# IMPACT OF CLIMATE CHANGE ON LONG TERM NUCLEAR POWER PLANT OPERATION

A Thesis

by

ADAM B. REDWINE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2010

Major Subject: Nuclear Engineering

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# ABSTRACT

Impact of Climate Change on Long Term
Nuclear Power Plant Operation. (August 2010)
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The present work examines the potential impact of changes in climatic conditions on the long-term functioning of nuclear power plants. Nuclear power plants are potentially susceptible to changes both in acute risks, such as severe storm events, and chronic risks, such as detrimental changes in the thermodynamics of plant operation. Extending plant lifetimes well beyond the lengths of operation for which they were originally designed suggests the necessity of studying the impacts such changes might have.

Potential threats are examined in light of earlier work performed by Business Continuity Consulting on commission for Entergy Nuclear. The fourteen risk drivers identified in that work as threats warranting additional investigation are studied individually, and their relevance and likely impact extrapolated for regions covered by the ten selected sites under examination. Thermodynamic effects are simulated with a plant analysis program known as PEPSE (Performance Evaluation of Plant Systems Efficiencies), with which a broad range of modeled environmental and plant conditions are analyzed for potential impacts to plant functioning.

Of the fourteen climatic risk drivers considered, changes in drought and flood severity and frequency resulting from climate change were determined to be the most likely detriments to plant operations. Precipitation figures indicate that plants located in the Midwest are particularly susceptible to future drought conditions while those in the Northeast are likely to experience more frequent flooding. Many of the risk drivers specified by the earlier work were only cursorily examined in light of the complex nature of these phenomena and lack of well defined correlation to climate change. Other risks were analyzed using the gathered data, but were determined not to pose significant threats to plant operations.

In addition to large scale climatic effects, changes related to coolant fluid temperature rise and plant component efficiency were examined to qualify their effect on the thermodynamics of the model plant. Plant operating conditions were modeled for a wide range of conditions related to theoretical environmental changes. These examinations showed negligibly small impacts caused by increased coolant water temperature and moderate impact caused by changes in air humidity.

# ACKNOWLEDGMENTS

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# CHAPTER I

# INTRODUCTION

## A. Importance of Climate Change to Nuclear Power Plants

At 10:00 AM, August 28, 2005, Hurricane Katrina was upgraded to a category five storm, prompting the mayor of New Orleans to order the first ever mandatory evacuation of the city. At 10:59 AM, plant shutdown was initiated at Waterford Nuclear Power Station, located just to the west of the city. A staff of 138 persons oversaw the temporary suspension of operations and safely brought the reactor and turbine offline by 1:16 PM later that day [8].

Though the Waterford reactor was shutdown safely, the damage it did receive, and the short time it was offline (restart completed September 9 [8]), prompted the company to claim and win over $60 million in insurance reimbursement [9]. The storm also resulted in longterm damage to the utilities consumer base. Nearly three years after the storm, the metropolitan population of New Orleans was estimated to remain more than 35% below pre-Katrina levels [10].

Although Hurricane Katrina has played a significant role in altering American attitudes toward government, there appears to have been very little association made between the storm and nuclear power. Indeed, one of the more widely circulated post-Katrina articles linking the disaster and nuclear issues does not even mention the Waterford plant. The article was written in October of 2005 and was entitled “Preventing a Nuclear Katrina” [11].

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The journal model is *The International Journal of Energy Research*.

Not all storm-related nuclear events have been treated with such little concern. In June 1998, a tornado rating F2 on the Fujita scale (with winds estimated between 113 and 157 miles per hour) touched down near the Davis-Besse Nuclear Power Station outside of Toledo, Ohio [12]. The plant was shut down automatically when outside transmission lines were downed by the storm. The incident prompted several news stories immediately after the event [12, 13] and remained sufficiently in the public conscience to be mentioned two years later in an article about general nuclear security [14].

Though there is great variability year by year, storms have struck, or nearly missed, nuclear power plants on a number of occasions. These include, notably, an F5 (winds estimated at 261–318 miles per hour) tornado passing within two miles of Calvert Cliffs Nuclear Power Plant, in Maryland, in 2002 [15] and Hurricane Andrew passing over Florida's Turkey Point in 1992, during which it "caused extensive onsite and offsite damage." [16].

Of course, high winds and funnel clouds are not the only danger of storms. In 1993, large areas of the Midwest received unprecedented amounts of precipitation resulting in the "most significant flood event ever to occur in the United States" [17]. The flood affected an enormous area across nine states and is estimated to have caused $15 billion in damage. On July 23 of that year, Cooper Nuclear Station, in Nebraska, was shutdown due to the flooding. A report by the NRC [18] indicated that some of the below-grade rooms "inside radiologically controlled areas in the turbine building and the reactor building, had extensive inleakage."

The flood of 1993 was in many locations (including at the Cooper Nuclear Station site) above the 1,000 year flood level. Floods of a lesser magnitude, however, can also disturb power plant operations. In 2005, a petition was filed with the NRC to shutdown Vermont Yankee Nuclear Power Plant because of the fear of risk to spent fuel storage by unusually high river levels [19].

While no action was taken in that specific case, the threat of flooding at nuclear power plant sites looms large in the minds of some planners. According to Halcrow Group, an engineering consultancy firm, the cost of mitigating an increased risk of flood associated with global climate change could add up to two percent to the cost of new plant construction [20].

For plants that rely on massive quantities of cooling water, a lack of water can be as, or more, detrimental than an overabundance. In the summer of 2007, operations of Unit 2 of the Browns Ferry plant in Alabama were temporarily suspended due to "inadequate streamflow needed to cool the reactor"[21]. This event, and the prolonged drought in the American South between 2007 and 2008 prompted journalist Michael Weiss to inquire into the potential necessity for nuclear power plants to close due to lack of water [22]. His assessment that lack of sufficient cooling water could effect "...reactors across the southeast..." prompted the vice president of the Nuclear Energy Institute, Scott Peterson, to write a rebuttal that drought affects all steam power plants alike [23]. While Mr. Peterson's statement that nuclear power plants would not be uniquely affected is valid, neither are they uniquely exempted.

The United States is not the only place to face such climate-induced challenges. In 2003, large portions of Europe suffered from an extreme heatwave. Even though there was no unusual lack of water in many of the affected areas, the high temperatures in some locations came to within two degrees of automatic shutdown setpoints[24]. Though the hot weather of 2003 was unusual, the problem of lack of cooling capacity has persisted. Electricité de France (EDF) had to cut back operations of nuclear power plants in 2006 and 2007 as well [25]. In the summer of 2009, France's nuclear power generating capacity was at times reduced by as much as 30 percent, causing EDF to purchase up to 1,000 MW of electricity from Britain [26].

Only a few studies have seriously investigated specifically the impact of climate on the operations of nuclear power stations. Business Continuity Consulting, on behalf of Entergy Corporation, conducted a broadly based examination of the question [27] in 2006. This study was intended as a preliminary investigation into the subject and sought to provide guidance for the focus of future investigations. It took into account a wide range of factors such as changes in storm frequency and salt water intrusion due to rising sea levels. Though no follow-up was ever completed, the piece served as a guide for the collection of data in the current work.

In 2004, a research group from the University of Extremadura in western Spain examined the cooling water system of the Almaraz Nuclear Power Plant, located in Campo Arañuelo [28]. The research was an attempt to predict the effect of adding a cooling tower to the plant and, specifically, to evaluate the potential for such a change to increase the thermal efficiency of the plant and thereby to increase its electrical output. The study of the Almaraz plant closely approaches the goals of this thesis, but the findings are unique to the specific location and difficult to apply to other plants.

Similarly, in 2000, a group from Pennsylvania State University studied the cooling water system of Three Mile Island Nuclear Power Plant [29]. The aim of this work was to determine how changes to the auxiliary cooling system would effect the thermal efficiency of the plant. This work showed that altering the plant cooling system configuration could indeed alter the thermal efficiency of the plant, but the focus of the study was limited to plant systems and no consideration was made regarding the change in inlet conditions. In so far as auxiliary cooling systems share many common features, this study is applicable to a wide range of plants, but it does not address the variability of climate and how these changes impact the system.

A 2005 investigation by researchers at Istanbul Technical University addressed both of the restrictive aspects of the aforementioned studies [30]. This group studied the impact of cooling water temperature on the efficiency of a “conceptual pressurized-water reactor.” Because the model they used is applicable to all pressurized water reactors (PWRs), their results are much more general. Additionally, the study encompassed the entire plant system and addressed the change of temperatures that can result from climate change. Their theoretical analysis, however, was not validated with either computer simulation or historical plant performance.

In 1991, a group of researchers associated with the Hitachi Energy Research Laboratory examined the thermal efficiency of a generic BWR system using the concept of exergy, a quantitative measure of the potential maximum amount of work that can be extracted from a given system [31]. This work identified sources of exergy loss and made suggestions regarding the potential for improvement of thermal efficiencies. Like the analysis of Durmayez and Sogut[30], however, their analyses were not supported by computer modeling of the system.

## B. Motivation for Research

While risk analysis is a well developed field, applications of risk analysis techniques to the nuclear industry typically address specific plants or concerns rather than the industry as a whole. In fact, risk analysis of individual plants is a part of the United States nuclear regulatory framework [32] and is becoming increasingly used abroad [33]. Climate change, with its potentially broad reaching consequences, could impact a large number of nuclear power plants in a manner not identified by such individual analyses. The aforementioned BCC study [27] began to examine the potential impact of climate change on a broader scale but stopped short of analyzing the risks it identified.

The present work extends and applies these findings in order to improve the understanding of the relative magnitude of climate change induced threats and to identify the areas of most concern. The long-term nature of climate change suggests that continued work will be needed in analyzing the risks posed to nuclear power plants. The present work should serve to highlight the need for future cooperation among climate scientists and risk engineers.

Climate change has the potential to impact nuclear power plants in a variety of ways. The two primary categories of risk are acute risks such as would be associated with a notice of unusual event, and chronic risks that pose long-term threats. For the purposes of this work, acute risks are those defined by a clearly identifiable period of time and a specific, correlated event. Alternatively, chronic risks are the kinds of risks posed by long-term changes to the thermodynamic balance of plant. Both of these have been considered in limited cases such as those described above, but there has been very little work to examine the relative nature of these risks.

Examinations of climate induced acute risks have generally[34] been of a much broader scope. As the science of climate change develops, established methodology[35, 36] can be used to examine more specific questions such as those at hand. While some examinations of such effects have been made on a large scale[37, 38, 39], none have been made examining specifically the unique conditions of the nuclear industry.

Though temperature changes may be small, the long and extending lifespans of nuclear power plants might mean that cumulative effects could be significant to operations. It is obvious, however, that a well informed decision regarding the thermal balance of a plant can not be made until a thorough analysis of the relative importance of contributing factors has been completed.

A thorough, cross-validated study of how climate impacts the operation of nuclear power plants will provide a useful guide for operators when making decisions about plant operations, and for energy companies when making decisions about future fleet development. It will also serve as a basis for future investigations into the nature of plant thermal efficiencies and how those efficiencies relate to the system as a whole. As the science of climate change develops, focus is likely to turn from the nature of the impact of industry on climate, to that of climate on industry. Recommendations developed as a result of the current work will help guide such future examinations.

Whether or not the effect of climate on nuclear power plants is significant, a quantitative understanding of the interaction is presently lacking. In a 2007 interview, Luis Echavarri, director-general of the Nuclear Energy Agency was asked if global climate change would effect the operations of nuclear power plants; his response was “Because what we are talking about is between 1.5 and five degrees equal 100 years. So we don’t think, from that point of view, it’s a challenge” [25]. Though his surmise that higher temperatures would not pose a problem might well prove accurate, it is a desire to clarify the uncertainty behind this response that underlies the motivation for this thesis.

## C. Objectives

The complications arising from climate induced changes in “event” frequency and intensity, such as has been posited for tornadoes and droughts, are relevant to power plant operations and management, but a detailed examination of each potential impact is outside the scope of this investigation. A survey of changes that are likely to impact a representative number of sites, however, is feasible. This work offers qualitative assessment of the level of risk of the 15 drivers identified in the BCC study[27].

These are examined individually in Chapter III and Section A. These analyses are intended to elucidate the relative concerns for a representative number of nuclear power plant sites. The data examined are specific to the ten selected sites, but broader extrapolations are intended to apply to nuclear power plants within a much larger geographical area.

The climate data collected for these sites is used to qualify the examination of nuclear power plant thermodynamics. This study examines temperature related impacts of climate change by performing thermodynamic balances of plant on a representative nuclear power plant for a wide variety of environmental conditions including worst-case scenarios. Conclusions about likely impacts are made by comparing observed changes in the model plant with the range of outcomes suggested by climate analysis.

The present work seeks to integrate the findings of the papers described above, to test their findings with computer modeling, and to extrapolate for a wide range of potential changes. Ultimately, this work examines the effect of long-term climate change on the operation of nuclear power plants by applying findings as widely as reasonable.

# CHAPTER II

# STATUS OF THE QUESTION

Though large-scale investigations have identified trends in climate change, and academic investigations have treated individual nuclear power plant susceptibilities, this work seeks to answer the question: how will climate change effect local areas on a scale that will impact power plant operations and what is the relative nature of those impacts?

Climate change is a rapidly growing subject in the scientific community;[1] many of the efforts in this field are directed at assessing the magnitude of change and the possible courses of action that can be taken to prevent it. It is generally recognized, however, that regardless of future measures aimed at limiting climate change, significant alterations in traditional climate patterns are likely to occur [35, 36, 40].[2] In addition, changes in climate are expected to cause secondary effects such as altering the rate of wildfires [41] and the migration patterns and habitats of wildlife [42].

Though it is very difficult to predict with great certainty the exact extent of the changes that will take place, climate change research has produced widespread agreement on the range of possible changes [34]. The most widely referenced work is that of the Intergovernmental Panel on Climate Change (IPCC), which received the

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[1] For geoscience journal articles available through the Texas A&M University library's journal search system, there are 25,848 referencing "climate change" dating from 2008; the corresponding numbers are 22,713 and 18,983 for the years 2007 and 2006 respectively. In the case of "global warming," the numbers of articles are 7,864, 8,054, and 6,645 for the same years.

[2] These are, of course, merely a sampling of the numerous articles predicting long term changes in climate.

2007 Nobel Peace prize for their efforts to examine the nature and impact of climate change on a global scale [43]. This group describes several possible scenarios with predictions of global average temperature increases ranging between 1 and 6.5°C by the year 2100.

This organization provides compilations of focused studies of climate change by monitoring the academic work in the field and consolidating the findings into various formats accessible to politicians and scientists. It consists of several working groups, each focusing on different aspects of climate change. These different groups publish individual reports covering the global aspect of their particular area of concern, and also more locally focused works tailored to different audiences.[3]

Despite the fact that the United States has been seen as slow to accept the predictions of climate change scientists, many of the federal government bodies that deal with weather and climate, such as the National Oceanographic and Atmospheric Administration (NOAA) and the US Global Change Research Program,[4] have produced their own studies of the subject.[5]

NOAA in particular is a key source of data for the present work; though their resources are comprehensive, they are in the form of raw data from individual climate stations. The IPCC predictions are applied at a large scale and do not give resolution to small scale. The present work seeks intermediate level predictions based on compilation of NOAA station data and conservative application of climate change prediction methodology [35, 36, 44, 45].

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[3] A synopsis of the IPCC's reporting methodology and links to most of its reports can be found at `http://www.ipcc.ch/ipccreports/index.htm`

[4] Formerly the Climate Change Science Program

[5] The Environmental Protection Agency (EPA) maintains a website detailing the US efforts on climate change and containing links to other US departments dealing with the subject at `http://www.epa.gov/climatechange/`.

While a majority of engineering studies of power plant thermal efficiency matters focus on the individual components of a power plant [46, 47],[6] several studies have been done on the thermal efficiency as related to the balance of plant [32, 48, 49]. Some studies, such as those mentioned above [28, 30], have even been made specifically regarding the effect of cooling water on plant efficiency, though the results of these analyses are not widely applicable. The subject of nuclear power plant thermal balance as a whole is not often treated academically and there is, to date, no comprehensive body of experience covering the topic. There are, of course, academic works in the fields of mechanical and nuclear engineering that cover plant systems [49], but these primarily cover theory and rarely treat more than a generic model of the plant system as a whole. Where they do examine component behavior, these analyses are difficult to apply to a wide range of scenarios such as is necessitated by the current investigation.

Though many different methods and computer programs are used to study these systems, there is no widely accepted standard method. Unfortunately for the academic community, the codes used by industry are far from standard and universally applied, and the records produced by these codes are almost entirely unavailable. Only the one study mentioned above [28] was found predicting a specific plant response to climate conditions. Though it is possible that some studies have been made for other plant sites, these might have been done privately by corporations and not released to the public. At present, the examination of how the operation of nuclear power plants is affected by changes in environmental temperature is answered on a plant by plant, as-needed basis.

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[6] These are, of course, just a couple of examples.

# CHAPTER III

# METEOROLOGY

## A. Site Selection

This investigation focuses on a sample of plants, which is representative of the US nuclear power fleet and their climate conditions. While large scale trends in climate are expected to affect all areas of the globe, the sites selected for analysis in this paper are all from the United States. There are several advantages to this, primarily that such a selection allows for consistency of weather data collection while still allowing a wide variety of climate region conditions to be examined.

The specific plant sites selected are those of the Entergy fleet: Arkansas Nuclear One (ANO), Cooper Station, Fitzpatrick, Palisades, Vermont Yankee, Pilgrim, Indian Point, Grand Gulf, River Bend, and Waterford 3. The relevant plant details are summarized in Table I. A brief description of each of the plants, as obtained from the EIA[50] follows. Images of each site are provided in Appendix A.

ANO and Cooper Station are located in the Midwest with significant seasonal variability in temperature. The Cooper station power plant, the largest electricity producer in Nebraska, is located on the Missouri River some 63 miles downstream from Omaha. The plant draws water from, and discharges it to, the Missouri River after passing through a once-through system without cooling towers. While the flow of the Missouri at the plant site is substantial, there is a seasonal variation in temperature between approximately 34 and 73°F[1]. The ANO site is located on

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[1] The use of British units of measurement is retained throughout this thesis because that is the standard used by PEPSE for calculations. Though the program allows for using SI units, if they are provided as input, they are converted to British and then the results are re-converted to SI, thus reducing fidelity.

Table I. Summary of plant sites examined

| Plant | State | Reactor type | Start of Commercial Operation |
|---|---|---|---|
| ANO | Arkansas | PWR (x2) | Dec. 1974 / Mar. 1980 |
| Cooper | Nebraska | BWR | Jul. 1974 |
| FitzPatrick | New York | BWR | Jul. 1975 |
| Grand Gulf | Mississippi | BWR | Jul. 1985 |
| Indian Point | New York | PWR (x2) | Aug. 1974 / Aug. 1976 |
| Palisades | Michigan | PWR | Dec. 1971 |
| Pilgrim | Massachusetts | BWR | Dec. 1972 |
| River Bend | Louisiana | BWR | Jun. 1986 |
| Vermont Yankee | Vermont | BWR | Nov. 1972 |
| Waterford | Louisiana | PWR | Sep. 1985 |

Lake Dardanelle, a 34,300 acre reservoir on the Arkansas River. There is seasonal variability in temperatures, though they do not typically fall as low as at Cooper Station.

ANO has two PWR units on site, each of which uses dedicated primary coolant loops; these systems do share some components, especially in the tertiary coolant loop at the intake and discharge portions of the cycle. The cooling systems of both units utilize once-through cooling though only unit two uses the cooling tower. The sole water intake for the plant is a concrete structure at the end of a 3,220 foot canal located on the south side of the facility. The short intake canal can be seen in the lower portion of Figure 1 and the longer coolant outlet flow canal can be seen on the right side of this image. The plant system has a condenser flow rate of approximately $2.11 \times 10^8$ pounds per hour and a condenser temperature rise of approximately 25 °F. Remaining waste heat is discharged in the form of blowdown from the circulating water system to a 520foot long canal east of the plant (see Figure 1) that discharges into Lake Dardanelle.

The James A. Fitzpatrick plant is located on the southeast corner of Lake Ontario, 63miles east of Rochester. The Entergy-managed unit at the Fitzpatrick

Fig. 1. Arkansas Nuclear One

site selected for climate analysis is one of three that serve the Rochester/Oswego area. The other two units are located half a mile away at the Nine Mile Point site and collectively generate over 1,500 MWe. The region experiences slightly cooler temperatures on average than the Cooper Station location.

The intake structure for the plant lies submerged at a depth of 25 feet, 900 feet from shore. While the size of the lake moderates the temperature range of the intake water, the lake still nearly freezes in the winter with temperatures ranging from 37 to 67°F. The plant uses a once-through cooling system with a condenser flow rate of 350,000 galons per minute. The condenser has a design temperature rise of 32°F.

The Grand Gulf Nuclear Station is just off of the Mississippi River 55 miles southwest of Jackson, Mississippi. While the plant is located within a mile and half of the river, it has a non-traditional intake system. The cooling system draws ground water from multiple radial-collector wells rather than directly from the Mississippi, though the local water table certainly depends on the river. The collector well system consists of a large vertical well with horizontal intake pipes radiating from it.

The plant system has a condenser flow rate of 572,000 galons per minute with a temperature rise of 30°F. The primary cooling mechanism is a 520 foot cooling tower. Waste water is discharged into the Mississippi river.

The Indian Point plant is situated in the northern greater New York City urban center 36 miles north of Manhattan. The plant uses a once-through cooling system fed by the Hudson River. The intake is a concrete structure on the river bank and the discharge flows back into the river. The condenser has a flow rate of 840,000 gallons per minute with a temperature rise of 16.6°F.

The Palisades plant is located 76 miles east across Lake Michigan from Chicago. The climate at the Palisades location is very similar to that of the northeastern plants. Palisades draws water directly from Lake Michigan through an intake crib 3,300 feet from shore and discharges from a 108 foot canal. The cooling system utilizes a mechanical draft cooling tower.

Pilgrim is on the rocky west coast of Cape Cod Bay 39 miles southeast of Boston. The Pilgrim facility cooling uses a once-through system with water drawn from Cape Cod Bay through a concrete structure protected by a breakwater. The unit condenser has a flow rate of 310,000 gallons per minute with an associated temperature rise of 29°F.

River Bend is located on the Mississippi River 24 miles northwest of Baton Rouge Louisiana. The intake structure draws directly from the river bank and the discharge water emerges from a pipe extending into the river. The condenser flow rate is 507,000 gallons per minute with a temperature rise of 27°F. The facility has four mechanical draft cooling towers.

The Vermont Yankee Nuclear Power Station is approximately 5 miles southeast of Brattleboro, Vermont. The Connecticut River is the source for cooling water for the main condenser. The concrete intake structure, located on the west bank of Vernon Pool approximately 160 feet east of the Reactor Building, is approximately 114 feet long by 77 feet wide by 50 feet deep.

The plant has an unusual adjustable cooling system which can operate as an open-cycle (also called once-through cooling), hybrid-cycle, or closed-cycle. In the open-cycle mode, the cooling towers are bypassed and, after entering the discharge structure, the water returns to the river through an aerating structure. In both the closed-cycle and hybrid cycle, after entering the discharge structure, the circulating water is pumped up to the cooling towers. After being cooled, the water returns to a weir collection chamber in the discharge structure. A gate inside this chamber allows all or a portion of the water to return to the intake structure. In the hybrid cycle mode of operation, a portion of the water returns to the intake structure for re-use in the condenser while the remainder is returned to the river through the aerating structure. In the closed-cycle mode, all of the tower cooled water is returned to the intake structure.

The exact amount of water returned to both the intake structure and the river in hybrid mode depends on seasonal variation in environmental conditions, particularly the flow rate and temperature of the Connecticut River. The plant has two mechanical draft cooling towers, one of which has a deep basin holding

1,400,000 gallons of water for emergency cooling.

Waterford-3 is located on the outskirts of New Orleans, Louisiana. Waterford uses cooling water drawn from Mississippi River via a 162 foot intake canal leading to intake structure with four pumps. The component cooling water system is a closed loop that utilizes wet- and dry-type mechanical draft cooling towers to indirectly cool the reactor coolant and reactor auxiliary water systems. The discharge water represents an increase of 16°F over intake temperatures.

As can be seen from this survey, nuclear power plant cooling systems vary widely. Nonetheless, the exact nature of the interface of a plant and the environmental heat sink is a significant consideration when making decisions about plant operations. The range of thermodynamic values examined in this study is sufficiently broad to cover all of the potential configurations of these systems.

## B. Data Collection

Throughout the United States, various government and private entities have been recording local weather on a daily basis for many years, in some cases regularly since the mid-nineteenth century. The US government has been studying climate since the founding of the Weather Bureau in 1870. This information has recently been organized and compiled by NOAA and has been made available to the public.[2] Though the dates for which information is available may not be the most amenable to making long-term climate predictions, they are the most reliable for a significant period of time and match very closely to the dates upon which IPCC findings are made and by which predictive climate models are judged. This data is a primary source of information for the present work; the IPCC has issued a number of reports

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[2] This information can be accessed at `http://www.ncdc.noaa.gov/oa/climate/stationlocator.html`

that also serve as reference for the current research [31, 34, 51, 52].

For each of the locations cited above, historical weather data (dating as far back as records allow) was retrieved from NOAA's website. This was accomplished by entering the latitude and longitude of each of the plant sites, as acquired by Google Earth, into the station locater and retrieving data from all of the locally reporting stations. For each location a variety of types of data were collected. In addition to the obvious importance of temperature, several types of data were selected for analysis based largely on the earlier findings of the BCC study mentioned in Chapter I [27]. This work identified the following fourteen risk drivers as being the most significant to the operation of nuclear power plants in the face of potential climate change:

- degree days cooling
- degree days heating
- drought
- episodic flooding
- hurricane
- ice storms
- plant/animal shift
- lower river levels
- saltwater intrusion
- sea level rise

- abrupt temperature change
- thunderstorms
- tornadoes
- wetlands loss
- wildfire

Because the current focus is on long-term trends and plant average effects, as well as the thermodynamic balance, not all of these risk drivers were examined in depth. For each of the sites, the following data were retrieved from NOAA:

- degree days cooling
- degree days heating
- monthly precipitation
- departure from normal monthly precipitation
- maximum one-day precipitation per month
- departure from normal temperature
- days with temperature above 90°F
- monthly extreme low temperature
- monthly extreme high temperature
- monthly mean temperature
- all recorded tornadoes in the county of interest and contiguous counties

The official definition of a degree day cooling [53] is a degree of the average daily temperature above some reference temperature (in this study, 65 °F). For example, if the average temperature of a day was 77 °F, the day would be recorded as having 12 degree days cooling. Degree days cooling are a record of the average daily temperature in excess of the reference and are typically summed over a seasonal basis to measure the relative average heat of a period of interest.

Climatically, long-term trends in degree days cooling can be effective predictors of future mean temperature. This statistic can also be applied to predictions of changes in water temperature and to estimates of changes in evaporation rates from cooling towers and water sources.

Degree days heating is the opposite of degree days cooling. The official definition of a degree day heating is a degree of the average daily temperature below some reference temperature (also 65 °F). Degree days heating have some of the opposite implications on cooling water and evaporation as degree days cooling.

If the climate is generally warming, it would be expected to see a correlated reduction in degree days heating and increase in degree days cooling. Following this line of reasoning, degree days heating can be added to degree days cooling to indicate the nature of the predicted change. A large positive value of the change in "total degree days" indicates a greater increase in degree days cooling than drop in degree days heating and thus a significant increase in hot summer temperatures and warmer spring and fall seasons. A large negative value indicates a greater decrease in degree days heating than rise in degree days cooling and correspondingly much warmer winter temperatures and earlier springs. Changes small in magnitude imply a very general warming or cooling trend for the site.

Monthly precipitation and departure from normal monthly precipitation data were collected for a number of different analyses. Droughts are directly linked to the monthly mean precipitation and temperature. Floods are more difficult to predict based solely on precipitation data, but information such as extreme single-day precipitation can more accurately account for variance in precipitation. Similarly, river levels, wildfire risk, and even saltwater intrusion risk depend to some extent on levels of precipitation.

The various temperature data collected have a number of implications on the risk drivers identified by BCC[27]. These are described in depth in Section A where applicable. Hurricane and tornado frequency is also cursorily examined in Section A.

## C. Techniques

Plant components respond to changes in local temperatures on different time scales. Consequently, when considering the balance-of-plant thermodynamics, care must be taken in selecting appropriate data and time scales. Components that depend on ambient air temperature, such as cooling towers, are sensitive to day/night fluctuations as well as changes in humidity and wind conditions. Sources of cooling water, such as rivers and lakes, are typically insensitive to these daily changes, but in many instances change greatly with the seasons and often depend to some extent on the recent precipitation history.

Accordingly, it is desirable to analyze a broad range of possible conditions and to determine average weather recordings for the sites under examination. For this thesis, data were collected from all reporting weather stations within one degree[3] of each plant. For some of the sites[4] data could only be collected for stations within

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[3] The terms degree and minute here refers to measurements of longitude. One degree is approximately 69 miles and one minute is approximately 1.2 miles.

[4] Indian Point, Vermont Yankee, and Waterford 3

30 minutes because of the large amount of information and the download limit imposed by NOAA. This data was then averaged over all reporting sites for the longest available period of time.

Long-term climate predictions are often based on complex computer models that are designed to make very long-term predictions as accurate as possible for global and regional trends. In analyzing medium-term local trends, climatic variability prohibits accuracy in predictions greater than a couple of degrees [34]. Because the predicted negative effects to a power plant increase with temperature, the most conservative predictions to use are those that result in the highest temperatures. While much is made of the exponential increase in mean temperature, for the data used in this study, linear extrapolations were found to predict higher mean temperatures for the period of interest. All simple extrapolations of the data collected for this examination result in predictions that lie within the margin of error of the IPCC predictions (-0.36 to 1.8°C) [34].

In order to provide the most conservative, plausible predictions, a simple assumption of climate change superposition was assumed. That is to say that simple (linear) extrapolations of data for the selected sites would demonstrate local trends in climate, but would not account for the exponential changes predicted by some climate models [34]. Predictions for each local area, then, could be produced by summing the change predicted by a linear extrapolation and the change predicted for the area by the findings of climate change specialists such as the IPCC. It is expected, for example, that a two-degree change in the regional average conditions would correspond to a two-degree change in local average conditions in addition to the locally observed change. This technique has been applied in climate change science journal articles [44, 45] and is here applied as a conservative prediction. The data given in the appendixes does not include any supplementary warming and reflects only trends in the collected data.

The information from NOAA is given in the form of comma separated lists. These lists contain a row for each weather station per type of data per year. The row begins with a numeric station identifier and then provides the type of data referenced in the row, the year, and monthly values with data flags (various indicators about the data). These data files contain on the order of 60,000 lines of data for each plant and so are not provided in whole with this work. An excerpt from the data file for the Cooper Station plant, is given in Appendix B.

Preliminary organization of the data could easily be done with standard spreadsheet manipulations. In this case, Open Office was used to import the comma separated lists, remove unnecessary columns and to sort the rows by type of data and the year collected. After this initial organization, for each site, the collection of data consisted of a column identifying the type of data of the row (eg. monthly total precipitation or maximum monthly temperature), a column giving the year that data was taken, and twelve columns giving the monthly values. At this point, the data was arranged as shown in Table II for the monthly mean temperature (MNTM) given in degrees Fahrenheit recorded in the vicinity of Pilgrim Nuclear Station. Each row represents the reported values from a single weather station for a single year. A value of -99999 indicates that no data was available from that station for that month.

For most years, data from several stations needed to be averaged to provide a geographically-averaged value. Additionally, the number of sites reporting data for any particular month varied from year to year, such as can be seen by comparing the month of March, 1896 to other months of that year in Table II. Because there is no built-in spreadsheet function to perform this task, these simplified sources were exported as comma separated lists for further manipulation.

Table II. Excerpt from partially processed NOAA data for Pilgrim site[1]

| ELEM | YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL |
|---|---|---|---|---|---|---|---|---|
| MNTM | 1896 | 254 | 299 | 324 | 490 | 622 | 664 | 718 |
| MNTM | 1896 | -99999 | -99999 | -99999 | -99999 | -99999 | -99999 | -99999 |
| MNTM | 1896 | 222 | 281 | -99999 | 488 | 599 | 648 | 721 |
| MNTM | 1896 | 211 | 258 | 301 | 483 | 622 | 669 | 732 |
| MNTM | 1896 | 255 | 288 | 309 | 458 | 578 | 633 | 696 |
| MNTM | 1896 | -99999 | -99999 | -99999 | 486 | 621 | 659 | 724 |
| MNTM | 1897 | 254 | 276 | 342 | 464 | 556 | 600 | 692 |
| MNTM | 1897 | 270 | 280 | 358 | 495 | 585 | 622 | 728 |

The newly generated lists were used as input for a program written for the purpose. This program provides as output a new list wherein each row represents the average of all reporting stations for the site location for a particular type of data for each year. This was accomplished by first reading the year of the row, then adding the values for each of the columns for each of the following rows that had a matching date, and then dividing the value in each column by the number of rows for which data was collected. It is not necessary for the program to discriminate among types of data because the sorting described above always results in contiguous rows containing differing data types to pertain to different years. A flowchart of the program organization is shown in Figure 2 and the program proper is given in Appendix C.

These newly condensed output files were then imported to QtiPlot, a statistical analysis program, and used to generate graphs and extrapolations for data analysis. These graphs can be found in Appendixes D through M. The graphs in the appendixes use lines to connect data points for clarity.

Along with the direct, geographically averaged data, many of these graphs include lines indicating temporal averages. In most cases, “year to date” averages were generated by setting a value for each month as the mean value of that month

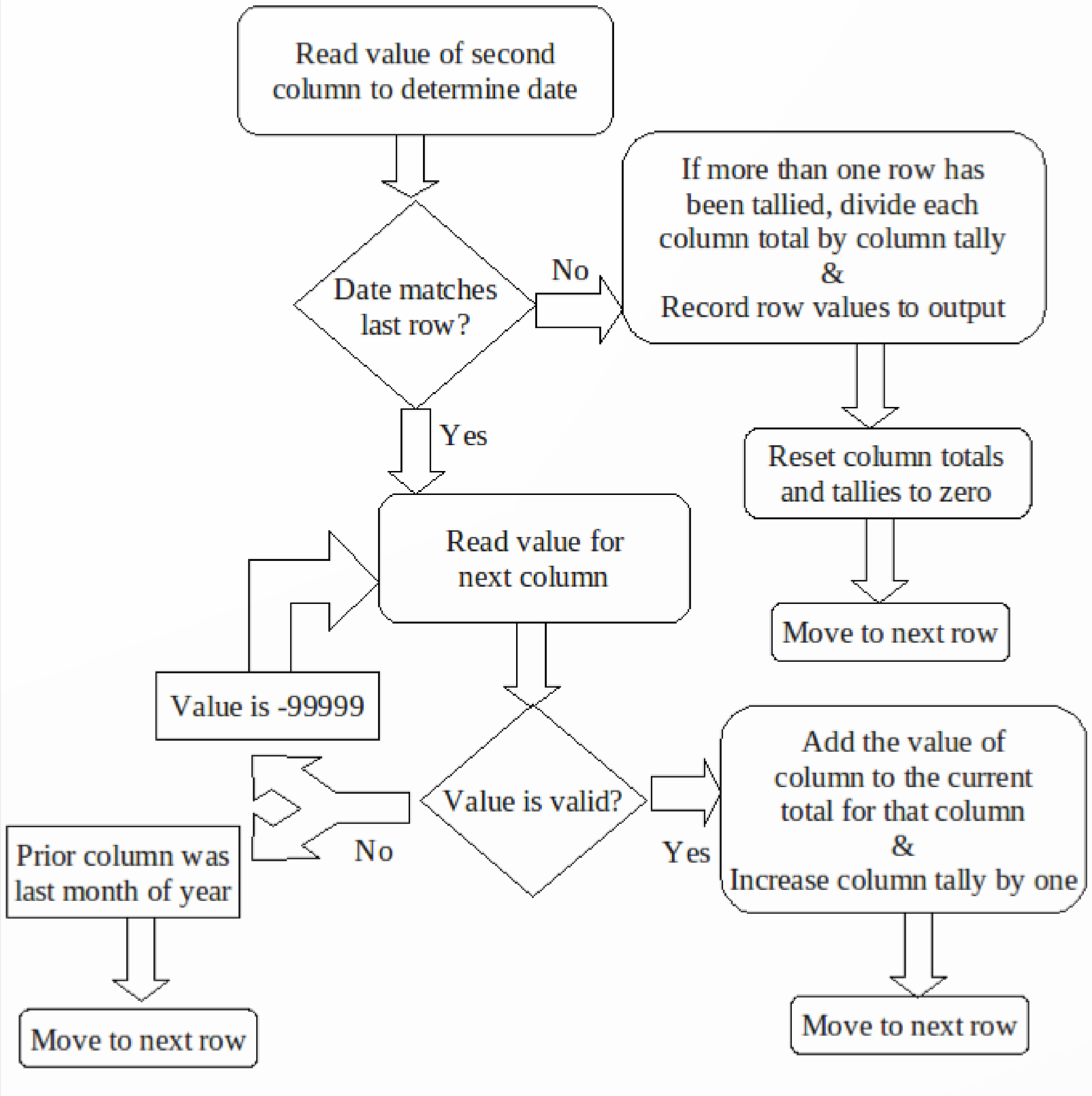

Fig. 2. Climate data processing program flowchart

and the previous 11. Because data used to generate these lines contains one value for each month of the year, they reduce the effect of seasonal changes and more clearly demonstrate long-term and cyclic trends like those of el niño.

Additionally, many of these graphs include linear regressions. Linear regression type and statistics are given in the appendixes immediately preceding the relevant graphs. These linear regressions were used to make the predictions of changes in climate. An example showing the monthly mean temperature data for the ANO site is shown in Figure 3.

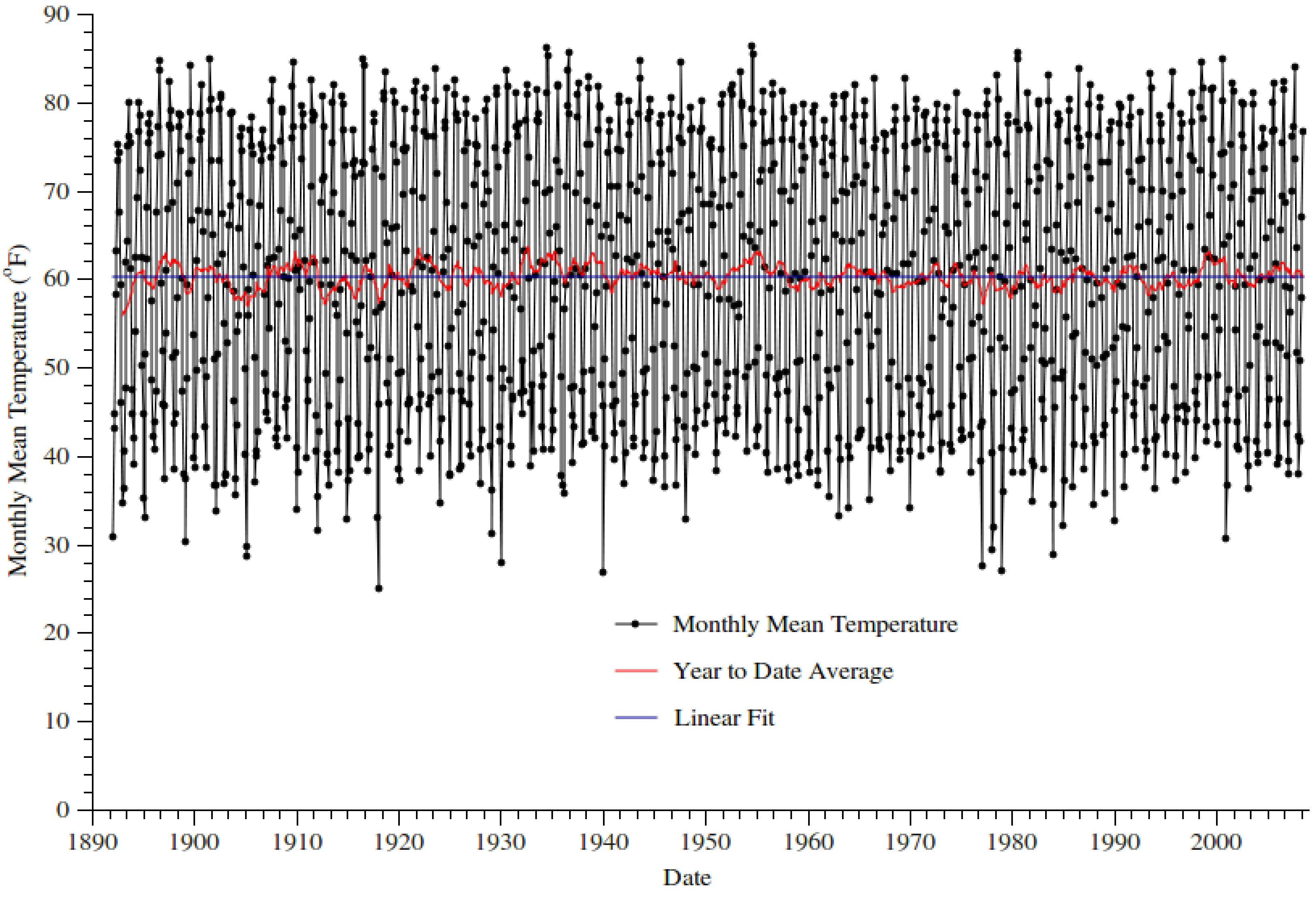

Fig. 3. ANO Monthly Mean Temperature

# CHAPTER IV

# PLANT MODEL

## A. Description of Plant Model

The thermodynamic balance-of-plant computer modeling for this thesis was performed with the industrial analysis code Performance Evaluation of Power Systems Efficiencies (PEPSE)[1]. This code is developed and maintained by Scientech, a subsidiary of the Curtiss Wright Flow Control Company. A copy of the program was made available for this research and was run on a variety of windows-based computers for the simulation cases.

PEPSE calculates conservation of mass and conservation of energy for each component; if either of these are not conserved, the program run fails and reports a calculation error. The nature calculation for each component varies depending on manufacturer specifications, but ultimately the program uses a control mass approach for each component. The component calculations most relevant to this study are described in section 1. PEPSE calculates a steady-state solution to the thermodynamic balance of a plant system. Steady-state means that the final solution represents a model of the plant for which time is not a consideration.

The thermodynamic computer modeling performed for this thesis examines a PEPSE model based on the Arkansas Nuclear One power plant (ANO). This site operates two reactors, both pressurized water reactors (PWRs), that were built within a few years of each other (1974 and 1978) but which use different cooling systems. Unit One uses a once-through system, rejecting waste heat into abut-

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[1] A demo of this program can be obtained from `http://famos.scientech.us/PEPSE.html`.

ting Lake Dardanelle and Unit Two utilizes a cooling tower. Because these two cooling mechanisms provide different interfaces to the local environment, it was expected that any significance between the two systems would appear in the results of calculations.

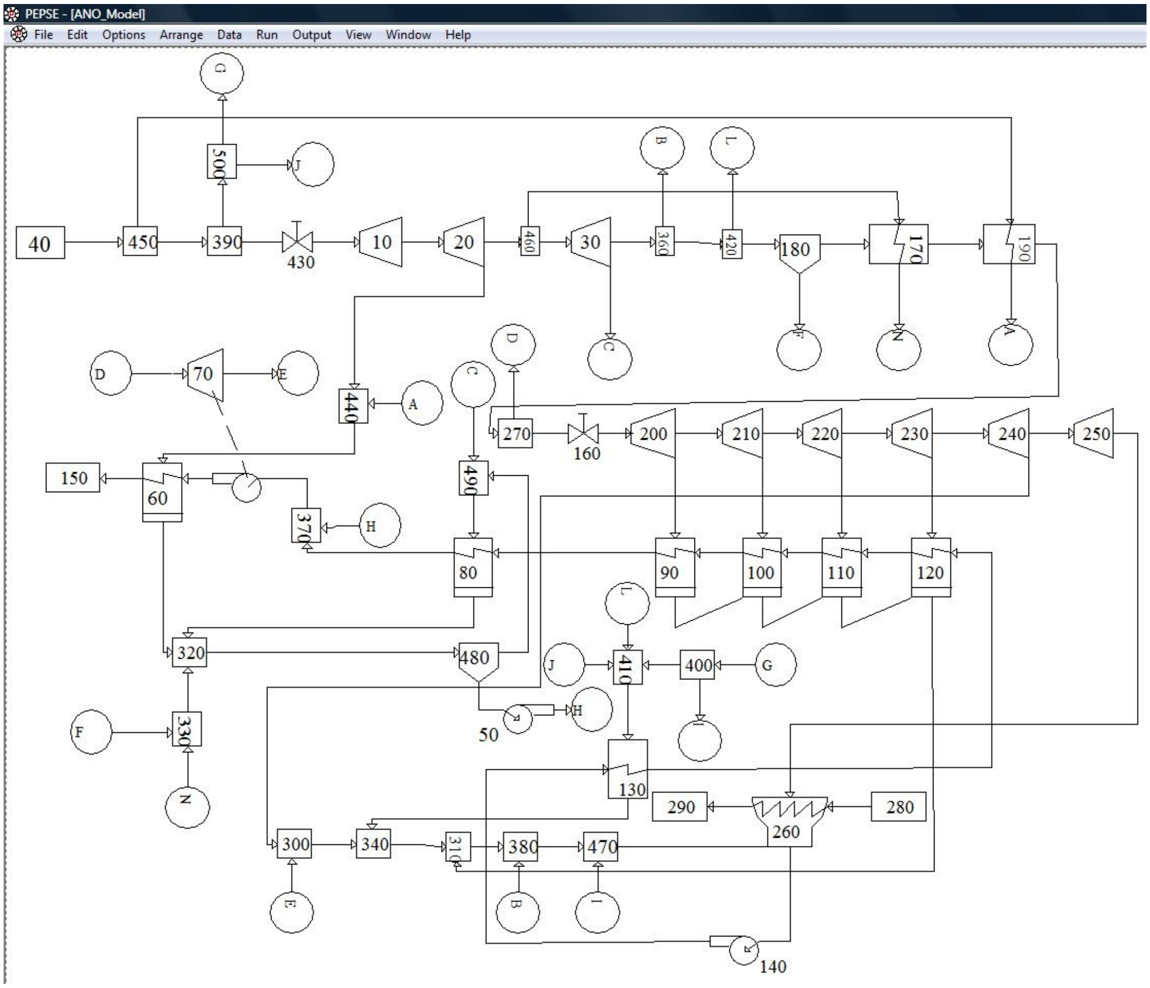

Fig. 4. PEPSE model of Arkansas Nuclear One

The models used for the units were provided by Entergy Corporation [54] and are used in regular plant analysis. These models do not detail all of the plant minutia, but they do contain all of the major components of the plant systems. The system without a cooling tower is represented by PEPSE as shown in Figure 4.

These components are numbered for machine-readable identification. Though the numbering is arbitrary and can be overridden manually, it is used throughout the input and output files associated with a run of the program. The conceptual design of the plant system is easier to recognize if a series of components are condensed into a single graphic as depicted in Figure 5.

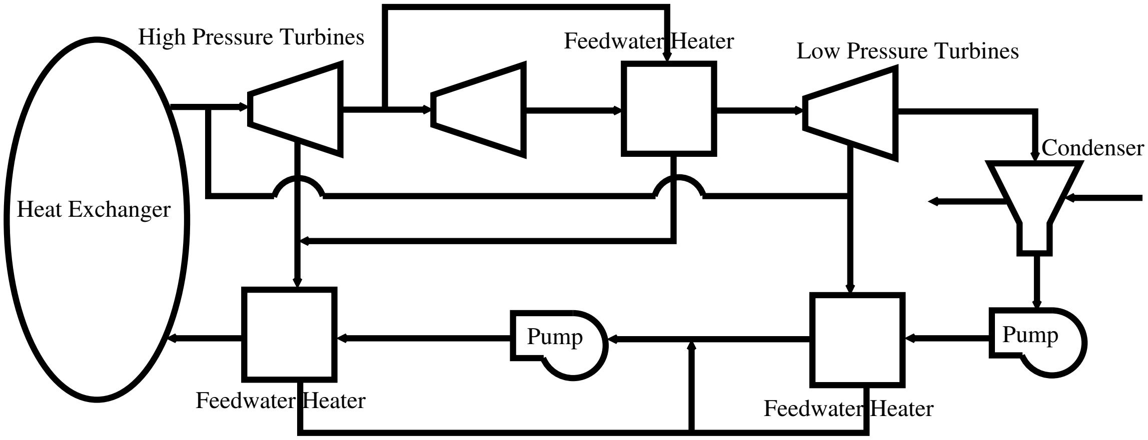

Fig. 5. Simplified model of Arkansas Nuclear One

Models are created by adding the necessary component objects and then connecting these components with pathways representing coolant streams. The lines connecting components represent piping that transfers coolant from one component to the next. For the purposes of the present work, these streams are left as "passive" streams that merely serve to connect the outlet conditions of one component to the inlet conditions of another. Initially, components are added as generic plant items such as turbines and condensers. These components are then detailed by specifying normal operating conditions to be used as boundaries to allow the program to converge on a solution.

As can be seen in Figures 4 and 5, the secondary coolant fluid passes through the shell-side of the condenser, through a series of feedwater heaters and into the primary coolant heat exchangers; this flow is driven by several pumps. Upon leaving the heat exchangers the coolant path diverges with the majority of coolant flowing through a series of turbines and some being diverted to the shell sides of the main series feedwater heaters. Additionally, two feedwater heaters are located between the high and low pressure turbines. This arrangement increases the amount of energy extracted by the low pressure turbines and thus reduces irreversibilities in the system.

## B. PEPSE Computations

The program models the entire primary cooling system as a single unit of heat exchangers. This is because this system is essentially thermodynamically decoupled from the secondary cooling fluid. The energy transferred into the primary cooling fluid from the reactor is a design feature of the system and, while the temperature of the coolant entering the reactor is variable, it effects the reactor operation and so cannot be used as a secondary coolant fluid control mechanism. Therefore, the entire primary coolant fluid can be effectively modeled by a constant temperature rise across the secondary coolant fluid inlet and outlet. The temperature rise for the ANO plant model was provided by engineers from that plant and was not modified in the calculations for this investigation.

Because the primary coolant fluid is thus simplified in these calculations, the only types of components of concern for the current investigation are feedwater heaters (and condensers), cooling towers, turbines, and pumps. The input for these components includes values for such figures as the shell-side pressure and coolant mass flux. Practically speaking, these values are not completely variable, rather, they are a function of the component design and system arrangement. Different plant systems have differing ability to change these parameters. Because the goal of this investigation is to produce results that are widely applicable, model calculations in this work vary such parameters well beyond what may be practical in a realistic situation in order to examine the results that such extremes would produce. How these parameters would be varied in practice (or how feasible such variations would be) will depend on the specifics of the plant in question.

When provided with a model and appropriate inlet and outlet conditions, PEPSE proceeds initially by determining the order in which component equations will be calculated. Though this order does not change, iterations are made over internal loops as necessary to converge on a solution. Convergence criteria can be specified by the user though the default value is 0.293 kW for energy calculations and $2.7777 \times 10^{-4}$ pounds per second for mass calculations. Steady-state solutions are determined for the system in iterative fashion until the difference between two successive calculations is less than the tolerance values stated for the system as a whole and also for each feedwater heater individually [55].

The program provides as output the converged solution that applies the inlet conditions while simultaneously satisfying the thermodynamic balance equations established for each of the components and streams. The system also requires the specification of boundary conditions. If either (not both) the condenser pressure or the inlet coolant flow rate are set as boundaries, the one of these two conditions not set as a boundary will be optimized for best performance. Because it is assumed that plants will run at conditions that are as close to optimal as possible, one of these two parameters was always allowed to vary during this investigation. Thus, it is important to remember that results are presented for optimal plant configuration. PEPSE output contains all of the thermodynamic results for each individual component. The component balance equations have been developed according to component manufacturer specifications and American Society of Mechanical Engineers (ASME) standards.

### 1. Condenser and Feedwater Heater Calculations

Condensers and feedwater heaters are heat exchange components used in power plant cooling systems. Both types of device promote the exchange of heat between two fluid streams with different inlet temperatures. While there are condensers, such as deaerating condensers, in which the flows are allowed to mix, generally the two streams are kept physically separated by tubing and other structural materials. Because of the similar nature of energy exchange, both condensers and feedwater heaters are modeled by PEPSE with the same thermodynamic equations.

Physically, condensers are designed to condense gases to their liquid state. Condensers used in nuclear power plants are typically shell-and-tube heat exchangers. These systems consist of an array of coolant tubing surrounded by a shell through which the steam is passed. The shell-side typically contains baffling that both supports the tubing and improves the exchange of heat by increasing the amount of time the shell-side fluid spends in the system. The shell-side is usually kept at a partial vacuum in order to lower the saturation temperature and thereby increase the heat removed through the process of condensation.

Feedwater heaters are often of a similar shell and tube design. While condensers are, by definition, designed to condense a vapor into a liquid, feedwater heaters do not necessarily perform this function. While power plants typically only use one or two condensers, they often employ multiple feedwater heaters in series along the coolant flow path from the condenser to the reactor. Such arrangements occassionally direct the drain outlet of one component to the drain cooler inlet of the next lower temperature component in what is known as “backward cascading.” Connections such as these improve thermal efficiency by reducing irreversibilities in the system. A thermodynamic schematic of the general feedwater heater/condenser

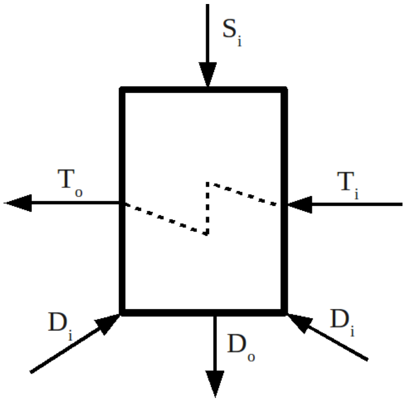

Fig. 6. Feedwater heater/condenser conceptual model

class object is shown in Figure 6 where the following nomenclature is used:

$S_i$ = Steam inlet
$T_i$ = Tube-side inlet
$T_o$ = Tube-side outlet
$D_i$ = Drain cooler inlet
$D_o$ = Drain outlet

The calculations for this system are based on a fundamental application of the laws of conservation of mass and energy. Because system calculations start with the environmental coolant source, the condenser is the first component analyzed for most systems. In this case, all of the characteristics of the tube-side inlet are known. Conservation of energy for the tube-side, neglecting potential and kinetic energy losses, gives the amount of heat transferred to the tube-side as

$$Q_T = w_{Ti}(h_{To} - h_{Ti}) \tag{4.1}$$

where

$Q_T$ = heat transferred to the tube-side fluid
$w_{Ti}$ = mass flow rate of the tube-side inlet
$h_{Ti}$ = enthalpy of the tube-side inlet
$h_{To}$ = enthalpy of the tube-side outlet.

This conservation equation can similarly be written for the shell-side if appropriate modifications are made to allow for backward cascading drain inlet. In this case the equation is

$$Q_S = w_{Si}(h_{Si} - h_{Do}) + w_{Di}(h_{Di} - h_{Do}) \tag{4.2}$$

where the letters refer to the same quantities as above and the subscripts are

S = steam-side
D = drain-side
i = inlet
o = outlet.

Neglecting losses, the heat transferred from the shell-side is assumed to equal the heat transferred to the tube-side and thus

$$w_{Ti}(h_{To} - h_{Ti}) = w_{Si}(h_{Si} - h_{Do}) + w_{Di}(h_{Di} - h_{Do}) \tag{4.3}$$

where all of the inlet values are known from the stated source conditions or from calculations made in the previous system iteration. There are still, however, two unknowns: the enthalpies of the drain-side and tube-side outlets. In order to calculate these values for condensers, PEPSE assumes that the fluid exiting the drain is liquid at saturation temperature. Because the shell-side pressure is required input, the program determines the enthalpy of the drain-side outlet by calculating the saturation temperature at the provided pressure.

Feedwater heaters assume that all fluids are liquid throughout and so cannot use this method. Instead, they use as input either the difference in temperature between the steam-side inlet and tube-side outlet, or that between the tube-side inlet and the drain-side outlet. These quantities are called the “terminal temperature difference” and the “approach temperature difference” respectively and can be represented mathematically as

$$\mathrm{TTD} = \mathrm{T}_{\mathrm{Si,sat}} - \mathrm{T}_{\mathrm{To}} \tag{4.4}$$

where

TTD = terminal temperature difference
$\mathrm{T}_{\mathrm{Si,sat}}$ = steam-side inlet (saturated fluid) temperature
$\mathrm{T}_{\mathrm{To}}$ = tube-side outlet temperature

and

$$\mathrm{DCA} = \mathrm{T}_{\mathrm{Do}} - \mathrm{T}_{\mathrm{Ti}} \tag{4.5}$$

where

DCA = approach temperature difference
$\mathrm{T}_{\mathrm{Ti}}$ = tube-side inlet temperature
$\mathrm{T}_{\mathrm{Do}}$ = drain-side outlet temperature.

### 2. Cooling Tower Calculations

For some plants, the cooling system returns water from the tube-side outlet of the main condenser directly back to the cooling water source. Because of the temperature limits imposed on plants by environmental regulations, however, the majority of plants include an additional cooling system. Such systems range from recirculation ponds to cooling towers. Though all of these systems interact with the local environment, and are thus relevant to the question at hand, the desire to produce results applicable to a wide variety of plants precludes an in-depth analysis of the many alternatives. Cooling towers, however, are widely used and well understood in thermodynamic terms.

The water flow in cooling towers is slightly more complex than that in feedwater heaters and condensers. The cooling tower is not simply a repository for cooling water leaving the system, rather, the cooling water flow is connected in parallel to

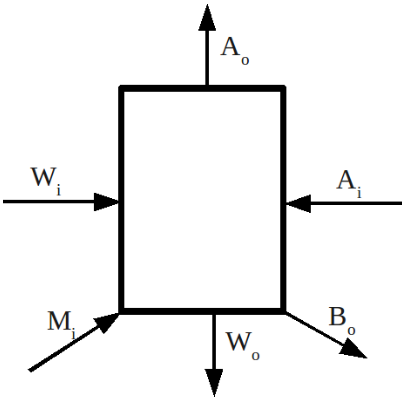

Fig. 7. Cooling tower conceptual model

the condenser through the cooling tower. Water flows through the cooling tower, entering from the source as makeup flow and leaving as blowdown. Water in the tower, known as the catchment, passes from the cooling tower to the condenser tube-side and returns back to the tower; this stream is labeled "circulating water." A significant amount of water is evaporated by the incoming air and leaves with the outgoing air as a mixture of air and steam.

The cooling tower calculations performed by PEPSE are based on the published standards of ASME [56], those of the Cooling Tower Institute (CTI) [57], and an academic work on the subject [58]. A schematic of the logical system is shown in Figure 7 where the following nomenclature is used:

$A_o$ = air outlet
$W_i$ = circulating water inlet
$A_i$ = air inlet
$M_i$ = makeup water inlet
$W_o$ = circulating water outlet
$B_o$ = blowdown water outlet.

As with feedwater heaters and condensers, cooling tower calculations are based on a conservation of mass and energy balance. For example, conservation of mass requires that the mass flow rate of the air outlet equals the sum of the mass flow rates of the air inlet and the mass rate of evaporation of cooling water. Thus,

$$w_{Ao} = w_{Ai} + w_e \tag{4.6}$$

where

$w_{Ao}$ = mass flow rate of air outlet
$w_{Ai}$ = mass flow rate of air inlet
$w_e$ = mass rate of evaporation.

Similarly, the mass flow rate of evaporated water must equal the difference between the water flowing into the system and the blowdown

$$w_e = w_{Mi} - w_{Bo}. \tag{4.7}$$

These equations simply result from the required conservation of mass between the inlet and outlet flows. They are used as boundary conditions in the iterative solution of the energy balance equation

$$(wh)_{Mi} + (wh)_{Ai} = (wh)_c + (wh)_{Ao} \tag{4.8}$$

which states that the sum of the energy of the water and air entering the system must equal the sum of the energy change in the catchment (indicated by subscript c) and the energy of the air leaving the system. In a steady-state system, of course, the change in energy entering the catchment equals that of the blowdown

$$(wh)_c = (wh)_{Bo} \tag{4.9}$$

Because the inlet conditions are set before calculation of the cooling tower begins, the values for the exit conditions are adjusted to satisfy this balance and are then used to recalculate the amount of evaporation in the original mass balance equations. This loop is repeated until convergence is obtained.

Additionally, the enthalpy of circulating water exiting the system ($h_{UW}$) is found from an energy balance with the catchment basin and the makeup water calculated as

$$h_{UW} = \frac{(wh)_c + (wh)_{Mi} - (wh)_{Bo}}{w_{Wo}} \tag{4.10}$$

where the enthalpy of the catchment water is determined from the tower approach A given by

$$A = T_c - T_{IA}^{wb} \tag{4.11}$$

in which $T_{IA}^{wb}$ is the wetbulb inlet air temperature calculated from the composition and thermodynamic state of the inlet air.

## C. Methodology

The plant analysis software used, PEPSE, is a steady-state modeling program. This means that for the program to provide thermodynamic balance-of-plant conditions, it is necessary to fully specify one plant condition and allow the program to iterate to a convergent solution. It is not possible, within the program, to examine continuous changes in plant or environmental conditions resulting from the variance of a particular parameter.

In order to observe such a change, it is necessary to create individual input for each of a series of values of the parameters concerned. While it is necessary to make at least one input file using the PEPSE modeling capabilities, it is then possible to use this initial input to create further input files. This input must then be individually analyzed by PEPSE in order to generate a point solution. The output

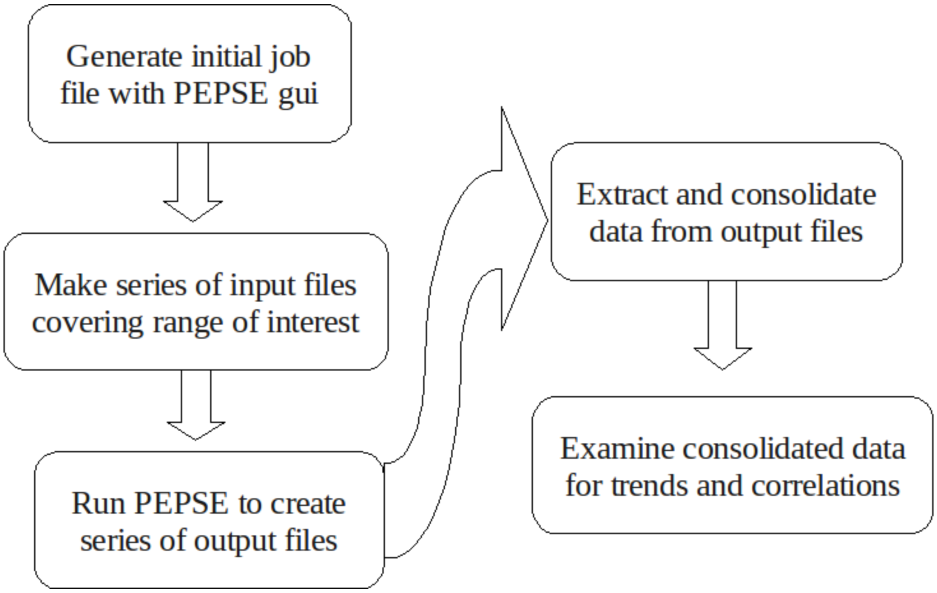

Fig. 8. Input generation process flowchart

is provided in the form of ASCII text files containing the calculated parameters of the system components. Examining plant solutions for a range of conditions in this manner necessitates extracting the relevant data from a series of output files. Figure 8 shows a flow chart illustrative of this process.

In order to calculate a thermodynamic balance, PEPSE requires two files, a model file and a job file. When run through the graphical user interface (GUI), PEPSE creates these files at the time of running. Results of such a run are then displayed on the interface. It is also possible, however, to run PEPSE in batch mode via the operating system command line. When this method is utilized, both the job file and model file must be specified by the user. Unlike the job files, the model file is written in machine code and is neither human readable nor human modifiable.

It was recognized early in this investigation that if the model file contained information specific to the values of the component parameters, a separate model would have to be created for each input. In order to determine if this was the case, several runs of PEPSE were made using differing models (those containing different component parameters) but utilizing the same job file. The output of these tests was identical. As long as the system geometry was consistent with that of the job file, the same model file could be used for any number of jobs and produce the same output. This finding assures that only one model file needed to be created for each system geometry.

As can be seen in the example given in Appendix N, these job files are organized by component in solution order. The parameters specified for each component are arranged by input order according to the user interface menus. By comparing the program user interface to the job file, it is possible to identify the value in the job file that correlates to a particular parameter in the model. Because these job files are created and used by PEPSE in a consistent manner, it is possible to modify the input by changing these values as desired. As an extension of this principle, it is possible to create multiple job files representing a range of input conditions by making copies of job files with only the values of interest modified as desired.

For this thesis, job files representing ranges of input data were created using recursive scripts written for the purpose. These scripts use a job file generated directly by PEPSE as a starting reference. The script then modifies this initial file by changing the relevant parameters of interest by a specified increment. The modified file is then saved under a new name and becomes the input for the next iteration of the script. While the details of the script vary depending on the initiating and desired input, a flowchart of this process is shown below in Figure 9 and an example of such a script is provided in Appendix O.

After PEPSE is run using the appropriate job file, a results file is created automatically. This file is also written in human readable ASCII text; it is arranged

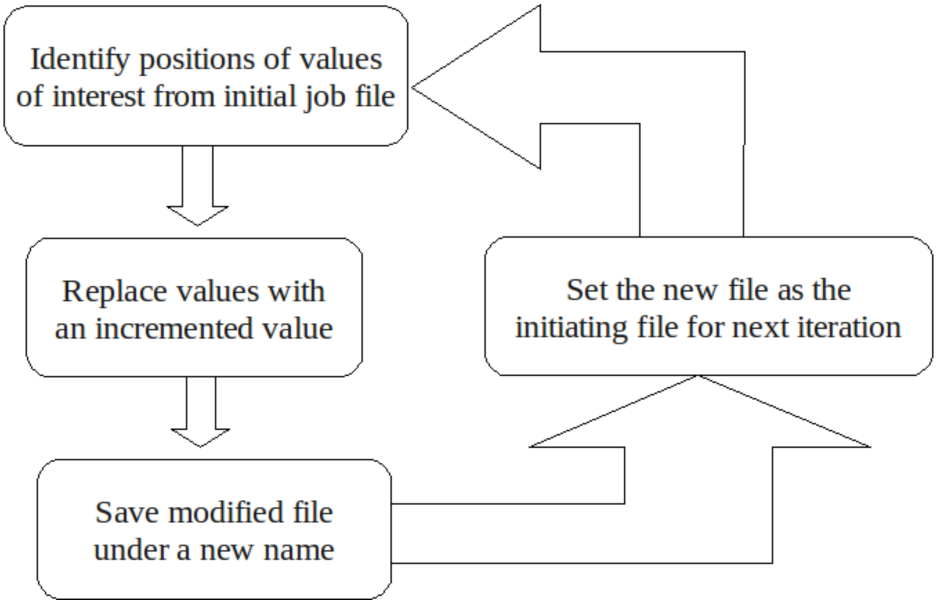

Fig. 9. Jobfile creation flowchart

essentially like the job file except that several new thermodynamic parameters such as component inlet and outlet temperature and enthalpy are provided. As with the job files, results files are created in a consistent manner such that it is possible to identify the position of a value of interest.

The current method of investigation necessitated the creation of tens of thousands of job files and thus the same magnitude of results files. In order to examine the changes in the thermodynamic balance over the range of input parameters, it was necessary to extract a particular result value over the range of results. This data was extracted with a script that iterated over the ranges involved to access each file and record the appropriate values in a comprehensive results file. A flowchart of the data extraction script is shown in Figure 10.

Under normal operating conditions, studies [29, 32, 48, 49] suggest that the components most significant to thermodynamic changes related to the tertiary coolant fluid are those in the condenser and correspondingly in the cooling tower.

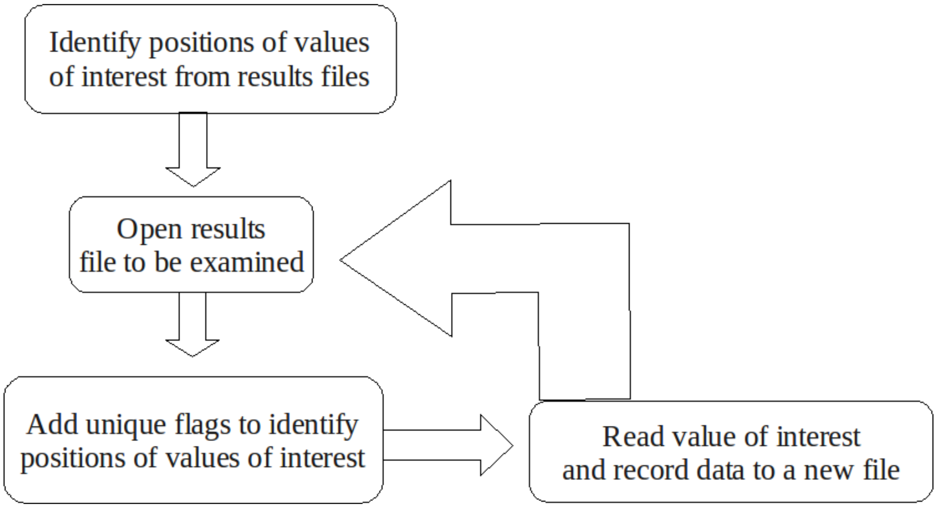

Fig. 10. Generated results retrieval flowchart

This makes sense because these components are the only ones with direct contact with this loop. Accordingly, input files were generated for a range of changes in these components and a range of inlet coolant temperatures.

For the model without a cooling tower, the only parameters relevant to the current investigation are the inlet coolant temperature, the condenser pressure, and the condenser flow rate. Normal operating conditions for these components were provided by Entergy[54] and are summarized in Table III[2].

Table III. Normal condition variable ranges

| Parameter | Normal Minimum | Normal Maximum |
|---|---:|---:|
| Inlet Water Temperature | 32°F | 65°F |
| Inlet Air Temperature | −20°F | 70°F |
| Condenser Temperature Change | 15°F | 20°F |
| Condenser Flow Rate | $190,000,000\frac{lb}{hr}$ | $350,000,000\frac{lb}{hr}$ |

In order to examine the widest possible range of circumstances these parame-

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[2] Weather data collected from NOAA [59], condenser flow rate based on report by the Environmental Protection Agency [60]

Table IV. Input variable ranges

| Parameter | Minimum Input | Maximum Input |
|---|---|---|
| Inlet Water Temperature | 32°F | 100°F |
| Shell Pressure | 0.5 inHg | 30 inHg |
| Flow Rate | $105,444,304\frac{lb}{hr}$ | $1,105,444,304\frac{lb}{hr}$ |
| Inlet Air Temperature | 32°F | 150°F |
| Air Humidity | 1% | 99% |

ters were varied well beyond normal operating ranges. The inlet temperature was examined between 32 and 100°F, the condenser pressure between 0.5 and 30 inHg, and the condenser flow rate between 105,444,304 and 1,105,444,304 pounds per hour. These ranges are summarized in Table IV.

In the case of the water temperature, freezing is the minimum temperature allowed by PEPSE because cases (such as with saltwater) where below freezing water might be used are the exception rather than the rule. The maximum environmental water temperature of 100°F is justifiable because if temperatures excede this value, cooling power plants would likely be a relatively minor issue compared to the likely environmental devastation [52]. Condenser pressures range between near vacuum and standard atmospheric pressure. Pressures above normal operating pressure yielded erroneous results. While attempts were made to resolve this phenomenon, it was determined that an examination of normal operating pressures would be sufficient because of the approach of using optimal plant operating conditions.

The low extreme of the flow rate values was determined experimentally; below this value PEPSE returns a low flow error. The high end corresponds to roughly four times the nominal flow rate, which is not necessarily a technical limit but rather an estimate of a value beyond which it would be unreasonable to expect real world implementation.

For the model with a cooling tower, there are more parameters that could impact the thermodynamic balance of plant. The tower itself requires the specification of the tower approach, the difference between the catchment basin temperature and the ambient wetbulb temperature. Additionally, the characteristics of the environmental air can be specified so that changes in humidity and air temperature are also important. For the calculations of this model, the water temperature was varied across the same range as described above, the air humidity was varied from 1 to 99%, and the air temperature from 32 to 150°F. While actual air temperature certainly will range outside this value, PEPSE returns an error if a value below freezing is used. These input ranges are summarized in Table IV.

As stated in Section B, when these conditions are varied, the condenser pressure is allowed to vary according to PEPSE's optimization algorithm. If either (not both) the condenser pressure or the inlet coolant flow rate are set as boundaries, the one of these two conditions not set as a boundary will be optimized for best performance. Because it is assumed that plants will run at conditions that are as close to optimal as possible, one of these two parameters was always allowed to vary during this investigation. Thus, it is important to remember that results are presented for optimal plant configuration. For the ranges provided in Table IV, the condenser pressure was allowed to vary while the condenser inlet flow rate was set at a normal operating condition value of $2.11 \times 10^8 \frac{lb}{hr}$. During examinations of the effect of changes in condenser pressure, this parameter was set as a boundary and the inlet flow rate was allowed to vary.

# CHAPTER V

# FINDINGS

## A. Climatic Impact on Analyzed Plant Sites

Throughout this section, climate data is presented based on the analysis methods described earlier. All figures represent the results of this new work and references to figures from other sources are cited where appropriate. Detailed reports of this information are given in Appendixes D-N. This section does not cover each data type individually, but rather progresses logically through the various risk factors identified for analysis. The risks covered are:

- Cooling degree days
- Heating degree days
- Departure from normal monthly precipitation
- Hurricanes
- Ice storms
- River water levels
- Monthly mean precipitation
- Shifting habitat
- Sea level
- Saltwater intrusion
- Abrupt temperature change

- Thunderstorms
- Tornadoes
- Wetlands loss

As described above, cooling degree days generally indicate warmth across seasonal weather. A relatively recently developed indicator, no meaningful studies observing cooling degree days were found that offered any predictive power. The NOAA data collected by the present investigation has records of degree days cooling and heating dating from 1980 to the present. This allows predictions to be made on the same basis used by the IPCC; that is a comparison of the predicted value to the average of the period between 1980 and 1999. Averages for the period from 1980-1999 presented in this section were generated for the present research from the data collected from NOAA.

NOAA reports cooling degree days as a cumulative total for a station on a monthly basis. This total is calculated by summing one hour for each of the hourly recordings made by the station over the course of the month. Information on the extrapolations made based on this data is provided in the appropriate appendixes.

Linear extrapolations of the available cooling degree day data for each examined site are listed in Table V, a graph illustrative of the terminology is shown in Figure 11.

Table V. Cooling degree days: Summary of Appendix F

| Plant | 1980-1999 Annual Average | Predicted Annual Average 2050 | Predicted Change |
|---|---|---|---|
| ANO | 148.5 | 155.9 | 7.4 |
| Cooper | 99.1 | 93.4 | -5.6 |
| FitzPatrick | 37.4 | 50.7 | 13.3 |
| Grand Gulf | 194.3 | 209.2 | 14.9 |
| Indian Point | 66.6 | 78.0 | 11.5 |
| Palisades | 62.0 | 62.0 | 0.1 |
| Pilgrim | 49.9 | 64.6 | 14.7 |
| River Bend | 212.0 | 230.0 | 18.1 |
| Vermont Yankee | 35.9 | 44.3 | 8.3 |
| Waterford | 234.3 | 280.3 | 46.0 |

Because of the relatively short period upon which these predictions are based, it is difficult to make strong assertions based on them. It is worthwhile noting that, though these values do not include the predictions of any anthropogenic warming models, all of the sites except one indicate some general warming trend. These trends generally indicate earlier onsets of spring as well as hotter and longer summers. The obvious economic implication of these changes is an increased demand for electricity to maintain indoor temperatures, but there might also be some ecological effects such as northward shifts in animal or plant habitats; such changes are discussed individually below.

For southerly sites, because the average temperatures are generally warmer, even the cool months contribute to annual average degree days cooling. Though the data is not conclusive, for the Waterford site there appears to be a legitimate increase in yearly average temperature; see the figure on page 156 in Appendix F. Though the data is given as cooling degree days, a direct inference to average temperature can be made based on consistent increase in cooling degree days throughout the twelve months of the year.

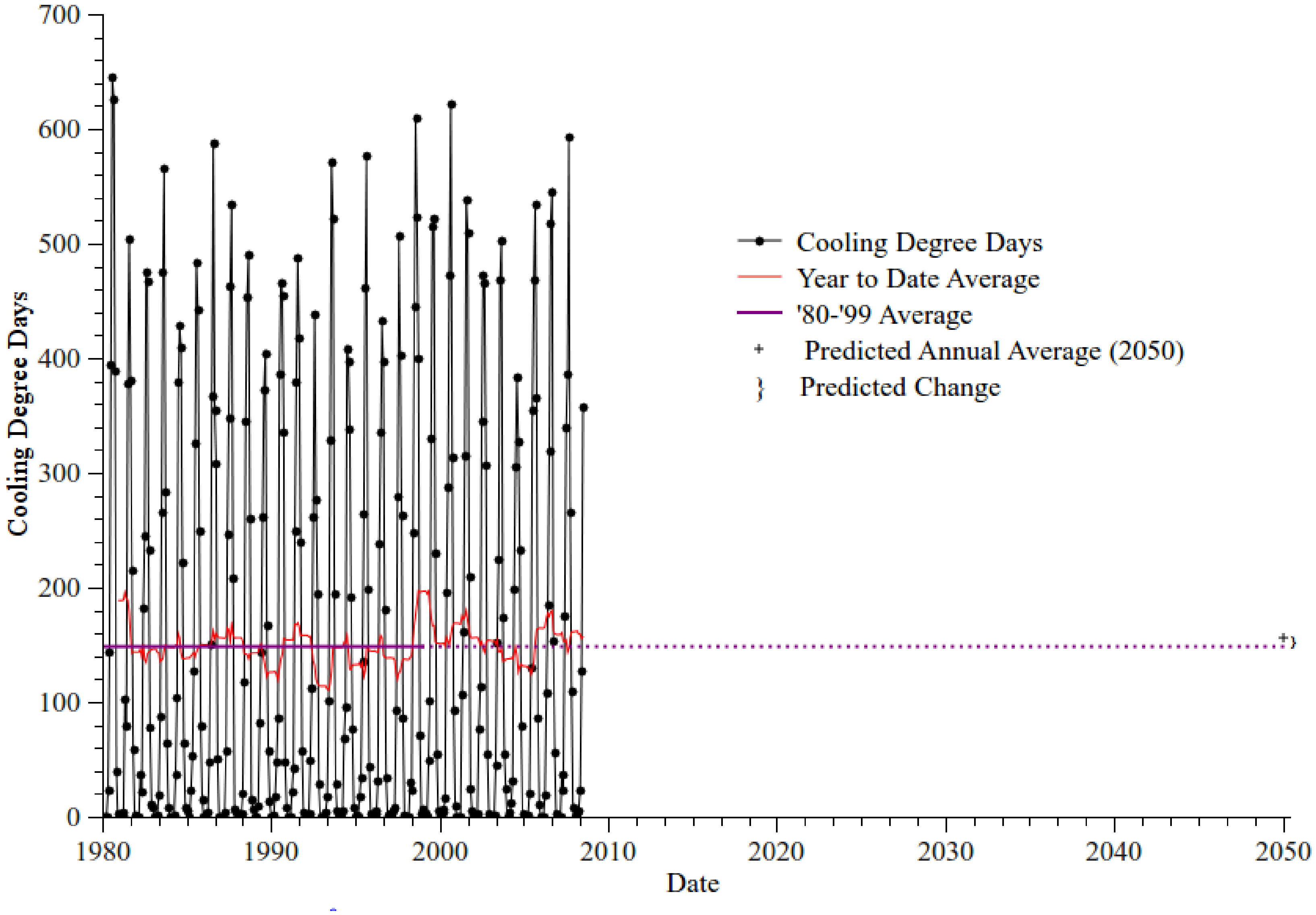

Fig. 11. ANO Cooling Degree Days

Table VI. Heating degree days: Summary of Appendix G

| Plant | 1980-1999 Annual Average | Predicted Annual Average 2050 | Predicted Change | Total Degree Days Change |
|---|---|---|---|---|
| ANO | 288.6 | 287.0 | -1.7 | 5.7 |
| Cooper | 486.0 | 487.7 | 1.7 | -3.9 |
| FitzPatrick | 605.9 | 598.7 | -7.2 | 6.1 |
| Grand Gulf | 186.9 | 185.6 | -1.4 | 13.5 |
| Indian Point | 477.3 | 447.9 | -29.4 | -17.9 |
| Palisades | 532.4 | 518.5 | -13.9 | -13.8 |
| Pilgrim | 504.2 | 482.6 | -21.6 | -6.9 |
| River Bend | 147.2 | 143.1 | -4.1 | 14.0 |
| Vermont Yankee | 608.7 | 599.4 | -9.4 | -1.1 |
| Waterford | 115.8 | 98.0 | 17.7 | 28.3 |

Degree days heating information is given in Appendix G and summarized in Table VI. Total degree days are the sum of degree days heating and cooling. This total degree days change, when large and positive, indicates a significant increase in hot summer temperatures and warmer spring and fall seasons. A large negative value predicts a much warmer winter temperatures and earlier springs. Changes small in magnitude imply a very mild warming or cooling trend for the site. As with the degree days cooling, the Cooper site data indicates a general cooling trend; the absolute quantity in this change, however, would likely be countered by the larger scale warming discussed above. The combined data for this site appears to predict slightly cooler summer temperatures with little change in winter temperatures.

