'Variations in upper troposphere temperatures and stability indices over the past 46 years in the Gulf of Mexico, and the Influence a Warming Earth has on Tropical Systems'

A Senior Honors Thesis

Presented in Partial Fulfillment of the Requirements for graduation with distinction in Geography in the undergraduate colleges of The Ohio State University

by

Andrew Annunzio

The Ohio State University
June 2006

Project Advisor: Professor Jay S. Hobgood

Abstract:

The 2005 hurricane season was the most active hurricane season on record, and it was as destructive as it was active, ravaging areas along the Gulf Coast, especially Louisiana and Mississippi. The 2005 hurricane season was a continuance of the recent trend in hurricane activity. Since 1995, the Atlantic Ocean has experienced a period of increased hurricane activity. A large debate has arose on the cause of the increased activity with many attributing the active period to global warming, while others tend to place blame on the North Atlantic Multi-decadal Oscillation. Both sides of the argument were examined in this research project by computing CAPE (Convective Available Potential Energy) and running a model developed by Holland to compute the maximum potential intensity of hurricanes given the thermodynamic state of the atmosphere. Especially strong storms have developed in the Gulf of Mexico during the past two years. Hence, the Gulf was chosen as the area for investigation. Monthly averaged reanalysis data were obtained throughout of the Gulf of Mexico (24 degrees N 90 degrees W, 27 degrees N 90 degrees W, 24 degrees N 85 degrees W, and 27 degrees N 85 degrees W) at the surface and at 12 different constant pressure levels (925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70 hPa). Data were collected for the months when the hurricane season is at its peak, which is August through October. It is hoped that the results will contribute to the global warming debate, and describe how hurricane strength and atmospheric instability has changed in the Gulf of Mexico since 1960.

Introduction:

In the scientific community it is well accepted global warming is occurring. There is still a lot of debate on the causes of warming (the earth's natural cycle or anthropogenic influences). However, the consensus is global warming is altering the Earth's surface temperature. Likewise, as the temperature increases at the Earth's surface, more energy will be present. The effect of an increase in energy on the earth's surface is described by the second law of thermodynamics. Mathematically, the second law is

$ds = 1/T\ dq.$

The second law states that in a system a change in entropy is directly related to the change in energy, dq, multiplied by the inverse of the temperature. In a closed system where irreversible processes are assumed to take place, the law of conservation of energy is followed meaning energy cannot be destroyed. In this case both dq and ds will always have a value greater than or equal to zero. The Earth is assumed to be a closed system in which all processes are irreversible. An incremental change in energy results in a subsequent change in entropy which will not lessen as we go into the future.

Repercussions of the increase in temperature and energy are seen in meteorology. A typical mid-latitude cyclone seen on your everyday weather map is driven by variations in pressure, temperature, and density in the x, y, and z directions creating a baroclinic zone. These pressure, density, and temperature gradients are caused by differential heating on the surface of the Earth. When the gradients become too large, the atmospheric attempt to equalize itself produces the cyclone. The cyclone acts as a means

for warmer, moister air to the south to mix with cooler, drier air to the north in the Northern Hemisphere. After the atmosphere reaches equilibrium, uneven energy transfers reestablish the thermal/density gradient, causing the occurrence of another cyclone. It is possible global warming will influence energy distribution in two different ways. Global warming may increase the energy gradients between the poles and equator producing more intense cyclones. On the other hand, if warming occurs more in the higher latitudes, meridional gradients would be lessened resulting in weaker mid-latitude storms.

Tropical systems, especially hurricanes, represent another method by which the atmosphere attempts to equalize energy and temperature differences present between the equator and poles, and more importantly between the surface and upper troposphere. Though hurricanes also redistribute energy, they are driven by latent heat released in moist convection. This process is much different than the processes which drive the mid-latitude cyclone (Riehl, 1954). Initiation of hurricanes results from energy differences between warm oceans and the atmosphere directly above (Kleinschmidt, 1951). Although the temperature difference between the atmosphere and ocean is small near the surface, a large energy difference is present since an ocean is saturated while the atmosphere directly above is not (Emanuel, 1991). As water evaporates, energy is transferred from the ocean to the lower atmosphere. The preliminary energy transfers between the ocean surface and air directly above is the first phase in initiating the storm system. Thereafter, the warmer, higher entropy air needs to be displaced aloft warming the upper levels of the atmosphere as well. As the air moves up in the atmosphere, clouds form from condensing water vapor releasing latent heat into the atmosphere and

warming the air. Further, the vertically displaced air causes pressure falls and increases the potential temperature of air at the surface, which in turn gets displaced upward until energy is equalized. The ability for surface air to be moved upward is made possible through surface convergence, low level vorticity, and an unstable atmosphere. The disequilibrium in energy between the ocean surface and the atmosphere above always exists. However ocean temperatures must be warm enough in order to produce large energy gradients to provide sufficient pressure falls and moist entropy transport. It is well established that sea surface temperatures greater than twenty six degrees Celsius are a prerequisite for hurricane development (Miller, 1958). Further, sea surface temperatures also provide an upper limit on hurricane intensity, allowing stronger hurricanes to develop with increasing surface temperatures (Gray, 1968).

Given the importance of sea surface temperatures in hurricane development it is obvious why global warming is a topic of concern. Global warming will cause sea surface temperatures to rise, potentially creating stronger hurricanes than we have seen in the past. Research has already been conducted on this issue, showing storms eighty years in the future will average a surface wind speed 5.8% greater and surface pressures 10.2 mb lower, along with higher precipitation rates than what is observed today (Knutson and Tuleya, 2004). The question now is whether global warming has already begun to influence the intensity of tropical cyclones. Between 1970 and 2004 global sea surface temperatures have risen by about .5 degrees Celsius (Agudelo and Curry, 2004). This increase, however, may be too small to provide significant changes in observed hurricane intensities during the period, since a 1 degree increase in ocean temperatures should result in a 5% increase in hurricane intensity (Emanuel, 1987). In light of this issue, a

study showed while the frequency of hurricanes have remained constant globally, the number of category four and five storms have nearly doubled between the 1970 through 2004 period (Webster, Holland, Curry, and Chang, 2005). Further, a parameter developed by Emanuel measuring the energy output of storms known as the Power Dissipation Index has risen remarkably since 1975. Storm Power Dissipation Index relates the total energy output of storms to the integrated time of the storm multiplied by the max wind speed at 10 meters. PDI is mathematically expressed as

$$PDI = \int |V|^3 \, dt \text{ (Emanuel, 2005)}$$

The integration is taken from 0 to t, where t represents the total lifetime of the storm. The integration will need to be split up into different time intervals as the intensity of the hurricane varies through time. Given the increase in SST's, PDI values should have only increased by 8 - 12 percent, but Emanuel found the power dissipation in the Atlantic has doubled in the past thirty years representing a sharp increase in winds and longevity of storms (Emanuel, 2005).

While many feel global warming has already had an impact on tropical systems, others hypothesize the Multi - decadal Atlantic Oscillation has had a larger effect on tropical systems. It is hypothesized that this oscillation in the North Atlantic is the result of a current which provides periods when Atlantic sea surface temperatures are warmer followed by periods where SSTs are cooler. This hypothesis is supported by the trends in hurricanes seen in the past 55 years. The 1950's and 60's was an active period in which a greater number of tropical systems developed. Following the 1960's, the period between 1970 and 1994 was a period of relative hurricane inactivity where an average of nine

storms was seen in the Atlantic Ocean per year. 1995 brought an abrupt change in this trend when 19 storms developed. Since 1995 an average of fifteen storms has developed per year, which is an average of six storms greater than the previous twenty-five year average. While the oscillation has produced periods of increased frequency in storms, it should also engender periods of increased hurricane intensity with warmer SSTs. The studies mentioned above were conducted from a period from the 1970s till last year and support this notion. But, Emanuel as well as other researchers claim this jump is far too significant to be attributed solely to an oscillation.

A.) The Reanalysis Project

The reanalysis project was undertaken by a collaboration of NCEP/NCAR, NOAA, and CDC beginning in 1996 and continuing to present day. The initial project covered the forty years prior to 1996, while today reanalysis data is available for 1948 – 2005. The main source used to derive the data comes from rawindsonde data being taken everyday from March 1962 onward. Other data sources include aircraft data, the Comprehensive Ocean-Atmosphere Data Set, surface land synoptic data, satellite data, and remote sensing data (Kalney, et al, 1996). After the data have been collected, a monitoring system checks for major errors for every 6 hour period of each month. Checks are also conducted on monthly means through statistics of monthly climatology. Quality control checks for large variations in monthly means compared to climatology by examining if the value attained is less than 2 standard deviations away from the 7 year climatology average. If the data is greater than two standard deviations from

climatology, then bad input rawindsonde and satellite data is sought for and discarded (Kalney, et al, 1996). The temperature data used in this study is just as accurate as observed data, since there is plenty of rawindsonde data to interpolate the temperature field. Other variables, such as relative humidity, are not as accurate, since ample observational data is not available and the derived data is influenced by model biases. Unreliable data of relative humidity may play a factor in this study when computing Convective Available Potential Energy. CAPE is strongly dependent on the temperature profile and relative humidity at the surface; hence some values may deviate from the actual CAPE values during the period.

B.) MPI

As a hurricane develops, latent energy is transferred from the warm ocean surface to the cold upper levels of the atmosphere. The entropy displaced then warms the upper levels of the atmosphere and this transfer of moist entropy results in pressure falls at the surface (Malkus and Riehl, 1960). It has been shown the ability for a tropical storm or hurricane to develop depends on the thermodynamic environment in which the moist entropy can be redistributed establishing a warm core near the center (Holland, 1997). Based on this principle, Holland developed a model establishing the maximum potential intensity a hurricane can attain given the thermodynamic state atmosphere directly in the center of circulation. The model works as follows: An initial pressure fall results from a redistribution of moist entropy at the surface given the relative humidity which is assumed to be 90%. All energy present is available to warm the upper levels, develop the tropical system, and establish an eye wall. For simulations with a thermodynamic environment supportive enough to produce large pressure falls at the surface, an eye will

form with constant equivalent potential temperature at the surface underneath it. As the air in the upper atmosphere warms, pressure falls are calculated by

$$\Delta P_s = P_s/(T_v(p_s)) * \int \Delta T_v \, d \ln(p)$$

where P_s is the surface pressure, ΔT_v is the difference in virtual temperature between P_s and P_t, $T_v = T(1 + .61q)$, and P_t is the pressure at the equilibrium level in the upper atmosphere where the atmospheric instability is no longer present and the saturated adiabat re-crosses the environmental temperature profile in the eye wall (Holland, 1997). Since temperatures are only known at certain levels in the atmosphere below the equilibrium level, we split the integral which is take from P_s to P_t, into intervals such that we integrate over subsequent layers. In performing the integration, ΔT_v is assumed to remain constant and moved outside of the integral. As pressure falls at the surface, equivalent potential temperature defined by

$\theta_e = (T_v)* (1000/p)^{(R/CP)}$ where R = 287.4 and Cp = 1004

will increase. This higher entropy air will then be redistributed aloft, warming the upper levels and lowering the surface pressure further. The process becomes cyclical and will repeat until the temperature profile of the hurricane equals the saturated adiabatic lapse rate negating transfers of moist entropy from the surface to above and hence surface pressure falls (Holland, 1997).

In my study, I used this model to compute the average maximum potential intensity (MPI) hurricanes can attain in the Gulf of Mexico given the average monthly vertical temperature distribution. As mentioned before, I examined the years 1960 through 2005. My objective is to investigate trends of MPI in hurricanes throughout this

period. In plotting the MPI, a curve representing a cosine function with higher MPI values in the 1960, 1990s and 2000s will support the notion the North Atlantic Multi-decadal Oscillation is influencing hurricane MPI. A downward linear trend will enhance the global warming argument, while no trend will indicate MPI in the Gulf of Mexico has not been influenced by either global warming or the North Atlantic Multi-decadal Oscillation.

C.) Convective Available Potential Energy

It has been hypothesized by Dr. Gray that six variables govern the development of tropical systems. These variables include low-level relative vorticity, a location far enough away from the equator such that the Coriolis parameter has an effect on rotation, weak vertical shear, high relative humidity in the lower and middle troposphere, conditional instability, and Sea Surface Temperatures greater than 26 degrees Celsius (Gray, 1975). While other factors influence hurricane development, these six parameters have the greatest effect. The first three parameters mentioned represent the dynamical limitations of hurricane intensity, which are not examined in this research. The latter three parameters represent the thermodynamic limitations of hurricane intensity, relevant to this study since the MPI calculation is an estimate of hurricane intensity given the thermodynamic state of the atmosphere (Gray, 1975). Convective Available Potential Energy is a parameter used to measure the potential instability of the atmosphere. The stability parameter tells us when a parcel is moved vertically in the atmosphere whether it will stay in the position placed, move higher in the atmosphere, or sink back to its original position. CAPE is computed by using a skew-T diagram where the

environmental lapse rate and the parcel lapse rate are plotted. At the surface, we raise a parcel of air dry adiabatically until it reaches the saturation mixing ratio, a level known as the lifting condensation level. After moisture condenses and clouds form, the parcel of air rises moist adiabatically throughout the rest of the sounding. If the environmental lapse rate is relatively steep and sufficient moisture is present at the surface the environmental lapse rate will cross the lapse rate of the parcel at a point known as the Level of Free Convection. The vertical profiles of the atmosphere and the parcel will form an area when the two lapse rates cross again at the Equilibrium Level higher in the atmosphere. CAPE is the area enclosed by the trajectories and is computed by integrating the temperature difference of the two vertically in the enclosed area. The numerical value obtained upon integration is the amount of energy per kilogram the parcel of air has to rise freely. This energy can be used by the parcel to accelerate vertically in the atmosphere. While there is a lot of debate on the role of CAPE in actual hurricane development, CAPE is a good indicator of the thermodynamic profile and atmospheric stability. The presence of CAPE in the atmosphere allows air of higher entropy and temperature to be driven up in the atmosphere, which is necessary in hurricane development. As warmer, moister air is distributed throughout the upper atmosphere; CAPE values will decline, lessening the gradient between the environment and the saturated adiabat. When the environmental lapse rate is equal to the saturated adiabatic lapse rate, instability is no longer present providing thermodynamic limitations on intensity. After it establishes a warm inner core, thermodynamic processes in a hurricane are similar to a Carnot Cycle in which air rises adiabatically near the eye wall, undergoes isothermal compression as it moves way from the eye, sinks adiabatically to

the surface, and expands isothermally as it travels back to the center of circulation (Emanuel, 1991). Holland proposes hurricanes represent an open Carnot cycle in which diabatic processes take place with the parcel of air exchanging moist entropy with the ocean surface (Holland, 1997).

As mentioned before, a lot of debate is occurring on the importance of CAPE in hurricanes. Montgomery and Persing proposed CAPE has no impact on the intensity of tropical systems (Persing and Montgomery, 2005). This study was done by observing variations in intensity after lowering the temperature at certain constant pressure levels and increasing CAPE values. The premise behind this argument is that other, dynamical factors such as low level vorticity, forced convection, and surface convergence greatly contribute to storm intensity. Limitations arise in this argument, since surface convergence is established as pressure falls occur at the surface. Using the argument proposed, low level vorticity is then the main contributor in cyclone development providing forced convection and pressure falls at the surface as the air moves upward. While a primary circulation in the atmosphere is needed for hurricane development, negating the importance of atmospheric stability and hence CAPE is not pragmatic. Air requires a mechanism beyond low level vorticity to rise to the upper levels of the troposphere, which it is allowed to do with the presence of instability. An environmental lapse rate steeper than the saturated adiabatic lapse rate is needed to first cause large initial pressure falls at the surface and allow the hurricane to establish a warm core in the upper levels. Once this is established and central surface pressure is already low enough such that air accelerates towards the center, then factors such as forced convection may supplant instability. Further, even when a hurricane has reached strong intensity, fast

vertical motions and CAPE are present in the eye wall for some tropical cyclones (Ebert and Holland, 1992). Also, Holland provides support for hurricanes dependence on instability through the work of other scientists. Willoughby, Shapiro, and others have proposed the total potential energy of a hurricane is represented by $TPE = g \int (T_p - T_e)/T_e \, dz + Rd*T_s*\ln(P_{env}/P_{eyewall}) + L_v(q_{eyewall} - q_{env})$ where T_p is the temperature sounding provided by the saturated adiabatic lapse rate on a sounding. The integration is taken between a height z_o at the surface and z at the top of the atmosphere (Holland, 1997). Cape in the above equation is represented by the integral taken when $(T_p - T_e)$is a positive value, meaning CAPE does play a role in TPE and hence hurricane intensity. Lastly, reiterating Dr. Gray's statement conditional instability is one of the driving forces behind hurricane development. Negating the effects of this important driving force not only underestimates hurricane strength, but also overstresses the importance of surface convergence and primary cyclonic atmospheric spin in the lower levels.

My main purpose in examining values of Convective Available Potential Energy in the Gulf of Mexico is to observe whether the Gulf of Mexico has become more unstable. Increasing CAPE values implies warmer temperatures and higher water vapor concentrations at the surface in the Gulf and/or cooling of the upper levels. Both factors support lower central minimum pressure at the center of circulation in hurricanes. A combination of warmer surface temperatures and cooler temperatures near the tropopause creates a superposition allowing hurricanes to become even stronger. Although both contribute greatly to MPI, it is surface temperatures which play the greatest role in MPI and also Convective Available Potential Energy. Increasing temperatures at the surface

should support increasing CAPE and instability, assuming reanalysis data for relative humidity is accurate. Similar to MPI, upward, linear trends in this parameter will support the global warming argument.

4. The Multi-Decadal Oscillation

The Multi-decadal Oscillation is a result of the thermohaline circulation in the North Atlantic Ocean. The thermohaline circulation is the overturning of water in the North Atlantic in response to salinity. In the upper kilometers of the ocean there are periods when the water near the surface undergoes salinificaiton and increases temperature resulting in higher Sea Surface Temperatures. Warming occurs while the layer below decreases in salinity and cools. This process occurs until gradients become large and overturning occurs (Polyakov, Journal of Climate, 2005). The circulation also acts to drive warmer water in the tropics poleward. The current acts in the same manner as the atmosphere and attempts to equalize temperature and density variations between the surface and the water below, and also between warmer water in the tropics and cold water in polar-regions. The Multi-decadal oscillation is a North Atlantic phenomenon, which engenders anomalous periods where sea surface temperatures have a positive anomaly followed by periods where the opposite occurs. Surface temperature anomalies generally are about .3 degrees Celsius in both warm and cool periods. The increase in SST's creates an environment more conducive for hurricane development. This is shown in the multi-decadal oscillation in hurricane activity in the Atlantic, where 10 – 40 years of increased hurricane activity are followed by 10 – 40 years of hurricane inactivity. The oscillation complicates matters greatly in global warming arguments. Many attribute

most of the increase in hurricane activity over the past ten years to the oscillation and belittle the role global warming plays with hurricanes.

Methodology

In order to compute CAPE and the Maximum Potential Intensity of hurricanes in the Gulf of Mexico, I first needed to obtain temperature data at the surface and 12 different constant pressure levels in the atmosphere. I obtained temperatures from reanalysis data by picking out certain points of latitude and longitude in the Gulf of Mexico and recording the temperature exactly at that point each time. Since the study investigates changes over time, monthly temperature averages were recorded, which decreases any substantial daily anomalies and cancels day to day variations. Further, choosing monthly averages is an advantage in using reanalysis data since the temperatures are checked by climatology and are more accurate than daily values. After all temperature data was collected, I computed CAPE by plotting the temperature profile of each month on a skew-T diagram. CAPE is computed by the following equation

$$CAPE = -R_d \int (T_p - T_e)\, d(\ln p)$$

The integral is taken from the Level of Free Convection when the saturated adiabat first crosses the environmental lapse rate to the Equilibrium Level when the temperature provided by the saturated adiabat equals the environmental temperature profile. At the present time, it is nearly impossible to provide a function for (Tp – Te). To combat this problem, we divide our integral into 50 hPa intervals and take the average temperature difference between the environment and the parcel. This average is assumed to remain constant throughout the entire 50 hPa column. As a result we are able to pull (Tp – Te) outside of the integral and perform an easy integration. In my computation I did not

convert the temperature to the virtual potential temperature to adjust for the moist environment. I kept the temperature provided by the reanalysis because of suspicion the relative humidity data provided by the reanalysis is inaccurate, especially at constant pressure levels above the earth's surface. After computing CAPE, I then simulated the model proposed by Holland to compute the maximum potential intensity of tropical cyclones. The program computes initial pressure falls and subsequent warming aloft. The process is looped until Pfall_n – Pfall_(n-1) begins to converge to zero. Once convergence is established the program is terminated and the MPI value is attained.

Results

1. MPI

The calculation of Maximum Potential Intensity in the Gulf was to examine if the thermodynamic environment has become more favorable to produce more intense hurricanes. Downward linear trends in MPI will support the notion global warming is influencing the maximum potential intensity hurricanes can attain. Oscillatory trends which show lower MPI values in the 60s, higher MPI values from 1970 – 1994, and lower MPI values again since 1995 will support the argument the multi-decadal oscillation is playing a greater role in influencing hurricane intensity. MPI is directly influenced by Sea Surface Temperatures and the atmosphere above. Therefore, MPI can be used as a parameter when examining the global warming vs. multi-decadal oscillation debate.

In the month of August MPI values show a general decrease in minimum central pressure as we move from 1960 through 2005, meaning potential hurricane intensity is increasing. This is supported by the graphs shown in figures 1 - 8. In the 1960s we have

higher minimum central pressures, and the pressures decreased through time. This is reflected with the linear regression and subsequent r^2 values in figures 2, 4, 6, and 8. 24 north 90 west data has an r^2 of .512, .401 at 27 north 90 west, .328 at 24 north 85 west, and .276 at 27 north 85 west. The linear regression shows a minimum potential pressure decrease of 15 hPa from 1960 through 2005. The results at each point are statistically significant when a 95% confidence interval is taken. It is interesting to note the mulit-decadal oscillation is not clearly seen in the August MPI data. Theoretically, the 1960s should have a lower central pressure than the 1970s, since the 1960s was a period of increased hurricane activity due to the thermohaline circulation creating warmer sea surface temperatures. There seems to be more consistency in hurricane maximum potential intensity between the 1960s and 1970s, which is different from the oscillatory trend expected. A surprising finding is the year of 1969 had one of the highest minimum central pressures out of all the years. 1969 is the year hurricane Camille ravaged the Gulf of Mexico and hit Louisiana. Camille had a minimum central pressure of 905 hPa and brought wind gusts of over 200 miles per hour. The reason this year shows such high MPI values is because of the use of monthly mean composites. The monthly means smoothed out short term variations in sea surface temperatures and troposphere temperatures. It is hypothesized hurricane Camille passed over a warm core eddy in the Gulf of Mexico allowing it to achieve category five status, which it theoretically could not attain given the MPI. The MPI value at each location in 1969 shows hurricane Camille may not have been as destructive as what occurred if it did not pass over the favorable environment at exactly that time. Another interesting value is the 887 hPa MPI at 24 degrees north 85 degrees west in 2005. In August 2005, hurricane Katrina made

landfall in a similar area as Camille. Hurricane Katrina did pass over a warm core eddy in the Gulf. However, the monthly mean composites smooth out the occurrence of a warm core eddy. Therefore, if dynamical conditions were favorable it is possible hurricane Katrina could have attained the same intensity without the presence of a large anomaly at the surface.

