CHAPTER 15

AEROBIOLOGY

15.1 INTRODUCTION

This chapter deals with practical aspects of aerobiology relating to agricultural meteorology and presents an interdisciplinary approach to the properties and airborne movement of biota that are significant to plants, animals, pests and diseases. Owing to the recent expansion of Internet access to weather, climate, pest, plant and animal data, models and management guidelines, it was considered that updating specific parts of this chapter on aerobiology would be of benefit to readers and meteorological services users.

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 encompasses 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. Finally, this discipline deals with agriculturally significant insects such as locusts, bush flies and moths.

Any movement of biota, particles or gases through the atmosphere that may have an adverse effect on vegetation or animal life must concern the agricultural meteorologist. Particles less than 0.1 µm in size, which include viruses, are in permanent suspension in the atmosphere and are subject to Brownian movements. The most important disease organisms that affect agriculture vary in size from 0.1 to 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 that may cause allergic reactions, thus allowing for the timely use of preventive medications.

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

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 and 300 degree-wetness hours correspond approximately to light, moderate and heavy infections of apple or pear scab for optimum temperatures ranging from 18°C to 24°C. 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 bush flies. The interdisciplinary approach to aerobiology incorporates the sampling routines and instrumental observations of entomologists, plant pathologists and other biologists, together with real-time weather or climatic data of meteorologists, for use in models specifically designed to simulate certain disease infections or insect infestations. In addition, the aerobiological techniques may include monitoring and modelling of airborne movement of beneficial biota and their impact on pest populations.

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

15.2 TYPES OF SERVICE TO BE PROVIDED TO USERS

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

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

Once an interdisciplinary body is established, its ultimate challenge is to provide the right information to the right farm, nursery, forest, and so on, 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 feed the data collected 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) A serious pest or disease problem must exist for which low-cost solutions, such as host resistance, are unavailable and unreliable;
(b) It should be possible to explain efficiently and predict accurately the variations in the incidence of problems by means of a model;
(c) Facilities must exist for communication of model predictions so that timely control measures can be taken;
(d) Control measures must be available that are effective, economically justified and non-hazardous to the environment.

A study of the modelling of disease epidemics (WMO, 1989*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 of these methods is 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, while the BLITECAST model (Krause et al., 1975) provides a model for early disease control. Models used for aerobiological investigation could profit from adoption of the principles outlined by Johnson (1987).

15.3 DATA AND MODELS AVAILABLE FOR USE BY AEROBIOLOGISTS

Climatic data are 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 on the Internet (for instance, from http://lwf.ncdc.noaa.gov/oa/ncdc.html). Increasingly, weather data are being generated by parameterization of remotely sensed data (for example, 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 locations 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 of 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 15.1.

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.

Temperature is a vitally important element for agriculture. Degree-day indices can be used to indicate critical phases for pests and diseases, thus 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 favoured by faint light; *Phytophthora* sporulates germinate overnight with favourable 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 reaches 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).

15.3.1 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 airflow, 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 are useful in the analysis of charts and the establishment of trajectories. Cloud-top temperatures have been well correlated with rainfall probability. Satellite-derived vegetation indices (such as the normalized difference vegetation index (NDVI)) can be used to locate host vegetation for pests and diseases, thus enabling the application of preventive actions (for example, 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.

Table 15.1. 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		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

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

15.3.2 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 analysed to establish a mixing level. The dry adiabatic lapse rate (–9.8°C 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°C is often added to the morning temperature to allow for the heat island effect (Figure 15.1). The product of the mixing height and the mean wind speed is a measure of the ventilation rate.

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, such as 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 shown in Figures 15.2 and 15.3 The atmospheric stability indicators after Pasquill (1961) are shown in Table 15.1. 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 the following:
(a) There is continuous or instantaneous emission from a source.
(b) There is an absence of rain (washout).
(c) Theory is constrained to a flat, featureless terrain (grasslands) because the dispersion coefficients in Figures 15.2 and 15.3 were measured under such conditions.
(d) Once an atmospheric stability class is selected (from Table 15.1) it must remain fixed, in other words, there is no allowance for a change in turbulent structure.
(e) Once selected, the mean wind velocity cannot change and thereafter remains constant with height.
(f) 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 in which those limitations have been overcome to some extent is the Roberts model (Roberts et al., 1972), where a trajectory-diffusive model replaces a purely diffusive model.