There are many definitions of drought, and drivers of drought conditions are not well understood. In addition, because droughts effect different regions with variable frequency and intensity, it is difficult to predict drought likeliness for very specific locations. Some academic analysis has been done on the possible influence of climate change on droughts for large geographic areas of North America [58, 61, 62].

Droughts pose a severe risk for seasonal disturbances to cooling water availability. This point was made very clearly by the massive drought in the southeastern United States in 2007-2008 during which one reactor at Brown's Ferry was shutdown and the other two operated at reduced power [22, 63]. The TVA produced a report in 2005 predicting that increasing temperatures would force the Brown's Ferry site to reduce output once every three to five years [63]. Though it is outside the scope of this paper, a similar analysis of the prospects of the effects of drought on those plants not located on lake or ocean shores could prove useful for planning future plant operations and financial management.

While droughts are a significant risk for any large consumers of water resources, they have particularly significant impacts in agricultural areas where the competition for water resources is fierce. Drought is of relatively little concern for those sites located on the Great Lakes, and of little concern to those sites located on the coasts except in relation to saltwater intrusion discussed below. For the Midwestern sites, drought is a much greater concern because it not only affects the quantity of water available for cooling, but has the potential to effect the nature of water available because changes such as the lowering of water levels in lakes has the coupled potential to increase the temperature of the body of water from which coolant is extracted. Such changes, though necessarily specific to each particular plant, could impact the flexibility of the balance of plant thermodynamics due to heat rejection both by increasing the incoming coolant temperature and decreasing the maximum allowable temperature of the coolant outlet.

Precipitation rates generally exhibit significant variability roughly associated with the El Niño and La Niña oceanic trends. These phenomena result in oscillations between greater and lesser amounts of precipitation on a roughly six year cycle; peak precipitation for the most recent period is likely to occur in 2010. Longer term

Table VII. Departure from mean monthly precipitation ($^1/_{10}$in): Summary of Appendix L

| Plant | 1980-1999 Annual Average | Predicted Annual Average 2050 | Predicted Change |
|---|---|---|---|
| ANO | 21 | 31 | 9 |
| Cooper | 12 | -21 | -33 |
| FitzPatrick | 12 | 35 | 23 |
| Grand Gulf | 41 | 48 | 7 |
| Indian Point | 16 | 31 | 16 |
| Palisades | 21 | 22 | 1 |
| Pilgrim | 17 | 32 | 15 |
| River Bend | 42 | 50 | 8 |
| Vermont Yankee | 6 | 59 | 52 |
| Waterford | 32 | 48 | 16 |

variability can be examined by observing longer term averages; predictions made on the same bases as above for changes in the departure from normal monthly precipitation are given below in Table VII. It should be stressed that because these are values of departure from normal precipitation, positive values indicate increased periodic precipitation relative to stable levels. Large positive values indicate increased likelihood of flooding and abnormally wet seasonal weather while large negative values indicate increased likelihood of droughts and abnormally dry seasonal weather.

Like drought, floods have many sources and can be very difficult to predict. The likely sources of flood are different for the various locations studied. In the northeast, earlier and greater scale snow melt has the potential to cause spring flooding and reduce the availability of water later in the summer.

For both the Midwest and the Gulf Coast, it is storms that are likely to bring flooding, though unusually wet seasons can form the basis of flooding that is then triggered by a shorter period of thunderstorms. The small change in seasonal wetness, and the likely increase in seasonal dryness for Cooper Station, however, indicate that storm variation is the more significant indicator of future floods for these areas.

The degree days data presented earlier indicate that northern winters are likely to become less severe, resulting in less snow buildup and thus a reduced risk for spring time flooding caused by runoff. Earlier warming in spring, on the other hand, might more quickly melt the snow that does collect. In addition, the precipitation data indicates a likely increase in abnormally wet seasons in the northeastern region in particular.

No weather data specifically was examined for hurricane predictions, but several studies have linked climate change to increasing frequency and intensity of hurricanes [64, 65]. These studies generally conclude that hurricanes will increase in frequency and intensity as global temperatures rise. However, lack of long-term ocean temperature data "complicate[s] the detection of long-term trends" [66]. Furthermore, the 2001 report of the IPCC indicated that no discernible link could be made between climate change and hurricane occurrence. Because hurricanes are such a complex phenomenon, it is likely that any direct link between climate change and hurricanes will be debated for a long time.

Though only of significance in the Gulf Coast, hurricane Katrina demonstrated the power of a hurricane to alter the geographic, geologic, and political landscape of a significantly sized region. Hurricanes pose a significant direct threat to the Waterford site and have historically had an impact on other sites located on the southern Mississippi [9], as well as to the previously mentioned incident in Florida. Generally speaking, any site located in the American Southeast faces threats posed by hurricanes. In addition to direct damage, hurricanes have the potential to impact both the viability of future plant sites and the regional demand for electricity. Irrespective of the purported link between climate change and hurricanes, maintaining hurricane preparedness for those sites located near the Gulf and East Coasts will remain a priority throughout their operational lifetimes.

Like other severe weather events, ice storms effect the employee and consumer base of utilities plants, and while not a direct threat to the structural integrity of plants, ice storms could conceivably have a short-term impact on plant construction or renovation projects. In at least one instance [67], icing has restricted coolant flow sufficiently to stop plant operations. Ice storm predictions are made for this work based on the basis of changing temperature and precipitation patterns.

Though ice storms are a cold weather phenomenon, and thus not of significant concern to the more southerly located plants, they occur most frequently when temperatures are near the freezing point. As a consequence, those plant sites most likely to see increased frequency and intensity of ice storms are those expected to have increased seasonal wetness and more moderate winters; from the data cited above, this corresponds to the plants located in the northeast.

For plants located in riverine ecosystems, perhaps the greatest threat to plant operational security is reduced river water levels. The departure from normal monthly precipitation data indicates variations in seasonal wetness. Water levels indicate the relative abundance or scarcity of water resources and could directly effect the amount of cooling water available to a plant. While extreme events such as drought (mentioned above) could alter plant operations due to cooling water loss, the frequency of such events could depend on the stable water table levels and thus on long-term precipitation trends.

Long-term average precipitation rates indicate increased wetness throughout the year. Predictions are given in Table VIII. Increasing wetness in the case of ANO helps to allay concerns of drought for that plant. No statistically significant

Table VIII. Mean monthly precipitation (1/10 in): Summary of Appendix K

| Plant | 1980-1999 Annual Average | Predicted Annual Average 2050 | Predicted Change |
|---|---|---|---|
| ANO | 428.8 | 460.8 | 32.0 |
| Cooper | 287.1 | 289.3 | 2.2 |
| FitzPatrick | 332.6 | 374.7 | 42.2 |
| Grand Gulf | 498.3 | 509.2 | 10.9 |
| Indian Point | 401.8 | 427.1 | 25.3 |
| Palisades | 317.7 | 325.7 | 8.0 |
| Pilgrim | 391.5 | 407.3 | 15.8 |
| River Bend | 539.7 | 545.9 | 6.2 |
| Vermont Yankee | 343.4 | 369.5 | 26.1 |
| Waterford | 547.0 | 553.2 | 6.2 |

increase in precipitation is predicted for the Cooper Station site where coupled seasonal dryness might foreshadow spreading desertification in the American Midwest. Increasing wetness in the Northeast somewhat increases the likelihood of flooding events.

The generally small magnitude of the increases for most of the plants implies, though by no means guarantees, stable water supplies under ordinary circumstances for the foreseeable future. Rather than reduced supply, possibly the greatest restriction on stable supplies of water could result from increased demand by other local or upriver interests. This is especially the case for Cooper Station and other plants in heavily agricultural areas where increased temperatures and decreased seasonal rain will likely greatly increase the agricultural demand for water.

As the climate warms, traditional climate zones are likely to shift northward as will the plant and animal populations that are adapted to them. Plant and animal migrations can directly effect plant operations by altering the local environment [68, 61] but the most significant impact will be on the alteration of consumer demographics and thus on the long-term viability of future plants. Unfortunately, because of the relative novelty of climate change concerns, and the immensity of the task of predicting ecosystem shifts, there has been little reliable work done in the area. Marshall et al. [68] examined four different drivers/impacts of climate change: drought, fire, snow pack, and temperature change. They described the interconnected nature of these phenomena such as a correlation between fire frequency and the regularity of drought-like conditions, but judged that the current state of knowledge precluded making predictions about ecosystem shifts.

As was described previously, the most significant climatic change regarding long-term ability to sustain current or expanded population is the apparent increasing desertification of the upper Midwest. Because of the age of the plant, and the use of nuclear plants for base load power, it is unlikely that Cooper Station will have to draw down operations due to lack of demand within the plants projected operating lifespan. Future decisions about the necessity of base load capacity would, however, likely benefit from further analysis of predicted future population shifts.

Because plant cooling systems use high precision equipment whose operation is dependent on the flow characteristics of the water, cooling water must generally be purified before running through the system. While plant material and other debris can be effectively removed by filters, chemical contamination of cooling water is a much more complicated threat to the reactor system. Because of its corrosive nature, the intake of saltwater can be particularly undesirable. The negative effects of salt water in the tertiary cooling fluid can be accommodated by the use of specially designed, and thus more expensive, condensers. Though plants drawing sea water directly utilize such equipment, those plants located near river deltas do not necessarily and are thus at risk due to saltwater intrusion.

Unfortunately, the combination of lower water tables and increased sea levels heightens the risk of salt water intrusion into cooling water sources. In addition, studies [34, 52, 69] suggest that warmer temperatures will contribute to increased salinity of freshwater resources because of increased evaporation, decreased precipitation, and reduced outflow from lakes. While it is very likely that water resources will increase in salinity in the future, the concentrations under investigation in the cited studies suggests that they will remain below dangerous levels for the lives of the current generation of nuclear plants. For future plants to be sited near the coasts, scrutiny should be paid to the potential for saltwater intrusion as the potential for increased salinity is significant at river deltas, especially if those rivers suffer from reduced precipitation and increased water demand upstream.

In addition to the risk of saltwater intrusion, sea level rise is a unique risk of its own, posing a threat to physical plant structures, the viability of future plant sites, and consumer and worker lives. Though typically considered a very long-term effect, a dramatic rise in sea water could be possible in the event of a major ice sheet collapse. Barring this sort of extreme event, even moderate sea water rise, when combined with land subsidence, could effect existing plants. Fortunately, construction standards and the lack of historical subsidence problems to an extent necessary to impact plant operations indicates that sea level rise will not pose a threat to currently existing plants.

Most temperature changes are predicted to be relatively slow and prolonged, but because of the unprecedented changes taking place in the atmosphere, some [70] have warned of possible abrupt alterations in regional climate. While there are, by definition, essentially no indicators of abrupt climate change, abruptness on a climatic scale is still relatively slow. Because abrupt changes could result in either rapid cooling or heating, it is nearly impossible to take precautionary measures other than general risk assessment. Though the dangers posed by abrupt temperature change are significant, the scale of such an event would likely mean that remediation measures would be undertaken by the regional or federal government.

As discussed above, a change in the frequency or intensity of thunderstorms could impact the potential for flooding, but these storms do carry some unique dangers as well. While not as significant an impact as hurricanes, severe storms can cause direct damage to plant equipment as well as customers and employees.

As described above, if waterways experience increased levels generally, thunderstorms increase the likelihood of flooding. Though thunderstorm frequency and intensity could itself be a function of climate change, little correlation has been found and some studies [38] even suggest a reduction in recent history. While thunderstorms certainly pose a threat to nuclear power plant operations, they are also the trigger of greater dangers such as flooding and should be considered as such in the preparation for these risks.

Though often conceptually linked, thunderstorms and tornadoes are not clearly connected and an increase in storms does not necessarily correlate with a corresponding increase in tornadoes. That being said, according to the IPCC "[t]here is insufficient evidence to determine whether trends exist in ... phenomena such as tornadoes, hail, lightning and dust storms" [34]. Accordingly, it is reasonable to base predictions of tornado behavior on historical trends rather than broader climate change models.

Such historical trends suggest [34, 71, 72] that tornado occurrences will shift with weather patterns. Most models, therefor, indicate a northward trend in tornado frequency though no linkage has been conclusively shown between climate change and tornado intensity. Historical tornado frequencies have been analyzed for all of the examined plant locations except for those in the northeast where tornadoes are a relatively rare event. These analyses do not identify any trends except possibly a slight increase in frequency near the Grand Gulf plant in the past decade; see the figure on page 253 in Appendix N. Charts of annual tornado occurrences within the county of plant location and contiguous counties are given in Appendix N.

Like hurricanes and desertification, wetlands loss due to climate change could have an impact on the consumer and employee base. Like saltwater intrusion, wetlands loss is significantly effected by rising sea levels and reduced water tables. As with several other risk drivers, wetlands loss can indicate a change in viability of future planned operations.

Because of the stability, or even increase, in water availability to the American Southeast, future wetlands loss will likely be driven much more by human-induced pressures than by climate change. Human-induced wetlands loss has long been a concern of environmentalists and is in many cases being effectively addressed [73, 74, 75].

Among the 15 risks identified in the BCC study [27], that which will likely have the least impact on the operations of nuclear power plants would be a change in the frequency of wildfires. Though it is possible to make some predictions about such changes, wildfires, like wetlands loss, primarily effect nuclear power plants by impacting the lives of consumers and employees. That being said, the precipitation and temperature data given above, when considered with the suggested [68] link between wildfires and drought, indicates that plants in the Midwest would be the only ones likely to be threatened with increased fire frequency. Wildfires, of course, are a perennial concern for areas in the desert southwest such as Southern California.

Though future investigation of the impact of climate change on nuclear power plants should include more targeted examinations of each of these specific risks, several important conclusions can be drawn from the present work. These certainly include the following potential risks to plants in the United States: significant reductions in available cooling water for plants located in the Midwest, increased frequency and intensity of floods at sites located in the Northeast, and increased hurricane frequency and intensity affecting those plants in the Southeast.

Furthermore, in the analysis of potential sites for new plants, consideration should be taken of possible changes in the availability of cooling water as well as those factors typically examined in Probability Risk Assessments. This is especially significant for future plants with very long projected operational lives. While water usage rights have long been a topic of concern in the American Southwest, data suggests that the issue will become of increasing importance to the Midwest and Southeast.

For nuclear power plants and large consumers of water generally, due diligence should be paid to trends in early spring warming and subsequent changes to seasonal availability of water. Related to this is the risk of shifts in river water levels; additionally, natural forces acting on river levels could be compounded by agricultural use. The risk of changes in average environmental temperature in their own right is examined in the following section.

## B. Thermodynamic Balance of Plant Analysis

### 1. Coolant Temperature Change Without Cooling Tower

The thermodynamic impact of changes in environmental conditions can be viewed from multiple perspectives. As was suggested in several of the articles mentioned above [24, 25, 26, 63], difficulty keeping the thermal effluent within regulatory limits is one of the primary concerns arising from increasing temperatures. Typically, though not in every instance, reducing the temperature of coolant re-entering the environment can satisfy constraints. A related change more closely associated with operating conditions is a reduction in the change of coolant temperature between the point of extraction and the point of rejection. For pressurized water reactors, this change in temperature is referred to as the change in tertiary coolant fluid temperature. The term “tertiary” arises from the fact that the this coolant is physically isolated from the working fluid as it passes through the plant condenser. The working fluid that drives the turbines forms the secondary coolant loop which is isolated from the primary fluid that passes through the reactor system.

As described above, for plant models without a cooling tower, the only relevant environmental parameter is the temperature of inlet cooling water. However, because PEPSE relies on idealized models of plant components, any change in coolant water inlet temperature translates directly to the coolant water outlet temperature. In other words, the program does not show any propagation of cooling temperature increase through the plant system. One way to examine how thermal changes effect the plant system, then, is to relate the change in tertiary coolant fluid temperature to other changes in the plant system and to examine how environmental conditions effect these relationships.

One of the simplest changes that can be made in systems without a cooling tower is to increase the mass flow rate of the coolant passing through the condenser. Doing so decreases exposure time of the cooling water to the heat being transferred from the shell-side of the condenser. In Figure 12, the change in temperature of the tube-side coolant passing through the condenser is plotted against the change in condenser flow rate where the condenser flow rate is set as a boundary condition.

Equation 4.1 is the governing equation for the amount of heat transferred. The non-linear trend reflects the fact neither $Q_T$ nor $h_{To}$ are solely functions of $w_{Ti}$, rather, they arise from the complex arrangement of the plant system.

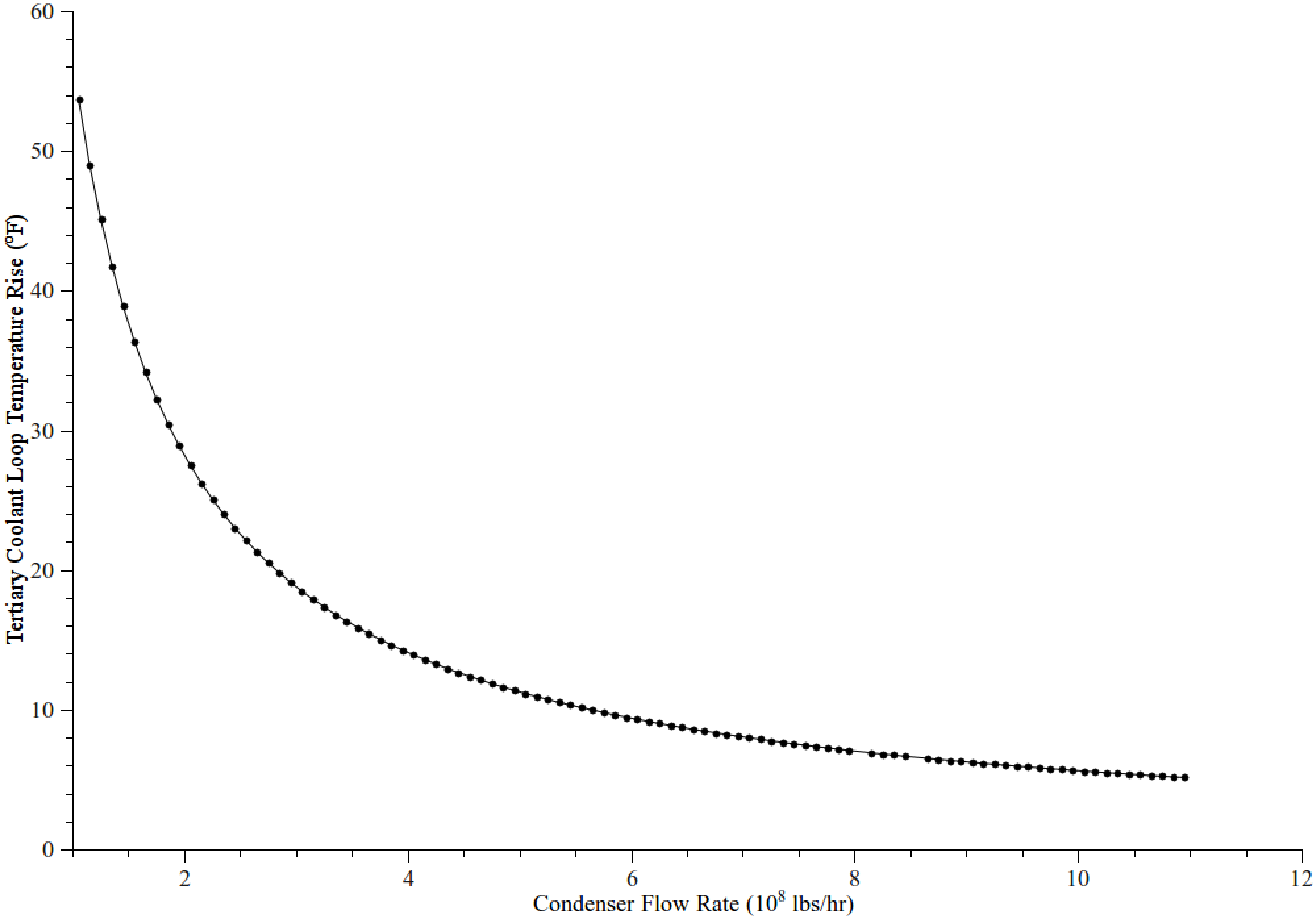

Fig. 12. Effect of condenser flow rate change with 60°F inlet temperature

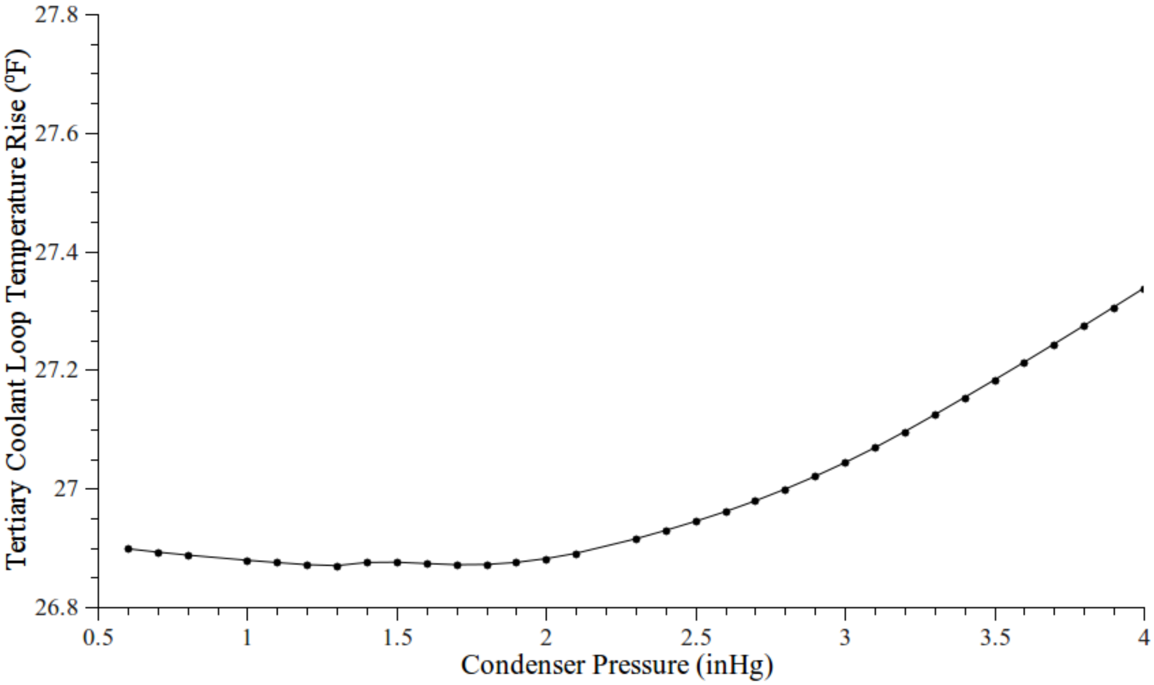

Fig. 13. Effect of condenser pressure change with 65 °F inlet temperature

$$Q_T = w_{Ti}(h_{To} - h_{Ti}) \tag{4.1}$$

As expected, an increase in condenser mass flow rate reduces the increase in temperature of the waste heat. The exponential decay indicates that increasing condenser mass flow in order to reduce the amount of heat rejected to the environment would yield diminishing returns. This is especially so considering that more energy is required to increase the condenser flow rate.

The other condenser parameter examined is the pressure at which the shell-side is maintained. This data (plotted in Figure 13) clearly shows that changes in condenser pressure[1] within a reasonable range have only a negligible impact on the effectiveness of the system. As with changes in condenser flow rate, comparing the

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[1] Condenser pressure is set as the boundary condition in these calculations

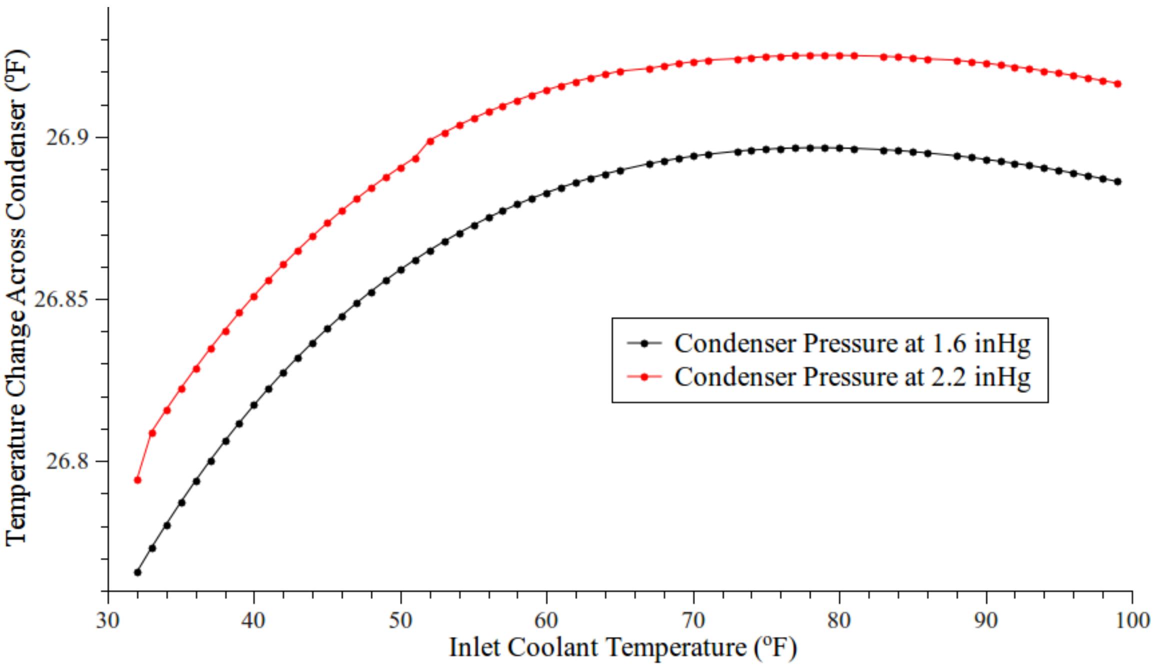

Fig. 14. Comparison of condenser pressure vs. inlet temperature effect

impact of inlet coolant temperature for multiple conditions of condenser pressure is useful for understanding the nature of the effect. Such a comparison is made in Figure 14.

As with changes in flow rate, higher inlet temperatures increase the change in coolant temperature passing through the tube-side of the condenser. That there are clear trends for different condenser pressures indicates that an effect is being calculated by the program; however, the scale of the changes involved are so minute that it would be extraordinarily difficult even to measure in a real world situation. In fact, the effect calculated likely lies beyond any reasonable expected degree of certainty in measurement. Even more so than with changes in flow rate, the impact of coolant inlet temperature on condenser pressure importance is negligible. It can therefore be concluded that for nuclear power plants without a cooling tower, the ability of the plant to reduce thermal effluent is in no significant way impacted by climate change.

The effect of maintaining proper condenser flow rate on the ability of this system to remove heat from the secondary coolant fluid is obviously much more significant than the effect of coolant inlet temperature. Coolant temperature does have at least a theoretical effect on the operation of the condenser, though such effect is negligible for practical applications.

### 2. Coolant Temperature Change With Cooling Tower

When a cooling tower is added to the model, there are several newly introduced variable parameters as described above. As with the previous model, direct changes to the cooling water inlet do not propagate through the system. The effect of cooling water on changes in other system components, however, can be shown. Changes to makeup water or blowdown flow rates effect coolant water temperature inlet by altering the average temperature of the catchment basin. However, these changes to coolant temperature entering the condenser have the same effects as described in the previous section. Cooling tower calculations do, however, also take into account air temperature and humidity. It is the impact of these parameters that will be discussed in this section.

One of the most significantly impacting environmental attributes was found to be the tower approach as defined in Equation 4.4. Because this parameter is a measure of the difference between the catchment temperature and the wet bulb air temperature, it cannot be directly manipulated by plant operators. However, for mechanical draft cooling towers, there is some ability to alter the catchment temperature and thus the effect of tower approach on coolant temperature rise is relevant.

That changes in the tower approach should translate to changes in tertiary coolant fluid temperature rise is intuitive. This is because for any given inlet temperature a change in tower approach is equivalent to a change in catchment basin temperature; the end of the tertiary coolant fluid is the blowdown, whose temperature is calculated directly from that of the catchment basin. It is not quite so obvious, however, what effect the environmental air temperature should have on temperature change of the tertiary coolant fluid relative to changes in the tower approach.

Figure 15 shows a comparison of the effect of a range of environmental air temperatures on the tertiary coolant fluid temperature rise for a given tower approach. The relatively high values for higher temperatures reflect an unusually large tower approach. As described, however, changes in tertiary coolant loop temperature are proportional to tower approach. Though the relationship is not quite linear, an unweighted, scaled Levenberg-Marquardt linear regression indicates a 0.56 degree rise in tertiary coolant fluid temperature change per degree Fahrenheit rise in environmental air temperature.

Examination of Appendix D shows that the Pilgrim site is likely to have the largest change in monthly mean temperature. Even for this case, though, the effect of rising environmental air temperature is unlikely to increase the change in coolant loop temperature rise beyond 4 degrees Fahrenheit. The obvious conclusion is that it is extremely unlikely that changes in environmental air temperature will effect the ability of a power plant to maintain a constant change of coolant temperature through the tertiary loop in an operationally significant way.

While the average change in thermal discharge is important for long-term operational planing, extreme heat events can have a significant impact on plant operations in light of thermal discharge limits. The frequency of these types of events can be predicted based on the historical records. Appendix J gives data relating

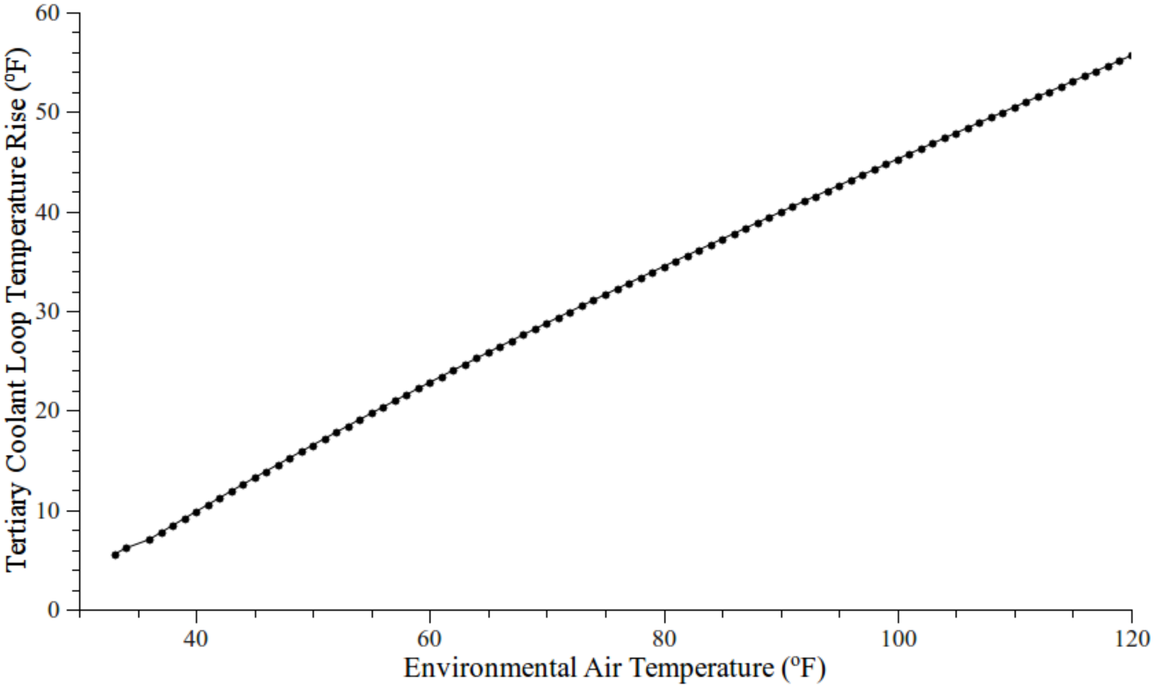

Fig. 15. Comparison of environmental air temperature vs. tower approach effect

to the amount of time per month for which the temperature was above 90°F. As with trends in monthly mean temperature, the Pilgrim site indicates an increase, though in this case only a slight one ($\Delta = \pm 3 \times 10^{-4} \frac{days/month}{month}$).

Appendix I includes figures for trends in the extreme high temperatures. Several of the sites (FitzPatrick, Indian Point, Pilgrim, and Vermont Yankee) indicate increasing extreme high temperatures. However, when considered in conjunction with the trends from Appendix J, these increases must be arising from lengthening hot seasons rather than more regular or more extreme highs. The risk of plants necessitating shutdown due to extremely hot temperatures appears to be reducing for the sites examined.

Apart from air temperature, the humidity also impacts tertiary coolant fluid characteristics. This effect can be seen in Figure 16. Again, the tower approach has

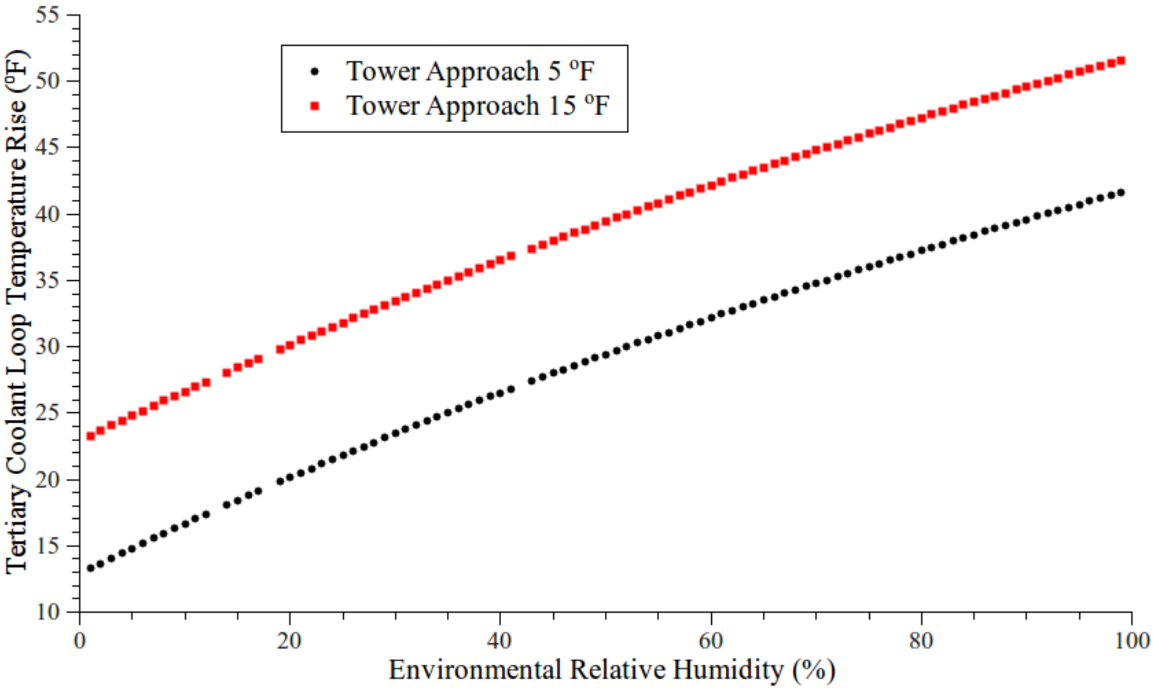

Fig. 16. Comparison of humidity vs. tower approach effect

a linear effect on coolant fluid temperature rise. The humidity effect, though, is not quite linear. It follows that dry conditions are beneficial in reducing the temperature rise through the tertiary coolant fluid. It is also relevant to note, however, that this benefit physically arises from the rate of evaporation in the cooling tower. A higher rate of evaporation also means that the system will require a higher rate of makeup water withdrawal from the environment. Forecasts of humidity as well as temperature should thus be taken into consideration in planning for long-term nuclear power plant water needs. It should be noted, however, that the effect of humidity on cooling tower operation is already well classified [76] even if it's relevance to climate change has not been elucidated.

### 3. Enthalpy Impact Without Cooling Tower

As described above, there is a potential for changes in environmental conditions to impact the operating conditions of plant components. The most important thermodynamic condition of the plant is overal plant efficiency; this value is closely related to the enthalpy of plant components. Even while changes in inlet coolant temperature translate directly to changes in outlet temperature, the thermodynamic balance of plant within the system is slightly altered. For the purposes of the present work, only a small subset of plant components will be examined. This selection is representative of the major processes of plant operation and can be roughly seen as corresponding to energy use (pumps), energy generation (turbines), and heat rejection (condenser).

There are many definitions of efficiency in mechanical systems. For the purposes of this paper, the most useful quantity to examine is thermal efficiency ($\eta_{\mathrm{th}}$). For an idealized system, this quantity is[77]

$$\eta_{\mathrm{th}} = \frac{\dot{\mathrm{W}}_{\mathrm{u,actual}}}{\dot{\mathrm{m}}_{\mathrm{p}}(\Delta \mathrm{h})_{\mathrm{reactor}}} \tag{5.1}$$

where

$\eta_{\mathrm{th}}$ = Thermal efficiency
$\dot{\mathrm{W}}_{\mathrm{u,actual}}$ = Actual useful work
$\dot{\mathrm{m}}_{\mathrm{p}}$ = Mass flow of coolant
$\Delta \mathrm{h}$ = Enthalpy change across reactor.

The value of $\dot{\mathrm{W}}_{\mathrm{u,actual}}$ in an idealized system is given by

$$\dot{\mathrm{W}}_{\mathrm{u,actual}} = \dot{\mathrm{m}}_{\mathrm{p}}(\Sigma \Delta \mathrm{h}) \tag{5.2}$$

where the changes in enthalpy are those of all of the components within the control volume. For the system of concern, Equations 5.1 and 5.2 become

$$\eta_{\mathrm{th}} = \frac{(\Delta h)_r m_r - |(\Delta h)_p m_p| - |(\Delta h)_t m_t| - |(\Delta h)_c m_c|}{(\Delta h)_r m_r} \tag{5.3}$$

where the subscripts indicate

r = reactor
p = pump
t = turbine
c = condenser.

All of the turbines in the ANO system are connected in series so that calculating the inlet enthalpy of the highest pressure turbine and the outlet enthalpy of the lowest pressure turbine suffice to provide information on the entire series. As can be seen in the figure on page 30, the ANO system has three pumps. Because these pumps are located in different areas of the system, for this study, the changes in enthalpy were calculated individually and then added together. The system only has one condenser and the enthalpy cited is that of the secondary coolant fluid from the shell-side inlet to the shell-side outlet.

The changes in condenser flow rate such as those used to generate the figure on page 62 did not in any way effect the enthalpy changes across these components. Accordingly, changes in condenser flow rate would reduce plant efficiency by increasing the last term in Equation 5.3. Nonetheless, as can be seen in Figure 17, changes in inlet temperature had a negligible impact on this enthalpy change. Thus, changes in inlet temperature do not correspond to changes in plant efficiency provided that the plant operating conditions are optimized for the prevailing conditions.

As would be expected from Equation 4.2, changes in the condenser pressure did impact component efficiency as measured by the change in enthalpy across plant systems. Of course, the effect of condenser pressure on system efficiency has been well documented elsewhere[49, 58, 76, 57] and is not the focus of the current

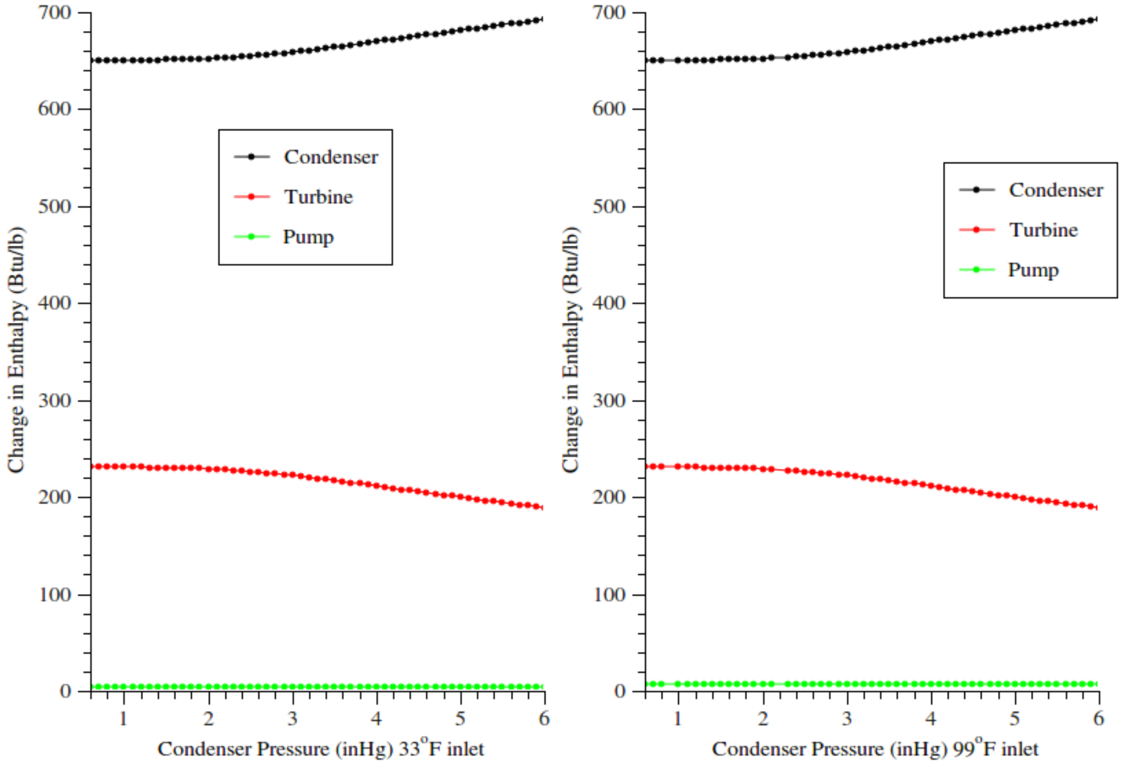

Fig. 17. Effect of condenser pressure for various inlet temperatures

work. The impact of coolant temperature on the effectiveness of condenser pressure, however, is relevant. As with the effect on thermal effluent, the impact was minimal but identifiable.

Figure 17 shows the impact on enthalpy change across these components of changes in condenser pressure for two different temperatures of inlet coolant. Obviously, the impact is minimal, in fact there are no differences for either the condenser or the turbine enthalpy changes. What differences there are for the pumps can be seen more clearly by examining just these changes as in Figure 18.

Evidently, changes in inlet temperature impact the operation of system pumps. These enthalpy calculations are those of the coolant entering and leaving the pump and so do not exactly represent the amount of energy used or lost by pump oper-

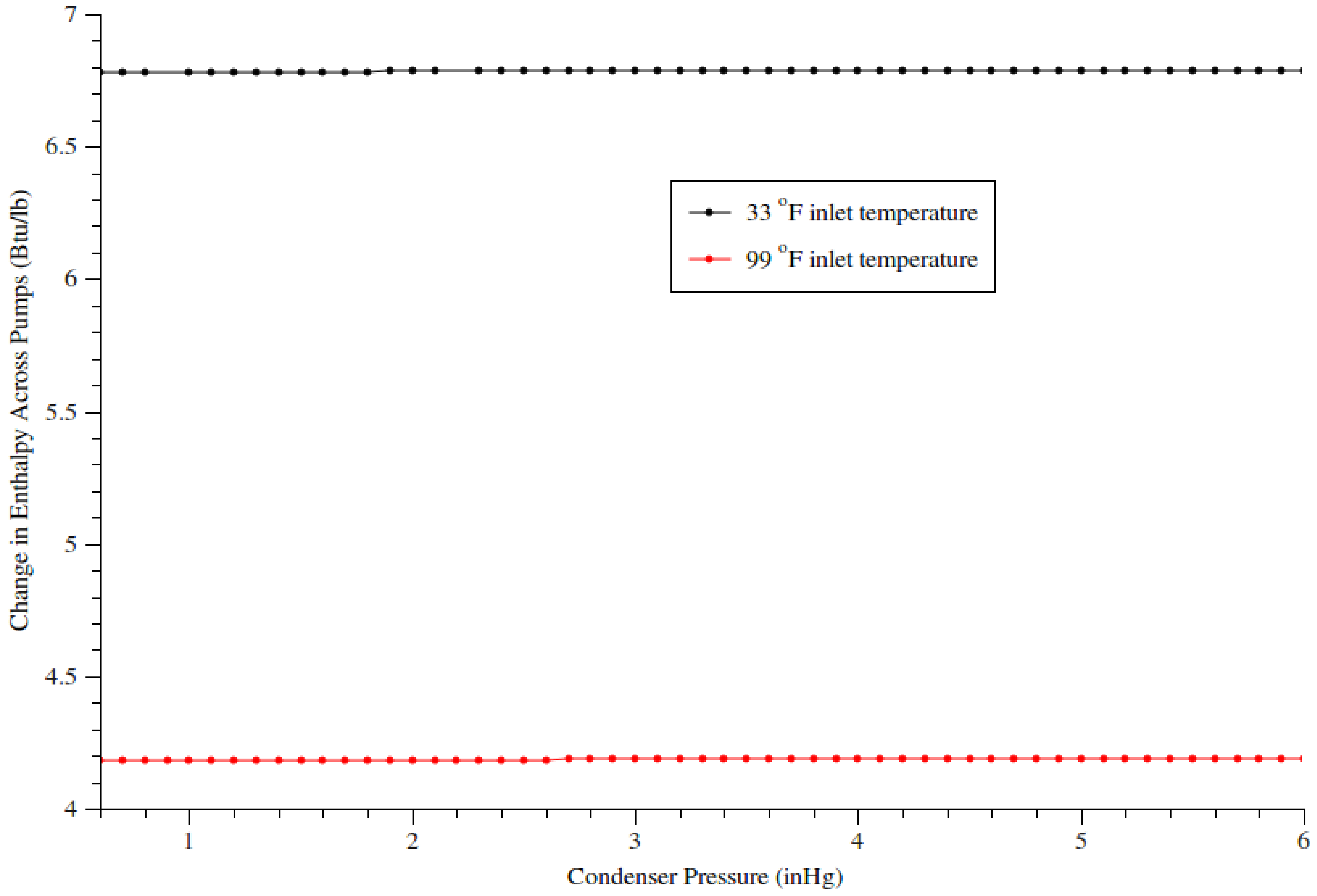

Fig. 18. Effect of condenser pressure on pump enthalpy change

ation. However, because these values represent the change in enthalpy, they are a measure of inefficiencies in the system.

In this case, the increase in coolant temperature reduces the amount of enthalpy change, and thus decreases efficiency. Because of the modeling performed by PEPSE, however, these inefficiencies are not realized in the turbines but are directed to the coolant outlet transferred to the environment.

### 4. Enthalpy Impact With Cooling Tower

As with the model without a cooling tower, there is potential for secondary coolant fluid components to be effected by environmental changes. It was found that, despite running 43,300 cases with PEPSE to examine this issue, there was no change whatsoever in the enthalpy changes of secondary coolant fluid components dependent on either air temperature or humidity. While changes in condenser flow rate and pressure had the same effects as described in Subsection 3, no changes in any secondary loop component were observed as the result of changes in air temperature or humidity for a plant utilizing cooling towers.

# CHAPTER VI

# CONCLUSIONS AND RECOMMENDATIONS

## A. Conclusions

This document addressed the question of how climate change will impact the long-term operation of nuclear power plants. The question was addressed in consideration both of acute disturbances and chronic thermodynamic shifts. Climate data was gathered and analyzed and used to qualify predictions based on plant modeling.

The literature survey performed for this work clearly indicates that climate change and the effects associated with it can have significant impacts on the long-term operation of nuclear power plants. Apart from changes in the frequencies of events such as tornadoes and hurricanes, shifts in precipitation and temperature patterns are potential threats. These event related climatic impacts primarily include, but are not limited to, decreased availability of water in the American Midwest and increased potential for flooding in the American Northeast.

Historic precipitation and temperature data indicate a shifting of seasonal water availability to earlier in the year. Significant warming in areas with a large amount of snow runoff could lead to increased flood risks in the spring and drought concerns later in the year. While these impacts will be a somewhat local phenomenon, plants in northerly lattitudes are more likely to face this risk.

As described, potential lack of water appears to be the threat of most concern to plants located in heavily agricultural regions. A coupling of higher temperatures and drier summers will greatly increase demand for water and thereby restrict availability. Though the climate analysis performed for this paper focused exclusively on North America, IPCC predictions[34] indicate that similar statements could be made for many agricultural areas in Europe and Africa.

Thermodynamically, environmental changes pose only minor threats (if any) to power plant operations. Of concern are both the impact on cooling resources that allow plants to remain within regulatory limits on thermal effluent discharge and the potential impact of changes in environmental temperatures on the efficiency of plant components. In all cases it was shown that plant conditions could be optimized so as to negate any potential threat.

It was shown that relative humidity significantly impacts the temperature of the catchment basin and thus of the thermal effluent discharge. This effect must be considered in conjunction with changing demand for water based on the rate of evaporation in the cooling tower. Such characteristics of these systems are generally recognized by operators but should be taken into consideration when possible effluent temperature-related cessations of operations are a realistic possibility.

PEPSE code was used to model changes to the coolant inlet temperature. No significant effect on the operation of the condenser was shown and the ability of a nuclear power plant to reduce thermal effluent is in no significant way impacted by climate change. For plants utilizing cooling towers, it was shown that it is extremely unlikely that changes in environmental air temperature will effect the change of coolant temperature through the tertiary loop greater than one degree Fahrenheit on average. This minimal impact is negligible compared to other parameters examined.

A minimal impact on the operation of the plant pumping systems was observed as the result of changes in coolant temperature related to condenser pressure settings. Such changes as might be seen, however, were not realized in greater plant efficiency because of propagation through the system and ultimately back to the environment. No impact at all on secondary coolant fluid plant components was found as the result of changes in air temperature or humidity.

While the effects of climate change are not entirely predictable, conservative analysis of the available data allows for generalizations to be made for much of the United States where long-term data is available. Even with highly conservative predictions, only a negligible impact was found to potentially arise from changing temperatures. Possible changes in the frequency or intensity of climate-related events were determined to pose a greater threat to nuclear power plants.

Real world systems are subject to much greater restrictions arising from losses due to friction and other irreversibilities. While not all of these characteristics of real systems were modeled by PEPSE, the software provided a more detailed examination of the impact of environmental changes on plant systems than had previously been performed. Even considering extreme changes in environmental conditions, no significant impact on the thermodynamic balance-of-plant is expected.

## B. Recommendations

Because of the possibility of reduced water supply, plants located in or planned for construction in the Midwest area should carefully consider cooling water requirements and would likely benefit from the installation of cooling towers or other cooling devices that reduce water consumption. Contrarily, plants located in, or planned for, the Northeast should consider the impact of increased water supply in the form of earlier and greater spring floods. Plants located on rivers or in floodplains would benefit from assessment of their flood preparedness.

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# APPENDIX A

# SATELLITE IMAGERY OF SELECTED SITES

The first figure in this appendix identifies all of the plant sites examined for the current work as seen from above the eastern half of the United States. The following figures depict each individual plant site. All of the imagery was obtained through Google Earth and is here presented as fair use material as defined by the US Copyright Act of 1976, 17 U.S.C. 107.

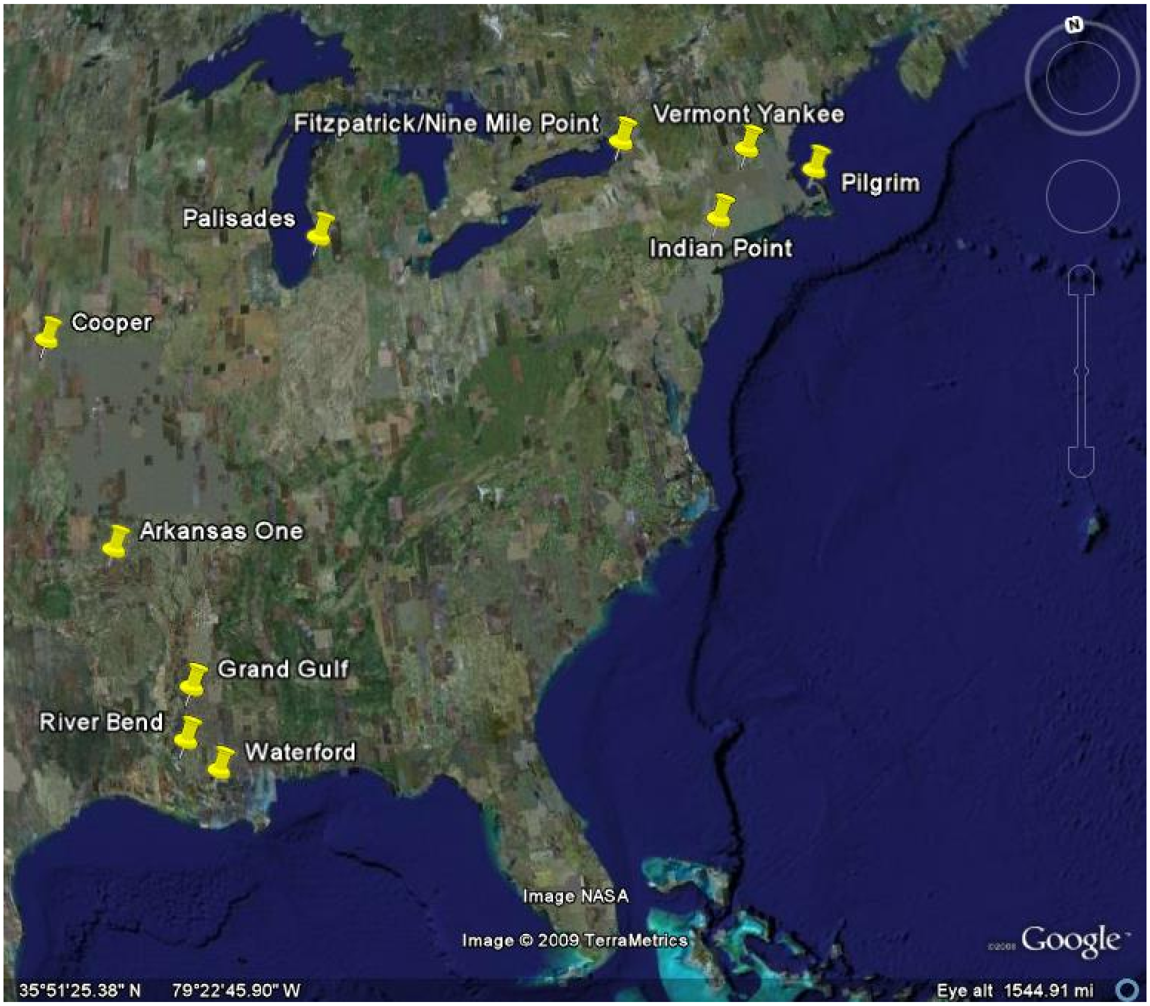

Fig. 19. All of the sites examined in this work

Fig. 20. Arkansas Nuclear One revisited

Fig. 21. Cooper Station

Fig. 22. James A. FitzPatrick

Fig. 23. Grand Gulf

Fig. 24. Indian Point

Fig. 25. Palisades

Image © 2008 TerraMetrics
Image MassGIS, Commonwealth of Massachusetts EOEA

Fig. 26. Pilgrim

Fig. 27. River Bend

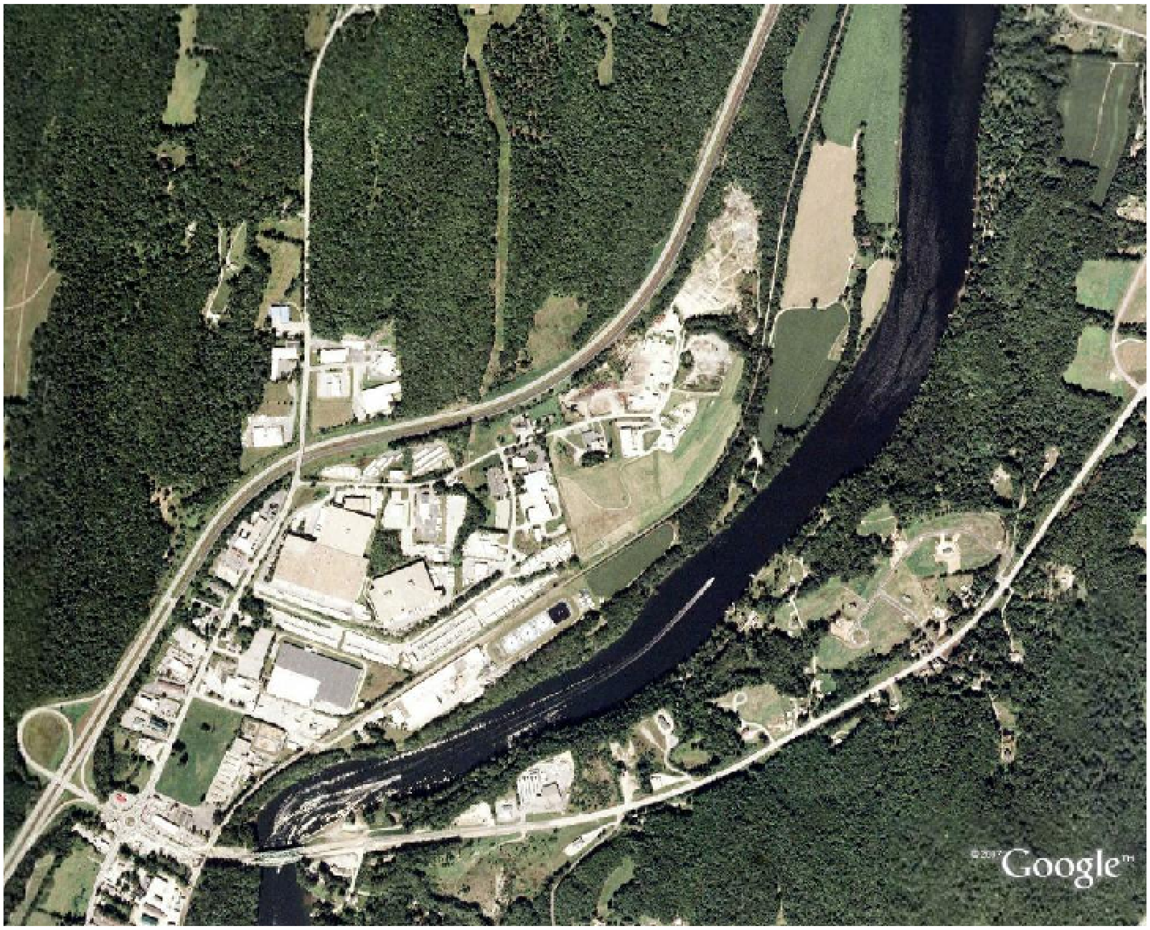

Fig. 28. Vermont Yankee

Fig. 29. Waterford

# APPENDIX B

## EXCERPT FROM COOPER STATION NOAA RAW DATA

The following table is a small portion of a raw data file as obtained from NOAA. The original files consist of very long rows of ASCII plain text which are shown here in word wrap format with hanging indentations. The first row in this table gives abbreviations describing the column values; the second row is a dash-filled comma separated row identifying the maximum number of characters per column; several rows of raw data follow.

The data provided by NOAA is dynamically generated at the request of the user. The data for this appendix was obtained from the National Environmental Satellite, Data, and Information Service[59].

```
COOPID,WBNID,CD,ELEM,UN,YEAR,A,S,MO,DA,   JAN  ,F,F,MO,DA,
   FEB  ,F,F,MO,DA,   MAR  ,F,F,MO,DA,   APR  ,F,F,MO,DA,   MAY  ,F
   ,F,MO,DA,   JUN  ,F,F,MO,DA,   JUL  ,F,F,MO,DA,   AUG  ,F,F,MO,
   DA,   SEP  ,F,F,MO,DA,   OCT  ,F,F,MO,DA,   NOV  ,F,F,MO,DA,
   DEC  ,F,F,MO,DA,ANNUAL,F,F
------,-----,--,----,--,----,-,-,--,--,------,-,-,--,--,------,-,-,--,-

030006,99999,10,EMXP,HI,1941,9,9,01,99,-99999,M,
   ,02,99,-99999,M,  ,03,99,-99999,M,  ,04,99,-99999,M,
   ,05,99,-99999,M,  ,06,99,-99999,M,  ,07,11, 00070, ,
   ,08,13, 00144, ,  ,09,25, 00325, ,  ,10,31, 00225, ,
   ,11,20, 00048,+,  ,12,26, 00047, ,  ,13,99,-99999,M,
030006,99999,10,TPCP,HI,1941,9,9,01,99,-99999,M,
   ,02,99,-99999,M,  ,03,99,-99999,M,  ,04,99,-99999,M,
   ,05,99,-99999,M,  ,06,99,-99999,M,  ,07,00, 00117, ,
   ,08,00, 00494, ,  ,09,00, 00557, ,  ,10,00, 00632, ,
   ,11,00, 00126, ,  ,12,00, 00186, ,  ,13,99,-99999,M,
030006,99999,10,TSNW,TI,1941,9,9,01,99,-99999,M,
   ,02,99,-99999,M,  ,03,99,-99999,M,  ,04,99,-99999,M,
   ,05,99,-99999,M,  ,06,99,-99999,M,  ,07,00, 00000, ,
   ,08,00, 00000, ,  ,09,99,-99999,M,  ,10,99,-99999,M,
   ,11,99,-99999,M,  ,12,99,-99999,M,  ,13,99,-99999,M,
030006,99999,10,DP0Q,NA,1942,9,9,01,00, 00002, ,  ,02,00,
   00003, ,  ,03,00, 00004, ,  ,04,00, 00005, ,  ,05,00, 00004,
    ,  ,06,00, 00006, ,  ,07,00, 00002, ,  ,08,00, 00004, ,
   ,09,00, 00003, ,  ,10,00, 00001, ,  ,11,00, 00005, ,
   ,12,00, 00002, ,  ,13,99,-99999,M,
030006,99999,10,DP10,NA,1942,9,9,01,00, 00001, ,  ,02,00,
   00001, ,  ,03,00, 00000, ,  ,04,00, 00002, ,  ,05,00, 00002,
    ,  ,06,00, 00002, ,  ,07,00, 00000, ,  ,08,00, 00000, ,
   ,09,00, 00000, ,  ,10,00, 00001, ,  ,11,00, 00002, ,
   ,12,00, 00001, ,  ,13,99,-99999,M,
030006,99999,10,EMXP,HI,1942,9,9,01,30, 00140, ,  ,02,09,
   00200, ,  ,03,02, 00058, ,  ,04,08, 00255, ,  ,05,20, 00200,
    ,  ,06,13, 00215, ,  ,07,11, 00084, ,  ,08,10, 00073, ,
   ,09,08, 00060, ,  ,10,30, 00210, ,  ,11,03, 00160, ,
   ,12,27, 00332, ,  ,13,99,-99999,M,
```

```
030006,99999,10,TPCP,HI,1942,9,9,01,00, 00256, , ,02,00,
   00289, , ,03,00, 00168, , ,04,00, 00542, , ,05,00, 00564,
    , ,06,00, 00529, , ,07,00, 00147, , ,08,00, 00248, ,
   ,09,00, 00217, , ,10,00, 00250, , ,11,00, 00420, ,
   ,12,00, 00405, , ,13,99,-99999,M,
030006,99999,10,TSNW,TI,1942,9,9,01,00, 00060, , ,02,00,
   00050, , ,03,00, 00070, , ,04,00, 00000, , ,05,00, 00000,
    , ,06,00, 00000, , ,07,00, 00000, , ,08,00, 00000, ,
   ,09,00, 00000, , ,10,99,-99999,M, ,11,00, 00000, ,
   ,12,00, 00000,T, ,13,99,-99999,M,
030006,99999,10,DP0Q,NA,1943,9,9,01,00, 00000, , ,02,00,
   00002, , ,03,00, 00004, , ,04,00, 00004, , ,05,00, 00008,
    , ,06,00, 00002, , ,07,00, 00000, , ,08,00, 00000, ,
   ,09,00, 00004, , ,10,00, 00005, , ,11,00, 00001, ,
   ,12,99,-99999,M, ,13,99,-99999,M,
030006,99999,10,DP10,NA,1943,9,9,01,00, 00000, , ,02,00,
   00000, , ,03,00, 00002, , ,04,00, 00000, , ,05,00, 00004,
    , ,06,00, 00001, , ,07,00, 00000, , ,08,00, 00000, ,
   ,09,00, 00000, , ,10,00, 00001, , ,11,00, 00000, ,
   ,12,99,-99999,M, ,13,99,-99999,M,
030006,99999,10,EMXP,HI,1943,9,9,01,26, 00014, , ,02,03,
   00048, , ,03,13, 00152, , ,04,11, 00088, , ,05,11, 00737,
    , ,06,27, 00192, , ,07,25, 00003, , ,08,17, 00016, ,
   ,09,07, 00076, , ,10,13, 00270, , ,11,02, 00034, ,
   ,12,99,-99999,M, ,13,99,-99999,M,
030006,99999,10,TPCP,HI,1943,9,9,01,00, 00014, , ,02,00,
   00111, , ,03,00, 00369, , ,04,00, 00305, , ,05,00, 01409,
    , ,06,00, 00343, , ,07,00, 00003, , ,08,00, 00029, ,
   ,09,00, 00210, , ,10,00, 00561, , ,11,00, 00049, ,
   ,12,99,-99999,M, ,13,99,-99999,M,
030006,99999,10,TSNW,TI,1943,9,9,01,00, 00020, , ,02,00,
   00000, , ,03,00, 00012, , ,04,00, 00000, , ,05,99,-99999,
   M, ,06,00, 00000, , ,07,00, 00000, , ,08,00, 00000, ,
   ,09,99,-99999,M, ,10,99,-99999,M, ,11,00, 00000, ,
   ,12,99,-99999,M, ,13,99,-99999,M,
030006,99999,10,DP0Q,NA,1944,9,9,01,99,-99999,M, ,02,00,
   00004, , ,03,99,-99999,M, ,04,99,-99999,M, ,05,99,-99999,
   M, ,06,99,-99999,M, ,07,00, 00003, , ,08,00, 00006, ,
```

```
    ,09,00, 00001, , ,10,00, 00002, , ,11,00, 00004, ,
    ,12,00, 00006, , ,13,99,-99999,M,
030006,99999,10,DP10,NA,1944,9,9,01,99,-99999,M, ,02,00,
    00002, , ,03,99,-99999,M, ,04,99,-99999,M, ,05,99,-99999,
    M, ,06,99,-99999,M, ,07,00, 00002, , ,08,00, 00003, ,
    ,09,00, 00000, , ,10,00, 00001, , ,11,00, 00001, ,
    ,12,00, 00001, , ,13,99,-99999,M,
030006,99999,10,EMXP,HI,1944,9,9,01,99,-99999,M, ,02,14,
    00200, , ,03,99,-99999,M, ,04,99,-99999,M, ,05,99,-99999,
    M, ,06,13, 00188, , ,07,28, 00124, , ,08,27, 00260, ,
    ,09,29, 00044, , ,10,07, 00102, , ,11,08, 00130, ,
    ,12,06, 00130, , ,13,99,-99999,M,
030006,99999,10,TPCP,HI,1944,9,9,01,99,-99999,M, ,02,00,
    00497, , ,03,99,-99999,M, ,04,99,-99999,M, ,05,99,-99999,
    M, ,06,00, 00277, , ,07,00, 00312, , ,08,00, 00791, ,
    ,09,00, 00066, , ,10,00, 00161, , ,11,00, 00307, ,
    ,12,00, 00435, , ,13,99,-99999,M,
030006,99999,10,TSNW,TI,1944,9,9,01,99,-99999,M, ,02,00,
    00000,T, ,03,99,-99999,M, ,04,99,-99999,M, ,05,99,-99999,
    M, ,06,00, 00000, , ,07,00, 00000, , ,08,00, 00000, ,
    ,09,00, 00000, , ,10,00, 00000, , ,11,00, 00000, ,
    ,12,00, 00002, , ,13,99,-99999,M,
030006,99999,10,DP0Q,NA,1945,9,9,01,00, 00002, , ,02,00,
    00007, , ,03,00, 00008, , ,04,00, 00008, , ,05,00, 00004,
     , ,06,00, 00009, , ,07,00, 00005, , ,08,00, 00003, ,
    ,09,00, 00007, , ,10,00, 00003, , ,11,00, 00002, ,
    ,12,00, 00001, , ,13,99,-99999,M,
030006,99999,10,DP10,NA,1945,9,9,01,00, 00000, , ,02,00,
    00003, , ,03,00, 00004, , ,04,00, 00002, , ,05,00, 00004,
     , ,06,00, 00003, , ,07,00, 00001, , ,08,00, 00000, ,
    ,09,00, 00004, , ,10,00, 00001, , ,11,00, 00000, ,
    ,12,00, 00000, , ,13,99,-99999,M,
030006,99999,10,EMXP,HI,1945,9,9,01,19, 00076, , ,02,21,
    00332, , ,03,19, 00321, , ,04,13, 00236, , ,05,15, 00254,
     , ,06,11, 00256, , ,07,27, 00133, , ,08,19, 00073, ,
    ,09,13, 00252, , ,10,22, 00136, , ,11,10, 00057, ,
    ,12,27, 00028, , ,13,99,-99999,M,
```

```
030006,99999,10,TPCP,HI,1945,9,9,01,00, 00124, , ,02,00,
   00959, , ,03,00, 01234, , ,04,00, 00642, , ,05,00, 00750,
    , ,06,00, 01053, , ,07,00, 00393, , ,08,00, 00195, ,
   ,09,00, 00905, , ,10,00, 00250, , ,11,00, 00131, ,
   ,12,00, 00078, , ,13,99,-99999,M,
030006,99999,10,TSNW,TI,1945,9,9,01,00, 00010, , ,02,00,
   00035, , ,03,00, 00000, , ,04,00, 00000, , ,05,00, 00000,
    , ,06,00, 00000, , ,07,00, 00000, , ,08,00, 00000, ,
   ,09,00, 00000, , ,10,00, 00000, , ,11,00, 00000, ,
   ,12,00, 00005, , ,13,99,-99999,M,
030006,99999,10,DP0Q,NA,1946,9,9,01,00, 00006, , ,02,00,
   00003, , ,03,00, 00005, , ,04,00, 00006, , ,05,00, 00009,
    , ,06,00, 00002, , ,07,00, 00002, , ,08,00, 00001, ,
   ,09,00, 00002, , ,10,00, 00003, , ,11,00, 00009, ,
   ,12,00, 00003, , ,13,99,-99999,M,
030006,99999,10,DP10,NA,1946,9,9,01,00, 00002, , ,02,00,
   00001, , ,03,00, 00001, , ,04,00, 00003, , ,05,00, 00003,
    , ,06,00, 00000, , ,07,00, 00000, , ,08,00, 00000, ,
   ,09,00, 00000, , ,10,00, 00000, , ,11,00, 00005, ,
   ,12,00, 00002, , ,13,99,-99999,M,
030006,99999,10,EMXP,HI,1946,9,9,01,05, 00110, , ,02,13,
   00180, , ,03,06, 00100, , ,04,24, 00590, , ,05,03, 00118,
    , ,06,29, 00065, , ,07,20, 00064, , ,08,04, 00083, ,
   ,09,02, 00047, , ,10,11, 00034, , ,11,04, 00215, ,
   ,12,10, 00272, , ,13,99,-99999,M,
030006,99999,10,TPCP,HI,1946,9,9,01,00, 00461, , ,02,00,
   00355, , ,03,00, 00305, , ,04,00, 01214, , ,05,00, 00704,
    , ,06,00, 00130, , ,07,00, 00142, , ,08,00, 00138, ,
   ,09,00, 00146, , ,10,00, 00121, , ,11,00, 01104, ,
   ,12,00, 00530, , ,13,99,-99999,M,
030006,99999,10,TSNW,TI,1946,9,9,01,00, 00000, , ,02,00,
   00040, , ,03,00, 00000, , ,04,00, 00000, , ,05,00, 00000,
    , ,06,00, 00000, , ,07,00, 00000, , ,08,00, 00000, ,
   ,09,00, 00000, , ,10,00, 00000, , ,11,00, 00000, ,
   ,12,00, 00010, , ,13,99,-99999,M,
```

# APPENDIX C

# WEATHER DATA PROCESSING PROGRAM

This appendix describes the nature of the weather processing program written for the current investigation. This program was written in the C++ computer language utilizing the function libraries provided by the Qt toolkit. The makefile generator qmake was used to compile the code on a Gateway personal computer running Ubuntu Linux 9.04.

The intent of this program is to take as input chronologically ordered rows of raw NOAA data in the form of a comma separated list such as that shown in Appendix B, and to provide as output the same data averaged geographically. This is accomplished by summing the monthly value for each station within the selected radius of the relevant site and dividing by the number of stations reporting.

```
#include <iostream>
#include <fstream>
#include <string>

#include <qlist.h>
#include <qstring.h>

using namespace std;

QList<string> titleList;
QList<double> groupIDList;
QList<QList<double>*> averageAdressList;
QList<QList<double>*> elementAdressList;
QList<QList<QList<double>*>*> elementGroupAdressList;

void arrangeElementsByGroups();
void averageGroups();
void collectData(const string infile);
void groupElementsBySimilarColumn(int columnNumber);
void matchOneColumn(int columnNumber);
void matchMultipleColumns(QList<int> columnHeirarchy);
void numericColumnSort(int columnNumber, bool
   leastToGreatest);
void showElements();
void showAverages();
void showGroups();
void showStats();
void writeToFile(string infile);
void writeChartFormat(string infile);

int main(){
string file;

cout << "what␣file?␣";
cin >> file;

collectData( file);
numericColumnSort(2, true);
```

```
arrangeElementsByGroups();
matchOneColumn(2);
groupElementsBySimilarColumn( 0);
averageGroups();
showAverages();
showElements();
showGroups();
showStats();
writeChartFormat( file);

return 0;
}

void arrangeElementsByGroups()
{
QList<QList<double>*> tempElementAdressList;
QList<QList<double>*> elementGroup;

for(int i=0; i < elementGroupAdressList.size(); i++)
{
elementGroup = *elementGroupAdressList.at(i);
        for(int j=0; j < elementGroup.size(); j++)
        {
        tempElementAdressList << elementGroup.at(j);
        }
}
elementAdressList = tempElementAdressList;
}

void averageGroups()
{
cout << "Averaging␣Groups...\n";

QList<double> tempElementList;
QList<QList<double>*> elementGroup;
double currentNumber, average, dataNumber =0, columnTotal
   =0;
int columnNumber;
```

```
for(int i=0; i < elementGroupAdressList.size(); i++){
        QList<double> averageList;
        elementGroup = *elementGroupAdressList.at(i);
        tempElementList = *elementGroup.first();
        columnNumber = tempElementList.size();
        for(int j=0; j < columnNumber; j++){
                for(int k =0; k < elementGroup.size(); k++){
                        tempElementList = *elementGroup.at(k
                           );
                        currentNumber = tempElementList.at(j
                           );
                        if(!(currentNumber == -99999)){
                                columnTotal += currentNumber
                                   ;
                                dataNumber++;
                        }
                }
                average = columnTotal/dataNumber;
                averageList << average;
                columnTotal = 0;
                dataNumber = 0;
        }
        QList<double>* averageAdress = new QList<double> (
           averageList);
        averageAdressList << averageAdress;
}
}

void collectData(const string infile)
{
QList<double> elementList;
string line;
QString num;
double number;
int columnCount =0;
unsigned int pos =0;
```

```
ifstream file_in;
file_in.open(infile.c_str());

cout << "Reading␣spreadsheet...␣\n";

//ignore title line and count columns
        getline(file_in, line);
while(pos <= line.size()){
        pos = line.find(',', pos +1);
        columnCount++;
}
        file_in.seekg(0);

for(int i=0; i< columnCount -1; i++){
        getline(file_in, line, ',');
        titleList << line;
}

getline(file_in, line);

while(file_in >> ws && !file_in.eof()){
        for(int i=0; i< columnCount -1; i++){
                getline(file_in, line, ',');
                num = line.c_str();
                number = num.toDouble();
                elementList << number;
        }
        getline(file_in, line);
        num = line.c_str();
        number = num.toDouble();
        elementList << number;

        QList<double>* elementListAdress = new QList<double>
            (elementList);
        elementList.clear();
        elementAdressList << elementListAdress;
}
elementAdressList.removeFirst();
```

```
file_in.close();
}

void groupElementsBySimilarColumn(int columnNumber)
{
QList<double> elementList;
QList<double> sortColumnValues;
QList<double> groupLabels;
double elementToSort, element;
int groupadresslistindex =0;
int index=-1;

for(int i=0; i < elementAdressList.size(); i++){
        elementList = *elementAdressList.at(i);
        elementToSort = elementList.at(columnNumber);
        sortColumnValues << elementToSort;
}

for(int i=0; i < elementAdressList.size(); i++){
        QList<QList<double>*> elementGroup;
        if(!groupIDList.contains(sortColumnValues.at(i))){
                groupIDList << sortColumnValues.at(i);
                elementGroup << elementAdressList.at(i);
                QList<QList<double>*>* elementGroupAdress =
                    new QList<QList<double>*> (elementGroup);
                elementGroupAdressList << elementGroupAdress
                    ;
                groupadresslistindex++;
        }else if(groupIDList.contains(sortColumnValues.at(i)
            )){
                for(int j=0; j < elementGroupAdressList.size
                    (); j++){
                        elementGroup = *
                            elementGroupAdressList.at(j);
                        elementList = *elementGroup.first();
                        double elementString = elementList.
                            at(columnNumber);
```

```
                        double sortColumnString =
                           sortColumnValues.at(i);
                        if(elementString == sortColumnString
                           ){
                                index = j;
                                break;
                        }
                }
                elementGroup = *elementGroupAdressList.at(
                   index);
                elementGroup << elementAdressList.at(i);
                *elementGroupAdressList.at(index) =
                   elementGroup;
                }
        }
}

void matchOneColumn(int columnNumber)
{
QList<QList<double>*> elementGroup;
QList<QList<double>*> tempElementAdressList;

groupElementsBySimilarColumn(columnNumber);

for(int i =0; i < elementGroupAdressList.size(); i++){
        elementGroup = *elementGroupAdressList.at(i);
        for(int j=0; j <elementGroup.size(); j++){
                tempElementAdressList << elementGroup.at(j);
        }
}
elementAdressList = tempElementAdressList;
}

void matchMultipleColumns(QList<int> columnHeirarchy)
{

}
```

```
void numericColumnSort(int columnNumber, bool
   leastToGreatest)
{
QList<QList<QList<double>*>*> tempElementGroupAdressList;
QList<int> groupOrder;

matchOneColumn(columnNumber);

double firstvalue;
firstvalue = groupIDList.first();

for(int i =0; i < groupIDList.size(); i++)
        groupOrder << i;

cout << "first␣value␣is␣" << firstvalue;
for(int i =0; i < groupIDList.size(); i++){
        for(int j =0; j < groupIDList.size(); j++){
                if(groupIDList.at(j) < firstvalue){
                        groupOrder.replace(i, j);
                        firstvalue = groupIDList.at(j);
                        cout << "␣but␣" << firstvalue << "␣
                           is␣less␣";
                }
        }
}

for(int i =0; i < elementGroupAdressList.size(); i++){
        tempElementGroupAdressList << elementGroupAdressList
           .at(groupOrder.at(i));
}
elementGroupAdressList = tempElementGroupAdressList;
}

void showGroups()
{
cout << "\nSHOW␣GROUPS" << '\n';
QList<double> elementList;
QList<QList<double>*> elementGroup;
```

```
for(int i=0; i < elementGroupAdressList.size(); i++){
        elementGroup = *elementGroupAdressList.at(i);
        for(int j=0; j < elementGroup.size(); j++){
                elementList = *elementGroup.at(j);
                for(int k=0; k < elementList.size(); k++){
                        cout << '[' << elementList.at(k) <<
                           ']';
                        }cout << '\n';
        }
        cout << '^' << i << '^' <<'\n';
}
}

void showElements()
{
cout << "\nSHOW␣ELEMENTS" << '\n';
QList<double> elementList;
for(int i=0; i < elementAdressList.size(); i++){
        elementList = *elementAdressList.at(i);
        for(int j=0; j < elementList.size(); j++){
                cout << '[' << elementList.at(j) << ']';
        }cout << '\n';
}
}

void showAverages()
{
cout << "\nSHOW␣AVERAGES" << '\n';
QList<double> elementList;
for(int i=0; i < averageAdressList.size(); i++){
        elementList = *averageAdressList.at(i);
        for(int j=0; j < elementList.size(); j++){
                cout << '[' << elementList.at(j) << ']';
        }cout << '\n';
}
}
```

```
void showStats()
{
cout << "Number␣of␣elements␣is␣" << elementAdressList.size()
   << '\n';
}

void writeChartFormat( string infile)
{
cout << "Writing␣to␣file...␣\n";
QList<double> elementList;
string outfile;

outfile += infile.c_str();
outfile += "Mod";
ofstream file_out;
file_out.open(outfile.c_str());

for(int i=0; i < averageAdressList.size(); i++){
        elementList = *averageAdressList.at(i);
        file_out << elementList.first() << ',' <<
           elementList.at(1) << '\n';
        for(int j=2; j < elementList.size(); j++){
                file_out << ',' << elementList.at(j) << '\n'
                   ;
        }
}

file_out.close();
}

void writeToFile( string infile)
{
cout << "Writing␣to␣file...␣\n";
QList<double> elementList;
string outfile;

outfile += infile.c_str();
outfile += "Mod";
```

```
ofstream file_out;
file_out.open(outfile.c_str());

file_out << titleList.first();
for(int i=1; i < titleList.size(); i++){
        file_out << ',' << titleList.at(i);
}
file_out << '\n';

for(int i=0; i < elementAdressList.size(); i++){
        elementList = *elementAdressList.at(i);
        file_out << elementList.first();
        for(int j=1; j < elementList.size(); j++){
                file_out << ',' << elementList.at(j);
        }file_out << '\n';
}

file_out.close();
}
```

# APPENDIX D

# MONTHLY MEAN TEMPERATURE

The results of the climate data collected from NOAA[78], and the analysis as described in section 3.3 are presented in this and the following appendixes. Each data point represents the average value reported by all weather stations within 1 degree of the relevant power plant, except in the cases of Indian Point, Vermont Yankee, and Waterford. Each of these three cases use all stations within 30 arc-minutes due to data transfer limits imposed by NOAA.

