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Measuring Maritime Connectivity to Puerto Rico and the Virgin Islands Using Automatic Identification System (AIS) Data

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PURPOSE: The purpose of this Coastal and Hydraulics Engineering technical note (CHETN) is to summarize a portion of recently published work (Young, Kress, et al. 2022) that used archival Automatic Identification System (AIS) data to measure the commercial vessel traffic connected to Puerto Rican and US Virgin Island (USVI) port areas from January 2015 to June 2020. Vessel movement derived from AIS was aggregated to construct a network that measured the port-to-port connectivity for all ports in the network and the interconnectivity of traffic between those ports. AIS data provided a description of vessel movement and the identification of specific vessel classes. Metrics such as interconnectedness can be used in conjunction with standard US Army Corps of Engineers (USACE) metrics describing waterway utilization, which traditionally have included total tonnage and specific commodity tonnage. The ability to consider the self-selected vessel-type broadcast via AIS, as well as dominant commodity type and tonnage reported through statistical publications, provides a fuller and more accurate description of waterway capacity utilization. This knowledge, along with port-to-port interconnectedness, reveals potential redundancies between ports, robustness across supply chains, and the impacts of seasonality, thereby allowing the USACE to expand its understanding of maritime supply-chain resilience.

INTRODUCTION: Maritime commerce is the backbone of the US economy and a particularly crucial link in the supply chains to Puerto Rico and the USVI. These islands rely on the marine transportation system to maintain daily life, economic activity, and government services; thus, it is critical to disaster preparedness, response, and recovery efforts (Ecola et al. 2020). Describing the baseline operations of the marine transportation system (MTS) connections is a critical first step in enhancing resilience under the framework of *Prepare, Absorb, Recover, and Adapt* (USACE 2017). Metrics describing the connectivity of a port and its position within a network of trading partners are key data points to describing the criticality of any individual port and its contribution to the flow of vessel traffic. Traditional metrics of port activity such as tonnage or commodities handled are ideal for describing port activity in isolation, but do not communicate a port's place in the larger system of maritime commerce. They also lack sufficient temporal resolution to describe traffic flow through disruptive events (Scully and Chambers 2019, 311–321).

This report examined commercial maritime vessel traffic between Puerto Rican and USVI port areas using archival vessel data broadcast by vessels through the AIS. AIS operates on the VHF maritime band and is therefore limited by distance and line-of-sight (USCG, n.d.). AIS was originally developed as an aid to maritime-domain awareness and vessel-collision avoidance. However, it has matured sufficiently that the archival information can be utilized to study for a multitude of maritime issues (Young and Scully 2018; Kress et al. 2020; Scully et al. 2020; Kress et al. 2021; Young, Scully, and Chambers 2022; Young, Kress, et al. 2022). AIS carries a wide range of information regarding dynamic time-stamped vessel operating conditions such as the vessel's current position, course, heading, and speed-over-ground. Static information related to vessel identification is additionally available, including the vessel's name, Maritime Mobility Service Identity (MMSI) number, dimensions, and type (ITU 2014; USCG-NAVCEN, n.d.). AIS carriage requirements within US territorial waters are governed by 33 CFR § 164.46 (US CFR 2020). The overwhelming majority of vessels engaged in commercial activity are mandated to be equipped with AIS. Consequently, the data are an ideal tool for monitoring maritime traffic. This report uses AIS data to quantify the motion of vessels transiting the network of Puerto Rican and USVI port areas.

Quantifying the movements of vessels through AIS records describes the *connectivity* of all ports in a specified network (e.g., Puerto Rico and the USVI). Logging the arrivals and departures of every vessel during this process also facilitates the analysis of vessel dwell times and port-to-port transit times. The inclusion of vessel-type information further allows descriptions of the distribution of vessel types at individual port areas across the network. Furthermore, AIS data are sampled at VHF (1 min[*] timescale for the data in this report) relative to other metrics used to describe ports (e.g., yearly tonnage). As a result, it is capable of describing port and port network activity at the monthly, weekly, or even daily timescale.

METHOD

Vessel Data. AIS data are available from several public and proprietary sources. The data used in this report are a publicly available aggregation of AIS data from the Nationwide AIS (NAIS) system (USCG, n.d.) called Marine Cadastre (BOEM NOAA 2023). Several features of Marine Cadastre data are ideal for quantifying vessel movement between ports: multiple years of data are available, the data are in a standard format and sampled at a regular 1 min frequency, and the spatial coverage is sufficiently expansive. The Marine Cadastre data from January 2015 to June 2020 were analyzed for the present study. AIS records without a valid nine-digit MMSI number or country code were excluded from analysis, removing 6.8% of the records. Nearly 6 yr of nationwide AIS data consume approximately 2 TB of disk space, and the computational requirements for analyzing this amount of data are high. The data were processed with a single node of a Department of Defense high-performance computer, constituting 44 Intel Xeon cores running at 2.3 GHz with 144 GB of accessible memory using Python code (van Rossum and Drake 2001). The distributed computing requirements are managed by Apache Spark (Zaharia et al. 2016).

