

Statistical and state space methods unravel marsh stage response to rainfall and water management

GEER2025

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GEER

Greater Everglades Ecosystem Restoration

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Coral Springs, FL

UC San Diego



SCRIPPS INSTITUTION OF
OCEANOGRAPHY



Sugihara Lab

Quantitative Ecology and Data-Driven Theory

How does one disentangle influences of rainfall and water management in the hydrologic response of the Everglades?

Have water level conditions in the Everglades changed or entered new state regimes as a result of management plans?



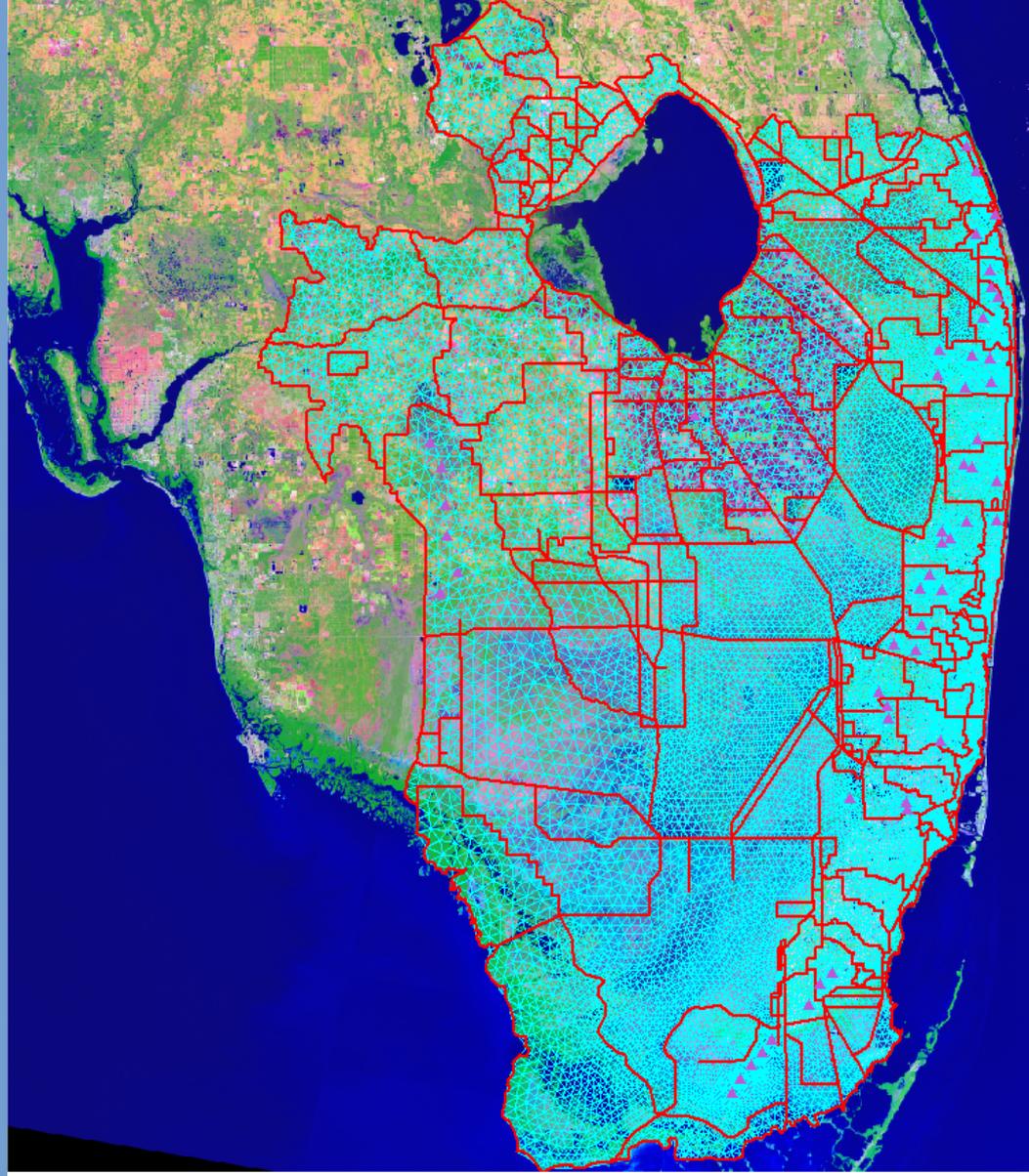
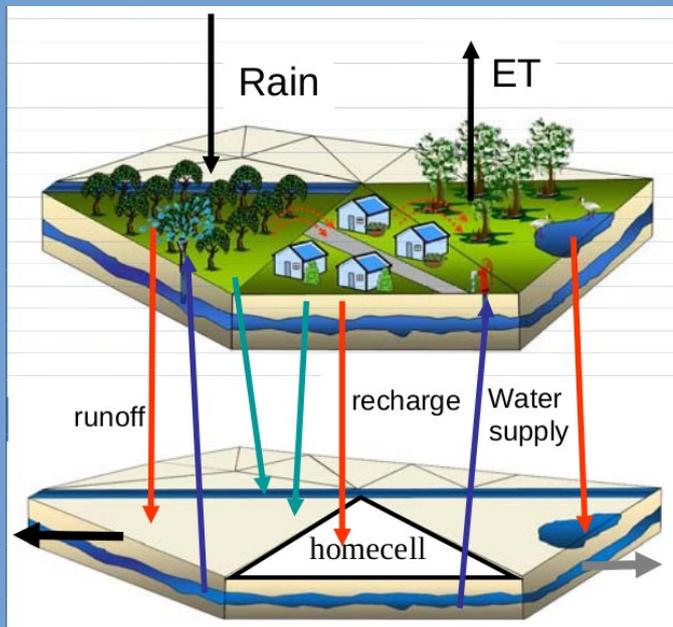
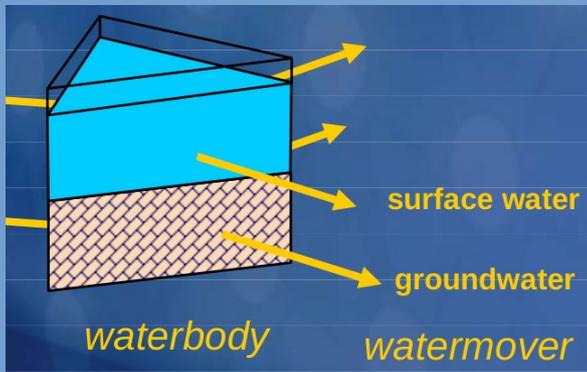






RSM

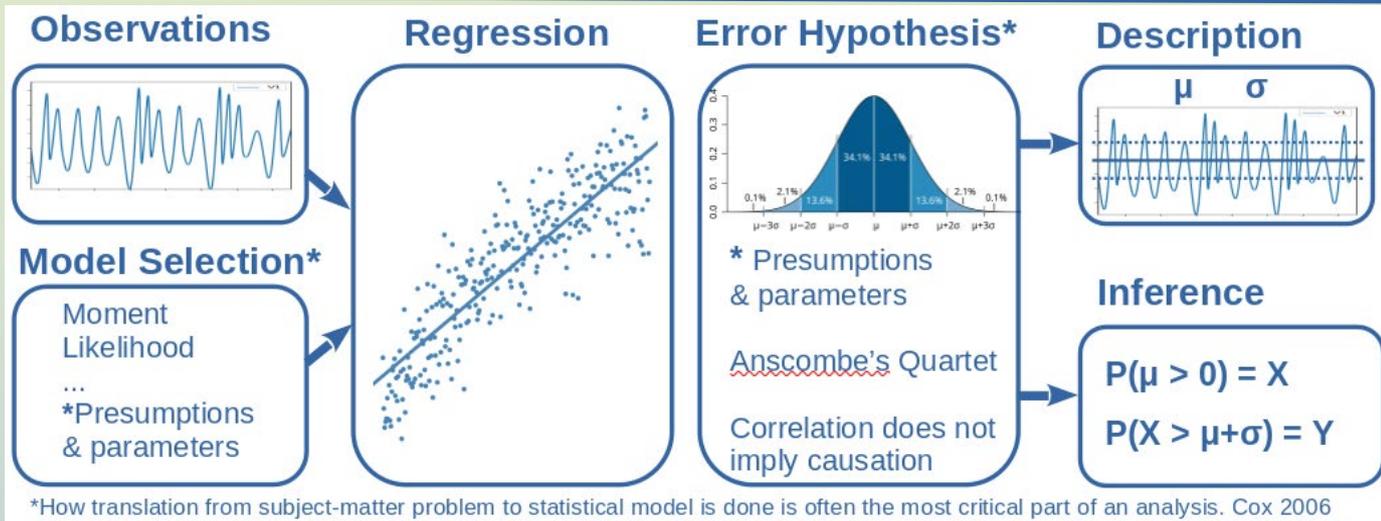
$$0 = \frac{\partial}{\partial t} \int_{cv} d\mathcal{V} + \int_{cs} (\mathbf{E} \cdot \mathbf{n}) dA$$



