Changes were made to the *Evaporation Trends in South Florida* section on pages 2B-43 through 2B-55 on November 22, 2022.

Chapter 2B: Water and Climate Resilience Metrics

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BACKGROUND

This chapter introduces the water and climate resilience metrics being established by the South Florida Water Management District (SFWMD or District) Resiliency Team. The District Resiliency Team leads this effort in collaboration with an internal workgroup consisting of technical leads from multiple District bureaus, including Hydrology and Hydraulics, Water Supply, Water Quality, Applied Sciences, Information Technology, and Geospatial Services, with contributions from other SFWMD staff.

The water and climate resilience metrics effort was initiated in June 2020 with the goal of tracking and documenting trends and shifts in water and climate data monitored by the SFWMD. This effort supports the SFWMD's resiliency goals of ensuring ecosystem restoration, flood protection, and water supply mission elements while accounting for current and future climate conditions. Furthermore, the SFWMD Resiliency Team is collaborating with local, state, and federal agencies in South Florida.

Although many aspects of climate change are still uncertain, the SFWMD is assessing the current and predicted impacts of climate change on South Florida's ecosystems and water resources. The combination of changes to climate variables (e.g., rainfall, temperature, evapotranspiration) and their consequential impacts (e.g., sea level rise, saltwater intrusion, groundwater elevation) could substantially alter water management system operations and infrastructure needs.

To ensure the SFWMD's resilience planning and projects are founded on the best available science, the Resiliency Team and internal workgroup have prioritized the analysis of District-managed water and climate data. The analysis of trends and shifts in observed data, along with the collective experience and best professional judgment of SFWMD technical staff, serves as the foundation for more robust infrastructure planning and operational decisions. The Resiliency Team uses the analysis results to evaluate sea level rise and extreme events, including flood and drought, under current and future climate conditions, and how they affect water resources management.

As part of the SFWMD's communication and public engagement priorities, the Resiliency Team provides continued information about the water and climate resilience metrics to stakeholders, the general public, and partner agencies, while also supporting local resilience strategies. The ultimate purpose of the Resiliency Team's efforts is to ensure water resource and ecosystem resilience into the future.

INTRODUCTION

As part of its resilience initiatives, the SFWMD developed a set of water and climate resilience metrics to track and document shifts and trends in District-monitored water and climate data. **Table 2B-1** summarizes key aspects of the water and climate resilience metrics. Each metric is categorized as a climate metric or a resilience metric. Climate metrics are the primary drivers of observed changes in climate conditions that impact the hydrological cycle. Resilience metrics are the observed consequences of changing climate conditions and can be directly or indirectly managed or mitigated through operation of the water management system or implementation of adaptation strategies. Additional findings of the initial trends observed from historical data, along with a more detailed description of the adopted approaches to data analysis, are reported in *The Water and Climate Resilie nce Metrics Phase I: Long-term Observed Trends Final Report* (SFWMD 2021).

With the goal of continuously advancing water and climate data analysis and developing a better understanding of the extent by which these observations may be influenced by climate change and other determinant factors, this chapter has been introduced in the *2022 South Florida Environmental Report* (SFER). This first-year chapter contains additional technical analysis and scientific considerations for the following seven water and climate resilience metrics:

- Rainfall
- Evapotranspiration
- Tidal Water Levels at Coastal Structures
- Water Quality
  - Temperature
  - Dissolved oxygen
  - Specific conductance
  - pH

The following sections describe the main findings of these seven metrics and include discussion on influencing factors, recommended improvements to data monitoring, and additional analyses that could help differentiate influences from climate and non-climate factors. Assessment of these metrics is an important step toward planning for the future. Observed trends in long-term water and climate data demonstrate the implications of a changing climate and inform water management and resiliency priorities.

Table 2B-1. Summary of the water and climate Resilience metrics

Metric	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Rainfall	Climate Metric	Rainfall intensity, duration, extension, and frequency cannot be controlled by the District.	Rainfall is used to estimate the water budget, forecast inflows to the system, plan the management of water resources, and determine water management operations.	Annual trend analysis provides insights about average rainfall. Regional trend analyses on daily maxima, daily minima, and peaks over/under thresholds for selected return frequencies and durations are necessary to fully understand the impacts of rainfall on flooding, water supply, and ecosystem restoration.
Evapotranspiration	Climate Metric	Evapotranspiration cannot be controlled by the District.	Together with rainfall, evapotranspiration drives the hydrologic cycle and water budget.	Evapotranspiration is projected to increase in a warming climate and impact seasonal patterns and trends in precipitation. Increasing evapotranspiration might contribute to increasing demand on the water management system (due to associated canal levels, flooding, etc.). During drought events, evapotranspiration might deplete already limited water supplies. Evapotranspiration data trends inform District operation and planning efforts.
Tidal Elevations at Coastal Structures	Climate Metric	Tidal elevations at coastal structures can partially be controlled by the District. Tidal elevations at coastal structures impacted by the activities of other jurisdictional agencies cannot be controlled by the District.	Headwater (freshwater canal levels) and tailwater (tidal levels) elevations are the drivers of stormwater discharge operations. Coastal structures must be opened to release stormwater as part of flood control operations and closed during high tailwater conditions to prevent saltwater intrusion inland.	Long-term data trends, combined with flood level of service performance data, inform the District on the limitations and deficiencies of flood control infrastructure. This information provides guidance on the priority investments where resources are most needed for adaptation planning and mitigation strategies. For instance, coastal structures are a vital component of the prevention strategy for the Biscayne aquifer minimum flow and minimum water level (MFL).

Table 2B-1. Continued.

Metric	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
High Tide Events	Climate Metric	Tidal stages and high tide events cannot be controlled by the District.	High tide events represent extreme values of the tidal stages used to assess trends in sea level rise and identify potential flooding hazards, risks to water supply, and impacts to structural design standards.	Long-term data trends in tidal stages and high tide events and level of service performance inform the District on the limitations and deficiencies of natural and structural assets. This information provides guidance on where the District might allocate resources for adaption strategies and planning.
Groundwater Levels/ Elevations/Stages	Resilience Metric	Groundwater levels can partially be controlled by the District. In urban areas, water levels can be manipulated in canal systems. Higher sea levels that increase hydrostatic pressure and impact groundwater cannot be controlled by the District.	Groundwater level data are used to monitor water supply, as inputs to surface water and groundwater modeling, for the establishment of MFL criteria, and for compliance and permitting reviews. Groundwater levels at key sites are evaluated weekly as indicators of potential water shortages.	Trends in groundwater level data inform a broader understanding of the impacts of sea level rise in terms of timing and extent of groundwater stages during the wet season, threats to water supply, the need for additional monitoring, urgency of mitigation strategies, and places the need for communicating risks through visualization at the forefront of resilience planning. Data are available for long-term groundwater level trends for the surficial, intermediate, and Floridan aquifer systems. Data also are available through the United States Geological Survey (USGS) Water Level and Salinity Analysis Mapper online tools, showing trends over the past 20 years.
Saltwater Intrusion/ Saltwater Interface – Chloride Levels	Resilience Metric	The saltwater interface can partially be controlled by the District. The water management system has limited/variable capacity to maintain higher elevations in inland canal systems to stall saltwater intrusion.	Analytical chloride data are used to monitor freshwater aquifers and map the inland movement of saltwater.	Historical and projected movement of saltwater inland, and current water use data and future water use projections, identifies vulnerabilities to public water supply utilities. Saltwater intrusion has a large impact in water use permitting as an increased number of wells/wellfields/utilities vulnerable to loss of supply or reduced availability during droughts are identified to be at risk or of concern.

Table 2B-1. Continued.

Metric	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Minimum Flows and Minimum Water Levels (MFLs) – Exceedances/ Violations	Resilience Metric	MFLs are defined as the minimum flows or minimum water levels, adopted by the District Governing Board pursuant to Sections 373.042 and 373.0421, Florida Statutes, at which further withdrawals would be significantly harmful to the water resources or ecology of the area. The District monitors exceedances and violations of MFLs within each of its five water supply planning areas to identify priority water bodies and develop recovery and prevention strategies. Through water management, operational, and regulatory practices, the District may achieve adequate MFL status.	MFLs identify a range of water levels and/or flows above which water could be permitted for consumptive use and are established to protect water resources from harm that may result from permitted water withdrawals and to safeguard water quantities necessary for ecosystem resilience. Minimum levels have been established for lakes, wetlands, and aquifers. Minimum flows have been set for rivers, streams, and estuaries. Flow and water level data are used to ensure that water bodies are in compliance with their minimum requirements and to identify the occurrence of exceedances and violations.	MFL data identify threats to water supply sources and ecosystems, and the need to develop recovery or prevention strategies in cases where a water body currently does not or will not meet MFLs that are adopted. The MFL program supports the District's regional water supply planning process, the consumptive use permitting program, and the environmental resource permitting program. MFLs are used in decision making and affect permit applications as water uses cannot be permitted if they cause any MFL to be violated. MFL data are also used in assessments of water supply sources and declarations of water shortages.
Flooding Events	Resilience Metric	The District has the capacity and mission to control and protect communities from flooding events through effective operation and maintenance of its water management system and through infrastructure investments to implement flood adaptation and mitigation strategies.	Flood data are used to assess and monitor (pattern, extent, and depth) flooding events that occur after storms, heavy rainfall, and extreme tides.	Comprehensive analysis of flood event data identifies where investments and reinforcements in flood control systems are necessary. Formally tracking trends of reported flooding and comparing to other trends, such as rainfall, will help determine if observed changes are part of a long-term trend or represent a shift in climate.

Table 2B-1. Continued.

Metric	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Water Temperature	Resilience Metric	The District can indirectly control water temperature in the system through operational and management decisions, and through coordination with state and local agencies as part of basin management action plan (BMAP) implementation.	Water temperature is used to monitor water supply and aquatic and marine ecosystems.	Water temperature informs effective water management practices and helps assess restoration efforts. Resilience-driven interventions may reduce the impacts of poor water quality in critical areas and help identify areas that require implementation of restoration strategies.
Dissolved Oxygen	Resilience Metric	The District can indirectly control dissolved oxygen in the system through operational and management decisions, and through coordination with state and local agencies as part of BMAP implementation.	Dissolved oxygen is used to monitor water supply sources and availability for uptake in aquatic and marine ecosystems.	Dissolved oxygen informs effective water management practices and helps assess restoration efforts. Resilience-driven interventions may reduce the impacts of poor water quality in critical areas and help identify areas that require implementation of restoration strategies.
pH	Resilience Metric	The District can indirectly control pH in the system through operational and management decisions, and through coordination with state and local agencies as part of BMAP implementation.	Water pH is an indicator of the chemical state and changes within a water body. Water pH is used to monitor water supply sources and aquatic and marine ecosystems.	Water pH informs effective water management practices and helps assess restoration efforts. Resilience-driven interventions may reduce the impacts of poor water quality in critical areas and help identify areas that require implementation of restoration strategies.

Table 2B-1. Continued.

Metric	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Specific Conductance	Resilience Metric	The District can indirectly control specific conductance in the system through operational and management decisions, and through coordination with state and local agencies as part of BMAP implementation.	Specific conductance is used to monitor water supply sources and aquatic and marine ecosystems. Analyses of specific conductance allow for the removal of altering variables and accounts for fluctuations in water temperature. High specific conductance values indicate a high amount of substances and chemicals dissolved in water. Conductivity may also be used as a conservative tracer to monitor the movement of water and contamination.	Specific conductance informs effective water management practices that promote resilience and helps assess restoration efforts. This metric identifies critical areas that require implementation of restoration strategies.
Estuarine Inland Migration – Everglades	Resilience Metric	The District can partially control the extent of estuarine inland migration through water management by maintaining higher freshwater levels inland.	Estuarine inland migration is used to monitor shifts in species composition in freshwater marshes. Trends in estuarine inland migration provide insights to the impacts of sea level rise in coastal areas and the Everglades.	Estuarine inland migration informs the District on the efficacy of water management practices in creating favorable conditions for marshes and mangroves to keep up with sea level rise. Information on estuarine inland migration provides guidance to align/plan practices to adapt and mitigate for sea level rise and other climate change impacts.

Table 2B-1. Continued.

Metric	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Soil Subsidence	Resilience Metric	The District can partially control the extent of soil subsidence through water management by maintaining higher freshwater levels inland and improving the physical and biological processes that promote accretion and subsurface root and peat accumulation.	Soil subsidence, or expansion, is the result of elevation change minus accretion rate, incorporating both surface and subsurface processes. The District has been studying mangrove environments in northeastern Florida Bay and Taylor River to determine soil subsidence at non-flooded, frequently flooded, and permanently flooded areas. The main objective of the study is to determine whether mangrove soil surface elevation can keep pace with increasing sea level rise.	The rate of soil subsidence informs the District on the effectiveness and benefits of Everglades restoration. This information guides water management practices that aim to uplift land to reduce the impacts of sea level rise and promote the seaward migration of coastlines (i.e., increasing freshwater input into the salinity transition zone of Taylor Slough).
Salinity in the Everglades	Resilience Metric	The District can partially control Salinity through water management by maintaining higher freshwater levels inland.	Salinity is used to monitor water quality and evaluate the effectiveness of restoration strategies.	Salinity informs the District on the effectiveness and benefits of Everglades restoration and guides water management practices.

RAINFALL TRENDS IN SOUTH FLORIDA

BACKGROUND

Rainfall is the main driver of hydrology and water management in South Florida. While other chapters of the SFER detail rainfall volumes for the purposes of monitoring and reporting, this chapter introduces the analysis of historical rainfall data as part of the water and climate resilience metrics effort. The analysis identifies the frequency and long-term trends in available historical rainfall data. Rainfall is a key metric in the context of resilience to understand the influence of climate factors on observed trends and current conditions. This section presents the initial findings of the analysis and the validity of the observed trends. The analysis covers the entire District using model input rainfall data, based on the District gauge network rainfall data sets nearest to each of the District's two-mile by two-mile model grid cells and summarized by the District's 14 operations and maintenance rainfall basins (Ali et al. 2006), as shown in **Figure 2B-1**.

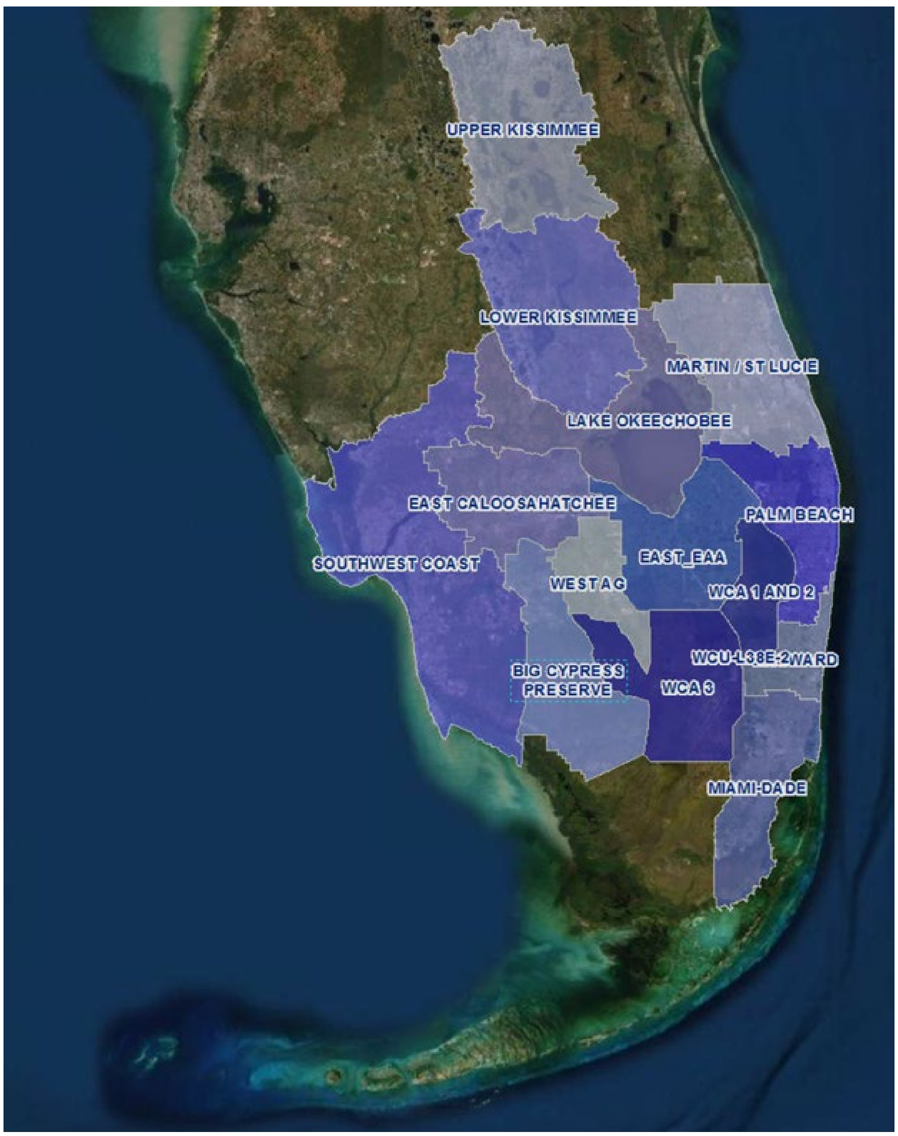

Figure 2B-1. Map of rainfall basins adopted in the rainfall frequency and trend analysis.

In South Florida, annual rainfall exhibits immense climatic variability. South Florida has a humid, semi-tropical climate and a very flat, low topography. Rainfall amounts and seasonal rainfall patterns vary across the state because rainfall is highly influenced by the oceans surrounding the Florida peninsula and the large lakes within it (e.g., Lake Okeechobee). The intense sunlight Florida receives year-round heats the land surface, forming convective storms over cities and natural areas when sea breezes from both coasts move inland. Each year, tropical storms and hurricanes bring heavy rainfall to the region. South Florida's climate is divided into three distinct seasons, based on the amount of rainfall received throughout the year (**Table 2B-2**) (Ali and Abtew 1999). Long-term averages indicate South Florida has an annual rainfall of 52 to 53 inches, and three-quarters of it occurs during the wet season and transitional months.

Table 2B-2. Seasonal rainfall averages in South Florida.

Season	Months	Average Rainfall
Dry	November – April	~2 inches/month
Transitional	May and October	~4 inches/month
Wet	June – September	~7 inches/month

The amount of rain from one year to another can cause the area to swing between extreme dry and extreme wet conditions. Such extreme annual changes in precipitation are a major challenge to water management given the competing water supply demands and uncertain climatic variability constrained by limited system storage capacities and complex flood control requirements. While surface water and groundwater storage compensate for short-term variations, the South Florida hydrologic system does not have a storage buffer to accommodate long-term drought and wet conditions. With increasing temperatures and other climate change observations, there is a need to document and interpret how rainfall patterns are responding now and into the future, and how extreme rainfall events may disrupt the ability of water management systems to provide adequate flood control to local communities. Understanding climatic variability is vitally important to operate the water management system in the short and long term.

RAINFALL DATA AND TREND ANALYSIS

Historical rainfall data are available beginning as early as 1914. Although rainfall data in the early period of record underwent extensive quality assurance (QA)/quality control (QC), substantial data gaps were identified. To ensure consistent rainfall estimates in the region, data gaps in the period of record are often interpolated using available data across the spatial domain or adjusted using areal reduction factors. Filling data gaps is essential to ensure continuous records if subsequent rainfall analyses are performed using selected groups of rainfall stations. This study, however, uses continuous records at each cell of the model grid. Ali et al. (2006) found it more appropriate to directly interpolate rainfall at each model grid cell using only stations with available records, removing the need for gap filling and thereby eliminating gap-filling uncertainty. The spatial interpolation scheme requires sufficient data availability for each day. Ali et al. (2006) determined 1940 to be an appropriate starting year to ensure sufficient data. A review for the records prior to 1940 found it useful to extend the data back to 1935 to better serve the trend analysis without suffering data scarcity. Therefore, the trend analysis period of record spans 1935 to 2018. Furthermore, Ali et al. (2006) found the results of a frequency analysis on spatially interpolated data at each pixel (as opposed to interpolating frequency estimates calculated for a group of stations with inconsistent gap filling) produced more robust results.

Trend analyses are briefly described below. A detailed statistical approach of each analysis is provided in The Water and Climate Resilience Metrics Phase I: Long-term Observations report (SFWMD 2021) Three types of trend analyses were performed:

1. Monthly, seasonal, and annual analyses to determine trends in rainfall volume over long durations.
2. One-, three-, and five-day rainfall maxima analyses to determine trends in rainfall extreme events.
3. One-, three-, five-day peak over threshold (POT) analyses to identify extreme values above certain thresholds.

Trend analyses were performed using the Mann-Kendall Tau test with a 95% confidence band around the trend slope for the 14 rainfall basins. A trend is considered significant if a double-sided Z test rejects the null hypothesis that there is no significant trend. All variables tested are assumed to be independently, identically distributed.

Results for average monthly, seasonal, and annual average rainfall trend analyses at each rainfall basin are presented in **Figures 2B-2** through **2B-15**. **Table 2B-3** summarizes the results of the monthly, seasonal, and annual trend analyses. Notably, upward trends in average rainfall were observed in historically wetter months.

Table 2B-3. Results for monthly, seasonal, and annual trend analyses.

Trend Analysis	Observed Trend
January	No significant trend
February	No significant trend
March	No significant trend
April	No significant trend
May (transitional month)	No significant trend
June	No significant trend
July	Downward trend: Miami-Dade, Lake Okeechobee, Upper Kissimmee
August	Upward trend: Big Cypress, East Caloosahatchee, Martin – St. Lucie, SW Coast
September	No significant trend
October (transitional month)	Downward trend: Broward, Miami-Dade, East Agricultural Area, Martin – St. Lucie, Palm Beach, Water Conservation Areas 1, 2 and 3
November	No significant trend
December	No significant trend
Wet Season	Upward trend: East Caloosahatchee, SW Coast Downward trend: East Agricultural Area
Dry Season	Not analyzed
Annual	Downward trend: East Agricultural Area

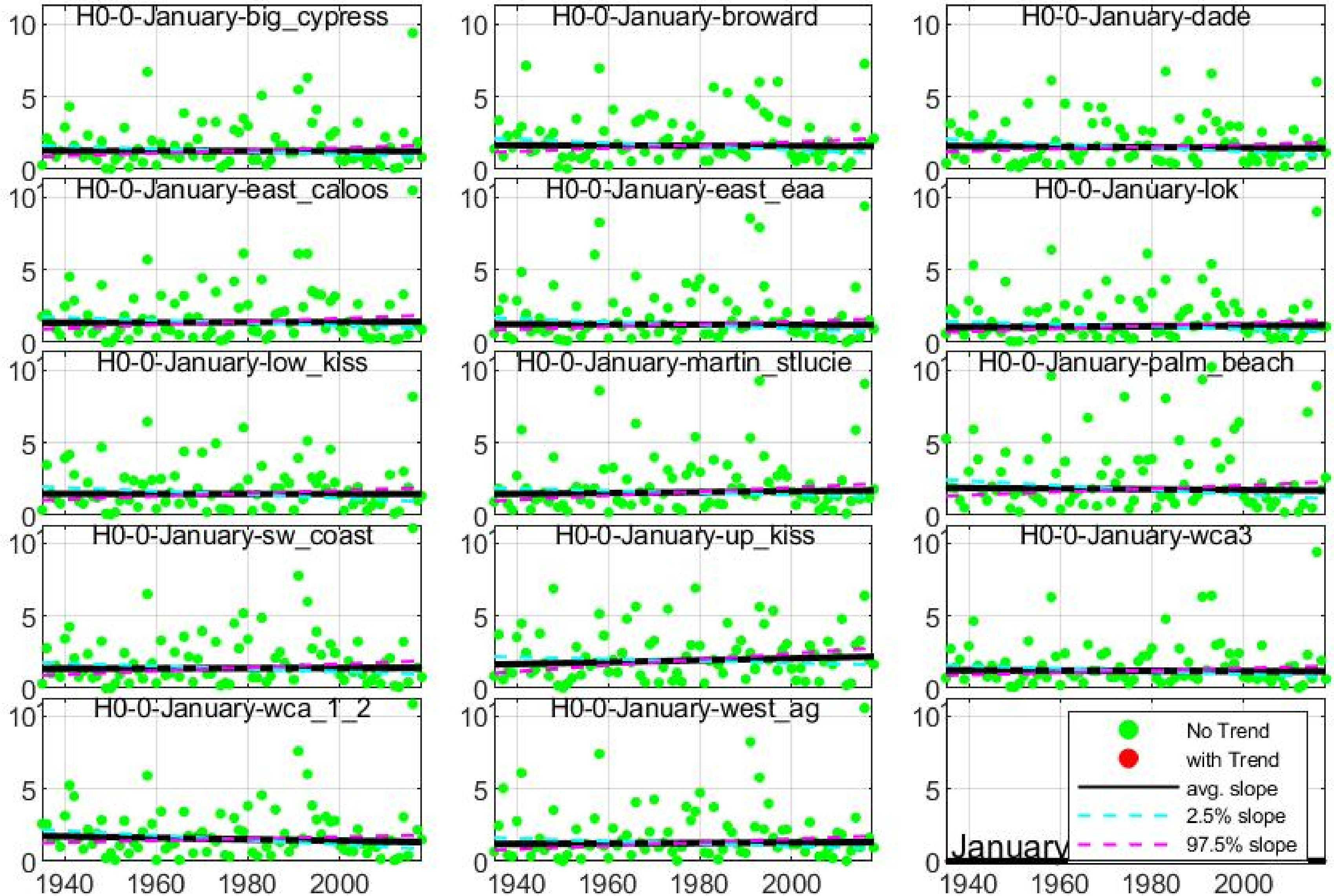

Figure 2B-2. Results of the rainfall trend analysis for January, 1935 to 2018.

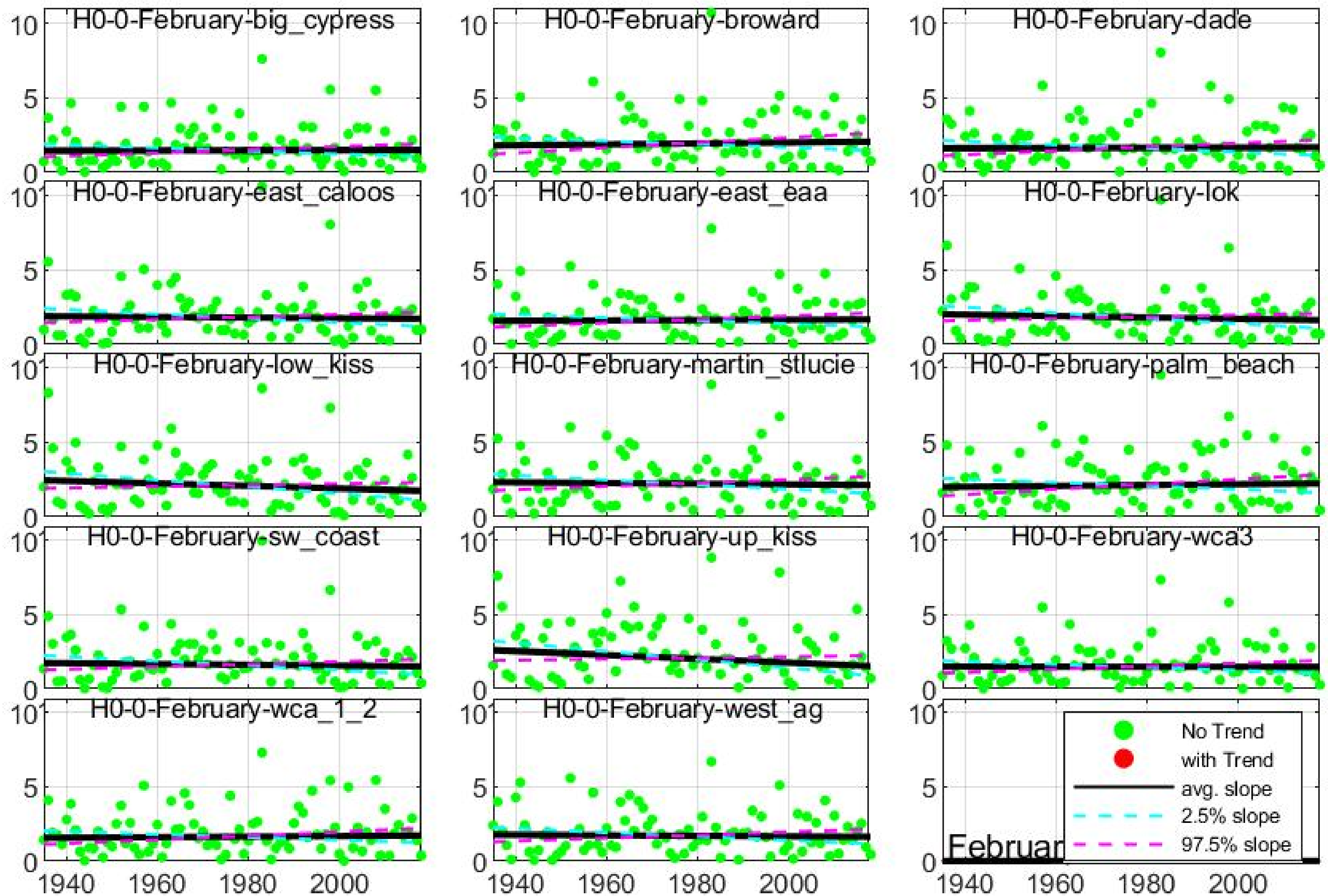

Figure 2B-3. Results of the rainfall trend analysis for February, 1935 to 2018.

