Using Operational Weather Data to Schedule Fungicide Sprays on Tomatoes in Southern Ontario, Canada

T. J. GILLESPIE

Agrometeorology, University of Guelph, Guelph, Ontario, Canada

B. SRIVASTAVA

Atmospheric Environment Services, Ontario Region, Toronto, Ontario, Canada

R. E. PITBLADO

Ridgetown College of Agricultural Technology, Ridgetown, Ontario, Canada

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ABSTRACT

A fungicide-spray scheduling scheme for tomatoes called TOM-CAST (tomato forecaster) was adapted for use with operational weather data in order to increase the number of users by eliminating the need for in-field measurements of hourly temperature and leaf wetness duration. Such schemes reduce cost, environmental risk, and the development of resistance to the fungicide. Duration of wetness was estimated as the length of time that the dewpoint depression ($T - T_d$) remained between two specified limits, indicating the onset and offset of wetness. Several methods of obtaining the necessary temperature and dewpoint data were investigated. The preferred method, considering accuracy and simplicity, involved synthesis of hourly temperatures from locally observed daily maximum and minimum temperatures, and estimation of dewpoints from two Environment Canada hourly weather stations. With appropriate calibration, the scheme was able to match the number of sprays required by TOM-CAST exactly or within one spray.

1. Introduction

Weather has an important influence on diseases in a number of economically important crops. Recent reviews on this subject have been published by Jones (1986), Madden and Ellis (1988), and WMO (1988). For high-value crops, it has been economically feasible to control diseases with sprays of fungicide. But recently the practice of applying fungicides at regular intervals after a fixed calendar date has been replaced by more rational schemes that often use weather data to withhold sprays when they are not necessary (Madden and Ellis 1988). Such schemes have the distinct advantages of reducing costs and the risk of environmental contamination, and delaying or eliminating the development of resistance in the target disease organism.

Weather-based plant-disease management schemes typically concentrate on a "weak link" in the disease cycle. For example, newly arrived spores often require liquid moisture to germinate, and are very susceptible to death by desiccation. The rate at which they can penetrate to safety within a leaf depends on warmth. Therefore, simple disease predictors use temperature in combination with some estimate of surface wetness duration. The basis for the research described in this paper is a temperature–moisture scheme for disease management in tomatoes originally described by Madden et al. (1978) and modified for use in southern Ontario by Pitblado (1992). The mean temperature during each period of surface wetness (rain or dew) is used to assign a disease severity value (DSV) from 0 (no disease risk) to 4 (high disease risk), depending on the combination of warmth and duration of wetness (Table 1). DSVs are accumulated until the first day that a target sum of at least 35 is reached. At this time the first fungicide spray is applied, and the DSV "counter" is reset to 0. Applications are repeated, and the counter is reset to 0 again, the first day after each additional accumulation of at least 20 DSV (using chlorothalonil fungicide). The scheme is called TOM-CAST (tomato forecaster).

This method requires the direct measurement of temperature and wetness duration in the tomato fields of cooperating growers, which involves specialized equipment and limits the number of sites that can be monitored. Our objective was to use simpler meteorological inputs in order to encourage wider applica-

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Corresponding author address: Terry J. Gillespie, Ontario Agricultural College, Agrometeorology, University of Guelph, Guelph, Ontario, Canada N1G 2W1.

TABLE 1. Disease severity values (DSVs) for various combinations of temperature and leaf wetness duration.

Mean temperature (°C)	Leaf wetness duration (h) required to produce (DSVs) of				
	0	1	2	3	4
13–17	0–6	7–15	16–20	21+	—
18–20	0–3	4–8	9–15	16–22	23+
21–25	0–2	3–5	6–12	13–20	21+
26–29	0–3	4–8	9–15	16–22	23+

tion. We have measured only on-site temperatures and used dewpoint depression ($T - T_d$) as an operational surrogate for the duration of wetness. The use of both hourly measured temperatures and hourly temperatures synthesized from daily maximum and minimum temperatures was evaluated. The present paper describes the development and testing of this operational scheme for tomato disease management over four growing seasons.