Port Areas in the Network. The MTS is a global system; however, the network of vessel activity described in this study consists of traffic flow among 325 spatially defined port areas in North America, all of which fall within the receiving range of US terrestrial NAIS sites. The Marine Cadastre AIS data were used to monitor the movement of vessels by determining when vessels entered and departed 325 US port areas. Port areas included high-tonnage port areas (USCG, n.d.) as well as low-tonnage and subsistence ports that play a critical role in supplying remote areas of the country (e.g., Kahului Maui, Hawai'i, and Ketchikan, Alaska). The 325 port areas constituting the network depicted in this study are not an exhaustive list of all port areas in the United States, but they are

[*] For a full list of the spelled-out forms of the units of measure and unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248–52 and 345–7, respectively. *https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf*.

sufficient to describe the macroscale migration of cargo-bearing vessels within US waters—they account for over 84% of the total US tonnage in 2019 (USCG, n.d.).

Port areas were determined by identifying each port's local terminals and adjoining waterways as polygons within ArcGIS Pro software (Esri, n.d.). These terminals were then combined to generate a single polygon outlining the total port area for each port. Figure 1 provides an example of the port area polygon for Jacksonville, Florida. Figure 2 shows the port areas used in the study.

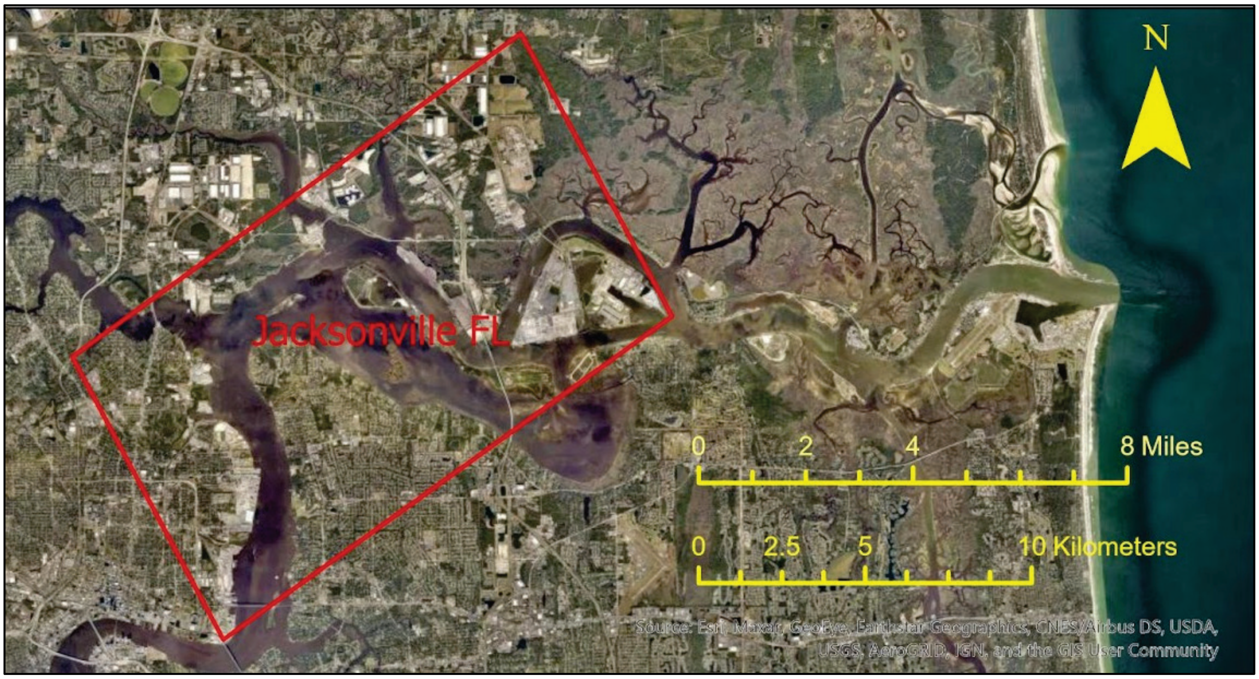

Figure 1. Port area polygon for the Port of Jacksonville, Florida.