Data Driven Analysis

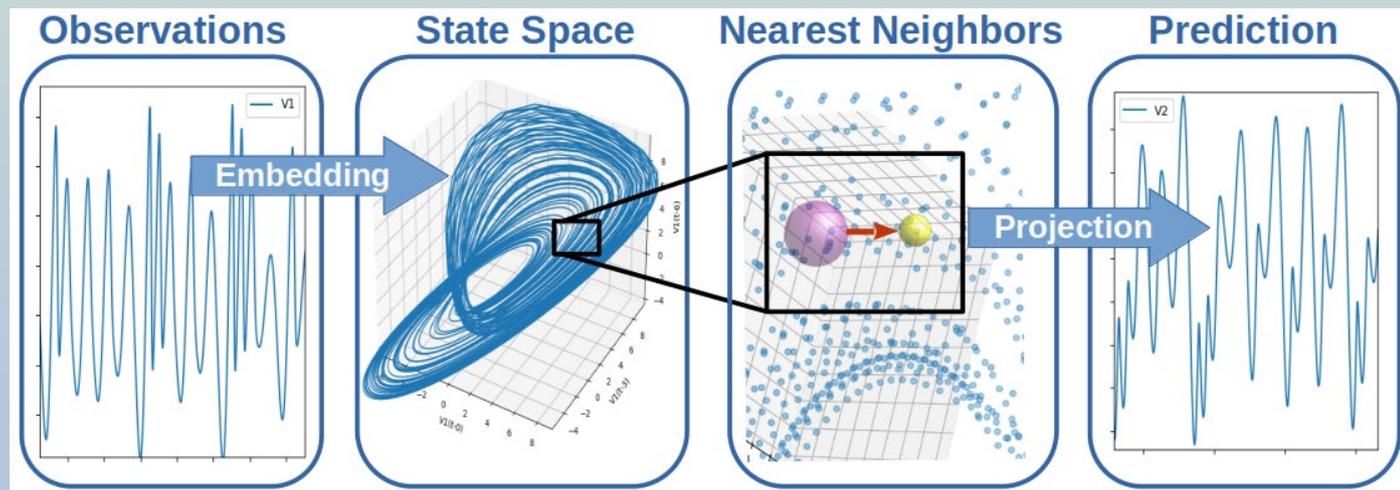
Statistics

Descriptive
Inference

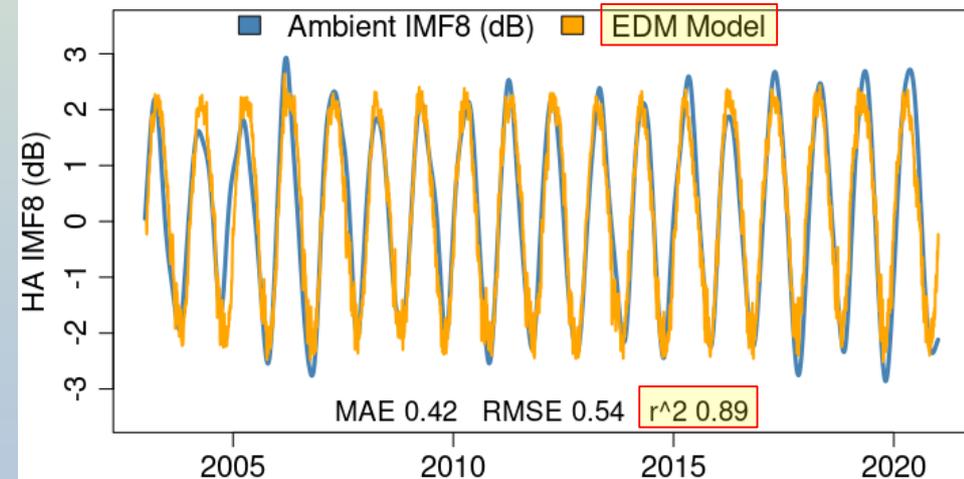
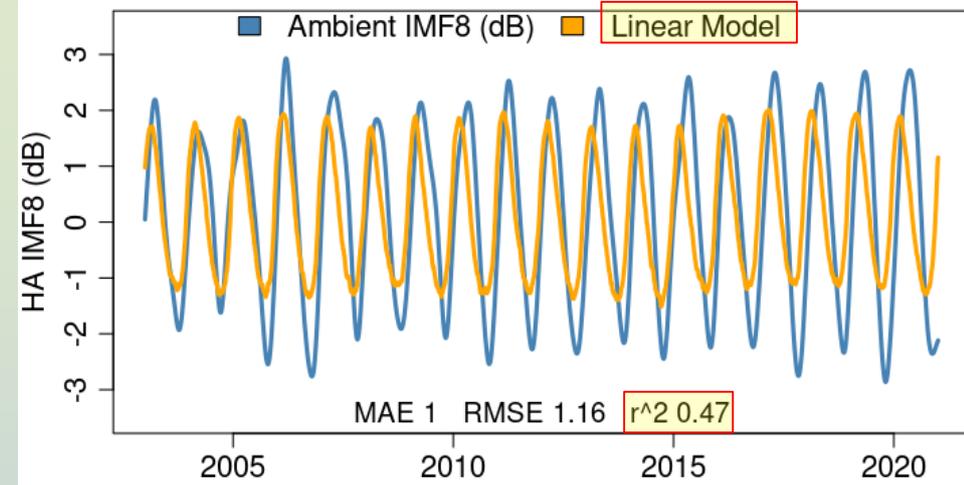
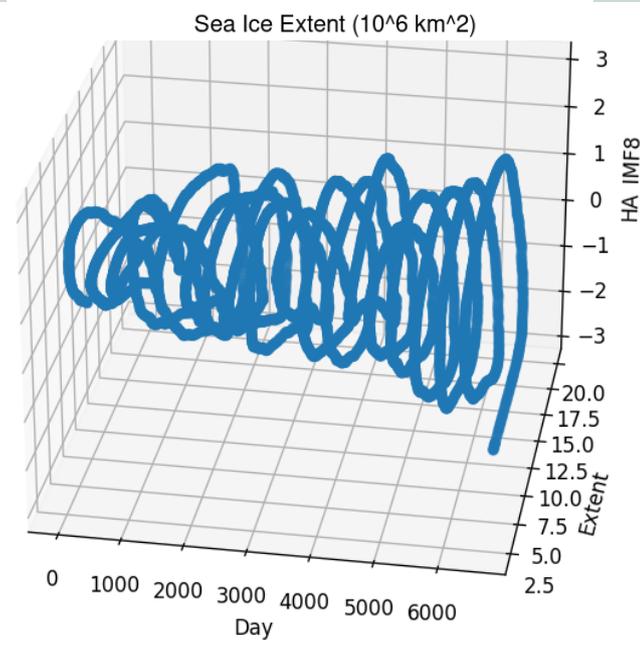
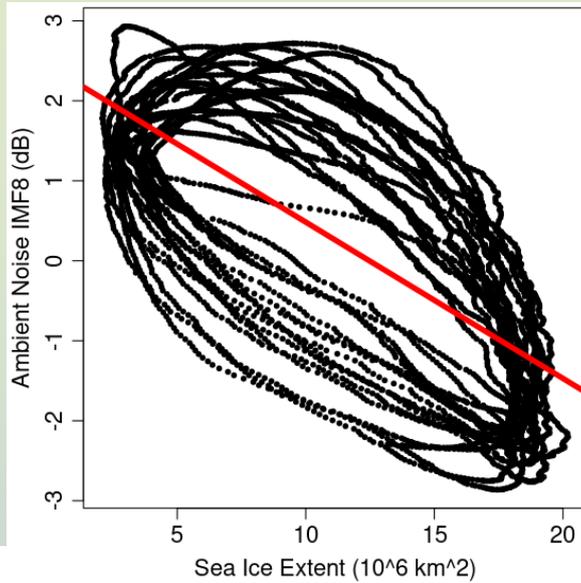


State space

Model free
Inference



State space techniques are predicated on identifying an appropriate dimension of the the state space from which predictions and inferences can be made.

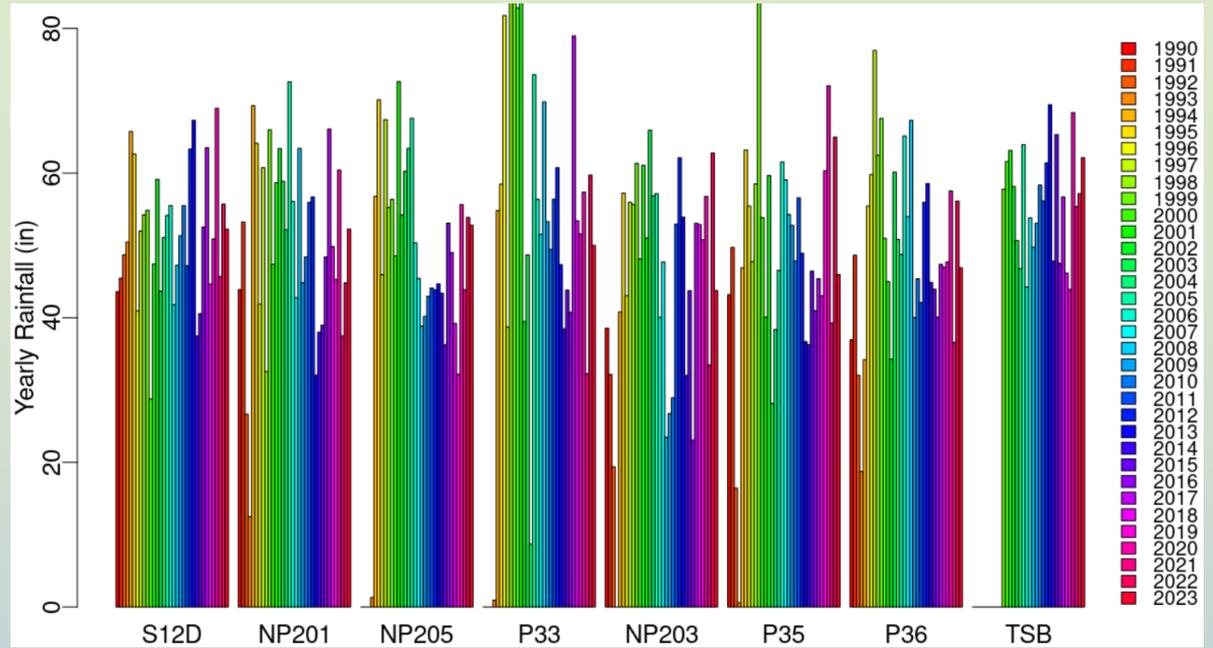


Rain



Long term analysis finds no trends in rainfall

[Southeast Florida Regional Climate Change Compact \(2020\). Southeast Florida Climate Indicators: 2020 Update](#)



Mean of yearly rain during water management plan periods, and differences between IOP : COP
IFT : COP.

Station	IOP	ERTP	IFT	COP	$\Delta R_{IOP:COP}$	$\Delta R_{IFT:COP}$	SD
S-12D	48.6	52.2	54.0	55.9	7.3	1.9	8.0
NP-201	55.4	41.4	51.6	52.5	-2.9	0.9	10.5
NP-205	52.4	42.0	43.9	55.6	3.2	11.7	10.0
P33	56.9	47.6	54.8	55.6	-1.3	0.8	11.0
TSB	55.0	61.0	47.8	61.7	6.7	13.8	8.6
R-127	50.8	56.6	50.6	57.3	6.5	6.7	9.6

Water levels

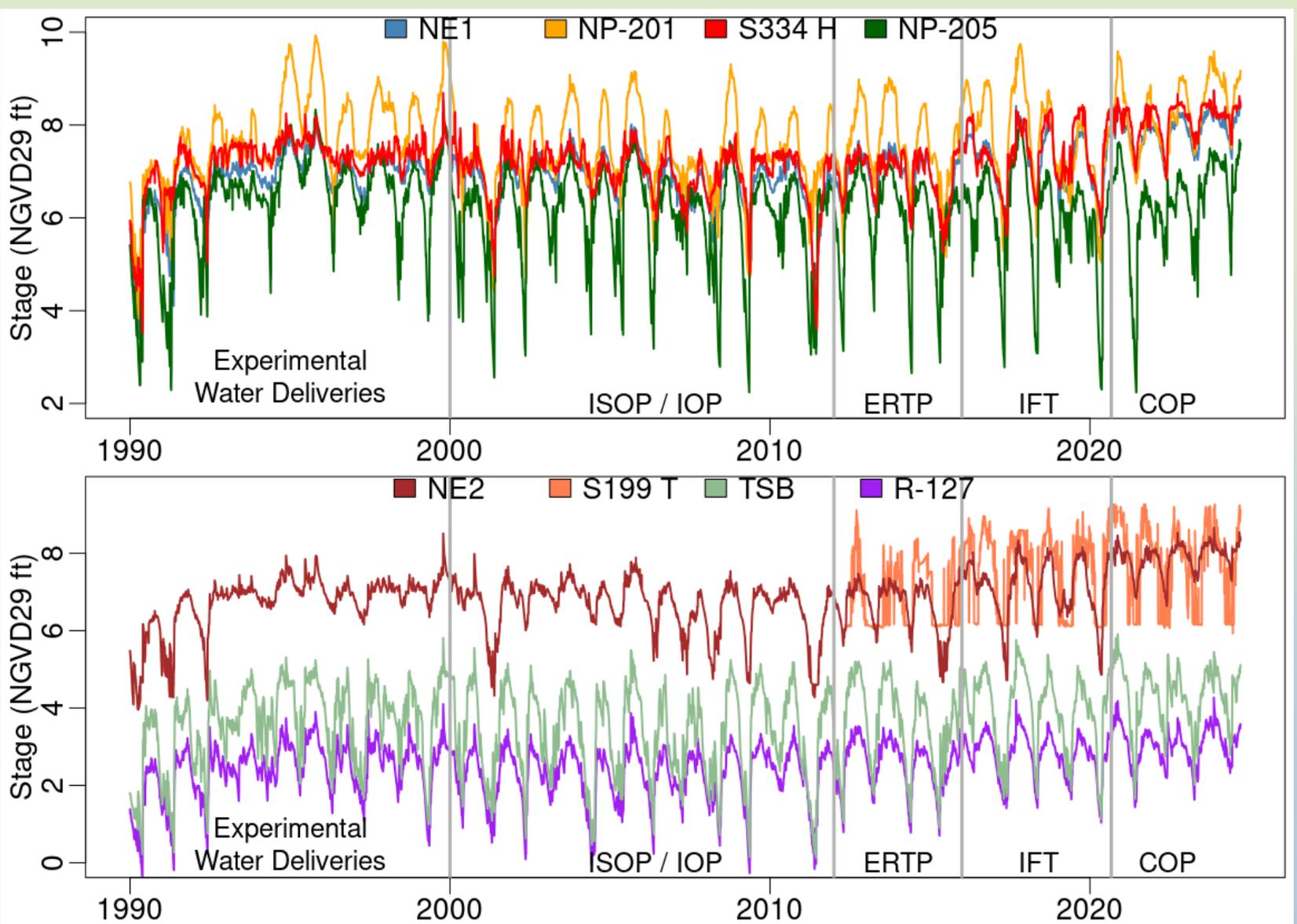
ISOP: Interim
Structural
Operational Plan