2. Methods

Data were analyzed from the growing seasons of 1987, 1989, 1990, and 1991. The early summer of 1988 was quite dry in southern Ontario, so disease development was too slow to provide an adequate test. Experimental sites were located in the two southwestern counties of Ontario, Essex and Kent. Dewpoint data were obtained from two Environment Canada hourly reporting weather stations in this area, London (43°02′N, 81°09′W) and Windsor (42°16′N, 82°58′W). In 1987 the test site was at the experimental farm of the Ridgetown College of Agricultural Technology, located about 110 km east of London, while in each of 1989, 1990, and 1991 at least six of the eight sites shown in Fig. 1 (research stations and growers' fields) were used.

a. TOM-CAST data

Data taken by the method of direct observation of temperature and wetness duration in tomato fields are referred to as "TOM-CAST data" and are assumed to provide the correct DSVs. Other schemes involving dewpoint depression are judged according to their ability to mimic TOM-CAST DSV values. The direct TOM-CAST observations were made just below the crop top in tomato fields using a thermistor mounted in an unventilated radiation shield and a horizontally deployed cylindrical surface-wetness duration sensor (Gillespie and Duan 1987). Output consisted of an average temperature and wet–dry indication for each hour, from which durations of wetness and average temperatures during wet periods were calculated and converted to DSV values. Calculations of DSV began on 23 May, which is during the period when tomato seedlings are being transplanted in the fields.

b. Hourly temperatures

At some sites, hourly temperature data were recorded with shielded thermistors located near the test fields at an elevation of 1.5 m and connected to automatic data loggers (Campbell Scientific, Logan, Utah). These instruments were purposely located so that they did not interfere with any field operations, and therefore would typify a practical on-farm temperature monitoring system. The sites involved were Ridgetown (1987, 1989, 1990), Blenheim and Leamington (1989, 1990), and Tilbury (1990). The use of these temperatures in estimates of dewpoint depression (as described in the following) will be referred to as HOURLY tests.

c. Daily maximum and minimum temperature

Daily maximum and minimum temperatures from shielded thermistors located near the test fields at 1.5-m elevation were also obtained at Ridgetown in

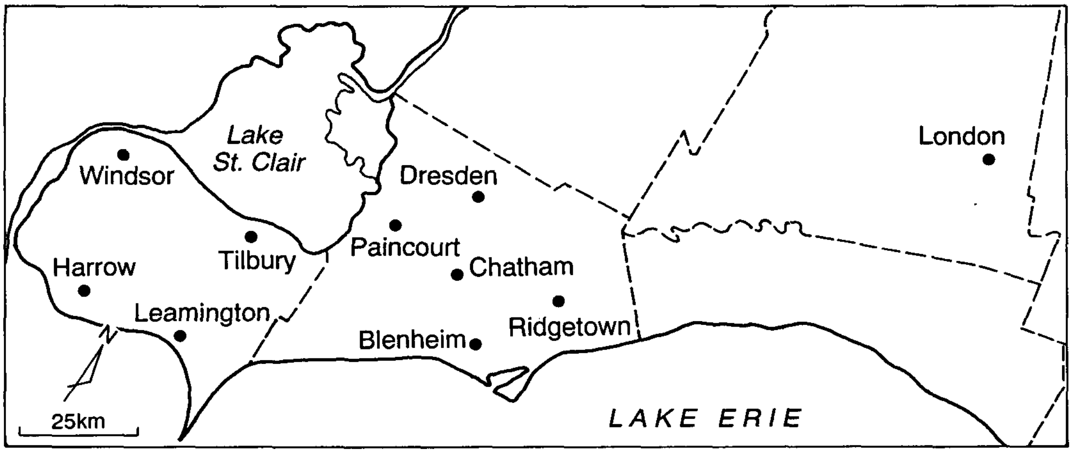

FIG. 1. Study sites in southwestern Ontario, Canada.

1987; at Blenheim, Leamington, Tilbury, Dresden, Ridgetown, and Harrow in 1989 and 1990; and at Blenheim, Leamington, Chatham, Ridgetown, Harrow, and Paincourt in 1991.

