

Regional sea-level variability captures low-frequency transport through the Gulf of Mexico gateways

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Key Points:

- Gateway transport variability is embedded in regional sea-level patterns beyond local section gradients
- Regional altimetry supports empirical reconstruction of low-frequency gateway transport from 1993 to 2025
- Yucatan transport extremes reflect regional sea-level patterns beyond Loop Current extension alone

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Abstract

Transports through the Yucatan Channel, Florida Straits, and Bahamas passages form the western-boundary gateway connecting the Caribbean Sea, Gulf of Mexico, and North Atlantic. Yet, the extent to which low-frequency transport variability along this pathway is expressed in regional sea-level structure remains unclear. Here we combine direct velocity-based transport estimates from the Canek mooring arrays, the Florida Cable record, and satellite altimetry to explore whether coherent altimetric modes can recover gateway transport variability. The observed records show substantial low-frequency variability, with seasonal harmonics explaining only a modest fraction of the total variance. Finite-window Monte Carlo experiments show that mean transports, seasonal amplitudes, and especially linear trends are sensitive to the sampled period, emphasizing the need for sustained observations. Correlation and partial least-squares analyses reveal that the transport signal projects onto coherent sea-level patterns spanning the northwestern Caribbean, Yucatan Channel, Cuba, Florida Straits, and Bahamas passages. Sea-level-based reconstructions reproduce much of the withheld observed variability, with withheld validation R^2 values ranging from 0.6 to 0.8 and root-mean-square differences comparable to the observational uncertainty scale. These results show that regional sea-level variability reflects a recoverable portion of the low-frequency transport variability along the Caribbean–Gulf–Florida pathway. Applied to the full satellite-altimetry era, the reconstructions provide empirical transport proxies from 1993 to 2025.

Plain Language Summary

Ocean currents carry large amounts of water, heat, and salt through the Caribbean Sea, Gulf of Mexico, Florida Straits, and nearby passages around the Bahamas. These flows are usually measured with moored instruments, but such observations are difficult to maintain and often cover only limited periods. In this study, we ask whether satellite measurements of sea level can be used to estimate changes in the amount of water flowing through these passages over time. We show that the observed transports vary substantially, and that statistics such as the mean flow, seasonal cycle, and long-term trend can depend strongly on the years sampled. We then show that transport changes are linked to broad sea-level patterns extending from the northwestern Caribbean to the Gulf of Mexico, Cuba, Florida Straits, and Bahamas passages. Using these regional patterns, we reconstruct transport variability over the satellite era, from 1993 to late 2025. The reconstructions reproduce much of the observed variability, suggesting that satellite sea-level measurements provide a useful way to extend sparse ocean-current observations and study long-term changes in this connected current system.

1 Introduction

The western-boundary branch of the North Atlantic subtropical gyre forms a dynamically active segment of the wind-driven subtropical circulation and a regional pathway for the upper-ocean return flow associated with the Atlantic meridional overturning circulation (Schmitz Jr & Richardson, 1991; Schmitz Jr & McCartney, 1993; Johns et al., 2002; McCarthy et al., 2015). It links the Caribbean Sea, the Gulf of Mexico, the Florida Straits, the Bahamas passages, and the western North Atlantic (**Figure 1**), contributing to the redistribution of upper-ocean mass, heat, and salt across the subtropical North Atlantic (Richardson, 2005; Candela et al., 2019; Todd et al., 2019). The Yucatan Channel and the southern Florida Straits are primary gateways for monitoring this flow through the Gulf of Mexico, while the Bahamas passages provide complementary pathways for transport redistribution around Cuba (Johns et al., 2002; Sheinbaum et al., 2002; Hamilton et al., 2005; Lin et al., 2009; Candela et al., 2019).

Variability along this pathway spans a broad range of time scales. At subseasonal-to-mesoscale periods, westward-propagating Caribbean eddies, boundary-current mean-

ders, and the extension–retraction and ring-shedding cycles of the Loop Current can strongly impact the regional variability (Maul & Vukovich, 1993; Sturges & Leben, 2000; Abascal et al., 2003; Oey et al., 2005; Richardson, 2005; Athié et al., 2012; Mildner et al., 2013; Hamilton et al., 2016; Jouanno et al., 2016; Sheinbaum et al., 2016; van Westen et al., 2018; Durante, 2025). At interannual periods, Caribbean mean currents, mesoscale activity, and along-path transport variability may also respond to broader sea-level and climate variability, including ENSO-related changes in Caribbean sea-level gradients (Athié et al., 2015; Rivero-Ordaz et al., 2022; Huang et al., 2023) and spatially nonuniform transport trends along the Florida Shelf (Torres-Córdoba & Valle-Levinson, 2025).

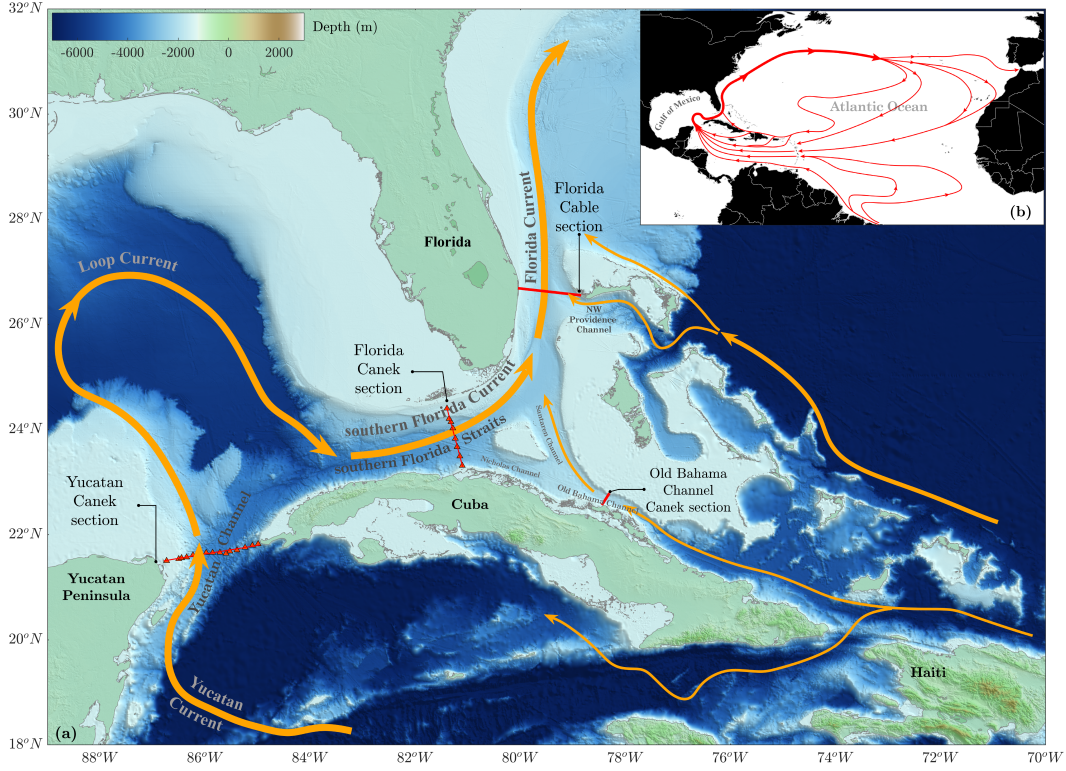


Figure 1. (a) Bathymetric map of the Caribbean Sea, Gulf of Mexico, and Florida–Bahamas region from GEBCO 2026, overlaid with climatological near-surface streamlines derived from the Global Drifter Program (Laurindo et al., 2017), and showing the locations of the transport sections analyzed in this study: the Florida Cable section, the Old Bahama Channel Canek section, the Florida Canek section, and the Yucatan Canek section. The inset (b) illustrates the mean surface circulation of the North Atlantic Subtropical Gyre, adapted from (Schmitz Jr & McCartney, 1993).

The flow through the Gulf of Mexico (**Figure 1a**) enters from the northwestern Caribbean Sea as the Yucatan Current, which follows the western side of the Yucatan Channel and accounts for most of the section-integrated transport variability (Sheinbaum et al., 2002; Athié et al., 2015; Candela et al., 2019; Athié et al., 2020; Durante et al., 2025). It is therefore useful to distinguish the northward Yucatan Current transport from the total Yucatan Channel transport, because the latter also includes recirculating flows, compensating currents, and vertical or lateral structure within the channel (Athié et al., 2015, 2020; Hirschi et al., 2019). After entering the Gulf, the main stream forms the Loop Current, which alternates between retracted and extended states and may shed warm-core rings into the western Gulf (Coats, 1992; Sturges & Evans, 1983; Elliott, 1982; Vi-

dal et al., 1992; Weisberg & Liu, 2017; Gentil et al., 2024). The flow exits through the southern Straits of Florida and continues downstream near 27°N across the Florida Cable section (Hamilton et al., 2005; Meinen et al., 2010; Johns et al., 2011; Frajka-Williams et al., 2019; Volkov et al., 2020).