IOP: Interim
Operational Plan

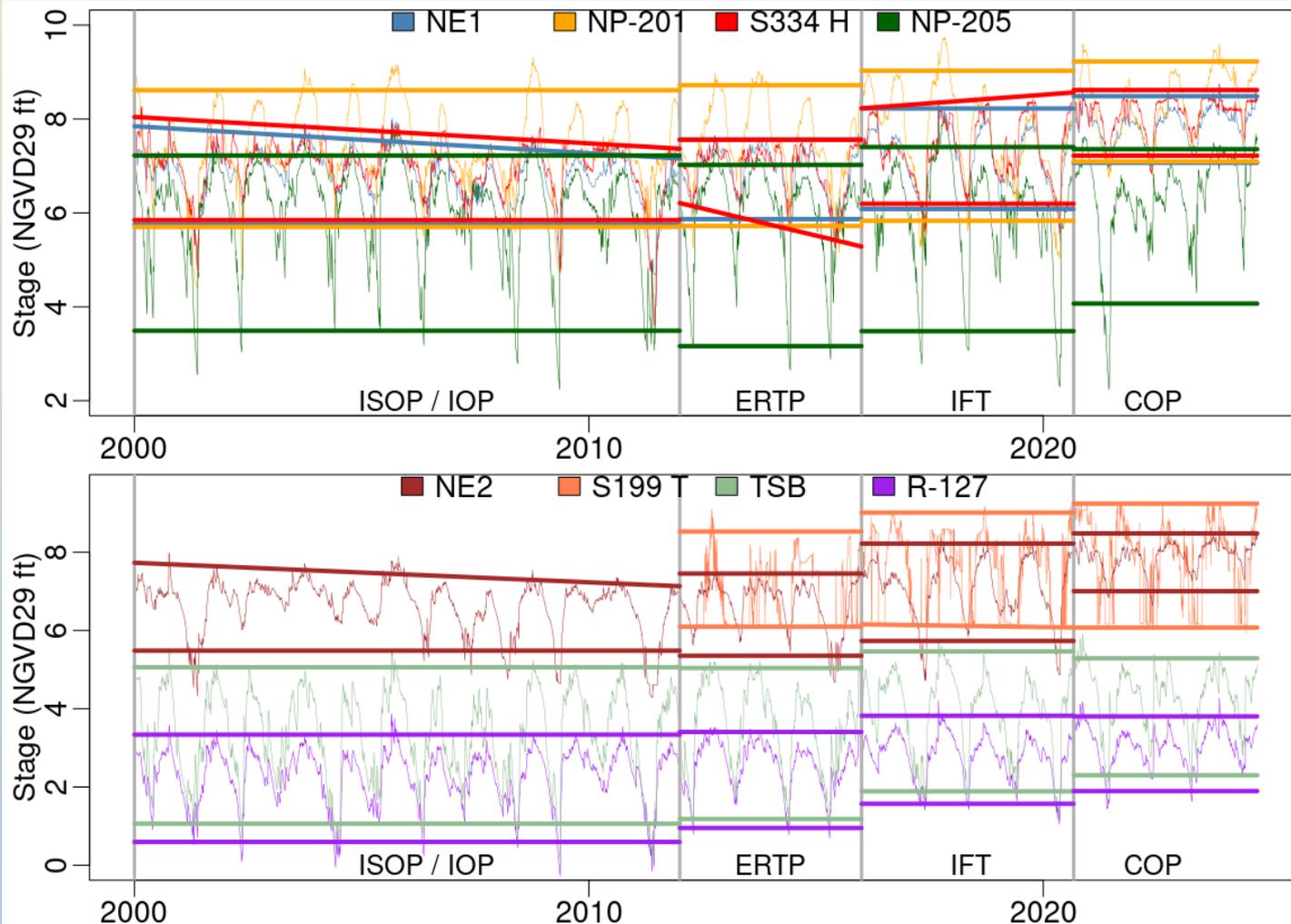
ERTP: Everglades
Restoration
Transition Plan

IFT: Incremental
Field Tests

COP: Combined
Operational Plan



Changes in Minimum and Maximum Stage

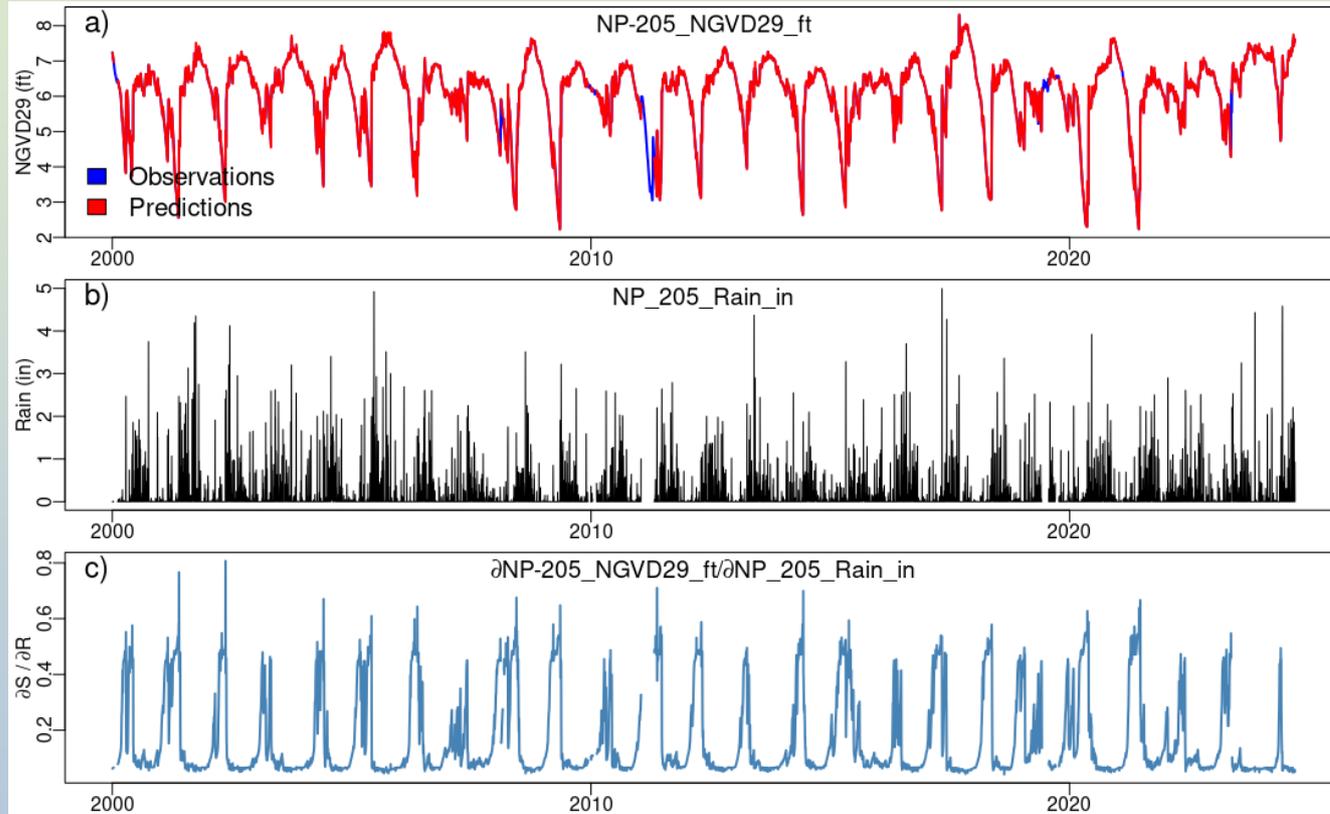


Probability that IOP+ERTP
yearly water level maxima
 S_{IOPM} are above the mean
COP yearly water level
maxima S_{COPM}

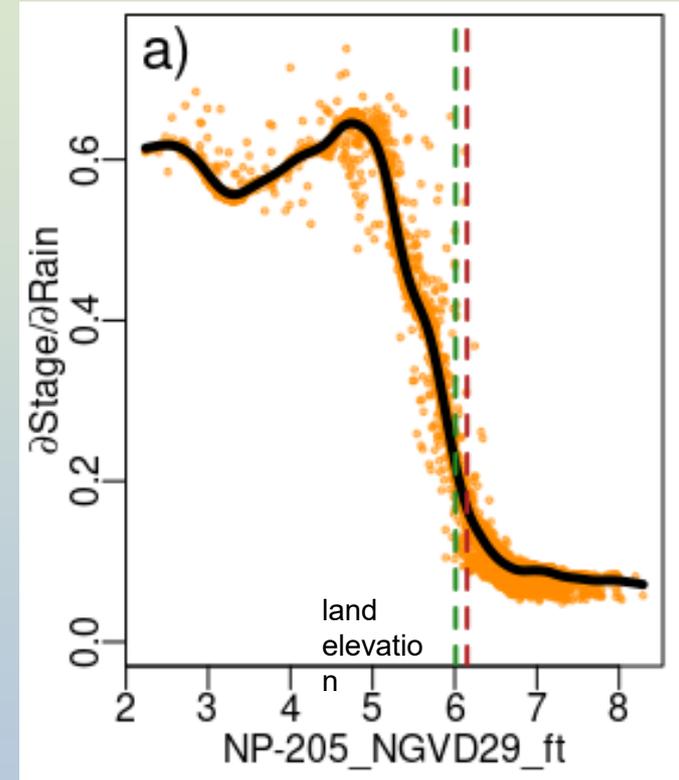
Station	$P(S_{IOPM} > \overline{S_{COPM}})$
NP-205	0.02378
NP-201	0.00034
NESRS1	0.00000
NESRS2	0.00000
S334_H	0.00000
G620	0.00421
P33	0.00000
TSB	0.00290
R-127	0.00034