Hourly temperature estimates T were obtained from the daily maximum and minimum data ($T_{\max}$ and $T_{\min}$) using the model of Parton and Logan (1981), which assumes a sinusoidal temperature trend from sunrise to sunset and an exponential decay from sunset to the following sunrise ($T_{\min}$ assumed near sunrise). The equations are

$$\text{daytime: } T = (T_{\max} - T_{\min}) \sin\left(\frac{\pi m}{Y + 2a}\right) + T_{\min}, \quad (1)$$

$$\text{nighttime: } T = (T_s - T_{\min}) \exp\left(\frac{-bn}{z}\right) + T_{\min}, \quad (2)$$

where

a = lag coefficient for $T_{\max}$ = 2.86,
b = nighttime decay coefficient = 3.20,
m = number of hours after $T_{\min}$,
y = day length (h),
z = night length (h),
n = number of hours after sunset,
T_s = sunset temperature.

The coefficients a and b were modified slightly from those used by Parton and Logan in order to enhance the model's performance for our region. Our values were obtained by fitting the model to monthly averaged diurnal temperature data from London, which yielded a correlation coefficient of 0.97 between measured and modeled average temperatures (Srivastava et al. 1989). Models that use hourly temperatures synthesized from Eqs. (1) and (2) are called DAILY models.

d. Dewpoints and dewpoint depressions

Dewpoints at the test sites were estimated in two ways. At some locations (Ridgetown, Blenheim, Tilbury), on-site observations of relative humidity (and hence dewpoint, when combined with concurrent temperature observations) were available (Rotronic humidity probe model MP100F, Huntington, New York, or Vaisala model HMP35A, Helsinki, Finland) for selected periods of time. These measured site dewpoints were regressed against observed dewpoints from both London and Windsor hourly weather stations, yielding equations with correlation coefficients that exceeded .9. The second simplified method for estimating dewpoint at a site ($T_{d,\text{site}}$) was

$$T_{d,\text{site}} = \propto (T_{d,\text{London}}) + \beta(T_{d,\text{Windsor}}), \quad (3)$$

where $T_{d,\text{London}}$ and $T_{d,\text{Windsor}}$ are the observed dewpoints at London and Windsor, and α and β are weighting factors that describe the relative distance between the site and the two Environment Canada stations ($\alpha + \beta = 1$).

Dewpoint depressions ($T - T_d$) at test sites could therefore be estimated by combining either measured hourly temperatures (HOURLY models) or hourly temperatures estimated from daily maximum/minimum temperatures (DAILY models), with dewpoints estimated by either regression r or distance weighting w. This results in four possible formulations of dewpoint depression, which were compared for effectiveness as a surrogate for duration of wetness.

e. Estimating wetness duration and DSV from dewpoint depression

Duration of wetness was estimated as the length of time that the dewpoint depression remained between two specified limits or "wetness criteria," a smaller value of $T - T_d$ to signal the onset of wetting (e.g., at Ridgetown less than 2.0°C), and a larger value to indicate ending or offset (e.g., Ridgetown greater than 4.3°C).

To develop the wetness criteria for a site, wetness observations were required for one season to match against derived dewpoint depressions. The estimated $T - T_d$ values for the first and last hour of wetness in each wet period were averaged to give the respective onset and offset criteria. These criteria showed some variation through the growing season, so one set of criteria was used for 23 May–15 July, and a second set from 16 July to the end of the season in early September (e.g., at Harrow; less than 4.5°C and greater than 5.7°C before 15 July, and less than 3.8°C and greater than 5.1°C after 15 July).

The use of wetness criteria derived from one summer allowed calculation of wetting duration and DSVs in other summers. In describing our results, we will indicate the year's data that were used to derive the wetness criteria in parentheses; for example, DAILY $w(89)$ is a model that uses temperatures synthesized from daily maximums and minimums, dewpoints obtained from distance weighting, and wetness criteria derived from the 1989 season.

f. Calibration

The $T - T_d$ criteria derived to estimate wetness duration in a particular growing season do not always transfer satisfactorily to other growing seasons. To cope with this seasonal variability, a simple calibration scheme was devised that requires that a "base station" be established where both the $T - T_d$ scheme and the full TOM-CAST equipment (measured on-site temperature and wetness duration) are simultaneously maintained.

