NOAA Technical Memorandum ERL AOML-77

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THE VARIABILITY OF THE SOUTH FLORIDA MEAN ANNUAL SURFACE AIR TEMPERATURE DURING THE LAST THREE DECADES

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ABSTRACT. The observed mean annual surface air temperature at Miami International Airport (MIA) exceeded the 30-year (1961-1990) mean by 1.2 to 2.4 standard deviations between 1989 and 1992. This was the result of a warming trend that started in the late 1960's and accelerated sharply in the mid 1980's. Unfortunately, the MIA surface temperature data cannot be taken at face value. At times during these years, the site for measuring daily surface maximum and minimum temperature was poorly positioned. There was a significant relocation of the equipment in the late 1970's. There have been three important changes of instrumentation from the original liquid in glass extreme thermometers to a series of electronic hygrothermometers, culminating in the installation of the less than ideal HO-83 in 1985. To determine the impact of these activities, the MIA temperature data were compared with data obtained at Palm Beach International Airport (PBI) and Page Field at Fort Myers (FMY). The latter are the NWS first-order stations closest to MIA. Comparisons were also made with data from nearby cooperative (COOP) stations and with data from the FAA station at Fort Lauderdale International Airport (FLL). Comparisons were also made with precipitation data from MIA, PBI, and FMY.

At least part of the accelerated warming in the 1980's must be attributed to a general south Florida warming during these years. However, MIA and PBI warmed faster than their neighboring COOP stations during the late 1980's, indicating that some artificial warming resulted from the HO-83 installations. The MIA mean annual daily minimum temperatures show systematic fluctuations but not a statistically-significant, long-term trend. These temperatures show a sharp, temporally-local rise starting in the mid 1980's similar to the rise found in the maximum temperatures which, therefore, provides support for the contention that this warming event is, at least partially, a natural event since previous investigators found no bias in the HO-83 minimum temperature data. This conclusion is supported by the results of our precipitation analyses.

The MIA and FLL maximum temperatures both showed a warming trend that started in the late 1970's, which lends support to the conclusion that this trend is natural. The analyses support the contention that the MIA mean annual daily minimum temperature warmed somewhat through the effects of nearby jumbo jet operations and parking lot construction during the early 1970's. However, comparisons with other stations indicate that a general natural warming process impacted south Florida during this period and that the warming of MIA's mean annual daily minimum temperature was not entirely a result of human activities. Regardless of the mechanisms that were responsible, the trend ended abruptly in the early 1970's and these temperatures thereafter fell to a new low point in the mid 1980's.

1. INTRODUCTION

Extremely high mean annual surface air temperatures[1,2] have been observed at the National Weather Service's (NWS) Miami International Airport (MIA) station during the last few years. These temperatures exceeded the 30-year (1961-1990) mean by 1.7, 2.4, 2.2, and 1.2 standard deviations, respectively, in 1989, 1990, 1991, and 1992 (Table 1). The years 1990 and 1991 were the two warmest years between 1961 and 1992; 1989 was the fourth warmest year in that period. Overall, the MIA record shows a long-term warming trend that started in the late 1960's upon which is superimposed a sharper warming

Table 1. Miami (MIA) Mean Annual Temperature (deg. F).

Year	Temperature	Normalized Temperature
1961	75.9	0.0
1962	74.7	-1.3
1963	74.7	-1.3
1964	76.4	0.5
1965	75.9	0.0
1966	74.3	-1.8
1967	75.8	-0.1
1968	74.3	-1.7
1969	75.5	-0.4
1970	75.8	-0.2
1971	76.4	0.5
1972	75.9	0.0
1973	76.0	0.1
1974	77.3	1.5
1975	77.0	1.1
1976	75.3	-0.7
1977	75.4	-0.5
1978	75.4	-0.6
1979	75.7	-0.2
1980	75.8	-0.1
1981	75.7	-0.2
1982	77.5	1.8
1983	75.4	-0.6
1984	75.1	-0.9
1985	75.0	-1.0
1986	76.4	0.5
1987	76.5	0.7
1988	76.6	0.8
1989	77.5	1.7
1990	78.1	2.4
1991	77.9	2.2
1992	77.0	1.2

Average (1961-1990) = 75.9; Standard Deviation = 0.9

trend that started in the mid 1980's. However, as we will see below, the homogeneity of the MIA record is questionable and must be carefully evaluated before these temperature variations can be accepted as manifestations of natural physical processes. This paper presents the results of such an evaluation.

2. POTENTIAL SOURCES OF INHOMOGENEITIES AND ANALYSIS CONSIDERATIONS

The HO-83 hygrothermometer became the official instrument for measuring the MIA daily maximum and minimum temperatures in July 1985. This device has been found to produce spuriously high maximum temperatures at Tuscon International Airport (Gall *et al.*, 1992) and at Albany County Airport (Kessler *et al.*, 1993). In the late 1970's, Schwartz (1978-79) compared minimum temperatures for 1970-1975 with those from the previous six years for MIA and for the NWS cooperative (COOP) stations at Miami Beach and Homestead. The MIA readings from 1970-1975 were found to average 1.7°F[3] greater than those for 1964-1969. This difference is statistically significant at the 99% level according to Student's t-test. At Miami Beach and Homestead, the average minimum temperatures for the period 1970-1975 were only 0.7°F greater than those for 1964-1969. Schwartz (1978-79) concluded that the anomalous warmth at MIA during 1970-1975 was the result of aircraft taxiing on a nearby ramp and taking off from a runway 850 ft to the southwest of the observational site which, under mean conditions, was only 150 ft upwind of the instrument. Schwartz (1978-79) further concluded that these effects substantially increased when wide body (jumbo) jets replaced older, smaller jet aircraft starting in 1970. A secondary warming mechanism, according to Schwartz (1978-79), was associated with a large (about 1,000,000 sq ft) asphalt parking lot about a mile east of the observational site that was constructed between 1968 and 1970.

An HO-61 hygrothermograph officially replaced the liquid in glass maximum and minimum thermometers in 1965 (Schwartz, 1978-79). According to the MIA station history (U.S. Dept. Comm., 1990b), the HO-61 was moved 9,200 ft to the west-northwest sometime between 1977 and 1978. The purpose of this move was to diminish the effects of the jumbo jets and the parking lot (Hebert, 1993). Unfortunately, a new (but presumably smaller) source of error was introduced by this move because the instrument was placed just west of a heavily traveled city street (Perimeter Road), thereby allowing the prevailing east and southeast winds to bring warm air from passing automobiles towards the instrument. In the summer of 1983, the HO-61 was replaced by an HO-63 which, in turn, was replaced by the HO-83 only two years later. In the early 1990's, Perimeter Road was relocated to the west of the HO-83, putting an end to whatever effect the traffic might have had on the MIA surface temperature readings on days with prevailing easterly winds.

The inhomogeneities of a climatic element manifest themselves as abrupt discontinuities or as gradual increases or decreases over time (Conrad and Pollack, 1962; WMO, 1966). Many temperature records contain inhomogeneities that result from urbanization (Mitchell, 1961; Easterling and Peterson, 1992) which most strongly affects daily minimum temperature and the diurnal temperature range and has little affect on the daily maximum temperature (Jones *et al.*, 1989).

To establish the homogeneity of a climatological record, it is customary to compare the time series in question to those from nearby stations (Conrad and Pollack, 1962; WMO, 1966). In this study, we make use of the two NWS first-order stations closest to MIA. These are West Palm Beach (Palm Beach International Airport (PBI)) and Page Field Airport at Fort Myers (FMY). PBI is about 75 miles north-northeast of MIA, and FMY is on the west coast of Florida about 120 miles northwest of MIA and about the same distance west-southwest of PBI. At PBI, the HO-61 hygrothermometer replaced the liquid in glass extreme thermometers sometime between February 1964 and December 1966. Although PBI was moved 0.9 miles on 1 March 1977, the HO-61 was not moved at that time and, apparently, the official hygrothermometer has not been moved since. The HO-83 was commissioned at PBI on 3 March 1986 (U.S. Dept. Comm., 1961-1991c). At FMY, the HO-61 was commissioned on 24 June 1960. It was moved 325 ft in November 1965 and was replaced by an HO-83 on 15 December 1985 (U.S. Dept. Comm., 1961-1991a). Comparisons have also been made with the NWS COOP stations at Miami Beach, Homestead, Hialeah, Pompano Beach, and Naples. Data from the Federal Aeronautical Administration (FAA) station at the Fort Lauderdale International Airport (FLL) have also been used. Detailed station histories are not available for either the COOP stations or FLL. The station locations are shown in Figure 1.

In a few previous studies, the evaluation of homogeneity has often been accomplished through a process whereby the time series from the station in question and that from a nearby station thought to be homogeneous were differenced and the resulting series of differences statistically tested for evidence of nonrandomness (WMO, 1966). If the test led to the conclusion that there was no statistically-significant nonrandomness, the two series were declared "relatively" homogeneous (WMO, 1966). It is easy to see that this approach can be misleading. If each of the time series is the sum of systematic and random components, the difference series will be random only if the two series have the same systematic components. Since nearby stations may have slightly different systematic components as a result of completely natural factors, randomness in the difference series should not be considered a necessary condition for relative homogeneity. Along these same lines, a statistically significant drift of central tendency has been taken as evidence of inhomogeneity in a few previous studies (WMO, 1966). However, we now know that such a drift may be the result of natural, decadal-scale oscillations and, therefore, cannot be taken as a sufficient condition for inhomogeneity.

Another difficulty in the analysis of climatic records is the common occurrence of trend-like behavior. When such behavior is observed, it is necessary to determine whether there is a genuine trend or merely a set of random fluctuations that fall within the range that could be expected by chance from a stationary time series. Statistical tests of significance[4] are of use in addressing this question. A recommended procedure (WMO, 1966) is to form means over an early portion and a later portion of the sample and to use Student's t-test (Hoel, 1954) to determine the probability that the two subsamples are drawn from populations with the same mean. Least squares fitting of linear trends is another commonly used technique to check for the temporal drift of central tendency (see, for example, Karl *et al.*, 1991; Cayan and Douglas 1984; Panofsky and Brier, 1958). In this case, a Student t-test (Hoel, 1954) can be used to evaluate the null hypothesis that the trend line has zero slope. The Mann-Kendall rank test (WMO, 1966) is a nonparametric test designed to test randomness against trend (be it linear or nonlinear).

3. COMPARISONS OF MEAN ANNUAL TEMPERATURES

Figures 2a and 3a show that decadal scale fluctuations completely dominate the MIA mean annual temperature record and that these decadal fluctuations are superimposed on a warming trend that started in the late 1960's.[5] The data also show a steeper warming event that started in 1986 that might be associated with the switch to the HO-83 at about that time. While one might expect the change of instrumentation to lead to a discontinuity in the record rather than to a trend, the error at Tuscon (Gall *et al.*, 1992) appeared to slowly increase with time and was not apparent when the instrument was first installed. The PBI mean annual temperatures are shown by Table 2 and Fig. 2b. We see that smoothed data (Figs. 3a and 3b) for MIA and PBI are remarkably similar. The correlation coefficient between the MIA and PBI mean annual temperatures is 0.81, while the correlation between the two smoothed series is 0.87. The PBI smoothed mean annual temperatures (Fig. 3b) indicate a warming trend starting in the late 1960's and a sharp warming event starting in the mid 1980's. This is similar to the situation at MIA. The FMY mean annual temperatures (Table 3, Figs. 2c and 3c) also show the sharp warming event starting in the mid 1980's and the longer term warming trend starting in the late 1960's.[6]

When the mean annual temperatures at MIA, PBI, and FMY are normalized (by subtracting the mean and dividing by the standard deviation) and smoothed, the similarities between the three stations becomes even more evident (Fig. 4). All three stations show decreasing temperatures to a minimum in the late

Table 2. West Palm Beach (PBI) Mean Annual Temperature (deg. F).

Year	Temperature	Normalized Temperature
1961	75.1	0.3
1962	74.3	-0.5
1963	74.3	-0.5
1964	75.0	0.2
1965	75.2	0.4
1966	73.9	-0.9
1967	74.5	-0.2
1968	72.4	-2.3
1969	73.1	-1.6
1970	73.8	-1.0
1971	74.9	0.1
1972	76.5	1.7
1973	75.5	0.7
1974	75.7	0.9
1975	75.3	0.5
1976	73.7	-1.1
1977	74.1	-0.6
1978	74.2	-0.5
1979	74.1	-0.7
1980	74.3	-0.4
1981	74.2	-0.6
1982	76.5	1.7
1983	74.4	-0.4
1984	74.0	-0.7
1985	74.8	0.0
1986	75.7	0.9
1987	75.1	0.4
1988	75.2	0.4
1989	76.0	1.2
1990	77.5	2.6

Average (1961-1990) = 74.8; Standard Deviation = 1.0

Table 3. Fort Myers (FMY) Mean Annual Temperature (deg. F).