Rainfall as a Driver of Stage

$$S(t+1) = \text{SMap}[S(t), S(t-1), R(t), R(t-1)]$$



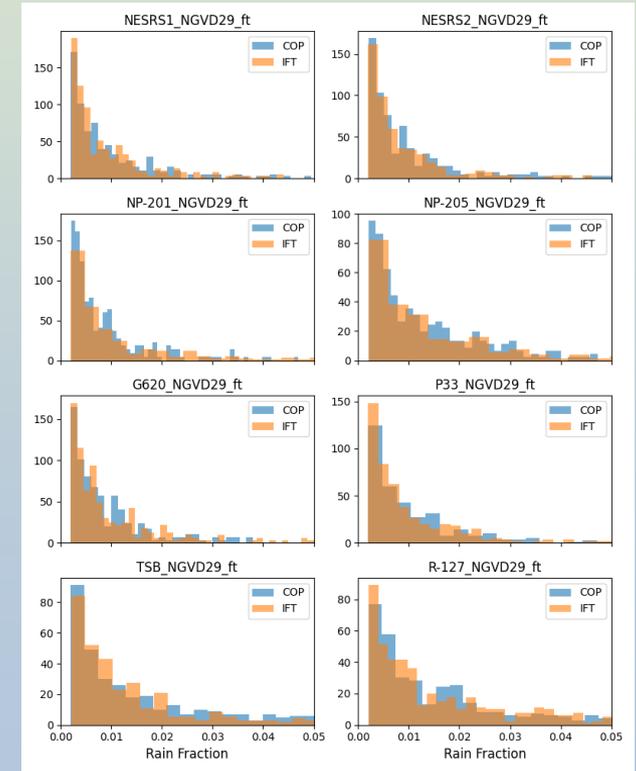
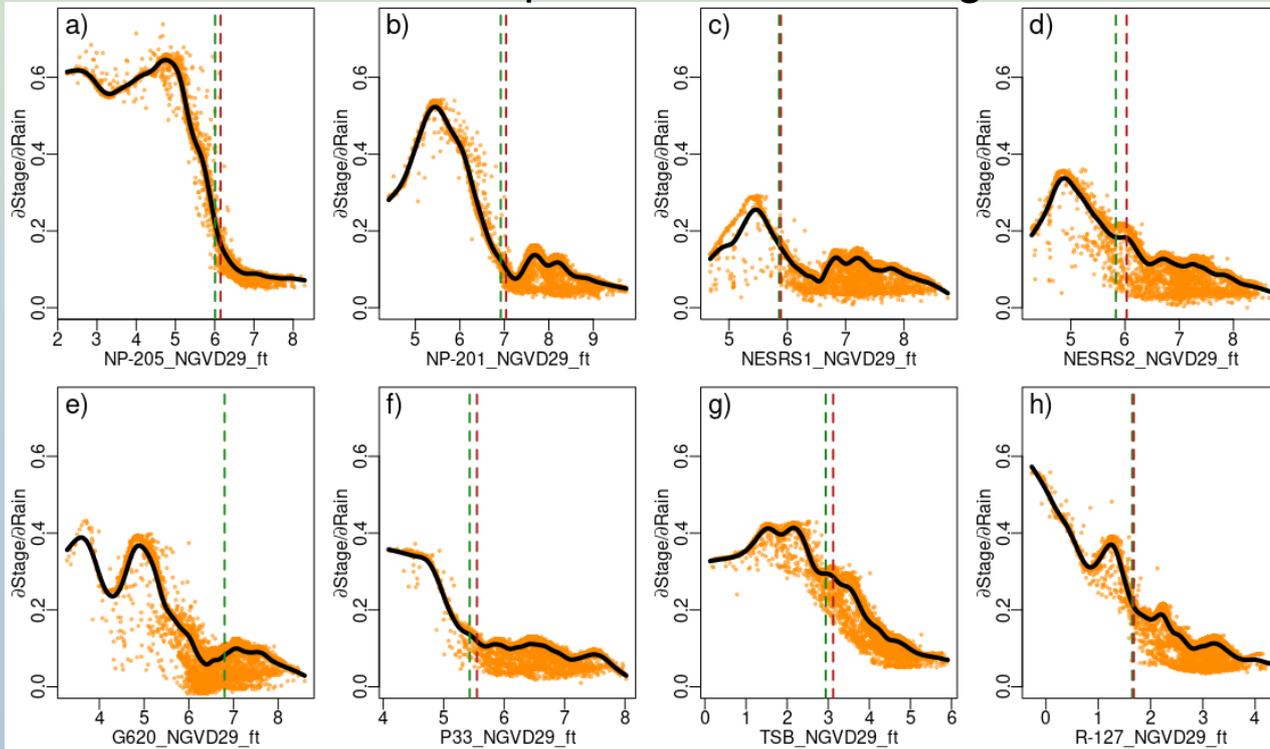
$\partial S / \partial R$



SMap: Nonlinear forecasting for the classification of natural time series.

[Philosophical Transactions: Physical Sciences and Engineering, 348 \(1688\) : 477-495](#)

- Subterranean stage produces larger changes in stage from rain
- The stage dependence reflects local hydrogeological conditions
- Stage-dependence of $\partial S/\partial R$ has not changed since 2000
- The component (fraction) of stage response attributed to rain has not changed from IFT to COP even though water levels and rainfall have increased, and management infrastructure and operations have changed.



Emergency Deviation to 2020 Combined Operational Plan Water Control Plan



DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS, SOUTH ATLANTIC DIVISION
60 FORSYTH STREET, SW ROOM 10M15
ATLANTA, GA 30303-8801

FINDING OF NO SIGNIFICANT IMPACT 2020 EMERGENCY DEVIATION TO PROVIDE TEMPORARY RELIEF TO TERRESTRIAL WILDLIFE DUE TO HIGH WATER LEVELS IN WATER CONSERVATION AREA 3 Broward and Miami-Dade Counties, Florida

The U.S. Army Corps of Engineers, Jacksonville District (Corps) has conducted an environmental analysis, in accordance with the National Environmental Policy Act (NEPA) of 1969, as amended, on an emergency deviation to the 2020 Water Control Plan for the Water Conservation Areas (WCAs), Everglades National Park (ENP) and ENP to South Dade Conveyance System (SDCS), hereafter referred to as the 2020 Combined Operational Plan (COP) Water Control Plan. The Central and Southern (C&SF) Flood Control Project is authorized by Section 203 of the Flood Control Act of 1948, Public Law (PL) 80-858, and modified by Section 203 of the Flood Control Act of 1968, PL 90-483. The Environmental Assessment (EA) dated November 2020, addresses an emergency deviation from the 2020 COP Water Control Plan to provide relief of high water levels in WCA 3A in Broward and Miami-Dade counties, Florida.

2023 to 2024 Planned Temporary Deviation to Lower Water Levels in Water Conservation Area 3A



DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS, JACKSONVILLE DISTRICT
701 SAN MARCO BOULEVARD
JACKSONVILLE, FLORIDA 32207-8175

30 October 2023

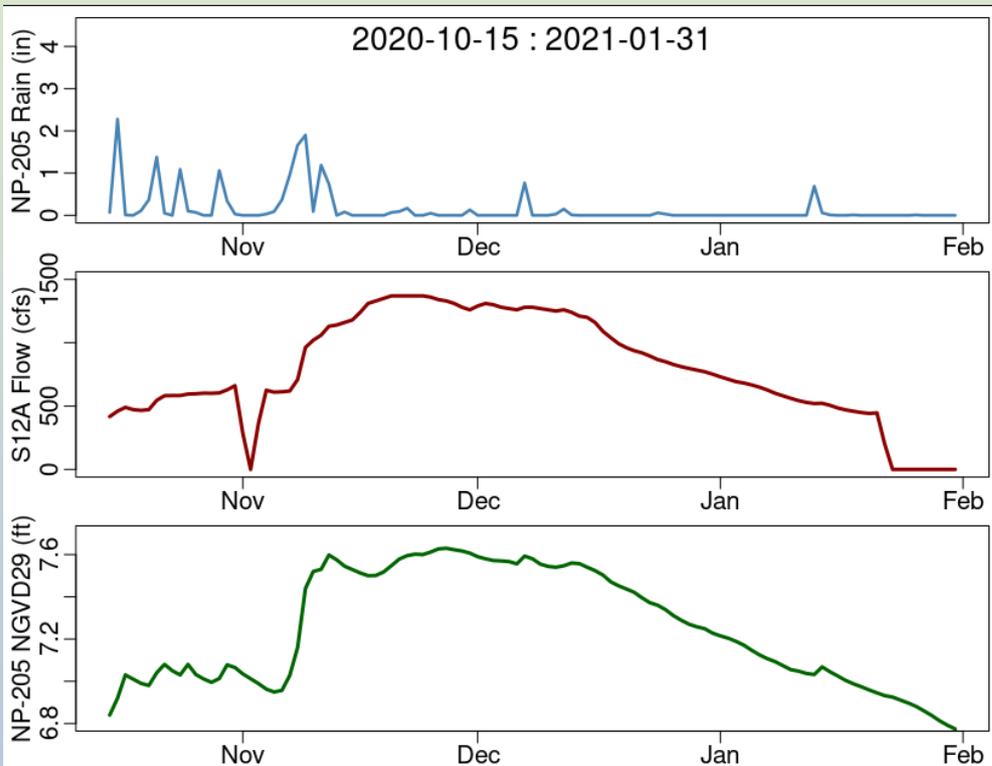
Planning and Policy Division
Environmental Branch

To Whom it May Concern,

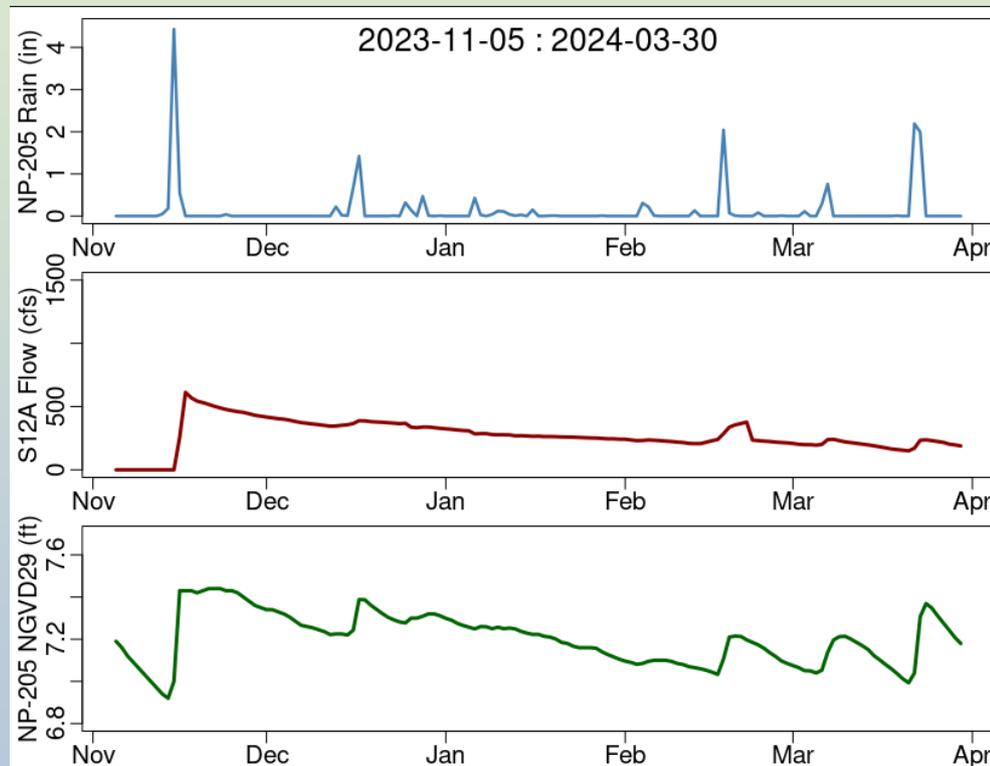
The U.S. Army Corps of Engineers, Jacksonville District (Corps) has prepared a National Environmental Policy Act (NEPA) EA and proposed Finding of No Significant Impact (FONSI) for the planned, temporary deviation from the 2020 Combined Operational Plan. The proposed planned, temporary deviation is being pursued to address the current water level concerns in WCA-3A and potential El Niño conditions in early 2024.