For each climate element gathered, the results for the statistical analysis are presented first. All of the linear regressions were performed using the Scaled Levenberg-Marquardt method without weighting as calculated by QtiPlot. Unless otherwise stated, data points are given as one value per month. Accordingly, linear regression data is given with increments of one month on the horizontal axis.

For each data set, a slope, a starting date, an initial value, and the root mean square error (RMSE) are given. This initial value refers to the “zeroth” month of the data. In order to find the linear regression fit for any particular month, for example, it is necessary to count the number of months from the starting date, including the starting month, and then multiply by the slope and add the initial value.

Arkansas Nuclear One[59]

| | |
|---|---|
| Starting Date | January, 1892 |
| Slope | $8 \times 10^{-5} \pm 9.9 \times 10^{-4} \frac{^oF}{month}$ |
| Initial Value | $60.184 \pm 0.80126$°F |
| RMSE | 14.971 |

Cooper Station[79]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $-3.4 \times 10^{-4} \pm 1.26 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $52.501 \pm 1.0093$°F |
| RMSE | 18.778 |

FitzPatrick[80]

| | |
|---|---|
| Starting Date | January, 1884 |
| Slope | $-4.5 \times 10^{-4} \pm 1.05 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $46.707 \pm 0.90184$°F |
| RMSE | 17.420 |

Grand Gulf[81]

| | |
|---|---|
| Starting Date | February, 1891 |
| Slope | $-6.4 \times 10^{-4} \pm 8.2 \times 10^{-4} \frac{^oF}{month}$ |
| Initial Value | $65.797 \pm 0.06695$°F |
| RMSE | 12.558 |

Indian Point[82]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $1.22 \times 10^{-3} \pm 1.99 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $50.373 \pm 1.0689$°F |
| RMSE | 16.285 |

Palisades[83]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $1.5 \times 10^{-4} \pm 1.18 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $49.114 \pm 0.94855$°F |
| RMSE | 17.546 |

Pilgrim[1]

| | |
|---|---|
| Starting Date | January, 1832 |
| Slope | $2.71 \times 10^{-3} \pm 5.7 \times 10^{-4} \frac{^oF}{month}$ |
| Initial Value | $45.128 \pm 0.70252$°F |
| RMSE | 15.823 |

River Bend[84]

| | |
|---|---|
| Starting Date | February, 1891 |
| Slope | $8 \times 10^{-5} \pm 7.6 \times 10^{-4} \frac{^oF}{month}$ |
| Initial Value | $66.977 \pm 0.61621$°F |
| RMSE | 11.559 |

Vermont Yankee[85]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $6.8 \times 10^{-4} \pm 2.14 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $45.495 \pm 1.1485$°F |
| RMSE | 17.499 |

Waterford[86]

| | |
|---|---|
| Starting Date | January, 1894 |
| Slope | $2.8 \times 10^{-4} \pm 8.3 \times 10^{-4} \frac{^oF}{month}$ |
| Initial Value | $68.343 \pm 0.70421$°F |
| RMSE | 11.058 |

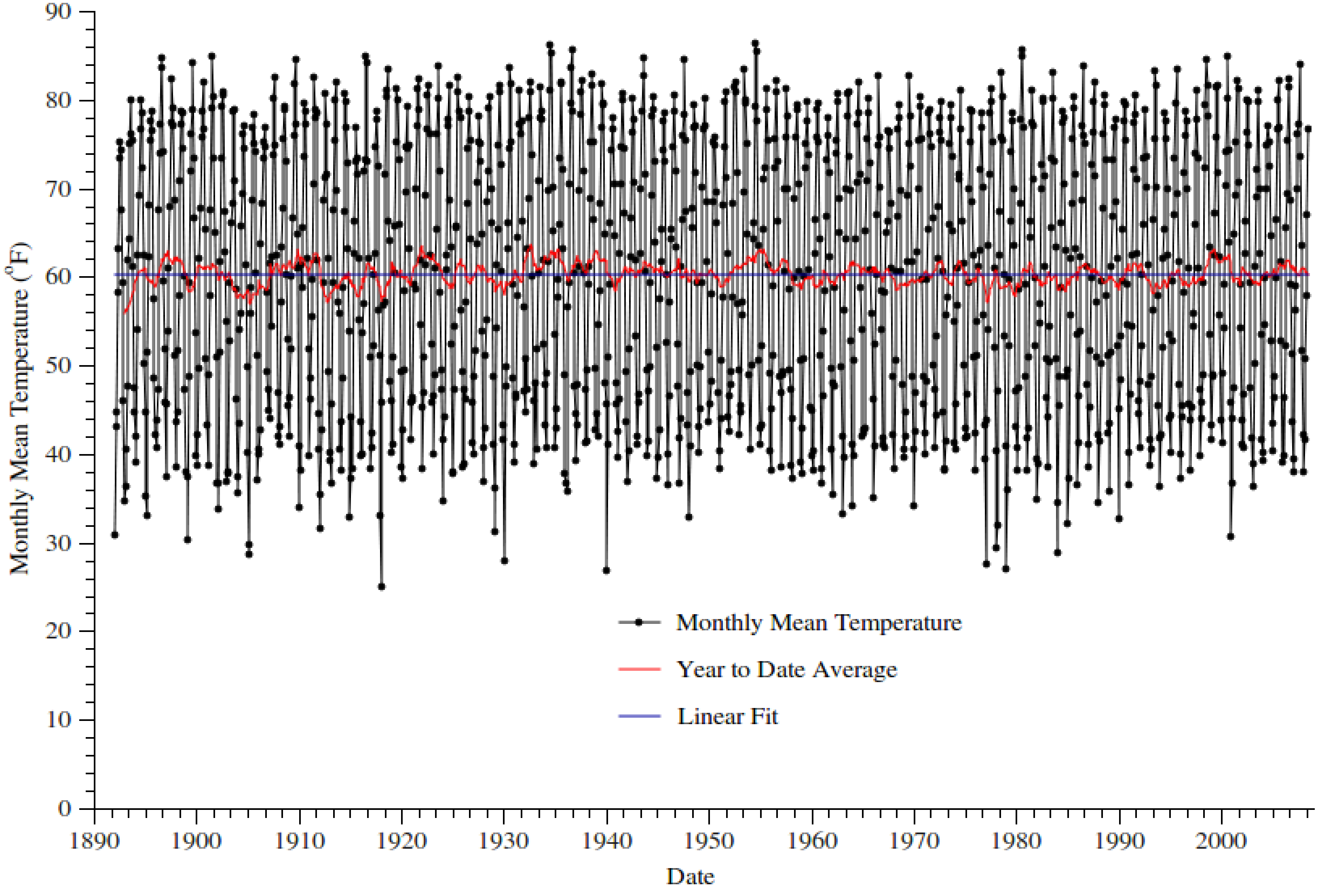

Fig. 30. Arkansas Nuclear One monthly mean temperature

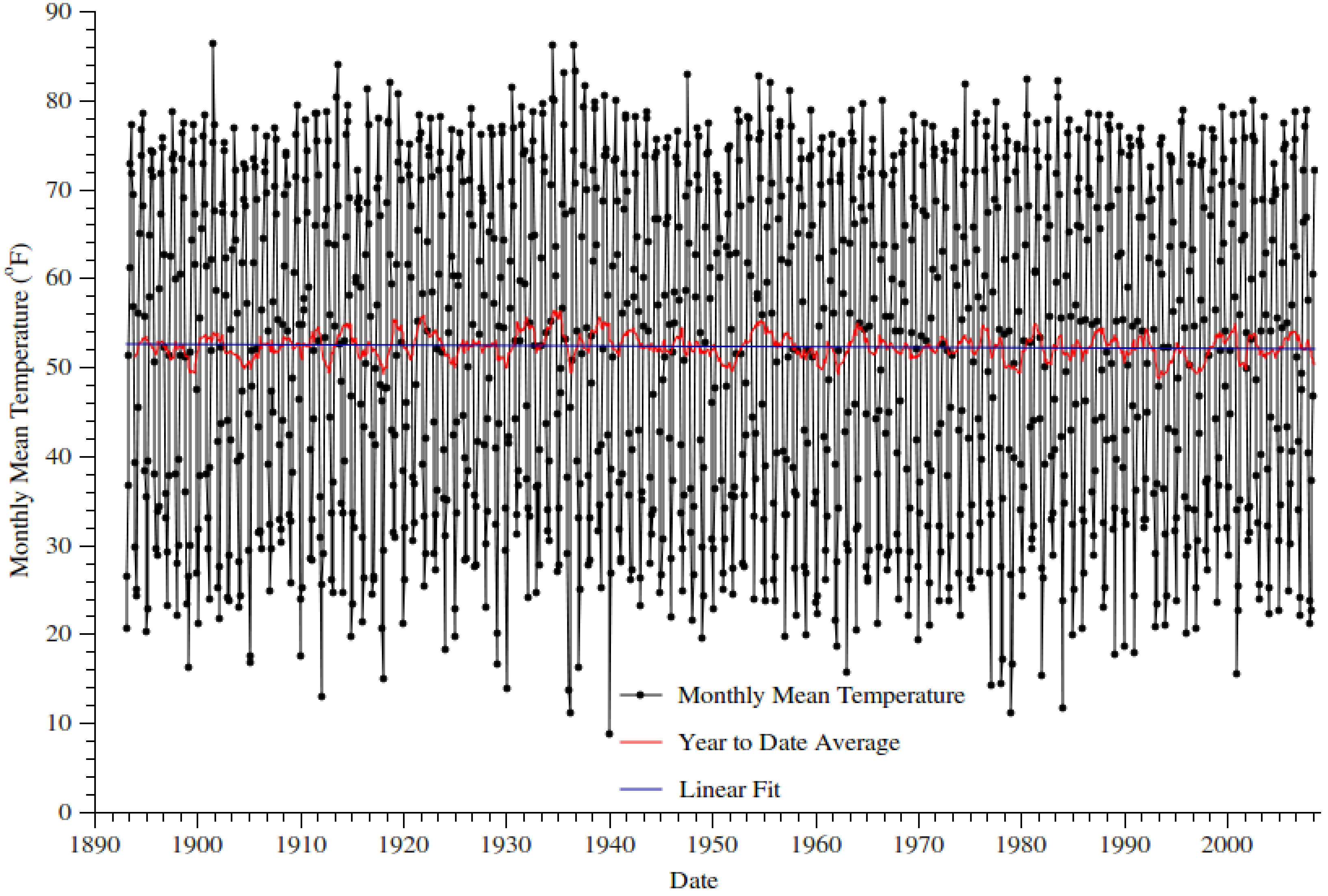

Fig. 31. Cooper Station monthly mean temperature

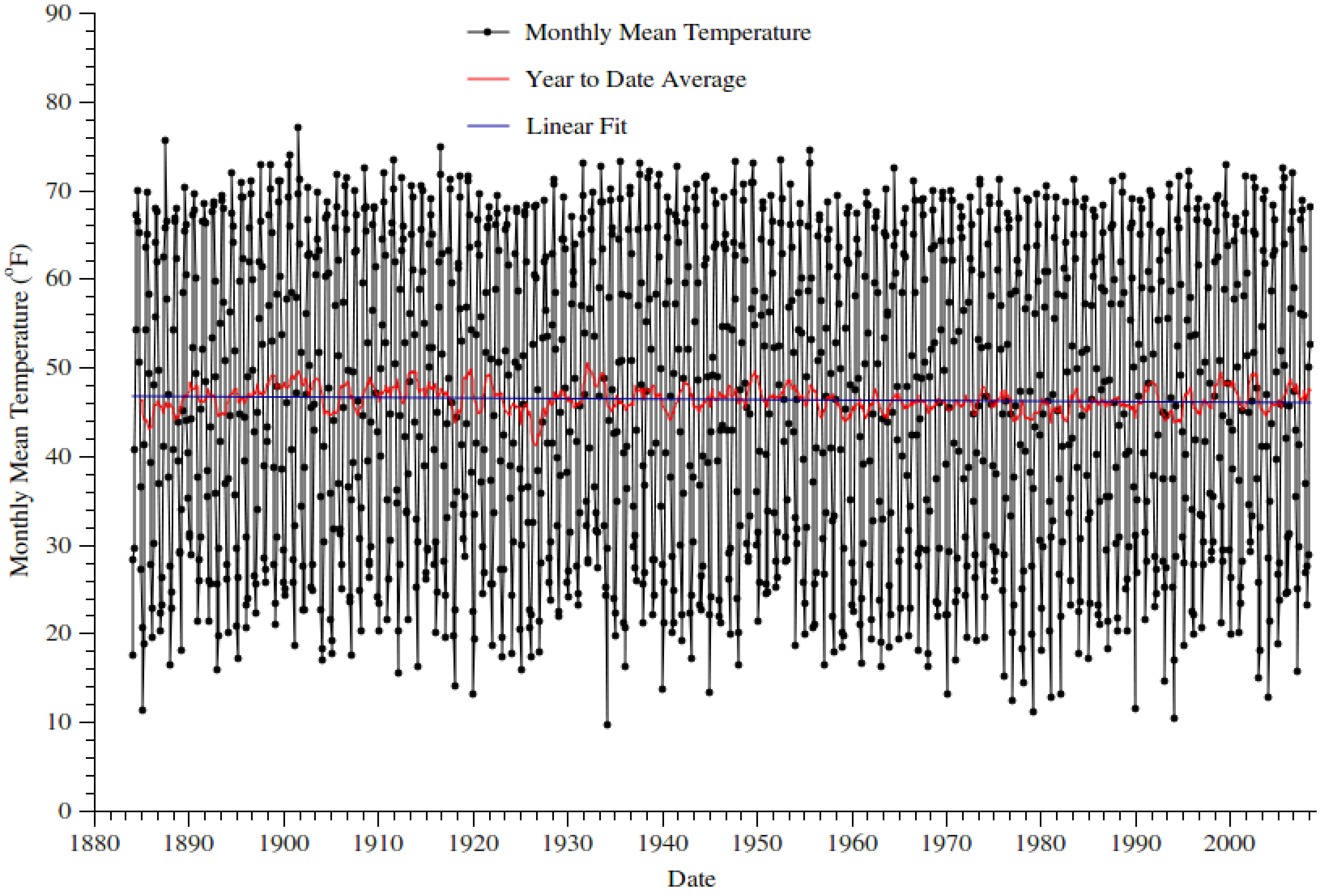

Fig. 32. James A. FitzPatrick monthly mean temperature

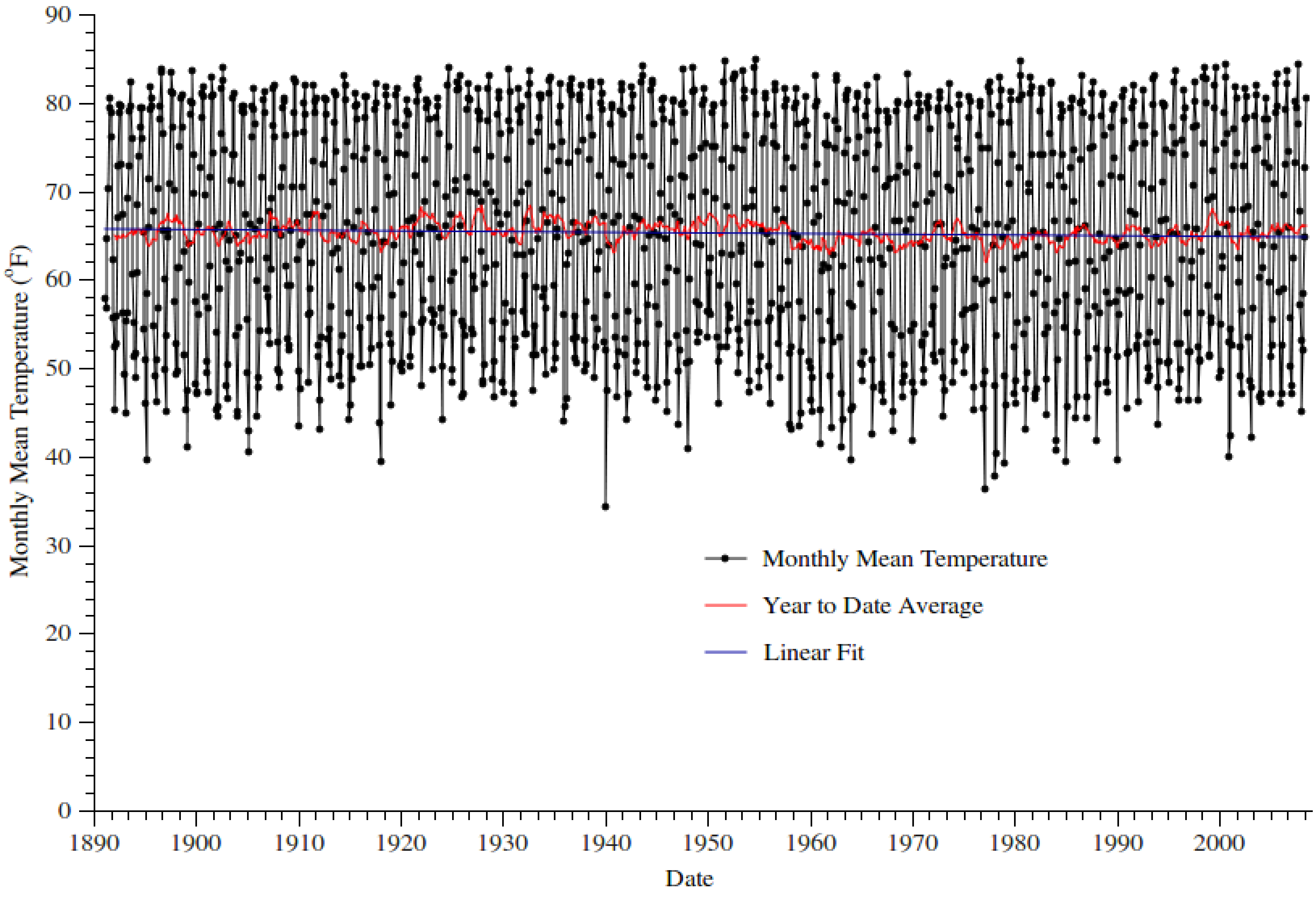

Fig. 33. Grand Gulf monthly mean temperature

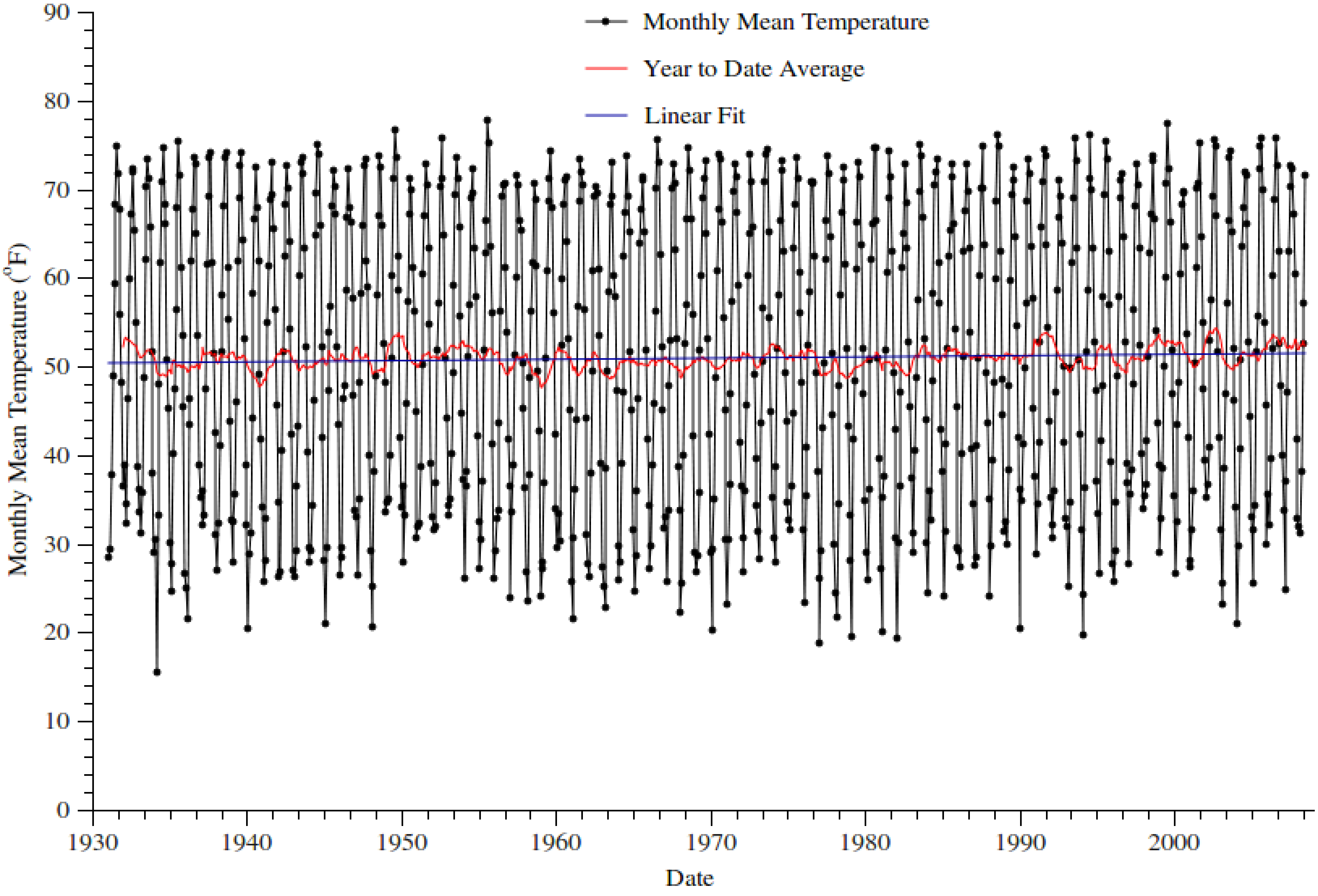

Fig. 34. Indian Point monthly mean temperature

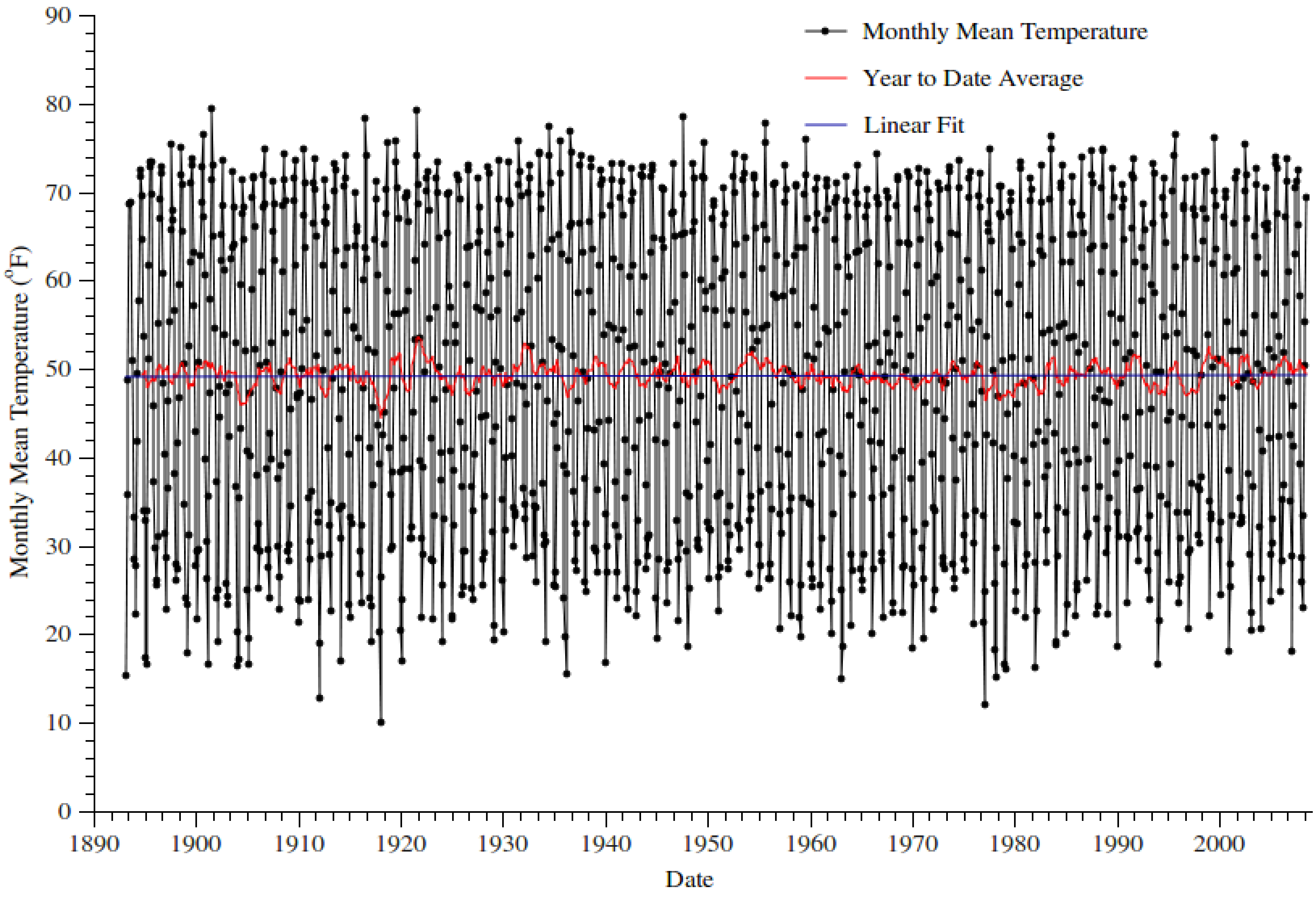

Fig. 35. Palisades monthly mean temperature

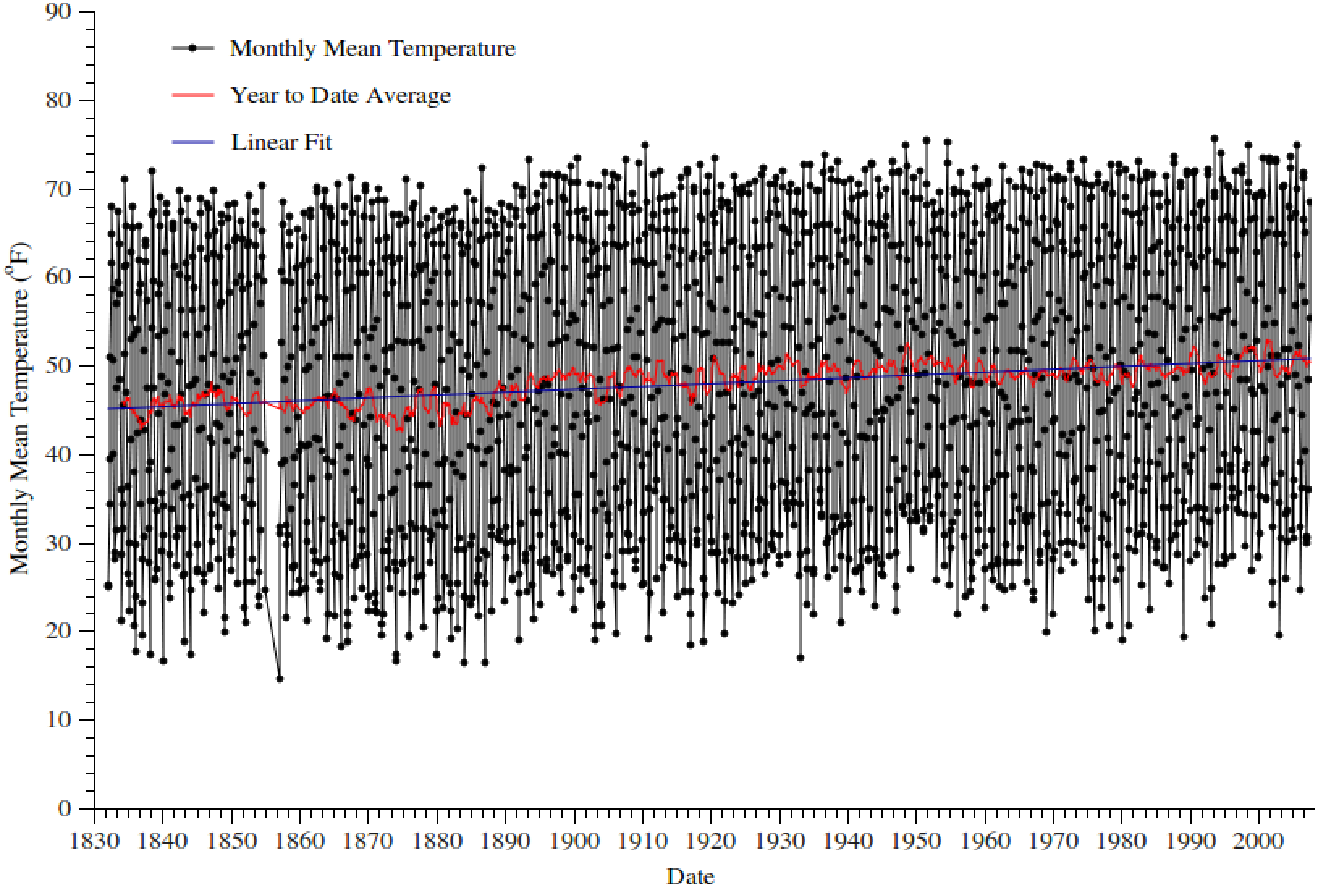

Fig. 36. Pilgrim monthly mean temperature

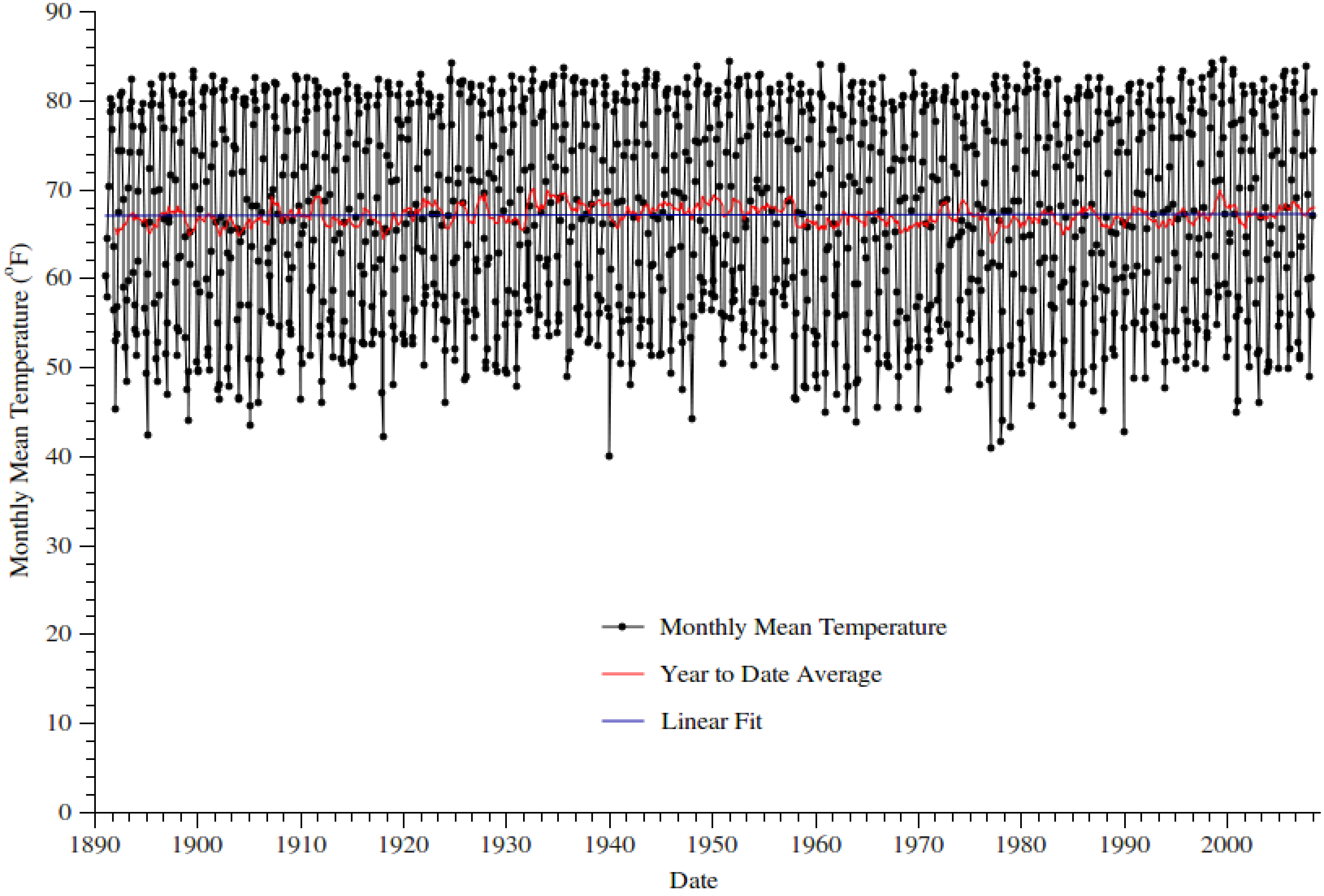

Fig. 37. River Bend monthly mean temperature

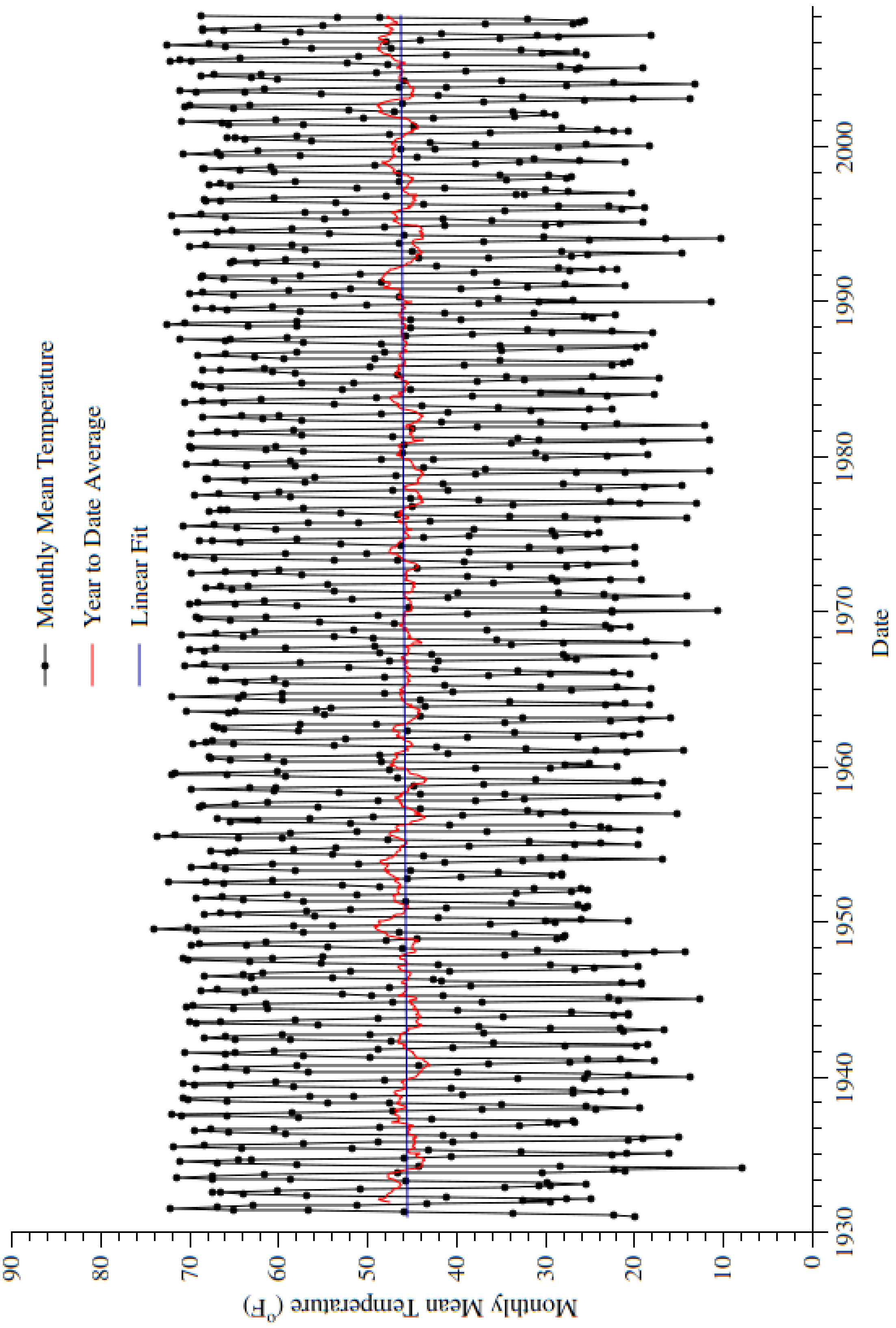

Fig. 38. Vermont Yankee monthly mean temperature

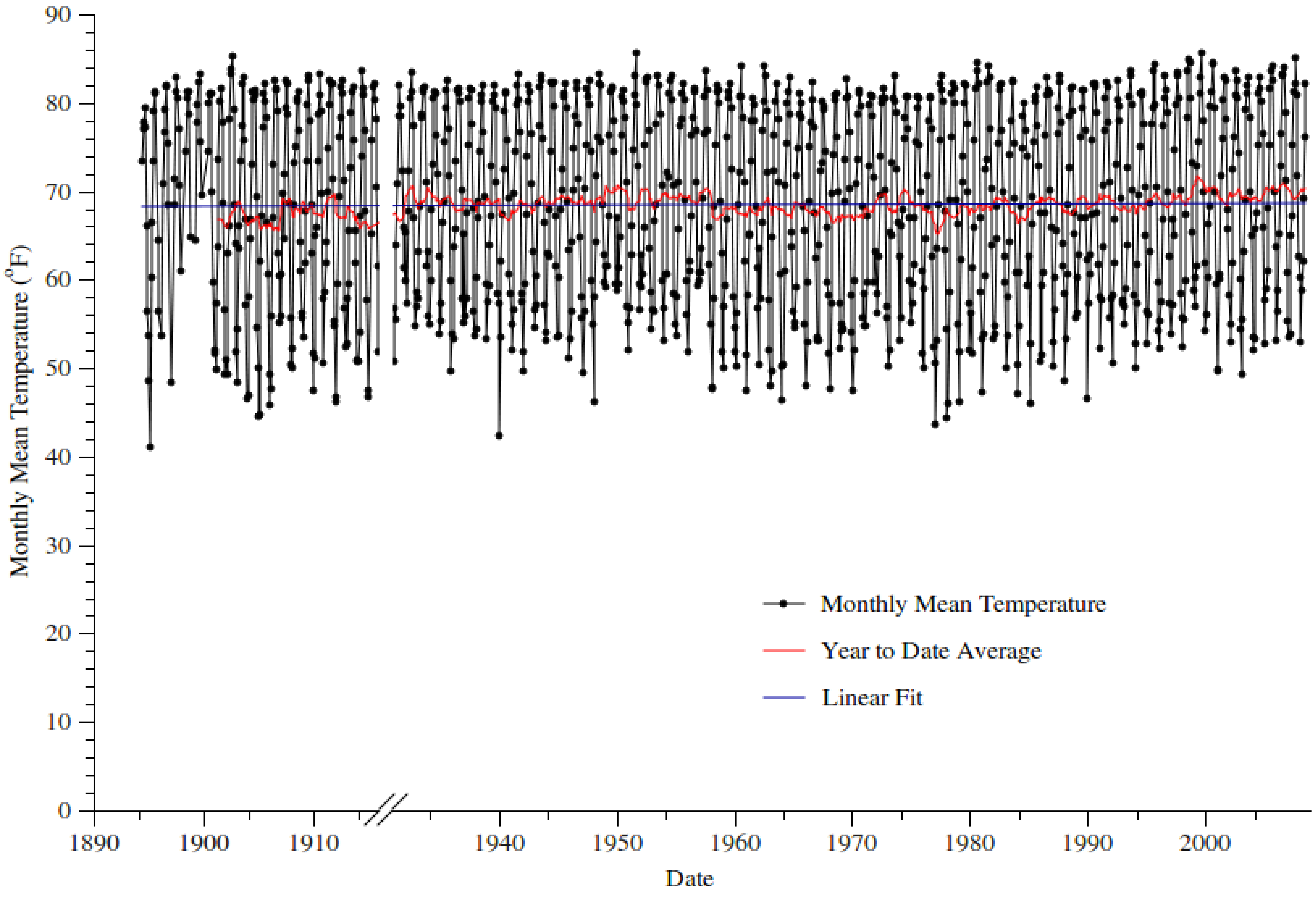

Fig. 39. Waterford monthly mean temperature

# APPENDIX E

## DEPARTURE FROM NORMAL MONTHLY TEMPERATURE

The departure from normal monthly temperature is an indication of the relative stability of climate conditions. The “normal” temperatures are calculated as the mean average temperature recorded for that month, by that station, over the period from 1961-1990.

The data for these composite graphs, including averages, was obtained from NOAA [78] and processed as described in section 3.3.

Arkansas Nuclear One[59]

| | |
|---|---|
| Starting Date | January, 1947 |
| Slope | $1.065 \times 10^{-2} \pm 5.49 \times 10^{-3} \frac{\frac{1}{10}{}^{o}F}{month}$ |
| Initial Value | $-5.4393 \pm 2.3585 \frac{1}{10}\,^{\circ}\mathrm{F}$ |
| RMSE | 31.121 |

Cooper Station[79]

| | |
|---|---|
| Starting Date | January, 1946 |
| Slope | $9.66 \times 10^{-3} \pm 7.011 \times 10^{-3} \frac{\frac{1}{10}{}^{o}F}{month}$ |
| Initial Value | $-3.6693 \pm 3.0631 \frac{1}{10}\,^{\circ}\mathrm{F}$ |
| RMSE | 40.820 |

FitzPatrick[80]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $1.220 \times 10^{-2} \pm 6.01 \times 10^{-3} \frac{\frac{1}{10}{}^{o}F}{month}$ |
| Initial Value | $-3.3902 \pm 2.5239 \frac{1}{10}\,^{\circ}\mathrm{F}$ |
| RMSE | 33.967 |

Grand Gulf[81]

| | |
|---|---|
| Starting Date | January, 1947 |
| Slope | $1.679 \times 10^{-2} \pm 5.32 \times 10^{-3} \frac{\frac{1}{10}{}^{o}F}{month}$ |
| Initial Value | $-8.3275 \pm 2.2308 \frac{1}{10}\,^{\circ}\mathrm{F}$ |
| RMSE | 30.023 |

Indian Point[82]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $1.245 \times 10^{-2} \pm 5.23 \times 10^{-3} \frac{\frac{1}{10}{}^{o}F}{month}$ |
| Initial Value | $-0.69562 \pm 2.1929 \frac{1}{10}\,^{\circ}\mathrm{F}$ |
| RMSE | 29.507 |

Palisades[83]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $1.458 \times 10^{-2} \pm 6.34 \times 10^{-3} \frac{\frac{1}{10}{}^{o}F}{month}$ |
| Initial Value | $-3.3347 \pm 2.6820 \frac{1}{10}\,^{\circ}\mathrm{F}$ |
| RMSE | 35.030 |

Pilgrim[1]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $1.24 \times 10^{-3} \pm 5.16 \times 10^{-3} \frac{\frac{1}{10}{}^{o}F}{month}$ |
| Initial Value | $3.7975 \pm 2.1822 \frac{1}{10}$ °F |
| RMSE | 28.502 |

River Bend[84]

| | |
|---|---|
| Starting Date | February, 1947 |
| Slope | $1.522 \times 10^{-2} \pm 4.95 \times 10^{-3} \frac{\frac{1}{10}{}^{o}F}{month}$ |
| Initial Value | $-7.4546 \pm 2.1291 \frac{1}{10}$ °F |
| RMSE | 28.093 |

Vermont Yankee[85]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $1.356 \times 10^{-2} \pm 5.91 \times 10^{-3} \frac{\frac{1}{10}{}^{o}F}{month}$ |
| Initial Value | $-1.7657 \pm 2.4800 \frac{1}{10}$ °F |
| RMSE | 33.377 |

Waterford[86]

| | |
|---|---|
| Starting Date | January, 1894 |
| Slope | $1.633 \times 10^{-2} \pm 4.94 \times 10^{-3} \frac{\frac{1}{10}{}^{o}F}{month}$ |
| Initial Value | $-5.351 \pm 2.0716 \frac{1}{10}$ °F |
| RMSE | 27.880 |

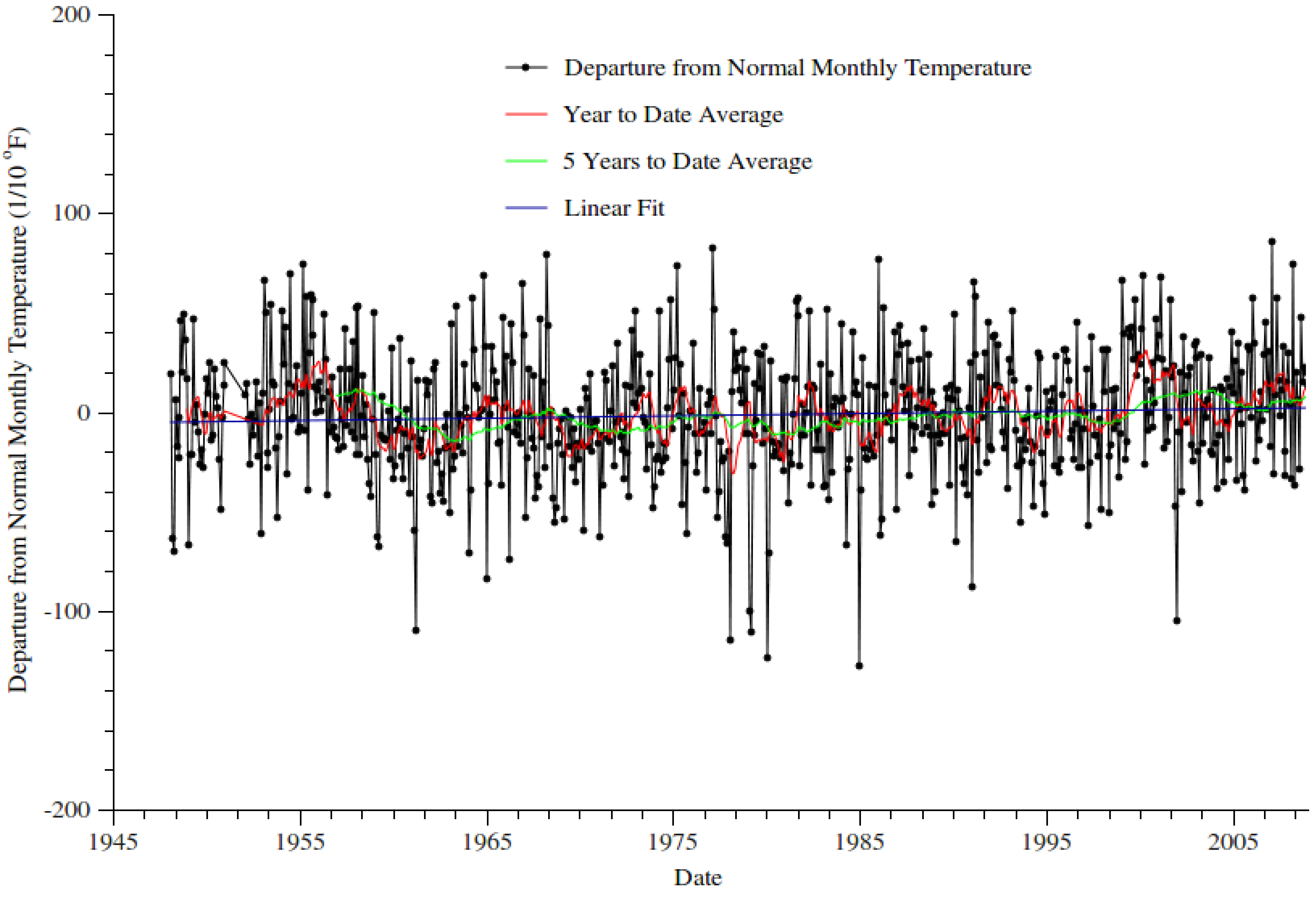

Fig. 40. Arkansas Nuclear One departure from normal monthly temperature

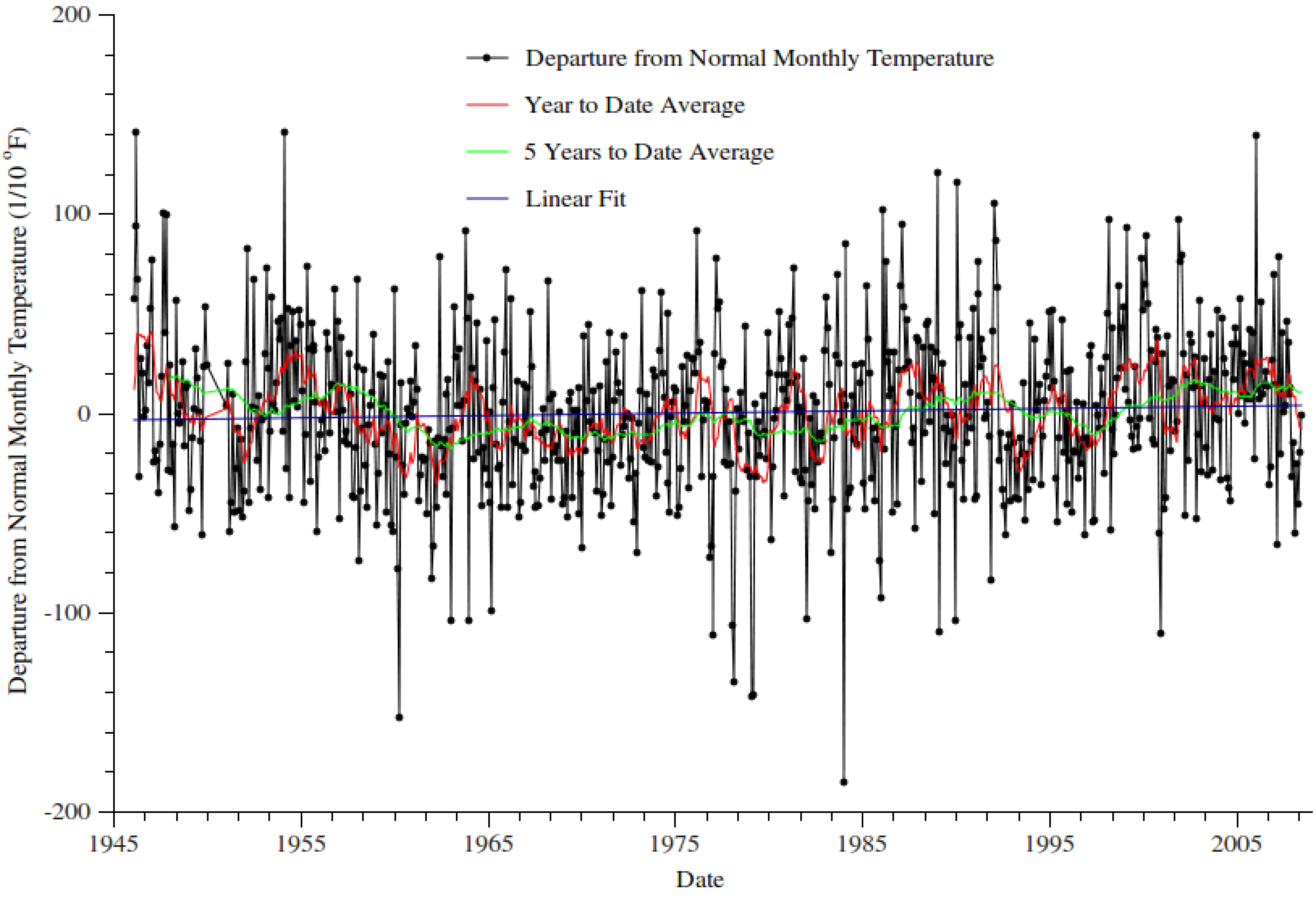

Fig. 41. Cooper Station departure from normal monthly temperature

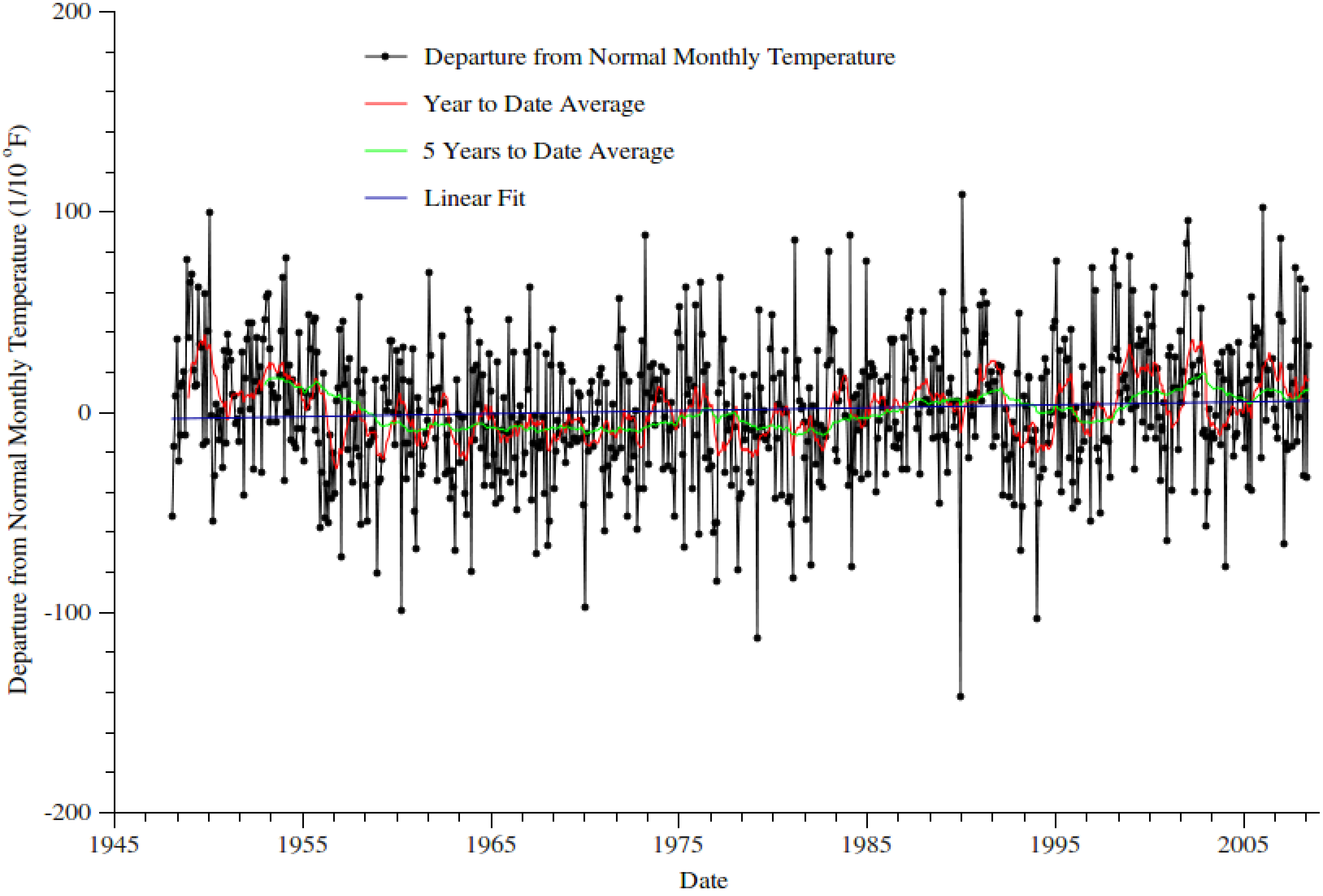

Fig. 42. James A. FitzPatrick departure from normal monthly temperature

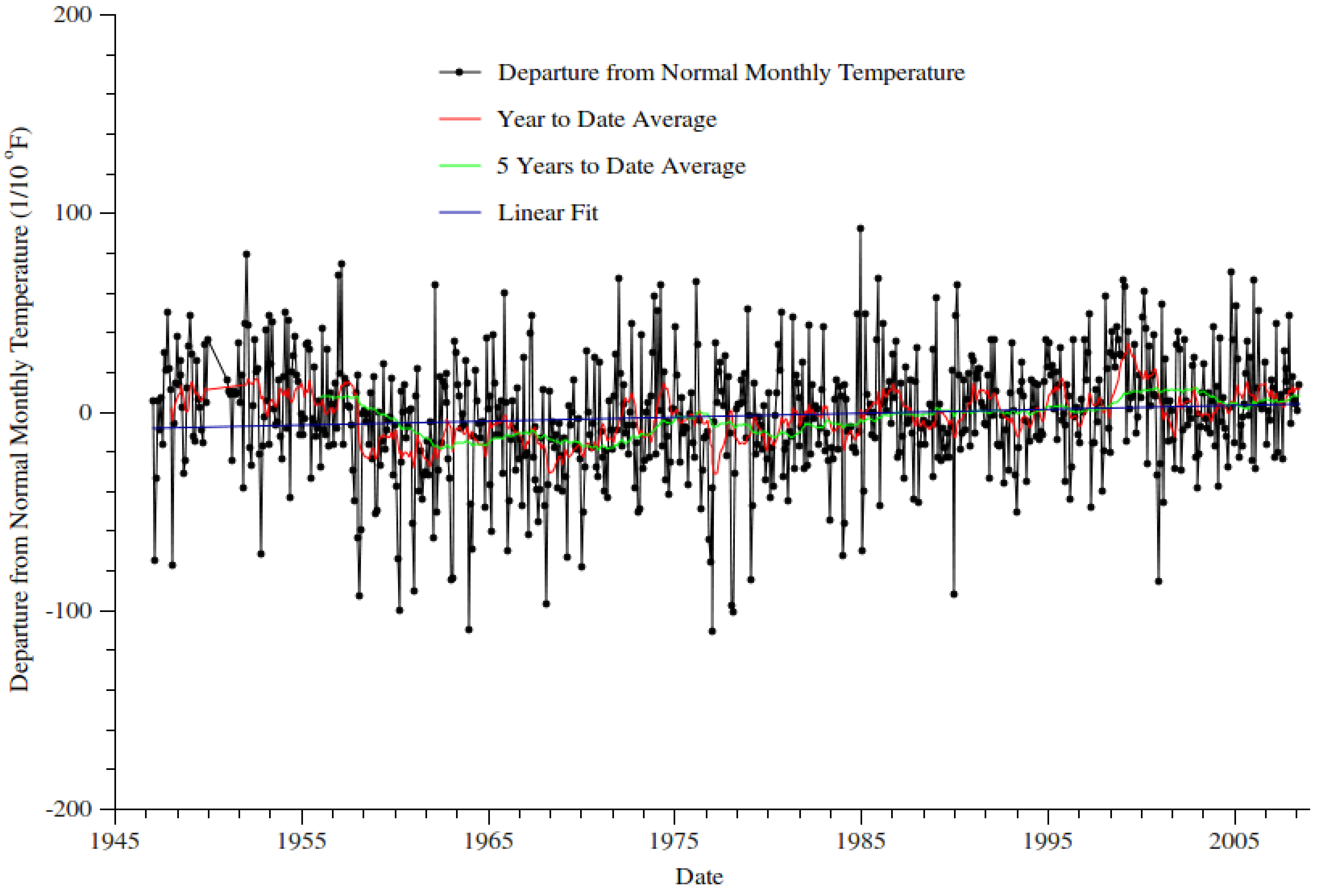

Fig. 43. Grand Gulf departure from normal monthly temperature

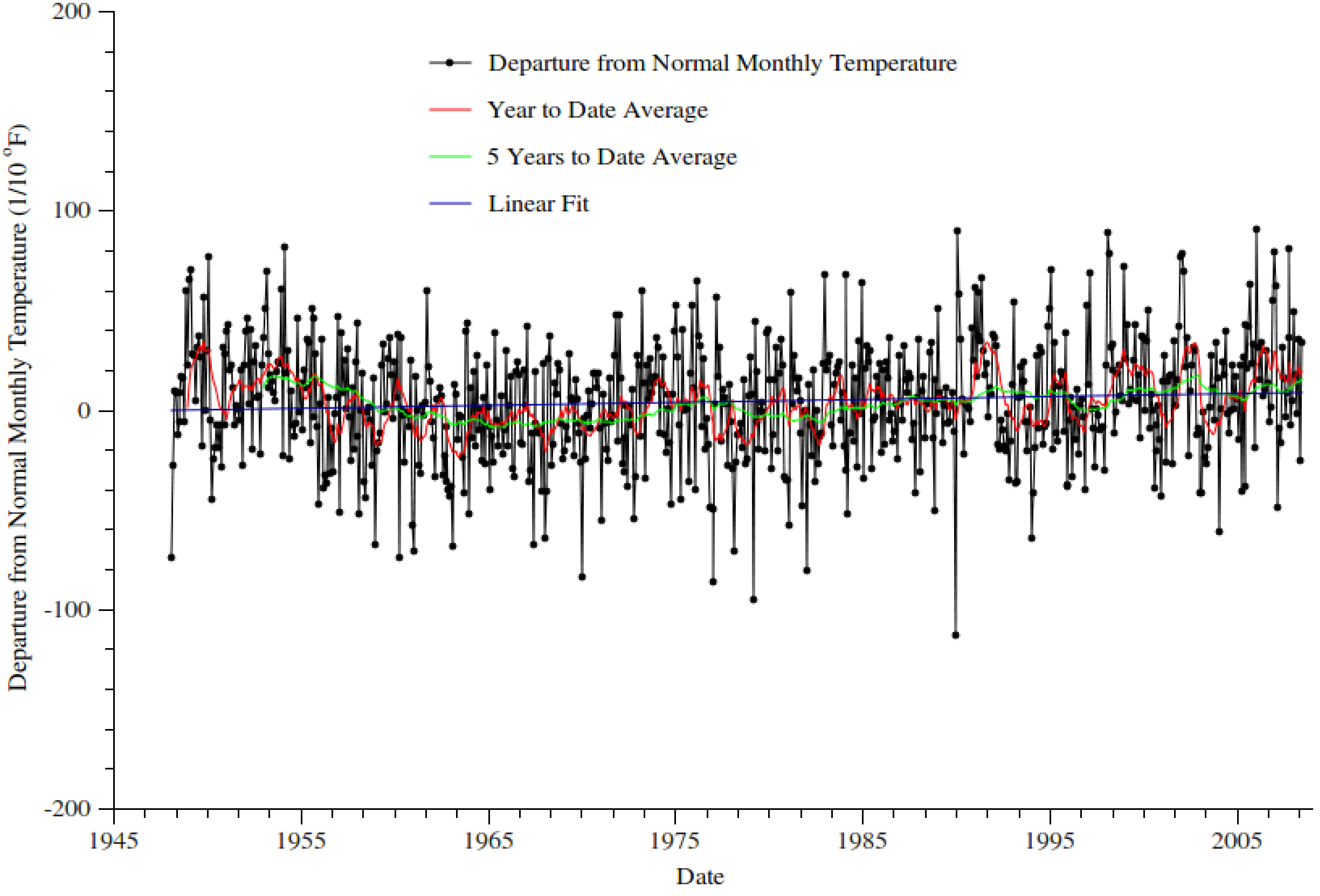

Fig. 44. Indian Point departure from normal monthly temperature

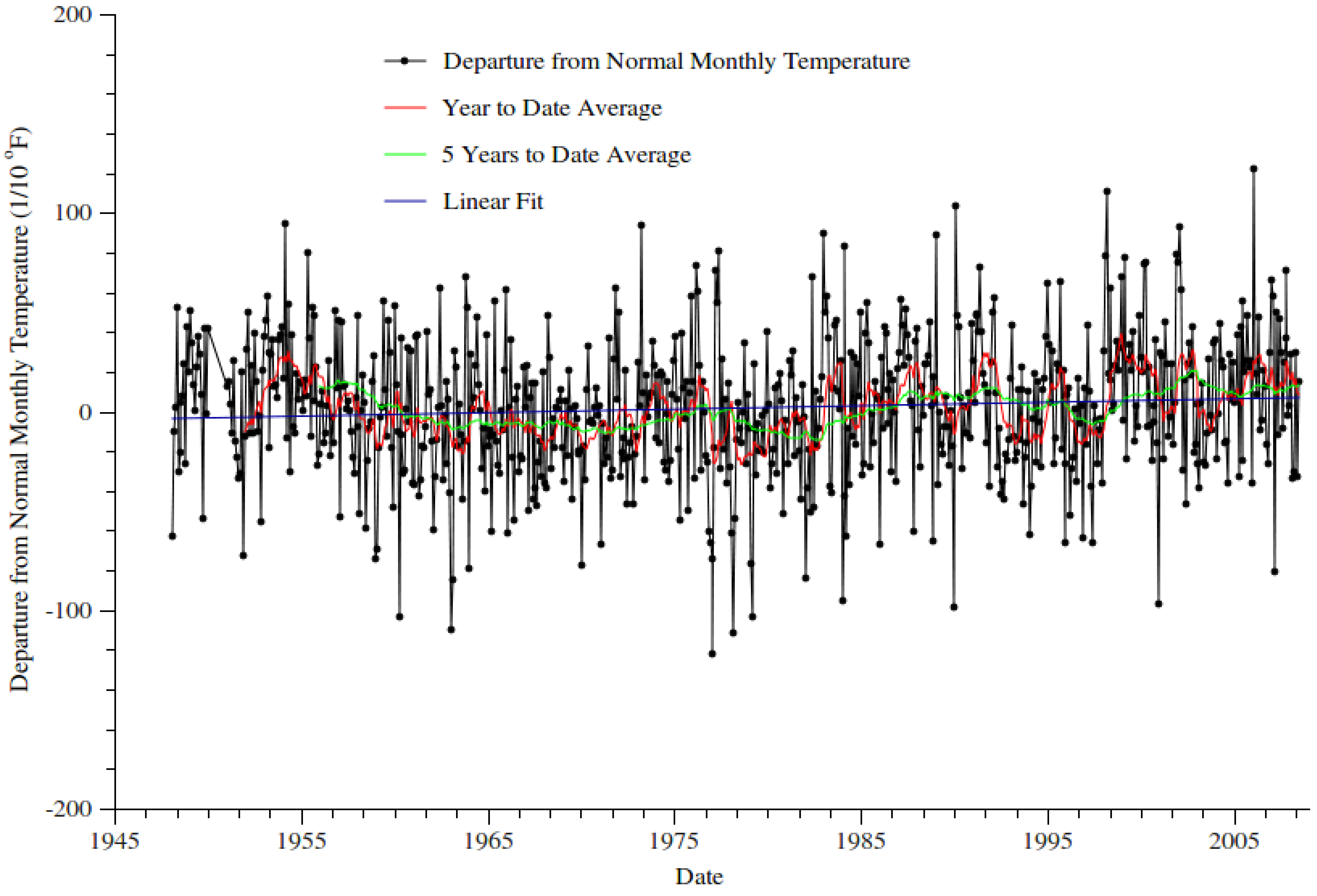

Fig. 45. Palisades departure from normal monthly temperature

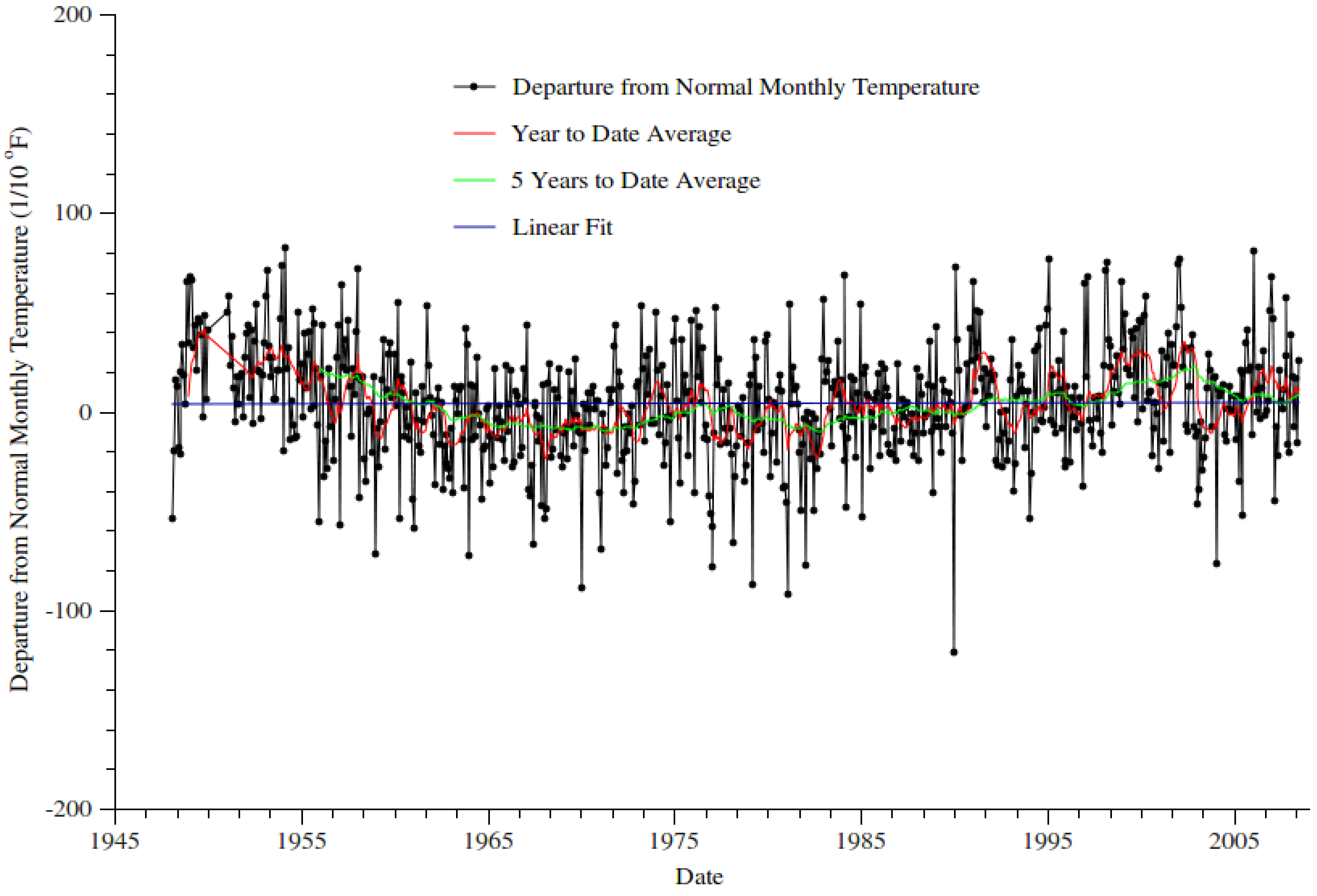

Fig. 46. Pilgrim departure from normal monthly temperature

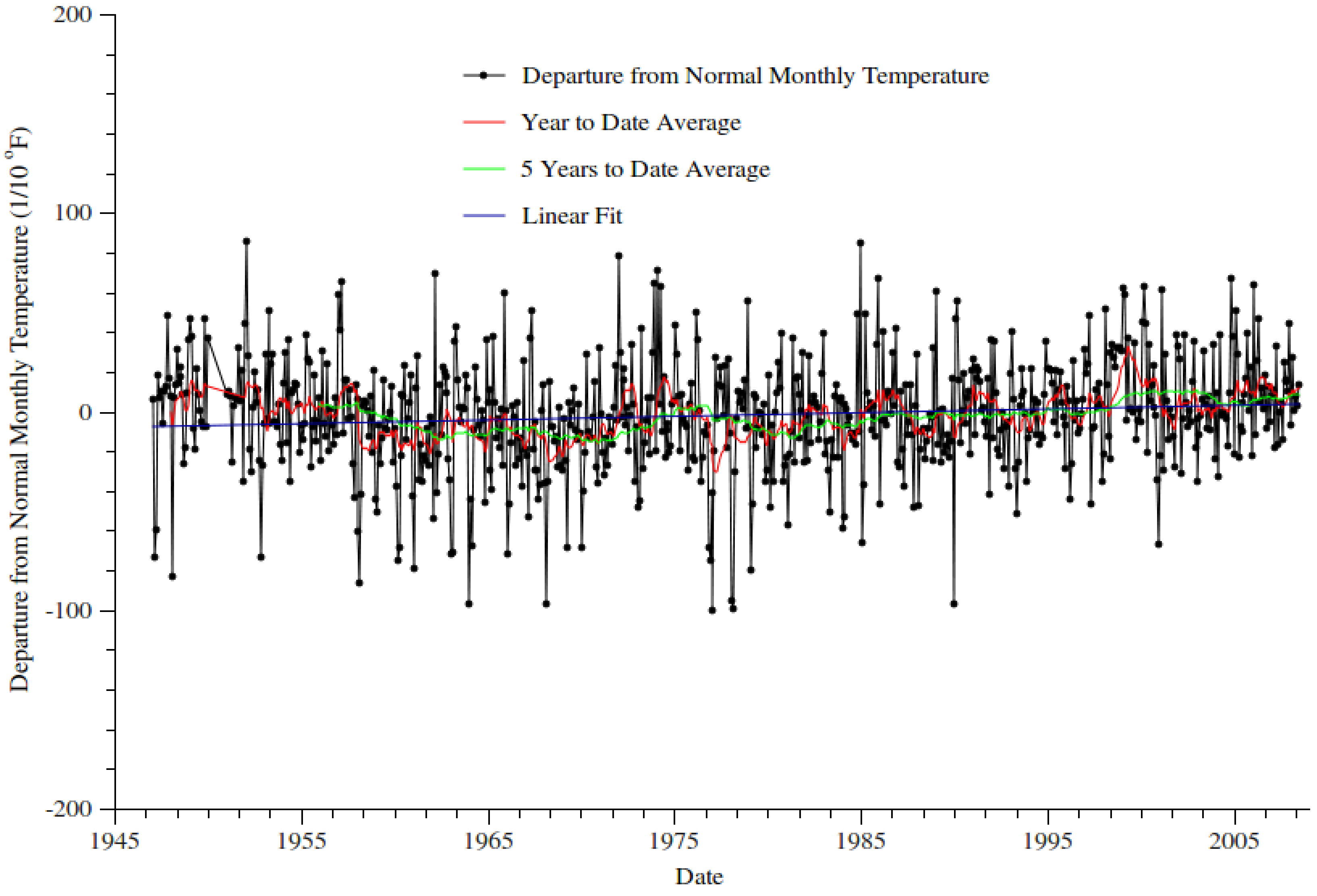

Fig. 47. River Bend departure from normal monthly temperature

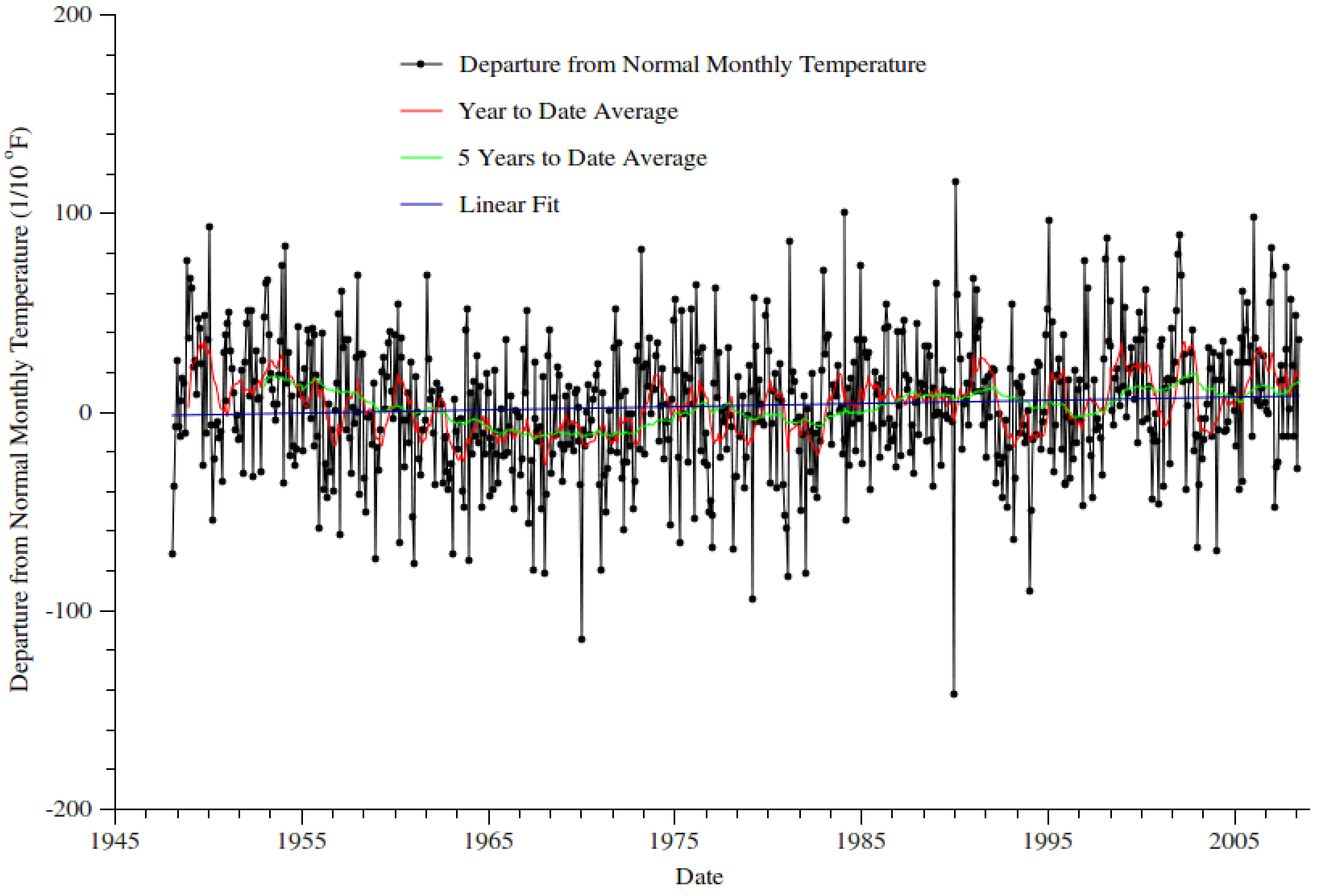

Fig. 48. Vermont Yankee departure from normal monthly temperature

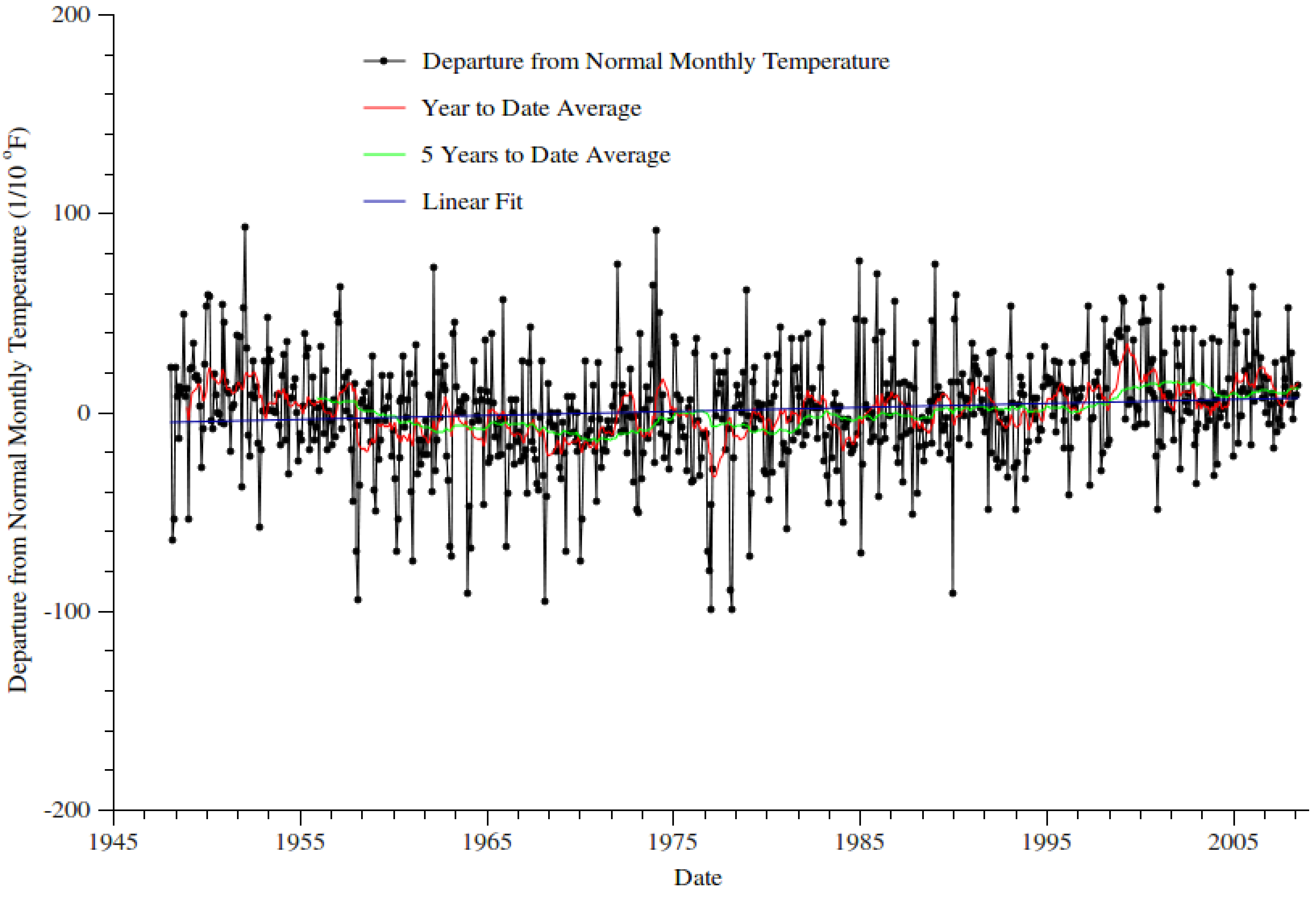

Fig. 49. Waterford departure from normal monthly temperature

# APPENDIX F

## COOLING DEGREE DAYS

As described above, cooling degree days are a measure of the amount of time during which the temperature is above the specified baseline of 65 °F. An increase in cooling degree days indicates milder winters and longer warm seasons.