The Web-based Real-time Environmental Applications and Display sYstem (READY) allows users to access meteorological data and run atmospheric trajectory and dispersion models (http://www.arl.noaa.gov/ready.php). READY can be used to model the transport of any airborne

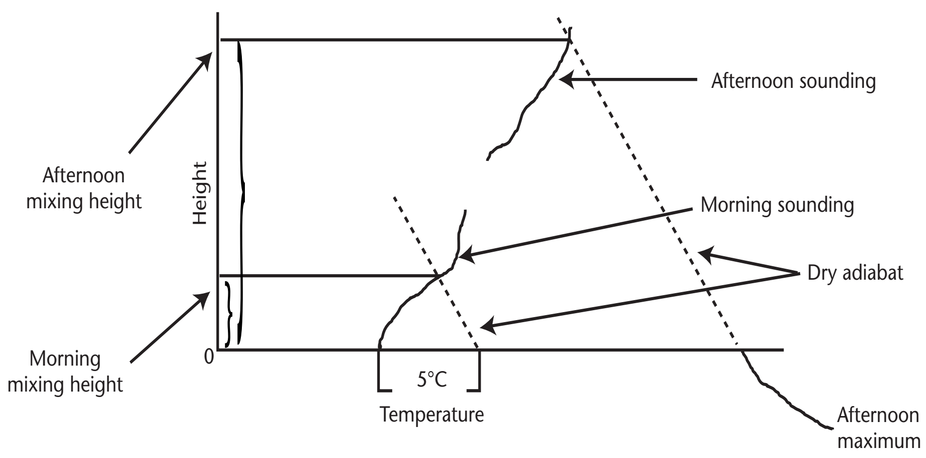

Figure 15.1. Determination of mixing height from soundings (after Edmonds and Benninghoff, 1973)

material, including spores, insects and air pollutants. READY allows users to access archived meteorological data and run the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model to generate customized georeferenced maps of atmospheric trajectories and dispersion concentrations. Use of READY or similar systems that integrate database access and modelling software will advance the capabilities of aerobiologists by drastically reducing the data-processing burden and by providing efficient and accurate analytical results.

15.3.3 Additional data required

Sampling data collected by entomologists involve 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 analysed and contribute to the essential aerobiological database.

Information provided by plant pathologists results from field observations of lesions and infection levels 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 the weather, one element at a time, was investigated and documented. Eventually, a computer model or simulation was created that incorporated the complete system of host, pathogen and environment. Five years of climatic data were used to parallel the behaviour 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 a

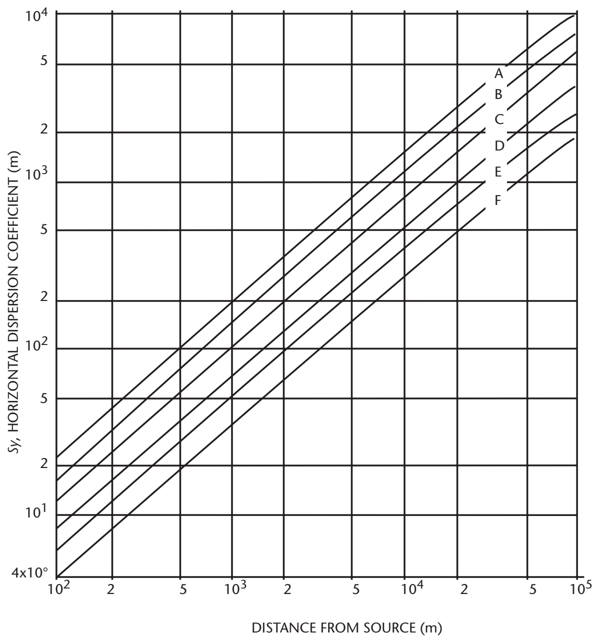

Figure 15.2. Lateral dispersion vs. downwind distance from point source. A = extremely unstable; B = moderately unstable; C = slightly unstable; D = neutral; E = slightly stable; F = moderately stable (after Slade, 1968)

