Introduction of Sugarcane Rust into the Americas and Its Spread to Florida

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ABSTRACT

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Sugarcane rust appeared in the Americas in 1978, probably as a result of transoeceanic transport of urediospores of *Puccinia melanocephala* from the Cameroons in West Africa to the Dominican Republic in the Caribbean. Based on upper-air wind trajectories, urediospores could have arrived in the Dominican Republic 9 days after they were airborne over the Cameroons. After rapid disease development in the Dominican Republic on the very susceptible sugarcane cultivar B 4362, the rust spread in the Americas to Venezuela in the south and to Florida in the north by wind transport of urediospores.

Plant disease epidemics in general are analyzed retrospectively because extensive disease development may not always occur. Such analyses, however, can be used to predict disease onset and subsequent disease development for certain pathosystems. Such predictions might relate to seasonal or yearly development of disease in crops that grow where disease inoculum is known to be present during each cropping season. Potato late blight, peanut leaf spot, and banana leaf spot (sigatoka) represent such endemic situations. Other epidemics, such as fusiform rust of pine in the southeastern United States, have been in progress for years, and analyses of such systems have improved disease management. There are other cases where analysis is always retrospective, namely those epidemics that appear unexpectedly in geographic locations far removed from any source of inoculum. Coffee rust in Brazil, corn rust in Africa, and sigatoka in the Americas are epidemics that appeared spontaneously.

The rust disease of sugarcane (interspecific hybrids of *Saccharum*) caused by *Puccinia melanocephala* H. & P. Sydow has been present in scattered locations in Africa and Asia as localized outbreaks of minor significance for many years. During July 1978, sugarcane rust first appeared in the Dominican Republic (18). About 1 yr later, it had spread to almost all sugarcane-growing areas in the Americas except the regions south of Colombia and Venezuela. In this paper, we examine the question regarding the source of inoculum that triggered the Pan-American epidemic of sugarcane rust through a retrospective analysis of mesocale meteorology during the 30-day period before 3 July 1978. The emphasis is on establishing Africa as the likely source of pathogen inoculum and its subsequent movement to the Dominican Republic and spread to the Caribbean and Florida.

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There are few if any well-documented cases of transport of fungal spores that resulted in transoceanic spread of plant diseases. Much retrospective information about the movement of *Phytophthora infestans* in the mid-1850s has been presented (3). Also, movement of spores of the blue mold pathogen from mainland Europe to England has been analyzed (20). Examples of transoceanic movement of fungal spores and spread of disease include corn rust (6), coffee rust (4,22), and banana leaf spot (sigatoka) (*Mycosphaerella musicola*) (25). Of these, sigatoka is of considerable interest. The disease spread from Africa and Asia to the Caribbean within 1 yr (1933–1934). The path of transport followed a straight line from Australia through the Cameroons to the Caribbean, a distance of 15,000 mi. (25). Stover (25) suggested that a "fortuitous combination of disease, climate, and air turbulence superimposed on the belt of easterlies" resulted in the introduction of the disease into the Caribbean.

Bowden et al (4) provided data on the frequency of surface winds from southwestern Africa to Bahia, Brazil, where coffee rust (*Hemileia vastatrix*) was introduced. They suggested that coffee rust spores could have traveled from Africa to Brazil within 5–7 days. Pady and Kelly (17) trapped fungal spores during flights over the North Atlantic at elevations of 2,440–2,745 km (8,000–9,000 ft). They observed that tropical air masses contained more fungal spores than arctic air masses and suggested that where an abundance of fungal spores are produced (such as the tropics), their injection into the upper air may occur. Hirst and Hurst (11) concluded that these flights added little to the knowledge gained from shipboard trappings except that spore concentrations at the measured heights exceeded those at sea level. Presence of particulate matter such as volcanic ash, smoke, Saharan sand, etc., in upper-altitude air has been demonstrated by satellite imagery (14–16). Horizontal movement of particulate matter in upper air may be similar to that of fungal spores even though densities and terminal deposition velocities of some of the particulate matter may differ from those of fungal spores. For example, a Saharan dust cloud traveled through the Atlantic trade winds from the coast of West Africa to the Caribbean area within 5 days in June 1977 (Fig. 1).

