient to make one total RIMPUFF simulation covering the whole period of interest instead of multiple runs, each corresponding to a 24-hour period. Due to the fact that RIMPUFF outputs the virus concentration integrated over time from the beginning of the weather records included in the calculation, one will have to make differences between the output time integral at a given time and the time integral corresponding to 24 hours before. This task is performed by the Rimpuff2ArcInfo module, cf. Sect. 3.3.3.

3.3.3 Interfacing RIMPUFF with Arc/Info

In order to present the results of the RIMPUFF model by the Arc/Info GIS, the RIMPUFF output needs to be converted to the right format. The Arc/Info GIS expects values associated with the centres of the grid cells. The Rimpuff2ArcInfo programme, written by Dr. Jens Havskov Sørensen, splits the binary RIMPUFF output file into separate ASCII files, one for each output time step. These files comply with the Arc/Info format, and contain the calculated 24-hour average concentrations bilinearly interpolated to the centres of the grid cells. The average concentrations, output by Rimpuff2ArcInfo in units of $TCID_{50}/m^3$, are calculated by making 24-hour differences in the RIMPUFF dose output (3.3.2) as noted in Sect. 3.3.2,

$$\begin{aligned} \bar{c}(\mathbf{r}, T, \Delta T) &= \frac{1}{\Delta T} \int_{T-\Delta T}^{T} c(\mathbf{r}, t)\,\mathrm{d}t \\ &= \frac{1}{\Delta T} \left(\int_0^T c(\mathbf{r}, t)\,\mathrm{d}t - \int_0^{T-\Delta T} c(\mathbf{r}, t)\,\mathrm{d}t \right), \qquad (3.3.3) \end{aligned}$$

with $\Delta T = 24$ hr, so as to be directly comparable with the threshold average concentrations listed in Table 2.1.

3.4 RIMPUFF Benchmark

DMI has taken part in a benchmark of the RIMPUFF atmospheric dispersion model. The purpose was to compare different implementations of the code with respect to output and execution time using the same input parameters.

When transferring the original code from a PC platform using Lahey Fortran to a (Sun) workstation, the code was changed somewhat. But despite the changes made, the benchmark showed that the output of the version of RIMPUFF used in EpiMAN (EU) is fully consistent with the "master" version of the Risø National Laboratory.

The benchmark was run on ten different platforms (PCs and workstations). Concerning CPU time requirements for dose calculations, the benchmark showed that the Sun Sparc 10 workstation at Institute for Animal

Health, Pirbright Laboratory, was only defeated by a Silicon Graphics Challenge workstation, and that the Sun had the same CPU time as a Silicon Graphics Indy and a Silicon Graphics Indigo workstation.

3.5 Meteorological Data

The LINCOM/RIMPUFF flow and dispersion model system requires input either from meteorological ground-based weather observations or from a high-resolution numerical weather-prediction (NWP) model. The necessary data are *wind (recorded at e.g. 10 metres height), precipitation, relative humidity* and *cloud cover.*

3.5.1 Meteorological Stations

In case an FMD outbreak occurs, it is of great significance to obtain relevant meteorological data without undue delay.

First, one will have to locate existing meteorological weather-recording stations in the vicinity of the infected farm(s). If such meteorological stations (towers) exist, they may be owned and run by e.g. a national meteorological institute, research institutions or private companies. In case data are available, and also historical data for the past days, the data will probably not have the same quality. Some wind-recording devices may provide digital data, others may not. And the format may be different. Also the time intervals between recordings may vary (e.g. 1, 3 or 6 hours). This will of course imply difficulties for the user of the system when interfacing with the flow and dispersion module.

Furthermore, the meteorological stations may not be positioned ideally for the scenario. The weather-recording station(s) should represent the average conditions for the area of concern. Possibly, there are no weather recordings at all near the infected area. If the airborne transport takes place across a large lake or a strait, relevant data are likely to be missing. And if the airborne transmission takes place across a national frontier, the provision of relevant meteorological observations may be obstructed by bureaucracy, cf. Sect. 3.5.3.

Of course, the emergency headquarter may decide to set up one or more meteorological towers at relevant positions in the area of interest. But in such a case, there will be a lack of historical data.

3.5.2 Numerical Weather Prediction (NWP) Models

A meteorological database containing the output of a numerical weather-prediction (NWP) model, e.g. the HIRLAM model (HIgh Resolution Limited Area Model) [14, 15, 16] running operationally at the Danish Meteorological Institute (DMI), contains historical meteorological data as well as forecasts. Some of the benefits gained by using such a database are *real-time* and *historical* meteorological data consisting of analysed meteorological fields, as well as *forecasts.* Analysed meteorological data are consistent with the available observations and the governing equations for atmospheric motion. Limited-area NWP models cover large areas, e.g. the whole EU and third countries.

Today, the horizontal resolution of limited-area high-resolution NWP models is typically 20–50 km with 20–30 layers in the vertical, but through the development of still faster computers, this resolution is constantly being reduced. Presently, NWP models with a horizontal resolution of about 5 km are being developed at a number of meteorological institutes throughout the world. From the output of an NWP model, one may obtain parameters such as wind (speed and direction) at different heights, precipitation intensity, cloud cover and relative humidity. In addition, one may derive e.g. the atmospheric stability, the height of the atmospheric boundary layer (the mixing layer), the wind shear and temperature gradients. The latter parameters, which may be utilised as additional input to the LINCOM/RIMPUFF model complex, are not recorded by standard weather-recording stations.

Today limited-area NWP models normally utilise a basic time step of 3–4 minutes and dump the meteorological fields each three hours which, in fact, is quite adequate for the purpose of describing the airborne spread of FMD virus.

An atmospheric flow- and dispersion-model complex as e.g. LINCOM/ RIMPUFF may well utilise data from a limited-area NWP model. From the output of the NWP model, one may simulate (hypothetical) meteorological weather-recording stations. The LINCOM flow model may subsequently be used to take into account the effect of the high-resolution terrain data (from the DEM of the GIS) on the wind. As an example, a hypothetical weather-recording station ideally positioned in the Dutch pilot area was simulated by using an interface, developed at DMI by Dr. Jens Havskov Sørensen, between the operational meteorological HIRLAM database and archive at DMI, and the flow and dispersion model system used by EpiMAN (EU), cf. Sect. 3.7.2.

A dispersion calculation based upon an operational NWP database gives, with insignificant delay, a prediction of the spread of virus even for outbreaks outside national frontiers and for airborne transmission across water.

Dispersion models not utilising data from NWP models but from a single (or a few) weather-recording stations assume persistent weather conditions when making forecasts for the plume spread. However, the time scale of interest for FMD outbreaks (days) is so long that the assumption of persistence is seldomly valid. Also for this purpose, numerical forecasts are beneficial.

3.5.3 Availability of Meteorological Data

Regarding the availability of meteorological data useful to the flow and dispersion model complex LINCOM/RIMPUFF from national meteorological offices or the European Center for Medium-range Weather Forecast (ECMWF), the following informations have been obtained:

- Provision of meteorological data from ECMWF within an ECMWF member state must always be requested through the national meteorological service

- All weather recordings available to the ECMWF are sent out on the Global Telecommunication System (GTS) to the ECMWF member states

- In general, national meteorological services *do* have weather data which are not transmitted on the GTS. Certain countries transmit only a fraction of their available data

- The horizontal resolution of the observational data available from the GTS varies considerably, but a resolution of 100–200 km seems to be common

- The time resolution of the data available from the GTS for 10-m wind, relative humidity and cloud cover is in general 1 hour for U.K., Denmark and Germany, while it is 3 hours for most other countries. The time resolution of the data available from the GTS for precipitation is in general 3 hours for Denmark and France, while it is 6 hours for most other countries

- The required meteorological data for the LINCOM/RIMPUFF system may, alternatively, be obtained from a high-resolution NWP model, e.g. the HIRLAM model (HIgh Resolution Limited Area Model) [14, 15, 16] which is operational at DMI, and which covers all of EU and third countries. Thus, the data may be obtained from *one* meteorological service only. This implies a prediction of the spread of virus with insignificant delay, even for outbreaks where there are no ideally positioned weather-recording stations

To conclude this section, it is advised to have the option to run the flow and dispersion module in the EpiMAN (EU) system on meteorological data either from meteorological stations or from a high-resolution limited-area NWP model.

3.6 European Tracer Experiment (ETEX)

The content of this section is not directly related to the development of the EpiMAN (EU) system. It does, however, have relevance for the project because it addresses long-range atmospheric transport as well as validation of atmospheric dispersion models based on numerical weather-prediction (NWP) data.

In 1994, an experiment involving long-range atmospheric transport over the European continent was performed. This programme has been given the acronym ETEX standing for the European Tracer Experiment. ETEX is organised and financed by WMO, IAEA and EU.

The objectives of ETEX are to conduct a long-range atmospheric tracer experiment involving controlled releases with coordinated sampling at distances up to some 2 000 km, to test the capability of real-time forecasts for atmospheric dispersion on this scale, and to assemble a database of environmental measurements of the tracer and the source terms allowing for evaluation of long-range transport models.

Air samples were taken by a network of nearly 200 sampling stations located mainly at WMO meteorological stations covering a large part of Europe. DMI participated with 11 such air sampling stations.

Two releases of a harmless non-toxic tracer gas were performed. The first release took place on October 23, 1994. The gas was released from a site in Brittany over a period of 12 hours. On November 14, 1994, the experiment was repeated.

DMI participated in ETEX also on the modelling side. The atmospheric long-range transport model DERMA (Danish Emergency Response Model for the Atmosphere), which is developed at DMI by Dr. Jens Havskov Sørensen, was utilised for this purpose.

