PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Detection of Mesoscale Synoptic Features Associated with Dispersal of Spruce Budworm Moths in Eastern Canada [and Discussion]

R. B. B. Dickison, P. J. Mason, K. A. Browning, R. W. Lunnon, D. E. Pedgley, J. R. Riley and R. J. V. Joyce

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Detection of mesoscale synoptic features associated with dispersal of spruce budworm moths in eastern Canada

By R. B. B. Dickison

Department of Forest Resources, University of New Brunswick, Bag Service no. 44555, *Fredericton, New Brunswick, Canada E3B 6C2*

Radar studies in eastern Canada of spruce budworm moth distribution patterns and associated windfields frequently revealed mesoscale synoptic features induced by the strong thermal contrast between the heated land surface and the surrounding coastal waters that resulted in significant redistribution of the airborne moths. Experience gained during a four-year study in New Brunswick enabled meteorologists to identify the synoptic situations favouring the development of these mesoscale features. This paper examines the details of a particular case, on 15–16 July 1976, when insect detection teams were alerted in advance to the existence and location of a significant wind convergence zone.

1. Introduction

A collaborative study of spruce budworm moth dispersal in eastern Canada in the mid-1970s (Greenbank *et al.* 1980) involved the use of ground-based and airborne radar for detecting insects, and the use of a Doppler radar equipped aircraft for determining windfields. The project was coordinated by the Canadian Forest Service, but the radar and atmospheric components of the study were mainly carried out by researchers from the Cranfield Institute of Technology and the (then) Centre for Overseas Pest Research. The author provided meteorological forecast interpretation during the study.

This paper deals with operations in 1976, when two aircraft were used: a DC-3, primarily for windfield determination but also equipped with insect-detecting radar, and a Piper Aztec equipped for insect detection. The equipment and operating procedures are described in detail by Schaefer (1979) and Greenbank *et al.* (1980).

(*a*) *The eastern spruce budworm and its dispersal*

The eastern spruce budworm *Choristoneura fumiferana* (Clem.) spends only about one week of its one-year cycle in the moth stage. In eastern Canada, phenological spacing spreads this period throughout the month of July. Female moths emigrate from the forest canopy in vast numbers each evening, and remain aloft in dispersal flights of a few hours duration (Greenbank *et al.* 1980), at altitudes mostly 100–300 m above ground. While in flight the moths are often subject to significant redistribution within the general windfield, either due to migratory meteorological systems (Dickison *et al.* 1983, 1986) or systems, such as sea breezes, which are features of the local geography.

(*b*) *Significance of convergence zones to dispersal*

Wind convergence zones are not only of concern with respect to their effect on any particular occasion, but collectively, they may indeed be the key factor in establishing new outbreaks and thus sustaining the species. It was once thought that outbreaks resulted when conditions locally favoured a rapid increase in an endemic population – the 'epicentre' concept (Hardy *et al.* 1983). Later, Royama (1984) presented analytical evidence against the epicentre concept. Attempts at modelling the spread of epidemics suggested that dispersal in the moth stage was an absolutely crucial factor and more complex than originally postulated (Clark 1979); it was this requirement in the population model which led to the intensive study of moth dispersal. Even after incorporating this new knowledge into the model, Clark (1979) concluded that extensive dispersal alone cannot account for new outbreaks, unless a population threshold of some critical level is exceeded. Rainey & Haggis (1988) then offered the 'new hypothesis' that, although general uniform moth dispersal may not be a critical factor, immigration in situations with marked convergence zones embedded in the general windfield would lead to a new outbreak 'without necessarily involving any prior build-up or even existence of local low density populations.' T. Royama (personal communication) maintains that this still does not fully explain the mechanisms for population outbreaks.

Early in the study it became apparent that sea breeze effects, especially those induced by the very cool Bay of Fundy to the south, played a significant role in the distribution and movement of the moths. Inland air temperature in July is markedly warmer than that of the sea which borders New Brunswick to the south and east. This thermal contrast results in changes in the synoptic pattern, which is frequently characterized by mesoscale features induced by regional geography. Neumann & Mukammal (1979) examined critical conditions for the establishment of marine air intrusions into the province and Burns *et al.* (1980) examined the particular case of easterly flows. If the windfield features (particularly zones of convergence) can be detected and forecast, and their occurrence and movement considered in relation to insect development and behaviour (period of moth activity, time of exodus flights, temperature and light controls, duration of flights), an opportunity exists for better monitoring and management of the movement of insect populations and better control of epidemic outbreaks.

