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Wind Speed and Atmospheric Stability Trends for Selected United States Surface Stations

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ABSTRACT

Recently it has been suggested that global warming and a decrease in mean wind speeds over most land masses are related. Decreases in near surface wind speeds have been reported by previous investigators looking at records with time spans of 15 to 30 years.

This study focuses on United States (US) surface stations that have little or no location change since the late 1940s or the 1950s – a time range of up to 58 years. Data were selected from 62 stations (24 of which had not changed location) and separated into ten groups for analysis. The groups' annual averages of temperature, wind speed, and percentage of Pasquill-Gifford (PG) stability categories were fitted with linear least squares regression lines.

The results showed that the temperatures have increased for eight of the ten groups as expected. Wind speeds have decreased for nine of the ten groups. The mean slope of the wind speed trend lines for stations within the coterminous US was -0.77 m s^{-1} per century. The percentage frequency of occurrence for the neutral (D) PG stability category decreased, while that for the unstable (B) and the stable (F) categories increased in almost all cases except for the group of stations located in Alaska.

1. Introduction

One possible consequence of global warming is an observed decrease in mean wind speeds over most land masses including the mid-latitudes in the United States (US) and several other regions of the world (Zack et al. 2005). Studies by Klink (1999a, 1999b, 2002) show that indeed, surface winds at hourly reporting stations in the US have declined. Klink's (1999b) study showed that over a period of 30 years the wind speed for a majority of 187 surface stations analyzed has decreased. Klink also showed that at most sites in the United States, the mean maximum wind speeds had increased between 1961 and 1990; in contrast, the mean minimum wind speeds decreased at nearly all stations. Other recent studies (Pittman et al. 2004; Galletta 2005; Weber et al. 2005) over more limited locations in the eastern US provided additional evidence that mean surface wind speeds have decreased over the last couple of decades. Data from a group of eight 61-m towers at the Savannah River Site (SRS) (Weber et al. 2006) showed a decreasing wind speed trend; however the length of record from these particular towers was limited to 1991-2005, a fifteen year span.

Possibly the most important effect of slower wind speeds is a decrease in frictional forces as air moves over land and water surfaces. This decrease ultimately affects large scale atmospheric and oceanic circulation patterns and ultimately the rate of heat transfer between equatorial and polar regions.

The slowing of wind speed over time, although small on a per year basis, also affects a number of important commercial processes including wind energy production and agricultural processes and production. The power available in wind energy production is dependent on the cube of the wind speed, thus a small decrease in wind speed can have important consequences over periods of decades since ultimately the threshold of profitability for wind energy farms cannot be attained.

The Pasquill-Gifford stability category (PG) (Pasquill 1961; Gifford 1975; Turner 1964), denoted by letters from A to G, is a measure of the dispersive power of the atmosphere and can be used to predict the rate of spread of a cloud of material as it moves downwind. The PG stability category can be shown to be related to the atmospheric turbulence intensity and ultimately to the frictional force of the wind on the surface. PG stability categories are now most easily determined from observations of the wind speed, cloudiness, and maximum incoming solar radiation as determined from a station's location and the local time of day (EPA 2000). PG categories A-C denote unstable atmospheric conditions with A being the most unstable and C the least, category D is for neutral conditions, and categories E-G are for stable categories with G being the most stable and E the least.

In this paper, the trends in hourly wind speed, temperature and surface stability frequency over the past 50 to 60 years associated with National Weather Service (NWS) surface stations in the US (including Alaska and Hawaii) are examined. A few stations in Alaska and Hawaii that have changed locations were examined since it was of interest to determine the effects on speed, temperature, and stability for significant shifts in latitude and longitude from stations in the coterminous US.

2. Data and method

a. Hourly NWS surface observations

The US NWS has collected (nominally) hourly meteorological observations including wind speed at a number of stations for the past 50 to 60 years mostly since the end of World War II. These observations have utilized different instruments throughout any given station's history, but prior to the Automated Surface Observing System (ASOS) implementation in the mid-1990s, the wind observations were mostly taken by an observer examining a strip chart or watching a wind dial and estimating the wind speed and direction for about a two-minute time period and recording the result. This method was not always consistent from site to site or from one observer to another (NWS 1995). The current ASOS system uses a two-minute computer-averaged wind speed at the top of the hour similar to what the human observer did, but it does so far more accurately and reliably since it relies on computer memory (NWS 1995).

NWS weather observers were forced to go to a three-hour observation schedule during some of the years in the period 1965-77 because of budget restrictions at NWS offices. Also, during some years, some stations terminated observations between midnight and 8:00 A.M. local standard time (LST). Other stations may have chosen different hours during which observations were not taken. A sample illustration of the observation gaps produced by these lapses in the usual hourly observations for a single station is shown in Fig. 1 for Meridian, MS.

In order to try to assess the effect that ASOS might have on the wind speed trends, the annually averaged data were analyzed as two groups, one containing only the years prior to 1990 (before ASOS implementation could have possibly affected any station) and a second containing the complete time series for the years 1948-2005.

b. Data used in this study: representativeness

Ideally, the observations of wind speed, temperature, cloudiness, and other meteorological parameters should be taken from stations whose tower location, elevation, and setting had not changed over the time period of interest. Unfortunately, none of the stations examined fit those criteria exactly, since various factors, including the need for standardization and government legislation involving airport runway safety, and natural growth or decimation of forests, have necessitated changes in the location, elevation, and siting of the sensors.

It was decided to restrict the selected stations for this analysis and allow only stations with a long period of record and whose location either had not undergone a change or undergone minimal changes in latitude and longitude during the period of National Climatic Data Center's (NCDC) published records. One should be aware that even though anemometer location changes are available in published station histories, small spatial displacements of an instrument's location may have been outside the recorded resolution of longitude or latitude (since these coordinates are only recorded to the nearest 1 minute value) or may not have been recorded. Thus, displacements up to about 1.5 km could have taken place with no evidence of change in the published record. A station's relocation might have influenced the station's wind records since the location change may have pushed the wind tower closer to, or farther away from, tree lines, forests, or nearby airport runways. In most cases the relocation of a station was accomplished by trained technicians who most likely chose as representative a site as was available under the circumstances.

In spite of these possible complicating factors, after obtaining hourly observations from a number of candidate stations from the NCDC (2005), the published station history descriptions were examined and only those stations whose latitude and longitude had no recorded change or those that recorded minimal changes during the period 1948-2005 were accepted. A subset of 62 stations was chosen for inclusion in this study, 24 of which had no recorded change in location (Table 1). While we had hoped to impose a second criterion, namely that the station's wind sensor height had not changed over the same period, this was much more difficult to satisfy and would have amounted to only a handful of stations for the resulting analysis. Indeed, only six of our stations met this criterion exactly, although a much greater number had undergone minimal (less than 10 meters) change over the period of record.

Table 1 and Fig. 2 show that the instrument elevation changes of the stations selected for this analysis are divided roughly equally between positive (upward) and negative (downward) displacements of the wind sensor. A displacement of the wind sensor height affects the wind speed greater during the nighttime hours (stable atmospheric conditions) than during the daytime since the boundary layer wind speeds vary approximately linearly with height at night, whereas the wind is more nearly constant with height during the daytime hours.

c. Wind speed adjustment for measurement height

In order to account for the measurement height changes in a simple manner, the wind speed for each station, U_{ref}, was adjusted by using the 1/7th power law to the current ASOS standard reference height of 10 meters (U_{10}),

$$\frac{U_{10}}{U_{ref}} = \left(\frac{10}{Z_{ref}} \right)^{1/7} \tag{1}$$

(where Z_{ref} was the measurement height of the sensor prior to the ASOS standard of 10 meters). This correction is commonly performed when studying surface winds (Touma 1977; Panofsky and Dutton 1984).

Wind observations were set to missing for any hour's observation if the wind speed had an assigned NCDC quality code indicating questionable data. This was done to ensure selecting and using the best quality data for the analysis.

d. Estimation of PG stability categories

Guidance from the Environmental Protection Agency (EPA 2000) (Section 6.4.1) was followed in order to estimate the PG stability categories. This guidance was implemented from among those stations whose hourly observations had acceptable quality assurance codes. The information extracted included station identifier, date, time, latitude and longitude, wind speed and direction, cloud ceiling, visibility, temperature, dew point, cloud cover, and the corresponding quality codes. Nighttime and daytime conditions were determined using the station's latitude, longitude, time and date of the observation. This information together with the fraction of sky cover, wind speed, and ceiling was used to determine a net radiation class and ultimately a Pasquill-Gifford-Turner stability class (A-G) for each hour of valid data following EPA's guidance (EPA 2000).

e. Grouping and presentation of data

In order to present the plotted results and for discussion purposes, the 51 stations within the coterminous US were divided into eight groups based mainly on region of the country and distance from a coastline (insofar as reasonably possible). In addition, separate groupings of 5 Hawaiian stations, and 6 Alaskan stations were analyzed. These ten groups are listed in the first column of Table 1 and shown on the map given in Fig. 3.

Annual averages of wind speed and temperature were determined for each station selected. The percentage of time within a given year for each PG stability category (based on the number of hours of valid observation in the year's data) was determined and plots were made to determine the changes over the total span of a station's data (usually 58 years). The annually averaged winds, temperatures, and percentages of PG stability categories were subjected to linear least square regression routines for each of the ten groups of stations to determine trend lines over the period of record. Plots were also made in order to visually assess the suitability of fitting a linear trend to the group's long term record. A summary of the slopes for each of the groups and for the various meteorological parameters is given in Table 2.

4. Results

a. Wind speed and temperature

Group 1 (IMW) represents deep inland stations stretching from the Midwest to the Intermountain West. The individually annually averaged temperature trends from these seven stations (not shown) were slightly downward from the late 1940s to the 1970s and then increasing to the end of the records in 2005 for six of seven stations. The single exception to this behavior for the temperature was Pueblo, Colorado, which remained relatively constant until the 1990s followed by an increase. Group 1's seven-station annually-averaged temperature is shown in Fig. 4 where the behavior just described is shown. Annually averaged wind speeds (also in Fig. 4) show greater variability for the period from the late 1940s through the 1960s followed by less variability and a decrease after the 1970s. During the 1990s there is a significant drop in the hourly averaged wind speeds.

Group 2 represents a second group of inland stations all within the borders of Texas (ITX). The annually averaged temperature for all five stations in Group 2 is shown in Fig. 5. As with Group 1, the annually averaged temperatures from these five stations decrease from the late 1940s to the 1970s and then increase to the end of the records in 2005. Annually averaged wind speeds show a large amount of variability for the period from the late 1940s through the 1960s followed by a decrease from the 1970s to the early 1990s, then a slight rise in 1991 then decreasing to 2005.

Group 3 consists of inland stations from the South and Southeast from Mississippi through North Carolina (SEI). As with Groups 1 and 2 the ten SEI annually averaged temperatures show a slight decline from the late 1940s to the 1970s and then an increase to the end of the records in 2005 (Fig. 6). Annually averaged wind speeds show higher speeds for the period from the late 1940s through the 1960s followed by a drop during the 1970s, increasing in the 1980s to the mid 1990s, followed by another drop after 1996.

Group 4 consists of a mixed group of inland and near coastal stations mostly in the Northeast US (NEO). Again, the annually averaged temperatures from seven of eight stations show a decline from the late 1940s to the 1970s and then an increase to the end of the records in 2005 (the exception being Akron, Ohio). The annually averaged temperature for all stations in Group 4 is shown in Fig. 7. The group's annually averaged wind speeds show a larger variability during the period from the late 1940s through the 1960s but an overall decrease through the 1970s, then an increase in the 1980s followed by a significant drop after 1990 and into the 2000s.

Group 5 consists of a mixed group of coastal and near coastal stations in the Mid-Atlantic region (ATM). Again, the annually averaged temperatures from the five stations (Fig. 8) decrease from the late 1940s until the 1970s and then increase to the end of the record in 2005. The group's annually averaged wind speeds decrease from the 1940s through the 2000s.