Most of the air samples taken from the first experiment have now been analysed at the Joint Research Centre at Ispra, Italy. Based on these observations, a model evaluation has been performed. The model evaluation involved 28 models from mainly Europe, but also Canada, USA and Japan participated. At the time of writing, the results are described in a draft report only. DMI obtained high scores in this evaluation implying ample justification of using high-resolution NWP data for atmospheric dispersion modelling.

3.7 Implementation of LINCOM/RIMPUFF at Member States

Assistance was given to the Institute for Animal Health, Pirbright Laboratory, and the Wageningen Agricultural University in the implementation of the EpiMAN (EU) system. The LINCOM/RIMPUFF atmospheric flow and dispersion model complex, and the Rimpuff2ArcInfo interface between the RIMPUFF output and the Arc/Info GIS, have been compiled and implemented on the Sun Sparc 10 workstation at the Pirbright Laboratory and on a DECstation at Wageningen Agricultural University.

3.7.1 LINCOM/RIMPUFF at Massey University

Prof. Roger Morris, Massey University, New Zealand, has signed an agreement with the Risø National Laboratory, Denmark, concerning the use of the LINCOM and RIMPUFF models. The source codes and corresponding Sun (and PC) executables of the models have been transferred to Prof. Morris so that EpiMAN (NZ) will use the same versions of the codes as is being used in EpiMAN (EU).

Furthermore, assistance has been given to Prof. Morris and Mr. Mark Stern, Massey University, New Zealand, in implementing and running the EpiMAN (EU) version of the LINCOM and RIMPUFF atmospheric flow and dispersion model complex, as well as the Rimpuff2ArcInfo interface between the RIMPUFF output and the Arc/Info GIS. Mr. Mark Stern visited the DMI in October 1995 where he obtained assistance in implementing and running the LINCOM and RIMPUFF model complex as well as the Rimpuff2ArcInfo interface.

3.7.2 Meteorological Data for the Dutch Pilot Area

A hypothetical weather-recording station with hourly recordings in Doetinchem, which is situated in the central part of the Dutch pilot area, has been simulated for a two-week period in December 1994.

The simulation was performed by using an interface developed at DMI by Dr. Jens Havskov Sørensen between the operational meteorological HIRLAM database and archive at DMI, and the flow and dispersion model system used by EpiMAN (EU) (LINCOM and RIMPUFF). The database contains output from the numerical weather-prediction (NWP) model HIRLAM, and consists of both analysed (historical and real-time) meteorological data as well as forecasts. The simulation was based on analysed data. The version of HIRLAM used for the simulation has 162×136 points in the horizontal covering most of the EU with a grid distance of 23 km, and it has 31 levels in the vertical.

3.8 Maximum Plume Ranges

Based on the threshold values of 24-hour average concentrations listed in Table 2.1 in comparison with RIMPUFF model output, is is possible to estimate the maximum ranges of infectious FMD virus plumes for different combinations of excreting and recipient species (for a fixed number of excreting animals).

A relatively large infected herd of 100 animals of a given species with lesions (clinical signs) of the same age has been assumed, and the calculations have been performed for the 24-hour period in which the virus production is the largest according to the virus-production model developed at the Institute for Animal Health, Pirbright Laboratory. Optimum meteorological conditions for airborne virus spread (persistent wind direction and speed of approximately 5 m/s, high degree of atmospheric stability (class F), no precipitation, and relative humidity above 55% to ensure virus survival) have further been assumed in order to simulate a long, narrow and intense virus plume. Furthermore, decay of virus has not been taken into account, cf. Sect. 3.3.1. Similar atmospheric conditions applied to the cases reported on below in Sect. 3.9, where airborne transmission took place over the longest distances ever recorded. In these cases, the virus plumes went over sea surfaces which were several degrees colder than the atmosphere thus creating a high degree of atmospheric stability. Since the virus concentration is averaged over 24 hours, it is of utmost significance that the wind direction is nearly constant within this period, in order to obtain an intense plume in combination with a high degree of atmospheric stability.

The resulting maximum plume ranges are listed in Table 3.1. As it appears, inter-farm airborne spread of FMD is an issue mainly in case of infected pigs being the source of airborne virus. Note that there are large differences in the virus-production rates for the animal species in question (more than three orders of magnitude).

Excreting species	Recipient species: Cattle	Pigs	Sheep
Pigs	120 km	40 km	15 km
Cattle	0.4 km	0.2 km	< 0.1 km
Sheep	0.4 km	0.2 km	< 0.1 km

TABLE 3.1. Maximum plume ranges obtained by using the threshold values of 24-hour average concentrations listed in Table 2.1 in comparison with RIMPUFF model output. A large infected herd of 100 animals of a given species has been assumed under optimum meteorological conditions for airborne virus transport.

3.9 Case Studies of FMD Outbreaks

At the Danish Meteorological Institute (DMI) we have performed extensive simulations of known FMD outbreaks in Europe, occurring in the early eighties. These outbreaks have previously been pointed out as possible scenarios where airborne spread played an active role in the transmission of FMD over long distances.

In the studies reported on here, we have not taken into account any exponential decay of virus, cf. Sect. 3.3.1.

3.9.1 Data Retrieval and Preprocessing

In order to make computer simulations of airborne virus spread, it is necessary to obtain substantial and reliable data for both the epidemiological and meteorological conditions at the time.

Epidemiological Data

Previously, at the time of the epidemics, the necessary data were not systematically collected as required for detailed computer simulations. However, great interest has been shown for the study of the evolution of these outbreaks, also in conjunction with airborne spread, cf. e.g. Refs. [17, 18, 19, 20, 21]. Extensive veterinary reports were made at the time of events – at least in the western European countries.

To model the excretion from a given farm during an outbreak, a good estimate is necessary of the number of infected animals on each day as well as the state of their illness given by the age of lesions on the animals. Of great importance are of course also the locations of the farms – though only roughly for the long-range dispersion modelling.

Data for the Danish outbreaks were taken from an extensive report prepared by the Danish Veterinary Service at the time of the outbreak [22]. These data are quite adequate and precise. The locations of the Danish farms were pin-pointed utilising CD ROM based topographical maps. Most farms were quite accurately identified. The locations of the East German premises were estimated by using the Times Atlas of the World, but more accurate information is necessary in order to model the internal GDR outbreak scenario, cf. Sect. 3.9.2.

The epidemiological data from Brittany/U.K. and East Germany were provided by Dr. Alex Donaldson who also provided estimates of the number of virus excreting animals on each day in the Brittany/U.K. case. The East German data were extracted from a series of telexes released by the GDR during and after the outbreaks. Donaldson further provided the locations of infected farms in Brittany and U.K.

Whereas the data for Brittany are quite good – Dr. Donaldson revised the data thoroughly with all known information in his keeping – more uncertainties are associated with the GDR outbreaks: dates of outbreaks, number of infected animals, location of infected premises and possible causes of virus transport.

The source strengths (rates of virus excretion) were calculated by using the virus-production model, developed at the Pirbright Laboratory, Institute for Animal Health.

Provision of Meteorological Data

The simulations were performed utilising the meso-scale dispersion model RIMPUFF, cf. Sects. 3.1 and 3.3 which takes as input homogeneous recordings of weather conditions at meteorological stations, and source strengths of the infected premises (rate of virus excretion). The source strengths are based on the number of infected animals and the age of lesions. In this section we will describe how meteorological data were obtained and preprocessed to provide the input usable by the RIMPUFF dispersion model.

Meteorological data for the Danish outbreaks were available at DMI, but the meteorological data for the historic outbreaks in France/U.K. and East Germany were obtained from the European Center for Medium Range Weather Forecast, ECMWF, through the DMI membership, cf. Sect. 3.5.3. Since the recordings from some stations were irregular and of low quality, extensive validation had to be performed. The data from the selected stations were subject to homogenisation.

As noted in Sects. 3.5.2 and 3.7.2, software enabling simulation of meteorological stations at any point in time and any geographic location based on the output from the operational DMI-HIRLAM model has been developed at DMI. The advantages of using NWP data are described in Sects. 3.5 and 3.6. High-resolution NWP data were obtained by running the Danish version of the HIRLAM model for the areas and periods of interest.

3.9.2 Case Study Results

The scenarios we have studied have previously been subject for combined epidemiological/meteorological studies identifying possible periods of airborne transfer of virus. These studies were mainly based on trajectory calculations and analyses of weather charts. In our studies, however, we have used a meso-scale dispersion model to describe the outbreak scenarios. This model is the dispersion model RIMPUFF used operationally in the EpiMAN (EU) system.

Brittany/U.K. Outbreaks 1981

Event Sequence

No.	Location	Coordinates	date of lesion	cattle	pigs/piglets	sheep
1	Henansal	(48°31′15″N, 2°27′00″W)	01/03/81	0	8/0	0
2	Henanbihen	(48°33′45″N, 2°24′30″W)	05/03/81	0	15/40	0
3	Henansal	(48°33′00″N, 2°26′15″W)	07/03/81	0	8/0	0
4	Henanbihen	(48°33′30″N, 2°25′50″W)	07/03/81	0	14/0	0
5	Juhel Henansal	(48°31′20″N, 2°25′50″W)	10/03/81	0	1/0	0
6	Henansal	(48°31′25″N, 2°26′30″W)	11/03/81	0	0/0	2
7	Henansal	(48°33′50″N, 2°27′45″W)	13/03/81	1	0/0	0
8	Henansal	(48°31′15″N, 2°27′00″W)	11/03/81	0	25/0	0
9	Henanbihen	(48°34′10″N, 2°22′30″W)	13/03/81	0	2/0	0
10	Plengouenoual	(48°31′15″N, 2°33′45″W)	14/03/81	0	8/0	0
11	Henansal	(48°32′10″N, 2°25′15″W)	16/03/81	0	?	0
12	Henansal	(48°31′45″N, 2°26′15″W)	16/03/81	0	?	0
13	Plenee Jugon	(48°22′00″N, 2°22′55″W)	26/03/81	0	?	0
14	Le Mesnil	Manche County	21/03/81	?	0/0	0

TABLE 3.2. Epidemiological and geographical data of the infected premises in Brittany, 1981.