2. Identification and forecasting of wind convergence zones

The analytical and forecast problems related to passive insect dispersal are mesometeorological in scale – specifically the meso-β scale as defined by Orlanski (1975), with time-scales 2–24 h and space-scales 20–200 km. As such, they are barely sub-synoptic in most regions (and certainly sub-synoptic in New Brunswick, where, at the time of the exercise, there were only five synoptic meterological observing stations in an area of nearly 75000 km^2). Most mesoscale concerns relate to severe weather phenomena, for which weather radar and (to a lesser extent) satellite imagery can provide the observational base. Phenomena significant to insect dispersal, however, are likely to be too benign to show up on radar or satellite imagery.

A workshop on the problem of forecasting mesoscale features, sponsored by the Canadian Meteorological and Oceanographic Society (1983), stated that 'forecasting of the probability of the occurrence of mesoscale events is often possible through deductions made from synoptic scale information,' and that 'It is also possible to infer the presence of mesoscale structures from the time sequence of events at the stations of a conventional synoptic scale network.' However, many of the features important to insect dispersal are not only difficult to detect by radar or satellite imagery, but are so obscure and generally irrelevant as to escape the notice of an operational forecaster. On the other hand, an alert analyst, if conditioned by local experience and solely dedicated to the insect problem, can often identify and forecast the location and behaviour of significant features sufficiently well to provide valuable guidance to the pest manager.

This paper reviews the conditions for the development of non-migratory mesoscale structures, detectable from synoptic data and therefore forecastable, focusing mainly on a particular case: the evening of 15 July 1976, during one of the insect dispersal/windfield detection exercises conducted in New Brunswick. In this case, and practically all of those which received special attention during those exercises, the features were apparently coastal in origin, induced by the thermal contrast between land and sea.

3. Marine flow convergence zones

Features of coastal origin have been called 'sea breezes' and 'marine flows,' but the distinction may be largely semantic. Neumann (1980), examining sea breezes during the spruce budworm moth dispersal study in New Brunswick, used a method of classification based on the lake breeze work of Biggs & Graves (1962) and Lyons (1972). This method was successful in predicting many of those sea-breeze cases in New Brunswick which resulted in line concentrations of airborne moths detected by radar (Schaefer 1979). The deep inland penetration of the sea breeze (Schaefer 1979) resembled cases described by Simpson *et al.* (1977) in southern England.

Burns *et al.* (1980) described synoptic situations that could be recognized subjectively by an analyst as favouring development of marine flow convergence zones. They reviewed cases from the moth dispersal study to show the synoptic conditions that favour these developments – essentially, whenever a flat pressure field tracks into the region at the time of day when the

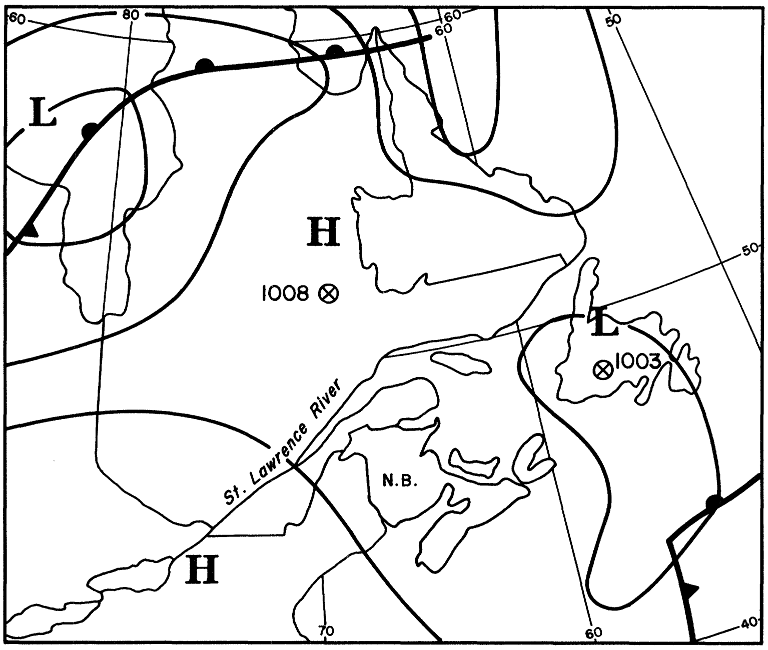

FIGURE 1. Canadian Meteorological Centre surface analysis for 15h00 A.D.T. (18h00 G.M.T.) 15 July 1976. Isobar interval = 4 mbar.

thermal contrast is greatest. Although the evening of 15 July 1976 was not among those cases described by Burns *et al.* (1980), it is nevertheless an exemplary case, and its detection allowed researchers to locate and document significant moth concentrations.