Group 6 consists of a group of near coastal stations in the Southeast (SEC). The annually averaged temperatures from these four stations decrease from 1953 to 1969 and then increase to 1990 followed by a slight drop into the 2000s (Fig. 9). The group's annually averaged wind speeds show a fairly steady decrease from the 1940s until 1978 followed by a slight increase from the 1980s through the 2000s.

Group 7 consists entirely of coastal stations along the Gulf Coast (GUL). Again, the annually averaged temperatures from these eight stations decline after 1953 to the 1970s and then increase to the end of the records in 2005. The annually averaged temperature for all stations in Group 7 is shown in Fig. 10. The group's annually averaged wind speeds (also in Fig. 10) show a fairly steady drop over the entire period (with a perturbation from 1963 to 1981).

Group 8 consists of one inland and three coastal stations in California (PCA). These annually averaged temperatures depart somewhat from the previously described groups in that they show an almost steady increase from the late 1940s to the mid 1990s and then a slight drop in temperatures in the 2000s (Fig. 11). On closer inspection, one can see a leveling off during 1965-75 followed by a jump to higher temperatures during 1976-96 and then a decrease. The group's annually averaged wind speeds indicates a large amount of variability for the period from the late

1940s through the 1960s followed by a drop during the 1970s, increasing to 1990 followed by a very slightly negative trend from 1990 to 2005. The slope of the wind speed trend line is almost zero over the entire time period 1948-2005.

Group 9 consists of stations in Hawaii (HAW). It was important to examine a group of stations at more westerly longitudes than those in the previous eight groups. Three stations in this group changed their published positions slightly mostly in the 1990s. The net changes in location were all in the range of 1.7 to 1.8 km (computed from the change in latitude and longitude of the station's records). These annually averaged temperatures resemble Group 8 somewhat in that they show an increase from the late 1940s to the mid 1990s and then a slight drop in temperatures in the late 1990s (Fig. 12). The group's annually averaged wind speeds indicates a large amount of variability for the period from the late 1940s to the mid-1970s followed by a fairly flat slope through 1995, and then a dip in the late 1990s followed by increasing speeds after year 2000.

Group 10 consists of eight stations in Alaska (ALK). The reason for examining Alaskan stations was that it was felt to be important to examine a group of stations at more northerly latitudes than those in the previous nine groups.. All stations in this group changed their published position slightly after December 1997 thus affecting less than 20% of the annually averaged time series. The net changes in location were all in the range of 0.9 to 2.5 km (computed from the change in latitude and longitude of the station's records). This group's slopes for the speed and temperature trends resemble the PCA group. The annually averaged temperatures increase from 1948 to 1975 (Fig. 13). After a sudden jump in the late 1970s, the temperature oscillates with a second increase beginning during the early 1990s. Wind speeds decline from the early 1950's to 1970 before rising again in the late 1980's and early 1990's. A drop in wind speeds is observed after 1996. The overall trend for the entire period through 2005 is slightly positive but almost zero.

b. PG stability categories

The percentage of all available hours that the PG stability category was B, D, or F (unstable, neutral, or stable) was calculated for each year from 1948 to 2005 (whenever possible) for each of the ten groups of stations discussed previously. The results showed that over 45% of all times were characterized by a neutral atmospheric stability (D) for eight of ten groups. The two exceptions to this statement were the groups SEC and SEI with 40% and 33%, respectively.

An example plot showing the percentage of these categories, as well as the linear trends over the period is given in Fig. 14 for the ATM group. Eight of the groups show a decrease in the D stability category with time over the time spans available (Table 2). The two exceptions are for the Pacific Coast group of stations (PCA) and the Alaska stations (ALK), where, as was the case for the wind speed and temperature, these two groups appear to differ from the other eight. The PCA and ALK groups show a decrease in the percentage of the D stability category until the mid-1970s followed by increasing percentages of the D stability category from mid-1970s through the mid 1990s for ALK, and through 2005 for PCA. For the remaining groups the deficit in D stability categories is made up by small increases in the remaining categories, and quite frequently, the stable and unstable categories gain in percentage at the expense of the decrease in D categories.

5. Discussion

The annually averaged temperature trends for eight of the ten groups (IMW, ITX, SEI, GUL, NEO, ATM, SEC, and GUL), all show similar behavior, namely, decreasing temperatures from the late 1940s to the mid-1970s, followed by a steady increase in the temperature (Table 2). The overall trend for the entire period (1948-2005) is positive for all groups but SEI, which is essentially unchanged. Interestingly, the remaining groups representing the California Coast (PCA) and Alaska (ALK) show a more steadily increasing temperature overall.

The annually-averaged wind speed trend line slopes from nine of the ten groups for the period 1948-2005 are negative (Table 2); the exception is the Alaska group (ALK). The largest magnitude of negative slope is for the Mid-Atlantic (ATM), followed by inland Texas (ITX), Southeast Coast (SEC), Northeast Coastal (NEO), Southeast inland (SEI), Gulf Coast (GUL), inland Midwest (IMW), Hawaii (HAW), and Pacific Coast stations (PCA). The range of slopes for the wind speed for all the groups in the coterminous US is -0.0008 to -0.0163 m s^{-1} per year or about -0.08 to -1.6 m s^{-1} per century. The mean slope of the trends lines for stations within the coterminous US is -0.77 m s^{-1} per century.

a. The effect of ASOS

The fact that some individual station's time series of annually averaged wind observations noticeably decreased since the mid-1990s could indicate that the new ASOS instruments are measuring somewhat differently than some of the observers during the late 1940s through the 1980s. Shein (2006) noted differences in the frequencies of calms between ASOS and pre-ASOS observations in a group of stations in the Great Lakes region and suggested that further investigations were needed.

In order to evaluate the possible effect of ASOS instrumentation in our study, the analysis was repeated with the years 1948—1989 (years before any possible ASOS influence). In this case, the slopes of the annually averaged wind speed plots are negative for seven out of the ten groups (Table 2). With this change the range of slopes for wind speeds is from +0.0050 to -0.0341 m s^{-1} per year or +0.5 to -3.41 m s^{-1} per century. The mean slope of the trend lines for stations within the coterminous US for this subgroup is -1.00 m s^{-1} per century. It seems that the ASOS effect on wind speed did not appear when the stations were combined into groups, although individual stations could be seen that seem to confirm some effect of the newer ASOS observations.

The temperature trend lines for the period 1948-1989 show an increasing tendency to switch sign from warming to cooling. Indeed, six of the groups show cooling (negative slopes) during the 1948-1989 period. After examining the individual plots to determine the cause of this behavior, it was noticed that the cooling period prior to the mid-1970s sometimes dominated the regression line's slope when the 16 years of possible ASOS data are omitted. This can be readily seen in the NEO and ATM group plots for temperature (Figs. 7 and 8).

b. The effect on wind power

For wind turbine generators the theoretical power per unit area, Π, swept out by the turbine blades available in the wind is given by (Gorban 2001)

$$\Pi = \frac{P}{\rho D^2} = 0.5 \rho V^3 \qquad (2)$$

where P is the power, • is the density of air, D is the turbine blade length, and V is the wind speed. Thus one can estimate the trend in theoretical wind energy production at different sites.

For illustration, Fig. 15 shows the theoretical wind power using Eq. (2) for the ITX (inland Texas stations) group. This plot shows a significant decrease in the production of wind energy over the period 1948-2005.

c. Possible ramifications

The frictional force on the earth's surface due to the wind in neutral thermal stability is related to the vertical turbulent shear stress given by

$$u^* = U \ln\left(\frac{z_0}{z}\right). \qquad (3)$$

where z is the elevation above the surface, and z_0 is the surface roughness. The results of this study have shown that the most frequently occurring PG stability category is for neutral conditions (category D), thus Eq. (3) should be a reasonable climatological average condition. Since the frictional force follows the wind speed trend, it too is decreasing at least as measured at stations over the coterminous US. Also, since u^* is related to the standard deviation of vertical wind direction fluctuations, the decrease in wind speed can be seen to affect atmospheric dispersion. While these effects may be small on an annual or decadal time scale the implications are for much larger effects on time scales of a century or more. Of course, one should also be aware that once the wind speed falls below a certain point, the average frictional effects would no longer be those for neutral conditions, but would rather tend toward increasing stable or unstable conditions.

6. Conclusions

The wind speed decreases for nine of ten groups of the stations in the US that have either not changed their location or changed location by a minimal amount for the 58 years of data examined. The Alaska stations group is the only one for which the wind speed is increasing. The decline in wind speed is also present even if one removes the time period for which newer ASOS instrumentation and methods of capturing the data had possible influence. The fact that that the Alaskan stations were the only ones to show an increase in speed over the period examined may suggest an effect due to the more northerly latitude of these stations, however more data is needed to establish this conclusion.

The percentage of Pasquill-Gifford neutral (D) stability category decreases for eight of the ten groups studied over the same time period. The deficit in D stability category is usually made up by small increases in the remaining categories. Quite frequently, the stable and unstable categories gain in percentage at the expense of the decrease in neutral D categories. These trends have implications for reducing wind energy production and frictional forces near the earth's surface.

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FIGURE CAPTIONS

Figure 1: Indication of available station data as a function of the year and the time of day (UTC). Color-coding and size of each marker indicates the percentage of available observations for the given year and hour. This plot indicates the availability of wind speed data for Meridian, Mississippi from 1948 to 2005.

Figure 2. Distribution of the elevation changes (m) for the stations examined in the coterminous US. Positive values indicate that the tower was raised and negative changes indicate that the tower was lowered.

Figure 3: Map of the United States showing the locations of the stations and groupings used in this study, differentiated by location. Insets are for the Alaskan (ALK) and Hawaiian (HAW) stations.

Figure 4: Trends of annually averaged wind speed and temperature from 1948-2005 for the IMW subgroup of stations.

Figure 5: Trends of annually averaged wind speed and temperature from 1948-2005 for the ITX subgroup of stations.

Figure 6: Trends of annually averaged wind speed and temperature from 1948-2005 for the SEI subgroup of stations.

Figure 7: Trends of annually averaged wind speed and temperature from 1948-2005 for the NEO subgroup of stations.

Figure 8: Trends of annually averaged wind speed and temperature from 1948-2005 for the ATM subgroup of stations.

Figure 9: Trends of annually averaged wind speed and temperature from 1948-2005 for the SEC subgroup of stations.

Figure 10: Trends of annually averaged wind speed and temperature from 1948-2005 for the GUL subgroup of stations.

Figure 11: Trends of annually averaged wind speed and temperature from 1948-2005 for the PCA subgroup of stations.

Figure 12: Trends of annually averaged wind speed and temperature from 1948-2005 for the HAW subgroup of stations.

Figure 13: Trends of annually averaged wind speed and temperature from 1948-2005 for the ALK subgroup of stations.

Figure 14: Trends of annually averaged atmospheric stability frequency of occurrence (expressed as a percentage) for the B, D, and F categories for the ATM station subgroup from 1948 to 2005.

Figure 15: An estimate of the theoretical power per unit area (watts/m^2) swept out by the blades of a wind generator for the ITX group of stations.