Additional transport can also enter the downstream Florida Current through smaller passages between the Bahamas banks, particularly the Northwest Providence Channel and the Old Bahama Channel. These passages have been identified as relevant components of the regional volume balance, although their mean contribution is limited relative to the main Yucatan–Florida pathway (Leaman et al., 1995; Johns et al., 1999; Hamilton et al., 2005; Lin et al., 2009; Rousset & Beal, 2011, 2014; Athié et al., 2015; Candela et al., 2019). Their variability and dynamical role remain less well characterized, motivating their inclusion here as secondary routes for transport redistribution around Cuba.

Observational and numerical studies have suggested that the extension–retraction phases and ring-shedding behavior of the Loop Current may depend more strongly on the cross-sectional structure of the Yucatan Current than on the total channel transport alone (Athié et al., 2015; Sheinbaum et al., 2016; Athié et al., 2020). Lateral shifts of the current core and changes in the velocity distribution within the upper 1,000 m (Reid, 1972; Molinari & Morrison, 1988; Androulidakis et al., 2021; Durante, 2021; Laxenaire et al., 2023; Manta et al., 2023; Durante, 2025), as well as deep return flow through the channel (Maul, 1977; Bunge et al., 2002; Nedbor-Gross et al., 2014), have been linked to variations in Loop Current extension, frontal configuration, and growth–retraction cycles. These results complicate the classical expectation from idealized and intermediate-complexity models (*e.g.*, Pichevin & Nof, 1997; Nof, 2005; Moreles et al., 2021), that the inflow through the Yucatan Channel is the key to determine the Loop Current penetration and eddy detachment.

At the same time, other studies have observed or modeled connections between Loop Current variability and transport redistribution along the Yucatan–Florida–Bahamas pathway. Lin et al. (2009) found that Yucatan Channel transport in their model simulations reached a minimum during strong Loop Current intrusion, typically before ring shedding, and argued that these variations are partly compensated by flow around Cuba. Sturges et al. (2010) identified pulses of enhanced Florida Current transport preceding ring-separation events, while Mildner et al. (2013) proposed that coherent eddies embedded in the Loop Current can partially block Yucatan Channel inflow before large Loop Current intrusions into the Gulf, reducing Florida Current transport. Hirschi et al. (2019) suggest that Loop Current growth is associated with reduced transport through the Straits of Florida, whereas contraction is associated with enhanced transport, consistent with mass-continuity adjustments between the Gulf interior and its downstream outflow in a river-like conceptual model of the regional current system.

These previous studies suggest a regional perspective in which transport variability need not map onto a single Loop Current extension metric, but may instead be expressed through coherent sea-level patterns spanning the Yucatan Channel, Loop Current region, and Florida Straits. We therefore examine whether low-frequency transport variability along this pathway can be recovered from regional sea-level modes. Building on previous local sea-level metrics, including altimetry-based end-point methods (Maul et al., 1985; Athié et al., 2015, 2020; Volkov et al., 2020), we apply partial least squares (PLS) regression (Wold et al., 2001) to observed transport and satellite altimetry records. PLS extracts a small set of regional modes that maximize covariance with the observed transports, allowing the transport-related sea-level structure to emerge from the broader field (see, for example, Smoliak et al., 2010; Kinnard et al., 2011; Ye & Wu, 2021; Ivanova et al., 2021). We show that regional sea-level variability contains recoverable information about low-frequency transport across the Caribbean–Gulf of Mexico–Florida Straits system. The resulting transport proxies extend across the satellite-altimetry era while

preserving the observed transport–sea-level correlation structure, providing a dynamically interpretable view of low-frequency gateway variability.

2 Data and methods

2.1 Observational transport records

2.1.1 *Canek mooring sections*

The Canek program is a Mexican-led observing program, conducted in close collaboration with Cuban scientific institutions, that deploys tall velocity moorings across the principal inflow and outflow passages of the Gulf of Mexico (**Figure 1**). The moorings are equipped with acoustic Doppler current profilers (**ADCP**), single-point current meters, and auxiliary temperature–salinity sensors, providing direct velocity measurements and transport estimates through the Gulf of Mexico (Durante et al., 2025).

The first cross-channel mooring array was deployed in the Yucatan Channel in 1999 to monitor the Yucatan Current, the principal inflow pathway into the Gulf (Sheinbaum et al., 2002; Ochoa et al., 2003). After the initial deployments, part of the observing effort shifted toward the Mexican Caribbean along the Mesoamerican Barrier Reef, interrupting the Yucatan Channel record during 2002–2008 (Badan et al., 2005; Athié et al., 2015). The Yucatan section was re-established in 2009 and remains the primary Canek monitoring line for the Gulf inflow. A second Canek array was deployed in the Florida Straits in 2012, enabling simultaneous monitoring of the Loop Current inflow and outflow sections (Candela et al., 2019; Durante et al., 2025). The Florida section record was interrupted in 2025 when the instruments were reassigned to other observational missions, and the duration of this interruption remains uncertain.

In this study, we use the Level-4 (**L4**) gridded velocity products derived from the Canek mooring observations to compute volume transport across the Yucatan and Florida sections (Durante et al., 2023). Details on quality control, volume-conserving objective mapping, uncertainty estimation, mooring configurations, and record coverage are provided in Durante et al. (2025) and **Figure S1** in the supporting information (**SI**). The database now includes the latest recovered campaign data from 2023–2025; however, the Yucatan section data for this period are still undergoing processing and quality control. Therefore, only the updated Florida section data are used here.

An approximately eight-month interruption affected both the Yucatan and Florida mooring records during 2020–2021, when field operations were delayed during the COVID-19 pandemic and the instruments could not be serviced before battery depletion. This gap, together with other shorter gaps between maintenance missions, was retained as missing data and was not filled prior to the empirical reconstruction described below.

To complement the Gulf inflow–outflow sections, the Canek program extended its observations to the Bahamas in 2014, deploying a three-mooring array across the Old Bahama Channel (Candela et al., 2019). Complete section coverage was obtained during 2014–2016, but the northernmost mooring was not recovered during later campaigns, leaving incomplete coverage between 2016 and 2020. Missing velocity profiles were reconstructed from the available mooring observations using a multiple regression trained and tested during periods of complete section coverage. The resulting observationally constrained dataset spans 2014–2020 and forms the basis for the Old Bahama Channel transport estimates used here; methodological details are provided in **Text S1** and **Figure S2**. Negative transport corresponds to the dominant westward flow toward the Florida Straits under the section-normal convention of Candela et al. (2019).

2.1.2 Florida Cable transport

We use the Florida Cable transport record as an additional observational estimate of downstream Florida Current transport through the Straits of Florida near 27°N. This daily record, available since 1982, is derived from voltage measurements across a retired submarine telecommunications cable between Florida and the Bahamas and is calibrated against direct ship-based transport estimates (Meinen et al., 2010; Johns et al., 2011; Frajka-Williams et al., 2019; Volkov et al., 2020). We use the updated Cable product described by Volkov et al. (2024), which includes the correction for secular changes in Earth’s magnetic field. The record contains a major gap from November 1998 to June 2000, as well as shorter interruptions. Gaps longer than 20 days were retained as missing, whereas shorter gaps were linearly interpolated only when required for filtering. We use only the highest-quality flagged Cable estimates and do not include alternative Florida Current transport estimates during periods when Cable measurements are unavailable.

2.1.3 Satellite altimetry and regional sea-level fields

We used sea-level anomalies, absolute dynamic topography (**ADT**) and geostrophic velocity fields from the multi-satellite Level-4 delayed-mode altimetry product distributed by the Copernicus Marine Service (**CMEMS**, <https://doi.org/10.48670/moi-00148>). This product provides daily gridded maps at 1/8° horizontal resolution and spans the satellite-altimetry era from 1993 to October 2025. Although the fields are distributed as daily maps, their effective temporal resolution within the study area is between 18 and 26 days when compared to pressure gauges (Ballarotta et al., 2019). For the empirical reconstructions, the altimetry fields were cropped to a regional domain bounded by 92.28°W–75.56°W in longitude and 14.00°N–30.67°N in latitude, containing the Loop Current domain in the Gulf of Mexico and the northwest Caribbean Sea.