Introduction of sugarcane rust into the Americas. In 1978, a sugarcane rust epidemic began in the Dominican Republic on the cultivar B 4362 that had been grown free of rust in the Caribbean region for more than 20 yr (27). The nearest known source of *Puccinia melanocephala* to the Americas in early 1978 was the Cameroons in West Africa (9,27). The rust initially developed on B 4362 in the Dominican Republic during 1978 because of two important events: 1) Viable urediospores of *P. melanocephala* were deposited on leaves of B 4362, and 2) infection occurred. Purdy et al (19) mentioned at least three possible sources for the inoculum that triggered the American epidemic:

1. *P. melanocephala* was always present in the Dominican Republic on other hosts or on cultivars of sugarcane other than B 4362, and the rust suddenly exploded into a severe problem as a result of changes in crop management practices. The demonstrated susceptibility of B 4362 to *P. melanocephala* is ample evidence to reject this option, because if rust had been in the Dominican Republic before 1978, its presence would most certainly have been obvious on this very

susceptible cultivar. Also, there were no changes in the crop management practices in the Dominican Republic from 1977 to 1978.

2. Rust was introduced into the Dominican Republic through transport of infected plant material or by use of contamiated implements. This option has a low probability because 1) rust pustules are very rare on leaf sheaths, 2) infection of buds on seed cane has not been demonstrated, 3) infection of emerging shoots has also not been demonstrated, and 4) there has been no transfer of labor force and equipment to the Dominican Republic from areas where rust occurred in 1978 or before.

3. Viable urediospores were probably transported to the Dominican Republic by wind. Prevailing winds in the southern hemisphere are east to west. It is probable that coffee rust (*Hemileia vastatrix*) arrived in Brazil from Africa by such wind transport. Intercontinental spread of the sigatoka disease of banana into Central America probably resulted from spores carried across the Atlantic Ocean. Inoculum production sites for sigatoka, East Africa and the Cameroons (25), are almost identical to locations in Africa where sugarcane rust occurred in early 1978.

Prevailing wind direction accounts for the average direction of wind movement but does not consider the frequent directional changes within a stated time period. Cyclonic winds are common in areas where sugarcane is cultivated, and disturbances associated with cyclonic winds may be responsible for vertical movement of urediospores to high altitudes and horizontal movement over a long distance in directions not normally influenced by the prevailing winds. Such a process appears to have introduced urediospores of *P. melanocephala* into the Dominican Republic from their most likely site of origin, the African continent. Bernard (2) speculated that rust arrived in the Dominican Republic in a dust cloud.

Localized epidemics seem to have developed in the direction of surface or near-surface winds coupled with high-altitude winds, as with coffee rust in Brazil (22). From the Dominican Republic, sugarcane rust moved to adjacent areas, southward as far as Venezuela and Colombia; westward to Jamaica, Cuba, Central America, and Mexico; and northward to Florida, Louisiana, and Texas—all by wind movement of urediospores. Thus, within 1 yr, sugarcane rust had attained a Pan-American distribution.

A common source of inoculum for the outbreaks of sugarcane rust in the Americas and Australia is not likely according to Egan and Ryan (9). They speculate that the Australian sugarcane rust epidemic, first reported in October 1978, might have originated from urediospore transport to Australia in mid-1978 by the winds of the northwest monsoonal inflow from areas of the Indian Ocean (9). This may be possible, but the Caribbean seems a more probable source of spores for the Australian outbreak of rust because of the massive amounts of urediospores produced on B 4362, the cultivar that occupied much of the sugarcane-planting region in the Caribbean in 1978. Urediospores from the Caribbean arriving in Australia any time before September 1978 could have initiated the epidemic reported in October 1978. Whittle (27) observed that there were no differences in the dimensions of urediospore populations from 36 collections of *P. melanocephala* from locations around the world. Thus, the dimensions of urediospores from Australia were within the limits of the