Year	Temperature	Normalized Temperature
1961	74.6	0.2
1962	74.2	-0.2
1963	73.6	-0.6
1964	74.6	0.2
1965	74.3	-0.1
1966	73.5	-0.8
1967	74.5	0.1
1968	72.8	-1.3
1969	72.6	-1.5
1970	72.8	-1.3
1971	74.0	-0.4
1972	75.6	1.1
1973	74.3	-0.1
1974	74.4	0.0
1975	75.7	1.2
1976	72.4	-1.7
1977	72.3	-1.8
1978	73.8	-0.5
1979	75.5	1.0
1980	75.1	0.6
1981	74.7	0.3
1982	75.9	1.3
1983	72.7	-1.4
1984	74.2	-0.1
1985	75.6	1.1
1986	75.8	1.2
1987	74.6	0.2
1988	74.8	0.4
1989	75.4	0.9
1990	76.9	2.2

Average (1961-1990) = 74.4; Standard Deviation = 1.1

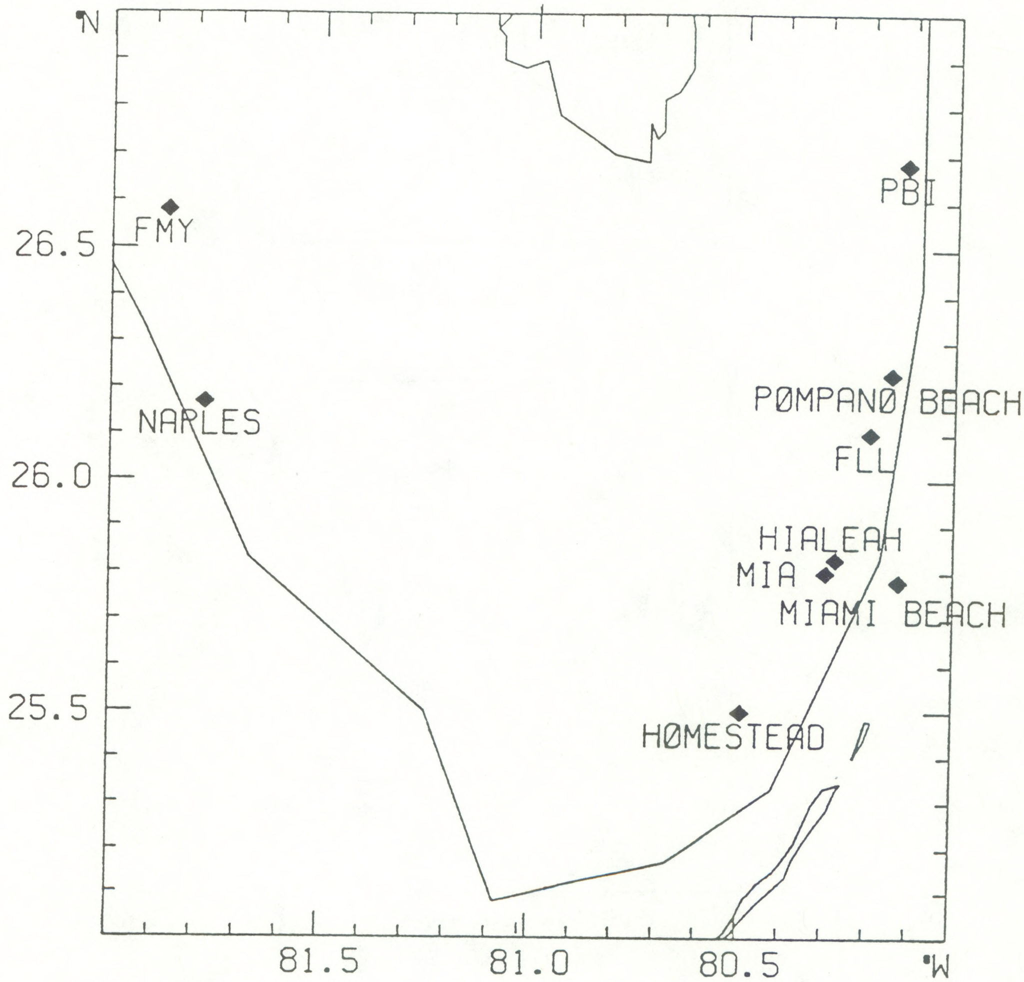


Figure 1. Map of south Florida showing the locations of the stations used in this study. FMY is Page Field, Fort Myers. PBI is Palm Beach International Airport. FLL is Fort Lauderdale International Airport. MIA is Miami International Airport. The remaining stations shown are cooperative stations. The lower edge of the figure is marked with longitude in degrees and tenths of a degree. The left edge is marked with latitude in degrees and tenths of a degree.

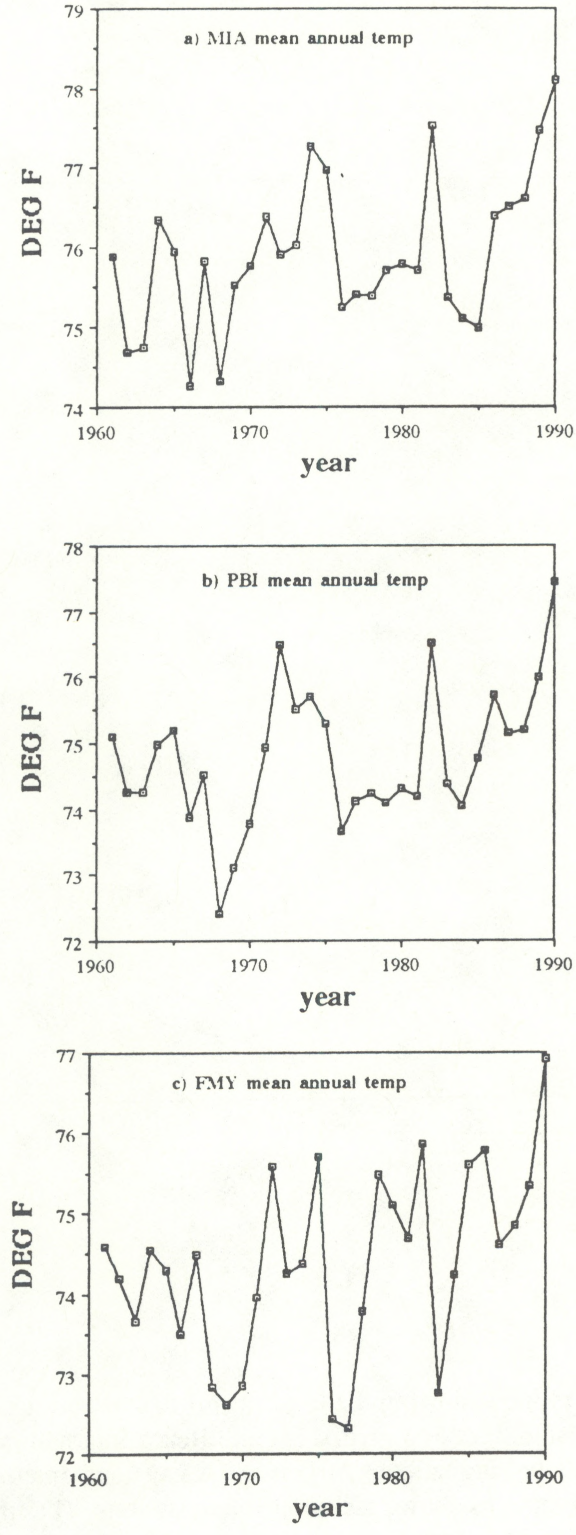


Figure 2. Mean annual temperatures for (a) MIA, (b) PBI, and (c) FMY.

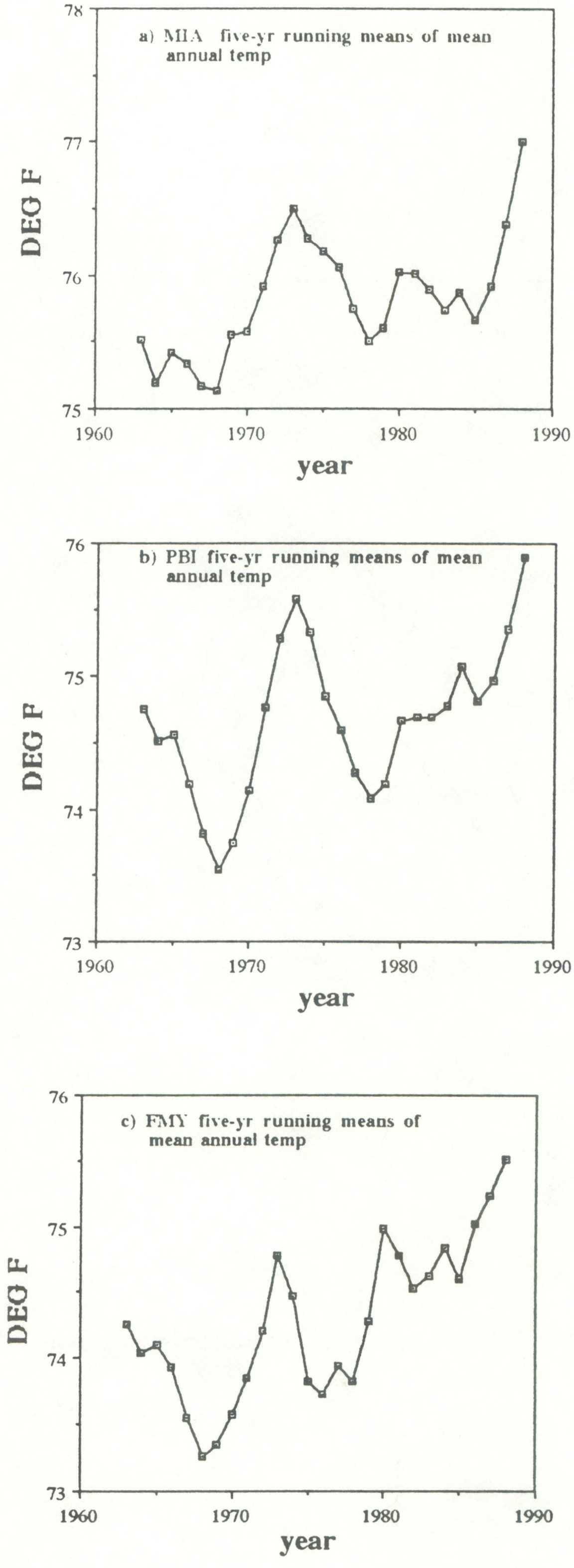


Figure 3. Five-year running means of mean annual temperatures at (a) MIA, (b) PBI, and (c) FMY.

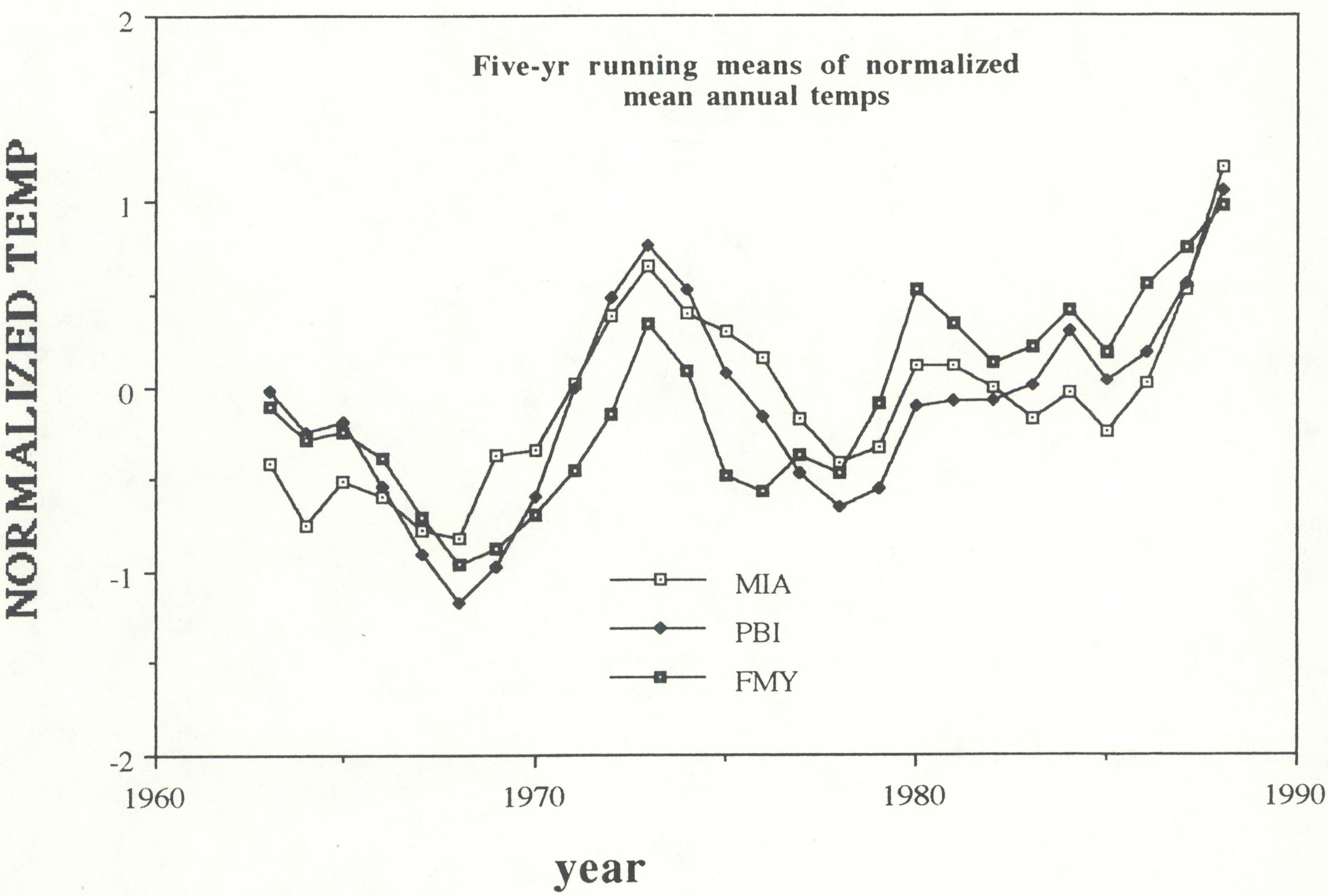


Figure 4. Five-year running means of normalized mean annual temperatures.