In Table 3.2 we list epidemiological and geographical data of the infected premises in the 1981 outbreaks in Brittany, France (Donaldson, private communication). The first outbreak was noticed in the Henansal municipality on March 4, 1981, but mortality on the farm was initiated on February 28. The epidemic lasted until March 26, and in total 14 French and 2 British farms were infected. Out of these, 13 farms were located in the vicinity of the city of Henansal. The remaining French farm was situated across the bay at Le Mesnil. The British outbreaks took place on Jersey and the Isle of Wight. The majority of the outbreaks occurred among pigs which, as described in Sect. 2.1, have the largest minimum infectious dose and excretion rate. The outbreaks on Jersey, Le Mesnil and the Isle of Wight were all on cattle farms – cattle being the most susceptible species to infection.

Transmission Across the English Channel

In the meteorological data for the English Channel area, we found evidence of a period of highly stable and persistent meteorological conditions which, in connection with an outbreak in a large amount of pigs near the coast of Brittany, may have caused a transfer of virus by air on March 7–8, 1981. In Fig. 3.1 we show the model calculation of the 24-hour average concentration pattern from an infected premise close to the coastline. The source-strength

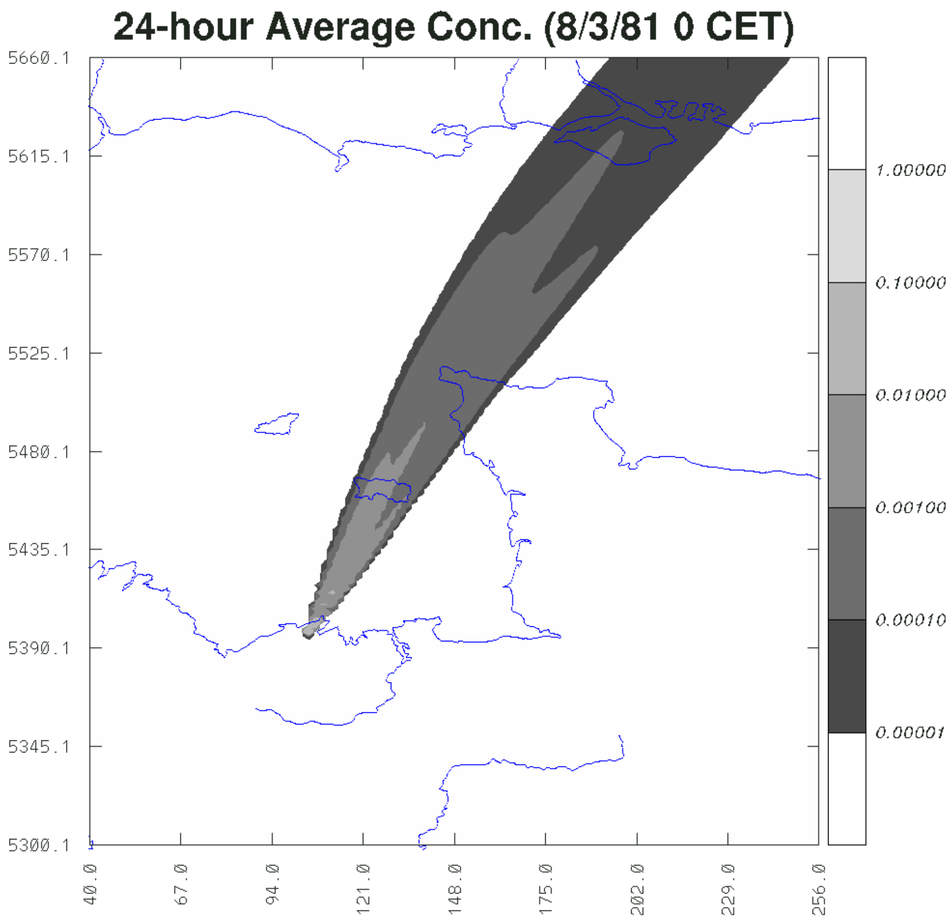

FIG. 3.1. Virus plume from an outbreak on a pig-holding farm in Brittany reaching Jersey and the Isle of Wight. The contours indicate 24-hour average FMD virus concentrations on March 8, 1981, at 0 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 31.

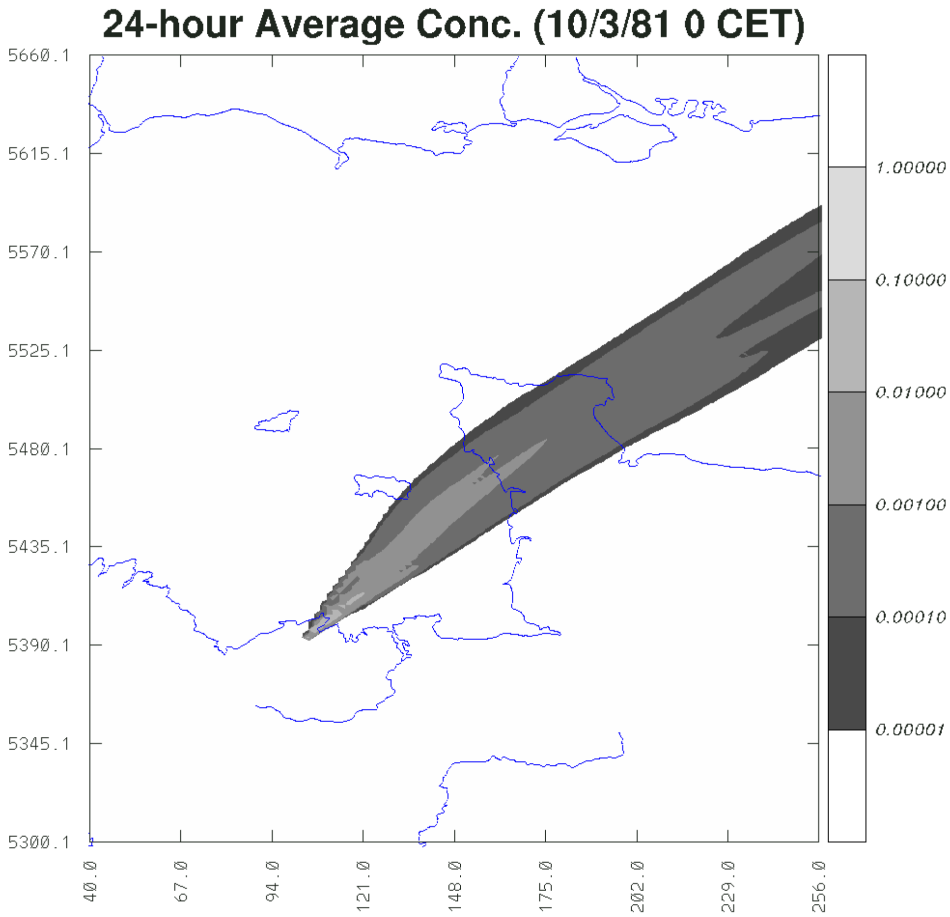

Fig. 3.2. Virus plume from an outbreak on a pig-holding farm in Brittany reaching Le Mesnil across the Golfe de St. Malo. The contours indicate 24-hour average FMD virus concentrations on March 10, 1981, at 0 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 31.

calculation was based on the twelve clinically verified infected pigs out of a household of 2 109 pigs. The narrow intense virus plume is seen to reach Jersey and the Isle of Wight. The valid time of the figure is March 8, 1981, at 0 CET. The virus plume depicted is the average concentration in units of $TCID_{50}/m^3$ over the preceding 24 hours. On March 9 the area around Le Mesnil is seen to be subject to quite intense concentrations, cf. Fig. 3.2.

In our first attempt to model the airborne spread across the English Channel, we utilised the available direct observations from meteorological stations in the area. These stations were positioned close to the coast lines. Therefore, the wind conditions recorded may not represent the flow over the English Channel very well.

We have obtained high-resolution NWP data from the Danish version of the HIRLAM model which has been run for this purpose. The area covers the region of concern (and more), as well as the period. This should remedy the above deficiency of the meteorological stations. Using the DMI-HIRLAM wind fields further allows us to use the wind at different heights (which of course is not possible for meteorological stations). Correspondingly, we have made a sensitivity study with the result that as long as this height is reasonable (below say 300 metres), the dose patterns do not change significantly.

Having available DMI-HIRLAM data enables us to run the long-range transport model DERMA (Danish Emergency Response Model for the Atmosphere) which performed well in the ETEX (European Tracer Experiment) model evaluation, cf. Sect. 3.6. The results of DERMA are highly consistent with the RIMPUFF results.

Utilising DMI-HIRLAM data instead of data from the meteorological stations implies a more narrow plume in the direction of the Isle of Wight. The plume, which is the most likely candidate for infecting the Isle of Wight, shows the 24-hour average concentration from March 7, 0 CET till March 8, 0 CET, 1982, cf. Fig. 3.1. The 24-hour average concentrations are, however, about a factor 500 too small to cause infection on the Isle of Wight as compared to a threshold value of 0.06 $TCID_{50}/m^3$ for cattle, cf. Table 2.1.

As noted by Donaldson *et al.* [23], no source of virus transport to the Isle of Wight other than airborne could be established. Along with the fact that most of the farms in Brittany were situated in a small north-north-easterly oriented valley, giving rise to channeling effects, this might strengthen the hypothesis of airborne spread as the route of transmission.

Internal Spread in the Henansal Area

Farm no. 9, cf. Table 3.2 could easily have been infected by airborne spread from either premises 2, 3 or 4 since it is subjected to substantial doses caused by plumes reaching it in the period from March 7–9. This is illustrated in Fig. 3.3. The outbreak on premise no. 9 starts on March 13. This implies an incubation period of 4–6 days which is in accordance with established knowledge.