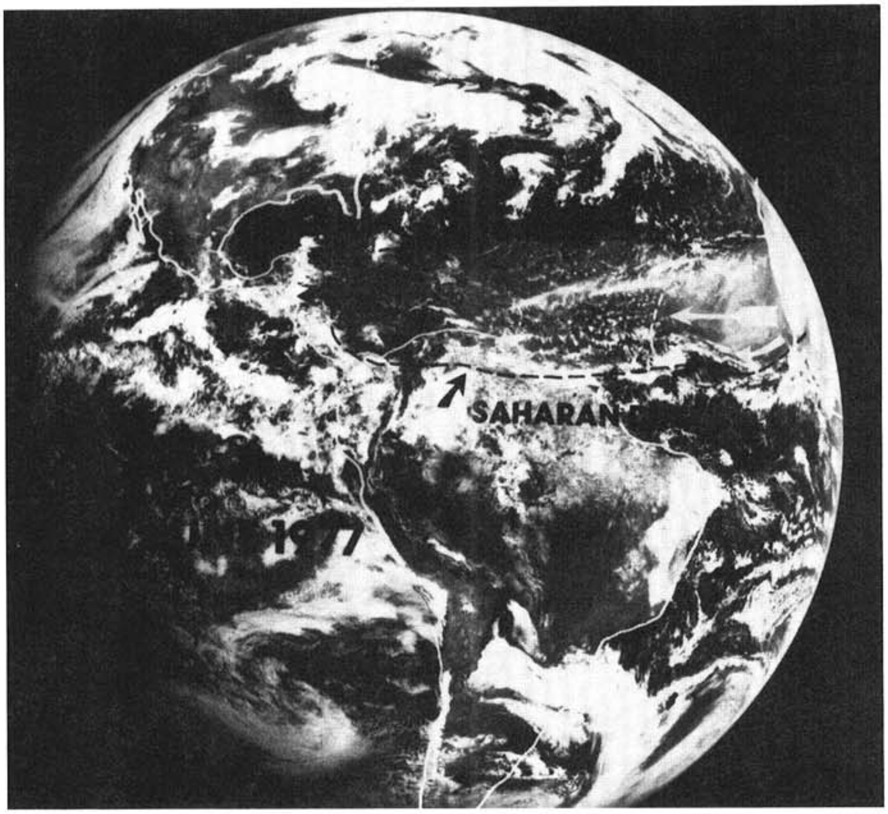

Fig. 1. "Full disk" visible GOES satellite image showing a massive Saharan dust cloud extending from West Africa into the Caribbean. The leading edge of this dust cloud crossed the Atlantic ocean within about 5 days in June 1977.

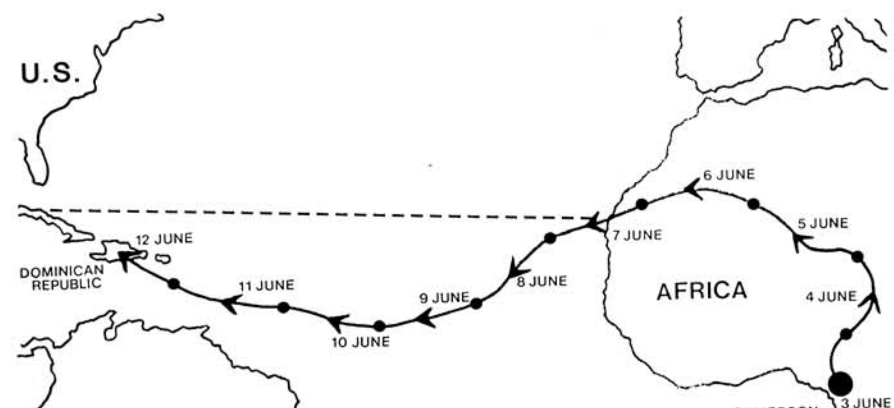

Fig. 2. Forward trajectories for air parcels, presumably containing urediospores of sugarcane rust, injected into the lower atmosphere over the Cameroons on 00Z, 3 June 1978, showing their crossing of the Atlantic ocean and landing in the Dominican Republic on 12 June 1978.

range of variation of the West Indian samples.