(*a*) *Synoptic situation on* 15 *July* 1976

At 18h00 G.M.T. (15h00 A.D.T.) the Canadian Meteorological Centre showed New Brunswick in a region of slack pressure gradient (figure 1). A weak ridge of high pressure lay just north of the St Lawrence River, with a very weak northwesterly gradient flow across New Brunswick behind a weak low pressure centre over Newfoundland. The diabatic effect of daytime heating over the land led to slight pressure decreases, and a marine flow developed. At the time of the pre-flight briefing, 18h00 A.D.T., an easterly flow was evident over most of the province and a north–south convergence zone was located over western New Brunswick. Initially it was positioned near the Maine–New Brunswick border, but post-analysis (figure 2) suggests a location at 18h00 A.D.T. about 50 km further east. Four to six hours later, the insect detection flight showed concentrations of airborne moths at about the position shown for the front at 18h00 A.D.T. There is no concrete evidence on which to judge the motion of the front, but a westward movement of 50 km in that time seems reasonable.

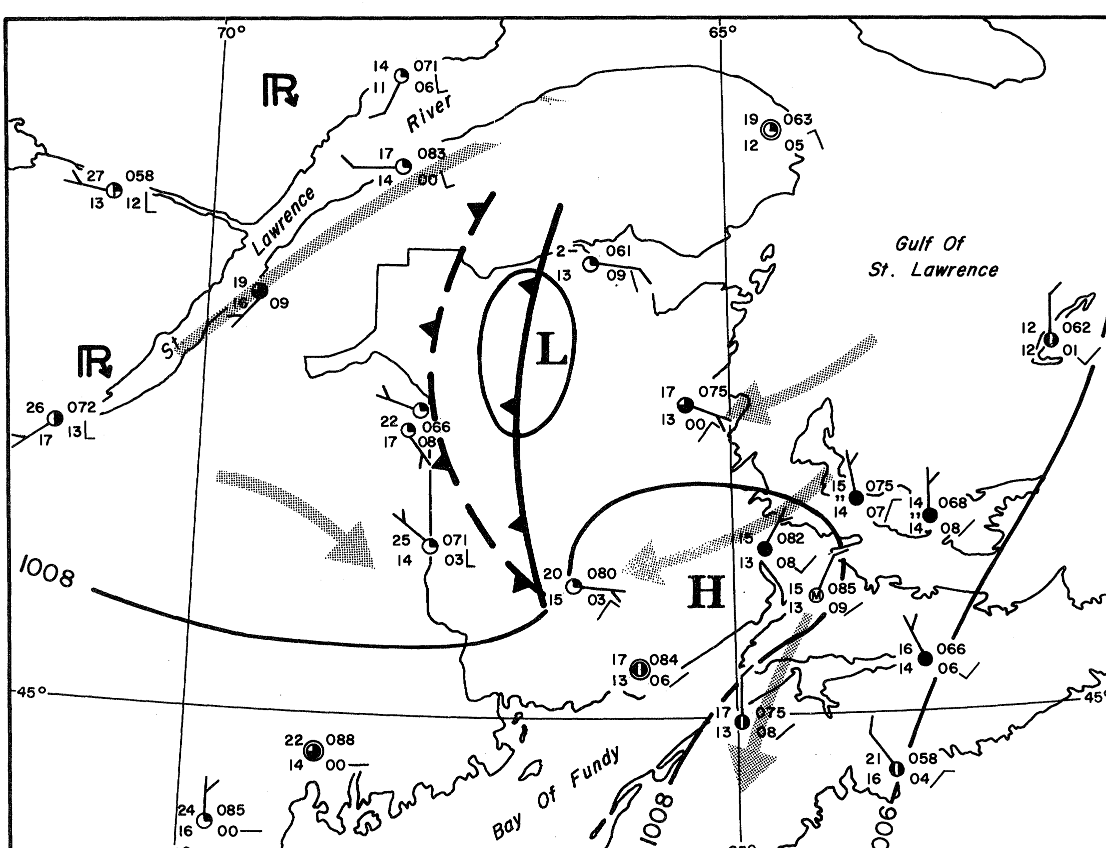

FIGURE 2. Detailed surface analysis for 18h00 A.D.T. (21h00 G.M.T.) 15 July 1976. Isobar interval = 2 mbar. Broken line, analysed position of sea-breeze front shown at pre-flight briefing; solid line, position determined in final analysis.