The base station serves a number of satellite stations as follows. Each day at the base station, the DSV is computed from both TOM-CAST data ($\text{DSV}_{b,\text{TOM}}$)

and dewpoint depression criteria (DSV_{b,T_d}). A calibration factor (CF) is calculated from

$$\mathrm{DSV}_{b,T_d} - \mathrm{DSV}_{b,\mathrm{TOM}} = \mathrm{CF}. \qquad (4)$$

This CF is applied to each satellite station's disease severity value (DSV_s) on that day to obtain a new, calibrated satellite value ($\mathrm{DSV}_{s,c}$) with reference to the following rules:

1) $\mathrm{DSV}_{s,c} = \mathrm{DSV}_s - \mathrm{CF}$.
2) If $\mathrm{DSV}_{s,c} > 4$, adjust to 4.
3) If $\mathrm{DSV}_{s,c} \leq 0$, maintain at 0, except adjust to 1 if $\mathrm{DSV}_{b,\mathrm{TOM}}$ and DSV_s are both greater than 0.

Rule 2 simply prevents $\mathrm{DSV}_{s,c}$ values from exceeding the allowed maximum of 4. Rule 3 has two functions. It prevents negative $\mathrm{DSV}_{s,c}$ values, and it provides a safety feature because it does not allow $\mathrm{DSV}_{s,c}$ to become zero when *both* the base and uncalibrated satellite station indicate positive disease potential.

g. *Field fungicide spray trials*

At the Ridgetown research site in 1989 and 1990, fungicide sprays were applied to field plots of tomatoes according to direct measurements of temperature and wetness in the fields (TOM-CAST) and according to HOURLY and DAILY models. In each case, the first spray was applied when the measured or modeled accumulated DSV became at least 35 DSV, and spraying was repeated each time a further 20 DSV were accumulated. For comparison, some additional plots were sprayed on a regular 10-day schedule (in 1989), and some were not sprayed at all (check plots).

Plots were 8 m × 5 rows, each row 1.4 m apart, with four replications arranged in a randomized block design. At the end of the season, yields, foliar disease, and percent diseased fruit were measured in each plot and tested for significant differences between treatments.

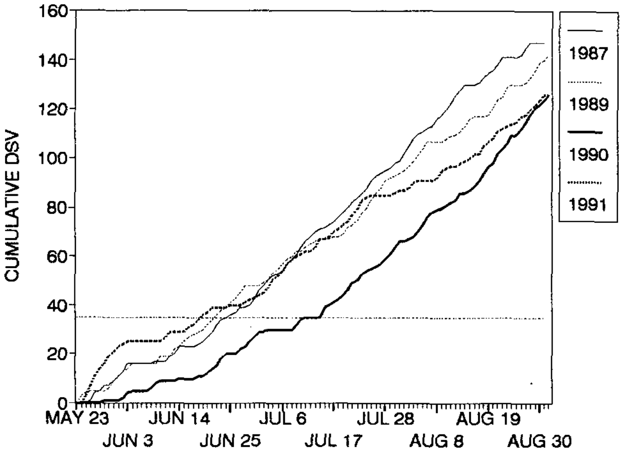

FIG. 2. Seasonal accumulation of DSVs at Ridgetown in 1987, 1989, 1990, and 1991. Horizontal line is at the first recommended spray date (35 DSV).

TABLE 2. Seasonal DSV totals and number of sprays for TOM-CAST and DAILY models with input data and derived $T - T_d$ criteria from same season. No "same-season" criteria derived in 1991.