The MPI's for the month of September shown in figures 9 - 16 also illustrate increasing hurricane intensity between 1960 and present day. The correlation between year and MPI is not as prevalent at all four points. Hence, r^2 has lower values at all points than the previous month. R^2 values attained are .259 at 24 degrees north 90 degrees west, .138 at 24 degrees north 85 degrees west, .231 at 27 degrees north 85 degrees west, and .220 at 27 degrees north 85 degrees west. The linear regression shows about 10 hPa pressure falls in MPI from 1960 through 2005 at each location. The data is statistically significant at all data points when a 95 % confidence interval is taken. Although the correlation is not as strong, the MPI values of September also support the notion global warming is influencing the maximum potential intensity hurricanes can attain. The Multi-decadal Oscillation is not apparent in the September MPI graphs. We generally have higher minimum central pressures in the 1960s and 1970s and decreasing pressures through the 1990s and 2000s. An interesting feature of the graphs is the year of 2004, which had MPI values ranging from 910 – 920 at the data points, when hurricane Ivan ravaged the Gulf. While Ivan occurred in 2004, it is of note 2004 did not have the lowest MPI value out of all the years in the study. These MPI's, especially in 1996, show a hurricane such as Ivan could have occurred in other years given the thermodynamic environment. However, the lack of intense hurricanes is due to the dynamical state of the

atmosphere not being conducive for strong intensification. Storms most likely did not form in the year of 1996, since an El Nino occurred this year providing an environment dynamically unfavorable with strong shear aloft.

The month of October shows a very slight decreasing trend at each of the data points, but to a much lesser extent than what is observed in the previous two months. This is shown in figures 17 – 24. In fact, the data does not produce significant statistical results at three of the four locations. The insignificant data does not lessen the global warming argument. When computing MPI, surface temperature data is used instead of sea surface data. In the month of October air from the mid-latitudes may influence mean temperatures in the gulf, which directly influences MPI. Therefore, the MPI values may not reflect global warming due to the temperature influence provided by land. This is seen in October, because during this month, temperatures at the high latitudes are cooling. The cooling increases the thermal gradient between the equator and the poles resulting in cyclones. If the weather pattern is highly amplified as a result of the thermal gradients, air from the land will spread out over the Gulf decreasing surface temperatures. The surface temperature trends shown below at the four locations in the gulf support this notion.

In two of the three months, statistically significant results support stronger increasing potential intensity of hurricanes. The month which did not provide significant results is October where mid-latitude air may be influencing surface temperatures and hence MPI values. A trend expected with the Mulit-Decadal Oscillation is not shown in the data. Absence of multi-decadal variability and increasing trends in MPI support the

notion global warming is having an effect on potential hurricane intensity in the Gulf of Mexico.

2. Surface and Troposphere Temperatures:

Starting from the surface and working up through the troposphere, I examined variations in these temperatures throughout the decades as a by-product of the data for the Maximum Potential Intensity. I wanted to examine if either the multi-decadal oscillation or global warming is playing a role in these temperatures and what the repercussions are pertaining to the maximum potential intensity of hurricanes. Surface temperatures were recorded surface temperatures as opposed to sea surface temperatures, as the former are used in CAPE computations. It is generally accepted the surface temperature is 1 Kelvin cooler than the sea surface temperature. Hence temperatures at the surface directly reflect sea surface data.

The surface temperatures for the month of August show a definite upward trend in temperatures. The trends in sea surface temperatures reflect the trend in maximum potential intensity of hurricanes. From 1960 through 2005 there is a warming bias in surface temperatures seen in figures 25-32. R^2 for the month of August is .437 at 24 degrees north 90 degrees west, .418 at 27 degrees north 90 degrees west, .434 at 24 degrees north 85 degrees west, and .439 at 27 degrees north 85 degrees west. All 4 locations have p values near zero when a 95 % confidence interval is taken, showing the results are significant. Further, trends shown in the mean August surface temperatures do not reflect trends expected from the multi-decadal oscillation. Surface temperatures remain consistent in the 1960s and early 1970s and then begin an upward trend until

present day. A similar pattern is seen September, which is reflected in figures 33 – 40. All locations have results that are statistically significant at a 95% confidence interval, and an increase in temperature of 1 degree Kelvin from 1960 to 2005 is shown by the linear regression. There are some different results for October shown in figures 41 - 48 than September and August. In October, the trend is not as prevalent, but each location produces data that is statistically significant. There is a large variance in surface temperature at each of the locations, which is reflected in the MPI values. Although, a lot of variance is present at each point, the temperatures at 27 degrees north average 1.5 Kelvins cooler than the surface temperatures at 24 degrees north. This large gradient in temperatures supports the notion mid-latitude air is influencing temperature data in the Gulf of Mexico as expected. Further, the northern Gulf is shallower than the central Gulf supporting why these large temperature differences occur. Despite the intrusion mid-latitude air in October and the varying depth of the Gulf, there is a general increase in temperature of .75 Kelvin provided by the linear regression. Therefore, there is an apparent upward trend in surface temperatures in the Gulf of Mexico, a trend that does not reflect the effects of an oscillation, but one that reflects consistent warming throughout the years.

Between the constant pressure surfaces 925 hPa and 300 hPa, there appears to be no trends in temperatures. There is year to year variance which has effects on MPI, but no upward or oscillatory trends are present. In the upper troposphere in levels 250 through 150 hPa, there is a very slight warming bias. The correlation between year and temperature for each of the levels is near .2 in the month of August, which is of some significance. The graphs provide no insight to trends in these temperatures. Correlations

do differ between the surface and the upper troposphere. At the surface the correlation between surface temperature and year was .67, while the correlation in the upper troposphere is .2 at 24 degrees north 90 degrees west. The differing correlations represent warming occurring at the surface while little warming is occurring aloft. The variations in warming between the surface and the upper atmosphere create a larger thermal gradient between the surface and the top of the troposphere, which reflects back in the MPI as more potentially intense hurricanes. The larger thermal gradient provides means for high entropy air at the surface to be driven up in the atmosphere and enable hurricanes to establish a warm core at the center of circulation.

Temperature trends at the 100 hPa and 70 hPa levels shown in figures 49 through 56 are somewhat enigmatic. At the 100 hPa level there is and oscillatory trend which is prevalent in the months of September and October. The trend is sinusoidal where 100 hPa temperatures are warmer between in the early 1960s and between 1980 and 1994, and cooler in the late 1960s and 70s and from 1994 on ward. The cause of this oscillation warrants further investigation, but cooler temperatures aloft will again increase the thermal gradient allowing hurricanes to become more intense. Although the thermal gradient between the surface and the tropopause is greater, variations in 100 hPa temperatures do not alter MPI values to a large extent. In the 70 hPa data there is a steady trend in stratospheric temperatures until the early 1990s. In the 1990s stratospheric temperatures drop suddenly, by 3 – 5 Kelvins. Scientists suggest this change in stratospheric temperatures is cause by loss of ozone in the stratosphere (Agudelo, 2004). Ozone retains heat from the sun, thus when ozone levels decline in the stratosphere it is reflected in cooler temperatures. Therefore the sharp decline in

temperatures at 70 hPa is a result of ozone loss. Temperature fluctuations at 70 hPa appear to have repercussions in the maximum potential intensity of hurricanes. Although most trends in 70 hPa temperatures have statistically significant effects on potential hurricane intensity, it is likely this correlation is spurious. This is because the decrease in 70 hPa temperatures occurs during the period of warmer surface temperatures and higher MPI values. However, there are years which produce equivalent potentially intense hurricanes when 70 hPa temperatures are warmer. Therefore, the high MPI values are a result from warmer surface temperatures as opposed cooler 70 hPa temperatures. This is pragmatic since 70 hPa temperatures are in the stratosphere above the equilibrium level and do not have an effect on atmospheric instability.

3. Results of Convective Available Potential Energy

My computation of Convective Available Potential Energy was designed to provide insight as whether the environment in the Gulf of Mexico has become more unstable. My results though were inconclusive as there was no trends present in CAPE throughout the years. There was a great amount of variance from year to year in each month, but no trends were present. The result can most likely be attributed to errors in surface relative humidity in reanalysis data. In the Gulf, there is not ample surface relative humidity data causing a large model bias in computations. As a result, we have large variances in CAPE from year to year, which most likely does not reflect the true CAPE values present during that time. Although CAPE values are affected by surface relative humidity data, there is still a trend between maximum surface pressure falls and CAPE shown in figures 57 - 59. The correlations in August, September, and October are

.539716, .584889, and .554405 respectively. Since CAPE is a reflectance of atmospheric instability, and MPI is strongly influenced by an unstable vertical profile, I concluded the CAPE values were altered. If surface relative humidity data was more accurate, then a much stronger correlation would be expected.

Conclusion

Given the correlation between MPI values and year, and surface air temperature and year, it is evident global warming is having an effect on both surface temperatures and potential hurricane strength. Global warming appears to be the culprit in causing changes since the trends are linear and do not have an oscillatory motions. Further, the Multi-Decadal Oscillation is not reflected by the data. It is possible the multi-decadal oscillation does not have as great as an effect in the Gulf of Mexico as it does in the Atlantic. This is plausible since land may partially block the current in the Atlantic Ocean from reaching the area, and further the oscillation takes place in the loop current, which surrounds the Gulf but not cover the whole area. This shows the Multi-Decadal Oscillation is more prevalent in the North Atlantic and does not have as great of an impact on hurricane frequency or intensity in the Gulf of Mexico. Another interesting feature is there generally is less of a trend in MPI and surface temperatures between the 1960s and early 1970s compared to the period thereafter. An explanation for this may be the cooling which should have occurred in the early 70s as a result of the multi-decadal oscillation may have been hindered by global warming. A general increase in SST's may have negated the effects of cooling showing more linear trends in the graphs than oscillatory trends. As a result, the powerful hurricanes seen in the Gulf the past two years

may have been influenced by global warming. Atmospheric dynamics also played a role in providing favorable conditions allowing hurricanes to feed off the warmer ocean surfaces in the gulf. Although hurricanes can attain greater intensities in the Gulf as a result of global warming, it needs to be noted other years in the past could have produced similar destruction.

While other years may have seen similar storms, what is of significance is warmer sea surface temperatures not only increases potential intensity, but also increases the frequency of hurricanes. Therefore, it is plausible we will see powerful storms more frequently in the Gulf in response to warming. In the troposphere, little warming is taking place between 925 hPa and 300 hPa. There is a slight warming trend at the 250 hPa – 150 hPa levels. However, r values are small meaning the surface is warming at a faster pace. A surface which warms faster than the upper atmosphere brings about a larger thermal gradient in the troposphere creating a more unstable environment and more transfers of energy. This has repercussions in the Gulf of Mexico by creating an environment favorable for more intense hurricanes, which is reflected in the MPI. Lastly, abrupt cooling takes place at the 70 hPa constant pressure level in the stratosphere. The cause of this sharp decline is lower concentrations of ozone in the stratosphere causing temperatures to cool. Cooling at the 70 hPa level appears to enhance a greater potential intensity of hurricanes. However, this correlation is spurious, since drops in 70 hPa levels occur during the period when surface temperatures are the warmest. In the near future, I would expect the trends to stay the same, since global warming will be an issue in the years to come. If trends continue for the next 46 years, surface temperatures in the Gulf will continue to increase providing more energy for hurricane development. As a

result, we should expect to see stronger hurricanes more frequently in the Gulf of Mexico.

Acknowledgements

Special Thanks to Dr. Hobgood who made this research project possible. Thanks to project honors representatives Dr. Jacobs and Dr. Rogers. Also, thanks to Todd Jones for help on computer programming.

Works Cited

P. Agudelo, Curry, J.A., 2004: Analysis of spatial distribution in tropospheric temperature trends. Geophys. Res. Lett. 31, L22207, doi:10.1029/2004GL020818.

Ebert, D. D., and Holland, 1992: Observations of record deep convection in Tropical Cyclone Hilda. Mon. Wea. Rev., 120, 2240 – 2251.

Emanuel, K.A., DesAutels, C., Holloway, C., & Korty, R. 2004: Environmental Control of Tropical Cyclone Intensity. J. Climate. 61, 843-858.

-., 2005: Increasing Destructiveness of tropical cyclones over the past 30 years. Nature, 436, 686 – 688.

-, 1987: The Dependence of Hurricane Intensity on Climate. Nature 326, 483-485.

-, 1991: The Theory of Hurricanes. Annu. Rev. Fluid Mechanics., 43, 585 – 604.

Gray, W.M., 1968: Global view of the origin for tropical disturbances and storms. Mon. Wea. Rev., 96, 669 – 700.

-, 1975: Tropical Cyclone Genesis, Atmospheric Science Paper 234, 121 pp.

Holland, G. J. 1996: The maximum Potential intensity of tropical cyclones. J. Atmos. Sci., 54, 2519 – 2541.

Kalnay, E., Kanamitsue, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saba, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J, Mo, K. C., Ropelewski, C., Wang, J., Jenne, R. and , Joseph, D., 1996: The NCEP/NCAR 40 - Year Reanalysis Project. Bull. Amer. Meteo. Soc., 77, 437 - 471

Kleinshmidt, E., Jr., 1951: Grundlagen einer Theorie des tropischen Zyklonen. Arch. Meteo. Geophys. Bioklimatil., Ser A, 4, 53-72.

Knutson, T.R. & Tuleya, R.E. 2004: Impact of CO2 Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the choice of Climate Model and Convective Parameterization. J. Climate. 17, 3477-3495.

Malkus, J.S., and Riehl, H., 1960: One the dynamics and energy transformations in steady-state hurricanes. Tellus, 12, 1 – 20

Miller, B.I., 1958: On the Maximum Intensity of Hurricanes. J. Meteor., 15, 184-195.

Persing, J., and Montgomery, M. T., 2005: Is Environmental CAPE Important in the Determination of Maximum Possible Hurricane Intensity? J. Atmos. Sci., 62, 542 – 553.

Polyakov, I.V., Bhatt, U.S., Simmons, H.L., Walsh, D., Walsh, J., Zhang, X., 2005: Multidecadal Variability of North Atlantic Temperature and Salinity during the twentieth century. J. Climate, 18, 5462 – 4581.

Ramaswamy, V. Schwarzkopf, M.D., and Randel, W.J., 1996: Fingerprinting of Ozone Depletion in the spatial and temporal pattern of recent lower-stratospheric cooling. Nature, 382, 616 – 618.

Riehl, H., 1954: Tropical Meteorology. McGraw-Hill, 392 pp.

Webster, P. J., Holland, G. J., Caurry, J. A., and Chang, H.-R., 2005: Changes in Tropical Cyclone Number Duration, and Intensity in a Warming Environment. Science, 309, 1844 - 1846