2.1.4 Transport filtering and uncertainty treatment

For consistency with the effective temporal resolution of the satellite altimetry product, all transport series were filtered with a Lanczos low-pass filter using a nominal 20-day cutoff. This choice is supported by previous comparisons showing improved agreement between altimetry-derived geostrophic velocities and moored measurements at similar filtering periods (see Manta et al., 2023).

Transport uncertainties were assigned according to record type. For the Canek Yucatan, Florida, and Old Bahama Channel transports, time-varying daily uncertainties were computed following Durante et al. (2025), using the formal mapping uncertainty of the objectively interpolated velocity field and propagating it through the section-integrated transport estimates following Wunsch (1996, p. 202). For the Florida Cable record, we used the reported cable uncertainty, based on comparisons with independent ship-based velocity-section estimates, including Pegasus and lowered-ADCP observations (Meinen et al., 2010; Volkov et al., 2020). This uncertainty is constant and treated as an empirical observational uncertainty.

Unless otherwise stated, transport statistics such as mean and standard deviation are computed using inverse-variance weights based on the daily transport uncertainty estimates to give more weight to data with less error. Mean transports are reported with $\pm$ their standard error of the mean (**SEM**), computed following Panofsky and Brier (1958)

$$\text{SEM} = \frac{\sigma_T}{\sqrt{N_{\text{eff}}}},$$

where σ_T is the weighted standard deviation and N_{eff} is the effective number of independent observations. The latter was estimated from the integral autocorrelation time scale of de-seasonalized and detrended transport anomalies.

2.2 Methods

2.2.1 Partial least-squares regression

We used partial least-squares (PLS) regression (Wold et al., 2001) to relate regional sea-level variability to observed volume transport. The PLS method is well suited to this problem because it extracts a small set of low-dimensional, mutually orthogonal, transport-sensitive modes from the regional altimetry field. This allows spatially distributed sea-level information to be used while managing the strong collinearity among neighboring grid points.

The procedure is implemented as follows: let $\mathbf{X} \in \mathbb{R}^{N_t \times N_x}$ denote the matrix of regional altimetry, where each row corresponds to one time step and each column to one grid point, and let $\mathbf{y} \in \mathbb{R}^{N_t}$ denote the corresponding transport time series for a given section. Here, N_t is the number of daily observations used in the regression and N_x is the number of altimetry grid points.

The transport uncertainty was incorporated through inverse-variance row weights. Let

$$w_i = \sigma_{y_i}^{-2}, \quad \tilde{w}_i = \frac{w_i}{N_t^{-1} \sum_{i=1}^{N_t} w_i},$$

where σ_{y_i} is the transport uncertainty standard deviation at time i , and $\tilde{w}_i$ is the normalized inverse-variance weight. Before applying PLS, each altimetry grid-point time series and the transport time series were centered, scaled, and weighted as

$$\tilde{X}_{ij} = \left[\frac{X_{ij} - \bar{X}_{j,w}}{s_{X_j,w}} \right] \sqrt{\tilde{w}_i}, \quad \tilde{y}_i = \left[\frac{y_i - \bar{y}_w}{s_{y,w}} \right] \sqrt{\tilde{w}_i},$$

where $i = 1, \dots, N_t$ indexes time, $j = 1, \dots, N_x$ indexes altimetry grid points, overbars with subscript w denote weighted temporal means, and $s_{X_j,w}$ and $s_{y,w}$ are the corresponding weighted temporal standard deviations. This weighting gives lower-uncertainty transport estimates greater influence in the PLS fit.

Instead of regressing the transport anomalies $\tilde{\mathbf{y}}$ directly onto the full high-dimensional altimetry field, PLS represents the matrix $\tilde{\mathbf{X}}$ using a reduced set of m transport-sensitive or *latent* modes,

$$\tilde{\mathbf{X}} = \mathbf{S}\mathbf{P}^T + \mathbf{E}, \quad (1)$$

where $\mathbf{S} \in \mathbb{R}^{N_t \times m}$ is the score or time-coefficients matrix containing the time-dependent amplitudes of the retained modes, $\mathbf{P} \in \mathbb{R}^{N_x \times m}$ is the predictor loading matrix containing their associated spatial patterns, and $\mathbf{E} \in \mathbb{R}^{N_t \times N_x}$ is the residual sea-level anomaly matrix, which contains the portion of $\tilde{\mathbf{X}}$ not represented by the retained modes.

To perform the decomposition in **Equation (1)**, we used the statistically inspired modification of partial least squares (SIMPLS) algorithm introduced by de Jong (1993). SIMPLS sequentially constructs the time-coefficients matrix $\mathbf{S}$ as linear combinations of $\tilde{\mathbf{X}}$, choosing projection directions that maximize covariance with $\tilde{\mathbf{y}}$ while constraining successive time-coefficients vectors to be mutually orthogonal. The resulting projection can be written as

$$\mathbf{S} = \tilde{\mathbf{X}}\mathbf{R}, \quad (2)$$

where

$$\mathbf{R} = \mathbf{W} (\mathbf{P}^T \mathbf{W})^{-1}.$$

Here, $\mathbf{W} \in \mathbb{R}^{N_x \times m}$ contains the PLS weight vectors, and $\mathbf{R} \in \mathbb{R}^{N_x \times m}$ is the adjusted projection matrix that maps the predictor field onto the retained PLS time-coefficients space.

Once the time-coefficients $\mathbf{S}$ are obtained, the representations of $\tilde{\mathbf{y}}$ and their fitted values $\hat{\mathbf{y}}$ in the score space are written as

$$\hat{\mathbf{y}} = \mathbf{S}\mathbf{q} \quad (3)$$

with

$$\tilde{\mathbf{y}} = \hat{\mathbf{y}} + \boldsymbol{\epsilon},$$

where $\hat{\mathbf{y}}$ denotes the fitted transport anomaly, $\mathbf{q} \in \mathbb{R}^m$ contains the score-space regression coefficients, and $\boldsymbol{\epsilon} \in \mathbb{R}^{N_t}$ is the residual transport anomaly vector. Thus, $\mathbf{q}$ defines the linear relationship between the retained transport-sensitive altimetric time-coefficients and the transport anomalies.

Each retained PLS mode contributes to the fitted standardized transport anomaly through the product $q_k \mathbf{s}_k$. Thus, the fitted transport anomaly can be decomposed as

$$\hat{\mathbf{y}} = \sum_{k=1}^m q_k \mathbf{s}_k.$$

The relative contribution of each mode can be quantified from the incremental variance explained in the observed transport anomaly.

3 Results

The results progress from updated direct transport observations to regional altimetry-based reconstruction and dynamical interpretation. We first revisit low-frequency transport variability across the Yucatan Channel, southern Florida Straits, Florida Cable, and Old Bahama Channel records, which sample complementary segments of the western-boundary pathway (**Figure 2e**). We then identify the regional sea-level patterns carrying the transport signal and use them to reconstruct transport variability over the satellite-altimetry era.

Unless otherwise stated, transport statistics are computed using inverse-variance weights based on daily transport uncertainty estimates. Mean uncertainties are reported as the standard error of the mean (**SEM**; **Section 2.1.4**).

3.1 Observed transport variability across the western-boundary gateway

The observed transport records differ substantially in duration, statistical independence, and variance structure (**Figure 2**; **Table 1**). The Florida Cable provides the longest record, spanning more than 40 years, with a weighted mean transport of 31.9 ± 0.2 Sv (Sverdrups; $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$).

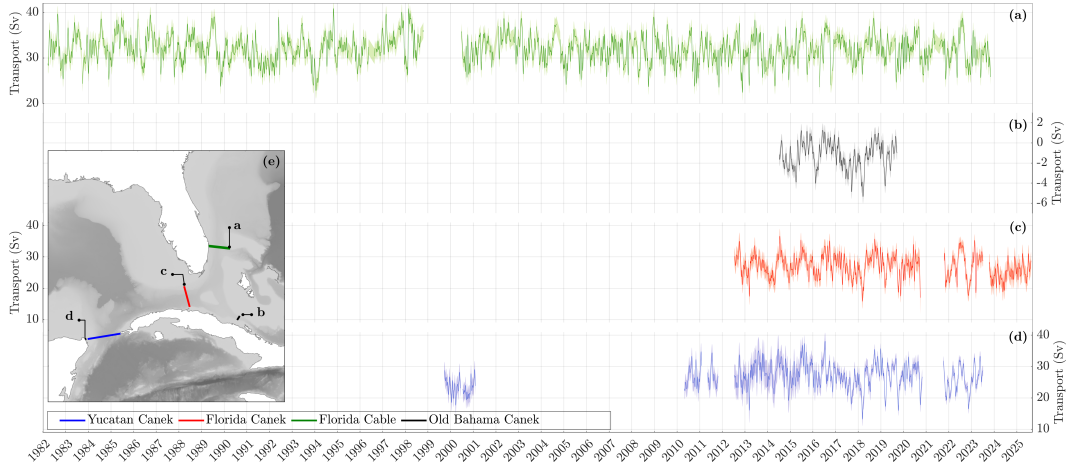


Figure 2. Observed low-pass-filtered transport records used in this study. Panels show volume transport from the (a) Florida Cable, (b) Old Bahama Channel Canek, (c) Florida Canek, and (d) Yucatan Canek sections. Thin lines show the filtered daily records and shaded envelopes indicate the estimated transport uncertainty envelope. Panel (e) shows the location of each section: Florida Cable (green), Old Bahama Channel Canek (black), Florida Canek (red), and Yucatan Canek (blue).