Sugarcane rust present in the Cameroons in 1978 (9,27) was the closest source of inoculum (urediospores) to the Caribbean. The urediospores of *P. melanocephala* are similar to urediospores of *P. graminis* in size ($20 \times 30\ \mu m$), shape (obovoid), and density ($1\ g/cm^3$) with a terminal deposition velocity of 12.2 mm/sec (26). A urediospore of *P. melanocephala* at an altitude of 3,000 m would take 2.3 days to settle to the earth's surface in nonturbulent airflow. With a uniform wind speed of 10 m/sec, horizontal transport of 2,000 km would occur during the 2.3 days, according to W. A. Lyons (*unpublished*) in a 1983 report to University of Florida. These theoretical aspects apply directly to the transport of urediospores because the gravitational force acts in a constant manner on urediospores suspended in the atmosphere (23). Introduction of urediospores into upper air layers may occur in updrafts associated with thunderstorms. Land masses in the Gulf of Guinea have some of the highest frequencies of thunderstorms in the world (W. A. Lyons, *unpublished*). Also, burning of sugarcane fields immediately before harvest creates convective columns of rapidly rising air that would also elevate urediospores. Once urediospores are elevated to several thousand meters, they could be resuspended continually because of the normal turbulence that is commonly high in tropical regions. Temperatures in the tropical atmosphere generally remain above 0 C until heights of at least 6 km. Lower temperatures at greater heights would seemingly have little or no effect on urediospore viability.

The intertropical convergence zone (ITCZ) separates the tropical air masses of the northern and southern hemispheres and resembles a front between these air masses. During June 1978, the ITCZ located across northern Africa crossed the Atlantic Ocean at a latitude of about 10° N and passed across northern South America and the southern Caribbean (7). Urediospores of sugarcane rust may have been elevated by convective updrafts, thunderstorms, or other means into free air over the Cameroons and drifted north toward the ITCZ under the influence of southwesterly trade winds. Subsequently, the urediospores may have moved into altitudes of 1,500–3,000 m as a result of broad-scale synoptic vertical motion or a thunderstorm system. Urediospores could have then been imbedded in the easterly trade wind at a latitude of about 10–15° N.

Available weather data support the view that a urediospore injected into the lower atmosphere over the Cameroons on 3 June 1978 could have drifted north and northeast in the general pattern of surface airflow. After 72 hr, the urediospores would have been over west central Africa at a height of 1,500–2,000 m, at which time they would have begun a decisive transoceanic trajectory. During this period, the Azores high was strong, and that provided a well-developed east-northeast flow north of the ITCZ. From satellite cloud-tracking procedures and sparse overocean wind reports, cloud motions were found that are typical of the airflow conditions in the layer 1,500–2,000 m. This information, combined with geostatic winds represented by isobars, provided wind directions for a streamline analysis.

A wind trajectory analysis was performed by drawing streamlines on each surface map for 00 and 12 Greenwich Mean Time (GMT), and the rust spores were considered to have followed the streamlines for 6 hr before and 6 hr after the map time (Fig. 2). The location of the spores was then transferred to the map and the process was repeated until the spores reached the Caribbean. Forward wind trajectories