Figure #1

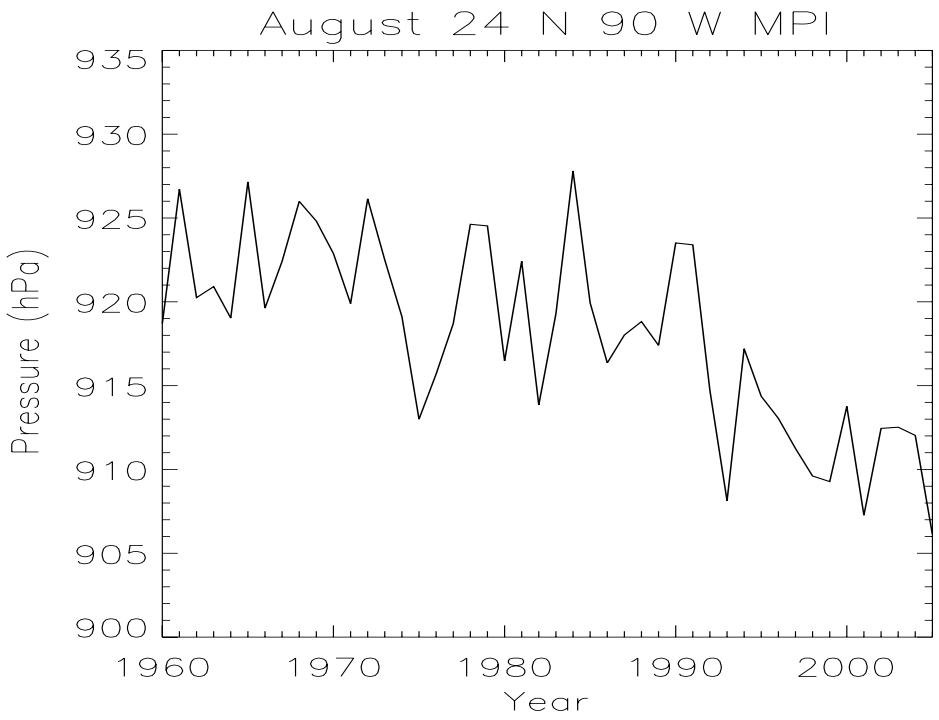


Figure #2

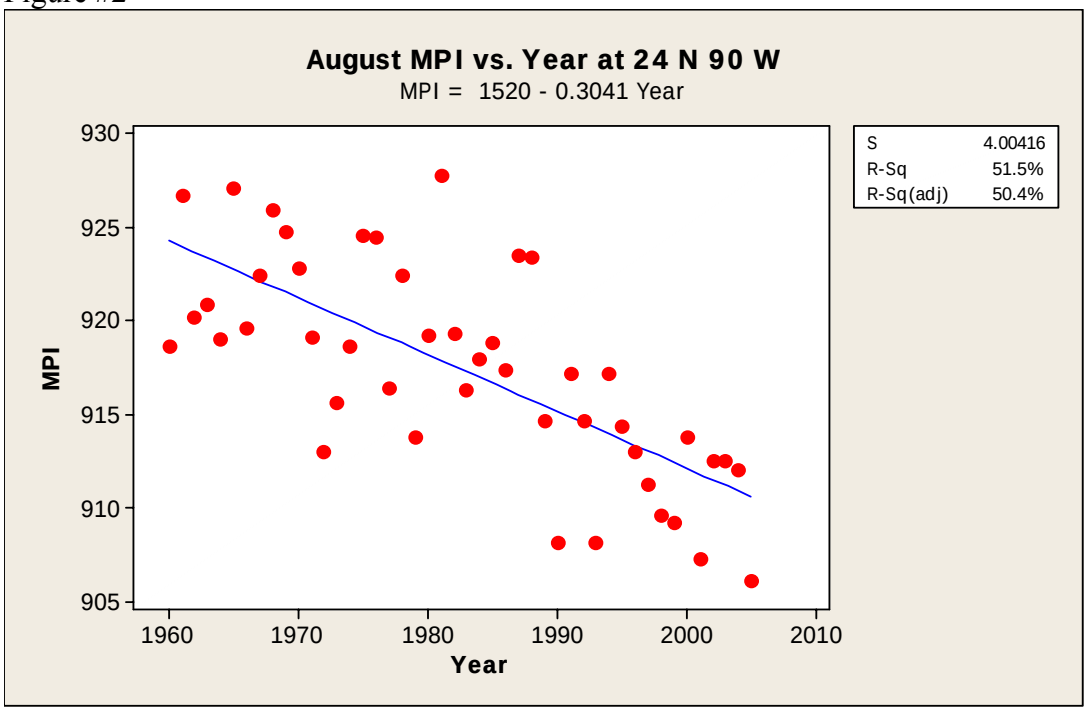


Figure #3

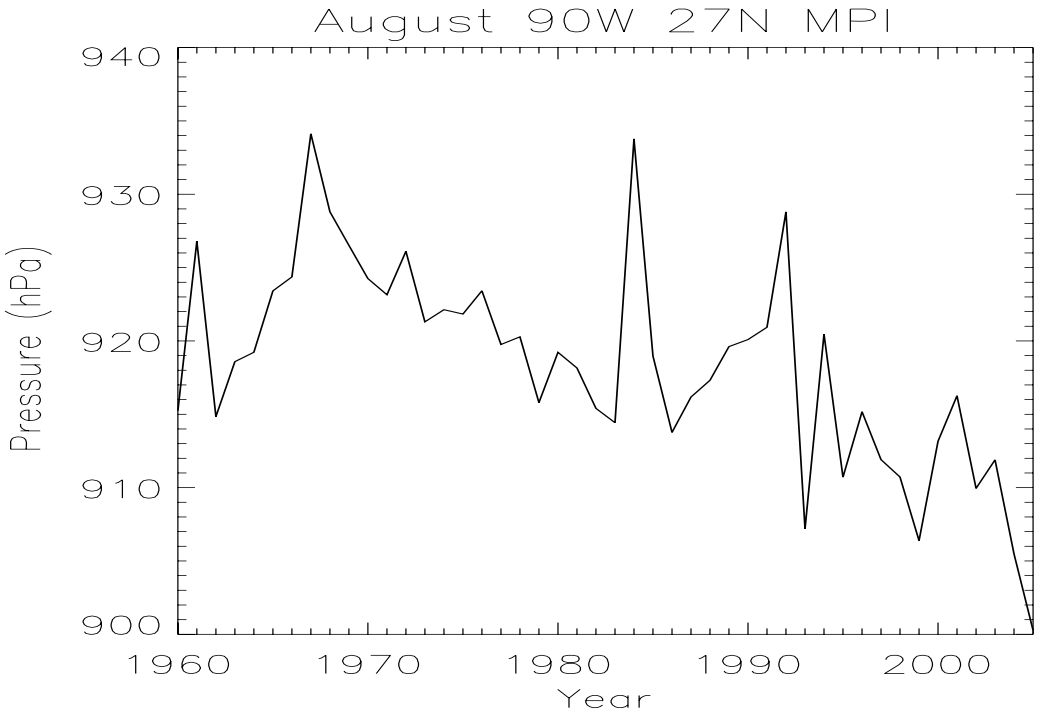


Figure #4

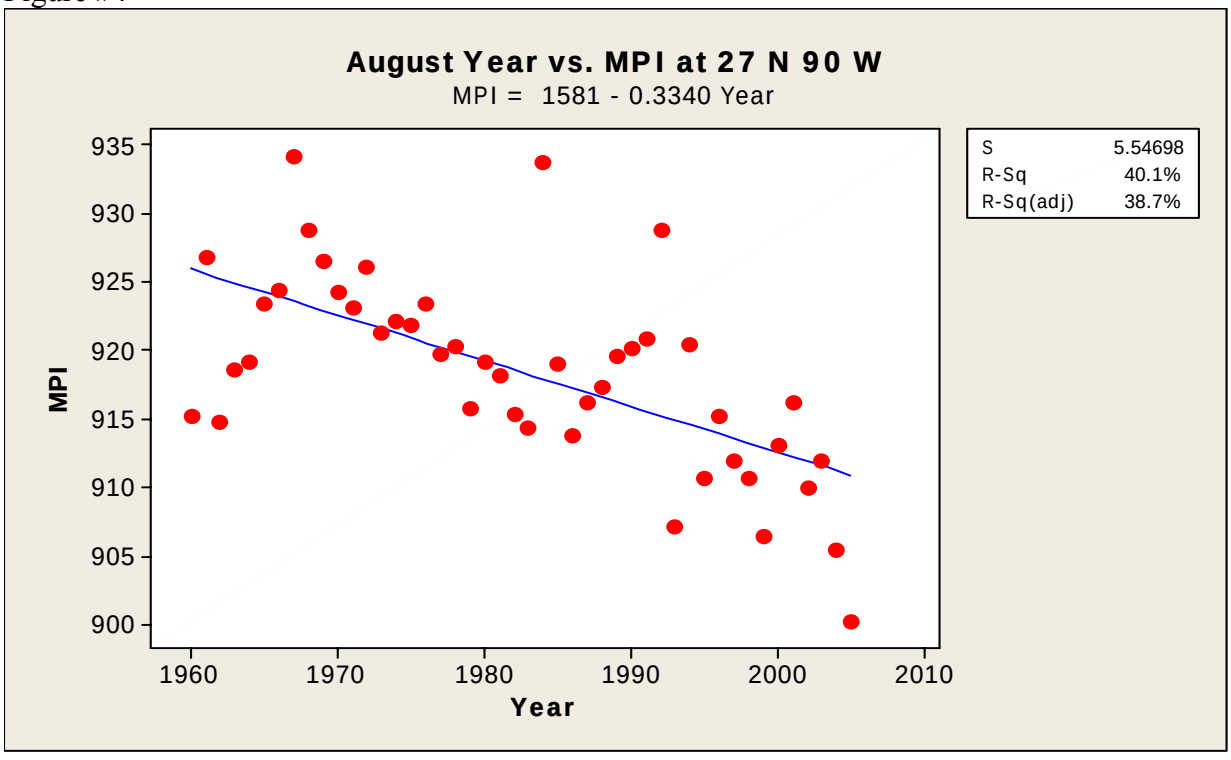


Figure #5

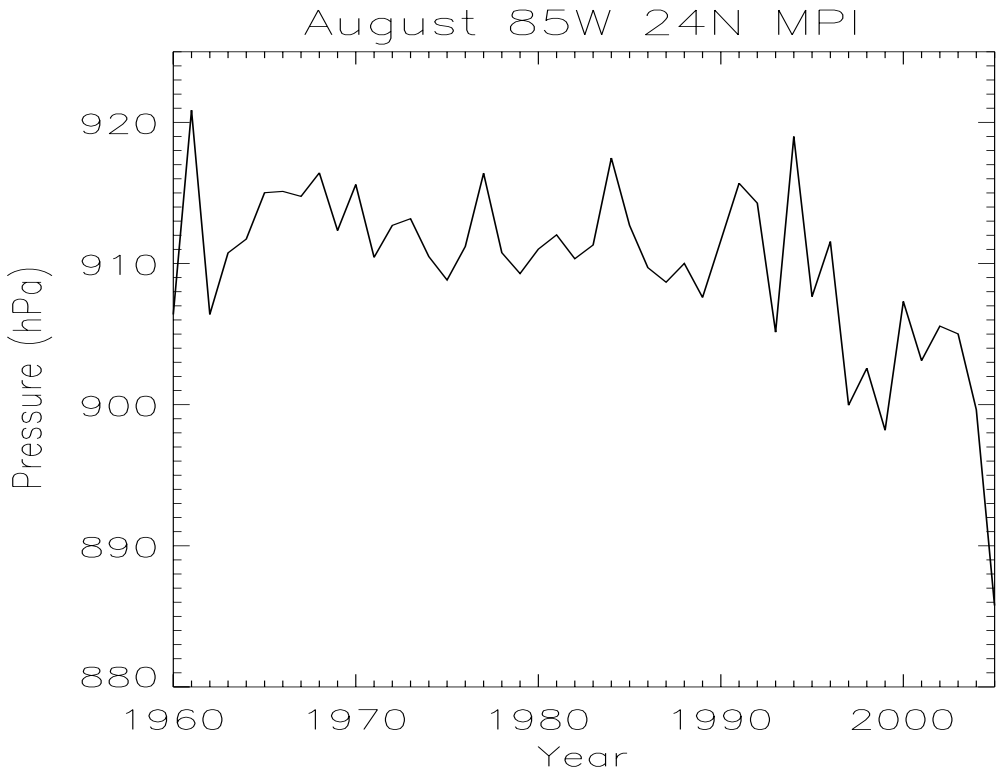


Figure #6

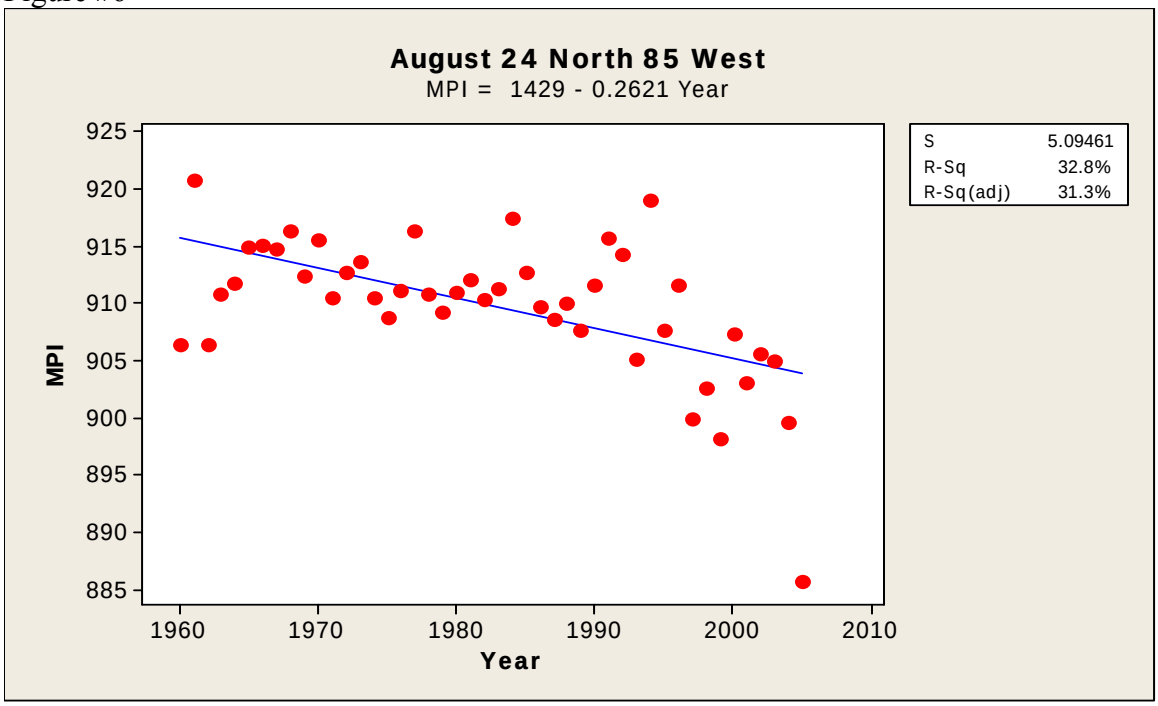


Figure #7

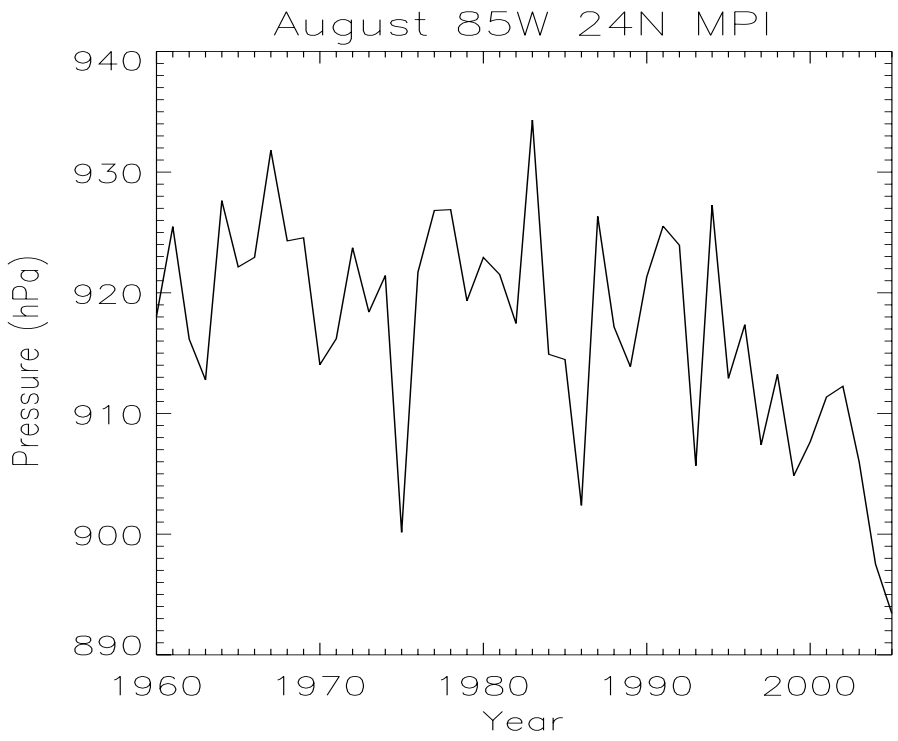


Figure #8

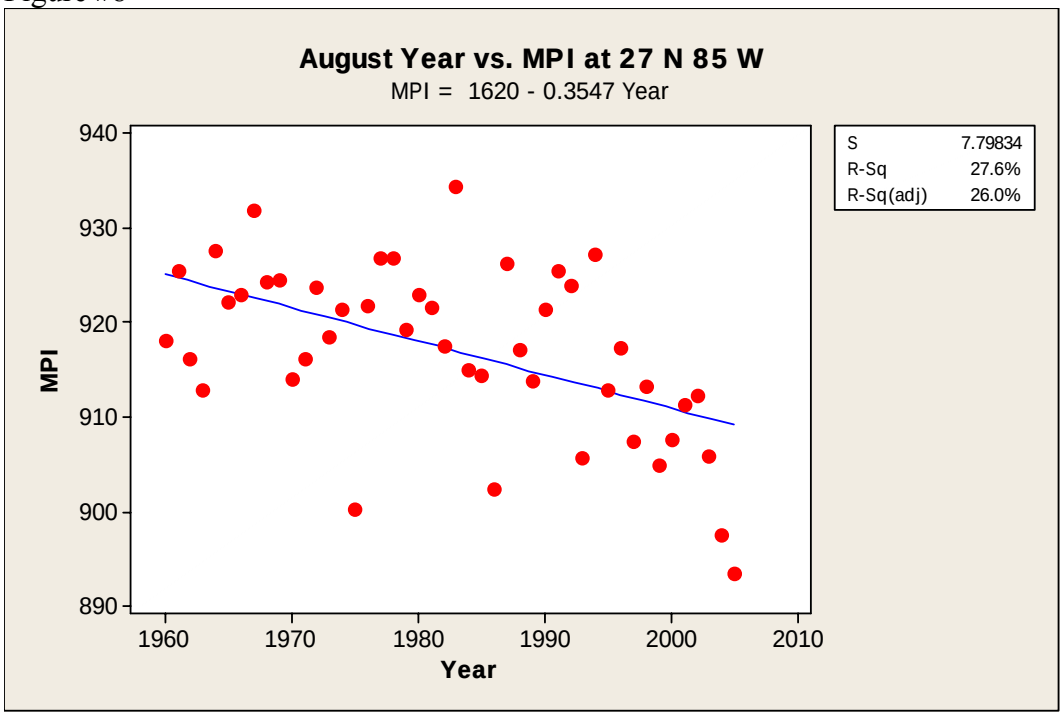


Figure #9

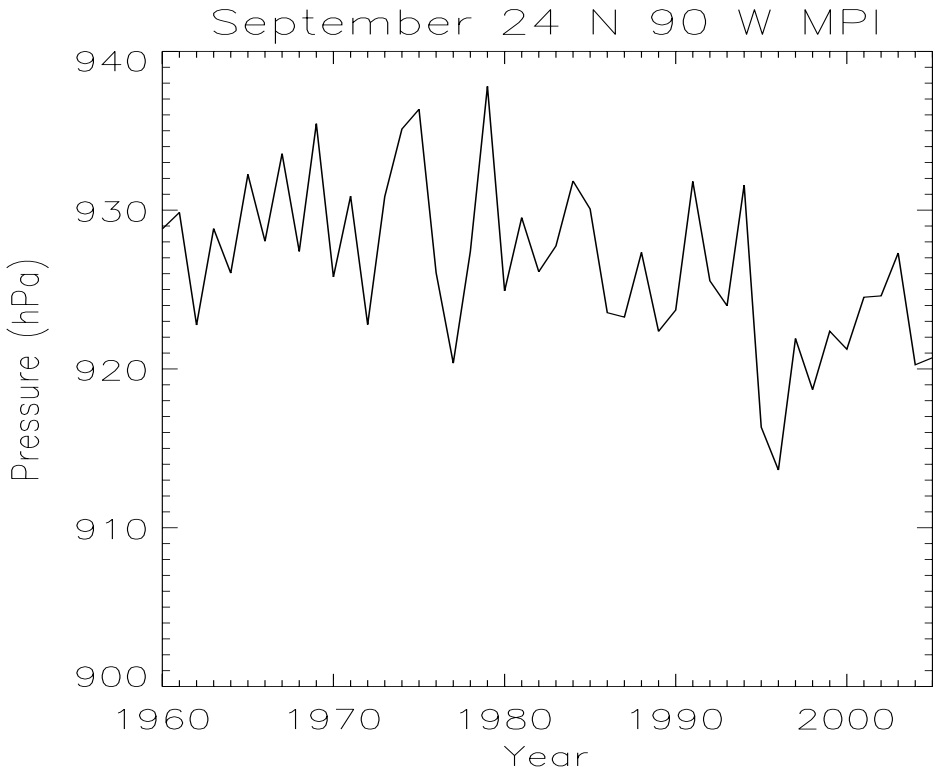


Figure #10

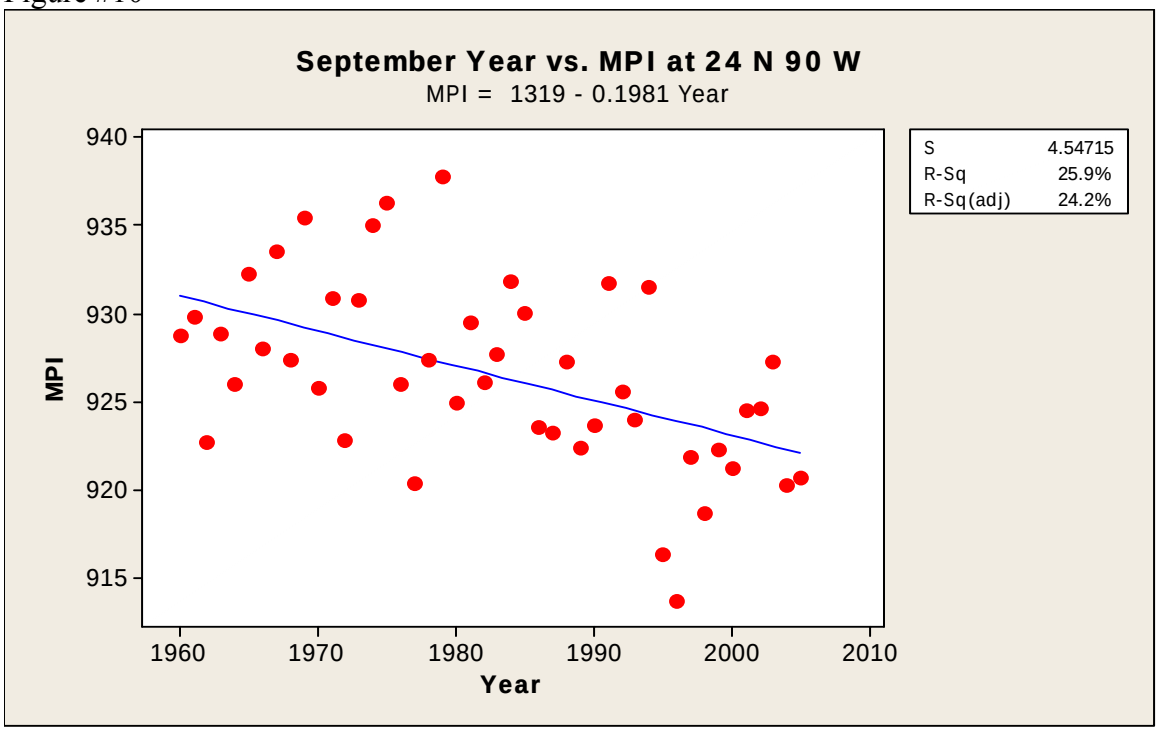


Figure #11

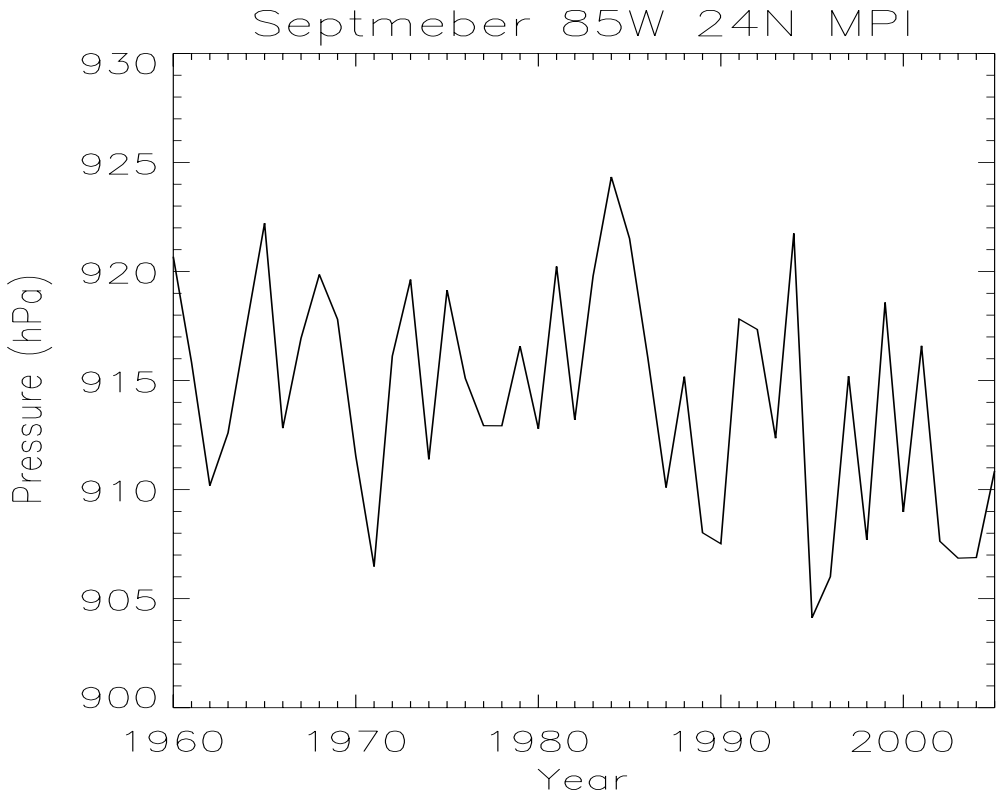