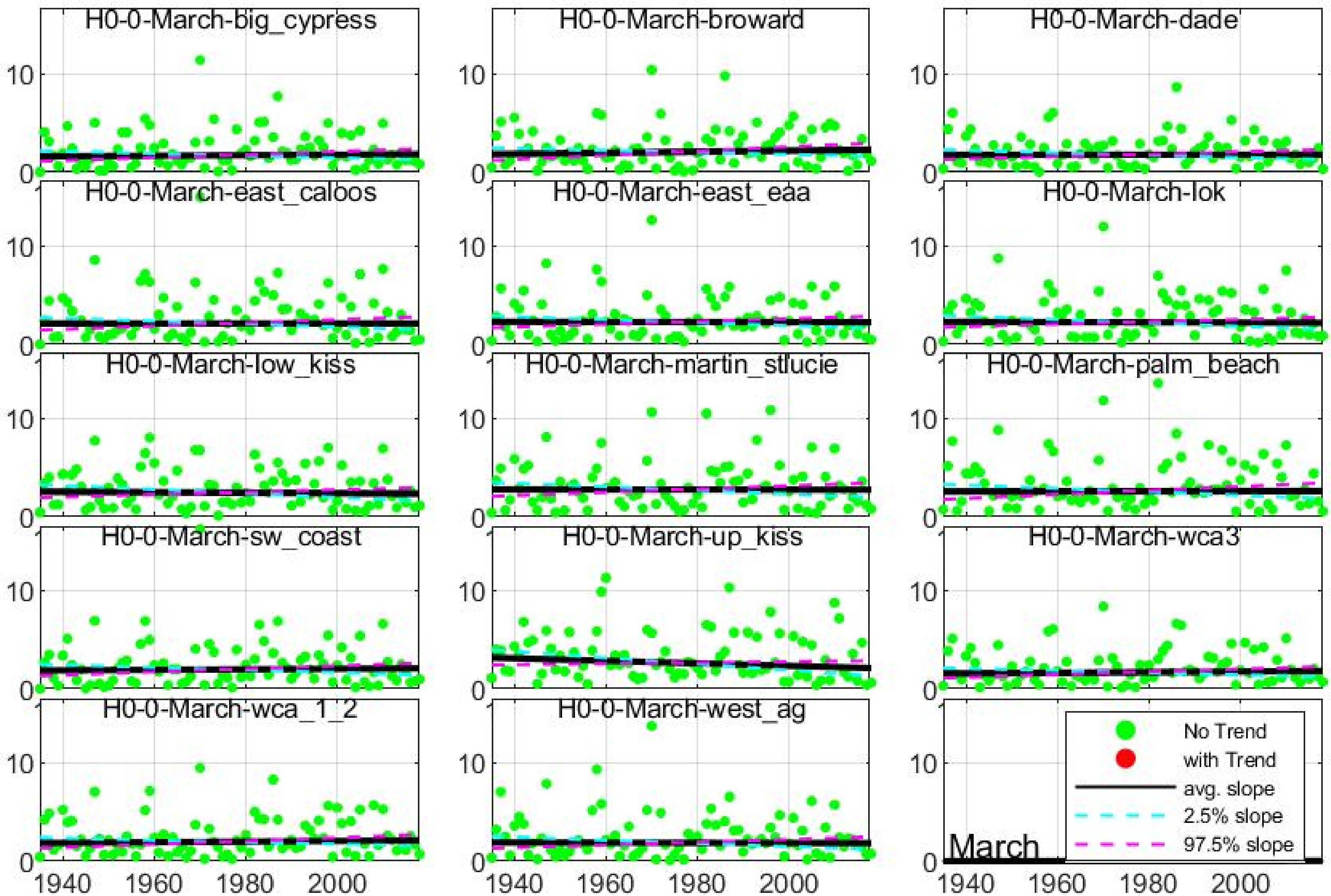

Figure 2B-4. Results of the rainfall trend analysis for March, 1935 to 2018.

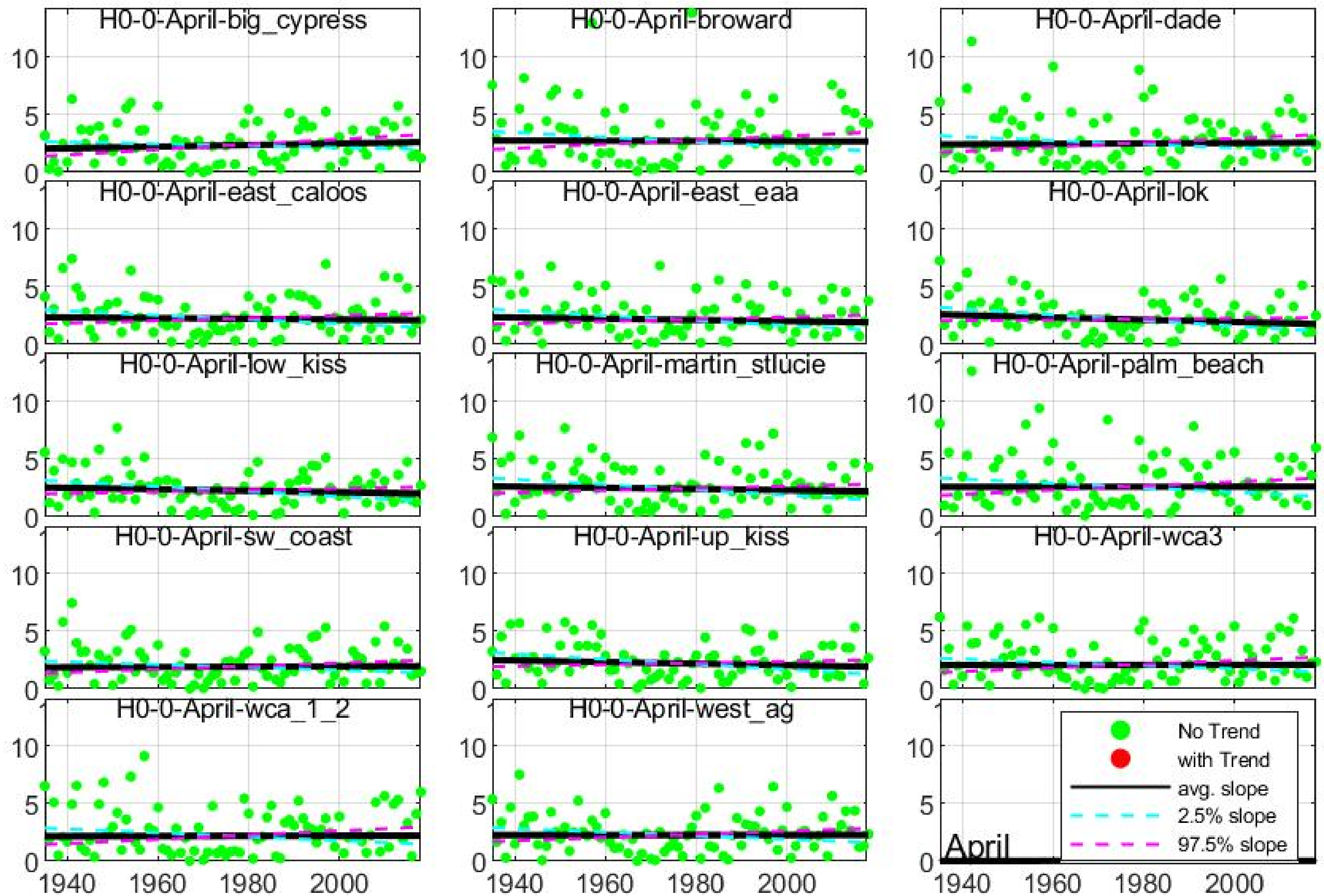

Figure 2B-5. Results of the rainfall trend analysis for April, 1935 to 2018.

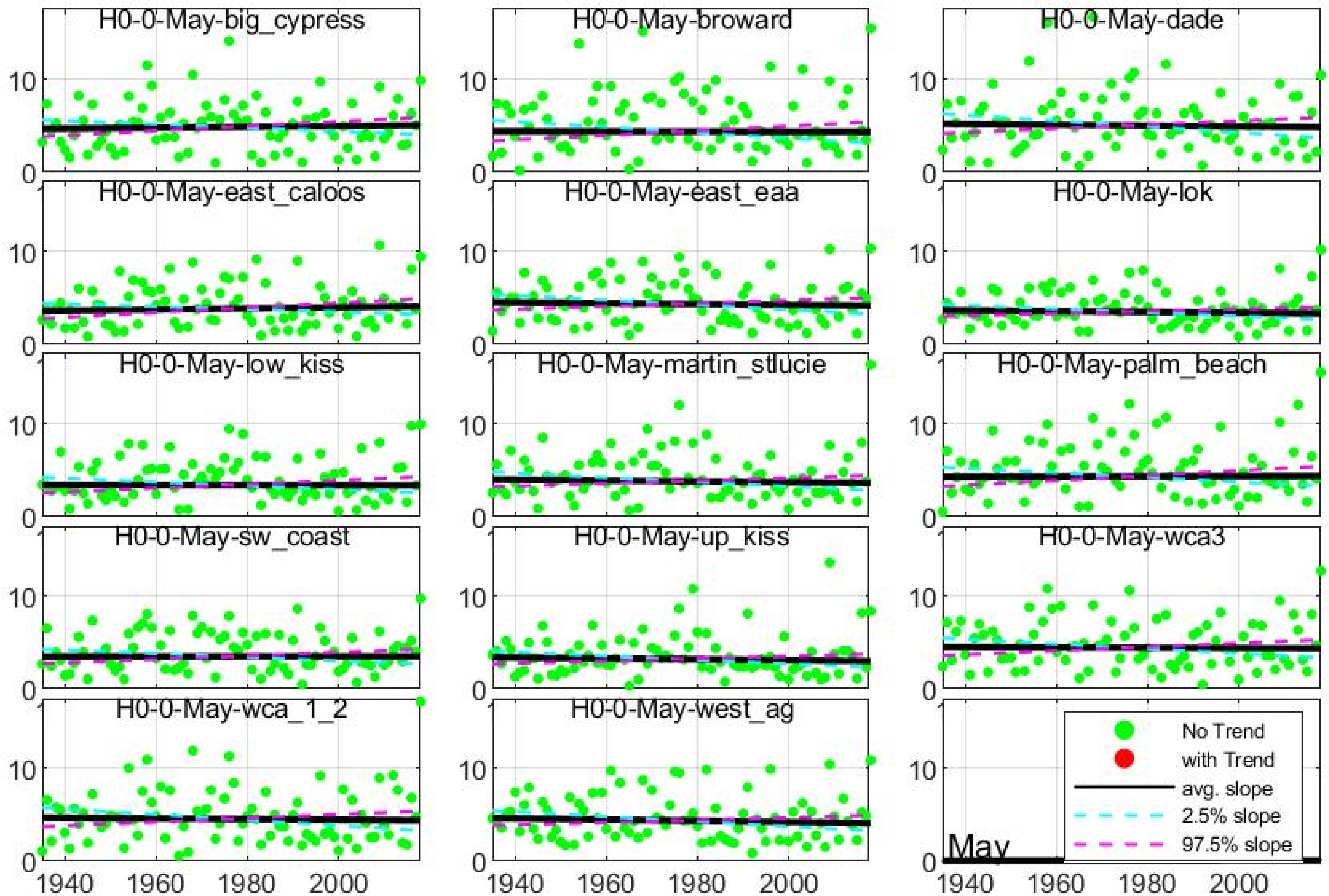

Figure 2B-6. Results of the rainfall trend analysis for May, 1935 to 2018.

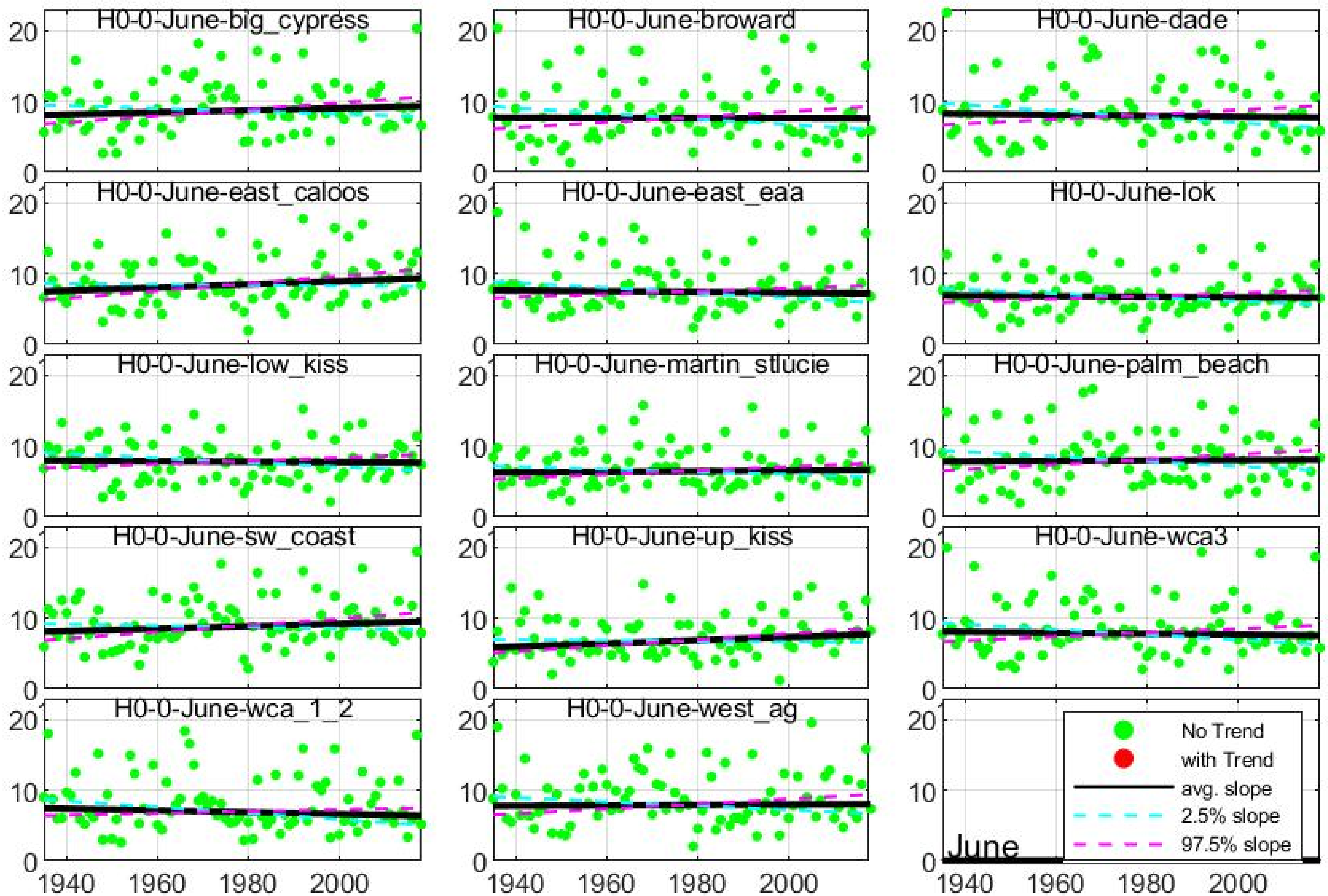

Figure 2B-7. Results of the rainfall trend analysis for June, 1935 to 2018.

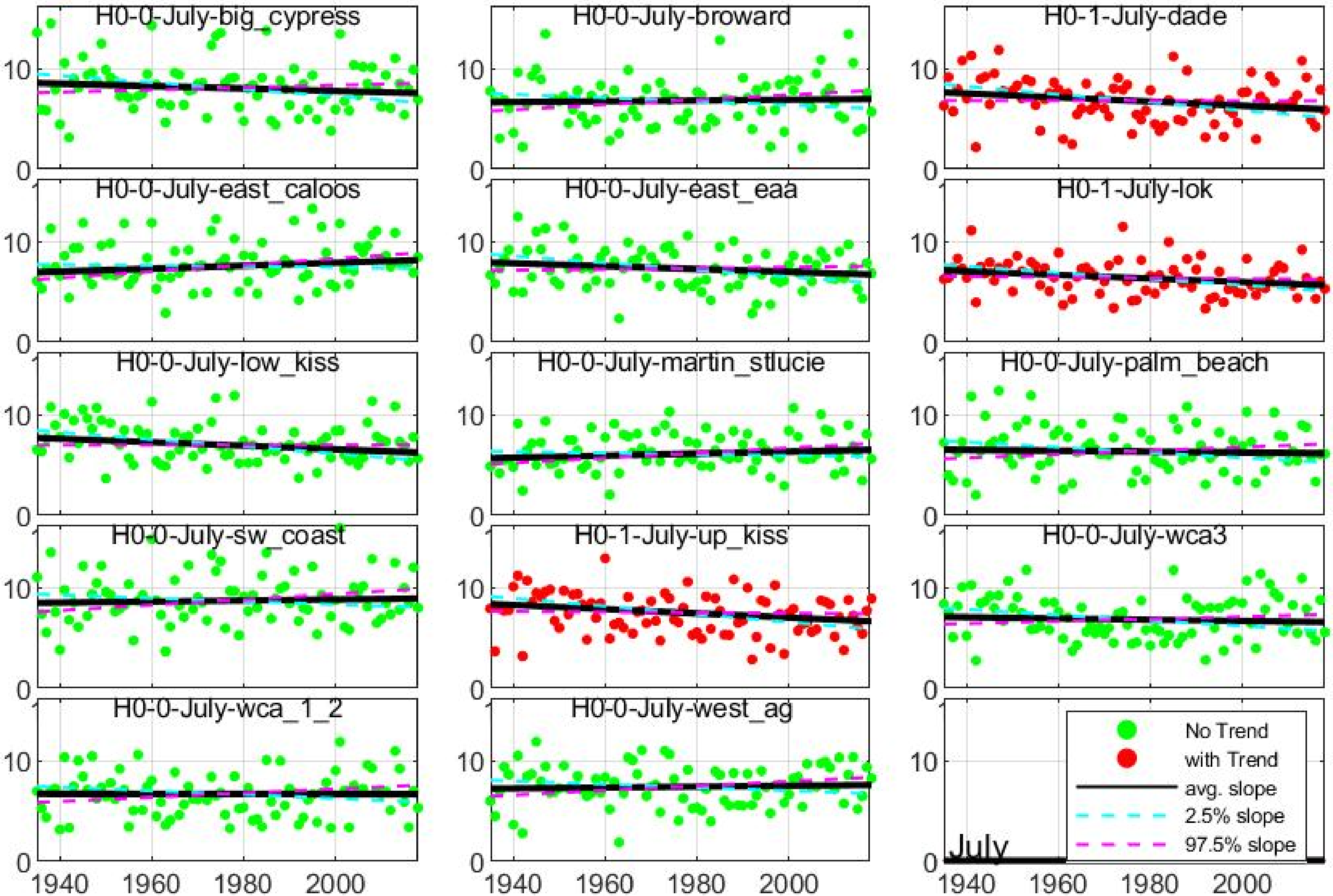

Figure 2B-8. Results of the rainfall trend analysis for July, 1935 to 2018.

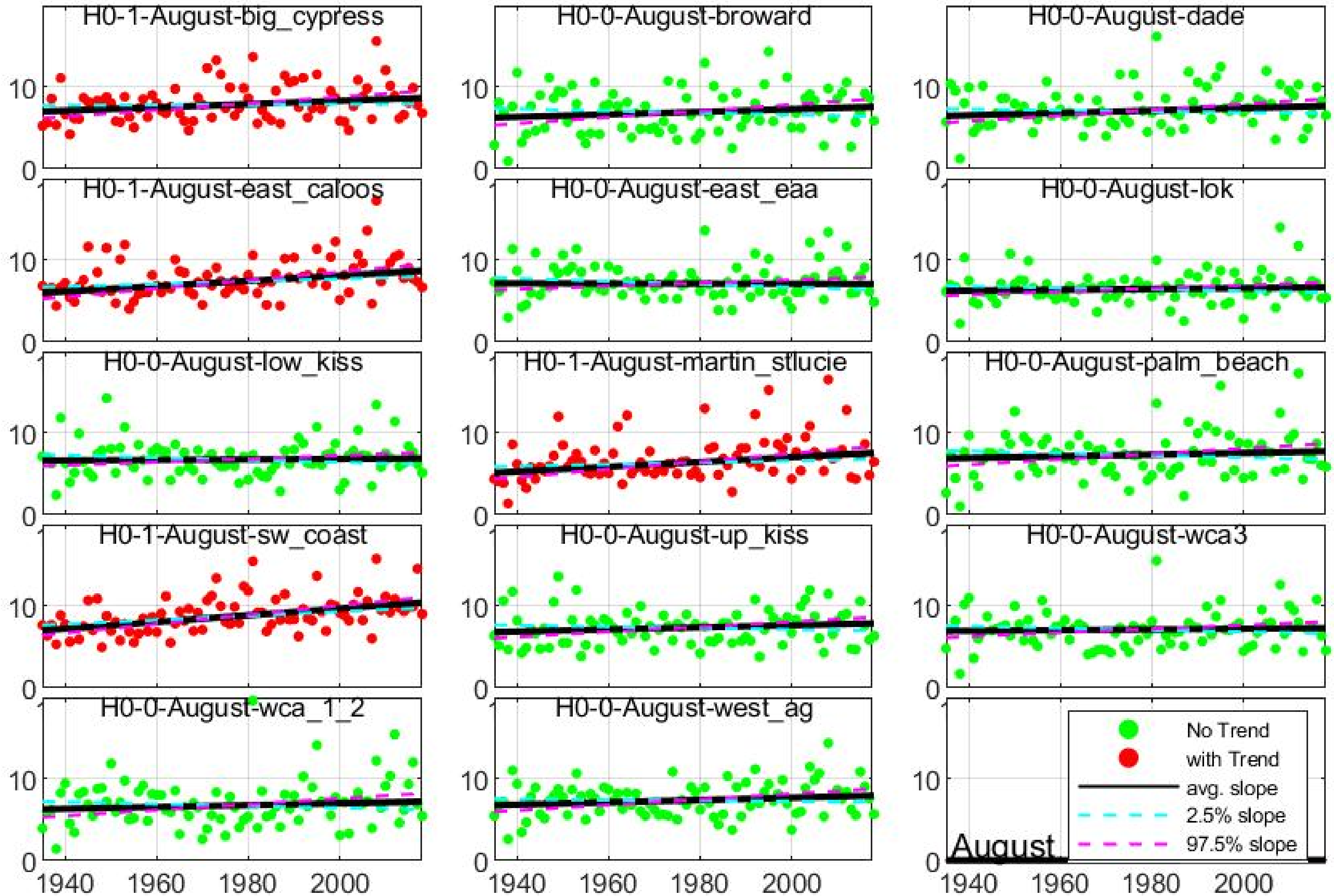

Figure 2B-9. Results of the rainfall trend analysis for August, 1935 to 2018.

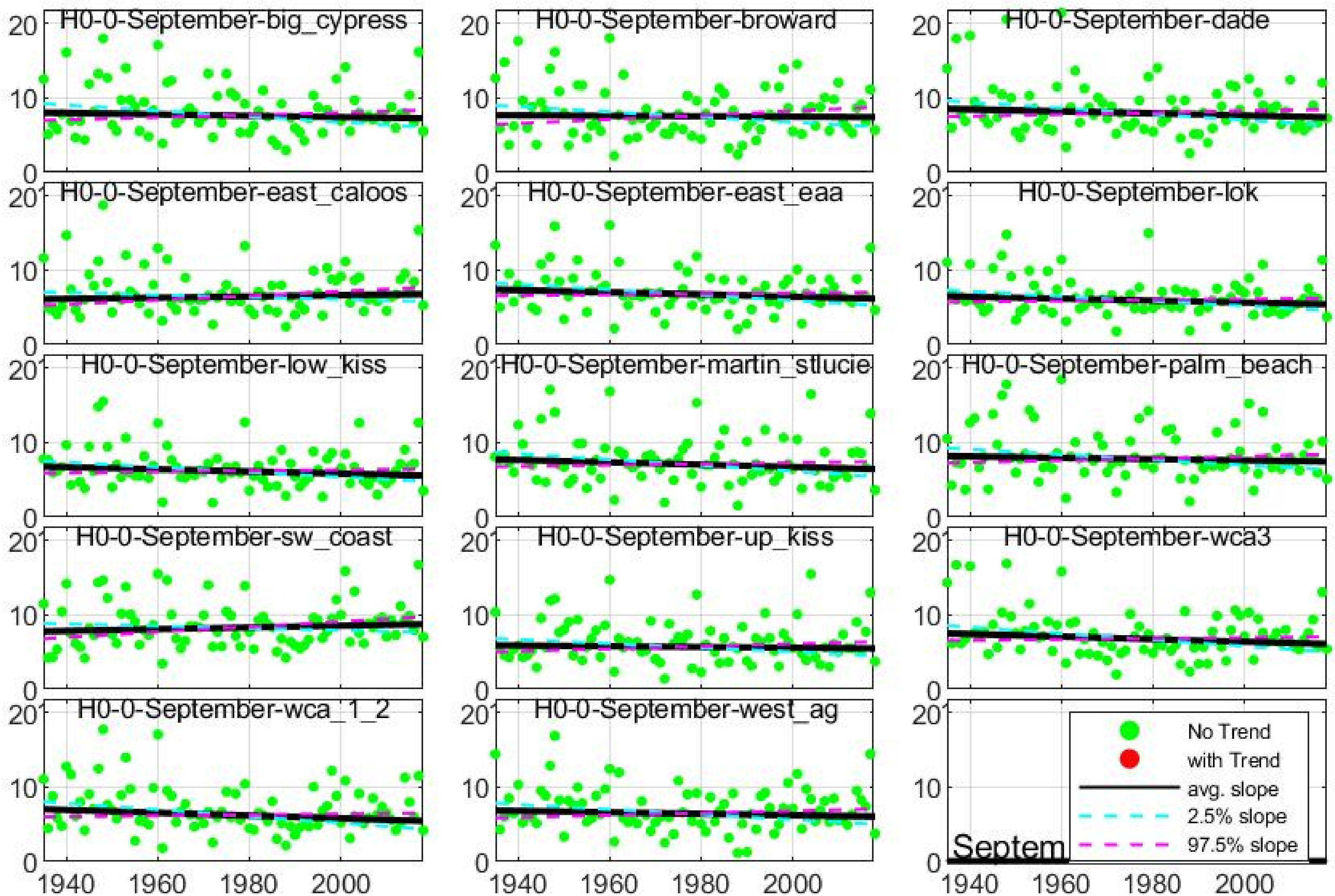

Figure 2B-10. Results of the rainfall trend analysis for September, 1935 to 2018.

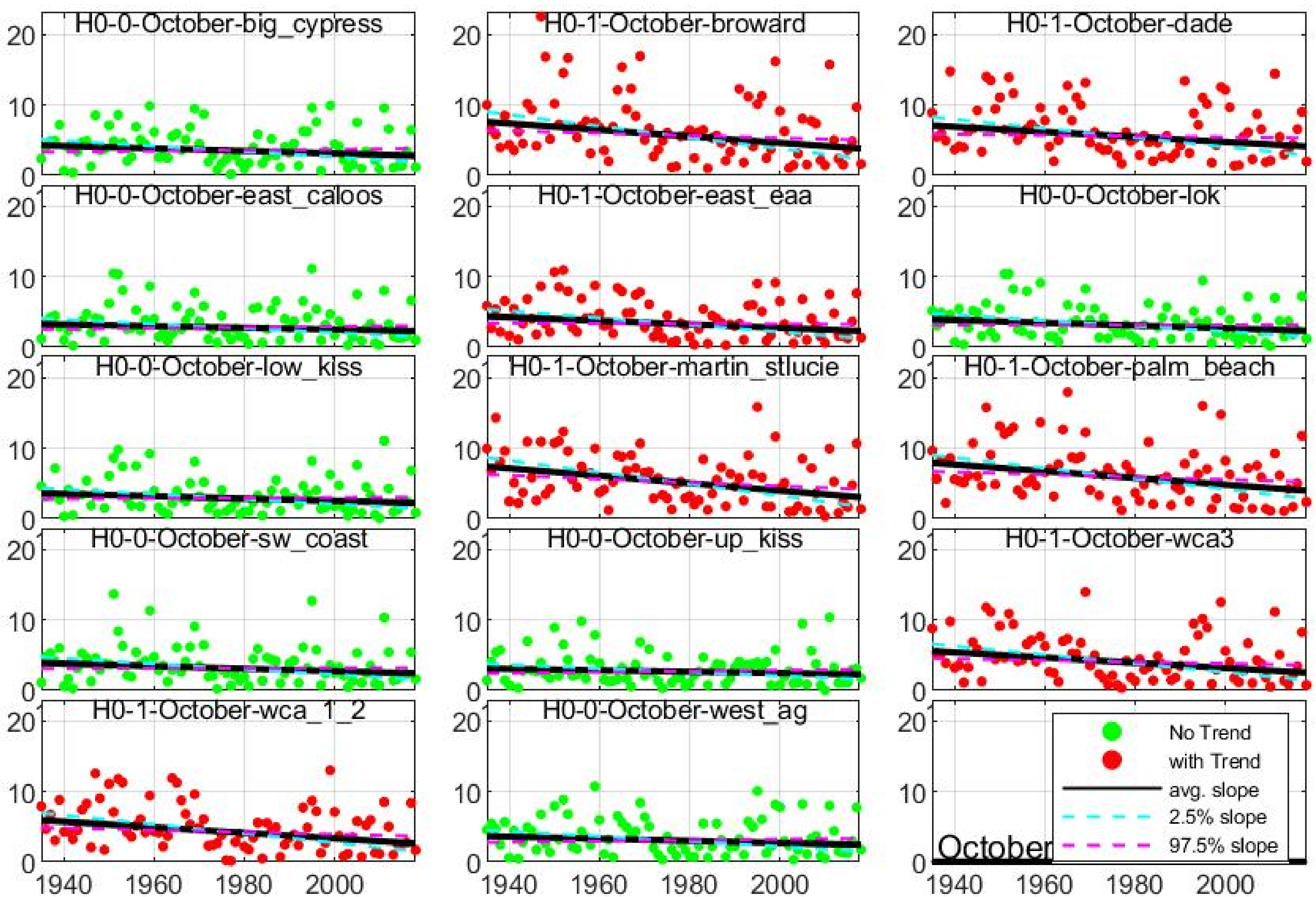

Figure 2B-11. Results of the rainfall trend analysis for October, 1935 to 2018.

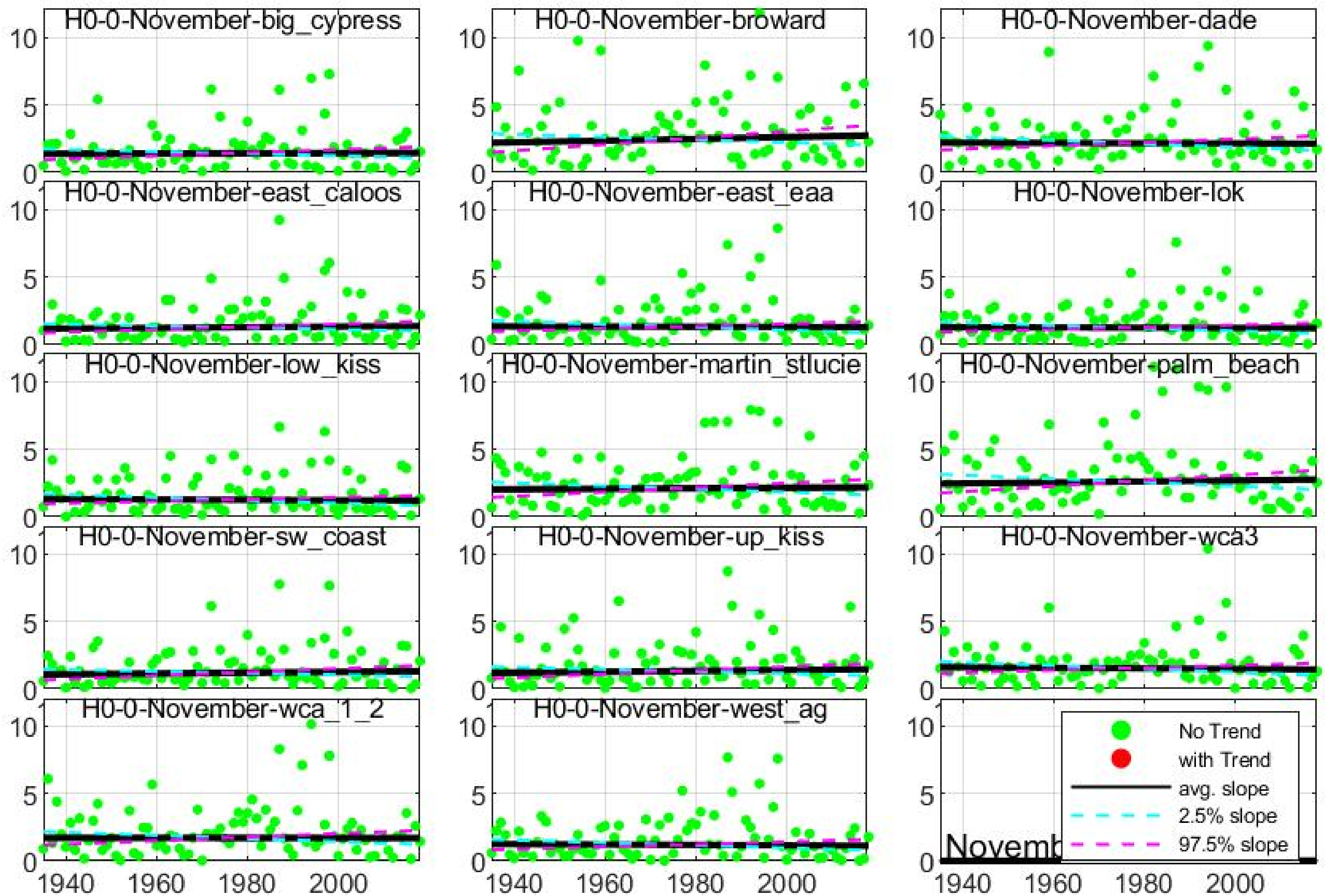

Figure 2B-12. Results of the rainfall trend analysis for November, 1935 to 2018.