TABLES

Table 1a: Stations Examined for This Study (IMW, ITX, SEI, NEO Groups) (*Stations moved, see text)

Group	Station	Location [Lat (N)	Lon (W)	Elev (m)]	Period Used [mo/yr]	ASOS Start [mo/dy/yr]	Elev. Changes (m)	Date of Change [mo/yr]
IMW	Salt Lake City UT*	40°47'	111°58'	1287.8	01/48 – 12/05	03/01/98	-9.7. -0.3, +0.9, +0.9	01/54, 07/78, 08/94, 03/98
IMW	Pueblo, CO	38°17'	104°30'	1438.7	01/54 – 12/05	10/01/92	+11.6, +11.0	01/70, 04/99
IMW	St. Louis, MO*	38°45'	90°22'	161.8	01/48 – 12/05	06/01/96	-4.0, -8.8, +10.0, -11.3	01/59, 01/78, 03/89, 01/02
IMW	Evansville, IN*	38°03'	87°31'	121.9	01/48 – 12/05	02/01/96	-1.9, -0.3, +0.3, +5.8	02/51, 04/89, 02/96, 08/02
IMW	Amarillo, TX*	35°13'	101°42'	1093.0	01/48 – 12/05	11/01/92	-1.5, -5.0	01/75, 02/90
IMW	Tulsa, OK*	36°12'	95°53'	198.1	01/48 – 12/05	10/01/92	+1.0, -8.9	01/56, 01/70
IMW	Ft. Smith, AR	35°20'	94°22'	136.9	01/48 – 12/05	08/01/94	+0.7	01/82
ITX	San Antonio, TX	29°32'	98°28'	246.6	01/48 – 12/05	06/01/95	-0.9, +6.4	01/53, 07/95
ITX	Ft. Worth, TX	32°46'	97°27'	185.3	01/48 – 12/05	06/01/90	+5.8, -8.8, -2.8	01/54, 12/57, 10/94
ITX	San Angelo, TX*	31°21'	100°30'	584.0	01/48 – 12/05	02/01/96	-4.9, -0.6, +4.6	01/65, 06/93, 02/96
ITX	Midland, TX*	31°57'	102°11'	872.3	01/48 – 12/05	03/01/96	+4.0, -2.8	01/60, 04/72
ITX	Abilene, TX*	32°25'	99°41'	545.6	01/48 – 12/05	05/01/96	+3.1, +6.7, +1.8	01/54, 01/72, 04/96
SEI	Augusta, GA	33°22'	81°58'	40.2	01/49 – 12/05	05/01/94	-4.9	05/94
SEI	Columbia, SC	33°57'	81°07'	64.9	01/48 – 12/05	12/01/95	-2.1	01/67
SEI	Raleigh, NC	35°52'	78°47'	126.0	01/48 – 12/05	02/01/96	-2.7, -5.5	01/54, 12/79
SEI	Columbus, GA*	32°31'	84°57'	119.5	05/55 – 12/05	05/01/94	+5.1, +13.8, -17.4	01/51, 01/78, 01/82
SEI	Montgomery, AL	32°18'	86°24'	61.6	01/48 – 12/05	07/01/95	-2.5, +8.9, +0.2	01/59, 01/82, 06/95
SEI	Birmingham, AL*	33°34'	86°45'	187.5	01/48 – 12/05	09/25/98	-3.0, -1.5	01/66, 09/98
SEI	Meridian, MS	32°20'	88°45'	89.6	01/48 – 12/05	07/01/95	-4.0, -2.7, +1.2	01/49, 01/59, 01/91
SEI	Jackson, MS	32°19'	90°05'	100.6	01/48 – 12/05	07/01/93	+5.8, +6.1	02/89, 08/03
SEI	Fayetteville, NC*	35°10'	79°01'	66.4	01/48 – 12/05	NA	+1.2, -3.3, +5.7	09/48, 02/72, 01/78
SEI	Warner Robbins, GA	32°38'	83°36'	92.0	01/48 – 12/05	NA	-7.9	01/65
NEO	Akron, OH	40°55'	81°26'	368.2	01/48 – 12/05	09/01/95	-1.8	01/62
NEO	Willow Grove, PA	40°12'	75°09'	102.1	01/48 – 12/05	06/01/90	+2.8, -16.8	01/50, 01/56
NEO	Pittsburgh, PA*	40°30'	80°14'	350.5	01/49 – 12/05	07/01/96	-26.5, +3.9	01/68, 06/92
NEO	Scranton, PA*	41°20'	75°44'	283.5	01/49 – 12/05	04/01/96	+5.1, -5.1, +0.6	01/54, 01/55, 01/64
NEO	Atlantic City, NJ*	39°27'	74°34'	18.3	01/48 – 12/05	09/01/95	+15.9, -15.9, -0.6, -1.2	10/68, 10/71, 01/82, 10/92
NEO	McGuire, NJ*	40°01'	74°36'	45.1	01/49 – 12/05	NA	-3.0, +9.1	01/55, 01/57
NEO	Boston, MA*	42°22'	71°01'	6.1	01/48 – 12/05	04/01/96	-3.0, -4.0	01/51, 01/64
NEO	Hartford, CT	41°56'	72°41'	48.8	01/49 – 12/05	04/01/96	+11.9, -13.4, -2.7	01/53, 01/59, 01/82

Table 1b: Stations Examined for This Study (ATM, SEC, GUL, PCA, HAW, and ALK Groups) (*Stations moved, see text)

Group	Station	Location [Lat (N)]	Lon (W)	Elev (m)]	Period Used [mo/yr]	ASOS Start [mo/dy/yr]	Elev. Changes (m)	Date of Change [mo/yr]
ATM	Norfolk, VA*	36°54'	76°12'	9.1	01/48 – 12/05	03/01/96	-4.6, +1.8	01/52, 03/96
ATM	Oceana, VA*	36°49'	76°02'	7.9	01/48 – 12/05	06/01/90	+0.9, +1.2, -1.2	01/55, 01/65, 01/67
ATM	Roanoke, VA	37°19'	79°58'	358.1	01/48 – 12/05	05/01/96	-15.9, +7.9	01/52, 05/96
ATM	Dover, DE	39°08'	75°28'	7.0	01/51 – 12/05	NA	-0.9, +1.8, +2.2, +1.8, -4.9	08/50, 01/53, 01/55, 01/58, 01/67
ATM	Baltimore, MD*	39°10'	76°41'	47.5	01/50 – 12/05	04/01/96	+2.4	04/96
SEC	Savannah, GA*	32°08'	81°13'	14	10/50 – 12/05	04/01/96		(none)
SEC	Cherry Point, NC	34°51'	76°53'	13.1	01/48 – 12/05	06/01/90	-4.0	01/56
SEC	New River, NC*	34°42'	77°23'	4.9	01/48 – 12/05	06/01/90	+0.9, -1.8, +0.9, -2.1	01/56, 01/60, 01/62, 01/65
SEC	Key West, FL	24°35'	81°41'	7.0	01/54 – 12/05	06/01/90		(none)
GUL	New Orleans, LA*	30°00'	90°15'	1.2	01/48 – 12/05	05/01/96	+0.3	05/69
GUL	Baton Rouge, LA	30°32'	91°09'	19.5	01/48 – 12/05	05/01/93	-0.6	10/78
GUL	Lake Charles, LA*	30°07'	93°14'	2.7	01/48 – 12/05	01/01/96		(none)
GUL	Port Arthur, TX	29°57'	94°01'	4.9	01/48 – 12/05	07/01/95	-4.2	01/82
GUL	Brownsville, TX*	25°55'	97°25'	7.3	01/48 – 12/05	05/01/94	-4.3, +1.5	01/72, 05/94
GUL	Corpus Christi, TX*	27°46'	97°31'	13.4	01/48 – 12/05	12/01/95	-0.6, +0.9	01/64, 08/04
GUL	Kingsville, TX*	27°30'	97°49'	17.1	01/48 – 12/05	06/01/90	-0.9	01/54
GUL	Pensacola, FL	30°21'	87°19'	10.1	01/48 – 12/05	06/01/90		(none)
PCA	San Diego, CA*	32°42'	117°12'	14.9	01/48 – 12/05	06/01/90		(none)
PCA	Long Beach, CA	33°49'	118°09'	9.4	01/48 – 12/05	09/01/96	-5.5, +1.8	01/60, 09/96
PCA	Fresno, CA*	36°47'	119°43'	101.5	01/48 – 12/05	09/01/95	-3.0, +2.4, -0.9	01/61, 02/85, 09/95
PCA	Point Mugu, CA	34°07'	119°07'	3.0	01/48 – 12/05	NA	+4.2, -5.1, +3.9, +15.0, -19.0	01/50, 01/56, 01/62, 01/64, 01/96
HAW	Honolulu, HI*	22°21'	157°56'	2.1	01/48 – 12/05	02/01/98	+3.9, -13.7	01/63, 01/76
HAW	Kahului, HI	20°54'	156°26'	15.5	01/59 – 12/05	03/01/98	+2.4, +0.9	04/64, 03/98
HAW	Kaneohe, HI	21°27'	157°47'	3.0	01/48 – 12/05	06/01/90	-8.9	07/52
HAW	Molokai, HI*	21°09'	157°06'	137.2	01/73 – 12/05	06/01/99	+0.3	01/78
HAW	Lihue, HI*	21°59'	159°20'	30.5	01/50 – 12/05	01/01/99	-0.9	01/99
ALK	Kodiak, AK*	57°45'	152°29'	5.8	01/48 – 12/05	01/01/97	-31.1, +1.2, +0.6	01/60, 01/73, 08/01
ALK	Barrow, AK*	71°17'	156°46'	9.4	01/48 – 12/05	06/01/98	+2.8, -2.5	01/67, 01/82
ALK	Anchorage, AK*	61°12'	150°00'	40.2	01/54 – 12/05	06/01/98	+3.1, +2.8, -13.2, +5.5	03/64, 01/65, 01/82, 06/98
ALK	Juneau, AK*	58°21'	134°35'	3.7	01/48 – 12/05	03/01/98	-0.9, -2.4	01/59, 01/92
ALK	Nome, AK*	64°31'	165°27'	4.0	01/48 – 12/05	07/01/98		(none)
ALK	Kotzebue, AK*	66°53'	162°36'	3.0	01/48 – 12/05	12/01/97	-3.1	01/82

Table 2: Slopes of linear least squares regression lines for wind speed, temperature, and stability frequency for various groups. The time periods reflect the full period of record in this study (48-05), and the pre-ASOS era (48-89). Only the D, B, and F categories are listed since the remaining stable and unstable categories follow the same pattern.

	Wind Speed (m/s per year)		Temperature (deg C per year)		Unstable (B) (% per year)		Neutral (D) (% per year)		Stable (F) (% per year)	
	48-05	48-89	48-05	48-89	48-05	48-89	48-05	48-89	48-05	48-89
IMW (1)	*-0.0038*	+0.0050	+0.0094	*-0.0012*	+0.0105	*-0.0294*	*-0.0462*	+0.1073	*-0.0108*	*-0.0427*
ITX (2)	*-0.0152*	*-0.0148*	+0.0022	*-0.0211*	+0.0626	+0.0486	*-0.2429*	*-0.2429*	+0.0677	+0.0682
SEI (3)	*-0.0088*	*-0.0089*	*-0.0001*	*-0.0185*	+0.0278	+0.0181	*-0.1379*	*-0.1074*	+0.0296	+0.0551
NEO (4)	*-0.0100*	*-0.0136*	+0.0035	*-0.0150*	+0.0047	*-0.0219*	*-0.1254*	*-0.1261*	+0.0517	+0.0922
ATM (5)	*-0.0163*	*-0.0211*	+0.0064	*-0.0066*	+0.0210	+0.0225	*-0.1608*	*-0.2080*	+0.0496	+0.0903
SEC (6)	*-0.0150*	*-0.0341*	+0.0137	+0.0178	+0.0452	+0.0941	*-0.1844*	*-0.4373*	+0.0426	+0.1148
GUL (7)	*-0.0083*	*-0.0063*	+0.0041	*-0.0148*	+0.0332	+0.0178	*-0.1090*	*-0.0479*	+0.0157	+0.0421
PCA (8)	*-0.0008*	*-0.0071*	+0.0320	+0.0496	+0.0380	+0.0712	+0.0140	*-0.0896*	*-0.0558*	*-0.0336*
HAW (9)	*-0.0023*	+0.0003	+0.0111	+0.0198	+0.0182	+0.0155	*-0.1179*	*-0.1463*	+0.0291	+0.0589
ALK (10)	+0.0020	+0.0043	+0.0395	+0.0409	*-0.0059*	*-0.0205*	+0.0505	+0.0730	*-0.0307*	*-0.0524*

