Chapter 9

AEROBIOLOGY

CONTENTS

Formattato: Destro 0.63 cm

Chapter 9

Formattato: Tipo di carattere: 16 pt, Grassetto

AEROBIOLOGY

Formattato: Tipo di carattere: 18 pt

This Chapter was written by John Westbrook

The Chapter was reviewed by Katrina Frank and Daniel Friedman

Formattato: Tipo di carattere: 12 pt

9.1 Introduction

This chapter deals with practical aspects of aerobiology related to agricultural meteorology, and it presents an interdisciplinary approach to the properties and airborne movement of biota significant to plants, animals, pests and diseases. One of the primary updates of this chapter on aerobiology is due to the proliferation of Internet access to weather, climate, pest, plant and animal data, models, and management guidelines.

Aerobiology is a scientific discipline that deals with the transport of organisms and biologically significant materials through the atmosphere (Isard and Gage, 2001). Aerobiology also embodies the generation, uptake, translocation, dispersion, viability, deposition and infection/infestation of seeds, viruses, fungi, bacteria and other agents including insects, such as aphids and mosquitoes, which act as virus vectors, as well as dealing with agriculturally significant insects like locusts, bushflies, and moths.

Any movement of biota, particles or gases through the atmosphere which may have an adverse effect on vegetation or animal life must concern the agricultural meteorologist. Particles less than 0.1 µm, which include viruses, are in permanent suspension in the atmosphere subject to Brownian movements. The most important disease organisms that affect agriculture vary in size between 0.1 and 100 µm. These airborne particles are in a transitory state, each with a specific fall speed. Particles above 100 µm cannot be sustained in the atmosphere for any significant time by strong winds, unless powered flight is a factor, such as for insects, birds, and bats. Allergy is also of concern to the aerobiologist who can provide warnings of pollen episodes, which may cause allergies, enabling preventive medications to be taken.

A common procedure adopted by agricultural meteorologists is to use seasonal meteorological indicators to signify the last stage, i.e., the infection episode, rather than proceeding from the first phase, i.e., the generation. When considering the end phase, *per se*, the inoculum is assumed to be present unless information to the contrary is provided by a plant pathologist. An index such as degree-days or heat units is sometimes used to indicate the phase where infection would probably occur if a suitable pathogen was present.

For specific purposes an index such as the product of temperature and wetness duration is used to signify a potential infection period (Mills and Laplante, 1951). Products of 140, 200, 300 degree-wetness hours corresponded approximately to light, moderate and heavy infections of apple or pear scab for optimum temperatures ranging from 18℃ to 24℃. This approach can also be applied to brown rot in peaches and can be used to indicate fungal infection on grass leading to facial eczema in sheep. Various combinations of meteorological elements are used for other diseases.

While these established routines will continue to play an important role in the field of agrometeorology, the widespread use of aerobiology promises to improve the service. Pedgley (1982) provides a broad survey of airborne dispersal of plant pathogens, human allergens, livestock diseases, and pest insects and other organisms. Aerobiological techniques have already been used successfully in some areas. These include practices such as tracking the spread of foot-and-mouth disease (Moutou and Durand, 1994), locusts and bushflies. The interdisciplinary approach to aerobiology incorporates the sampling routines and instrumental observations of entomologists, plant pathologists, and other biologists with real-time-weather or climatic data of meteorologists for use in models specifically designed to simulate certain disease infections or insect infestations. Additionally, the aerobiological techniques may include monitoring and modeling of airborne movement of beneficial biota and their impact on pest populations.

Agronomic management must maintain environmental quality at an acceptable level when applying counter-measures to pests and diseases. Judicious use of chemical sprays and biological control tactics is needed to reduce environmental risk and maintain the long-term effectiveness of pesticides and biological control tactics for pest management.

9.2 Types of service to be provided to users

The ecological systems approach to aerobiology (Edmonds and Benninghoff, 1973) described potential products that could be delivered to users. An interdisciplinary team, comprising a plant pathologist, entomologist, agronomist, animal scientist, etc., and an air pollution chemist, meteorologist and systems mathematician, could form the nucleus of an aerobiology unit which could offer:

- A research unit to investigate airborne biota, in particular the generation, release, dispersion, viability, deposition and infection stages;
- A specific program to assess (*a*) the magnitude of problems of aerial transport of economically important diseases and pests of crops and forests and (*b*) the need for aerobiological surveys for improved understanding of the problems and for the monitoring that would assist in control measures (e.g., leaf hoppers, cereal rusts, corn blight, fire blight, fusiform rust, white pine blister rust, gypsy moth, Douglas-fir tussock moth);
- Investigations into the contribution that aerobiological techniques could make to various methods of biological control of pests and diseases;
- A focus for the development and implementation of a program for progressive improvement in the estimation of crop losses due to diseases and pests utilizing the appropriate methods from aerobiology and aerobiological models;
- Encouragement for further simulation modeling of aerobiological phenomena in the context of ecosystems.

Having established an interdisciplinary body, its ultimate problem is to provide the right information to the right farm, nursery, forest, etc., in the right form at the right time. The host-pathogen relationship is determined mainly by the microclimate and is thus related to weather as modified by the crop. The agricultural meteorologist is the obvious person to monitor the weather continuously and have input into an approved model. The meteorologist also has an excellent communication link with farmers who rely on weather information.

Criteria for the successful implementation of specific pest and disease management systems have also been given by Johnson (1987) as follows:

- A serious pest or disease problem must exist for which low-cost solutions, e.g. host resistance, are unavailable and unreliable;
- It should be possible to explain efficiently and predict accurately the variations in the incidence of problems by means of a model;
- Facilities must exist for communication of model predictions so that timely control measures can be taken;

- Control measures must be available which are effective, economically justified and non-hazardous to the environment.

Angus (1988*a*) mentions strategic methods, such as host resistance, crop rotation and fertilizer practices, along with tactical methods, such as the application of pesticides or fungicides, in response to model indications of infections or epidemics. The aim being to achieve prevention rather than containment of damage. The EPIPRE system (Djurle and Jonsson, 1985), among other models, considers the cost of application of a mixture of pesticides and fungicides in a single operation and the BLITECAST model (Krause *et al.*, 1975) provides a model for early disease control. Models used for aerobiological investigation could profit by adopting the above principles.

9.3 Data and models available for use by aerobiologists

Climatic data is useful in the development of computer models to simulate outbreaks of pest and disease infection. The introduction of a new crop and its susceptibility to disease infection or pest infestation can be tested using a simulation model (Waggoner and Horsfall, 1969). Real-time-weather reports are vital during operational investigations. Real-time-weather data and climatic data are widely available for free access over the Internet (e.g., http://lwf.ncdc.noaa.gov/oa/ncdc.html). Increasingly, weather data are being generated by parameterization of remotely sensed data (e.g., radar reflectivity, and Doppler radar radial velocity).

Wind data at all heights are quite important. Wind shear and gustiness at the surface of plants can assist in spore release, uptake, dispersal and deposition. Tromp (1980) reported long-range transport by wind of yellow rust spores over 1,000 km. The temporal distribution of wind direction at specific location can provide valuable information regarding the state of the atmosphere. If R is the range of extreme wind direction values over a given period, then R/6 is a good approximation to the standard deviation of the wind direction. Values of the standard deviation of wind directions of 2.5, 10 and 25 degrees represent very stable, neutral and unstable atmospheric conditions, respectively. An alternative system to deduce the state of the atmosphere is shown in Table 9.1.

Table 9.1
Stability categories

Surface wind speed at 10 m ($m\ s^{-1}$)	*Day*			*Night*	
	Incoming solar radiation			*Thinly overcast or*	
	Strong	*Moderate*	*Slight*	*≥4/8 Low Cloud*	*<3/8 Cloud*
< 2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

A, B, C, D, and E are stability indicators. The neutral class, D, should be assumed for overcast conditions day or night.

Formattato: Destro 0.63 cm

Wind analyses using constant-altitude, isothermal, isentropic, or isobaric surfaces or the three-dimensional sigma model can be used to obtain trajectories at the higher latitudes, while in the tropics streamline analyses are preferable to pressure-height contours.

Commento [JKW1]: and others?