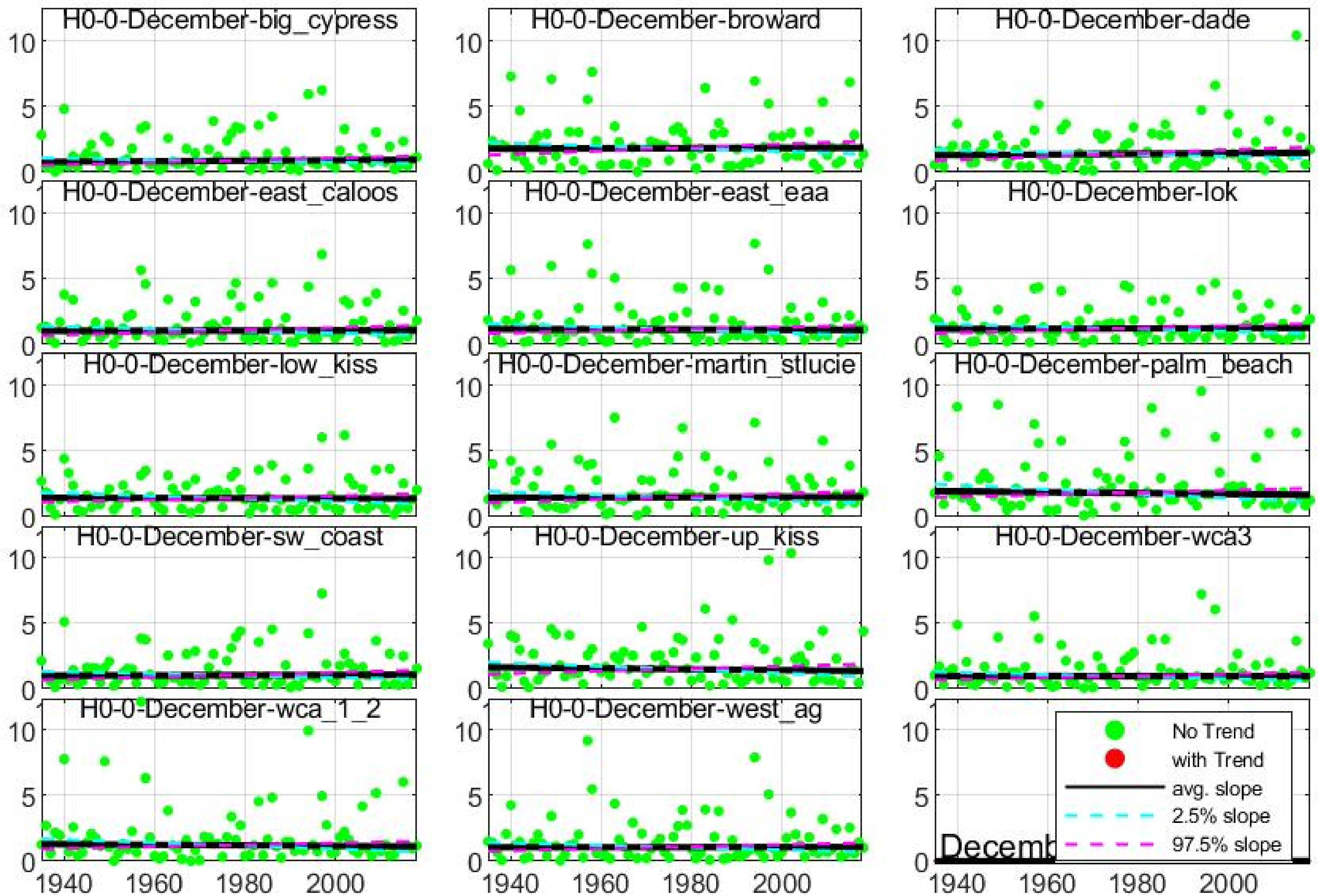

Figure 2B-13. Results of the rainfall trend analysis for December, 1935 to 2018.

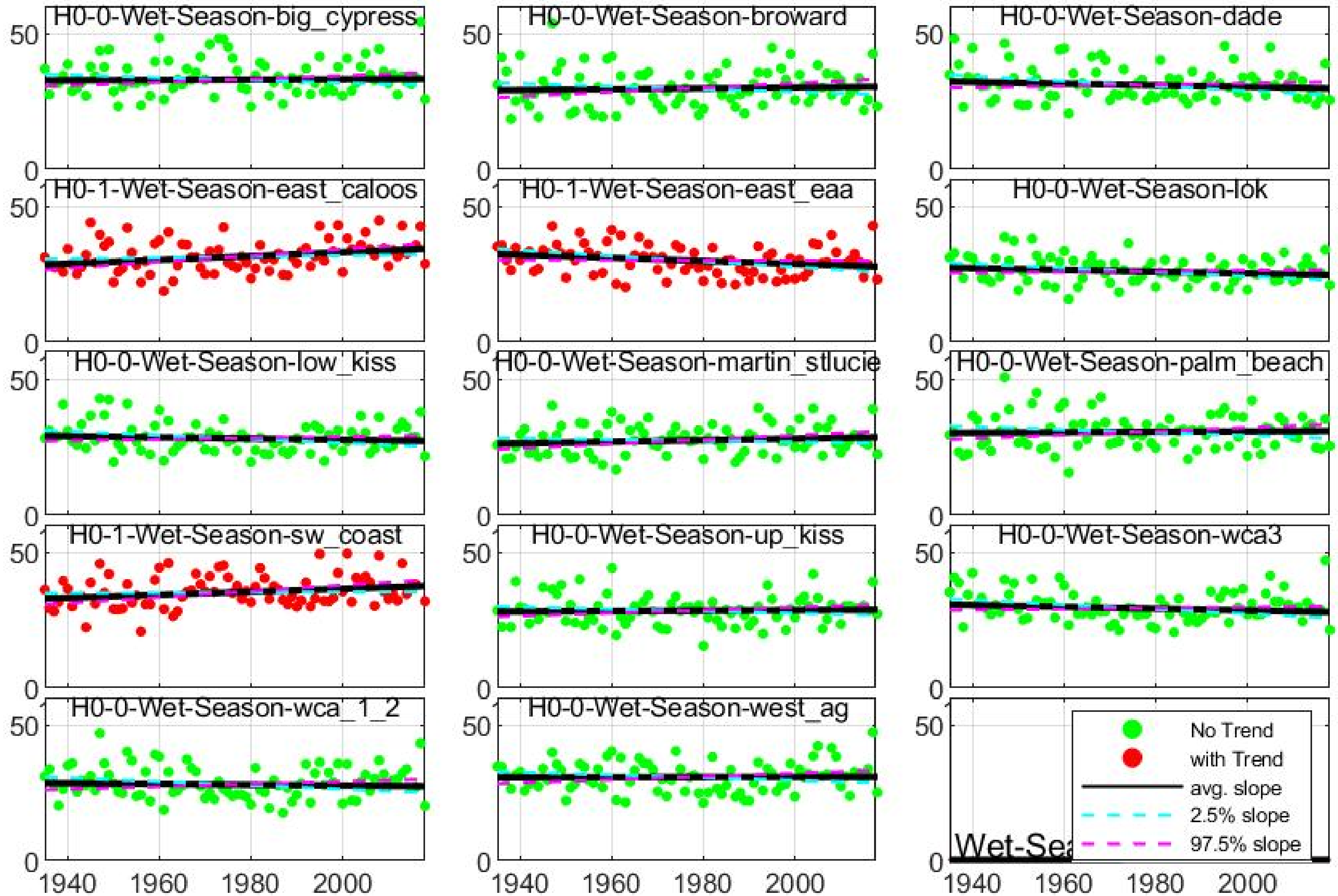

Figure 2B-14. Results of the wet season rainfall trend analysis, 1935 to 2018.

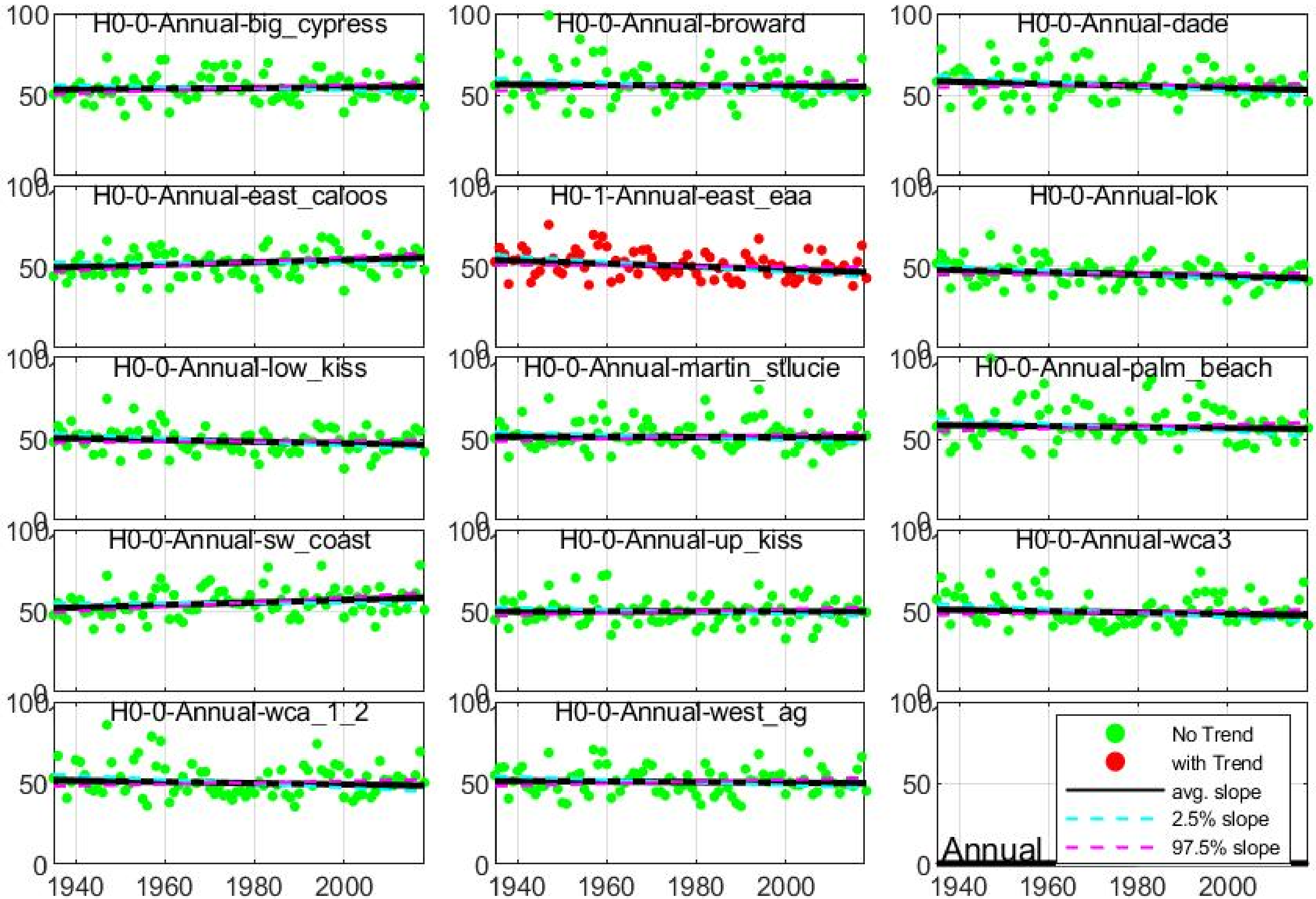

Figure 2B-15. Results of the annual rainfall trend analysis, 1935 to 2018.

In this analysis, a log normal distribution was used for annual 1-, 3-, and 5-day maxima. Frequency results were obtained for 2-, 5-, and 10-year return period data sets (**Figures 2B-16** through **2B-24**). Frequencies of 25-year or greater return periods produced too few data for a meaningful trend analysis. In general, results are sensitive to the frequency and type of distribution being fit. The higher the return period, the fewer the observations, resulting in higher uncertainty in the trend analysis. Results show insignificant trends in most cases, with a few exceptions. **Table 2B-4** summarizes the results of the 1-, 3-, and 5-day rainfall maxima trend analyses.

Table 2B-4. Results of the annual 1-, 3-, and 5-day maxima frequency trend analyses.

Frequency Trend Analysis	Observed Trend
1-day, 2-year	No significant trend
1-day, 5-year	Upward trend: East Agricultural Area, Martin – St. Lucie, Upper Kissimmee
1-day, 10-year	Upward trend: Lake Okeechobee, Upper Kissimmee
3-day, 2-year	No significant trend
3-day, 5-year	No significant trend
3-day, 10-year	No significant trend
5-day, 2-year	No significant trend
5-day, 5-year	Downward trend: Broward
5-day, 10-year	Upward trend: East Caloosahatchee

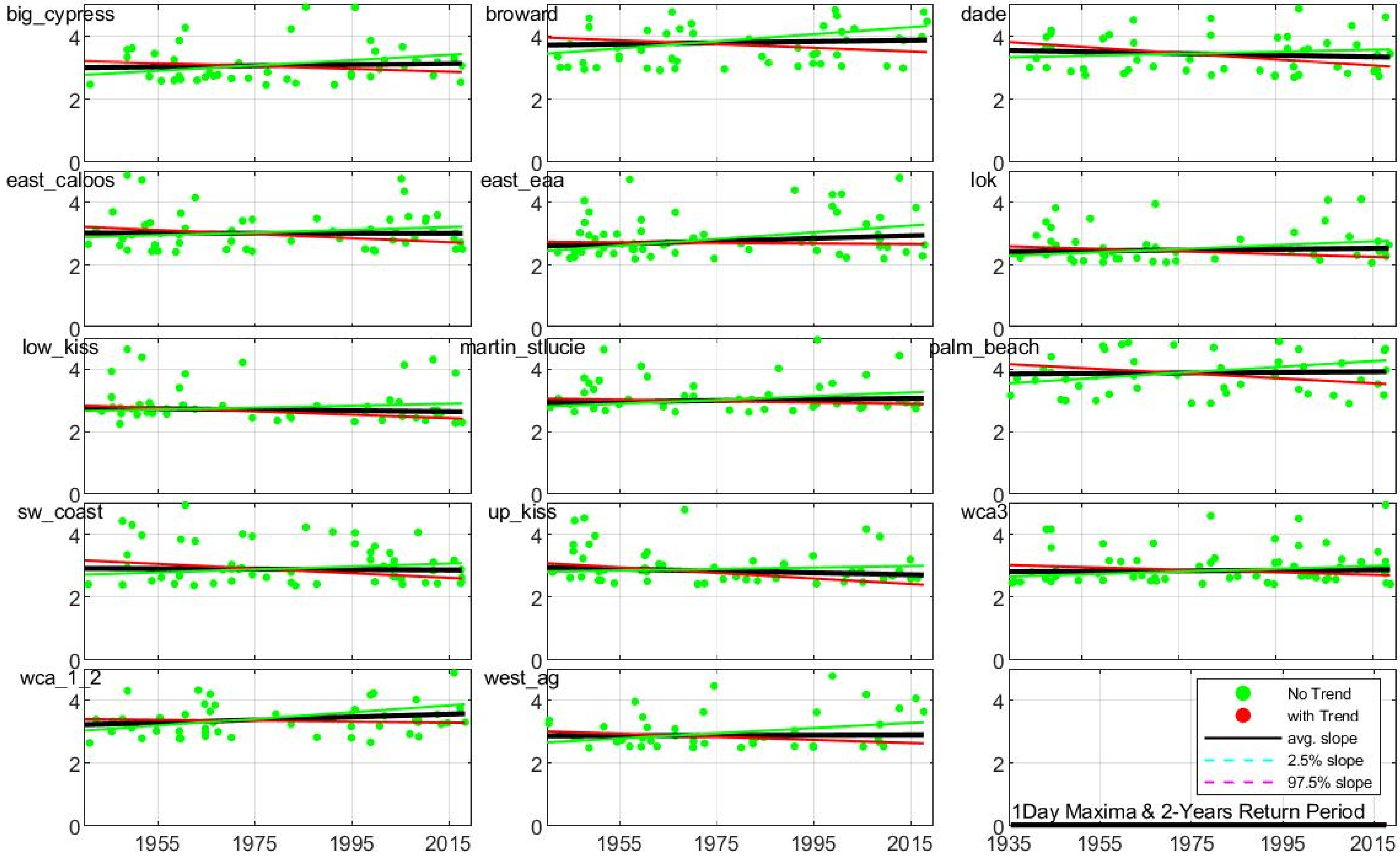

Figure 2B-16. Results of the 1-day maxima, 2-year return frequency trend analysis, 1935 to 2018.

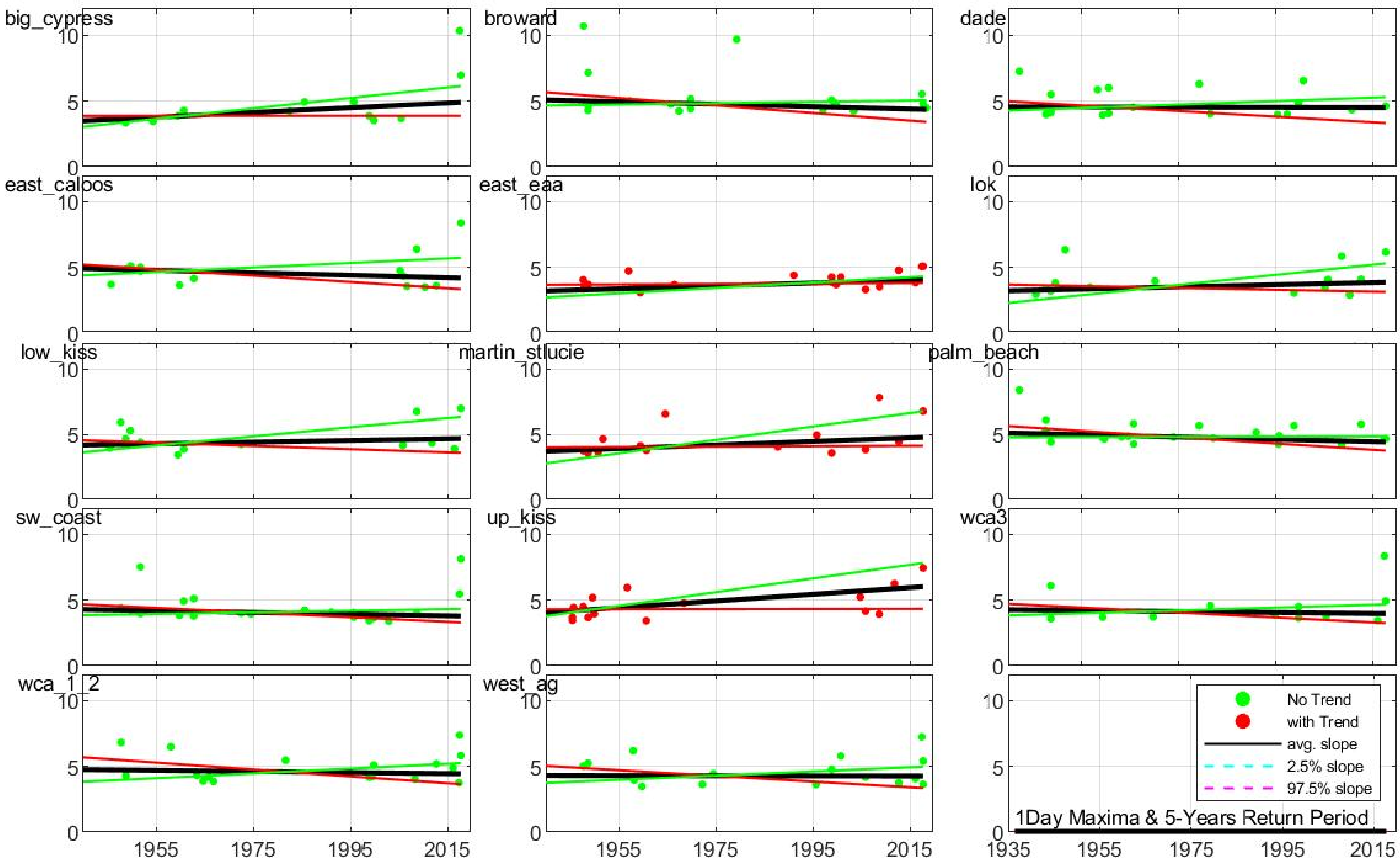

Figure 2B-17. Results of the 1-day maxima, 5-year return frequency trend analysis, 1935 to 2018.

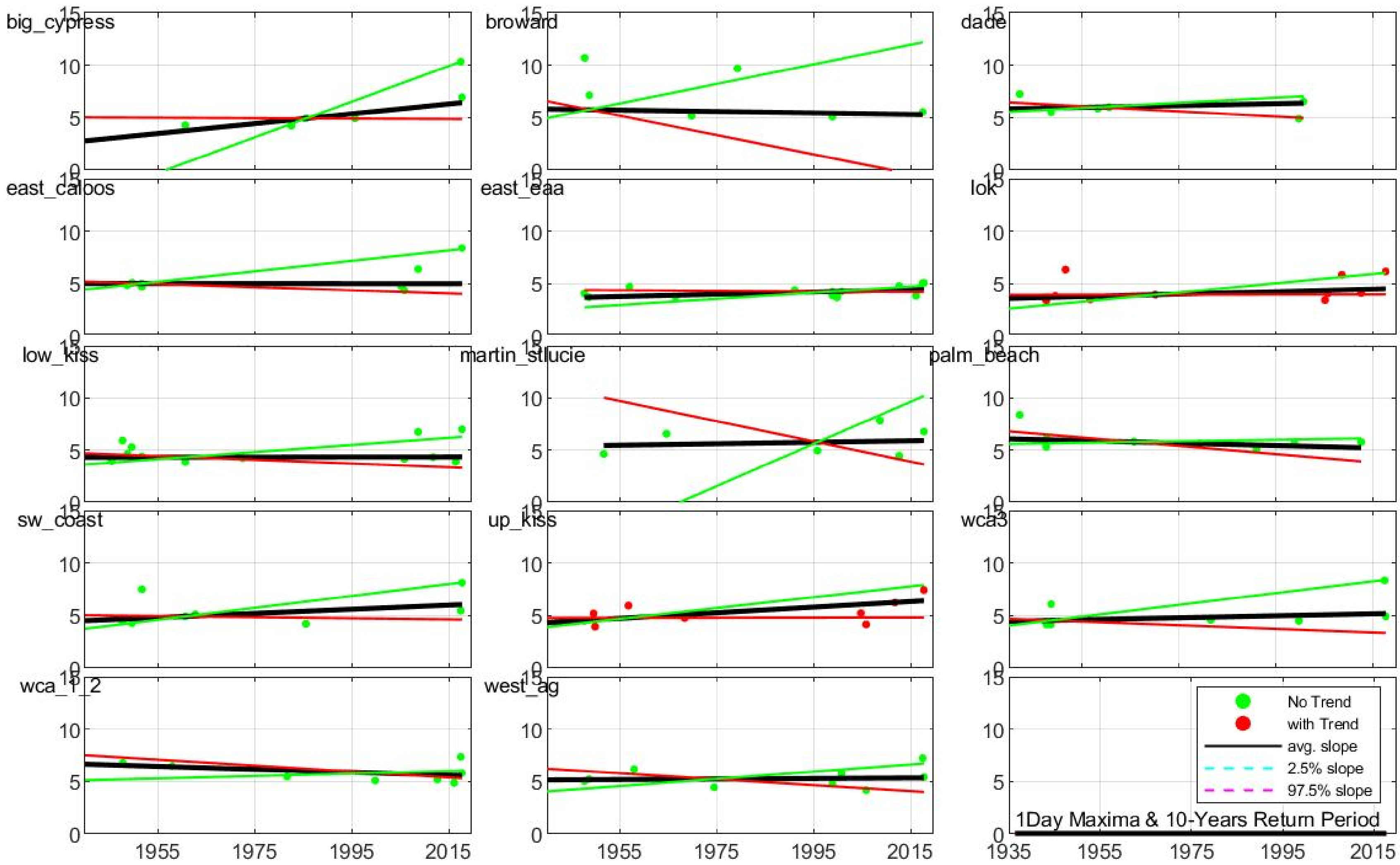

Figure 2B-18. Results of the 1-day maxima, 10-year return frequency trend analysis, 1935 to 2018.

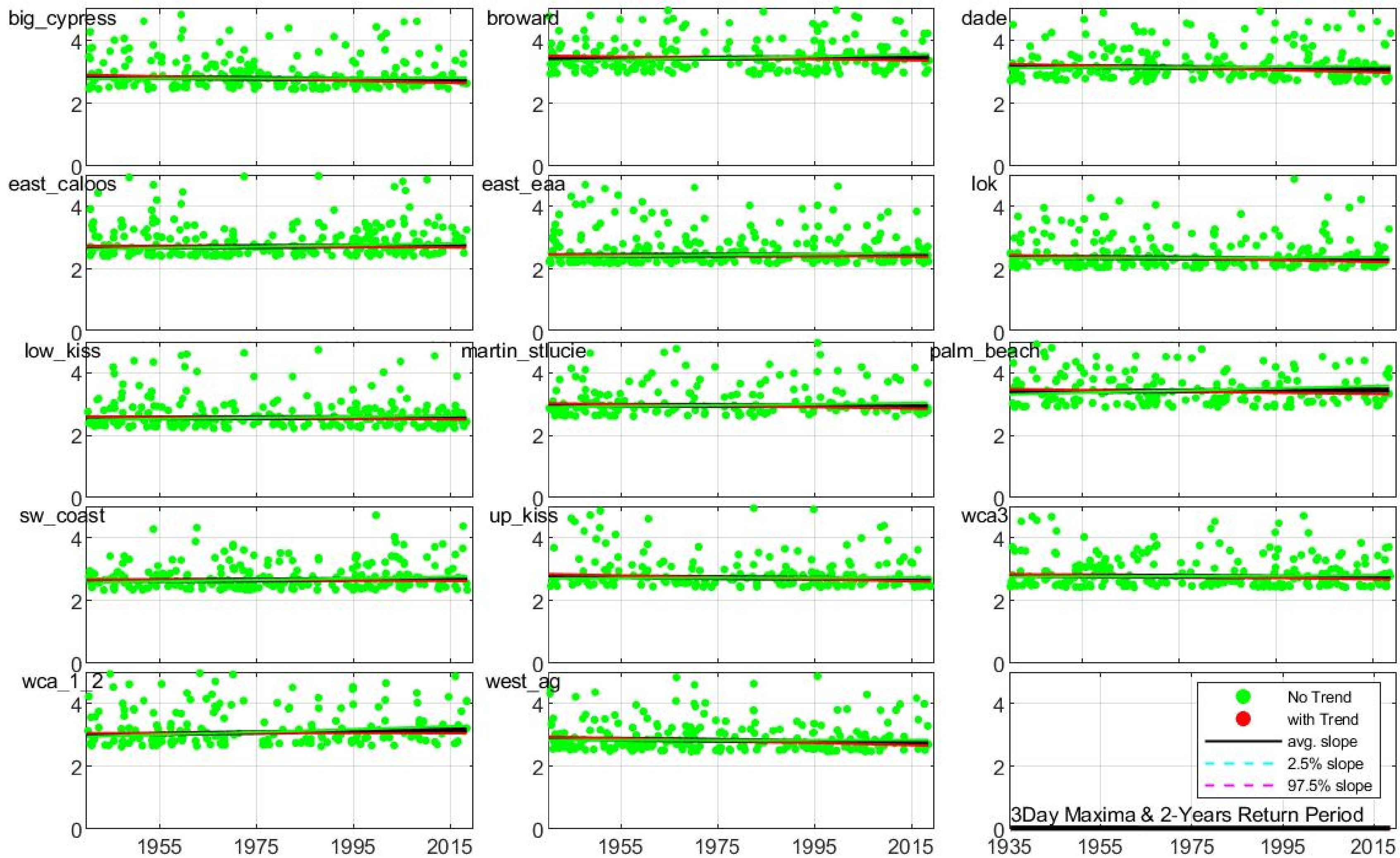

Figure 2B-19. Results of the 3-day maxima, 2-year return frequency trend analysis, 1935 to 2018.