FIGURES

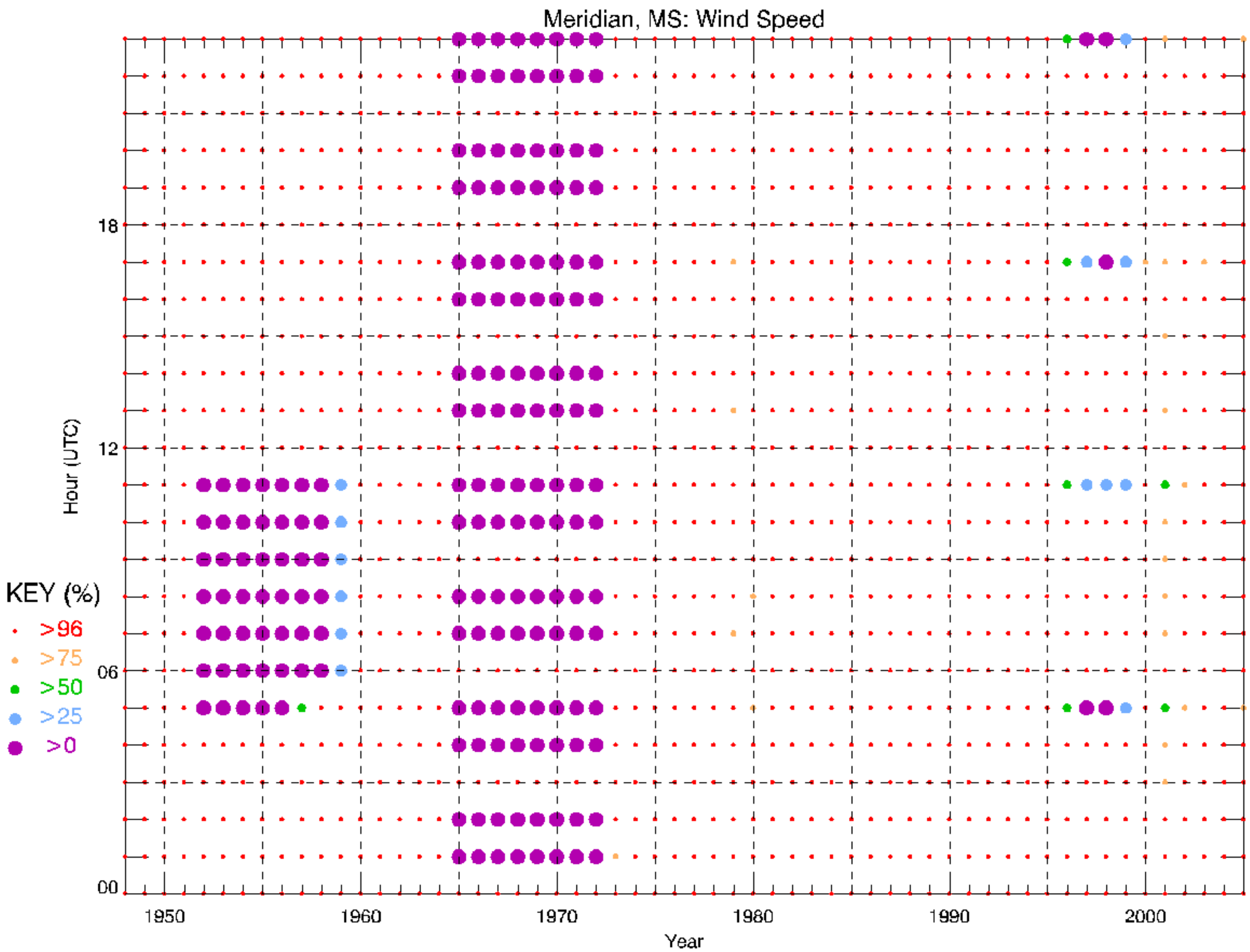

Figure 1: Indication of available station data as a function of the year and the time of day (UTC). Color-coding and size of each marker indicates the percentage of available observations for the given year and hour. This plot indicates the availability of wind speed data for Meridian, Mississippi from 1948 to 2005.

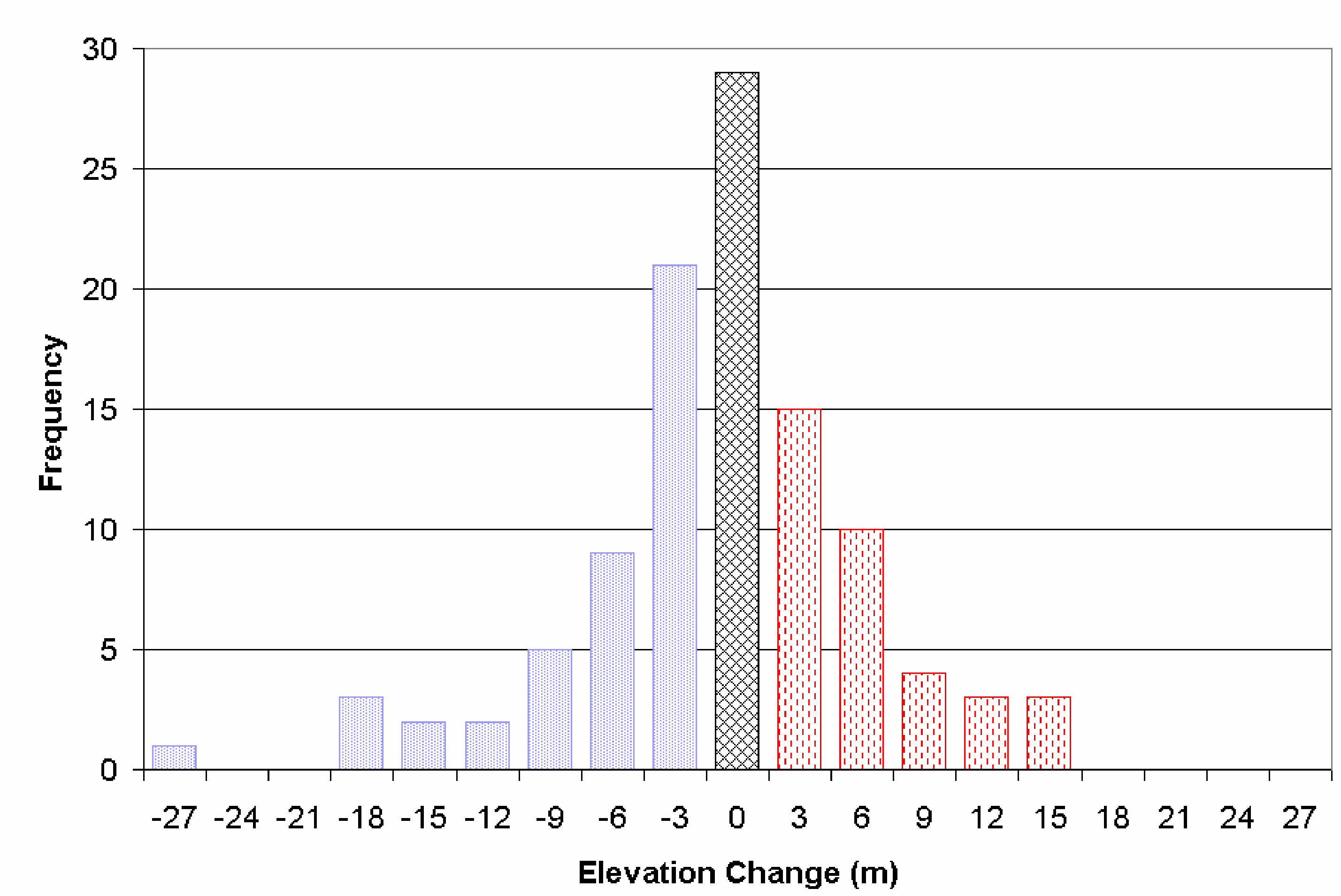

Figure 2. Distribution of the elevation changes (m) for the stations examined in the coterminous US. Positive values indicate that the tower was raised and negative changes indicate that the tower was lowered.

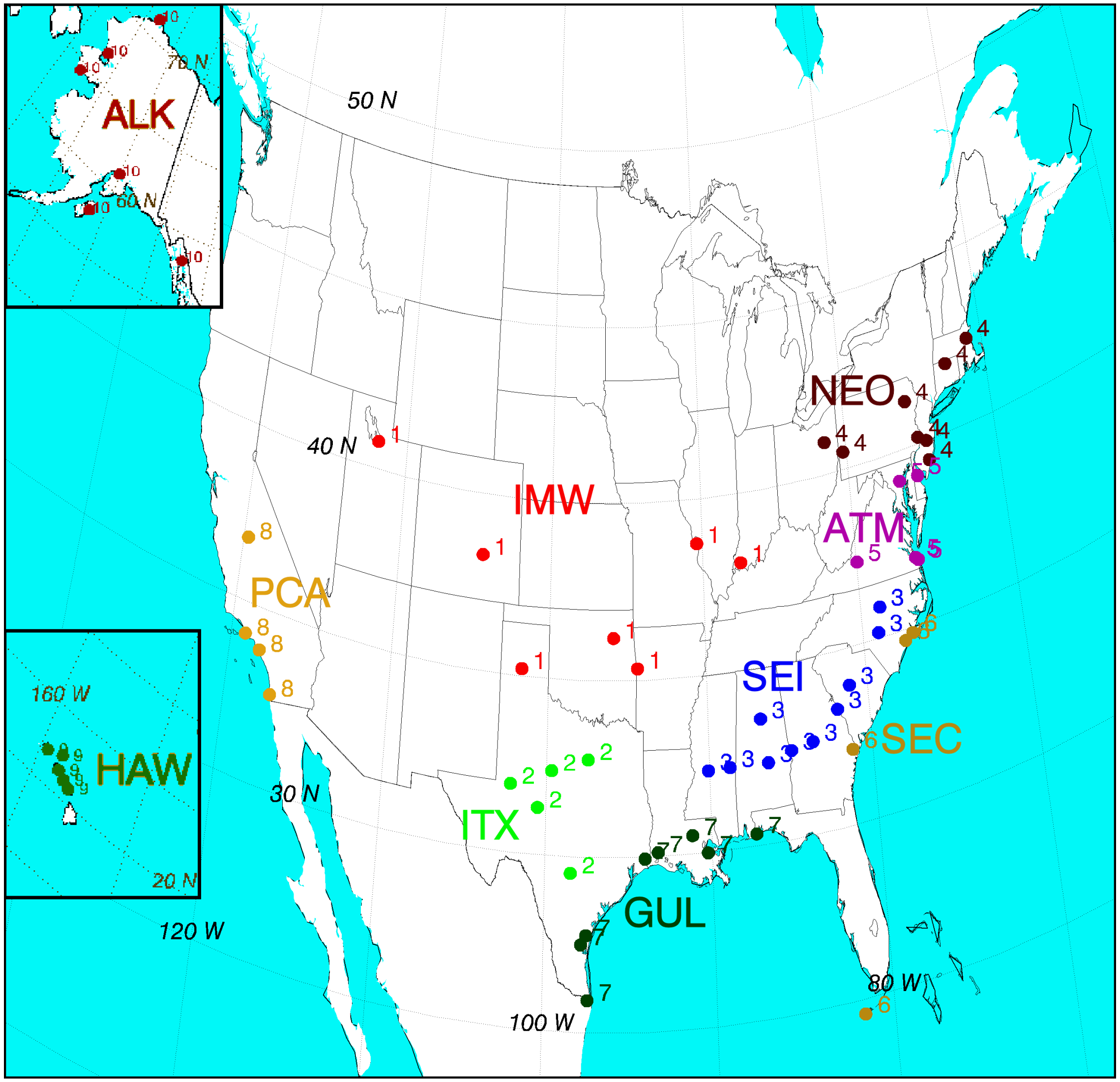

Figure 3: Map of the United States showing the locations of the stations and groupings used in this study, differentiated by the location. Insets are for the Alaskan (ALK) and Hawaiian (HAW) stations.