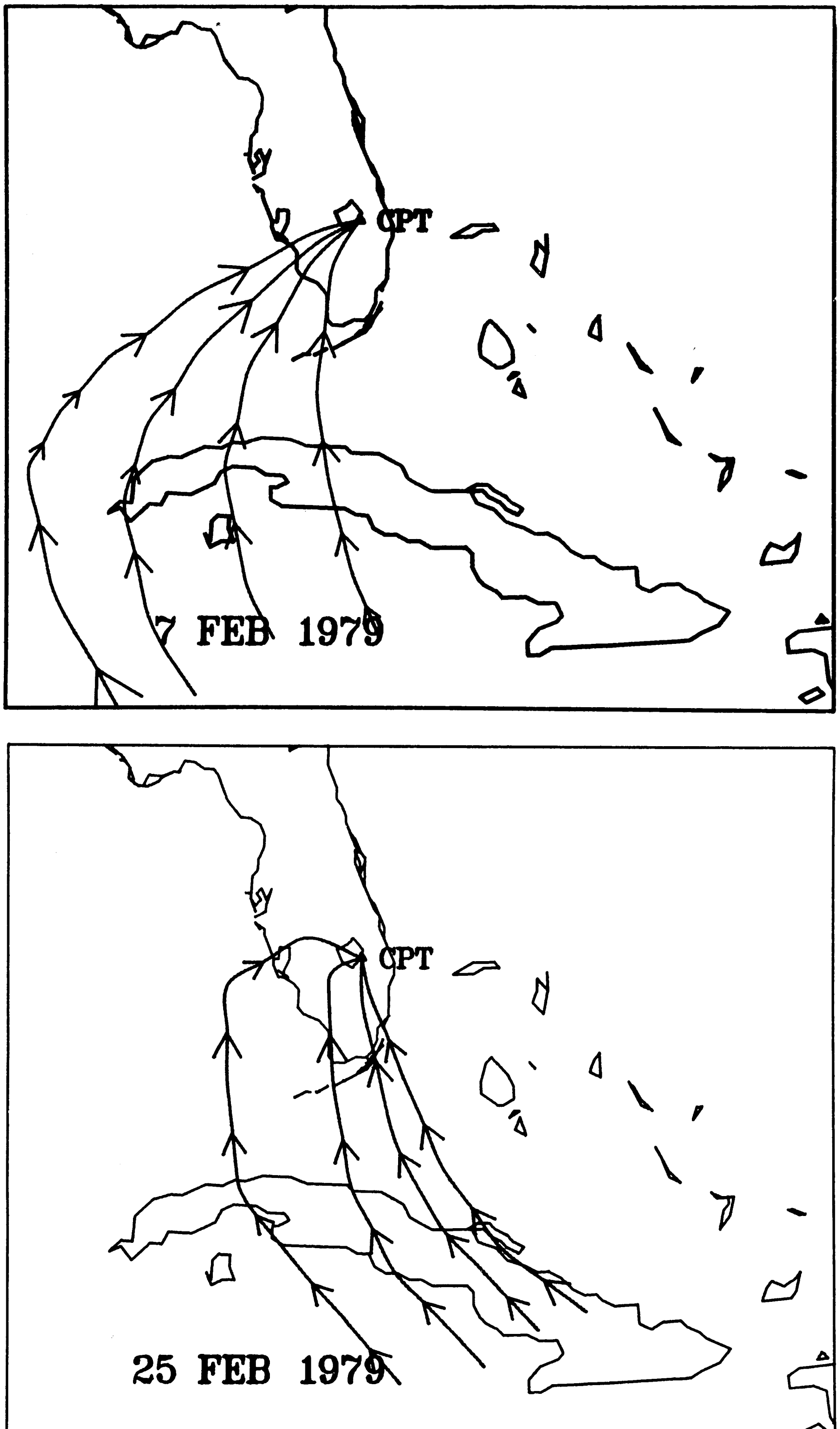

Fig. 3. Back air-parcel trajectories for Canal Point, FL, for 7 and 25 February 1979 that show the origin of the air parcels directly over Cuba.

show that rust spores originating in the Cameroons and starting a transoceanic crossing at 00Z GMT, 3 June 1978, could have arrived in the Dominican Republic (the Caribbean) around 2100 GMT, 12 June 1978, 9 days after the spores became airborne. Possible errors in trajectory analysis limit accuracy of the landing site in the Caribbean. In spite of this limitation, wind-flow patterns show that a trans-Atlantic passage of urediospores from the Cameroons to the Caribbean was possible during June 1978. Therefore, we suggest that sugarcane rust was indeed introduced into the Americas as we have described.