Observations

Deviation 2020-10-14 : 2021-01-30



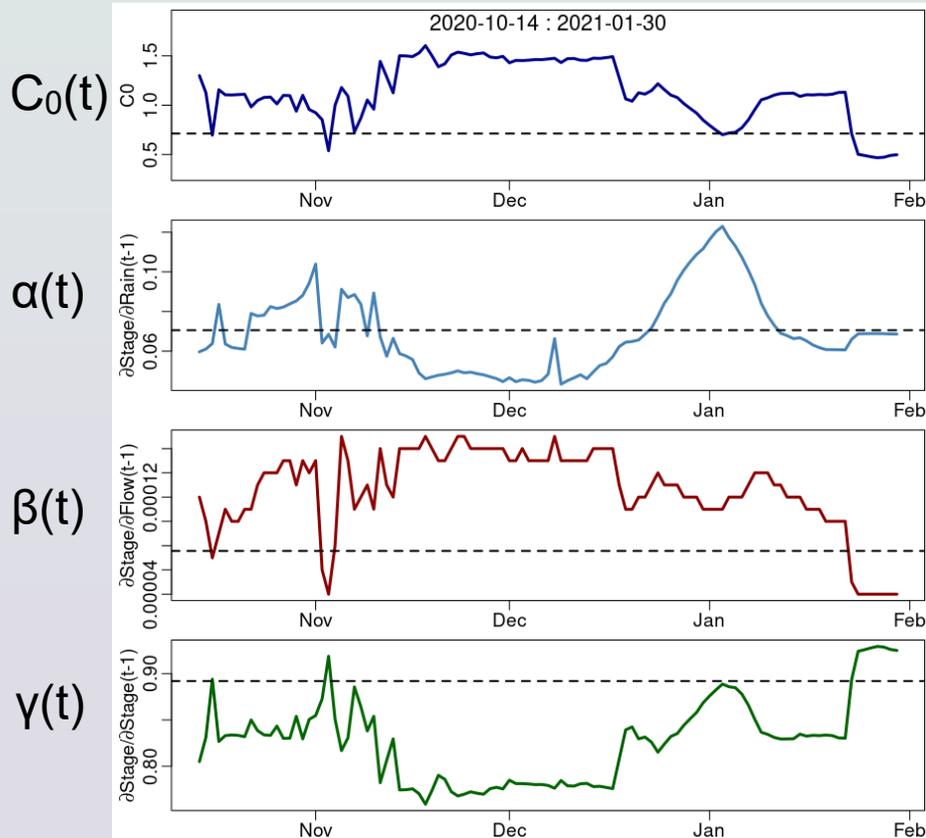
Deviation 2023-11-04 : 2024-03-29



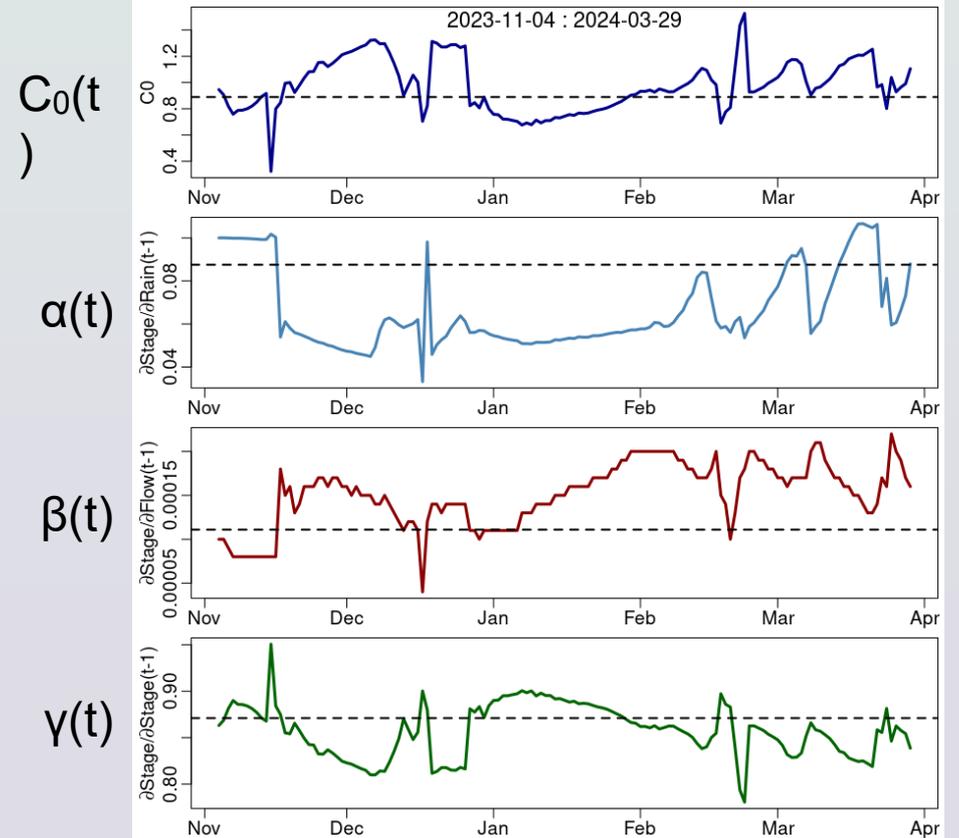
Three component dynamic model of previous days' rain (R) and stage (S) measured at NP-205, flow (F) measured at S12A + S12B.

$$S(t) = C_0(t) + \alpha(t) R(t-1) + \beta(t) F(t-1) + \gamma(t) S(t-1)$$

Deviation 2020-10-14 : 2021-01-30

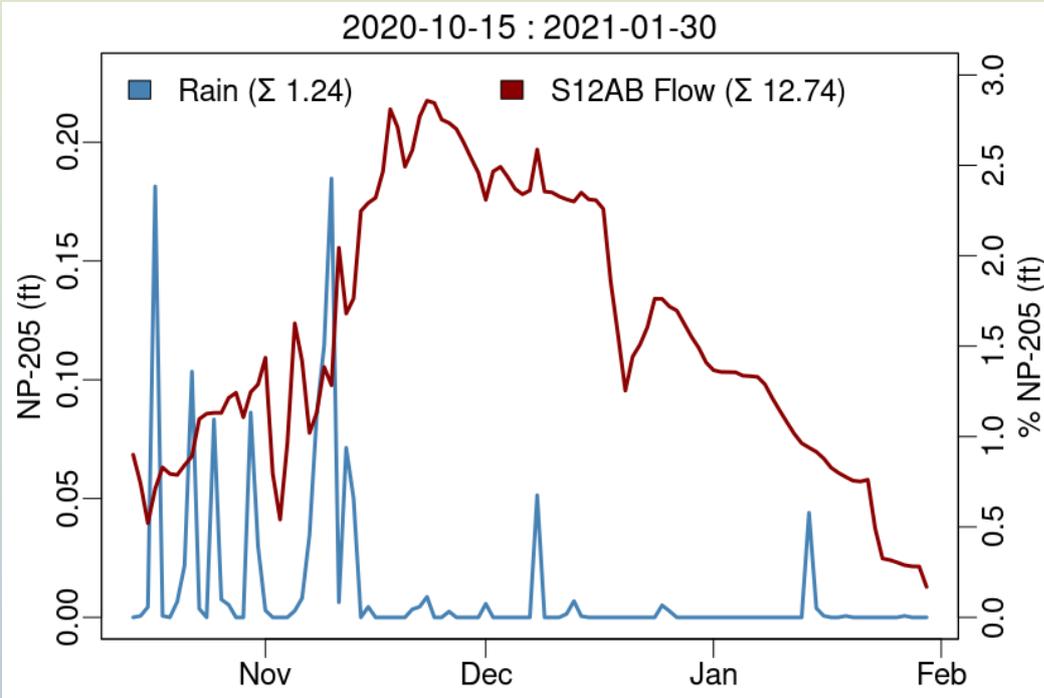


Deviation 2023-11-04 : 2024-03-29



Components contributing to NP-205 stage

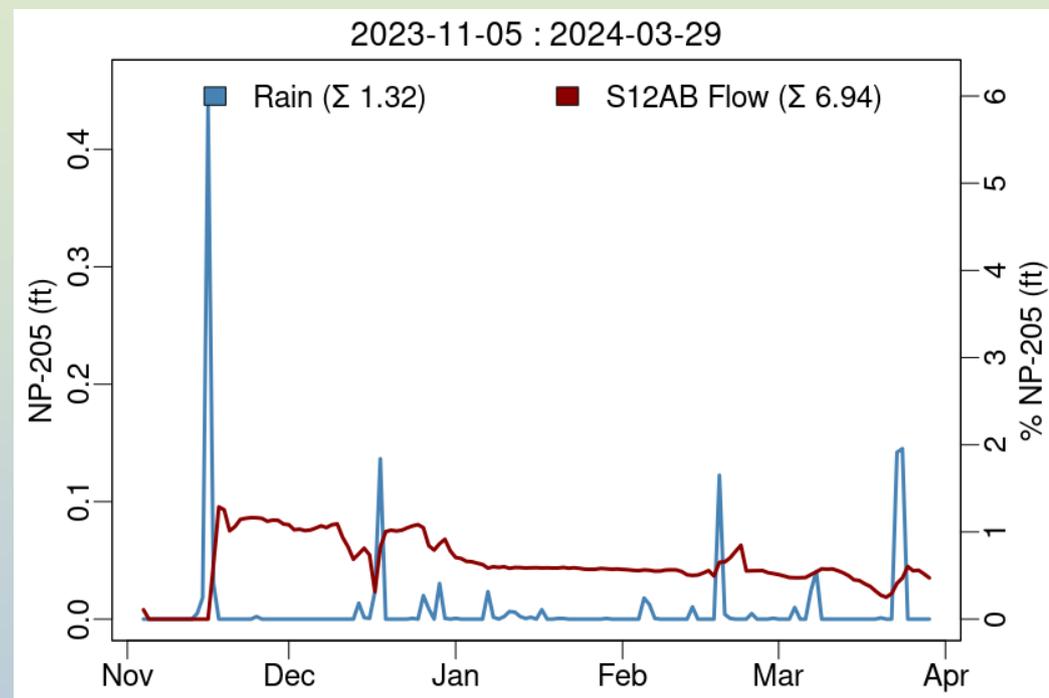
► Dry Season: Rain dominates short time scale, Flow dominates long time scale



Ratio of components of NP-205 rain to S12A+B flow over the deviation:

$$1.24 / 12.74 = 0.097$$

Rain contributed roughly 10% of what flow contributed to stage changes at NP-205.