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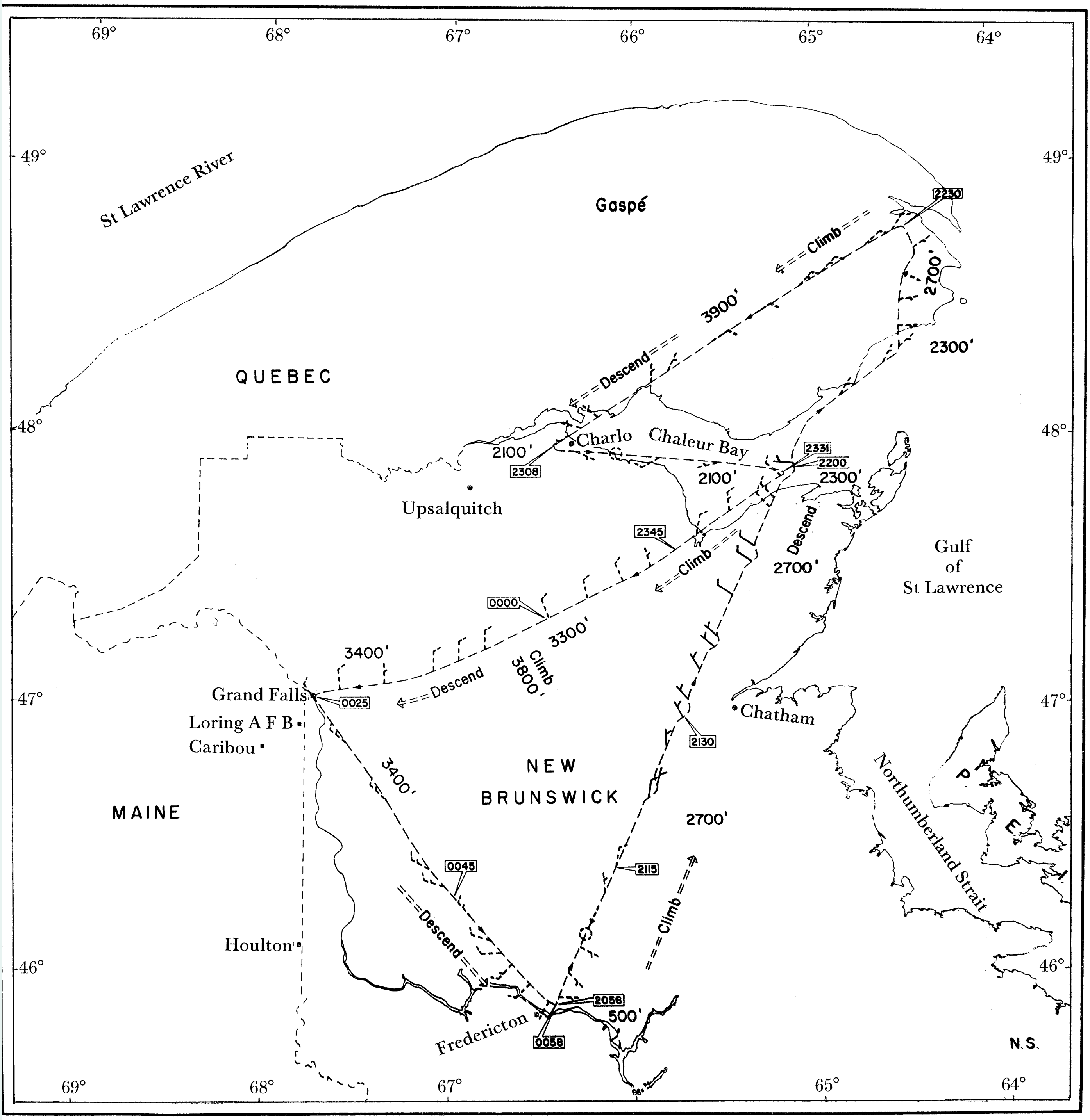

FIGURE 3. Flight track of DC-3, and Doppler drift wind measurements over New Brunswick and Gaspé, 20h56–00h58 A.D.T. 15–16 July 1976. Aircraft winds: ⌊___, multiple-drift winds: ⌊_ _ _, single-drift winds; 1 full barb ≡ 10 kt (5 m s^{-1}). ◯, calm; →- - -, aircraft track (flight altitudes shown in feet above mean sea level, alongside track); times of observations are shown boxed. (Data supplied by R. C. Rainey and M. J. Haggis.)