The data for these composite graphs was obtained from NOAA [78] and processed as described in section 3.3.

Arkansas Nuclear One[59]

| | |
|---|---|
| Slope | $2.79\times10^{-3}\pm0.10064\frac{CLDD}{month}$ |
| Initial Value | $148.50\pm19.916$CLDD |
| RMSE | 183.75 |

Cooper Station[79]

| | |
|---|---|
| Slope | $-3.313\times10^{-2}\pm7.641\times10^{-2}\frac{CLDD}{month}$ |
| Initial Value | $104.85\pm15.121$CLDD |
| RMSE | 139.51 |

FitzPatrick[80]

| | |
|---|---|
| Slope | $3.198\times10^{-2}\pm3.411\times10^{-2}\frac{CLDD}{month}$ |
| Initial Value | $33.060\pm6.7502$CLDD |
| RMSE | 62.280 |

Grand Gulf[81]

| | |
|---|---|
| Slope | $3.205\times10^{-2}\pm0.10990\frac{CLDD}{month}$ |
| Initial Value | $190.19\pm21.747$CLDD |
| RMSE | 200.65 |

Indian Point[82]

| | |
|---|---|
| Slope | $2.389\times10^{-2}\pm5.564\times10^{-2}\frac{CLDD}{month}$ |
| Initial Value | $63.523\pm11.010$CLDD |
| RMSE | 101.58 |

Palisades[83]

| | |
|---|---|
| Slope | $-4.62\times10^{-3}\pm5.025\times10^{-2}\frac{CLDD}{month}$ |
| Initial Value | $62.368\pm9.9437$CLDD |
| RMSE | 91.744 |

Pilgrim[1]

| | |
|---|---|
| Slope | $3.292\times10^{-2}\pm4.493\times10^{-2}\frac{CLDD}{month}$ |
| Initial Value | $45.457\pm8.8910$CLDD |
| RMSE | 82.031 |

River Bend[84]

| | |
|---|---|
| Slope | $4.095 \times 10^{-2} \pm 0.11091 \frac{CLDD}{month}$ |
| Initial Value | $206.92 \pm 21.947$CLDD |
| RMSE | 202.49 |

Vermont Yankee[85]

| | |
|---|---|
| Slope | $1.878 \times 10^{-2} \pm 4.63 \times 10^{-3} \frac{CLDD}{month}$ |
| Initial Value | $33.753 \pm 0.93676$CLDD |
| RMSE | 8.1233 |

Waterford[86]

| | |
|---|---|
| Slope | $0.10306 \pm 1.145 \times 10^{-2} \frac{CLDD}{month}$ |
| Initial Value | $221.83 \pm 2.3173$CLDD |
| RMSE | 20.095 |

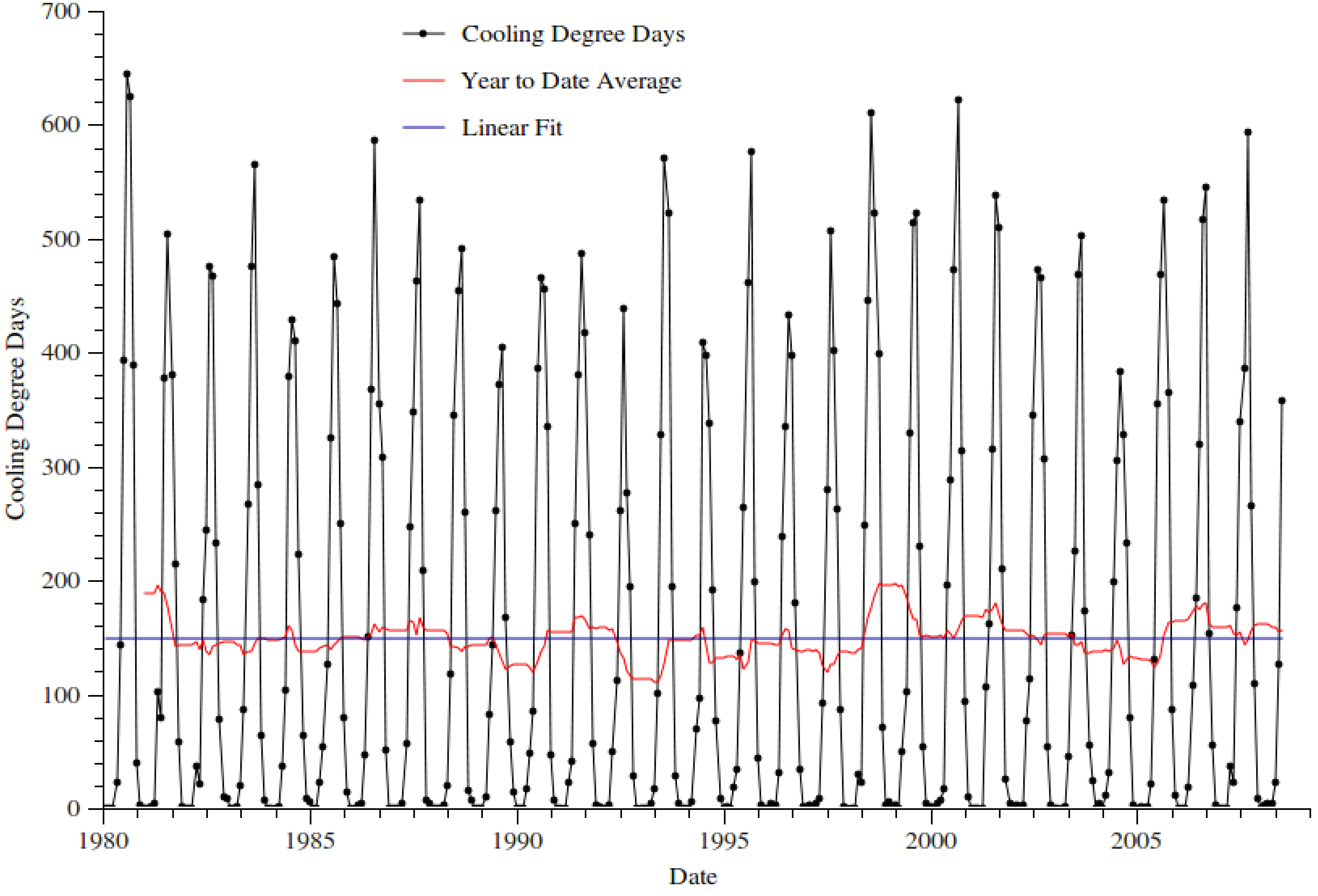

Fig. 50. Arkansas Nuclear One cooling degree days

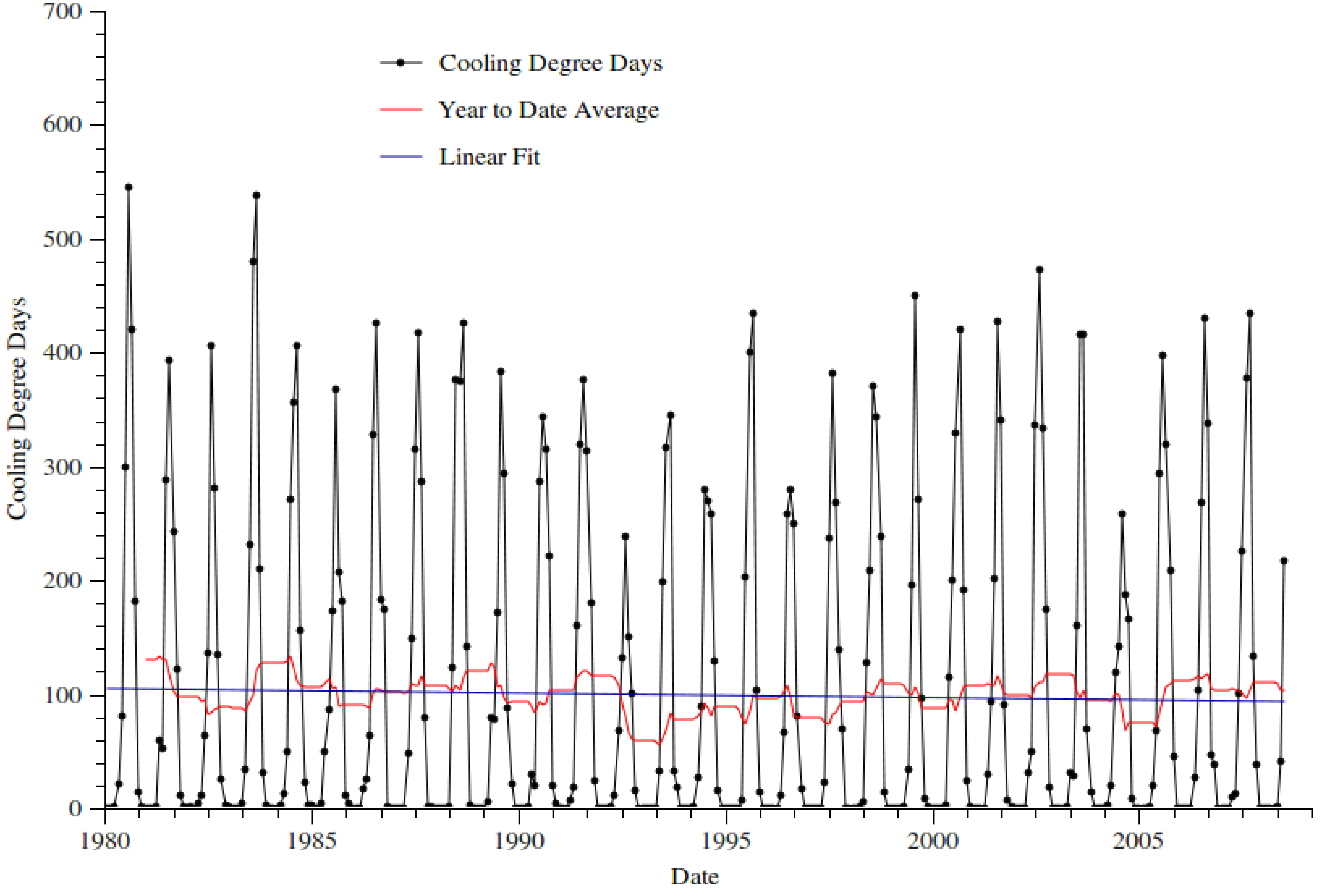

Fig. 51. Cooper Station cooling degree days

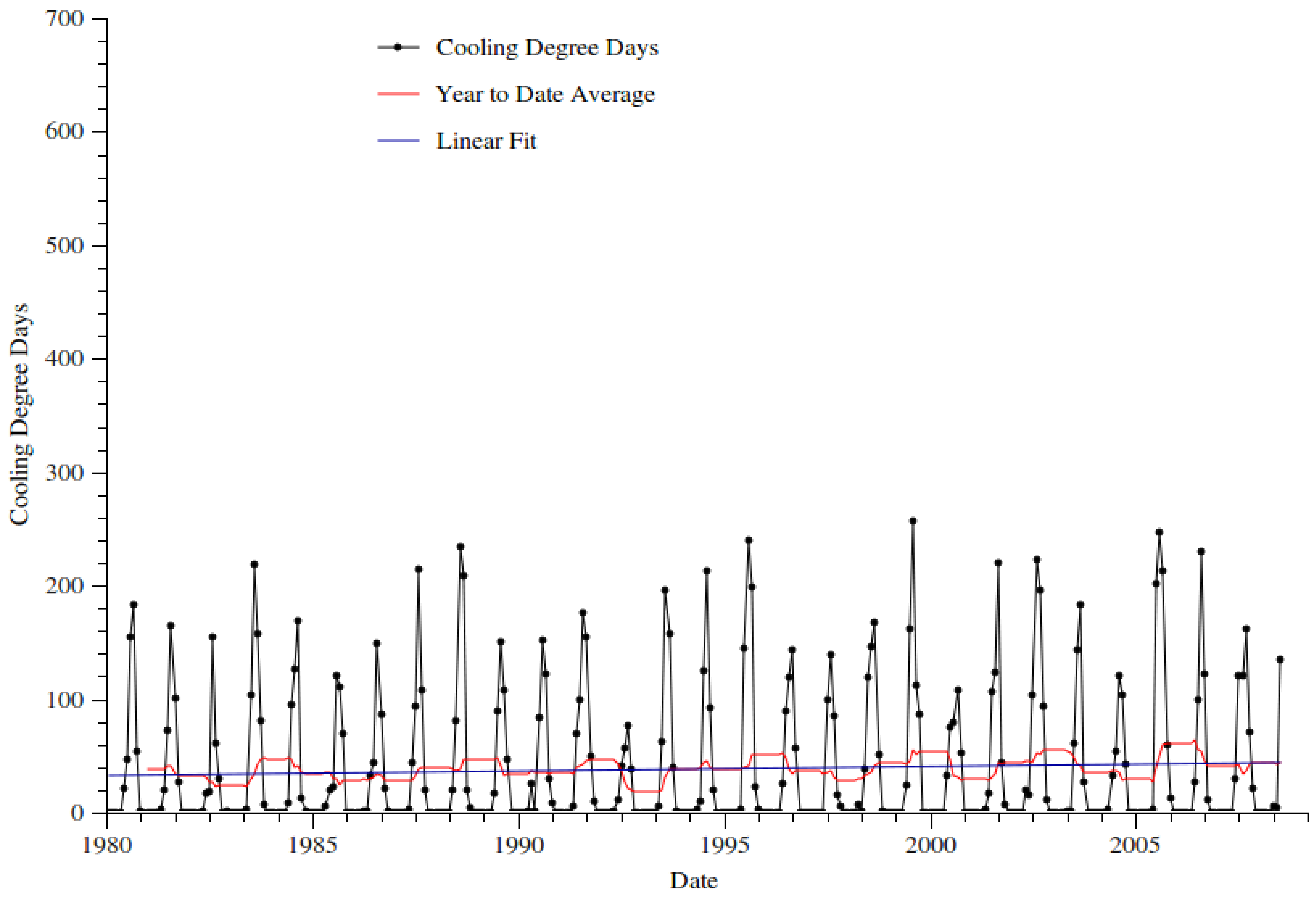

Fig. 52. James A. FitzPatrick cooling degree days

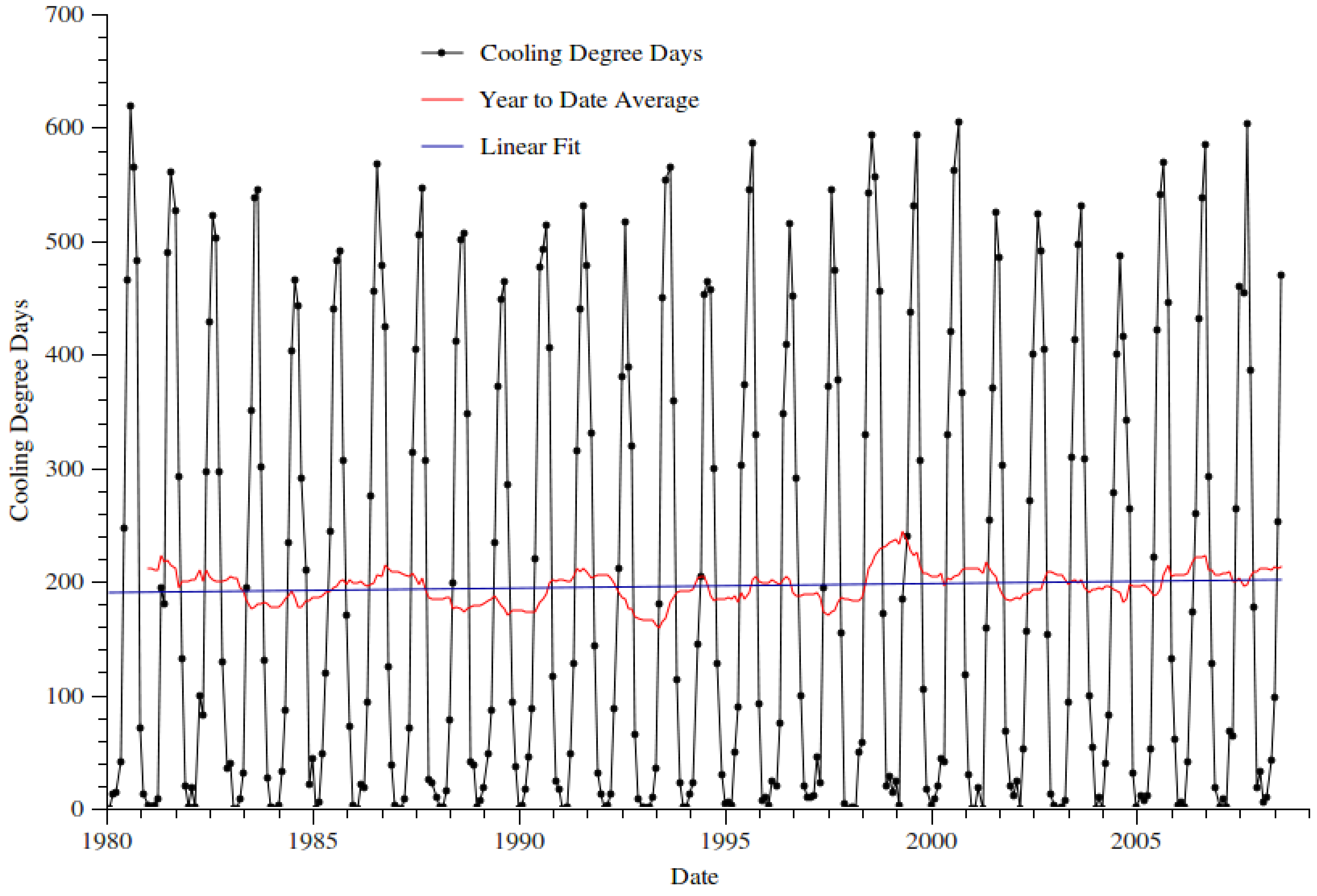

Fig. 53. Grand Gulf cooling degree days

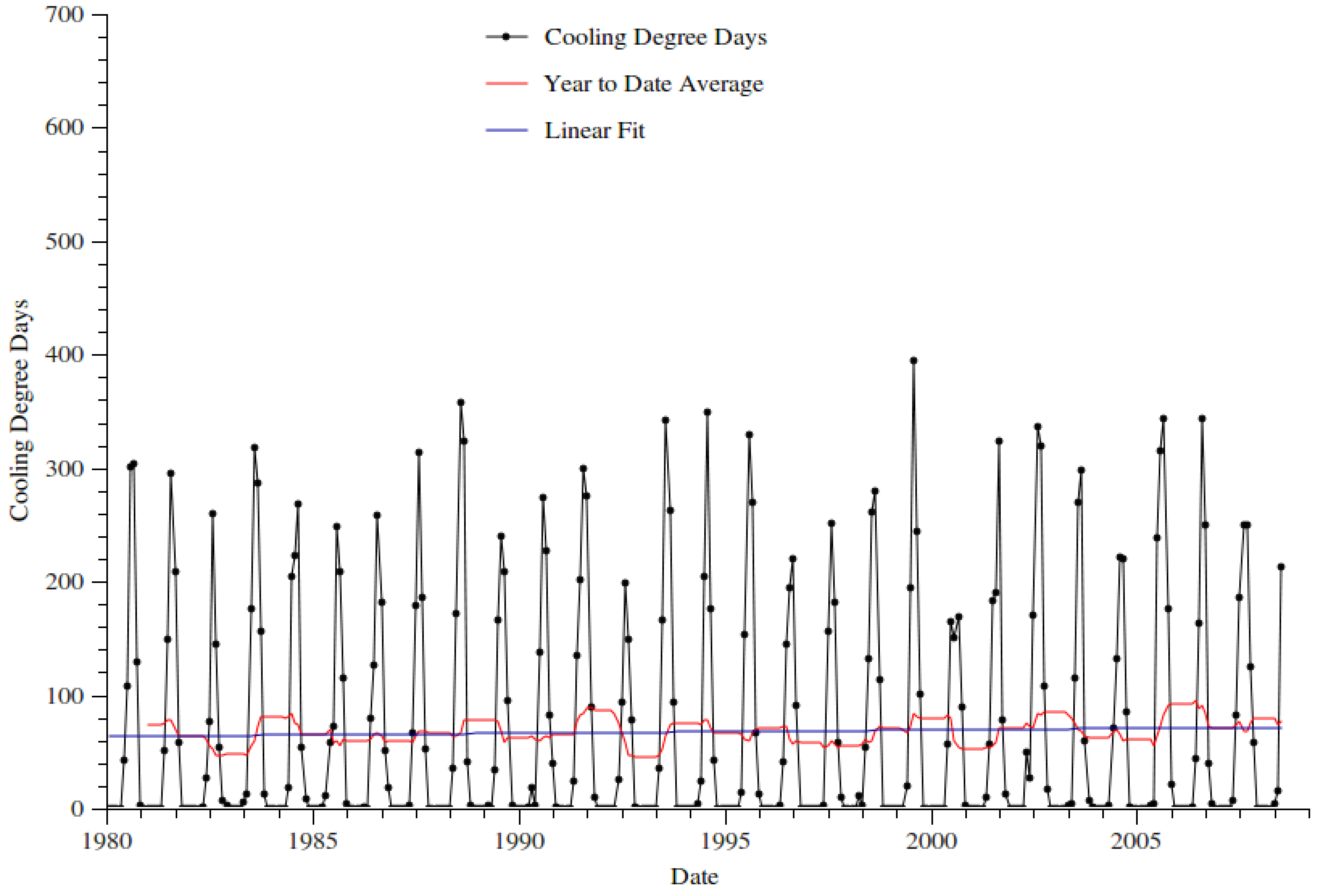

Fig. 54. Indian Point cooling degree days

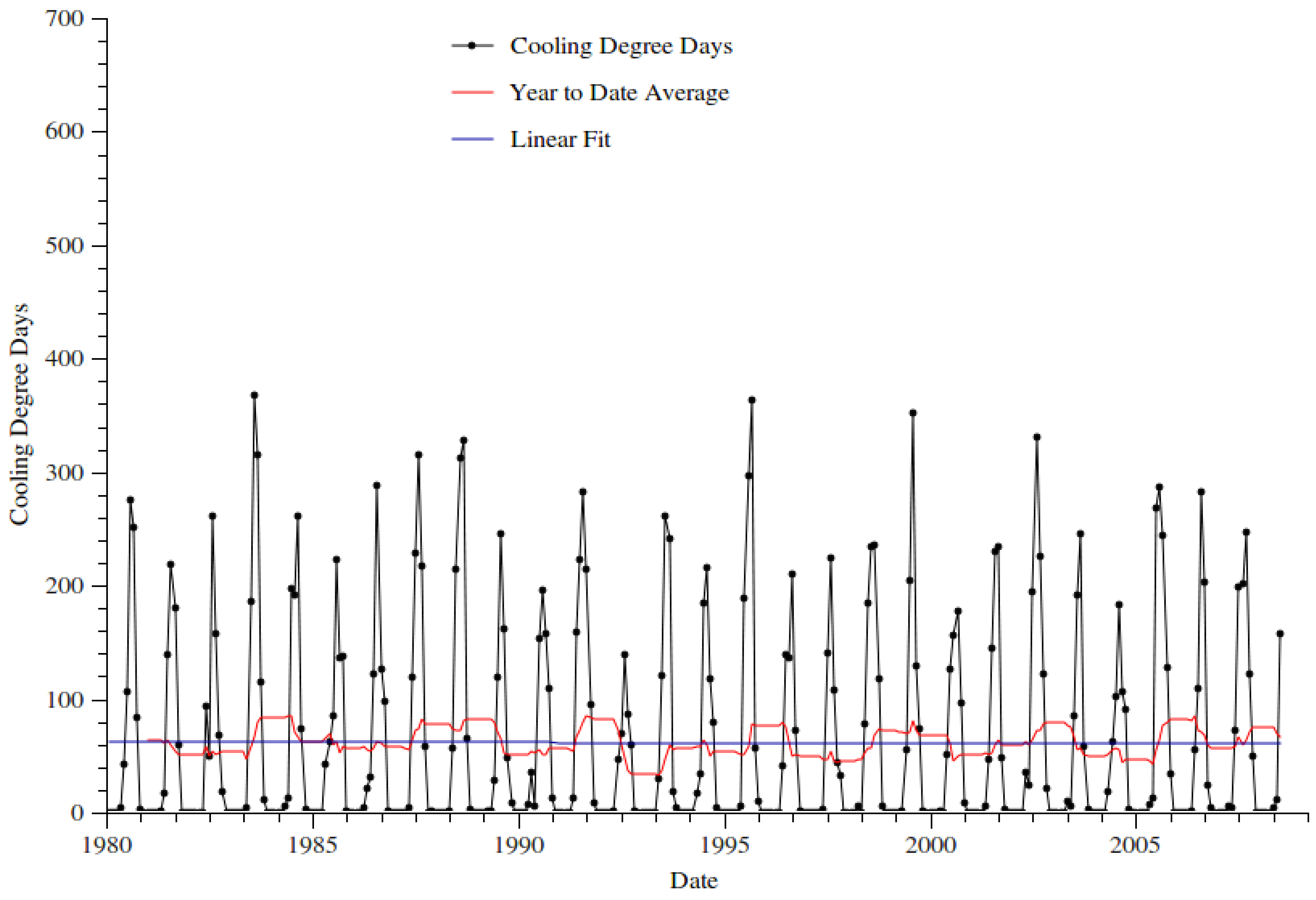

Fig. 55. Palisades cooling degree days

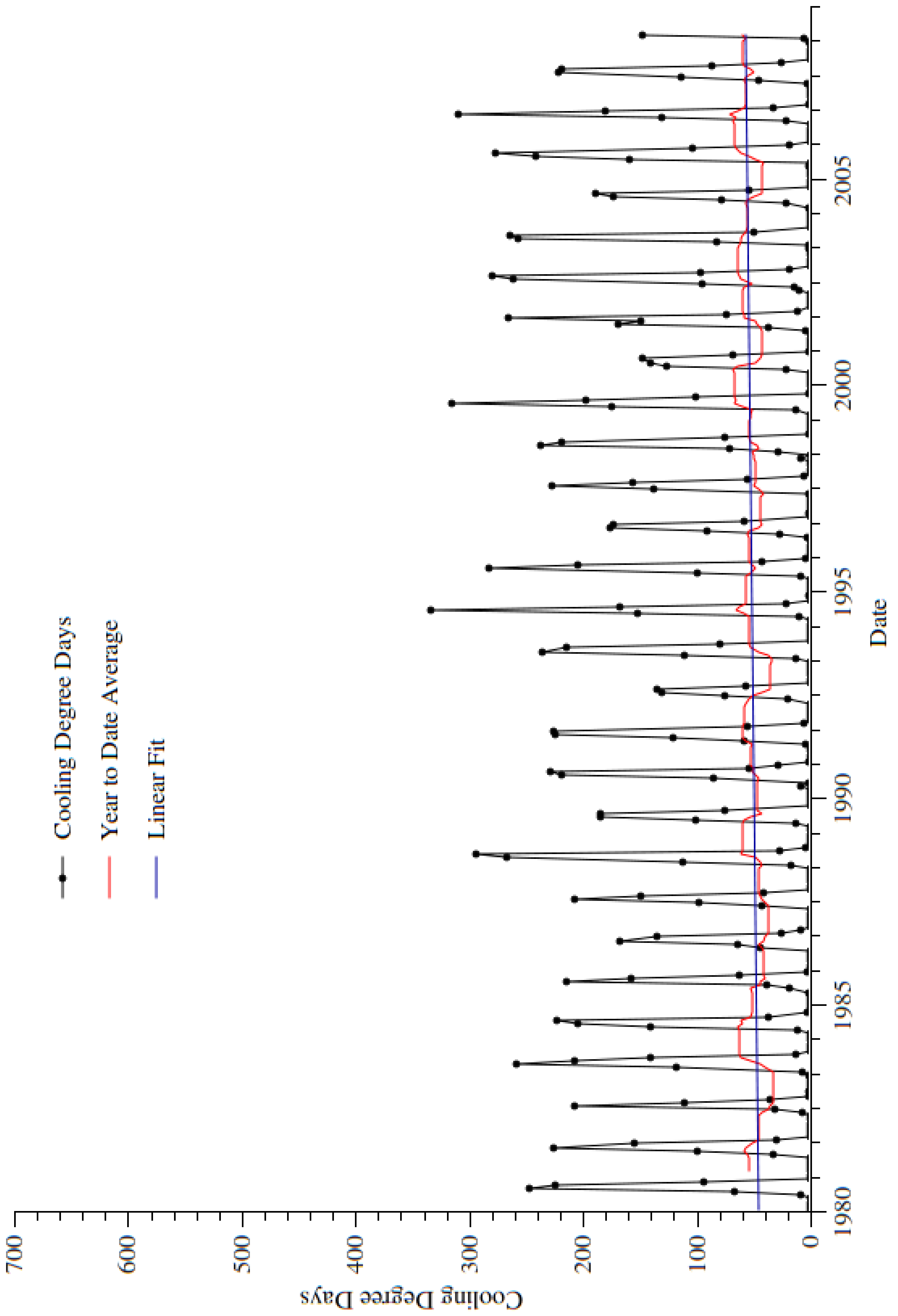

Fig. 56. Pilgrim cooling degree days

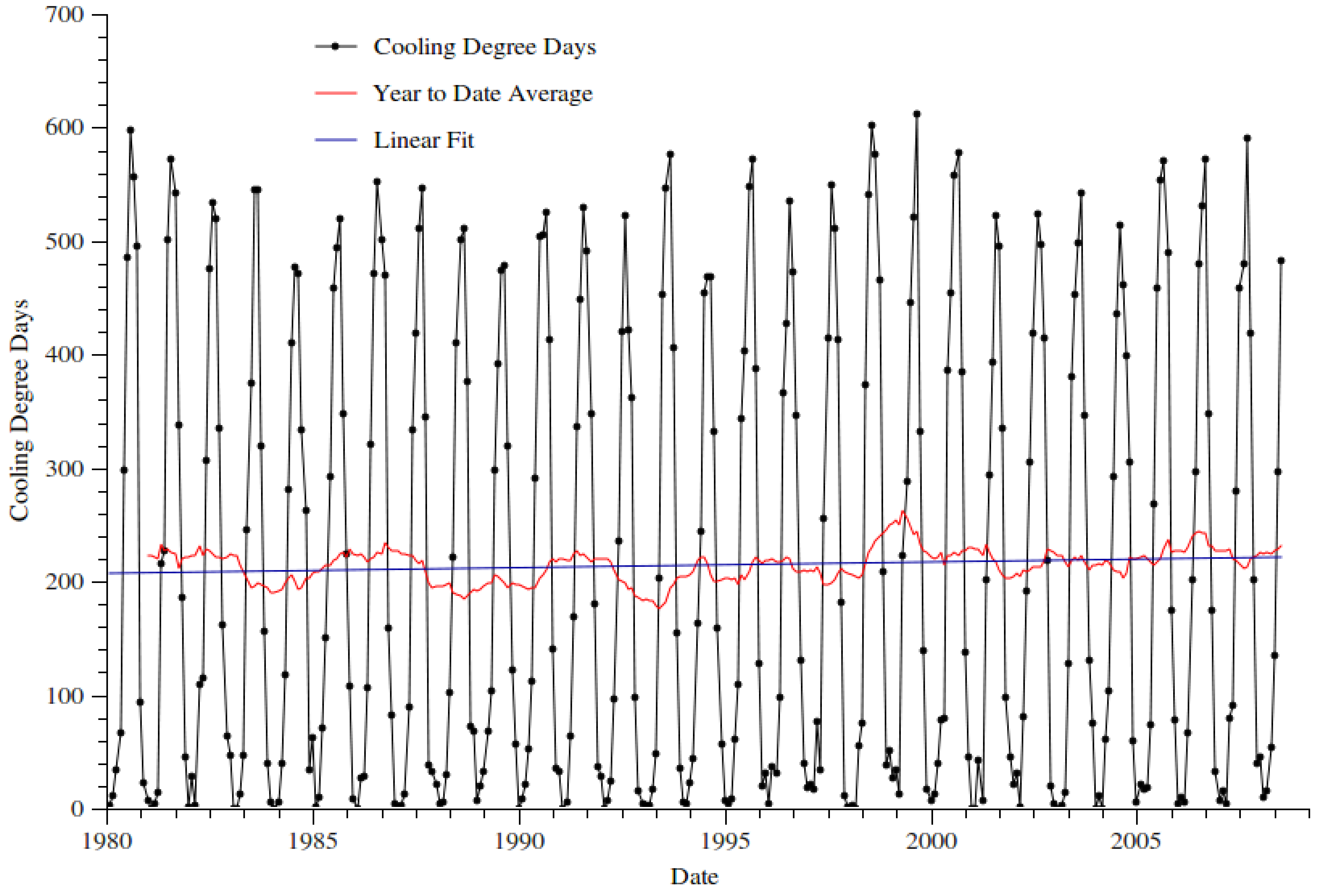

Fig. 57. River Bend cooling degree days

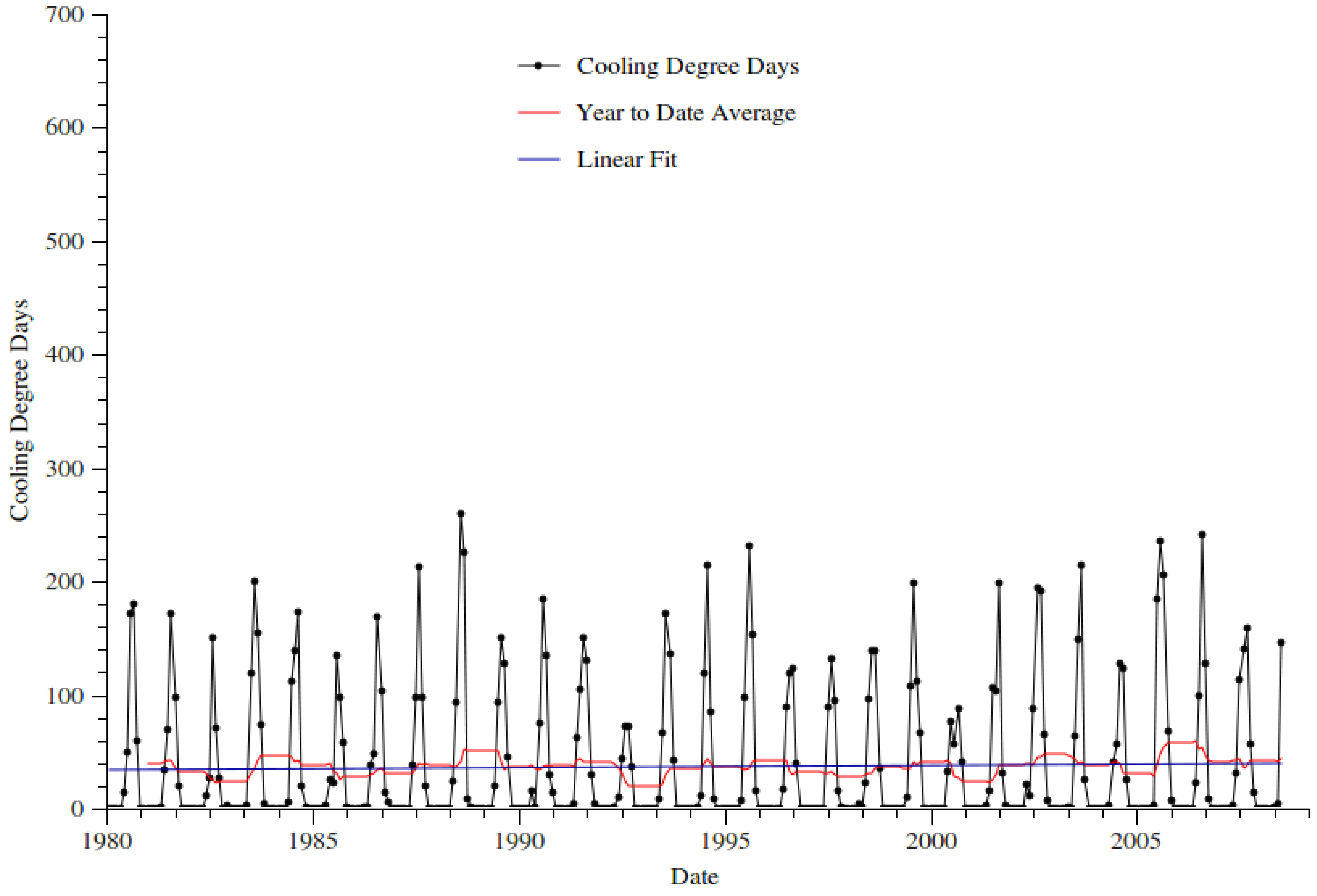

Fig. 58. Vermont Yankee cooling degree days

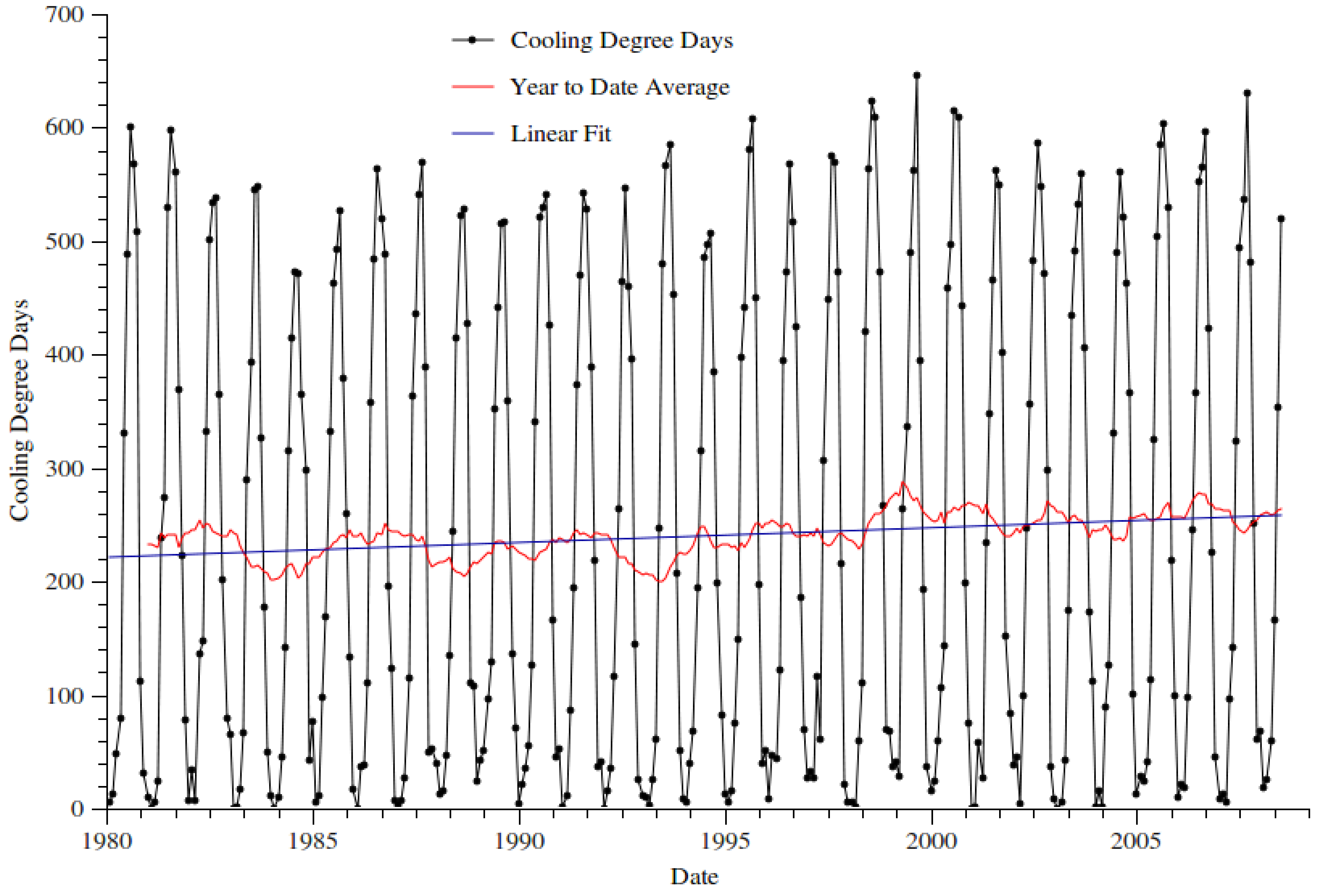

Fig. 59. Waterford cooling degree days

# APPENDIX G

## HEATING DEGREE DAYS

Heating degree days is a measure of the amount of time below 65°F. Contrary to cooling degree days, an increase in heating degree days indicates cooler summers and shorter warm periods.

The data for these composite graphs was obtained from NOAA [78] and processed as described in section 3.3.

Arkansas Nuclear One[59]

| | |
|---|---|
| Slope | $1.12\times10^{-3}\pm5.778\times10^{-2}\frac{HTDD}{month}$ |
| Initial Value | $286.26\pm23.043$HTDD |
| RMSE | 302.31 |

Cooper Station[79]

| | |
|---|---|
| Slope | $6.35\times10^{-3}\pm8.808\times10^{-2}\frac{HTDD}{month}$ |
| Initial Value | $483.15\pm35.127$HTDD |
| RMSE | 460.85 |

FitzPatrick[80]

| | |
|---|---|
| Slope | $-4.55\times10^{-3}\pm9.153\times10^{-2}\frac{HTDD}{month}$ |
| Initial Value | $604.70\pm36.502$HTDD |
| RMSE | 478.89 |

Grand Gulf[81]

| | |
|---|---|
| Slope | $-1.2\times10^{-4}\pm4.134\times10^{-2}\frac{HTDD}{month}$ |
| Initial Value | $186.09\pm16.489$HTDD |
| RMSE | 216.33 |

Indian Point[82]

| | |
|---|---|
| Slope | $-3.900\times10^{-2}\pm7.963\times10^{-2}\frac{HTDD}{month}$ |
| Initial Value | $495.52\pm31.757$HTDD |
| RMSE | 416.64 |

Palisades[83]

| | |
|---|---|
| Slope | $-1.493\times10^{-2}\pm8.693\times10^{-2}\frac{HTDD}{month}$ |
| Initial Value | $538.01\pm34.670$HTDD |
| RMSE | 454.86 |

Pilgrim[1]

| | |
|---|---|
| Slope | $-2.442\times10^{-2}\pm7.866\times10^{-2}\frac{HTDD}{month}$ |
| Initial Value | $515.08\pm31.370$HTDD |
| RMSE | 411.57 |

River Bend[84]

| | |
|---|---|
| Slope | $-3.93 \times 10^{-3} \pm 3.420 \times 10^{-2} \frac{HTDD}{month}$ |
| Initial Value | $147.88 \pm 13.638$HTDD |
| RMSE | 178.92 |

Vermont Yankee[85]

| | |
|---|---|
| Slope | $-7.25 \times 10^{-3} \pm 9.196 \times 10^{-2} \frac{HTDD}{month}$ |
| Initial Value | $609.31 \pm 36.673$HTDD |
| RMSE | 481.13 |

Waterford[86]

| | |
|---|---|
| Slope | $-2.353 \times 10^{-2} \pm 2.887 \times 10^{-2} \frac{HTDD}{month}$ |
| Initial Value | $135.45 \pm 11.513$HTDD |
| RMSE | 151.05 |

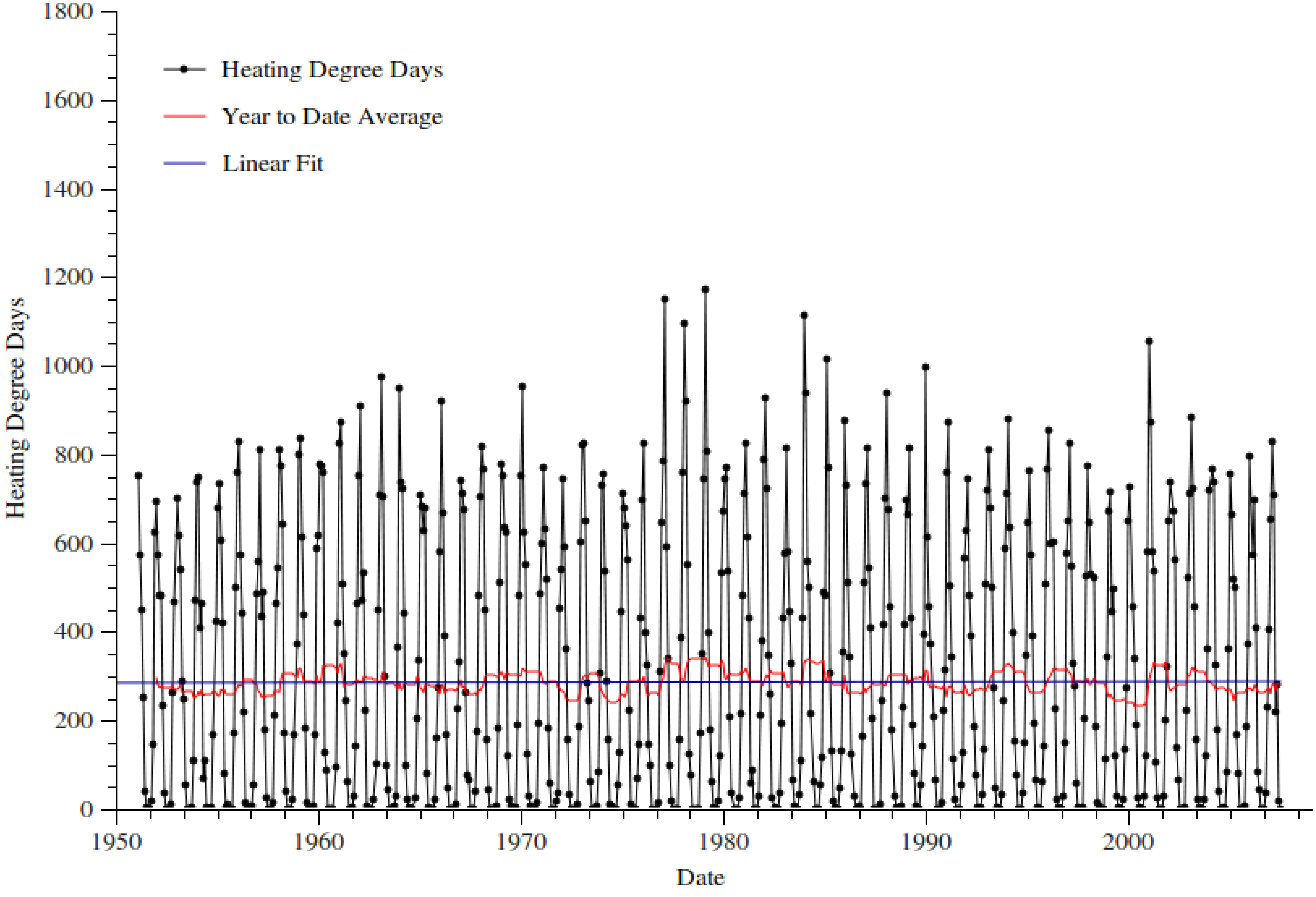

Fig. 60. Arkansas Nuclear One heating degree days

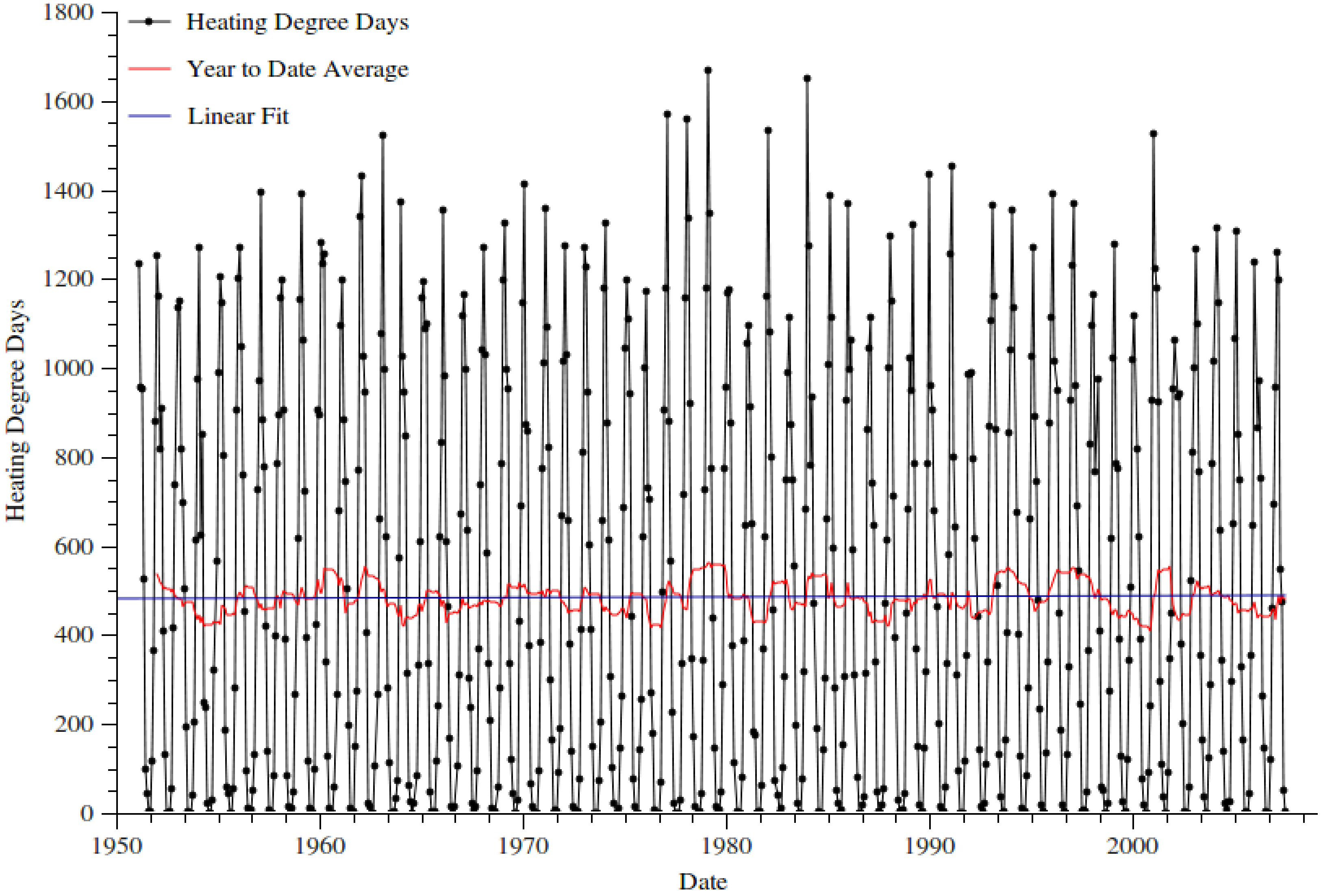

Fig. 61. Cooper Station heating degree days

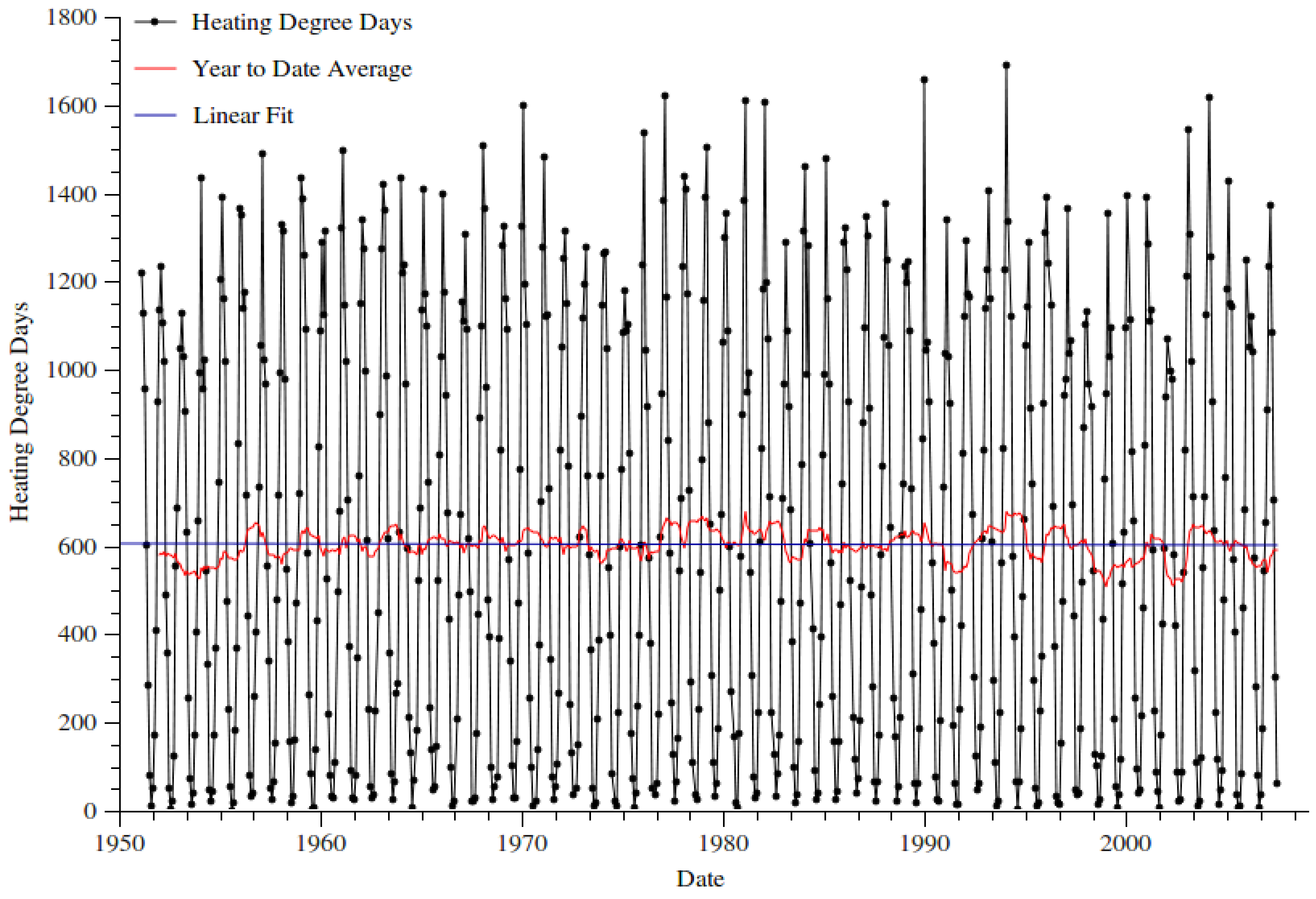

Fig. 62. James A. FitzPatrick heating degree days

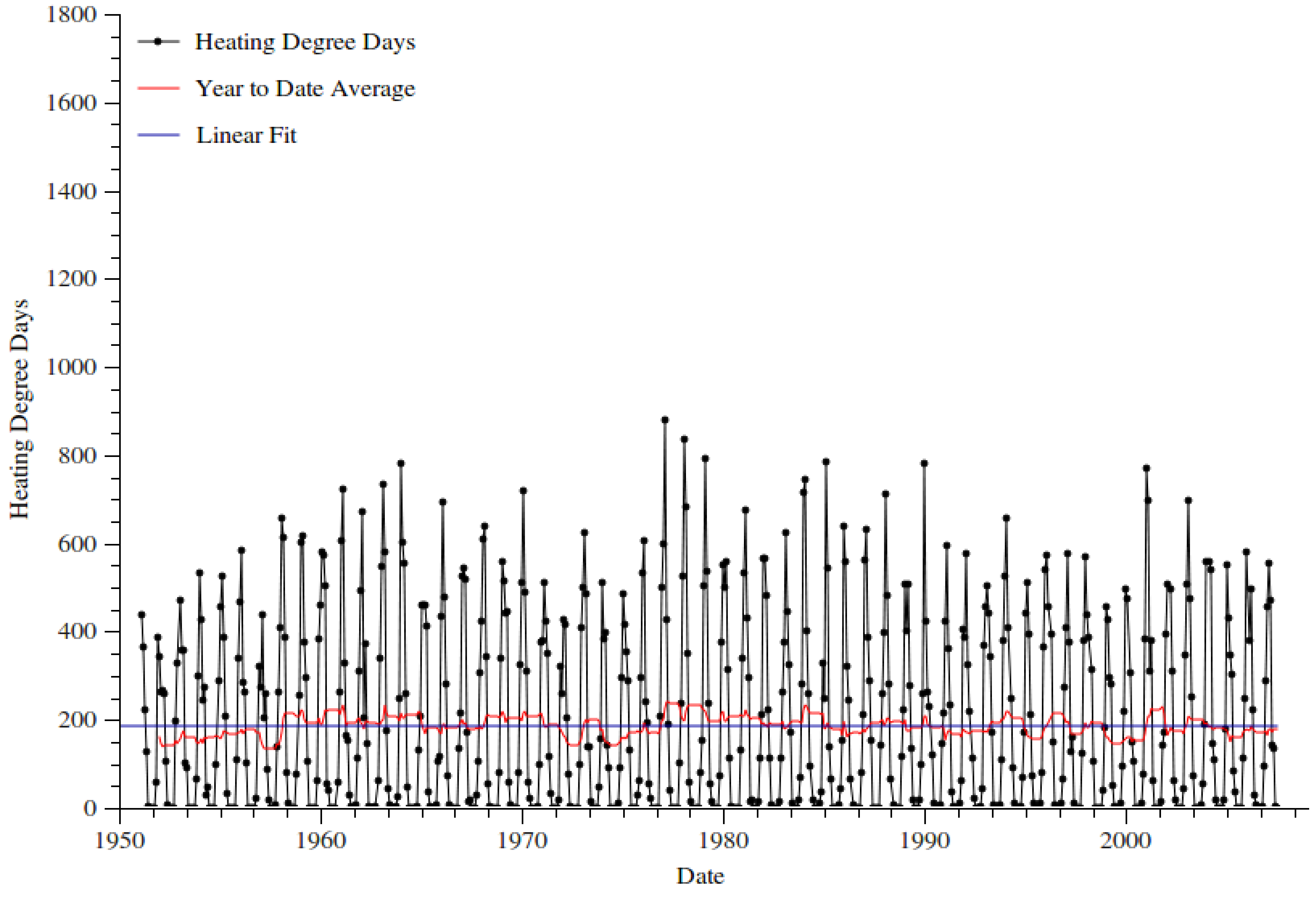

Fig. 63. Grand Gulf heating degree days

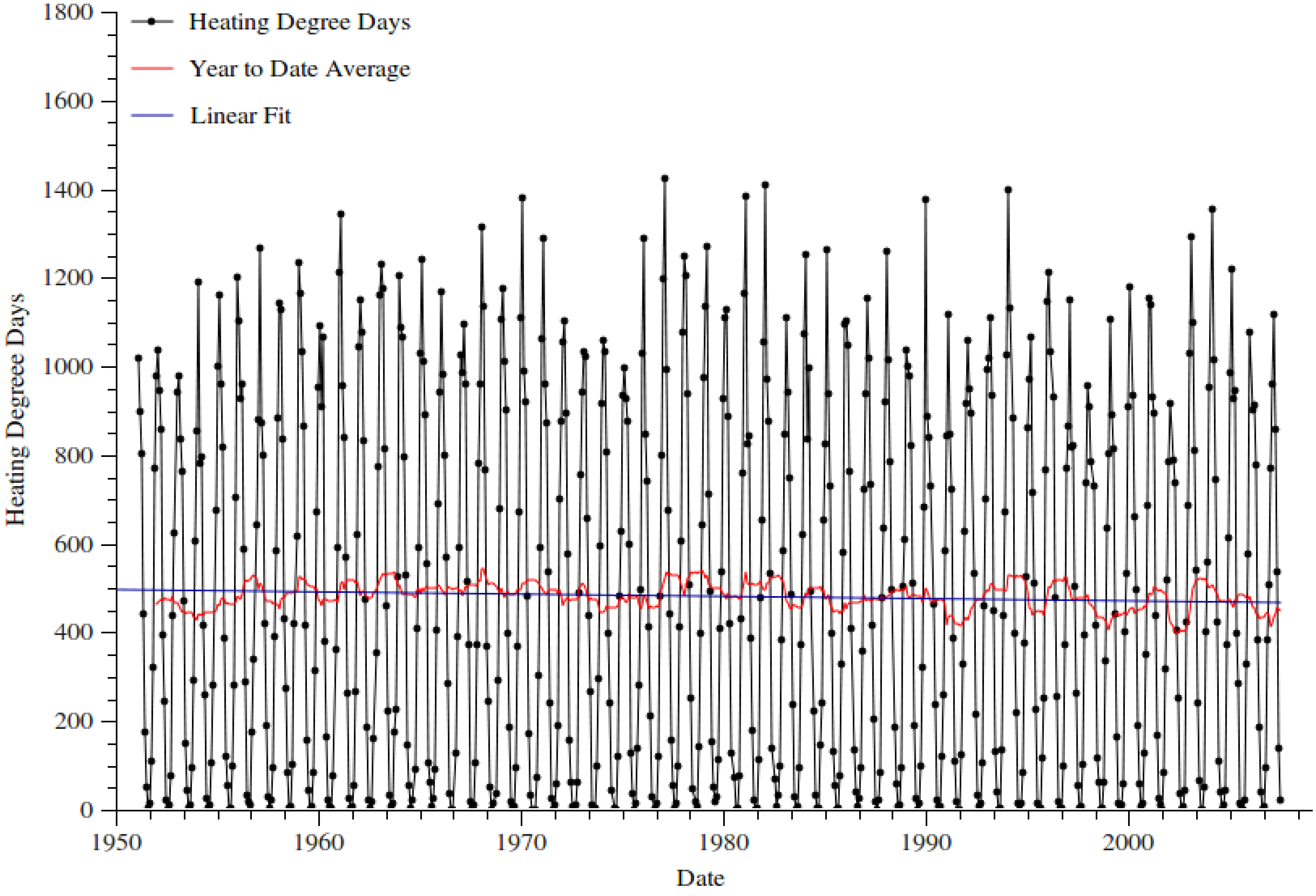

Fig. 64. Indian Point heating degree days

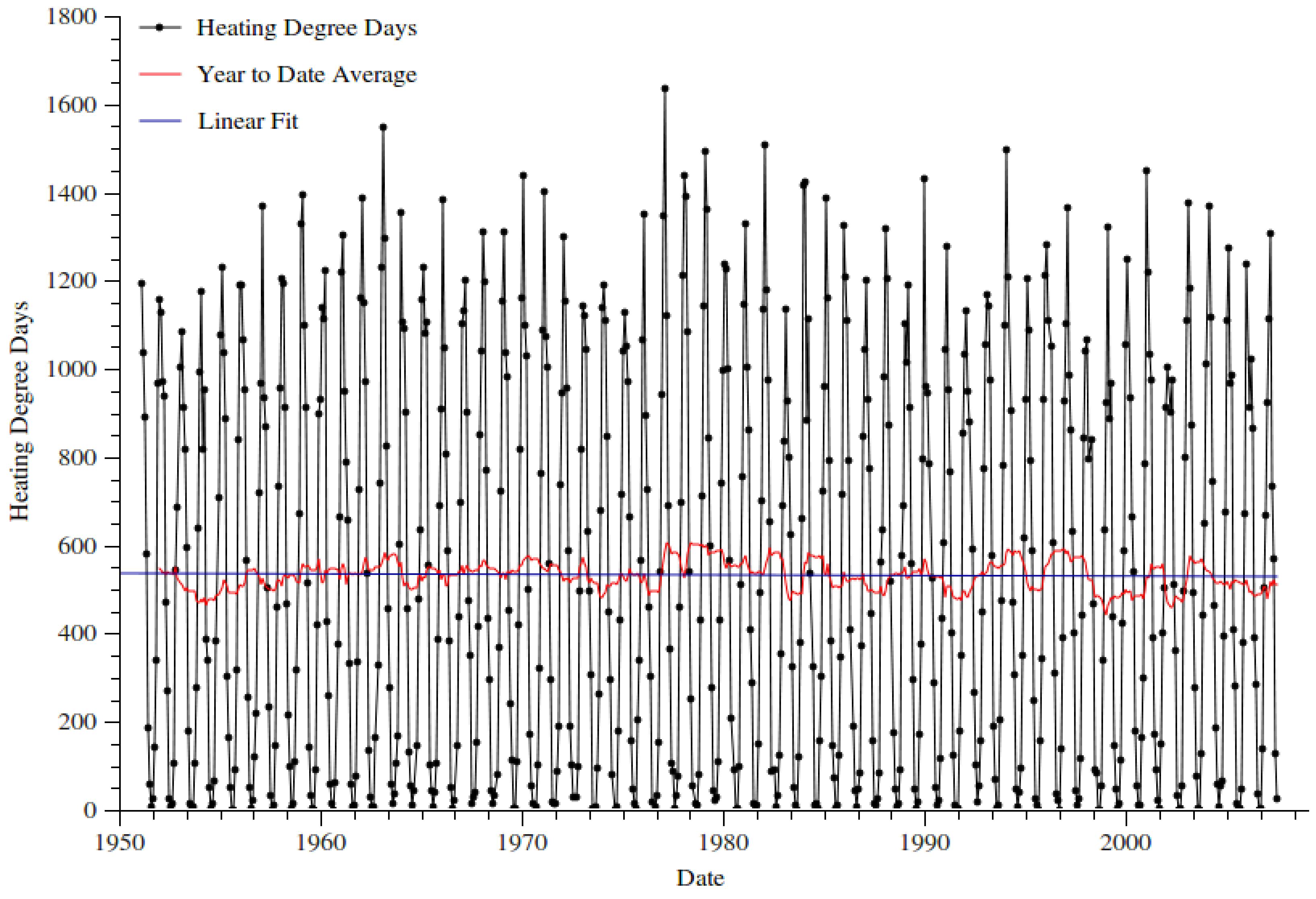

Fig. 65. Palisades heating degree days

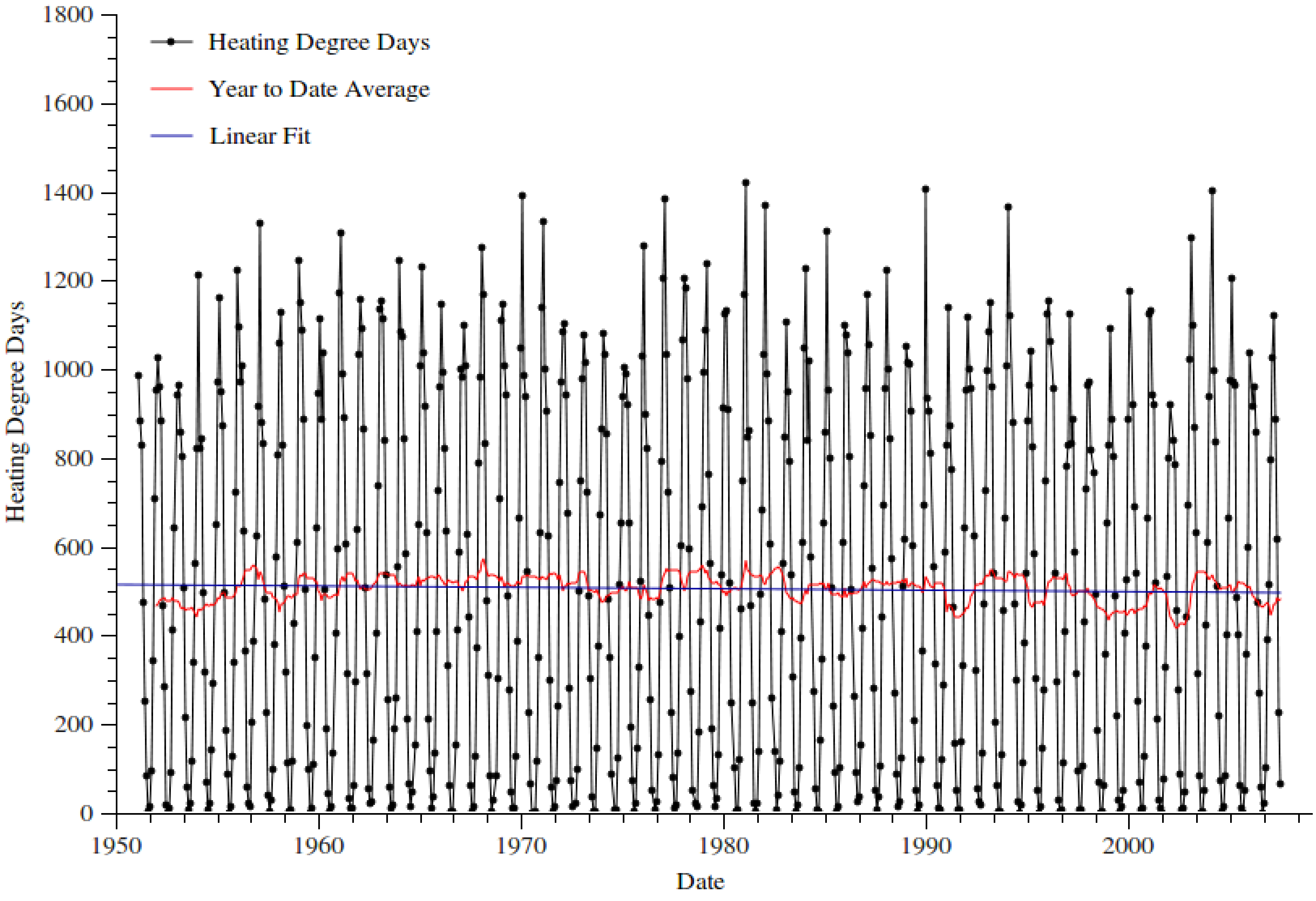

Fig. 66. Pilgrim heating degree days

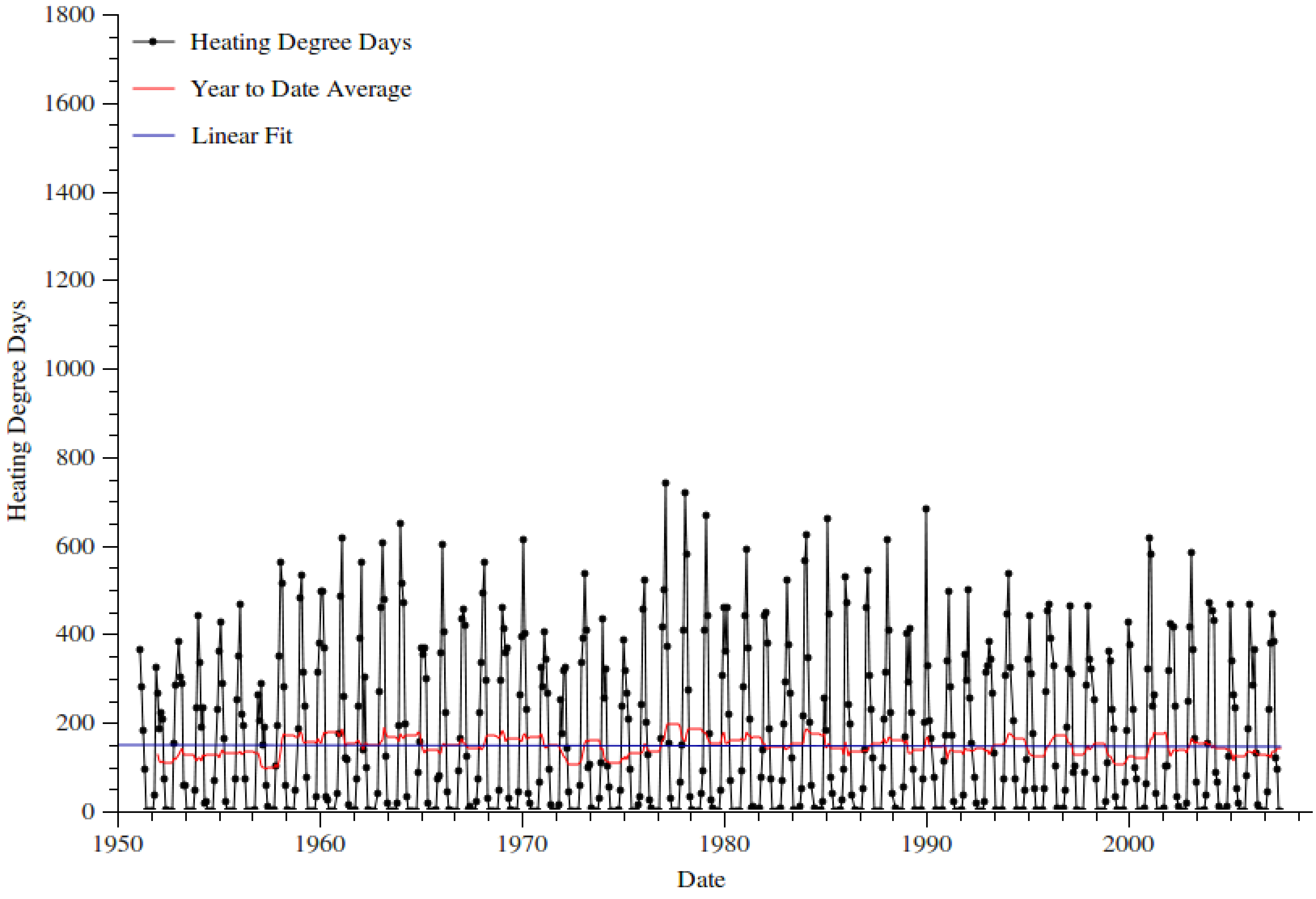

Fig. 67. River Bend heating degree days

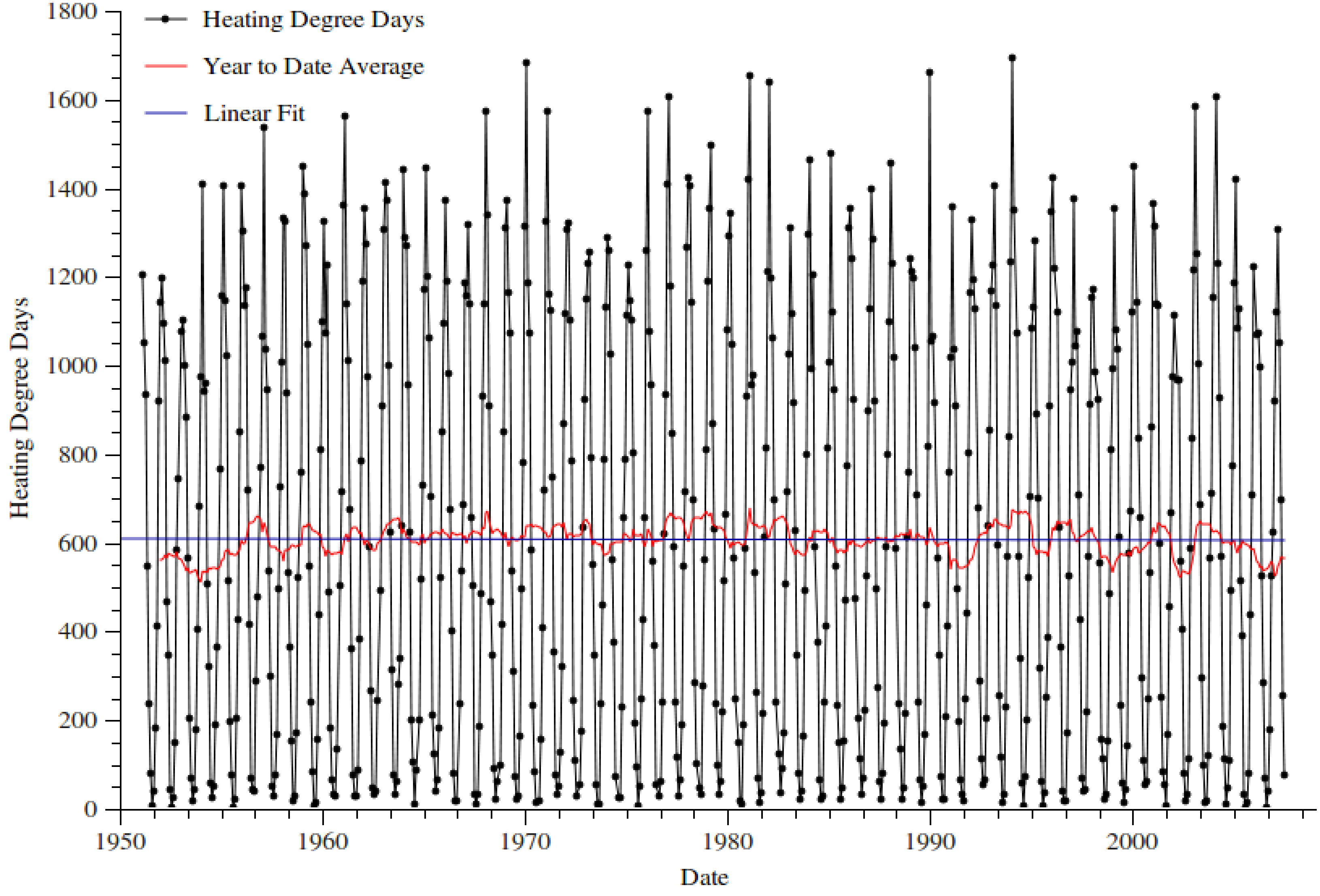

Fig. 68. Vermont Yankee heating degree days

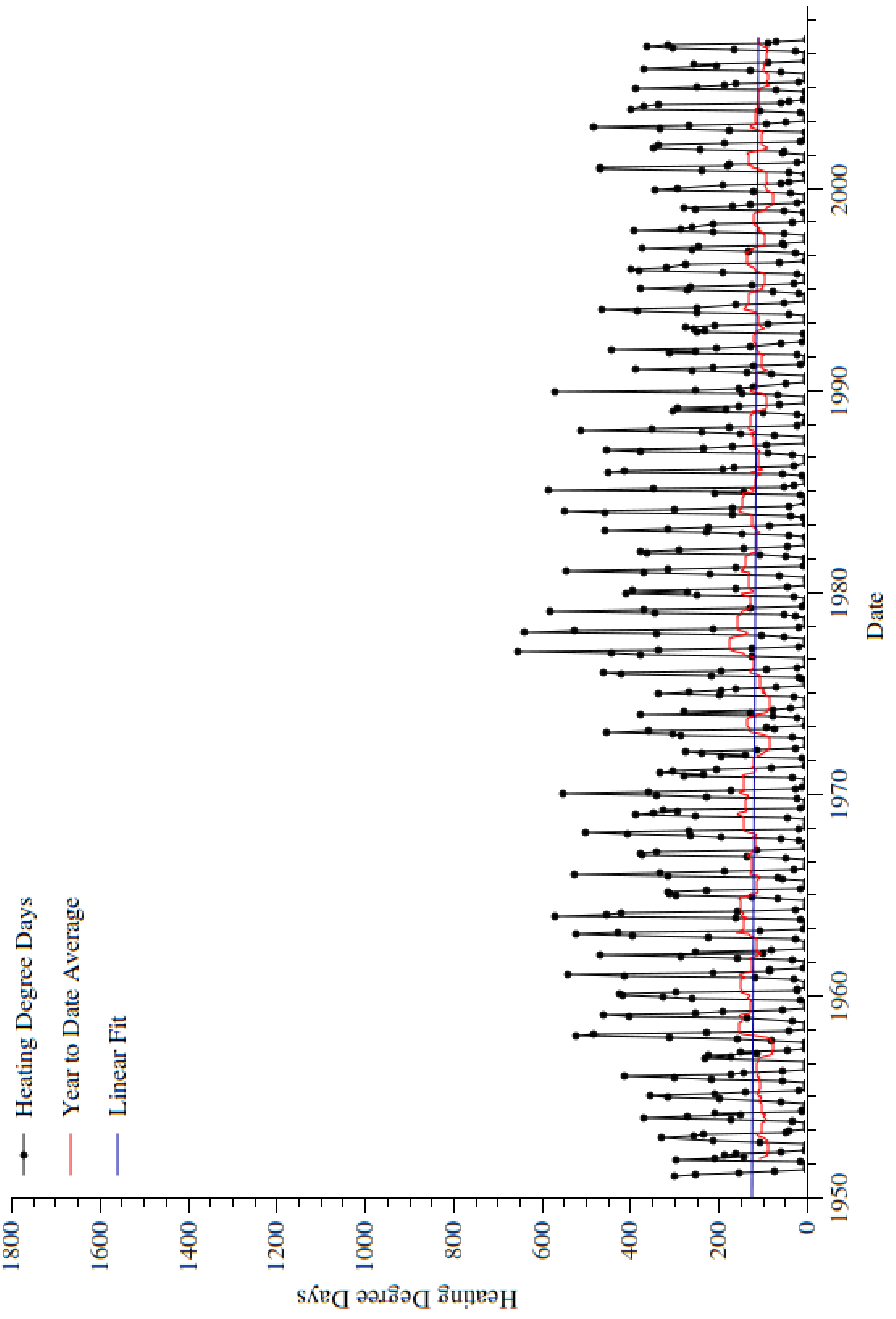

Fig. 69. Waterford heating degree days

# APPENDIX H

## MONTHLY EXTREME LOW TEMPERATURE

The extreme low temperature recorded in a month provides similar indications to cooling and heating degree days. Falling extreme low temperatures indicate harsher winters and milder summers. Conversely, rising extreme low temperatures indicate milder winters and hotter summers.