The Canek sections provide shorter, but direct velocity-based, estimates of transport across the main Gulf inflow and outflow sections. The available sampling periods sum to approximately 14 years for the Yucatan section and 12 years for the Florida section, with weighted mean transports of 26.5 ± 0.4 Sv and 27.0 ± 0.5 Sv, respectively.

The Old Bahama Channel record is shorter, with 5.7 years of data, and has a smaller mean transport magnitude of -1.2 ± 0.3 Sv. However, as previously reported by Candela et al. (2019), transport events can reach values of order -5 Sv and increase the corre-

Table 1. Summary statistics of the observed transport records used in this study. Means, standard deviations, trends, and harmonic seasonal fits were computed using inverse-variance weights based on the daily transport uncertainty. The decorrelation time scale, effective degrees of freedom, and standard error of the mean (**SEM**) summarize the statistical independence of each record. Seasonal explained variance is the fraction of variance explained by annual and semi-annual harmonics. Effective degrees of freedom and standard error of the mean were estimated from the integral autocorrelation time of de-seasonalized and detrended transport anomalies, integrated to the first zero crossing.

	Florida Cable	Old Bahama Canek	Florida Canek	Yucatan Canek
Years covered	41.2	5.7	11.9	13.7
Decorrelation time scale (days)	22	55	23	40
Effective degrees of freedom	305	17	94	57
Weighted mean transport $\pm$ SEM (Sv)	31.9 ± 0.2	-1.2 ± 0.3	27 ± 0.4	26.5 ± 0.5
Weighted standard deviation (Sv)	2.9	1.3	3.6	3.8
Median daily uncertainty (Sv)	1.7	0.6	2.3	2.1
Annual amplitude (Sv)	1.21	0.71	1.94	0.85
Semiannual amplitude (Sv)	0.62	0.45	0.92	1.10
Seasonal explained variance (%)	11.26	19.42	17.88	6.33

lation with the cable data, reflecting the role of this channel as a relevant secondary passage relative to the main Yucatan–Florida pathway.

The weighted standard deviations indicate substantial transport variability in the major sections, with values of 3.8 Sv for the Yucatan Canek record, 3.6 Sv for the Florida Canek record, and 2.9 Sv for the Florida Cable record.

Seasonal harmonics explain only a modest fraction of the variance, ranging from about 6% in the Yucatan record to about 19% in the Old Bahama Channel record. Thus, although seasonal variability is considerable, most of the observed transport variance resides in nonseasonal fluctuations (Athié et al., 2020; Volkov et al., 2024; Durante et al., 2025).

Table 1 summarizes the basic statistics of the four observed transport records. These quantities are estimated from the longest observational records currently available for each section; however, they should be interpreted as period-conditioned estimates rather than time-invariant properties of the western-boundary circulation. Mean transport, seasonal amplitudes, and linear trends are especially sensitive to the years sampled, so the values reported here characterize the available records rather than definitive climatological constants.

3.2 Period-conditioned estimates of transport variability

To quantify this sampling sensitivity, we performed a finite-window Monte Carlo experiment based on random contiguous-window resampling. Continuous windows of fixed duration were randomly selected from each available transport record, preserving the temporal structure within each sampled segment. Window lengths from 2 to 8 years were tested, with additional 10-, 15-, and 20-year windows for the Florida Cable record. For each window length and each transport record, $n_{\text{MC}} = 2000$ accepted realizations were generated. A window was accepted only if at least 75% of the daily values were available and if no internal data gap exceeded 120 days. Within each accepted window, the same transport statistics were recomputed.

Daily transport uncertainty was propagated by generating one perturbed realization for each accepted window,

$$T^{(k)}(t) = T(t) + \sigma_T(t)\varepsilon^{(k)}(t),$$

where $T(t)$ is the observed transport at time t , $\sigma_T(t)$ is its estimated daily uncertainty, and $\varepsilon^{(k)}(t)$ is drawn independently from a standard normal distribution for each time and realization. Thus, each perturbed value is sampled from a normal distribution centered on the observed transport with standard deviation $\sigma_T(t)$. This perturbation treats the daily uncertainty estimates as independent in time; therefore, the experiment is intended to quantify the combined effect of reported daily uncertainty and finite-window sampling sensitivity, rather than to model temporally correlated observational uncertainty.

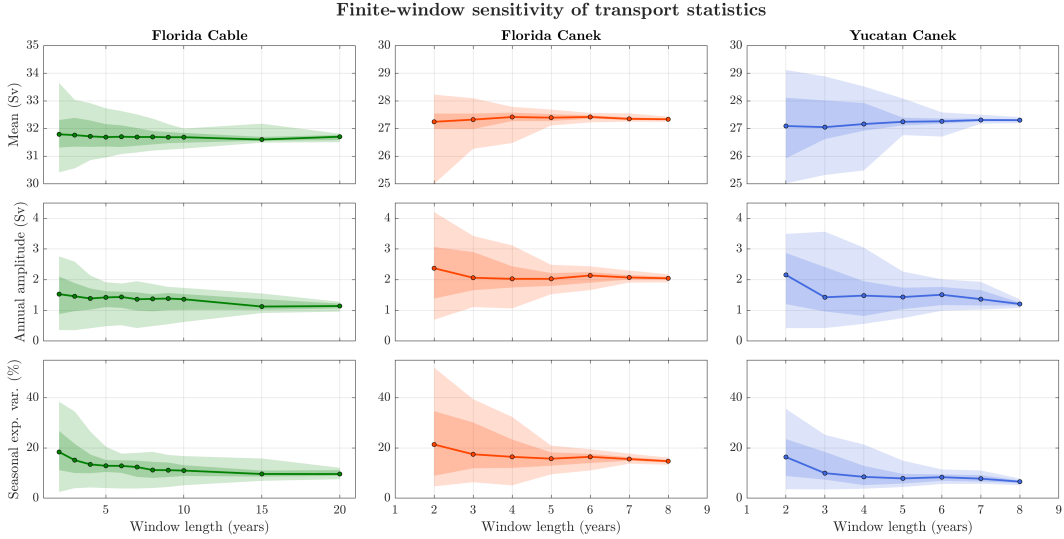


Figure 3. Finite-window sensitivity of selected transport statistics. Columns correspond to the Florida Cable, Florida Canek, and Yucatan Canek records, and rows show the weighted mean transport, annual harmonic amplitude, and seasonal explained variance. For each window length, continuous record segments satisfying the coverage criteria were randomly selected and perturbed according to the reported daily transport uncertainty. Solid lines show the median across accepted Monte Carlo realizations, darker shading indicates the 25–75 percentile range, and lighter shading indicates the 2.5–97.5 percentile range. Because the shaded envelopes are empirical percentile ranges, they are not constrained to be symmetric about the median.

As shown in **Figure 3**, finite-window estimates are sensitive to the sampled period, although the degree of sensitivity depends on the statistic. Mean transports are comparatively stable, with Monte Carlo medians remaining close to the full-record estimates,

but the percentile envelopes show that short-window means can still differ by dynamically meaningful amounts. In the Yucatan and Florida sections, the interquartile spread reaches about 1–3 Sv for the shortest windows and decreases with window length. Thus, short records can sample periods with substantially different mean inflow or outflow, with implications for volume balance and Gulf of Mexico sea-level adjustment (Candela et al., 2019; Durante et al., 2025).

The sensitivity is stronger for seasonal diagnostics. Both the annual amplitude and the seasonal explained variance show broad and asymmetric percentile ranges for short windows, indicating that a few years of observations can sample regimes in which the seasonal cycle appears either enhanced or weak relative to the total variability. The envelopes narrow progressively with increasing window length, highlighting the importance of sustained long-term observations for robustly estimating both mean transport and the structure of low-frequency variability (Athié et al., 2015, 2020; Durante et al., 2025; Volkov et al., 2024).