Figure #12

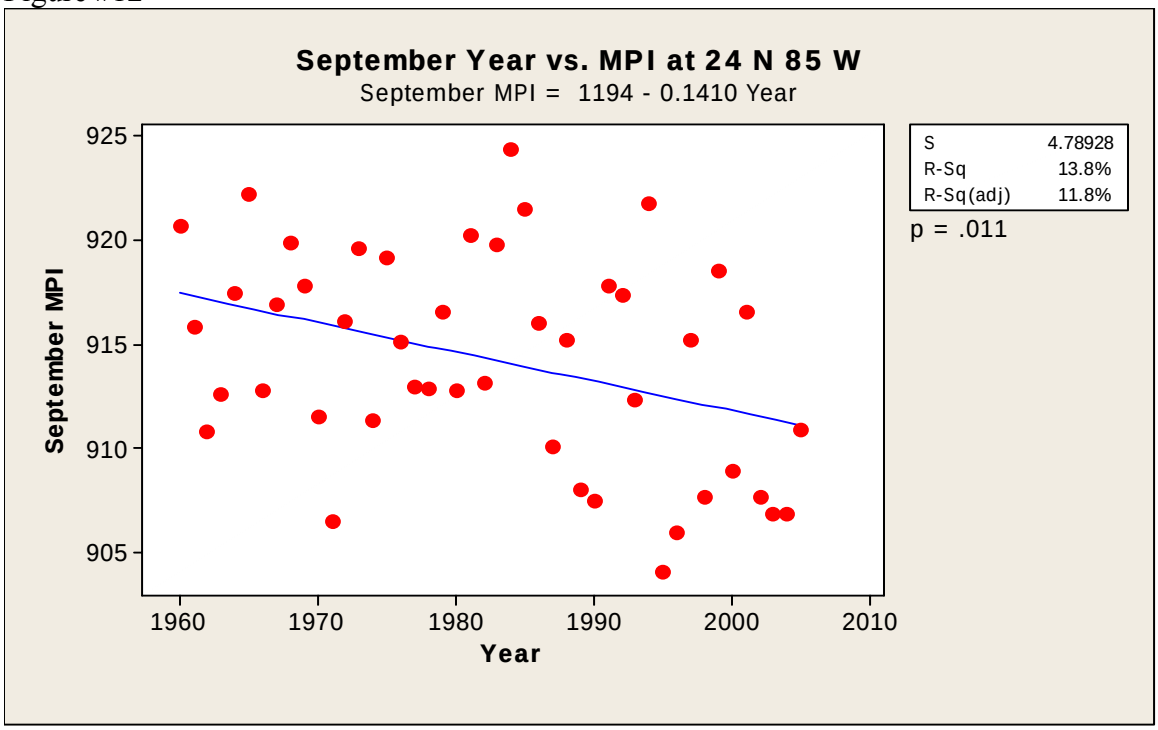


Figure #13

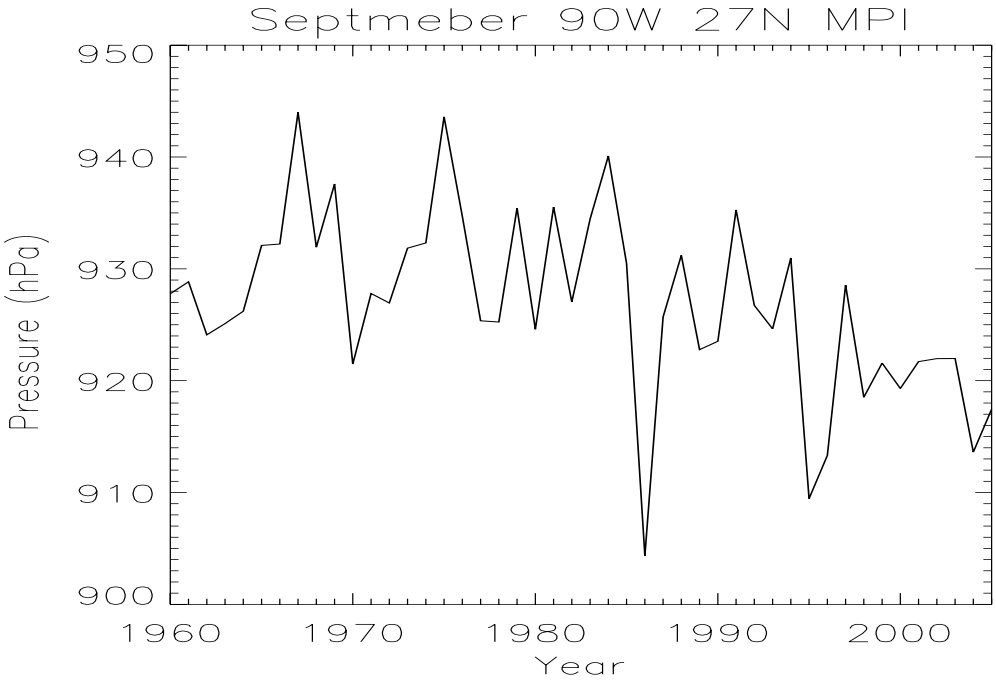


Figure #14

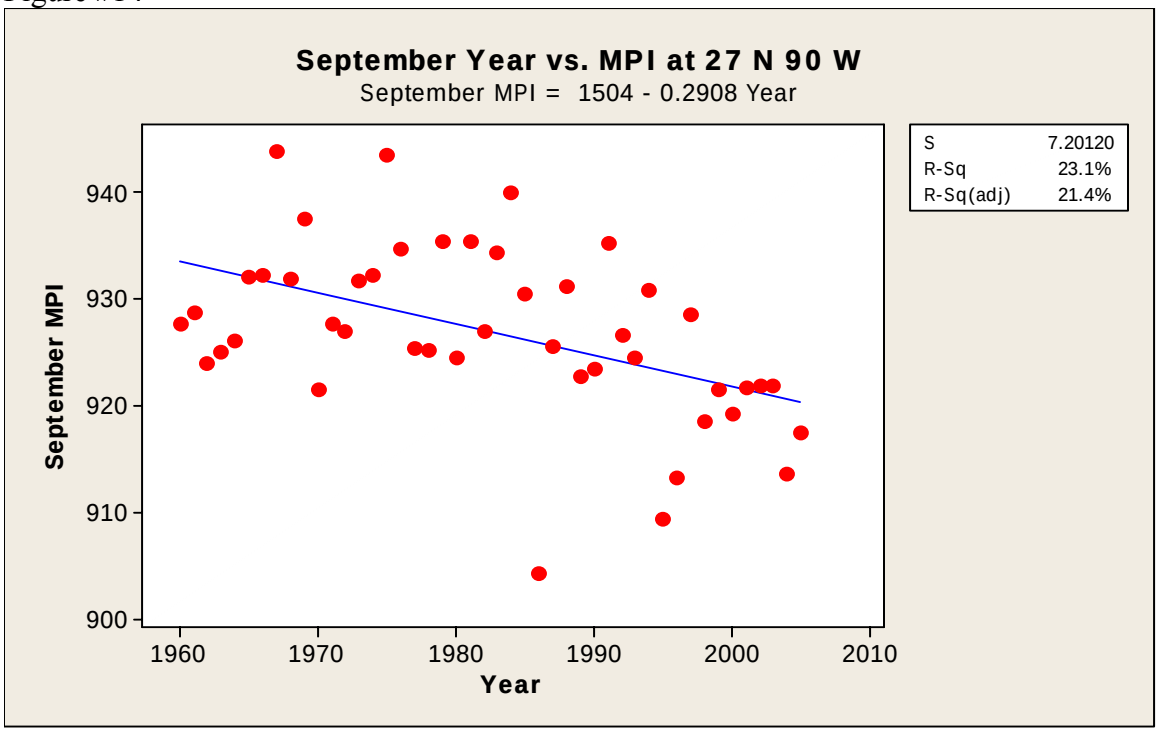


Figure #15

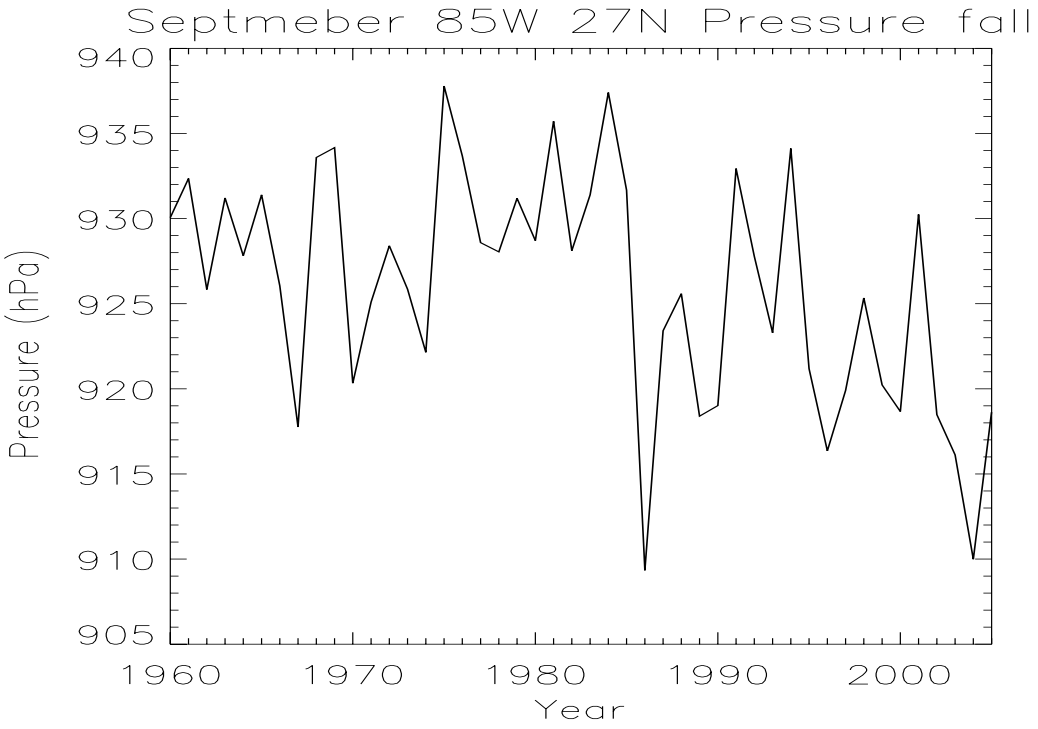


Figure #16

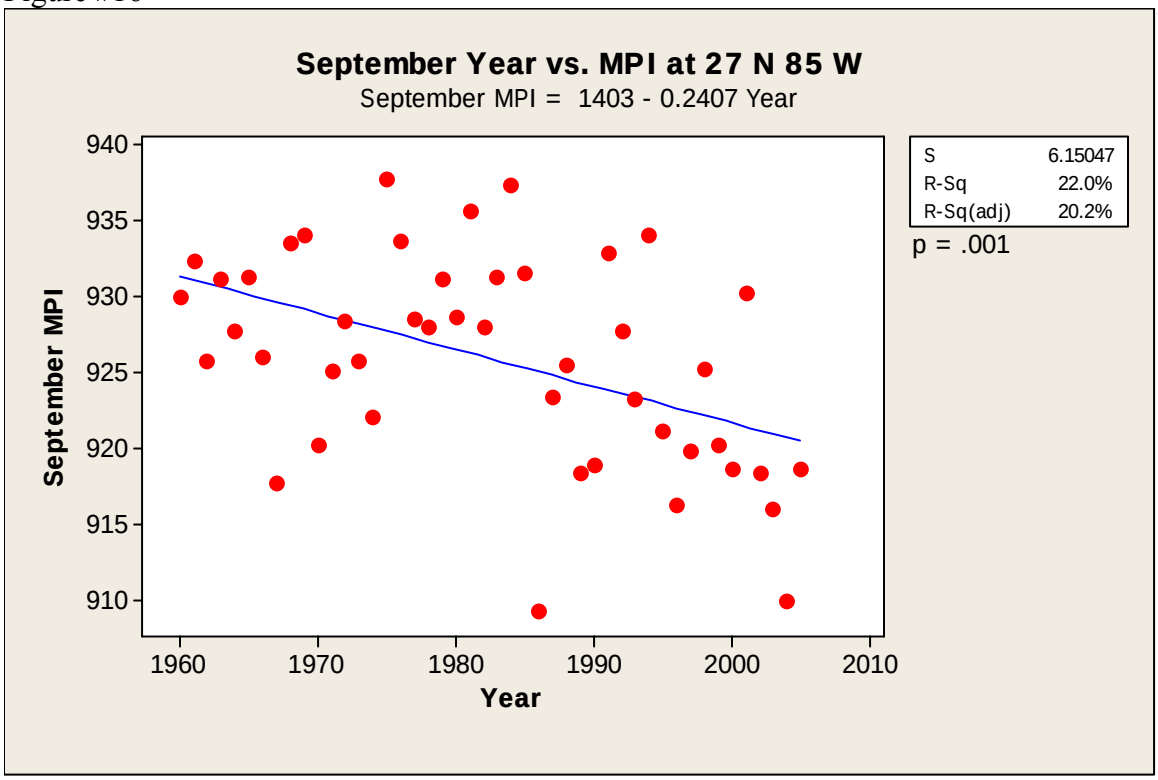


Figure #17

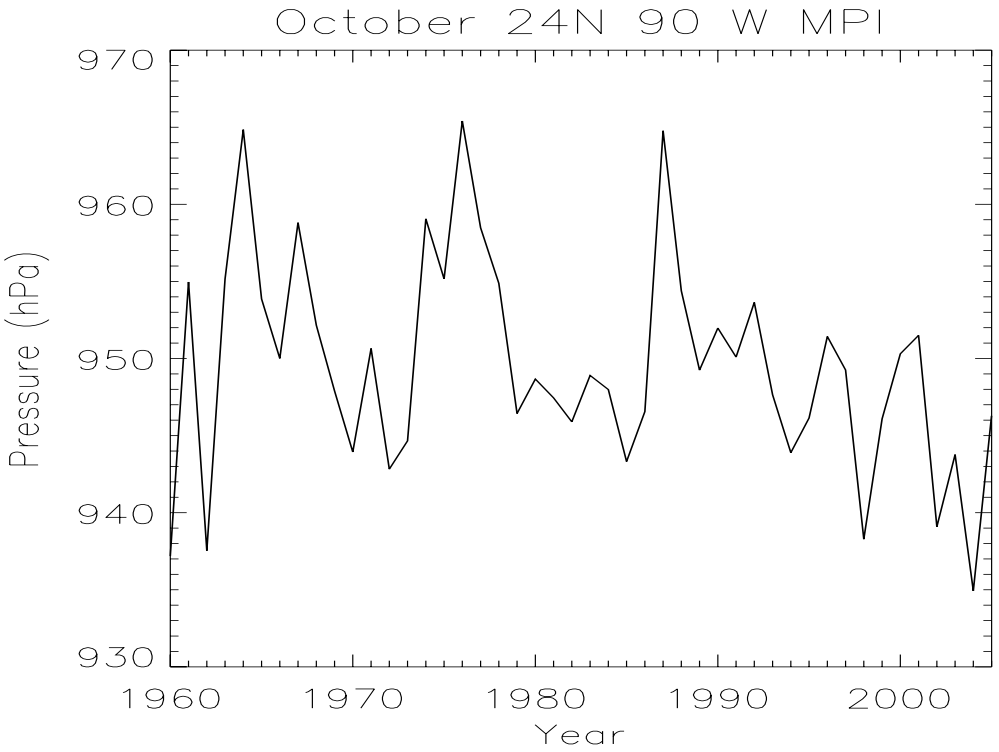


Figure #18

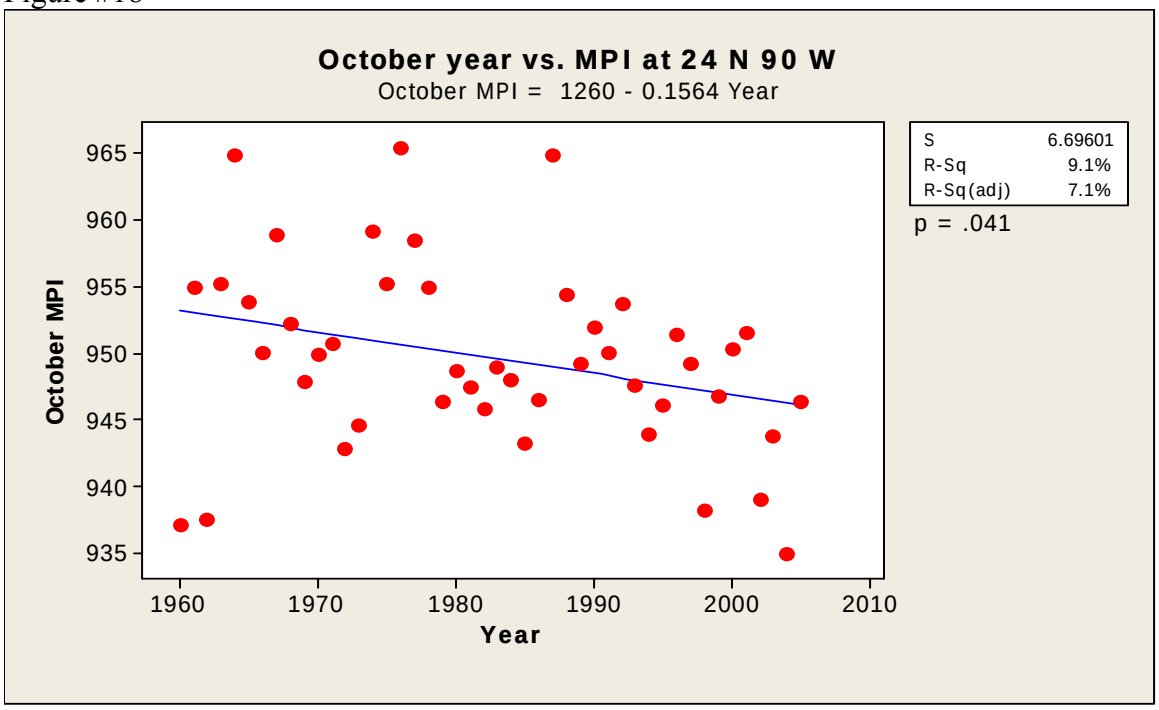


Figure #19

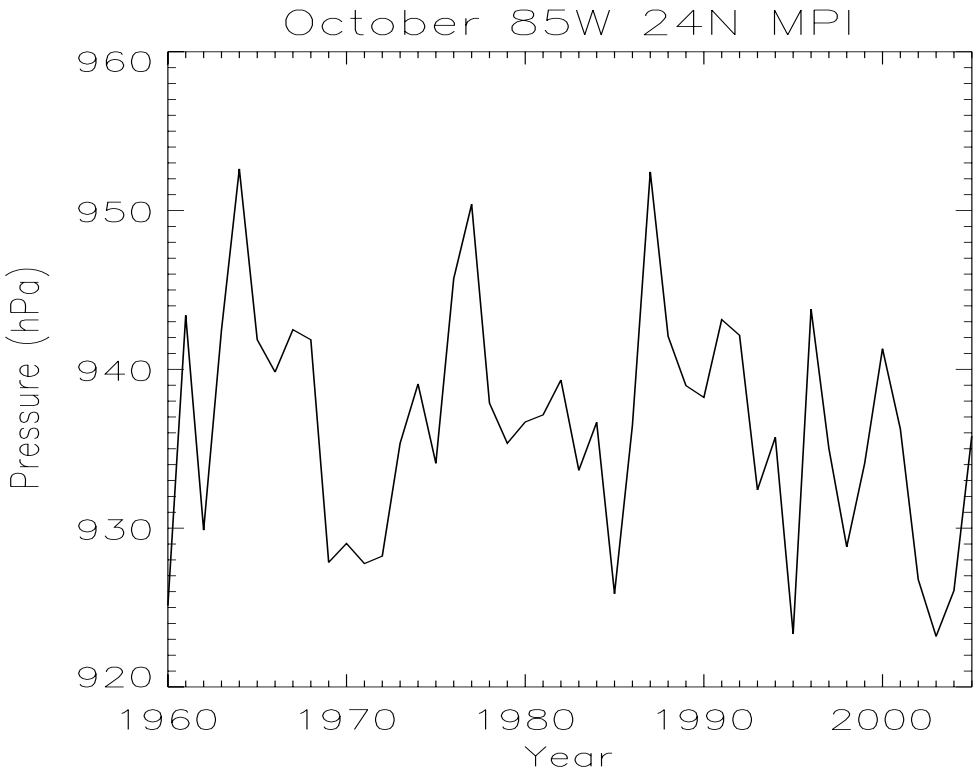


Figure #20

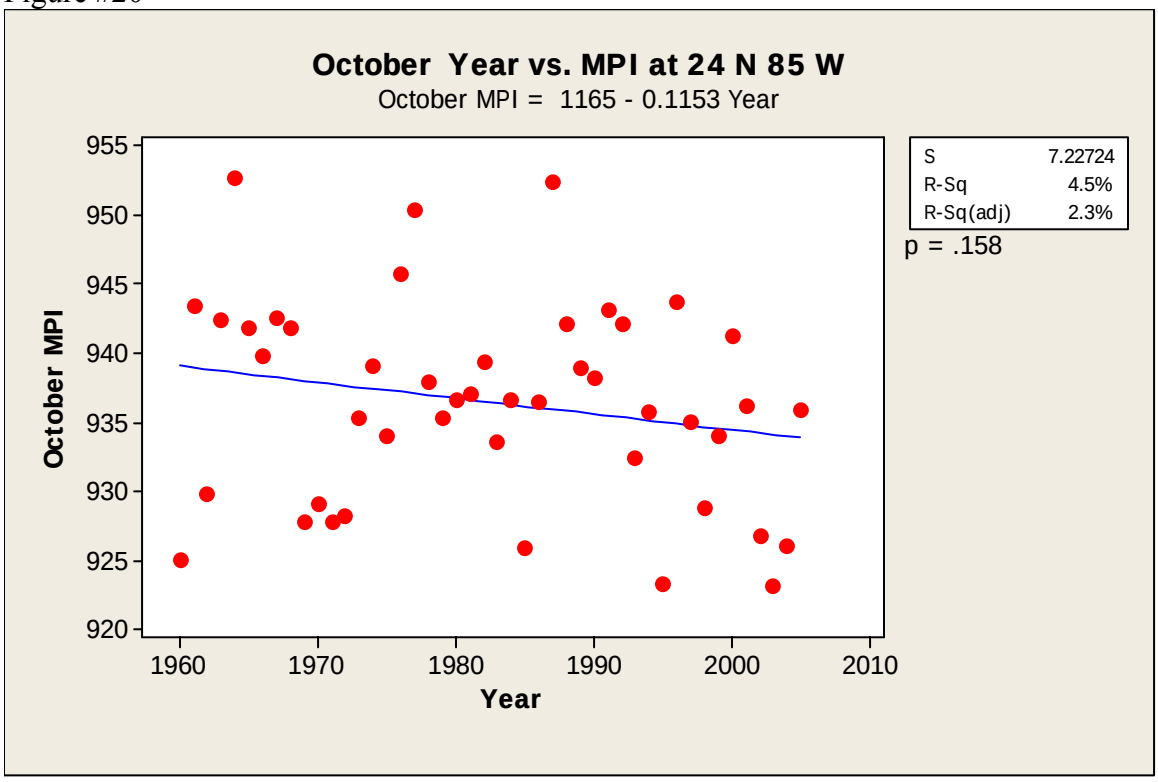


Figure #21

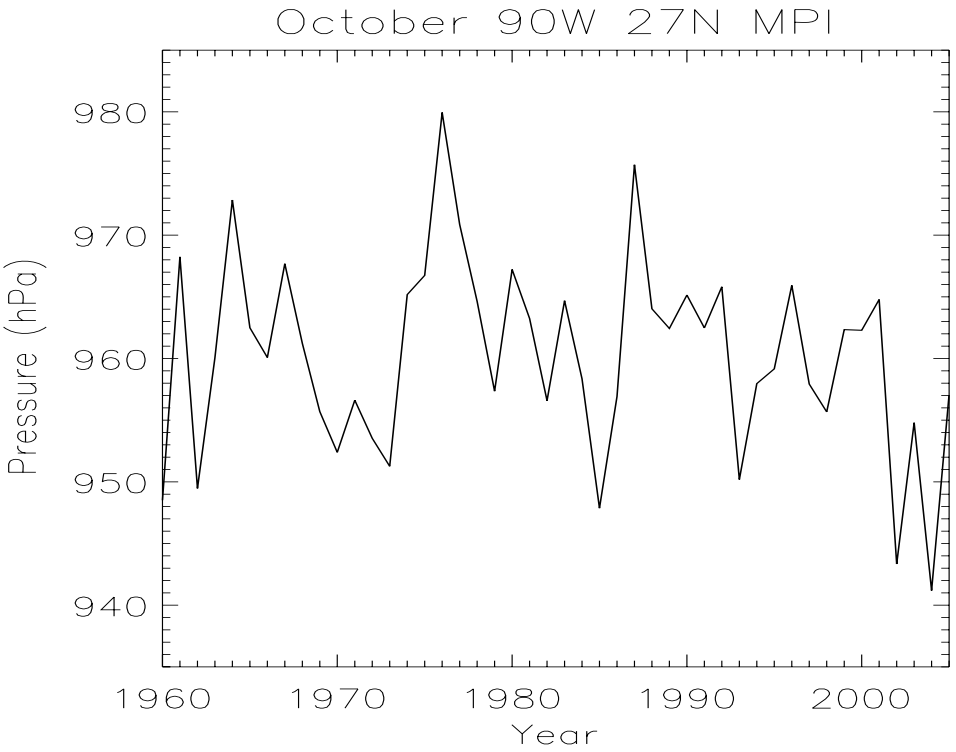


Figure #22