The data for these composite graphs was obtained from NOAA [78] and processed as described in section 3.3.

Arkansas Nuclear One[59]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $1.77 \times 10^{-3} \pm 1.22 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $31.276 \pm 0.97547$°F |
| RMSE | 18.148 |

Cooper Station[79]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $1.09 \times 10^{-3} \pm 1.49 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $22.187 \pm 1.1927$°F |
| RMSE | 22.19 |

FitzPatrick[80]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $-1.11 \times 10^{-3} \pm 1.35 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $20.587 \pm 1.0824$°F |
| RMSE | 20.137 |

Grand Gulf[81]

| | |
|---|---|
| Starting Date | February, 1891 |
| Slope | $5.4 \times 10^{-4} \pm 1.08 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $38.915 \pm 0.88111$°F |
| RMSE | 16.511 |

Indian Point[82]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $4.39 \times 10^{-3} \pm 2.18 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $24.032 \pm 1.1732$°F |
| RMSE | 17.875 |

Palisades[83]

| | |
|---|---|
| Starting Date | January, 1891 |
| Slope | $1.04 \times 10^{-3} \pm 1.25 \times 10^{-2} \frac{^oF}{month}$ |
| Initial Value | $22.034 \pm 1.0224$°F |
| RMSE | 19.029 |

Pilgrim[1]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $3.07 \times 10^{-3} \pm 1.22 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $22.234 \pm 0.97930$°F |
| RMSE | 18.219 |

River Bend[84]

| | |
|---|---|
| Starting Date | February, 1891 |
| Slope | $1.66 \times 10^{-3} \pm 1.06 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $40.911 \pm 0.86238$°F |
| RMSE | 16.177 |

Vermont Yankee[85]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $4.54 \times 10^{-3} \pm 2.52 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $15.718 \pm 1.3542$°F |
| RMSE | 20.633 |

Waterford[86]

| | |
|---|---|
| Starting Date | January, 1894 |
| Slope | $2.41 \times 10^{-3} \pm 1.19 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $43.212 \pm 1.0134$°F |
| RMSE | 15.977 |

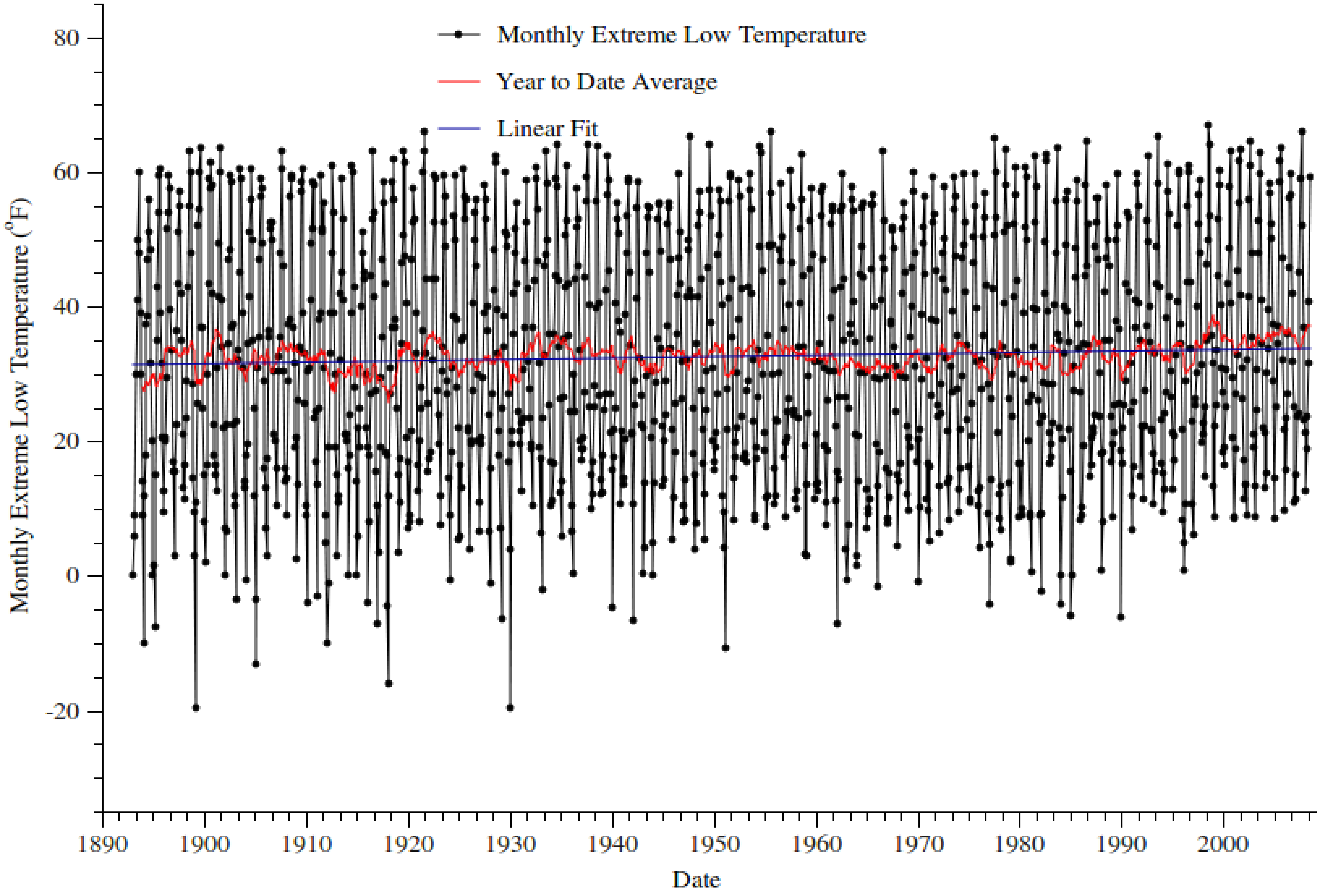

Fig. 70. Arkansas Nuclear One monthly extreme low temperature

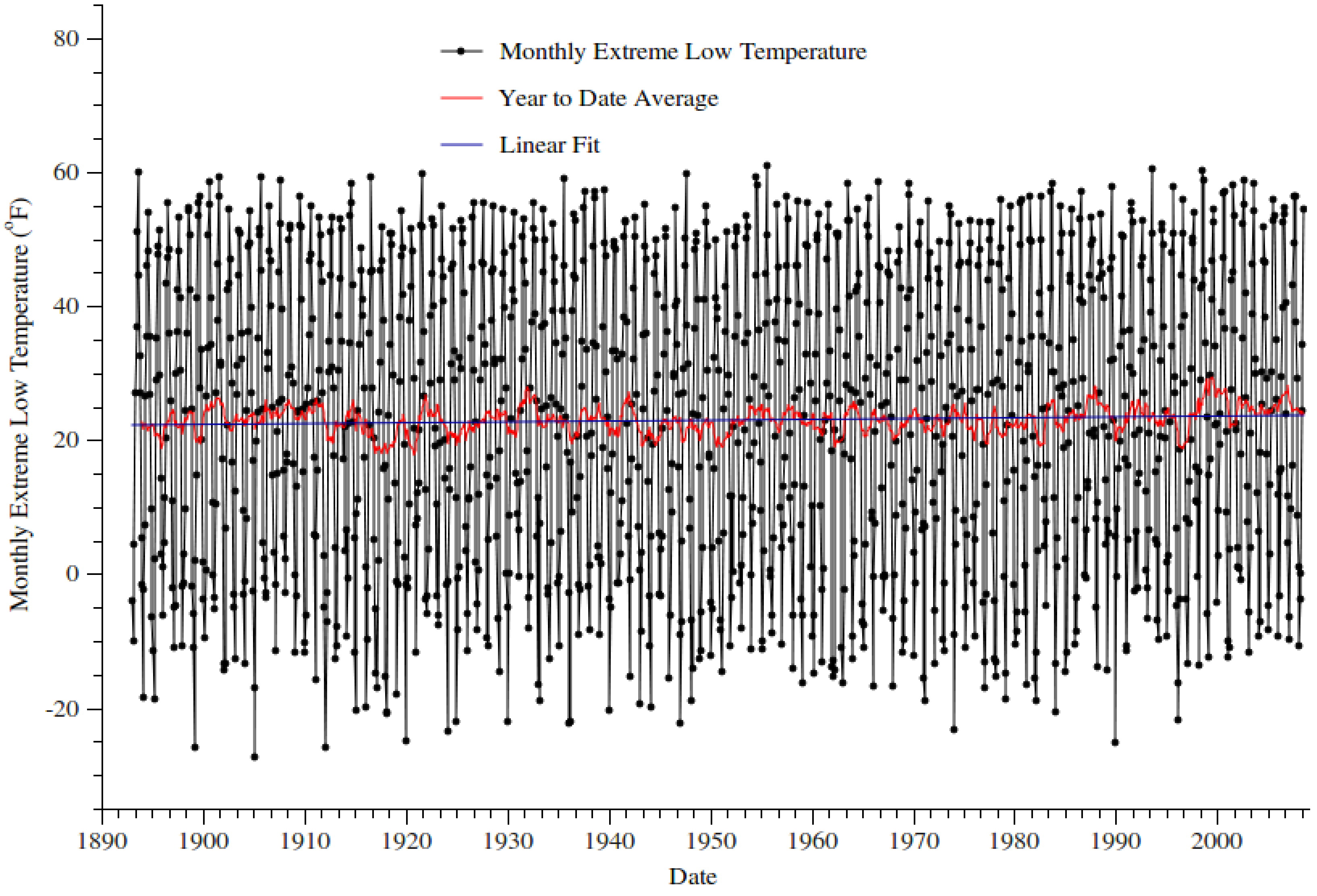

Fig. 71. Cooper Station monthly extreme low temperature

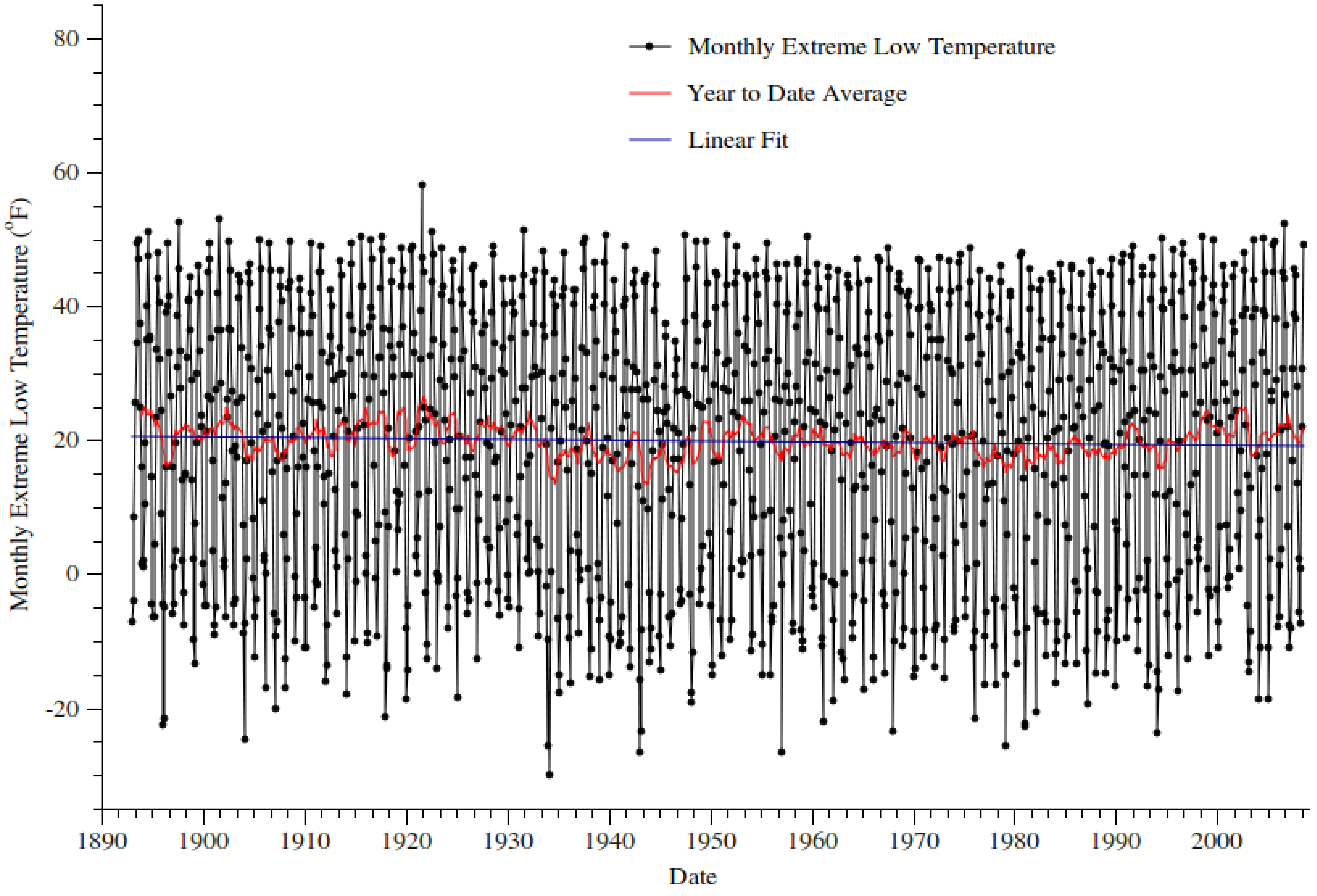

Fig. 72. James A. FitzPatrick monthly extreme low temperature

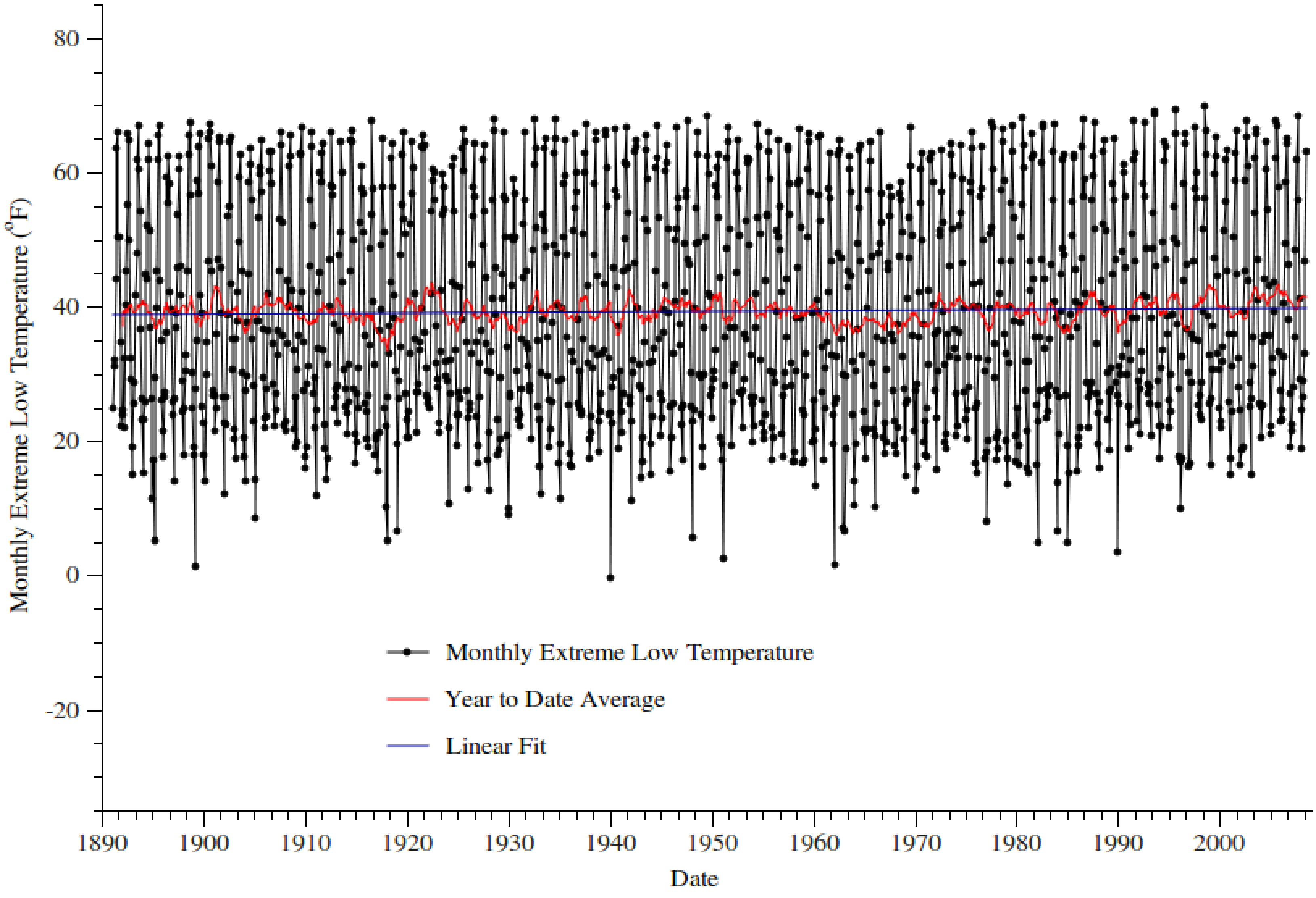

Fig. 73. Grand Gulf monthly extreme low temperature

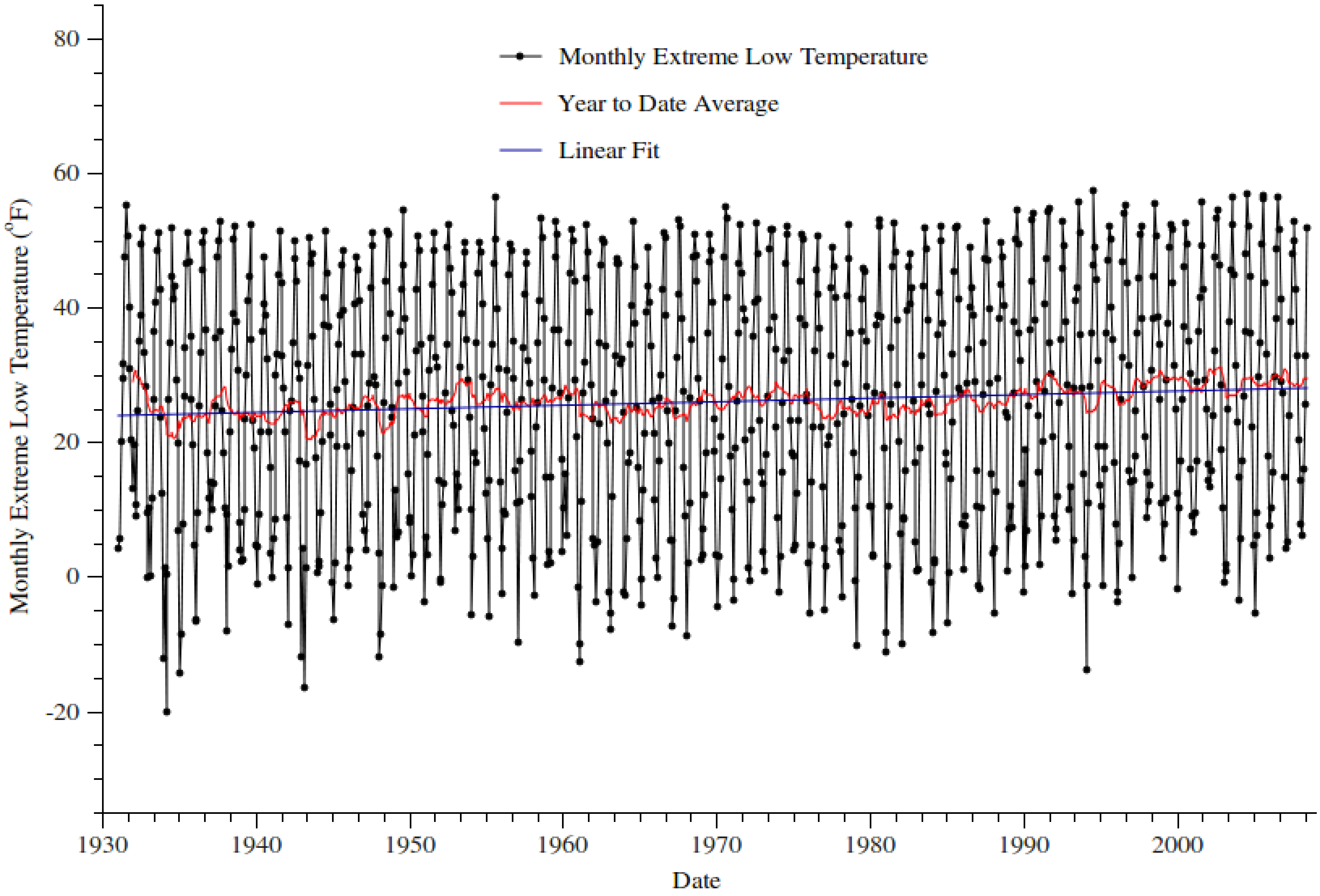

Fig. 74. Indian Point monthly extreme low temperature

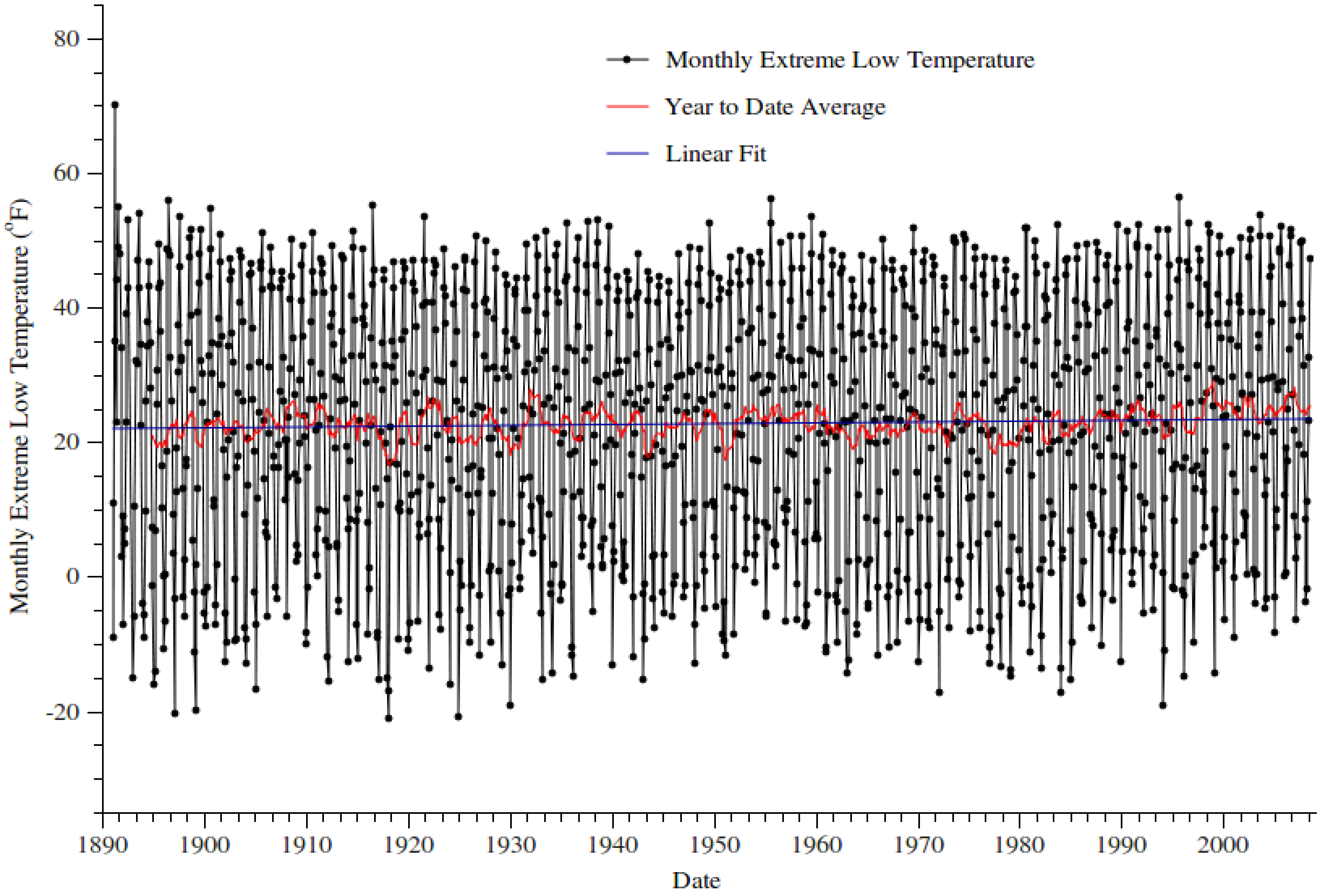

Fig. 75. Palisades monthly extreme low temperature

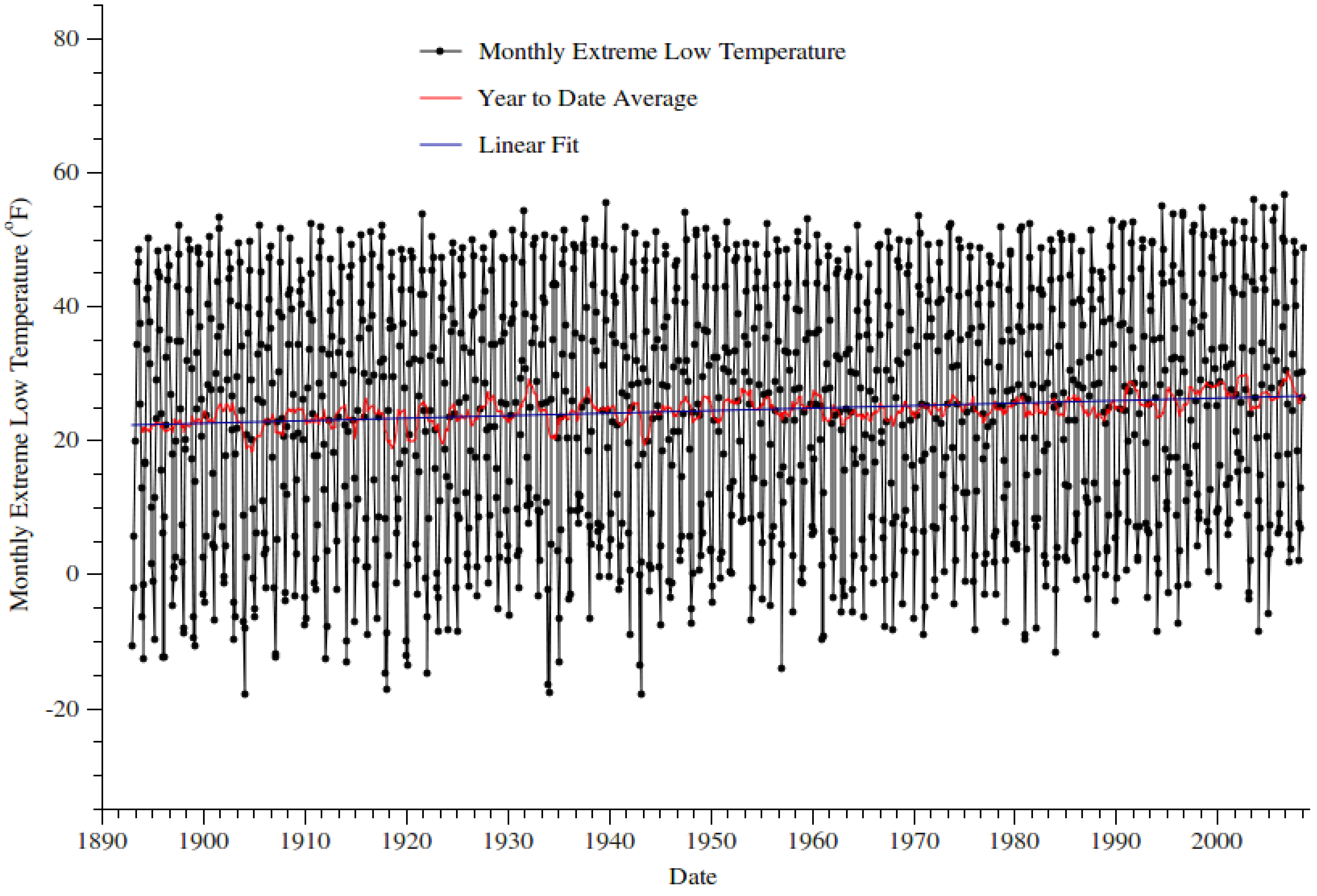

Fig. 76. Pilgrim monthly extreme low temperature

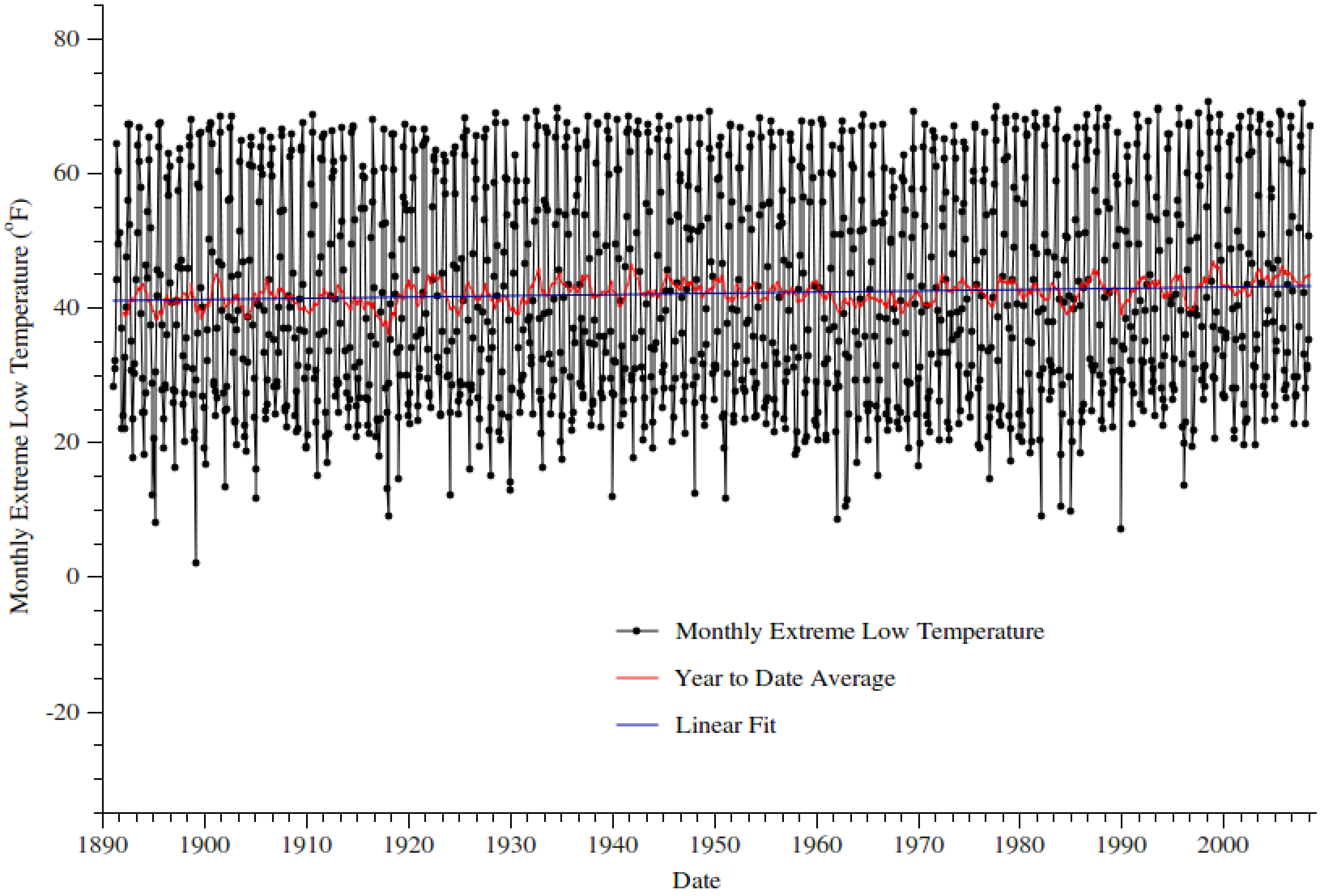

Fig. 77. River Bend monthly extreme low temperature

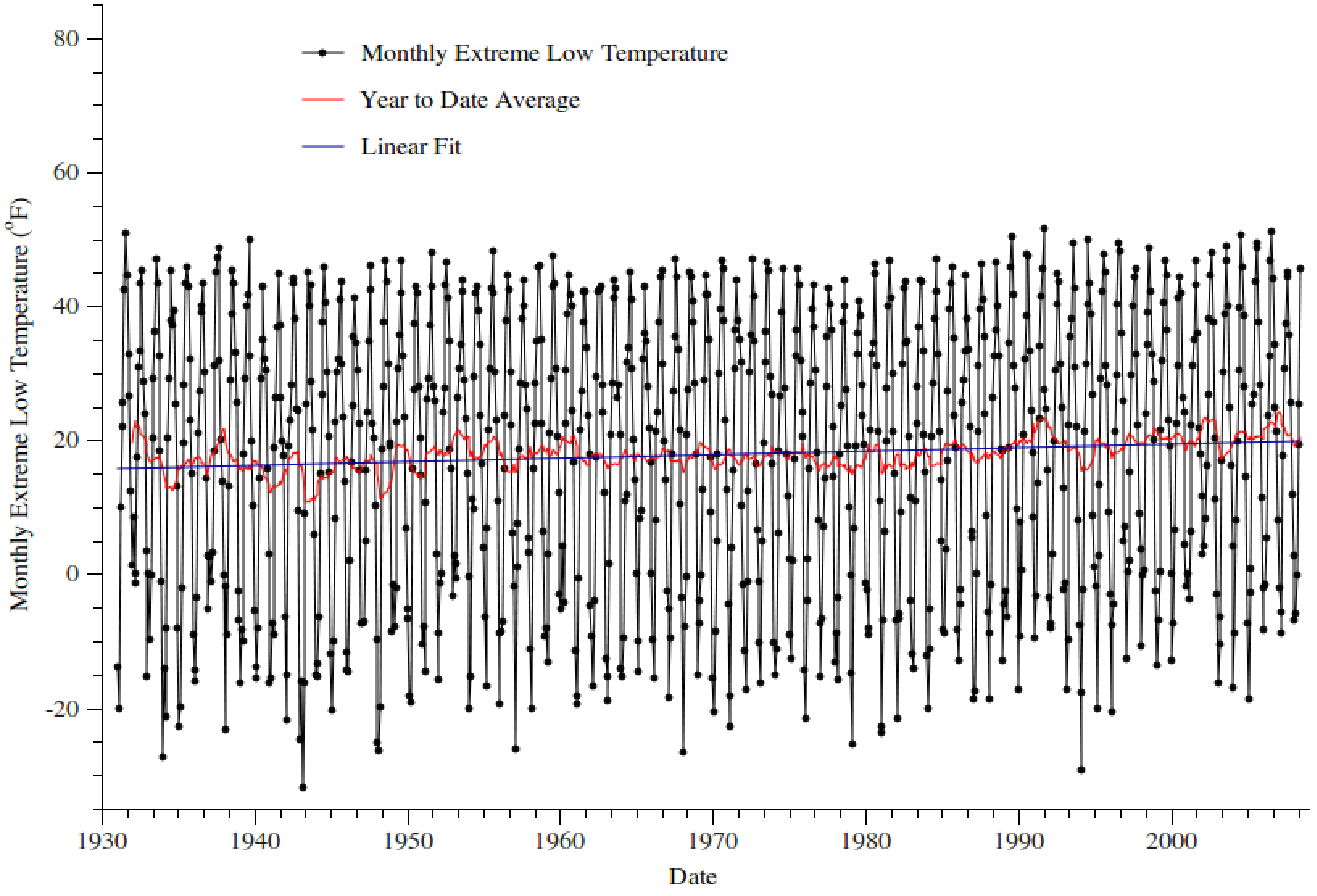

Fig. 78. Vermont Yankee monthly extreme low temperature

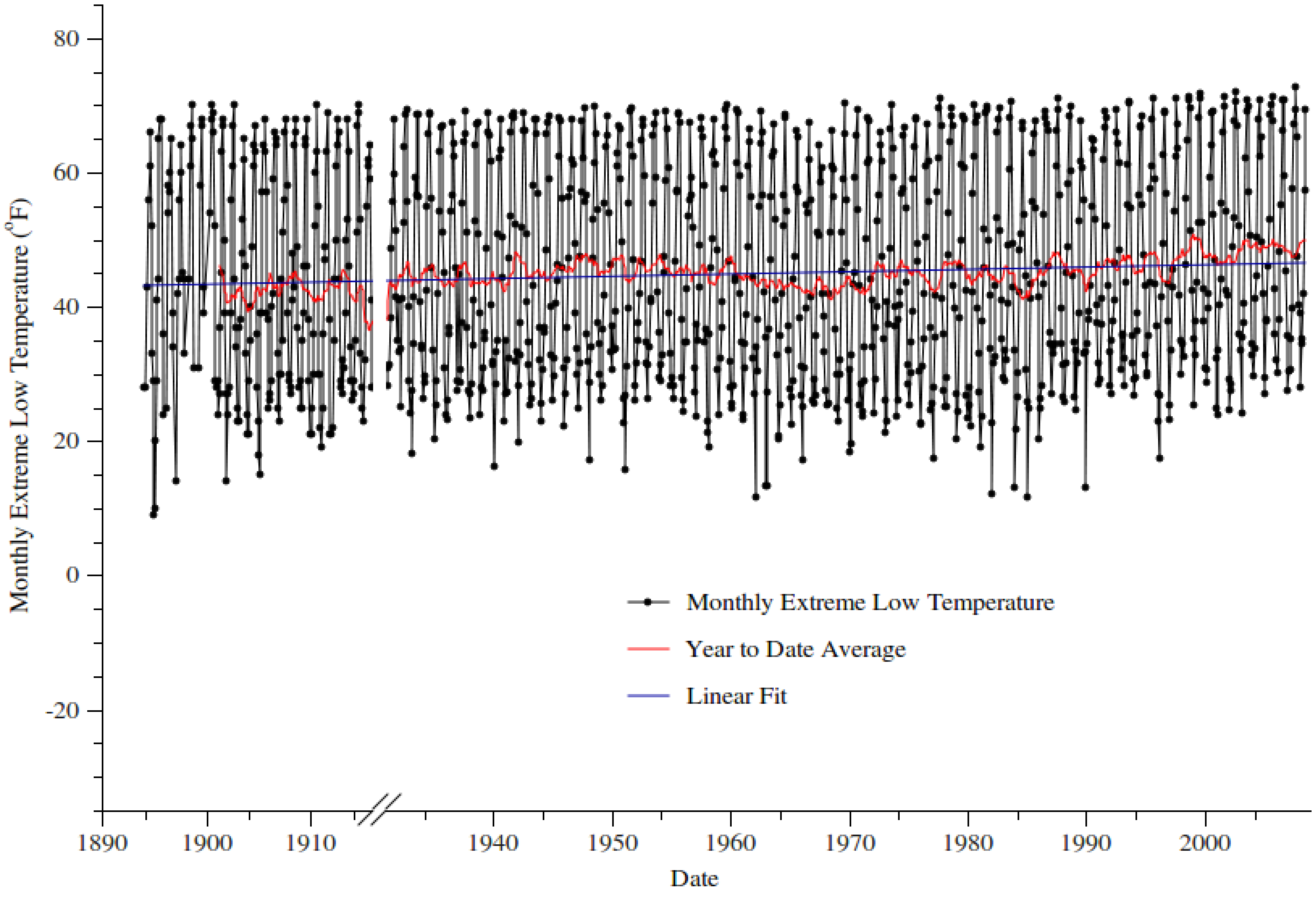

Fig. 79. Waterford monthly extreme low temperature

# APPENDIX I

## MONTHLY EXTREME HIGH TEMPERATURE

As with monthly extreme low temperature, the monthly extreme high temperature is an indication of the severity of the hot and cold seasons. If the average extreme high is increasing, summers are getting hotter, and winters milder. Alternately, if the average extreme high is decreasing, summers are getting milder and winters colder. In conjunction with the departure from normal monthly temperatures, comparing the changes in extreme high and lows can give an indication as to whether the site's climate is generally getting more severe or more temperate.

The data for these composite graphs was obtained from NOAA [78] and processed as described in section 3.3.

Arkansas Nuclear One[59]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $-2.3 \times 10^{-4} \pm 7.6 \times 10^{-4} \frac{^oF}{month}$ |
| Initial Value | $85.787 \pm 0.60817$°F |
| RMSE | 11.315 |

Cooper Station[79]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $-8.1 \times 10^{-4} \pm 1.06 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $81.980 \pm 0.84911$°F |
| RMSE | 15.979 |

FitzPatrick[80]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $3.3 \times 10^{-4} \pm 1.08 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $72.855 \pm 0.86966$°F |
| RMSE | 16.180 |

Grand Gulf[81]

| | |
|---|---|
| Starting Date | February, 1891 |
| Slope | $-8.1 \times 10^{-4} \pm 5.6 \times 10^{-4} \frac{^oF}{month}$ |
| Initial Value | $88.583 \pm 0.45471$°F |
| RMSE | 8.5295 |

Indian Point[82]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $3.3 \times 10^{-3} \pm 1.82 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $76.735 \pm 0.97825$°F |
| RMSE | 14.904 |

Palisades[83]

| | |
|---|---|
| Starting Date | January, 1891 |
| Slope | $-7.3 \times 10^{-3} \pm 1.10 \times 10^{-3} \frac{^oF}{month}$ |
| Initial Value | $76.200 \pm 0.89410$°F |
| RMSE | 16.618 |

Pilgrim[1]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $1.67 \times 10^{-3} \pm 1.0 \times 10^{-3} \frac{^{o}F}{month}$ |
| Initial Value | $73.616 \pm 0.79823^{o}$F |
| RMSE | 14.851 |

River Bend[84]

| | |
|---|---|
| Starting Date | February, 1891 |
| Slope | $-9.2 \times 10^{-4} \pm 5.1 \times 10^{-4} \frac{^{o}F}{month}$ |
| Initial Value | $88.587 \pm 0.41439^{o}$F |
| RMSE | 7.7651 |

Vermont Yankee[85]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $9.8 \times 10^{-4} \pm 1.94 \times 10^{-3} \frac{^{o}F}{month}$ |
| Initial Value | $72.852 \pm 1.0434^{o}$F |
| RMSE | 15.897 |

Waterford[86]

| | |
|---|---|
| Starting Date | January, 1894 |
| Slope | $-1.65 \times 10^{-3} \pm 5.5 \times 10^{-4} \frac{^{o}F}{month}$ |
| Initial Value | $89.324 \pm 0.46862^{o}$F |
| RMSE | 7.4033 |

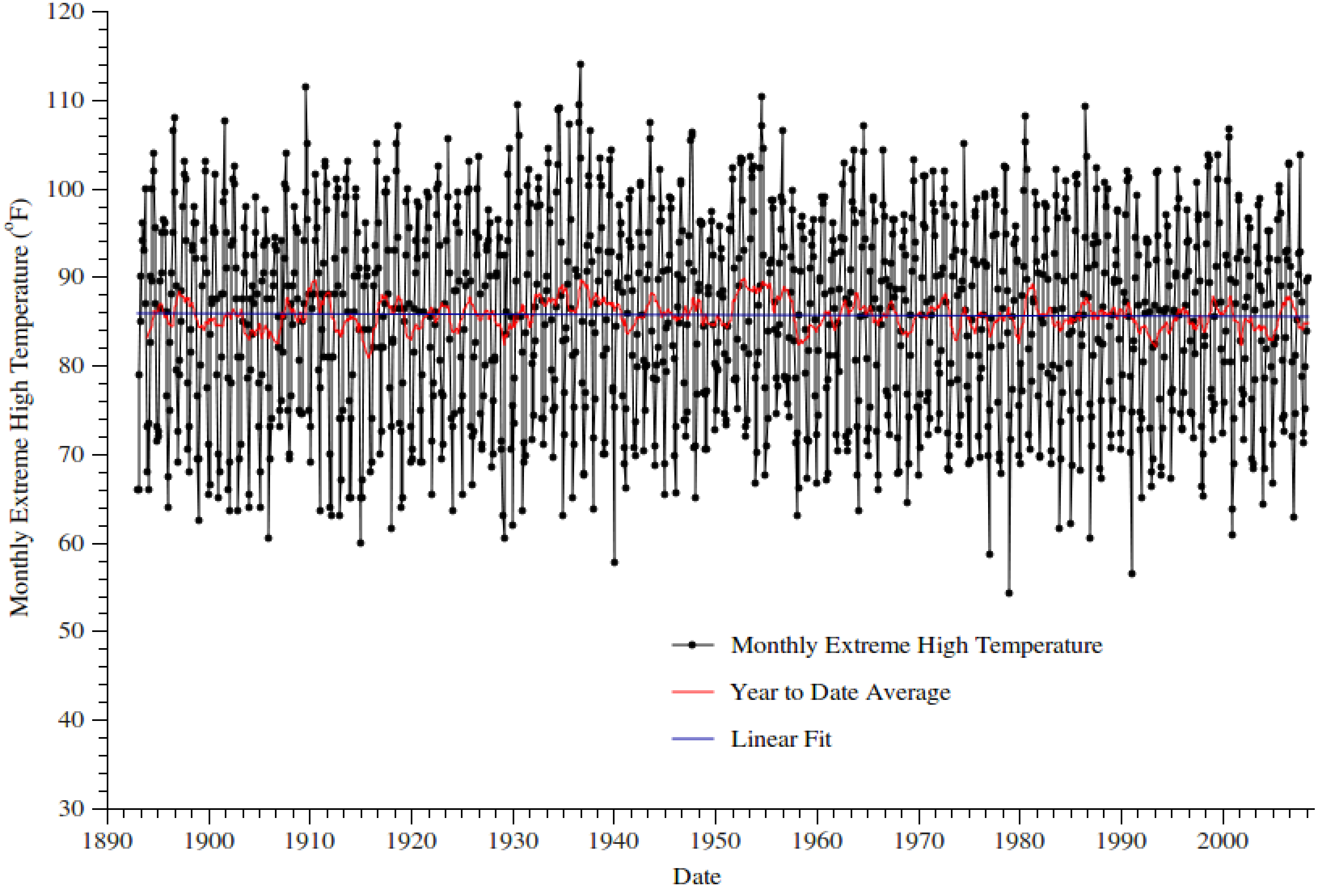

Fig. 80. Arkansas Nuclear One monthly extreme high temperature

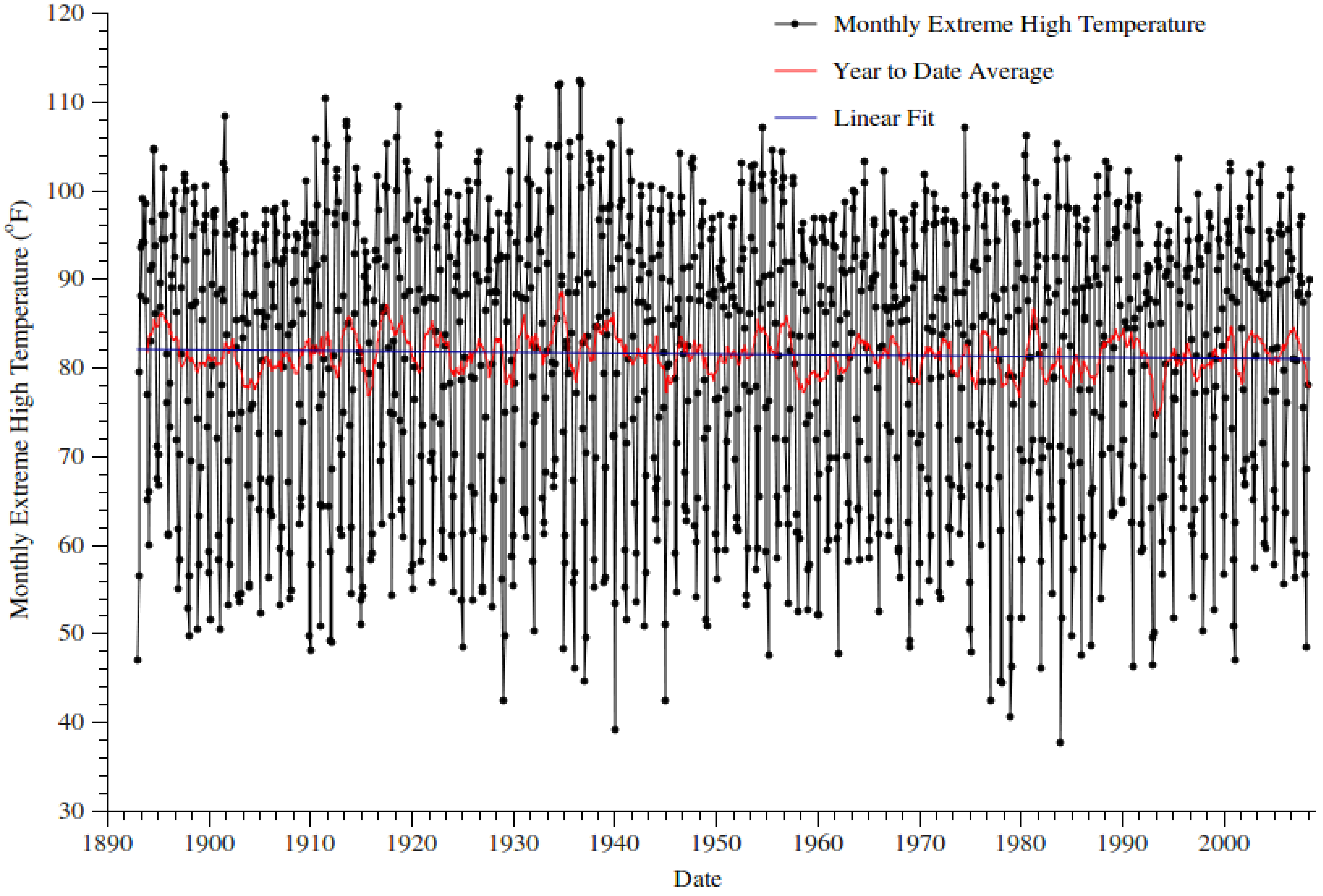

Fig. 81. Cooper Station monthly extreme high temperature

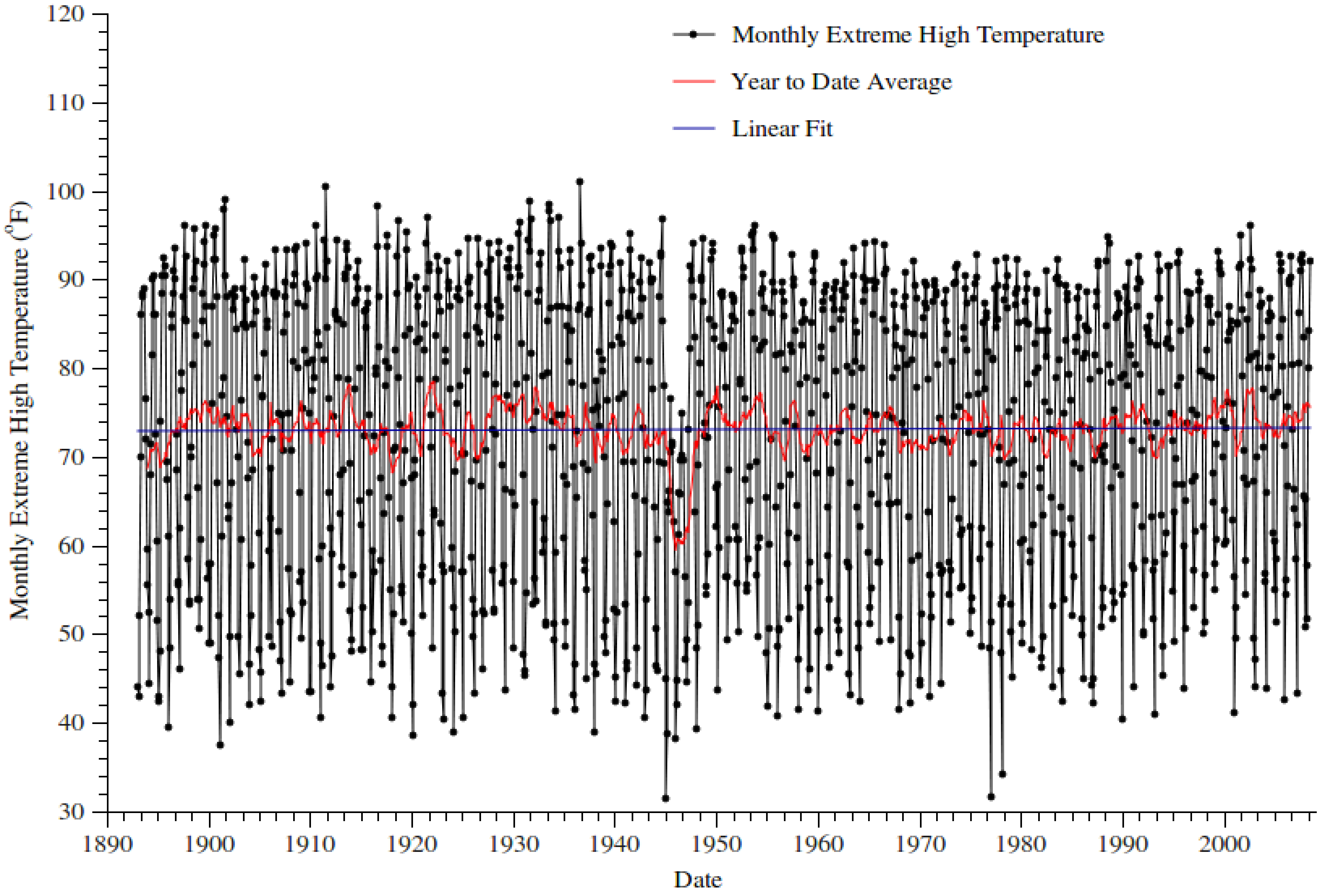

Fig. 82. James A. FitzPatrick monthly extreme high temperature

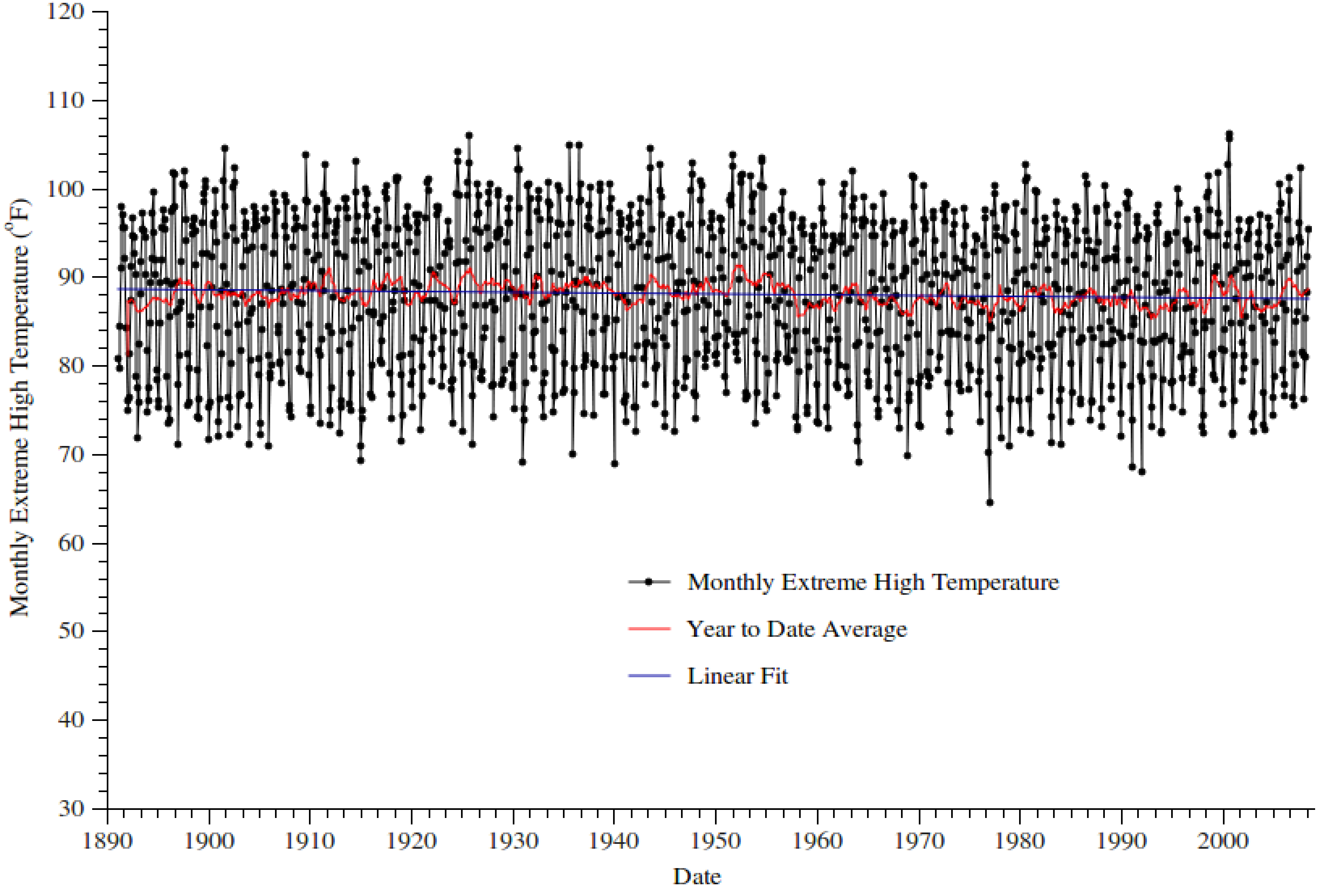

Fig. 83. Grand Gulf monthly extreme high temperature

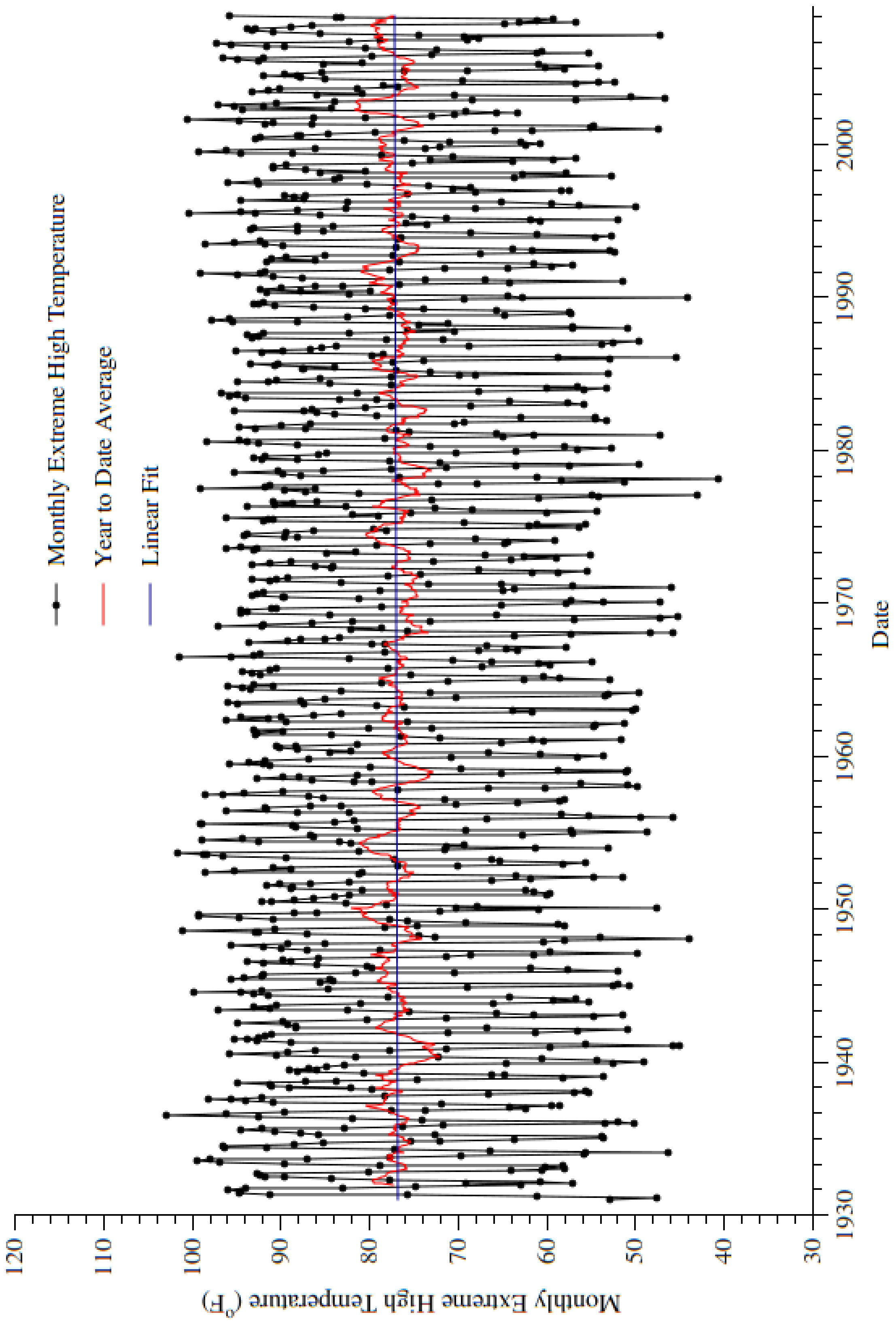

Fig. 84. Indian Point monthly extreme high temperature

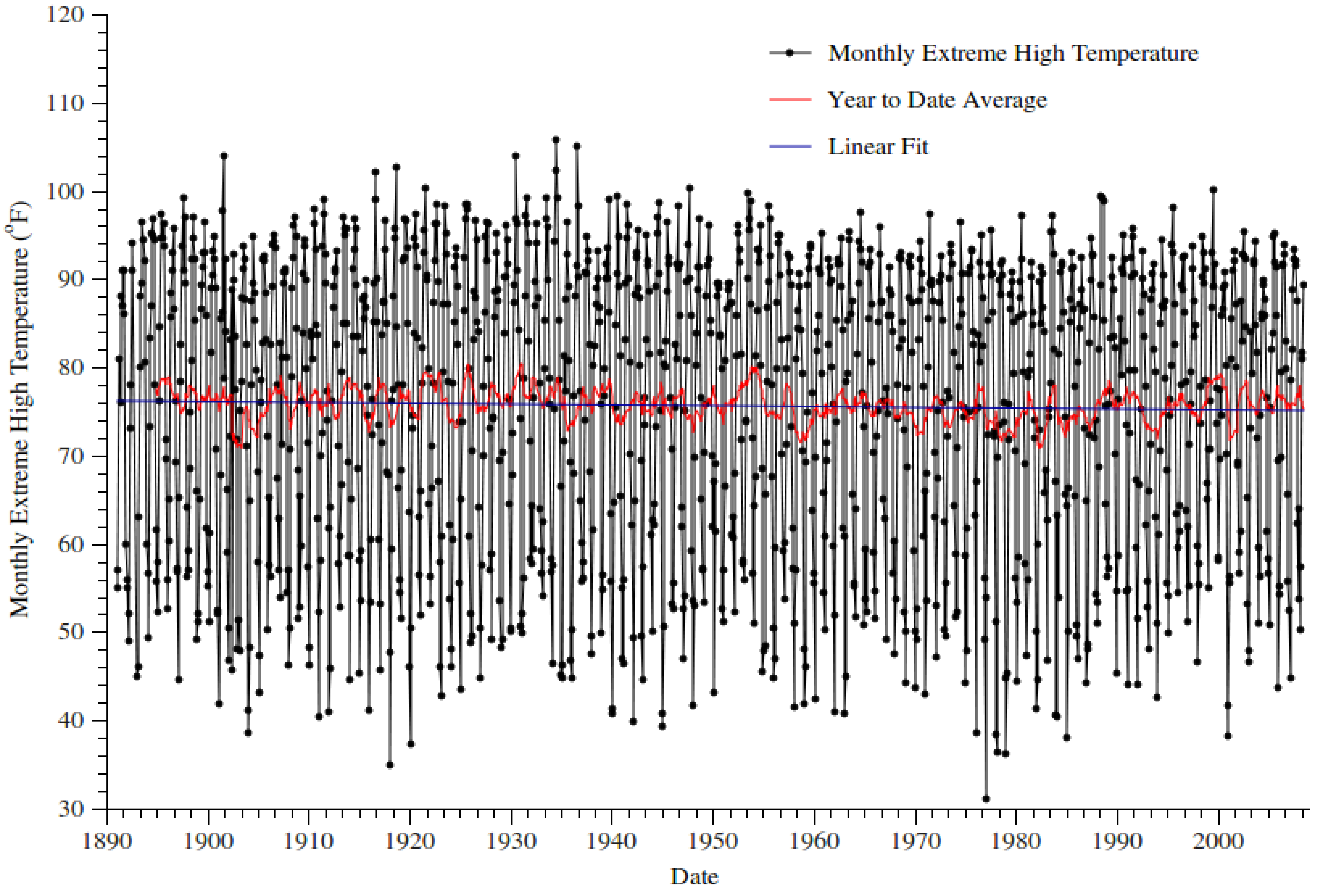

Fig. 85. Palisades monthly extreme high temperature

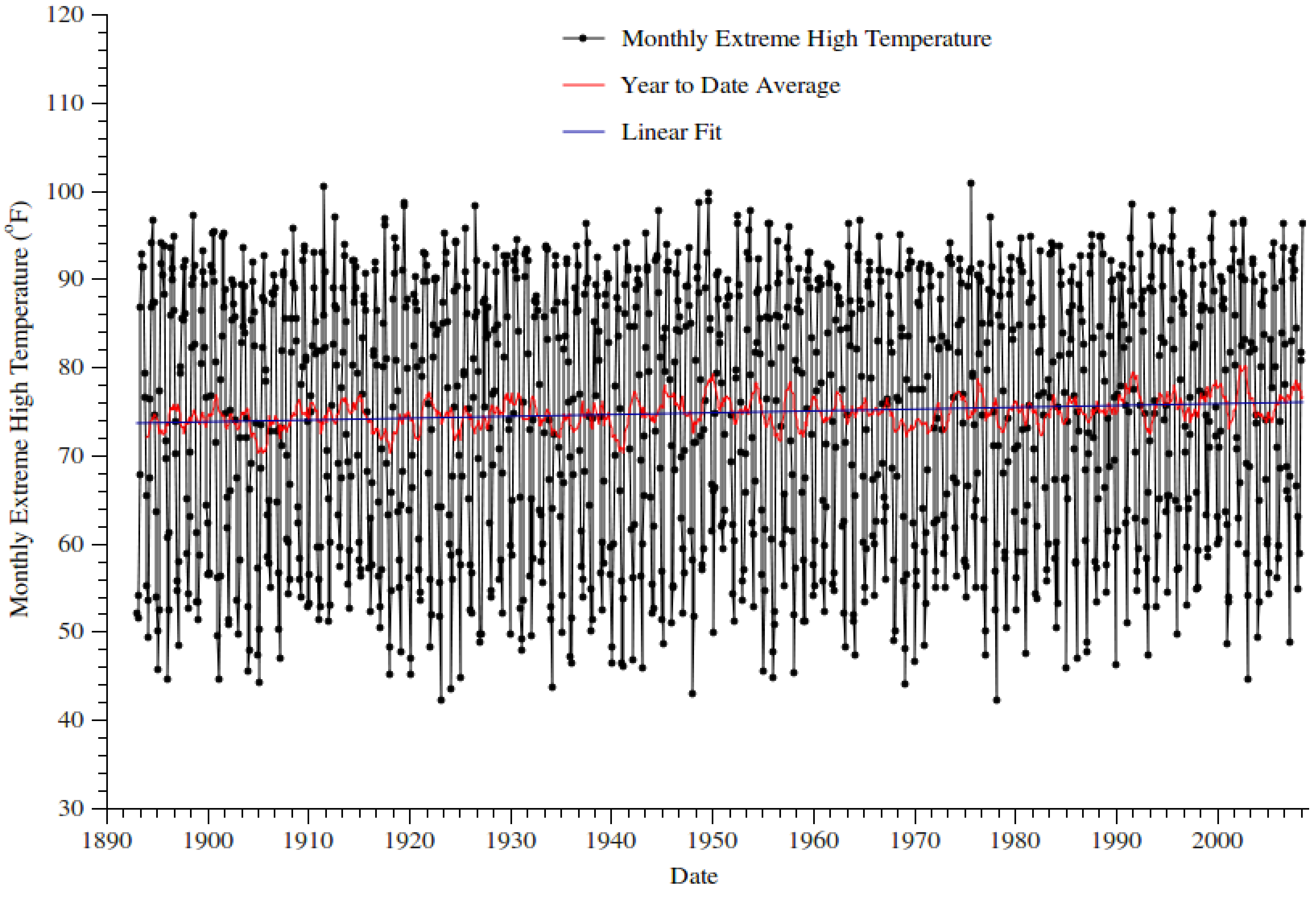

Fig. 86. Pilgrim monthly extreme high temperature

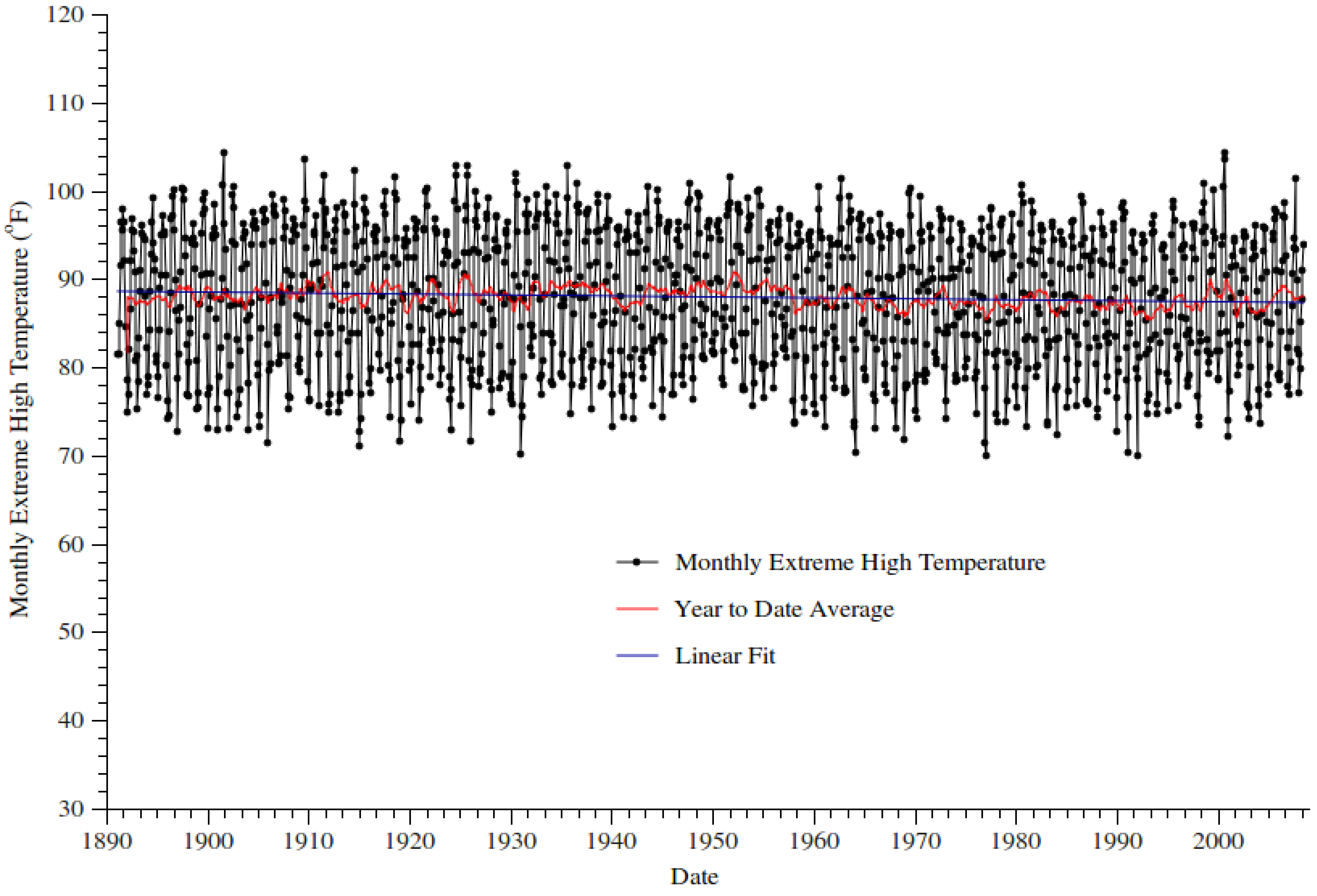

Fig. 87. River Bend monthly extreme high temperature

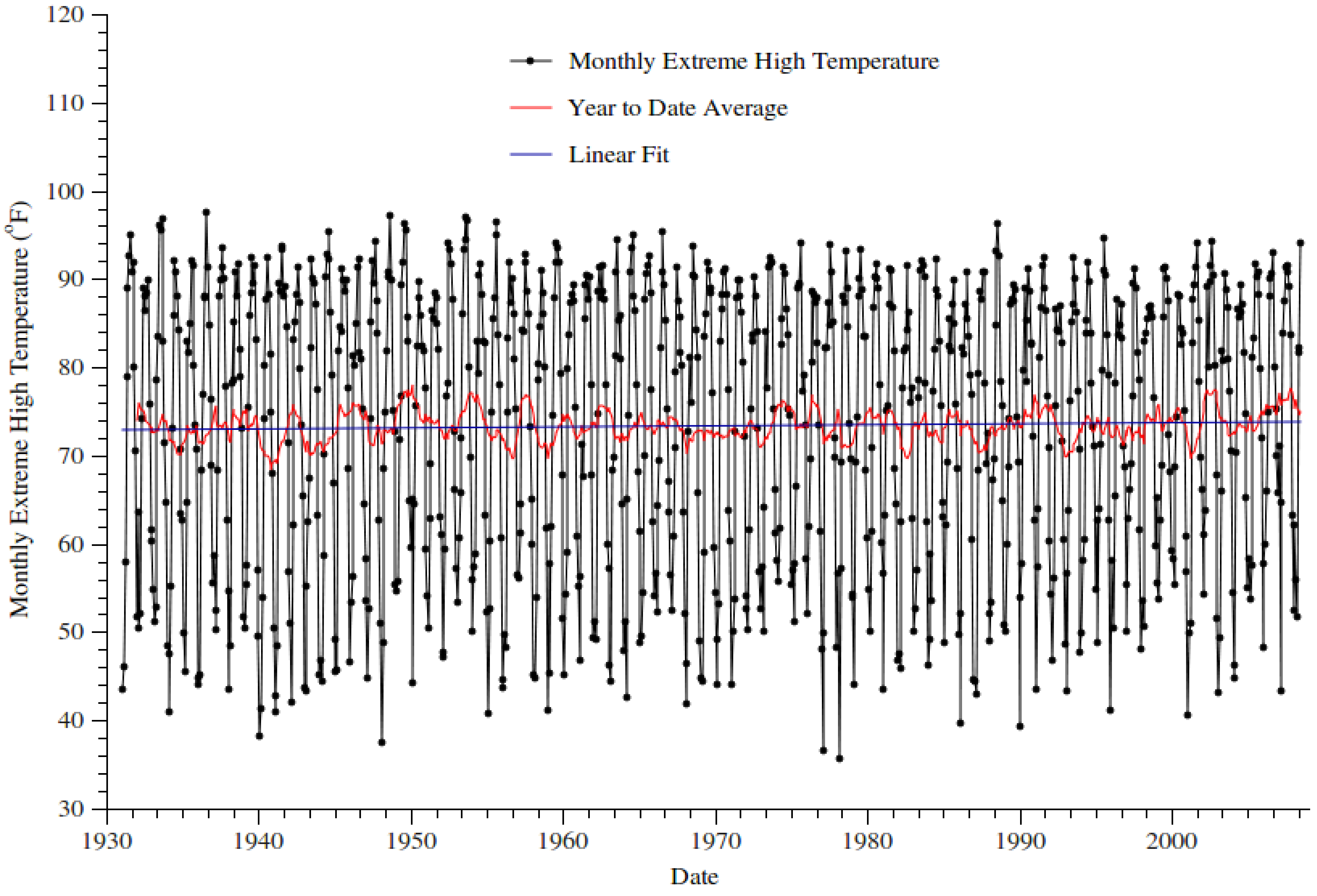

Fig. 88. Vermont Yankee monthly extreme high temperature

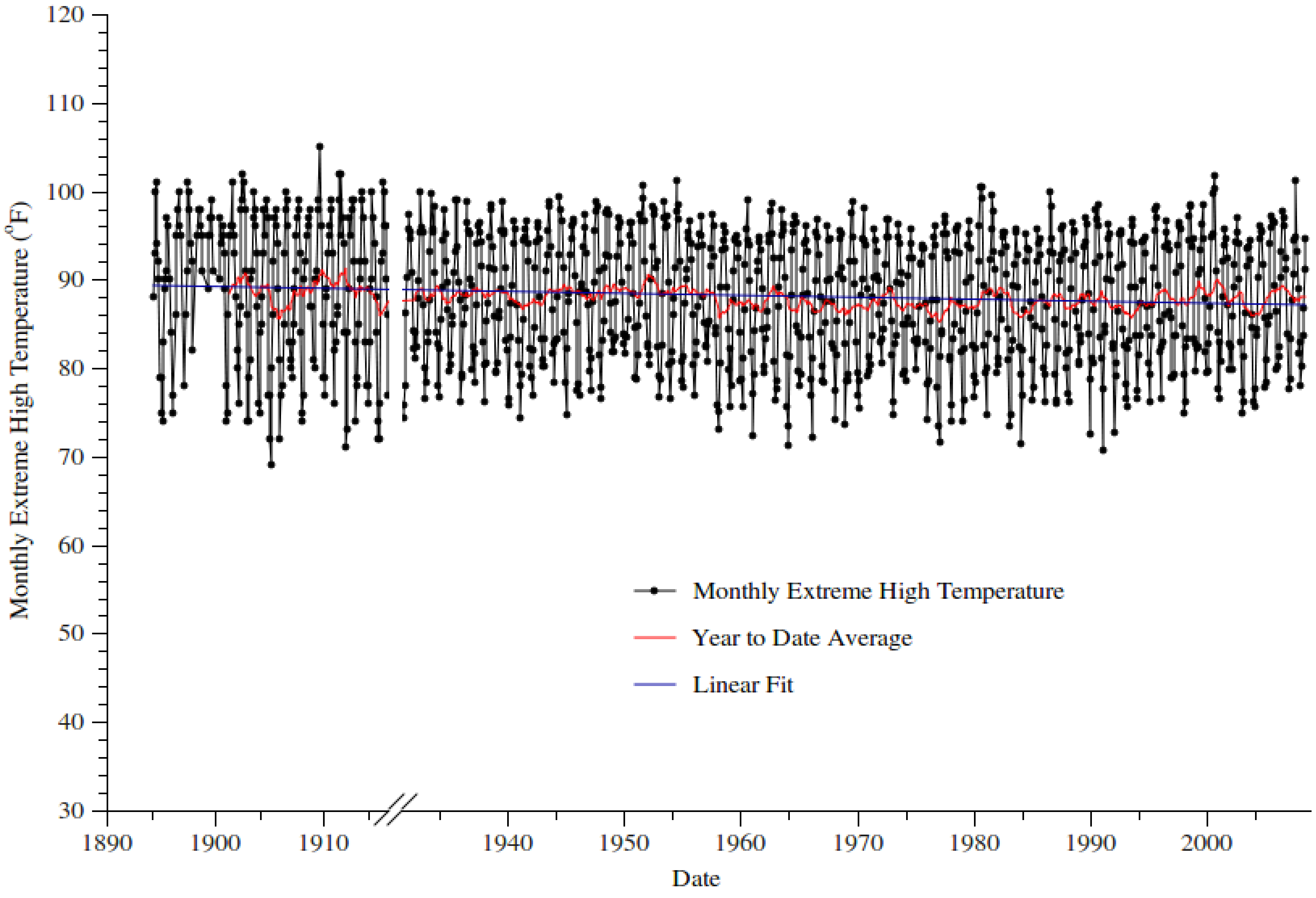

Fig. 89. Waterford monthly extreme high temperature

# APPENDIX J

## MONTHLY TOTAL DAYS ABOVE NINETY DEGREES FAHRENHEIT

The total number of days with temperature above 90 $\frac{°\mathrm{F}}{\mathrm{month}}$ is another indicator of the severity of the warm season. However, because the values are not weighted by the absolute value above this reference datum, this parameter is most closely associated with the length of the hottest portion of the year. Additionally, prolonged hot seasons can be an indication of drought risk.

The data for these composite graphs was obtained from NOAA [78] and processed as described in section 3.3.