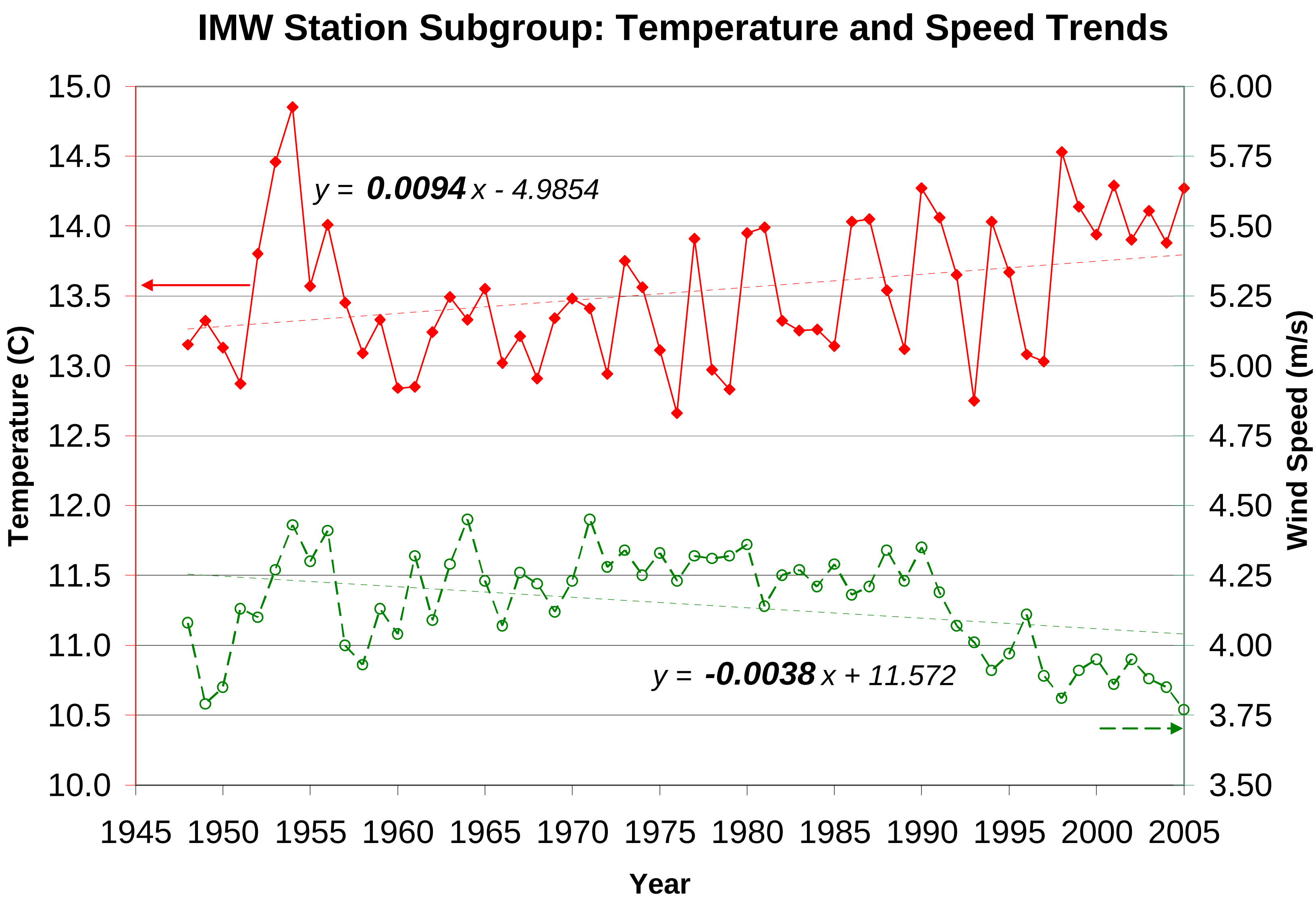

Figure 4: Trends of annually averaged wind speed and temperature from 1948-2005 for the IMW subgroup of stations.

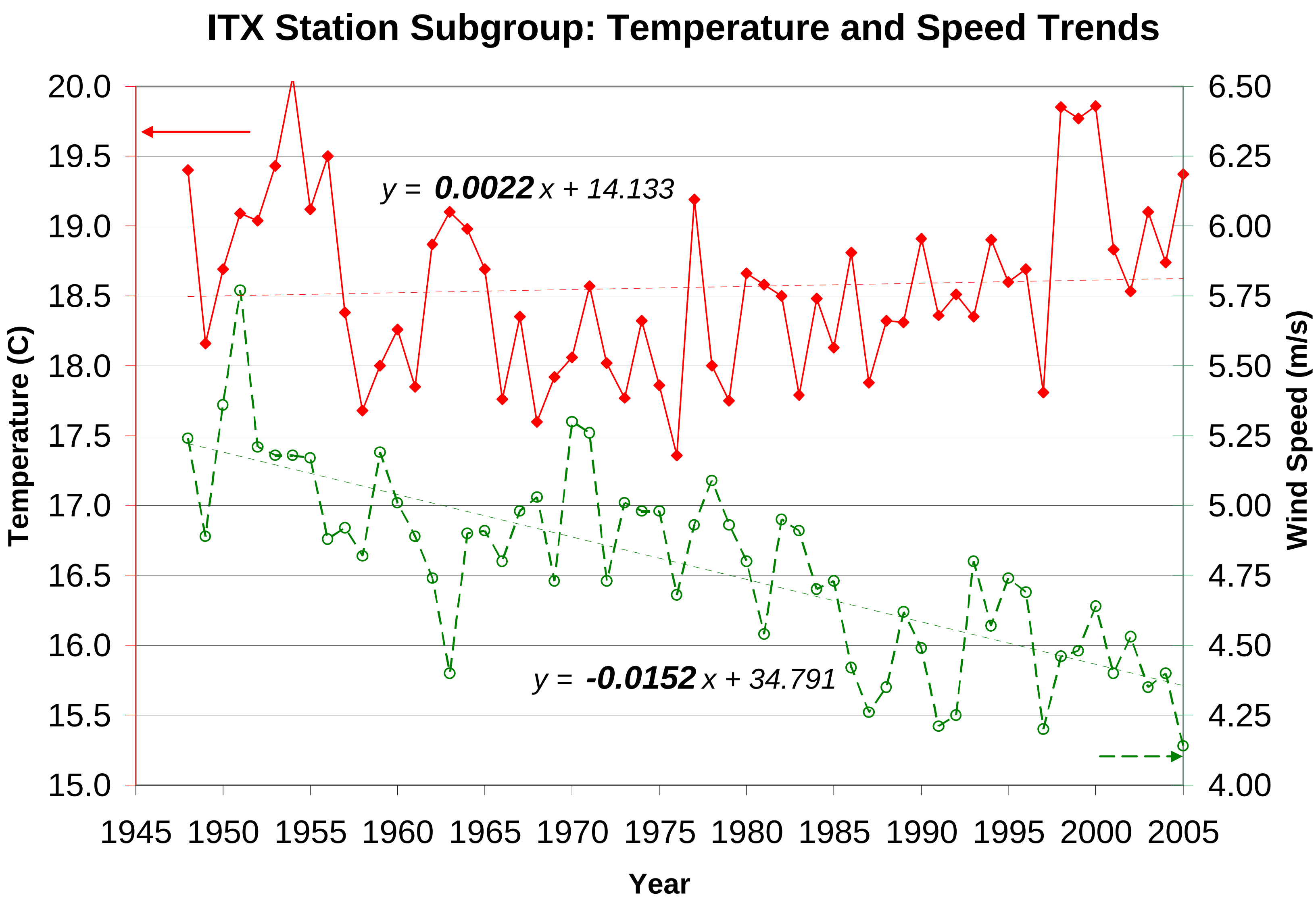

Figure 5: Trends of annually averaged wind speed and temperature from 1948-2005 for the ITX subgroup of stations.

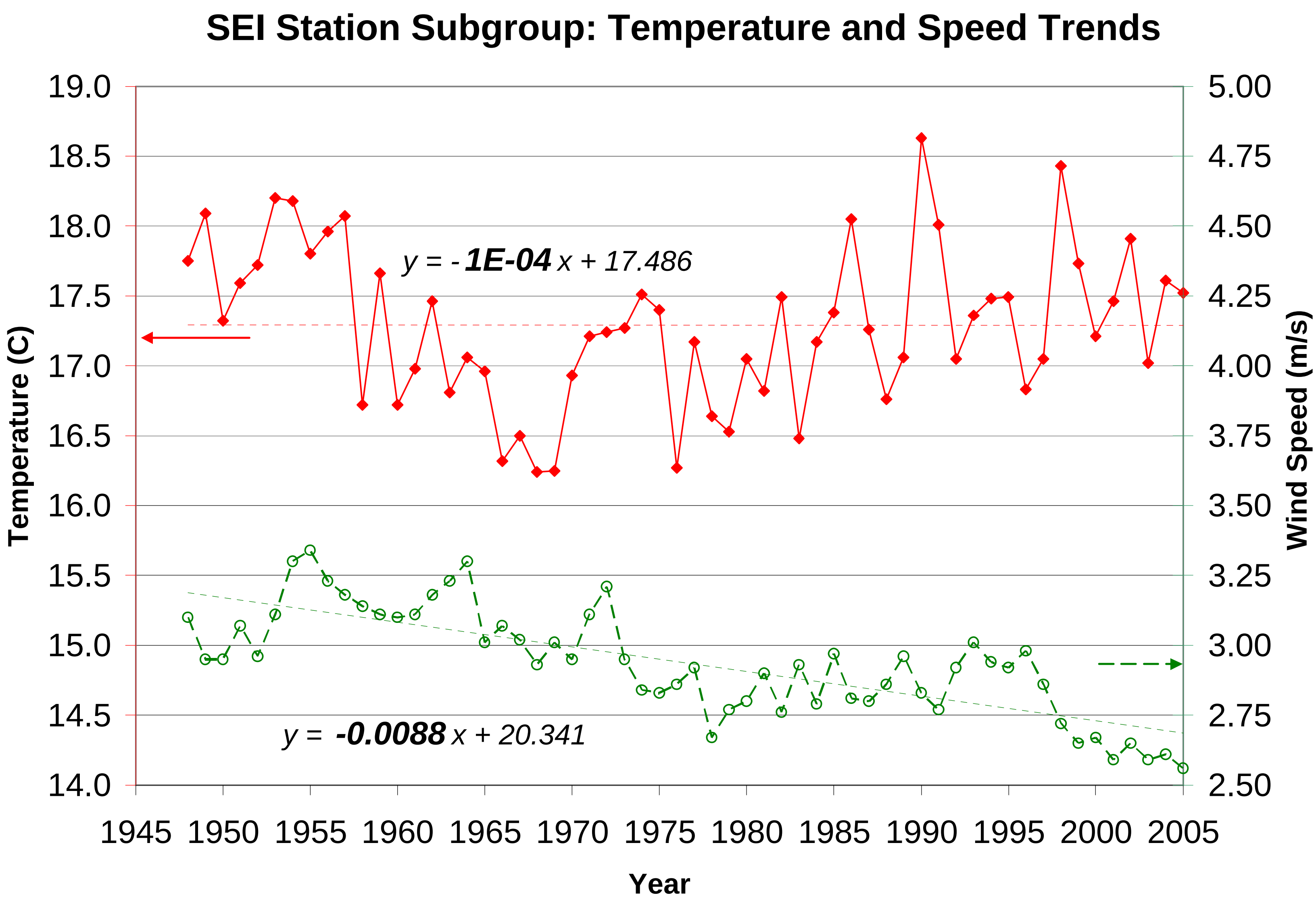

Figure 6: Trends of annually averaged wind speed and temperature from 1948-2005 for the SEI subgroup of stations.