Premise no. 7 could have been infected by no. 1 late in the excretion

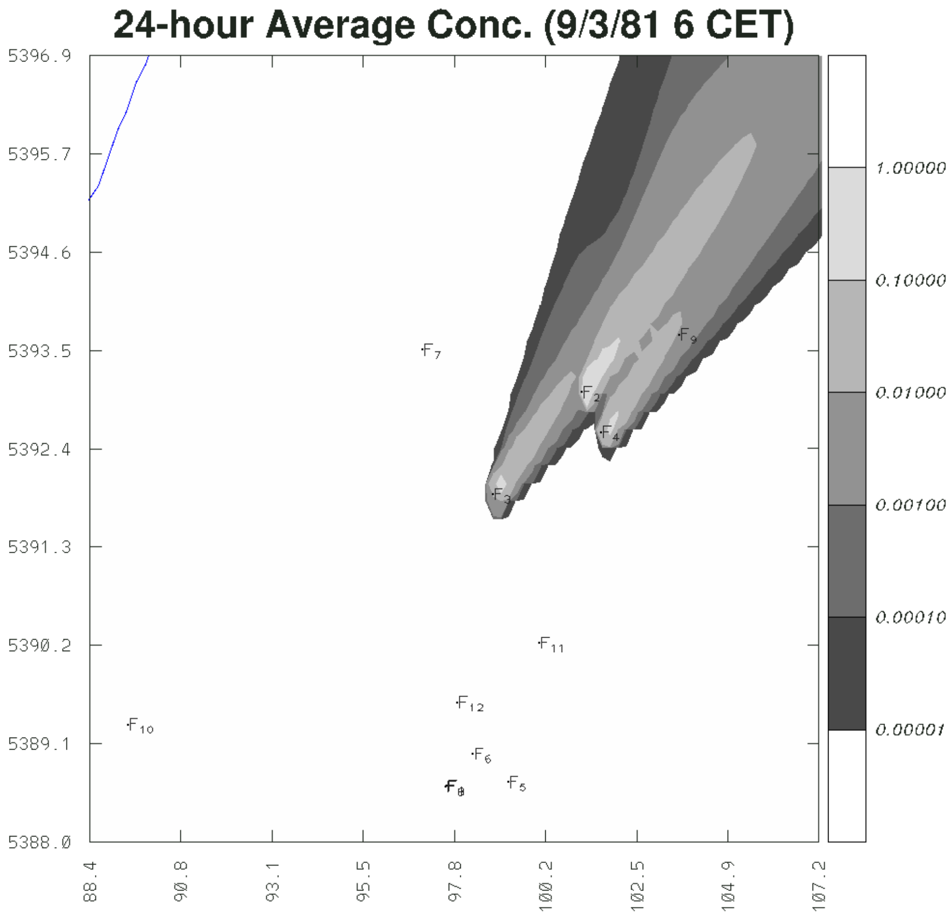

FIG. 3.3. Virus plume from infected premises no. 2, 3 and 4 reaching no. 9, cf. Table 3.2. The contours indicate 24-hour average FMD virus concentrations on March 9, 1981, at 6 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 31.

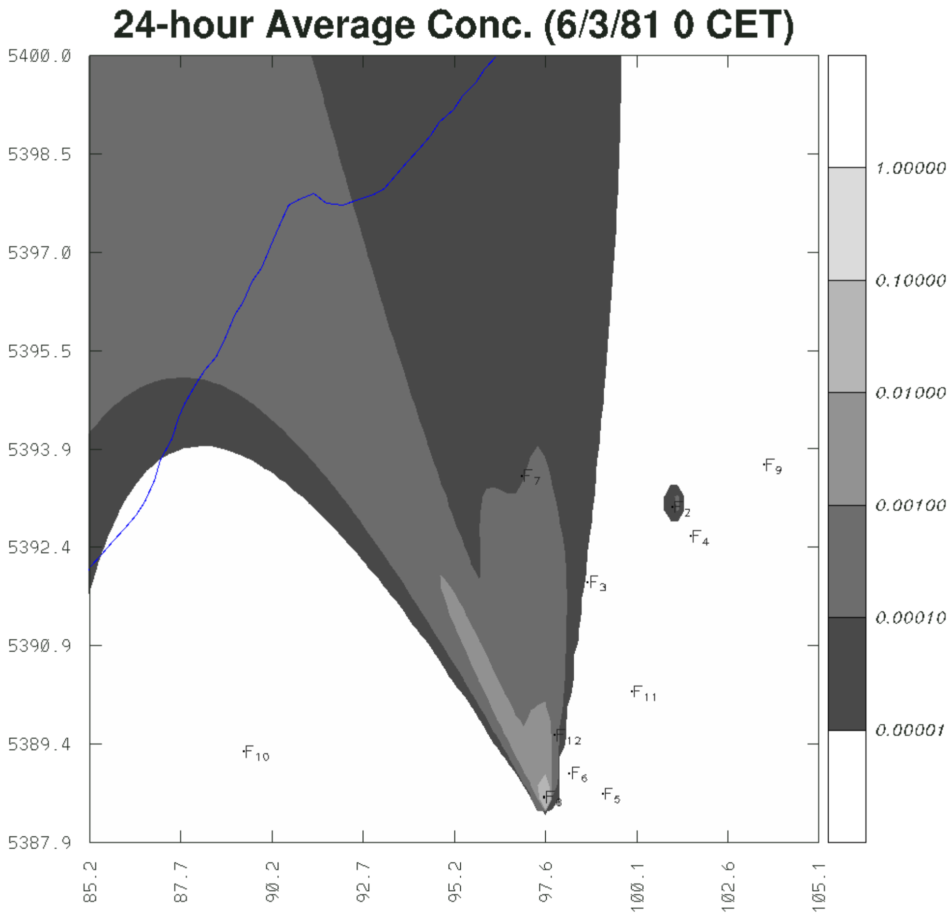

FIG. 3.4. Virus plume from infected premise no. 1 reaching no. 7, cf. Table 3.2. The contours indicate 24-hour average FMD virus concentrations on March 6, 1981, at 0 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 31.

period of this infected premise, cf. Fig. 3.4. Some uncertainty in the excretion rate from the 8 infected sows on March 4 and 5 could easily lead to substantially larger concentrations than the value of about 10^{-4} $TCID_{50}/m^3$ which our simulations predict. All pigs are assumed to have their maximum virus excretion on March 2–3, and a shift of just one day would lead to a dose increase by a factor of 30–50. This would imply a better correlation between high excretion rate and favourable meteorological conditions. Similarly to the case reported in the previous section, only 8 out of a large herd of 696 pigs on infected premise no. 1 where diagnosed as infected by FMD before de-population was initiated. In fact, it is likely that more pigs were infected than the ones clinically diagnosed. Correspondingly, a higher dose would be transmitted.

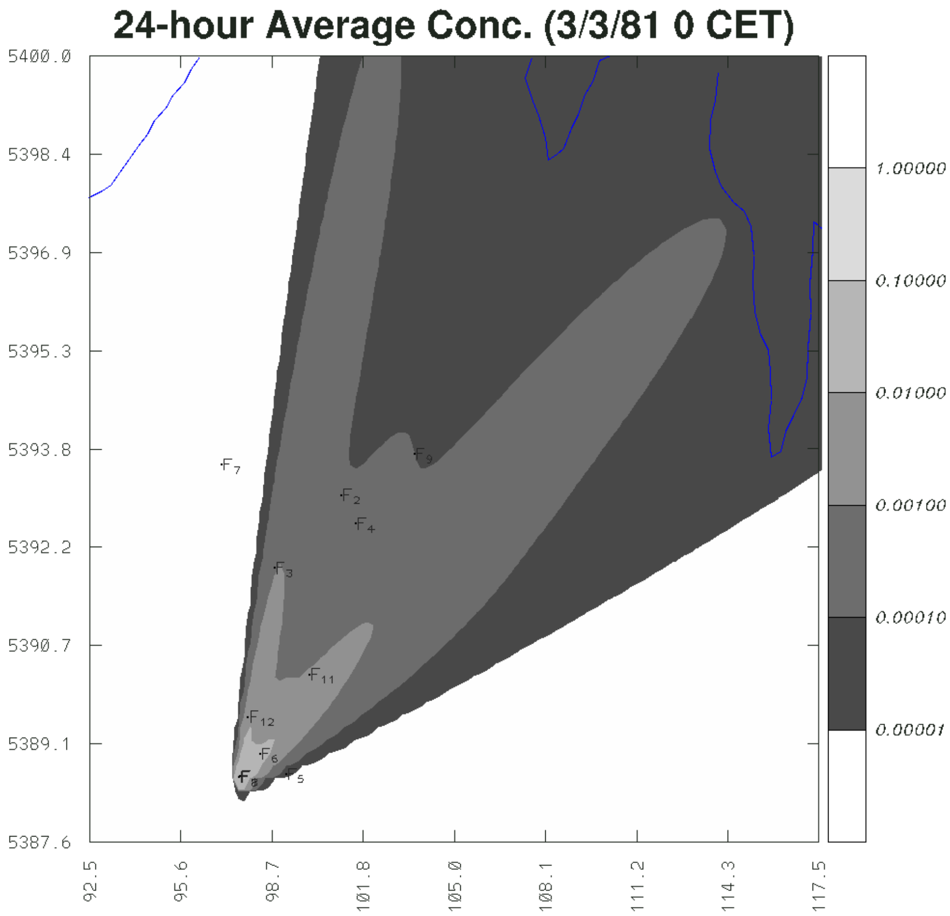

FIG. 3.5. Virus plume from infected premise no. 1 reaching no. 2, 3 and 4, cf. Table 3.2. The contours indicate 24-hour average FMD virus concentrations on March 3, 1981, at 0 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 31.