(*b*) *Windfield detection flight*

The survey flight by the DC-3 to describe the low-level windfield was north–northeastwards from Fredericton Airport to eastern Gaspé, thence returning by zigzag legs which extended westward to near Charlo, eastward to the mouth of the Bay of Chaleur, southwestward to Grand Falls, thence back to Fredericton (figure 3). Within New Brunswick, the flight was conducted at altitudes of 2100–2300 ft (690–755 m) over the Bay of Chaleur, and mainly 2700–3400 ft (885–1115 m) over the mainland. These altitudes were above the moth flight levels, in keeping with the intent of measuring moth density profiles. Sky conditions at synoptic observing stations were reported mostly as scattered stratocumulus and altocumulus, although a cumulonimbus cloud and a rainshower were reported within sight of Caribou, Maine at 21h53 A.D.T., and Loring Air Force Base weather radar registered a small area of echoes just east of Grand Falls, with maximum tops at 16000 ft (about 5250 m).

The flight altitude kept the aircraft above the marine flow throughout most of the flight. After take-off, the DC-3 flew over the Fredericton VOR (VHF omni-range navigation beacon) at 500 ft (197 m) at 20h56 A.D.T., heading about 025° true, and climbed steadily to 2700 ft (885 m) within 65 km. Surface winds at Fredericton before takeoff were 120°/5 kts. During the

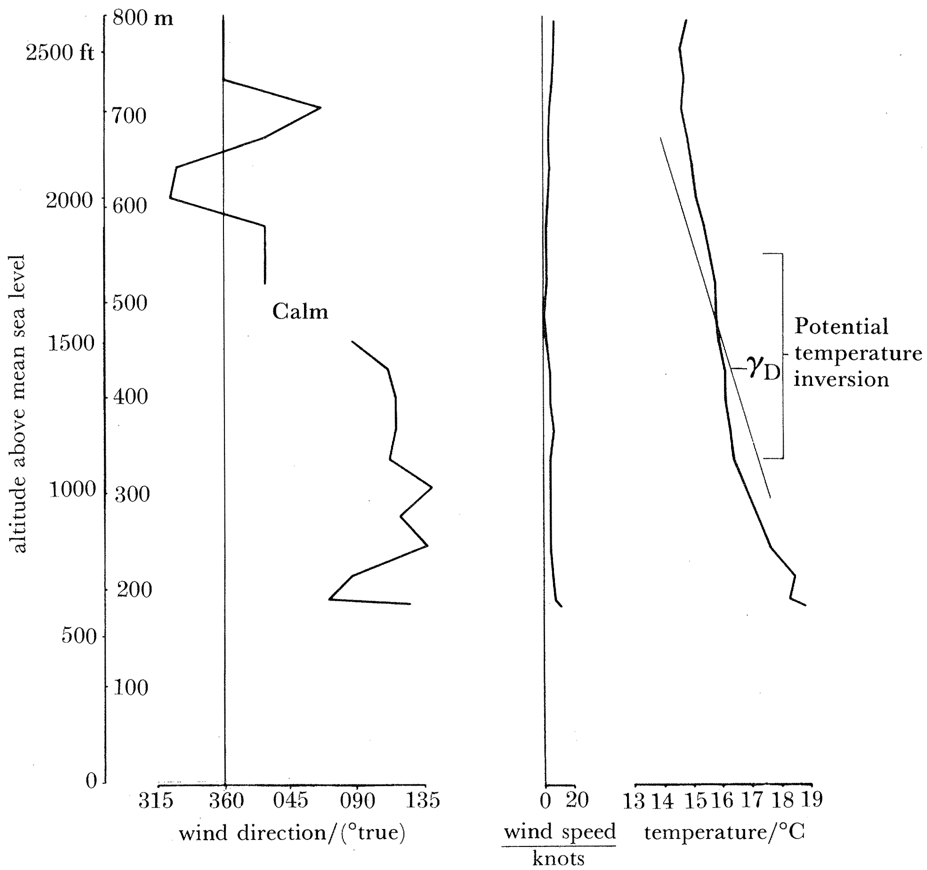

FIGURE 4. Vertical profiles of wind direction and speed, and air temperature, measured by DC-3 climbing northward from Fredericton, 20h57–21h15 A.D.T. 15 July 1976 (data supplied by R. C. Rainey and M. J. Haggis). γ_D indicates neutral (dry adiabatic) lapse rate.

climb, winds remained southeasterly to about 1500 ft (460 m), then shifted to northerly (figure 4); this windshift, and the corresponding potential temperature inversion through the layer 1100–1800 ft (330–550 m), placed the marine frontal surface at about 500 m. Beyond Chatham, winds were generally northwesterly and the aircraft was clearly above the marine air.