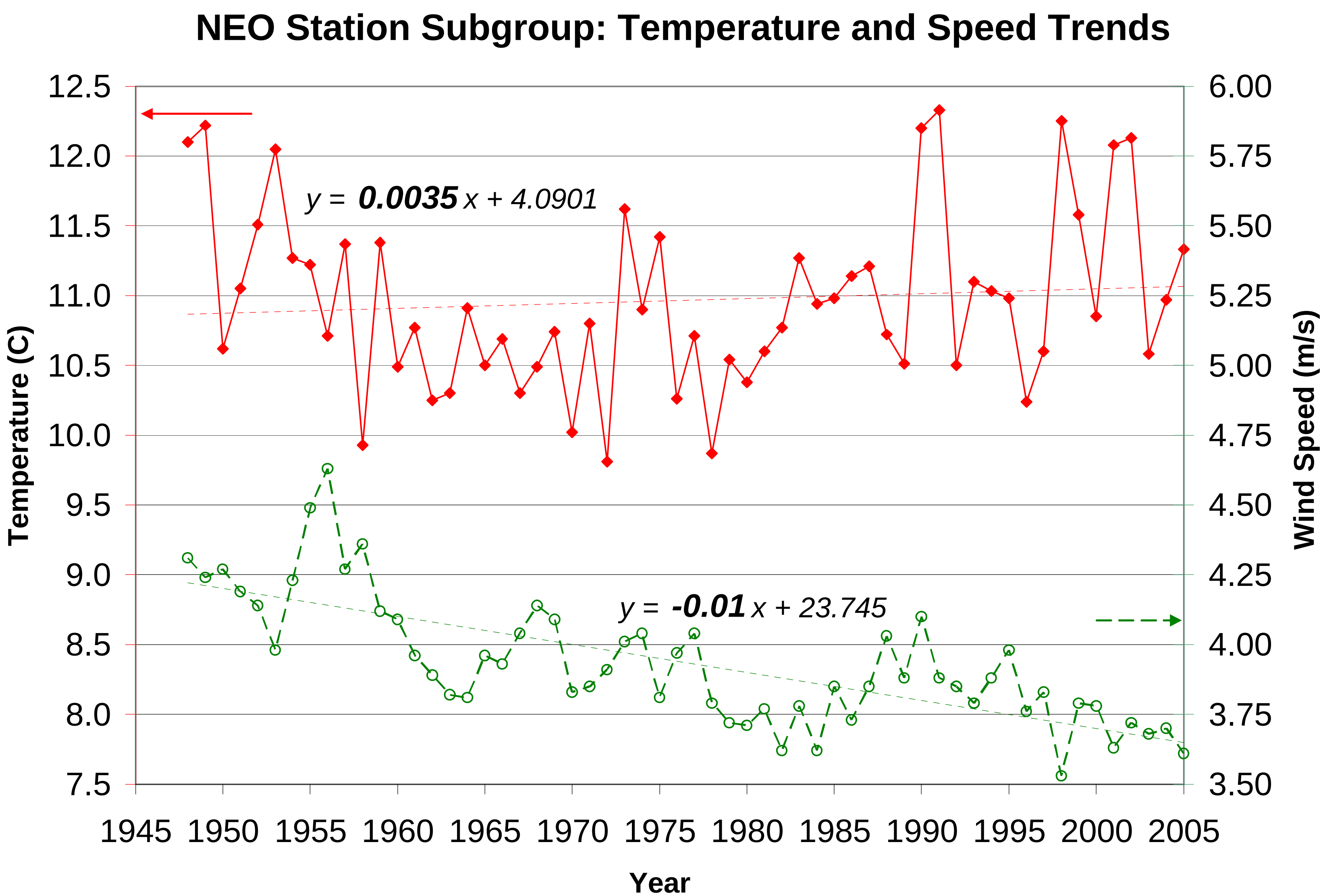

Figure 7: Trends of annually averaged wind speed and temperature from 1948-2005 for the NEO subgroup of stations.

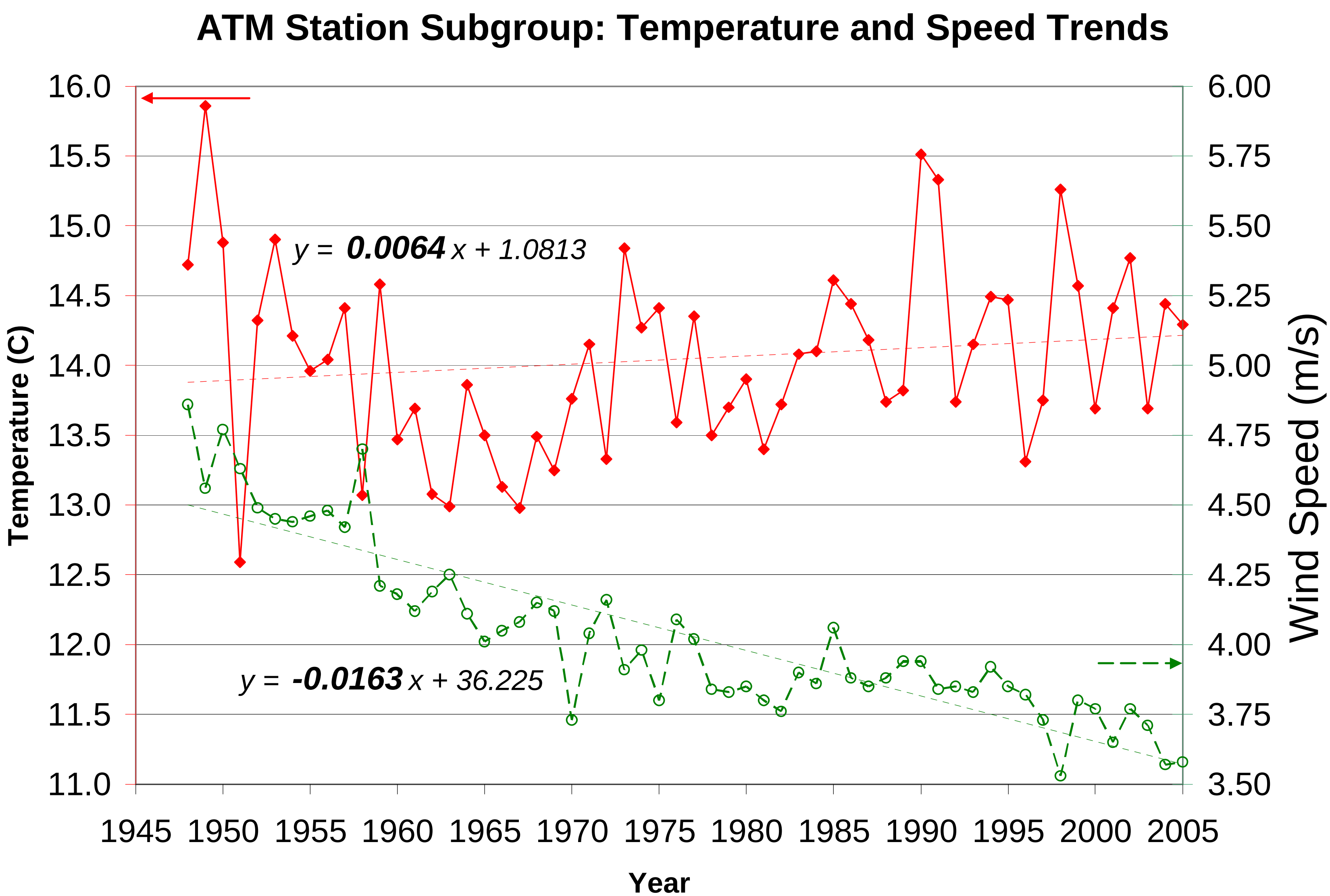

Figure 8: Trends of annually averaged wind speed and temperature from 1948-2005 for the ATM subgroup of stations.

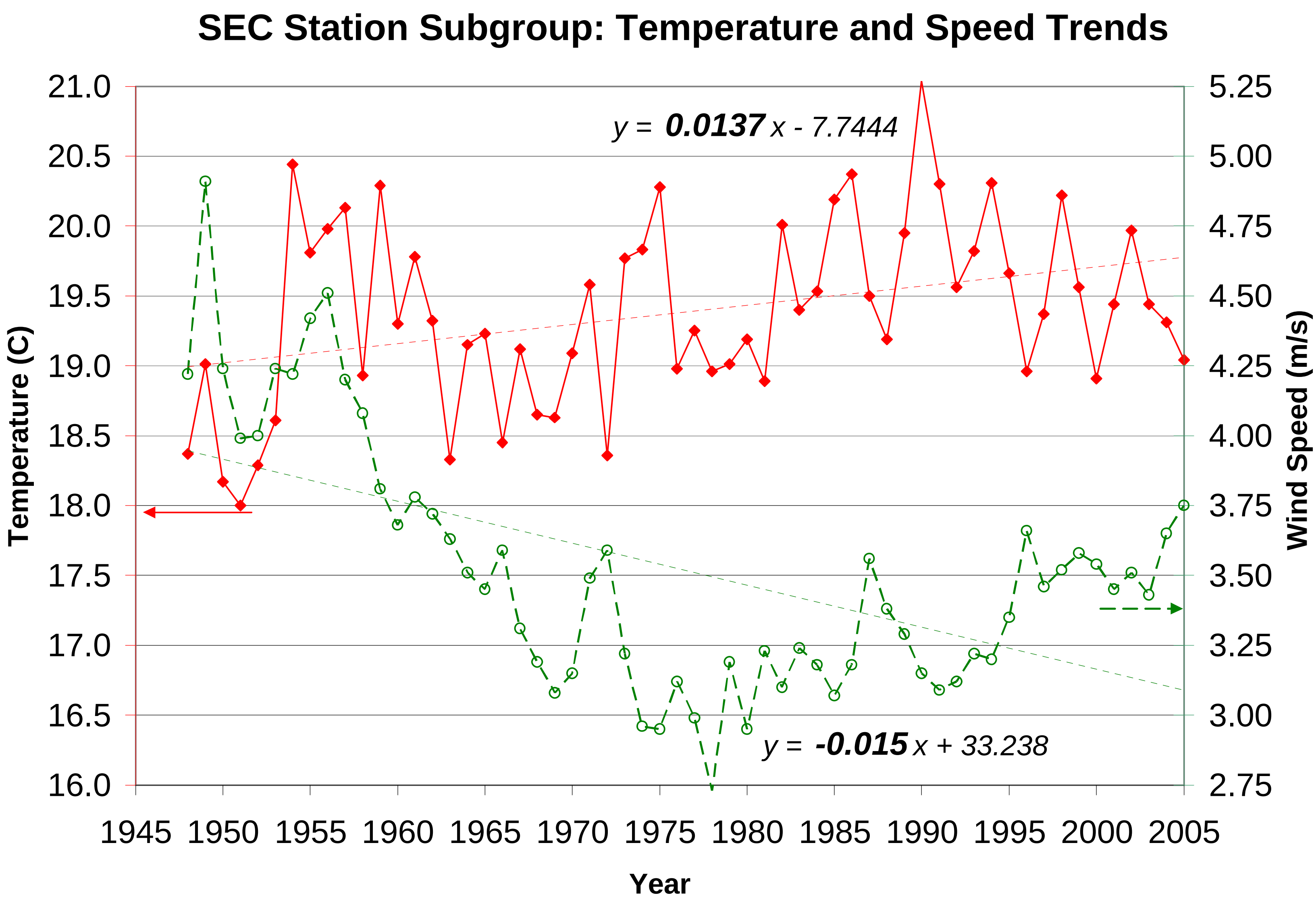

Figure 9: Trends of annually averaged wind speed and temperature from 1948-2005 for the SEC subgroup of stations.