Temperature is a vitally important element for agriculture. Degree-day indices can be used to indicate critical phases for pests and diseases enabling the timely application of cultural or chemical treatments. The temperature lapse rate, besides indicating the state of the atmosphere, is also used to estimate the mixing height, or the height to which all particles and gases are dispersed during the day. High surface temperatures can trigger the release of spores and seeds and set limits to fungal activity.

Precipitation, including dew and fog deposition, is an important factor in disease propagation and the microclimatic humidity conditions must be consistently monitored. Precipitation results in the wetting of vegetation and also the release of spores from plants. In the presence of rainfall, nearly all of the airborne particles can be washed out. Spores washed out by rain may be significant in the initiation of disease (Rowell and Romig, 1966).

Radiation, both visible (380-780 nm) and ultraviolet (UV) (190-380 nm), may have epidemiological significance. The germination of spores of blister blight is favored by faint light; *Phytophthora* sporulates germinate overnight with favorable humidity. While small doses of UV stimulate germination, large doses minimize infectivity. According to Aylor (1986) the combined effects of temperature, relative humidity and UV light found at the top of the mixing layer may be particularly lethal to spores. Ultraviolet radiation at wavelengths greater than 290 nm reach the ground with sufficient intensity on sunny summer days to kill sensitive spores in a few hours (Bashi and Aylor, 1983). The sensitivity of spores to UV radiation is enhanced when spores are wet (Rotem *et al*., 1985) or when maintained at high relative humidity. This effect may be greater at the lower temperatures near the top of the mixing layer because of the less efficient repair by photo-reactivation of their DNA (Maddison and Manners, 1973).

9.3.1 Remote sensing data

Radar can register rainfall, rainfall washout of biota, and also the aerial movement of many pest and beneficial organisms. Further, Doppler radars can also measure the speed and displacement direction of air flow, and consequently movement of airborne biota (Westbrook and Eyster, 2003). Satellite imagery can provide cloud and rainfall patterns along with vertical profiles of temperature and moisture which assist in the analysis of charts and the establishment of trajectories. Cloud-top temperatures have been well correlated with rainfall probability. Satellite-derived vegetation indices (e.g., Normalized Difference Vegetation Index [NDVI]) can be used to locate host vegetation for pests and diseases, thus enabling the application of preventive actions (e.g., sprays or cultural practices) after ground truth verification. Further, much activity is underway to use aerial imagery of vegetation to generate prescription maps for precision application of pesticides.

9.3.2 Vertical mixing and dispersion models

Many of the problems of dispersion depend on the mixing height, which is the atmospheric layer in which the bulk of material is distributed. If the mixing height is low, the materials are highly concentrated in a relatively small volume, and vice versa.

An aerological sounding can be analyzed to establish a mixing level. The dry adiabatic lapse rate (-9.8 ℃ km^{-1}) is followed from the surface temperature and pressure until it intersects with the environmental lapse rate and the intersection point determines the mixing height. If a rural trace is used in a built-up area, 5℃ is often added to the morning temperature to allow for the heat island effect (Figure 9.1). The product of the mixing height and the mean wind speed is a measure of the ventilation rate.

Formattato: Destro 0.63 cm

Predetermined results from Gaussian-type equations can be obtained for given wind speed and atmospheric stability for point, line, or area release of a unit source from ground level or from a given height. Solutions to potential problems such as these can be prepared for a variety of likely combinations of wind speed and stability for distribution to workers in the field for their information and experiment.

Computer models involving various forms of the Gaussian equations are available, e.g. Slade (1968), Turner (1967), Pasquill (1962) and Sutton (1953). The additional data required to use these equations are the standard deviations S_y and S_z, which are dispersal coefficients in the horizontal and vertical, respectively, as show in Figures 9.2*a* and 9.2*b*. The atmospheric stability indicators after Pasquill (1961) are shown in Table 9.1. The mixing height usually reaches a maximum during the afternoon and a minimum in the early hours of the morning.

The Gaussian equations make many simplifying assumptions which include:

- Continuous or instantaneous emission from a source;
- The absence of rain (washout);
- Theory is constrained to a flat featureless terrain (grasslands) because the dispersion coefficients in Figures 9.2*a* and 9.2*b* were measured under such conditions;
- Once an atmospheric stability class is selected (from Table 9.1) it must remain fixed, i.e. there is no allowance for a change in turbulent structure;
- Once selected the mean wind velocity cannot change and thereafter remains constant with height.

In view of the above assumptions, the Gaussian plume model is strictly valid only for a region close to the source and for a period during which no significant change in any important parameter occurs. An example where those limitations have been overcome to some extent is the Roberts model (Roberts *et al.*, 1972), where a purely diffusive model is replaced by a trajectory-diffusive model.

The Web-based Real-time Environmental Application and Display sYstem (READY) allows users to access meteorological data and run atmospheric trajectory and dispersion models (http://www.arl.noaa.gov/ss/transport/readyinfo.html). READY can be used to model the transport of any airborne material, including spores, insects, and air pollutants. READY allows users to access archived meteorological data and run the HYSPLIT model to generate customized georeferenced maps of atmospheric trajectories and dispersion concentrations. Use of READY or similar systems that integrate data base access and modeling software will advance the capabilities of aerobiologists by drastically reducing the data processing burden and by providing efficient and accurate analytical output.

9.3.3 Additional data required

Sampling data collected by entomologists involves instrumentation such as insect nets attached to manned aircraft, radio-controlled aircraft, tethered balloons and kites. Other data come from suction traps, light traps, and traps baited with sex-specific pheromones, aggregation pheromones, or feeding attractants placed in the vicinity of crops. Captured insects are identified and analyzed and contribute to the essential aerobiological database.

Information provided by plant pathologists results from field observations of lesions and infection amounts in crops, together with quantitative identifications and analyses of information from spore traps. Chemical analyses of air samples can be carried out as required. Air pollution data may also be necessary because of the possibility of an adverse impact on spore viability and plant health.

Plant simulation models, such as that created by Waggoner and Horsfall (1969), isolated single steps in the life of a pathogen which were recreated in a laboratory. The effect of varying

Formattato: Destro 0.63 cm

the weather, one element at a time, was investigated and documented. Eventually, a computer model or simulation was created which incorporated the complete system of host, pathogen and environment. Five years of climatic data were used to parallel the behavior of the fungal disease *Alternaria solani* in the simulated computer program.

The resultant simulator permitted exploration of extreme values of weather, pathogen and host. Slowing the sporulation process had little effect on an epidemic; shortening wetness duration decreased the incidence of disease but the interruption of wet periods with dry episodes simply decimated the disease. Irrigation turned out to have little effect on the incidence of the disease, while dew formation on the foliage caused an explosive epidemic with the set of data used.

The trial with a simulator demonstrated that a lifetime of experiments in weather modification with regard to plant disease can be carried out in a matter of hours. Waggoner *et al.* (1972) also created a simulation of southern corn leaf blight. However, there is a compelling need for more computer simulator models for the important diseases and pests that cause epidemics or plagues of economic significance. Models like SIRATAC (Hearn and Brook, 1983; Ives *et al.*, 1984) and BLITECAST (Krause *et al.,* 1975) and the EPIPRE system (Djurle and Jonsson, 1985) are good prototypes.

9.4 Scales on which to consider aerobiological problems

Scientists must determine the temporal and spatial scales that are relevant to their specific aerobiological problems. For example, Gage *et al.* (1999) discussed issues of ecological scaling that are important for vegetative development and aerobiological processes over the landscape. Intra- and inter-annual patterns of plant development form the foundation for atmospheric transport of pollen, spores, and other organisms associated with plant health. Meteorological scaling appropriate for particular aerobiological systems was summarized by Westbrook and Isard (1999). However, aerobiological dispersal remains incompletely incorporated into integrated pest management systems (Jeger, 1999).

9.4.1 Microscale transport

A systems approach which integrated biological, chemical, and cultural practices involved with the ecosystem containing the host, crop, pest and disease is suited to this type of transport. Getz and Gutierrez (1982) have reviewed pest modeling approaches on this scale and classified them into simulation and analytical and operations-research approaches. Angus (1988*b*) pointed out that there may be no significant meteorological component where pest dynamics are dependent on specific field conditions, e.g. rice paddies. However, an example of a pest management system that does employ weather is the SIRATAC system (Hearn and Brook, 1983; Ives *et al.*, 1984) which is applicable to the control of the tobacco cluster grub; this pest almost wiped out the irrigated cotton growing industry in the warm temperate regions of Australia.