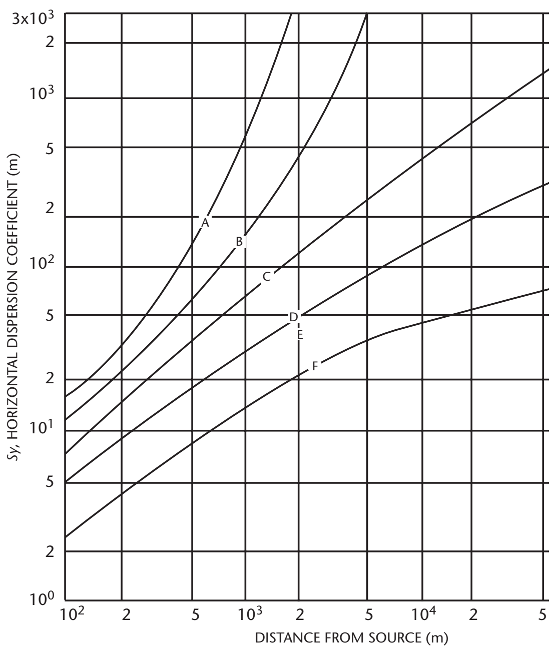

Figure 15.3. Vertical dispersion vs. downwind distance from point source. A = extremely unstable; B = moderately unstable; C = slightly unstable; D = neutral; E = slightly stable; F = moderately stable (after Slade, 1968)

view to investigating plant disease can be carried out in a matter of hours. Waggoner et al. (1972) also created a simulation of Southern corn leaf blight. There is a compelling need for more computer simulator models for the important diseases and pests that cause epidemics or plagues of economic significance, however. 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.

15.4 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 interannual 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). Aerobiological dispersal remains incompletely incorporated into integrated pest management systems, however (Jeger, 1999).

15.4.1 Microscale transport

A systems approach that integrates 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-modelling approaches on this scale and classified them by simulation, analytical and operations-research approaches. A study of the modelling of pest outbreaks (WMO, 1989*b*) pointed out that there may be no significant meteorological component when pest dynamics are dependent on specific field conditions, for example, rice paddies. An example of a pest management system that does employ weather, however, 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 in which 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 a eutrophied lake. The concentration of 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 dimensions of the lake were 100 m × 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 Table 15.1, stability class B was selected for strong incoming radiation. Since S_yO = 23.3 m, from Figure 15.2 the virtual distance X_y back to the virtual point source was found to be 125 m. Thus, the algae concentration can be determined 1 m above the surface at distances of 200, 400, 600, 800 and 1 000 m from the centre of the lake at 100 m and 200 m from the plume centre line.

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 15.2, and values for S_z were derived from x in Figure 15.3, which then provided the values in Table 15.2.

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 × 400 m grid. The results shown in Figure 15.4 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 the north-eastern United States. A dispersion pattern shown in Figure 15.5 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 by substituting appropriate values

Table 15.2. Horizontal (S_y) and vertical (S_z) dispersion coefficients

x (m)	200	400	600	800	1 000
S_Y (m)	55	88	115	145	180
S_Z (m)	20	40	70	90	125

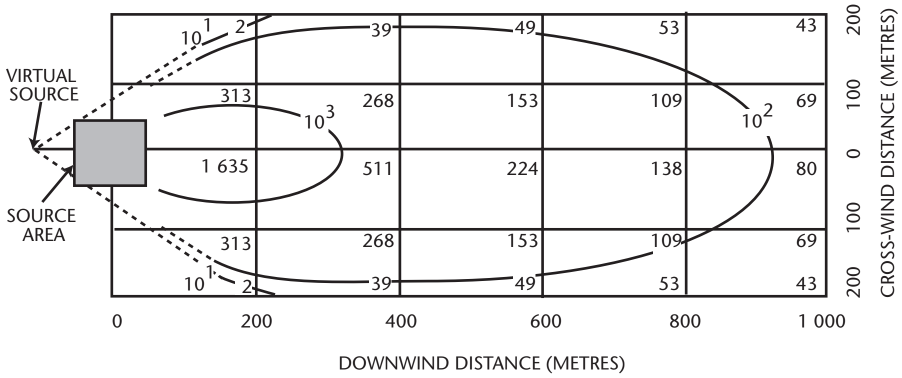

Figure 15.4. Predicted isopleths of algal concentration per cubic metre 1 m above the surface downwind from a 100 m × 100 m lake on a day with strong incoming radiation and a wind speed of 4 m s^{-1} (from Edmonds and Benninghoff, 1973)

of stability and fall velocity of the drops. The solution for the gypsy moth could also be applied to fire blight, a bacterial disease affecting pears and apples.