1960's, warming to a maximum in the early 1970's, a minimum in the late 1970's, and, for the most part, warming thereafter. All three stations show sharp warming events starting in the mid 1980's (possibly an HO-83 problem) and a longer term warming trend starting in the late 1960's.

The longer term warming trend found in the data for MIA is supported by the results of Student's t-tests which indicate that the difference between the means for the decades of the 1960's (75.3°F) and the 1970's (76.0°F) is significant. The difference between the means for the 1960's and the 1980's (76.4°F) is also significant. For the PBI mean annual temperatures, the difference between the averages for the 1960's (74.1°F) and the 1970's (74.8°F) and the difference between the averages for the 1960's and the 1980's (75.3°F) are both statistically significant. The mean annual temperatures at FMY for the decades of the 1960's and 1980's, respectively, are 73.8°F and 75.1°F. The difference between these means is also statistically significant. Table 4 shows that the least squares trend lines fit to these data all have statistically significant positive slopes. The Mann-Kendall rank test (WMO, 1966) verifies the presence of statistically significant positive trends in the mean annual temperatures at MIA and FMY.

To make a preliminary judgment of the impact of the HO-83 on the long-term trend, we repeat the trend-line calculations for samples that include only the years 1961-1984. The results of such calculations (Table 5) show that the slopes are substantially reduced and that they are no longer statistically significant. In view of the above, it is important to proceed with an evaluation of the HO-83 impact on the MIA, PBI, and FMY records. The studies by Gall *et al.* (1992) and Kessler *et al.* (1993) compared the temperature data measured by HO-83's to those measured by other instruments at nearby COOP stations and found that the maximum temperatures measured by the HO-83 had positive biases of 1°-2°C at Tuscon and biases of +0.5°C at Albany. Since a compensating negative bias was not found in the minimum temperatures, mean daily temperatures could be used to study this effect. Monthly and annual averages of such data for COOP stations in Florida are available from the U.S. Department of Commerce publication, *Climatological Data, Annual Summary, Florida.* For the work discussed below, annual averages of the mean daily temperature were extracted for 1961-1990 at Miami Beach and for 1981-1990 at Naples, Pompano Beach, and Hialeah.[7]

Figure 5 shows the five-year running means of the mean annual temperatures at MIA and Miami Beach for 1963-1988. While the similarity of the histories is clear, we see that the warming from the middle of the 1980's onward is more rapid at MIA. Figure 6 shows temperature differences between HO-83 sites and nearby COOP stations. Except for the comparison between Naples and FMY, it is clear that the HO-83 stations warmed relative to their COOP neighbors after the HO-83's came on line. (We have no explanation for the anomalous behavior of the FMY-Naples temperature difference.) Figure 7 shows the temperature histories for these stations between 1984 and 1990. In general, the HO-83 stations have similar features to those of the neighboring COOP stations. In particular, temperatures for both the first order and the COOP stations rose during the second half of the 1980's. In view of this, not all of the accelerated warming at the first-order stations can be attributed to the HO-83.

The first four rows of Table 6 show the mean temperatures for 1981-1985, 1986-1990, the difference between these means (Delta T), and the one-tail probabilities (obtained from an unpaired Student t-test comparing the means of the first five years with the means of the second five years) that the means for the two periods would differ by if the two samples were drawn from populations with the same mean. We see that 1986-1990 is warmer than 1981-1985 at all stations. At MIA, the difference between means is significant at the 95% level. If we had selected the 90% level of significance, the differences at PBI, Naples, and Pompano Beach would have also been significant. Rows 5-7 of Table 6 show, respectively, the percent variance explained by a linear least squares fit to the data at each station, the slope of the trend line, and the Student t-probability of finding a slope as large or larger than that indicated in a sample drawn from a population with zero slope. Because the data in Fig. 6 show (except for FMY) that the temperatures at the first-order stations decrease relative to the COOP stations during the early years of the 1980's, the trend line analysis was repeated using only data from 1984-1990. The last three lines of Table

Table 4. Least square trend line fits to mean annual temperatures (1961-1990) and results of Mann-Kendall trend tests. Student t-probability is for the null hypothesis that the sample is drawn from a population with zero slope.

Station	Slope (Deg. F per yr)	Student t-Probability	Mann-Kendall Test
MIA	.05	.01	Significant
PBI	.05	.04	Not significant
FMY	.05	.02	Significant

Table 5. Least square trend line fits to mean annual temperatures (1961-1984). Student t-probability is for the null hypothesis that the sample is drawn from a population with zero slope.

Station	Slope (Deg. F per yr)	Student t-Probability
MIA	.03	.24
PBI	.01	.74
FMY	.02	.55

Table 6. Comparison statistics for averages of mean annual temperatures over the periods 1981-1985, 1986-1990, and 1984-1990. Temperatures are in degrees Farenheit. Slopes are in degrees Farenheit per year. Section 3 explains this table in detail.

	MIA	PBI	NAP	POM	FMY	HIA	MIA BCH
Mean 1981-1985	75.7	74.8	74.2	76.4	74.6	75.8	76.0
Mean 1986-1990	77.0	75.9	75.1	77.2	75.5	76.6	76.5
Delta T	+1.3	+1.1	+0.9	+0.8	+0.9	+0.8	+0.5
Student t-probability for Delta T	.03	.06	.08	.08	.13	.13	.15
Least squares trend line 1981-1990							
Percent variance explained	32	33	47	15	20	23	25
Slope	.20	.21	.22	.11	.16	.17	.13
Student t-probability for slope	.09	.08	.03	.26	.20	.16	.14
Least squares trend line 1984-1990							
Percent variance explained	93	76	44	30	31	60	41
Slope	.51	.44	.24	.16	.23	.33	.20
Student t-probability for slope	.001	.01	.11	.21	.19	.04	.12

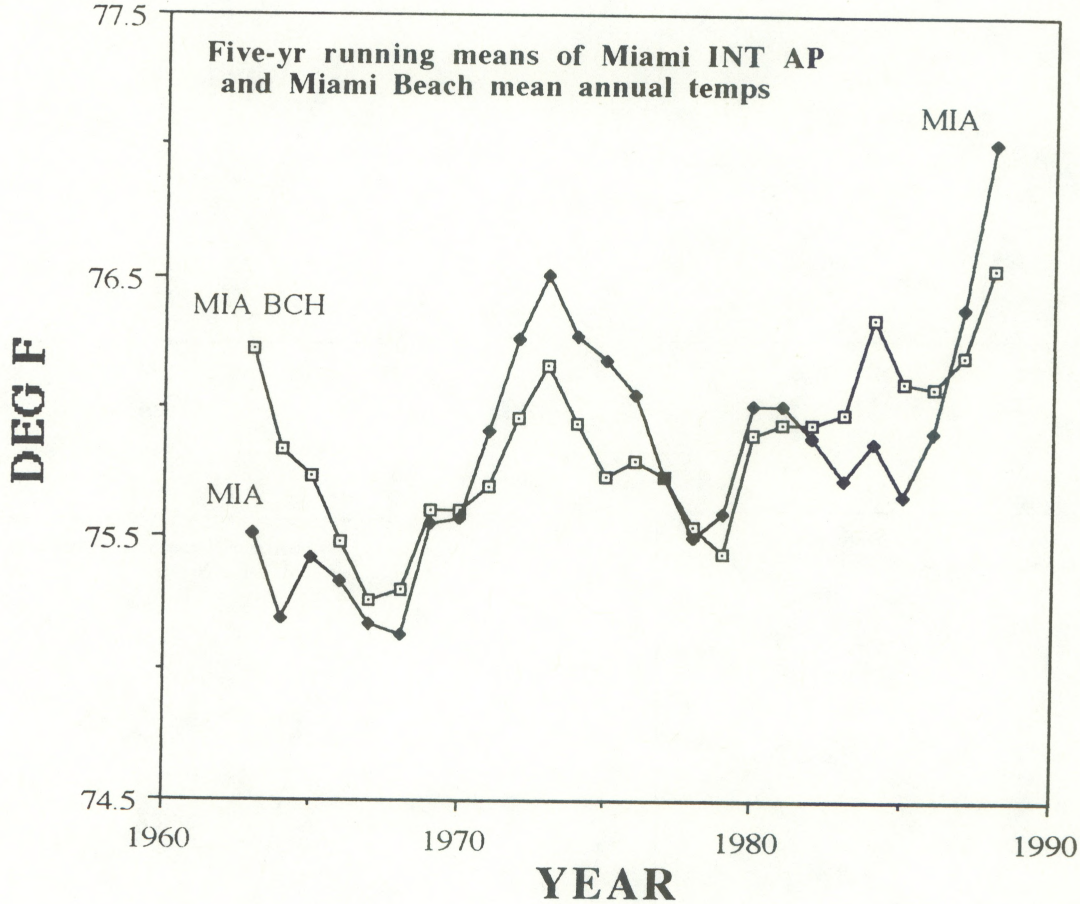


Figure 5. Five-year running means of Miami International Airport (MIA) and Miami Beach (MIA BCH) mean annual temperatures.

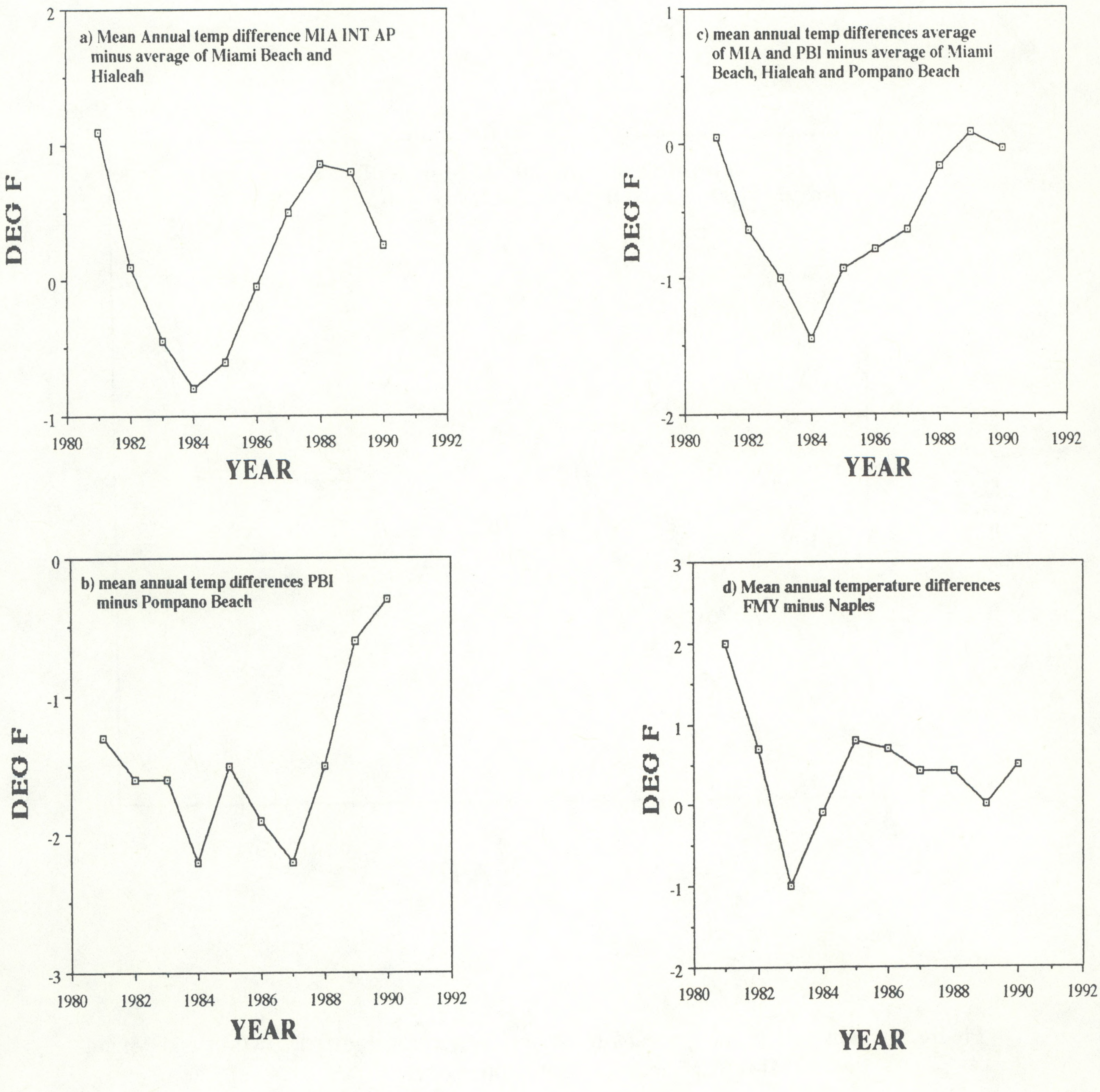


Figure 6. Differences in mean annual temperature: (a) MIA minus average of Miami Beach and Hialeah; (b) PBI minus Pompano Beach; (c) average of MIA and PBI minus average of Miami Beach, Hialeah, and Pompano Beach; and (d) FMY minus Naples.