Examples where aerobiology is useful on this scale can be found. A human disease and allergy group (Edmonds and Benninghoff, 1973) investigated the dispersion of algae cells downwind from an eutrophied lake. The concentration of the algae in the lake was a function of nutrients, temperature and light, following work by Blanchard and Syzdek (1972). Taking the algal population as 2×10^3 cells ml^{-1} (Labine and Wilson, 1973), the rate of algal emission from the lake becomes 0.2267 algae cells sec^{-1} cm^{-2} of lake surface. The lake was 100 m x 100 m or 10^8 cm^2 and hence the emission rate $Q = 0.2267 \times 10^8$ algae cells sec^{-1}. Turner (1970) allowed for an area source to be treated as a point source by taking the initial standard deviation of the plume in the cross wind direction $S_yO = s/4.3$, where s is the dimension of one side of the square (100 m). Hence S_yO (the value at the virtual point source) = 100 m/4.3 = 23.3 m. From

Formattato: Destro 0.63 cm

Table 9.1 stability class B was selected for strong incoming radiation. Since S_yO = 23.3 m from Figure 9.2*a*, the virtual distance X_y back to the virtual point source was found to be 125 m. Thus, the algae concentration one meter above the surface at distances 200, 400, 600, 800 and 1000 m from the center of the lake at 100 m and 200 m from the plume centre line can be found.

Wind speed was taken as 10 m s^{-1} and the deposition velocity of algae as 0.01 m s^{-1}. Values for S_y were found using x + X_y in Figure 9.2*a* and S_z using x from Figure 9.2*b* which then provided the values in Table 9.2.

Table 9.2.Horizontal (S_y) and vertical (S_z) dispersion coefficients

x (m)	200	400	600	800	1000
S_Y (m)	55	88	115	145	180
S_Z (m)	20	40	70	90	125

These values were used in a Gaussian formula (Turner 1970) to obtain the predicted isopleths of algae concentration 1 m above the surface, downwind from the source, on a 1,000 m x 400 m grid. The results shown in Figure 9.3 are compatible with values measured by various investigators.

Another problem treated in a similar fashion was that of the airborne dispersal of gypsy moth larvae (*Porthetria dispar* L.) which cause severe leaf defoliation to shade and orchard trees in north-eastern USA. A dispersion pattern shown in Figure 9.4 was obtained for a source release height of 20 m and a sampling height at 1 m above the surface. Although concentrations are extremely small, the pattern was used to estimate potential defoliation. Using similar techniques, the concentration of spray from an aircraft or ground source can be assessed substituting appropriate values of stability and fall velocity of the drops. The solution for the gypsy moth could also be applied to the bacterial disease for pears and apples, i.e. fire blight.

9.4.2 Mesoscale transport

A framework for examining inter-regional transport of spores has been provided by Aylor (1986), which will be followed in section 9.5 because it is an example that spans the meso- and macro-scales. Aylor (1986) sought to gauge the effect on a hypothetical New England (USA) target tobacco crop from a 500 ha source infected with the downy mildew *P. tabacina* or blue mold disease of tobacco. The infected field was located 700 km south of the target area. For comparison, a small patch of abandoned tobacco plants diseased to the same level as the larger field but only at a 2 km distance from the target area was considered for infection capacity (Figure 9.5). Five stages were considered by Aylor (1986) in solving the problem, as described in section 9.5.

9.4.3 Macroscale transport

Commento [JKW2]: also monitored by tetroons, satellite imagery, and aircraft sampling

For very large- or global-scale transport at a high altitude, say 6 -12 km, where the wind flow tends toward simple meandering patterns, the wavelengths are of the order of continental scale and wind speeds may vary between 150 to over 200 km h^{-1}. Wind flows at these upper levels have been studied using the Global Horizontal Sounding Technique (GHOST) balloon program (Lally and Lichfield, 1969). Macroscale transport can be very important.

Super-pressure balloons are designed to rise to a selected isentropic level and remain at that level. One balloon at the 20 kPa isobaric level was tracked around the world for 102 d, while it made ten circumnavigations (Figure 9.6). An interesting fact about the average lifetime

Formattato: Destro 0.63 cm

of these balloons is that it is similar to that of small particles, in spite of the very large difference in size.

The lifetime at 50 kPa (about 5.48 km) is about seven to ten days, while at 10 kPa (16.76 km) the lifetime varies from one to one and a half months. Volcanic dust high injected into the atmosphere distributes around the globe in a manner similar to that of the super-pressure balloon. An extreme amount of volcanic dust, say five or six major eruptions per year for two or three years, would form a dust veil over the globe and screen global radiation to such an extent that significant cooling could occur.

9.5 Examples of aerobiological modeling – Spore transport

Isard et al. (2005) adopted the general aerobiological process model (Fig. 9.7) identified by Edmonds (1979) and conceived a specific aerobiological process model for soybean rust (*Phakopsora pachyrhizi*) (Fig. 9.8). Notable in the development of the aerobiological process model for soybean rust (Soybean Rust Aerobiology Prediction System [SRAPS]) was its incorporation using the Integrated Aerobiology Modeling System IAMS) (Fig. 9.9). The IAMS incorporates multidisciplinary data sources, biological and atmospheric models, and computer analysis to prepare pest management advisories for scientists and non-scientific users on continental and inter-continental scales. The SRAPS was used to predict deposition patterns of hypothetical cohorts of soybean rust spores released from South America and arriving in the southeastern USA. Subsequently, the SRAPS-predicted deposition patterns (Fig. 9.10) were found to represent the region of soybean infections when validated by polymerase chain reaction (PCR) tests of soybean plants in the southeastern USA. Isard et al. (2005) note that the IAMS can be used with other biological data sets to create a specific process model for other biota.

Following are the five aerobiological components used by Aylor (1986) in a spore transport model:

9.5.1 *Production (P) of spores*

Commento [JKW3]: also in microscale

For a given level of disease, the spore production, P, per ha of source is obtained from the product of: spores lesion^{-1} day^{-1} = 2 x 10^{4}; the lesions cm^{-2} of leaf area index = 2.8 and finally a conversion factor to ha of 10^{8}. For 500 ha, the total spore production is P = 6.44 x 10^{13} spores day^{-1}. Estimates such as these can be obtained from a direct survey or by a computer simulation of disease after Waggoner and Horsfall (1969) or Waggoner *et al.* (1972).

9.5.2 *Escape (E) of spores from the canopy*

Commento [JKW4]: also in microscale

The escape factor E depends considerably on the canopy architecture and the vertical distribution of spore release in the canopy. It also depends, to an important but lesser extent, on the exact functional form used to describe wind speed and eddy diffusivity in the canopy. Although the eddy diffusivity theory gives estimates that seem reasonable, it does not hold when gusts of wind penetrate from above to deep within a canopy where local sources cause the aerial spore concentration to vary rapidly with height.

There is a diurnal variation in the release of spores due partly to spore maturity and partly to diurnal variation in solar irradiance, wind speed, turbulence and relative humidity. The time of peak spore release is correlated well with the time that the ambient relative humidity falls below about 70% (Aylor and Taylor, 1983). The fraction (FRACT) of spores released at 10 a.m. is taken as 0.33, and FRACT at 3 p.m. is taken as 0.05 using local time. Hence the number of spores injected into the air at 10 a.m. = 6.44 x 10^{13} x 0.15 x 0.33 = 3.2 x 10^{12}, and the number of spores leaving the crop at 3 p.m. becomes $6.4 \times 10^{13} \times 0.15 \times 0.05 = 0.5 \times 10^{12}$. Here the escape factor E was taken as 0.15.

9.5.3 *Turbulent transport (T) and dilution*

The methodology of Aylor (1986) is meant to be used for calculating the probability of successful spore transfer and not necessarily to prove that a particular transport was responsible for starting an epidemic. A combination of the spore transport model with an air parcel trajectory between source and receptor was advocated to develop a climatology of disease spread. The extent of the vertical dispersion coefficient S_Z is limited by the mixing height, H, which in turn is often limited by a temperature inversion. Thereafter, concentration becomes approximately uniform with height and the subsequent spread is largely two-dimensional.