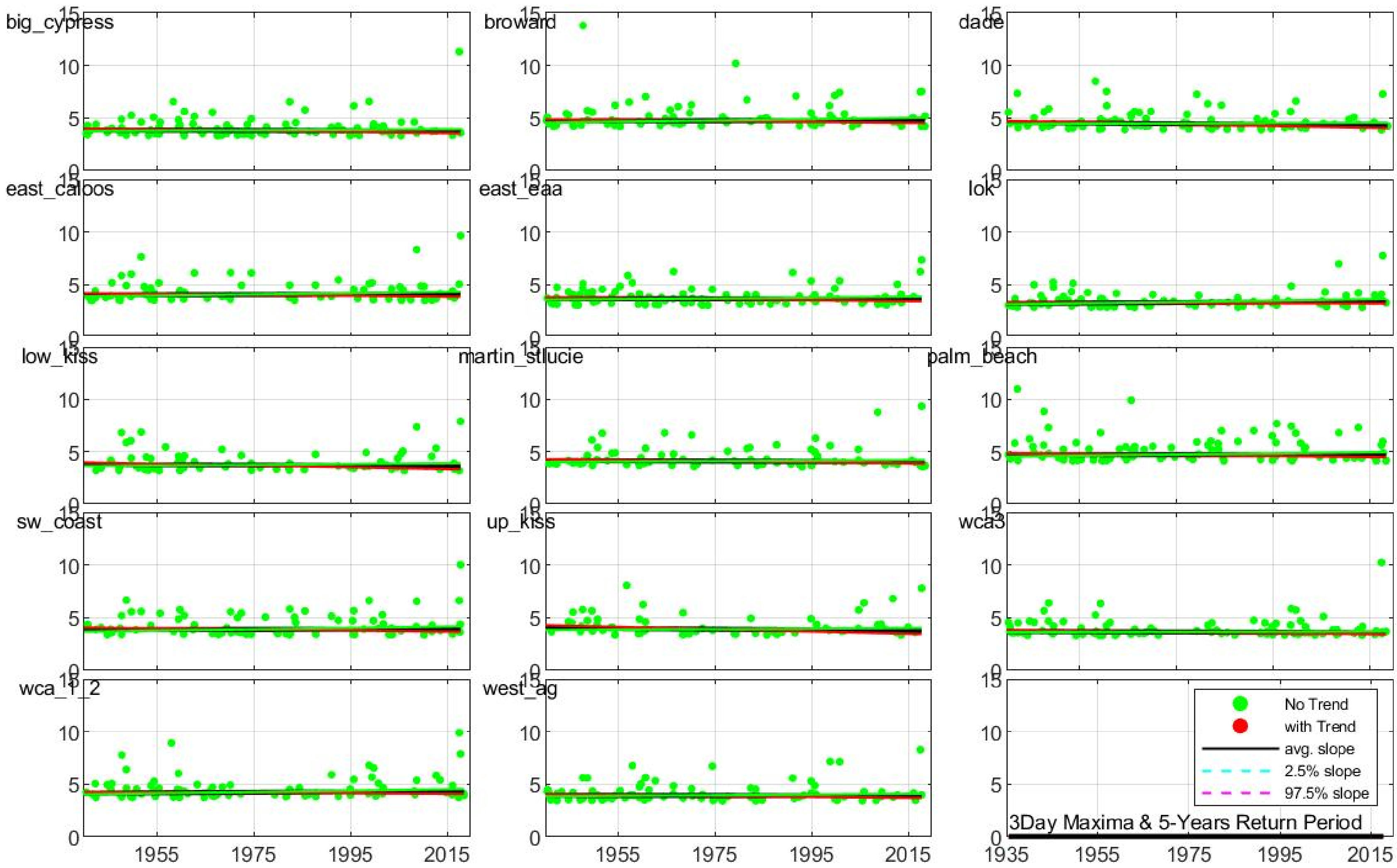

Figure 2B-20. Results of the 3-day maxima, 5-year return frequency trend analysis, 1935 to 2018.

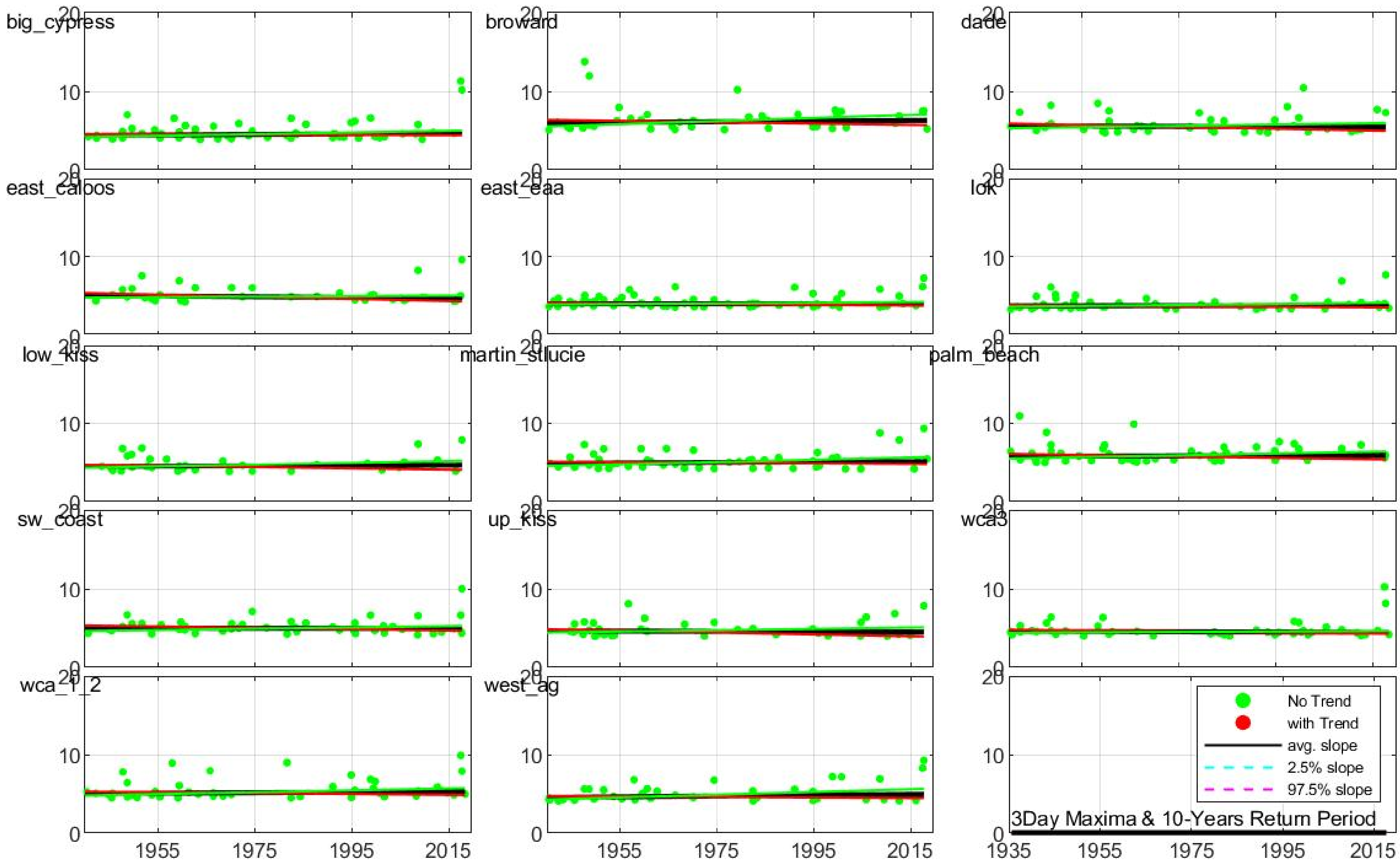

Figure 2B-21. Results of the 3-day maxima, 10-year return frequency trend analysis, 1935 to 2018.

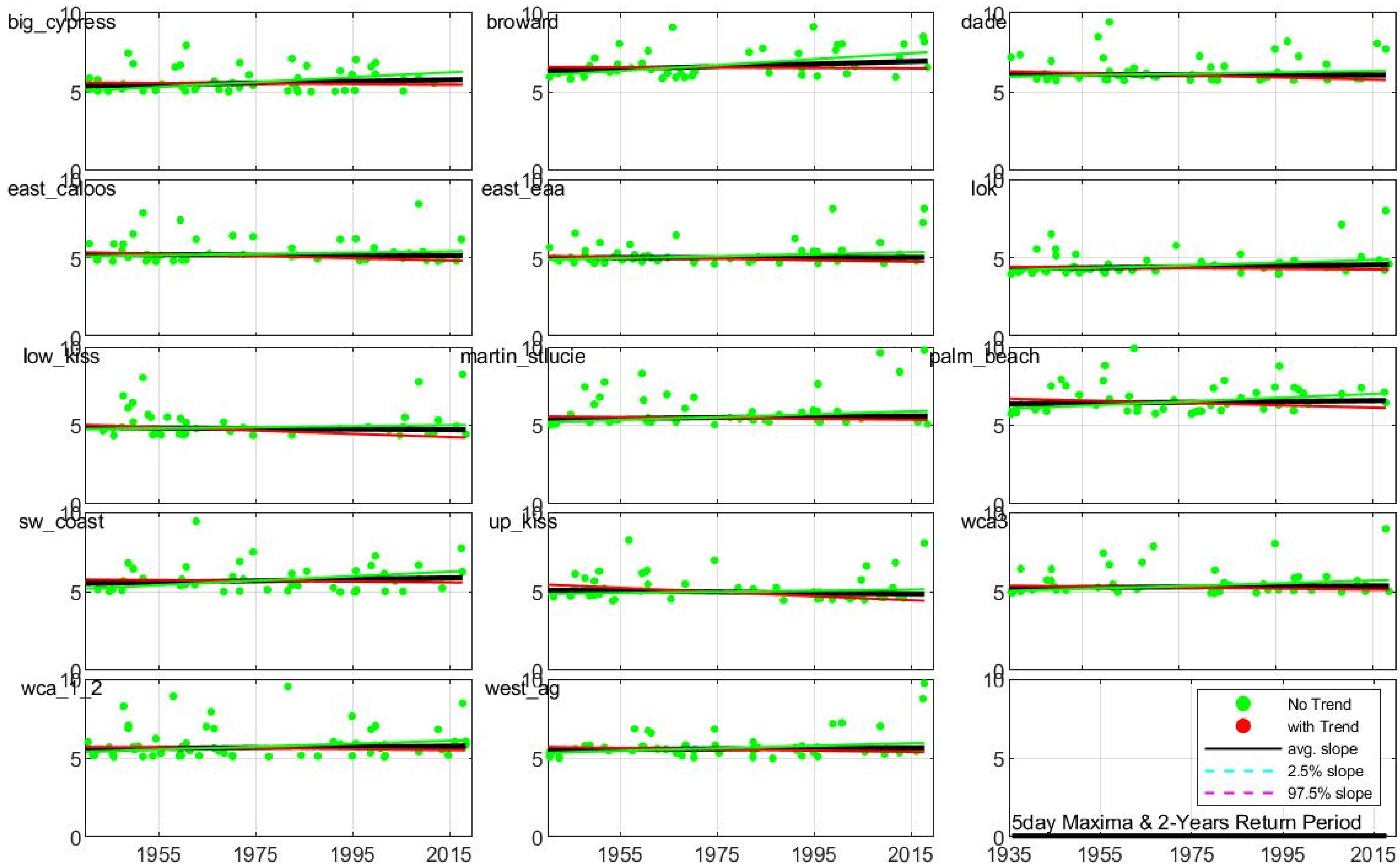

Figure 2B-22. Results of the 5-day maxima, 2-year return frequency trend analysis, 1935 to 2018.

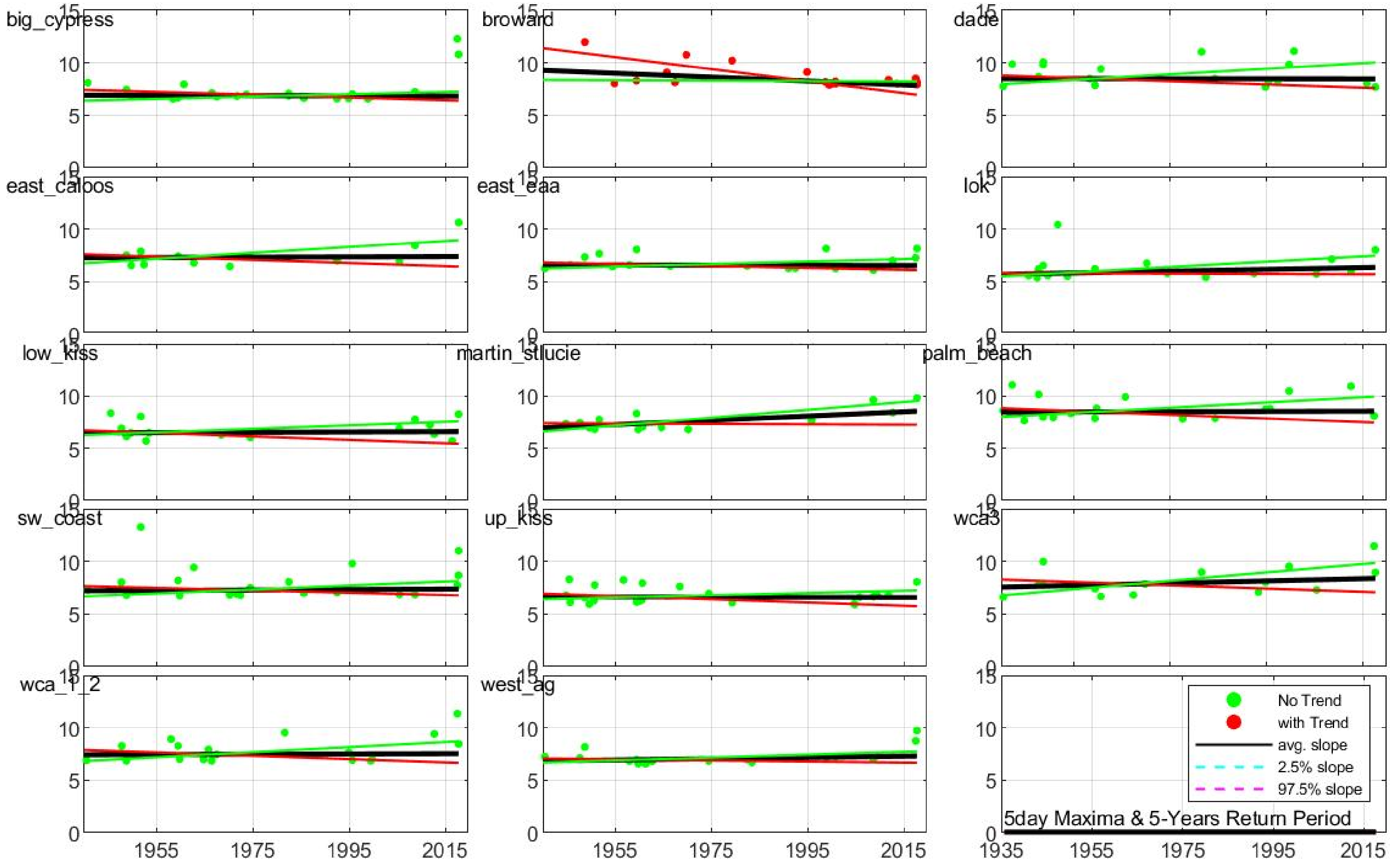

Figure 2B-23. Results of the 5-day maxima, 5-year return frequency trend analysis, 1935 to 2018.

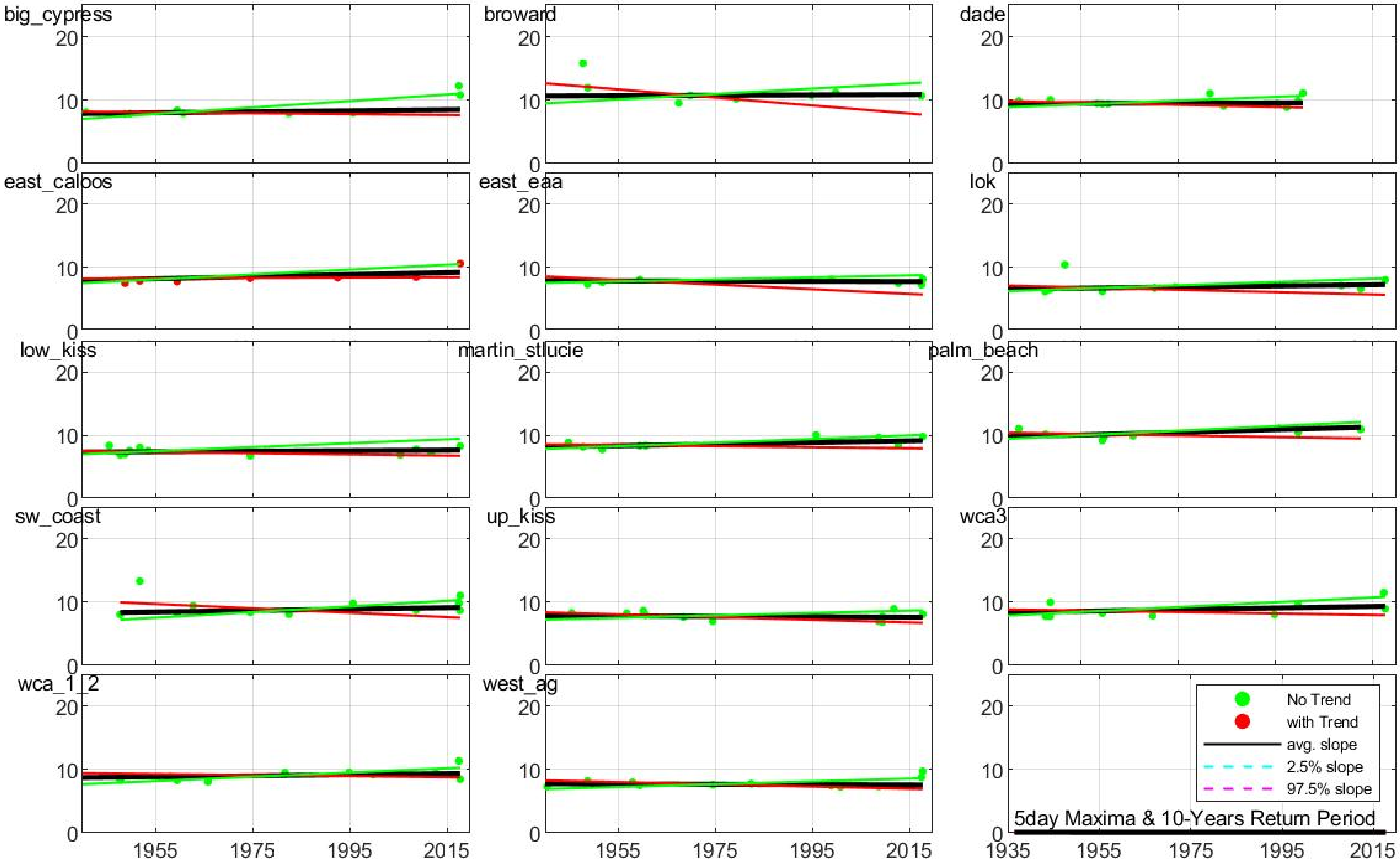

Figure 2B-24. Results of the 5-day maxima, 10-year return frequency trend analysis, 1935 to 2018.

The POT trend analysis is another technique to identify extreme observed rainfall values for a subset of the data that exceeds specified thresholds. The analysis identifies the exceedances above six thresholds for a 5-day event and 2-year return period. Two thresholds (3.1 and 3.9 inches) correspond to K largest observations, considering two formulas [k = sqrt(n), k = n^(2/3)/log(log(n))] (while the remaining thresholds (4.0, 4.5, 5.0, and 5.5 inches) are higher values in 0.5-inch increments. A Poisson distribution was fit to the event count exceeding the threshold and a Pareto distribution was fit to the event exceedance. POT trend analysis results for 1-, 3-, and 5-day events for a 2-year return period are presented in **Figures 2B-25** through **2B-30**. **Table 2B-5** summarizes the results of the POT trend analysis.

Table 2B-5. POT trend analysis results.

Trend Analysis	Observed Trend
5-day, 3.1 inches, 2-year return	No significant trend
5-day, 3.9 inches, 2-year return	Upward trend: SW Coast
5-day, 4.0 inches, 2-year return	Upward trend: Big Cypress, SW Coast
5-day, 4.5 inches, 2-year return	Upward trend: Big Cypress
5-day, 5.0 inches, 2-year return	Upward trend: West Agricultural Area
5-day, 5.5 inches, 2-year return	Upward trend: West Agricultural Area

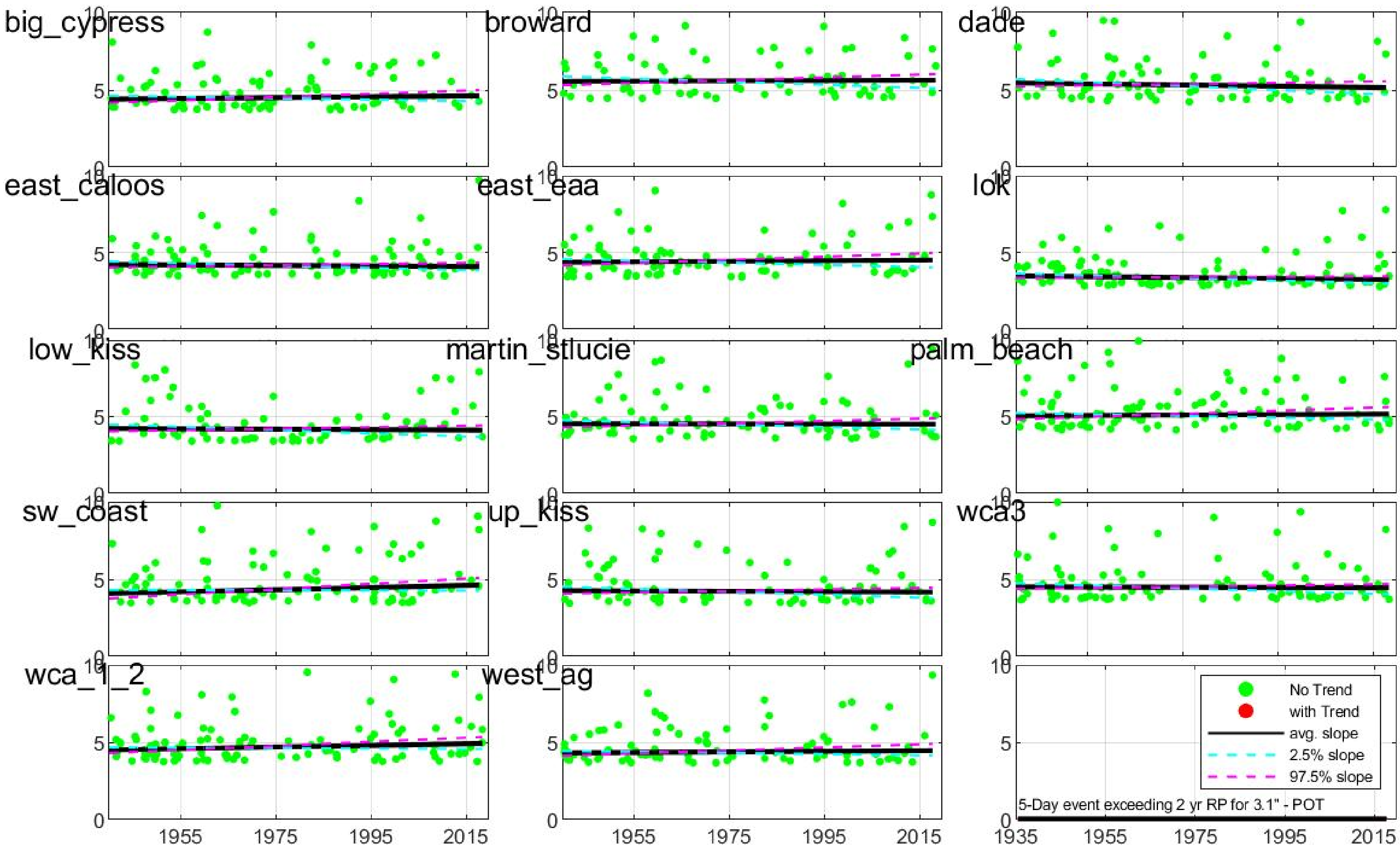

Figure 2B-25. POT trend analysis results for a 5-day event exceeding 3.1 inches of rainfall for a 2-year return period.

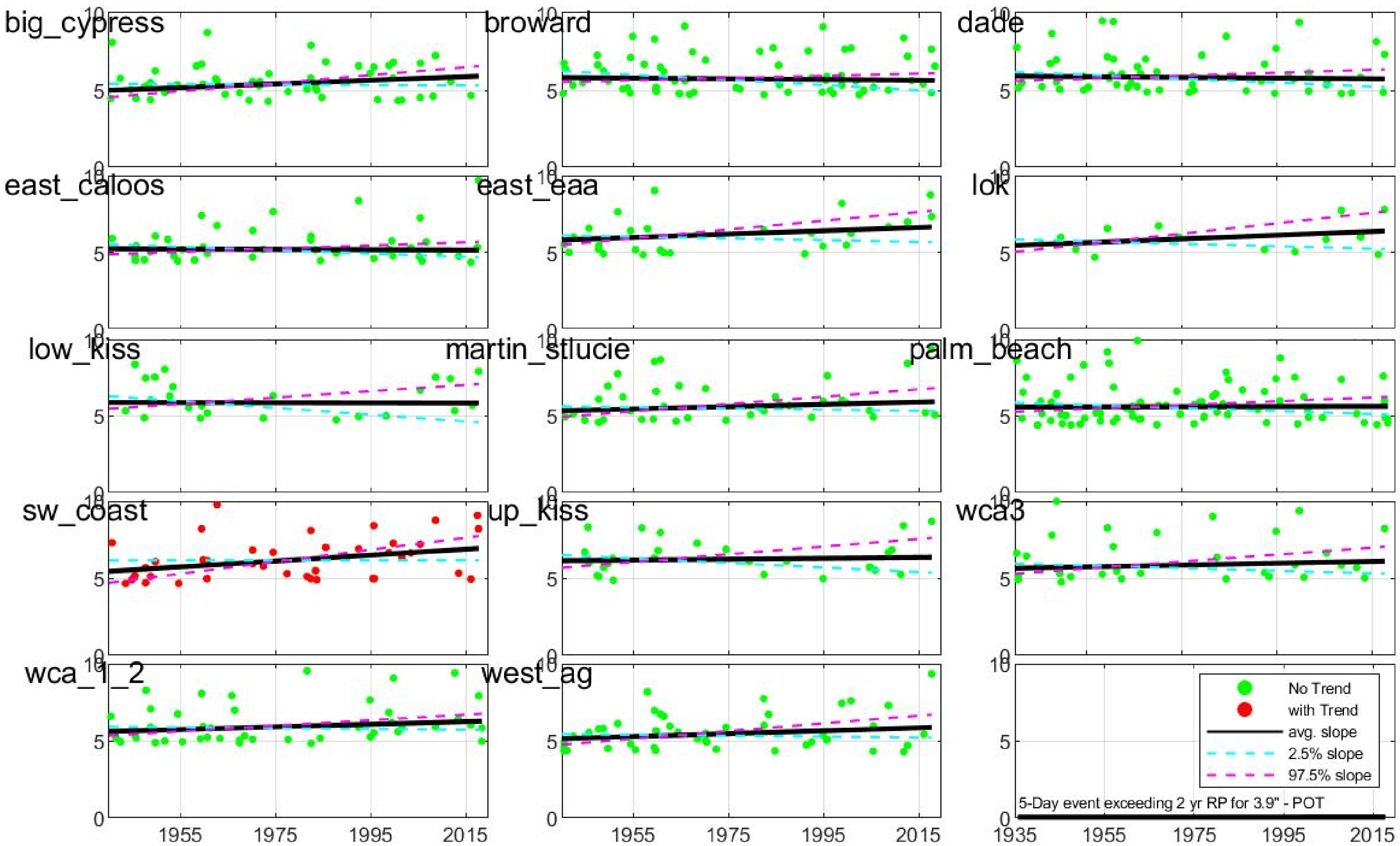

Figure 2B-26. POT trend analysis results for a 5-day event exceeding 3.9 inches of rainfall for a 2-year return period.

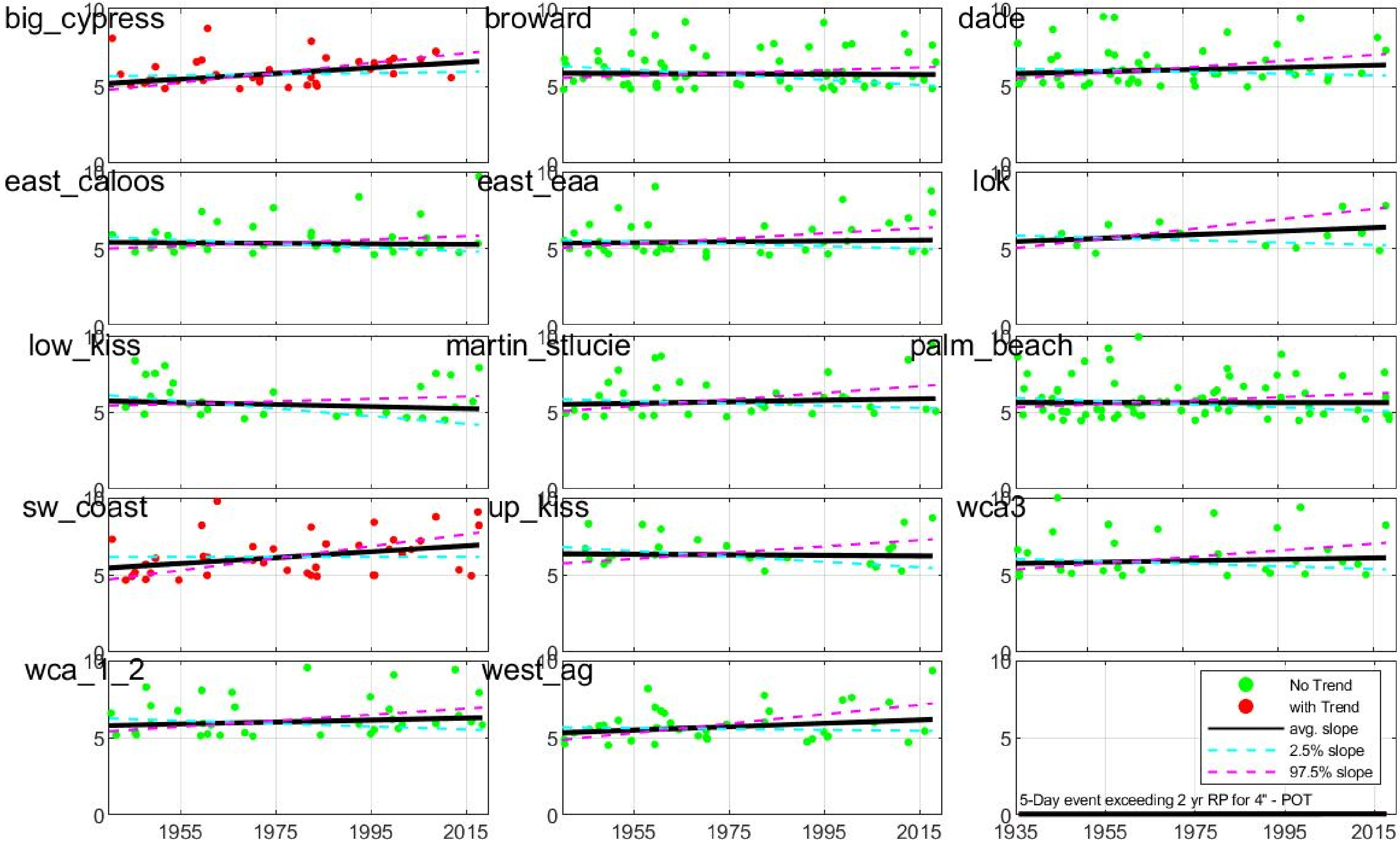

Figure 2B-27. POT trend analysis results for a 5-day event exceeding 4.0 inches of rainfall for a 2-year return period.