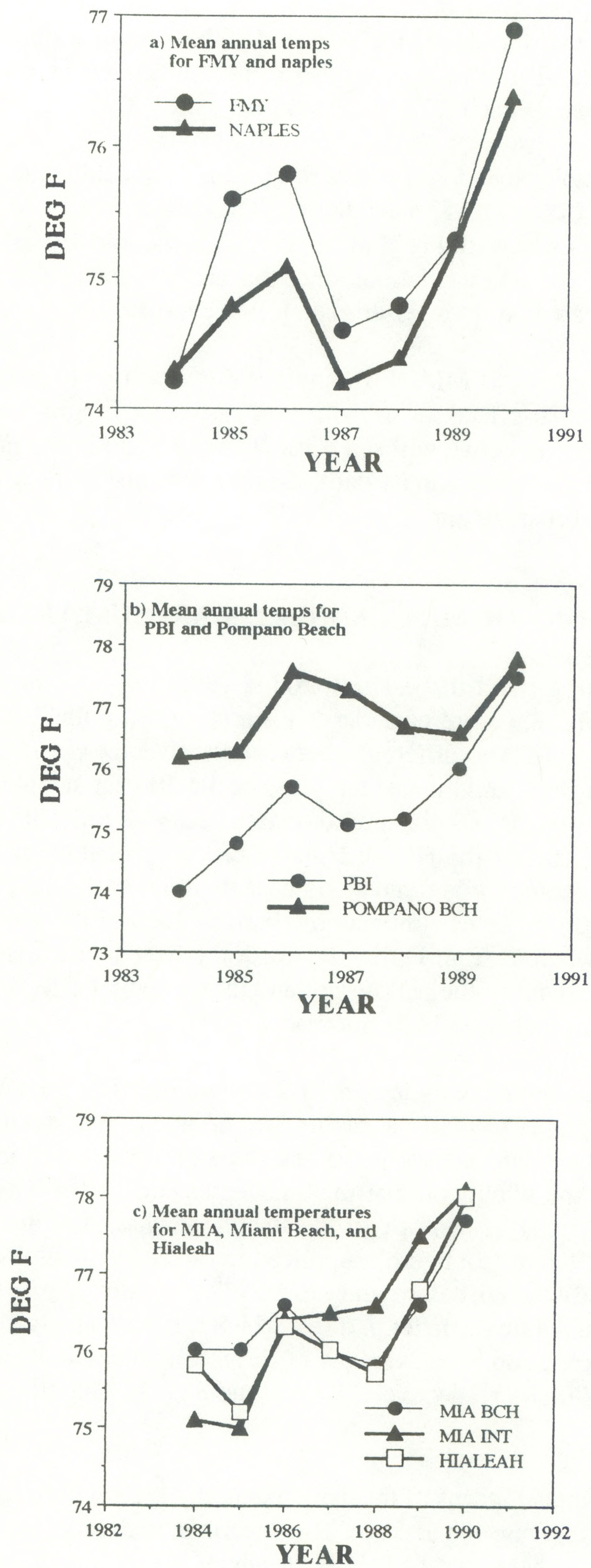


Figure 7. Mean annual temperatures for (a) FMY and Naples, (b) PBI and Pompano Beach, and (c) Miami Beach, MIA, and Hialeah.

6 show these results. We see that the slopes for MIA and PBI are significant. However, the slope for the Hialeah data is also significant. Trend lines were also fit to the differences between MIA-Miami Beach, MIA-Hialeah, and PBI-Pompano Beach. The results are shown by Table 7.

Based on Figs. 5-7 and Tables 6 and 7, it seems reasonable to conclude that MIA and PBI show some artificial warming as a result of the HO-83 installation. (The data do not provide strong support for such an effect at FMY.) The accelerated warming at these stations in the mid 1980's, however, does not appear to be entirely the result of the HO-83 installations since this acceleration is also seen at the COOP stations (Naples, Miami Beach, Hialeah, and, to a lesser extent, Pompano Beach).

The commonality of the events at MIA, PBI, and FMY tempts one to attribute the trend that begins in the late 1960's to the coupled effects of urbanization early in the period and the installation of the HO-83's in the mid 1980's. However, we will see below that the trend in the mean annual temperature at MIA is the result of trend in the mean annual daily maximum temperature which is not consistent with our current understanding of urbanization.

4. COMPARISONS OF MEAN ANNUAL MAXIMUM TEMPERATURES

As a result of the warming trend that started around 1978, the MIA mean annual daily maximum temperatures (Table 8 and Fig. 8a) were considerably warmer during the 1980's than during the earlier portion of the 1961-1990 sample. The difference between the averages of mean annual daily maximum temperatures for the first ten years and the last ten years of the 30-year sample, and the slope of the least squares trend line fit to the 30-year sample, are both statistically significant. This warming trend seems to start too early to be the result of the HO-83 installation and probably starts too late to be mainly a jumbo jet effect. Strangely enough, this trend starts near the time when the HO-61 was moved 9,200 ft (U.S. Dept. Comm., 1990b) in order to eliminate the parking lot and the jumbo jet effects. While this move placed the HO-61 downwind from Perimeter Road, the heat source associated with the latter was thought to be small in comparison to the parking lot and the jumbo jet effects (Hebert, 1993). However, Fig. 9a indicates that this may not have been the case.

The smoothed MIA mean annual daily maximum temperatures (Fig. 9a) show more or less stationary behavior from 1961 through 1976 with a rapid rise of about 3°F taking place after 1977. The Wald-Wolfowitz test (WMO, 1966) allows us to test the significance of the lag-one serial correlation coefficient (r_1) to determine the likelihood that the time series consists of only random variations (r_1 not significantly different from zero) in contrast to the likelihood that the time series contains systematic variation (r_1 significantly different from zero). Application of the Wald-Wolfowitz test separately to the portions of the (unsmoothed) record before and after 1977 indicates that the earlier part of the record (r_1=0.28) is probably random, while the latter part (for which r_1 has a statistically-significant value of 0.73) probably has a systematic variation. The averages of the mean annual daily maximum temperatures for 1961-1976 and for 1978-1990 are. respectively, 82.4°F and 83.4°F. The difference is statistically significant.

The raw and smoothed annual means of the daily maximum temperatures at FLL also show a warming trend starting in the late 1970's (Figs. 8b and 9b). The Spearman rank order correlation coefficient between the maximum temperatures at MIA and FLL is 0.78, which is statistically significant at the 99% level. When the mean maximum temperatures for the first 14 years are compared to those for the last 13 years in the 1964-1990 sample at MIA and FLL, they are found to differ by 1.1°F in the former case and by 0.7°F in the latter case. The difference is significant at the 99% level for MIA and at the 96% level for FLL. While the move of MIA to a location downwind from Perimeter Road could have led to this warming, none of the known anthropogenic effects have the correct timing to explain the FLL temperature increase. The similarities between the MIA and FLL mean annual maximum temperature variations, there-

Table 7. Comparison statistics for least square trend line fits to differences in mean annual temperatures between stations as indicated for the period 1984-1990.

	MIA-MIA Bch	MIA-Hialeah	PBI-Pompano Beach
Percent variance explained	62	22	59
Slope (deg. F per yr)	.30	.11	.30
Student t-probability	.06	.34	.08

Table 8. Miami (MIA) Mean Annual Daily Maximum Temperature (deg. F).

Year	Temperature	Normalized Temperature
1961	83.1	0.2
1962	82.5	-0.3
1963	82.1	-0.7
1964	82.7	-0.1
1965	83.1	0.3
1966	81.3	-1.4
1967	82.8	0.0
1968	81.2	-1.5
1969	82.2	-0.6
1970	82.1	-0.6
1971	82.9	0.1
1972	82.2	-0.6
1973	82.1	-0.7
1974	83.5	0.7
1975	83.1	0.3
1976	81.3	-1.4
1977	81.6	-1.1
1978	81.5	-1.2
1979	81.9	-0.9
1980	82.5	-0.3
1981	83.5	0.7
1982	84.3	1.4
1983	82.9	0.1
1984	82.6	-0.2
1985	82.6	-0.2
1986	84.2	1.3
1987	84.0	1.1
1988	83.9	1.1
1989	85.3	2.3
1990	85.3	2.3
1991	84.9	1.9
1992	84.1	1.2

Average (1961-1990) = 82.8; Standard Deviation = 1.1

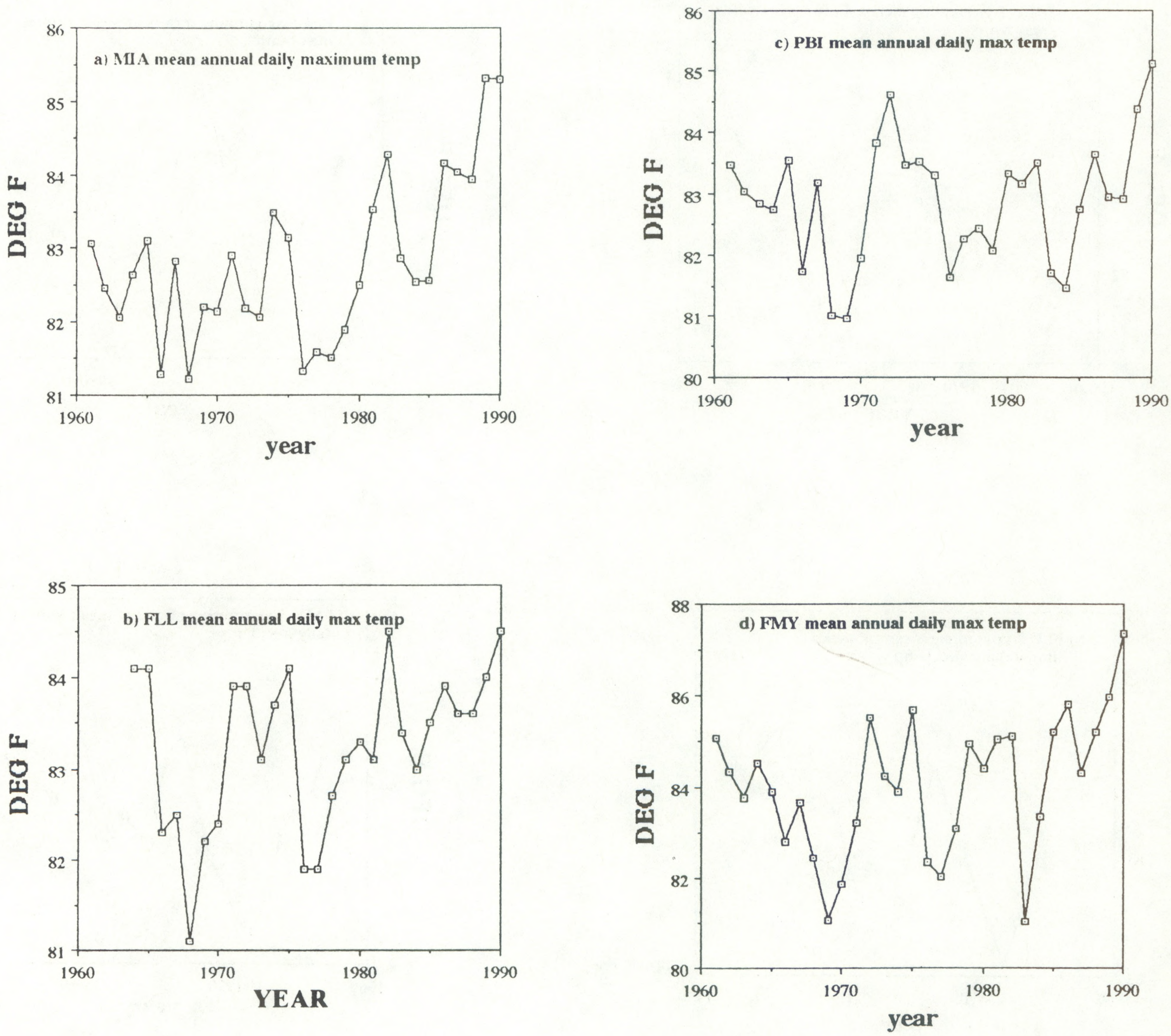


Figure 8. Mean annual daily maximum temperatures for (a) MIA, (b) FLL, (c) PBI, and (d) FMY.