An airborne connection between premises no. 1 and 2, 3 or 4 can be established in the beginning of the first outbreak, cf. Fig. 3.5. Since the weather-recording stations are not located in the immediate vicinity of the farms, but outside the above mentioned valley, these stations do not catch the eventual channeling effect of the valley which may have caused higher doses.

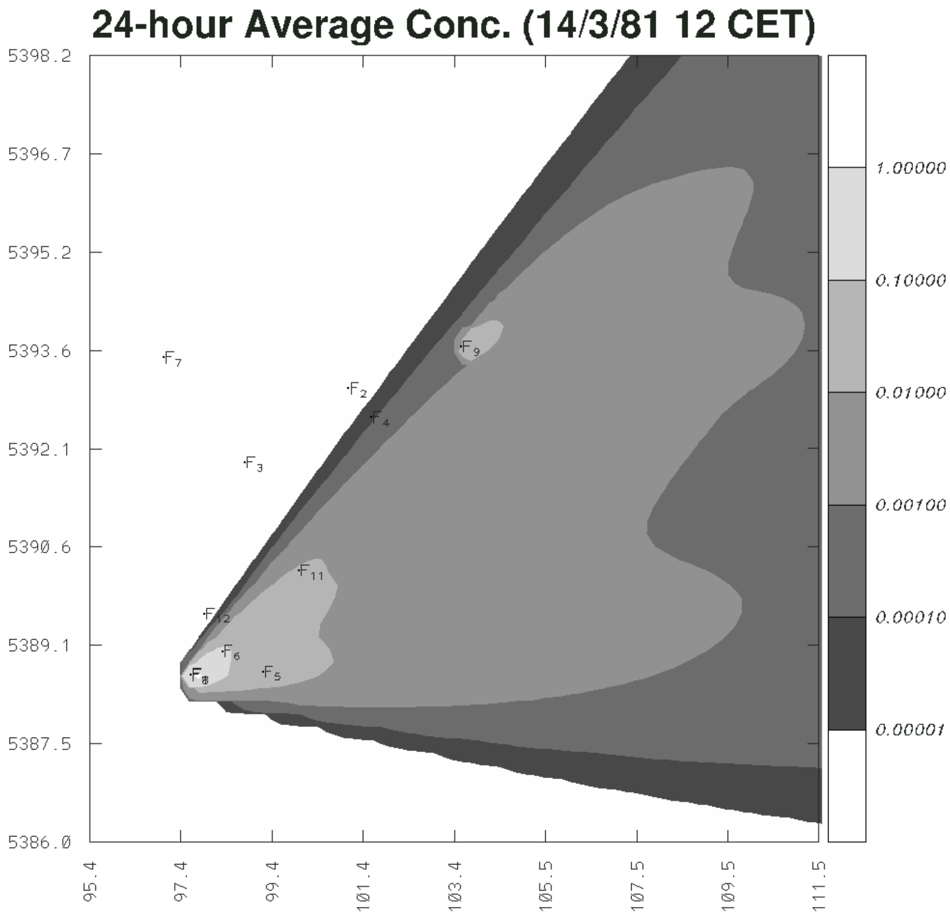

FIG. 3.6. Virus plume from infected premise no. 1 reaching no. 5, 6 and 8, cf. Table 3.2. The contours indicate 24-hour average FMD virus concentrations on March 14, 1981, at 12 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 31.

Premises no. 5, 6, and 8 are less than 1.5 km away from no. 1 so airborne spread is indeed a possibility here. This is confirmed by the simulation shown in Fig. 3.6.

The infected premises no. 5, 6, and 8 could have been the cause of infection on premises no. 11 and 12 since these are subject to high doses over a period of 5 days from March 10–14, 1981. The outbreaks on farms 11 and 12 are reported on March 16 and 17.

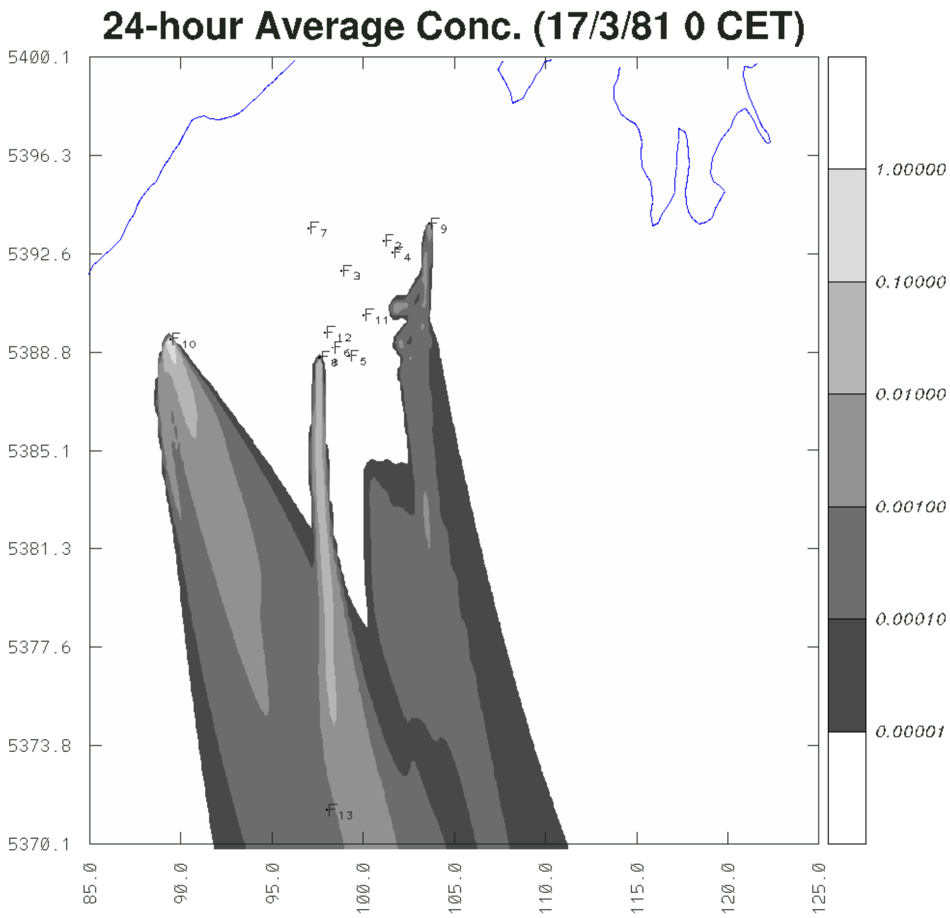

FIG. 3.7. Virus plume from several infected premises reaching no. 13, cf. Table 3.2. The contours indicate 24-hour average FMD virus concentrations on March 17, 1981, at 0 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 31.

Premise no. 13, which is located in Plenee-Jugon approximately 15 km south of the outbreaks in the Henansal municipality, have an isolated outbreak starting on March 26. As seen from Fig. 3.7, a persistent wind carries high doses directly towards this farm.

Danish Outbreaks 1982

Event Sequence

The Danish outbreaks in 1982 are well documented in the report by the Danish Veterinary Service [22]. We will here give a brief summary: On

March 14, 1982, the first outbreak was noted in a small cattle farm on the island of Funen, Denmark, but it was not until March 18 that FMD was identified, and de-population was initiated. During the next one and a half month a total of 22 outbreaks occurred, all but one on Funen. The last episode was just across the Great Belt on the island of Zealand. This outbreak occurred two weeks later than the outbreaks on Funen. On Funen the first 17 outbreaks were in the south-eastern region whereas the last 4 were in a small region on the northern coast.

In Table 3.3 detailed epidemiological and geographical data regarding the Danish FMD epidemic in 1982 are listed.

No.	Location	Coordinates	date of lesion	cattle	pigs/piglets	sheep
1	Brenderup	(55°10′58″N, 10°39′14″E)	14/03/82	46	0/0	0
2	Kappendrup	(55°19′55″N, 10°34′06″E)	22/03/82	1	0/0	0
3	Kværndrup	(55°10′40″N, 10°32′35″E)	22/03/82	1	0/0	0
4	Oure	(55°07′52″N, 10°44′06″E)	22/03/82	1	0/0	0
5	Kappendrup	(55°20′25″N, 10°35′02″E)	23/03/82	2	0/0	0
6	Kappendrup	(55°09′36″N, 10°40′30″E)	22/03/82	2-5	0/0	0
7	Gislev	(55°12′25″N, 10°37′49″E)	23/03/82	0	2/0	0
8	Ringe	(55°15′39″N, 10°29′06″E)	24/03/82	5	0/0	0
9	Gislev	(55°12′25″N, 10°37′49″E)	24/03/82	0	10/0	0
10	Allerup Torup	(55°20′11″N, 10°29′14″E)	30/03/82	1	0/0	0
11	Ellinge	(55°19′00″N, 10°37′11″E)	30/03/82	5	0/0	0
12	Gudme	(55°09′44″N, 10°42′12″E)	03/04/82	7	0/0	0
13	Søllinge	(55°17′15″N, 10°32′56″E)	05/04/82	1	0/0	0
14	Boveskov Huse	(55°19′54″N, 10°39′03″E)	06/04/82	1	0/0	0
15	Gudme	(55°09′35″N, 10°42′15″E)	06/04/82	3	0/0	0
16	Fraugde	(55°21′28″N, 10°30′07″E)	07/04/82	2	12/0	0
17	Havndrup	(55°19′09″N, 10°34′05″E)	13/04/82	4	0/0	0
18	Egebjerggård	(55°36′10″N, 10°21′01″E)	13/04/82	4	0/0	0
19	Tørresø	(55°34′45″N, 10°23′45″E)	21/04/82	1	0/0	0
20	Gyndstrup	(55°34′55″N, 10°19′22″E)	21/04/82	1	0/0	0
21	Tørresø	(55°34′58″N, 10°24′18″E)	21/04/82	1	0/0	0
22	Vedskølle	(55°13′43″N, 11°21′42″E)	03/05/82	1	0/0	0

TABLE 3.3. Epidemiological and geographical data [22] of the infected premises in Denmark, 1982.