Arkansas Nuclear One[59]

| | |
|---|---|
| Starting Date | December, 1941 |
| Slope | $-1.45 \times 10^{-3} \pm 1.28 \times 10^{-3} \frac{\frac{\text{days}}{month}}{month}$ |
| Initial Value | $5.9724 \pm 0.59100 \frac{\text{days}}{\text{month}}$ |
| RMSE | 8.2899 |

Cooper Station[79]

| | |
|---|---|
| Starting Date | January, 1942 |
| Slope | $-5.2 \times 10^{-4} \pm 8.3 \times 10^{-4} \frac{\frac{\text{days}}{month}}{month}$ |
| Initial Value | $3.3166 \pm 0.38374 \frac{\text{days}}{\text{month}}$ |
| RMSE | 5.3703 |

FitzPatrick[80]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $-3.4 \times 10^{-4} \pm 2.1 \times 10^{-4} \frac{\frac{\text{days}}{month}}{month}$ |
| Initial Value | $0.57549 \pm 8.693 \times 10^{-2} \frac{\text{days}}{\text{month}}$ |
| RMSE | 1.1470 |

Grand Gulf[81]

| | |
|---|---|
| Starting Date | December, 1941 |
| Slope | $-1.68 \times 10^{-3} \pm 1.49 \times 10^{-3} \frac{\frac{\text{days}}{month}}{month}$ |
| Initial Value | $7.7848 \pm 0.69027 \frac{\text{days}}{\text{month}}$ |
| RMSE | 9.6662 |

Indian Point[82]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $-4.8 \times 10^{-4} \pm 4.4 \times 10^{-4} \frac{\frac{\text{days}}{month}}{month}$ |
| Initial Value | $1.3769 \pm 0.18623 \frac{\text{days}}{\text{month}}$ |
| RMSE | 2.4696 |

Palisades[83]

| | |
|---|---|
| Starting Date | April, 1893 |
| Slope | $-9.7 \times 10^{-4} \pm 2.0 \times 10^{-4} \frac{\frac{\text{days}}{month}}{month}$ |
| Initial Value | $2.1155 \pm 0.16392 \frac{\text{days}}{\text{month}}$ |
| RMSE | 2.9245 |

Pilgrim[1]

| | |
|---|---|
| Starting Date | January, 1943 |
| Slope | $4 \times 10^{-5} \pm 2.6 \times 10^{-4} \frac{\frac{\text{days}}{month}}{month}$ |
| Initial Value | $0.73940 \pm 0.11832 \frac{\text{days}}{\text{month}}$ |
| RMSE | 1.6307 |

River Bend[84]

| | |
|---|---|
| Starting Date | January, 1942 |
| Slope | $-2.11 \times 10^{-3} \pm 1.47 \times 10^{-3} \frac{\frac{\text{days}}{month}}{month}$ |
| Initial Value | $7.8989 \pm 0.68121 \frac{\text{days}}{\text{month}}$ |
| RMSE | 9.5488 |

Vermont Yankee[85]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $-4.2 \times 10^{-4} \pm 2.4 \times 10^{-4} \frac{\frac{\text{days}}{month}}{month}$ |
| Initial Value | $0.70382 \pm 0.10067 \frac{\text{days}}{\text{month}}$ |
| RMSE | 1.3318 |

Waterford[86]

| | |
|---|---|
| Starting Date | January, 1942 |
| Slope | $-5.9 \times 10^{-4} \pm 1.45 \times 10^{-3} \frac{\frac{\text{days}}{month}}{month}$ |
| Initial Value | $7.0873 \pm 0.67139 \frac{\text{days}}{\text{month}}$ |
| RMSE | 9.4113 |

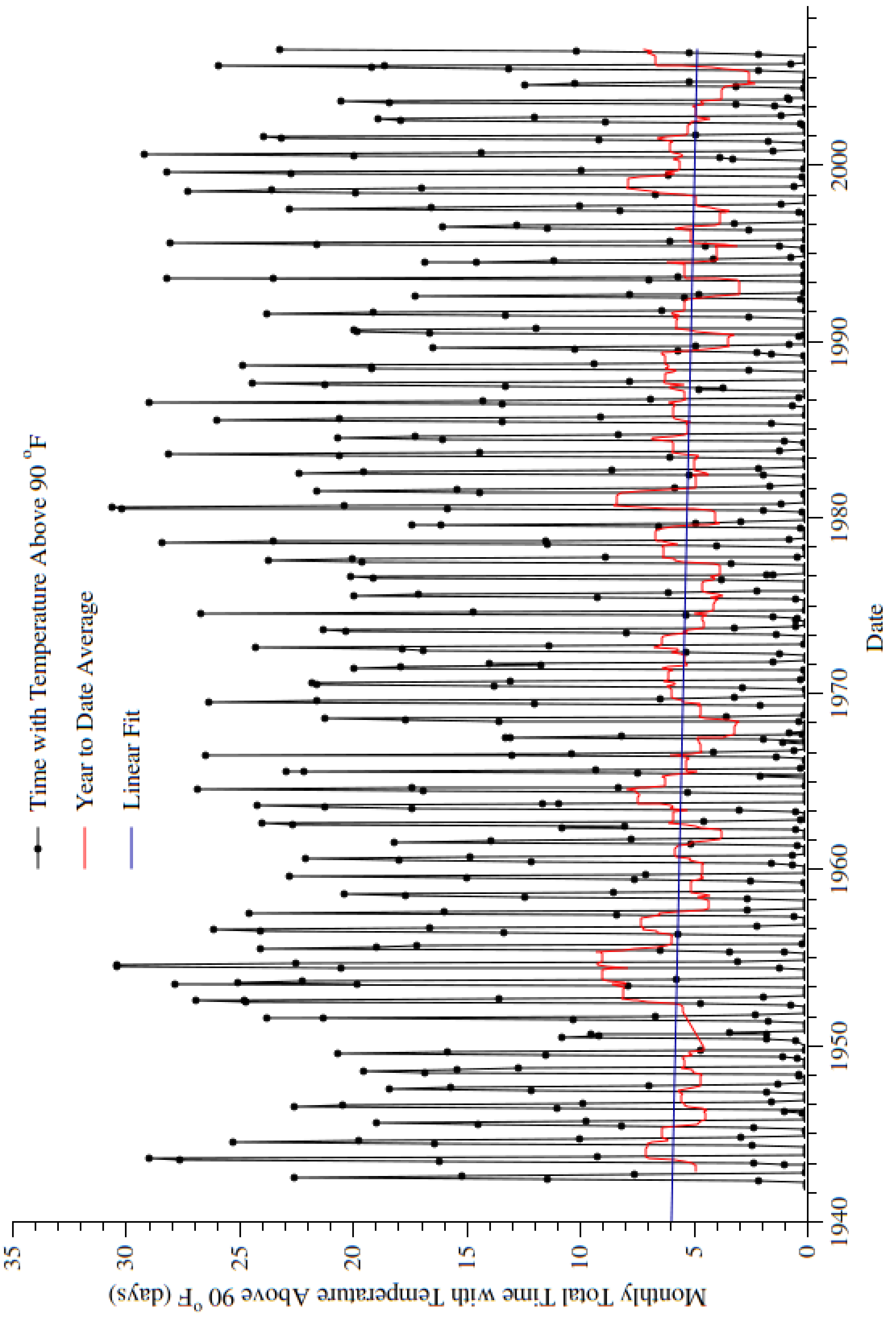

Fig. 90. Arkansas Nuclear One days above 90 $\frac{^{\circ}F}{month}$

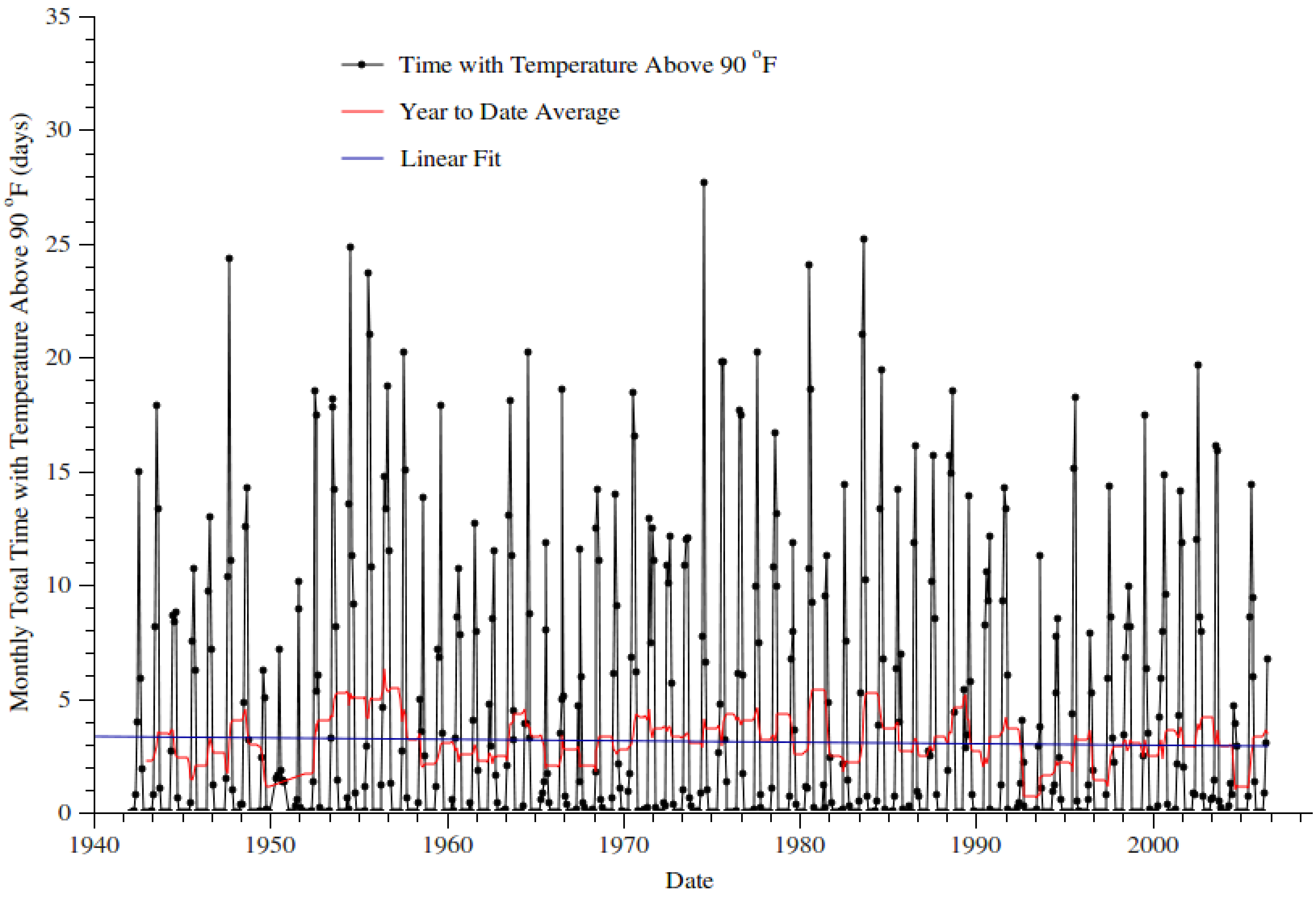

Fig. 91. Cooper Station days above 90 $\frac{^{\circ}\mathrm{F}}{\mathrm{month}}$

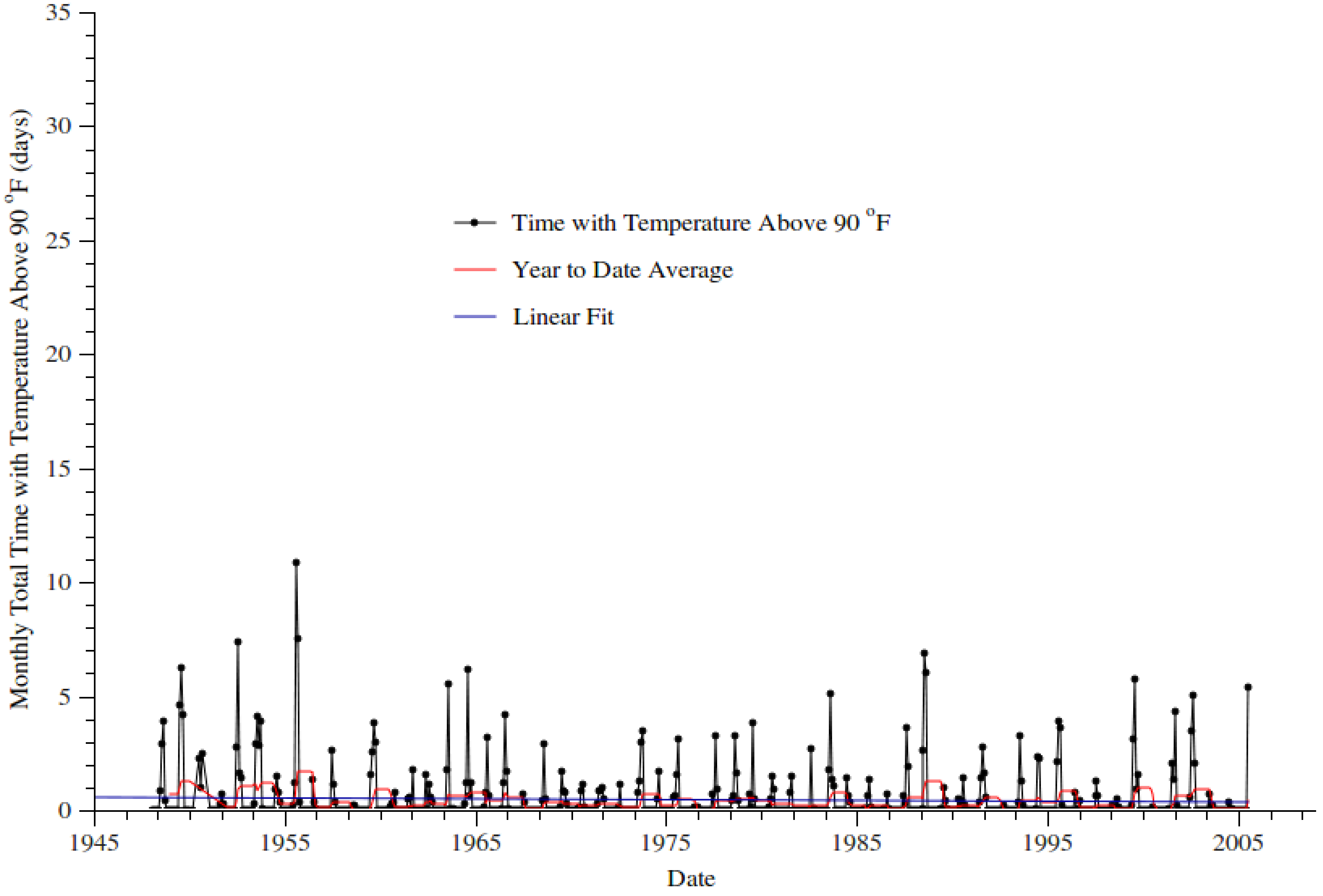

Fig. 92. James A. FitzPatrick days above 90 $\frac{^\circ F}{\text{month}}$

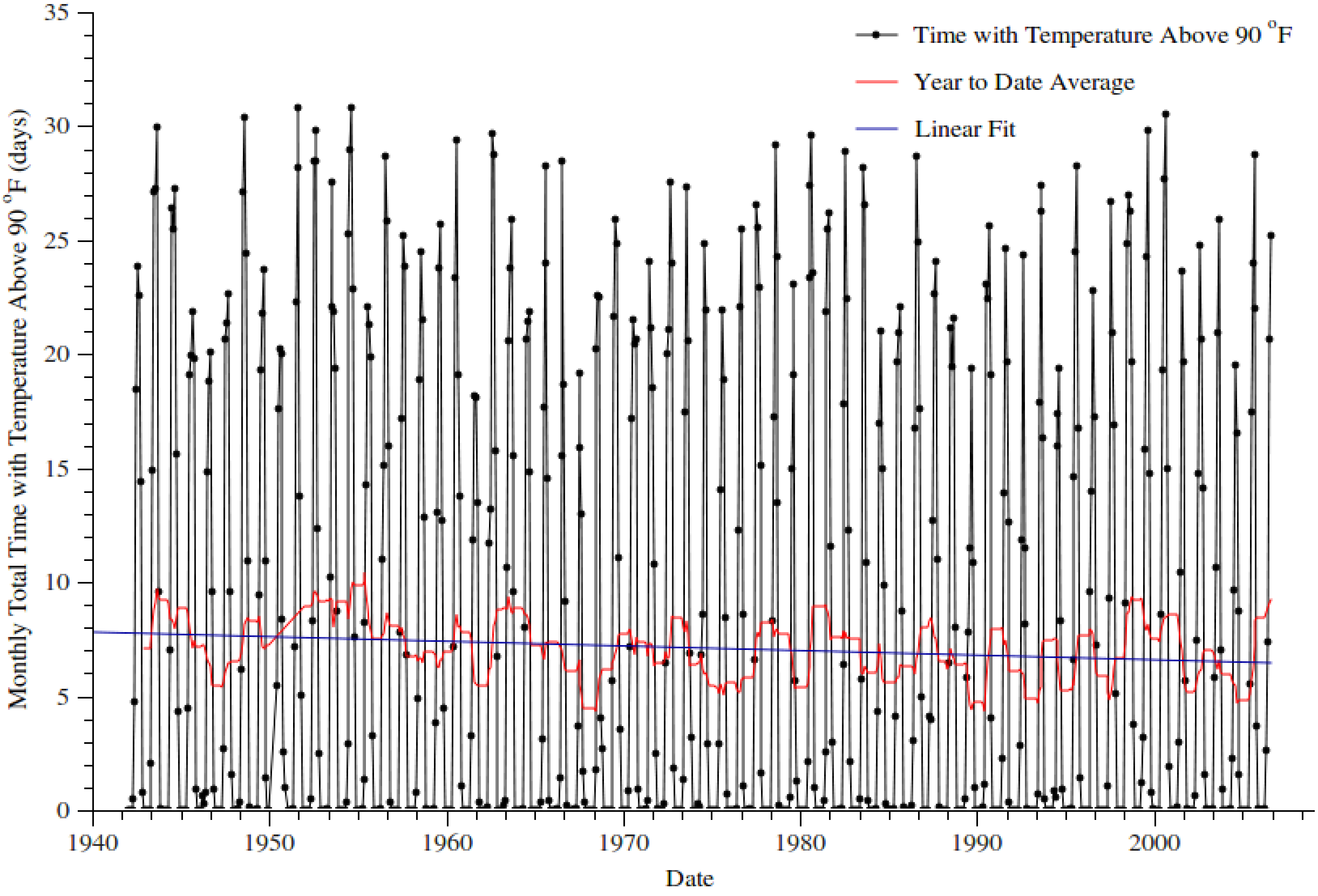

Fig. 93. Grand Gulf days above 90 $\frac{^{\circ}\mathrm{F}}{\mathrm{month}}$

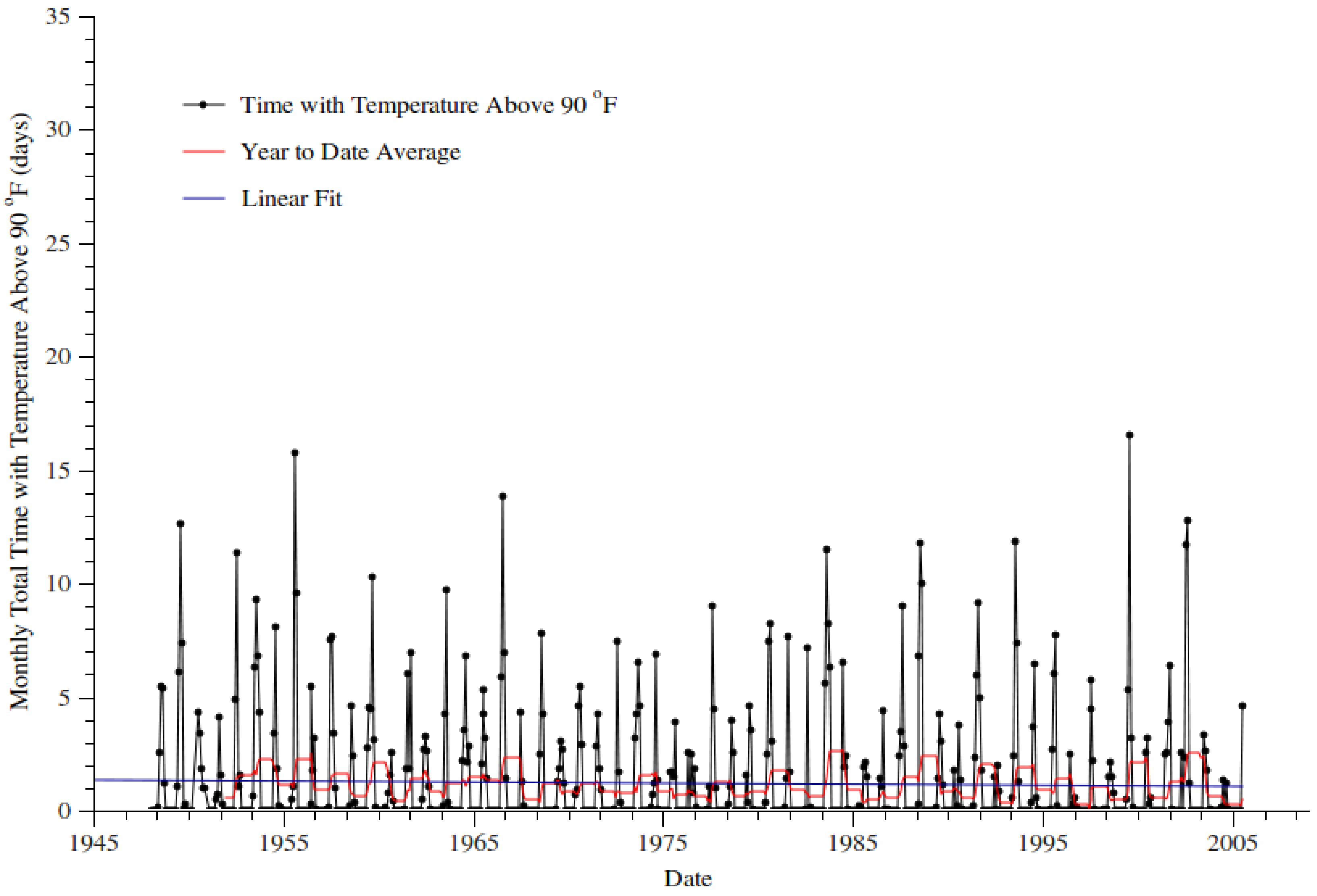

Fig. 94. Indian Point days above 90 $\frac{^{\circ}\mathrm{F}}{\mathrm{month}}$

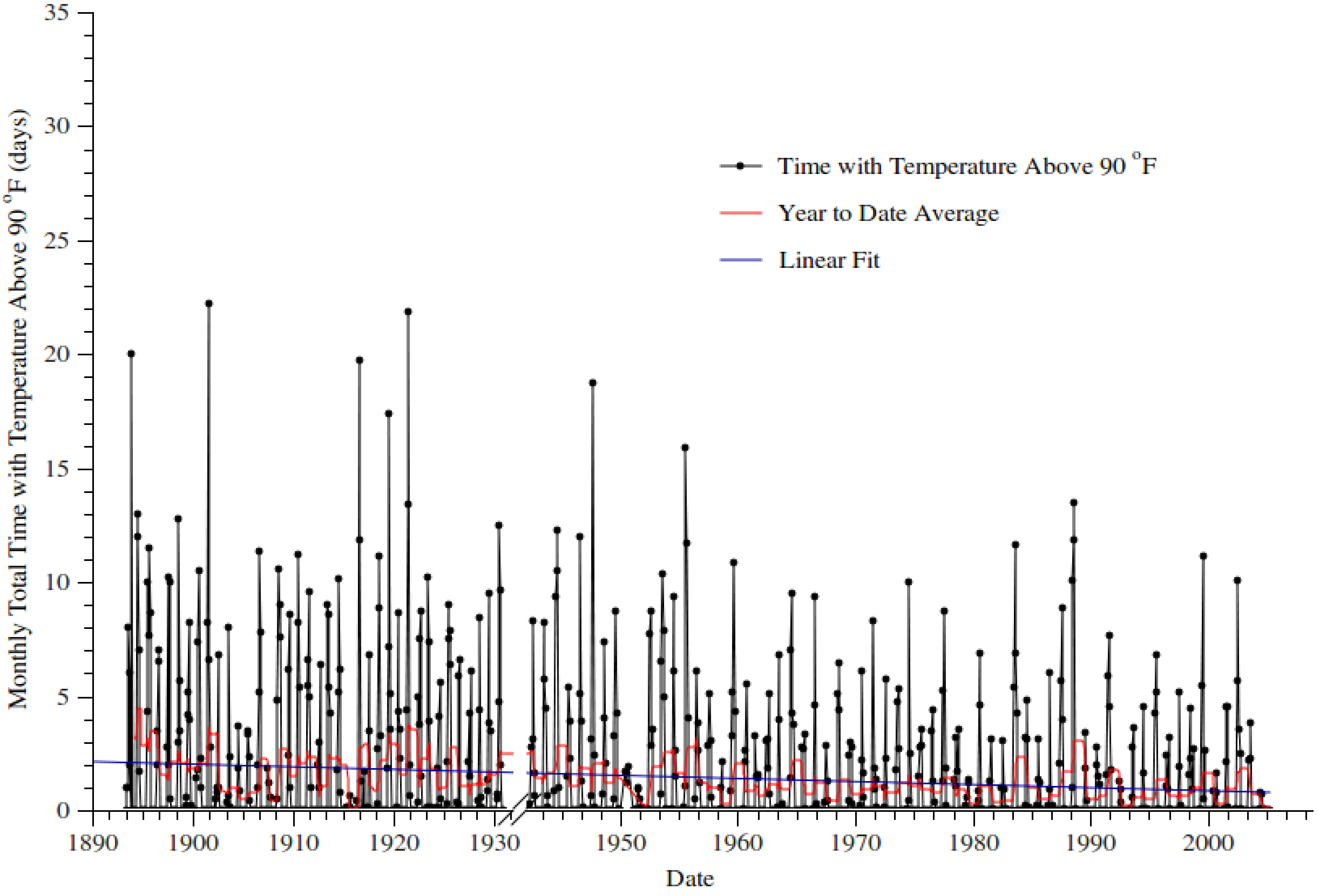

Fig. 95. Palisades days above 90 $\frac{^{\circ}\mathrm{F}}{\mathrm{month}}$

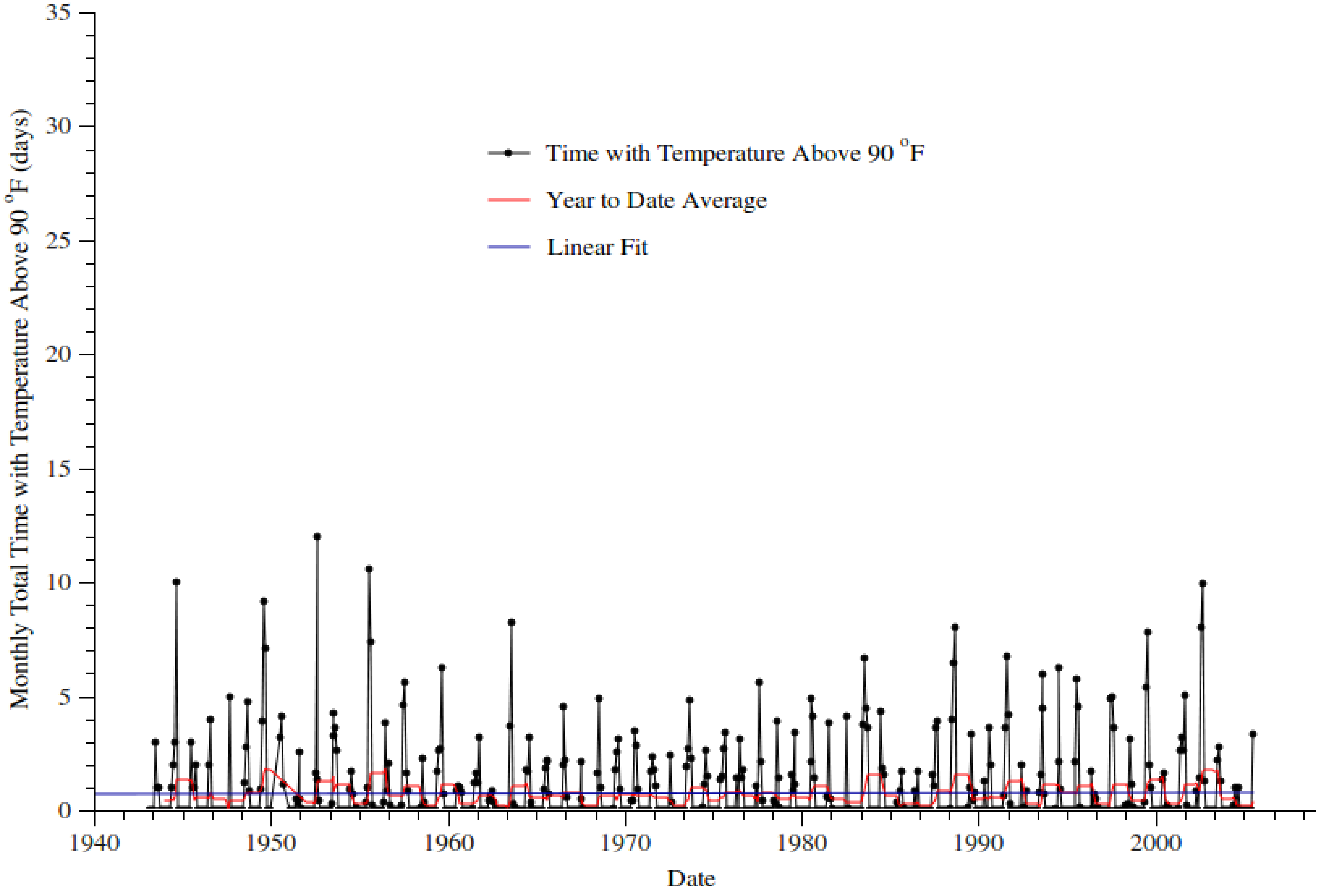

Fig. 96. Pilgrim days above 90 $\frac{^\circ\mathrm{F}}{\mathrm{month}}$

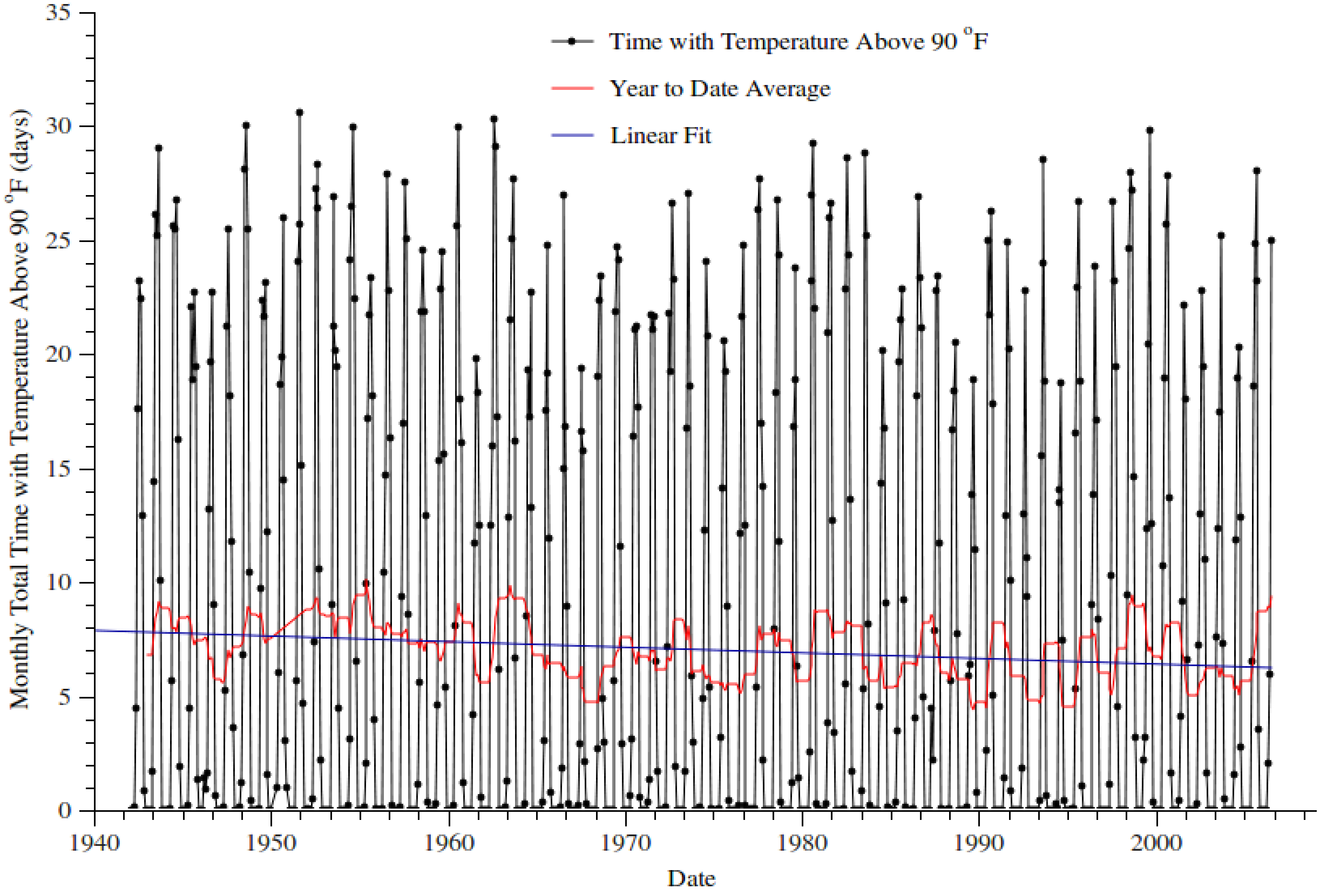

Fig. 97. River Bend days above 90 $\frac{^{\circ}\mathrm{F}}{\mathrm{month}}$

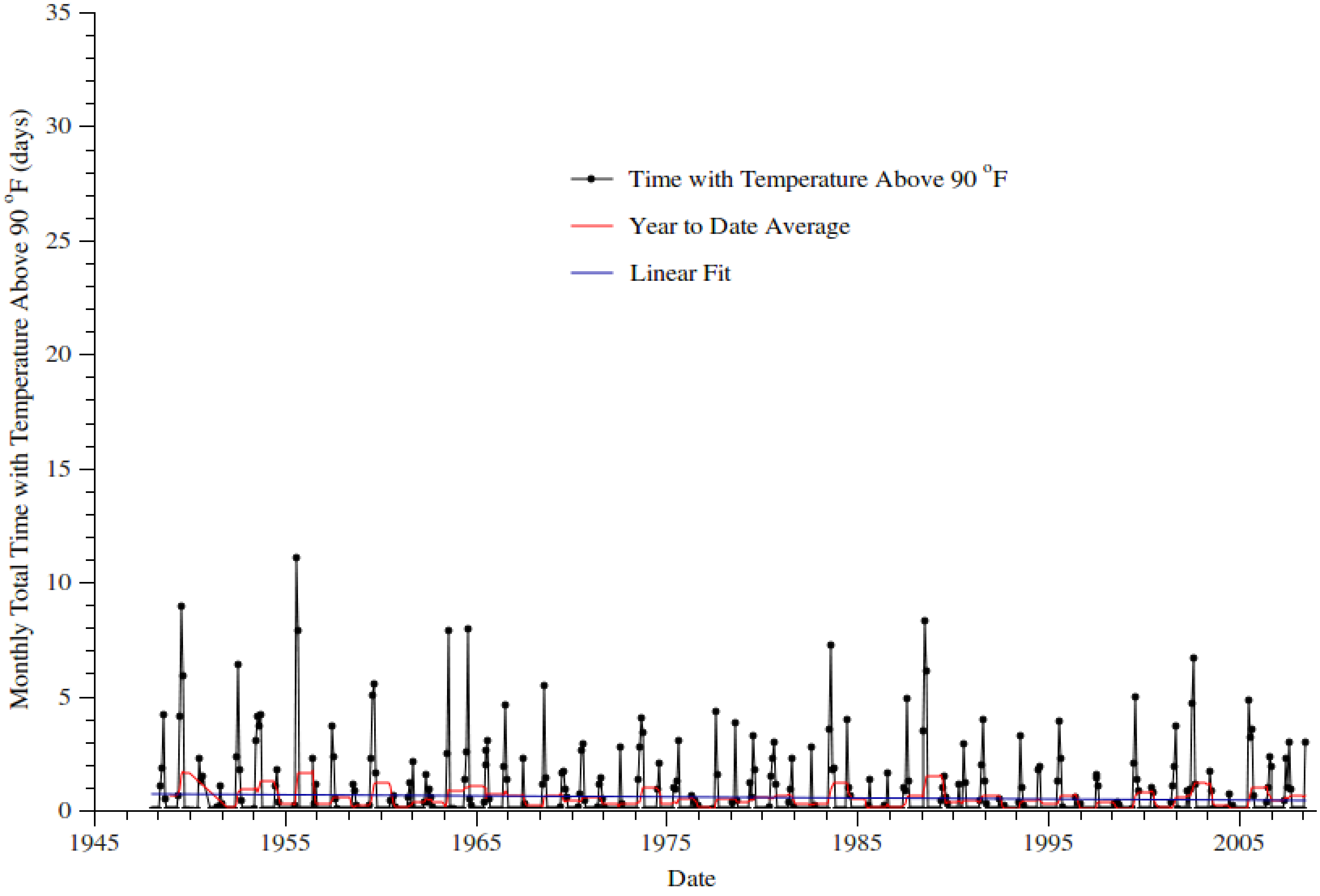

Fig. 98. Vermont Yankee days above 90 $\frac{{}^{\circ}\mathrm{F}}{\mathrm{month}}$

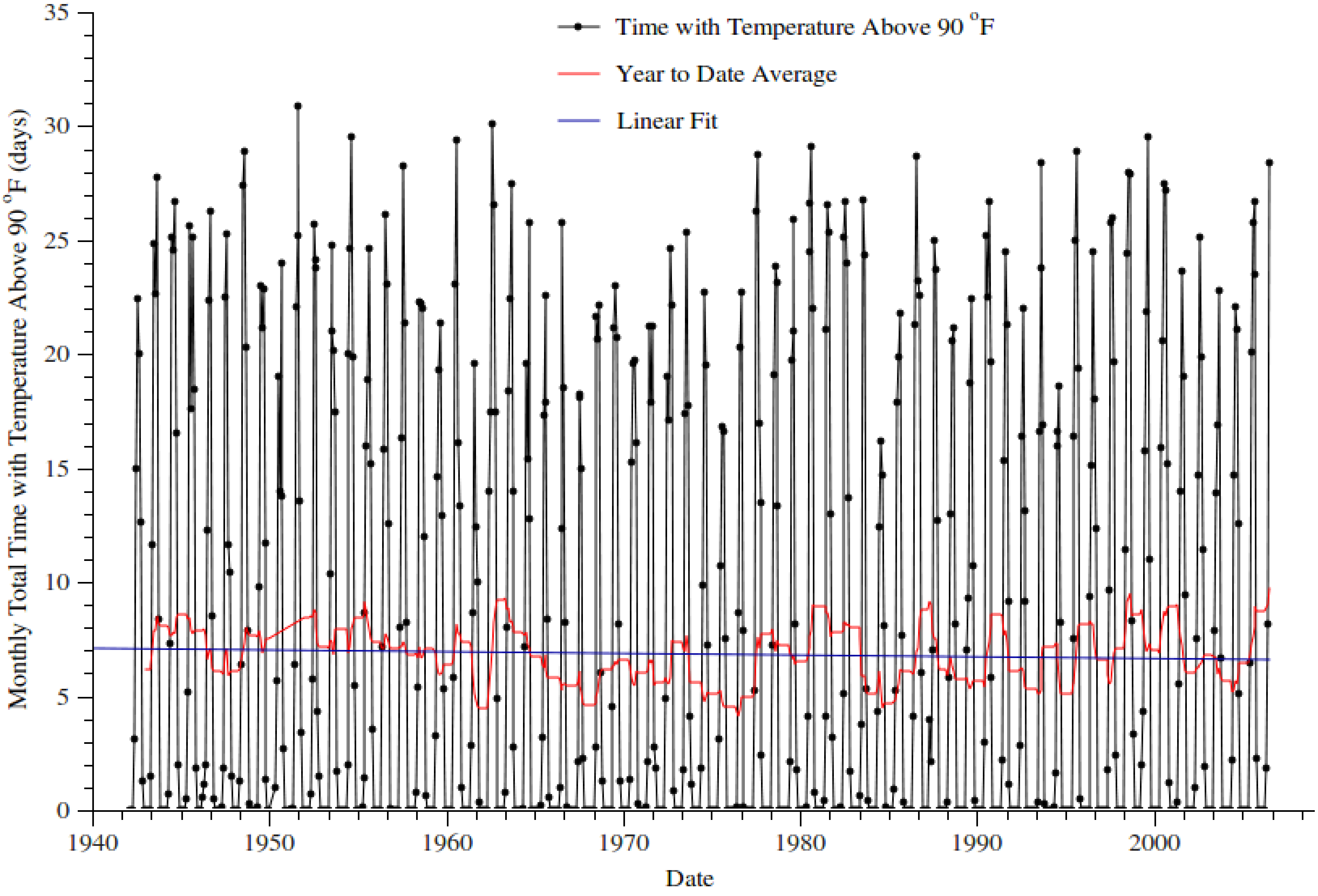

Fig. 99. Waterford days above 90 $\frac{^{\circ}\mathrm{F}}{\mathrm{month}}$

# APPENDIX K

## MONTHLY TOTAL PRECIPITATION

While the monthly total precipitation can indicate the likeliness of flooding, it is much more indicative of the general availability of water. The lack of correlation with floods is because floods result primary from the discrepancy between the rate of precipitation relative to the rates of absorption and transportation.

Changes in drought likeliness are more closely linked to total precipitation. Even in this case, however, the correlation is not perfect because significant precipitation over short periods of time can result in flooding with little absorption into the soil.

The data for these composite graphs was obtained from NOAA [78] and processed as described in section 3.3.

Arkansas Nuclear One[59]

| | |
|---|---|
| Starting Date | January, 1892 |
| Slope | $4.855 \times 10^{-2} \pm 1.521 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $367.25 \pm 12.280 \frac{1}{10}$ in |
| RMSE | 229.46 |

Cooper Station[79]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $2.331 \times 10^{-2} \pm 1.387 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $252.55 \pm 11.101 \frac{1}{10}$ in |
| RMSE | 206.53 |

FitzPatrick[80]

| | |
|---|---|
| Starting Date | January, 1884 |
| Slope | $5.922 \times 10^{-2} \pm 7.84 \times 10^{-3} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $26.757 \pm 6.7655 \frac{1}{10}$ in |
| RMSE | 130.69 |

Grand Gulf[81]

| | |
|---|---|
| Starting Date | January, 1891 |
| Slope | $3.316 \times 10^{-2} \pm 1.647 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $438.40 \pm 13.420 \frac{1}{10}$ in |
| RMSE | 351.47 |

Indian Point[82]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $4.558 \times 10^{-2} \pm 2.450 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $37.356 \pm 13.168 \frac{1}{10}$ in |
| RMSE | 200.62 |

Palisades[83]

| | |
|---|---|
| Starting Date | January, 1891 |
| Slope | $2.671 \times 10^{-2} \pm 9.67 \times 10^{-3} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $278.99 \pm 7.8942 \frac{1}{10}$ in |
| RMSE | 147.13 |

Pilgrim[1]

| | |
|---|---|
| Starting Date | January, 1887 |
| Slope | $2.493 \times 10^{-2} \pm 1.152 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $358.94 \pm 9.7021 \frac{1}{10}$ in |
| RMSE | 185.14 |

River Bend[84]

| | |
|---|---|
| Starting Date | February, 1891 |
| Slope | $3.557 \times 10^{-2} \pm 1.688 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $472.08 \pm 13.740 \frac{1}{10}$ in |
| RMSE | 257.74 |

Vermont Yankee[85]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $3.126 \times 10^{-2} \pm 1.5833 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $335.80 \pm 9.8521 \frac{1}{10}$ in |
| RMSE | 150.10 |

Waterford[86]

| | |
|---|---|
| Starting Date | January, 1894 |
| Slope | $2.854 \times 10^{-2} \pm 2.272 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $494.57 \pm 19.253 \frac{1}{10}$ in |
| RMSE | 307.08 |

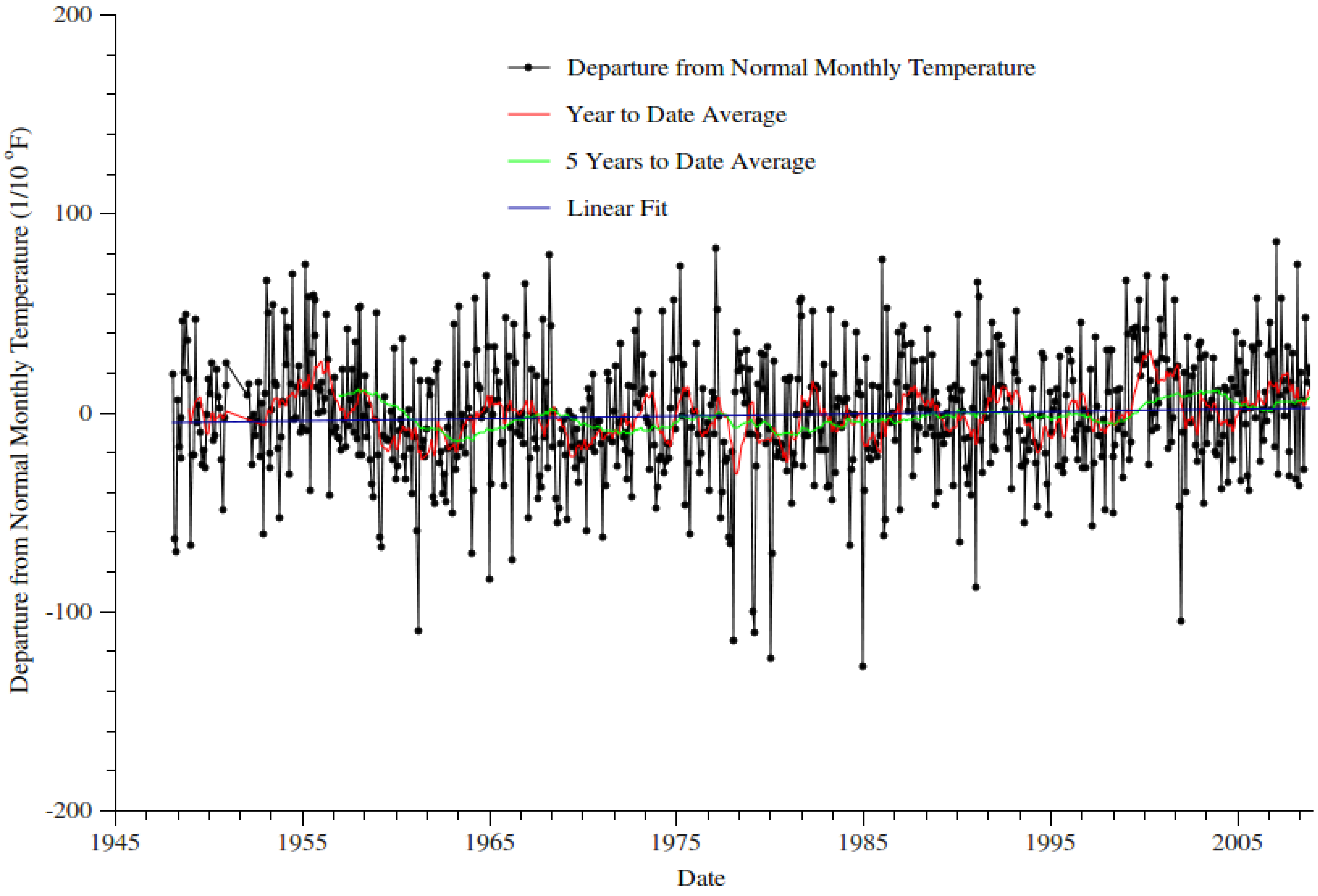

Fig. 100. Arkansas Nuclear One departure from normal monthly temperature

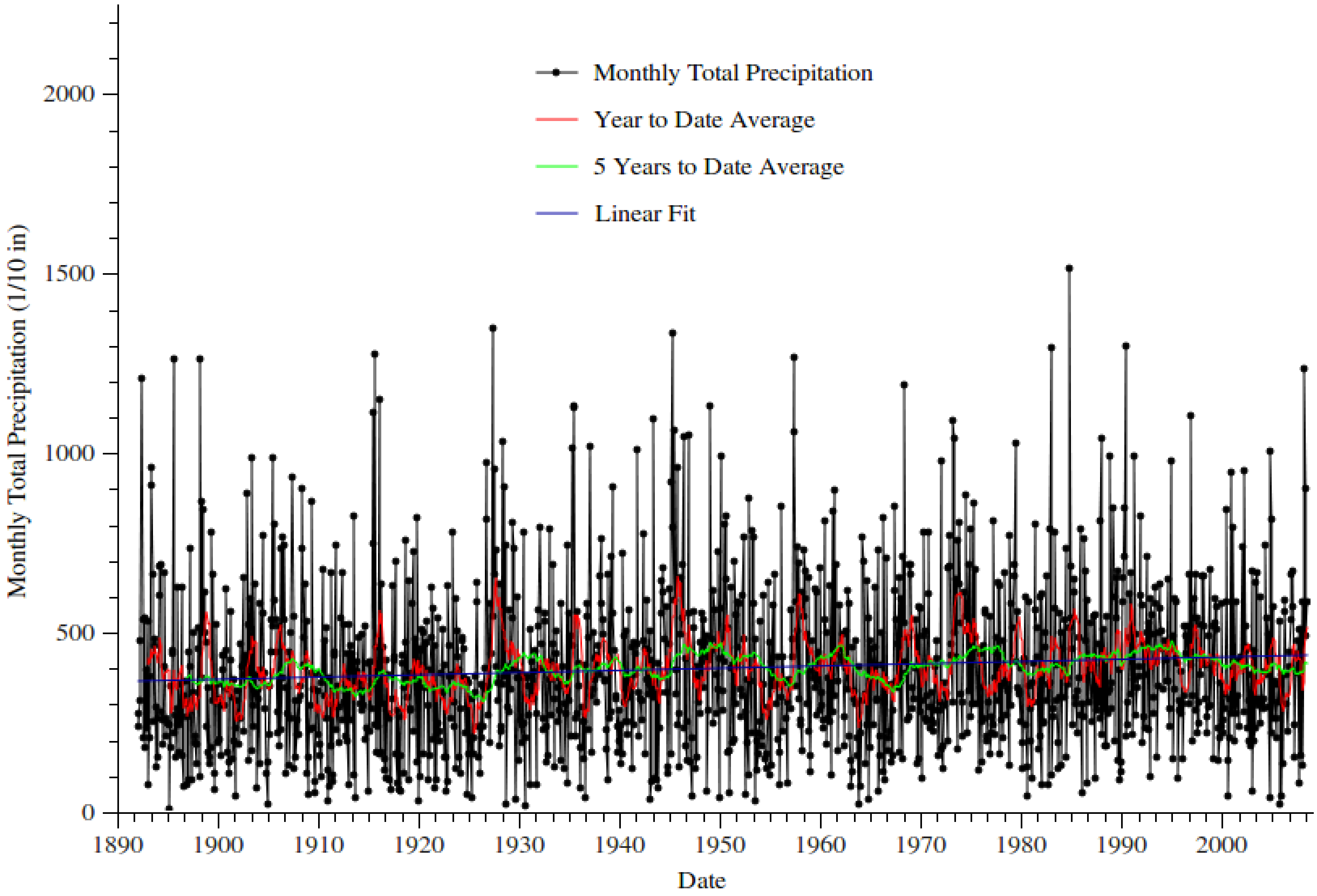

Fig. 101. Arkansas Nuclear One monthly total precipitation

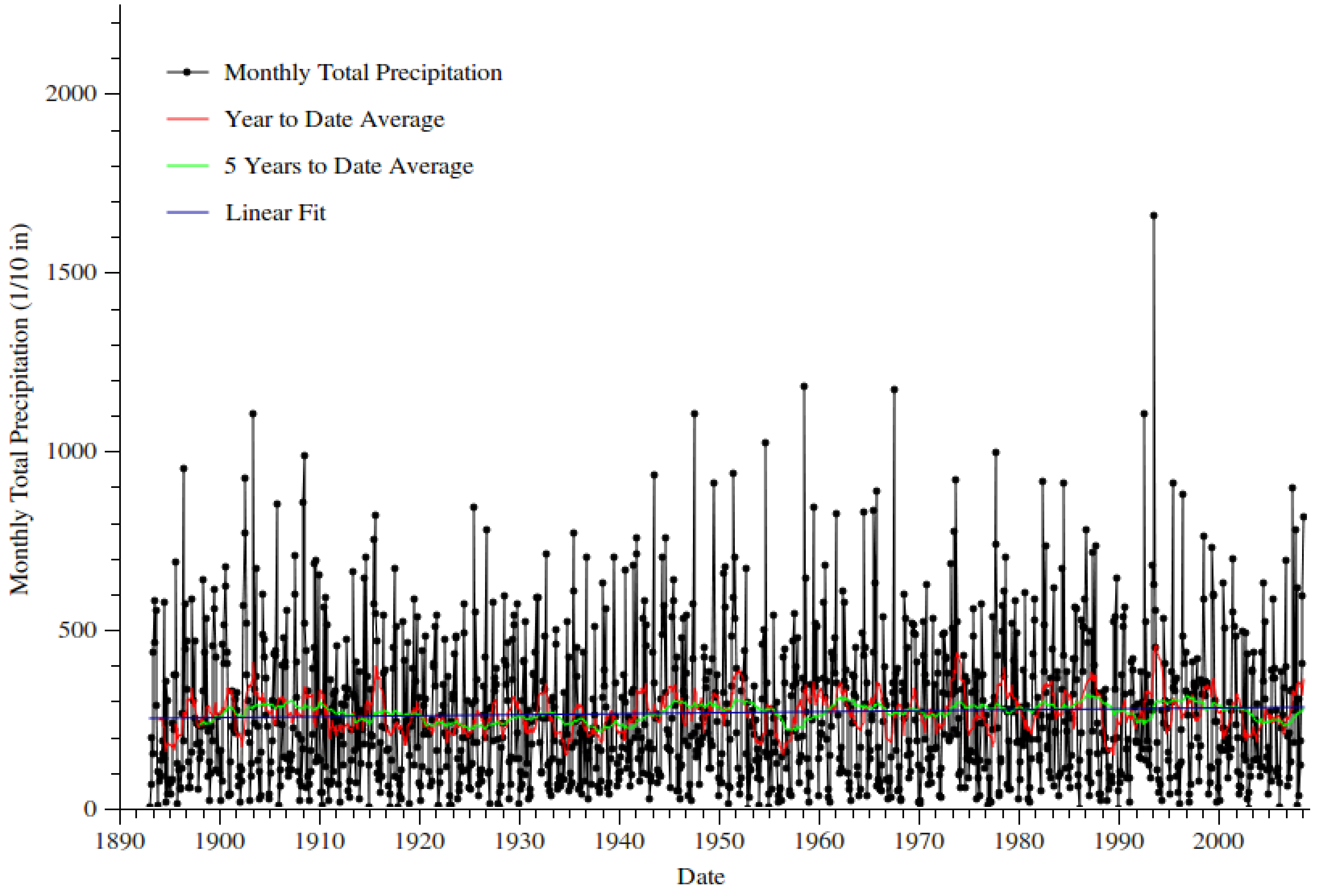

Fig. 102. Cooper Station monthly total precipitation

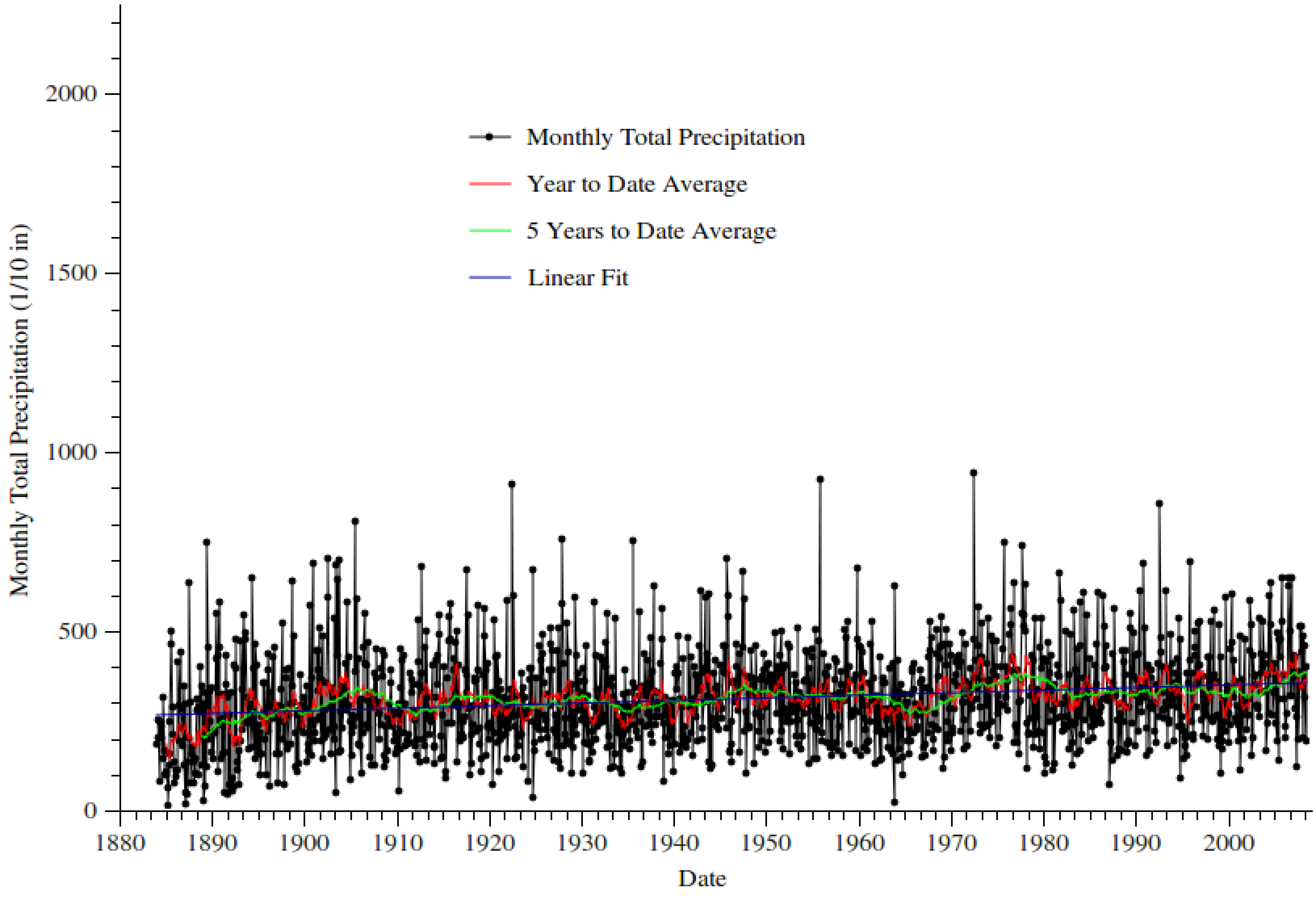

Fig. 103. James A. FitzPatrick monthly total precipitation

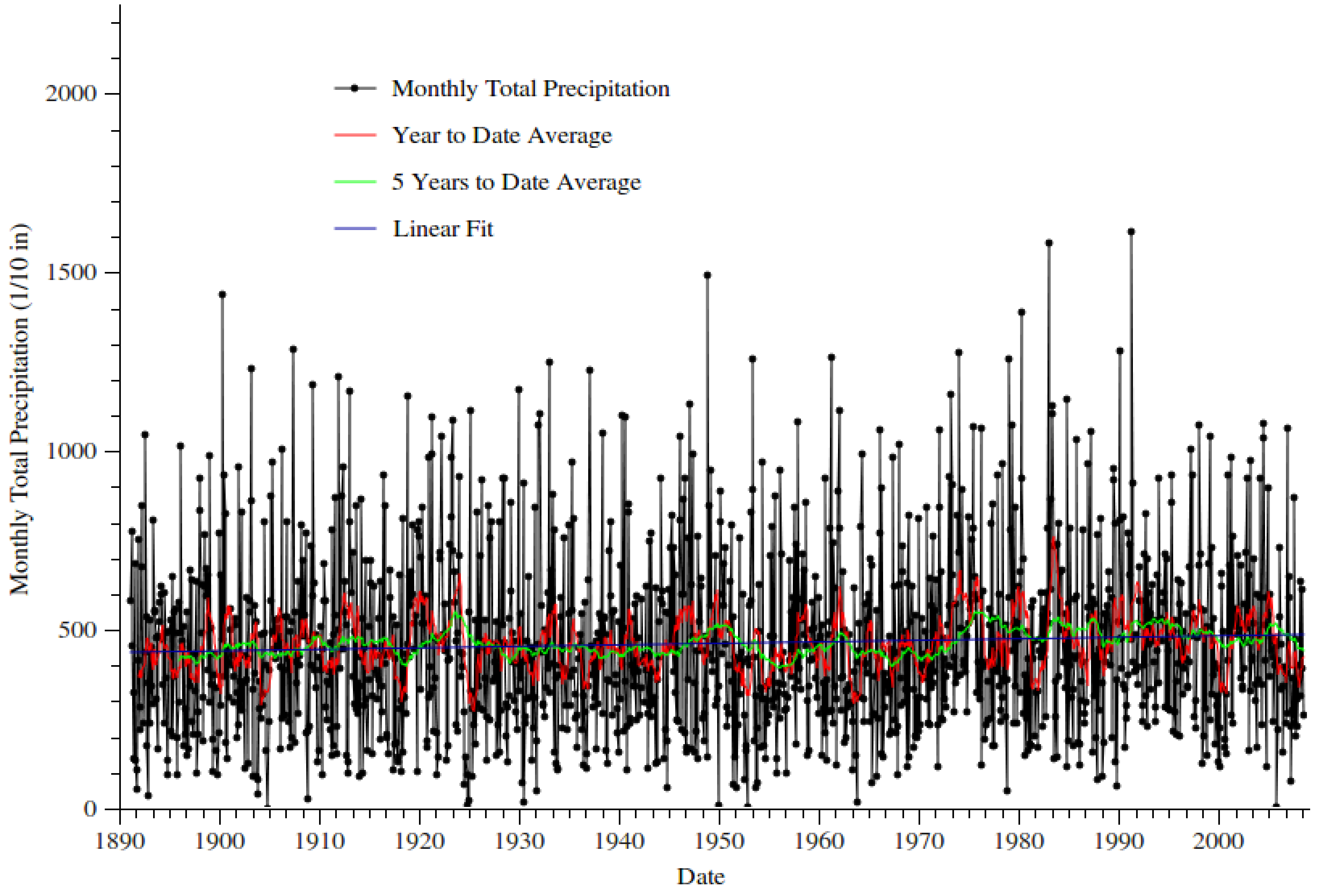

Fig. 104. Grand Gulf monthly total precipitation

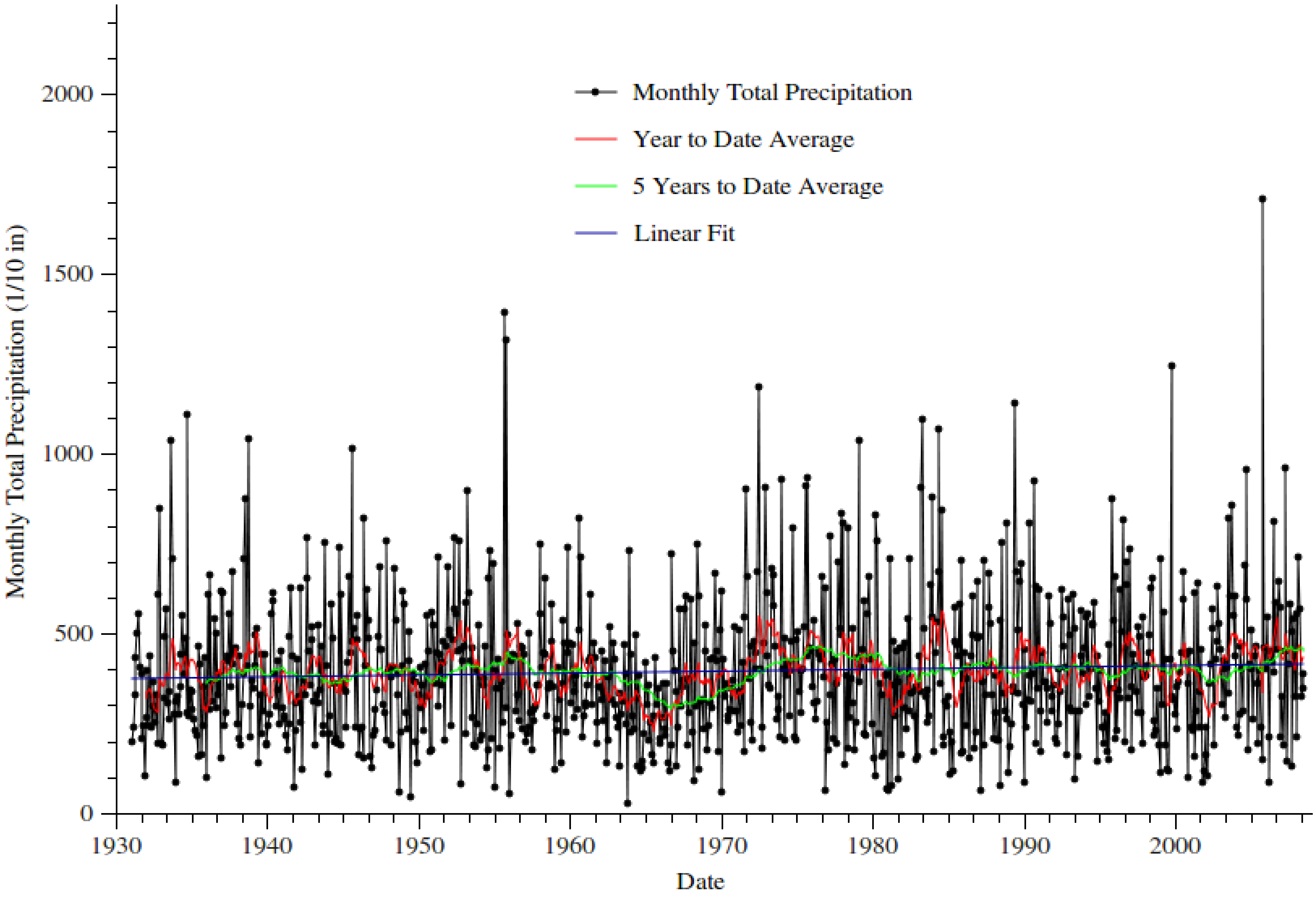

Fig. 105. Indian Point monthly total precipitation

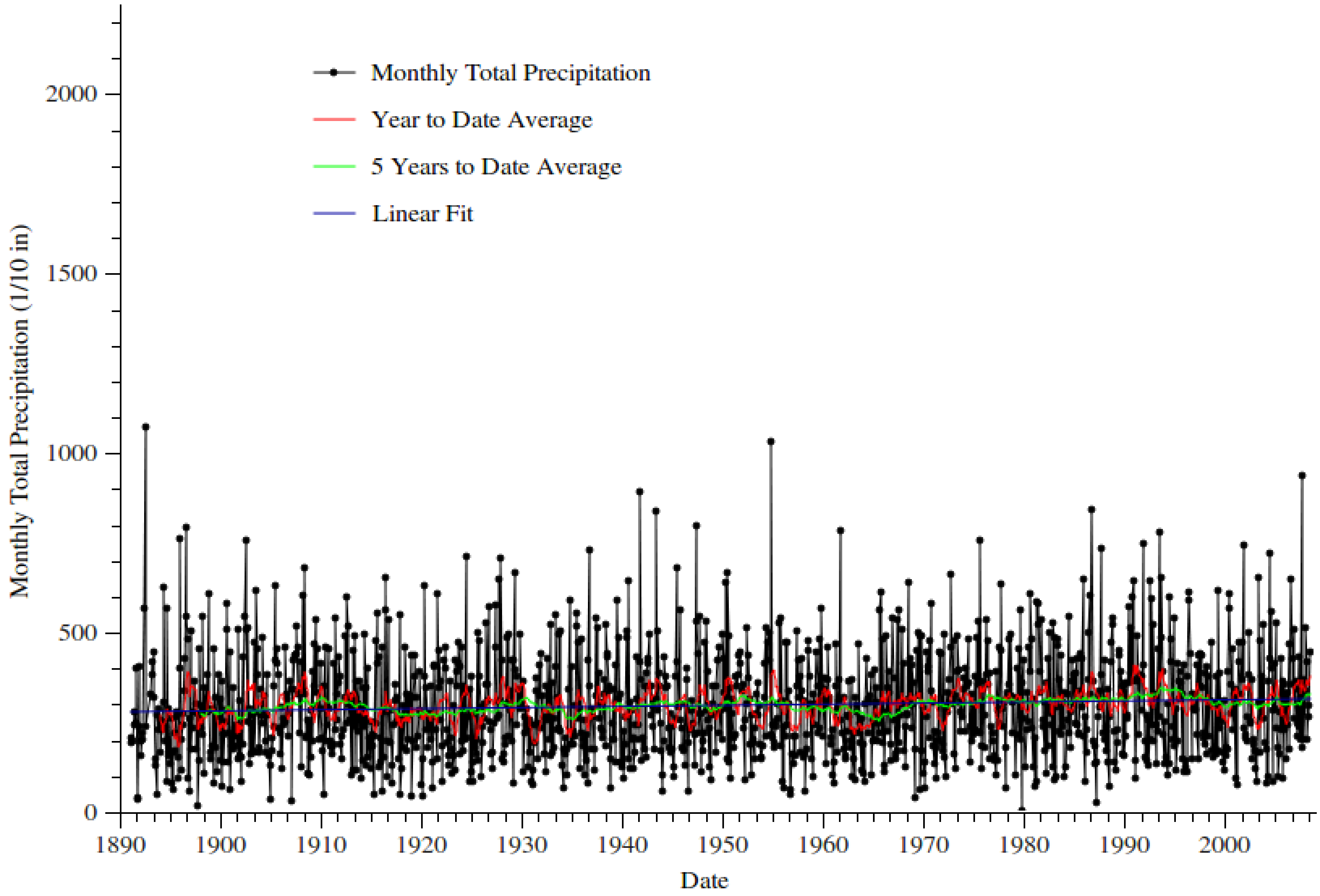

Fig. 106. Palisades monthly total precipitation

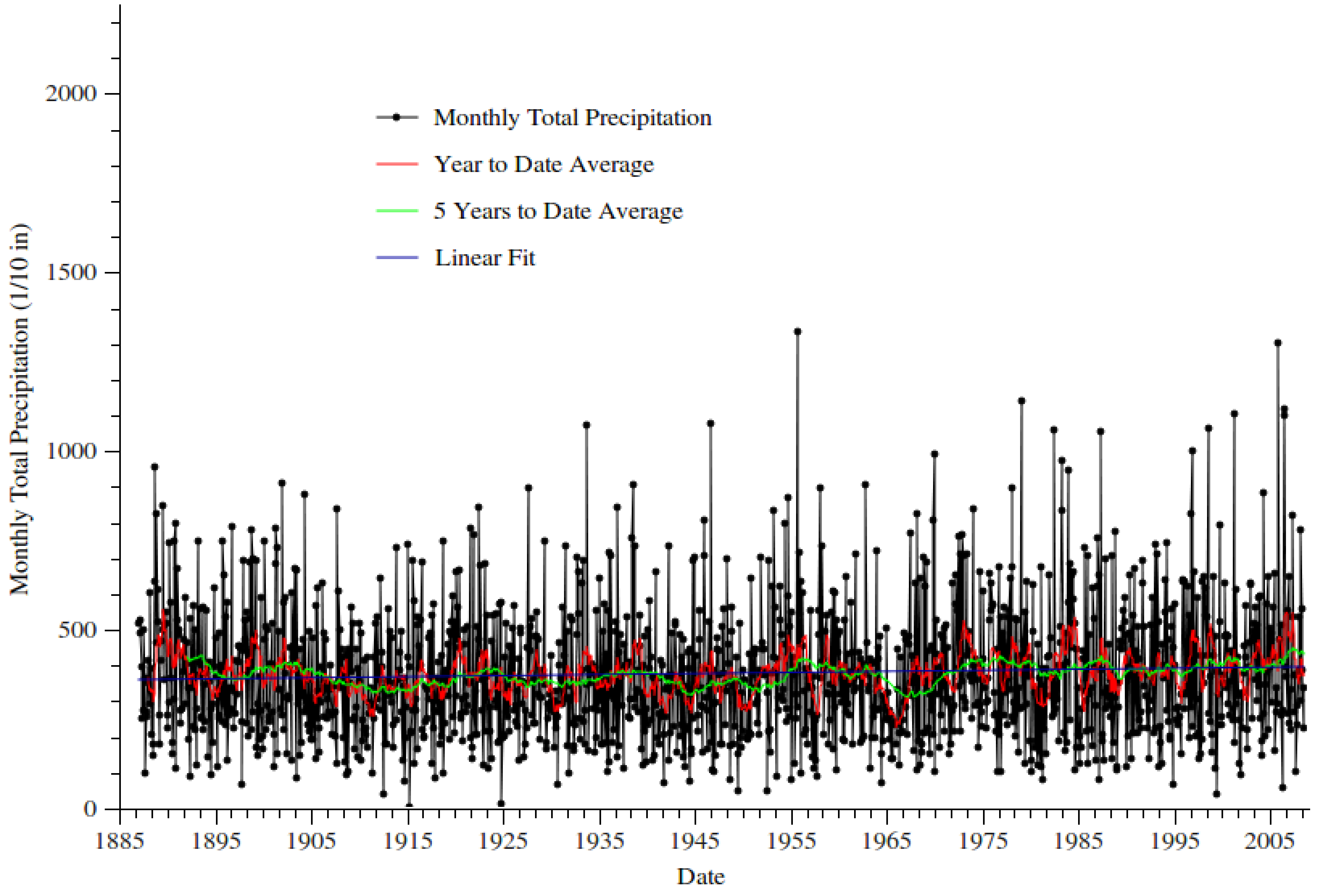

Fig. 107. Pilgrim monthly total precipitation

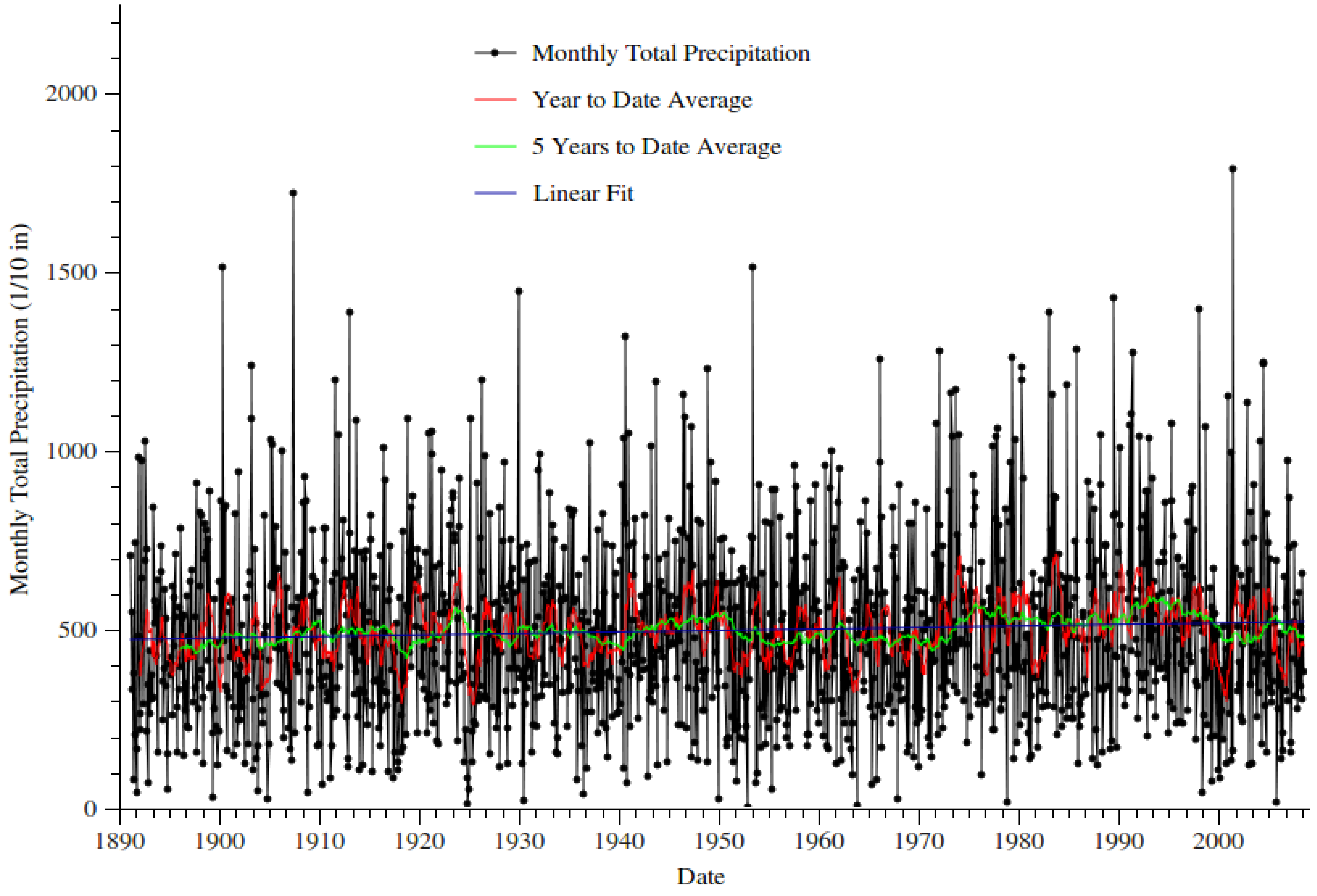

Fig. 108. River Bend monthly total precipitation

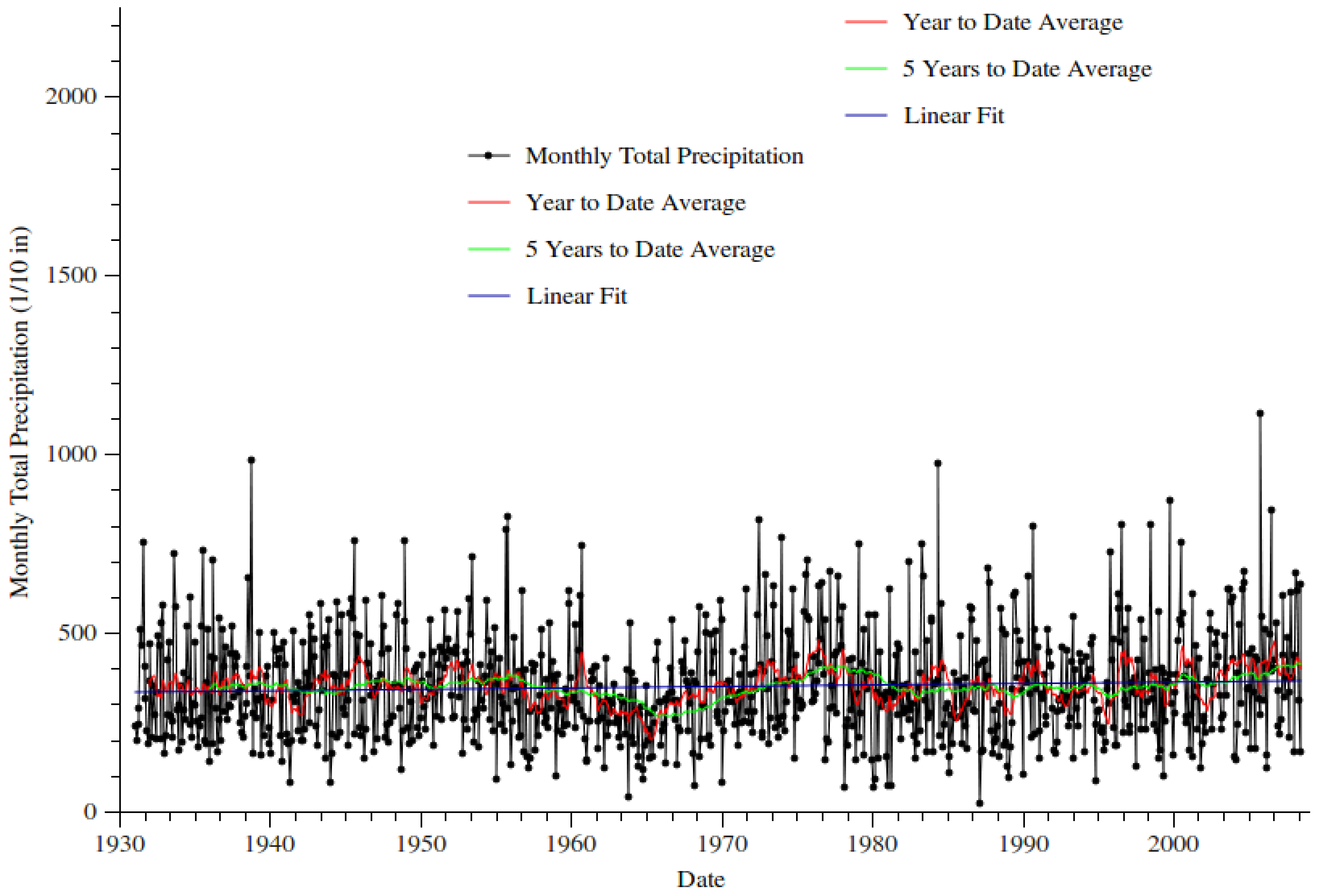

Fig. 109. Vermont Yankee monthly total precipitation

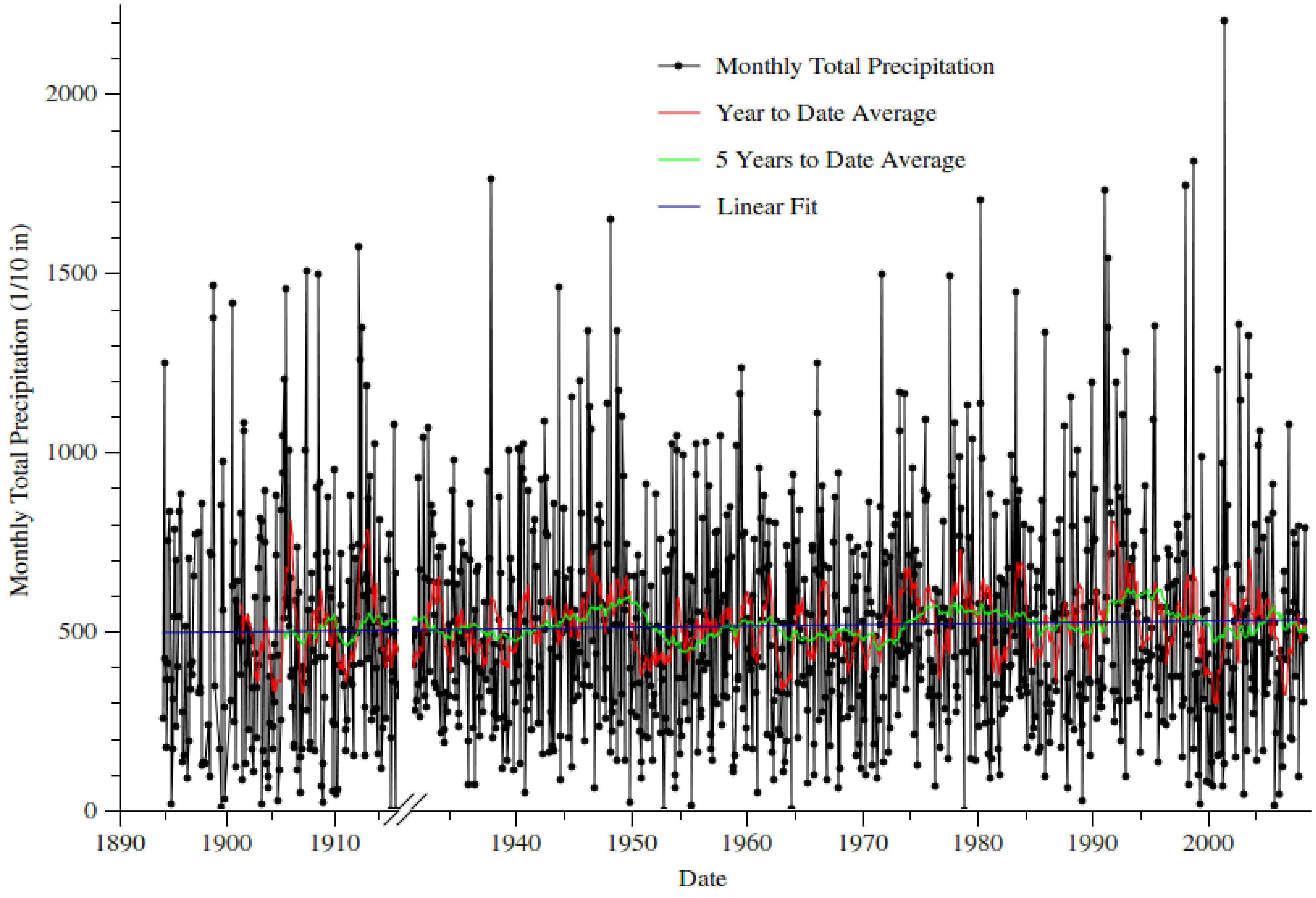

Fig. 110. Waterford monthly total precipitation

# APPENDIX L

## DEPARTURE FROM NORMAL MONTHLY PRECIPITATION

The departure from normal monthly precipitation, unlike total monthly precipitation, does give a good sense of flood risk. Large positive departures indicate significant precipitation in a relatively short time span (one month or less); these conditions are closely associated with flooding. Trending of the “year to date” average tends to indicate changes in the relative likelihood of flooding.