Site	Model	Seasonal DSV	Number of sprays
Ridgetown	TOM-CAST(87)	148	6
	HOURLY*r*(87)	147	6
	DAILY*r*(87)	156	6
	TOM-CAST(89)	140	5
	HOURLY*r*(89)	166	6
	HOURLY*w*(89)	168	6
	DAILY*r*(89)	158	6
	DAILY*w*(89)	158	6
	TOM-CAST(90)	144	6
	HOURLY*w*(90)	161	7
	DAILY*w*(90)	148	6
Blenheim	TOM-CAST(89)	153	6
	DAILY*r*(89)	153	6
	DAILY*w*(89)	149	6
	TOM-CAST(90)	169	7
	DAILY*w*(90)	193	8
Leamington	TOM-CAST(89)	174	7
	DAILY*w*(89)	153	6
	TOM-CAST(90)	163	7
	DAILY*w*(90)	174	7
Tilbury	TOM-CAST(89)	166	7
	DAILY*w*(89)	182	8
	TOM-CAST(90)	161	7
	DAILY*w*(90)	187	8
Harrow	TOM-CAST(89)	181	8
	DAILY*w*(89)	187	8
	TOM-CAST(90)	162	6
	DAILY*w*(90)	164	6
Dresden	TOM-CAST(89)	161	6
	DAILY*w*(89)	155	6
	TOM-CAST(90)	148	6
	DAILY*w*(90)	167	7

3. Results

a. *Season-to-season variations in DSV accumulation*

Considerable variation in DSV accumulation curves (TOM-CAST data from Ridgetown) occurred from one growing season to the next (Fig. 2). In the summer of 1987, DSV values accumulated moderately quickly to a recommended first spray in the last week of June. After mid-July in 1987, disease potential was quite strong and DSV values reached the highest sums recorded in this study. DSVs accumulated in the 1989, 1990, and 1991 growing seasons called for the first spray in the third week of June, the second week of July, and again in the third week of June, respectively. In 1991, disease potential advanced quite slowly from late July through August. A comparison of DSV accumulation curves for the four years indicates that there are opportunities at various times to make substantial adjustments in fungicide-spray timing for optimum disease control efficiency.

TABLE 3. DSV sums obtained from TOM-CAST by using DAILYr(87) in various years at Ridgetown.

	1987	1989	1990	1991
TOM-CAST	148	140	144	115
DAILYr(87)	155	168	217	133

b. Results using $T - T_d$ criteria from the current season

Seasonal DSV totals and number of sprays were calculated from several models applied at six sites (Table 2). In all cases, the input data are from the same year as the derived $T - T_d$ criteria. The Ridgetown results show there is only a 9–13-unit difference (about 7%) in seasonal DSV between HOURLY models (measured hourly temperatures) and DAILY models (hourly temperatures synthesized from daily maximum and minimum) in the same year. Only very small differences (<8%) between HOURLY and DAILY DSV sums were also found at other stations (data not shown). DAILY and HOURLY models at Ridgetown call for the same number of sprays, except in 1990 when the DAILY model is a better match to TOM-CAST. Equivalent or better performance, and the ease of dealing with only two temperatures per day, therefore make DAILY models the better choice for operational use.

Results (Table 2) from using regression dewpoint estimates (r) at Ridgetown and Blenheim are very similar to using distance-weighted (w) estimates [e.g., compare HOURLY r(89) with HOURLY w(89), or DAILY r(89) with DAILY w(89)]. Since the establishment of r equations requires a season of humidity observations at a site, while w equations do not, the operational choice was distance weighting. Requested sprays for DAILY w at Blenheim were the same as TOM-CAST in 1989, and one greater in 1990. At Leamington and Dresden in 1989, DAILY w models underestimated TOM-CAST DSV by 12% and 4%, respectively, and one fewer spray than TOM-CAST was requested at Leamington. Elsewhere, the DAILY w models overestimated DSV by 1%–16%, but required only one extra spray at Ridgetown in 1989, at Tilbury in 1989 and 1990, and at Dresden in 1990. Since the ultimate objective of the scheme is to match the number of sprays that would be required by TOM-CAST, it is clear that this goal is usually achieved (maximum error of one spray, usually "overprotection") when the input temperature and dewpoint data, and the $T - T_d$ criteria used to estimate leaf wetness duration (and hence DSV), are from the same year.

c. Results using $T - T_d$ criteria with input data from different seasons

Variations occur in $T - T_d$ criteria (used to signal onset and offset of wetness) when they are derived from different seasons' data. Therefore, these criteria may not work as well in a growing season other than the one from which they were derived. To test for this potential problem, we first selected our model with the longest history of application, DAILY r(87) from Ridgetown, and applied it to three other years (Table 3). The model performed well in 1989 and 1991, but gave results 50% higher than TOM-CAST in 1990. Further evidence of model deterioration in 1990 was obtained by selecting the $T - T_d$ criteria derived for each station in 1989 and applying them to the 1990 and 1991 data (Table 4). At all sites except Leamington in 1990, DAILY w(89) requested one to three more sprays than necessary. But in 1991, DAILY w(89) returned to good performance by requesting the correct number of sprays at four sites and only one extra spray at Ridgetown.