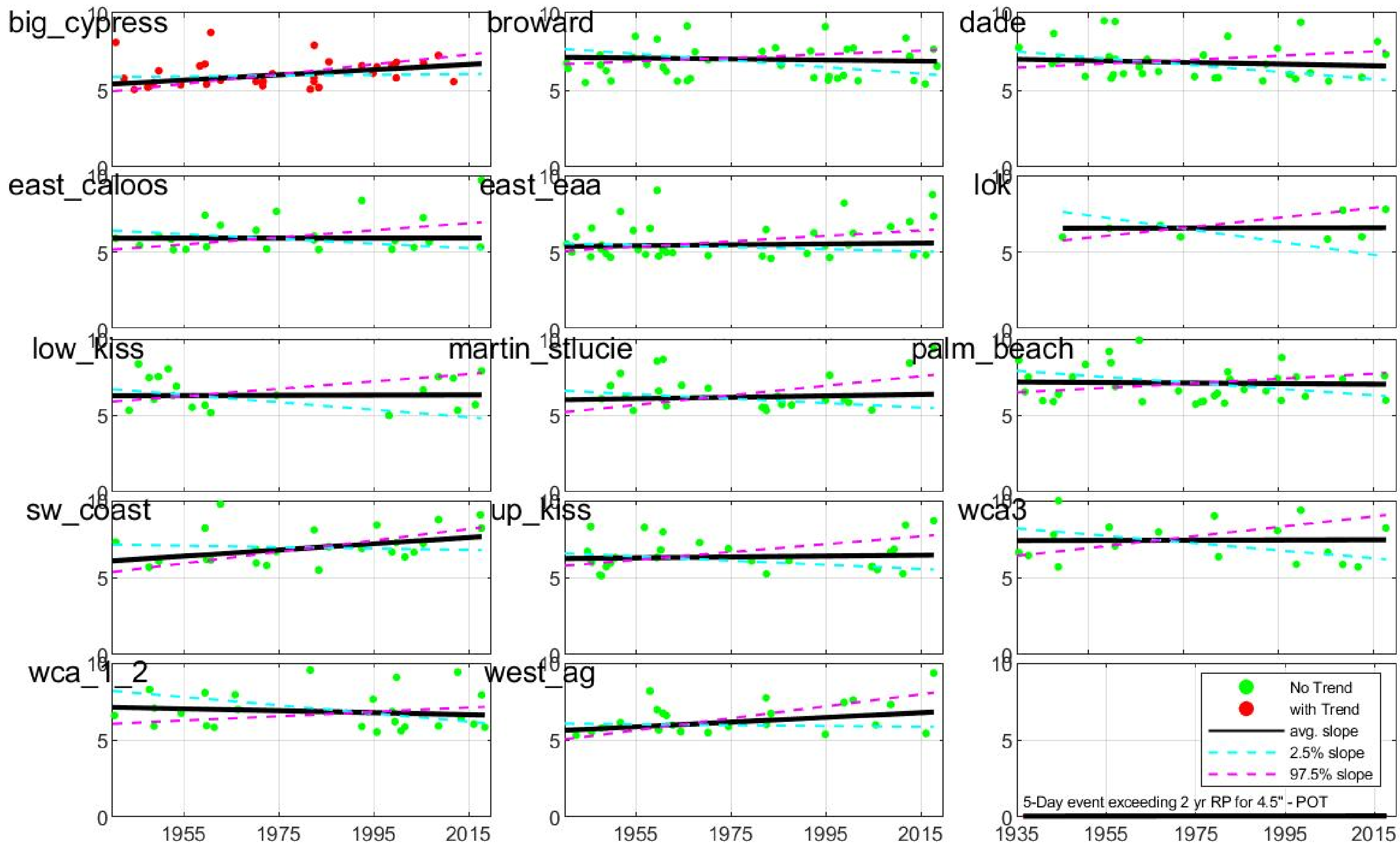

Figure 2B-28. POT trend analysis results for a 5-day event exceeding 4.5 inches of rainfall for a 2-year return period.

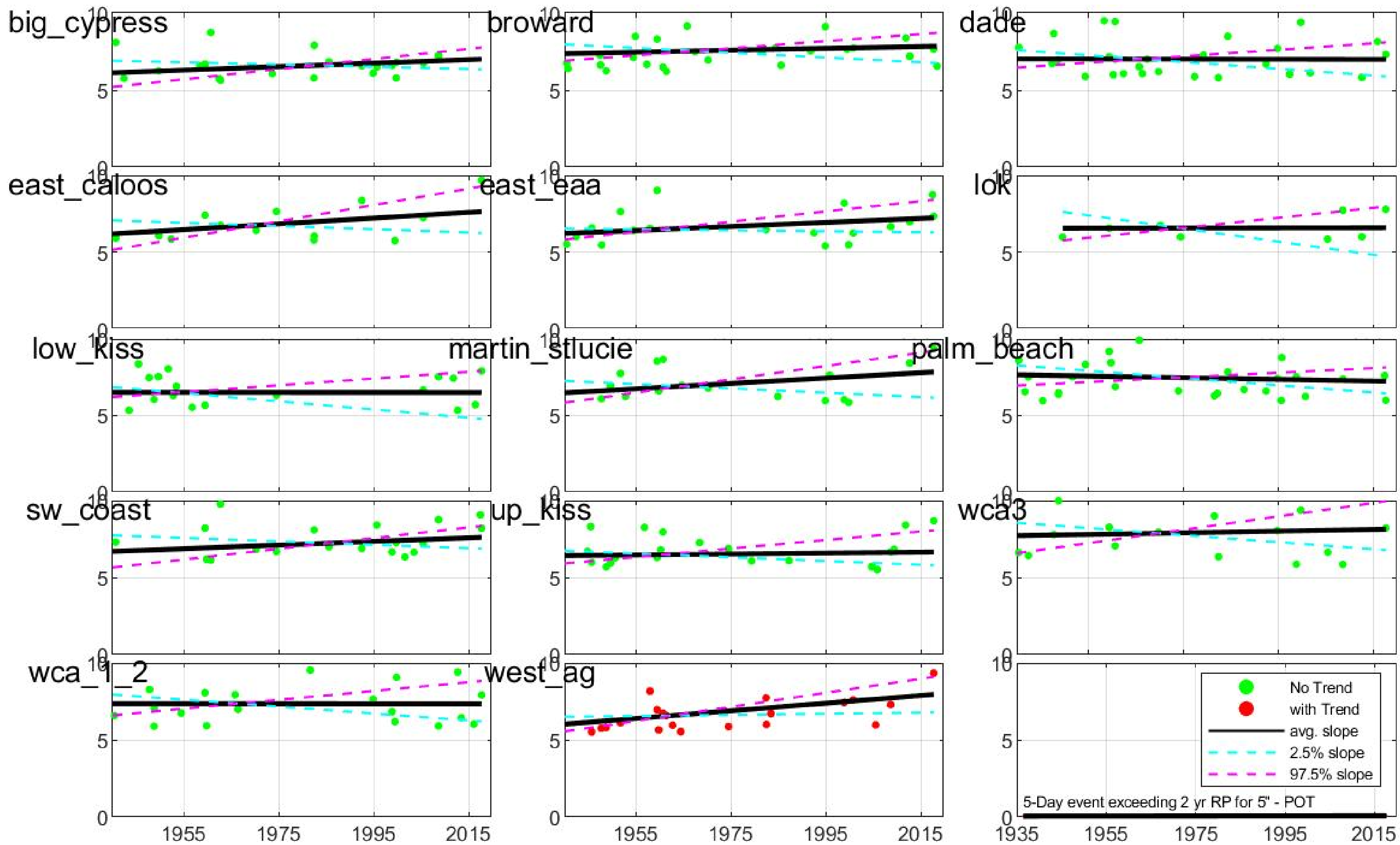

Figure 2B-29. POT trend analysis results for a 5-day event exceeding 5.0 inches of rainfall for a 2-year return period.

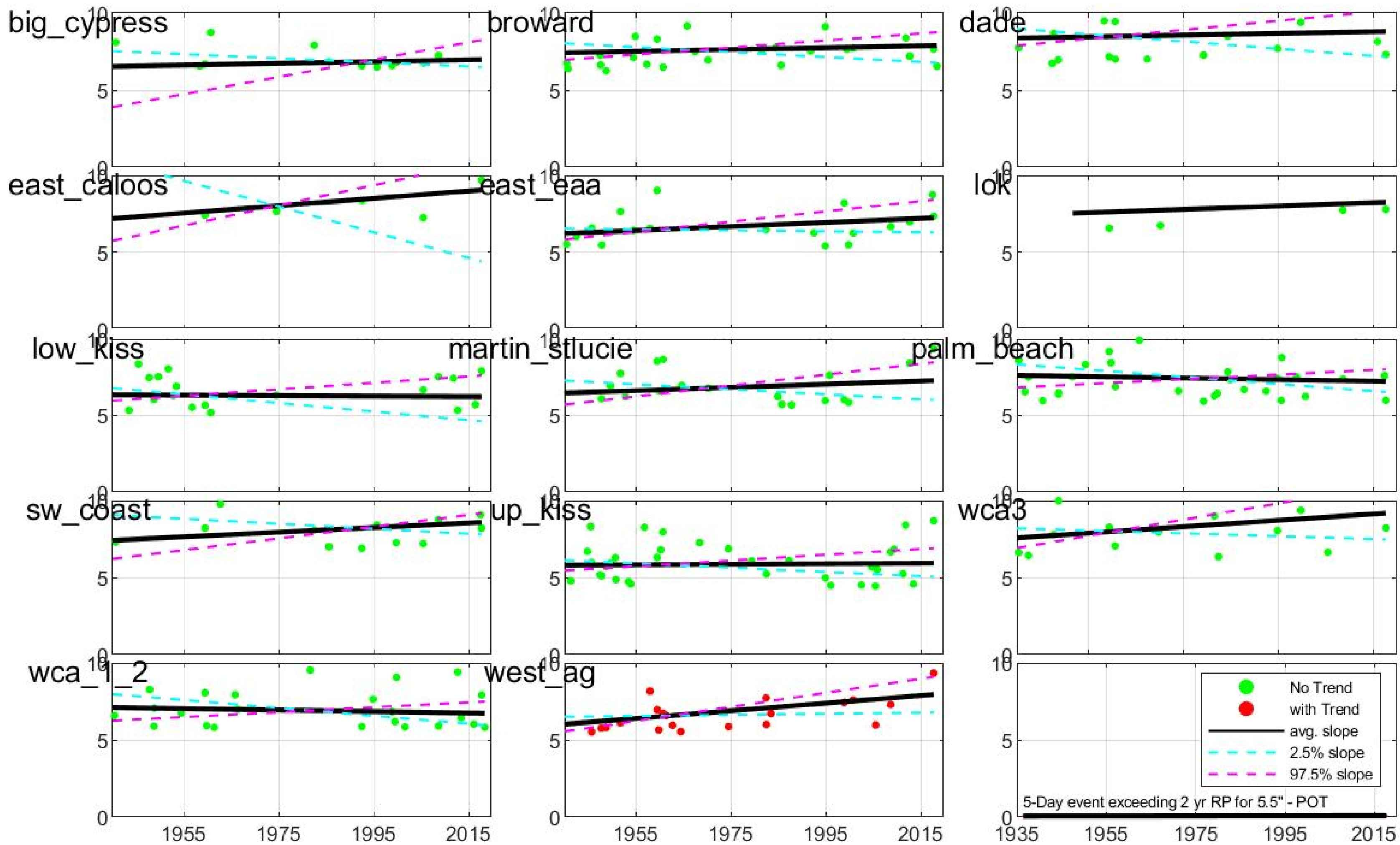

Figure 2B-30. POT trend analysis results for a 5-day event exceeding 5.5 inches of rainfall for a 2-year return period.

COMMENTS AND RECOMMENDATIONS

Overall, no significant upward or downward trends in average rainfall were identified in South Florida. Areas (rainfall basins) where significant trends were observed will be continuously evaluated to track and document how these trends evolve in the future. Additional monitoring can help determine what shifts in rainfall may mean for these regions and how trends in specific areas compare to regional trends. Given predicted increases in the frequency and intensity of extreme hydrological events with climate change (SFWMD 2009), local changes to extreme wet and dry conditions are likely in future years.

Further analysis is needed to confirm if changes in rainfall frequency and intensity are linked to other climatic influences and observed trends. The determination of rainfall thresholds and the associated number of events over/under these thresholds is needed to better understand extreme wet and dry conditions. Future analyses may look at rainfall minima trend analyses in parallel with rainfall maxima analyses because dramatic transitions from dry to wet periods can cause greater damage than either event alone and can put additional strain on the water management system. Findings from the National Oceanic and Atmospheric Administration's (NOAA's) Climate Observations and Monitoring program show dramatic dry-wet transitions have become more frequent over the past 30 years in localized parts of the United States (He and Sheffield 2020).

Predicting climate change and its consequences continues to be a challenging science. Many factors, including solar radiation, atmospheric composition, cloud cover, ocean currents, and land activities (e.g., deforestation, urbanization), influence climate and make long-term variability difficult to predict. Further complexity comes from the circular relationships between elements of the system. For example, as air temperatures rise, the atmosphere holds more water vapor, which in turn traps even more heat in the atmosphere and increases atmospheric temperature. Despite the broad range of unknowns and uncertainties, any significant change in the natural cycle, and mainly rainfall, could limit the flood control effectiveness of existing and planned water management infrastructure, increase the likelihood of further encroachment of sea water into groundwater supplies, and inundate low-lying areas. Understanding rainfall trends is critical to water resource planning and management, including future infrastructure project needs. Future efforts will further advance the scientific interpretation of these identified trends.

EVAPOTRANSPIRATION TRENDS IN SOUTH FLORIDA

BACKGROUND

Within the contiguous United States, about two-thirds of precipitation returns to the atmosphere through evapotranspiration (ET), which is greatest in the Southeast (Hanson 1991). A side-by-side comparison of Districtwide average monthly potential ET (ET_p) and rainfall (over the past 25 years) is presented in **Figure 2B-31**. In terms of rainfall amount, a year is evenly divided into two seasons; the wet season lasts from May to October (six months), and the dry season from November to April (six months). If assessed by the monthly differences of ET and rainfall, South Florida's wet season is from June to October (five months), and the dry season is from November to May (seven months). During a drought, the significance of ET is magnified because it depletes the limited remaining water supplies in water bodies and the soil (Hanson 1991).

Changes in red in the second paragraph on this page were made on November 22, 2022.

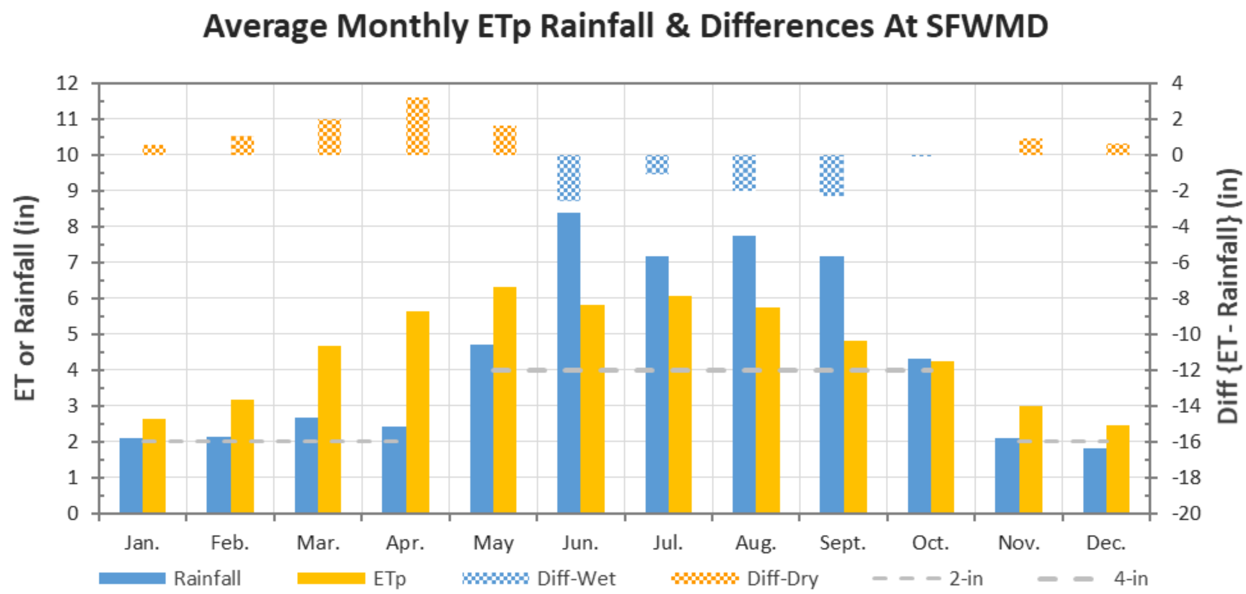

Figure 2B-31. Average monthly potential ET and rainfall across the District, and their differences.

ET includes two processes: 1) evaporation from any surfaces on the ground, and 2) transpiration from plants' biological processes (i.e., root systems absorb water from the soil and release it through the leaves). ET rate is mainly affected by solar radiation, along with wind speed, relative humidity (vapor pressure deficit), and air temperature. Solar radiation is called the radiative energy budget, while the latter three components are sometimes collectively called the advective budget.

Unlike the directly measurable components of hydrological cycle, namely precipitation and streamflow, ET rate is hard to directly measure, particularly the transpiration part, because of the difficulty in isolating the observation object (i.e. moisture or water vapor). Evaporation can be measured directly to some extent with the help of a pan that holds water for evaporation to occur, and the water level change reflects the evaporation rate. A lysimeter provides the most practical way for direct measurement of ET_p, but it is expensive to operate and maintain. Empirical equations and models have been developed to estimate ET rate, with input of the four driving parameters (solar radiation, wind speed, relative humidity, and air temperature).

ET_p, an upper limit to ET, means the maximum rate that only occurs when water availability in the soil is non-limiting. Actual ET (ET_a) is the ET that actually takes place, and it is strongly influenced by the level of soil moisture or precipitation and the type of vegetation coverage. ET_a rates are often estimated by multiplying ET_p with a proportion of water depth to the saturated soil zone and crop coefficients. However, their regional averages can be derived through a water budget by subtracting the surface water outflow, groundwater outflow, and consumptive use from the precipitation.

Where wetlands are extensive (e.g., in South Florida), ET_p is dominated by the radiative energy budget, and the evaporative conditions are known as energy-limited (Abtew 1996). Where the available water is not sufficient to meet the evaporative demand (e.g., in Arizona), ET_a will be less than the upper limit, and the conditions are said to be water-limited. In water-limited environments, over annual or longer periods, the trend in ET_a is usually very close to the trend in precipitation. By definition, ET_p and pan evaporation (E_{pan}) are two measurements fit to energy-limited conditions. E_{pan} measurements are widely used to estimate evaporative demand, because the equipment is readily available, affordable, and simple to operate (Roderick et al. 2009). Daily variations in E_{pan} do not necessarily resemble the ET_p from well-watered vegetation ground. However, over longer periods such as months to years, E_{pan}, when multiplied by the pan coefficient (discussed below), is a good measure of ET_p in the same location or area (McIllroy and Angus 1964, Rose et al. 1972, Stanhill 1976).

The most commonly used evaporation pan in the United States is the "Class A" of the National Weather Service. The cylinder pan is 47.5 inches in diameter and 10 inches in depth. Water level in the pan is required to be maintained at 2 inches from the rim, after each measurement. The pan usually is accompanied by a rain gauge to factor out the contribution of concurrent rainfall to the stage variation for the actual value of evaporation. The pan is made of metal and rests on a wooden platform, which is carefully leveled. The platform surface is about 5.9 inches from the ground. Because the pan has more exposure to the air (at its sides and bottom) than any natural water body, it absorbs more heat from the surroundings. This gives higher evaporation values than other measurements (e.g., lake evaporation, ET_p) under the same weather conditions. Therefore, the pan coefficient for a Class A pan is usually less than one and mostly around 0.7.

EVAPOTRANSPIRATION DATA, QUALITY, AND TREND

Figure 2B-32 shows two annual data sets from two manual evaporation pans (E_{pan}) and one data set of potential ET (ET_p). These data sets illustrate a clear upward trend in the observed ET time series, which are statistically verified by the Mann-Kendall Test. Monitoring stations were selected for trend analysis based on two criteria: (1) still in operation, so they can be used for trend watch in the future; (2) period of record longer than 25 years. The WPB.EEDD station, operated by the City of West Palm Beach, has a 36-year period of record (1985 to 2020). The S7 station, operated by the District, has the longest period of record at 60 years (1961 to 2020). Evaporation data from the S7 station have been used to produce the weekly Shark River Report since 1985 (for water releases from Water Conservation Area 3A to Everglades National Park, based on water budget analysis of rainfall, evaporation, and stage regulation). The weekly data quality check for the report and staff communication have made the manual measurements at S7 as consistent as possible.

The measurement quality of E_{pan} is subject to many potential errors, including pan environment bias (e.g., distance to surrounding trees or buildings, bird guard, platform material and height to ground, algae in water), operation bias (e.g., reading and recording errors of water level), rainfall estimation (e.g., different diameters of rain gauge and pan), among others (Gunderson 1989). E_{pan} often is measured manually, so the measurement frequency depends on staff availability. For example, the measurements are not conducted over weekends or holidays, and an accumulated value is obtained on the next workday. Also, a heavy rain event can cause overflow in the pan, resulting in a missing data point for that day. Large measurement errors at daily or weekly scales are unavoidable and random; however, when they are pooled up to monthly or yearly scale, the errors follow a normal distribution and lead to less biased summaries. Therefore, the monthly or annual values are more suitable for statistical analysis. The raw data for this study went through QA before being used in any statistical analysis.

Theoretically, annual evaporation rate should not vary much spatially and temporally because the meteorological variables (i.e., solar radiation, wind speed, relative humidity, and air temperature) in the region do not fluctuate widely on a yearly basis. Large variation between years is most likely due to operation errors; however, its influence on the evaporation trend will diminish with longer periods of record. Large differences between stations (e.g., S7 and WPB.EEDD) are likely due to a combination of local environment and operation bias. Although there are different magnitudes in values, the data from any station can be trusted for trend analysis as long as they have been consistently maintained (i.e., no change of location, surrounding, or equipment over the period of record).

Figure 2B-32 was updated on November 22, 2022.

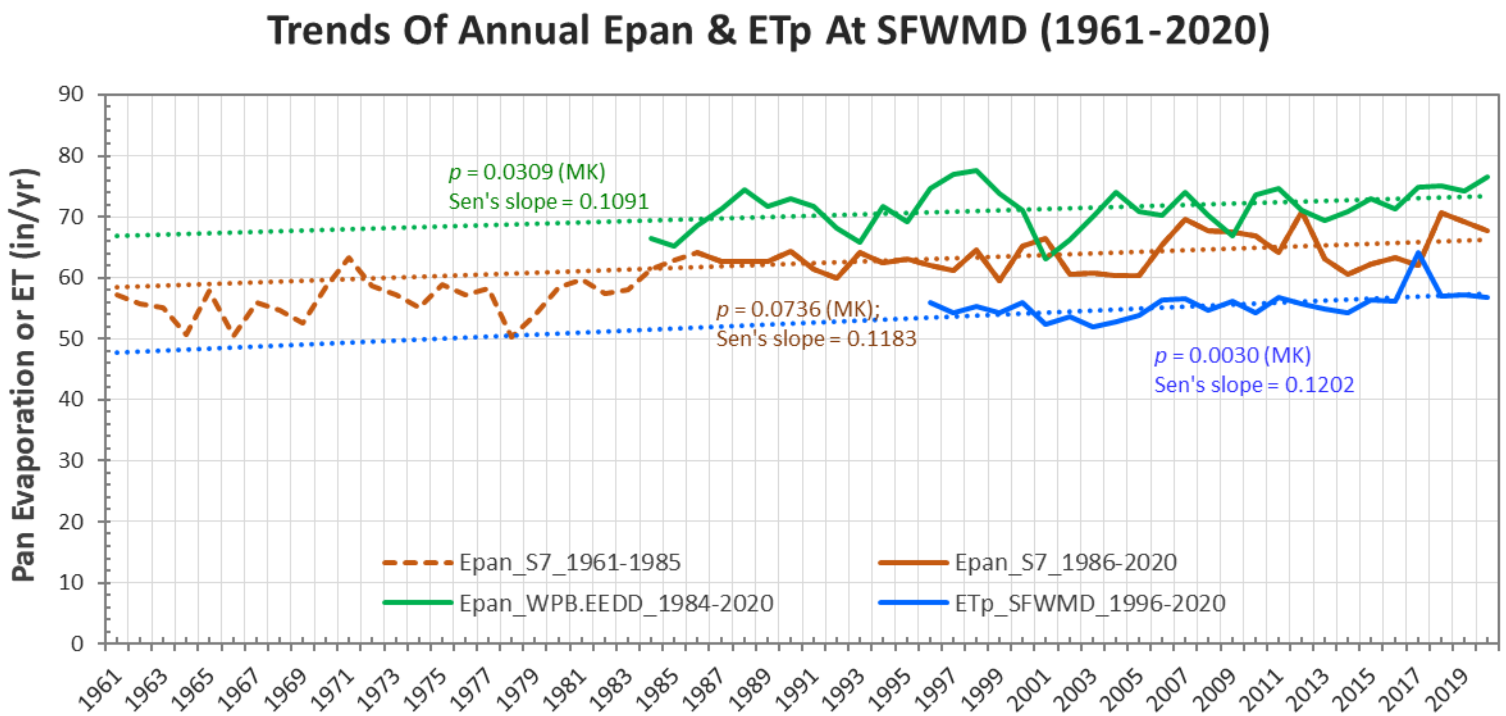

Figure 2B-32. Trend of annual pan evaporation (E_{pan}) and potential evapotranspiration (ET_p) across the District, 1961 to 2020.

ET_p data from the USGS have a 25-year period of record (1996 to 2020). The data were generated with input of insolation retrieved from satellite images of cloud cover. The calculated ET_p values were calibrated to ground pyranometers, with a high coefficient of determination ($R^2 = 0.93$). Thus, the ET_p data set is spatially consistent and temporally continuous (Mecikalski et al. 2018). The annual ET_p data shown in **Figure 2B-32** are the averages over the entire District.

The direct pan observations and the satellite-based ET_p data set were collected independently; therefore, they can be used to cross-check each other. The slope values of trendlines for the three data sets are quite close to each other (note: data from 1986 to 2020 were used in statistics for the S7 station). The Mann-Kendall test proves all three data sets show an upward trend at a significance level of 0.05.

The statistics of annual E_{pan} and ET_p are presented in **Table 2B-6**. The averaged ET_p rate of 54 inches/year is close to the long-term rainfall rate in South Florida (approximately 53 inches/year). The change rate of the upward trend is about 0.1 inch/year.

Table 2B-6. Statistics of annual pan evaporation (E_{pan}) and potential evapotranspiration (ET_p). Table replaced November 22, 2022.

Data Set	Agency	Period of Record	Period for Statistics	No. of Samples	Mean (in./yr)	Ratio of ET_p/E_{pan}	Standard Deviation	Change Ratio (in./yr)
E_{pan}_S7	SFWMD	1961 - 2020	1986 - 2020	35	63.97	0.87	3.17	+0.1183
E_{pan}_WPB.EEDD	City of WPB	1985 - 2020	1985 - 2020	36	71.51	0.78	3.41	+0.1091
ET_p_SFWMD	USGS	1996 - 2020	1996 - 2020	25	55.48	1	2.35	+0.1202

Figure 2B-33 illustrates the annual and seasonal E_{pan} data at S7. The orange and green dots in the upper part of the chart represent the annual data subsets of 1961 to 1984 and 1986 to 2020, respectively, to account for the measurement schedule change from every day to workdays only in 1985. Both subperiods show an upward trend. The two groups of dots in the lower part of the chart are the seasonal summaries over the 60-year period of records. The blue dots represent the wet season (May to October), and the brown dots represent the dry season (November to April). The Mann-Kendall test proves that both seasons have an upward trend at a significance level of 0.05.

Figure 2B-34 shows the monthly E_{pan} data at S7 over the 60-year period of record, including extreme occurrences with 1-in-10-year and 1-in-25-year return frequencies. The green dashed line represents the trendline of every year's maximum monthly values over the 60 years, and it illustrates a clear upward trend.

Figure 2B-33 was updated on November 22, 2022.

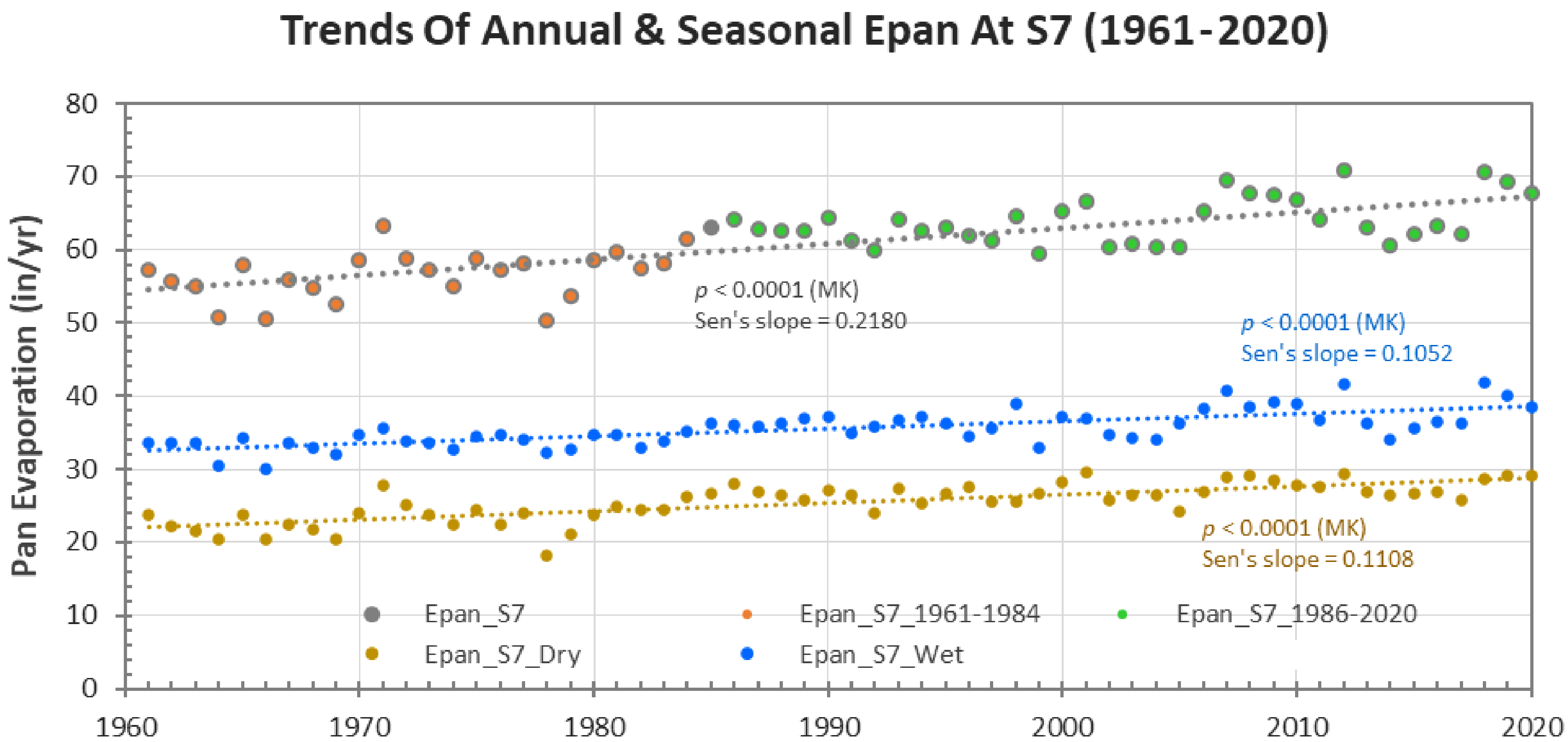

Figure 2B-33. Trend of E_{pan} data at S7 from 1961 to 2020: annual totals and seasonal summaries.