Internal Airborne Spread on Funen

4 outbreaks in south-eastern part of Funen, which did not have any other epidemiological links, were found in our simulations to qualify as candidates for airborne infection.

- The first farm which was infected by FMD is located near (10–15 km) premises no. 7 and 9, cf. Table 3.3. On March 16 and 17 the meteorological situation caused the virus plume of this farm to take the direction of premises no. 7 and 9 (cf. Fig. 3.8) which had outbreaks on March 23 and 24 in agreement with the incubation period of FMD.

- On March 31 premise no. 14 was downwind of the outbreak on premise no. 11 as shown in Fig. 3.9. The farm is located only 2 km from premise no. 11. The possibility of airborne spread was also emphasised by the official report on the eradication. Due to the low number of reported animals with clinical signs on premise no. 11, and the low virus excretion of cattle, the plumes are very small.

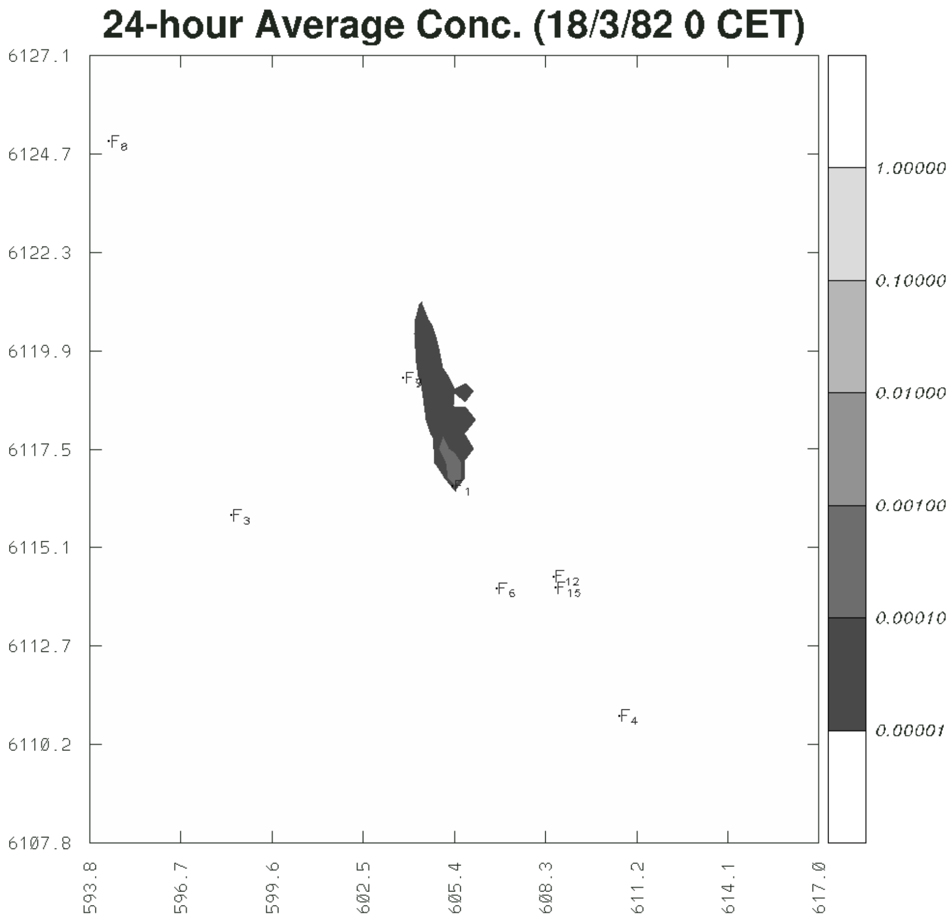

Fig. 3.8. Virus plume from infected premise no. 1 in direction of no. 7 and 9, cf. Table 3.3. The contours indicate 24-hour average FMD virus concentrations on March 18, 1982, at 0 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 32.

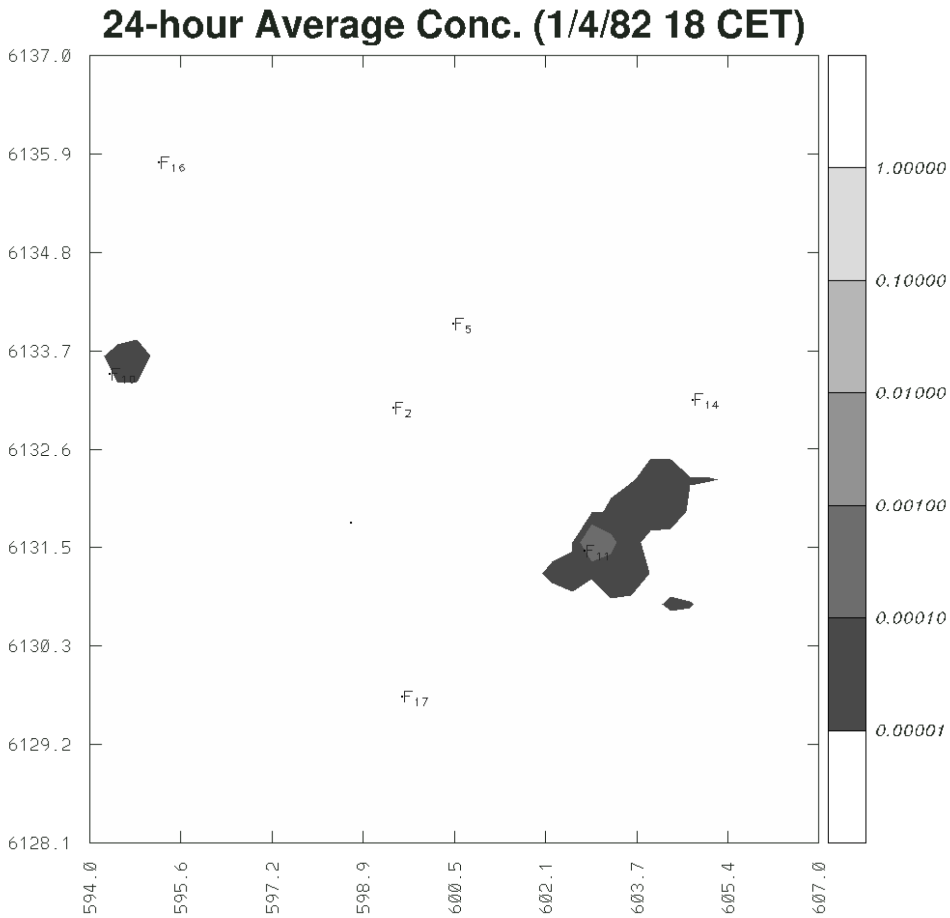

FIG. 3.9. Virus plume from infected premise no. 11 in direction of no. 14, cf. Table 3.3. The contours indicate 24-hour average FMD virus concentrations on April 1, 1982, at 18 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 32.

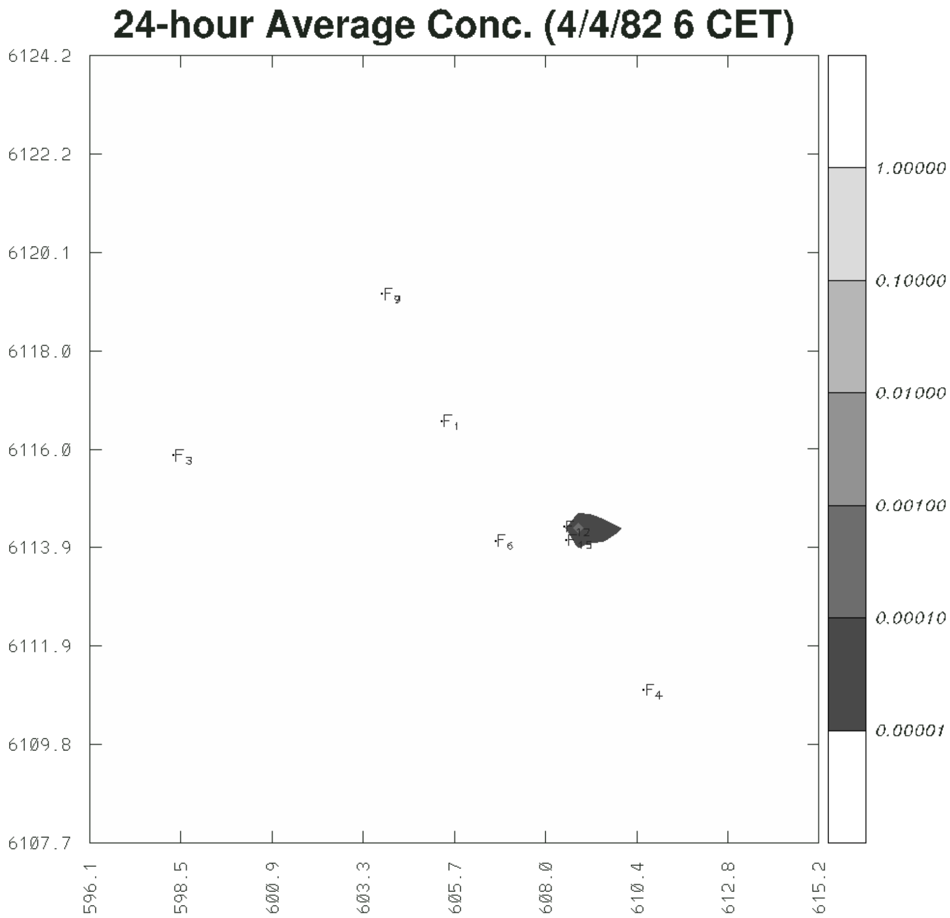

FIG. 3.10. Virus plume from infected premise no. 12 covering no. 15, cf. Table 3.3. The contours indicate 24-hour average FMD virus concentrations on April 4, 1982, at 6 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 32.