The dilution of spores in the air by wind shear, turbulent diffusion, ground deposition and loss of spore viability all increase with travel time between source and receptor. Both Turner (1970) and Heffter (1980) assume the equality of standard deviations S_x and S_Y; the dilution of a spore cloud that has grown until limited by the mixing height is proportional to $1/(S_Y^2H)$ and on the average $S_Y = 0.5t$ after Heffter (1965), where S_Y is in meters and travel time, t, in seconds.

A number of spores released instantaneously at a source should be come diluted in a volume of about HS_Y^2. Thus for H = 3,000 meters and time t = 30 hours the number of spores should be diluted by a factor of about 10^{13}. This dilution is comparable to spore production, P, hence spore survival becomes highly significant in determining the likelihood of success of long-distance transport. In the case of dry deposition, the number of spores remaining airborne is approximately one-tenth of the original number and hence dry deposition is insignificant compared to the dilution factor 10^{13}. Transport should be a function of time of day and, although not adopted in this example, could be described in an Eulerian frame after Eliassen (1980), which enables the treatment of change of mixing height more accurately than in the chosen Lagrangian frame of reference.

9.5.4 *Survival (S) of spores*

The UV component of solar radiation, which is the most lethal, along with temperature and relative humidity control survival of spores in the atmosphere. Most spores, which will be transported through the atmosphere and deposited within a few hundred kilometers of the source, remain with the mixed layer of the atmosphere (Clarke *et al.*, 1983) and generally reach altitudes of only 1 to 3 km. Although these spores do not normally encounter temperatures or relative humidities that can be lethal, the combination of temperature, relative humidity and UV radiation found at the top of the mixing layer can be fatal to such spores. The irradiance to which spores are exposed in the atmosphere may result in zero germination in a sample of 500 spores, yet there is still a 50 per cent probability that germination of spores drawn from the entire population can be as high as 1.385×10^3 (Fisher and Yates, 1948). Thus, if 10^5 spores were exposed to the same irradiation about 139 spores would probably be seen to germinate.

9.5.5 *Deposition (D) of spores onto plants*

Deposition mechanisms can be either dry or wet. Most wet deposition occurs as a result of washout by rain. The efficiency of raindrops to capture spores depends on the size of the spores and the raindrops, the rate and duration of rainfall, as well as the depth of precipitation and spore layers.

Formattato: Destro 0.63 cm

Wet and dry depositions are closer in number than has been suggested by their relative deposition rates because there are many more dry than wet hours. Spores delivered during rain will be more likely to initiate disease because leaves will be wet and infection can begin immediately. The uncertainty in estimating the rate of wet deposition is large and it is difficult to ascribe this mechanism a representative role (Smith, 1981). Calculations using this model have been carried out considering only dry deposition.

A solution of the problem of the total number of spores deposited during the total transport event is shown in Figure 9.5. The problem was solved for two wind speeds, 20 and 40 km h^{-1}, and for two sky conditions, sunny and overcast. The solution in Figure 9.5 shows the overwhelming importance of spore survival. The danger of infection from the small potentially unnoticed local source, plotted in Figure 9.5 as a solid bar at 700 km, 2 km away from the location of the target area, may be considerably more dangerous on a sunny day, or a comparable danger on a cloudy day, than the massive source 700 km away. Transport speed is very important during sunny weather as doubling the speed increased the number of spores deposited after traveling 700 km, by a factor of about 10^7. The time that the spore cloud leaves the source is important on clear days. Although fewer spores leave at 3 p.m. (dashed line and open square) compared to the 10 a.m. release (solid line and solid square), the 3 p.m. release spores are exposed to less sunlight and soon exceed the greater number of spores released at 10 a.m. which are exposed to greater hours of sunshine. At 700 km downwind there is a factor of about 10^{12} difference in the calculated spores deposited, depending on sky conditions and transport speed. The calculations in this model are subject to large uncertainties and are discussed in Aylor (1986). The methodology should provide pathologists with reasonable estimates of the likelihood of viable spores from distant sources reaching susceptible crops by aerial spore transport.

Aylor (1986) expressed the various uncertainties in his model in Table 9.3.

Table 9.3
Uncertainties in estimates of transport factors

Process	*Factor*
P	100-1000?
Simulation	
Survey	
T	2-5
Mixed layer (ML)	10-20
Escape from ML	?
S	
> 1%	2-5
< 0.1%	?
Dry deposition velocity	2-5
Wet deposition velocity	?

Synoptic models can be associated with specific trajectories. Investigation of the potential carriage of small particles, such as spores, from the Australian Continent to Macquarie Island, about 1,500 km south of Australia, was carried out by Pierrehumbert *et al.* (1984) by investigating 85 kPa temperatures and selecting abnormally high values which were up to three standard deviations above the average. The high temperatures were ascribed to advection of continental air to Macquarie Island, rather than vertical advection due to subsidence. Trajectories were then drawn for occasions when 85 kPa temperatures were two and three standard deviations above the mean. These trajectories were drawn from Macquarie Island and

Formattato: Destro 0.63 cm

invariably arrived back to the Australian Continent. A synoptic model was deduced which required the rear edge of an anti-cyclone to remain quasi-stationary over the area for several days. Such a model must assume the availability of particulate matter to be transported beneath a subsidence inversion and can only establish a possible means of transport.

9.6 Air pollution

Although not strictly aerobiological quantities, gaseous and particulate pollutants can be spread from source regions through the atmosphere to impact regions of sensitive biota including airborne spores. Major atmospheric pollutants include ozone, nitric oxides, volatile organic compounds, and sulfur dioxide, mostly generated by the burning of fossil fuels. Ozone is formed by the reaction of nitric oxides (NOx) and volatile organic compounds (VOCs) in the presence of heat and sunlight. Ozone disrupts plant physiological processes leading to poor plant health, susceptibility to disease, pest, and environmental stresses, and reduced yields. Sulfur dioxide combines with atmospheric water vapor to create sulfuric acid which then precipitates as acid rain that can acidify rivers and lakes, and damage crops, trees and other plants. Government environmental protection agencies establish and enforce allowable limits for air pollutants to prevent health hazards such as eye irritation, asthma, and other ailments.

9.7 Special considerations for flying organisms

Inanimate airborne objects were the predominant topic of discussion in preceding sections because similar physical processes can be applied. However, the impact of organismal flight is also important to agricultural production systems. Such organisms include numerous species of insects, birds, and bats. Aerobiological transport models presented in section 9.5 can be readily modified for use with flying organisms.

The flight ability of pest insects allows them to evade natural enemies and seek new habitats in search of mates, nutrition, and oviposition sites. Knowledge of insect biology is essential to the development of aeriobiological process models and agricultural management strategies. For example, one should know when to expect insects to attain the adult stage capable of flight, and under what atmospheric and other environmental conditions they are likely to do so. Web-based models are available to calculate pest development based on degree-day accumulations (e.g., http://www.ipm.ucdavis.edu/general/tools.html). Biophysical factors, including vertical distribution of airborne insects, flight speed, flight heading, and flight lateral spacing between organisms, and flight duration, must also be considered when investigating movement of pest insects. Empirical data is often difficult and expensive to acquire, and agricultural meteorologists may need to apply aerobiological factors among similar organisms (e.g., moths from caterpillar pests). For example, Wolf et al. (1990) tracked a broad dispersing cloud of insects for a distance of 400 km using aircraft-mounted radar, and determined dispersal characteristics which can be applied to other biota flying in the nocturnal boundary layer.

It is important to stress that beneficial organisms also disperse in the atmosphere. Insect parasites and predators have been captured in aerial nets, revealing that these natural enemies also disperse but generally not as fast as moderate- or fast-flying pest insects. For the agriculturist, natural predators are commonly considered to be other insect species. However, birds and bats also consume large quantities of insects. Migratory species of predators coincidentally appear to migrate along the same aerobiological pathways used by crop pest insects (Westbrook et al., 1995). For example, large populations of Brazilian free-tailed bats migrate from Mexico into central Texas and are known to consume a diverse diet of insects including major migratory insect pests of corn, cotton, and vegetable crops (McCracken and Westbrook, 2002).