Describing Network Movements. The first step to identify movements between port areas was to identify the sequential AIS position reports within each port area through a geospatial intersection. Next, the records for individual vessels (identified by their MMSI number (USCG, n.d.) were extracted from the AIS record then sorted in chronological order. This allowed the identification of the sequence of port area visits. For a set of sequential AIS records within a single port area polygon to register as a port visit (as opposed to a through-transit or a stray AIS position report), the longer of the two following conditions was required: the vessel had to spend (1) more than 1 hr within the port area polygon or (2) an amount of time longer than the number of hours required for a vessel traveling at 5 kn to transit the longest axis of the port area polygon. The results from this condition were especially important to distinguish port visits in areas with multiple adjacent ports, such as along the Lower Mississippi River (Ports of Plaquemines, New Orleans, South Louisiana, and Baton Rouge) and the Delaware River (Ports of Wilmington, Delaware; Paulsboro, New Jersey; Philadelphia, Pennsylvania; and Camden, New Jersey). Instances of vessels departing a port area for greater than 24 hr and then returning without appearing at another port area were excluded from further analysis. The vessel-traffic description in this study contains 325 ports, but the analysis focuses on the 30 ports in the Puerto Rico/Virgin Island (PR/VI) region, shown in Figure 2.

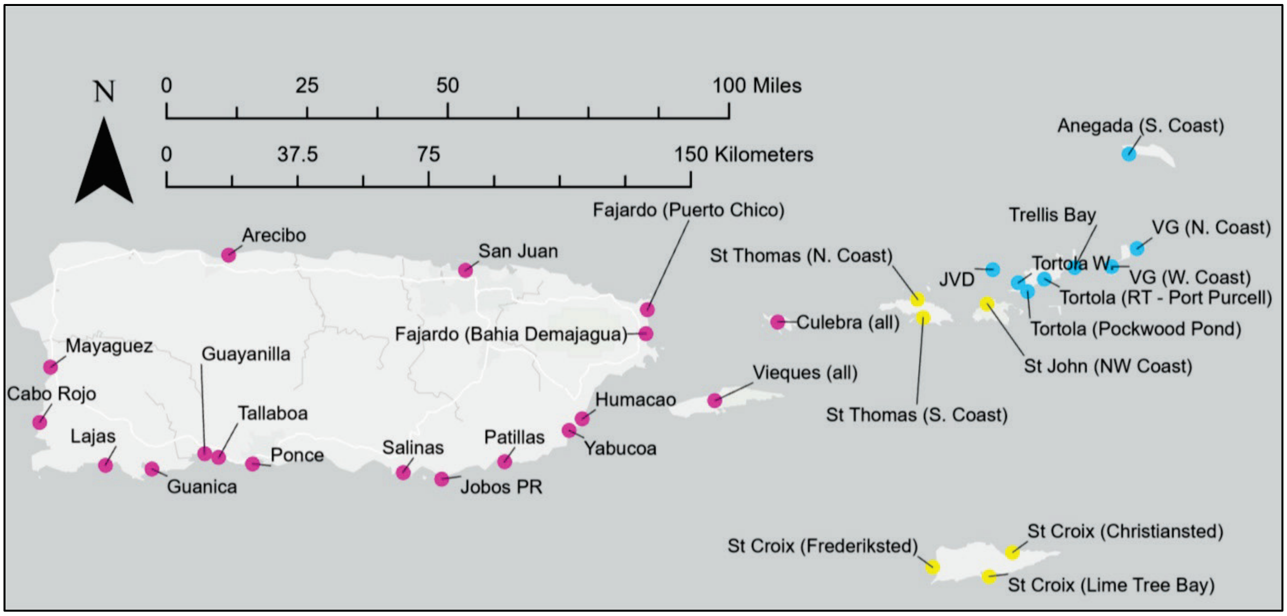

Figure 2. Map showing the 30 port areas in Puerto Rico and the Virgin Islands included in this study. *Pink dots* are Puerto Rican port areas, *yellow dots* are USVI port areas, and *blue dots* are British Virgin Island port areas.

RESULTS

Describing Connectivity. Vessel transits observed with AIS allow for the precise description of commercial connections between port areas. As an example, Figure 3 describes the arrivals of cargo vessels (AIS vessel type codes 70–79) from all 325 ports in the network into the San Juan port area and cargo vessel departures from San Juan to other PR/VI ports. Figure 3 shows how San Juan acts as a hub for cargo traffic among the PR/VI ports. San Juan receives large numbers of incoming cargo vessels from ports on the East and Gulf Coasts (i.e., Jacksonville, Houston, New York/New Jersey). In addition to the cargo that stays in PR, San Juan also exchanges cargo vessels with other smaller PR/VI ports (e.g., St. Thomas [South Coast] USVI and St. Croix (Lime Tree Bay) USVI. Note that Jacksonville serves as the largest single source of cargo vessel shipments from the mainland United States to the Port of San Juan, and by extension, the PR/VI region considered in this study. Presumably, this makes Jacksonville the most critical stateside source for maritime shipments to PR/VI, despite the lower amount of total tonnage handled by Jacksonville relative to the other stateside ports that trade with San Juan, such as Houston or New York/New Jersey.