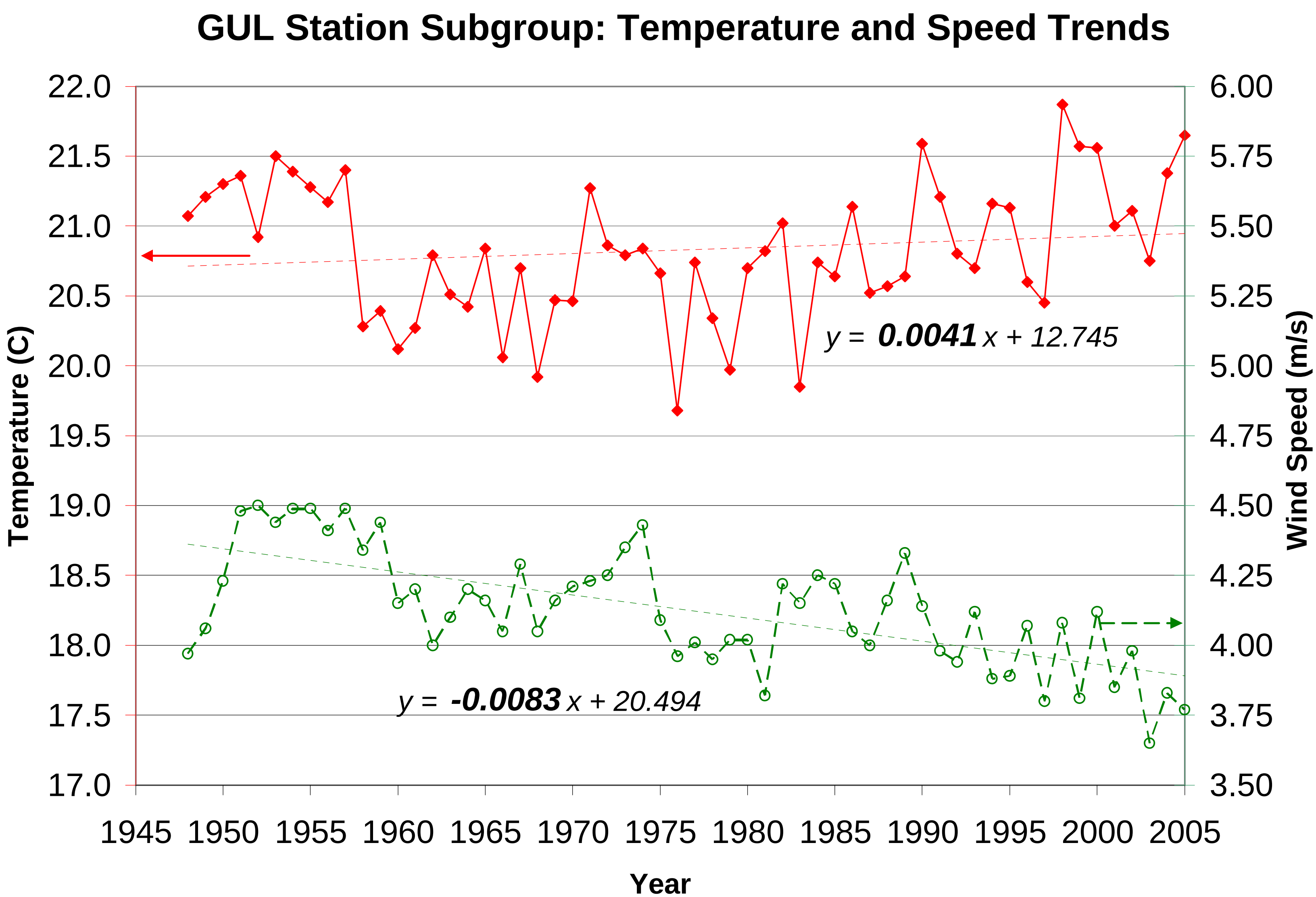

Figure 10: Trends of annually averaged wind speed and temperature from 1948-2005 for the GUL subgroup of stations.

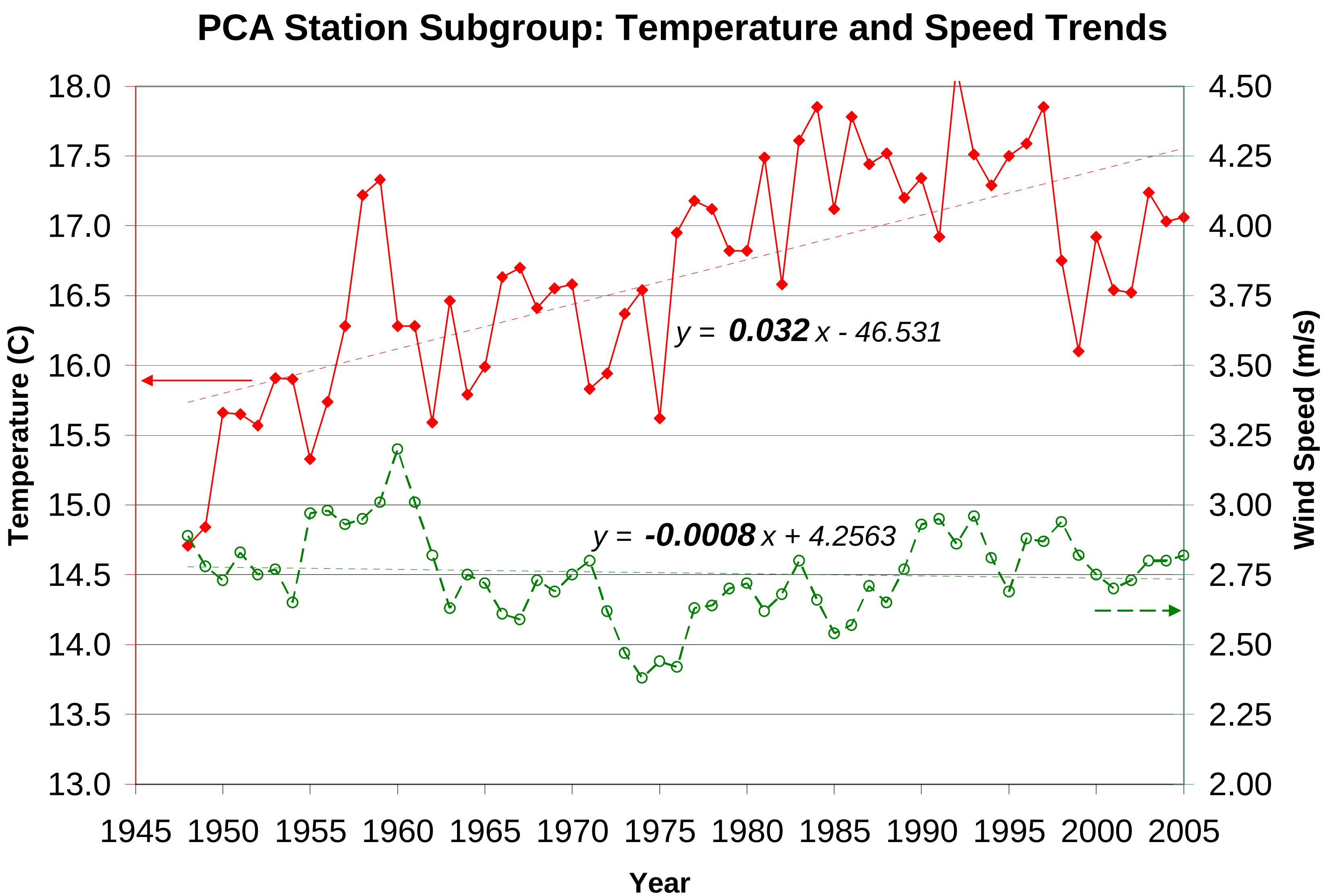

Figure 11: Trends of annually averaged wind speed and temperature from 1948-2005 for the PCA subgroup of stations.

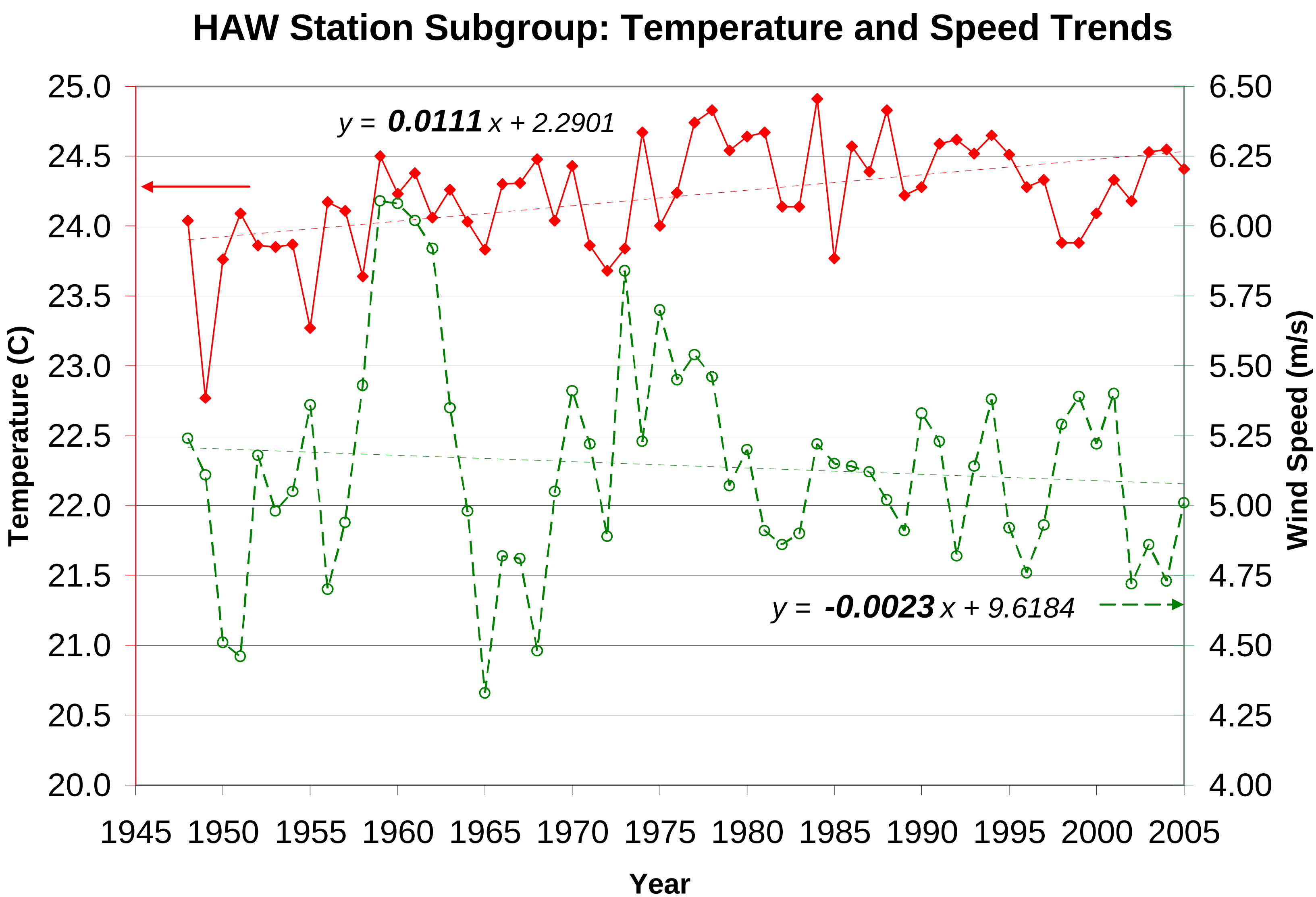

Figure 12: Trends of annually averaged wind speed and temperature from 1948-2005 for the HAW subgroup of stations.