Formattato: Destro 0.63 cm

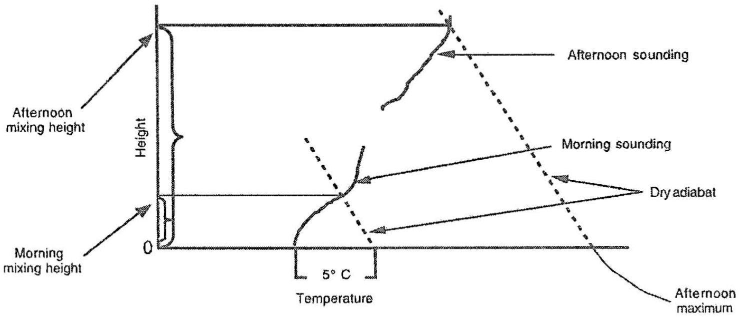

Figure 9.1 – Determination of mixing height from soundings (*after Edmonds and Benninghoff, 1973*)

Formattato: Destro 0.63 cm

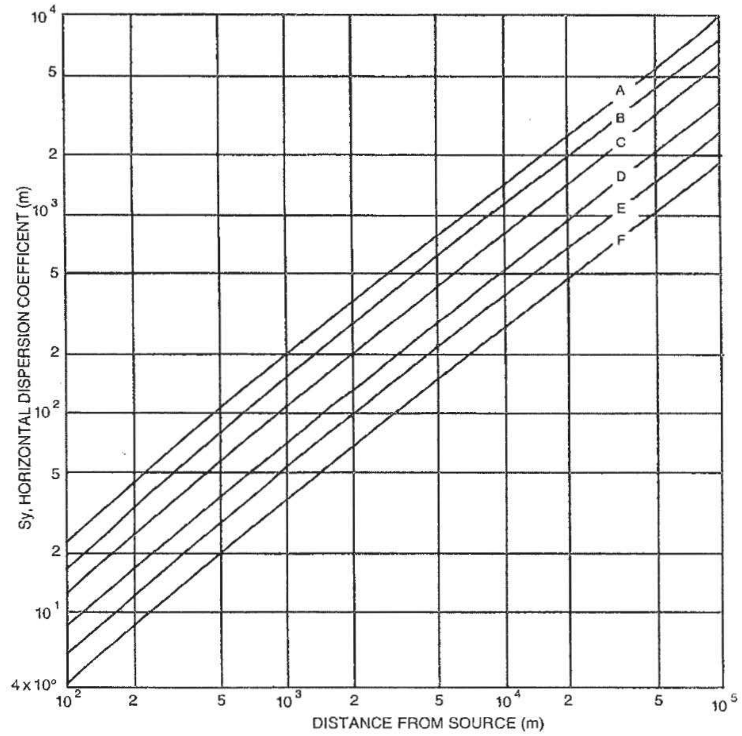

Figure 9.2*a* – Lateral dispersion vs. downwind distance from point source. A – Extremely unstable; B – Moderately unstable; C – Slightly unstable; D – Neutral; E – Slightly stable; F – Moderately stable (*after Slade 1968*)

Formattato: Destro 0.63 cm

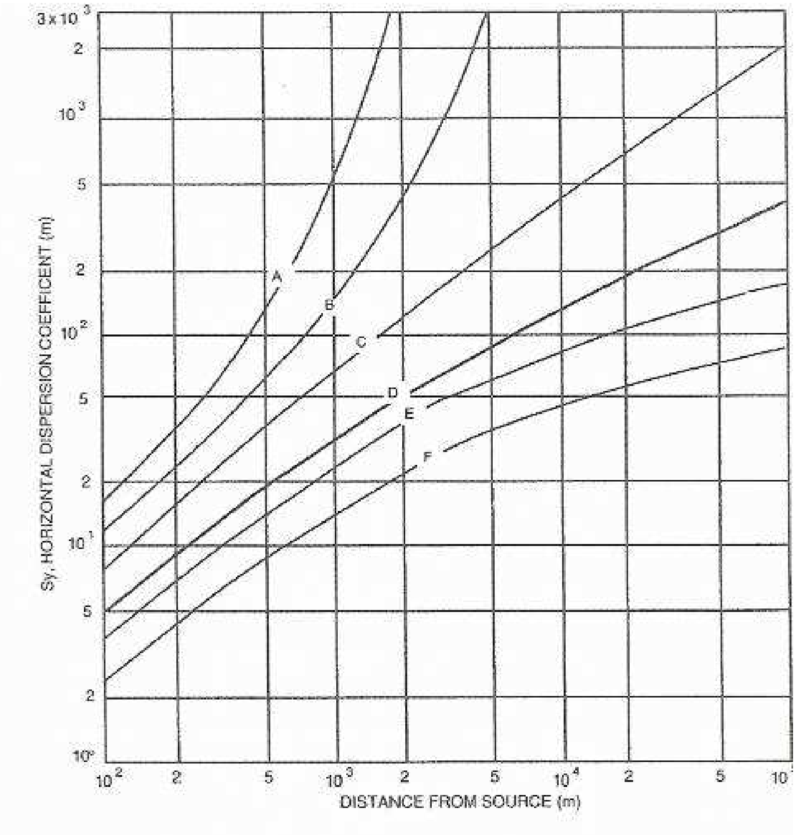

Figure 9.2*b* – Vertical dispersion vs. downwind distance from point source. A – Extremely unstable; B – Moderately unstable; C – Slightly unstable; D – Neutral; E – Slightly stable; F – Moderately stable (*after Slade, 1968*)

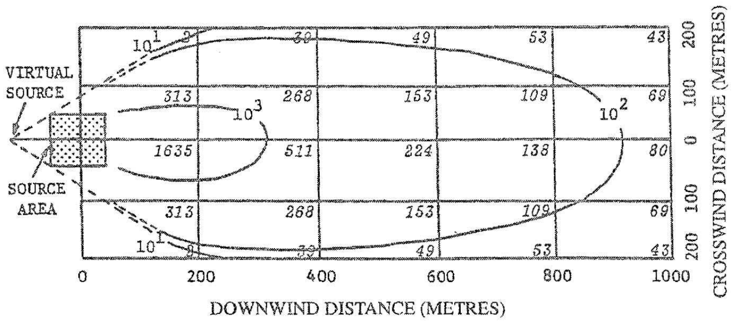

Figure 9.3 – Predicted isopleths of algal concentration per cubic meter one meter above the surface downwind from a 100 m x 100 m lake on a day with strong incoming radiation and a wind speed of 4 m s^{-1} (*from Edmonds and Benninghoff, 1973*)

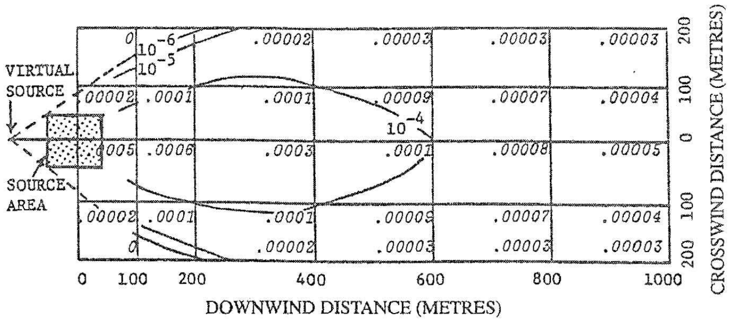

Figure 9.4 – Predicted isopleths of larval concentration per cubic meter one meter above the surface of a clearing downwind from a 100 m x 100 m source with the model variable values as follow:

Q = Source strength = 15.7 larvae s^{-1}
u = Wind speed = 4.0 m s^{-1}
v = Larval deposition velocity = 0.5 m s^{-1}
H = Source height = 20 m
z = Sample height = 1 m
Stability Class B, strong incoming radiation
(*from Edmonds and Benninghoff, 1973*)