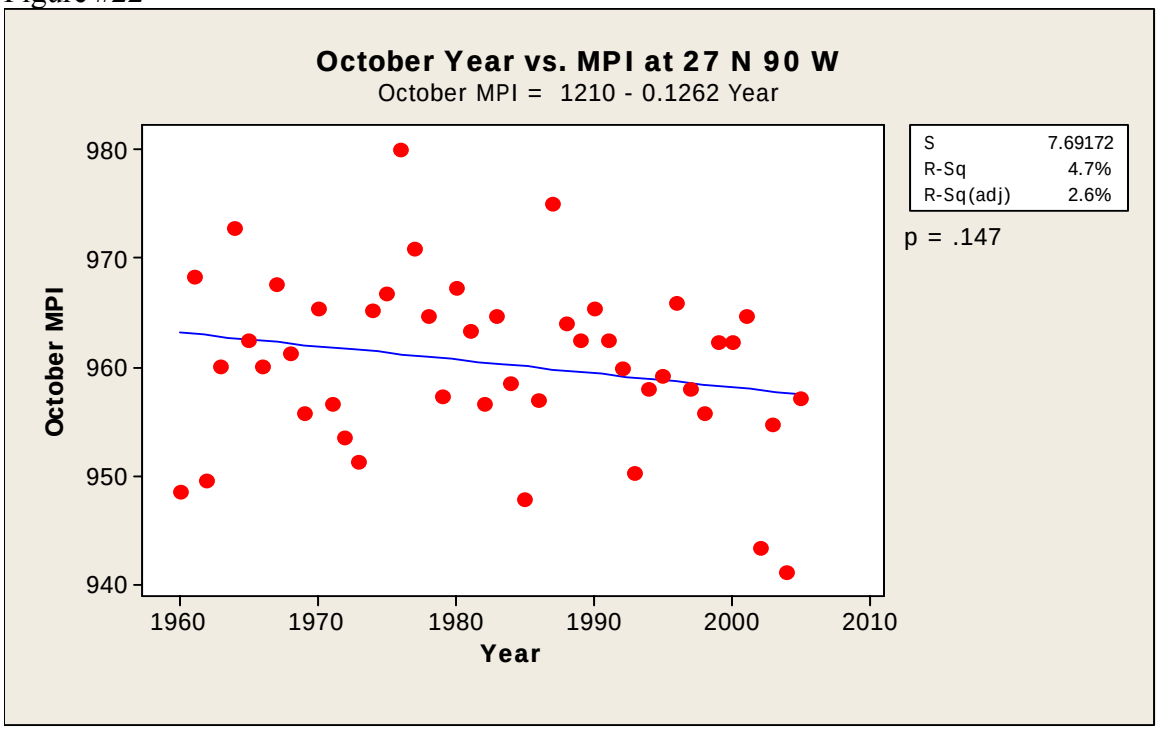


Figure #23

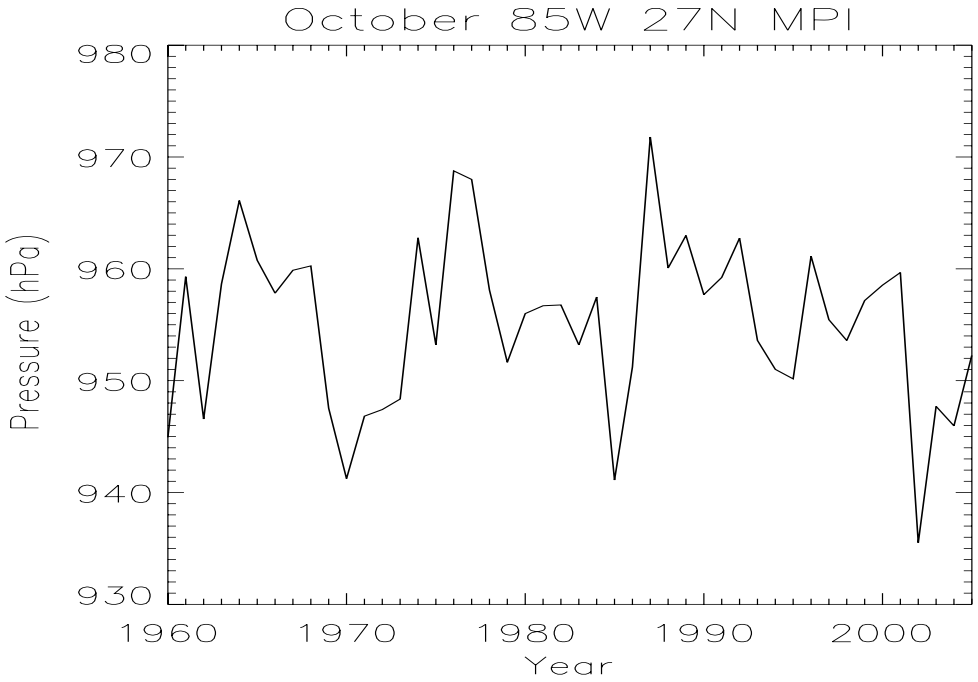


Figure #24

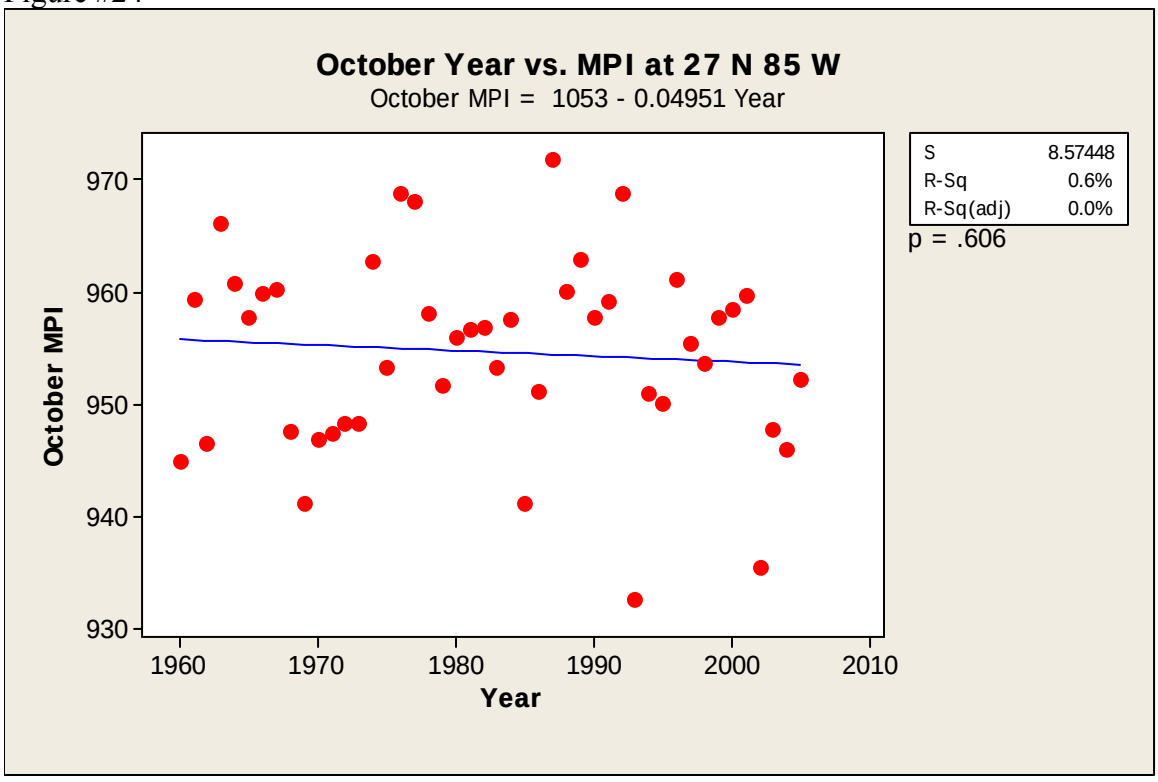


Figure #25

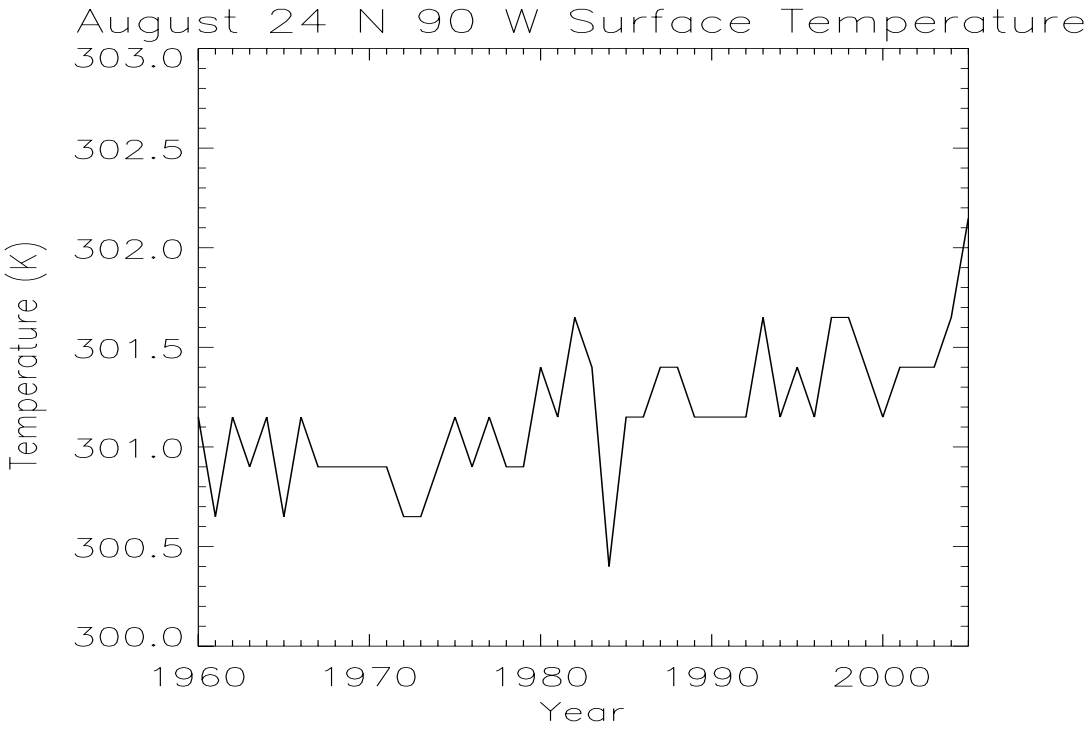


Figure #26

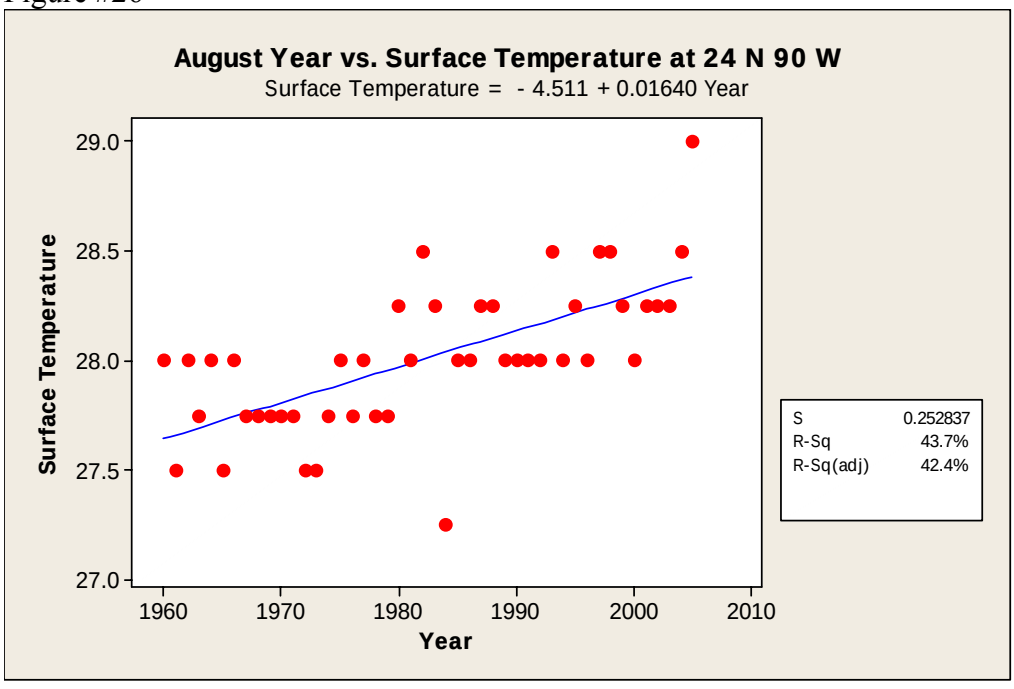


Figure #27

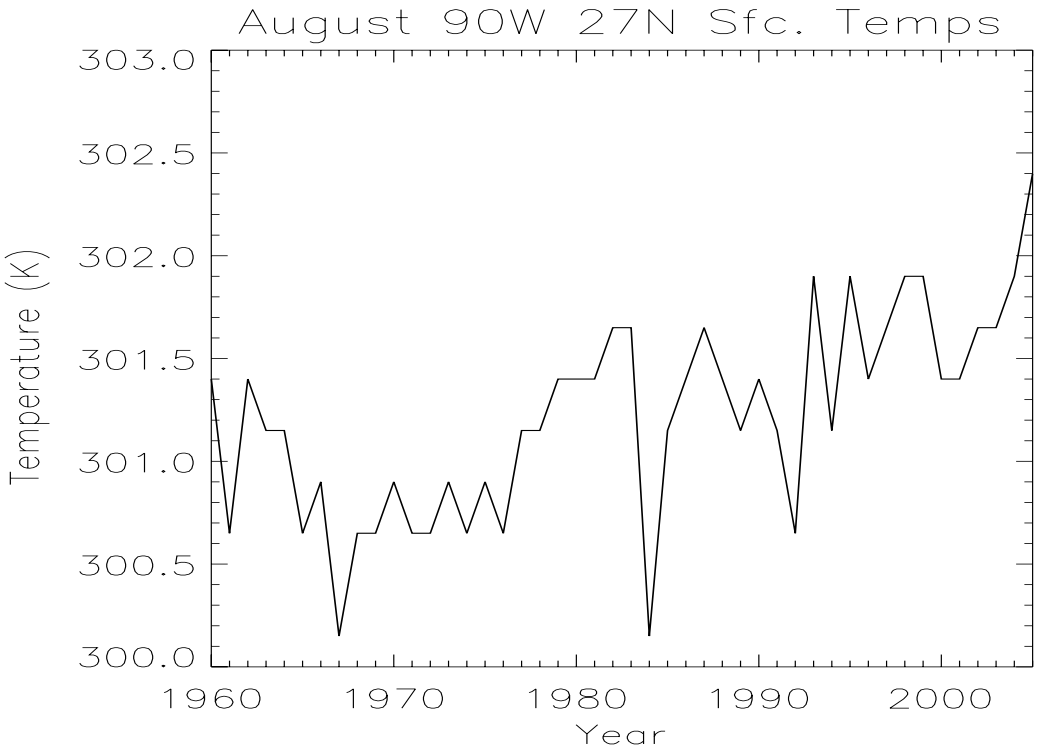


Figure #28

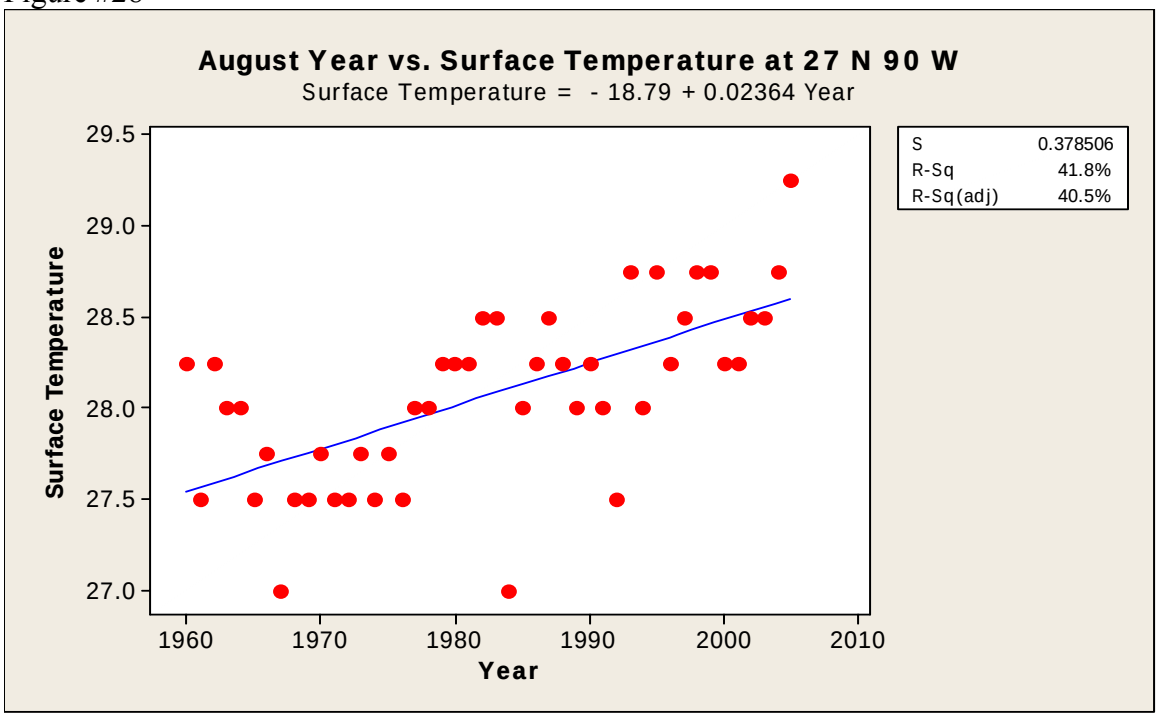


Figure #29

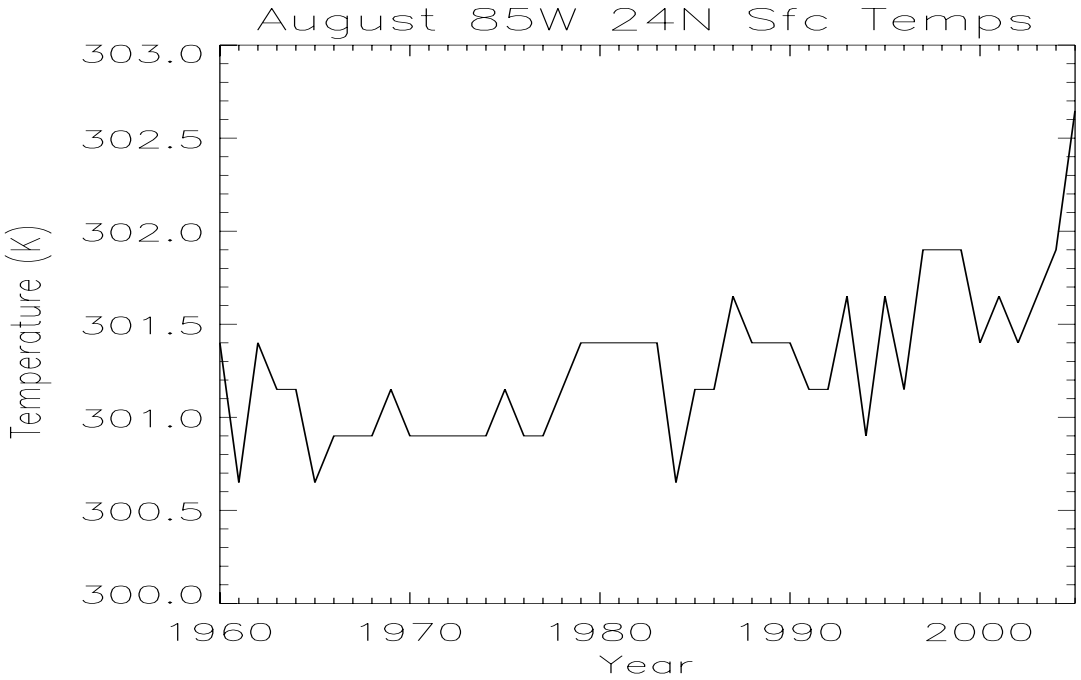


Figure #30

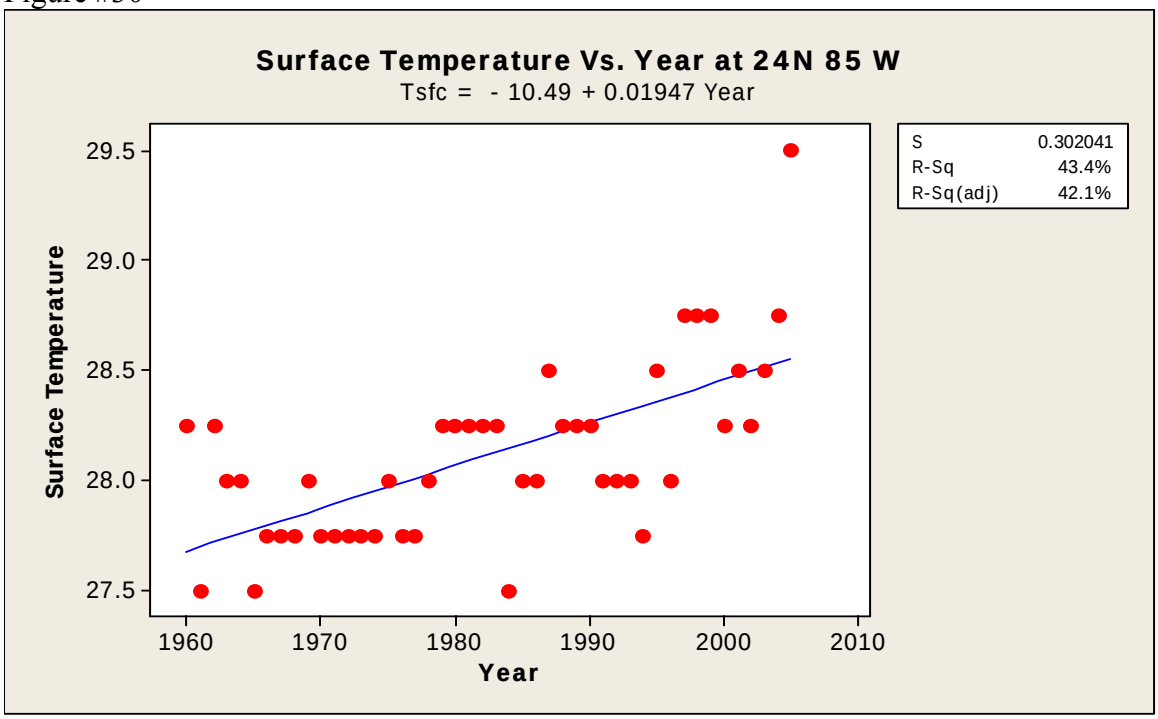


Figure #31

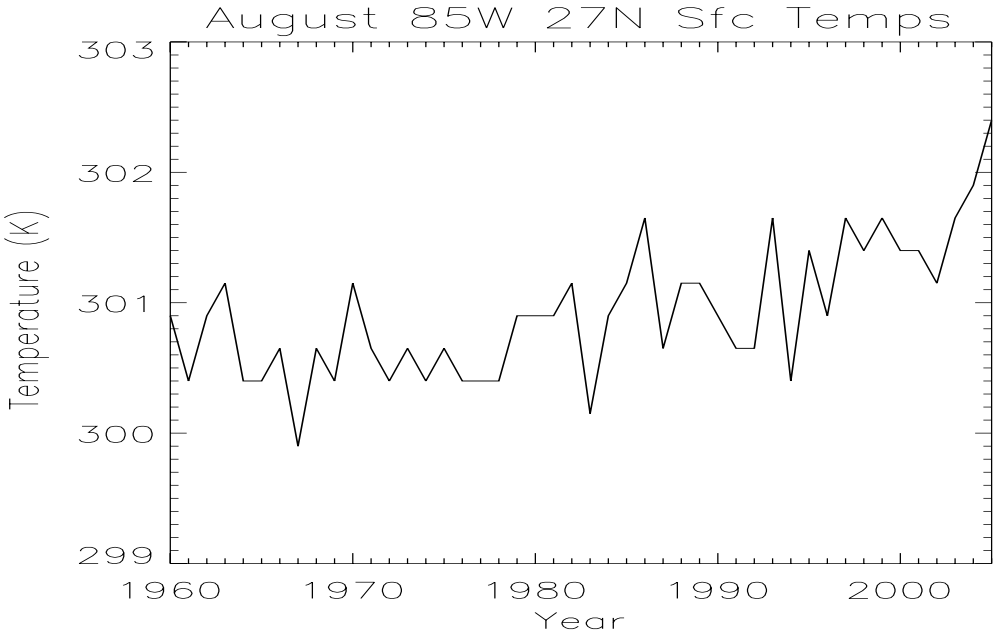


Figure #32

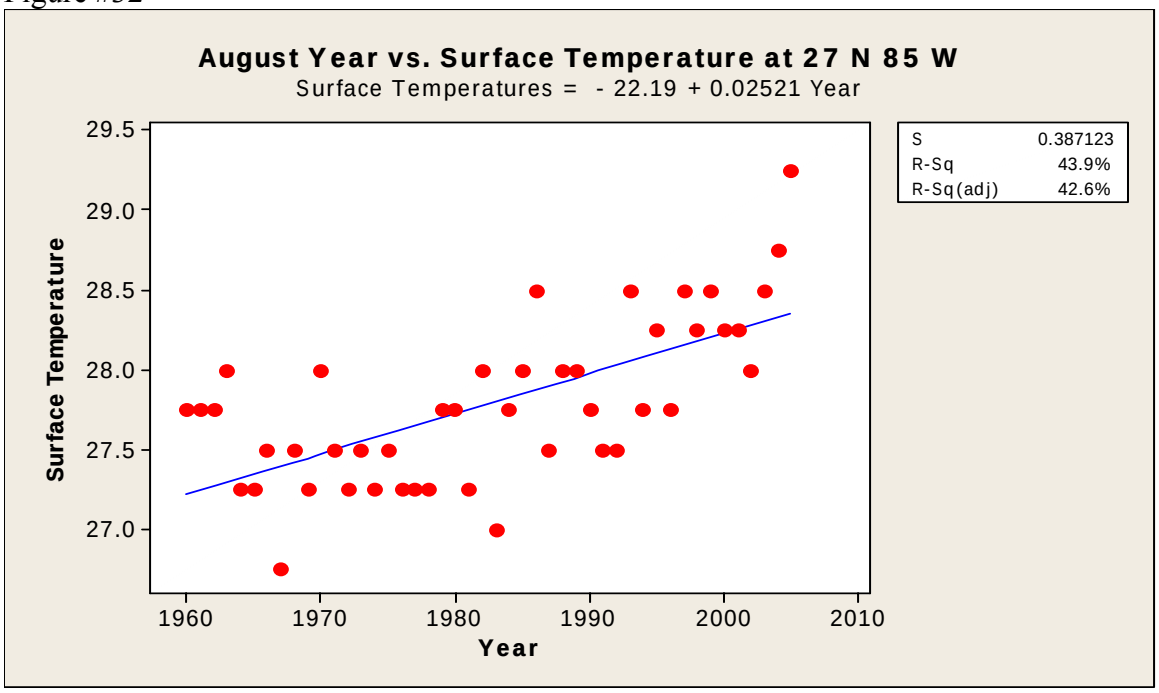