The intrusion of marine air, as evidenced by surface observations, extended to well west of Fredericton. Reports from Houlton, Maine showed a wind shift to southeasterly around 21h00–22h00 A.D.T., accompanied by a temperature drop of 5° C over two hours. Measurements from the aircraft, however, showed that the marine air was confined to a fairly low layer, as it was encountered on descent northwest of Fredericton, probably just above 2000 ft (near 600 m). Single-drift wind calculations above 2000 ft indicated backing of about 35°/100 m – from 297° 08 kt at 2500 ft (670 m) to 223° 13 kt at 1900 ft (580 m) – during descent within a marked potential temperature inversion of about 1° C per 100 m.

(*c*) *Insect detection flight*

The Piper Aztec was dispatched to northwestern New Brunswick to document moth populations within the convergence zone identified at the pre-flight briefing (figure 2). Figure 5 shows the track of the aircraft during five 24-min flight segments of radar sampling, over the period 22h01–00h17 A.D.T. The aircraft was flown at heights of 500–540 m above ground.

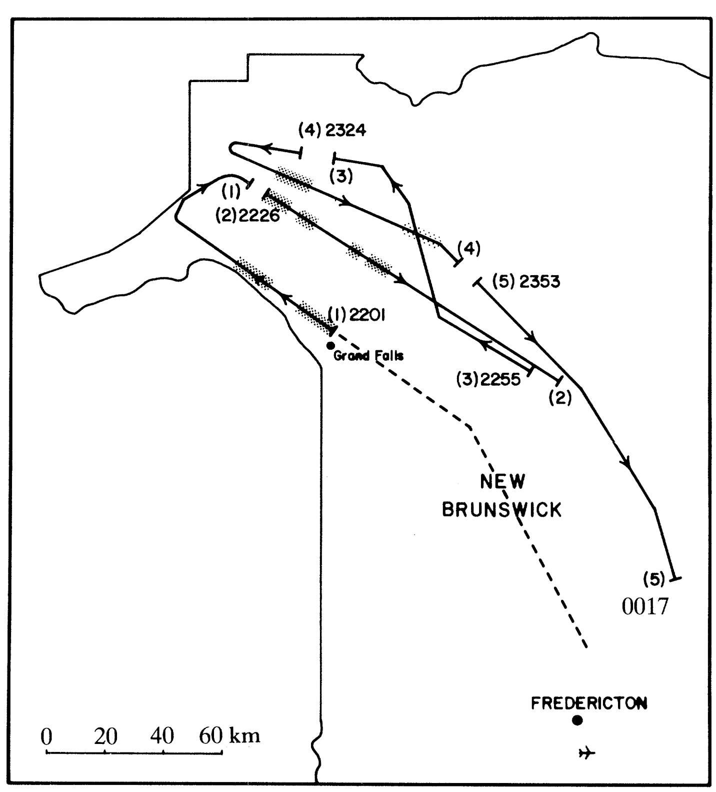

FIGURE 5. Track of Piper Aztec during radar insect-detection flight over northwestern New Brunswick, 15–16 July 1976, 22h01–00h17 A.D.T. (data supplied by K. Allsopp, Cranfield Institute of Technology). Stippled segments show zones of dense concentration of airborne moths; data in lightly stippled zone uncertain.

Areas of airborne moth concentration were observed on flight segments 1, 2 and 4 (figure 5), generally in the western part of the area sampled. The available information gives relative integrated echoes of moth populations in two layers, 75–315 m below the aircraft, and from thence to ground level (rather than detailed profiles as given by Schaefer (1979) for a case five days earlier). The moth density data cannot, then, be used to determine the structure of the meteorological feature; however, the presence of the concentrations is consistent with the existence of a zone of wind convergence in the area identified in advance by analysis of the surface meteorological observations.

4. Applicability of the research experience to pest management

The population dynamics of the eastern spruce budworm are related closely to the availability of extensive areas of mature forest. Management intervention in recent years has focused on keeping this forest in a marketable condition during an epidemic (Clark 1979). If it were feasible to control populations by spraying airborne moths – which, for sociopolitical reasons, is considered unacceptable – meteorological service support would be essential. But, during an epidemic, management strategy should at least include a programme of monitoring moth dispersal, which would include the use of radar equipped aircraft for insect detection and windfield determination (Rainey & Haggis 1988) with strong meteorological interpretation support.