Formattato: Destro 0.63 cm

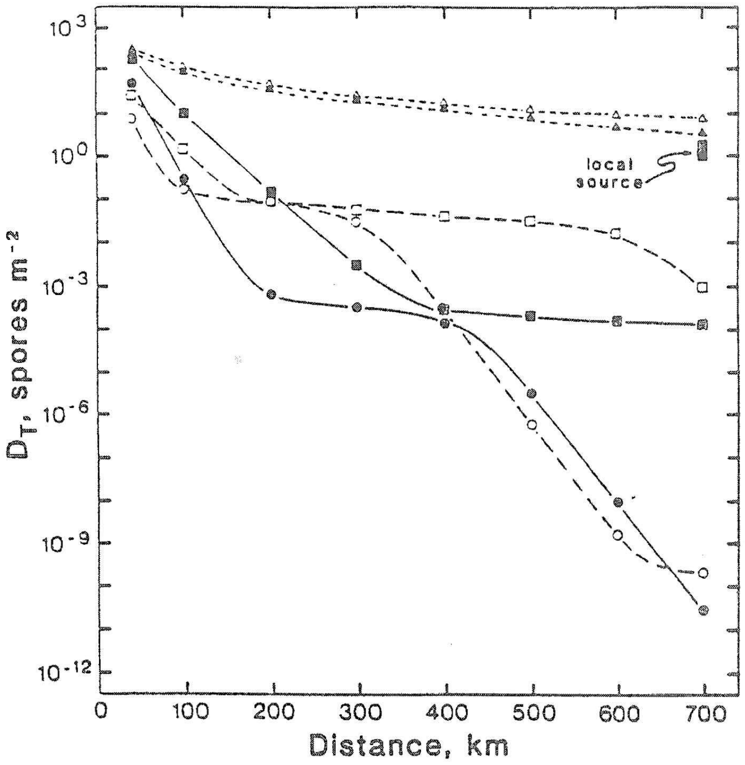

Figure 9.5 – Calculated transport of sporangia. Deposition, D_T (spores m^{-2}), of sporangia on the ground versus distance (km) from 500 ha of tobacco diseased with blue mold at severity X = 0.1. Also shown (solid bar at 700 km) is the D_T expected from spores released from 0.01 ha of similarly diseased tobacco located only 2 km away. The top two curves (triangles) are for spores leaving the source at 10 a.m. and traveling at speed U (solid triangles, 20 km h^{-1}; open triangles 40 km h^{-1}) during overcast conditions. The two solid lines marked by solid circles and solid squares are for spores leaving the source at 10 a.m. and traveling at U (circle, 20 km h^{-1}; square, 40 km h^{-1}) during clear sky conditions. The two dashed lines marked by open circles and open squares are for spores leaving the source at 3 p.m. and traveling at U (circle, 20 km h^{-1}; square, 40 km h^{-1}) during clear sky conditions. The number of spores, Q_0, injected into the air at the source is P x E x FRACT, which was set equal to 3.2 x 10^{12} for spores leaving at 10 a.m. and 0.5 x 10^{12} for spores leaving at 3 p.m. (*Aylor, 1986*)

Formattato: Destro 0.63 cm

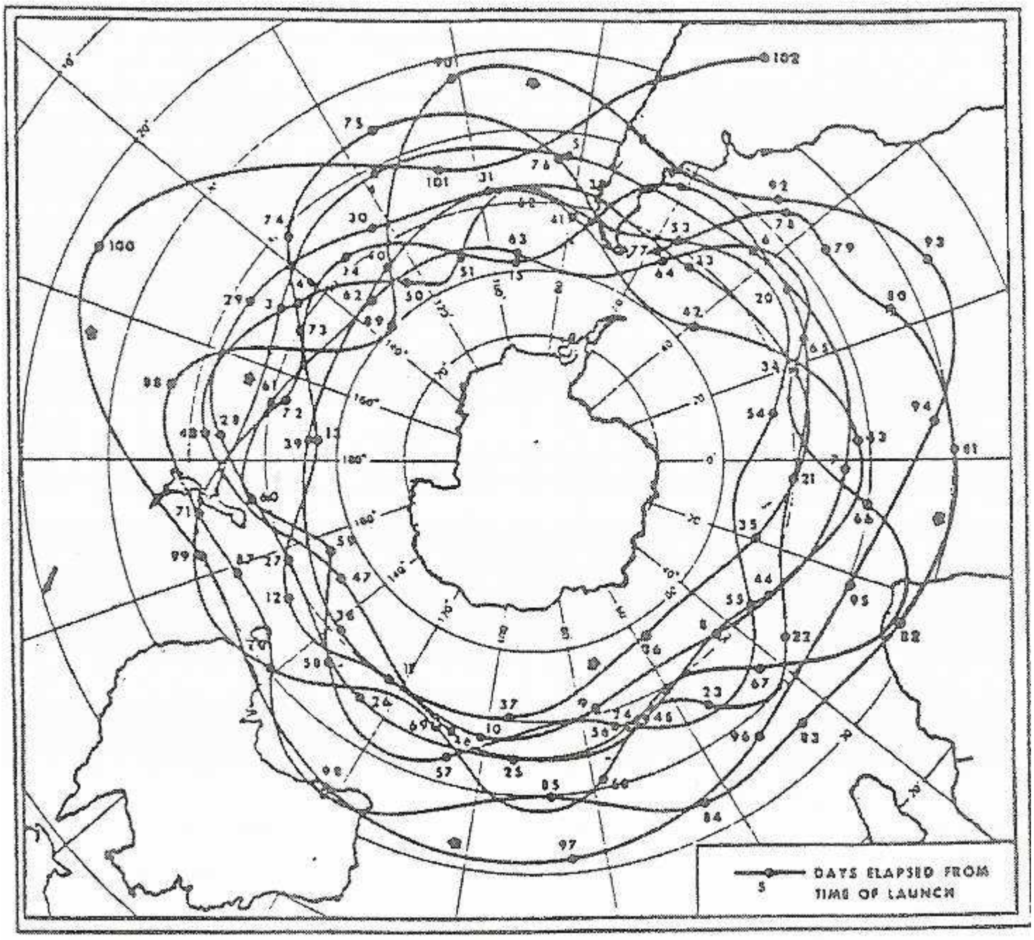

Figure 9.6 – Complete flight trajectory for Balloon No. 79R, launched from Christchurch, New Zealand. Flight level 20 kPa (*from Lally and Lichfield, 1969*)

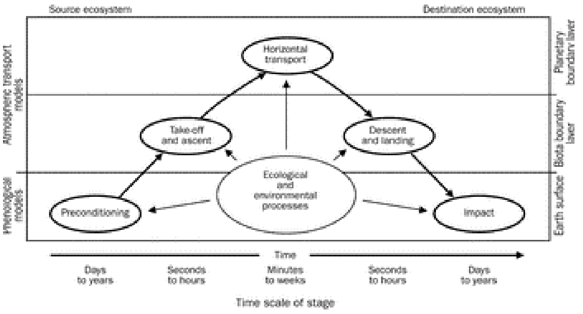

Fig. 9.7. General aerobiological process diagram (Isard et al. Principles of the atmospheric pathway for invasive species applied to soybean rust. 2005. Copyright, American Institute of Biological Sciences).

Formattato: Destro 0.63 cm

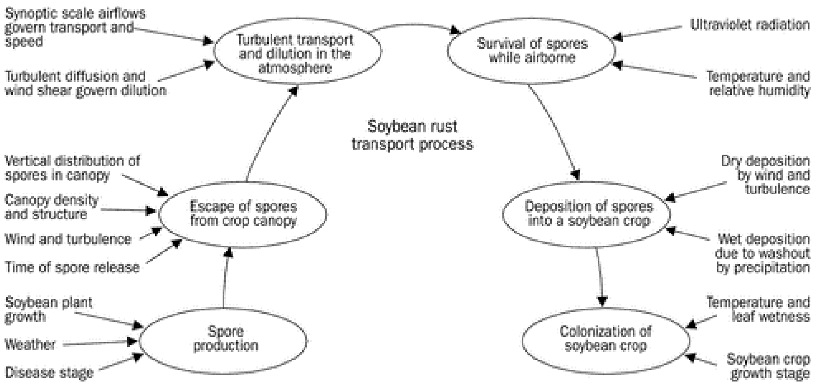

Fig. 9.8. Aerobiological process diagram for soybean rust (Isard et al. Principles of the atmospheric pathway for invasive species applied to soybean rust. 2005. Copyright, American Institute of Biological Sciences).