In this way, AIS data add an additional dimension onto total tonnage metrics by allowing the USACE to observe where vessels arrive from or depart to. Table 1 presents annual port tonnage totals for PR/VI locations where such data were publicly available from the USACE Waterborne Commerce Statistics Center (WCSC) (USACE-WCSC, n.d.). This tonnage table is complementary to the information in Figure 3. For example, Table 1 shows that San Juan, Puerto Rico, is the most critical port in PR/VI in terms of cargo vessel connectivity while also ranking highest among the examined PR/VI ports by tonnage (in keeping with its status as a regional traffic hub). By combining this information with that presented in Figure 3, it follows that Jacksonville must therefore be a key mainland hub for PR/VI cargo traffic.

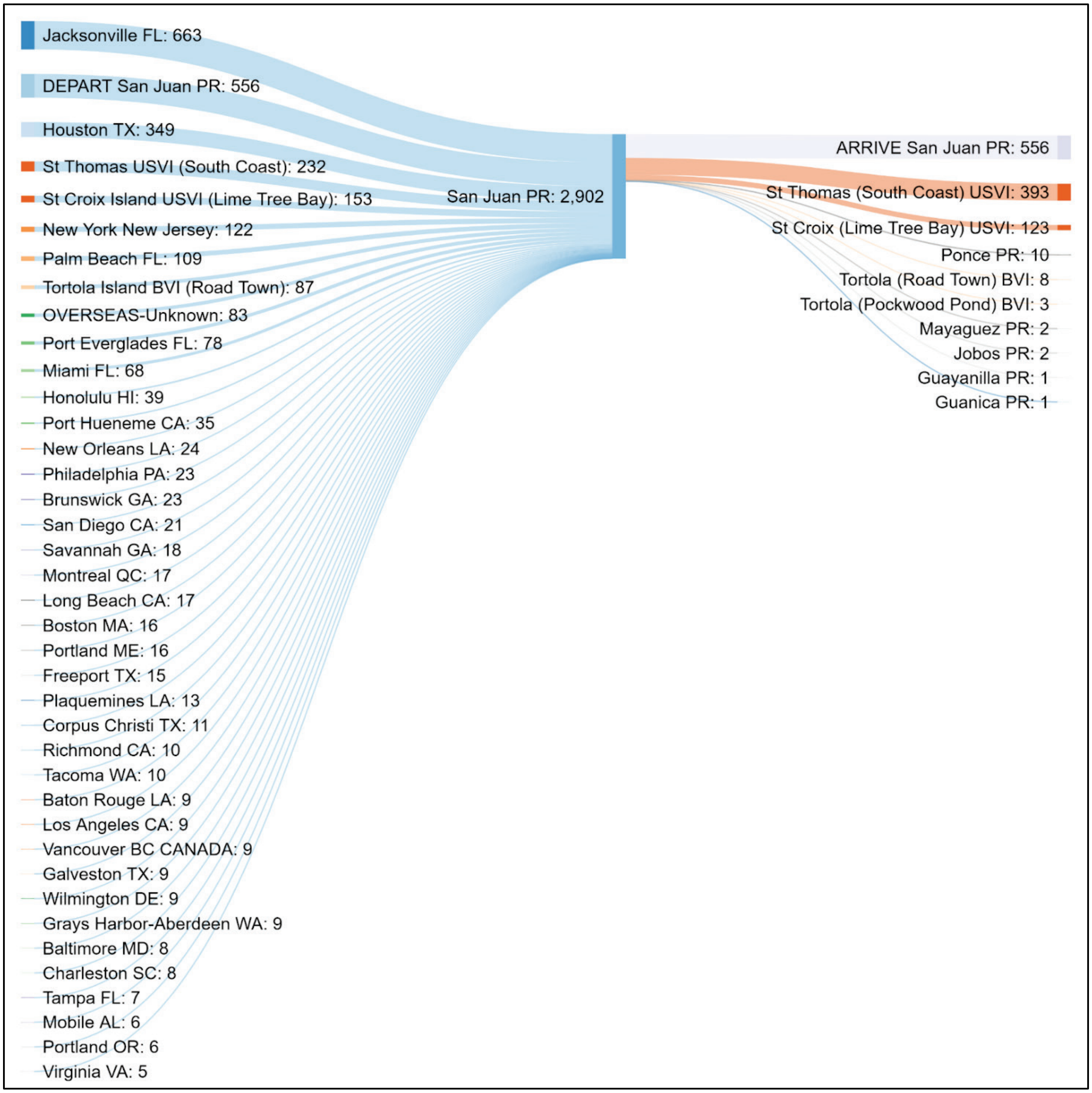

Figure 3. Cargo vessel arrivals into San Juan, Puerto Rico, port area (*blue lines* on left half of graph) from locations with five or more shipments during January 2015 to June 2020 and cargo vessel departures from San Juan to other PR/VI port areas in the network. Results based only on AIS data (figure processed in SankeyMATIC, https://sankeymatic.com/).

Table 1. Annual commercial port tonnage published by Waterborne Commerce Statistics Center (WCSC), calendar years (CYs) 2015–2020.

Port Name (WCSC designation)	Commercial Tonnage Total (rank, among top 150 ports by tonnage)					
	CY2020	CY2019	CY2018	CY2017	CY2016	CY2015
Jacksonville, FL (PORT)	16,701,370 (38)	17,727,173 (35)	17,999,036 (35)	18,526,157 (35)	18,519,505 (35)	17,577,034 (35)
San Juan Harbor, PR (WATERWAY)	11,379,230 (50)	10,416,667 (48)	11,737,059 (47)	10,296,551 (48)	10,686,817 (48)	11,065,257 (48)
Ponce Port Authority, PR (PORT)	2,127,875 (108)	2,225,718 (NR[a])	1,763,930 (138)	1,791,872 (139)	2,469,111 (133)	1,897,144 (128)
[Christiansted] St Croix, VI[e] (PORT)	100,752 (NR)	64,920 (NR)	169,614 (NR)	716,625 (NR)	580,301 (NR)	156,801 (NR)
Arecibo, PR (PORT)	77,625 (NR)	34,217 (NR)	30,017 (NR)	34,121 (NR)	38,385 (NR)	34,015 (NR)
Mayagüez, PR (PORT)	120,819 (NR)	27,458 (NR)	98,103 (NR)	79,297 (NR)	99,346 (NR)	128,797 (NR)