Ratio of components of NP-205 rain to S12A+B flow over the deviation:

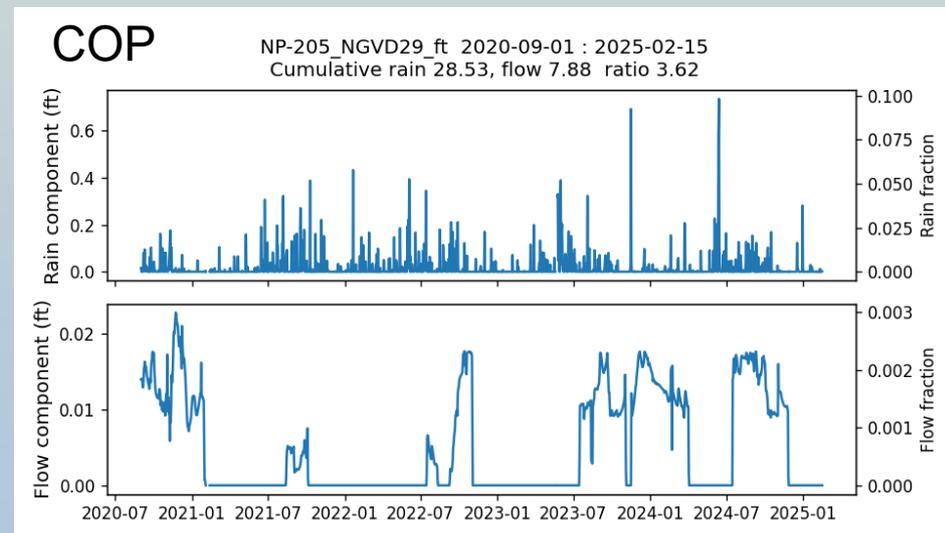
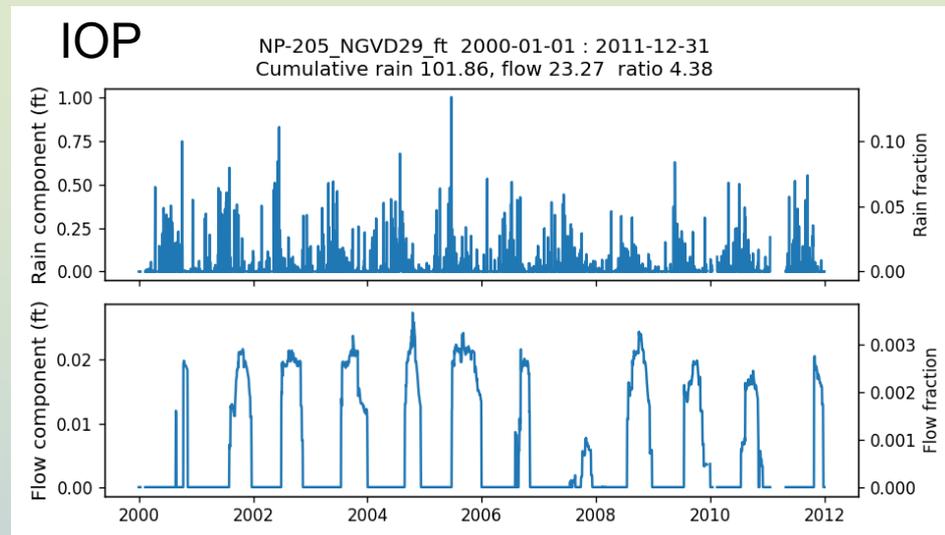
$$1.32 / 6.94 = 0.19$$

Rain contributed roughly 20% of what flow contributed to stage changes at NP-205.

Long Term Components contributing to NP-205 stage

Plan	Date	Σ Rain	Σ Flow	R/F
IOP	2000 : 2011	101.9	23.3	4.4
ERTP	2012 : 2015	27.4	6.7	4.1
IFT	2016-01-01 2020-08-31	38.3	10	3.8
COP	2020-09-01 2025-02-15	28.5	7.9	3.6

On long time scales rain dominates overall changes in stage with a decreasing ratio in relation to flow from IOP to COP.



Have water level conditions in the Everglades changed or entered new state regimes as a result of management plans?

Statistical and state space analysis suggest that in relation to the historical record starting in 1990 water levels during the Combined Operational Plan have entered a new state of generally higher stage.

How does one disentangle influences of rainfall and water management in the hydrologic response of the Everglades with data-driven methods?

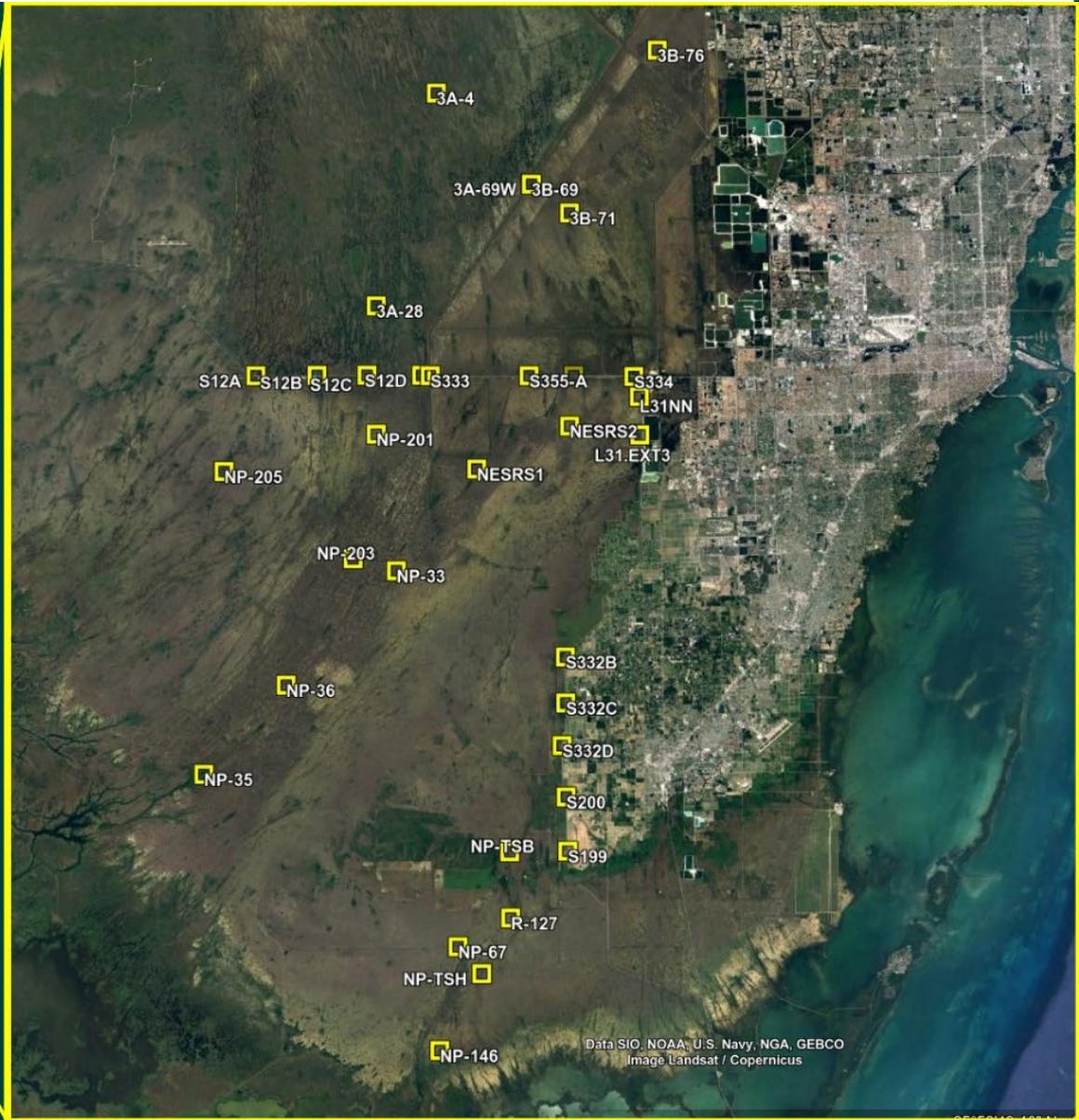
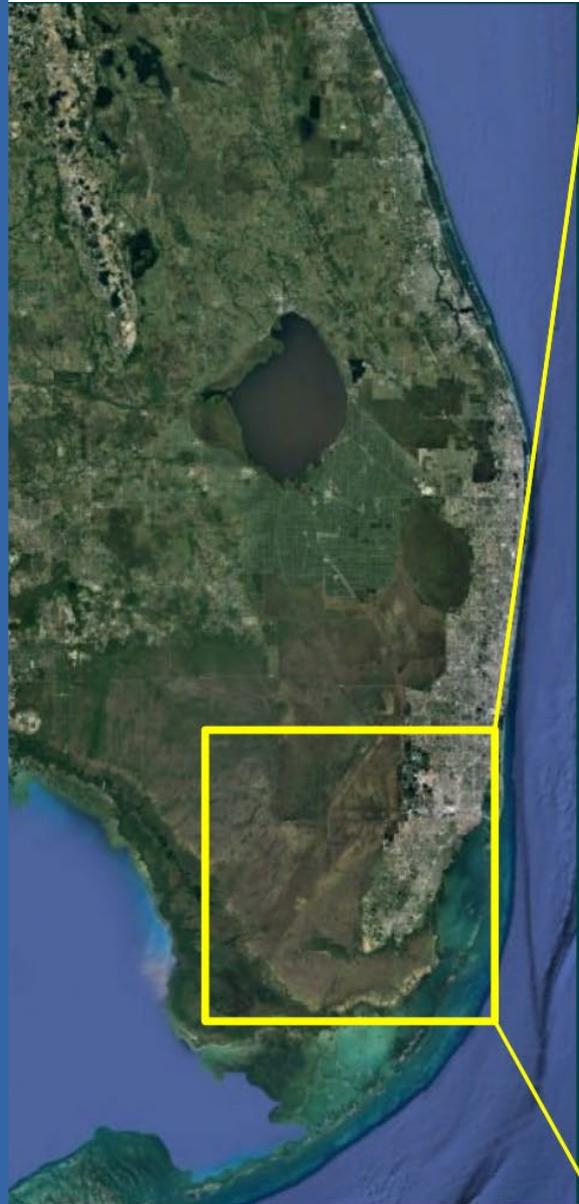
State space dynamic models provide time-dependent coefficients (derivatives) relating change in stage to changes in rain, flow or other variables. Projecting components of change in stage due to rain allows quantification of component contributions.

Time scale and state are important

- On short time scales in dry season rain can dominate flow response
- Dry season when flow is significant: flow can dominate
- Over multiyear time scales rain stage response 3-4 times of flow
- From IOP to COP it appears flow impact is increasing.