Figure #33

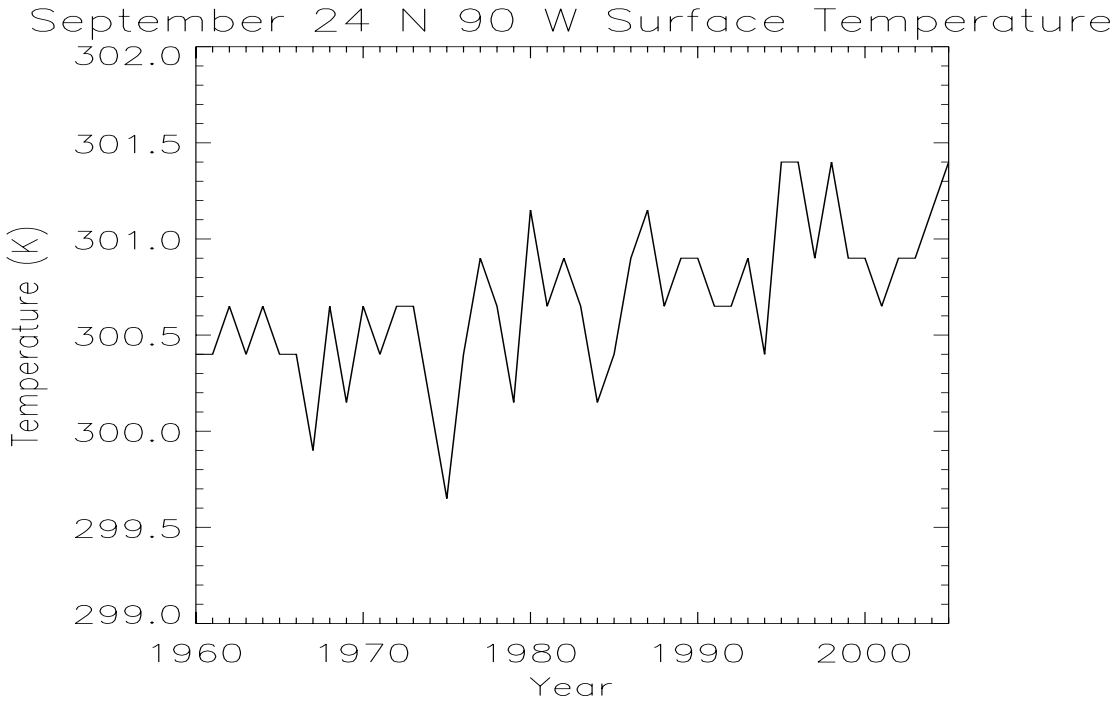


Figure #34

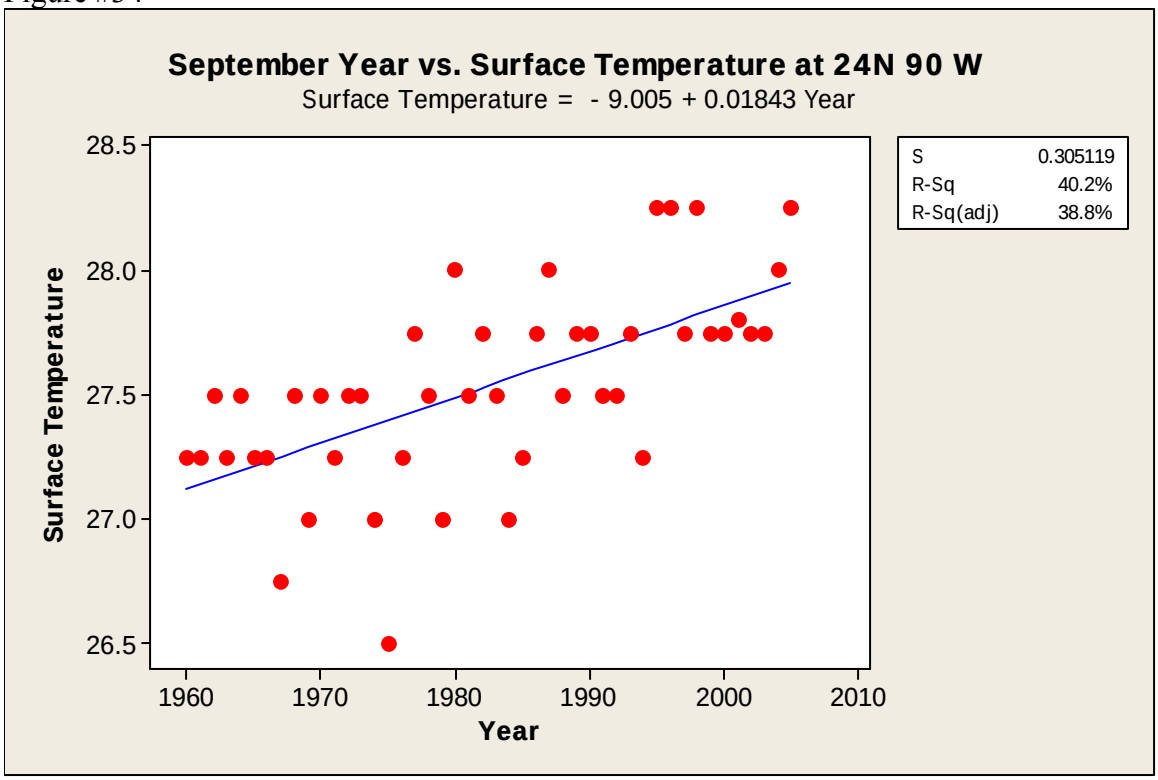


Figure #35

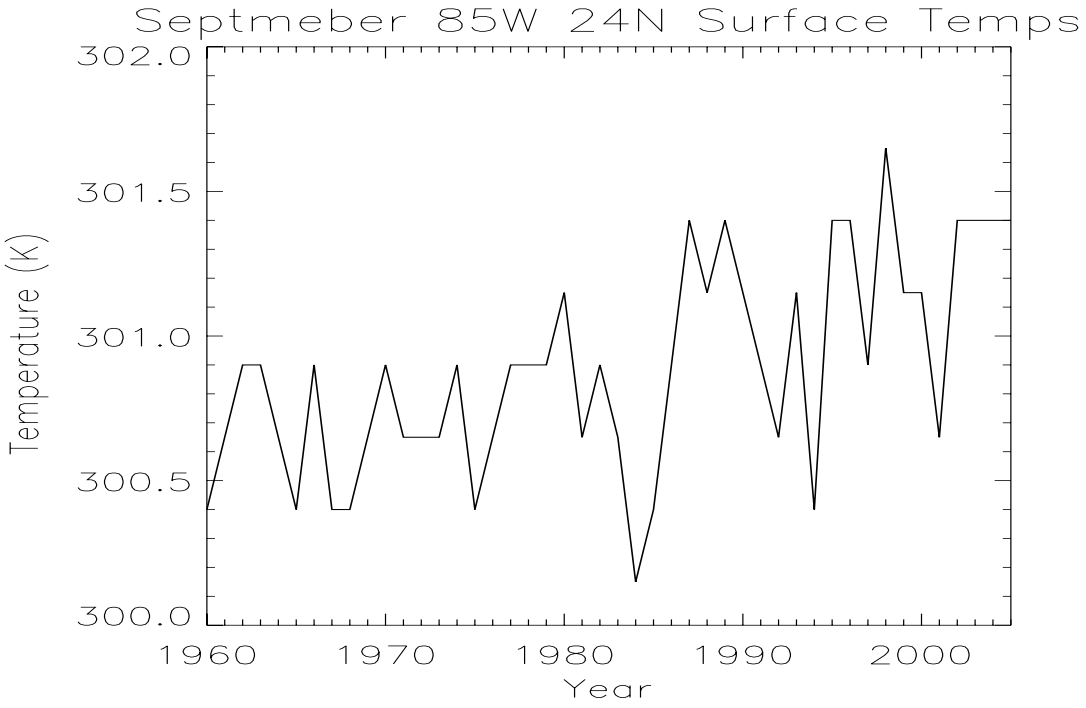


Figure #36

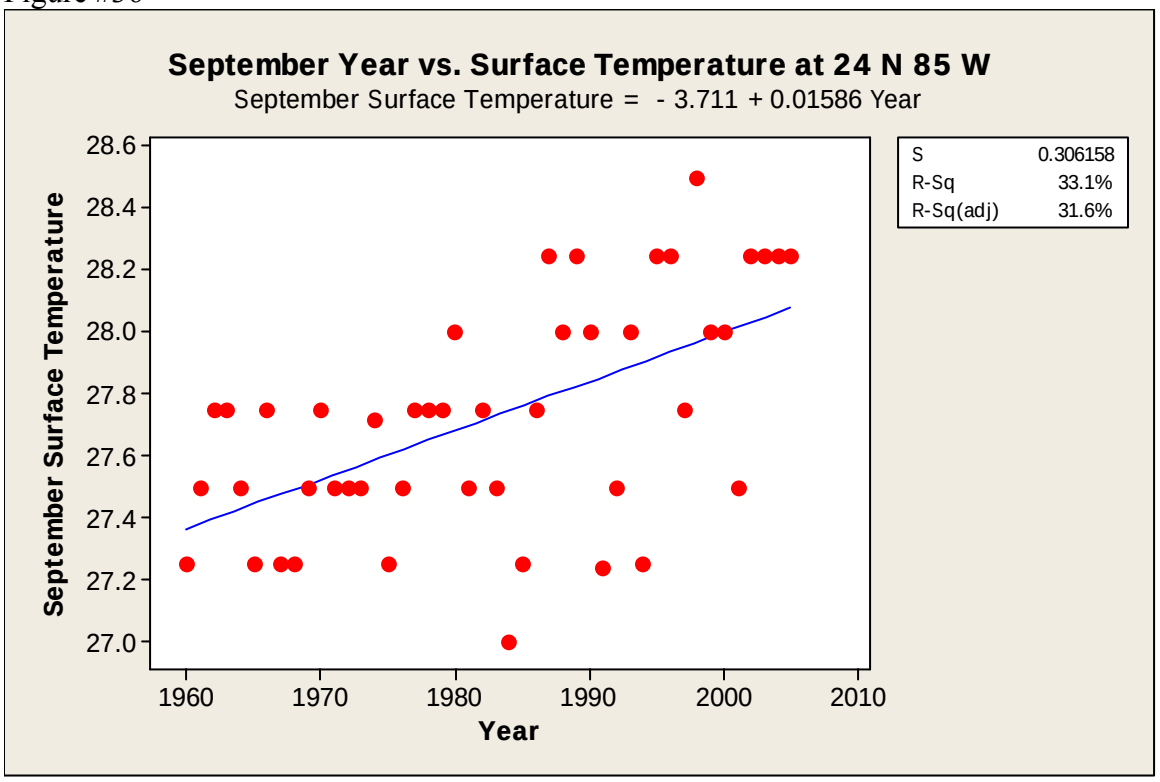


Figure #37

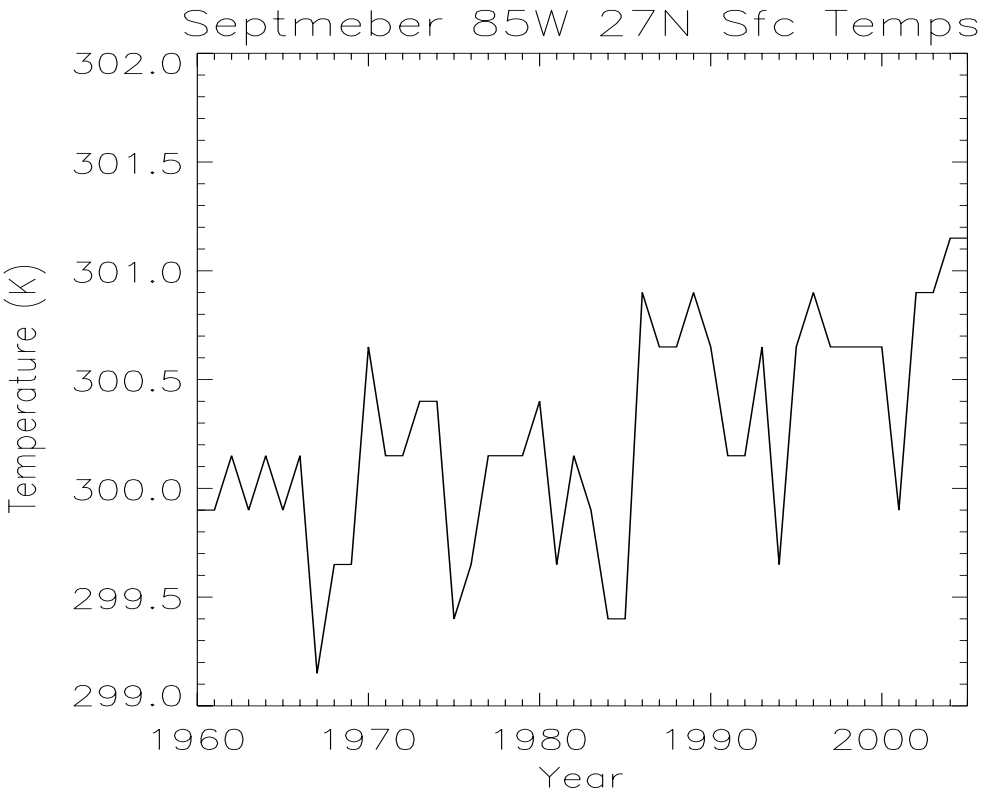


Figure #38

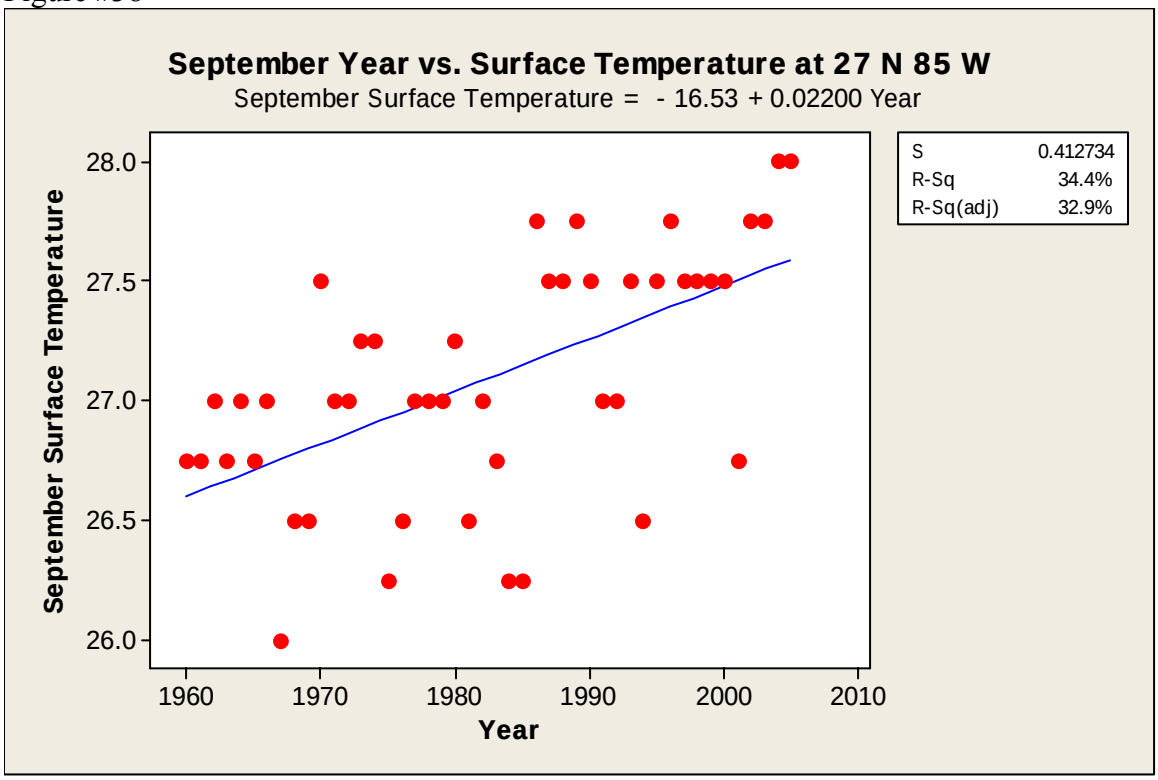


Figure #39

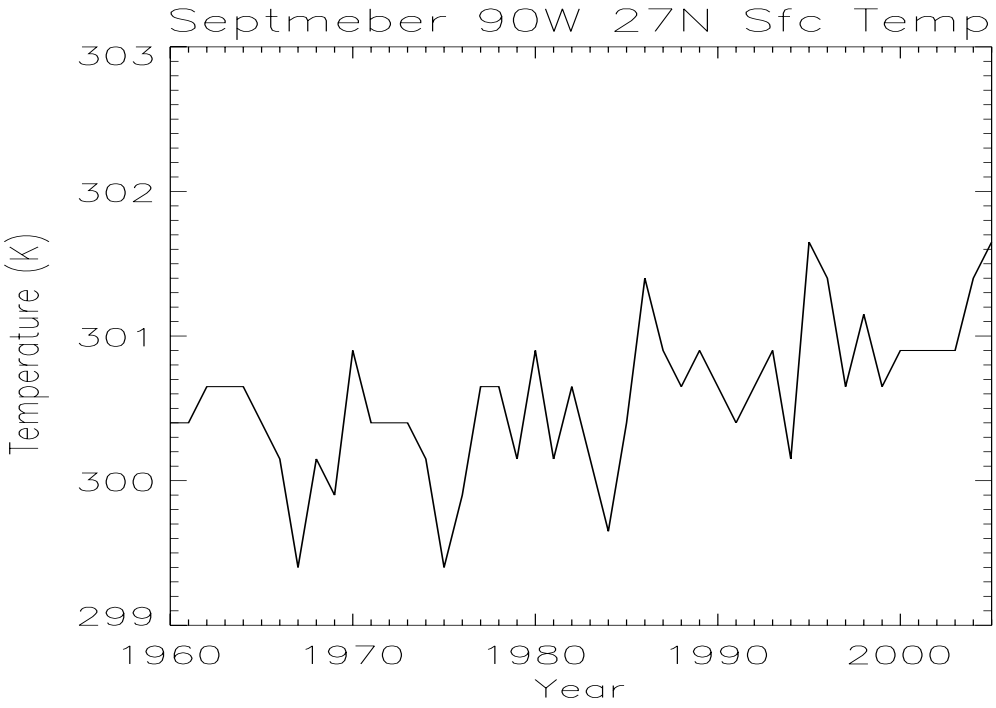


Figure #40

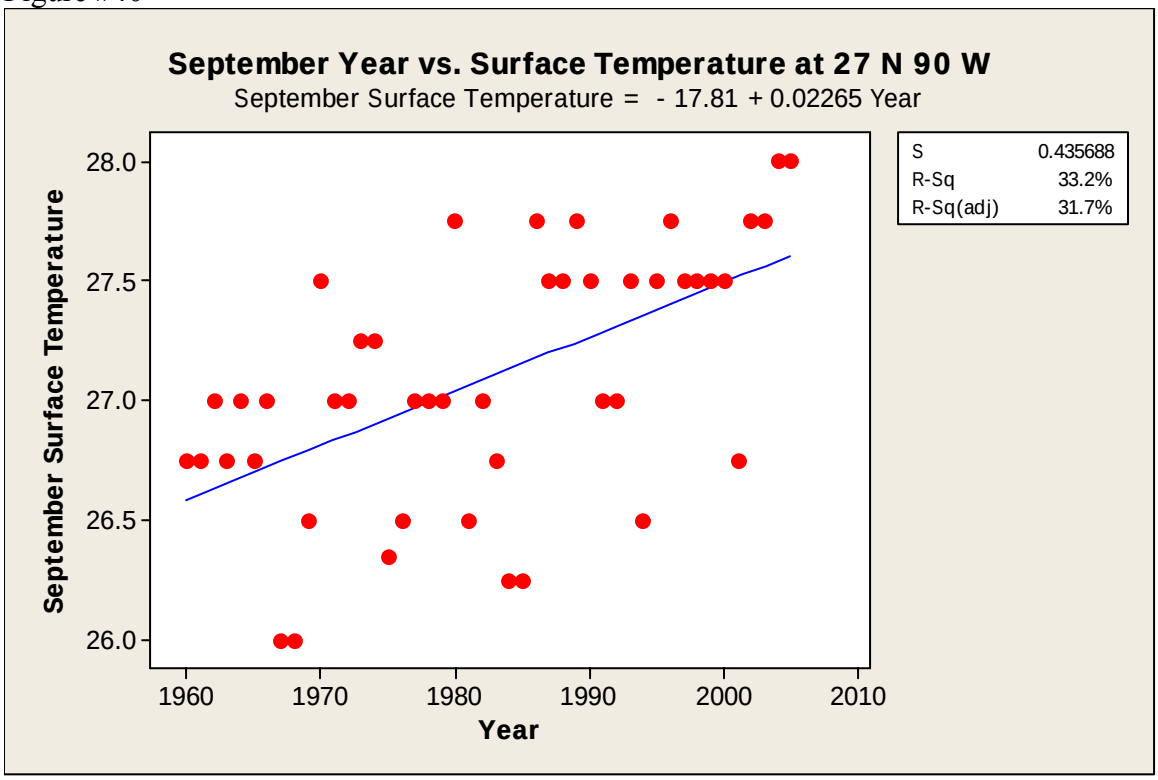


Figure #41

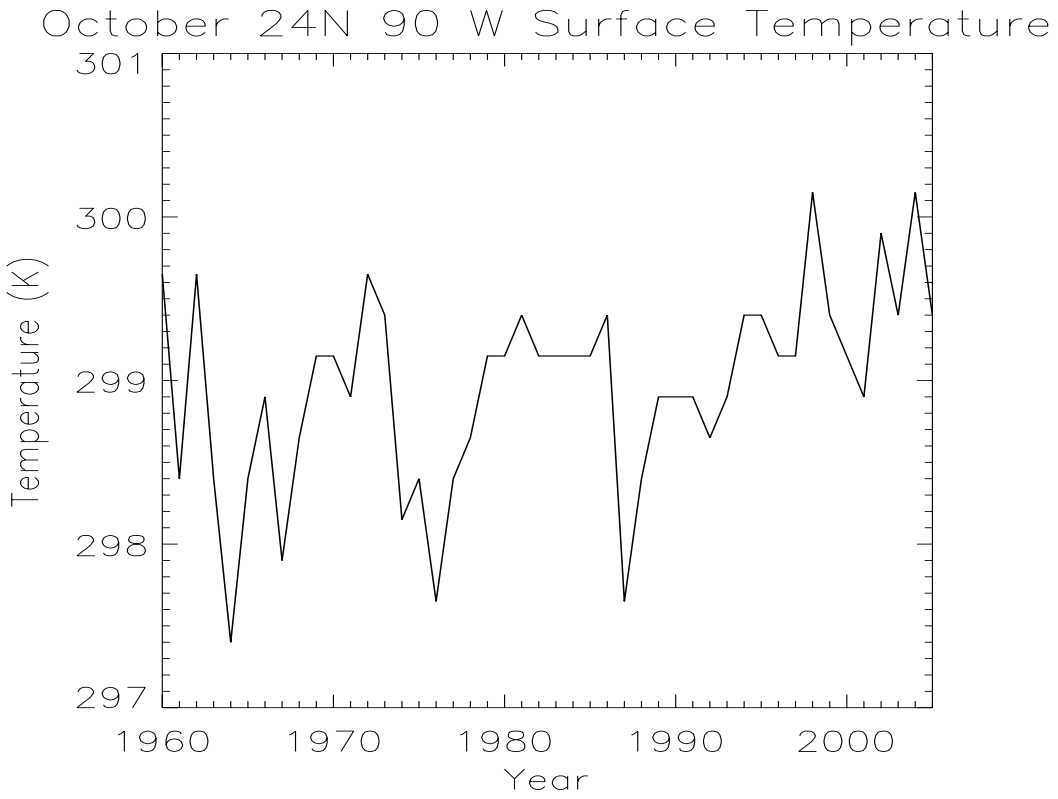


Figure #42

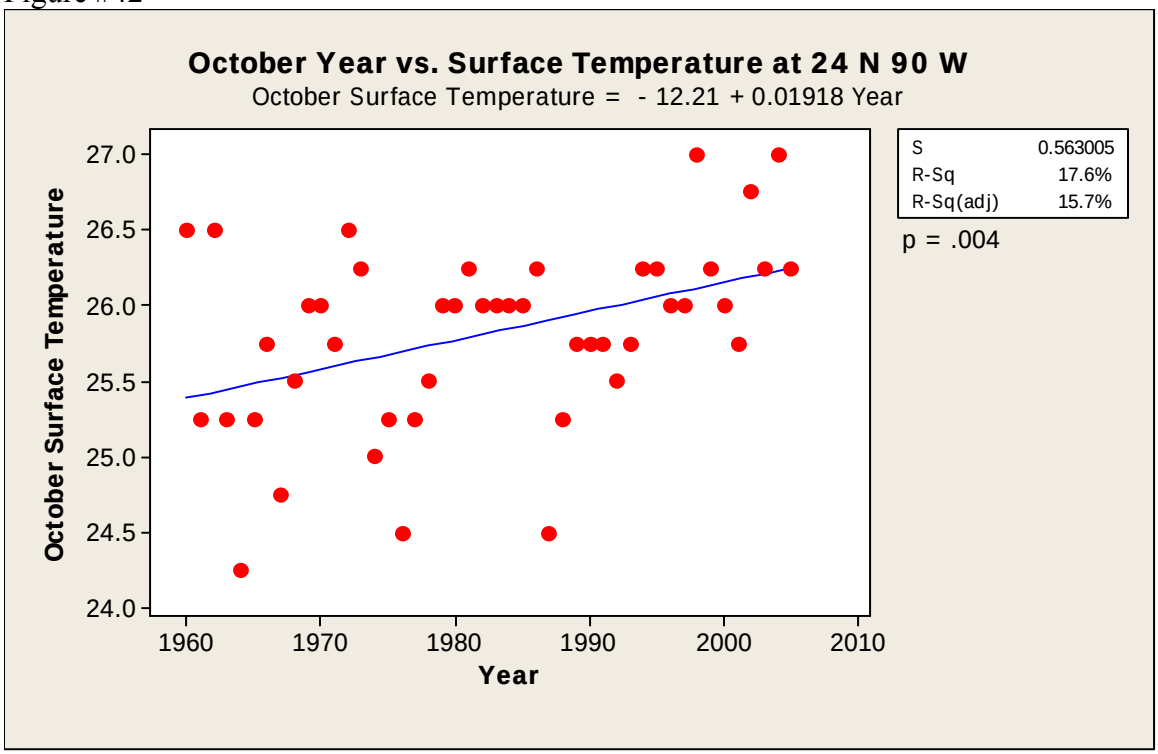


Figure #43