St. Thomas, VI (PORT)	13,106 (NR)	25,594 (NR)	53,426 (NR)	82,773 (NR)	32,815 (NR)	177,756 (NR)
Fajardo, PR (WATERWAY)	0 (NR)	0 (NR)	131,562 (NR)	184,555 (NR)	191,477 (NR)	189,725 (NR)
Guayanes, PR (PORT)	0 (NR)	0 (NR)	0 (NR)	0 (NR)	0 (NR)	0 (NR)
Yabucoa, PR (PORT)	1,806,066 (121)	2,334,844 (NR[f])	3,029,647 (NR[g])	3,051,699 (NR[b])	3,174,883 (NR[c])	2,312,854 (NR[d])

Note: Other study port areas not listed in WCSC publications. Tonnage statistics do not include passenger counts or fisheries landings (USACE-WCSC, n.d.).

Note: NR (Not Ranked). Rankings cover the top 150 ports by tonnage, from *Waterborne Tonnage for Principal US Ports and All 50 States and US Territories* (USACE-WCSC 2022).

[a] Not listed in the CY2019 WCSC principal US ports file; reported tonnage would place it at rank 117.

[b] Not listed in the CY2017 WCSC principal US ports file; reported tonnage would place it at rank 91.

[c] Not listed in the CY2016 WCSC principal US ports file; reported tonnage would place it at rank 88.

[d] Not listed in the CY2015 WCSC principal US ports file; reported tonnage would place it at rank 106.

[e] Listed as Virgin Islands–St. Croix, VI (PORT) in WCSC publications; description mentions Gallows Bay and Christiansted.

[f] Not listed in the CY2019 WCSC principal US ports file; reported tonnage would place it at rank 110.

[g] Not listed in the CY2018 WCSC principal US ports file; reported tonnage would place it at rank 89.

AIS data allow for the description of vessel traffic at ports for which little information is available in the WCSC tonnage numbers (e.g., Guayanes, Puerto Rico, in Table 1) using AIS-derived metrics such as number of arrivals and vessel type information. Because Marine Cadastre AIS data are reported at 1 min intervals, it could allow for the estimation of the docking capacities of various ports (i.e., to directly observe the number of concurrent vessels of a given type at a port). From that, various levels of temporal aggregation visualizations can be derived depending on user need. For example, Figure 4 shows the monthly arrivals of tanker vessels (AIS vessel codes 80–89) to the Yabucoa, Puerto Rico, port area.