Formattato: Destro 0.63 cm

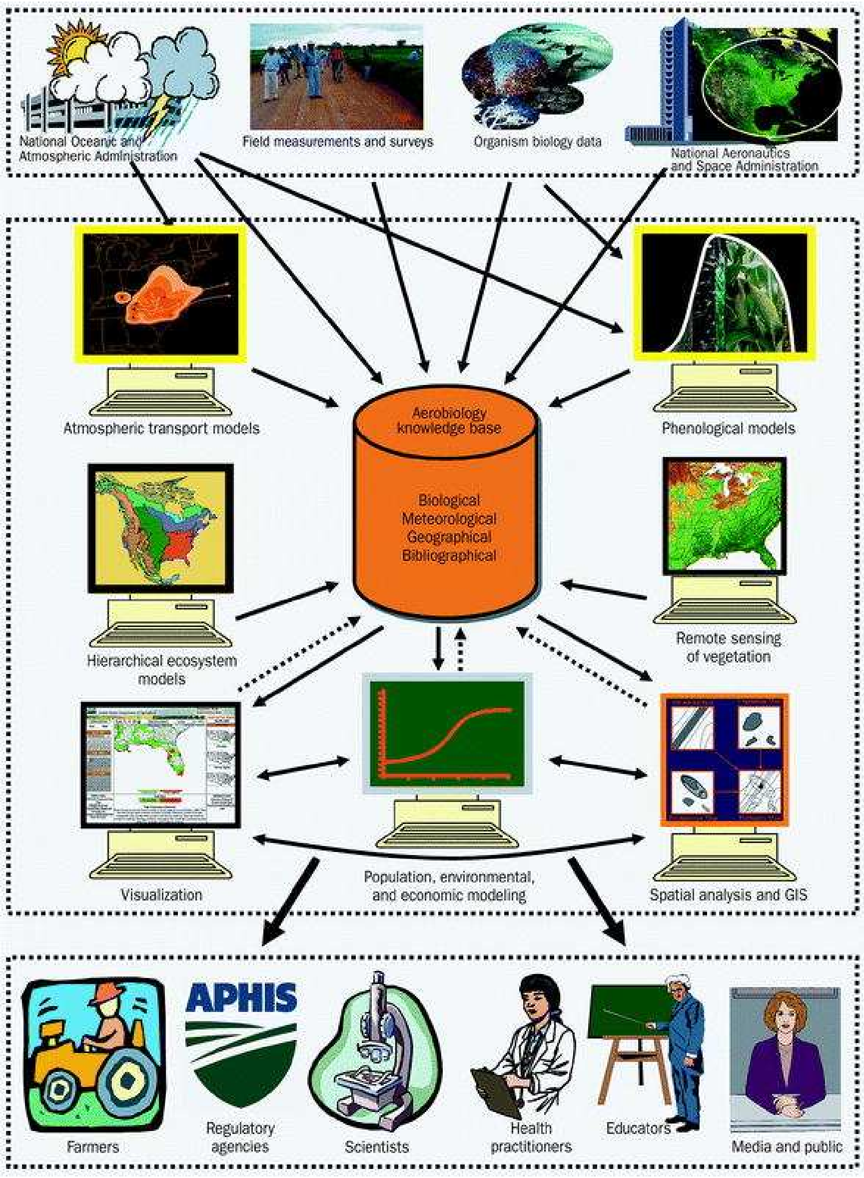

Fig. 9.9. Integrated Aerobiology Modeling System (IAMS) diagram (Isard et al. Principles of the atmospheric pathway for invasive species applied to soybean rust. 2005. Copyright, American Institute of Biological Sciences).

Formattato: Destro 0.63 cm

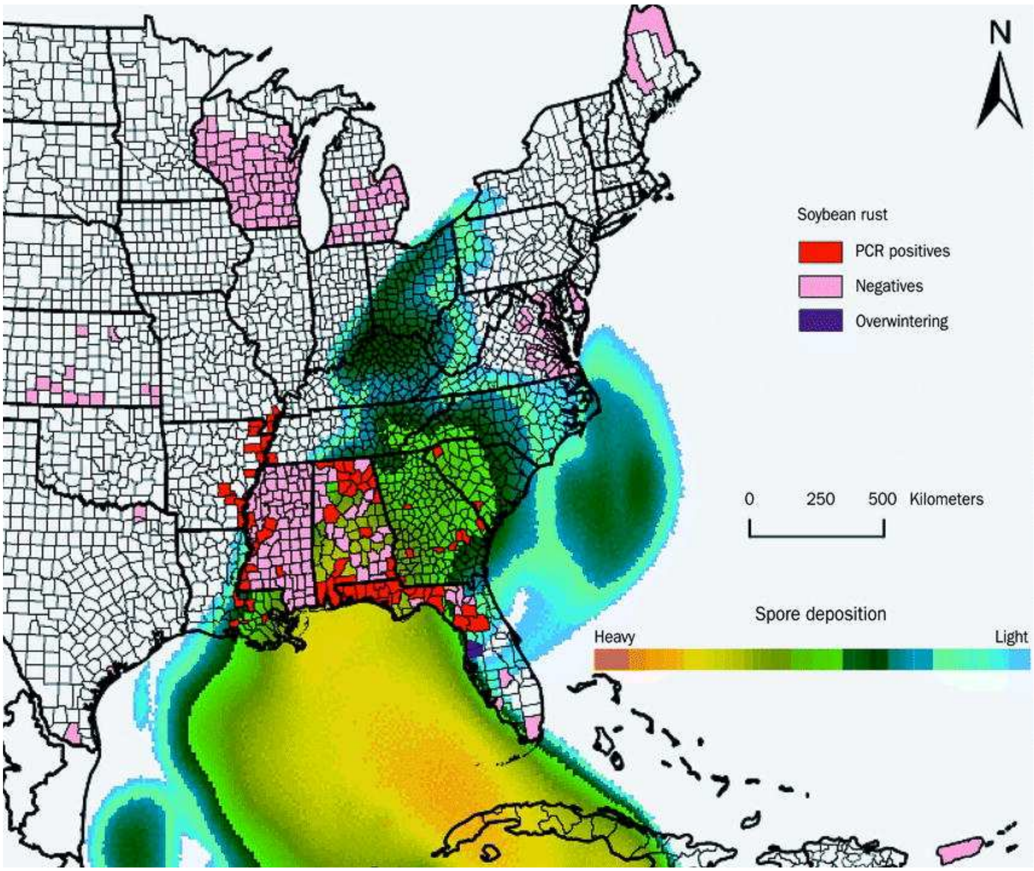

Fig. 9.10. Predicted deposition pattern for soybean rust aerobiology prediction system (SRAPS) simulation using hypothetical cohorts of spores released from the Rio Cauca source area on 7, 8, and 9 September 2004 (Isard et al. Principles of the atmospheric pathway for invasive species applied to soybean rust. 2005. Copyright, American Institute of Biological Sciences).

Formattato: Destro 0.63 cm

REFERENCES

Angus, J. F., 1988*a*: Modelling of disease epidemics. *Proceedings of Workshop on Agrometeorological Information for Planning and Operation in Agriculture with particular reference to Plant Protection*. Calcutta, India, pp. 307-312.

Angus, J. F., 1988*b*: Modelling of pest outbreaks. *Proceedings of Workshop on Agrometeorological Information for Planning and Operation in Agriculture with particular reference to Plant Protection*. Calcutta, India, pp. 313-318.

Aylor, D. E., 1986: A framework for examining inter-regional aerial transport fo fungal spores. *Agricultural and Forestry Meteorology*. 38, No. 4, pp. 263-288.

Aylor, D. E. and Taylor, G. S., 1983: Escape of *Peronospora tabacina* spores from a field of diseased tobacco plants. *Phytopathology*, 73, pp. 525-529.

Bashi, E. and Aylor, D. E., 1983: Survival of detached sporangia of *Peronospora destructor* and *Peronospora tabacina*. *Phytopathology*, 73, pp. 1135-1139.

Blanchard, D. C. and Syzdek, L. G., 1972: Concentration of bacteria in jet drops bursting from bubbles. *J. Geophysical Research*, 77, pp. 5087-5099.