A possible explanation for the modeled overestimates of DSV and required sprays in 1990 may be found in wind data. May, June, and to a lesser extent July, were abnormally windy in 1990 (Table 5). The effect of increased windiness would be to reduce wetness duration, but this is not explicitly described in our scheme, which used only dewpoint depression. The expected result is an overestimate of DSV by the dewpoint method, which matches the errors seen in 1990.

d. A calibration scheme

For an operational system, it is not practical to rederive $T - T_d$ criteria for each growing season. We therefore devised the base-station calibration scheme described earlier (section 2f) to account for season-to-season variability that can sometimes degrade the spray timing advice (e.g., 1990). The 1989 criteria were chosen as the "master set" to be used for all satellite stations in all years.

TABLE 4. Number of sprays requested by DAILY models using 1989 criteria in 1989, 1990, and 1991.

Site	TOM-CAST 1989	DAILYw(89) 1989	TOM-CAST 1990	DAILYw(89) 1990	TOM-CAST 1991	DAILYw(89) 1991
Ridgetown	5	6	6	9	4	5
Blenheim	6	6	7	8	5	5
Leamington	7	6	7	7	5	5
Tilbury	7	8	7	10	5	N/A*
Harrow	8	8	6	8	5	5
Kent A	6	6	6	7	5	5

* Temperature measurement equipment failed.

Harrow and Ridgetown are the most desirable choices as base stations in the test region because they are research station sites where the necessary maximum and minimum temperature observations for a DAILY w model, and the hourly temperature and wetness data for TOM-CAST, can be efficiently maintained. They are also near the east and west ends of the geographical area of this study. Harrow is close to Lake Erie, and Ridgetown is farther inland. Therefore, both these sites were tested as potential base stations in 1989, 1990, and 1991 to ensure that the calibration scheme did not degrade DAILY $w(89)$ performance in 1989 and 1991 and improved its performance in 1990 (Fig. 3).

In 1989, agreement with sprays requested by TOM-CAST was improved by calibration using Ridgetown as the base station at Tilbury and Ridgetown itself (self-calibration is designed to mimic TOM-CAST). Blenheim, Leamington, and Harrow were overcorrected (fewer sprays than required for TOM-CAST) by Ridgetown calibration factors in this year. Harrow-based calibration improved Tilbury in 1989 and did not degrade any station where the uncalibrated scheme already matched TOM-CAST. In 1990, Harrow corrections improved the estimates of required fungicide sprays relative to TOM-CAST at all sites except Leamington, but Ridgetown corrections only improved Leamington and Harrow. Ridgetown-based calibrations in 1990 resulted in overcorrections at three sites (Blenheim, Leamington, Dresden), two of which were changed from one spray more than TOM-CAST to one spray less. For 1991, Harrow-based calibration did not change the excellent performance of the uncalibrated scheme at most satellite sites (Paincourt excepted, one spray too few). Ridgetown calibrations gave one less spray at the Leamington satellite. Self-calibration would be used at both Harrow and Ridgetown themselves.