15.4.2 Mesoscale transport

A framework for examining interregional transport of spores has been provided by Aylor (1986), and it will be followed in 15.5 below because it is an example that spans the meso- and macroscales. Aylor (1986) sought to gauge the effect on a hypothetical New England (United States) target tobacco crop from a 500 ha source infected with the downy mildew *P. tabacina*, or blue mould 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 at only a 2 km distance from the target area, was considered for infection capacity (Figure 15.6). Aylor (1986) considered five stages in solving the problem, as described in 15.5.

15.4.3 Macroscale transport

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 from 150 km h^{-1} to over 200 km h^{-1}. Wind flows at these upper levels have been studied using the Global Horizontal Sounding Technique (GHOST) balloon programme (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 15.7). An interesting fact

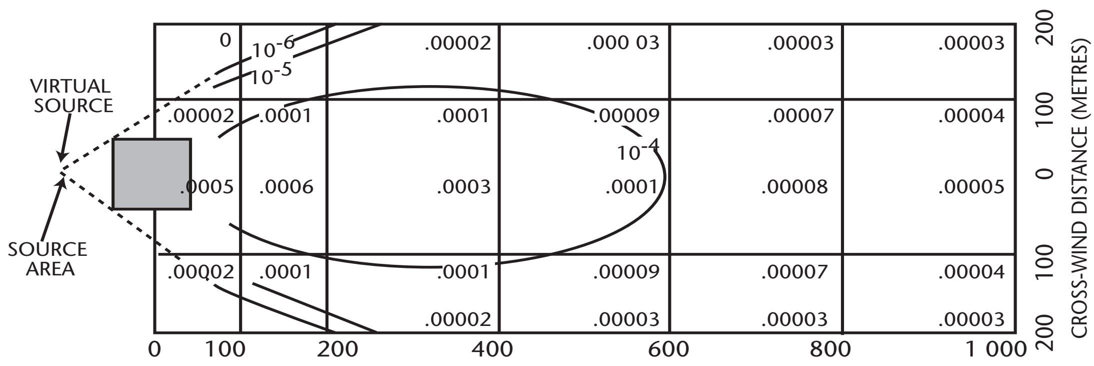

Figure 15.5. Predicted isopleths of larval concentration per cubic metre 1 m above the surface of a clearing downwind from a 100 m × 100 m source with the model variable values as follows: *Q* = source strength = 15.7 larvae s^{-1}; *u* = wind speed = 4.0 m s^{-1}; *v* = larval deposition velocity = 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)