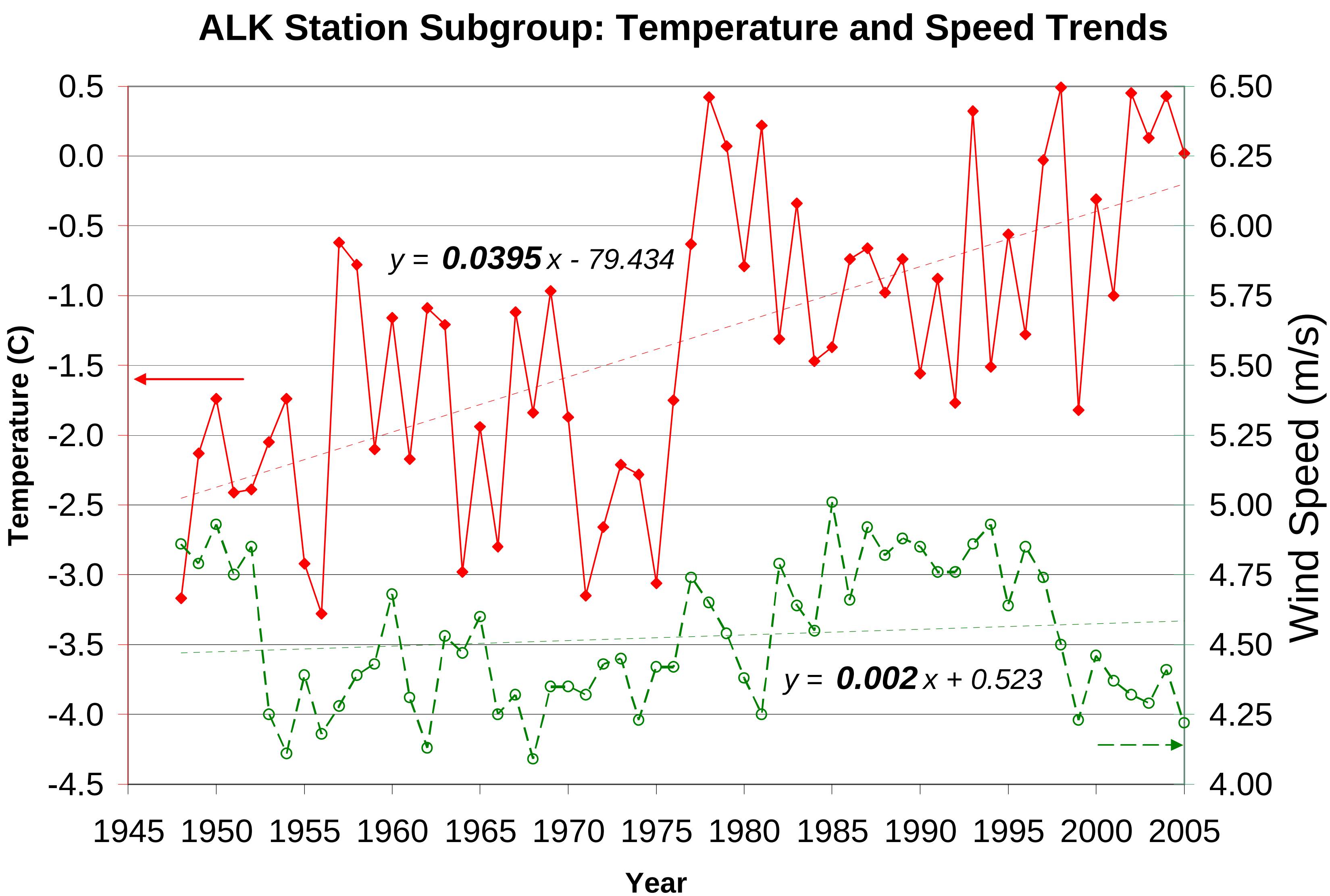

Figure 13: Trends of annually averaged wind speed and temperature from 1948-2005 for the ALK subgroup of stations.

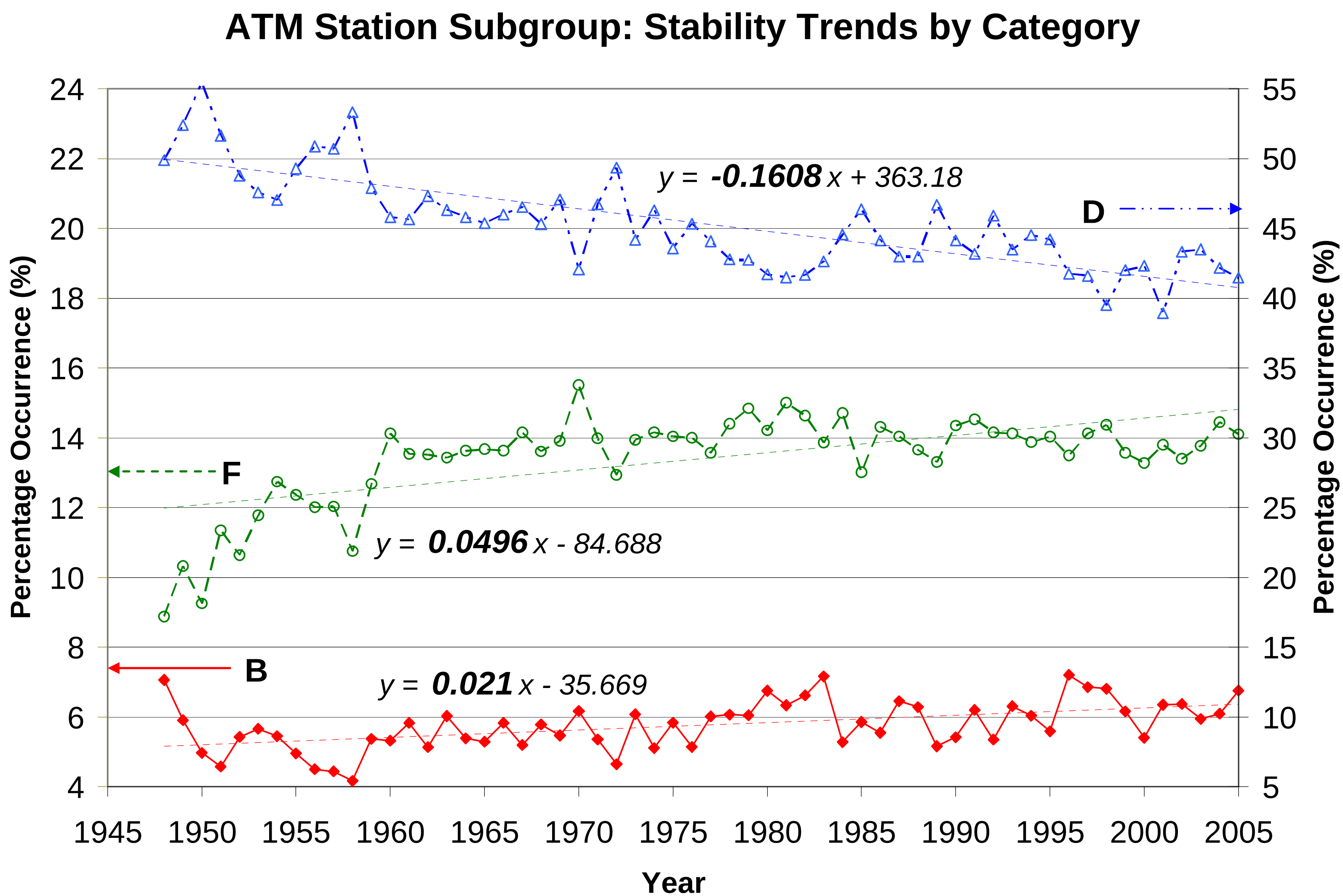

Figure 14: Trends of annually averaged atmospheric stability frequency of occurrence (expressed as a percentage) for the B, D, and F categories for the ATM station subgroup from 1948 to 2005.

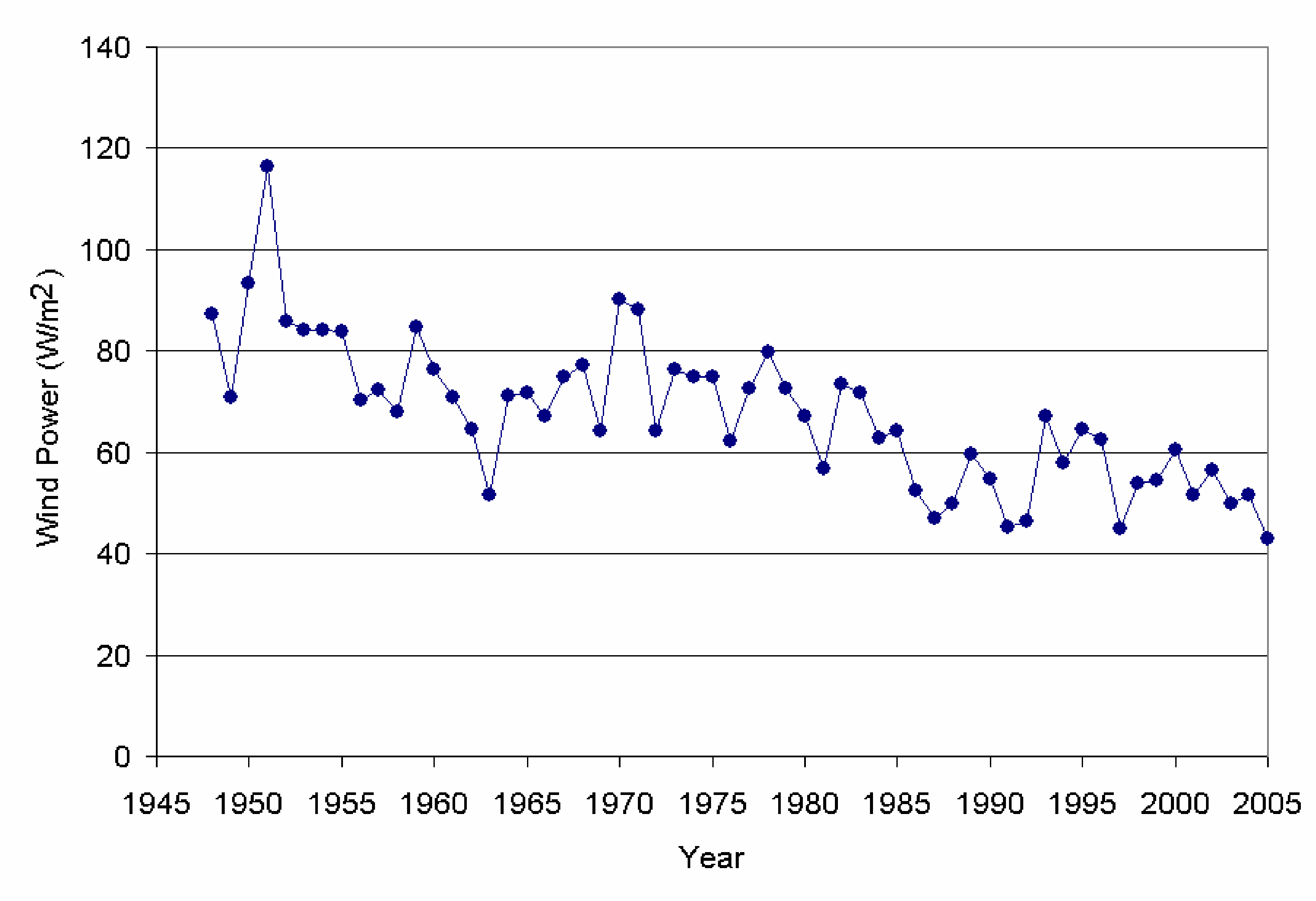

Figure 15: An estimate of the theoretical power per unit area (watts/m^2) swept out by the blades of a wind generator for the ITX group of stations.