During the moth dispersal phase intensive monitoring could be restricted to those evenings when the regional windfield is non-uniform. This would include cases with transient systems, and those with mesoscale systems such as that described here. One would need to distinguish, therefore, between situations when the flow pattern is governed by general synoptic patterns

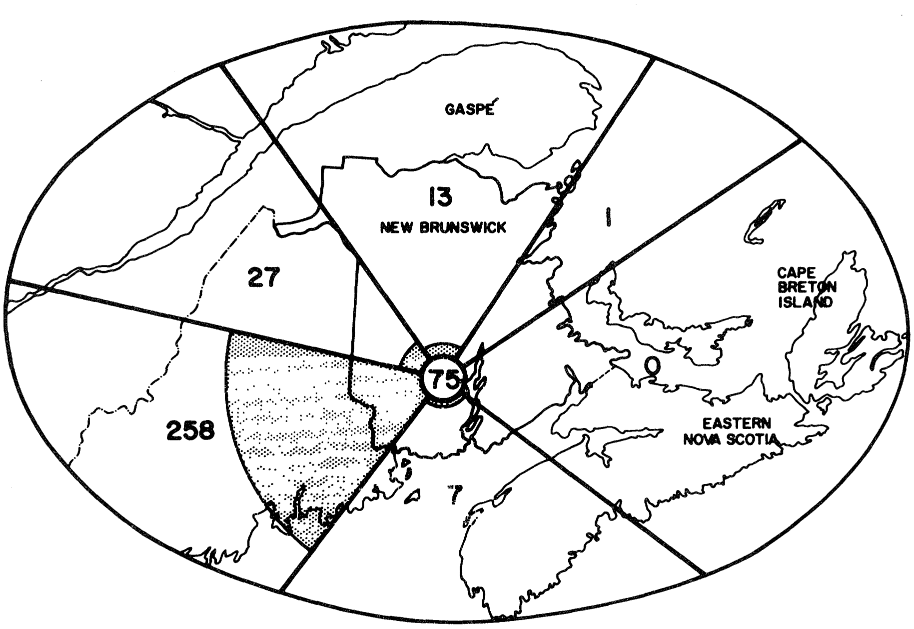

Figure 6. Frequency of occurrence of gradient-level winds flows within specified sectors over south/central New Brunswick during 586 July evenings with temperatures favourable for spruce budworm moth exodus, 1958–1976. The value in the centre of the circle is the frequency of light/variable wind conditions. On the remaining 205 evenings, temperatures were too cool for exodus flights. After Dickison (1989).

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and situations when sub-synoptic features may develop. The latter become of consequence only when the gradient of the general pressure pattern weakens. In an examination of synoptic maps of 586 July evenings (00h00 G.M.T., or 21h00 A.D.T.) during a 19-year period (Dickison 1989), 205 evenings were too cool for moths to undertake exodus flights from the canopy. For the remaining cases pressure gradient patterns were examined for the area centred on Fredericton. It was found that gradient-level flows were predominantly from westerly sectors (figure 6). Easterly flows at the synoptic scale were found to be extremely rare. This does not, however, represent an appraisal of the likelihood of easterly sea breezes, because these develop when general pressure gradients are too weak to be classified with respect to direction. Realistically, the 75 cases (12.8% of evenings) with light/variable wind conditions represent evenings when sub-synoptic features could be expected to develop.

I thank Dr Rainey and Miss Haggis for their support and encouragement in preparing this and other manuscripts, and for the extraordinary stimulation which our associations have provided. We are grateful for the support of the late Dr Glen Schaefer and Keith Allsopp, Cranfield Institute of Technology, and to Dr Frank Webb and David Greenbank of the Canadian Forest Service.

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Discussion

P. J. Mason (*Meteorological Office, Bracknell, U.K.*). To assist in understanding insect movements and for use in any control actions, it would be worth considering the application of mesoscale models, which have been shown to capture the dynamics of sea breeze circulations very well. They provide both details of flow for scientific studies and forecasts of expected sea breeze positions.

K. A. Browning, F.R.S. (*Meteorological Office, Bracknell, U.K.*). Presumably, there are some clouds in these systems; if there are clouds moving in different directions on either side of the sea breeze front, then with satellites, one would be able to observe the convergence directly.