Figure 2B-34 was updated on November 22, 2022.

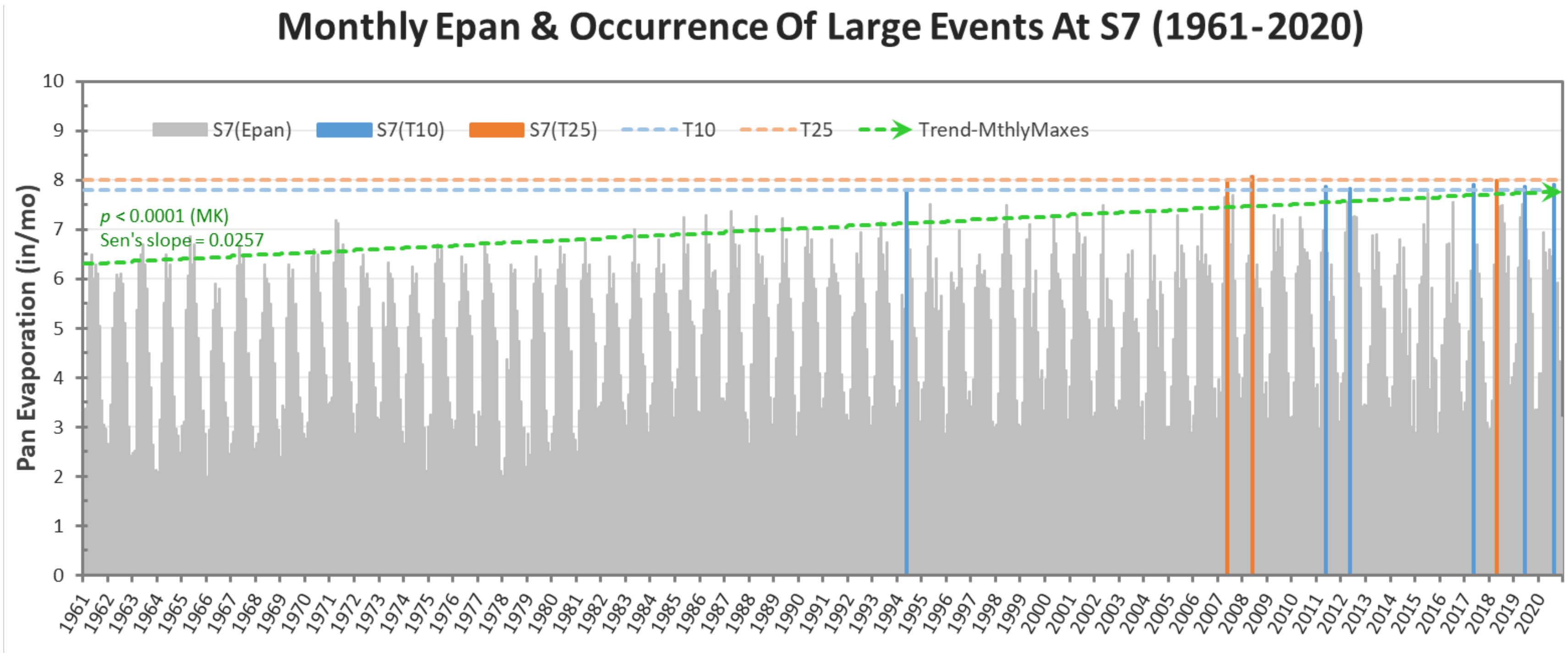

Figure 2B-34. Monthly E_{pan} data at S7 (gray), highlighting events above 1-in-10-year (blue) and 1-in-25-year (orange) return frequencies. The green dashed line represents the trendline of every year's maximum monthly values over the 60 years.

TRANSPIRATION IN ET

Transpiration is difficult to measure in practice; therefore, there is no monitoring system for it at the local level; in other words, there is no field data that can directly confirm a trend of transpiration in South Florida. However, other dedicated studies may help understand its magnitude and tendency.

Large-scale or global studies show that plant transpiration accounts for about 60% of global terrestrial ET. The ratio varies largely among different landscapes, from more than 90% in tropical rainforests to less than 10% in deserts (Schlesinger and Jasechko 2014, Good et al. 2015, Zhang et al. 2016, Wei et al. 2017). For most of the United States, evaporation returns less moisture to the atmosphere than transpiration (Hanson 1991). In Florida, evaporation and transpiration roughly share a 50/50 composition in total ET, as there are many wetlands and open water bodies (e.g., lakes, ponds, canals), where evaporation dominates over transpiration. In urban areas, hard surfaces (e.g., pavement, roofs) also contribute to greater evaporation than transpiration. In agricultural areas, transpiration is dominant during the growing season, while evaporation is prevalent during fallow periods.

Climate change theory has linked global warming to rising concentration of carbon dioxide (CO_2) in the atmosphere. The global mean atmospheric concentration of CO_2 is 410 parts per million, which is greater than 45% more than the concentration in 1750 (Arias 2021). The rising CO_2 concentration appears to influence transpiration rates due to less need for plants to open their stomates to obtain sufficient CO_2 for photosynthesis. With higher CO_2 concentrations, plants have evolved to have less stomatal density over recent centuries. However, it was also found that stomatal density decreases as CO_2 concentrations increase up to about 310 parts per million, but there is no effect to density found above this concentration (Woodward and Bazzaz 1988). Different plant species also show large differences in response of stomatal density to elevated CO_2 concentrations. For example, the stomatal density of rice and bean leaves is positively correlated to CO_2 concentrations (O'Leary and Knecht 1981, Rowland-Bamford et al. 1990). Stomatal functioning (opening and closing) also responds to other environmental cues, such as radiation or light intensity, leaf water status (drought), vapor pressure deficit, air pollution, and air temperature (van de Geijn and Goudriaan 1996). For example, air temperatures rise due to the greenhouse effect, and the associated increases in vapor pressure deficit may stimulate transpiration, or open the stomata (Urban et al. 2017, Kirschbaum and McMillan 2018).

ACTUAL EVAPOTRANSPIRATION VERSUS POTENTIAL EVAPOTRANSPIRATION

All else equal, ET_p and ET_a have a complementary relationship. During dry conditions or in water-limited environments, ET_p is at its highest values and ET_a is at its lowest values. With increased precipitation or humidity, water limitation on the evaporative process gives way to an energy limitation. When the ET_p decreases, the ET_a increases, and they converge under the wettest circumstances (Hobbins et al. 2001, Hobbins and Ramirez 2004). Therefore, the humid climate in South Florida results in a close relationship between ET_p and ET_a, especially in wetlands and lakes, or during the wet season.

Although there are no transpiration monitoring networks or established ET_a data sets for South Florida, some independent, large-scale studies support that the southeastern United States has been experiencing an upward trend in transpiration and ET_a due to climate warming and vegetation restoration, among other reasons (Zhang et al. 2016).

METEOROLOGICAL VARIABLES AS POTENTIAL INFLUENCING FACTORS ON ET TRENDS

The SFWMD's systematic weather monitoring network was established in the 1990s and includes ET-driving variables like solar radiation, wind speed, relative humidity, and air temperature. Examining trends in these components can help explain ET trends. There are 15 active weather stations operated by the District. Seven stations were selected for trend analysis because they have longer periods of record than the other eight stations. The seven weather stations, from north to south, are S61W, S78W, CFSW, Belle GL, LOXWS, S140W, and S331W.

The raw data for air temperature, relative humidity, and wind speed are daily mean values, while the total solar radiation is a daily summary. The raw data went through QA for missing gaps and abnormal values. Annual values at the seven stations were averaged to represent the whole region.

Figure 2B-35 depicts the trends of air temperature and relative humidity. The air temperature shows a slightly upward trend, but it is not statistically significant at 0.05 (MK Test p = 0.7576). The relative humidity shows a downward trend, and it is statistically significant at 0.05 (MK Test p = 0.0343). A downward relative humidity means there is an upward vapor pressure deficit, which contributes to an upward ET trend. Studies show that evaporation or ET rate is not very sensitive to air temperature variations when the vapor pressure deficit is constant; instead, it typically is more sensitive to variations in radiation, humidity, and wind speed (Monteith and Unsworth 1990). Relative humidity and air temperature are inversely proportional, if the moisture stays the same. As air temperature increases, its relative humidity decreases; when temperature drops, relative humidity increases (Thomson 1986). **Figure 2B-35** shows the trends of monitored relative humidity and air temperature match their theoretical relationship, though moisture was not considered. The discrepancy in statistical significance probably comes from data issues (i.e., monitoring accuracy and consistency).

Figure 2B-36 depicts the trends of solar radiation and wind speed. Wind speed shows a slightly downward trend, but it is not statistically significant at 0.05 (MK Test p = 0.1125). The total solar radiation measured by the District (black rings) shows a downward trend (MK Test p = 0.0473); however, the data quality appears to be an issue because the sensors did not catch some peaks that were witnessed during past drought events (e.g., the 2006–2007 drought). The USGS also has a solar radiation data set covering Florida. The data set was derived from insolation indexes, which were retrieved with scanning satellite images for cloud coverages. From 1996 to 2015, the average insolation of the second 10 years is approximately 1 megajoules per square meters per day (MJ/m^2/d) or 0.011574 kilowatt day per square meter (kW-day/m^2) greater than the first 10 years (Mecikalski et al. 2018). The USGS solar radiation data are also depicted in **Figure 2B-36** (pink diamonds) and are believed to be more reliable. The USGS data show an upward trend, with statistical significance at 0.05 (MK Test p = 0.0309).

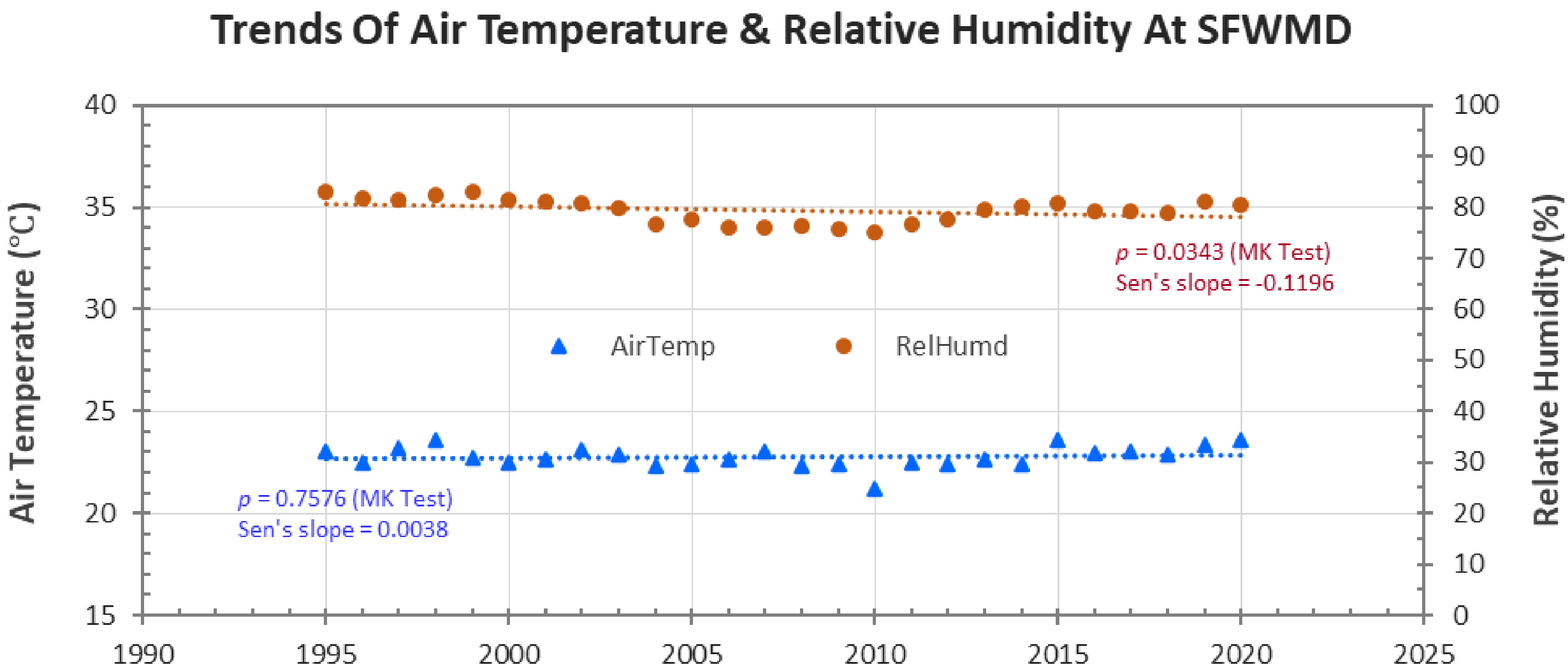

Figure 2B-35. Trends of air temperature and relative humidity across the District, 1995 to 2020.

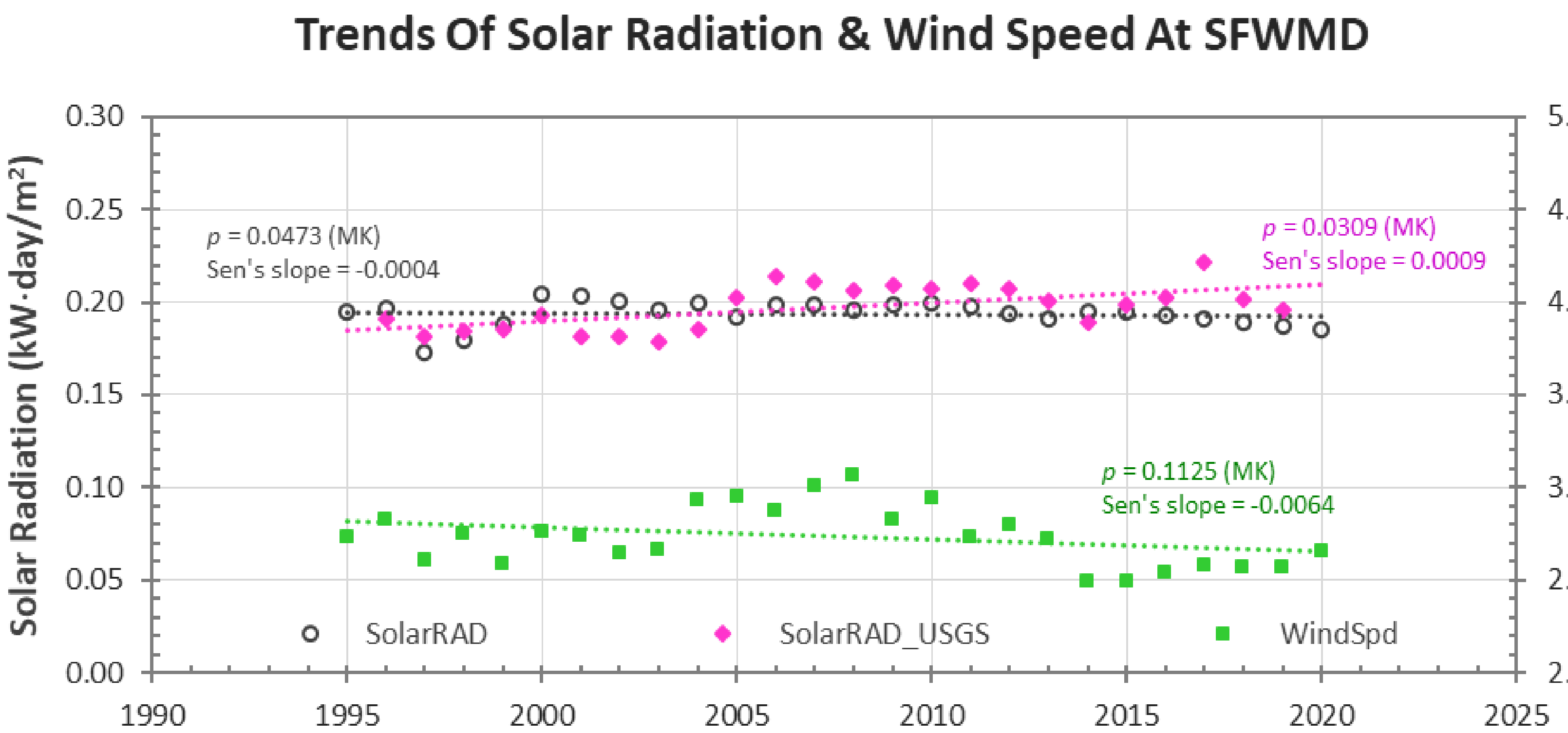

Figure 2B-36. Trends of total solar radiation and wind speed across the District, 1995 to 2020.

In summary, increasing solar radiation (insolation) and decreasing relative humidity were the two driving forces behind the upward ET trend in South Florida, while air temperature and wind speed have not had a strong affect on the trend (**Figure 2B-37**). Possible causes for increasing solar radiation include better air quality from stricter regulations on exhaust emissions (e.g., less aerosols from coal burning power plants and diesel engines), which results in less cloud cover and stronger ray penetration (Hidy et al. 2014). Changes in land use and land cover may also contribute to increases in solar radiation across the southeastern United States (Ellenburg et al. 2016). Changes (i.e., increases/decreases) in relative humidity and the rate of change is dependent on the interaction between temperature and the amount of water vapor (moisture) in the air. Because there is a lack of moisture data, the actual cause of the decreasing relative humidity cannot be determined at this point and should be further assessed in the future.

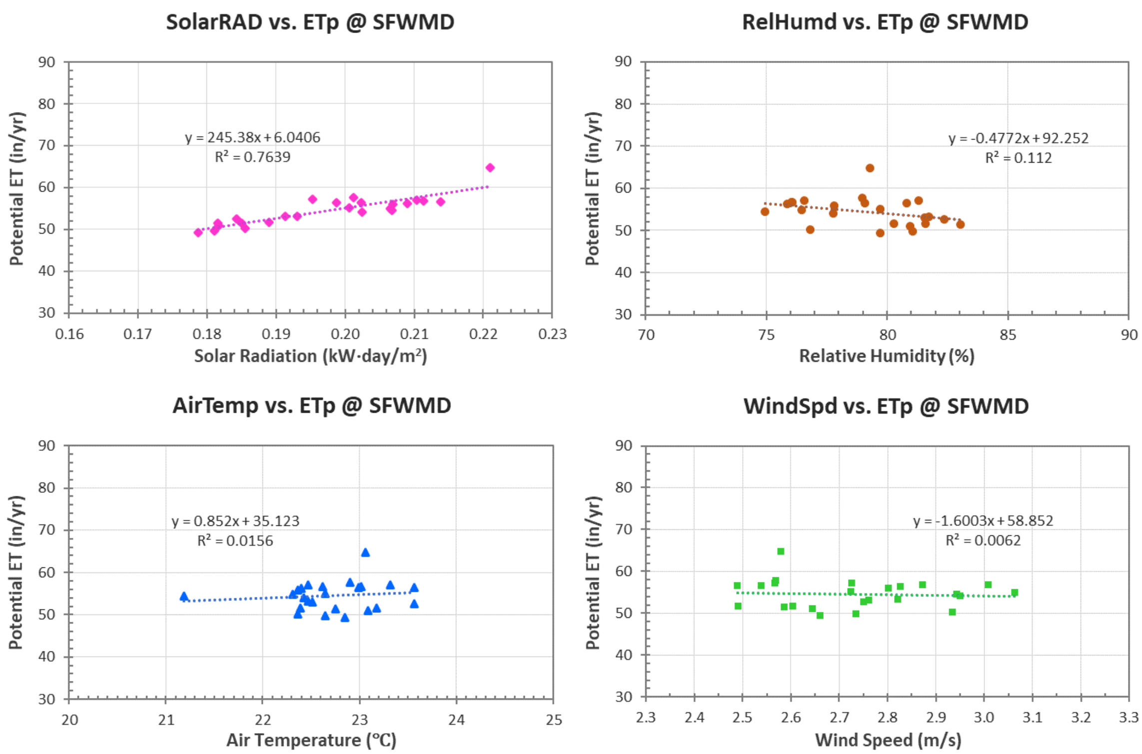

Figure 2B-37. Correlations between annual ET_p and environmental variables, 1995 to 2020.

Two other environmental factors (solar cycle and ozone depletion) were also reviewed for their roles in hydrological change in South Florida, but no significant contributions were found from them.

The Sun has an 11-year cycle of solar activities characterized by the rise and fall in the numbers and area of sunspots. Total solar irradiance is the radiant energy emitted by the Sun at all wavelengths outside Earth's atmosphere. Annual values of total solar irradiance vary slightly with the solar cycle, from 1,365.5 to 1,366.6 watt per square meter (W/m^2), only a 0.1% variation (Hathaway 2015). The amount reaching Earth's surface (as insolation) is reduced by atmospheric attenuation (e.g., reflection, absorption), which varies with location, time, and weather condition. The solar cycle plays a negligible role in driving global climate change because its magnitude is much smaller than the impact from greenhouse gases (Arias 2021).

Ozone is a gas that absorbs ultraviolet (UV) radiation from the Sun, especially UV-B (280 to 315 nanometers) and UV-C (100 to 280 nanometers), the shorter wavelength or higher energy rays that are harmful to all life forms. About 90% of Earth's ozone resides in the stratosphere (altitude 10 to 50 kilometers). Ozone distribution generally increases from the tropics (0 to 20°) to the mid-latitudes (30 to

60°) and polar regions (60 to 90°). There is little seasonal variation in tropics, but large variation in high-latitude regions. Ozone depletion was observed throughout the 1980s due to increases in reactive halogen gases (e.g., chlorine, bromine) resulting from human activities. In both hemispheres, ozone depletion is greater toward the poles and less near the equator. In the early 1990s, global ozone was depleted by 5% relative to the 1964–1980 average, but the depletion ratio has been declining since then due to the Montreal Protocol (1987), which controls the production and consumption of ozone-depleting substances. The abundance of total ozone is now 2%-3% below the 1964–1980 average, and it is projected to recover back to the 1964–1980 level around the middle of the 21st century. Although ozone depletion has led to increased UV radiation on Earth's surface, it is not the principal cause of global climate change because of its small volume compared to other potent greenhouse gases like CO_2 (Salawitch et al. 2019). Because of Florida's location between the tropics and mid-latitudes, the state's climate should not be heavily influenced by ozone depletion. In summary, the ET trend in Florida should be guided by interactive elements (e.g., humidity, cloudiness) within the troposphere (altitude 0 to 10 kilometers), rather than higher layers of the atmosphere.

COMMENTS AND RECOMMENDATIONS

Quality data are the backbone of any trend analysis. While all the parameters or variables involved in measurement, estimation, or assessment of ET demand come from a modern monitoring system, some need improvement. For example, solar radiation measured on the ground is extremely important because it is directly used in ET estimation and to calibrate other solar radiation estimating methods (e.g., the satellite image method). However, there are many data gaps and anomalies in the District weather stations, which impaired data usability; therefore, a more thorough monitoring scheme is under development for data enhancement. Air temperature is used globally to gauge climate change, and its importance cannot be overstressed. Besides the continuity of the current practice, its consistency among District weather stations should be improved with a tighter calibration procedure. The E_{pan} measurement has been collected at the S7 station for more than 60 years, the longest continuous observation in South Florida. This is a great asset to the District's monitoring network and should be preserved for future trend watch. A moisture (absolute) measurement currently is not in the monitoring system, but it is critical in assessing the trend of relative humidity; therefore, it should be considered for future monitoring plans to help understand the causes of the declining trend in relative humidity.

TIDAL ELEVATIONS AT COASTAL STRUCTURES

BACKGROUND

At the outskirts of the District's water management system, coastal gravity structures release inland water to tide while preventing saltwater intrusion. The District maintains an extensive hydrological monitoring network that includes coastal structures to support its day-to-day operation of the water management system, to meet reporting requirements, hydrologic and hydraulic modeling, and future project planning and design. Instantaneous water level data within the hydrological monitoring network is collected and archived in the District's hydrometeorological and water quality database, DBHYDRO. Historical water level data at downstream of coastal structures (tailwater stations) that are available in DBHYDRO were analyzed to detect any trend in time. Tailwater and headwater levels at the District's coastal structures are unique water and climate resilience metrics that indicate how sea level rise is affecting stormwater discharge capacity in South Florida. Movement of water through these coastal structures occurs via gravity, necessitating a sufficient hydraulic gradient between the inland canals (i.e., headwater) and tide (i.e., tailwater). The trend analysis metric characterizes sea level trend based on observed long-term historical water level data at coastal structures that can be used in addition to water level data at NOAA tidal stations.

The basic function of the region's stormwater management system is based on pre-determined operational ranges at which canal reaches are maintained. During wet conditions, coastal structures are opened to discharge stormwater to tide and prevent flooding. During dry conditions, coastal structures are closed to conserve water and prevent saltwater intrusion. The inland movement of saltwater could impact groundwater and drinking water systems.

When coastal structures discharge to the ocean, the water level difference between upstream (land side or headwater) and downstream (ocean side or tailwater) may be 6 inches or less for some structures, under design conditions. Higher tailwater conditions, as a result of sea level rise, reduce discharge capacity during high tides and impact the structure's ability to provide flood control, ultimately increasing flooding risks, as illustrated in **Figure 2B-38**.

OBSERVED TRENDS

Observed sea levels have been rising more rapidly over the past 20 years compared to previous periods of record, as indicated by the tidal water levels being monitored by SFWMD. Over the next 50 years, South Florida may experience sea levels that are 21 to 40 inches higher than 2000 levels, according to the latest Unified Sea Level Rise Projections (Southeastern Florida Regional Climate Change Compact 2019). To understand and summarize long-term water level conditions at coastal gravity structures, trend analyses on water level time series were conducted as part of the District's water and climate resilience metrics.

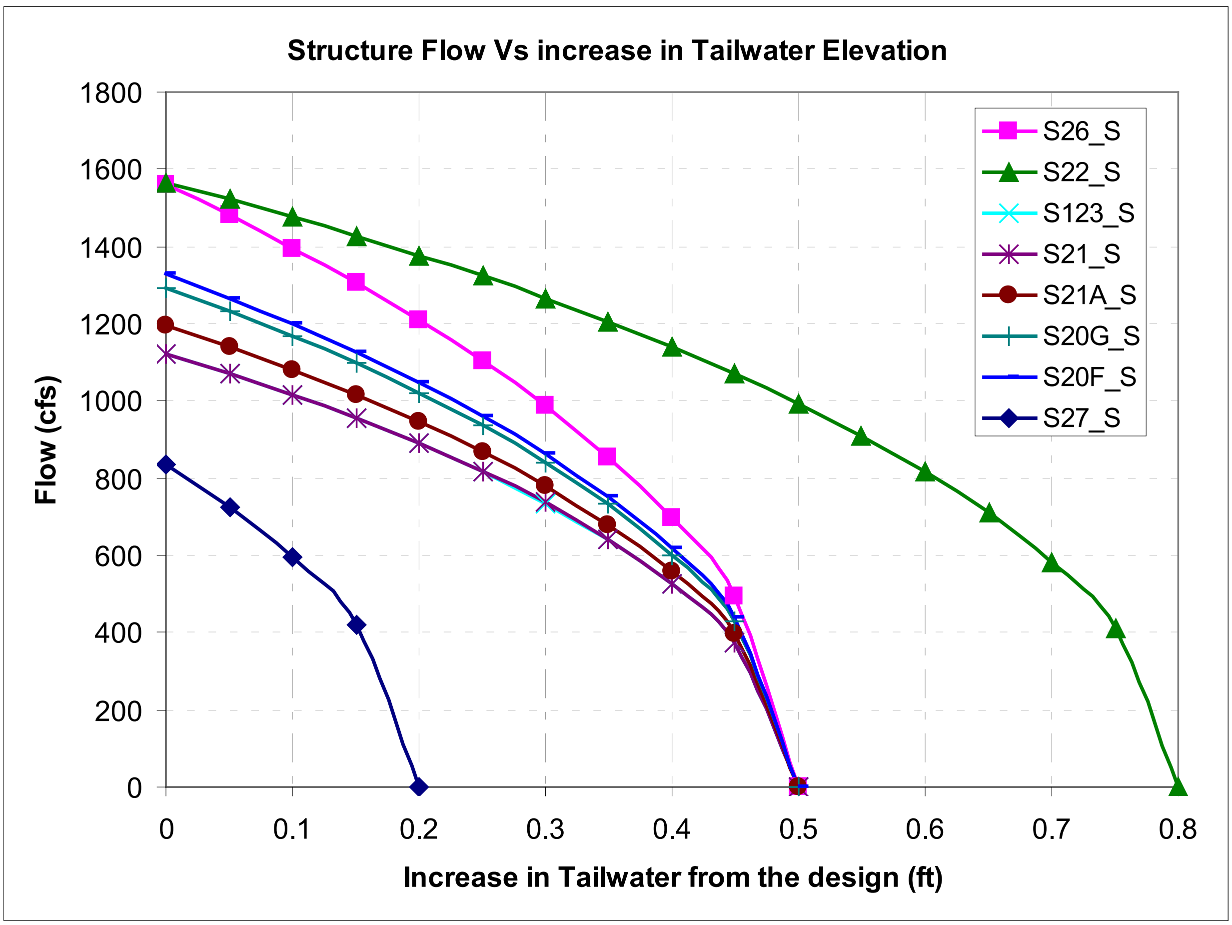

Figure 2B-38. Discharge capacity versus tailwater increase from design condition.

Figures 2B-39 through **2B-43** show the results of the trend analyses at selected coastal structures across the District over the period of record. Average annual tailwater stage is depicted by the blue line, and the linear trend of average annual tailwater stage is depicted by the red line. These figures illustrate an increasing trend in average annual water level downstream of coastal structures. Overall, the average annual water level increase ranges between 3.41 and 7.94 millimeters (mm)/year and the R^2 values for the linear trend range between 0.40 and 0.83, with a value closer to 1.0 indicating a significant trend. A comparison of the historical relative sea level trends at NOAA gauges confirmed an increasing annual average water level trend at coastal structures.