Clarke, J. F., Clark, T. L., Ching, J. K. S., Haagenson, P. L., Husar, R. B. and Patterson, D. E., 1983: Assessment of model simulation of long-distance transport. *Atmos. Environ*., 17, pp. 2449-2462.

Djurle, A. and Jonsson, U., 1985: EPIPRE – a computerized pest and disease management system for winter wheat in Sweden. *Vaxtskyddsrapporter*, Jordbruk 32, pp. 179-189.

Edmonds, R.L. (ed.), 1979: Aerobiology: The Ecological Systems Approach. Dowden, Hutchinson and Ross. Straudsberg, PA.

Edmonds, R. L. and Benninghoff, W. S. (Eds.), 1973: Ecological systems approaches to aerobiology. III. Further model development. *Proc. of Workshop/Conf III US/IBP Aerobiology*. Program Handbook No 4, Univ. of Michigan, Ann Arbor, USA.

Eliassen, A., 1980: A review of long-range transport modeling. *J. Appl. Meteorol*., 19, pp. 231-240.

Fisher, R. A. and Yates, F., 1948: *Statistical Tables*. Hafner Publishing, N.Y.

Gage, S. H., Isard, S. A. and Colunga-G., M., 1999: Ecological scaling of aerobiological dispersal processes. *Agricultural and Forest Meteorology*, 97, 249-261.

Getz, W. M. and Gutierrez, A. P., 1982: A perspective on systems analysis in crop production and insect pest management. *Ann. Rev. Entomol*., 27, pp. 447-466.

Hearn, A. B. and Brook, K. D., 1983: SIRATAC – Case study in pest management in cotton. In: *New technology in field crop production* (Eds.: D. E. Blythe, M. A. Foale, V. E. Mungomery, E. S. Wallis), pp. 199-211.

Heffter, J. L., 1965: The variation of horizontal diffusion parameters with time for travel periods of one hour or longer. *J. Appl. Meteorol*., 4, pp. 153-156.

Heffter, J. L., 1980: *Air Resources Laboratories Atmospheric Transport and Dispersion Model (ARL-ATAD)*. NOAA Technical Memorandum ERL ARL-81, Air Resources Lab., Silver Springs, MD. U.S.A.

Isard, S. A. and Gage, S. H., 2001: Flow of Life in the Atmosphere: an Airscape Approach to Understanding Invasive Organisms. Michigan State University Press, East Lansing, Michigan, USA, 240 pp.

Isard, S. A., Gage, S. H., Comtois, P. and Russo, J. M., 2005: Principles of the atmospheric pathway for invasive species applied to soybean rust. *BioScience* 55, pp. 851-861.

Ives, P. M., Wilson, L. T., Gull, P. O., Palmer, W. A. and Haywood C., 1984: Field use of SIRATAC: an Australian computer-based pest management system for cotton. *Prot. Ecol.*, 6, pp. 1-21.

Formattato: Destro 0.63 cm

Jeger, M. J., 1999: Improved understanding of dispersal in crop pest and disease management: current status and future directions. *Agricultural and Forest Meteorology*, 97, 331-349.

Johnson, K. B., 1987: Role of predictive systems in disease management. In: *Crop Loss Assessment and Pest Management* (Ed.: P. S. Teng), American Phytopathological Society, St. Paul, Minnesota, U.S.A. pp. 176-190.

Krause, R. A., Massie, L. B. and Hyre, R. A., 1975: BLITECAST: a computerized forecast of late potato blight. *Plant Disease Reporter*, 59, pp. 95-98.

Labine, P. A. and Wilson, D. H., 1973: A teaching model of population interactions: an algae-Daphnia-predator system. *BioScience*, 23, pp. 162-167.

Lally, V. E. and Lichfield, E. W., 1969: Summary of status and plans for the GHOST balloon project. *Bull. Amer. Meteorol. Soc.*, 50, pp. 867-874.

Maddison, A. C. and Manners, J. G., 1973: Lethal effects of artificial ultraviolet radiation on cereal rust uredospores. *Trans. Br. Mycol. Soc.*, 60, pp. 471-494.

Mills, W. D. and Laplante, A. A., 1951: *Diseases and insects in the orchard*. NY Agric. Exp. Stn. Ext. Bull. 53, pp. 423-435.

McCracken, G.F. and Westbrook, J.K., 2002: Bat patrol. National Geographic, 201, pp. 114-123.

Moutou, F. and Durand, B., 1994: Modelling the spread of foot-and-mouth disease virus. *Veterinary Research*, 25, 279-285.

Pasquill, F., 1961: The estimation of the dispersion of windborne material. *Meteorological Magazine*, No. 1063, 90, pp. 33-49.

Pasquill, F., 1962: *Atmospheric Diffusion*. D. van Nostrand Co. Ltd., London, 297 pp.

Pedgley, D. E., 1982: *Windborne Pests and Diseases: Meteorology of Airborne Organisms*. Ellis Horwood Ltd., West Sussex, England, 250 pp.

Pierrehumbert, C., Powell, F. A. and Oliver, S., 1984: Continental transport of particulate matter between Australia and Macquarie Island. *Eighth International Clean Air Conf*. (Melb. Aust.) Vol. 2, pp. 741-750. Clean Air Society of Australia and New Zealand.

Roberts, J. J., Croke, E. J. and Kennedy, A. A., 1972: An urban atmospheric diffusion model. *Proc. Symp. Multiple-source urban diffusion models*. Chapter 6. U.S. Environ. Prot. Agency, Research Triangle Park, N.C., U.S.A.

Rotem, J., Wooding, B. and Aylor, D. E., 1985: The role of solar radiation, especially ultraviolet, in the mortality of fungal spores. *Phytopathology*, 75, pp. 510-514.

Rowell, J. B. and Romig, R. W., 1966: Detection of uredospores of wheat rusts in spring rains. *Phytopathology*, 56, pp. 807-811.

Slade, D. H. (Ed.), 1968: *Meteorology and Atomic Energy*. U.S. Atomic Energy Commission. Div. Tech. Info. TID-24190, 445 pp.

Smith, F. B., 1981: Probability prediction of the wet deposition of airborne pollution. In: *Air Pollution Monitoring and Its Application* (Ed.: C. De Wispelaere). Plenum Press, N.Y. and London, pp. 67-98.

Sutton, O. G., 1953: *Micrometeorology*. McGraw-Hill, New York, London, Toronto, 333 pp.

Tromp, S. W., 1980: *Biometeorology*. Heyden, London, 346 pp.

Turner, D. B., 1967: *Workbook of Atmospheric Dispersion Estimates*. Public Health Service Publication No. 999-AP-26. U.S. Dept. of Health, Education and Welfare, 84 pp.

Turner, D. B., 1970: *Workbook of Atmospheric Dispersion Estimates*. EPA Office of Air Program, Research Triangle Park, N.C., U.S.A. 84 pp.

Waggoner, P. E. and Horsfall, J. G., 1969: *EPIDEM: a simulator of plant disease written for a computer*. Bull. Conn. Agric. Exp. Sta., New Haven, No. 698.

Waggoner, P. E., Horsfall, J. G. and Lukens, R. J., 1972: *EPIMAY: A simulation of southern corn leaf blight*. Bull. Conn. Agric. Exp. Sta. New Haven, No. 729.

Formattato: Francese (Francia)

Formattato: Destro 0.63 cm

Westbrook, J.K., Eyster, R.S., Wolf, W.W., Lingren, P.D., and Raulston, J.R., 1995: Migration pathways of corn earworm (Lepidoptera: Noctuidae) indicated by tetroon trajectories. *Agric. Forest Meteorol*., 73, 67-87.

Westbrook, J.K. and Eyster, R.S., 2003: Nocturnal migrations of cotton insect pests indicated by Doppler radar observations. Proc. Beltwide Cotton Conf. pp. 997-1003

Westbrook, J. K. and Isard, S. A., 1999: Atmospheric scale of motion for dispersing biota. *Agricultural and Forest Meteorology*, 97, 263-274.

Wolf, W.W., Westbrook, J.K., Raulston, J., Pair, S.D. and Hobbs, S.E., 1990: Recent airborne radar observations of migrant pests in the United States. *Phil. Trans. Roy. Soc. Lond*., B 328, 619-630.