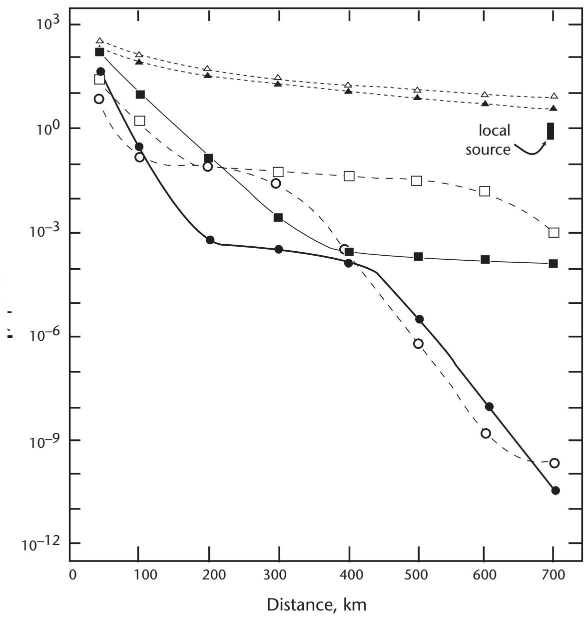

Figure 15.6. Calculated transport of sporangia. Deposition, D_T (spores m^{-2}), of sporangia on the ground versus distance (km) from 500 ha of tobacco diseased with blue mould at severity X = 0.1. Also shown (solid bar at 700 km) is the D_T expected from spores released from 0.01 ha of similarly diseased tobacco located only 2 km away. The top two curves (triangles) are for spores leaving the source at 10 a.m. and travelling 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 travelling 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 travelling 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 $P \times E \times$ FRACT, which was set equal to 3.2 × 1 012 for spores leaving at 10 a.m. and 0.5 × 1 012 for spores leaving at 3 p.m. (Aylor, 1986).

about the average lifetime 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 7 to 10 days, while at 10 kPa (16.76 km) the lifetime varies from 1 to 1.5 months. Volcanic dust injected high 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.

15.5 EXAMPLES OF AEROBIOLOGICAL MODELLING – SPORE TRANSPORT

Isard et al. (2005) adopted the general aerobiological process model (Figure 15.8) identified by Edmonds (1979) and conceived a specific aerobiological process model for soybean rust (*Phakopsora pachyrhizi*) (Figure 15.9). The Soybean Rust Aerobiology Prediction System (SRAPS), an aerobiological process model for soybean rust, was developed using the Integrated Aerobiology Modeling System (IAMS) (Figure 15.10). The IAMS model 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 intercontinental scales. SRAPS was used to predict deposition patterns of hypothetical cohorts of soybean rust spores released from South America and arriving in the south-eastern United States. Subsequently, the SRAPS-predicted deposition patterns (Figure 15.11) were found to represent the region of soybean infections when validated by polymerase chain reaction (PCR) tests of soybean plants in the south-eastern United States. Isard et al. (2005) note that IAMS can be used with other biological data sets to create a specific process model for other biota. The five aerobiological components used by Aylor (1986) in a spore transport model are described below.

15.5.1 Production (*P*) of spores

For a given level of disease, the spore production, *P*, per ha of source is obtained from the product of:

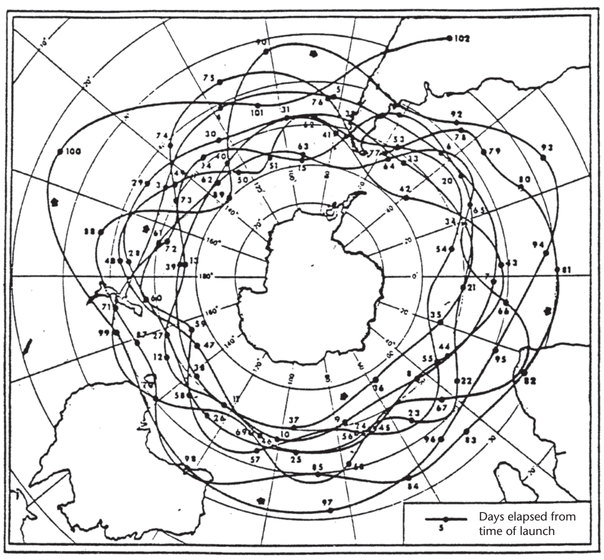

Figure 15.7. Complete flight trajectory for Balloon No. 79R, launched from Christchurch, New Zealand. Flight level 20 kPa (from Lally and Lichfield, 1969).

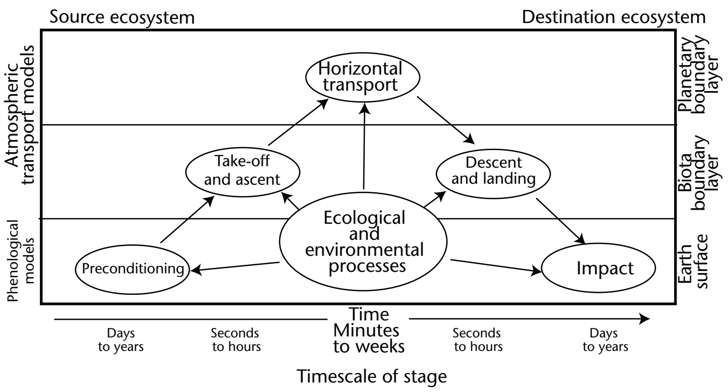

Figure 15.8. General aerobiological process diagram (Isard et al., 2005). Copyright: American Institute of Biological Sciences.

spores $lesion^{-1}$ day^{-1} = 2 × 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 $P = 6.44 \times 10^{13}$ 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).