Obviously, negative departures from the normal indicate drier than average conditions and can give an indication of drought risk. On a month to month basis, such changes can also foretell alterations in the start or end of the wet season.

As with departure from normal monthly temperature, the “normal” values are based on the mean average values from 1961-1990 as calculated by NOAA. The data for these composite graphs was obtained from NOAA [78] and processed as described in section 3.3.

Arkansas Nuclear One[59]

| | |
|---|---|
| Starting Date | January, 1947 |
| Slope | $2.124 \times 10^{-2} \pm 3.807 \times 10^{-2} \frac{\frac{1}{10} in}{month}$ |
| Initial Value | $-4.9883 \pm 16.369 \frac{1}{10}$ in |
| RMSE | 216.00 |

Cooper Station[79]

| | |
|---|---|
| Starting Date | January, 1902 |
| Slope | $-1.785 \times 10^{-2} \pm 1.707 \times 10^{-2} \frac{\frac{1}{10} in}{month}$ |
| Initial Value | $24.056 \pm 14.195 \frac{1}{10}$ in |
| RMSE | 169.45 |

FitzPatrick[80]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $3.463 \times 10^{-2} \pm 2.182 \times 10^{-2} \frac{\frac{1}{10} in}{month}$ |
| Initial Value | $-2.4924 \pm 9.1570 \frac{1}{10}$ in |
| RMSE | 123.24 |

Grand Gulf[81]

| | |
|---|---|
| Starting Date | January, 1947 |
| Slope | $-1.009 \times 10^{-2} \pm 4.398 \times 10^{-2} \frac{\frac{1}{10} in}{month}$ |
| Initial Value | $18.873 \pm 18.910 \frac{1}{10}$ in |
| RMSE | 249.51 |

Indian Point[82]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $3.561 \times 10^{-2} \pm 3.639 \times 10^{-2} \frac{\frac{1}{10} in}{month}$ |
| Initial Value | $-3.7156 \pm 15.271 \frac{1}{10}$ in |
| RMSE | 205.52 |

Palisades[83]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $1.636 \times 10^{-2} \pm 2.491 \times 10^{-2} \frac{\frac{1}{10} in}{month}$ |
| Initial Value | $2.3396 \pm 10.540 \frac{1}{10}$ in |
| RMSE | 137.66 |

Pilgrim[1]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $3.171 \times 10^{-2} \pm 3.615 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $5.9066 \pm 15.294 \frac{1}{10}$ in |
| RMSE | 199.76 |

River Bend[84]

| | |
|---|---|
| Starting Date | February, 1947 |
| Slope | $-6 \times 10^{-5} \pm 4.652 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $8.2015 \pm 20.004 \frac{1}{10}$ in |
| RMSE | 263.95 |

Vermont Yankee[85]

| | |
|---|---|
| Starting Date | January, 1948 |
| Slope | $6.120 \times 10^{-2} \pm 2.552 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $-13.644 \pm 10.708 \frac{1}{10}$ in |
| RMSE | 144.11 |

Waterford[86]

| | |
|---|---|
| Starting Date | January, 1947 |
| Slope | $-2.499 \times 10^{-2} \pm 5.462 \times 10^{-2} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $22.509 \pm 23.488 \frac{1}{10}$ in |
| RMSE | 309.92 |

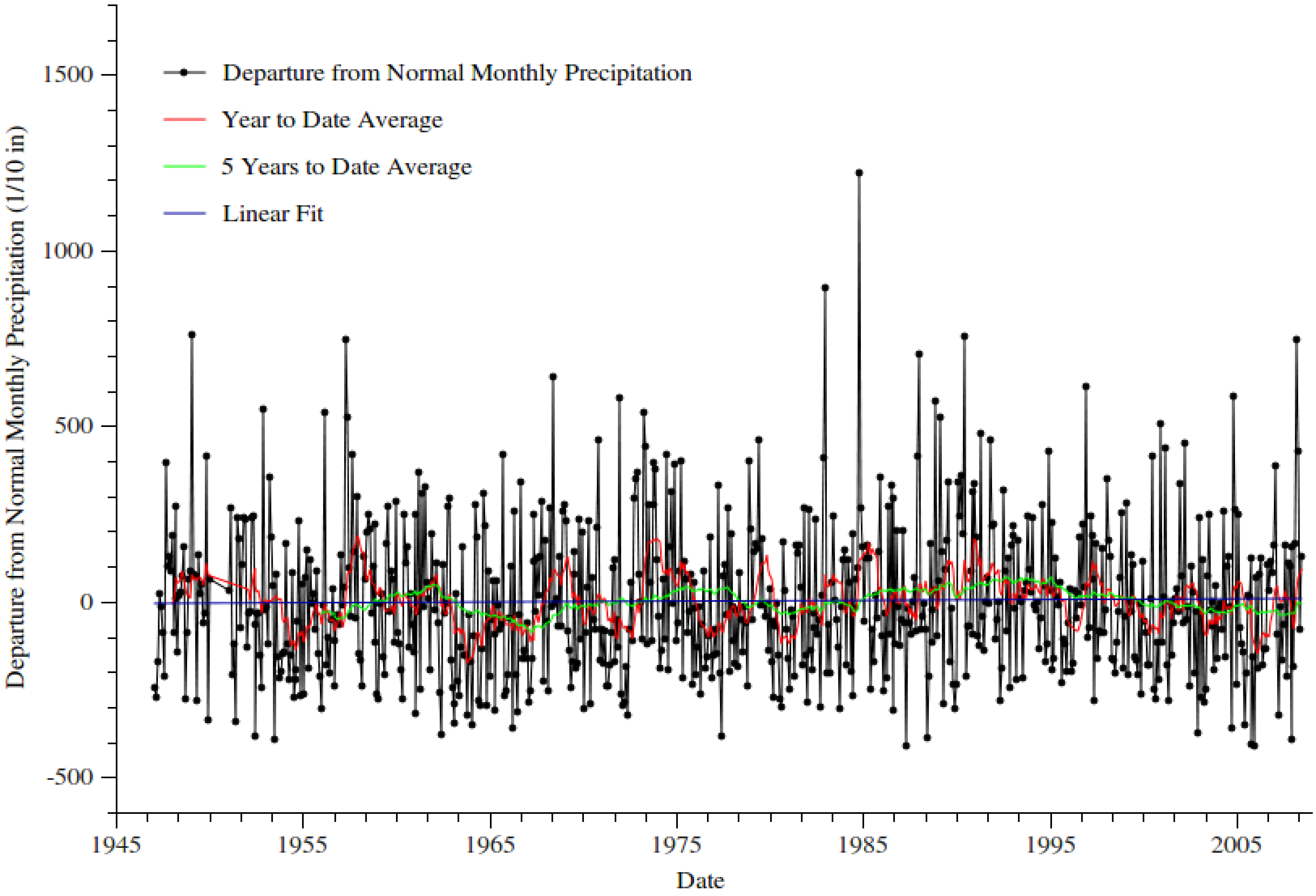

Fig. 111. Arkansas Nuclear One departure from normal monthly precipitation

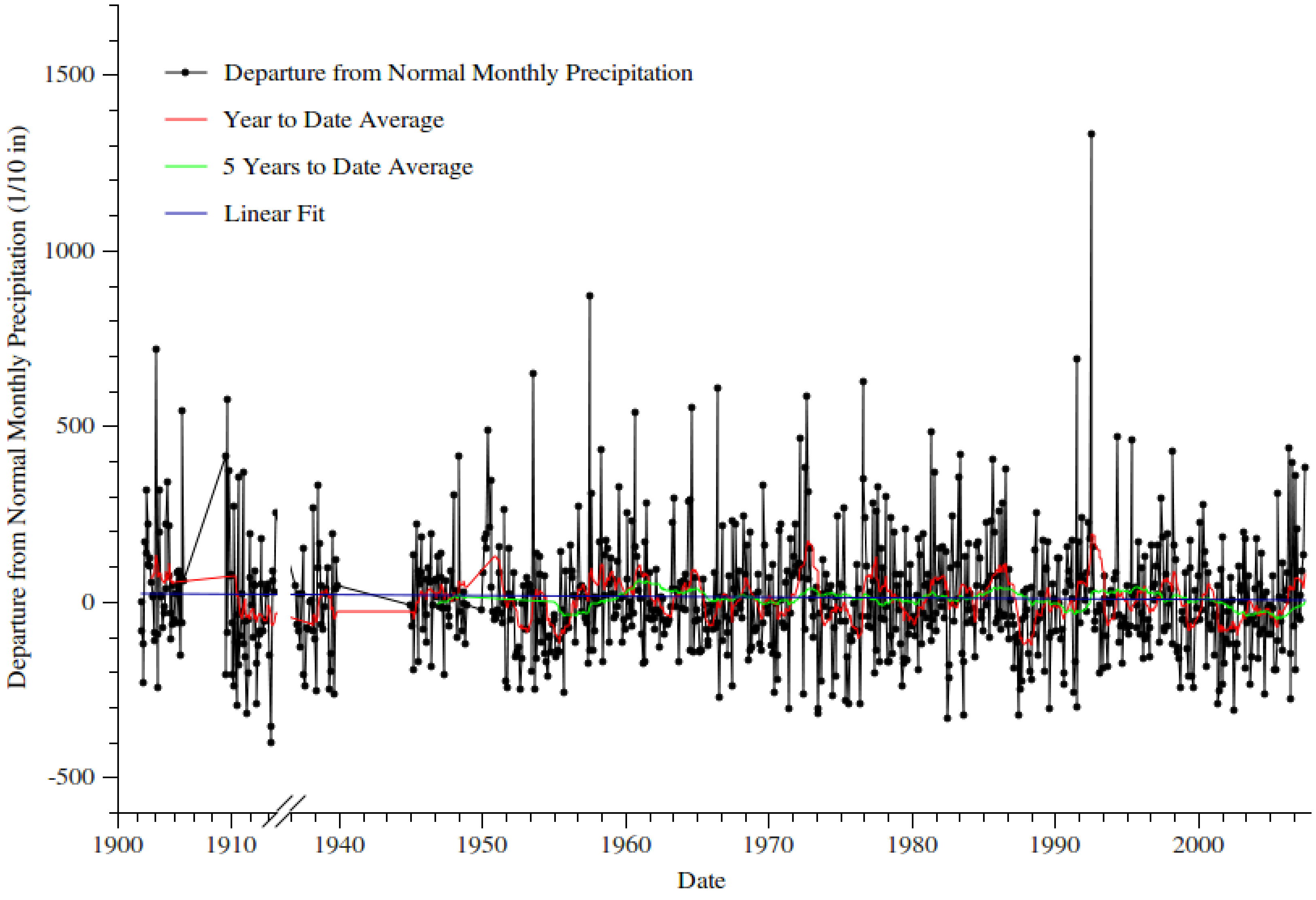

Fig. 112. Cooper Station departure from normal monthly precipitation

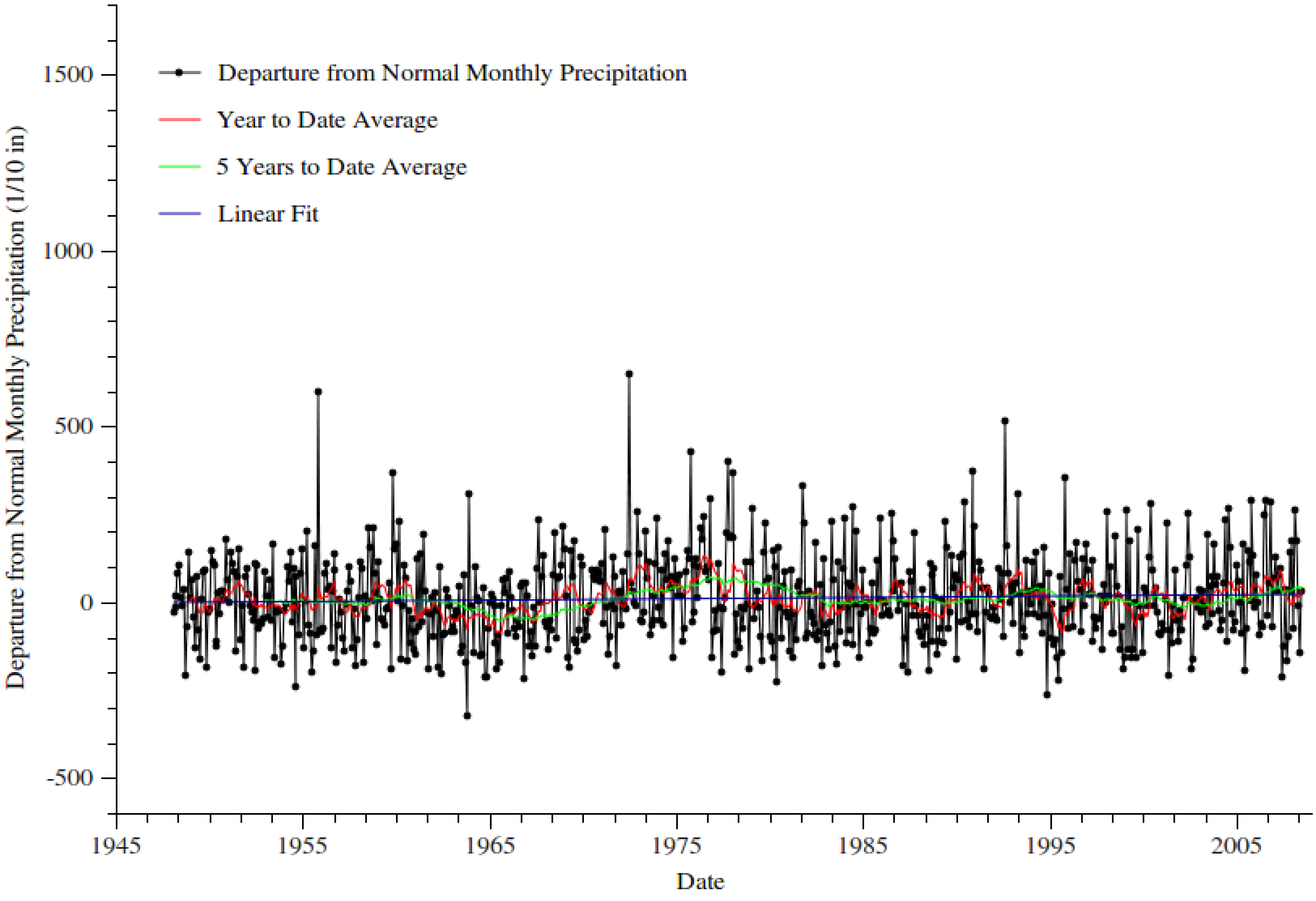

Fig. 113. James A. FitzPatrick departure from normal monthly precipitation

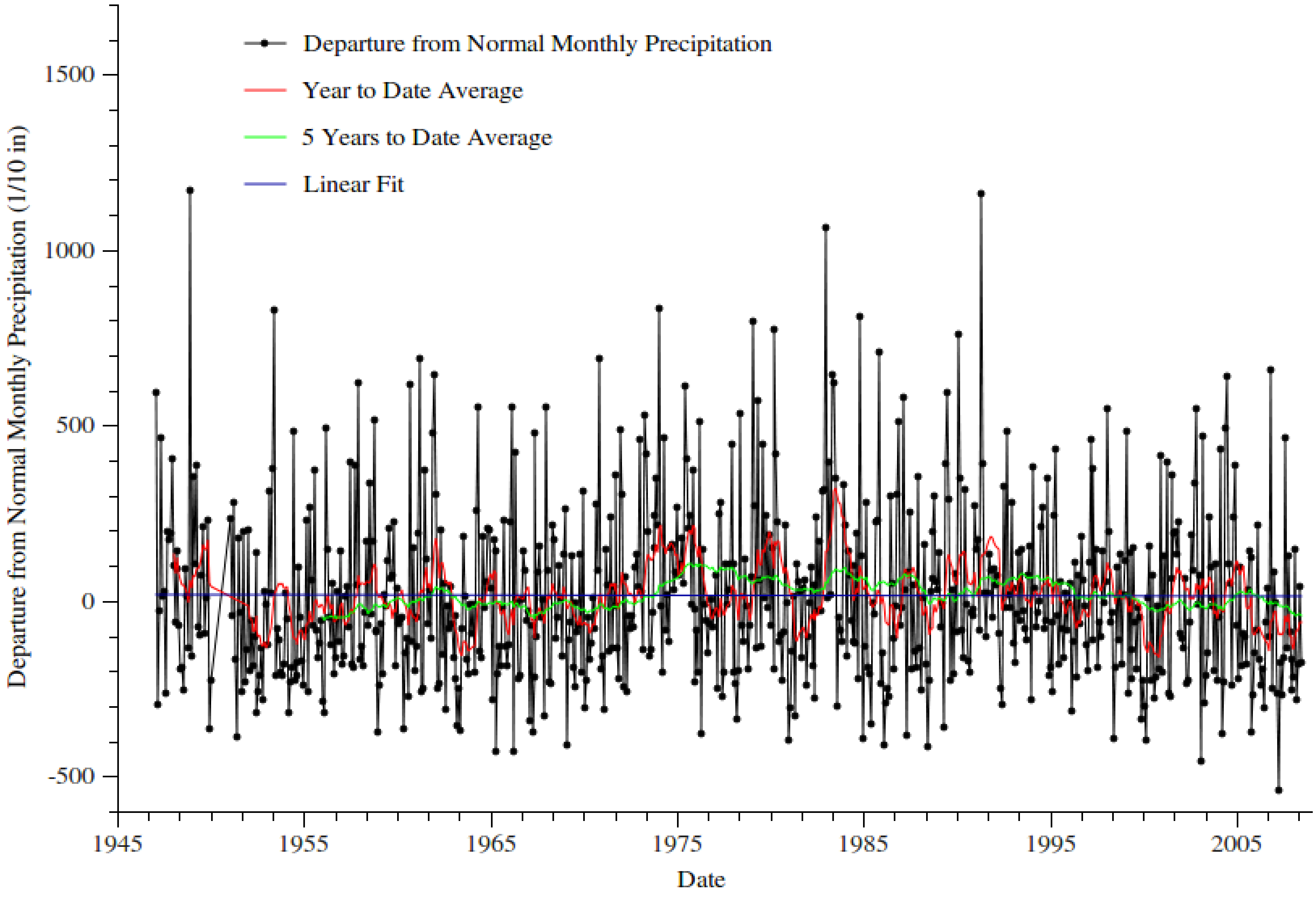

Fig. 114. Grand Gulf departure from normal monthly precipitation

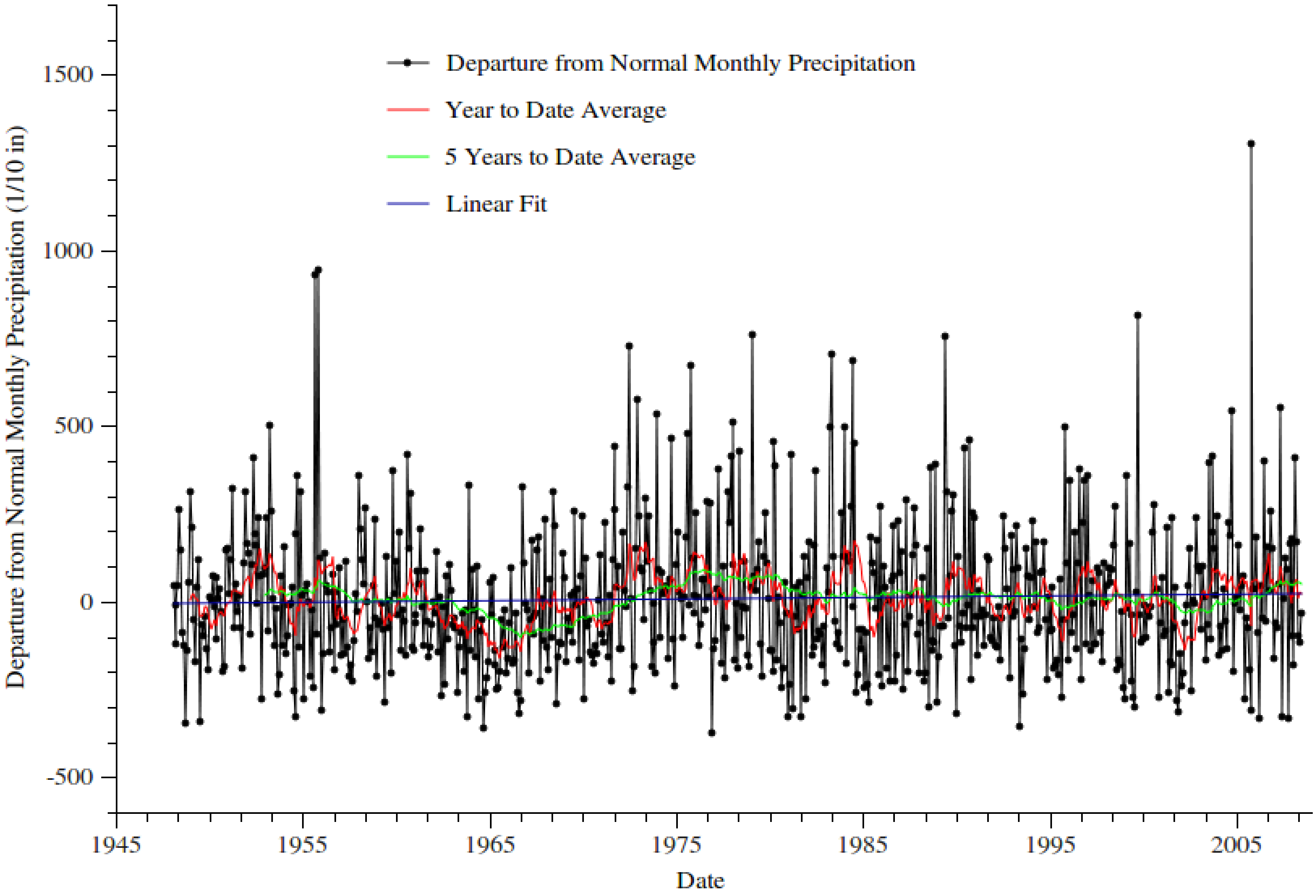

Fig. 115. Indian Point departure from normal monthly precipitation

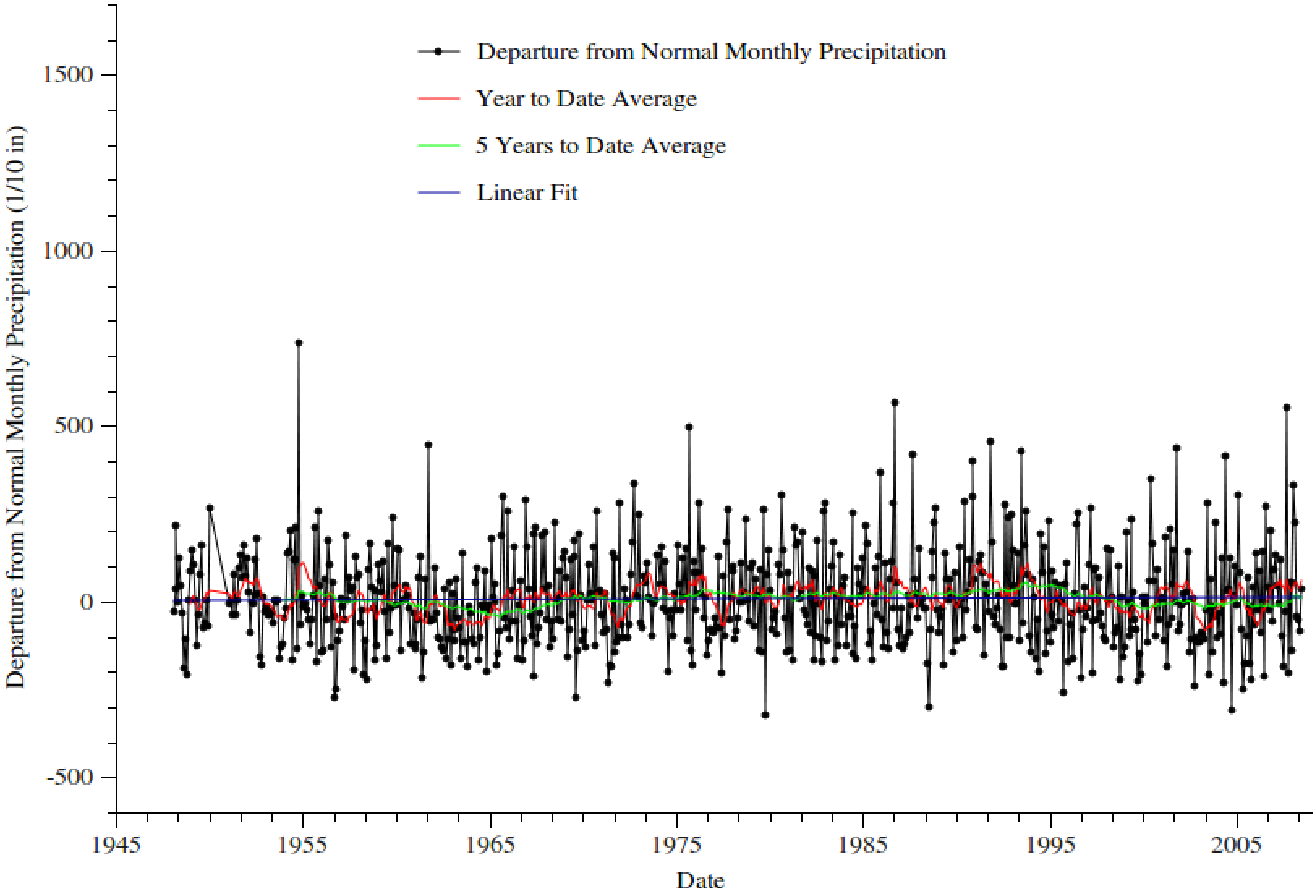

Fig. 116. Palisades departure from normal monthly precipitation

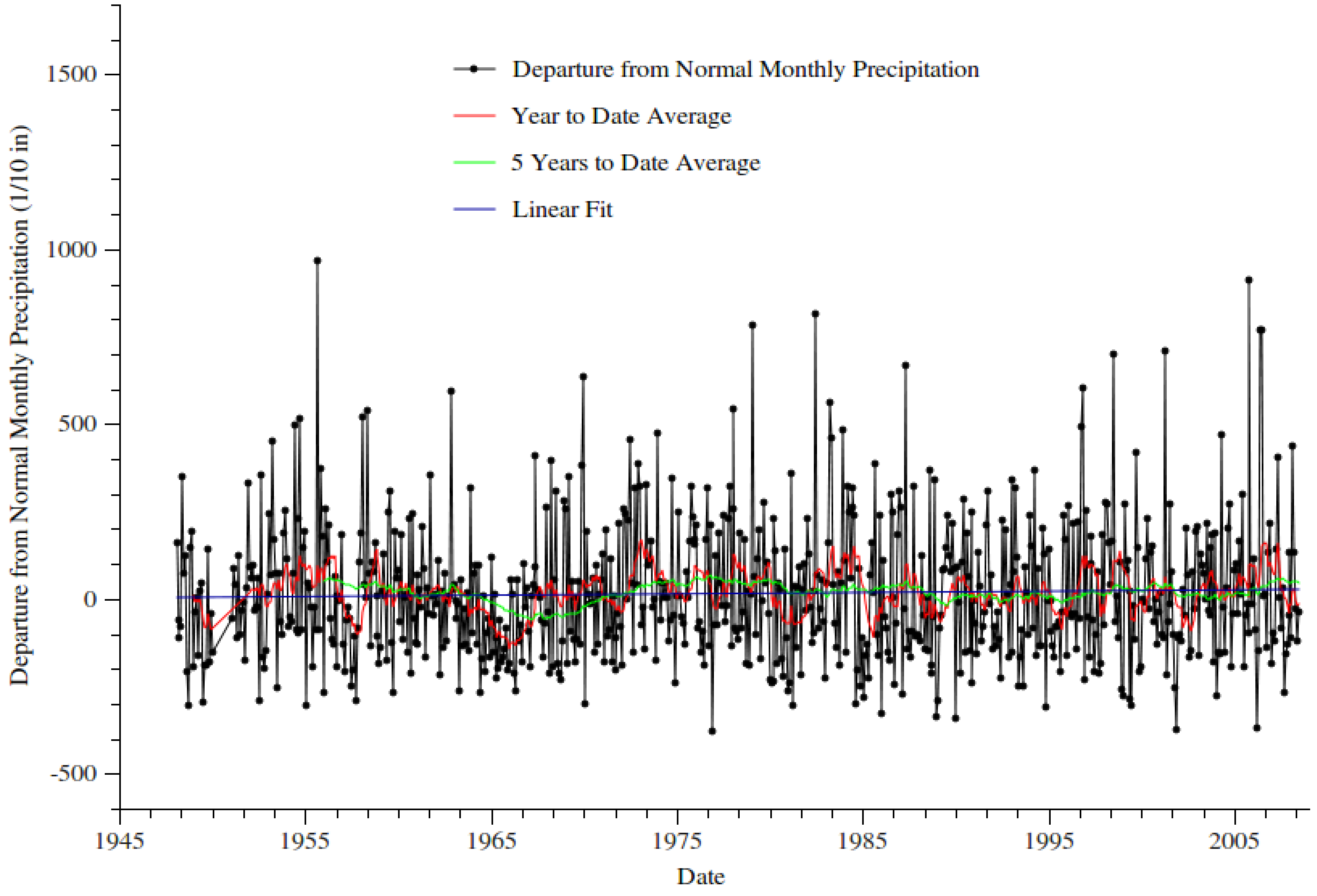

Fig. 117. Pilgrim departure from normal monthly precipitation

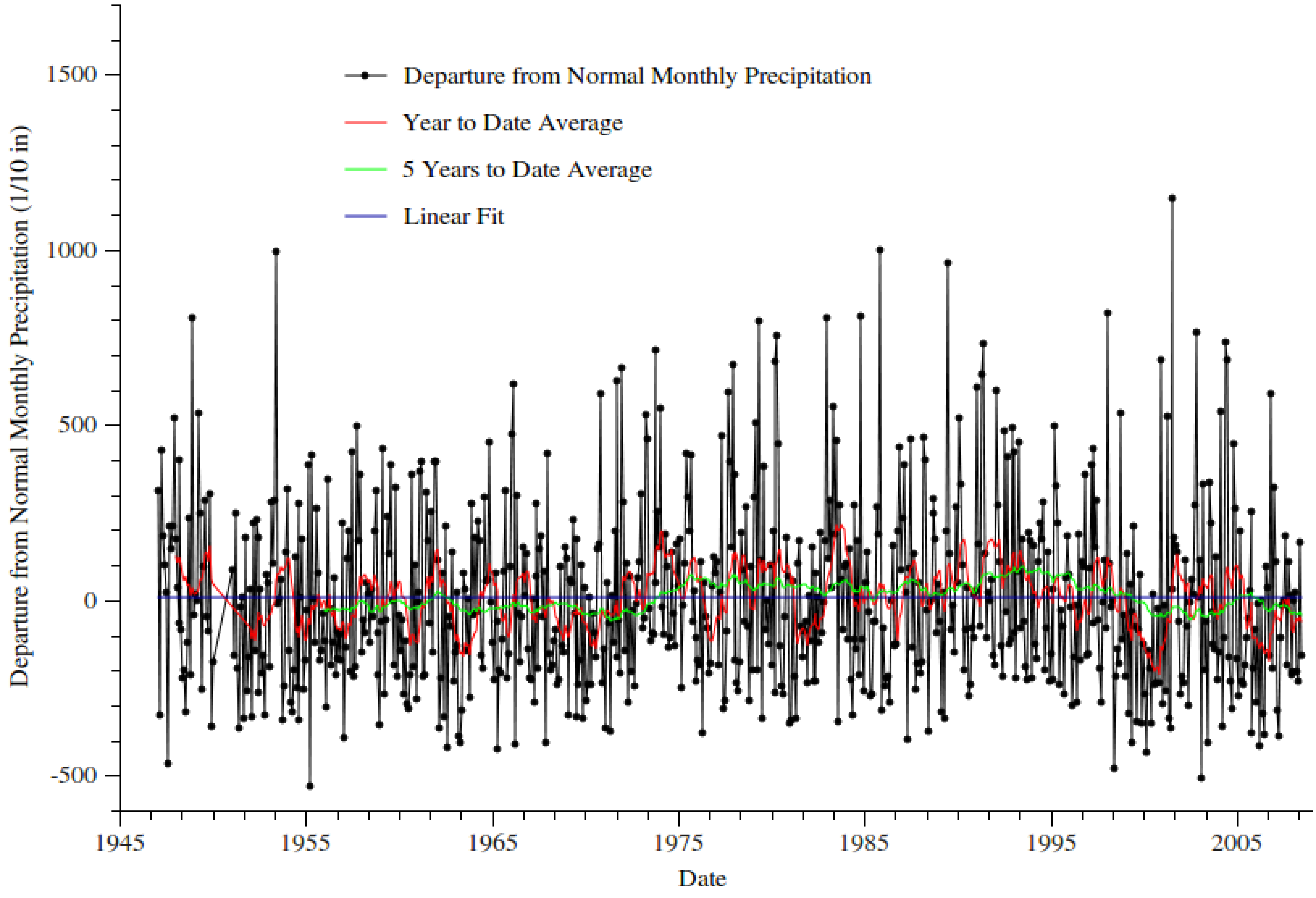

Fig. 118. River Bend departure from normal monthly precipitation

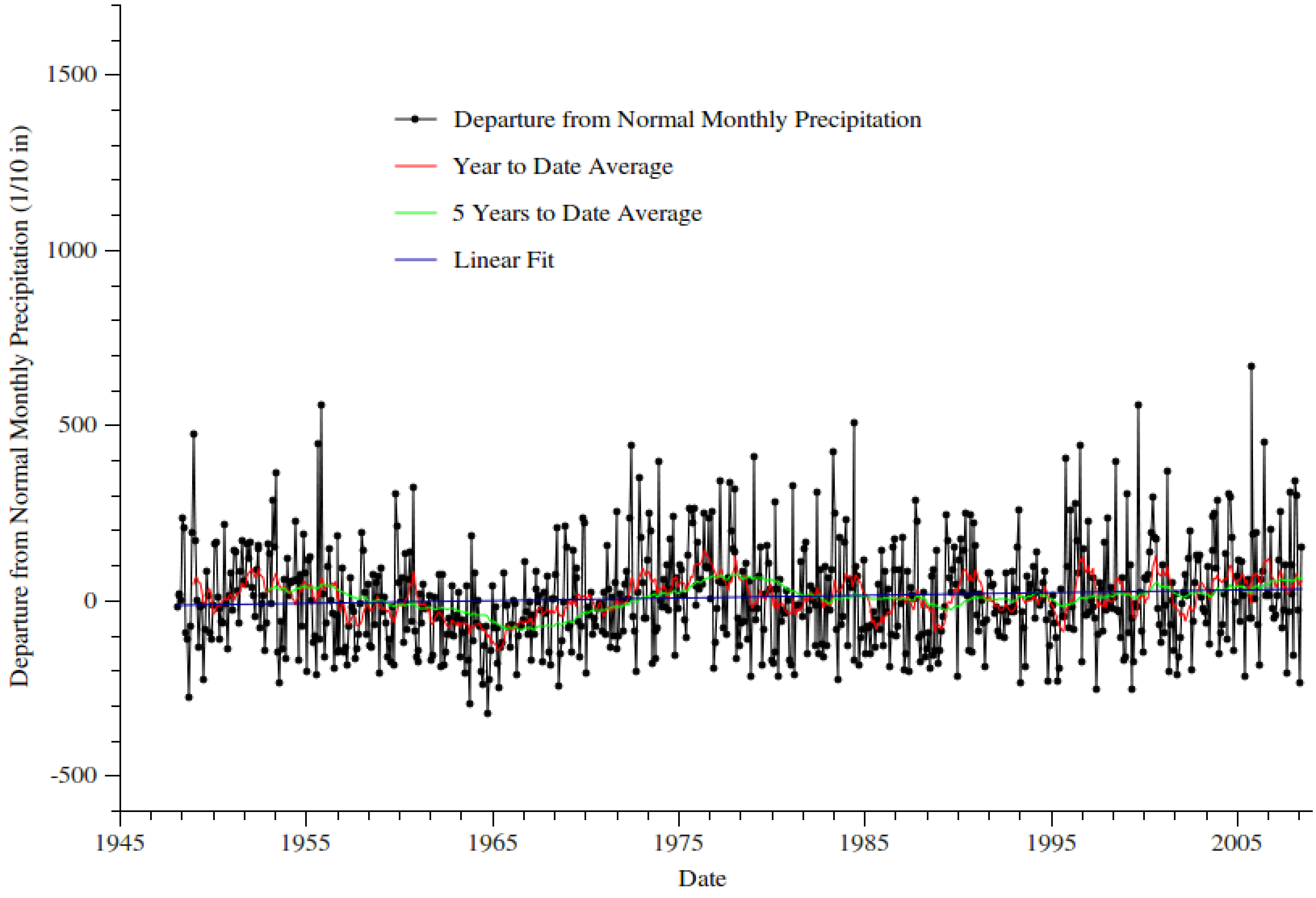

Fig. 119. Vermont Yankee departure from normal monthly precipitation

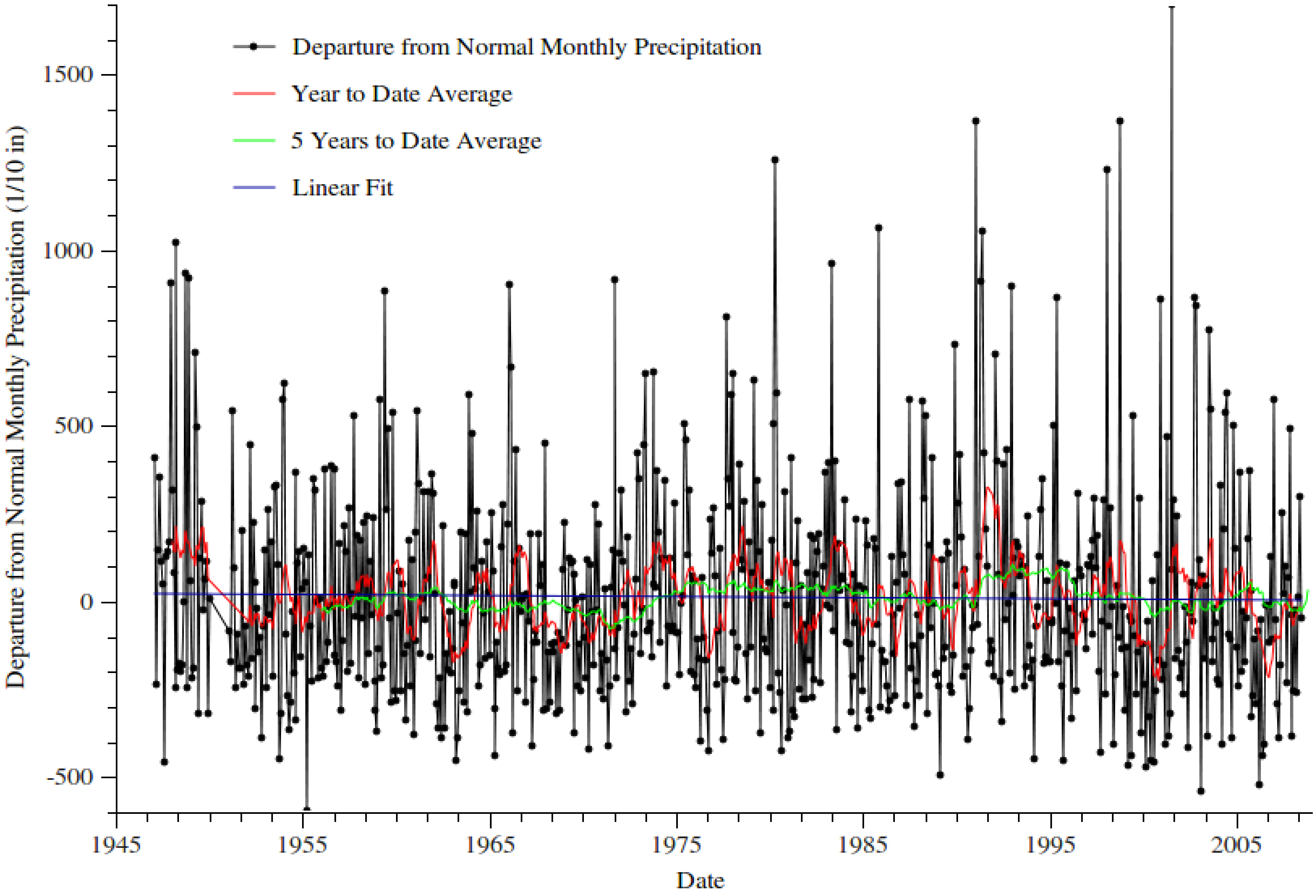

Fig. 120. Waterford departure from normal monthly precipitation

# APPENDIX M

## MAXIMUM ONE DAY PRECIPITATION

Like departure from normal monthly precipitation, the maximum one day precipitation is closely associated with flood conditions. Because absolute values are given for the data, this indicator provides a measure of the severity of precipitation. These values should be evaluated with caution since winter precipitation is often in the form of snow which either provides runoff in the warmer months or is manually melted into water systems over extended periods of time.

The data for these composite graphs was obtained from NOAA [78] and processed as described in section 3.3.

Arkansas Nuclear One[59]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $1.895 \times 10^{-2} \pm 5.04 \times 10^{-3} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $140.21 \pm 4.0394 \frac{1}{10}$ in |
| RMSE | 75.044 |

Cooper Station[79]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $9.66 \times 10^{-3} \pm 7.011 \times 10^{-3} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $-3.6693 \pm 3.0631 \frac{1}{10}$ in |
| RMSE | 40.820 |

FitzPatrick[80]

| | |
|---|---|
| Starting Date | March, 1893 |
| Slope | $6.98 \times 10^{-3} \pm 2.73 \times 10^{-3} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $90.614 \pm 2.1869 \frac{1}{10}$ in |
| RMSE | 40.599 |

Grand Gulf[81]

| | |
|---|---|
| Starting Date | January, 1891 |
| Slope | $1.797 \times 10^{-2} \pm 5.04 \times 10^{-3} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $159.65 \pm 4.1020 \frac{1}{10}$ in |
| RMSE | 76.947 |

Indian Point[82]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $2.313 \times 10^{-2} \pm 8.36 \times 10^{-3} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $126.53 \pm 4.4942 \frac{1}{10}$ in |
| RMSE | 68.472 |

Palisades[83]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $2.38 \times 10^{-3} \pm 3.24 \times 10^{-3} \frac{\frac{1}{10}in}{month}$ |
| Initial Value | $101.91 \pm 2.5931 \frac{1}{10}$ in |
| RMSE | 48.242 |

Pilgrim[1]

| | |
|---|---|
| Starting Date | January, 1893 |
| Slope | $7.77 \times 10^{-3} \pm 4.32 \times 10^{-3} \frac{\frac{1}{10} in}{month}$ |
| Initial Value | $126.10 \pm 3.4600 \frac{1}{10}$ in |
| RMSE | 64.314 |

River Bend[84]

| | |
|---|---|
| Starting Date | February, 1891 |
| Slope | $1.678 \times 10^{-2} \pm 5.42 \times 10^{-3} \frac{\frac{1}{10} in}{month}$ |
| Initial Value | $173.44 \pm 4.4148 \frac{1}{10}$ in |
| RMSE | 82.815 |

Vermont Yankee[85]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $1.564 \times 10^{-2} \pm 5.85 \times 10^{-3} \frac{\frac{1}{10} in}{month}$ |
| Initial Value | $102.29 \pm 3.1436 \frac{1}{10}$ in |
| RMSE | 47.895 |

Waterford[86]

| | |
|---|---|
| Starting Date | January, 1931 |
| Slope | $2.472 \times 10^{-2} \pm 9.00 \times 10^{-3} \frac{\frac{1}{10} in}{month}$ |
| Initial Value | $173.51 \pm 6.2718 \frac{1}{10}$ in |
| RMSE | 104.55 |

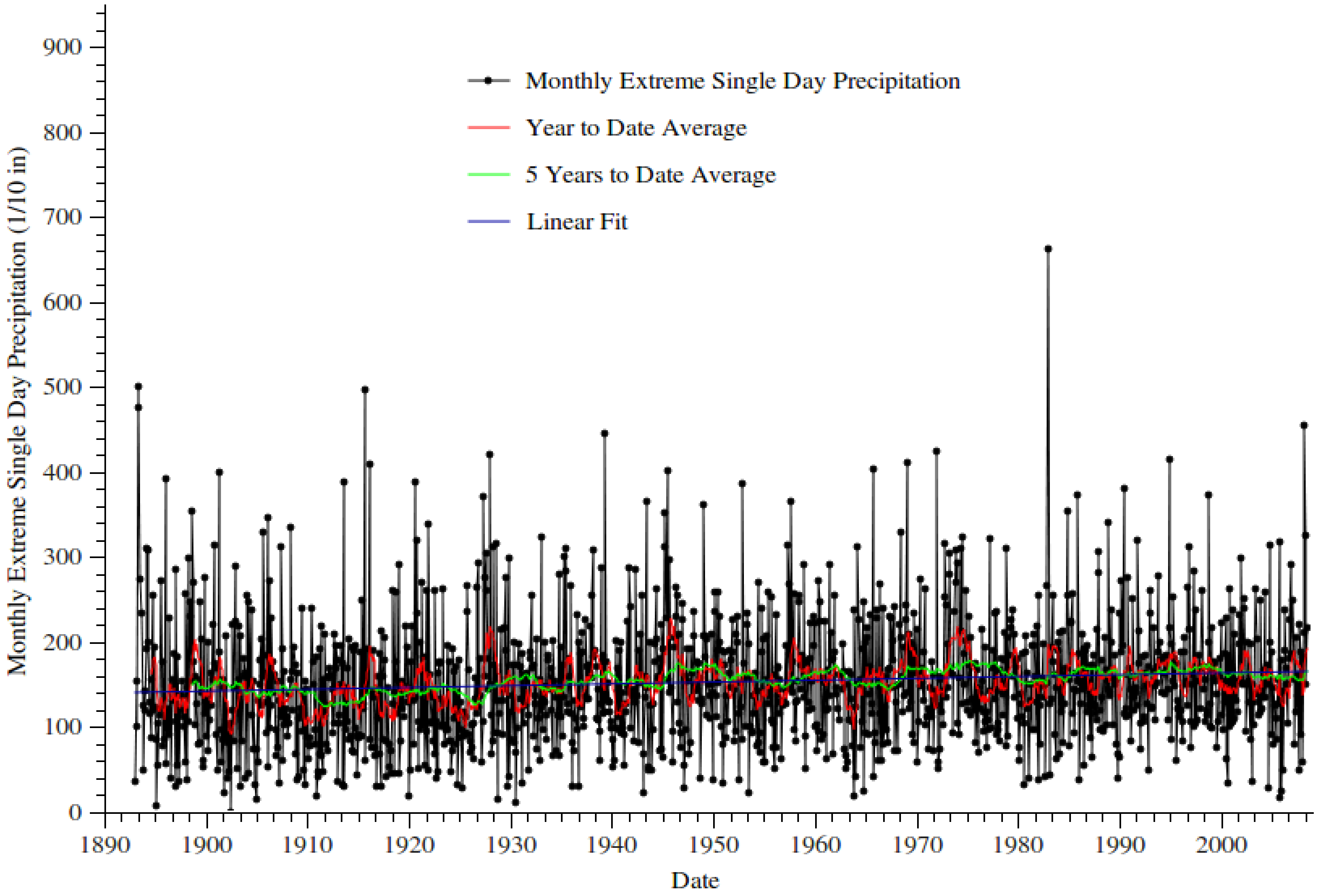

Fig. 121. Arkansas Nuclear One maximum one day precipitation

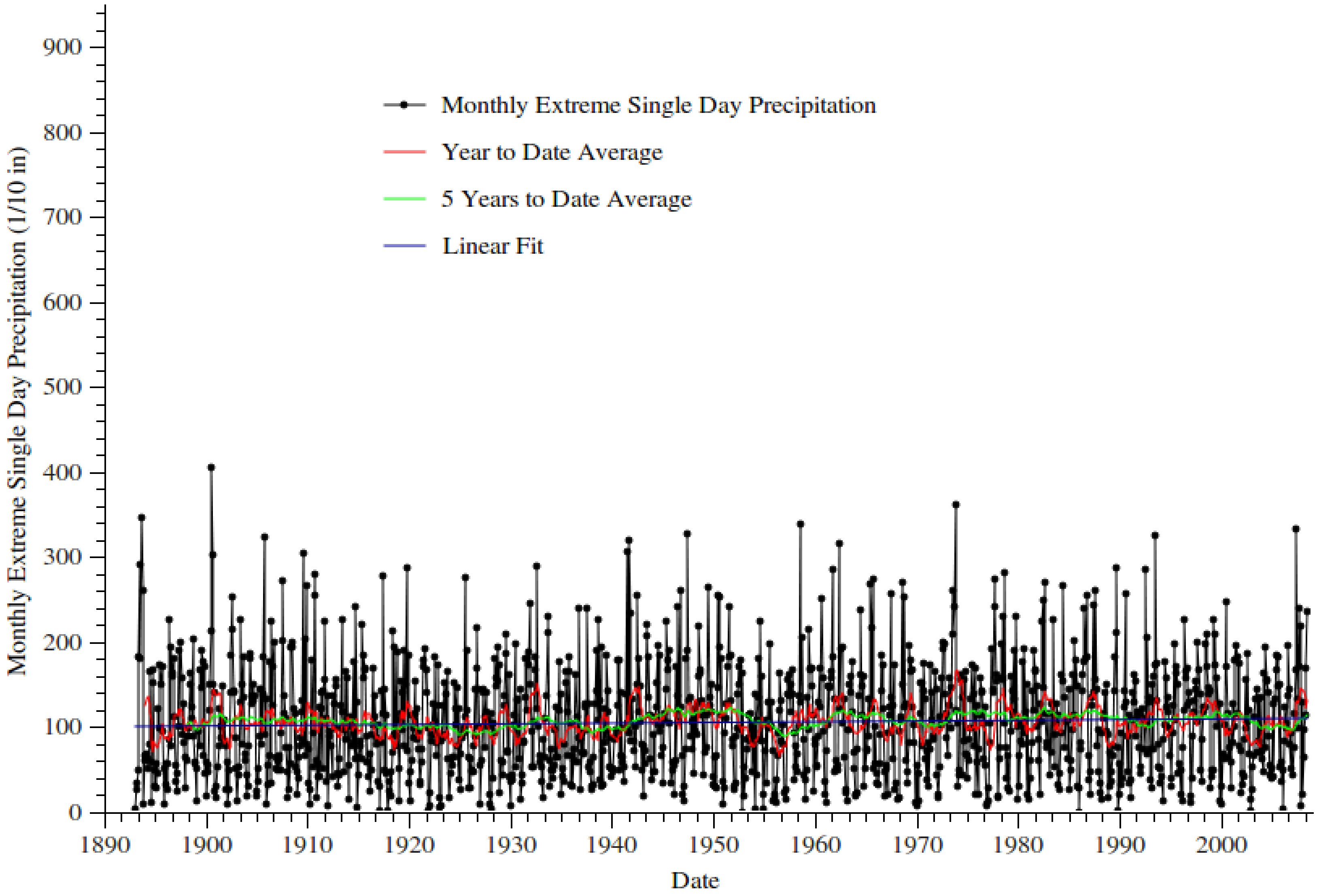

Fig. 122. Cooper Station maximum one day precipitation

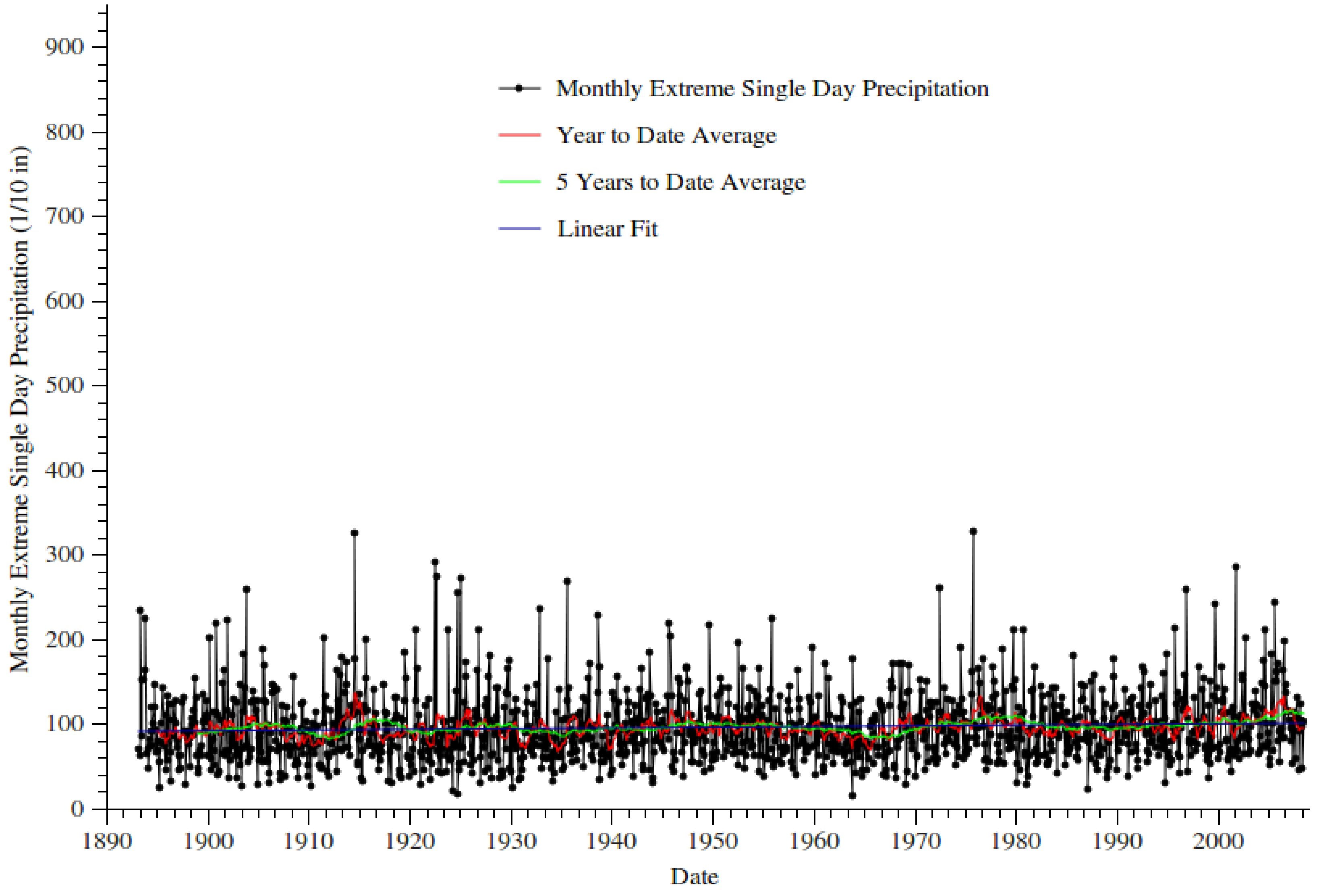

Fig. 123. James A. FitzPatrick maximum one day precipitation

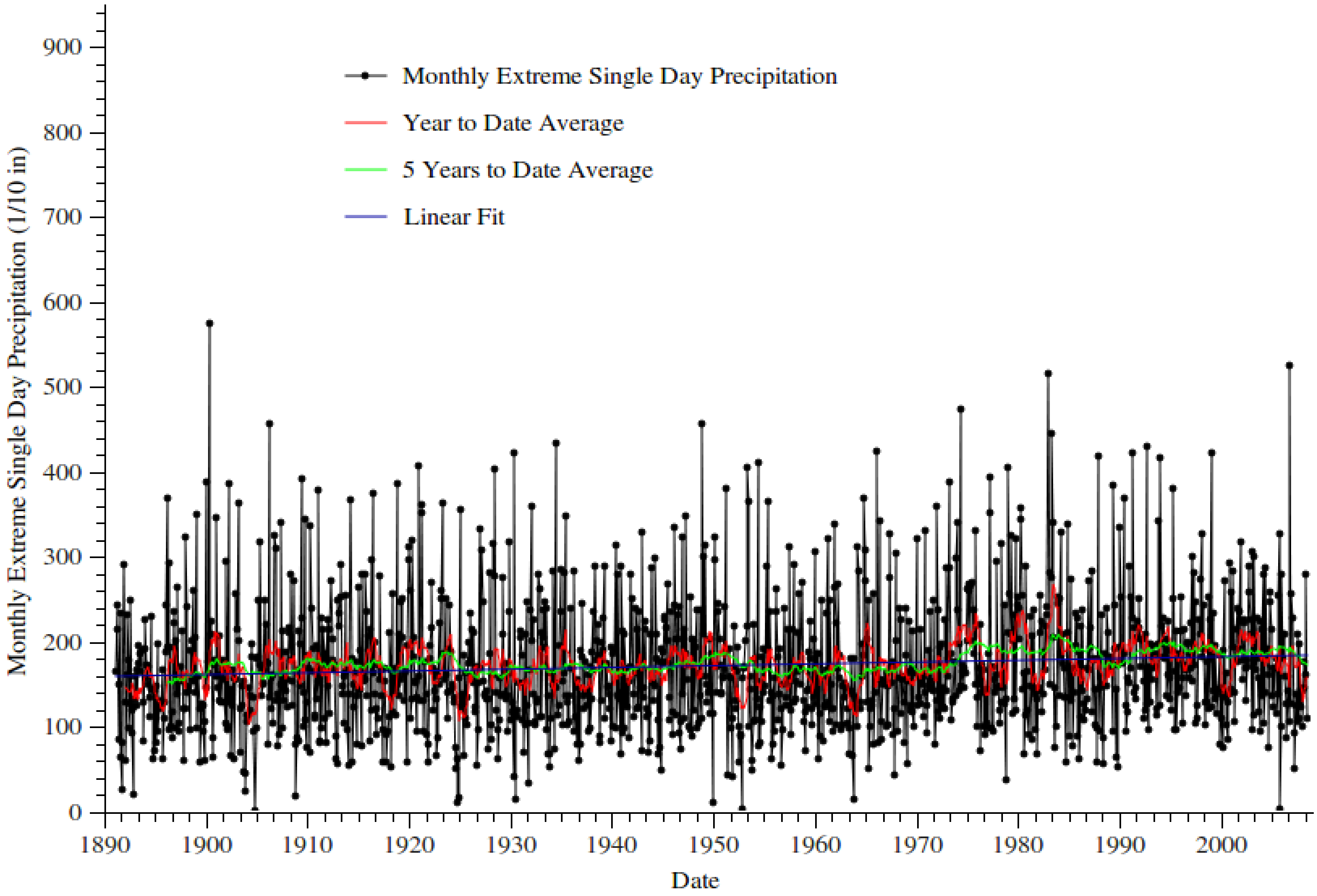

Fig. 124. Grand Gulf maximum one day precipitation

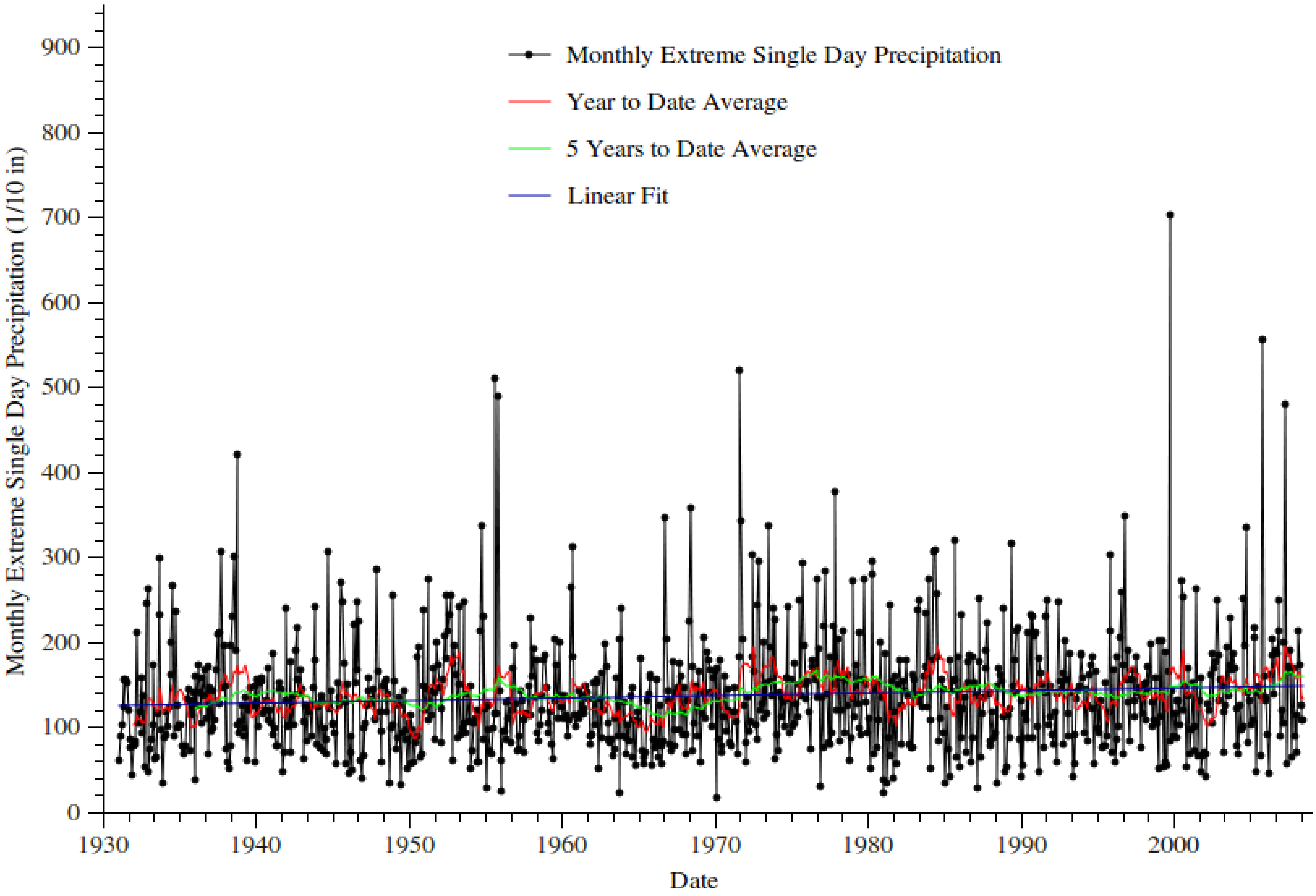

Fig. 125. Indian Point maximum one day precipitation

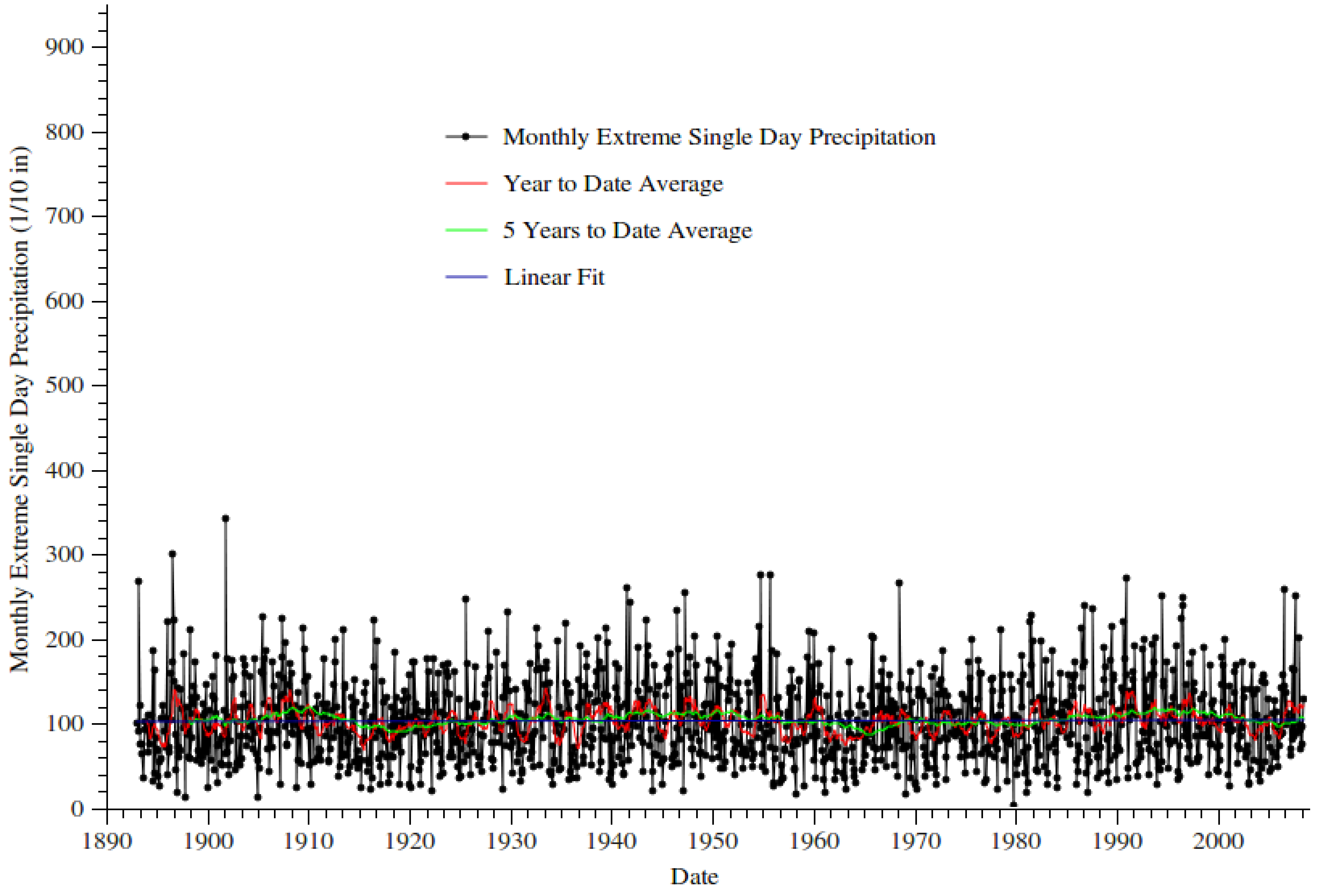

Fig. 126. Palisades maximum one day precipitation

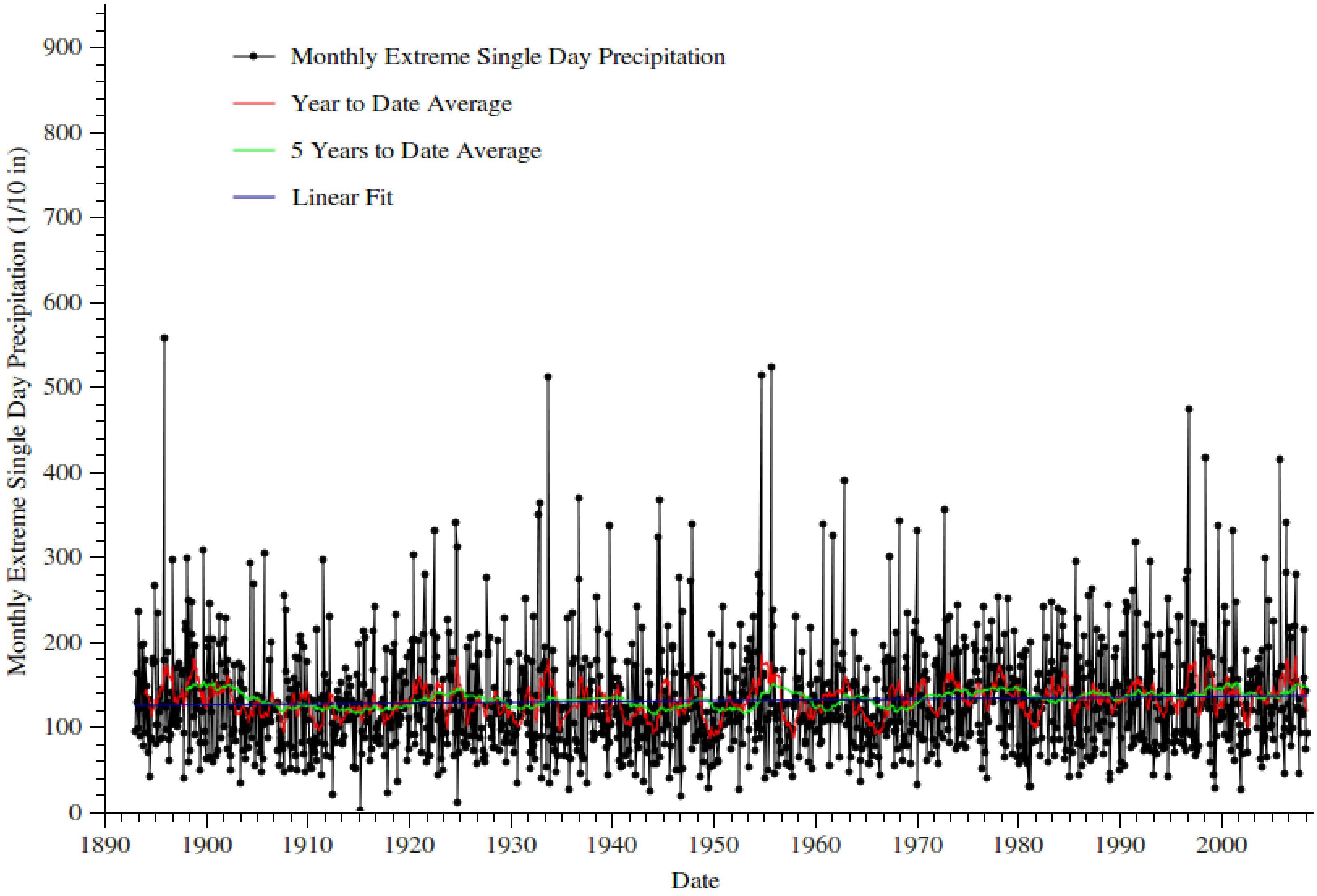

Fig. 127. Pilgrim maximum one day precipitation

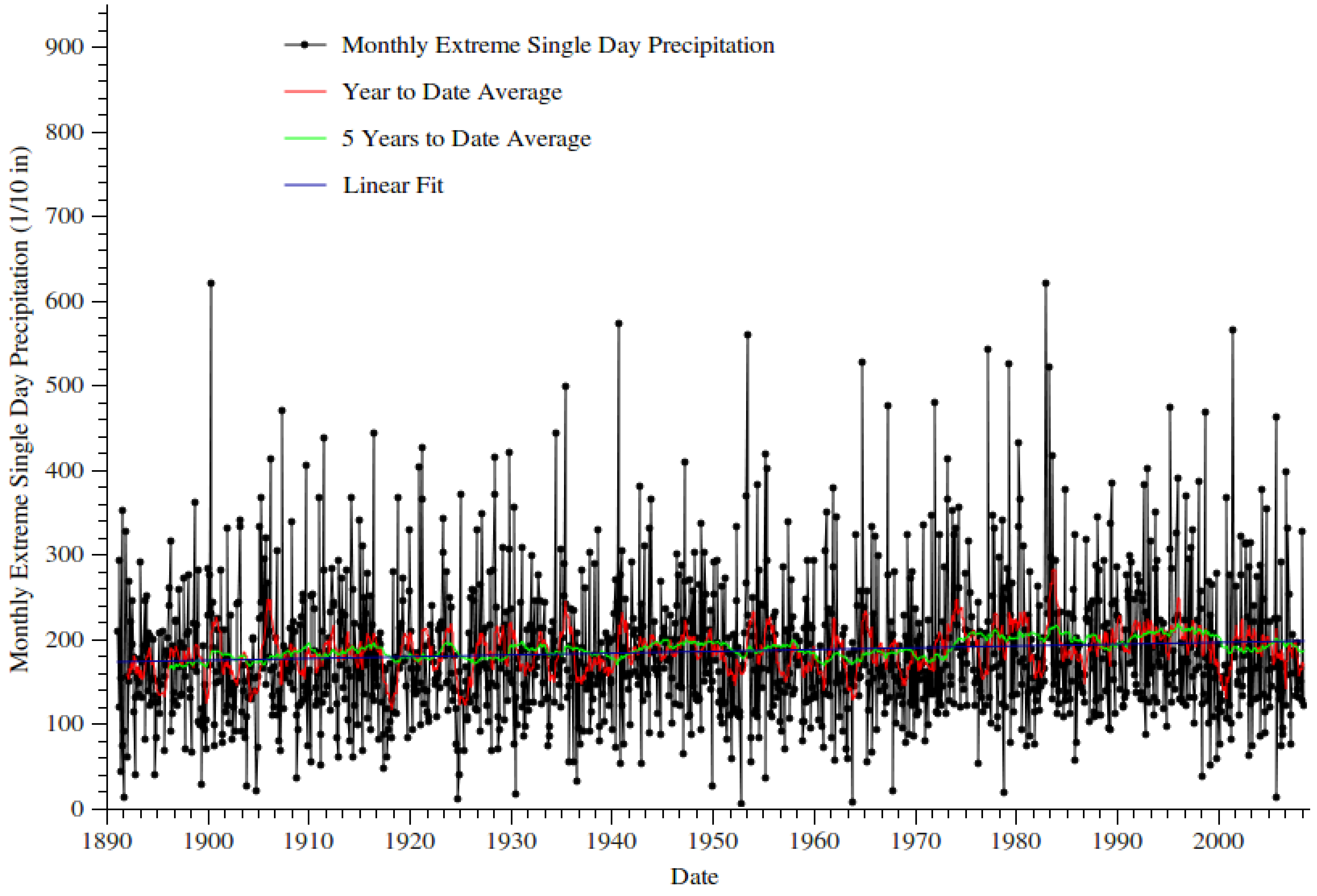

Fig. 128. River Bend maximum one day precipitation

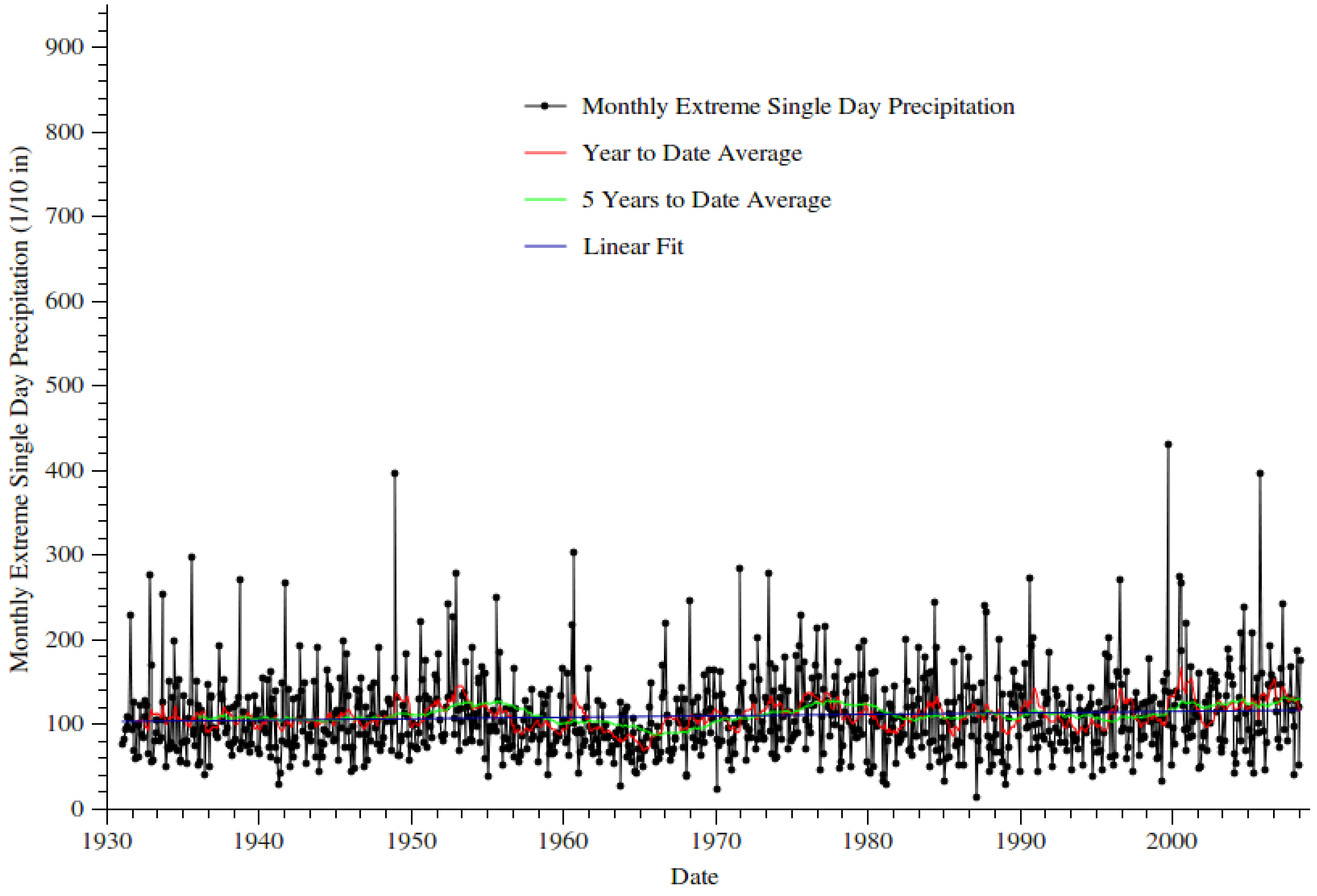

Fig. 129. Vermont Yankee maximum one day precipitation

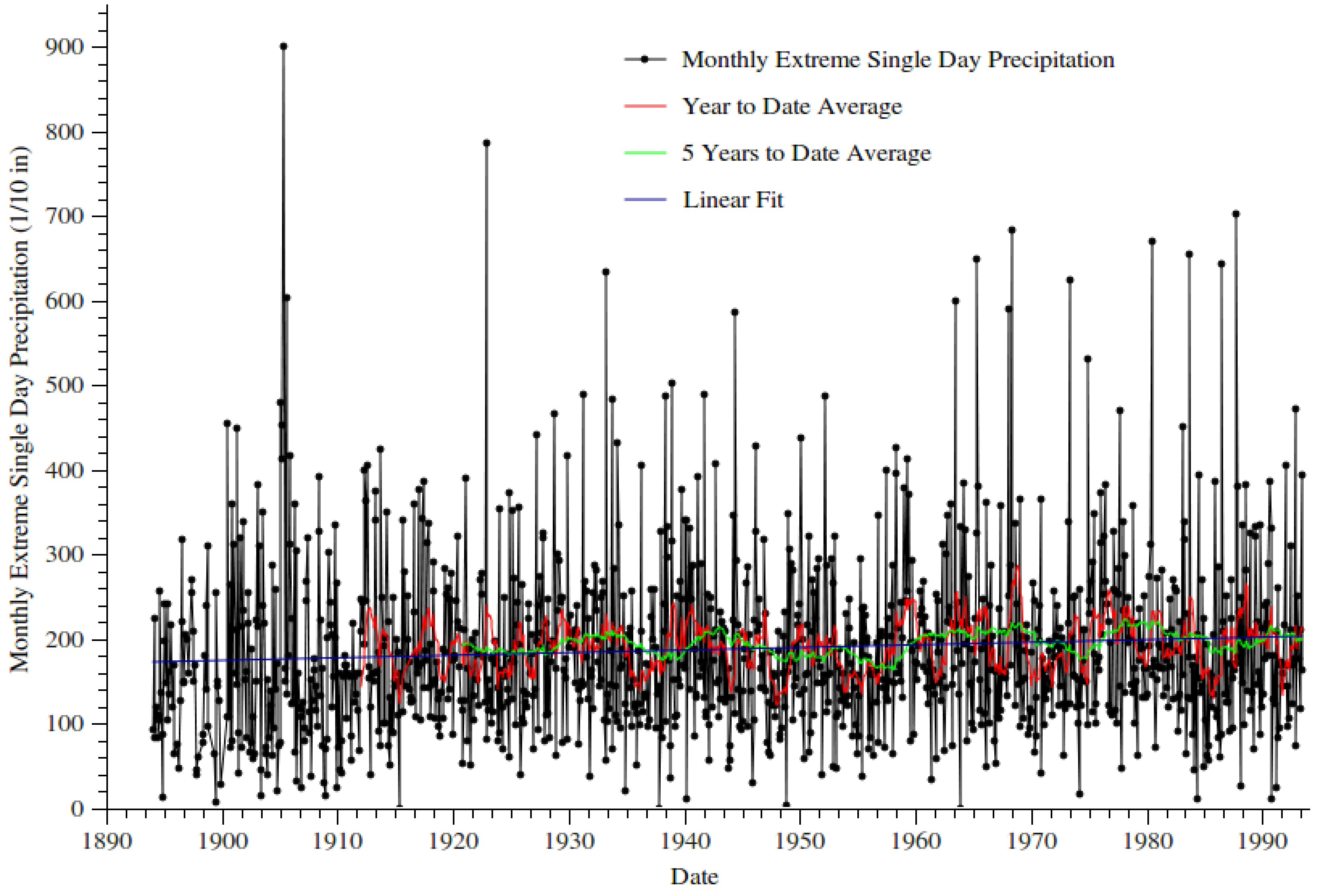

Fig. 130. Waterford maximum one day precipitation

# APPENDIX N

# TORNADO DATA

Because tornadoes are significantly less prevalent in some portions of the country, data was not collected for all ten sites. The following charts give the number of tornadoes occurring in the county of the power plant and all contiguous counties. Even including the surrounding counties, these values are too low to provides statistically significant results. Nonetheless, visualizing the historical tornado risk for these sites can be enlightening.