Although not included in **Figure 3**, linear trends are the most period-sensitive statistics. This is consistent with previous Florida Cable analyses showing that long-term transport changes must be interpreted in light of strong low-frequency variability and limited effective degrees of freedom (Meinen et al., 2010; Volkov et al., 2024). In our finite-window experiments, median trend estimates weakened as window length increased: for the Florida Cable record, trends changed from about -0.8 to -0.5 Sv decade $^{-1}$ in 5–10-year windows to -0.02 Sv decade $^{-1}$ in 20-year windows. Florida Canek trends weakened from -0.69 to -0.13 Sv decade $^{-1}$ between 5- and 8-year windows, while Yucatan Canek trends decreased in magnitude from -2.6 to -1.1 Sv decade $^{-1}$.

Overall, the finite-window experiments show that short records can yield period-dependent transport statistics, with sensitivity decreasing as window length approaches about 7–8 years for the mean transport and seasonal diagnostics, while trends remain more sensitive to the sampled interval. Thus, the Florida Cable, Yucatan Canek, and Florida Canek records provide a suitable basis for evaluating low-frequency transport variability, whereas the shorter Old Bahama Channel record is interpreted more cautiously, particularly for long-term statistics. Similar sensitivity was observed for the semiannual amplitude, whereas the standard deviation remained comparatively stable. The full Monte Carlo summary is provided in **Table S1**. We next examine whether the low-frequency transport variability is expressed in regional sea-level modes derived from satellite altimetry.

3.3 Regional sea-level patterns carrying the observed transport signal

As a first assessment of where regional altimetry contains transport-related information, we computed simultaneous correlations between each (20-day low-pass-filtered) transport record and the altimetric fields at each grid point (**Figure 4**). The upper row shows correlations with sea-level anomalies, whereas the lower row shows correlations with geostrophic speed. These maps provide a local correlation view of the spatial footprint of each transport record in the regional sea-level and surface velocity fields.

To a first order, the four transport records exhibit a common regional structure. In all cases, the transport-related signal is not confined to the immediate vicinity of the corresponding section, but projects onto a coherent sea-level pattern spanning the north-western Caribbean, the Yucatan Channel-Loop Current entrance region, Cuba, the Florida Straits, and the Bahamas passages (**Figure 4a-d**). This shared structure suggests that low-frequency transport variability along the Gulf of Mexico gateway is embedded in a broad regional sea-level modal configuration. In all four cases, sea-level-transport correlations include positive correlations around Cuba, and anti-correlations across the Yucatan Channel-Loop Current region. These correlation patterns broadly resemble the regional sea-level configurations previously reported by Athié et al. (2020) using a 4-year Yucatan transport series, the model-based compensation pattern described by Lin et al. (2009), and the Florida Cable transport-sea-level correlations shown by Mildner et al. (2013).

The geostrophic-speed-transport correlations (**Figure 4e-h**) also show organized structures across the gateway system, including dipolar patterns near the Yucatan Channel and Florida Straits, enhanced positive correlations along the western-boundary pathway from the northwestern Caribbean into the Florida Current, and notable correlations within the Old Bahama Channel. Similar dipolar structures in the Loop Current region have been associated with Loop Current extension-retraction variability and changes in the Yucatan Current pathway (Durante, 2025). These patterns suggest that transport variability is linked to organized regional surface-velocity structures, consistent with the altimetry-derived velocity signatures of Florida Cable transport variability reported by Hirschi et al. (2019).

Beyond first order similar patterns, the individual records exhibit localized differences in correlation amplitude and spatial organization. Particularly, the Florida cable record shows a more distinct correlation structure relative to the Canek records. Windowed correlations across the altimetry era (**Figure S3**) indicate that the dominant Florida Straits pattern is preserved, and suggest that this distinction is not primarily due to altimeter-era sampling. During the common Old Bahama Channel overlap period (2014–2019), removing the signed Old Bahama Channel transport anomaly from the Cable anomaly makes the sea-level correlation pattern more similar to the Canek patterns (**Figure 4j–l**). This suggests that part of the downstream Cable–Canek difference may reflect transport variability entering through the Bahamas passages between the Florida Canek and Cable sections, as previously suggested (Lin et al., 2009; Rousset & Beal, 2011; Candela et al., 2019).

Overall, the correlation maps show that the transport-related altimetric signal is spatially coherent but distributed across several dynamically connected regions, motivating a multivariate regional approach. We therefore use PLS to extract transport-sensitive spatial patterns from the regional sea-level and geostrophic-speed fields, *i.e.*, the patterns whose temporal amplitudes maximize covariance with each observed transport record. **Figure 5** shows the leading PLS spatial patterns for each section.

The leading PLS patterns broadly resemble the pointwise correlation maps in **Figure 4**, indicating that the modes capture the dominant transport-related altimetric signal. In the sea-level fields, all sections show coherent centers of action extending from

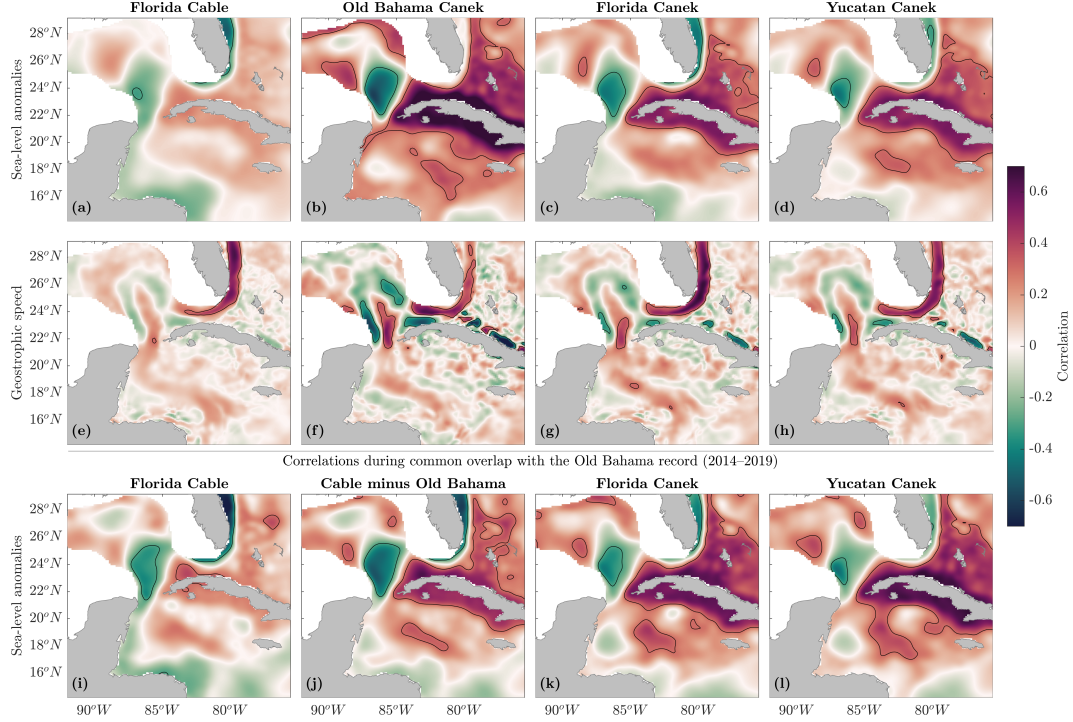


Figure 4. Simultaneous correlation maps between transport records and regional altimetric fields during periods of overlap. The upper row shows correlations between each transport record and sea-level anomalies at each altimetry grid point, and the middle row shows the corresponding correlations with geostrophic speed. Columns correspond to the Florida Cable, Old Bahama Channel Canek, Florida Canek, and Yucatan Canek records. The lower row shows an additional sea-level-anomaly diagnostic for the period of common overlap with the Old Bahama Channel record (2014–2019), comparing the Florida Cable transport, the Florida Cable transport after removing the signed Old Bahama Channel transport anomaly, the Florida Canek transport, and the Yucatan Canek transport.

the northwestern Caribbean and Yucatan Channel toward Cuba and the Florida Straits, with a recurrent contrast between positive amplitudes around Cuba and the Florida–Bahamas region and a negative lobe near the Yucatan Channel–Loop Current entrance. This structure suggests that the transport signal is linked to regional sea-level gradients and redistribution around Cuba, rather than to sea level adjacent to a single section. The geostrophic-speed PLS patterns also show coherent regional structures, but include additional smaller-scale patches that may reflect noise amplification from spatial derivatives.