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

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 per cent (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. = $6.44 \times 10^{13} \times 0.15 \times 0.33 = 3.2 \times 10^{12}$, 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.

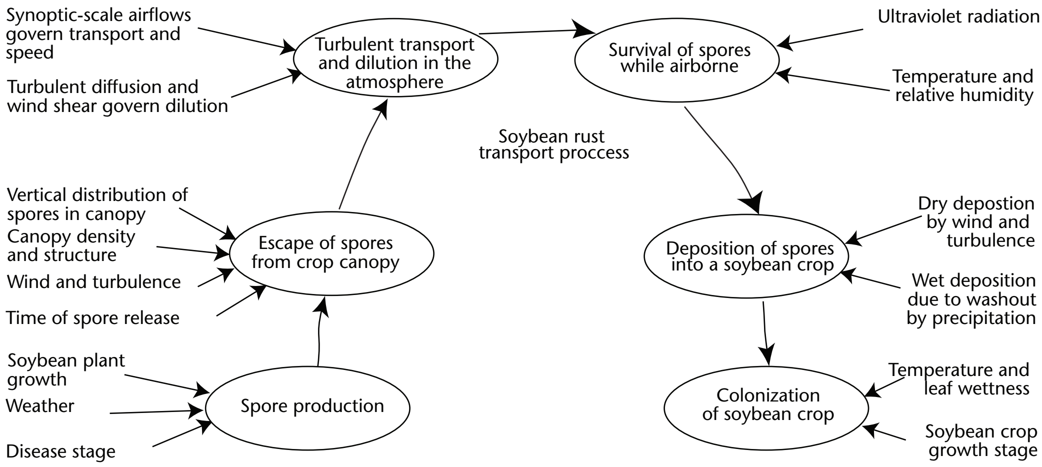

Figure 15.9. Aerobiological process diagram for soybean rust (Isard et al., 2005). Copyright: American Institute of Biological Sciences.