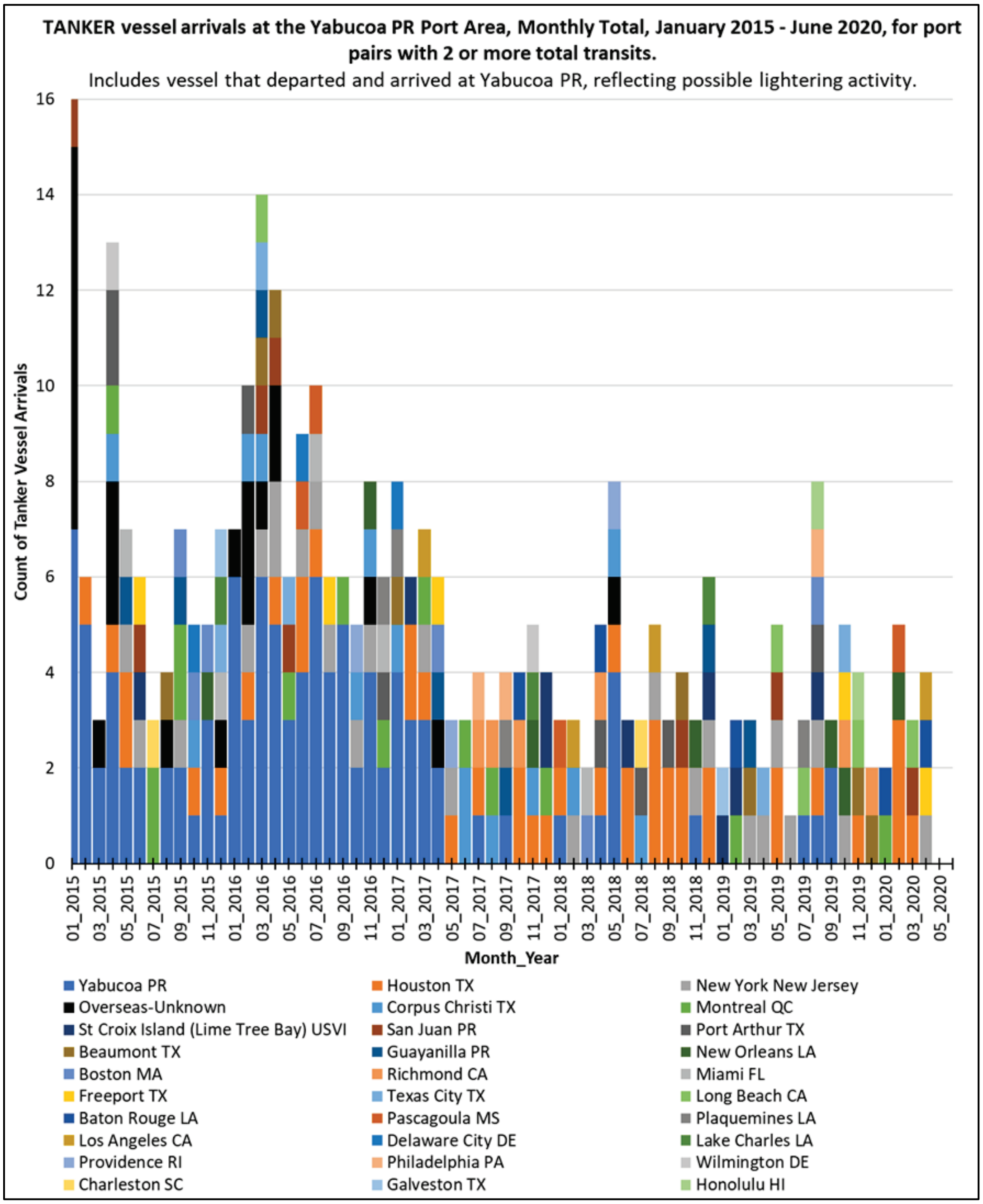

Figure 4. Monthly tanker vessel arrivals in the Yabucoa, Puerto Rico, port area for origin areas with two or more total transits to Yabucoa during January 2015 through June 2020.

Figure 4 shows that Yabucoa regularly received multiple tanker shipments per month, but there has been an overall downward trend since 2017. This trend may be due to changes in lightering practices, but the details of individual port operations were beyond the scope of this study. However, those types of details along with the number of tanker vessel berths and on-site storage capacity would be relevant if larger tanker vessel hubs were damaged during a disruptive event (e.g., a hurricane) and alternative sites to receive tanker traffic needed be considered. For port areas that handle critical energy commodities, resiliency planning could include not just an assessment of land-side infrastructure but the ability of available personnel to conduct at-sea procedures such as lightering.