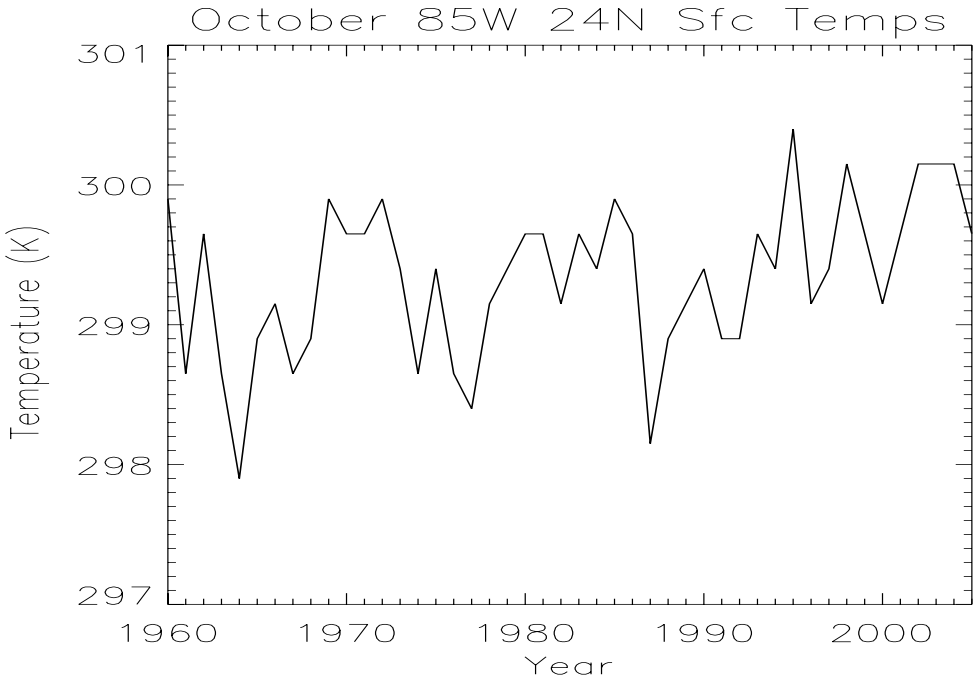


Figure #44

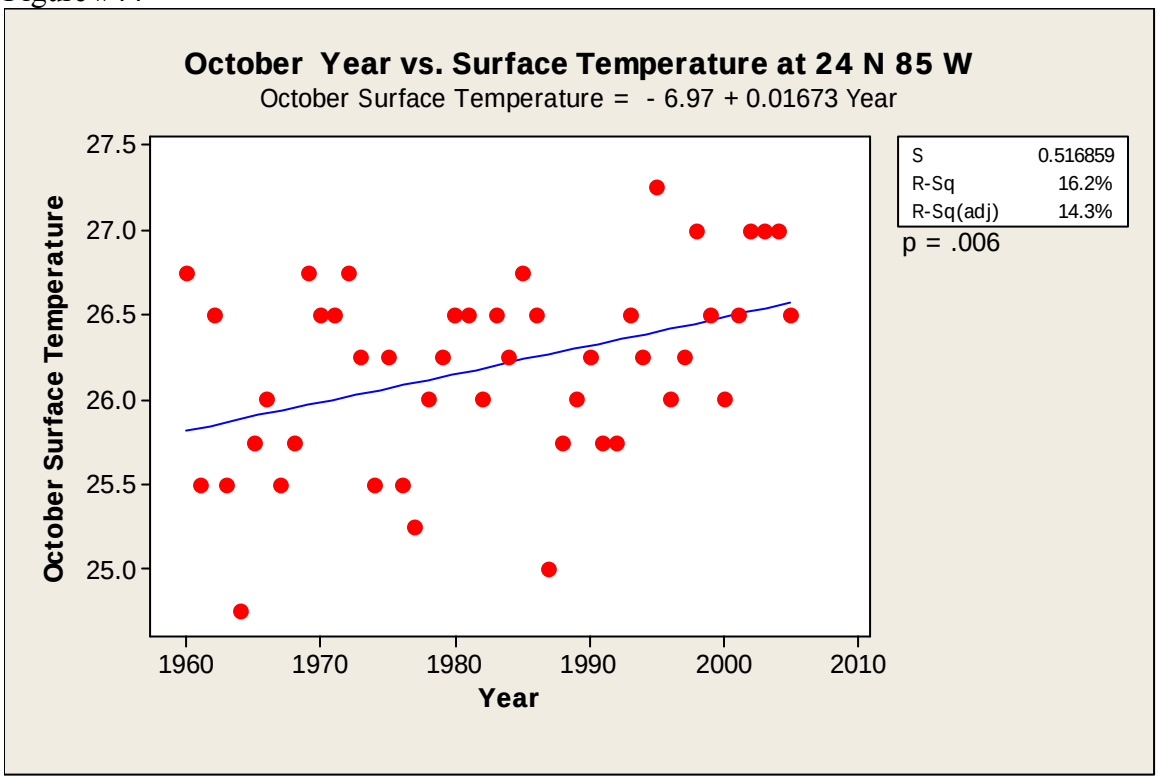


Figure #45

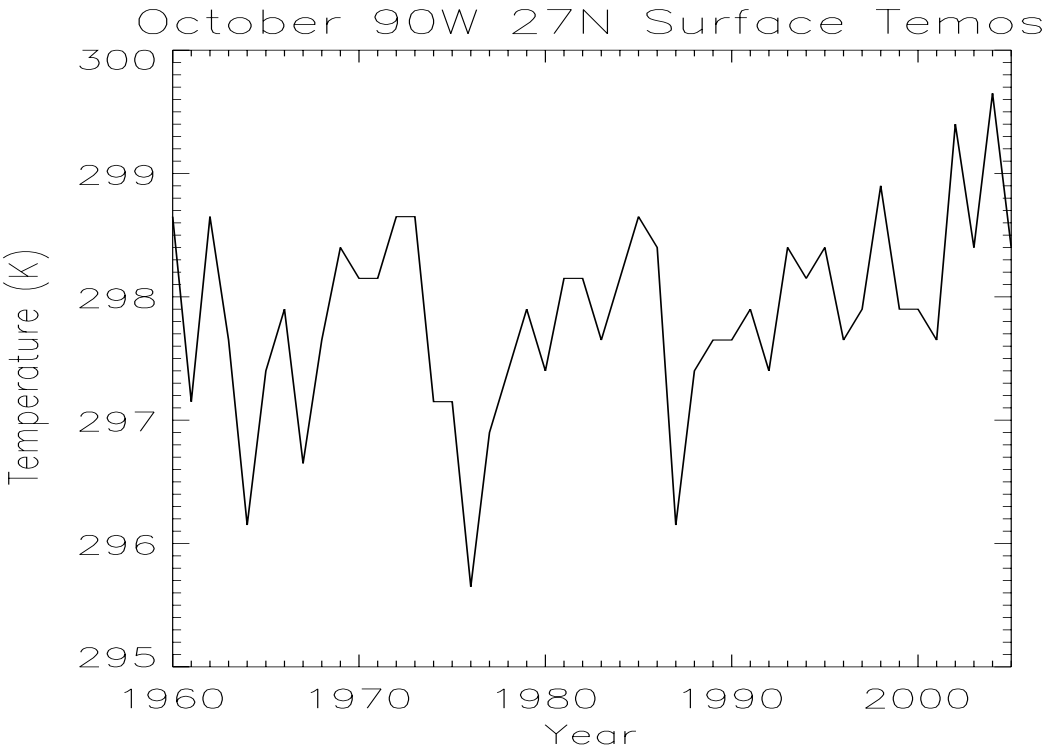


Figure #46

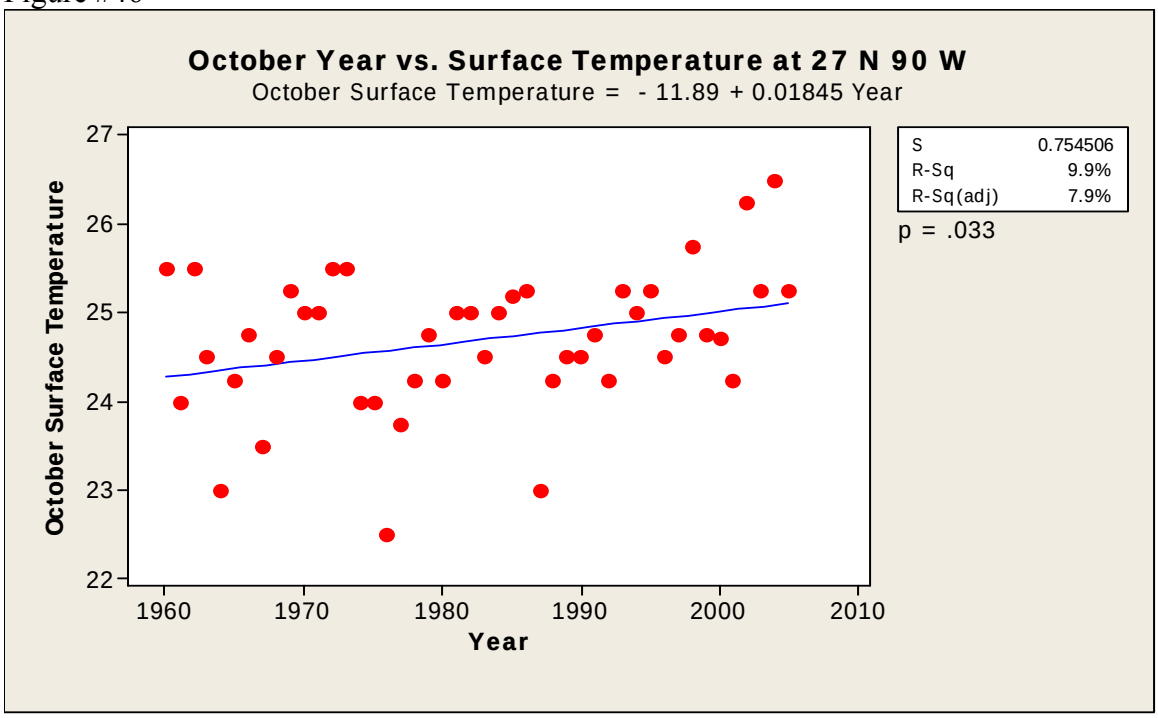


Figure #47

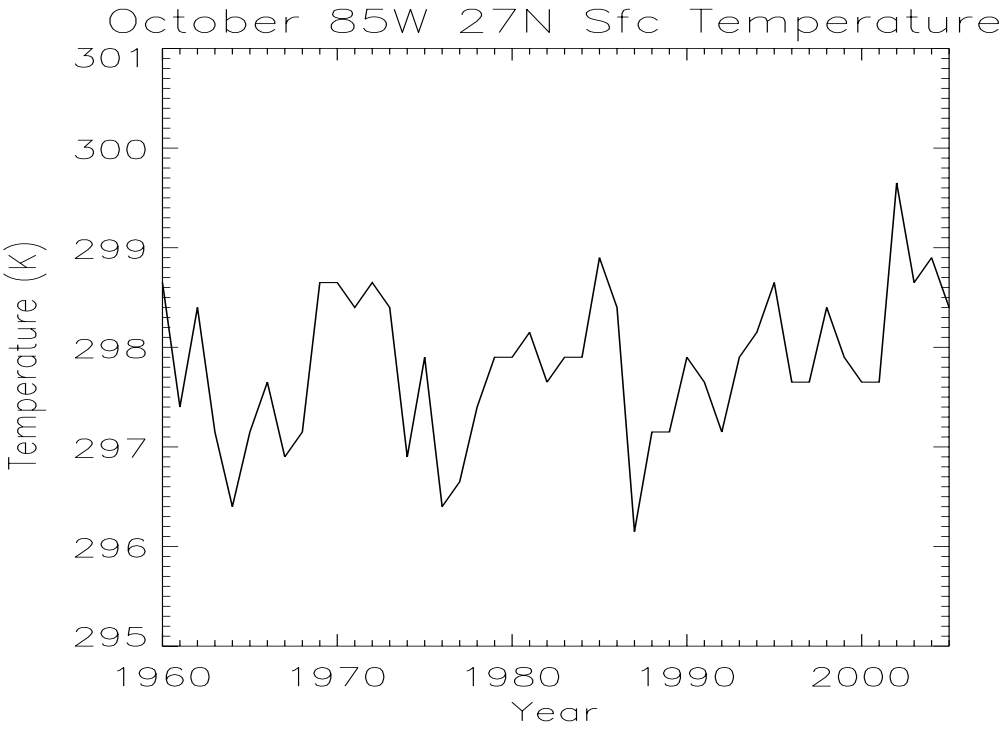


Figure #48

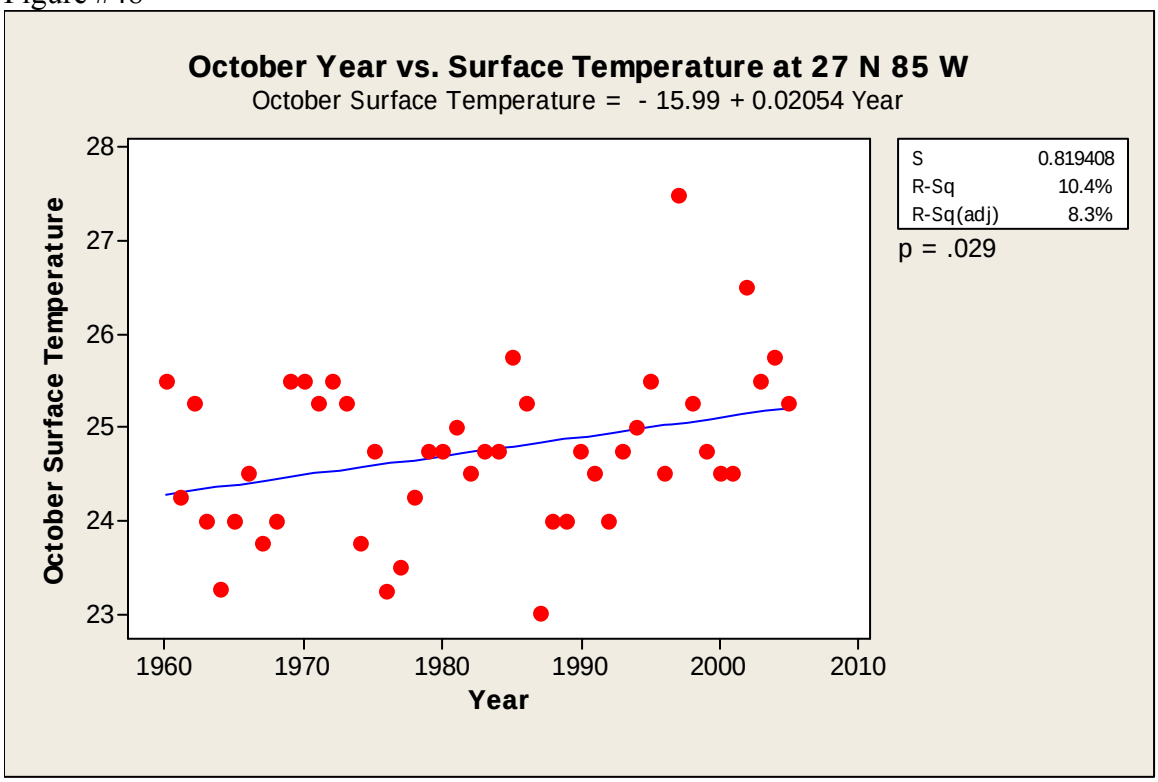


Figure #49

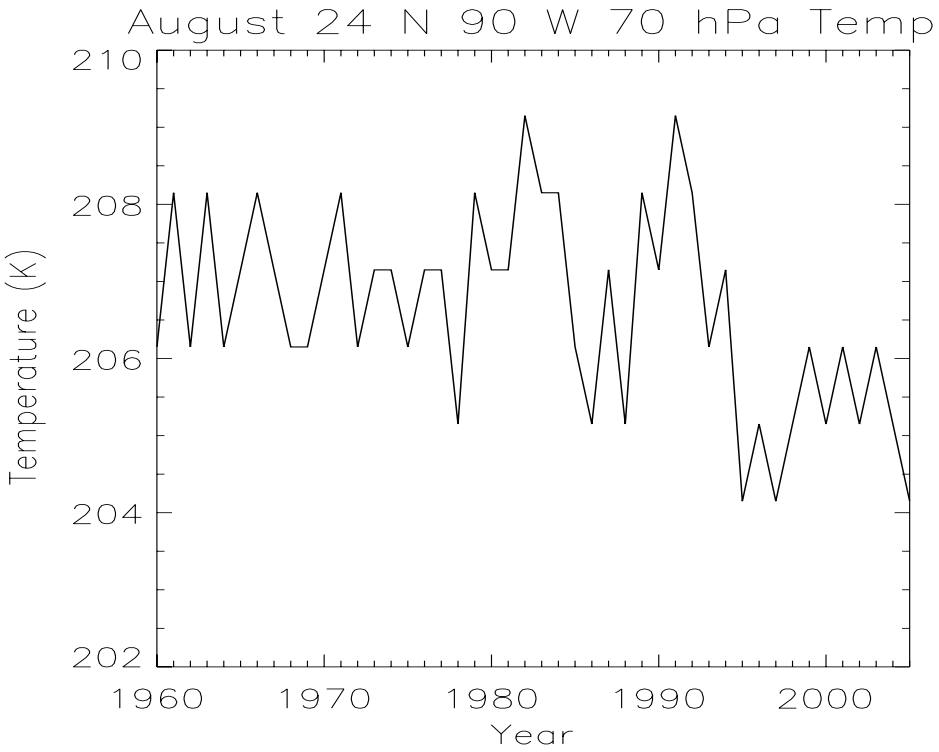


Figure #50

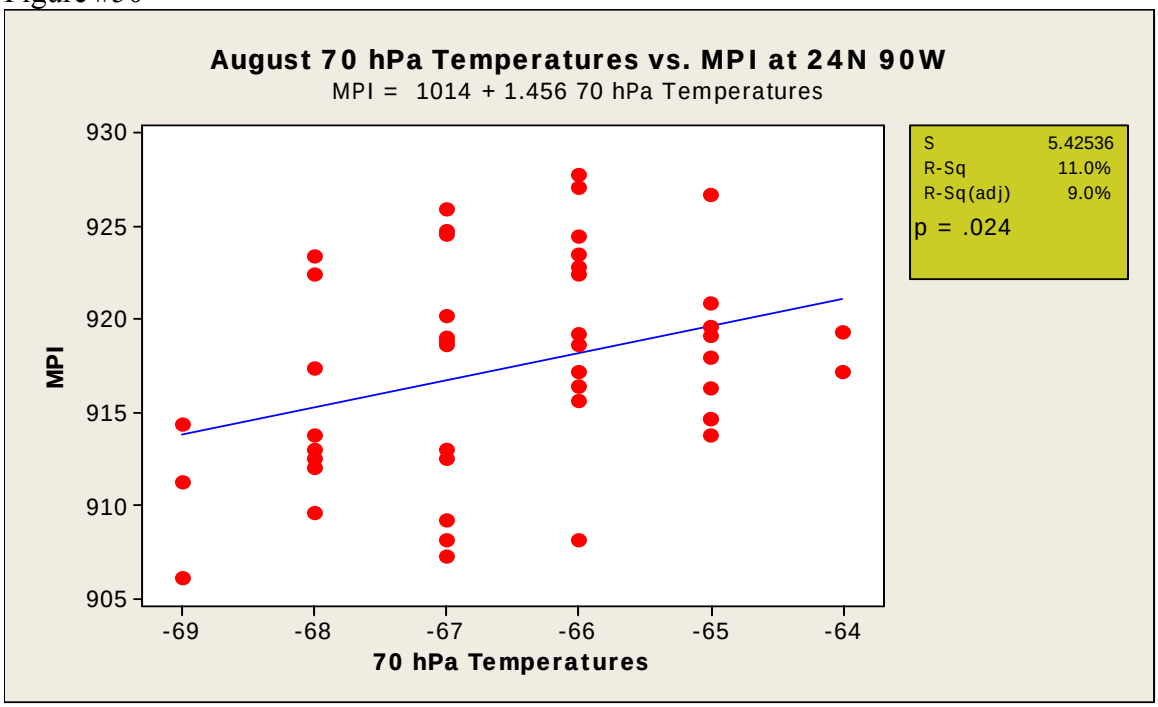


Figure #51

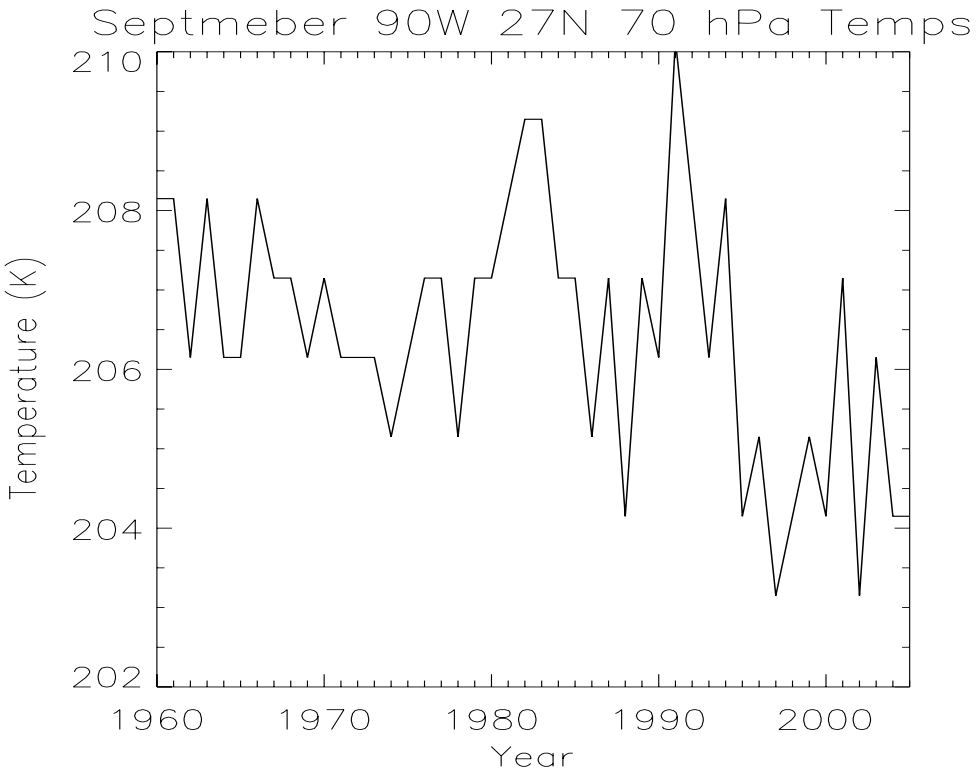


Figure #52

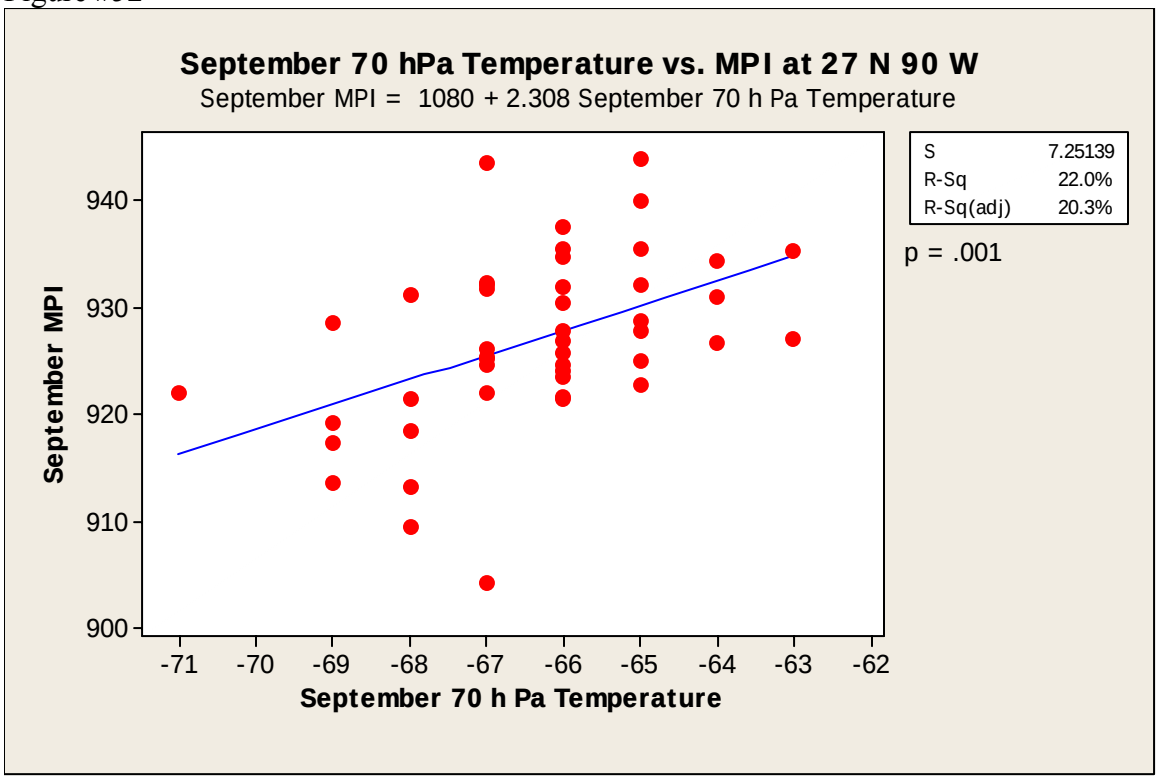


Figure #53

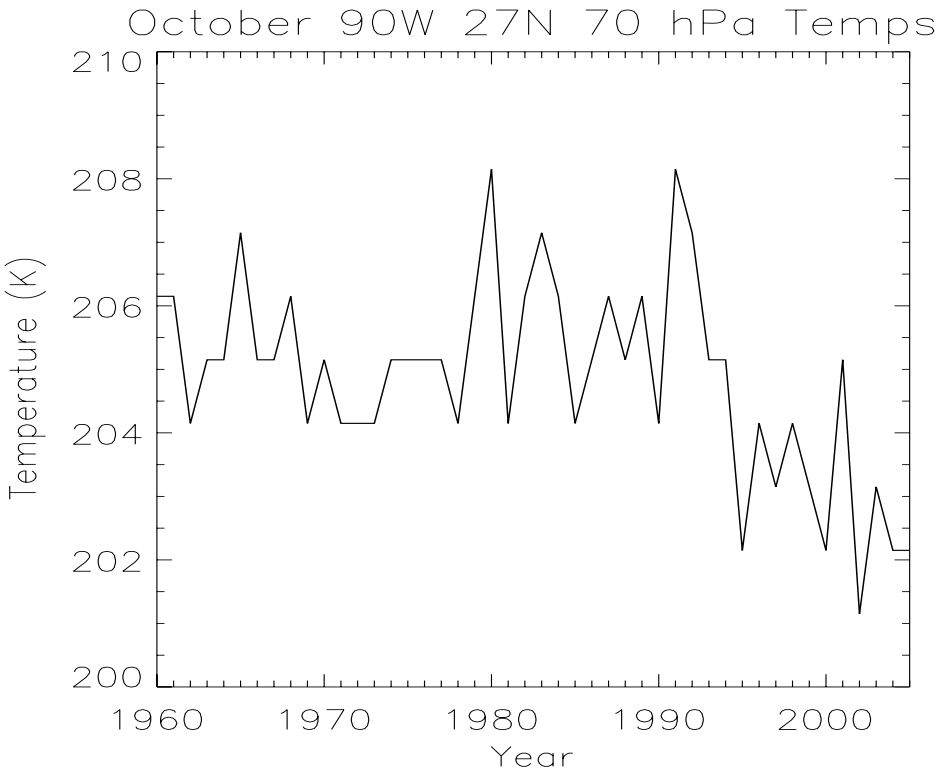