- Premise no. 15 which had an outbreak on April 7, is located only 1 km from premise no. 12, which was de-populated 4 days earlier. An indication that airborne spread might be the route of infection can be seen from Fig. 3.10.

In the report by the Danish Veterinary Service [22] it was suggested that airborne spread could have caused the spread from the south-eastern region to the northern region, since no other links have been established. It was also claimed that the winds during the outbreak on premise no. 16 in Fraugde were favourable for airborne spread. We have made simulations of this based on both direct meteorological observations and HIRLAM data, and none of these simulations support airborne transport: A strong wind from south-west persisted during these two days. But had the excretion started only one day earlier, the winds would have carried virus in the direction of these 4 farms on the northern part of Funen.

GDR Outbreaks 1982

Event Sequence

Our analysis of the chain of events in the GDR outbreaks are based on a set of telexes (in French, English and Spanish) send out by the GDR veterinary authorities (Professor Schwedler) following the outbreaks, and on private communications with Dr. A.I. Donaldson. We have summarised the facts concerning the individual premises in Table 3.4.

No.	Location	Coordinates	date of lesion	cattle	pigs/piglets	sheep
1	Murchin	(53°55′N, 13°45′E)	14/03/82	12	0/0	0
2	Lessen	(53°57′N, 13°52′E)	14/03/82	10	0/0	0
3	Giesendorf	(54°25′N, 13°27′E)	22/03/82	?	0/0	0
4	Reinberg	(54°13′N, 13°15′E)	22/03/82	?	0/0	0
5	Kemnitz	(54°05′N, 13°34′E)	22/03/82	?	0/0	0
6	Altenpleen	Stralsund	22/03/82	?	0/0	0
7	Gross-Jasedow	Anklam	26/03/82	4	0/0	0
8	Müggenburg	(54°15′N, 12°26′E)	28/03/82	11	0/0	0
9	Löebnitz	(54°18′N, 12°43′E)	28/03/82	3	0/0	0
10	Born	(54°18′N, 12°43′E)	29/03/82	18	0/0	0
11	Weick	(54°18′N, 12°43′E)	29/03/82	14	0/0	0
12	Lassan	(54°05′N, 13°50′E)	30/03/82	0	0/40	0
13	Barth	(54°18′N, 12°43′E)	31/03/82	6	0/0	0
14	Bushenhagen	(54°15′N, 13°00′E)	02/04/82	0	0/0	4
15	Altenpleen	Stralsund	02/04/82	0	0/0	180
16	Velgost	(54°17′N, 12°49′E)	03/04/82	2	0/0	0
17	Petersdorf	(54°05′N, 12°10′E)	04/04/82	0	3/0	0
18	Bushenhagen	(54°15′N, 13°00′E)	09/04/82	1	0/0	0
19	Barth	(54°18′N, 12°43′E)	10/04/82	2	0/0	0
20	Kenz	Ribnitz-Damgarten	11/04/82	0	2/0	0
21	?	data missing	11/04/82	?	?	?

TABLE 3.4. Epidemiological and geographical data of the infected premises in GDR, 1982. Coordinates from the Times Atlas of the World.

Internal Airborne Spread

Since the GDR epidemiological data are subject to confusion and in general of poor quality, we have only done few simulations of the possible internal spread in GDR, and we will refrain from making any conclusion.

Possibility of Spread to Denmark

As mentioned earlier the data available for the GDR outbreaks are rather poor, consisting only of brief telexes send out at the time of event. And according to these, the first GDR outbreaks are coincident in time with the first Danish, so an epidemiological connection of any kind would be ruled out. But the virus strains were similar (type O1), and since no other FMD outbreaks are known at the time, a link between the two was suspected.

Trajectory calculations performed at that time suggested the possibility of airborne transmission approximately one week before the first Danish outbreak, namely around March 7 and 8, 1982. These calculations, however, only considered transmission from the vicinity of the first reported GDR outbreak in Murchin, district of Anklam. No estimation of transmitted doses were attempted either.

Considering the geographical scale of the outbreaks of approximately 100 km, spread from other locations within this regional scale should also be considered. Especially since several outbreaks were located much closer to the Femern Belt, separating East Germany and Denmark, than the premises in Murchin.

As for the Brittany outbreaks in 1981, the DMI-HIRLAM numerical weather-prediction model has been run with high resolution for the relevant area and period of the East German and Danish outbreaks in 1982.

Based on the HIRLAM output, an attempt has been made to locate potential sources of airborne FMD virus reaching the first infected premise of the Denmark 1982 epidemic about one week before the onset of clinical signs. This involved calculation of three-dimensional back-trajectories applying to air parcels arriving inside the turbulent atmospheric boundary layer (ABL), also known as the mixing layer, above the first infected premise. 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 the large-scale transport of air masses reaching that location. The height of the mixing layer varies considerably from tens of metres to several kilometres. On March 7–8, 1982, this layer was very thin (less than a few hundred metres) 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 East Germany is a potential source of airborne FMD virus reaching Denmark on March 7–8, 1982. In Fig. 3.11 an example of such a calculation is shown. The longitudinal and latitudinal coordinates of the arrival point are written on the figure together with the date and time of arrival of the air parcels, and the back-trajectories are marked each 6 hours. The marks (letters) indicate the ratio of the height above ground and the mixing height.

In Fig. 3.12 we show a simulation of a hypothetical major outbreak involving 1 000 pigs in GDR south-west of Rostock. The virus plume is heading directly towards the first reported outbreak on Funen. With an incubation period of 7 days, this provides adequate conditions for airborne transmission. On Fig. 3.13, we show a similar result based on a source located at Murchin, the reported location of the first outbreak in the GDR epidemic. As seen

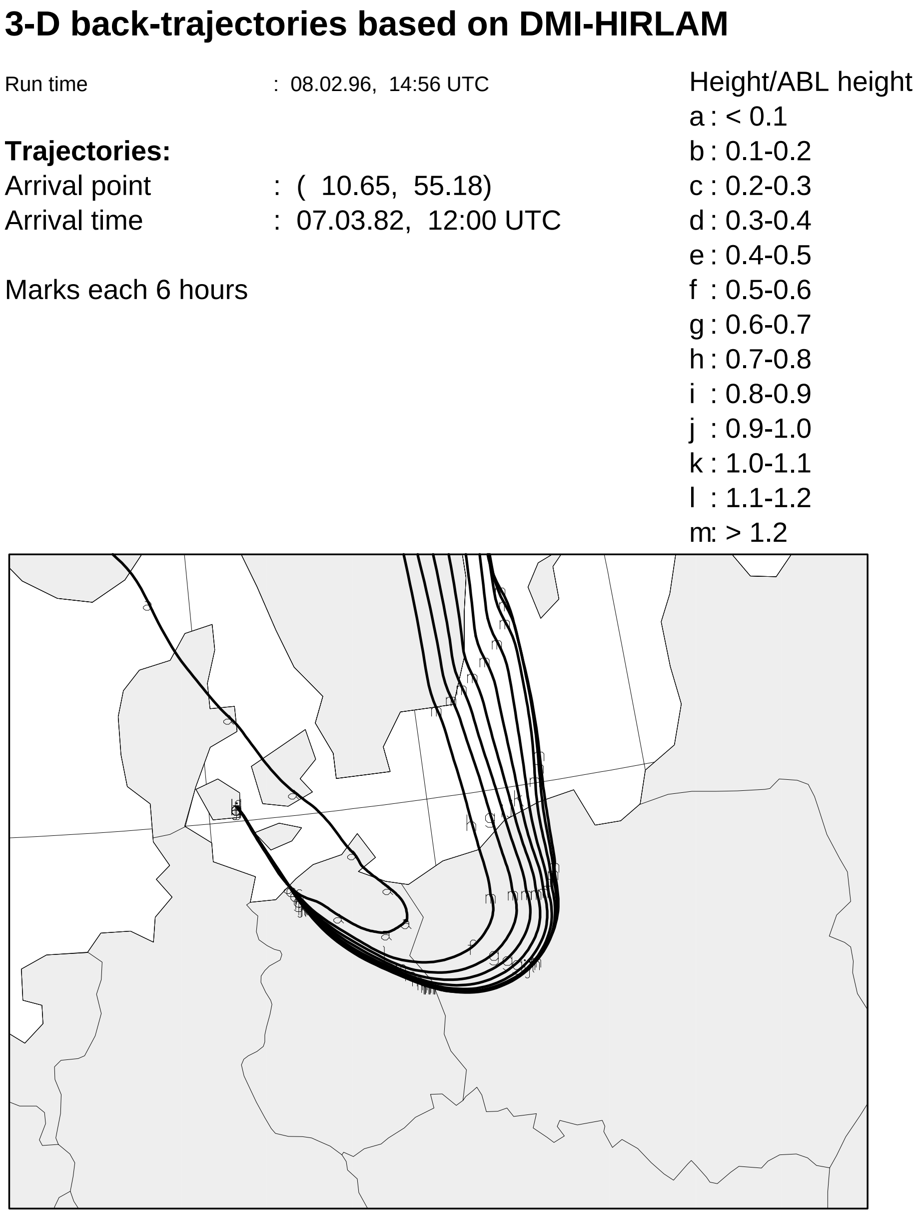

FIG. 3.11. Back-trajectories corresponding to ten arrival heights inside the atmospheric boundary layer in a column above the first infected premise of the Denmark 1982 epidemic. The arrival time is 12 UTC on March 7, 1982. Along the trajectories, the ratio of the height above ground and the atmospheric boundary-layer height is indicated each 6 hours.