Pan-American sugarcane rust epidemic. Sugarcane rust was observed for the first time in the Americas on 3 July 1978 in the Dominican Republic (18). The disease symptoms were observed in a 1.6-ha (4-acre) area on 3 July, suggesting that a spore shower had occurred at this site sometime before 3 July. The cycle from urediospore germination followed by infection and pustule formation takes place within 7 days at 25 C (24). Average temperature in June 1978 in the Dominican Republic was about 34 C and rainfall ranged from 2.7 to 155.2 cm (13). Liu and Bernard (13) concluded that temperatures lower than 35 C were not limiting factors to urediospore germination and host infection. A urediospore generation time of 7 days in laboratory studies supports the supposition that urediospores were deposited on leaves of sugarcane cultivar B 4362 before 25 June 1978. Thus, the urediospores arriving in the Dominican Republic on 12 June 1978 could have initiated the disease locus. Subsequently, one or more cycles of urediospores could have been produced, resulting in the 1.6 ha (4 acres) of disease observed on 3 July 1978. A short generation time and an abundance of urediospores produced on B 4362 could have ensured a successful epidemic and thus, 20 days later (23 July 1978), 51 ha (125 acres) of sugarcane were rusted.

There is little documentation of spread of rust from the Dominican Republic to other islands. Sugarcane rust appeared in Jamaica in early September 1978 (5), and by 11 October 1978, it was also observed in Puerto Rico (12). After the first appearance of sugarcane rust in Cuba in September 1978 (21), losses in production amounting to millions of pesos in 1979–1980 were attributed to the disease in that country. The rust should have arrived in Cuba soon after it appeared in Jamaica, and thus, the disease spread through B 4362 (40% of the sugarcane acreage) in Cuba. Spread to Florida followed, and on 23 March 1979, rust was observed on the eastern and western sides of Lake Okeechobee in south central Florida (8).

Forward and backward air-parcel trajectories for the period 7 February to 9 March 1979 were developed from the weather data collected by the National Oceanic and Atmospheric Administration by the method of Heffter (10). Airflow that impinged on Canal Point, FL (the eastern location where rust was first found), originated or passed over Cuba and nearby locations on 7, 16, 17, and 21–26 February and on 1–7 March 1979. As an example, air-parcel trajectories for 7 and 25 February 1979 are illustrated in Figure 3.

Sotomayor et al (24) reported urediospore germination of 97–98% in 6 hr over a temperature range of 15–30 C (59–86 F). Percentages of germinated urediospores where germ tubes formed appressoria ranged from 47 to 99 at the same temperatures. Water on segments of the leaf surface was present to support germination of urediospores in their studies. Percentages of germination were slightly lower as were percentages of appressoria after 4 hr, but percentages of germinated urediospores and appressoria were adequate to initiate disease. According to the data presented by Sotomayor et al (24), infection of sugarcane can be initiated over a temperature range of 5–30 C when water is present for at least 6 hr.

Minimal, maximal, and mean temperatures along with leaf wetness periods are presented in Table 1 for the days in February and March 1979 during which winds that impinged on Canal Point, FL, passed over Cuba and/or other nearby locations. These data (Table 1) were collected at Belle Glade, FL, 26 km (16 mi.) south of Canal Point. This information has geographic limitations relative to Canal Point; however, it provides a general view.

With 40% of the sugarcane production of Cuba in 1978–1979 consisting of the cultivar B 4362, it is expected that enormous quantities of urediospores were produced, much of which were probably elevated by turbulence and injected into upper winds that may have been influenced by the upper-air trajectories destined for Canal Point. Havana, Cuba, is roughly 450 air kilometers (280 mi.) from Canal Point. Based on wind velocities 6 m (20 ft.) above the surface at Belle Glade, FL, for the days of interest, air parcels from Havana could have covered the 450 km (280 miles) within roughly 1 day to as long as 4 days.