15.5.3 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

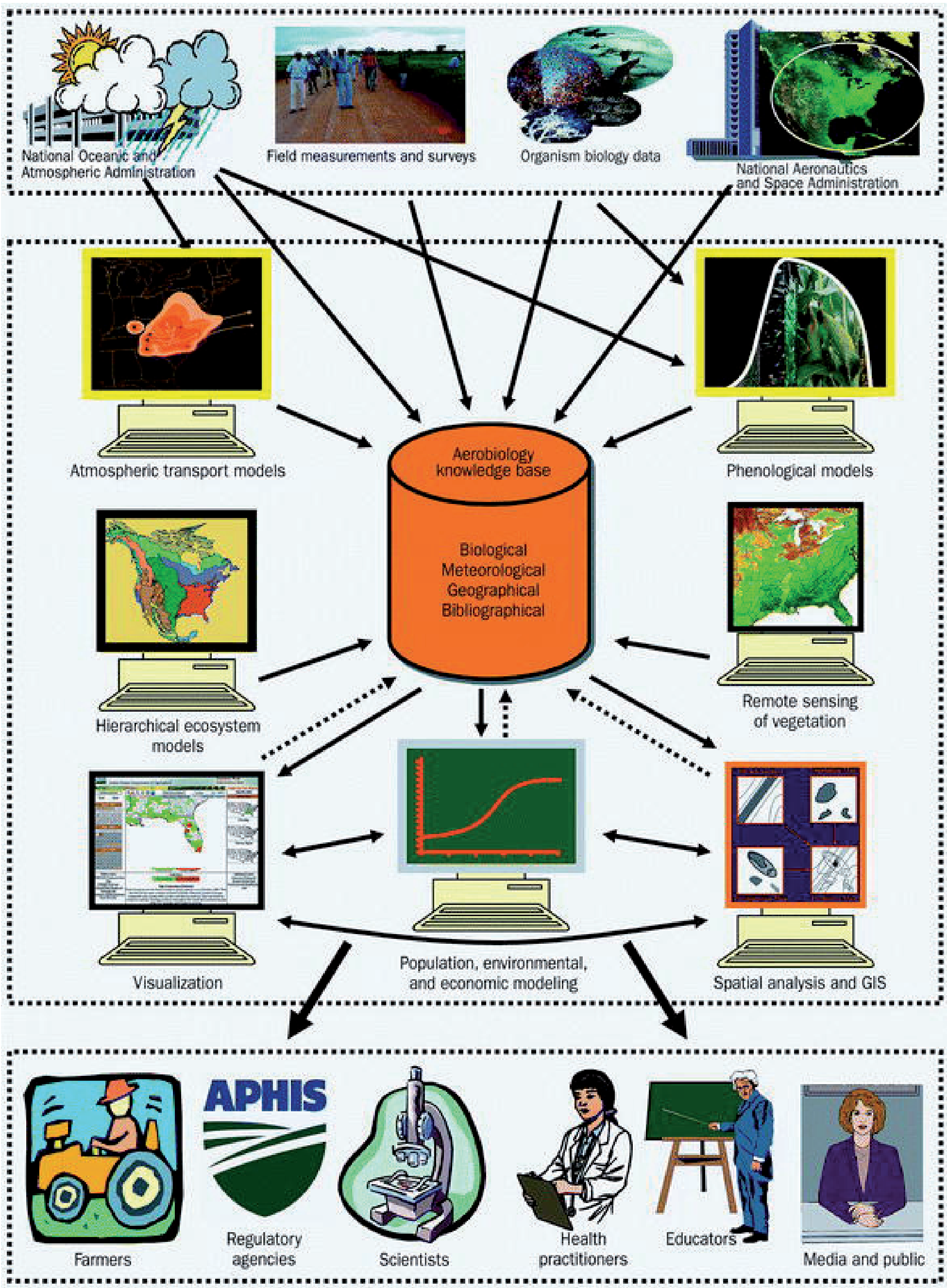

Figure 15.10. Integrated Aerobiology Modeling System (IAMS) diagram (Isard et al., 2005). Copyright: American Institute of Biological Sciences.