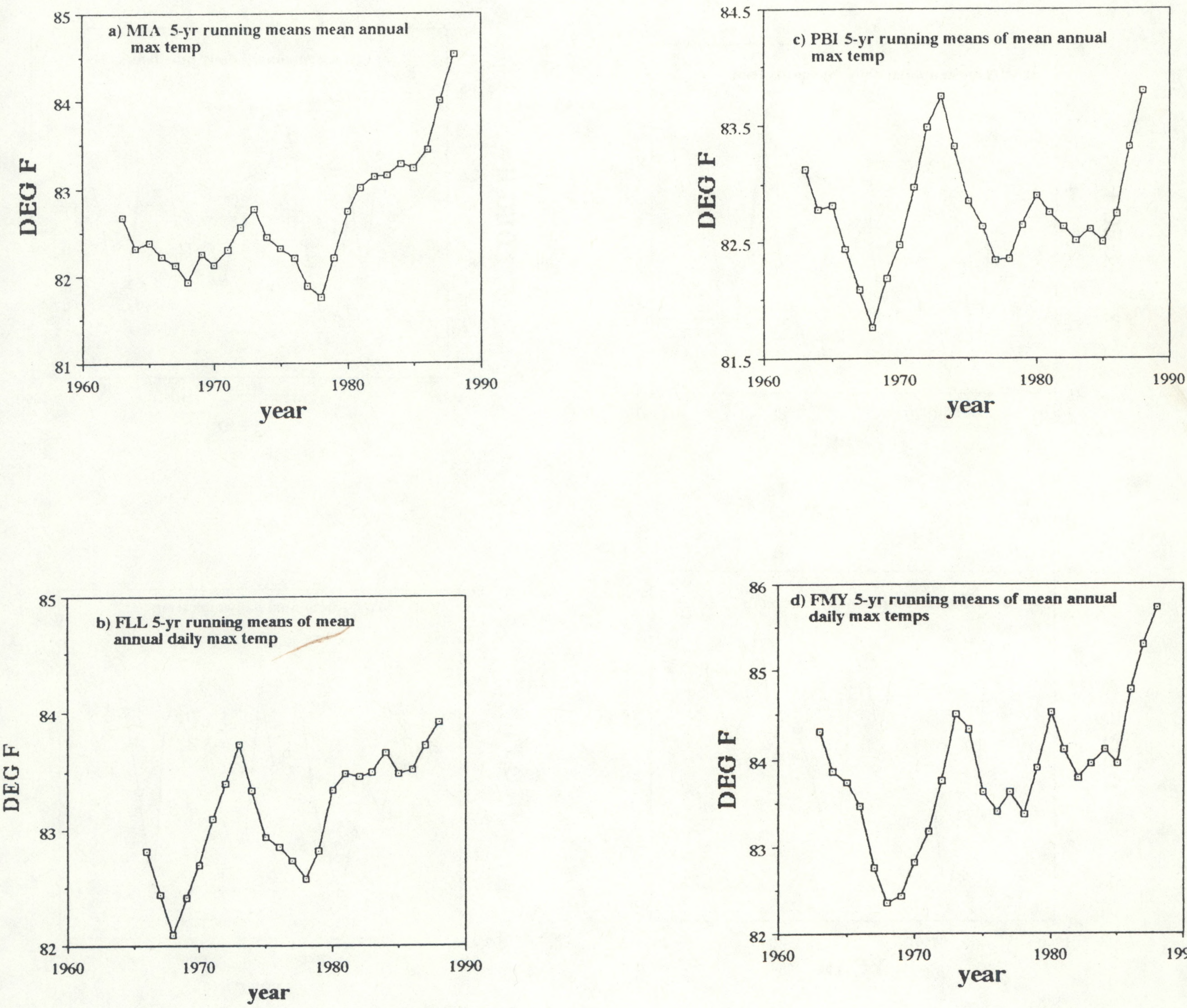


Figure 9. Five-year running means of mean annual daily maximum temperature for (a) MIA, (b) FLL, (c) PBI, and (d) FMY.

fore, lend support to the conclusion that the warming trend started in the late 1970's is at least partly of natural origin.

Table 9 and Fig. 8c show the mean annual daily maximum temperatures for PBI. Figures 9a and 9c compare the smoothed data for MIA and PBI. The warming trend discussed in the previous paragraph is not found at PBI. Decadal averages of the PBI mean annual daily maximum temperatures for 1961-1970, 1971-1980, and 1981-1990 are respectively, 82.4°F, 83.1°F, and 83.2°F. Despite the progressive warming found in these figures, no combination of two taken from these three values yields a difference that is statistically significant. The slope of the least squares trend line fit to the PBI mean annual daily maximum temperatures is positive but not statistically significant, and the Mann-Kendall test also indicates the absence of a statistically-significant trend. If the warming trends found at MIA and FLL are the result of natural variability, one would expect to find a similar trend at PBI. There is no obvious explanation for this discrepancy.

Table 10 shows the FMY mean annual daily maximum temperatures, and Fig. 9d shows the same data after smoothing. The warming trend that begins in the late 1960's and the sharp warming event in the second half of the 1980's associated with the installation of the HO-83 are both clearly evident at FMY. The Mann-Kendall test indicates that the longer range trend found in the FMY data is statistically significant and this is supported by Student's t-test of the slope of the linear regression trend line. The mean annual daily maximum temperature for the decade of the 1960's is 83.3°F and that for the decade of the 1980's is 84.8°F. The difference between these means is statistically significant.

Three statistically-significant trends have been found in the records of maximum temperatures at these stations. FLL and FMY show long-range trends that start in the late 1960's. This type of trend was noted previously in the mean annual temperatures at MIA, PBI, FMY, and Miami Beach. A second trend, found in the MIA and FLL maximum temperatures, starts around 1978. Finally, MIA, PBI, FMY, and FLL show rapid accelerations of their warming trends in the mid 1980's that appears to be a partial result of the installation of the HO-83.

5. COMPARISONS OF MEAN ANNUAL DAILY MINIMUM TEMPERATURES

The MIA mean annual daily minimum temperatures are shown by Table 11 and Figs. 10a and 11a. The average for the first ten years of the sample is 68.3°F, while that for the last ten years is 68.9°F. Neither the difference between these means nor the slope of the least squares trend line fit to these data are statistically significant. In addition, the Mann-Kendall test provides no support for a trend. The Wald-Wolfowitz test, on the other hand, shows that r_1 is statistically significant, which supports the presence of systematic variation.

Comparison of smoothed values of the mean annual daily maximum and minimum MIA temperatures (Figs. 9a and 11a) for the post-1977 period show that the maximum temperatures trend upward, but the minimum temperatures continue a downward slide that starts in the early 1970's and ends in the mid 1980's. The sharp rise of minimum temperature in the mid 1980's might lead us to suspect an HO-83 effect. However, previous investigators (Gall *et al.*, 1992; Kessler *et al.*, 1993) found no biases in the minimum temperatures measured by the HO-83. Although their results were obtained in climates different from that of south Florida, we feel they provide additional evidence in support of the contention that the sharp warming event starting in the mid 1980's at MIA is partially a natural event.

Table 12 and Fig. 10b show the mean annual daily minimum temperatures for PBI and Table 13 shows the data for FMY. The smoothed data (Fig. 11b) show that a warming event begins around 1980 that is similar to the warming event in the MIA mean annual daily maximum temperatures (see Fig. 9a) that begins around 1977. The history of the smoothed PBI mean annual daily minimum temperatures is

Table 9. West Palm Beach (PBI) Mean Annual Daily Maximum Temperature (deg. F).

Year	Temperature	Normalized Temperature
1961	83.5	0.6
1962	83.0	0.1
1963	82.8	0.0
1964	82.8	-0.1
1965	83.6	0.7
1966	81.7	-1.2
1967	83.2	0.3
1968	81.0	-1.9
1969	81.0	-1.9
1970	82.0	-0.9
1971	83.8	1.0
1972	84.6	1.7
1973	83.5	0.6
1974	83.5	0.6
1975	83.3	0.4
1976	81.7	-1.2
1977	82.3	-0.6
1978	82.4	-0.5
1979	82.1	-0.8
1980	83.3	0.4
1981	83.2	0.3
1982	83.5	0.6
1983	81.7	-1.2
1984	81.5	-1.4
1985	82.8	-0.1
1986	83.6	0.8
1987	82.9	0.0
1988	82.9	0.0
1989	84.4	1.5
1990	85.1	2.2

Average (1961-1990) = 82.9; Standard Deviation = 1.0

Table 10. Fort Myers (FMY) Mean Annual Daily Maximum Temperature (deg. F).

Year	Temperature	Normalized Temperature
1961	85.1	0.7
1962	84.3	0.2
1963	83.8	-0.2
1964	84.5	0.3
1965	83.9	-0.1
1966	82.8	-0.8
1967	83.7	-0.3
1968	82.4	-1.1
1969	81.1	-2.0
1970	81.9	-1.5
1971	83.2	-0.6
1972	85.5	1.0
1973	84.2	0.1
1974	83.9	-0.1
1975	85.7	1.1
1976	82.3	-1.1
1977	82.0	-1.4
1978	83.1	-0.6
1979	85.0	0.6
1980	84.4	0.2
1981	85.0	0.7
1982	85.1	0.7
1983	81.0	-2.0
1984	83.3	-0.5
1985	85.2	0.8
1986	85.8	1.2
1987	84.3	0.2
1988	85.2	0.8
1989	86.0	1.3
1990	87.4	2.2

Average (1961-1990) = 84.0; Standard Deviation = 1.5

Table 11. Miami (MIA) Mean Annual Daily Minimum Temperature (deg. F).

Year	Temperature	Normalized Temperature
1961	68.7	-0.3
1962	66.9	-1.9
1963	67.4	-1.4
1964	70.1	0.9
1965	68.8	-0.2
1966	67.3	-1.5
1967	68.8	-0.2
1968	67.4	-1.4
1969	68.8	-0.1
1970	69.4	0.3
1971	69.9	0.8
1972	69.6	0.5
1973	69.9	0.8
1974	71.0	1.8
1975	70.8	1.6
1976	69.2	0.2
1977	69.2	0.2
1978	69.3	0.2
1979	69.5	0.5
1980	69.1	0.1
1981	67.9	-1.0
1982	70.8	1.6
1983	67.9	-1.0
1984	67.6	-1.2
1985	67.4	-1.4
1986	68.6	-0.3
1987	69.0	0.0
1988	69.3	0.2
1989	69.6	0.5
1990	70.9	1.7
1991	70.8	1.7
1992	69.8	0.7

Average (1961-1990) = 69.0; Standard Deviation = 1.1

Table 12. West Palm Beach (PBI) Mean Annual Daily Minimum Temperature (deg. F).

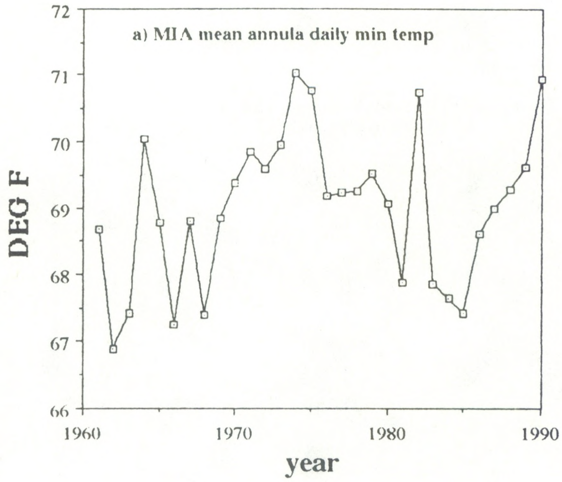
Year	Temperature	Normalized Temperature
1961	66.7	0.0
1962	65.5	-0.9
1963	65.7	-0.8
1964	67.2	0.4
1965	66.8	0.1
1966	66.0	-0.5
1967	65.9	-0.6
1968	63.8	-2.2
1969	65.3	-1.1
1970	65.6	-0.8
1971	66.0	-0.5
1972	68.3	1.3
1973	67.5	0.7
1974	67.9	1.0
1975	67.3	0.5
1976	65.7	-0.8
1977	66.0	-0.6
1978	66.0	-0.5
1979	66.1	-0.4
1980	65.3	-1.1
1981	65.2	-1.1
1982	69.5	2.3
1983	67.0	0.3
1984	66.6	0.0
1985	66.8	0.1
1986	67.8	0.9
1987	67.4	0.6
1988	67.5	0.6
1989	67.6	0.7
1990	69.8	2.5

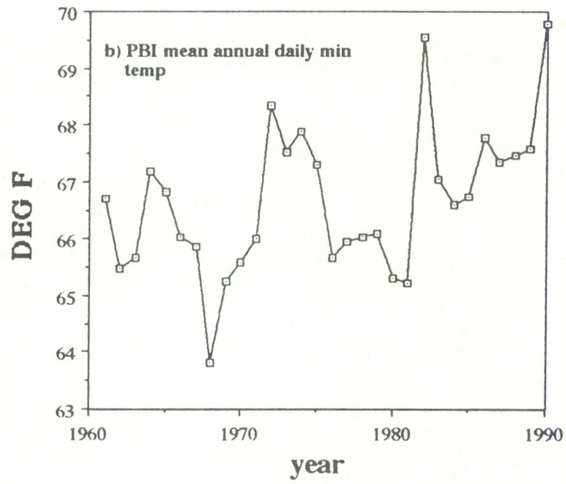
Average (1961-1990) = 66.7; Standard Deviation = 1.3

Table 13. Fort Myers (FMY) Mean Annual Daily Minimum Temperature (deg. F).

Year	Temperature	Normalized Temperature
1961	64.1	-0.6
1962	64.1	-0.6
1963	63.5	-1.2
1964	64.6	-0.1
1965	64.7	0.0
1966	64.2	-0.5
1967	65.3	0.6
1968	63.3	-1.5
1969	64.2	-0.5
1970	63.8	-0.9
1971	64.7	0.0
1972	65.6	0.9
1973	64.3	-0.4
1974	64.9	0.1
1975	65.7	1.0
1976	62.6	-2.2
1977	62.6	-2.1
1978	64.4	-0.3
1979	66.0	1.3
1980	65.8	1.1
1981	64.3	-0.4
1982	66.6	1.9
1983	64.5	-0.3
1984	65.1	0.4
1985	66.0	1.3
1986	65.8	1.0
1987	64.9	0.2
1988	64.5	-0.2
1989	64.8	0.0
1990	66.5	1.8

Average (1961-1990) = 64.7; Standard Deviation = 1.0





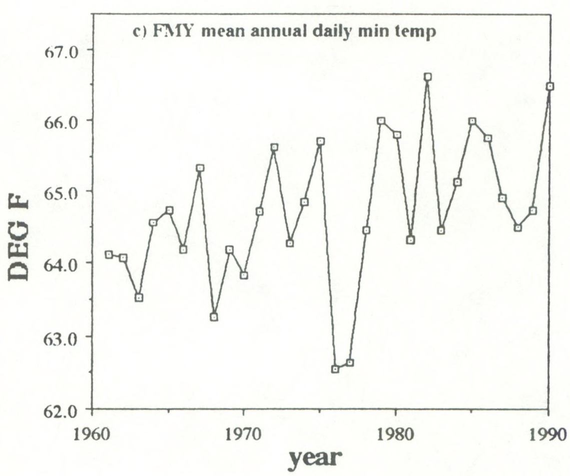


Figure 10. Mean annual daily minimum temperature for (a) MIA, (b) PBI, and (c) FMY.