For this diagnostic analysis, the PLS modes were computed using the full period of overlap between each transport record and altimetry. However, similar leading patterns are obtained when the calculation is repeated using independent 5-year windows in a Monte Carlo fashion, indicating that the dominant spatial structures are not controlled by a particular subset of the record. The spatial coherence and temporal robustness of the leading PLS patterns support the view that low-frequency transport variability is embedded in a regional sea-level and surface-velocity structure spanning the Yucatan Channel, Cuba, the Florida Straits, and the Bahamas passages.

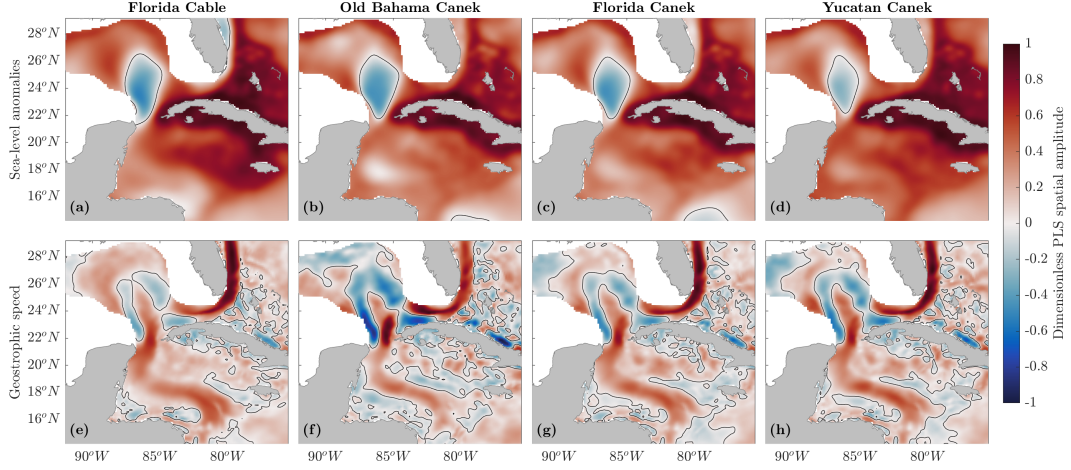


Figure 5. Spatial patterns of the leading PLS modes for the four transport records. The upper row shows the modes derived from sea-level anomalies, and the lower row shows the corresponding modes derived from geostrophic speed. Columns correspond to the Florida Cable, Old Bahama Channel Canek, Florida Canek, and Yucatan Canek records.

Diagnostic PLS fits based on geostrophic speed were more compact than those based on sea-level anomalies: the first geostrophic-speed mode explained 42–69% of the observed transport variance, compared with 23–45% for sea-level anomalies, and 90% of the variance was reached with 3–16 geostrophic-speed modes, compared with 6–35 sea-level modes (Table S2). However, this diagnostic compactness did not translate into stronger independent prediction. In calibration–validation experiments, sea-level anomalies produced more robust withheld reconstructions, with validation R^2 values of 0.6–0.8 and RMSE values of 0.74–2.0 Sv, outperforming both geostrophic speed and stacked sea-level–speed predictors (Table S3). The final transport proxies were therefore based on sea-level anomalies.

3.4 Altimetry-era reconstruction of gateway transport variability

The diagnostic analyses above show that observed transport variability is linked to coherent regional altimetric patterns. We now test whether these relationships can reconstruct transport variability over the full satellite-altimetry era. Sea-level anomalies were selected as predictors because they produced more robust out-of-sample reconstructions than geostrophic speed in the calibration–validation experiments. Although geostrophic speed also contains transport-related information, it generally yielded higher calibration skill but lower validation skill, consistent with reduced generalization and possible overfitting. This weaker validation performance may partly reflect noise amplification from spatial derivatives, as the geostrophic-speed correlation and PLS patterns contain smaller-scale structures than the smoother sea-level patterns. Stacked sea-level-anomaly and geostrophic-speed predictors also did not provide a consistent validation improvement (Table S3 in the SI).

For each section, the observed transport record was divided into calibration and validation subsets, with an overall split of approximately 60% for calibration and 40% for validation, adjusted slightly for data availability. For the Old Bahama Channel, both subsets included portions of the fully observed campaigns and the reconstructed extension based on partial mooring coverage. The PLS projection vectors, regression coefficients, retained components, and preprocessing parameters were estimated from the calibration subset only; validation data were then projected onto the calibrated model with-

out refitting. The final calibrated models were applied to the full satellite-altimetry record to obtain altimetry-era gateway transport reconstructions.

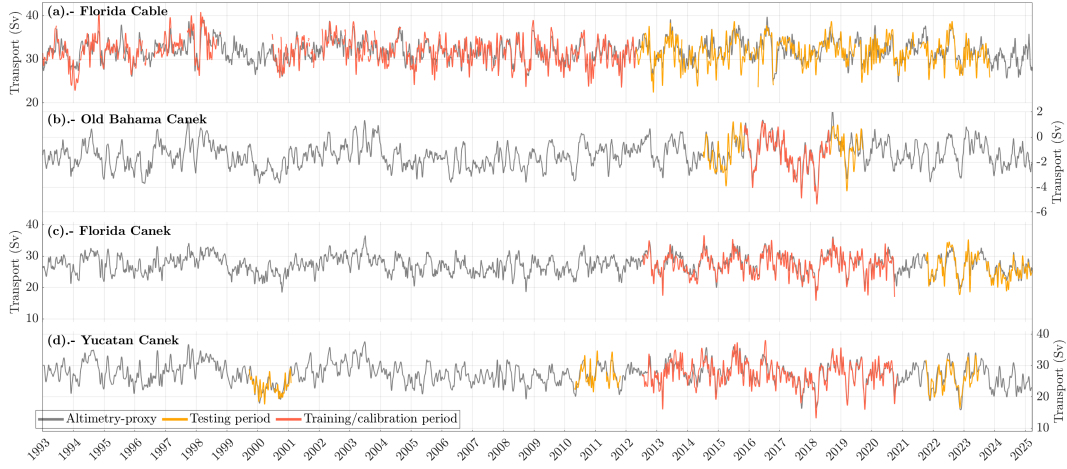


Figure 6. Gray curves show the reconstructed transport proxies obtained by applying the calibrated PLS models to the full satellite-altimetry record. Colored curves show the observed transport records during the periods used for calibration and withheld validation. Panels correspond to (a) Florida Cable, (b) Old Bahama Channel Canek, (c) Florida Canek, and (d) Yucatan Canek.

The resulting reconstructions reproduce a considerable fraction of the observed transport variability during the withheld validation periods, with withheld validation R^2 values of approximately 0.6 for the Florida Cable and Old Bahama Channel records, and 0.8 for the Florida Canek and Yucatan Canek records (**Figure 6**; **Table 2**).

It is worth noting that the Old Bahama Channel record occupies a distinct position in this analysis. Although the record was extended to its practical limit using reconstructed CVB3 profiles during incomplete mooring campaigns (**Figure S2**), it spans only about 5.7 years. As a result, the calibration period contains relatively few statistically independent samples, and the component-selection sensitivity analysis (**Figure S4**) does not show the clear validation plateau obtained for the longer records. The altimetry-based proxy for this section should therefore be interpreted cautiously, and its validation skill should be viewed as conditional on the limited calibration window rather than as evidence of a fully robust standalone reconstruction.

The corresponding validation root-mean-square error (**RMSE**) values range from about 0.74 Sv in the Old Bahama Channel to about 2 Sv for the Florida Cable and the Yucatan and Florida Canek records. These RMSE values are of the same order as the estimated uncertainties of the observed transport records (**Table 1**), indicating that the sea-level-based reconstructions recover the transport signal to within the observational uncertainty scale.

In practice, the regional PLS framework generalizes the end-point approach by using the spatial structure of sea level over the broader western-boundary gateway. Overall, the regional PLS proxies compare favorably with previous sea-level-based end-point estimates in the Yucatan Channel. There, previous satellite-altimetry proxies based on cross-channel sea-level differences captured a fraction of the observed transport variability, but robust skill was obtained only after strong low-pass averaging, with the proxy calibrated using 120-day running means (Athié et al., 2015, 2020). For the Florida Cable, the PLS proxy shows slightly improved skill relative to earlier sea-level-based esti-

mates, which recover about 55–60% of the cable-derived transport variance from along-track altimetry (Volkov et al., 2020).