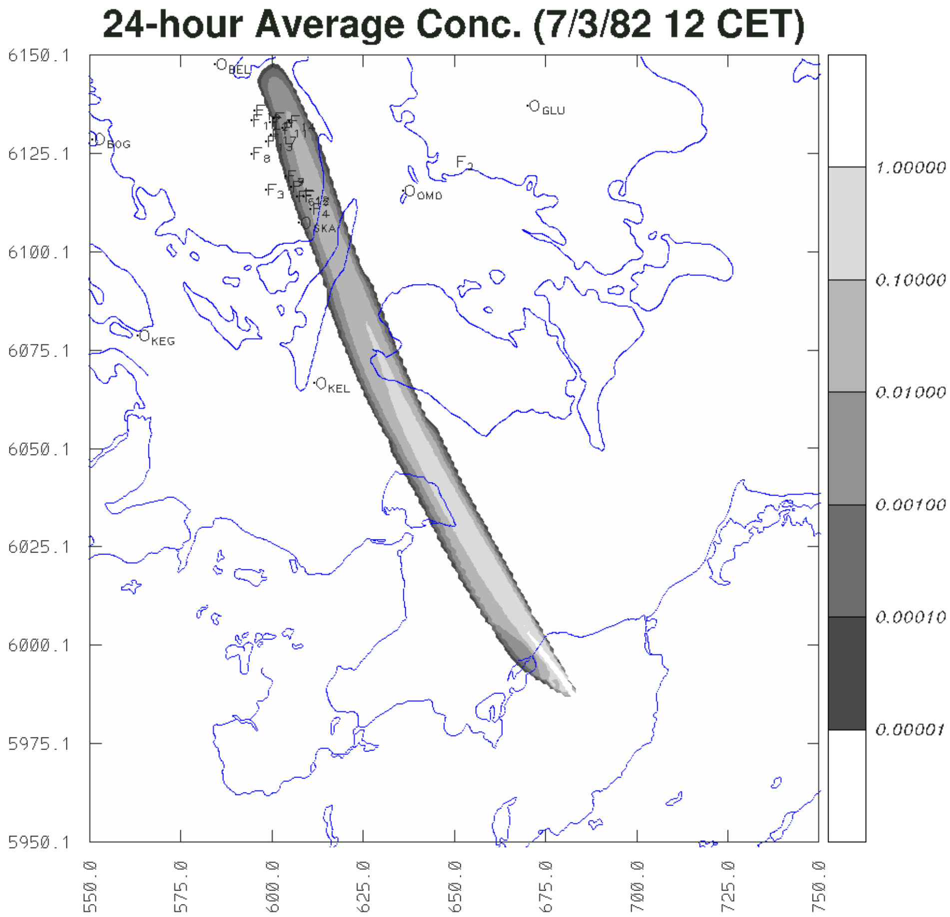

FIG. 3.12. Virus plume from a hypothetical infected premise in GDR south-west of Rostock reaching the first infected premise on Funen. The contours indicate 24-hour average FMD virus concentrations on March 7, 1982, at 12 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 32.

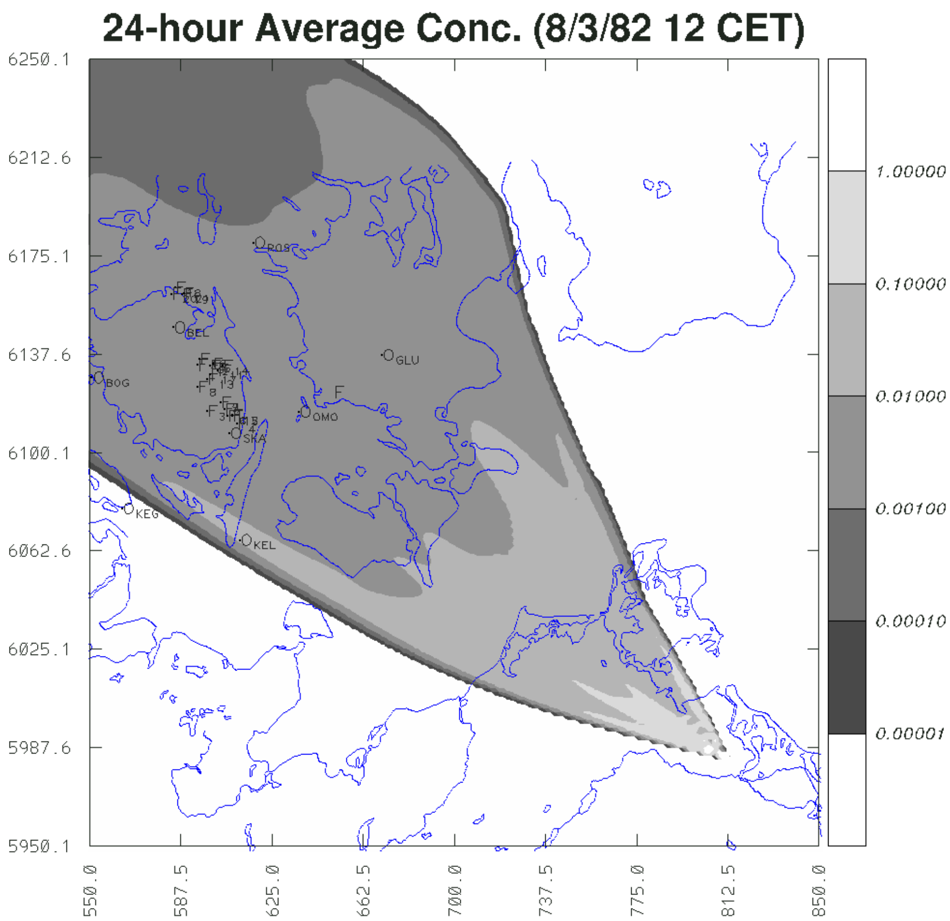

FIG. 3.13. Virus plume from a hypothetical infected premise in GDR at Murchin, the origin of the first reported outbreak in the GDR, only one week earlier than reported. The contours indicate 24-hour average FMD virus concentrations on March 8, 1982, at 12 CET, in units of $TCID_{50}/m^3$. The axis units are UTM coordinates, zone 32.

from the figure, airborne transmission from Murchin is less likely than the case of Fig. 3.12.

As for the airborne transmission across the English Channel, we have also here used the long-range transport model DERMA (Danish Emergency Response Model for the Atmosphere), cf. Sect. 3.6, to simulate these scenarios. Again the results of DERMA are in good agreement with the RIMPUFF results.

Chapter 4

Discussion

In the study of the possible transmission of virus across the English Channel in 1981, we predicted 24-hour average concentrations which were about a factor of 500 too small in comparison with a threshold value of 0.06 $TCID_{50}/m^3$ for cattle, cf. Table 2.1. A number of 12 infected pigs was used to create the plume of March 7–8, 1981. These pigs were from a household of 2 109 pigs. It is not a pleasant task for the veterinarian to catch and examine large numbers of pigs. Consequently, when the veterinarian has found a few with definitive lesions, that is taken as sufficient evidence to condemn the herd. It is likely that the number of clinically affected pigs were 10-fold higher or even more (Donaldson, private communication). Modelling errors or inadequacies may account for about a factor of 10.

For cattle the minimum infectious dose for 24-hour exposure to airborne FMD virus is about 10 $TCID_{50}$, cf. Table 2.1. It might be that a single (or a few) hyper-susceptible cattle were infected by a say ten-fold lower infectious dose, and that the infection then spread to the rest of the herd from these animals. Hyper-susceptible cattle – perhaps those with a damaged and, therefore, more "permeable" respiratory tract – may occur but there are no experimental data to support that (Donaldson, private communication). In fact, several cycles of infection did occur on the farm on the Isle of Wight but not on Jersey or the Cherboug Peninsula.

It is important to be aware that the concept of minimum infectious dose, as well as the atmospheric dispersion modelling, represents the most likely realisation from a probability distribution. Reality may represent a less likely realisation.

Sensitivity studies regarding the effects of atmospheric stability and the effective transport height were performed. In case of the latter, only insignificant differences resulted when transmission took place in the lower part, i.e. 250 metres, of the atmospheric boundary layer, no matter which degree of stability was assumed. With respect to stability, which is not easily (or accurately) determined, the effect of increasing the Pasquill-Turner stability category from e.g. category D to E and further to F is to intensify the plume in a narrow band provided that the wind direction is constant within the 24-hour period considered. In the observed meteorological data we found evidence that very stable conditions prevailed during the cases of suspected long-range transport of FMD virus. In these cases, the virus plumes went over sea surfaces which were several degrees colder than the atmosphere above implying a high degree of atmospheric stability. Correspondingly, stability class F was used for these simulations. Tests involving an extremely stable atmosphere (category G) did not give rise to significant alterations of the output results.

The meteorological data required by the LINCOM and RIMPUFF atmospheric flow and dispersion models may be obtained either from appropriately positioned meteorological stations or from a numerical weather-prediction (NWP) model with high resolution. In Sect. 3.5 the advantages and dis-advantages of these sources of meteorological data have been discussed. And in Sect. 3.6 validation, and justification, of atmospheric dispersion modelling based on NWP data has been reported.

In several of the case studies reported on in Sect. 3.9, we have based the atmospheric modelling on NWP data. Especially for the long-range transport scenarios, which took place over sea surfaces, there was a lack of observational data properly representing the flow. Simulations based on observed data gave rise to broader plumes than similar results based on NWP data. This is due to the fact that meteorological data from stations located in coastal areas are biased due to the influence of land-sea contrasts and orographically induced perturbations of the flow.

In conclusion, we recommend to base a real-time decision-support system such as EpiMAN (EU) on data derived from an operational NWP model of high quality and resolution.

Chapter 5

Finalisation of Tasks

It is hereby declared that all works foreseen under the contract between the State Veterinary Institute for Virus Research (the "contractor") and the Danish Meteorological Institute (the "sub-contractor") have been terminated.

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