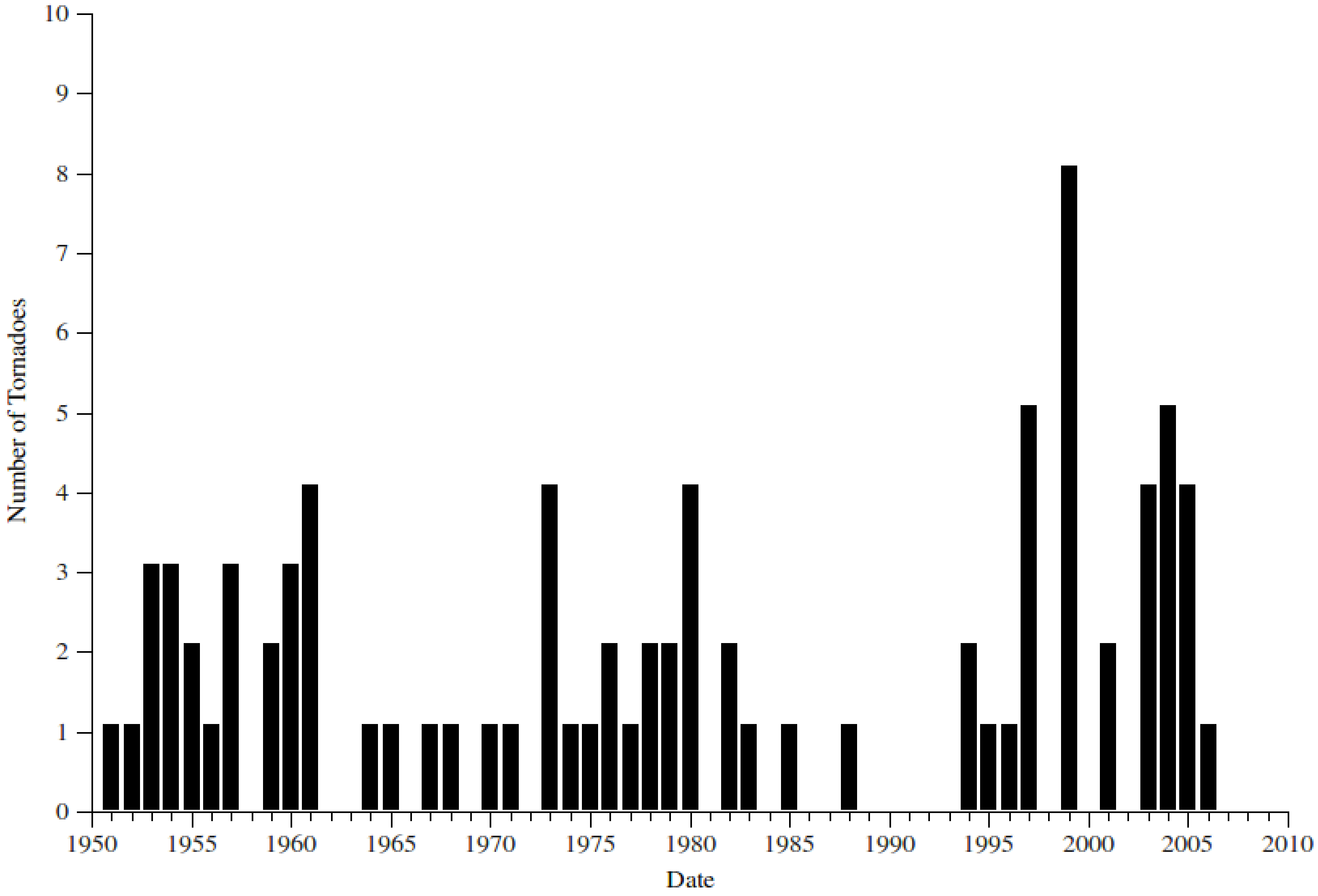

Fig. 131. Arkansas Nuclear One tornado occurances[2]

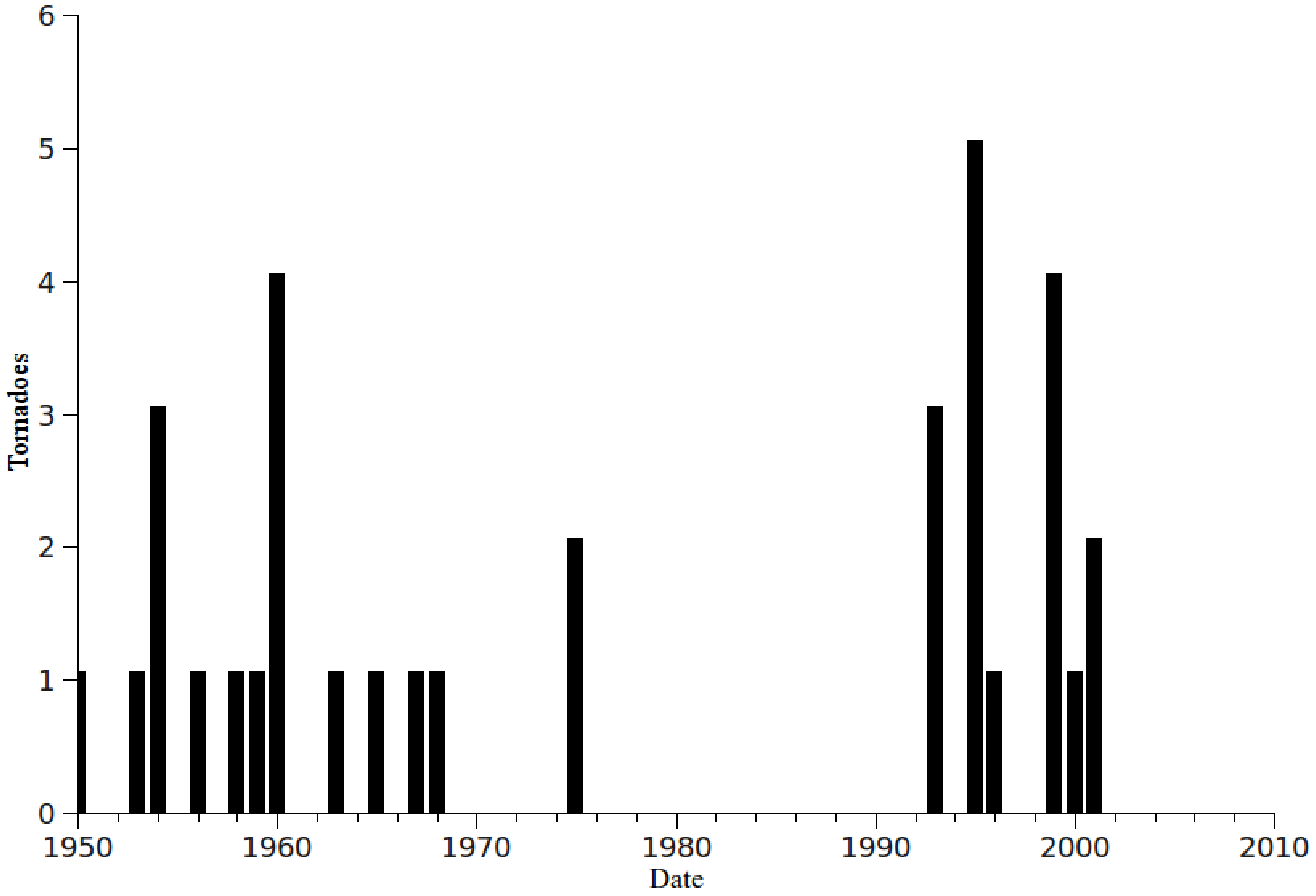

Fig. 132. Cooper Station tornado occurances[3]

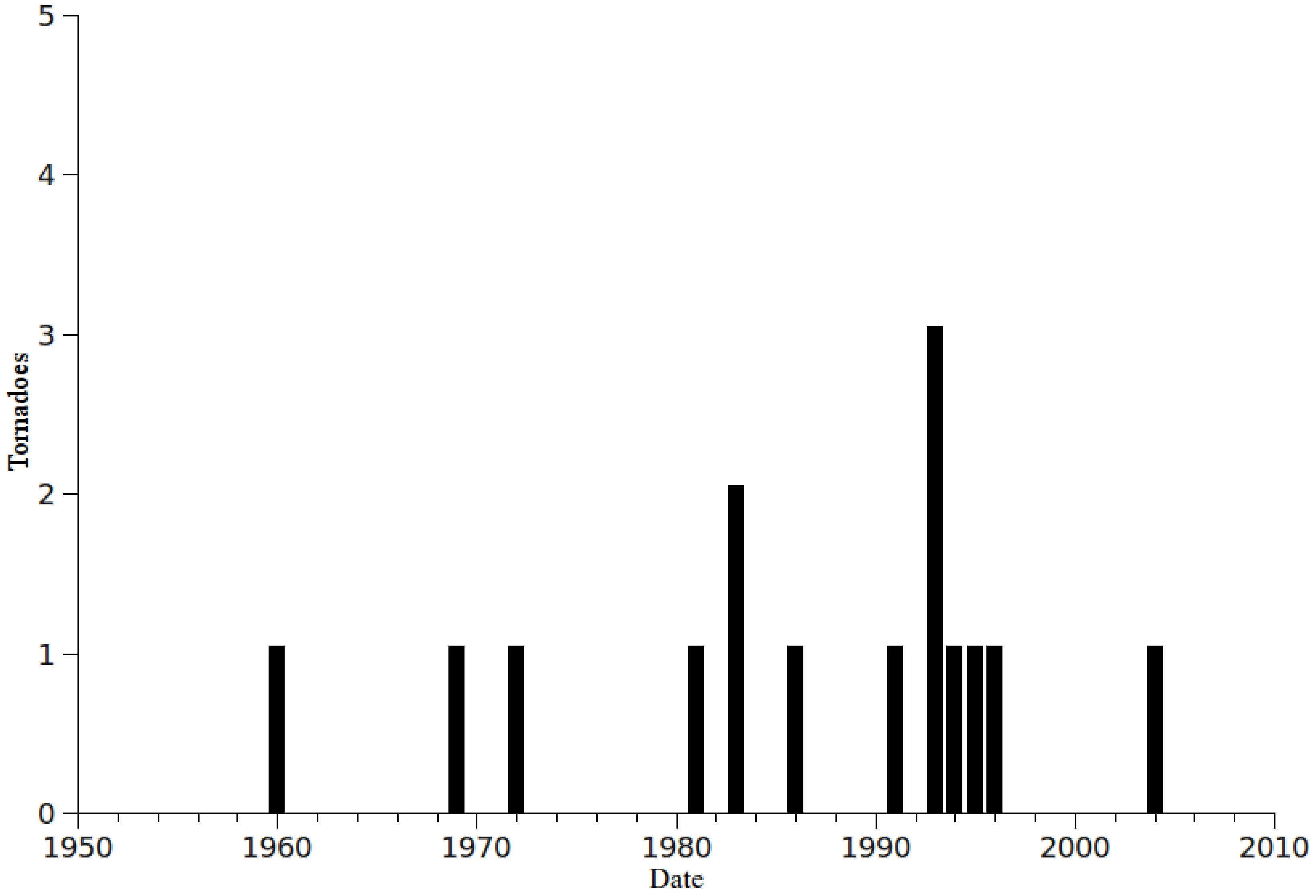

Fig. 133. James A. FitzPatrick tornado occurances[4]

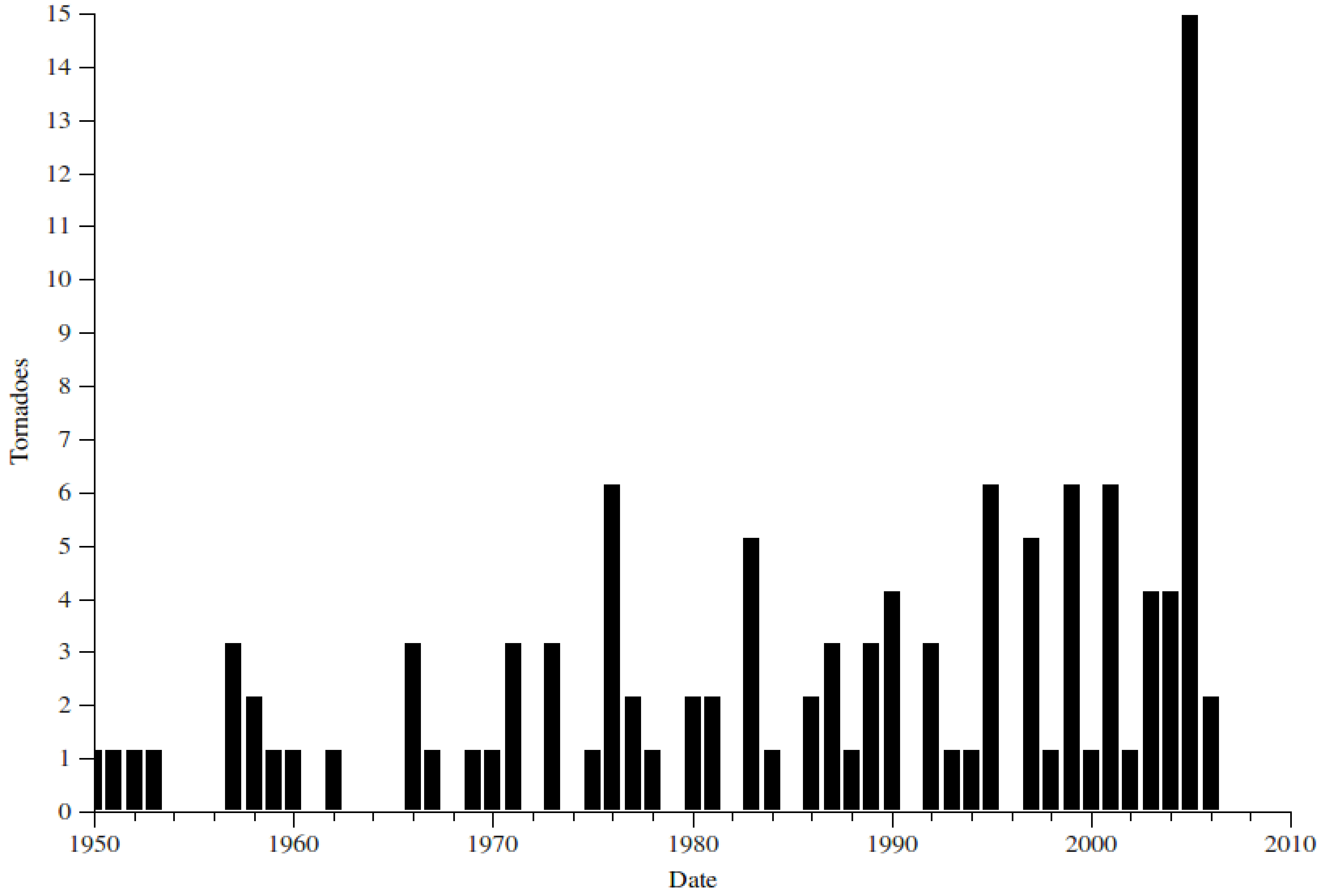

Fig. 134. Grand Gulf tornado occurances[5]

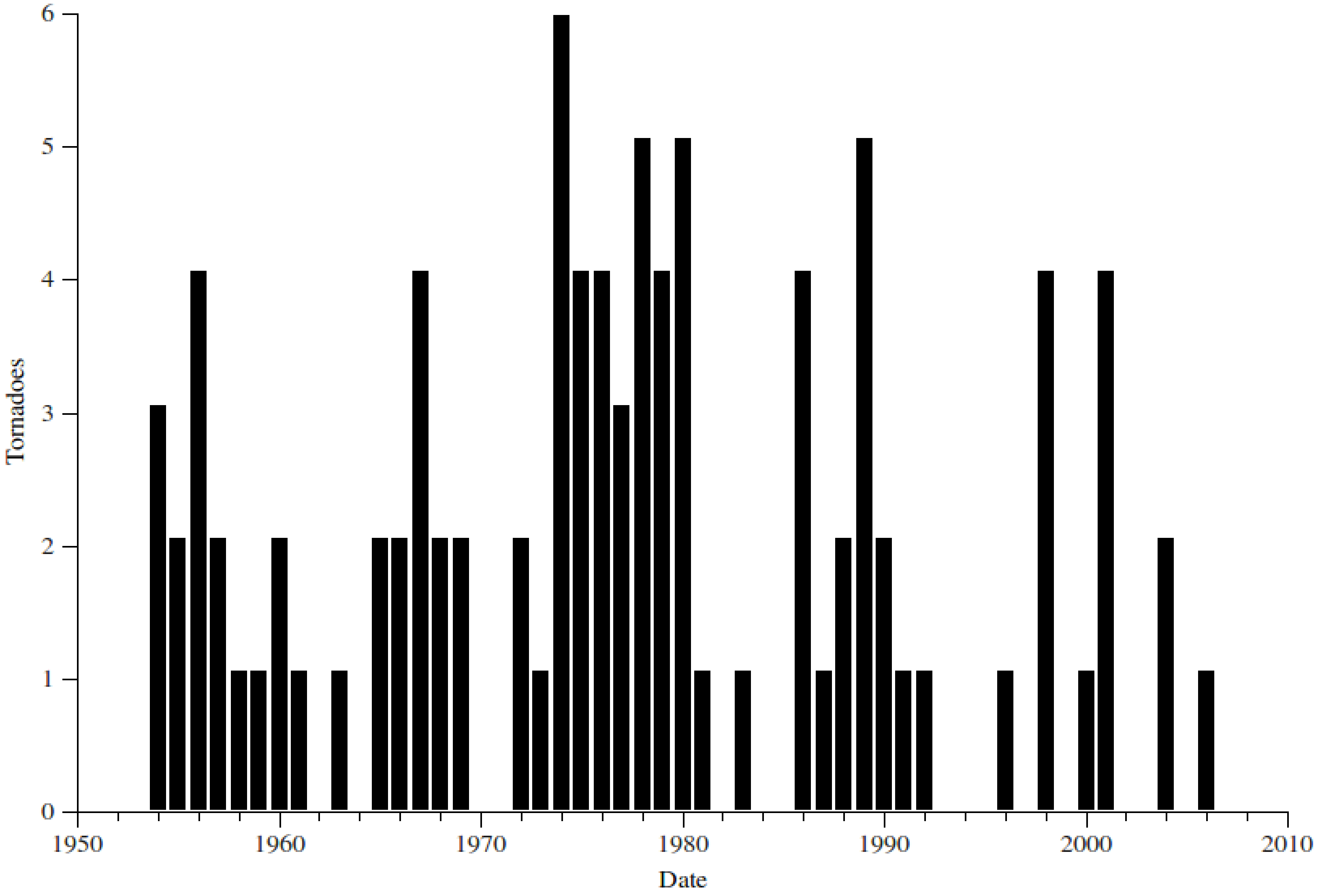

Fig. 135. Palisades tornado occurances[6]

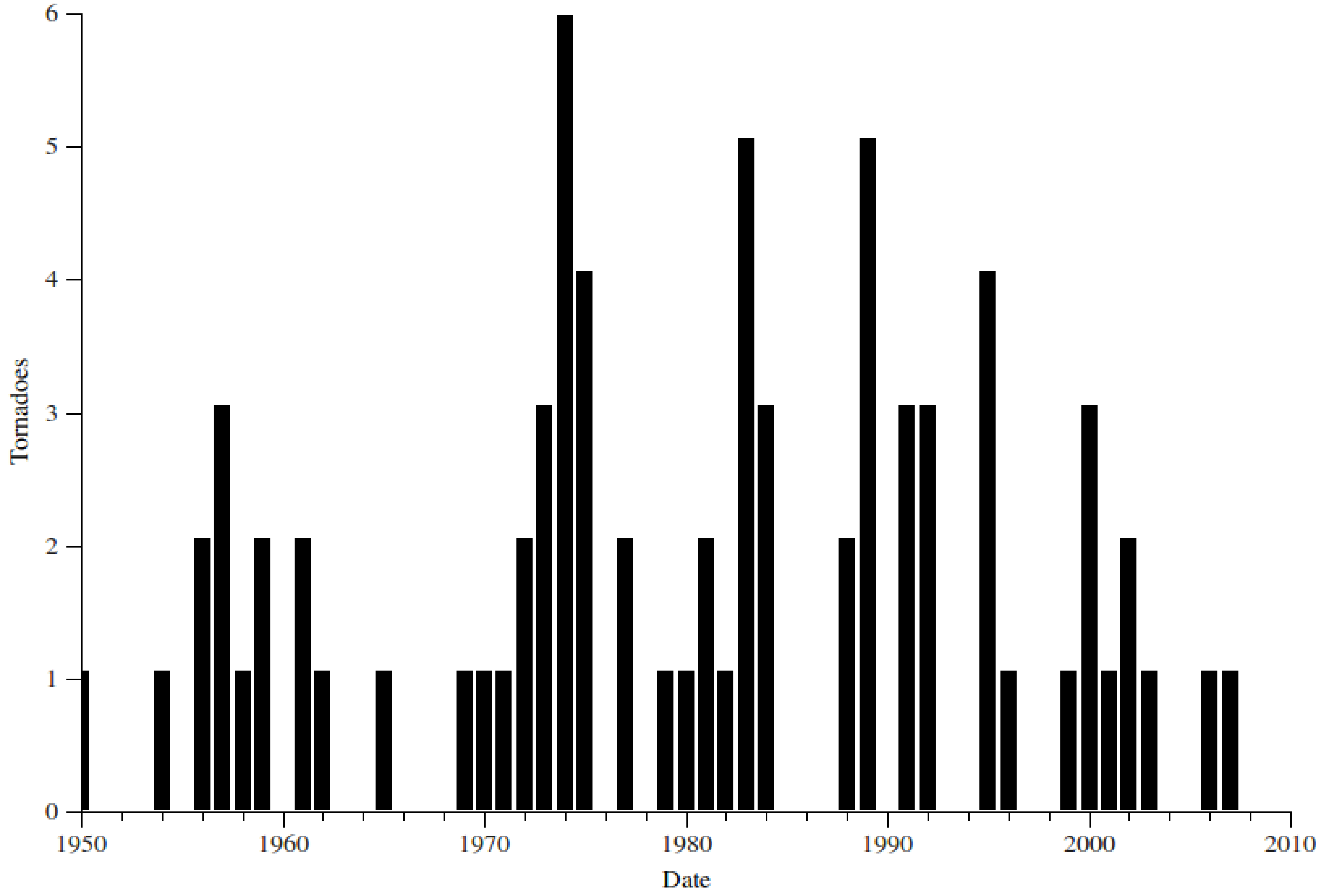

Fig. 136. River Bend tornado occurances[7]

# APPENDIX O

## EXAMPLE PEPSE JOB FILE

The ASCII text file reproduced in this appendix is an example of one of the two files made by PEPSE at runtime. This file controls the component thermodynamic attributes used by PEPSE. Because these job files are human readable ASCII text, it was possible to create job files describing different thermodynamic conditions for the same plant model by manipulating one file created by PEPSE. The process of how this manipulation was accomplished is described in subsection 4.2.1.

```
010001  80  PRINT
*
*
*        DATE: Saturday, October 24, 2009
*        TIME: 8:42 PM
*       MODEL: Unit1Normal.MDL
*    JOB FILE: C:\PEPSE\ABR\32Norm105444304.job
* OUTPUT FILE: C:\PEPSE\ABR\32Norm105444304.out
*
*
*
*
=ano-1
*
*****************************
*   GENERIC INPUT DATA
******************************
*
*
*
* Model for ANO-1
010200   1  0  1  2  1  0  0.0  0.0
*
010000  ENGLISH  ENGLISH
*
*
* UNIT ONE MAIN GENERATOR
011010   1  2  2  0  1800  1002600.  0.9  75.  75.  0.0
011011   2900.  10707.  0.0
*
* OUTPUT GLOBAL SUPPRESSION CARD
020000 NOPRNT   PRINT   NOPRNT
020027 PRINT    * Detailed Turbine Performance Output -
   Table D - Special Option 5
020034 PRINT    * Controls Input
020035 PRINT    * Scheduled Variable Values Calculated
020036 PRINT    * Controlled Variable Values Calculated
*
```

```
*
012000   200  0.0  0.0  0.0  0.0  0.0  5  0.0
*
*****************************
*  STREAMS
******************************
*
*
501400  140   U      130   T
501300  130   T      120   T
501200  120   T      110   T
501100  110   T      100   T
501000  100   T       90   T
500900   90   T       80   T
500700   70  UP       60   T
500600   60   T      150   I
500100   10   U       20   I
502000  200   U      210   I
502100  210   U      220   I
502200  220   U      230   I
502300  230   U      240   I
502400  240   U      250   I
502500  250   U      260   S
502620  260   D      140   I
502710  270   B       70  IT
502600  260   T      290   I
502800  280   U      260   T
500710   70  UT      300  IB
503300  330   U      320  IB
501810  180   B      330  IB
502010  200   E       90   S
502210  220   E      110   S
502310  230   E      120   S
500920   90   D      100   D
501020  100   D      110   D
501120  110   D      120   D
500800   80   T      370  IA
503700  370   U       70  IP
```

| | | | | |
|---|---|---|---|---|
| 503650 | 50 | U | 370 | IB |
| 503850 | 420 | B | 410 | IA |
| 504300 | 430 | U | 10 | I |
| 502110 | 210 | E | 100 | S |
| 500620 | 60 | D | 320 | IA |
| 500820 | 80 | D | 320 | IC |
| 500200 | 20 | U | 460 | I |
| 504600 | 460 | U | 30 | I |
| 501720 | 170 | T | 330 | IA |
| 504400 | 440 | U | 60 | S |
| 500210 | 20 | E | 440 | IA |
| 501600 | 160 | U | 200 | I |
| 502700 | 270 | U | 160 | I |
| 501220 | 120 | D | 310 | IB |
| 502410 | 240 | E | 300 | IA |
| 503000 | 300 | U | 340 | IA |
| 501320 | 130 | D | 340 | IB |
| 503400 | 340 | U | 310 | IA |
| 504350 | 190 | T | 440 | IB |
| 501800 | 180 | U | 170 | S |
| 504610 | 460 | B | 170 | T |
| 504510 | 450 | B | 190 | T |
| 501730 | 170 | D | 190 | S |
| 501920 | 190 | D | 270 | I |
| 503600 | 360 | U | 420 | I |
| 504200 | 420 | U | 180 | I |
| 503610 | 360 | B | 380 | IB |
| 503100 | 310 | U | 380 | IA |
| 504500 | 450 | U | 390 | I |
| 503900 | 390 | U | 430 | I |
| 503910 | 500 | U | 400 | I |
| 503800 | 380 | U | 470 | IA |
| 504650 | 400 | B | 470 | IB |
| 504700 | 470 | U | 260 | D |
| 500310 | 30 | E | 490 | IA |
| 504900 | 490 | U | 80 | S |
| 504800 | 480 | U | 490 | IB |
| 503200 | 320 | U | 480 | I |

```
504810  480   B        50   I
500400   40   U       450   I
503920  390   B       500   I
505010  500   B       410  IC
504000  400   U       410  IB
504100  410   U       130   S
500300   30   U       360   I
*
*
*
* LP steam to MFPT
602710    2  0.04839  0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
*
602010    2  0.05   0.0   0.0   0.0   0.0   0.0   0.0   0.0
602016
*
*
602210    2  0.015   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
*
602310    2  0.0435   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
*
602110    2  0.093   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
*
604610    2  0.001   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
*
604510    2  0.001   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
*
601730    2  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
*
601920    2  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
```

```
*
600310   2   0.0505   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
*
600400   2   0.02703   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
*
600300   2   0.01   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
******************************
*  COMPONENTS
*****************************
*
*
*
* First stage
700100   1   1   1   2   65.
700101   0.0   -0.9141   200.   0.0   0
*
* Intermediate HP stage group
700200   2   1   0   1   2   0.02
700201   660.   1200.   10787339.   517.   1594449.
700202   0.0   0.0   0.0   0.0   0.0   0
700203   0.0   0.0
*
* Last HP stage group
700300   2   1   1   1   2   0.0
700301   517.   1193.5   9619176.   200.   714248.
700302   0.0   0.0   0.0   0.0   0.0   0
700303   0.0   0.0
*
* FIRST LP STAGE GROUP
702000   3   1   0   1   0   4   0.0
702001   182.6   1274.   7638587.   72.8   285073.   0.0
702002   0.0   0.0   0.0   0.0   0.0   0.0
702003   0   0.0   0.0   0.0   0.0
702008   0.97234   0.0
*
```

```
* 2ND LP STAGE GROUP
702100   3  1  1  1  0  4  0.0
702101   72.8  1198.7  7353514.  42.5  419678.  0.0
702102   0.0  0.0  0.0  0.0  0.0  0.0
702103   0  0.0  0.0  0.0  0.0
702108   0.0  29.68
*
* 3RD LP STAGE GROUP
702200   3  1  1  1  1  4  0.05
702201   42.5  1159.4  6933836.  16.1  356768.  0.0
702202   0.0  0.0  0.0  0.0  0.0  0.0
702203   0  0.0  0.0  0.0  0.0
*
* 4TH LP STAGE GROUP
702300   3  1  1  1  1  4  0.0
702301   16.1  1104.  6642487.  6.9  592394.  0.0
702302   0.0  0.0  0.0  0.0  0.0  0.0
702303   0  0.0  0.0  0.0  0.0
702308   1.03276  0.0
*
* 5TH LP STAGE GROUP
702400   3  1  1  1  1  4  0.05
702401   6.9  1071.2  6147048.  3.2  153927.  0.0
702402   0.0  0.0  0.0  0.0  0.0  0.0
702403   0  0.0  0.0  0.0  0.0
702408   1.00652  0.0
*
* LAST LP STAGE GROUP
702500   3  1  3  0  0  4  0.0
702501   3.2  1047.1  5993121.  -1.6  0.0  127.4
702502   0.0  0.0  0.0  0.0  0.0  0.0
702503   0  0.0  0.0  0.0  0.0
702508   1.07971  0.0
*
* CONDENSER
702600   10  1  2  0.0  -1.6
702601   0.0  0.0  0.0  0.0  0.0  0.0
702602   0.0  0.0  0.0  0.0  20.
```

```
*
* #1 FEEDWATER HEATER
700600    16   0   20   2   0.0   3.25   7.5
700601    0.0   0.0   0.0   0.0   0.0   0.0
700602    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0
*
* #3 FEEDWATER HEATER
700900    16   0   200   2   0.0   5.   10.
700901    0.0   0.0   0.0   0.0   0.0   0.0
700902    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0
*
* #4 FEEDWATER HEATER
701000    16   1   210   2   0.0   5.   10.
701001    0.0   0.0   0.0   0.0   0.0   0.0
701002    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0
*
* #5 FEEDWATER HEATER
701100    16   1   220   2   0.0   5.   10.
701101    0.0   0.0   0.0   0.0   0.0   0.0
701102    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0
*
* #6 FEEDWATER HEATER
701200    16   1   230   2   0.0   5.   10.
701201    0.0   0.0   0.0   0.0   0.0   0.0
701202    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0
*
* #2 FEEDWATER HEATER
700800    17   0   30   2   0.0   5.
700801    0.0   0.0   0.0   0.0   0.0   0.0
700802    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0
*
* Gland steam condenser
701300    20   210.3
701301    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
*
* MSR HP Bundle
701900    22   450   2   25.
701901    0.0   0.00995   0.01509   0.0   0.0
```

```
701902    0.0   0.0   0.0   0.0   0.0   0.0
*
*
701700    22   460   2   25.
701701    0.0   0.0   0.01487   0.0   0.0
701702    0.0   0.0   0.0   0.0   0.0   0.0
*
* CIRC WATER OUTLET
702900    30
702902    0
*
* CIRC WATER SUPPLY
702800    31   32.   20.  105444304   0.0   0.0   0
702802  0   0   0
*
* Final  Feedwater
701500    32
701502    0
*
* Main  steam  inlet
700400    33   570.   925.   11177540.   2588.   0.0   0
700402  0   0
*
* LP  inlet  valves
701600    34   0.01828   0.0   0.0   0.0   0.0   0.0   0.0
*
* governer  valves
704300    35  -1.0  -1.0  -1.0   0.35   900.   1231.34   10787339.
704301    0.0   0.0   0.0
704309    0.0   0.0   0.0
*
* MAIN FW PUMP
700700    40   270   1088.   1.03143   0.0   0.75
700701    0.98   0.0   0.0   2.6   0.0   0.0   0.0   0.0
700709    0.0   0   0.0
*
* CONDENSATE PUMP
701400    41   350.   0.0   0.0   0.0
```

```
701401   0.0  0.0  0.0  0.0  0.0  0.0
*
* Heater Drain pump
700500   41  350.  0.0  0.0  0.0
700501   0.0  0.0  0.0  0.0  0.0  0.0
*
*
703700   50  4  0.0
*
* HDT vent
704900   50  0  0.0
*
*
703300   51  4  0.0
*
* HP bundle drain to top fw heater
704400   51  4  0.0
*
*
703100   51  4  0.0
*
*
703000   51  4  0.0
*
*
703400   51  4  0.0
*
* gland steam mixer
703800   51  4  0.0
*
*
704700   51  4  0.0
*
*
703200   54  4  0.0
*
*
704100   54  0  0.0
```

```
*
* STEAM SUPPLY TO FEEDPUMP TURBINE
702700   60  0.0  111830.  0.0  0  0.0
702701   0
*
* MSR HP bundle supply
704500   60  0.0  423296.  0.0  0  0.0
704501   0
*
* Steam supply to MSR lp Bundle
704600   60  0.0  433000.  0.0  0  0.0
704601   0
*
* hp shaft leakage
704200   61  0.0  971.
*
* hp shaft leakage
703600   61  1125.9  5896.
*
* gland steam supply
703900   61  0.0  9508.
*
*
704000   61  0.0  5880.
*
*
705000   61  0.0  462.
*
* moisture seperator
701800   62  1.  0.0298  0.0  0.0  0.0  0.0
*
* heater drain tank
704800   62  1.  0.0  0.0  0.0  0.0  0.0
*
******************************
*  SPECIAL FEATURES
*****************************
*
```

```
*
*
*
800100 "Moisture removal effectiveness"
* X VALUES
810100    2.   5.   10.   20.   50.
* Z AND Y VALUES
810110    0.0   20.   19.1   18.6   15.2   10.
* MULTIPLIERS
820100     0.01   0.0   0.0
*
* EFF 240
830100    1   EFFMOS   240   PP   240
*
* EFFMOS 230
830200    1   EFFMOS   230   PP   230
*
* EFFMOS 220
830300    1   EFFMOS   220   PP   220
*
*
*
*
*
* 1000
870010    1000.
*
*
*
*
880010     BBSTRM   40    SUB    BBSTRM   60    OPVB   50
880011     1.   1.   0.00029283
*
*
880020     OPVB   50    DIV    OPVB   1    OPVB   51
880021     1.   1.   1.
*
*
```

```
*****************************
*   SPECIAL OPTIONS
*****************************
*
*
*
850000
*
*
890010 "Thermal Output"
890011 OPVB   51  0.0    U
*
*
* PEPSE DEBUG
*
* Model for ANO-1
010200    1   0   1   2   1   1   0.0   0.0
*
*****************************
*     END OF BASE DECK
*****************************
*
.
```

# APPENDIX P

## JOB FILE MAKING SCRIPTJOB FILE MAKING SCRIPT

As described in the introduction to the Appendix N and Subsection 4.2.1., the job files created by PEPSE were manipulated in order to create job files for the same model but with differing thermodynamic boundary conditions. This was accomplished simply by altering the desired values and then saving the file under a different name. Though different scripts were required for each desired type of parameter change, one such script is provided below.

These scripts were written for a bash interpreter capable of using the sed language. This particular script was used to modify the incoming coolant temperature and the condenser flow rate. This script takes the job file given in Appendix N and creates job files for the same model with the condenser flow ranging from 105,444,304 to 1,105,444,304 pounds per minute by increments of 10,000,000 pounds per minute and with the inlet temperature ranging from 32 to 100°F by increments of 1°F.

```
#!/bin/bash
TEMPRISE=1
TEMP=32
STOPTEMP=100
RISEFLOW=10000000
FLOW=105444304
STOPFLOW=1105444304
while [[ ! "$FLOW" == "$STOPFLOW" ]]
    do
        TEMP=32
        while [[ ! "$TEMP" == "$STOPTEMP" ]]
            do
                NEWTEMP=$(echo "$TEMP + $TEMPRISE" | bc)
                sed '7 s@'$TEMP'@'$NEWTEMP'@' $TEMP'Norm'$FLOW.
                    job > tout
                mv tout $NEWTEMP'Norm'$FLOW.job
                sed '8 s@'$TEMP'@'$NEWTEMP'@' $NEWTEMP'Norm'
                    $FLOW.job > tout
                mv tout $NEWTEMP'Norm'$FLOW.job
                sed '278 s@'\ $TEMP\.'@'\ $NEWTEMP\.'@' $NEWTEMP
                    'Norm'$FLOW.job > tout
                mv tout $NEWTEMP'Norm'$FLOW.job
                TEMP="$NEWTEMP"
            done
        NEWFLOW=$(echo "$FLOW + $RISEFLOW" | bc)
        sed '7 s@'$FLOW'@'$NEWFLOW'@' 32Norm$FLOW.job > tout
        mv tout 32Norm$NEWFLOW.job
        sed '8 s@'$FLOW'@'$NEWFLOW'@' 32Norm$NEWFLOW.job >
            tout
        mv tout 32Norm$NEWFLOW.job
        sed '278 s@'\ $FLOW'@'\ $NEWFLOW'@' 32Norm$NEWFLOW.job
             > tout
        mv tout 32Norm$NEWFLOW.job
        FLOW="$NEWFLOW"
    done
echo "Finished"
```

# APPENDIX Q

# PEPSE RESULTS FILE

After converging upon a thermodynamic balance-of-plant consistent with the input conditions for the input model, PEPSE generates two output files. The file labeled with a ".out" extension, while plain ASCII text, is unintelligible. The file labeled with a ".res" extension, however, consists of a layout very similar to the job file input, but which includes the solution parameters as well. An example of such a results file is provided below.

```
TIT  ano-1
10/25/09   NORM TERMINATION        14   ENGLISH   --  V59
   9.147451E+02  9.118357E+02  9.642396E+03  9.684050E+03
      0.000000E+00        0
CYC   1.522499E+09  -7.297836E+09   0.000000E+00   0.000000E+00
     0.000000E+00  8.820335E+09  9.642396E+03  9.642396E+03
VER 65.0 (67 STEAM TABLES) OF 24 JUL 00
WRN   1
CMP    10     1  NUCL. TURB. - GS
   8.904952E-01  2.004983E+08  3.425503E+05  2.000000E+00
   0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00
      0.000000E+00
 IN      1  430     0     1.076307E+07
   5.610265E+02  8.635488E+02  1.049941E+00  1.231346E+03
      5.709550E-01  1.441551E+00
OUT      1   10     0     1.076307E+07
HPE   5.114457E+02  6.826897E+02  1.014724E+00  1.212718E+03
     6.915125E-01  1.443916E+00
CMP    20     2  NUCL. TURB. - HP
   9.172076E-01  2.722942E+08  3.969887E+05  0.000000E+00
   0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00
      0.000000E+00
 IN      1   10     0     1.076307E+07
   5.114457E+02  6.826897E+02  1.014724E+00  1.212718E+03
      6.915125E-01  1.443916E+00
OUT      1   20     0     9.604693E+06
   4.657242E+02  4.937951E+02  9.771621E-01  1.187419E+03
      9.184343E-01  1.446384E+00
OUT      2   21     0     1.158375E+06
   4.636533E+02  4.839192E+02  9.771815E-01  1.187419E+03
      9.374246E-01  1.448219E+00
CMP    30     2  NUCL. TURB. - HP
   8.588397E-01  5.726853E+08  8.668438E+05  0.000000E+00
   8.813236E-01  0.000000E+00  0.000000E+00  0.000000E+00
      0.000000E+00
 IN      1  460     0     9.205078E+06
```

```
   4.657242E+02  4.937951E+02  9.771621E-01  1.187419E+03
      9.184343E-01  1.446384E+00
OUT      1    30      0     8.478893E+06
   3.818045E+02  2.000000E+02  9.132336E-01  1.125205E+03
      2.090419E+00  1.458536E+00
OUT      2    31      0     7.261841E+05
   3.818045E+02  2.000000E+02  9.132336E-01  1.125205E+03
      2.090419E+00  1.458536E+00
CMP     40    33   INPUT COMPONENT
   0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00
   1.522499E+09  0.000000E+00  0.000000E+00
OUT      1    40      0     1.117754E+07
   5.700000E+02  9.250000E+02  1.053811E+00  1.231346E+03
      5.324888E-01  1.435436E+00
CMP     50    41   STD. ELE. PUMP
   1.000000E+00  1.601000E+02  1.000000E+00  5.428734E-01
      1.000000E+00  5.444724E+02
   0.000000E+00  0.000000E+00
 IN      1   481      0     3.422192E+06
P2EIN    3.774893E+02  1.899000E+02  0.000000E+00  3.508894E
   +02  1.833040E-02  5.383836E-01
OUT      1   365      0     3.422192E+06
P2EOUT    3.778003E+02  3.500000E+02 -7.353526E-02  3.514322E
   +02  1.831747E-02  5.383860E-01
CMP     60    16   FWHT. BACK-DRAIN
   3.250000E+00  7.500000E+00  1.029599E+09  9.880348E-01
      2.196126E+07  0.000000E+00
 IN      1    70      0     1.117754E+07
   3.756038E+02  1.088000E+03 -3.245225E-01  3.501203E+02
      1.821266E-02  5.338303E-01
 IN      2   440      0     1.563339E+06
   4.636533E+02  4.839192E+02  7.511501E-01  1.015850E+03
      7.251418E-01  1.262413E+00
OUT      1    60      0     1.117754E+07
   4.604033E+02  1.088000E+03 -1.791781E-01  4.422335E+02
      1.951545E-02  6.388103E-01
OUT      2    62      0     1.563339E+06
```

```
     3.831038E+02  4.839192E+02  -1.165046E-01  3.572606E+02
        1.837385E-02  5.447820E-01
CMP     70    40   STM.  DRIVEN PUMP
     9.581149E-01  7.380000E+02  9.800000E-01  2.600000E+00
        7.500000E-01  8.690934E+03
     0.000000E+00  0.000000E+00
  IN      1   370     0     1.117754E+07
P1EIN    3.741182E+02  3.500000E+02  -7.846115E-02  3.475203E
    +02  1.826913E-02  5.337044E-01
  IN      2   271     0     1.113346E+05
     5.039304E+02  1.773681E+02  1.090351E+00  1.273593E+03
        3.105517E+00  1.641617E+00
OUT       1    70     0     1.117754E+07
P1EOUT     3.756038E+02  1.088000E+03  -3.245225E-01  3.501203E
    +02  1.821266E-02  5.338303E-01
OUT       2    71     0     1.113346E+05
     1.027744E+02  1.031430E+00  9.043768E-01  1.007237E+03
        2.930354E+02  1.799474E+00
CMP     80    17   FWHT.  FORE-DRAIN
     5.000000E+00  8.072795E+01  6.117860E+08  9.369395E-01
        2.247832E+07  0.000000E+00
  IN      1    90     0     7.755348E+06
     2.967585E+02  3.500000E+02  -1.799669E-01  2.669084E+02
        1.739998E-02  4.322615E-01
  IN      2   490     0     7.846334E+05
     3.774864E+02  1.899000E+02  9.208489E-01  1.130599E+03
        2.215411E+00  1.469755E+00
OUT       1    80     0     7.755348E+06
     3.724864E+02  3.500000E+02  -8.063479E-02  3.457941E+02
        1.824794E-02  5.316320E-01
OUT       2    82     0     7.846334E+05
     3.774864E+02  1.899000E+02  0.000000E+00  3.508894E+02
        1.833040E-02  5.383836E-01
CMP     90    16   FWHT.  BACK-DRAIN
     5.000000E+00  1.000000E+01  2.919318E+08  9.894955E-01
        7.036733E+06  0.000000E+00
  IN      1   100     0     7.755348E+06
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     2.598709E+02  3.500000E+02  -2.273661E-01  2.292657E+02
        1.706690E-02  3.812449E-01
  IN       2   201      0     3.044845E+05
     3.338224E+02  6.878947E+01  1.019168E+00  1.197646E+03
        6.627727E+00  1.655397E+00
OUT       1    90      0     7.755348E+06
     2.967585E+02  3.500000E+02  -1.799669E-01  2.669084E+02
        1.739998E-02  4.322615E-01
OUT       2    92      0     3.044845E+05
     2.698709E+02  6.878947E+01  -3.593565E-02  2.388719E+02
        1.717194E-02  3.957342E-01
CMP    100     16   FWHT.  BACK-DRAIN
     5.000000E+00  1.000000E+01  4.090628E+08  9.828597E-01
        1.844989E+07  1.380194E+06
  IN       1   110      0     7.755348E+06
     2.076318E+02  3.500000E+02  -2.937832E-01  1.765198E+02
        1.666908E-02  3.051567E-01
  IN       2   211      0     4.039901E+05
     2.648709E+02  3.844957E+01  9.888099E-01  1.158516E+03
        1.077112E+01  1.665206E+00
  IN       3    92      0     3.044845E+05
     2.698709E+02  6.878947E+01  -3.593565E-02  2.388719E+02
        1.717194E-02  3.957342E-01
OUT       1   100      0     7.755348E+06
     2.598709E+02  3.500000E+02  -2.273661E-01  2.292657E+02
        1.706690E-02  3.812449E-01
OUT       2   102      0     7.084746E+05
     2.176318E+02  3.844957E+01  -5.113772E-02  1.858911E+02
        1.675715E-02  3.205203E-01
CMP    110     16   FWHT.  BACK-DRAIN
     5.000000E+00  1.000000E+01  3.083460E+08  9.666625E-01
        1.607092E+07  1.891057E+06
  IN       1   120      0     7.755348E+06
     1.679705E+02  3.500000E+02  -3.438476E-01  1.367607E+02
        1.642143E-02  2.437494E-01
  IN       2   221      0     3.528110E+05
     2.126318E+02  1.488111E+01  7.825564E-01  9.398112E+02
        2.073107E+01  1.442087E+00
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  IN       3   102      0      7.084746E+05
     2.176318E+02   3.844957E+01  -5.113772E-02   1.858911E+02
         1.675715E-02   3.205203E-01
OUT       1   110      0      7.755348E+06
     2.076318E+02   3.500000E+02  -2.937832E-01   1.765198E+02
         1.666908E-02   3.051567E-01
OUT       2   112      0      1.061286E+06
     1.779705E+02   1.488111E+01  -3.590018E-02   1.459823E+02
         1.649740E-02   2.599138E-01
CMP    120     16   FWHT.  BACK-DRAIN
     5.000000E+00   1.000000E+01   5.684299E+08   9.719259E-01
         1.966683E+07   4.085785E+06
  IN       1   130      0      7.755348E+06
     9.455373E+01   3.500000E+02  -4.361402E-01   6.346545E+01
         1.609529E-02   1.195809E-01
  IN       2   231      0      5.838578E+05
     1.729705E+02   6.413927E+00   7.760237E-01   9.126707E+02
         4.519069E+01   1.471894E+00
  IN       3   112      0      1.061286E+06
     1.779705E+02   1.488111E+01  -3.590018E-02   1.459823E+02
         1.649740E-02   2.599138E-01
OUT       1   120      0      7.755348E+06
     1.679705E+02   3.500000E+02  -3.438476E-01   1.367607E+02
         1.642143E-02   2.437494E-01
OUT       2   122      0      1.645143E+06
     1.045537E+02   6.413927E+00  -6.877418E-02   7.255833E+01
         1.614526E-02   1.376401E-01
CMP    130     20   GEN.  HT.  EXCH.
     4.733761E+06   0.000000E+00   0.000000E+00   0.000000E+00
         0.000000E+00
     0.000000E+00   0.000000E+00   4.733761E+06   8.985309E-01
         0.000000E+00
  IN       1   140      0      7.755348E+06
     9.394109E+01   3.500000E+02  -4.369088E-01   6.285506E+01
         1.609340E-02   1.184787E-01
  IN       2   410      0      4.599000E+03
     4.809553E+02   5.434582E+02   1.006167E+00   1.208936E+03
         8.623145E-01   1.460735E+00
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OUT      1   130      0     7.755348E+06
    9.455373E+01   3.500000E+02  −4.361402E−01   6.346545E+01
       1.609529E−02   1.195809E−01
OUT      2   132      0     4.599000E+03
    2.103123E+02   5.434582E+02  −3.757148E−01   1.796336E+02
       1.667645E−02   3.089305E−01
CMP    140     41   STD. ELE. PUMP
    1.000000E+00   3.492142E+02   1.000000E+00   1.040528E+00
       1.000000E+00   2.364983E+03
    0.000000E+00   0.000000E+00
 IN      1   262      0     7.755348E+06
P3EIN    9.380375E+01   7.858467E−01   0.000000E+00   6.181454E
   +01   1.611013E−02   1.184301E−01
OUT      1   140      0     7.755348E+06
P3EOUT    9.394109E+01   3.500000E+02  −4.369088E−01   6.285506E
   +01   1.609340E−02   1.184787E−01
CMP    150     32   OUTPUT COMPONENT
    0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
    0.000000E+00  −7.297836E+09   0.000000E+00
 IN      1    60      0     1.117754E+07
    4.604033E+02   1.088000E+03  −1.791781E−01   4.422335E+02
       1.951545E−02   6.388103E−01
CMP    160     34   STANDARD VALVE
    3.407162E+00   1.828000E−02   0.000000E+00   0.000000E+00
    0.000000E+00   0.000000E+00   0.000000E+00
 IN      1   270      0     7.627638E+06
    5.056557E+02   1.863874E+02   1.089893E+00   1.273593E+03
       2.954771E+00   1.636376E+00
OUT      1   160      0     7.627638E+06
    5.050051E+02   1.829802E+02   1.090060E+00   1.273593E+03
       3.009971E+00   1.638324E+00
CMP    170     22   NUCLEAR REHEATER
    2.955073E+08   2.499661E+01   2.499661E+01   0.000000E+00
       0.000000E+00
    0.000000E+00   0.000000E+00  −2.955073E+08   8.866493E−01
       2.856521E+00
 IN      1   180      0     7.738973E+06
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     3.794677E+02  1.920996E+02  1.000794E+00  1.198452E+03
         2.382075E+00  1.549642E+00
  IN      2   461     0     3.996150E+05
     4.656214E+02  4.933013E+02  9.771628E-01  1.187419E+03
         9.193661E-01  1.446475E+00
OUT       1   173     0     7.738973E+06
     4.406248E+02  1.892431E+02  1.046127E+00  1.236637E+03
         2.667256E+00  1.595132E+00
OUT       2   172     0     3.996150E+05
     4.656214E+02  4.933013E+02  0.000000E+00  4.479384E+02
         1.971881E-02  6.473332E-01
CMP    180    62  MOISTURE SEP.
     1.000000E+00  0.000000E+00
  IN      1   420     0     8.472026E+06
     3.809632E+02  1.980000E+02  9.134737E-01  1.125204E+03
         2.111287E+00  1.459460E+00
OUT       1   180     0     7.738973E+06
     3.794677E+02  1.920996E+02  1.000794E+00  1.198452E+03
         2.382075E+00  1.549642E+00
OUT       2   181     0     7.330535E+05
     3.784447E+02  1.920996E+02  0.000000E+00  3.519099E+02
         1.834290E-02  5.395930E-01
CMP    190    22  NUCLEAR REHEATER
     2.860084E+08  2.499844E+01  2.499844E+01  0.000000E+00
         0.000000E+00
     8.946018E+00  0.000000E+00 -2.860084E+08  8.705443E-01
         2.855678E+00
  IN      1   173     0     7.738973E+06
     4.406248E+02  1.892431E+02  1.046127E+00  1.236637E+03
         2.667256E+00  1.595132E+00
  IN      2   451     0     4.049649E+05
     5.662556E+02  8.990973E+02  1.052133E+00  1.231346E+03
         5.480606E-01  1.437955E+00
OUT       1   192     0     7.738973E+06
     5.056557E+02  1.863874E+02  1.089893E+00  1.273593E+03
         2.954771E+00  1.636376E+00
OUT       2   435     0     4.049649E+05
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   5.306542E+02  8.901512E+02  0.000000E+00  5.250909E+02
      2.119506E-02  7.263133E-01
CMP   200    3  NUCL. TURB. - LP
   8.925569E-01  5.793007E+08  2.159547E+06  0.000000E+00
   0.000000E+00  0.000000E+00  3.044845E+05  0.000000E+00
      0.000000E+00
 IN      1   160    0    7.627638E+06
   5.050051E+02  1.829802E+02  1.090060E+00  1.273593E+03
      3.009971E+00  1.638324E+00
OUT      1   200    0    7.323154E+06
   3.352820E+02  7.240997E+01  1.018151E+00  1.197646E+03
      6.296907E+00  1.649948E+00
OUT      2   201    0    3.044845E+05
   3.352820E+02  7.240997E+01  1.018151E+00  1.197646E+03
      6.296907E+00  1.649948E+00
CMP   210    3  NUCL. TURB. - LP
   9.153459E-01  2.865514E+08  3.328208E+06  0.000000E+00
   0.000000E+00  0.000000E+00  4.039901E+05  0.000000E+00
      0.000000E+00
 IN      1   200    0    7.323154E+06
   3.352820E+02  7.240997E+01  1.018151E+00  1.197646E+03
      6.296907E+00  1.649948E+00
OUT      1   210    0    6.919164E+06
   2.707763E+02  4.239203E+01  9.867176E-01  1.158516E+03
      9.808391E+00  1.654903E+00
OUT      2   211    0    4.039901E+05
   2.707763E+02  4.239203E+01  9.867176E-01  1.158516E+03
      9.808391E+00  1.654903E+00
CMP   220    3  NUCL. TURB. - LP
   8.486663E-01  4.175614E+08  8.020681E+06  0.000000E+00
   0.000000E+00  1.098168E+03  2.889914E+05  6.381960E+04
      1.842037E+02
 IN      1   210    0    6.919164E+06
   2.707763E+02  4.239203E+01  9.867176E-01  1.158516E+03
      9.808391E+00  1.654903E+00
OUT      1   220    0    6.566353E+06
   2.160066E+02  1.590287E+01  9.532048E-01  1.106676E+03
      2.372736E+01  1.683423E+00
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OUT      2   221      0     3.528110E+05
     2.133965E+02  1.510772E+01  7.821542E-01  9.398112E+02
         2.042956E+01  1.440804E+00
CMP    230      3   NUCL. TURB. - LP
     8.710499E-01  3.281974E+08  1.668756E+07  0.000000E+00
     0.000000E+00  1.056695E+03  4.843828E+05  9.947502E+04
         1.429179E+02
  IN      1   220      0     6.566353E+06
     2.160066E+02  1.590287E+01  9.532048E-01  1.106676E+03
         2.372736E+01  1.683423E+00
OUT      1   230      0     5.982495E+06
     1.749325E+02  6.705621E+00  9.341213E-01  1.070751E+03
         5.217470E+01  1.717232E+00
OUT      2   231      0     5.838578E+05
     1.749325E+02  6.705621E+00  7.749700E-01  9.126707E+02
         4.328822E+01  1.468127E+00
CMP    240      3   NUCL. TURB. - LP
     8.618077E-01  2.452257E+08  3.406469E+07  0.000000E+00
     0.000000E+00  1.029760E+03  2.991247E+04  1.085963E+05
         1.109144E+02
  IN      1   230      0     5.982495E+06
     1.749325E+02  6.705621E+00  9.341213E-01  1.070751E+03
         5.217470E+01  1.717232E+00
OUT      1   240      0     5.843986E+06
     1.429651E+02  3.116745E+00  9.244734E-01  1.046748E+03
         1.058990E+02  1.756328E+00
OUT      2   241      0     1.385088E+05
     1.409554E+02  2.960907E+00  2.014010E-01  3.130177E+02
         2.422124E+01  5.399063E-01
CMP    250      3   NUCL. TURB. - LP
     5.791920E-01  2.653544E+08  1.281732E+08  0.000000E+00
     7.347160E-01  0.000000E+00  0.000000E+00  0.000000E+00
         0.000000E+00
  IN      1   240      0     5.843986E+06
     1.429651E+02  3.116745E+00  9.244734E-01  1.046748E+03
         1.058990E+02  1.756328E+00
OUT      1   250      0     5.843986E+06
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LPE    9.380375E+01   7.858467E−01   9.028821E−01   1.001341E+03
     3.780194E+02   1.815933E+00
CMP    260     10   STD. CONDENSER
   8.133983E+00   0.000000E+00   5.662001E+09   9.219177E−01
       2.110962E+08   2.810311E+06
 IN       1   250      0      5.843986E+06
   9.380375E+01   7.858467E−01   9.028821E−01   1.001341E+03
       3.780194E+02   1.815933E+00
 IN       2   280      0      1.054443E+08
   3.199598E+01   2.000000E+01  −2.043910E−01   4.261276E−02
       1.602096E−02  −4.240260E−05
 IN       3   470      0      1.911362E+06
   1.027744E+02   1.031430E+00   7.796431E−02   1.514991E+02
       2.527668E+01   2.780121E−01
OUT       1   262      0      7.755348E+06
   9.380375E+01   7.858467E−01   0.000000E+00   6.181454E+01
       1.611013E−02   1.184301E−01
OUT       2   260      0      1.054443E+08
   8.566977E+01   2.000000E+01  −1.484601E−01   5.373921E+01
       1.608562E−02   1.036444E−01
CMP    270     60   DEMAND SPLITTER
   0.000000E+00   0.000000E+00
 IN       1   192      0      7.738973E+06
   5.056557E+02   1.863874E+02   1.089893E+00   1.273593E+03
       2.954771E+00   1.636376E+00
OUT       1   270      0      7.627638E+06
   5.056557E+02   1.863874E+02   1.089893E+00   1.273593E+03
       2.954771E+00   1.636376E+00
OUT       2   271      0      1.113346E+05
   5.056557E+02   1.863874E+02   1.089893E+00   1.273593E+03
       2.954771E+00   1.636376E+00
CMP    280     31   INFINITE SOURCE
   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  −1.154713E+11   0.000000E+00   0.000000E+00
OUTENDFLOW       1   280      0      1.054443E+08
TEMPIN    3.200000E+01   2.000000E+01  −2.043910E−01   4.261276E
   −02   1.602095E−02  −4.240260E−05
CMP    290     30   INFINITE SINK
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     0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
     0.000000E+00  -1.098093E+11   0.000000E+00
  IN        1   260      0      1.054443E+08
TEMPOUT     8.566977E+01   2.000000E+01  -1.484601E-01   5.373921
    E+01   1.608562E-02   1.036444E-01
CMP     300     51   FWHT-COND. MIXER
  IN        1   241      0      1.385088E+05
     1.409554E+02   2.960907E+00   2.014010E-01   3.130177E+02
         2.422124E+01   5.399063E-01
  IN        2    71      0      1.113346E+05
     1.027744E+02   1.031430E+00   9.043768E-01   1.007237E+03
         2.930354E+02   1.799474E+00
OUT         1   300      0      2.498434E+05
     1.027744E+02   1.031430E+00   5.327027E-01   6.223739E+02
         1.726125E+02   1.115205E+00
CMP     310     51   FWHT-COND. MIXER
  IN        1   340      0      2.544424E+05
     1.027744E+02   1.031430E+00   5.249745E-01   6.143714E+02
         1.701086E+02   1.100977E+00
  IN        2   122      0      1.645143E+06
     1.045537E+02   6.413927E+00  -6.877418E-02   7.255833E+01
         1.614526E-02   1.376401E-01
OUT         1   310      0      1.899586E+06
     1.027744E+02   1.031430E+00   7.181555E-02   1.451322E+02
         2.328447E+01   2.666920E-01
CMP     320     54   TRIPLE MIXER
  IN        1    62      0      1.563339E+06
     3.831038E+02   4.839192E+02  -1.165046E-01   3.572606E+02
         1.837385E-02   5.447820E-01
  IN        2   330      0      1.132668E+06
     3.784419E+02   1.920996E+02   4.005309E-02   3.857896E+02
         1.128454E-01   5.800131E-01
  IN        3    82      0      7.846334E+05
     3.774864E+02   1.899000E+02   0.000000E+00   3.508894E+02
         1.833040E-02   5.383836E-01
OUT         1   320      0      3.480641E+06
     3.774864E+02   1.899000E+02   1.679267E-02   3.651082E+02
         5.839651E-02   5.553646E-01
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CMP   330   51  FWHT-COND.  MIXER
 IN     1  172     0     3.996150E+05
   4.656214E+02  4.933013E+02  0.000000E+00  4.479384E+02
      1.971881E−02  6.473332E−01
 IN     2  181     0     7.330535E+05
   3.784447E+02  1.920996E+02  0.000000E+00  3.519099E+02
      1.834290E−02  5.395930E−01
OUT     1  330     0     1.132668E+06
   3.784419E+02  1.920996E+02  4.005309E−02  3.857896E+02
      1.128454E−01  5.800131E−01
CMP   340   51  FWHT-COND.  MIXER
 IN     1  300     0     2.498434E+05
   1.027744E+02  1.031430E+00  5.327027E−01  6.223739E+02
      1.726125E+02  1.115205E+00
 IN     2  132     0     4.599000E+03
   2.103123E+02  5.434582E+02 −3.757148E−01  1.796336E+02
      1.667645E−02  3.089305E−01
OUT     1  340     0     2.544424E+05
   1.027744E+02  1.031430E+00  5.249745E−01  6.143714E+02
      1.701086E+02  1.100977E+00
CMP   360   61  FIXED FLOW SPLIT
   0.000000E+00  0.000000E+00
 IN     1   30     0     8.478893E+06
   3.809632E+02  1.980000E+02  9.134742E−01  1.125205E+03
      2.111289E+00  1.459460E+00
OUT     1  360     0     8.472997E+06
   3.809632E+02  1.980000E+02  9.134737E−01  1.125204E+03
      2.111287E+00  1.459460E+00
OUT     2  361     0     5.896000E+03
   3.809632E+02  1.980000E+02  9.142987E−01  1.125900E+03
      2.113178E+00  1.460288E+00
CMP   370   50  STANDARD MIXER
 IN     1   80     0     7.755348E+06
   3.724864E+02  3.500000E+02 −8.063479E−02  3.457941E+02
      1.824794E−02  5.316320E−01
 IN     2  365     0     3.422192E+06
   3.778003E+02  3.500000E+02 −7.353526E−02  3.514322E+02
      1.831747E−02  5.383860E−01
```

```
OUT      1   370     0     1.117754E+07
     3.741182E+02  3.500000E+02 -7.846115E-02  3.475203E+02
         1.826913E-02  5.337044E-01
CMP    380     51   FWHT-COND.  MIXER
 IN      1   310     0     1.899586E+06
     1.027744E+02  1.031430E+00  7.181555E-02  1.451322E+02
         2.328447E+01  2.666920E-01
 IN      2   361     0     5.896000E+03
     3.809632E+02  1.980000E+02  9.142987E-01  1.125900E+03
         2.113178E+00  1.460288E+00
OUT      1   380     0     1.905482E+06
     1.027744E+02  1.031430E+00  7.474628E-02  1.481669E+02
         2.423403E+01  2.720875E-01
CMP    390     61   FIXED FLOW  SPLIT
     0.000000E+00  0.000000E+00
 IN      1   450     0     1.077258E+07
     5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
         5.475045E-01  1.437866E+00
OUT      1   390     0     1.076307E+07
     5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
         5.475045E-01  1.437866E+00
OUT      2   392     0     9.508000E+03
     5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
         5.475045E-01  1.437866E+00
CMP    400     61   FIXED FLOW  SPLIT
     0.000000E+00  0.000000E+00
 IN      1   391     0     9.046000E+03
     5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
         5.475045E-01  1.437866E+00
OUT      1   400     0     3.166000E+03
     5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
         5.475045E-01  1.437866E+00
OUT      2   465     0     5.880000E+03
     5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
         5.475045E-01  1.437866E+00
CMP    410     54   TRIPLE  MIXER
 IN      1   385     0     9.710000E+02
```

```
   3.809632E+02  1.980000E+02  9.134737E-01  1.125204E+03
       2.111287E+00  1.459460E+00
 IN      2   400     0     3.166000E+03
   5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
       5.475045E-01  1.437866E+00
 IN      3   501     0     4.620000E+02
   5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
       5.475045E-01  1.437866E+00
OUT      1   410     0     4.599000E+03
   4.809553E+02  5.434582E+02  1.006167E+00  1.208936E+03
       8.623145E-01  1.460735E+00
CMP    420    61   FIXED FLOW SPLIT
   0.000000E+00  0.000000E+00
 IN      1   360     0     8.472997E+06
   3.809632E+02  1.980000E+02  9.134737E-01  1.125204E+03
       2.111287E+00  1.459460E+00
OUT      1   420     0     8.472026E+06
   3.809632E+02  1.980000E+02  9.134737E-01  1.125204E+03
       2.111287E+00  1.459460E+00
OUT      2   385     0     9.710000E+02
   3.809632E+02  1.980000E+02  9.134737E-01  1.125204E+03
       2.111287E+00  1.459460E+00
CMP    430    35   THROTTLE VALVE
   3.644842E+01  4.049837E-02  9.977500E-01  9.977602E-01
   0.000000E+00  0.000000E+00  3.500000E-01
 IN      1   390     0     1.076307E+07
   5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
       5.475045E-01  1.437866E+00
OUT      1   430     0     1.076307E+07
   5.610265E+02  8.635488E+02  1.049941E+00  1.231346E+03
       5.709550E-01  1.441551E+00
CMP    440    51   FWHT-COND.  MIXER
 IN      1    21     0     1.158375E+06
   4.636533E+02  4.839192E+02  9.771815E-01  1.187419E+03
       9.374246E-01  1.448219E+00
 IN      2   435     0     4.049649E+05
   5.306542E+02  8.901512E+02  0.000000E+00  5.250909E+02
       2.119506E-02  7.263133E-01
```

```
OUT       1   440      0      1.563339E+06
    4.636533E+02  4.839192E+02  7.511501E-01  1.015850E+03
       7.251418E-01  1.262413E+00
CMP    450    60   DEMAND SPLITTER
    0.000000E+00  0.000000E+00
 IN       1    40      0      1.117754E+07
    5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
       5.475045E-01  1.437866E+00
OUT       1   450      0      1.077258E+07
    5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
       5.475045E-01  1.437866E+00
OUT       2   451      0      4.049649E+05
    5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
       5.475045E-01  1.437866E+00
CMP    460    60   DEMAND SPLITTER
    0.000000E+00  0.000000E+00
 IN       1    20      0      9.604693E+06
    4.657242E+02  4.937951E+02  9.771621E-01  1.187419E+03
       9.184343E-01  1.446384E+00
OUT       1   460      0      9.205078E+06
    4.657242E+02  4.937951E+02  9.771621E-01  1.187419E+03
       9.184343E-01  1.446384E+00
OUT       2   461      0      3.996150E+05
    4.657242E+02  4.937951E+02  9.771621E-01  1.187419E+03
       9.184343E-01  1.446384E+00
CMP    470    51   FWHT-COND.  MIXER
 IN       1   380      0      1.905482E+06
    1.027744E+02  1.031430E+00  7.474628E-02  1.481669E+02
       2.423403E+01  2.720875E-01
 IN       2   465      0      5.880000E+03
    5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
       5.475045E-01  1.437866E+00
OUT       1   470      0      1.911362E+06
    1.027744E+02  1.031430E+00  7.796431E-02  1.514991E+02
       2.527668E+01  2.780121E-01
CMP    480    62   MOISTURE SEP.
    1.000000E+00  0.000000E+00
 IN       1   320      0      3.480641E+06
```

```
    3.774864E+02  1.899000E+02  1.679267E-02  3.651082E+02
        5.839651E-02  5.553646E-01
OUT       1   480      0      5.844927E+04
    3.774840E+02  1.899000E+02  9.999981E-01  1.197618E+03
        2.404250E+00  1.549809E+00
OUT       2   481      0      3.422192E+06
    3.774893E+02  1.899000E+02  0.000000E+00  3.508894E+02
        1.833040E-02  5.383836E-01
CMP    490    50   STANDARD MIXER
 IN       1    31      0      7.261841E+05
    3.774864E+02  1.899000E+02  9.144782E-01  1.125205E+03
        2.200211E+00  1.463311E+00
 IN       2   480      0      5.844927E+04
    3.774840E+02  1.899000E+02  9.999981E-01  1.197618E+03
        2.404250E+00  1.549809E+00
OUT       1   490      0      7.846334E+05
    3.774864E+02  1.899000E+02  9.208489E-01  1.130599E+03
        2.215411E+00  1.469755E+00
CMP    500    61   FIXED FLOW SPLIT
    0.000000E+00  0.000000E+00
 IN       1   392      0      9.508000E+03
    5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
        5.475045E-01  1.437866E+00
OUT       1   391      0      9.046000E+03
    5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
        5.475045E-01  1.437866E+00
OUT       2   501      0      4.620000E+02
    5.663866E+02  8.999973E+02  1.052190E+00  1.231346E+03
        5.475045E-01  1.437866E+00
SOT    1  Thermal  Output                              OPVB
   51   2.582859E+03
GEN - GENERATOR VARIABLES
    1   1.800E+03  1.003E+06  9.000E-01  7.500E+01  3.168E+09
        0.000E+00  3.168E+09  9.284E+02  2.900E+00  1.071E+01
        9.147E+02
OPV - NON-ZERO OP VBS - PAIRS OF ID AND VALUE
      1,  1.00000E+03;   50,  2.58286E+06;   51,  2.58286E+03;
```

# APPENDIX R

# RESULTS FILE DATA COLLECTION SCRIPT

The results files printed by PEPSE represent point solutions to the system. In order to study the results of a range of conditions, it is necessary to retrieve data from each individual file of a series. Again, the results files are human readable ASCII text files so accomplishing this is simply a matter of writing a script to identify and record the relevant values.

The file given below is one such script. Because of the differences in the series of runs, a different data collection script was written for each. The file below covers the same range as the job making script given in Appendix O. Like that file, it is written for the bash scripting language.

On the first iteration over the ranges of interest, it utilizes the sed language to modify the original results file by adding signal flags to the lines containing pertinent data. After the data flags have been added, the script again iterates through the ranges of interest. On the second iteration it uses the data signals to identify the lines of interest and then records the relevant value(s) from those lines. These values are sent to a plain ASCII text file as a space separated list, which is then imported to QtiPlot for data analysis.

```
#!/bin/bash
RISETEMP=1
TEMP=32
STOPTEMP=100
RISEFLOW=10000000
FLOW=105444304
STOPFLOW=1105444304
while [[ ! "$FLOW" == "$STOPFLOW" ]]
   do
      TEMP=32
      while [[ ! "$TEMP" == "$STOPTEMP" ]]
         do
            NEWTEMP=$(echo "$TEMP + $RISETEMP" | bc)
            sed '262 s@'\ '@'AWKSIGTEMPOUT\ '@' $TEMP'Norm'
               $FLOW.RES > tout
            mv tout $TEMP'Norm'$FLOW.RES
            sed '13 s@'\ '@'AWKSIGHPE\ '@' $TEMP'Norm'$FLOW.
               RES > tout
            mv tout $TEMP'Norm'$FLOW.RES
            sed '232 s@'\ '@'AWKSIGLPE\ '@' $TEMP'Norm'$FLOW
               .RES > tout
            mv tout $TEMP'Norm'$FLOW.RES
            sed '58 s@'\ '@'AWKSIGP1EI\ '@' $TEMP'Norm'$FLOW
               .RES > tout
            mv tout $TEMP'Norm'$FLOW.RES
            sed '62 s@'\ '@'AWKSIGP1EO\ '@' $TEMP'Norm'$FLOW
               .RES > tout
            mv tout $TEMP'Norm'$FLOW.RES
            sed '41 s@'\ '@'AWKSIGP2EI\ '@' $TEMP'Norm'$FLOW
               .RES > tout
            mv tout $TEMP'Norm'$FLOW.RES
            sed '43 s@'\ '@'AWKSIGP2EO\ '@' $TEMP'Norm'$FLOW
               .RES > tout
            mv tout $TEMP'Norm'$FLOW.RES
            sed '136 s@'\ '@'AWKSIGP3EI\ '@' $TEMP'Norm'
               $FLOW.RES > tout
            mv tout $TEMP'Norm'$FLOW.RES
```

```
        sed '138 s@'\ '@'AWKSIGP3EO\ '@' $TEMP'Norm'
          $FLOW.RES > tout
        mv tout $TEMP'Norm'$FLOW.RES
        TEMP=$NEWTEMP
      done
    NEWFLOW=$(echo "$FLOW + $RISEFLOW" | bc)
    sed '262 s@'\ '@'AWKSIGTEMPOUT\ '@' $TEMP'Norm'$FLOW.
      RES > tout
    mv tout $TEMP'Norm'$FLOW.RES
    sed '13 s@'\ '@'AWKSIGHPE\ '@' $TEMP'Norm'$FLOW.RES >
      tout
    mv tout $TEMP'Norm'$FLOW.RES
    sed '232 s@'\ '@'AWKSIGLPE\ '@' $TEMP'Norm'$FLOW.RES >
       tout
    mv tout $TEMP'Norm'$FLOW.RES
    sed '58 s@'\ '@'AWKSIGP1EI\ '@' $TEMP'Norm'$FLOW.RES >
       tout
    mv tout $TEMP'Norm'$FLOW.RES
    sed '62 s@'\ '@'AWKSIGP1EO\ '@' $TEMP'Norm'$FLOW.RES >
       tout
    mv tout $TEMP'Norm'$FLOW.RES
    sed '41 s@'\ '@'AWKSIGP2EI\ '@' $TEMP'Norm'$FLOW.RES >
       tout
    mv tout $TEMP'Norm'$FLOW.RES
    sed '43 s@'\ '@'AWKSIGP2EO\ '@' $TEMP'Norm'$FLOW.RES >
       tout
    mv tout $TEMP'Norm'$FLOW.RES
    sed '136 s@'\ '@'AWKSIGP3EI\ '@' $TEMP'Norm'$FLOW.RES
      > tout
    mv tout $TEMP'Norm'$FLOW.RES
    sed '138 s@'\ '@'AWKSIGP3EO\ '@' $TEMP'Norm'$FLOW.RES
      > tout
    mv tout $TEMP'Norm'$FLOW.RES
    FLOW="$NEWFLOW"
  done
TEMP=32
FLOW=105444304
```

```
echo "TempIn   FlowRate   TempOut   HPE   LPE   P1EI   P1EO
    P2EI   P2EO   P3EI   P3EO" >> FlowAndTempResults.txt
while [[ ! "$FLOW" == "$STOPFLOW" ]]
  do
    TEMP=32
     while [[ ! "$TEMP" == "$STOPTEMP" ]]
       do
         NEWTEMP=$(echo "$TEMP + $RISETEMP" | bc)
         TEMPOUT=$(awk '/AWKSIGTEMPOUT/ {print$2}' $TEMP'
            Norm'$FLOW.RES)
         HPE=$(awk '/AWKSIGHPE/ {print$5}' $TEMP'Norm'
            $FLOW.RES)
         LPE=$(awk '/AWKSIGLPE/ {print$5}' $TEMP'Norm'
            $FLOW.RES)
          P1EI=$(awk '/AWKSIGP1EI/ {print$5}' $TEMP'Norm'
            $FLOW.RES)
         P1EO=$(awk '/AWKSIGP1EO/ {print$5}' $TEMP'Norm'
            $FLOW.RES)
          P2EI=$(awk '/AWKSIGP2EI/ {print$5}' $TEMP'Norm'
            $FLOW.RES)
         P2EO=$(awk '/AWKSIGP2EO/ {print$5}' $TEMP'Norm'
            $FLOW.RES)
          P3EI=$(awk '/AWKSIGP3EI/ {print$5}' $TEMP'Norm'
            $FLOW.RES)
         P3EO=$(awk '/AWKSIGP3EO/ {print$5}' $TEMP'Norm'
            $FLOW.RES)
          echo $TEMPIN $ENDFLOW $TEMPOUT $HPEOUT $LPEOUT
            $P1EI $P1EO $P2EI $P2EO $P3EI $P3EO >>
            NormResults
         TEMP=$NEWTEMP
       done
    NEWFLOW=$(echo "$FLOW + $RISEFLOW" | bc)
    TEMPOUT=$(awk '/AWKSIGTEMPOUT/ {print$2}' $TEMP'Norm'
       $FLOW.RES)
    HPE=$(awk '/AWKSIGHPE/ {print$5}' $TEMP'Norm'$FLOW.RES
       )
    LPE=$(awk '/AWKSIGLPE/ {print$5}' $TEMP'Norm'$FLOW.RES
       )
```

```
        P1EI=$(awk '/AWKSIGP1EI/ {print$5}' $TEMP'Norm'$FLOW.
            RES)
        P1EO=$(awk '/AWKSIGP1EO/ {print$5}' $TEMP'Norm'$FLOW.
            RES)
        P2EI=$(awk '/AWKSIGP2EI/ {print$5}' $TEMP'Norm'$FLOW.
            RES)
        P2EO=$(awk '/AWKSIGP2EO/ {print$5}' $TEMP'Norm'$FLOW.
            RES)
        P3EI=$(awk '/AWKSIGP3EI/ {print$5}' $TEMP'Norm'$FLOW.
            RES)
        P3EO=$(awk '/AWKSIGP3EO/ {print$5}' $TEMP'Norm'$FLOW.
            RES)
        echo $TEMP $FLOW $TEMPOUT $HPE $LPE $P1EI $P1EO $P2EI
            $P2EO $P3EI $P3EO >> NormResults
        FLOW="$NEWFLOW"
    done
echo "Finished"
```

# VITA

| | |
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