Certain classes of vessels (e.g., sailing, pleasure craft, fishing) are not included in tonnage metrics, but AIS-derived information can be used to account for those vessels that may contribute substantially to the local economy in places such as the Caribbean (Young, Kress, et al. 2022). Figure 5 displays total vessel exchanges at selected PR/VI port areas broken out by vessel type. Although San Juan, Puerto Rico, may be the largest port area in terms of combined tanker and cargo vessels, Figure 5 makes clear that the port area of St. Thomas (South Coast), USVI, exchanges the most vessels overall, due to the high passenger, sailing, and pleasure-craft vessel numbers. St. Thomas (South Coast), USVI; Tortola, British Virgin Islands, and the wider grouping of PR/VI port areas (All Others) serve large volumes of passenger vessel traffic that are of great concern to the wider PR/VI economy (Young, Kress, et al. 2022).

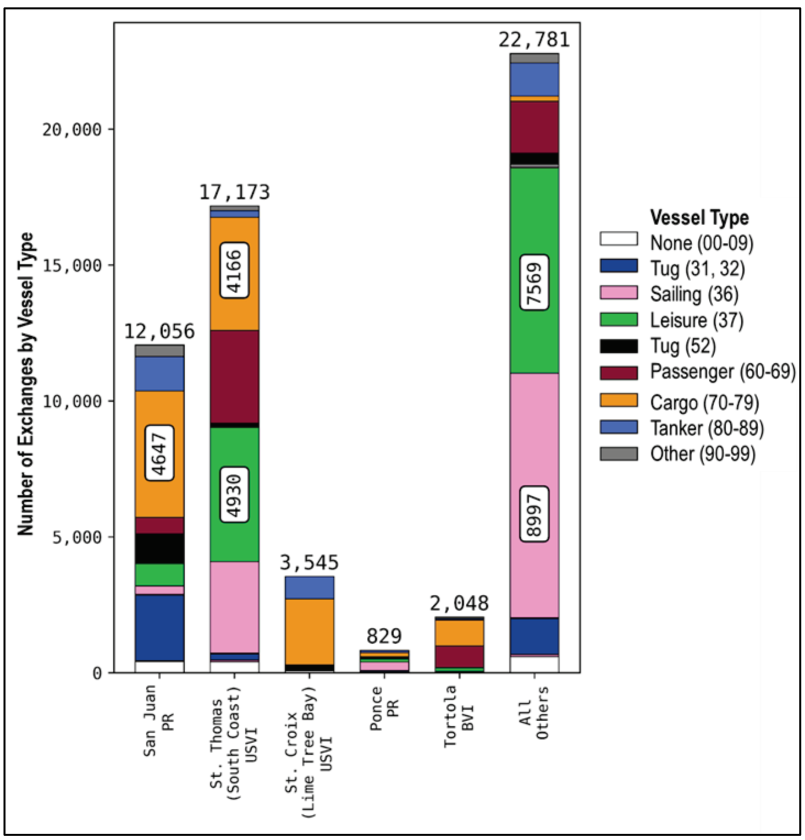

Figure 5. Total number of vessel exchanges at selected Puerto Rico/Virgin Islands (PR/VI) port areas broken out by selected vessel type and Automatic Identification System (AIS) codes during January 2015 through June 2020. All Others refers to the PR/VI port areas that are not specifically plotted.

Furthermore, Figure 6 shows that the passenger vessel traffic for St. Thomas (South Coast), USVI, is highly seasonal, peaking in the winter months and falling during the summer (Young, Kress, et al. 2022). Observing this seasonality is another advantage of utilizing AIS-derived metrics that can be calculated on finer time scales (Young, Kress, et al. 2022). Passenger vessels and their behaviors may need to be considered for navigation management in this region.