Figure #54

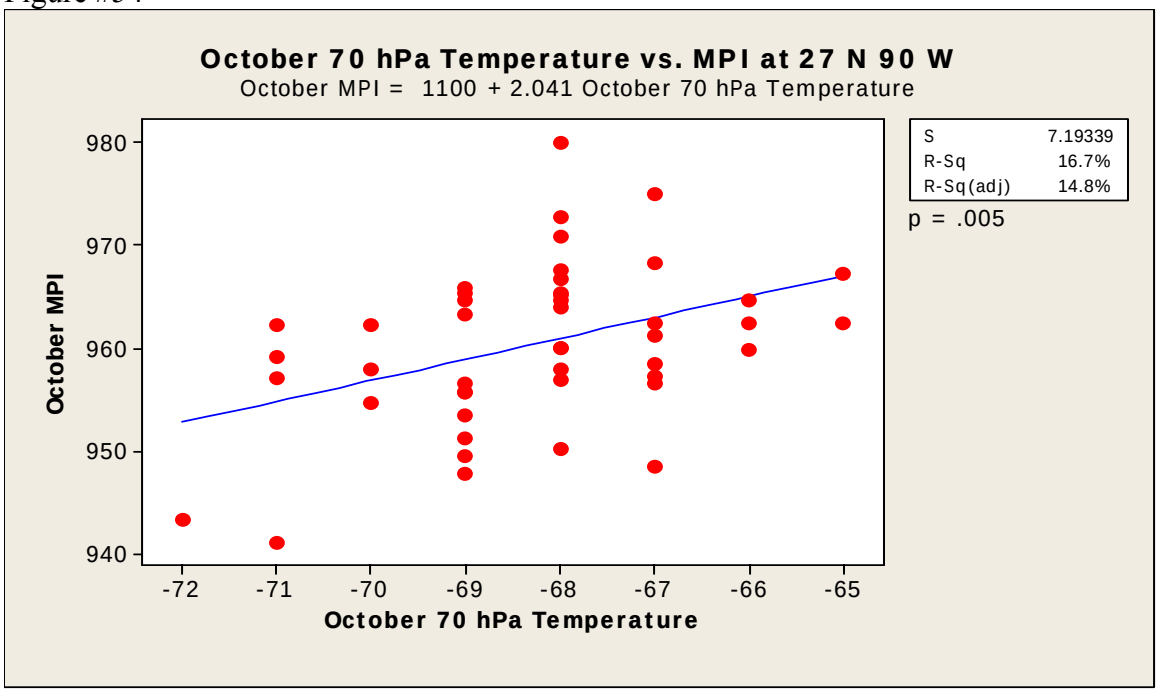


Figure #55: 100 hPa temperatures are at 24 degrees north and 90 degrees west

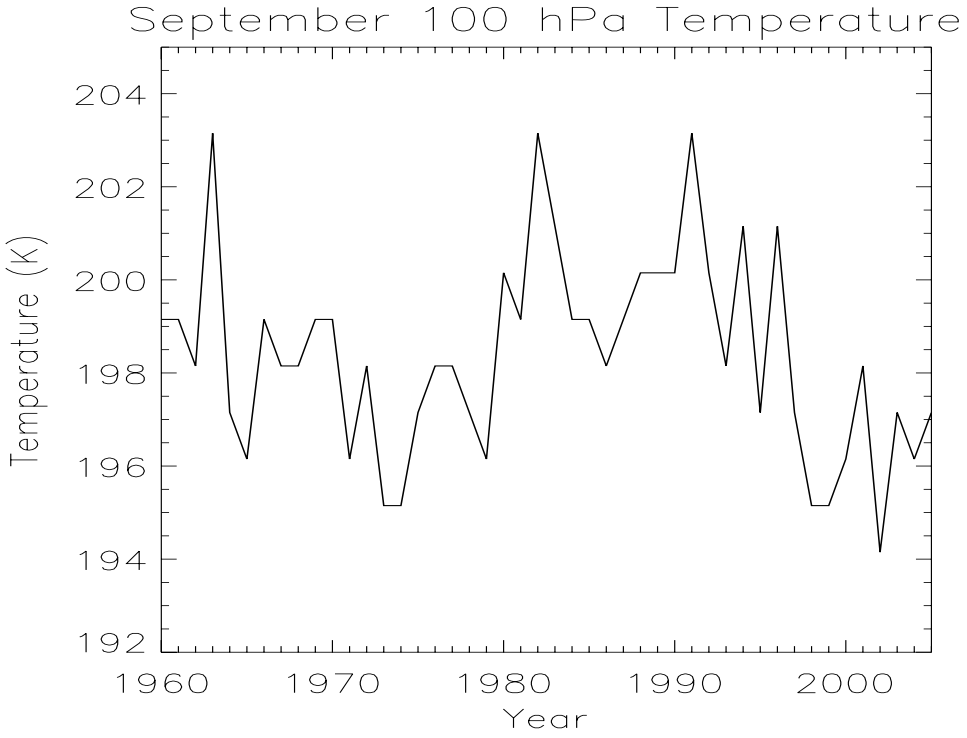


Figure #56

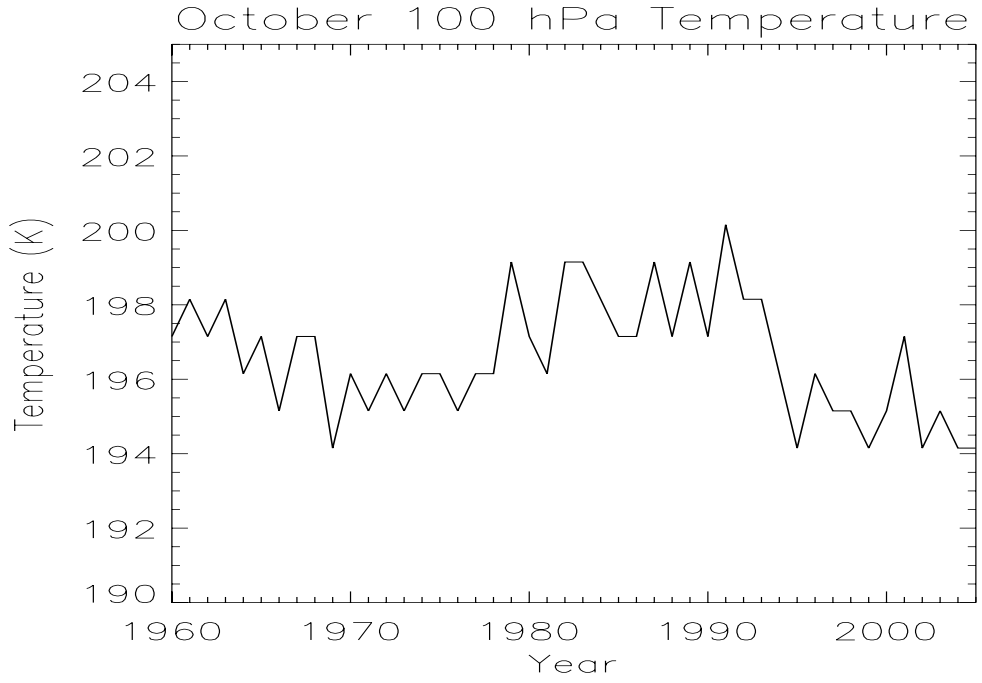


Figure #57: CAPE was computed at 24 degrees north and 90 degrees west

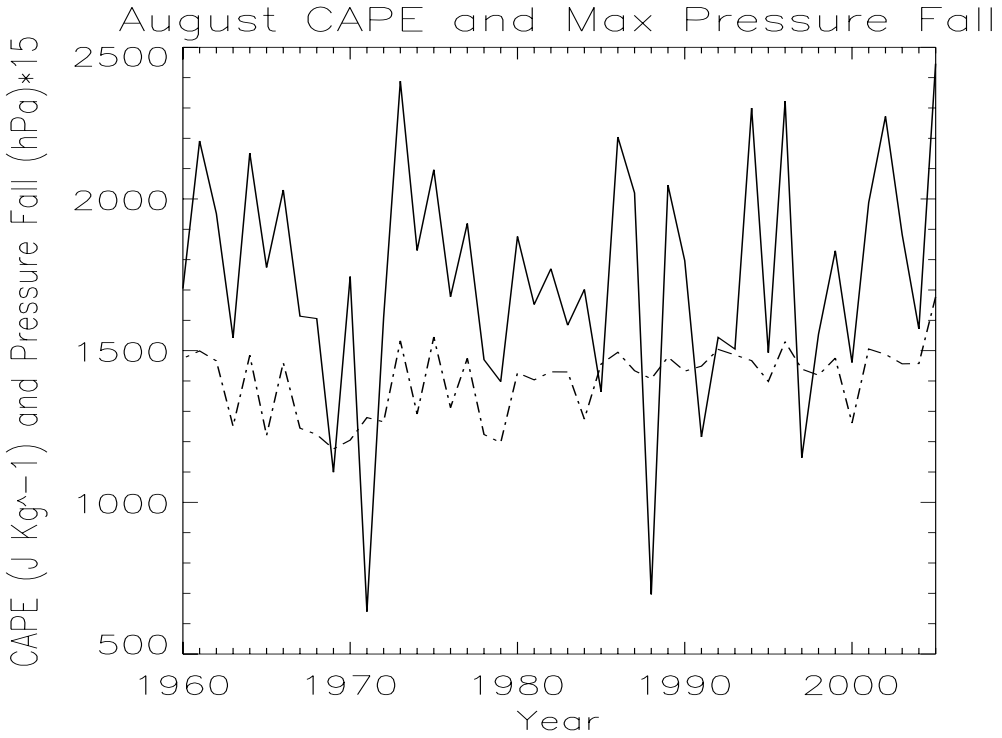


Figure #58

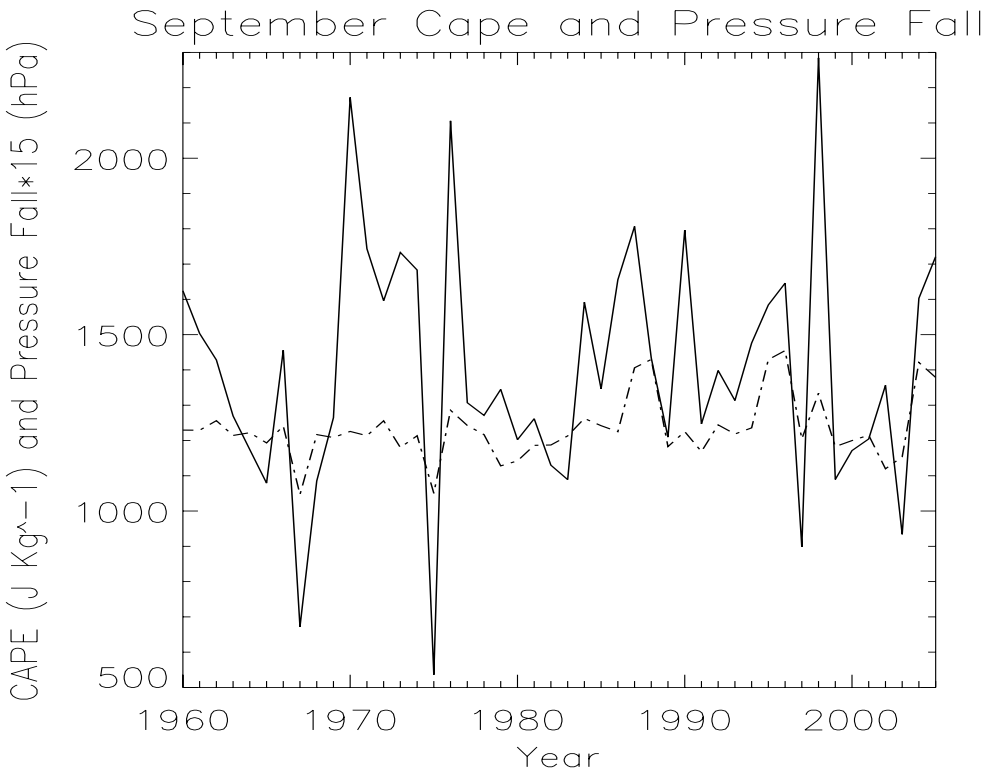
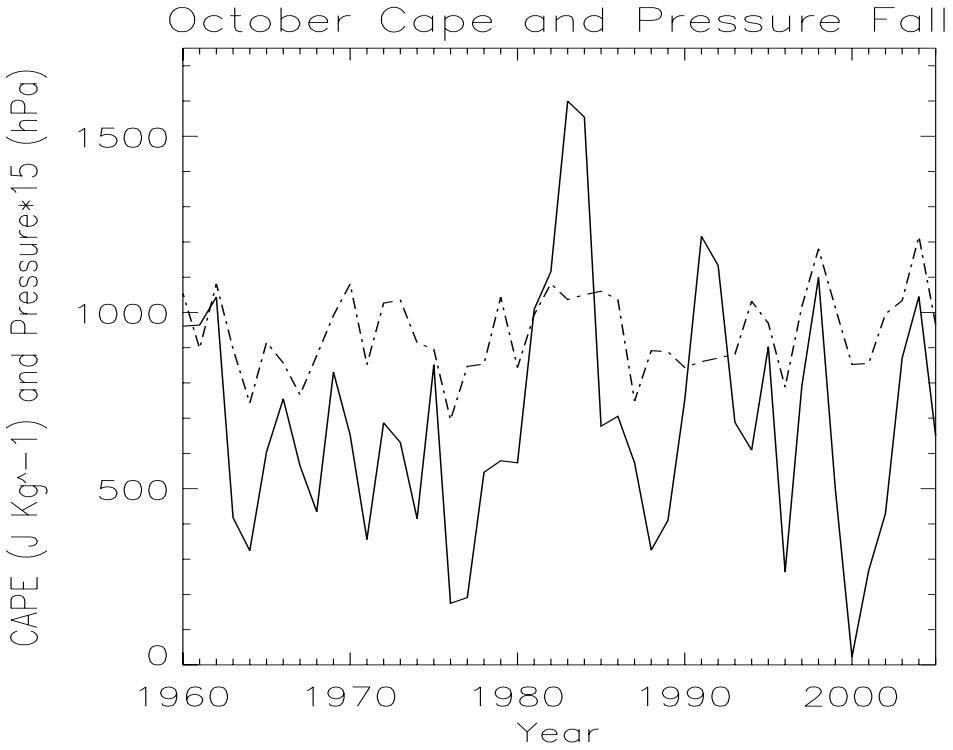


Figure #59


October Cape and Pressure Fall
CAPE (J Kg^-1) and Pressure*15 (hPa)
1500
1000
500
0
1960
1970
1980
1990
2000
Year