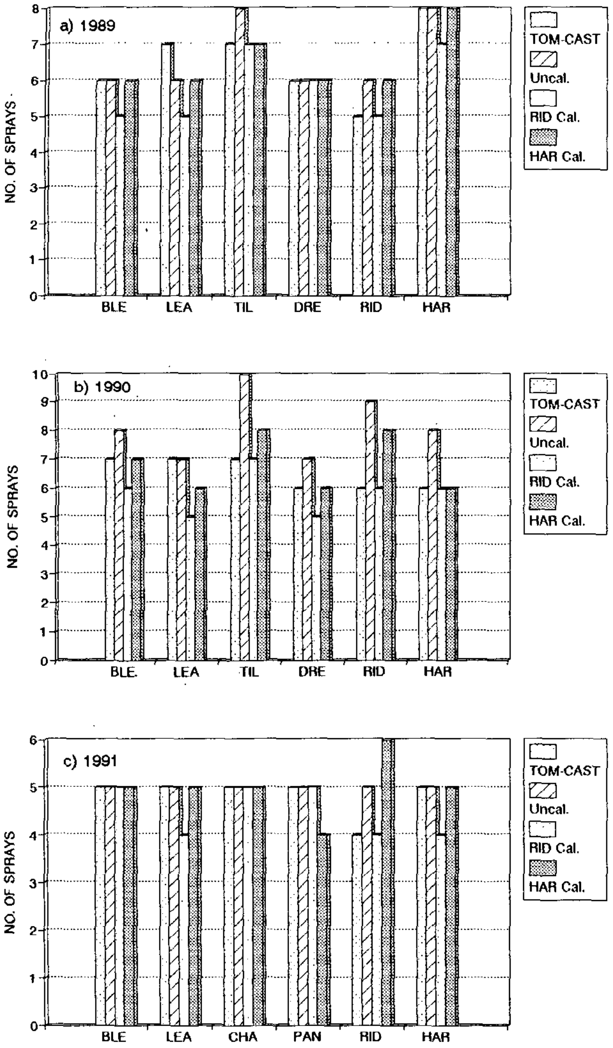

FIG. 3. Numbers of sprays requested by TOM-CAST and three DAILY $w(89)$ models: uncalibrated, Ridgetown-based calibration and Harrow-based calibration at Blenheim (BLE), Chatham (CHA), Dresden (DRE), Harrow, (HAR), Leamington (LEA), Paincourt (PAN), Ridgetown (RID), and Tilbury (TIL). (a) 1989, (b) 1990, (c) 1991.

TABLE 5. Average monthly wind speed (km h^{-1}) at Ridgetown.

	1989	1990	1991
May	11.6	17.4	14.3
June	9.7	17.2	12.2
July	10.3	12.9	11.1
August	11.0	9.5	10.5

Based on these results, calibration using Harrow as the base station was most successful in matching DAILY w models to TOM-CAST. Tilbury and Paincourt were exceptions; they were better calibrated from Ridgetown. Calibration using the appropriate base station did not interfere with the performance of DAILY w models when calibration was really not needed, except at Leamington, which matched TOM-CAST just as well when left uncalibrated. An analysis of this kind allows the best match between satellite and base stations to be established in a region.

e. *Field fungicide spray trials*

Table 6 summarizes the results from replicated field plot trials of several HOURLY and DAILY models in 1989 and 1990 at Ridgetown. Spray schedules based on all models provided yields that were not significantly different from TOM-CAST. This would be expected since these models called for an equal or greater number of sprays than TOM-CAST. The use of sprays that were rationally scheduled according to weather data significantly lowered foliar and fruit disease and increased yields over the check (no spray) treatment in both years. The calendar-timed 10-day schedule did not improve yields over a weather-timed scheme, even though it required a 40% increase (two more sprays) in fungicide use when tested in 1989.

Data presented earlier for 1990 (Table 4) have shown

TABLE 6. Ridgetown field fungicide trials: 1989 and 1990.

	Number of sprays		Disease ratings[a]				Yields (tons ha^{-1})	
			Foliage[b]		Fruit[c]			
Treatment	1989	1990	1989	1990	1989	1990	1989	1990
TOM-CAST	5	4	1.4 (1)[a]	2.0 (1)	7 (1, 2)	1 (1)	60 (2)	38 (2)
HOURLYr(87)	5	6	2.0 (1, 2)	1.4 (1)	9 (1, 2)	0 (1)	63 (2)	40 (2)
HOURLYw(89)	—[d]	5	—[d]	1.9 (1)	—[d]	0 (1)	—[d]	38 (2)
DAILYr(87)	5	6	2.5 (1, 2, 3)	1.7 (1)	7 (1, 2)	1 (1)	57 (2)	38 (2)
10-day schedule	7	—[d]	2.5 (1, 2, 3)	—[d]	10 (1)	—[d]	57 (2)	—[d]
Check (no fungicide)	0	0	6.2 (4)	5.7 (2)	28 (3)	15 (2)	36 (1)	29 (1)

[a] Values followed by the same parenthetical number are not significantly different at the 5% level (Duncan's multiple range test).