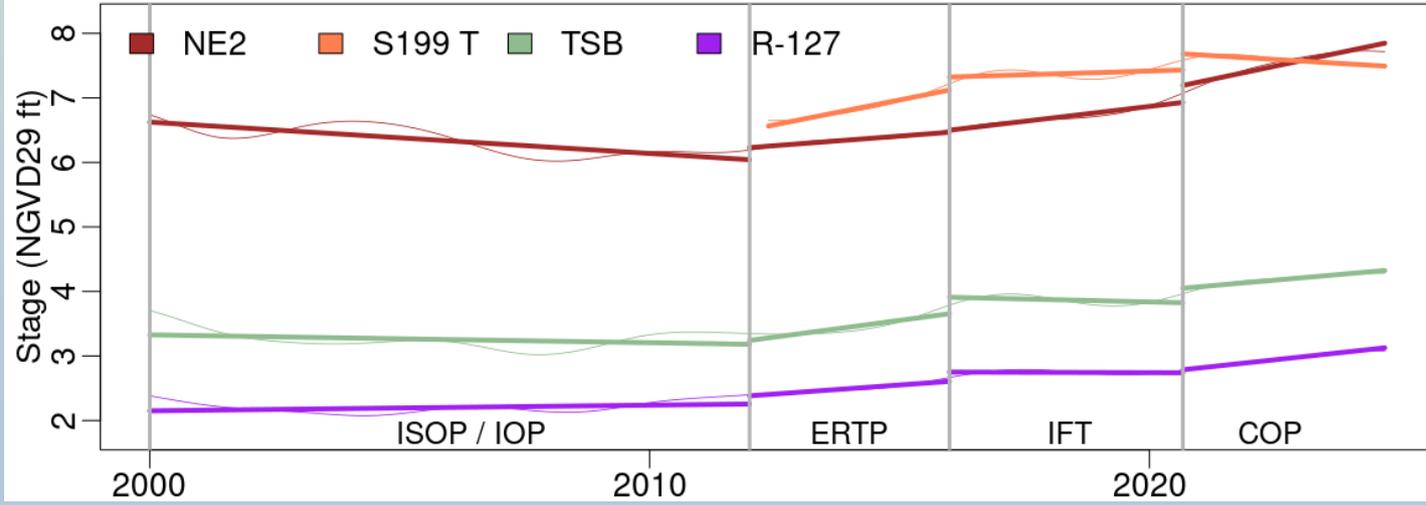
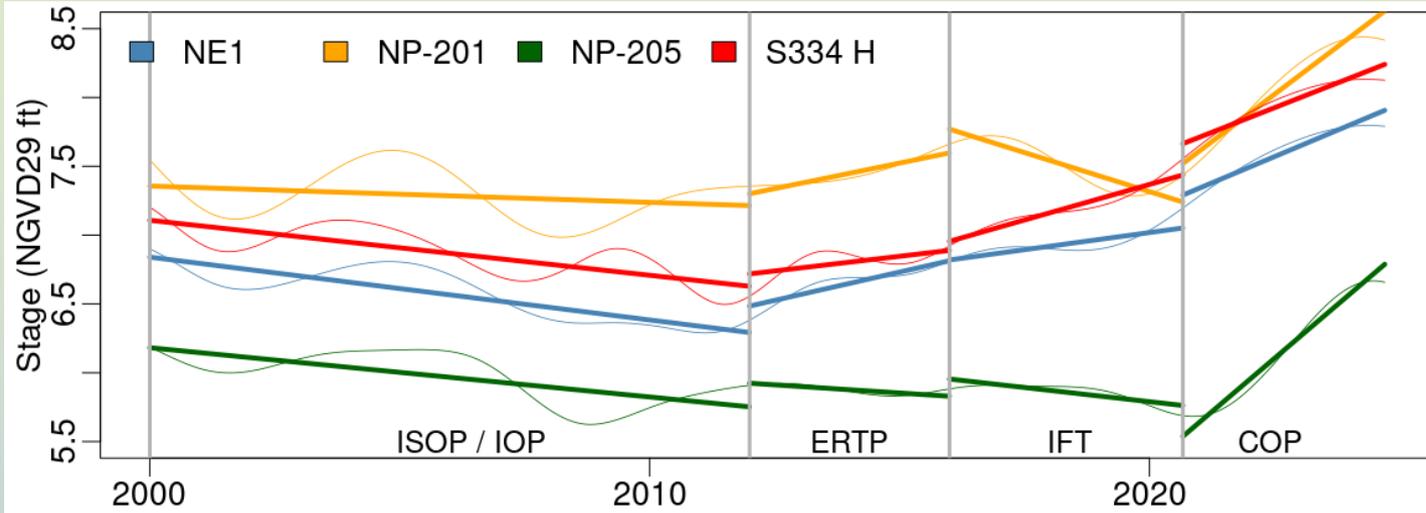
Thank
you!





Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus

Supplementary Information: Trends in stage

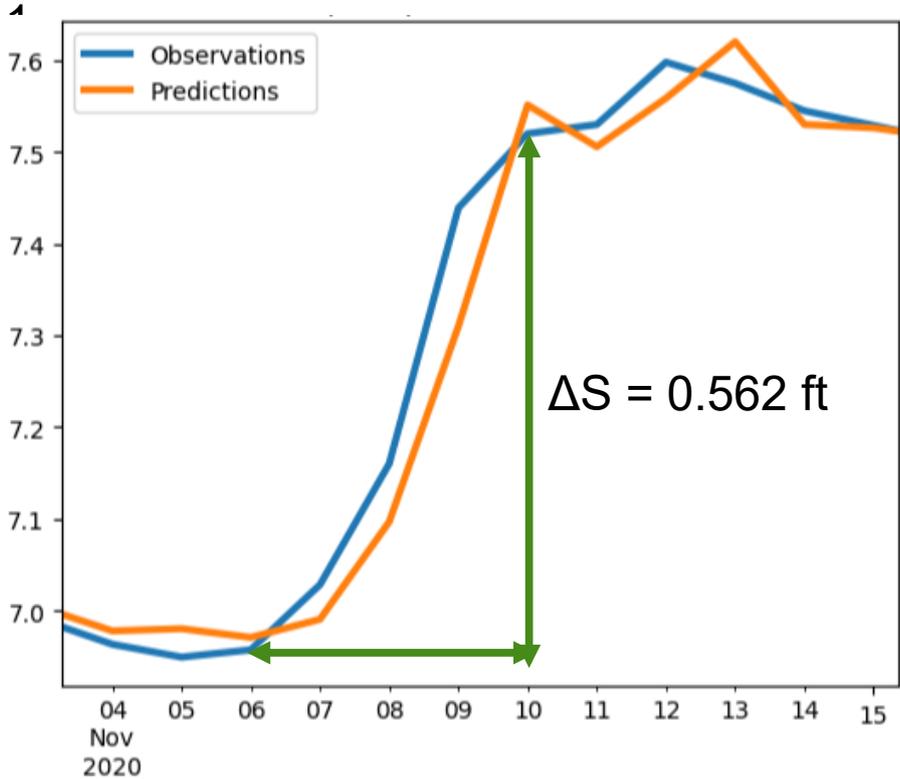


Probability that mean IOP+ERTTP water level trend values, T_{IE} , exceed the COP yearly water level trend mean value, T_{COP}

Station	$\overline{T_{IE}}$	$\overline{T_{COP}}$	$P(T_{IOP} > \overline{T_{COP}})$
NE1	6.587	7.599	0.00000
NP-201	7.327	8.074	0.00000
NP-205	5.945	6.163	0.08059
G620	6.293	6.918	0.00000
P33	6.283	6.920	0.00000
NE2	6.336	7.520	0.00000
TSB	3.302	4.187	0.00000
R-127	2.275	2.956	0.00000

Supplementary Information: Model Comparison

Deviation



Linear Model	Rain	Flow
2020-11-07	0.03520	0.14559
2020-11-08	0.07792	0.15283
2020-11-09	0.16410	0.11134
2020-11-10	0.12915	-0.09703
		$\Sigma = 0.719 \text{ ft}$

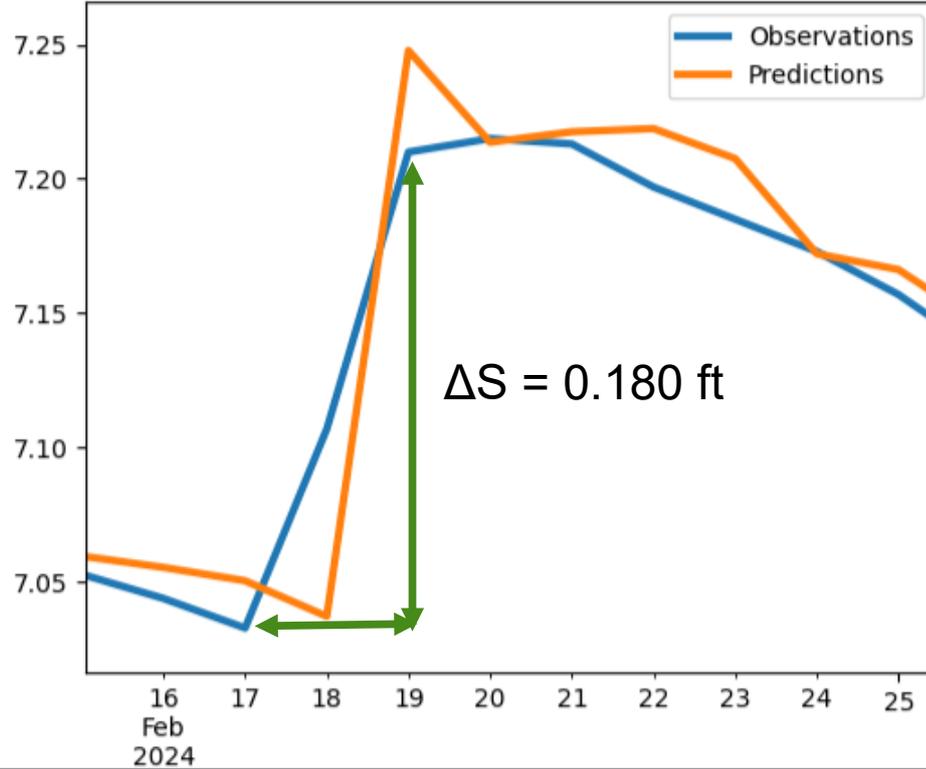
Nonlinear Model	Rain	Flow
2020-11-07	0.02611	0.04638
2020-11-08	0.06774	0.04683
2020-11-09	0.11714	0.05364
2020-11-10	0.13407	0.07286
		$\Sigma = 0.565 \text{ ft}$

Supplementary Information: Model Comparison

Deviation

2

$E=3$ $T_p=0$ $\rho=0.982$ $RMSE=0.023$



Linear Model

	Rain	Flow
2024-02-18	0	0.02662
2024-02-19	0.17858	0.03173

$\Sigma = 0.237$ ft

Nonlinear Model

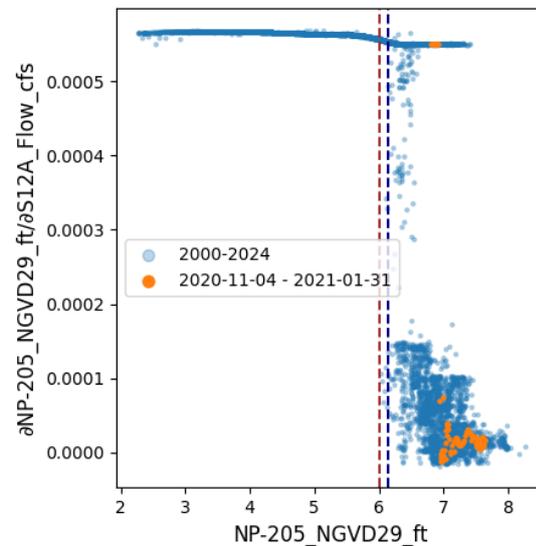
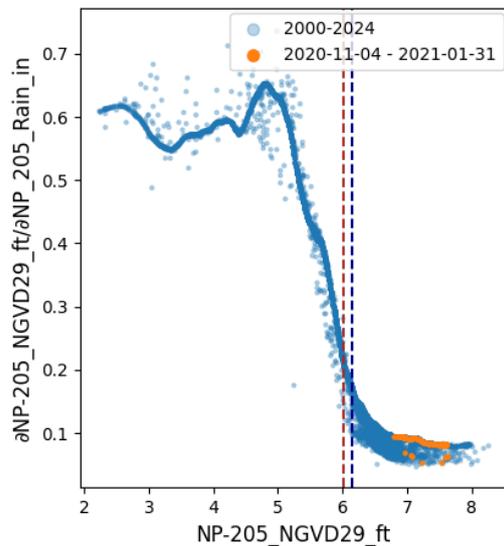
	Rain	Flow
2024-02-18	0	0.03132
2024-02-19	0.13419	0.04119