R. W. Lunnon (*Meteorological Office, Bracknell, U.K.*). I think one has to be a little careful in using satellites for cloud track winds in this sort of context, because it is quite likely that the steering level, to which the cloud motion pertains, might be subtly different on opposing sides of a sea breeze front. Quantitative estimates of divergence from such measurements might then be misleading. However, I think qualitatively one could use the regular 30 min geostationary satellite images in this way to get a very good indication of the geographical position of a zone of strong convergence.

D. E. Pedgley (*ODNRI, Chatham, U.K.*). What non-standard techniques of analysis, such as time sections, were used to get the maximum value out of the sparse, routine observations? And is there a case for installing a temporary meso-net during the short migration season? Concerning outbreaks, what proportion is derived from the re-concentration of moths streaming away from earlier and distant outbreaks rather than from local, low-density populations? I ask this, because there is growing evidence from studies of the African armyworm moths that some caterpillar outbreaks are not derived from earlier ones, particularly those at the beginning of the season that may lead to widespread infestations downwind in subsequent generations (Pedgley *et al.* 1989).

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R. B. B. Dickison. First, I did not do any time diagrams on this particular occasion, as the feature had apparently already tracked past the most interesting location and I anticipated that it would stall as it moved farther inland. However, it was a technique that I employed on other occasions.

Secondly, in the past one or two years, there has been a meso-network operating, but only for documentation and not for forecasting. This was before the days of the present data-logging and communications equipment, and we were not able to interrogate that network in real time. A network is soon to be established, which would enable that sort of analysis in the future, if there were any interest in it for insect dispersal. Incidentally, 1976 was the peak of the epidemic and since then there has been no appreciable build-up of budworm populations in the province. This is another reason why a lot of the financial support has been withdrawn.

J. R. Riley (*ODNRI*, *Malvern*, *U.K.*). Firstly, is there any evidence from ground observations that moths have appeared where mesoscale convergence zones were predicted? Secondly, in the light of political constraints on air-to-air spraying in Canada, has any practical use been made of the new knowledge about the entrainment of spruce budworm in convergence zones?

R. B. B. Dickison. Spruce budworm eggs are laid in July and the consequent feeding of the next generation does not begin until May, 10 months later. The traditional approach has been to sample for egg masses and then design the next year's air-to-ground larval insecticide control programme on that distribution of eggs. The suggestion was made by Rainey & Haggis (1988) that information about sea breezes could be used to carry out the sampling more efficiently. But there has been no meteorologist dedicated to the programme to capitalize on this.

R. J. V. Joyce (*Cranfield Institute of Technology*, *Bedfordshire*, *U.K.*). Professor Dickison's case study from which he draws the conclusions: 'Wind convergence zones...collectively may indeed be the key factor in establishing new outbreaks...', supporting the new hypothesis put forward by Rainey and Haggis (1988) that: 'moth immigration in situations with marked convergence zones embedded in the general windfield would lead to new outbreaks without necessarily involving any prior build-up or even existence of local low density populations' is of immense, and possibly revolutionary importance to concepts of pest outbreaks.

A pest outbreak occurs when the pest density in a crop reaches the economic injury level, defined as the level at which damage is roughly equal to the cost of control. It is customary to regard the 'economic threshold' as the pest density at which control measures should be applied to prevent an increasing pest population from reaching the economic injury level. This includes an element of short-term prediction. However, with almost every insect species studied it has been found that the flight activity has been grossly underestimated or wrongly assumed that, when it occurs, immigation is roughly compensated by emigration. Insect dispersal would be such a random process if the air that transports the insects were not structured. Wind fields, however, represent air structured in the horizontal and the vertical planes, so that insects entering this air leave eventually at very different densities. This can, on occasion, give rise to massive redistribution of populations so as to deplete numbers in one area and overwhelm natural controlling agents in another, thus giving rise to an outbreak. This is most clearly manifest in the case of insects that are obviously migratory, such as locusts, but I have had clear evidence of the same mechanism in the case of outbreaks of cotton pests such as jassids, whitefly and bollworm. It must be accepted, I believe, that the term 'economic threshold' can have no meaning unless it contains a statement of scale, and this scale is a function of the flight activity of the species which, rarely, is confined to field or farm boundaries. Insect pest control must therefore be regarded as lying in the domain of ecology and not agronomy.

Professor Dickison has performed a great service in establishing the dramatic effect that meteorological features 'so obscure and generally irrelevant that they are likely to escape notice' can have on one very important pest species.