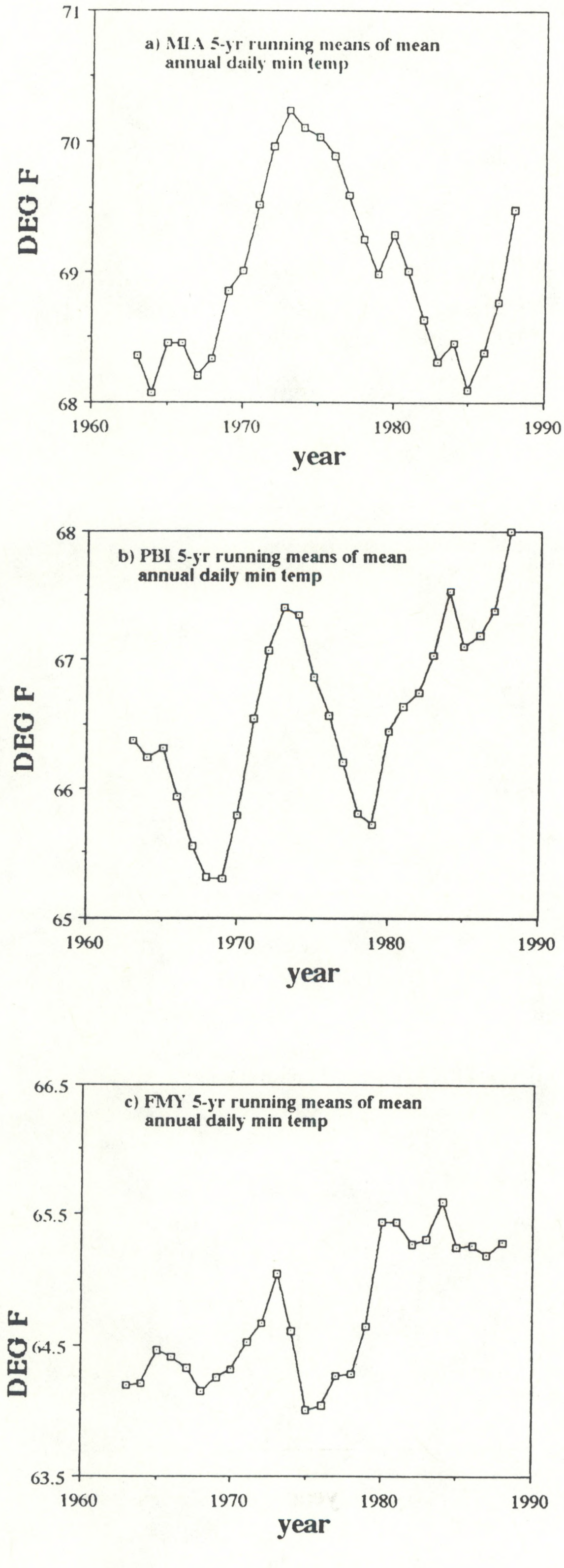


Figure 11. Five-year running means of mean annual daily minimum temperature for (a) MIA, (b) PBI, and (c) FMY.

reasonably similar to that of MIA minimum temperatures (Fig. 11) until the late 1970's. In the 1980's, however, PBI minimum temperatures warm throughout the decade, while warming of the MIA minimum temperatures is found only in the second half of the decade.

The PBI mean annual daily minimum temperatures also show a longer term warming trend that begins in the late 1960's (Figs. 10b and 11b). Averages for the decades 1961-1970, 1971-1980, and 1981-1990 are, respectively, 65.8°F, 66.6°F, and 67.5°F. The differences between the means for the three combinations that can be formed from these values are all statistically significant. The slope of the least squares trend line fit to the mean annual daily minimum temperatures is also statistically significant, and the Mann-Kendall test indicates a statistically-significant trend. It is reasonable to conclude that the PBI mean annual daily minimum temperatures, on the average, have been increasing since the 1960's, which may be, at least partially, the result of urbanization.

As discussed in section 1, Schwartz (1978-79) compared the MIA minimum temperatures for 1970-1975 with those from the previous six years. He made similar comparisons for the COOP stations at Miami Beach and Homestead. The MIA readings from 1970-1975 were found to average 1.7°F greater than those for 1964-1969. This difference is statistically significant at the 99% level. At Miami Beach and Homestead, the average minimum temperatures for the period 1970-1975 were only 0.7°F greater than those for 1964-1969. These differences are not statistically significant. Schwartz (1978-79) attributed the anomalous warmth at MIA during 1970-1975 to aircraft taxiing on a nearby ramp and taking off from a runway 850 ft to the southwest of the HO-61 site. He pointed out that this effect should have substantially increased with the advent of jumbo jets starting in 1970. He also noted that an additional warming mechanism was associated with a large asphalt parking lot completed in 1970 about a mile east of the HO-61 site.

Table 14 shows the difference in mean daily minimum temperatures for the periods (1975-1970) to (1969-1964) and the Student t-probability that differences this large, or larger, could have been obtained from samples of this size drawn from populations with the same mean. Only MIA shows a difference that is statistically significant at the 95% level. The largest differences between means for the two periods occur at MIA and PBI, which are the two airports expected to have the largest jumbo jet influence (Hebert, 1993). However, all five stations, including the COOP stations at Homestead and Miami Beach, show 1970-1975 to be warmer than 1964-1969. This would seem to indicate that in addition to the jumbo jet and parking lot effects at MIA there is also a natural warming process at work in south Florida during the 1964-1970 period.

Figures 10a and 11a show that the MIA mean annual daily minimum temperature starts to warm in 1970, peaks in 1974, and drops thereafter for about ten years. While this may be partly explicable by Schwartz's (1978-79) work, the fact that the minimum temperatures peak three to four years before the time that the HO-61 was moved indicates that other factors were also in operation. Examination of Figs. 8, 9, and 11 show that similar behavior is to be found in the mean annual daily maximum temperatures at FLL, PBI, and FMY, as well as in the minimum temperatures at PBI and FMY.

Figure 12, based on data taken directly from Schwartz's (1978-79) paper, compares the mean annual daily minimum temperatures at MIA, Miami Beach, and Homestead. The three stations show decreasing temperatures to a low point in 1968 followed by general warming through 1975. Since there is no jumbo jet effect at either Miami Beach or Homestead, these data support the contention of a general south Florida natural warming trend during this period. Figure 13 shows differences of the mean annual daily minimum temperatures at MIA and Homestead and between those at MIA and Miami Beach. We see that MIA was warming relative to these stations from 1966 onward and that the peak differences were reached in 1970, which is just about the time that the jumbo jet effect started. If the relative warming at MIA were solely due to the jumbo jet and parking lot effects, one would expect these curves to reach maxima later than 1970.

Table 14. Differences in the average mean daily minimum temperature between the periods 1970-1975 and 1964-1969. Student t-test probability is the probability that differences this large, or larger, could be obtained from samples of this size drawn from populations with the same mean.

Station	Temperature Difference (deg. F)	Student t-test Probability
MIA	1.6	.01
PBI	1.3	.08
FMY	0.4	.29
MIA BCH	0.7	.25
Homestead	0.7	.14

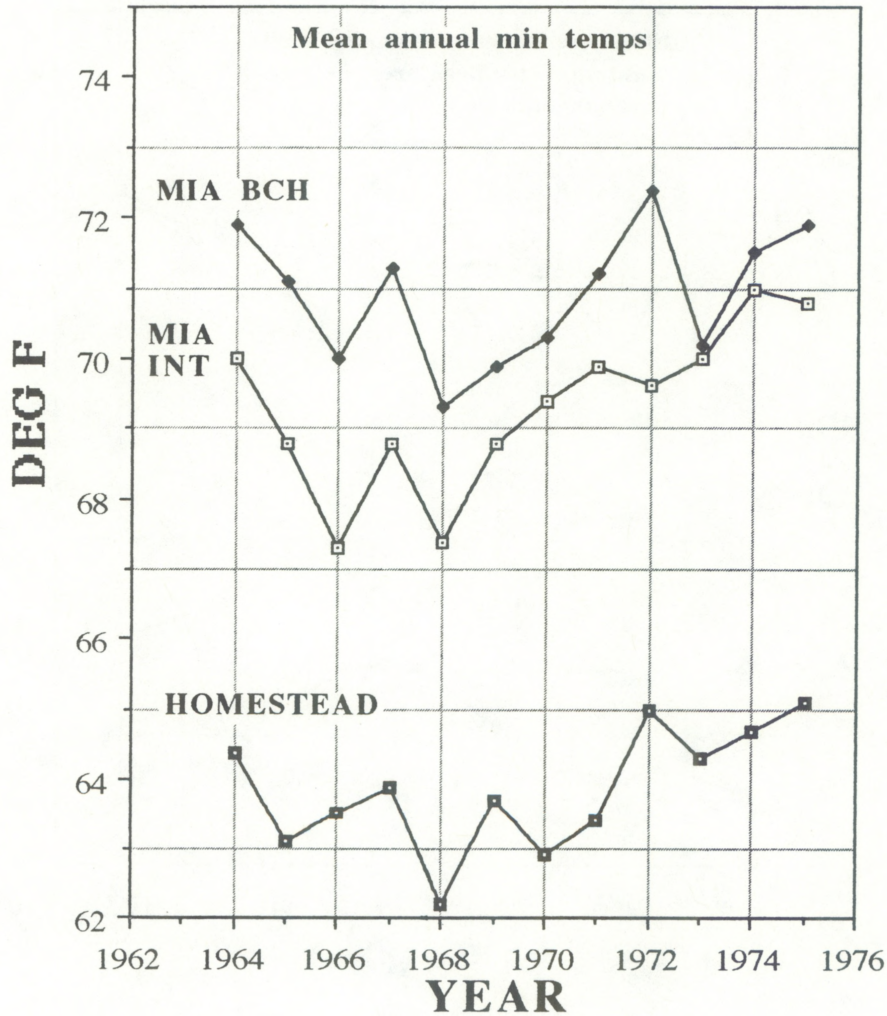


Figure 12. Mean annual daily minimum temperatures (1964-1975) for Miami Beach, MIA, and Homestead.

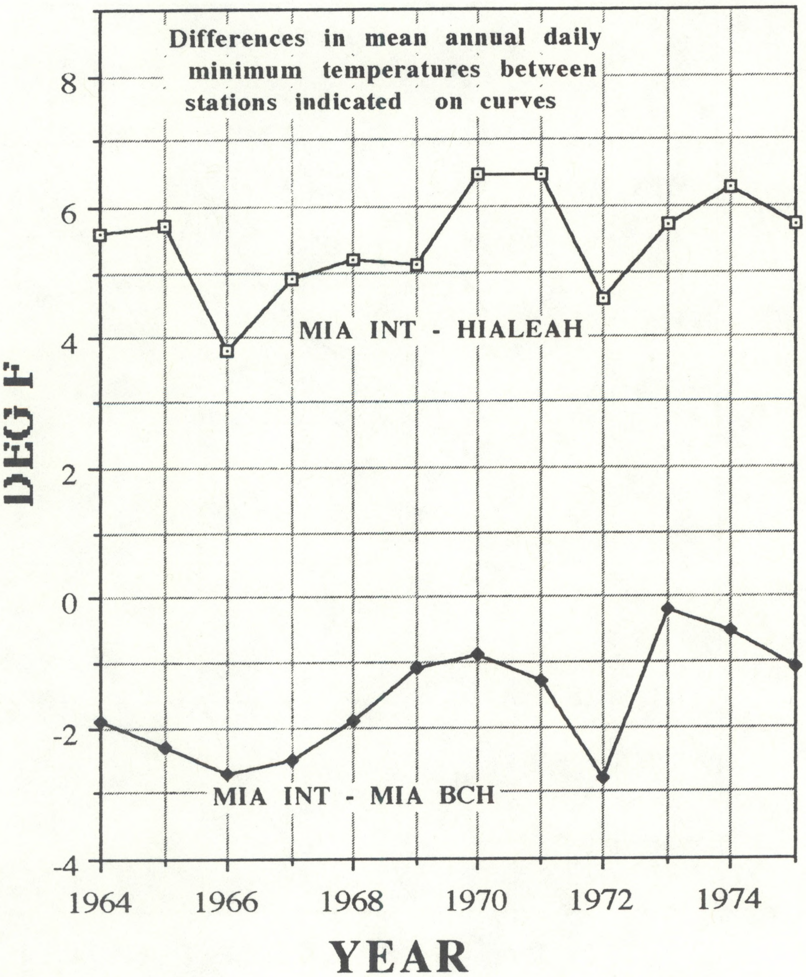


Figure 13. Differences in mean annual daily minimum temperatures between stations indicated on curves.