[b] Visual foliar disease rating (0 = no disease, 10 = all leaf area diseased).

[c] Percent fruit showing anthracnose.

[d] Not tested.

the difficulty of using $T - T_d$ criteria derived from 1989 in the 1990 season. Uncalibrated HOURLY and DAILY models from 1987 and 1989 both overpredicted the required number of sprays in 1990, relative to TOM-CAST, yet these extra sprays gave no yield advantage (Table 6). This supports our belief that calibration is necessary to permit a weather-timed scheme based on a fixed set of $T - T_d$ criteria to be used over several different growing seasons.

4. Conclusions

Several schemes have been tested that combine locally measured temperatures and regional-scale dewpoints to infer the duration of leaf wetness from $T - T_d$ criteria and hence to warn of potential disease on tomatoes. For operational purposes, DAILY w models based on locally measured maximum and minimum temperatures and distance-weighted dewpoints are preferred.

A different $T - T_d$ criterion was required for onset and offset of wetness for each station. When criteria were used in the same season for which they were derived, DAILY w models matched the number of sprays requested by TOM-CAST exactly, or within one spray. However, when criteria from one season were applied to data from a different season (e.g., 1989 criteria applied in 1990), overpredictions of up to three sprays were sometimes made by DAILY w models.

A calibration scheme, devised to compensate for season-to-season variation in criteria, required that both TOM-CAST and the "master" model be run at a base station. When a daily correction factor based on a comparison of TOM-CAST and the "master" model at the base station was applied to DAILY w models at appropriate satellite stations, they matched the TOM-CAST number of sprays exactly, or within one spray. Such a calibration scheme appears necessary in some seasons to compensate for the simplistic nature of a wetness-duration estimate that is based on dewpoint depression, and therefore does not fully account for other important influences on leaf wetting and drying, such as wind.

Because of its simplistic nature, the scheme has a very practical application. Rational timing of fungicide sprays according to weather information provides clear benefits to growers in terms of labor and cost savings, reduces the likelihood that the target disease organisms will become resistant to control because of chemical overuse, and decreases the chemical load on the environment. Each fungicide application is currently estimated to cost growers about $18 (Canadian) per acre. Since there are about 25 000 acres of tomatoes in our region, each reduced spray represents about one-half million dollars in saved revenue.

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REFERENCES

Gillespie, T. J., and R. X. Duan, 1987: A comparison of cylindrical and flat plate sensors for surface wetness duration. *Agric. For. Meteor.,* **40,** 61–70.

Jones, A. L., 1986: Role of wet periods in predicting foliar disease. *Plant Disease Epidemiology,* Vol. 1, K. J. Leonard and W. E. Fry, Eds., MacMillan, 87–100.

Madden, L. V., S. P. Pennypacker, and A. A. McNab, 1978: FAST: a forecast system for *Alternaria solani* on tomato. *Phytopathology,* **68,** 1354–1358.

Madden, L. W., and M. A. Ellis, 1988: How to develop plant disease forecasters. *Experimental Techniques in Plant Disease Epidemiology,* J. Kranz and J. Rotem, Eds., Springer-Verlag, 191–208.

Parton, W. J., and J. A. Logan, 1981: A model for diurnal variation in soil and air temperature. *Agric. Meteor.,* **23,** 205–216.

Pitblado, R., 1992: *The Development and Implementation of TOM-CAST.* Ont. Minist. Agric. Food, 25 pp.

Srivastava, B., R. E. Pitblado, and T. J. Gillespie, 1989: Estimation of disease severity in tomatoes from standard meteorological data in Ontario, Canada. *Proc. 19th Conf. on Agricultural and Forest Meteorology,* Charleston, Amer. Meteor. Soc., 64–66.

World Meteorological Organization, 1988: Agrometeorological aspects of operational crop protection. World Meteorological Organization Tech. Note No. 192, 165 pp.