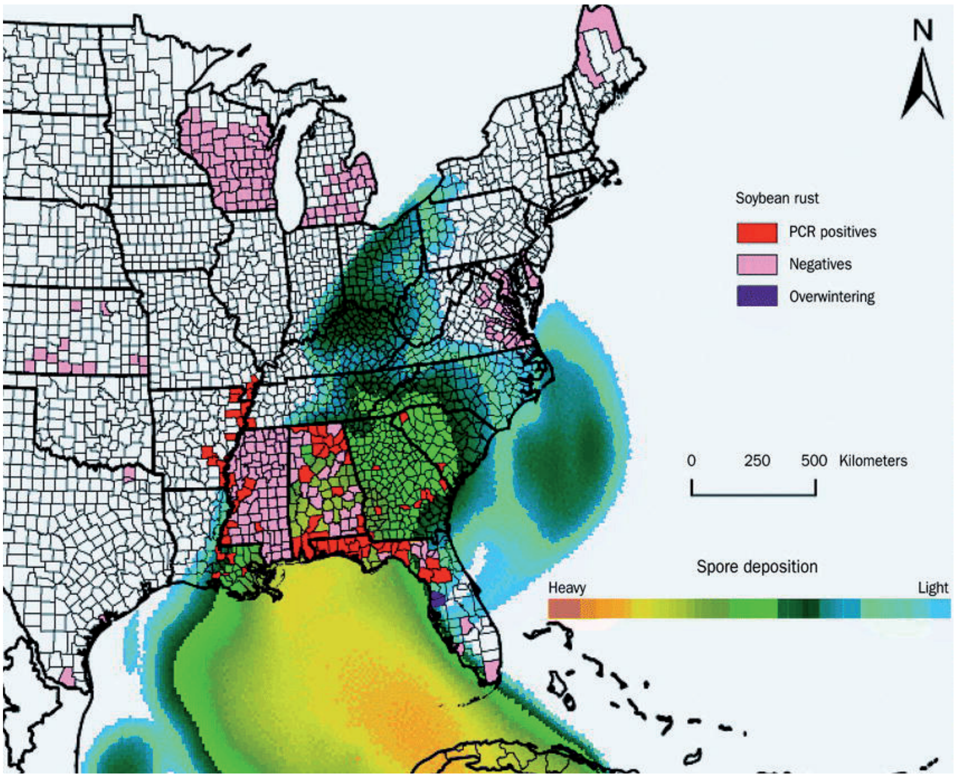

Figure 15.11. Predicted deposition pattern for Soybean Rust Aerobiology Prediction System (SRAPS) simulation using hypothetical cohorts of spores released from the Rio Cauca source area on 7, 8, and 9 September 2004 (Isard et al., 2005). Copyright: American Institute of Biological Sciences.

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 metres and travel time, t, in seconds.

A number of spores released instantaneously at a source should become diluted in a volume of about $HS_Y{}^2$. Thus for $H = 3\,000$ metres 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 with 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 allows a change in mixing height to be treated more accurately than does the chosen Lagrangian frame of reference.

15.5.4 **Survival (*S*) of spores**

Along with temperature and relative humidity, the UV component of solar radiation, which is the most lethal, controls survival of spores in the atmosphere. Most spores, which will be transported through the atmosphere and deposited within a few hundred kilometres 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.

15.5.5 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.

Wet and dry depositions are closer in number than has been suggested by their relative deposition rates because there are many more dry hours 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 to this mechanism a representative role (Smith, 1981). Calculations using this model have been carried out considering only dry deposition.

A solution to the problem of the total number of spores deposited during the total transport event is shown in Figure 15.6. The problem was solved for two wind speeds, 20 km h^{-1} and 40 km h^{-1}, and for two sky conditions, sunny and overcast. The solution in Figure 15.6 shows the overwhelming importance of spore survival. The danger of infection from the small, potentially unnoticed local source, plotted in Figure 15.6 as a solid bar at 700 km, 2 km away from the location of the target area, might be considerably more serious on a sunny day than the massive source 700 km away, or a comparable danger on a cloudy day. Transport speed is very important during sunny weather, as doubling the speed increased by a factor of about 10^7 the number of spores deposited after travelling 700 km. 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 with the 10 a.m. release (solid line and solid square), the spores released at 3 p.m. 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 difference factor of about 10^{12} 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 that viable spores from distant sources will reach susceptible crops by aerial spore transport. Aylor (1986) expressed the various uncertainties in his model in Table 15.3.

Table 15.3. Uncertainties in estimates of transport factors

Process	*Factor*
P	100–1 000?
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 continental Australia, was carried out by Pierrehumbert et al. (1984) by investigating 85 kPa temperatures and selecting abnormally high values that 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 drawn for occasions when 85 kPa temperatures were two and three standard deviations above the mean. These trajectories were drawn from Macquarie Island and invariably arrived back to the Australian continent. A synoptic model was deduced, which required the rear edge of an anticyclone 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.

15.6 AIR POLLUTION

Although not strictly aerobiological quantities, gaseous and particulate pollutants can be spread from source regions through the atmosphere to affect regions of sensitive biota, including airborne spores. Major atmospheric pollutants include ozone, nitric oxides, volatile organic compounds and sulphur 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, which leads to poor plant health and susceptibility to disease, pests and environmental stresses; ozone also leads to reduced yields. Sulphur dioxide combines with atmospheric water vapour to create sulphuric acid, which 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.

15.7 SPECIAL CONSIDERATIONS FOR FLYING ORGANISMS

Inanimate airborne objects were the predominant topic of discussion in preceding sections because similar physical processes may be applied to them. The impact of organism flight is also important to agricultural production systems, however. Such organisms include numerous species of insects, birds and bats. Aerobiological transport models presented in 15.5 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 aerobiological 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 (for instance, http://www.ipm.ucdavis.edu/general/tools.html). Biophysical factors, including vertical distribution of airborne insects, flight speed, flight heading, lateral spacing among organisms in flight and flight duration, must also be considered when investigating movement of pest insects. Empirical data are often difficult and expensive to acquire – as a result, agricultural meteorologists may need to apply aerobiological factors among similar organisms (such as 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 that 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. Birds and bats also consume large quantities of insects, however. 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).

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