The present results indicate that incorporating the regional sea-level structure allows a larger fraction of the transport variability to be recovered at the 20-day filtered time scale considered here. The number of retained PLS components ranges from 4 to 6 among the four reconstructions, indicating that the transport-relevant altimetric information is concentrated in a relatively compact set of regional covariance modes.

Beyond the aggregate skill metrics, the reconstructed time series reproduce the main temporal structure of the observed transports during the periods of overlap (**Figure 6**). Low-frequency variations are generally well captured by the altimetry-derived proxies. A clear example is the relatively low-transport period between late 1999 and early 2000 in the Yucatan Channel (Sheinbaum et al., 2002; Athié et al., 2020), when the observed record shows a sustained transport reduction and the absence of a clear annual maximum. A similar suppression of the annual maximum is observed during 2017–2018. Shorter low-transport episodes in 2013, 2018, 2019, 2020, and 2023 are also captured in the Yucatan and Florida Canek altimetry proxies.

In general, the largest transport excursions tend to have slightly larger amplitudes in the observations than in the reconstructions. However, the proxies capture their timing and sign, yielding high observation–proxy correlations of $r = 0.9$ for both the Yucatan and Florida Canek sections. This suggests that these transport anomalies project onto the regional sea-level field, even when their full amplitude is not completely recovered.

Because these maps are very similar to **Figures 4** and **5**, the correlation maps between the reconstructed transport proxies and regional sea-level anomalies during periods outside the calibration interval are not shown. Nevertheless, they reproduce the main spatial structures obtained from the observed transports in **Figure 4**. Although this similarity is expected from the PLS formulation, it shows that the reconstructed proxies remain dynamically consistent with the regional sea-level structures associated with the observed transport variability during unconstrained periods.

Table 2. Skill of the sea-level-based PLS reconstructions of gateway transport variability. The calibration/validation length column gives the amount of observed transport data used for model fitting and withheld validation, respectively. The retained components column gives the number of PLS modes used in the final reconstruction. Skill is reported using the coefficient of determination, R^2 , and RMSE in Sverdrups.

Section	Calibration/validation length (yr)	Retained components	Calibration R^2 / RMSE	Validation R^2 / RMSE
Florida Cable	16 / 11	5	0.7 / 1.70	0.6 / 2.00
Old Bahama Channel	3 / 2	4	0.9 / 0.43	0.7 / 0.74
Florida Canek	8 / 3	6	0.8 / 1.60	0.8 / 1.80
Yucatan Canek	8 / 4	6	0.7 / 2.03	0.8 / 2.00

These results strongly suggest that regional altimetry contains a substantial fraction of the low-frequency transport signal along the western-boundary pathway. The PLS framework extracts this information from a compact set of regional sea-level modes, allowing the observed transport records to be extended across the satellite-altimetry era.

3.5 Regional sea-level evolution during Yucatan transport extremes

The reconstruction skill and correlation maps indicate that the **PLS** proxy preserves the regional sea-level footprint of the observed transport variability. To interpret the physical structure captured by this proxy, particularly its relationship to Loop Current states and Yucatan Channel transport, we constructed time-normalized composites of large positive and negative transport anomalies. The composites were based on the altimetry-era **PLS** reconstruction and follow an event-composite approach similar to Mildner et al. (2013), but using Yucatan Channel transport anomalies rather than Florida Current transport minima.

Positive events were defined as local maxima exceeding 5 Sv and negative events as local minima below -7.5 Sv. For each event, onset was identified as the closest preceding zero crossing, and only onset-to-extreme durations shorter than about 65 days were retained. This procedure selected 24 positive and 12 negative events, with durations of about 20–65 days. To compare events of different duration, each evolution was normalized in time and sampled at five phases: onset, 25%, 50%, 75%, and the transport extreme. The corresponding sea-level anomaly fields were then averaged at each phase (**Figure 7**). These composites are used as diagnostics of the regional sea-level evolution associated with transport extremes, rather than as evidence of causality or predictability.

The resulting composites show that large positive Yucatan transport anomalies are accompanied by a coherent regional evolution of the sea-level anomaly field (**Figure 7c**). At event onset, when the transport anomaly is near zero, the Loop Current contour is already extended in the composite. As transport increases, the contour evolves toward a necked, eddy-detachment-like geometry, while the sea-level field sharpens into a stronger regional contrast. Near the transport peak, the largest horizontal gradients occur between the negative anomaly around the Loop Current necking region described by Schmitz Jr (2005) and positive anomalies north of Cuba and along the Florida Straits pathway. Transport growth is also accompanied by broadly positive sea-level anomalies around Cuba, consistent with the positive sea-level–transport correlations in **Figure 4**.

Conversely, low-transport events (**Figure 7f**) show a broadly opposite, although not perfectly antisymmetric, sea-level configuration. Positive anomalies occur near the Yucatan Channel and within much of the area enclosed by the Loop Current contour, while a persistent negative anomaly appears near the entrance to the Straits of Florida, resembling the cyclonic Tortugas eddies described by Fratantoni et al. (1998). Low sea-level anomalies around Cuba further resemble the correlation-map pattern. Thus, the Loop Current can remain extended during negative transport events, but with a different contour geometry and regional sea-level structure than during positive events.

The composite analysis shows a spatially coherent covariability pattern also reflected in the correlation maps and leading **PLS** modes linking Yucatan transport with regional sea level. In both positive and negative composites, the Loop Current is, on average, already extended before the transport extreme is reached. Thus, Loop Current extension alone is not a sufficient descriptor of the transport state, and total Yucatan transport does not uniquely determine Loop Current extension. Instead, the sign and magnitude of the Yucatan transport anomaly depend on the broader sea-level configuration and Loop Current geometry, reinforcing that the inflow–Loop Current connection is present but more complex than a simple extended-versus-retracted classification.

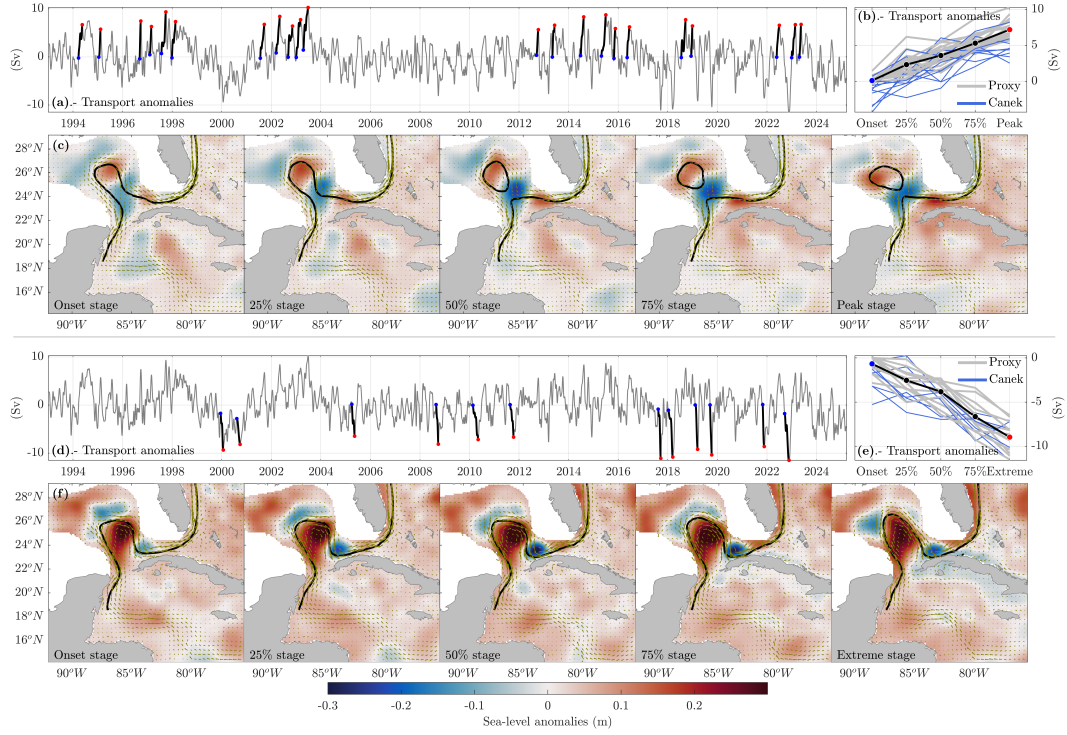


Figure 7. Time-normalized composites of positive and negative Yucatan transport anomalies. (a,d) Altimetry-derived Yucatan transport proxy, with selected positive and negative events marked in black; red dots indicate transport extrema and blue dots indicate the closest preceding zero crossing. Positive events are maxima above 5 Sv, and negative events are minima below -7.5 Sv. (b,e) Time-normalized evolution from onset to peak or extreme. Gray curves show proxy anomalies, blue curves show observed Canek anomalies during observational overlap, and black curves show the composite mean. (c,f) Composite sea-level anomaly fields at five normalized stages, from onset to peak for positive events and from onset to extreme for negative events. The black contour indicates the stage-dependent Loop Current contour following Leben (2005).