Along South Florida's west coast, annual water level ranges have increased between 5.12 and 7.94 mm at structures FU1, GG1, and HC1 (**Figure 2B-39**). **Figure 2B-40** depicts sea level trends at the Naples NOAA gauge based on monthly mean sea level. An increase of 3.11 mm/year in relative sea level trend has also observed at the Naples NOAA gauge (**Figure 2B-40**).

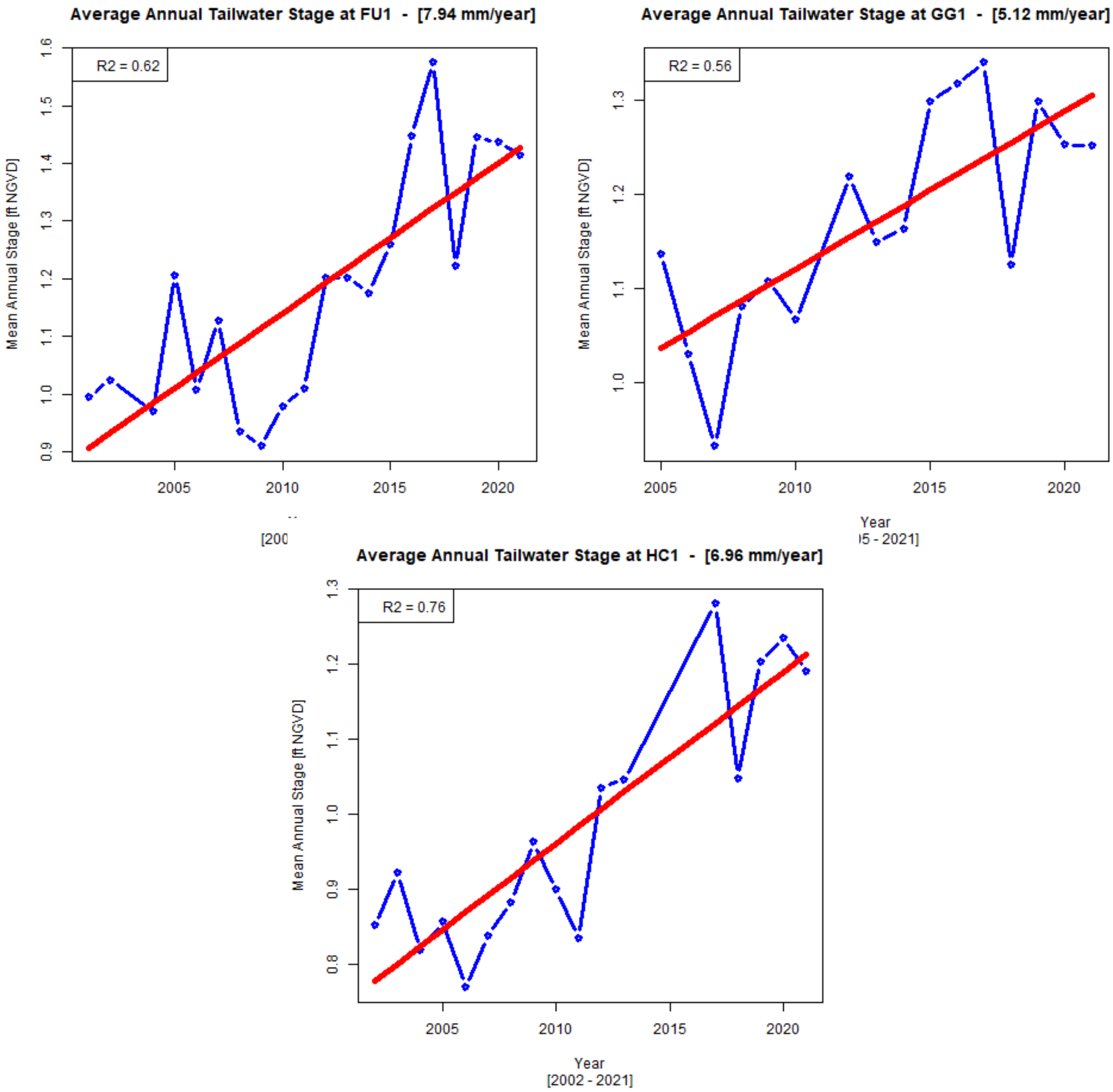

Figure 2B-39. Average annual tailwater stage at selected stations along South Florida's west coast. (Blue line is the average annual tailwater stage. Red line is the linear trend of average annual tailwater stage.)

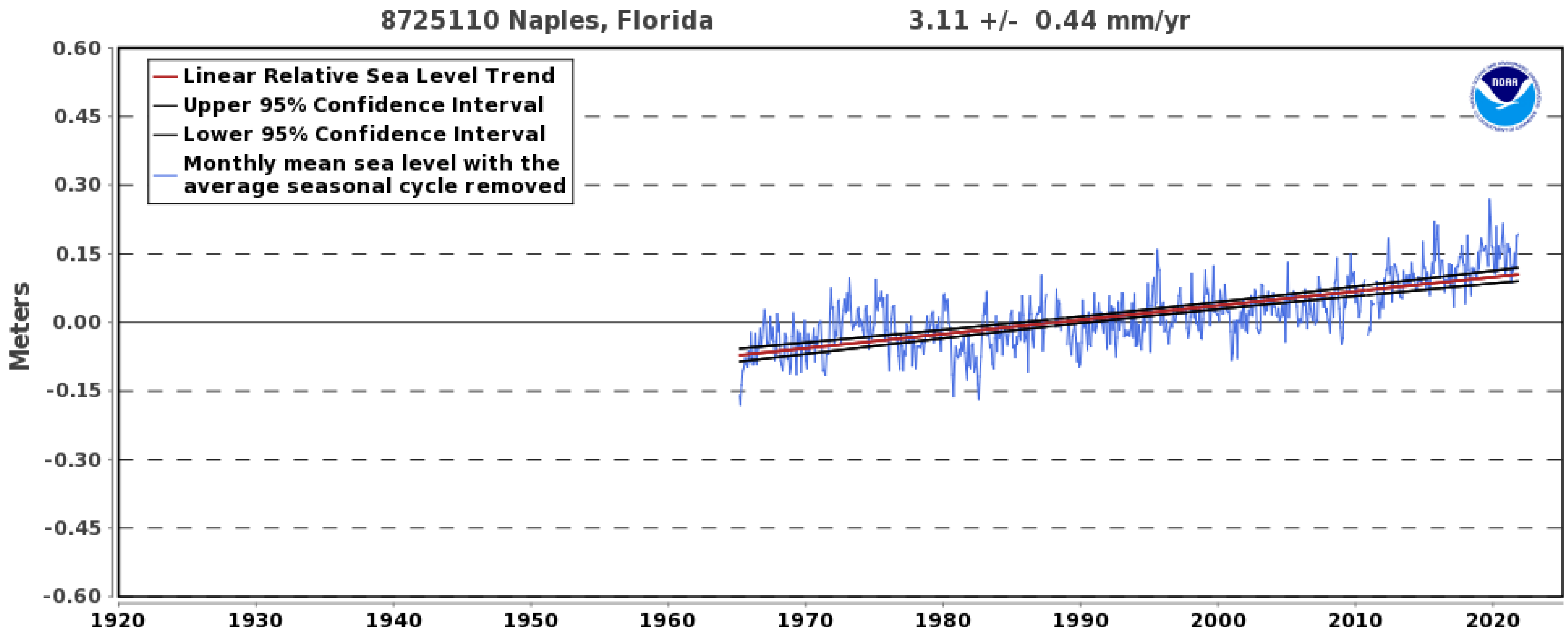

Figure 2B-40. Relative sea level trend at the Naples NOAA gauge.

Along South Florida's upper east coast, annual water level ranges have increased between 4.5 and 6.56 mm/year at structures S49, S44, S155, and S41 (**Figure 2B-41**).

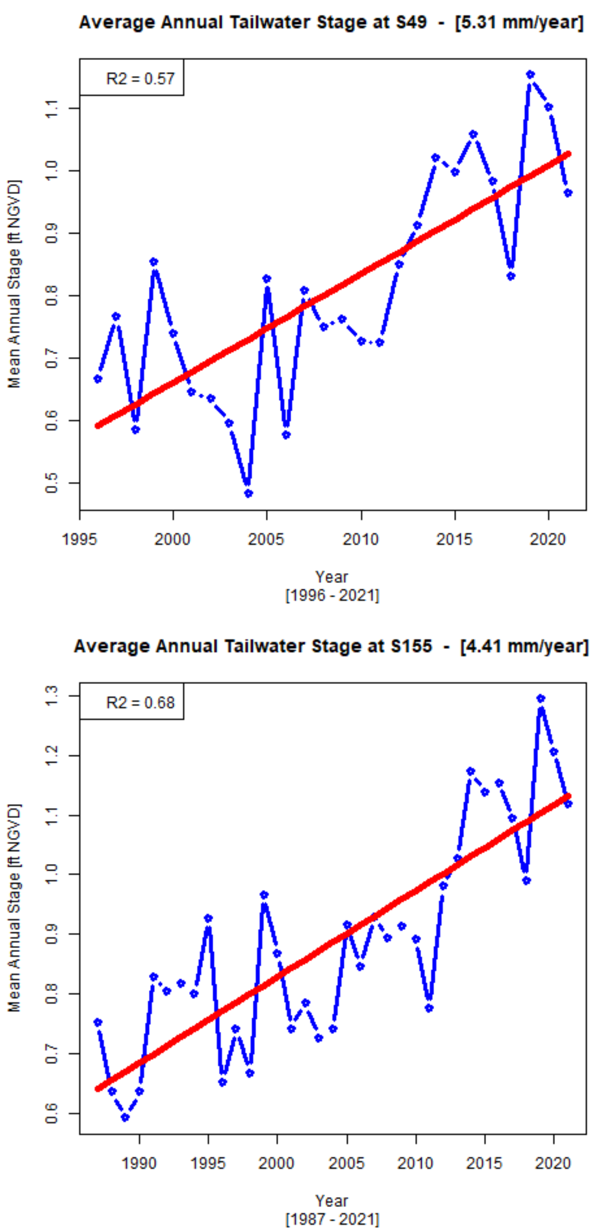

Figure 2B-41. Average annual tailwater stage at selected stations along South Florida's upper east. (Blue line is the average annual tailwater stage. Red line is the linear trend of average annual tailwater stage.)

In Broward County, within the Lower East Coast Planning Area, annual water level ranges have increased between 3.74 and 6.15 mm/year at structures G57, S33, G54, and S13 (**Figure 2B-42**).

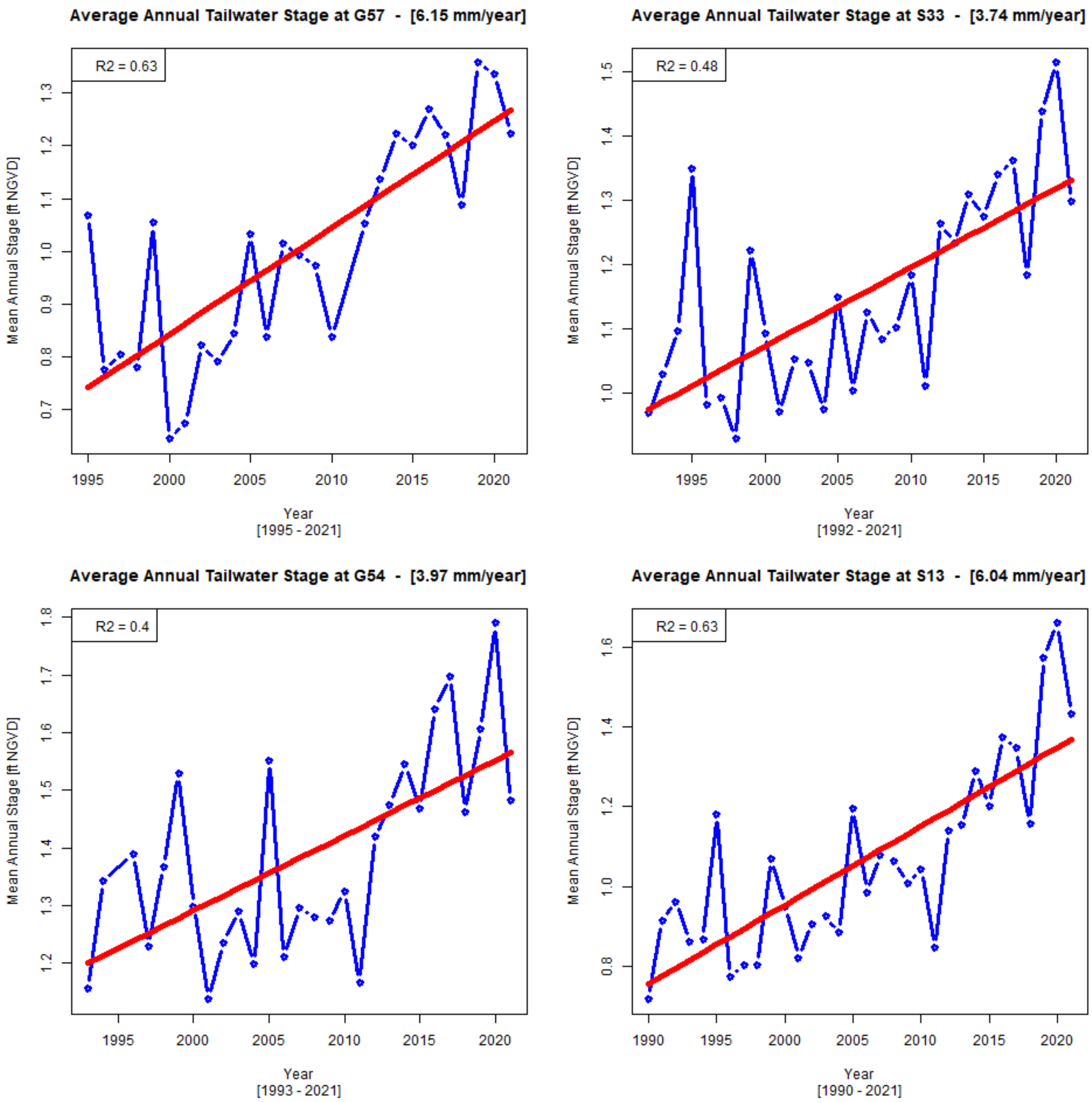

Figure 2B-42. Average annual tailwater stage at selected stations in Broward County. (Blue line is the average annual tailwater stage. Red line is the linear trend of average annual tailwater stage.)

In northern Miami-Dade County, within the Lower East Coast Planning Area, annual water level ranges have increased between 3.41 and 4.95 mm/year at structures S29, S28, S27, and S25B (**Figure 2B-43**).

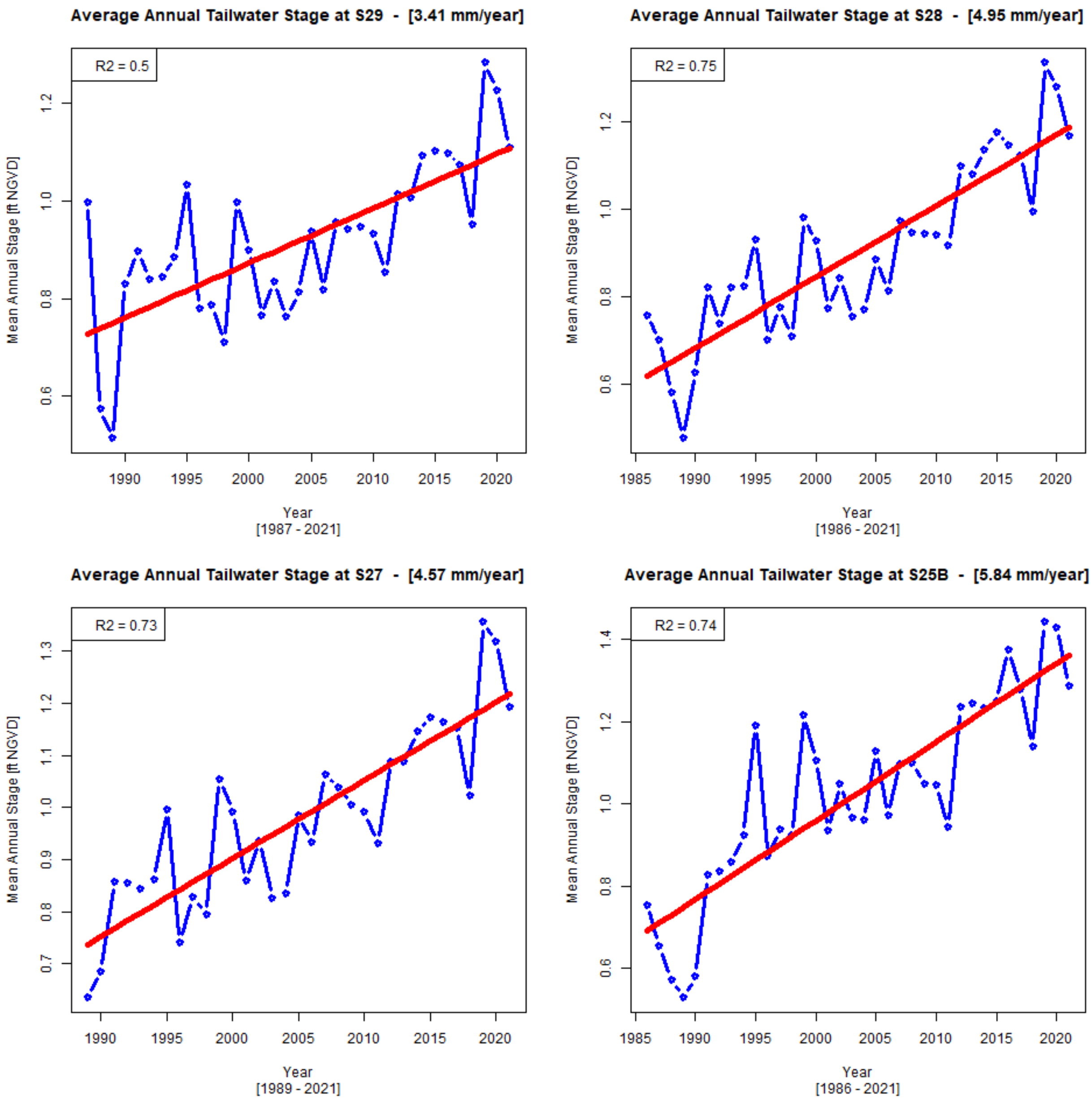

Figure 2B-43. Average annual tailwater stage at selected stations in northern Miami-Dade County. (Blue line is the average annual tailwater stage. Red line is the linear trend of average annual tailwater stage.)

In southern Miami-Dade County (**Figure 2B-44**), annual water level ranges have increased between 4.15 and 5.8 mm/year at structures S123, S22, S21A, and S20G. **Figures 2B-45** depicts sea level trends at the Virginia Key NOAA gauges based on monthly mean sea level. An increase of 2.97 mm/year in relative sea level trend has also observed at the Virginia Key NOAA gauge (**Figure 2B-45**).

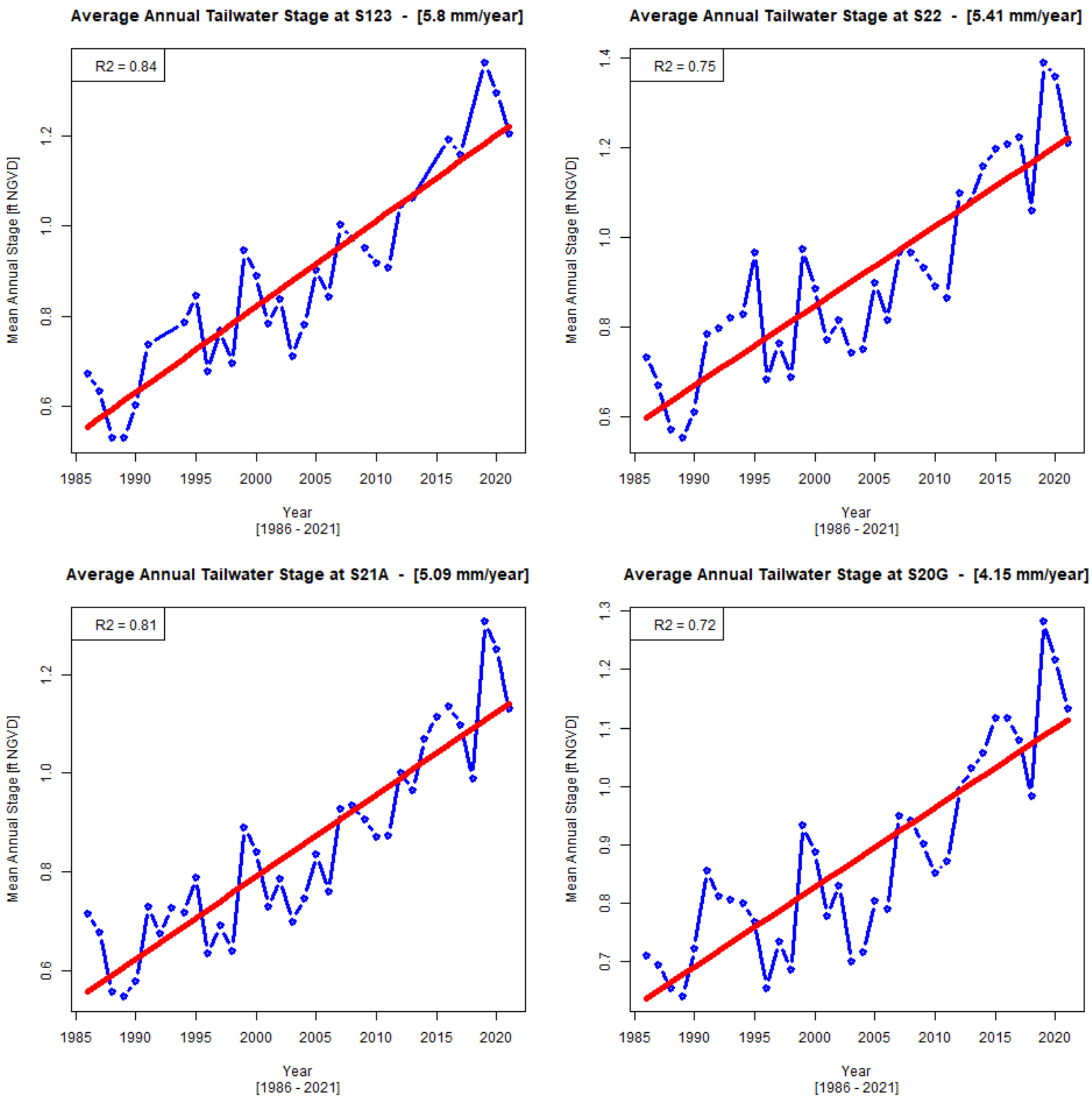

Figure 2B-44. Average annual tailwater stage at selected stations in southern Miami-Dade County. (Blue line is the average annual tailwater stage. Red line is the linear trend of average annual tailwater stage.)

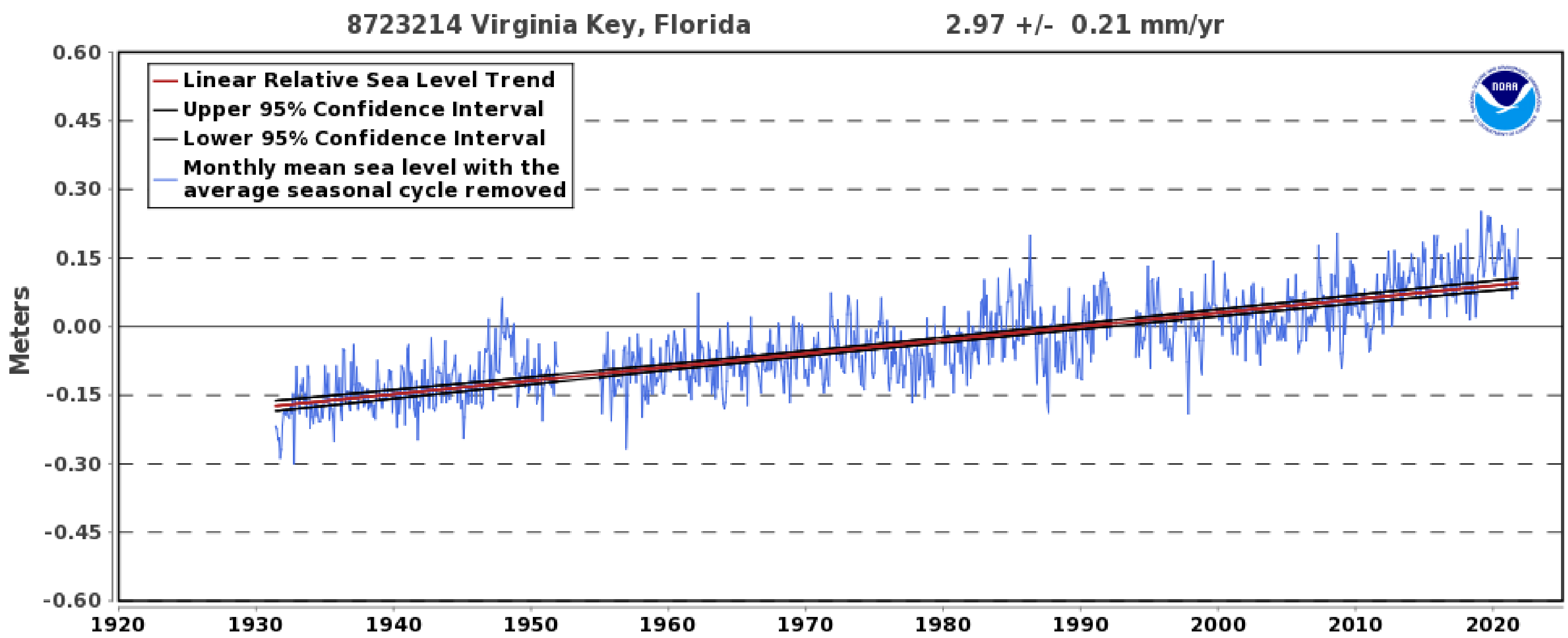

Figure 2B-45. Relative sea level trend at the Virginia Key NOAA gauge.

COMMENTS AND RECOMMENDATIONS

The headwater and tailwater levels at coastal structures data set is robust and unique to the SFWMD and constitutes an important metric that drives operations and informs resilience initiatives. The results of the trend analysis on historical observed data at coastal structures revealed that annual average water levels are increasing at coastal structures, and this was confirmed at NOAA gauges. Such conditions result in reduced flood discharge capacities at coastal structures and increase the potential for flooding in inland communities. Beyond flood protection, coastal structures are critical to protect water supply and coastal wellfields from saltwater intrusion.

The increasing trend in average annual water levels can be attributed to several influencing factors. These include global factors such as thermal expansion and sea level rise, and regional and local factors such as ocean currents, changes in rainfall, soil subsidence, and upstream flood control. In addition to adapting to and mitigating the negative impacts of increased water levels at coastal structures, there is a need to evaluate and better understand the extent of these influencing factors. As an example of the impacts to coastal structures from gravitational and ocean dynamics in South Florida, the Water Year 2021 Selected Storm Event Summaries in Chapter 2A, Volume I, of this year's SFER examines the extent and timing of the September through December 2020 king tides, as influenced by temperature, rainfall, storms, wind direction, and ocean currents. The findings concluded that the occurrence of king tides coinciding with inclement weather contributed to increased headwater levels at various coastal structures in South Florida during September and October 2020 specifically. Based on NOAA's extreme water level analysis at Miami Beach station, the maximum tidal water stages during the king tide event across five structures (S-27, S-28, S-29, S-20F, and S-13) corresponded to 10- to 100-year events. Coupled with the broader impacts of climate change and sea level rise, future king tide events could be more intense, last longer, and occur more frequently.

Future efforts could be enhanced through increased monitoring of the effects of ocean currents on water levels at coastal structures. Domingues et al. (2018) evaluated the acceleration of sea level rise along the East Coast (from Key West to North Carolina) from 2010 to 2015, which caused extensive flooding to large urban areas of Miami-Dade County. The rapidly rising sea level during that time period was predominantly caused by the warming of the Florida Current, which caused thermal expansion of the water column and therefore coastal sea level to rise. Parallel efforts by the SFWMD were conducted to assess how changes in the Florida Current affect the intensity of the Gulf Stream and long-term sea level rise and decadal variability. The analysis proved to be an important examination of the available data. Although the findings did not yield a strong correlation between the Gulf Stream and observed accelerated sea level rise, they did confirm a significant correlation with sea surface temperature and thermal expansion. Additionally, the study identified data gaps in the period of record and the need for continued monitoring. Applicable analyses and models were produced that could be used to fill the data gaps and capture weaker correlations, and the study concluded that considering additional variables can help understand these processes better and subsequently enhance model applications.

WATER QUALITY TRENDS IN SOUTH FLORIDA

BACKGROUND

Four water quality parameters (temperature, dissolved oxygen, specific conductance, pH) were selected as key resilience metrics because severe water quality impacts to water bodies are aggravated by weather conditions in which climate plays a part (Michalak 2016). Changes in temperature have strong implications on water and ecosystems (Jeppesen et al. 2020). While other chapters of the SFER report water quality for the purposes of water supply, ecosystem monitoring, and regulatory compliance, this chapter (1) introduces the long-term observations and trend analysis results for water quality, advanced as part of the water and climate resilience metrics effort, and (2) sets a foundation to incorporate water quality in the context of resiliency and to interpret the actual influence of climate factors in the context of observed trends, along with other possible influencing factors. There is a need to scientifically interpret the what factors are driving the trends identified in water quality, and this Year 1 report includes the initial findings at selected locations and the validity of the observed trends.

Water quality resiliency at the ecosystem level is the ability to protect waterways, natural and recreational areas, and agricultural lands. Water quality resiliency at the utility level is the ability to provide an uninterrupted supply of water. Events that may disrupt the continued delivery of safe water supply within the system pose risks to water quality. Water quality is directly affected by physio-biogeochemical processes within the system, as well as natural disturbances such as drought, rainfall, storm events, and local water conditions. With increasing temperature, sea level rise, and other climate change observations, there is urgent need to document and interpret current and future impacts to water quality. It is important to note that anthropogenic impacts at local, regional, and global levels will complicate determination of the effects of climate change on water quality. Anthropogenic impacts include water management, changes in land use, agricultural activity, deforestation, industrial and domestic effluents, and recreational activities (Khatri and Tyagi 2015).

Heat transfer from the atmosphere, sunlight, or other thermal source results in changes in water temperature, which influence physical, chemical, and biological reactions in the water column. Dissolved oxygen concentrations and water pH are inversely affected by water temperatures. As water temperatures increase, dissolved oxygen concentrations and water pH decrease. In contrast, rising water temperatures increase the rate of evaporation of a water body. As more water evaporates, specific conductance, which reflects the amount of dissolved material (e.g., major ions) in water, will also increase. Therefore, water temperature, dissolved oxygen, pH, and specific conductance were selected as water quality metrics for resiliency assessment because of their relationship to climate change and because they are the most frequently measured water quality parameters.