This analysis supports the contention that the MIA mean annual daily minimum temperature warmed somewhat through the effects of jumbo jets and parking lot construction during the period 1970-1974. However, by comparison to Homestead, Miami Beach, PBI, and FMY, it appears that a general natural warming process impacted south Florida during this period and that the warming of MIA's mean annual daily minimum temperature was not entirely a result of human activities. Figure 14 shows the mean annual daily minimum temperatures from 1968 to 1975 for MIA, PBI, FMY, Miami Beach, and Homestead. Table 15 shows the slope of the least squares trend line and the Student t-probabilities vis-a-vis the statistical significance of the slopes. All five stations show statistically significant positive slopes and, except for a dip in 1973, these mean annual daily minimum temperatures increase monotonically with time. This provides strong support for the existence of a natural, south Florida wide warming event during these years.

6. MEAN ANNUAL DIURNAL TEMPERATURE RANGE

Analysis of the diurnal temperature range can be helpful in the identification of human activities that have affected a temperature record. Urbanization, for example, decreases the diurnal range through an increase of the daily minimum temperature (Karl *et al.*, 1988). The effect amounts to an average of about +0.2°F in the daily minimum temperature and a decrease of about the same amount in the diurnal range (Karl *et al.*, 1988).[8] The HO-83 bias has led to an artificial increase of diurnal temperature range of about 3°F at Tuscon and of about 1°F at Albany. A similar increase at MIA is possible. On the other hand, the jumbo jet effect discussed by Schwartz (1978-79) could decrease the diurnal temperature range at MIA by about 1°F.

Figure 15 shows the five-year running means of the mean annual diurnal temperature range at MIA, PBI, FMY, and FLL. While FLL and PBI appear to have closely related downward trending diurnal ranges, there are few other similarities between these four stations. The correlation matrix (Table 16) further emphasizes the lack of association between the diurnal temperature ranges at these stations. Only the correlation coefficient between FLL and PBI is statistically significant.

The time history of the MIA diurnal range data is u-shaped with decreasing diurnal range from the early 1960's to the mid 1970's followed by an increase to a maximum in the mid 1980's. The decreasing diurnal range during the first half of this period is a result of the increase of minimum temperature discussed in section 5. The latter is partly the result of the jumbo jet effect, partly the result of parking lot construction, and partly the result of a natural warming event that can be seen in the data from all stations examined in this study. The increase of diurnal temperature range at MIA during the second half of the period is, for the most part, a result of the marked warming in the MIA maximum temperature that began in the late 1970's. This warming trend has its origin at about the same time the MIA HO-61 was moved 9,200 ft to a site downwind from Perimeter Road. Finally, the MIA data do not show an increase in the diurnal temperature range during the second half of the 1980's that could be attributed to the commissioning of the HO-83.

The histories of the diurnal range at FLL and PBI are, most likely, what one would expect at sites whose temperature records are dominated by urbanization. When least squares trend lines are fit to these diurnal range data sets, one finds that both stations have statistically significant negative trends that result from statistically significant positive trends in their minimum temperatures.

Table 15. Least squares trend line analysis of the mean annual daily minimum temperatures for the period 1968-1975. The slopes are given in degrees Farenheit per year. The Student t-probabilities are the probabilities that a slope as large as that obtained from the 1968-1975 sample could be obtained from a sample of the same size from a population with zero slope.

Station	Slope	Student t-Probability
Homestead	.37	.005
Miami Beach	.32	.038
PBI	.55	.006
FMY	.28	.018
MIA	.43	.001
FLL	.28	.051

Table 16. Linear correlation matrix for mean annual diurnal temperature range. Data are from the years 1961-1990 at MIA, PBI, and FMY. Data for FLL are from 1964-1990. The asterisk indicates statistical significance at the 95% level.

	MIA	PBI	FMY	FLL
MIA	1.00	----	----	----
PBI	-0.02	1.00	----	----
FMY	0.15	0.17	1.00	----
FLL	-0.24	0.47*	-0.18	1.00

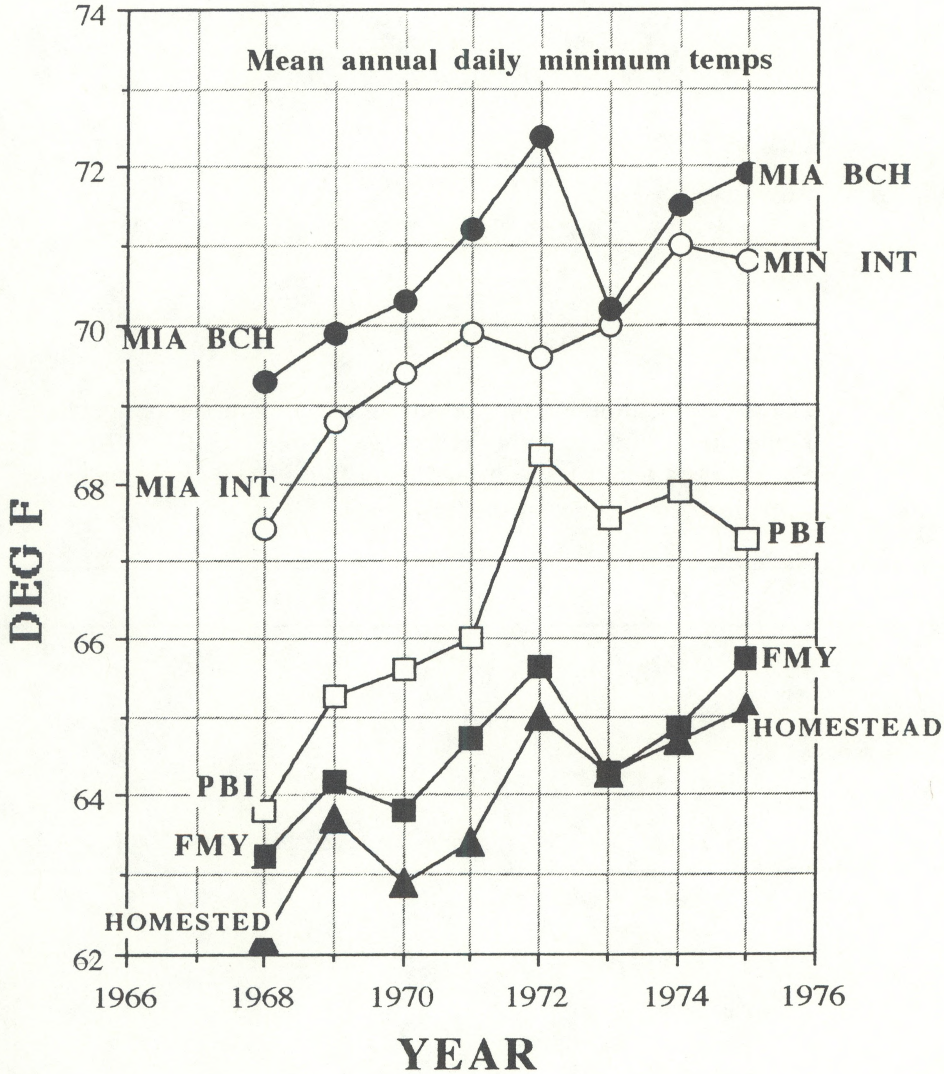


Figure 14. Mean annual daily minimum temperatures (1968-1975) for stations indicated on curves.

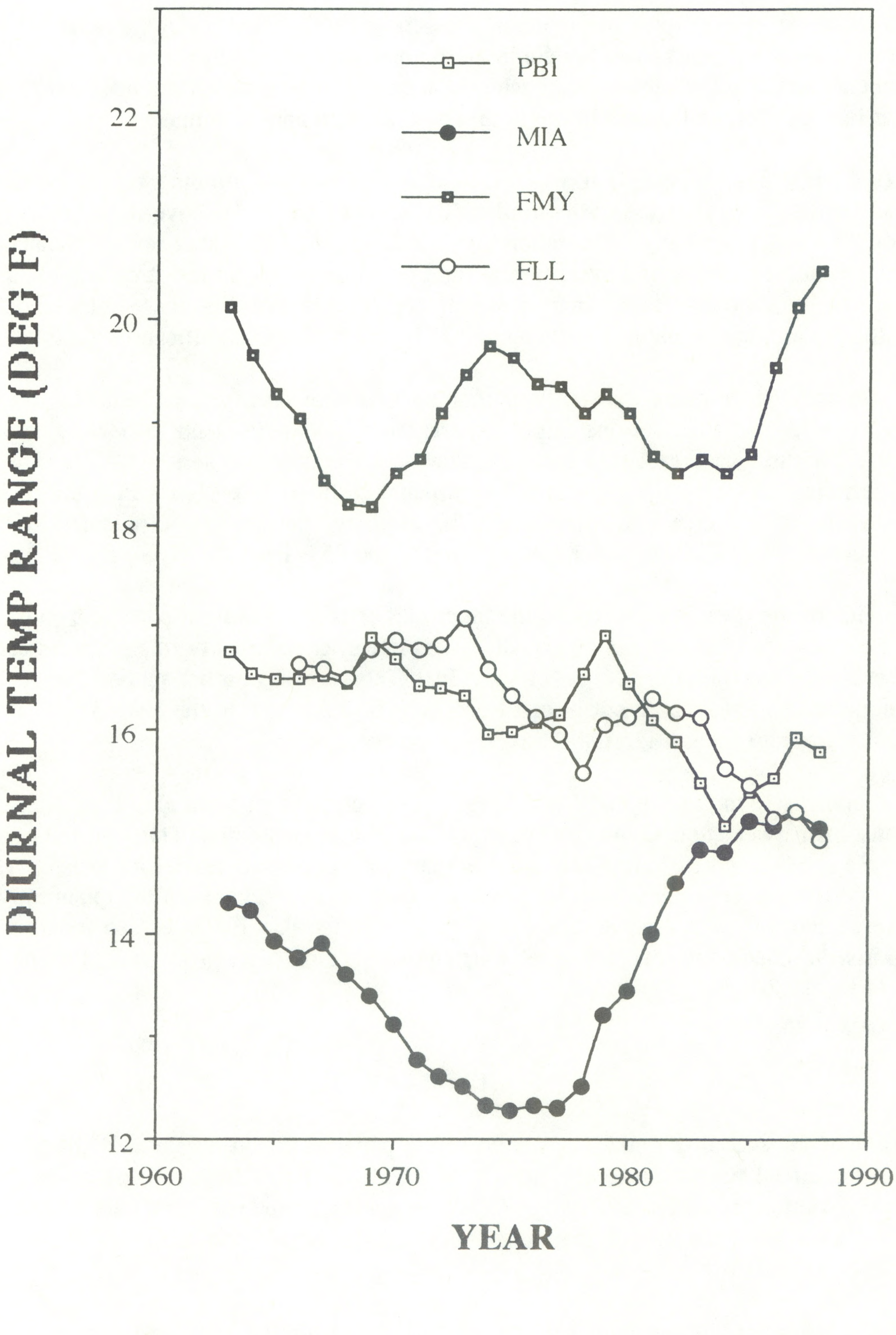


Figure 15. Five-year running means of mean annual diurnal temperature range.

7. RELATIONSHIPS BETWEEN ANNUAL RAINFALL AND MEAN ANNUAL TEMPERATURE

In this section, we will compare mean annual temperature and annual precipitation at MIA, PBI, and FMY. The purpose of this analysis is to determine the nature of the relationships between these climatological elements and to use whatever relationships that emerge to provide further information concerning the reality, or lack thereof, of features in the time series of mean annual temperature.

Earlier (see Figs. 3a, 3b, and 4) it was found that the five-year running means of mean annual temperatures at MIA and PBI were quite similar. These two time series have an ordinary correlation coefficient of 0.87 and a Spearman correlation coefficient of 0.82. The latter is significant at the 99% level. Figures 16a and 16b show that the five-year running means of the annual precipitation at these two stations are also very similar. The ordinary correlation coefficient between these smoothed time series is 0.87, and the Spearman correlation coefficient is 0.91, which is also significant at the 99% level.

Figures 17a and 17b compare the five-year running means of mean annual temperature and annual precipitation for MIA and PBI. As one might expect, these time series tend to be 180 degrees out of phase. At MIA, the ordinary correlation coefficient between the two time series is -0.71. The Spearman correlation coefficient has the same value and is significant at the 99% level. At PBI, the relationship is somewhat weaker but still clearly evident. Here, the ordinary correlation coefficient is -0.47 and the Spearman correlation is -0.43. The latter is significant at the 95% level.

The behavior of the these time series in the latter half of the 1980's is of particular interest. During this period, the sharp increase of temperature, discussed in earlier sections of this paper, is accompanied by sharp decreases of precipitation both at MIA and PBI. This provides further support for the conclusion that these temperature increases are not primarily artifacts of the switch to the HO-83 but, in fact, result from a natural warming of south Florida during these years.

Further support is found in the FMY data (Fig. 17c) where, except for a period in the early 1980's, phase relationships between temperature and precipitation that are qualitatively similar, but quantitatively weaker, to those at MIA and PBI are found. The ordinary linear correlation coefficient is only -0.19, and the Spearman correlation coefficient is -0.18. However, despite the weakness of the quantitative relationship, the inverse behavior of temperature and precipitation in the late 1980's is also found at FMY and further supports the conclusion that a natural warming event took place over south Florida during the second half of the 1980's.

8. SUMMARY

As a result of the warming trend that started in the late 1960's and accelerated sharply in the mid 1980's, the mean annual surface air temperature at MIA exceeded the 30-year (1961-1990) mean by 1.2 to 2.4 standard deviations between 1989 and 1992. Unfortunately, there are several potential problems with the homogeneity of the MIA record that must be examined before the reality of these temperature variations can be established.