4 Summary and Discussion

In this study, we examined whether the low-frequency transport variability along the Gulf of Mexico gateway system can be expressed by coherent regional sea-level structures. Using direct transport estimates from the Yucatan Channel, southern Florida Straits, and Old Bahama Channel Canek sections, as well as the Florida Cable record, we are able to quantify the main Gulf inflow–outflow pathway as well as a secondary passage around Cuba. The results indicate that transport variability at periods resolved by satellite altimetry projects strongly onto regional sea-level patterns spanning the study region. These transport-sensitive sea-level modes allow us to recover a considerable fraction of the observed transport variability and to extend the transport series over the satellite-altimetry era, from 1993 to 2025.

In the first part of the analysis, we show that transport statistics from finite records should be interpreted as period-conditioned quantities (**Figure 3**). The finite-window Monte Carlo experiments indicate that short records can yield substantially different estimates of mean transport, annual amplitude, seasonal explained variance, and especially linear trend, depending on the years sampled. This sensitivity decreases as the window length approaches about 7–8 years for the mean and seasonal diagnostics, whereas trends

remain more interval-dependent. This reinforces the importance of sustained direct observations for separating persistent transport characteristics from variability associated with the sampled periods (Athié et al., 2015, 2020; Volkov et al., 2024; Durante et al., 2025).

The transport signal is embedded in a broader sea-level configuration linking the Yucatan Channel, Loop Current system, Florida Straits, and pathways around Cuba, but its local versus regional expression differs among sections. For the Florida Cable, the strongest correlations remain concentrated near the Straits of Florida, consistent with local sea-level-gradient control on downstream Florida Current transport (**Figure 4**) and with the comparable skill of regional **PLS** and previous end-point or pressure-gauge estimates (Volkov et al., 2020, 2025). In contrast, the Yucatan Canek, Florida Canek, and Old Bahama Channel records show broader coherent correlations across the Yucatan Channel, Cuba, the Florida Straits, and the Bahamas passages. For the Yucatan Channel in particular, previous cross-channel sea-level-difference proxies required strong low-pass averaging to obtain robust skill (Athié et al., 2015, 2020), whereas the regional **PLS** proxy suggests that section-integrated transport is better represented by a distributed sea-level pattern involving the Loop Current entrance, Cuba, and the Florida Straits. This does not make local gradients dynamically uninformative (see, for example, van Westen et al., 2018; Torres-Córdoba & Valle-Levinson, 2025); rather, it suggests that transport variability includes spatially distributed contributions from pathway shifts, lateral displacement of the current core, and recirculating components (Nedbor-Gross et al., 2014; Sheinbaum et al., 2016; Athié et al., 2020). More broadly, this regional coherence supports the view of the Gulf of Mexico gateway as an interconnected set of passages where transport anomalies can be partially compensated among channels (Lin et al., 2009; Candela et al., 2019).

The composite analysis shows that extreme Yucatan transport events occur within spatially coherent sea-level anomaly configurations that resemble the correlation maps and leading **PLS** modes. Positive events are associated with an extended Loop Current evolving toward a necked, eddy-detachment-like geometry near the transport maximum (Schmitz Jr, 2005), together with positive sea-level anomalies north of Cuba and along the Florida Straits pathway. This pattern resembles the sea-level buildup northwest of Cuba associated with enhanced Yucatan transport in the compensation framework of Lin et al. (2009). Low-transport events show a distinct, broadly opposite configuration, consistent with studies linking reduced transport to extended or strongly intruding Loop Current states, partial compensation around Cuba, and possible inflow blocking by coherent anticyclonic eddies embedded in the Loop Current (Lin et al., 2009; Mildner et al., 2013). These results help reconcile the relationship between total Yucatan Channel transport and Loop Current dynamics: idealized and intermediate-complexity models suggest that stronger Yucatan inflow should favor greater Loop Current growth, penetration, or eddy size (Pichevin & Nof, 1997; Nof, 2005; Moreles et al., 2021), whereas observations and more complex models show that total transport does not have a one-to-one relationship with Loop Current extension or ring shedding (Lin et al., 2009; Sturges et al., 2010; Nedbor-Gross et al., 2014; Athié et al., 2015; Sheinbaum et al., 2016; Hirschi et al., 2019; Athié et al., 2020). Our composites support this latter view, showing that the transport–Loop Current link is present but expressed through regional sea-level patterns and geometry-dependent circulation states rather than through Loop Current extension alone. The Florida Straits expression of these composites is also consistent with previous links between Loop Current evolution and downstream transport variability, including surface-velocity anomalies and enhanced Florida Current pulses preceding ring separation (Sturges et al., 2010; Hirschi et al., 2019).

The altimetry-derived reconstructions complement rather than replace direct observations: they depend on the Canek and Cable records for calibration, while absolute transport, vertical structure, and uncertainty remain anchored by *in situ* measurements.

This role is especially relevant during observational gaps. The Florida Canek section was interrupted in 2025 for an uncertain duration (**Section 2.1.1**); its PLS proxy achieves validation $R^2 = 0.8$ and $\text{RMSE} \approx 1.8$ Sv, providing an observationally calibrated estimate of low-frequency Florida Straits transport variability with skill comparable to the uncertainty scale of the direct record (median daily uncertainty ~ 2.3 Sv; **Table 1**). Similarly, the ~ 8 -month COVID-related interruption in the Yucatan and Florida records during 2020–2021 is spanned continuously by the altimetry-era reconstructions, illustrating their practical utility for bridging gaps without imposing gap-filling assumptions on the direct records.

Overall, the coherent PLS modes and reconstruction skill reflect the regional connectivity between gateway transport and sea-level variability (Lin et al., 2009; Mildner et al., 2013; Candela et al., 2019; Athié et al., 2020). The Old Bahama Channel requires cautious interpretation because of its short record and partly reconstructed section coverage. Nevertheless, its coherent correlation and PLS patterns suggest that Bahamas-passage transport variability is dynamically connected to the Yucatan–Cuba–Florida pathway, consistent with the compensation mechanism of Lin et al. (2009) and the regional volume-balance perspective of Candela et al. (2019). Removing the Old Bahama Channel anomaly from the downstream Florida Cable anomaly makes the corresponding sea-level correlation pattern more similar to the Florida Canek pattern (**Figure 4j–k**), suggesting that part of the Cable-specific structure reflects Bahamas-passage variability added between the Florida Canek and Cable sections. A simple anomaly-budget comparison supports this interpretation: during the Old Bahama Channel overlap, the RMS difference between Florida Cable and Florida Canek anomalies decreases from 3.0 to 1.3 Sv when Old Bahama Channel transport is added to Florida Canek transport, and the correlation with the Cable record increases from $r = 0.5$ to $r = 0.7$. The remaining residual RMS is comparable to previous Northwest Providence Channel transport estimates (Leaman et al., 1995; Johns et al., 1999; Hamilton et al., 2005; Rousset & Beal, 2011, 2014), suggesting that variability through this passage may also contribute to the regional volume balance.

These proxies also have limitations. Because satellite altimetry has an effective temporal resolution lower than its daily mapped sampling, the proxies are not expected to recover higher-frequency variability. Surface altimetry alone also cannot robustly constrain vertical velocity structure without additional assumptions or *in situ* information. Broader-domain analyses including wind-stress-curl variability, basin-scale pressure-gradient adjustment, and transport contributions from the Antilles Current and Northwest Providence Channel could help separate regional Loop Current–Cuba–Florida dynamics from larger-scale western-boundary-current forcing. Sustained direct observations therefore remain essential for anchoring the proxies, improving their robustness, and resolving the vertical and cross-sectional structure that altimetry alone cannot provide.

Open Research

The processed datasets and code needed to reproduce the figures and tables, and to support the conclusions of this study, are openly available. The L4 gridded Canek V4 mooring products used to compute the observed transports are archived in Zenodo (Durante et al., 2023). The altimetry-derived transport proxies for the four sections, together with the code used to generate the figures and tables presented here, are also archived in Zenodo (Durante et al., 2026). The satellite altimetry product used in this study is distributed by the Copernicus Marine Service and is available at (E.U. Copernicus Marine Service Information, 2024).

Conflict of Interest Statement

The authors have no conflicts of interest to disclose.

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