Although upper-air wind trajectories originated in or near Cuba, leaf wetness was inadequate to support germination of urediospores on 3 and 26 February 1979 (1). However, all other days were favorable for urediospore germination, development of appressoria, and the penetration of leaves.

Sugarcane rust produced new urediospores after 7 days on detached sugarcane leaves in the laboratory at 25 C. Extrapolation of this data supports the contention that rust of sugarcane that was first detected in Canal Point on 23 March 1979 (8) could have been initiated on 7, 16, 17, 22, 24, and 25 February and on 1–7 March 1979. It is probable that at least two or more generations of urediospores were produced in Florida before the disease was detected in highly susceptible cultivars and selections in plots of the breeding program at the USDA Sugarcane Field Station at Canal Point.

Rust was also detected on 23 March 1979 in the plots of the breeding program of United States Sugar Corporation in Clewiston, FL, on the western shore of Lake Okeechobee after notification that rust was observed in Canal Point.

Conclusions. Retrospective analyses of airflow patterns from the Cameroons (West Africa) to the Dominican Republic

Table 1. Air temperature and leaf wetness recorded at the Agricultural Research and Education Center, University of Florida, Belle Glade, during 1979 for days in February and March 1979 when airflow that impinged on Canal Point, FL, originated over Cuba

Date	Air temperature (C)			Wetness[a]	
	Minimum	Maximum	Mean	Hr	Min
February					
7	19.0	29.7	24.4	14	40
16	9.5	25.8	17.6	10	0
17	12.8	26.3	19.6	9	40
21	17.3	27.4	22.4	3	0
22	18.5	27.4	23.0	16	10
23	17.9	28.0	23.0	13	30
24	19.6	29.1	24.4	10	40
25	18.5	28.0	23.2	12	30
26	12.3	19.6	16.0	4	0
March					
1	11.8	27.4	19.6	10	40
2	14.6	27.4	21.0	7	0
3	13.5	27.4	20.4	8	20
4	16.8	27.4	22.1	11	30
5	17.9	27.4	22.6	14	20
6	15.1	24.6	19.9	10	30
7	14.6	20.2	17.4	14	20

[a] Leaf wetness expressed as hours and minutes during which moisture from rain or dew was on foliar surface.

(the Caribbean) suggest that transoceanic movement of urediospores of sugarcane rust was possible in June 1978.

Tropical weather disturbances that originated over the Atlantic Ocean moved westward into the Caribbean. Transport of sugarcane rust urediospores from the Dominican Republic to Jamaica and Cuba, a distance of about 644 km (400 mi.), most likely occurred in association with a tropical disturbance. Additional movement of urediospores to various sites in the Americas also took place by wind flow from areas where the disease occurred and proceeded to other locations where the disease was introduced.

We believe that the information presented supports our conclusion that sugarcane rust was indeed introduced into the Americas as a result of transoceanic transport of urediospores from the Cameroons. The explosive, rapid spread of sugarcane rust within the Americas may have resulted from dissemination of urediospores by wind in patterns of movement associated with tropical weather disturbances. Also, we suggest that sugarcane rust detected in Queensland, Australia, developed as a result of additional transoceanic transport of urediospores from the Caribbean to Queensland.