WATER QUALITY DATA AND TRENDS

District projects with water quality components typically monitor water temperature, dissolved oxygen, pH, and specific conductance at various inland waterways, lakes, and estuaries. Each location has varying data collection frequencies and time-of-day sample collections. As a first step of investigating the potential use of water quality as a metric for climate change, trend analyses were performed using water temperature, dissolved oxygen, water pH and specific conductance data collected in Lake Okeechobee between November 1972 and June 2020. Data collected at six in-lake stations (**Figure 2B-46**) were aggregated into monthly averages, and trends were determined using the Seasonal Mann-Kendall (SK) test.

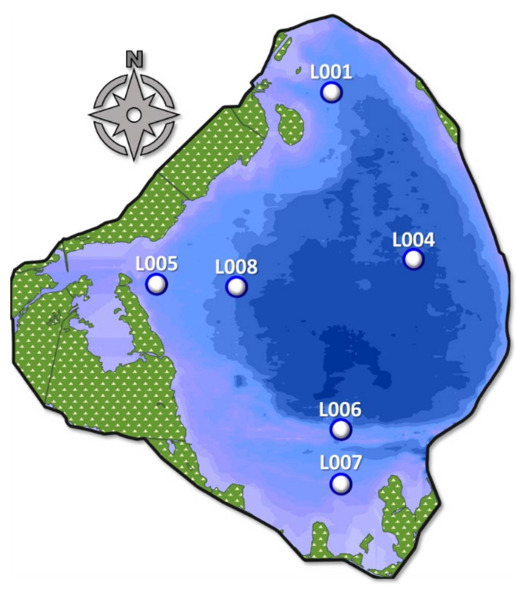

Figure 2B-46. Location of the six water quality stations (white dots) used in summarizing water quality data in Lake Okeechobee.

Trends observed in the water quality data were used to demonstrate if potential effects from climate change could be observed using a long period of record. A significance level (α) of 0.05 was used for the analyses. Lake Okeechobee was selected because it is one of the major receiving water bodies in South Florida, and a long period of record exists for water quality data. A summary of findings from the SK trend test for each parameter is provided in **Table 2B-7**. A more detailed discussion of the statistical approach and trend analyses is available in Maran et al. (2020).

Table 2B-7. Water quality trends initially observed using historical data in Lake Okeechobee (Maran et al. 2020).

Metric	Observed Trend
Water Temperature	Although, the trend in water temperature exhibits a positive trend (Sen = 0.001), the trend is not statistically significant (p = 0.81) and not measurable over the period of record (November 1972 through June 2020).
Dissolved Oxygen	Dissolved oxygen levels exhibited a statistically significant decreasing trend (Sen = -0.004; p-value = 0.040) over the period of record. However, the observed change in dissolved oxygen concentrations is not readily measurable over this period.
Water pH	Lake water pH exhibited an increasing trend (Sen = 0.001). However, the change in pH over the period of record was not statistically significant (p-value = 0.051), and the determined rate of change is not measurable.
Specific Conductance	A significant decreasing trend (p-value <0.001) in specific conductance levels was observed over the period of record. Over the 48-year period, specific conductance decreased 40% (Sen = -5.4) from 680 microsiemens per centimeter (µS/cm) in December 1972 to 400 µS/cm in June 2020.

The water temperature analysis provided some insight to the data set that were not obvious from the initial trend analysis. Water temperature data for cooler months showed an increasing trend over the period of record. The observed increases in water temperature are shown in **Figure 2B-47**, where monthly (seasonal) water temperatures are presented as averages by decade.

Figure 2B-48 provides the seasonal change in specific conductance in Lake Okeechobee during the period of record, by decade. The plot shows that specific conductance levels were consistently decreasing from an average of 624 microsiemens per centimeter (µS/cm) for 1973-1983 to an average of 396 µS/cm for 2013-2020. The latter reflects typical specific conductance levels observed in Florida lakes (Hand 2004).

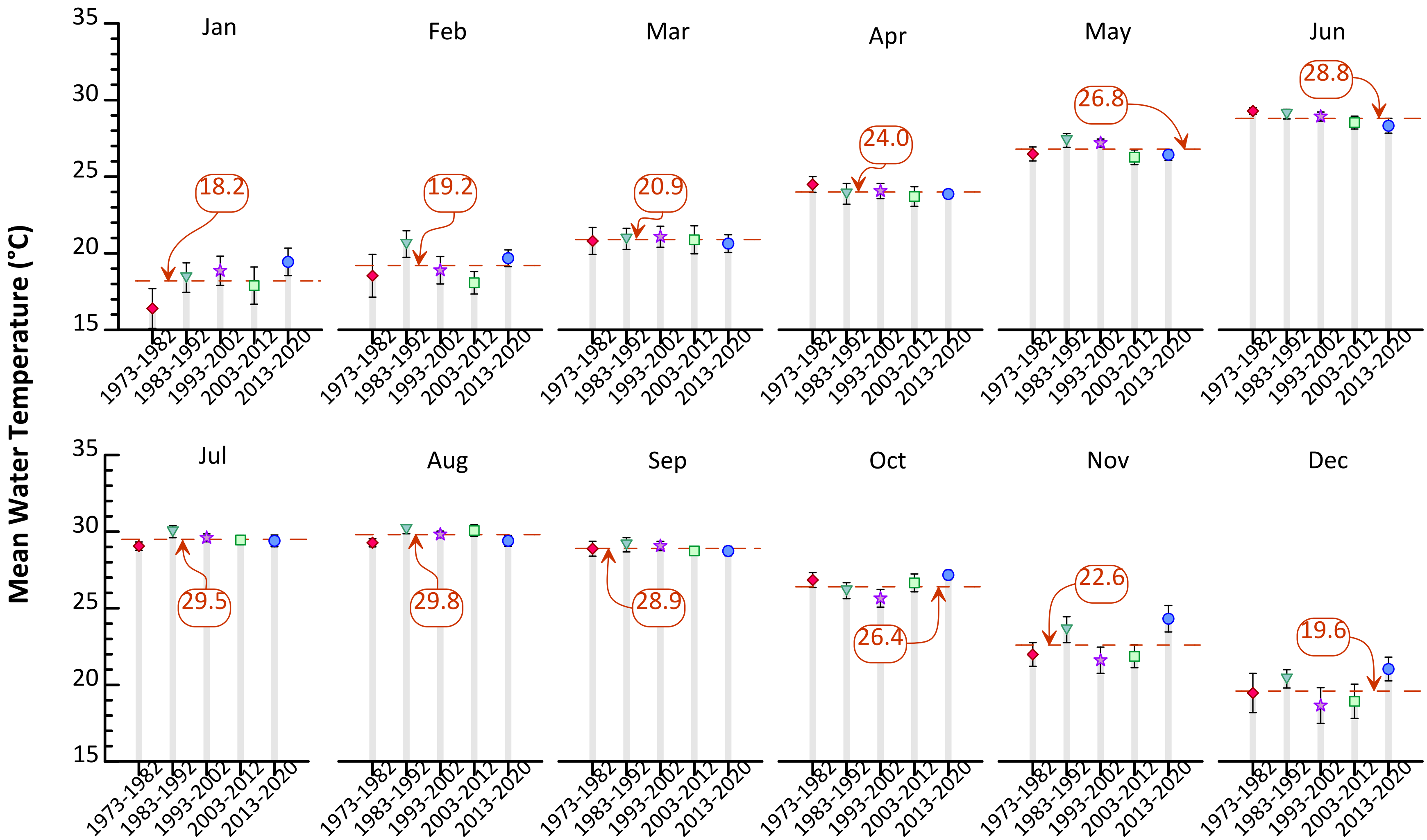

Figure 2B-47. Average seasonal/monthly water temperature (error bars = standard error) in Lake Okeechobee by decade. Red dashed line represents period of record mean (mean value provided in bubble).

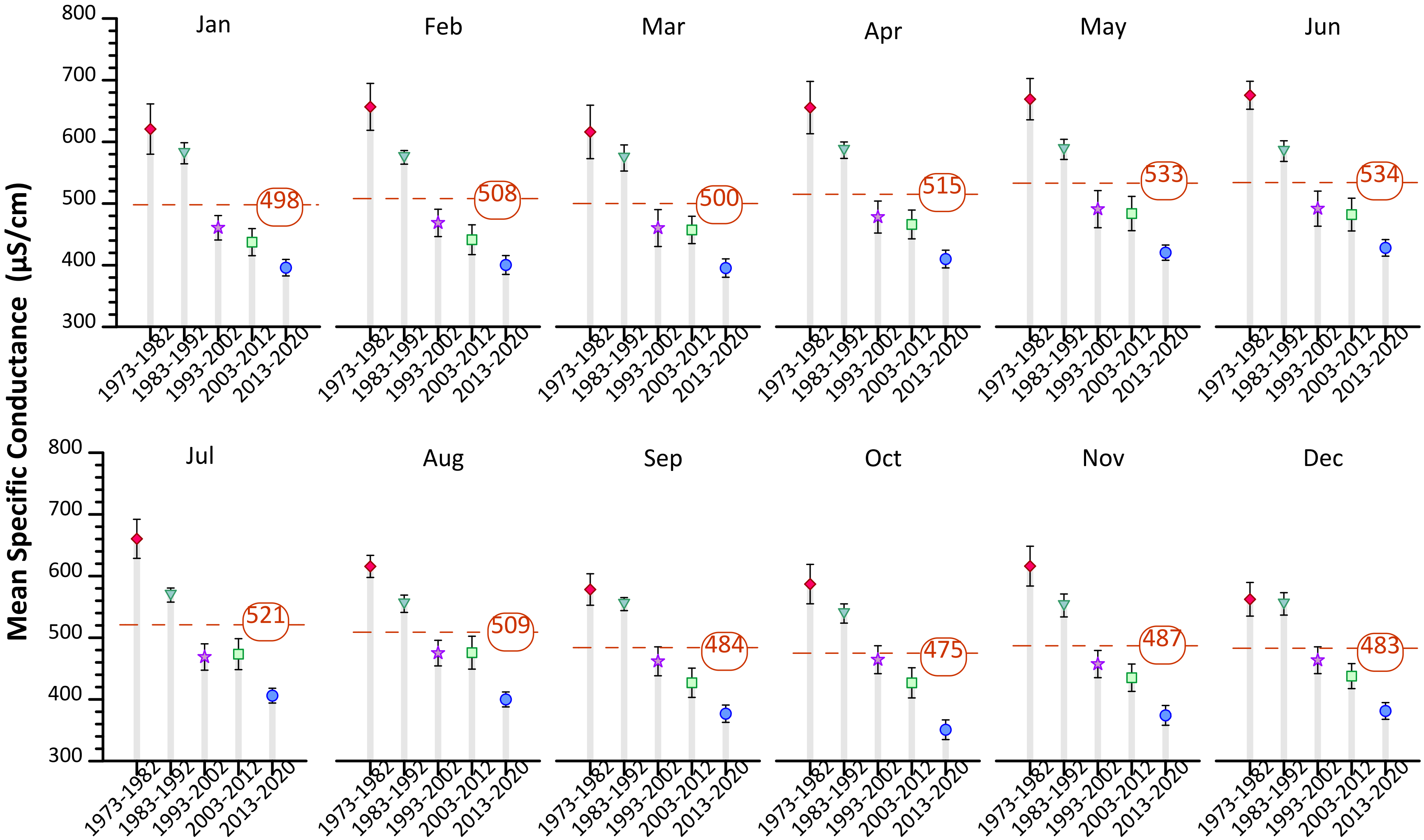

Figure 2B-48. Average seasonal/monthly specific conductance (error bars = standard error) in Lake Okeechobee by decade. Red dashed line represents period of record mean (mean value provided in bubble).

IONIC COMPOSITION AS A POTENTIAL INFLUENCING FACTOR ON SPECIFIC CONDUCTANCE TREND

The trend analysis for specific conductance provided the most apparent and significant change over the 48-year period of record. Thus, it is important to determine what produced the observed decreasing trend and to confirm if the observed trend could be associated with climate change or if other factor(s) influenced the results.

Data collected for major ions of calcium, magnesium, sodium, chlorine, bicarbonate, and sulfate (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO^{3-}, and SO_4^{2-}, respectively) in Lake Okeechobee were used to provide insight regarding the observed change of specific conductance levels. If the observed change resulted from dilution due to increased precipitation, then the ionic composition and inter-ionic ratios should remain relatively unaltered. However, if the ionic composition changes over time, then the resulting trend may be associated with a change of source water to the lake.

Figure 2B-49 shows the observed decrease in specific conductance in Lake Okeechobee may have resulted from a change in the source water to the lake. Stiff diagrams were used to graphically depict the ionic composition of Lake Okeechobee water by decade. During 1973-1982, lake water was co-dominated by Na-Cl and Ca-HCO_3. This composition changed over the decades to more Ca-HCO_3 dominated by 2013-2020. The Na:Ca ratios shown in **Figure 2B-49** support the observations that earlier decades were more dominated by Na-Cl than the latter decades. Na:K ratios showed an incremental decrease over the period of record. The high Na:K ratios observed in earlier decades suggest a more marine-like source, possibly connate seawater (i.e., relict seawater) underlying portions of the watershed (Chen et al. 2006; Pollman and James 2011). Maran et al. (2020) provides a more in-depth discussion regarding these initial findings.

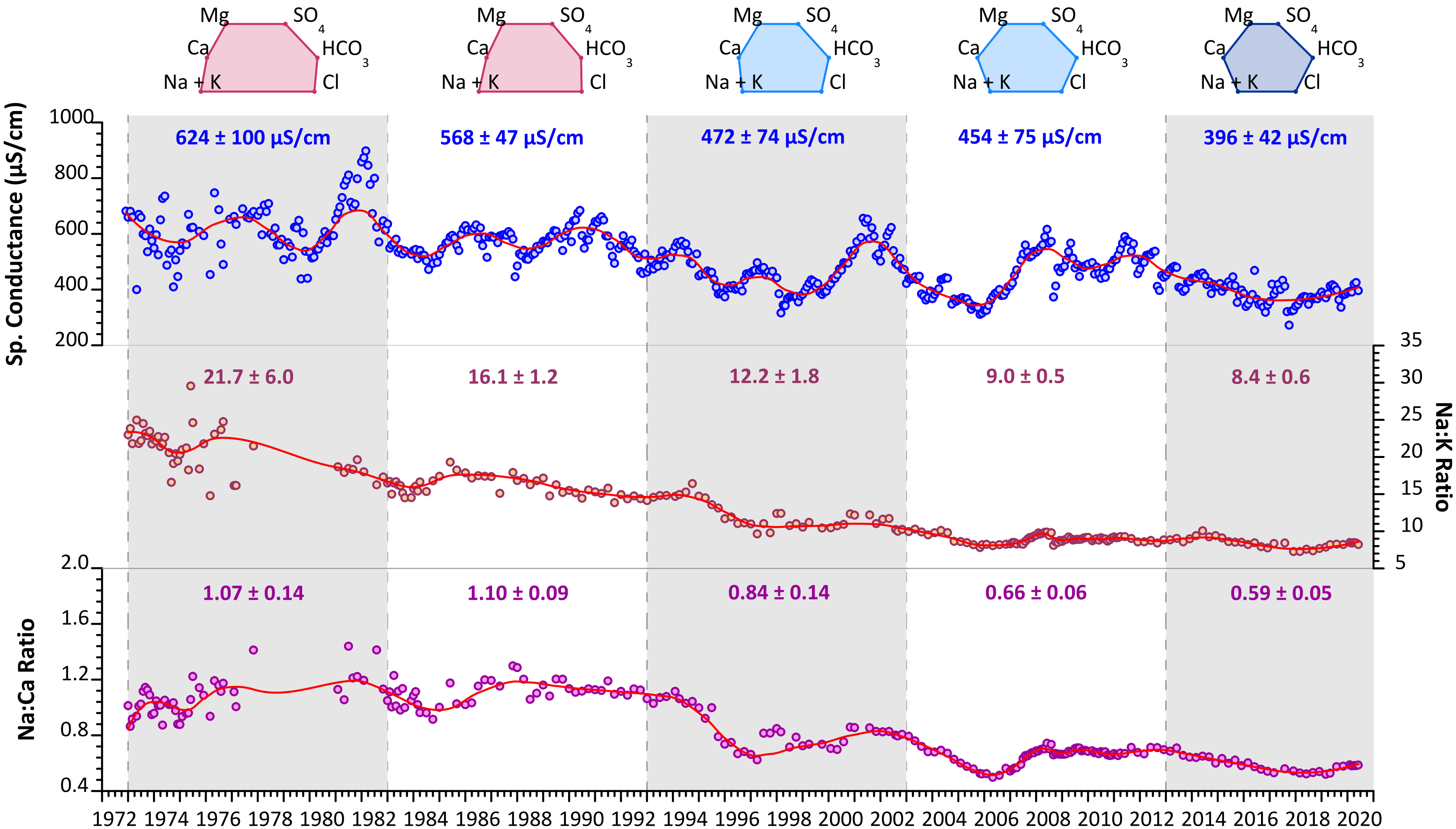

Figure 2B-49. Time series plots of monthly specific conductance, Na:K ratios, and Na:Ca ratios with decadal means and standard errors from November 1973 to June 2020. Stiff diagrams above the time series plots provide graphical representations of ionic compositions over the presented decades.

COMMENTS AND RECOMMENDATIONS

Changes in air and water temperature as well as precipitation have predictable effects on water quality. However, attributing variations in water quality as a function of climate change is complex due to multiple cascading factors that exert greater influence on water quality, such as changes in land use, water management, and other anthropogenic activities that can occur across local, regional, and global scales (Murdoch et al. 2000; Bates et al. 2008; Michalak 2016).

Any analysis used in resiliency assessment must attempt to differentiate natural processes, operational rules, and other controllable variables from those associated with climate change. Additional considerations (e.g., sampling regimes, frequency, and time of collection) must be accounted for in future analyses associating climate change with changes in water quality.

There are a multitude of local and regional interactions and risk events Districtwide that impact water quality. Additional water and climate resiliency metrics project efforts will attempt to identify more comprehensive approaches to water quality responses to climate change and evaluate the water system's abilities to respond to disturbances and improve resilience. Future recommendations include leveraging existing data from active, continuous monitoring water quality loggers with periods of record of at least five years. Statistical evaluation of these data will attempt to identify potential changes in water quality in responses to climatic influences. As continuous monitoring data are collected at finer and more consistent time intervals, a more robust data set can be assembled. Any future analysis of water quality data should include, at a minimum, statistical summaries, trend analyses (SK test), and change point analyses (to identify potential shifts in the data). Evaluation of other water quality parameters may be required to identify if changes in these parameters are associated with identifiable climatic changes for more robust metrics such as air temperature, rainfall, and ET.

CONCLUSION

The future of successful water resource management in South Florida will be influenced by the understanding of how climate-related long-term trends and other associated changing conditions are impacting the District's multiple objectives and the region's ability to provide flood protection, water supply, and ecosystem restoration. The continuous assessment and availability of water and climate resilience metrics established as part of this effort will be essential in achieving this understanding.

This chapter detailed the data and analyses, potential influencing factors, and future monitoring considerations for three climate metrics (rainfall, ET, and water levels at coastal structures) and four resilience metrics (water temperature, dissolved oxygen, specific conductance, and pH) to begin differentiating influences of climate and non-climate factors. The evaluation of these metrics and correlation with other metrics may be required to determine if observed changes are associated with identifiable climatic changes or other influencing factors, mainly system operations and other anthropogenic activities.

Overall conclusions for each of the seven metrics included in this chapter are presented below:

- Regional trend analyses of 83 years of data show rainfall trends vary among the District's 14 rainfall regions and among the wet, dry, and transitional seasons on a monthly and annual basis. Spatial variability of rainfall is large and highly influenced by the oceans surrounding the Florida peninsula, the large lakes within the state, and the inland flow of coastal sea breezes as well as tropical storms and hurricanes that bring heavy rainfall to South Florida. The results emphasize the need for continuous average rainfall and frequency trend analyses to link climatic influences and observed trends, as well as model projections. The determination of rainfall thresholds and the associated number of events over/under defined thresholds is needed to better understand extreme wet and dry extremes.

- Historical data from 1961 to 2020 show an upward trend in ET, specifically ET_p. Enhanced ET monitoring that is uniform and consistent during collection is needed to develop more reliable trend analyses for future projections. Additionally, it is recommended that atmospheric monitoring include moisture (absolute) to assess the observed decreasing trend in relative humidity.
- High tide events and increased tidal stages exceeding predetermined design standards at coastal structures are becoming more frequent and more intense, as observed in daily maximum sea level time series and upward trending monthly average mean sea levels. In addition to adapting to and mitigating the negative impacts of increased water levels at coastal structures, there is a need to evaluate and better understand the extent of these influencing factors such as global thermal expansion and sea level rise, and regional and local factors such as ocean currents, changes in rainfall, soil subsidence, and upstream flood control.
- Monthly water quality data collected between November 1972 and June 2020 at six monitoring stations within Lake Okeechobee exhibited an increasing trend in water temperature (though not statistically significant), a statistically significant decreasing trend in dissolved oxygen and specific conductance, and no quantifiable change in pH values. Attributing variations in these parameters to climate change is complex due to multiple cascading factors that influence water quality. Analyses of water quality parameters must differentiate natural processes, anthropogenic activities, and operational rules from those associated with climate change.

In future SFERs, Chapter 2B will present developments on the other water and climate resilience metrics, quantification of influencing factors, and correlation with other selected metrics. Future chapters also will explore additional resiliency monitoring considerations. These efforts provide a means to evaluate the significance of water and climate observations, and how they compare to historical trends. In addition, the links between major findings in Chapters 2A and 2B will continue to support the understanding of how the observations summarized in Chapter 2A are part of long-term trends or represent shifts documented in Chapter 2B, and how these long-term trends or shifts may be associated with climate change.

LITERATURE CITED

Abtew, W. 1996. Evapotranspiration measurements and modeling for three wetland systems in South Florida. *Journal of American Water Resources Association* 32(3):465-473.

Ali, A., and W. Abtew. 1999. *Regional Rainfall Frequency Analysis for Central and South Florida*. Technical Publication WRE 380, South Florida Water Management District, West Palm Beach, FL.

Ali, A., M. Hussein, and C. Aguirre. 2006. *Regional Frequency Analysis of Daily Rainfall Maxima*. South Florida Water Management District, West Palm Beach, FL.

Bates B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof (editors). 2008. *Climate Change and Water*. Intergovernmental Panel on Climate Change Secretariat, Geneva, Switzlerland.

Chen M., S.H. Daroub, T.A. Lang, and O.A. Diaz. 2006. Specific Conductance and Ionic Characteristics of Farm Canals in the Everglades Agricultural Area. *Journal of Environmental Quality* 35:141-150.

Domingues, R., G. Goni, M. Baringer, and D. Volkov. 2018. What caused the accelerated sea level changes along the U.S. East Coast during 2010–2015? *Geophysical Research Letters* 45(24):13,367-13,376, doi 10.1029/2018GL081183.

Ellenburg, W, R. McNider, J. Cruise, and J.R. Christy. 2016. Towards an understanding of the 20th Century cooling trend in the southeastern United States: Biogeophysical impacts of land use change. *Earth Interact* 20(18):1-31.

Good, S.P., D. Noone, and G. Bowen. 2015. Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. *Science* 349:175-177, doi:10.1126/science.aaa5931.

Gunderson, L.H. 1989. Accounting for discrepancies in pan evaporation calculations. *Water Resources Bulletin* 25(3):573-579.

Hand J. 2004. *Typical Water Quality Values for Florida's Lakes, Streams, and Estuaries*. Florida Department of Environmental Protection. Tallahassee, FL.

Hanson, R.L. 1991. Evapotranspiration and Droughts. In: R.W. Paulson, E.B. Chase, R.S. Roberts, and D.W. Moody (editors). *National Water Summary 1988-89: Hydrologic Events and Floods and Droughts*. Water-Supply Paper 2375, United States Geological Survey, Washington, DC.

Hathaway, D.H. 2015. The solar cycle. *Living Reviews in Solar Physics* 7(1), doi 10.12942/lrsp-2010-1.

He, X., and J. Sheffield. 2020. Lagged compound occurrence of droughts and pluvials globally over the past seven decades. *Advancing Earth and Space Science* 47(14), doi 10.1029/2020GL087924.

Hidy, G.M., C.L. Blanchard, K. Baumann, E. Edgerton, S. Tanenbaum, S. Shaw, E. Knipping, and I. Tombach. 2014. Chemical climatology of the southeastern United States, 1999–2013. *Atmospheric Chemistry and Physics* 14(21):11893-11914.

Hobbins, M.T., and J.A Ramirez. 2004. Trends in pan evaporation and actual evapotranspiration across the conterminous U.S.: Paradoxical or complementary? *Geophysical Research Letters* 31:L13503, doi: 10.1029/2004GL019846.

Hobbins, M.T., J.A. Ramirez, and T.C. Brown. 2001. Trends in regional evapotranspiration across the united states under the complementary relationship hypothesis. Pages 106–121 in: *Hydrology Days 2001*, Colorado State University, Fort Collins, CO.

Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld. 2021. Technical Summary. In: Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.), *Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, United Kingdom.

Jeppesen E., D.E. Canfield, R.W. Bachman, M. Søndergaard, K.E. Havens, L.S. Johansson, T.L. Lauridsen, T Sh, G. Warren, G. Ji, and M.V. Hoyer. 2020. Toward predicting climate change effects on lakes: A comparison of 1656 shallow lakes from Florida and Denamrk reveals substantial differences in nutrient dynamics, metabolism, trophic structures, and top-down control. *Inland Waters* 10(2):197-211.

Khatri, N., and S. Tyagi. 2015. Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Frontiers in Life Science* 8 (1):23-39.

Kirschbaum, M.U.F., and A.M.S. McMillan. 2018. Warming and elevated CO_2 have opposing influences on transpiration. Which is more important? *Current Forestry Reports* 4:51-71.

Maran A.C., A. Ali, C. Coronado, C. Carlson, K. Smith, N. Iricanin, Tibebe Dessalgne, and Y.K. Zhu. 2020. *Draft - Water and Climate Resiliency Metrics, Phase 1: Long-Term Observed Trends*. South Florida Water Management District. West Palm Beach, FL.

McIllroy, I.C. and D.E. Angus. 1964. Grass, water and soil evaporation at Aspendale. *Agricultural Meteorology* 1:201-224.

Mecikalski, J.R., W.B. Shoemaker, Q.L. Wu, M.A. Holmes, S.J. Paech, and D.M. Sumner. 2018. High-resolution GOES Insolation-evapotranspiration data set for water resource management in Florida: 1995–2015. *Journal of Irrigation and Drainage Engineering* 144(9):04018025.

Michalak A.M. 2016. Study role of climate change in extreme threats to water quality. *Nature* 21(535):349-350.

Monteith, J.L. and M. Unsworth. 1990. *Principles of Environmental Physics*, Second Edition. Edward Arnold, Lodon, United Kingdom.

Murdoch P.S., J.S. Baron, and T.L. Miller 2000. Potential effects of climate change on surface water quality in North America. *Journal of the American Water Resources Association* 36(2):347-366.

O'Leary, J.W. and G.N. Knecht. 1981. Elevated CO_2 Concentrations increase stomate numbers in *Phaseolus vulgaris* leaves. *Botanical Gazzette* 142:436-441.

Pollman C.D., and R.T. James 2011. A simple model of internal loading of phosphorus in Lake Okeechobee. *Lake and Reservoir Management* 27:1:15-27.

Roderick, M.L., M.T. Hobbins, and G.D. Farquhar. 2009. Pan evaporation trends and the terrestrial water balance. *Geography Compass* 3(2):746-760.

Rose, C.W., J.E. Begg, G.F. Byrne, B.W.R. Torssell, and J.H. Goncz. 1972. A simulation model of growth-field environment relationships for townsville stylo (*Stylosanthes humilis* H.B.K.) pasture. *Agricultural Meteorology* 10:61-183, dio 10.1016/0002-1571(72)90020-9.

Rowland-Bamford, A.J., C. Nordenbrock, J.T. Baker, G. Bowes, and L.H. Allen, Jr. 1990. Changes in stomatal density in rice grown under various CO_2 regimes with natural solar irradiance. *Environmental and Experimental Botany* 30:175-180.

Salawitch, R.J., D.W. Fahey, M.I. Hegglin, L.A. McBride, W.R. Tribett, and S.J. Doherty. 2019. *Twenty Questions and Answers About the Ozone Layer: 2018 Update, Scientific Assessment of Ozone Depletion: 2018*. World Meteorological Organization, Geneva, Switzerland. ISBN: 978-1-7329317-2-5.

Schlesinger, W.H., and S. Jasechko. 2014. Transpiration in the global water cycle. *Agricultural and Forest Meteorology* 189-190:115-117.

Southeastern Florida Regional Climate Change Compact Sea Level Rise Ad Hoc Work Group. *Unified Sea Level Rise Projection Southeast Florida, 2019 Update*. https://southeastfloridaclimatecompact.org/.

SFWMD. 2009. *Climate Change and Water Management in South Florida*. Interdepartmental Climate Change Group, West Palm Beach, FL.

SFWMD. 2021. *Water and Climate Resilience Metrics Report Phase I: Long-term Observed Trends*, West Palm Beach, FL.

Stanhill, G. 1976. *The CIMO International Evaporimeter Comparisons*. WMO Report No. 449, World Meteorological Organization, Geneva, Switzerland.

Thomson, G. 1986. *The Museum Environment*, *2nd Edition*. Butterworth-Heinemann, London, United Kingdom.

Urban, J, M.W. Ingwers, M.A. McGuire, and R.O. Teskey. 2017. Increase in leaf temperature opens stomata and decouples net photosynthesis from stomatal conductance in *Pinus taeda* and *Populus deltoides* x Nigra. *Journal of Experimental Botany*, 68(7):1757-1767.

van de Geijn, S.C., and J. Goudriaan. 1996. 5. The Effects of Elevated CO_2 and Temperature Change on Transpiration and Crop Water Use. Pages 101-121 in: Bazzaz, F.A., and W.G. Sombroek (eds.), *Global Climate Change and Agricultural Production*, Food and Agriculture Organization of the United Nations, Washington, DC.

Wei, Z.W., K. Yoshimura, L. Wang, D.G. Miralles, S. Jasechko, and X.H. Lee. 2017. Revisiting the Contribution of Transpiration to Global Terrestrial Evapotranspiration. *Geophysical Research Letters* 44: 2792-2801, doi: 10.1002/2016GL072235.

Woodward, F.I. and F.A. Bazzaz. 1988. The responses of stomatal density to CO_2 partial pressure. *Journal of Expirimental Botany* 39:1771-1781.

Zhang, Y.Q., J.L. J.L. Pena-Arancibia, T.R. McVicar, F.H.S. Chiew, J. Vaze, C.M. Liu, X.J. Lu, H.X. Zheng, Y.P. Wang, Y.Y. Liu, D.G. Miralles, and M. Pan, 2016. Multi-decadal Trends in Global Terrestrial Evapotranspiration and Its Components. *Scientific Reports* 6:19124.