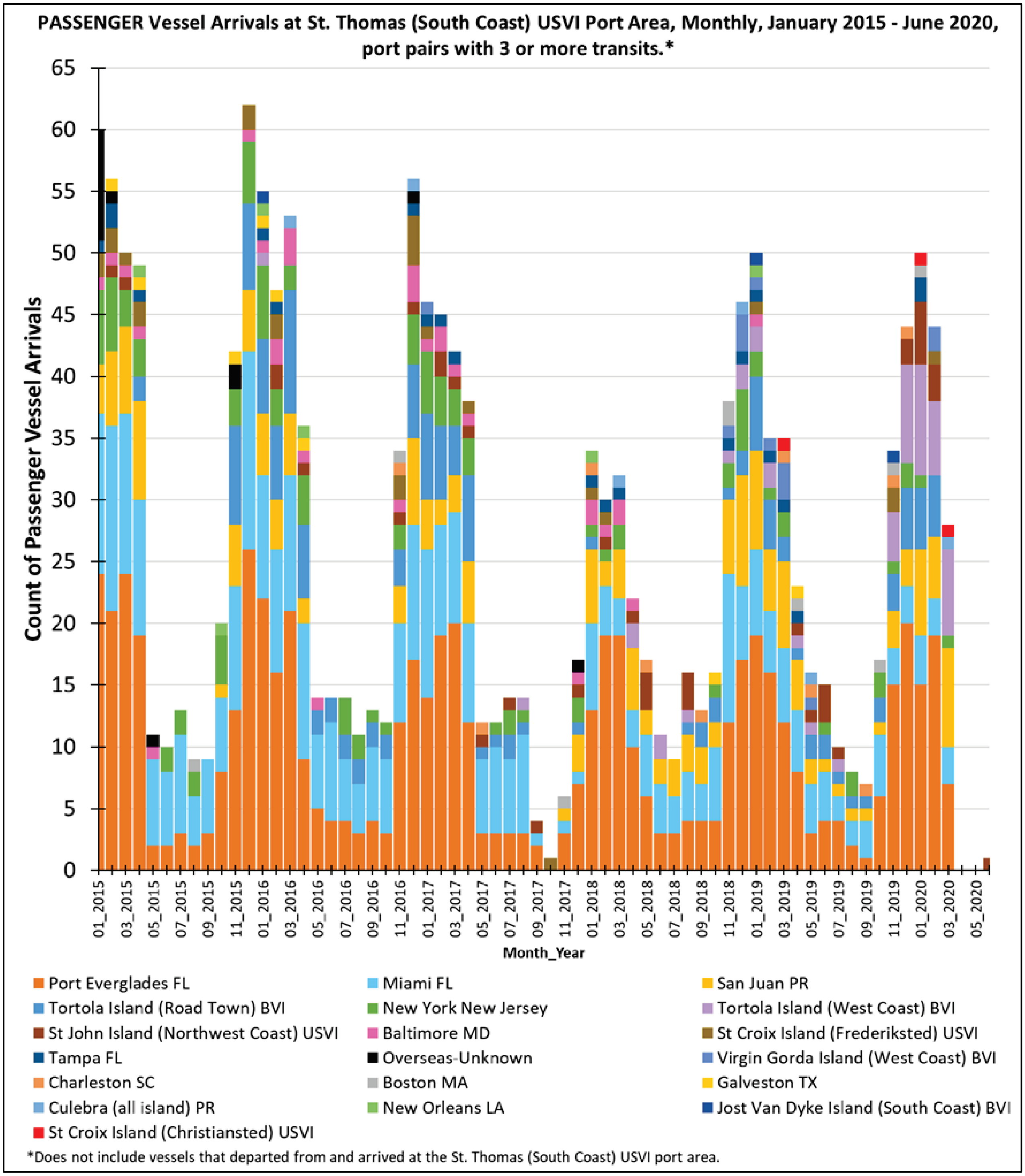

Figure 6. Monthly passenger vessel arrivals in the St. Thomas (South Coast), USVI, port area for origin areas with three or more transits during January 2015 through June 2020.

SUMMARY: This CHETN described how AIS-derived vessel traffic metrics can augment traditional tonnage metrics to better understand navigation as demonstrated for PR/USVI ports. Using a North American–wide dataset of AIS vessel position reports allowed for observation of the port-to-port migration of all AIS-equipped vessels transiting a network of 325 North American (primarily US) ports. These data were interrogated to analyze connectivity within a subset of 30 PR/USVI ports. AIS-derived metrics have the advantage of providing information for ports that are too small to be included in traditional WCSC tonnage rankings (e.g., Guayanes and Guayanilla, Puerto Rico). The vessel type information included in AIS allows for consideration of vessel types that would not traditionally be included in tonnage estimates (e.g., passenger, sailing, and pleasure craft vessels) but are likely critical to the Caribbean regional economy. Finally, the high sampling rate of AIS data allows the observation of vessel movement patterns at the monthly, weekly, or even daily timescale, which is not possible with yearly tonnage numbers. This unlocks the capability to observe the seasonality of vessel movement patterns (e.g., passenger vessels traffic to St. Thomas [South Coast]), USVI, the effects of disruptions such as vessel movement, and estimation of the berthing capabilities of smaller ports to be used as alternates in the emergencies caused by those disruptions).

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