$\Sigma = 0.207$ ft

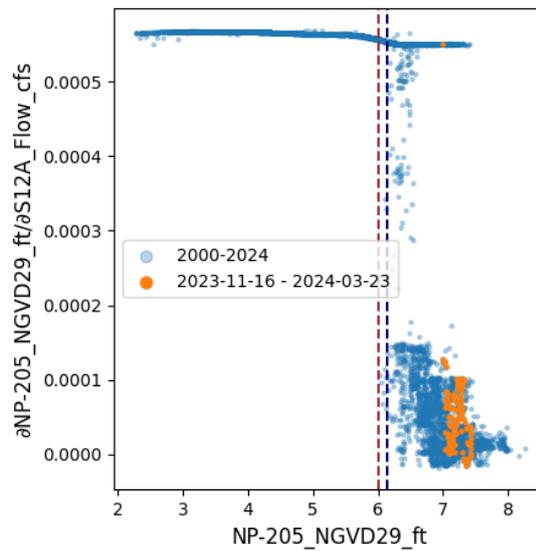
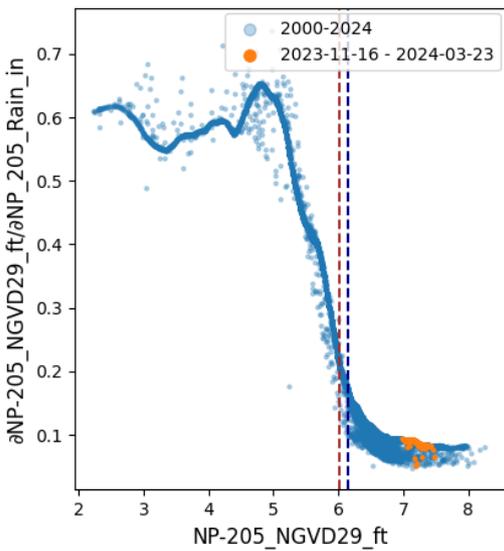
Supplementary Information:

NP-205 $\partial S/\partial R$, $\partial S/\partial F$
during 2020, 2023 COP
temporary deviations

NP-205 Deviation 2020-11-04 - 2021-01-31



NP-205 Deviation 2023-11-16 - 2024-03-23



Supplementary Information

Marsh stage response over COP / IFT / E RTP / IOP

Rain & flow drivers for SMap rain, flow

Stage	Rain	Flow
NP-205	NP-205	S12A + S12B
NP-201	NP-201	S12D
NESRS1	NP-201	S333 + S356
NESRS2	NP-201	S333 + S356
P33	P33	S12C + S12D + S333
G-620	P33	S12B + S12C + S12D
R-127	R-127	S199 + S200 + S332D

Specify flows for
each model

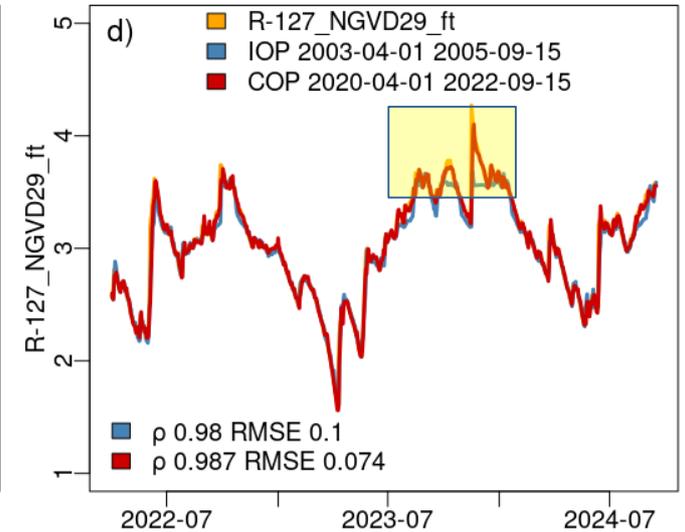
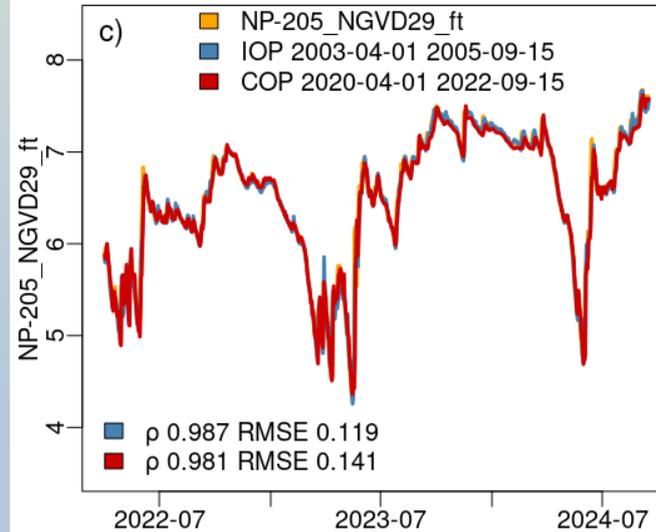
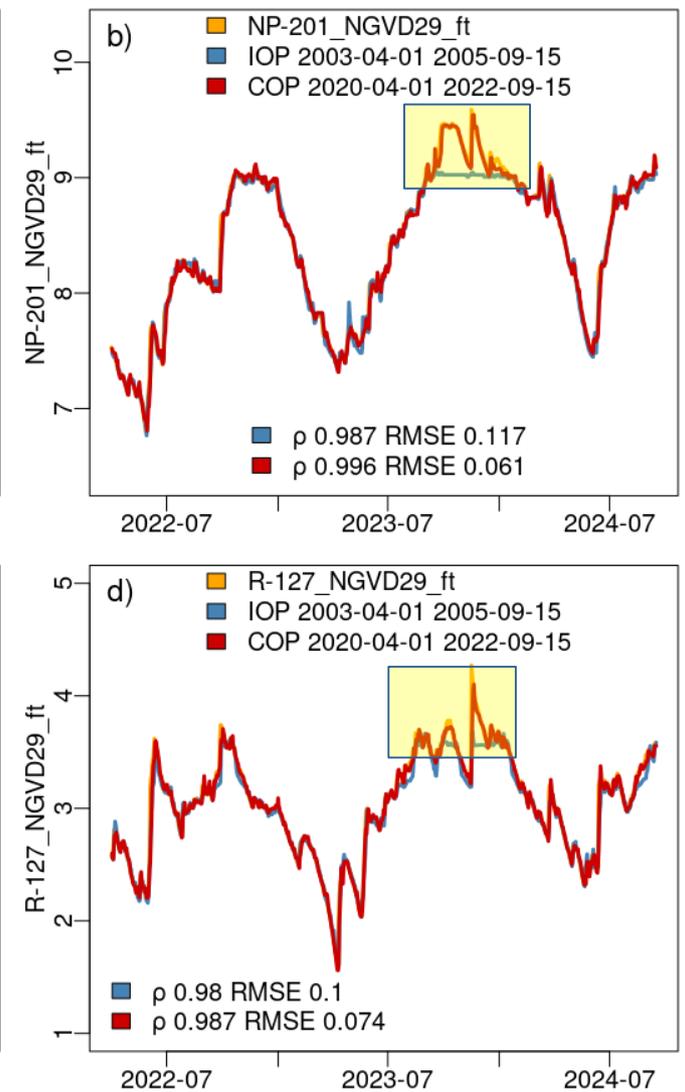
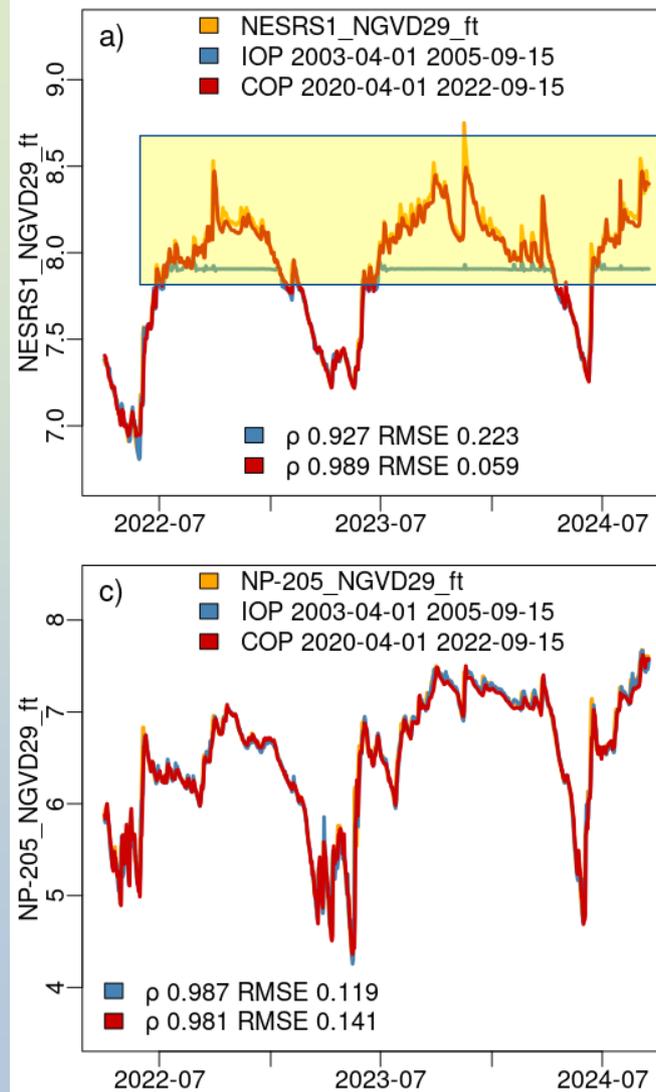


Dynamic Model of stage

during IOP : COP

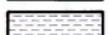
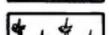
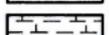
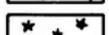
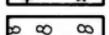
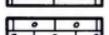
Comparison of out-of-sample simplex stage predictions during COP from state space libraries of equal length observed during IOP and COP

Based on observed states rather than probabilistic estimates this is consistent with statistical analysis suggesting it is improbable these stations would observe COP water levels under IOP conditions.



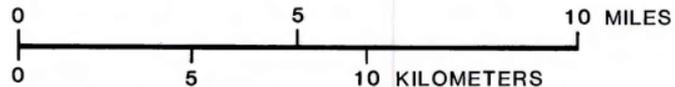
Supplementary Information: NE ENP Geology

EXPLANATION

	Fill		Freshwater shells
	Peat or muck		Silt
	Sand		Clay
	Sandstone		Claystone or siltstone
	Detrital carbonate sand		Micrite, lime mud
	Rock fragments		Limestone
	Concretions		Oolitic limestone
	Marine shells		Coralline limestone, biolithite

GEOLOGIC FORMATIONS

Ql	Lake Flirt Marl		Formation boundary
Qp	Pamlico Sand		
Qm	Miami Oolite		
Qa	Anastasia Formation		
Qk	Key Largo Limestone		
Qf	Fort Thompson Formation		
Tt	Tamiami Formation		
Th	Hawthorn Formation		
Tth	Tamiami Formation and Hawthorn Formation undifferentiated		Test well and number



Vertical Scale Greatly Exaggerated