The MIA site for measuring daily surface maximum and minimum temperature has been poorly positioned during part of this 30-year period. Prior to 1977, the MIA observational site was affected by exhaust from jet aircraft. This problem was magnified with the introduction of the "wide body" or "jumbo" jets in 1970 and with the construction of a large asphalt parking lot upwind (with the prevailing southeasterly flow) of the observational site that was completed in 1970. In an attempt to minimize these problems, the equipment was relocated (by 9,200 ft) sometime between 1977 and 1978. This move, however, placed the observational site slightly downwind (under prevailing southeasterly flow) from a

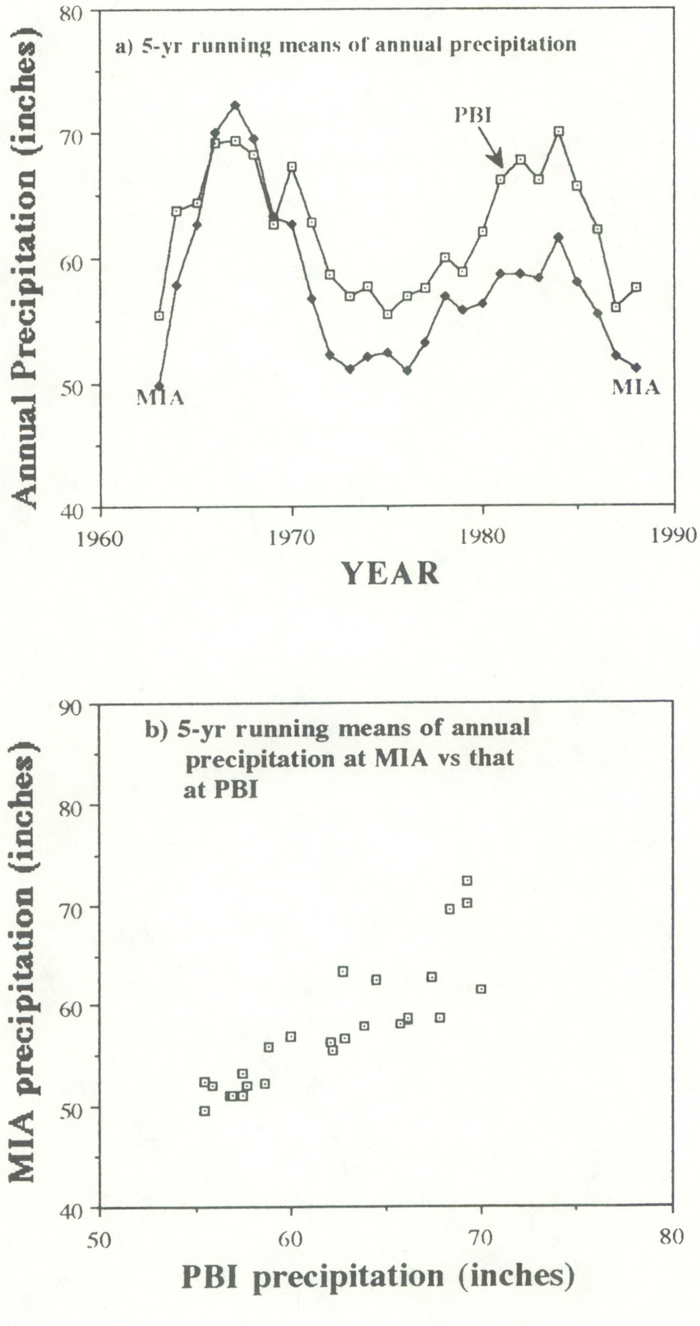


Figure 16. Five-year running means of annual precipitation at MIA and PBI: (a) in time series form; and (b) in scatter diagram form.

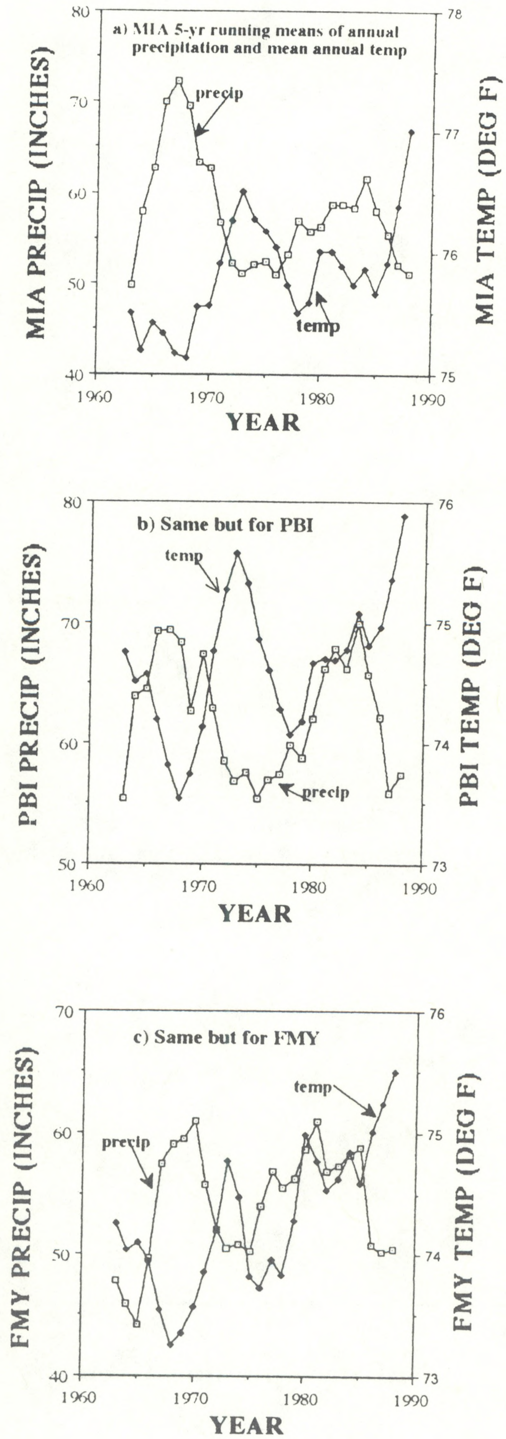


Figure 17. Five-year running means of annual precipitation and mean annual temperature for (a) MIA, (b) PBI, and (c) FMY.

busy city street (Perimeter Road). In the early 1990's, Perimeter Road was relocated to the east of the observational site which should have substantially reduced the influence of automobile exhaust. The HO-83 hygrothermometer, which has been found to have a serious bias in its maximum temperature measurements at Tuscon and Albany, was installed at MIA in the mid 1980's. This was the third significant change of instrumentation during the period studied.

To investigate the impact of these activities on the MIA temperature record, the latter was compared to data obtained at PBI and FMY, which are the NWS first-order stations closest to MIA. Comparisons were also made with data from COOP stations at Miami Beach, Homestead, Hialeah, Pompano Beach, and Naples and with the FAA station at FLL. Precipitation data from MIA, PBI, and FMY were also studied.

To evaluate the impact of the HO-83's, mean annual temperatures for the first-order stations (MIA, PBI, and FMY) were compared to the COOP stations (Miami Beach, Homestead, Hialeah, Pompano Beach, and Naples). It was found that the mean annual temperatures rose at all (first order and COOP) stations during the second half of the 1980's. In view of this, at least part of the accelerated warming at MIA, PBI, and FMY must be attributed to a general south Florida warming during these years. This result is supported by the precipitation data described in section 7. However, MIA and PBI warmed faster than their neighboring COOP stations, indicating that there was indeed some artificial warming as the result of the HO-83 installations.

Over the period 1961-1990, the mean annual temperatures at MIA, PBI, and FMY decreased to a minimum in the late 1960's, warmed to a maximum in the early 1970's, again reached a minimum in the late 1970's, and warmed for the most part thereafter. All three stations show sharp warming events starting in the mid 1980's (which, as we have seen, are only partially due to the HO-83) and longer term warming trends starting in the late 1960's. The latter are statistically significant.

The commonality of the behavior of the mean annual temperatures at MIA, PBI, and FMY tempts one to attribute the trend that begins in the late 1960's to the coupled effects of urbanization early in the period and to the HO-83's in the mid and late 1980's. However, the long-term trend at MIA was found to be the result of a trend in the daily maximum temperature. This is not consistent with our current understanding of urbanization. The MIA record of mean annual daily maximum temperature shows stationary behavior from 1961 through 1976 and a rapid warming thereafter. This warming starts too late to be primarily a jumbo jet and/or parking lot effect and too early to be an HO-83 effect. It may be partially the result of the 9,200 ft relocation of the HO-61 instrument downwind from Perimeter Road.

When the MIA and FLL maximum temperatures are compared for the period 1964-1990, a close similarity is found with regard to the warming trend just described. The Spearman rank order correlation coefficient between these time series is 0.78, which is statistically significant at the 99% level. Since none of the known anthropogenic effects have the correct timing to explain the FLL warming trend, the similarity between the MIA and FLL mean annual daily maximum temperatures lends support to the conclusion that the trend starting in the late 1970's is, in part, natural. However, the absence of such a trend at PBI is puzzling and weakens the case for natural variation.

The MIA mean annual daily minimum temperatures show systematic fluctuations but not a statistically significant long-term trend. These data show a sharp, temporally-local rise starting in the mid 1980's. Since previous investigators found no bias in the HO-83 minimum temperature data, accelerated warming of the minimum MIA temperature in the mid 1980's provides further support for the contention that this warming event is, at least partially, a natural event.

The analyses carried out here support the contention (Schwartz, 1978-79) that the MIA mean annual daily minimum temperature warmed somewhat through the effects of nearby jumbo jet operations and parking lot construction during the early 1970's. However, comparisons to Homestead, Miami Beach, PBI, and FMY indicate that a general natural warming process impacted south Florida during this period and that the warming of MIA's mean annual daily minimum temperature was not entirely a result of human activities. MIA's mean annual diurnal temperature range shows decreasing values from the early 1960's to the mid 1970's followed by an increase to a maximum in the mid 1980's. The decreasing diurnal range during the first half of the period is the result of an increase of minimum temperature possibly in part through the jumbo jet and parking lot effects and partly through natural warming as just described.

9. FOOTNOTES

[1]The daily average temperature is the mean of the daily maximum and the daily minimum temperatures. The monthly means of daily mean, daily maximum, and daily minimum temperatures are computed from the daily values. In turn, the annual averages are computed from the monthly values.

[2]The basic data for this study are the monthly means of surface daily maximum, daily minimum, and daily average temperature given by U.S. Dept. Commerce (1961-1991). Attention is limited to features that can be seen in the mean annual values computed from the monthly data. Seasonal features will be the subject of a later report.

[3]The data sources used in this research provide the data in English units and these units are used throughout this report.

[4]Unless otherwise specified, the term "statistical significance" will signify the 95% level.

[5]It is noted that a global warming trend started in the early 1960's (Hansen and Lebedeff, 1987), and continued through the 1970's and 1980's (Halpert and Ropelewski, 1992).

[6]For sake of brevity, the warming trend starting in the 1960's will be referred to as the "longer term" warming trend.

[7]According to Quayle *et al.* (1991), the NWS replaced more than half of the liquid in glass maximum/minimum thermometer installations at COOP stations with thermistor-based systems between 1986 and 1991. Analyses performed by these authors showed that this change, on the average, increased daily minimum temperatures by about 0.3°C and decreased daily maximum temperatures by 0.4°C. This would result in decreasing the daily mean temperature by about 0.1°F, which is negligible for the purpose of this discussion.

[8]Unfortunately, an appreciable number of nonurban stations have been identified that have statistically significant decreasing trends of diurnal temperature range that are of unknown cause (Karl *et al.*, 1984; Karl *et al.*, 1993).

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11. APPENDIX: STATISTICAL CONSIDERATIONS

(a) Effective Sample Size

Since successive values of climatological data are usually positively correlated, a time series of n values has effectively less information than would be the case in a random sample of n values (WMO, 1966). This, in turn, reduces the significance obtained from common statistical tests below that which would be obtained if successive observations were independent. Siegel (1956) developed an objective method for estimating the effective independent sample size from a serially correlated time series. When applied to the nine (3 stations × 3 temperature variables) time series of 30 interdependent values used in this research, Siegel's method gives 10-15 independent values depending on station and temperature variable.

(b) Student t-Tests

For a one-tailed Student t-test, as used in this paper to compare subsample means and the slopes of linear trend lines, the t-values critical at the 5% level are for 30, 15, and 10 degrees of freedom, respectively, 1.70, 1.75, and 1.81. With 30 degrees of freedom, only a 6% change of the computed slope would also change the t-value from 1.70 to 1.81. In the data sets used here, therefore, the critical t-values do not appear to be overly sensitive to the serial correlation in the data. From a qualitative point of view, persistence can be ignored in these tests. It is noted that these tests work well in the absence of normality (WMO, 1966).

(c) Wald-Wolfowitz Test

This test (WMO, 1966), is used to determine whether or not the lag-one serial correlation coefficient (r_1) is significantly different from zero. The test does not require normality.

(d) Ordinary Linear Correlation Coefficient

Standard text book tests, such as described in Hoel (1954), were used for the tests of the linear correlation coefficients described in section 6. Deviations from normality were ignored. However, the effective sample size was reduced to take into account serial correlation.

(e) Spearman Rank Correlation Coefficient

This coefficient is a correlation based on the ranks of the two variables being compared (Abacus Concepts, 1987; Ott, 1988). The corresponding test of significance is nonparametric. Serial correlation was ignored in these tests.

(f) Mann-Kendall Rank Statistic

This statistic allows us to test randomness in the time series against the alternative of trend (WMO, 1966). The trend can be linear or nonlinear. This is a nonparametric test. Serial correlation was ignored in these tests.

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