LITERATURE CITED

1. Allen, R. J., Jr. 1980. 1979 Climatological Report. Belle Glade AREC Res. Rep. EV-1980-5. Univ. Fla. 19 pp.
2. Bernard, F. A. 1980. Considerations of appearance of sugarcane rust disease in the Dominican Republic. Proc. Int. Soc. Sugarcane Technol. 17:1382-1386.
3. Bourke, P. M. A. 1964. Emergence of potato blight, 184346. Nature (Lond.) 203:805.
4. Bowden, J., Gregory, P. H., and Johnson, C. G. 1971. Possible wind transport of coffee rust across the Atlantic ocean. Nature 229:500-501.
5. Burgess, R. A. 1979. An outbreak of sugarcane rust in Jamaica. Sugarcane Pathol. Newsl. 22:4-5.
6. Cammack, R.H. 1959. Studies on *Puccinia polysora* Underw. II. A consideration of the method of introduction of *P. polysora* into Africa. Trans. Br. Mycol. Soc. 42:27.
7. Chang, J. 1972. Atmospheric Circulation Systems and Climate. Oriental Publishing Company, Honolulu, HI. 328 pp.
8. Dean, J. L., Tai, P. Y. P., and Todd, E. H. 1979. Sugarcane rust in Florida. Sugar J. 42(2):10.
9. Egan, B.T., and Ryan, C.C. 1979. Sugarcane rust caused by *Puccinia melanocephala* found in Australia. Plant Dis. Rep. 63:822-823.
10. Heffter, J. L. 1980. Air resourses laboratories atmospheric transport and dispersion model. NOAA Tech. Memo. ERL ARL 81, Nat. Oceanic Atmos. Admin., Silver Spring, MD. 17 pp.
11. Hirst, J. M., and Hurst, G. W. 1967. Long distance spore transport. Pages 307-344 in: Airborne Microbes. P. H. Gregory and J. L. Montieth, eds., Cambridge University Press, Cambridge.
12. Liu, L.-J. 1979. Rust of sugarcane in Puerto Rico. Plant Dis. Rep. 63:256-258.
13. Liu, L.-J., and Bernard, F. 1979. Sugarcane rust in the Dominican Republic. Sugarcane Pathol. Newsl. 22:5-7.
14. Lyons, W. A. 1975. Satellite detection of air pollutants. Pages 263-290 in: Remote Sensing Energy Related Studies. T. N. Vezeroglu, ed. John Wiley & Sons, New York.
15. Lyons, W. A. 1980. Evidence of transport of hazy air masses from satellite imagery. Ann. N.Y. Acad. Sci. 338:418-433.
16. Lyons, W. A., and Husar, R. B. 1976. SMS/GOES visible images detect synoptic scale air pollution episodes. Mon. Weather Rev. 103:1623-1626.
17. Pady, S. M., and Kelly, C. D. 1954. Aerobiological studies of fungi and bacteria over the Atlantic Ocean. Can. J. Bot. 32:202-212.
18. Pressley, J. T., Perdomo, R., and Ayats, J. D. 1978. Sugarcane rust found in the Dominican Republic. Plant Dis. Rep. 62:843.
19. Purdy, L. H., Liu, L.-J., and Dean, J. L. 1983. Sugarcane rust, a newly important disease. Plant Dis. 67:1292-1296.
20. Rayner, R. W., and Hopkins, J. C. F. 1962. Blue mold of tobacco. A review of current information. Comm. Mycol. Inst. Misc. Publ. 16:1.
21. Sandoval, I. 1979. *Puccinia erianthi* Padw. & Khan, agente causal de la roya de la cana de asucar en Cuba. Pages 152-153 in: ATAC 42nd Conf.
22. Schieber, E. 1975. Economic impact of coffee rust in Latin America. Annu. Rev. Phytopathol. 10:491-510.
23. Schrodter, H. 1960. Dispersal by air and water—the flight and landing. Pages 169-277 in: Plant Pathology: An Advanced Treatise. Vol. 3. J. G. Horsfall and A. E. Dimond, eds. Academic Press, New York.
24. Sotomayor, I. A., Purdy, L. H., and Trese, A. T. 1983. Infection of sugarcane leaves by *Puccinia melanocephala*. Phytopathology 75:695-699.
25. Stover, R. H. 1962. Intercontinental spread of banana leaf spot (*Mycospherella musicola*). Trop. Agric. Trinidad 39:327-338.
26. Weinhold, A. R. 1955. Rate of fall of urediospores of *Puccinia graminis tritici* Erikss. and Henn. as affected by humidity and temperature. Tech. Rep. Off. Naval Res. Contract N 9 onr 82400, Task Order 82402. 104 pp.
27. Whittle, A. M., and Holder, D. 1980. The origin of the current rust epidemic in the Caribbean. Sugarcane Pathol. Newsl. 24:4-7.