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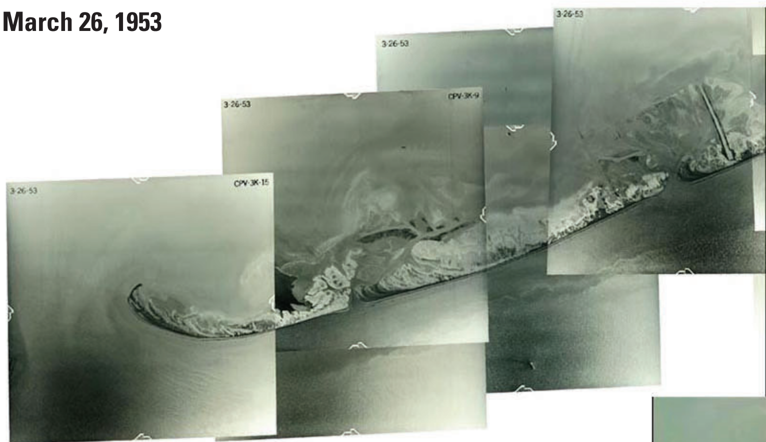
Core Science Systems and the National Civil Applications Center

Using Global Fiducials Library High-Resolution Imagery, Commercial Satellite Imagery, Landsat and Sentinel Satellite Imagery, and Aerial Photography to Monitor Change at East Timbalier Island, Louisiana, 1953–2021

March 26, 1953



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Front cover. Top left: Historical aerial photograph of East Timbalier Island, Louisiana, from March 26, 1953. Bottom right: WorldView–2 satellite image of East Timbalier Island, Louisiana, from September 11, 2021, showing the remnants of the Island.

Back cover. Photograph of President Theodore Roosevelt visiting East Timbalier Island, Louisiana, in 1915. East Timbalier Island was one of the Nation's first wildlife refuges, although its protections were rescinded in 1969. Photograph courtesy of the U.S. Fish and Wildlife Service.

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Conversions Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983.

Abbreviations

BICM	Barrier Island Comprehensive Monitoring
CWPPRA	Coastal Wetlands Planning, Protection and Restoration Act
DOQ	digital orthophoto quadrangle
GFL	Global Fiducials Library
GFP	Global Fiducials Program
GSD	ground sample distance
ha	hectare
km	kilometer
km^2	square kilometer
m	meter
m^2	square meter
NAD 83	North American Datum of 1983
NAPP	National Aerial Photography Program
NCAC	National Civil Applications Center
NGVD 29	National Geodetic Vertical Datum of 1929
NHAP	National High Altitude Photography
NOAA	National Oceanic and Atmospheric Administration
NOAA–ERI	National Oceanic and Atmospheric Administration Emergency Response Imagery
TD	tropical depression
TS	tropical storm
UTM	Universal Transverse Mercator
USNIS	U.S. National Imaging Systems
USGS	U.S. Geological Survey

Using Global Fiducials Library High-Resolution Imagery, Commercial Satellite Imagery, Landsat and Sentinel Satellite Imagery, and Aerial Photography to Monitor Change at East Timbalier Island, Louisiana, 1953–2021

By Gary B. Fisher,[1] E. Terrence Slonecker,[1] Shawn J. Dilles,[2] Bruce F. Molnia,[3] and Kim M. Angeli[1]

Abstract

This report documents morphological changes between 1953 and 2021 at East Timbalier Island, Louisiana, a Gulf of Mexico barrier island. East Timbalier Island, which was located west of the Mississippi River Delta at the front of Timbalier Bay, was one of the most rapidly changing barrier islands on Earth. Since aerial photographs were initially taken in 1953, the Island steadily lost length and area, finally eroding away by early summer 2021. After major storm events, sediment eroded from the Island and migrated hundreds of meters north. In August 1992, Hurricane Andrew breached the Island in several places, resulting in increased erosion and land loss. Until it completely eroded away, the Island underwent a repeating cycle of washovers, vegetation removal, breaching, and erosion with sediment transport to the north. Satellite imagery shows that three such cycles occurred between 1992 and 2017, despite the partial restoration of the Island between 1998 and 2000. Each cycle increased the distance between the Island and the mainland to the east, reducing both the sediment supply from the east and the protection that Timbalier Bay and the adjacent coastal lands received from the barrier island.

Previously, the U.S. Geological Survey (USGS) National Civil Applications Center used 1-meter resolution imagery archived at the USGS Global Fiducials Library (GFL), collected between 2000 and 2010 by U.S. National Imaging Systems, to monitor the changes at the Island. New research expands this study retrospectively and prospectively using aerial photography collected from 1953 to 2012 and in 2020; declassified imagery collected in 1962, 1972, and 1975; DigitalGlobe satellite imagery collected since 2004; Landsat satellite imagery collected since 1972; Sentinel–2 satellite imagery collected since 2015; and GFL imagery collected from 1992 to 2020.

[1]U.S. Geological Survey.

[2]U.S. Geological Survey, volunteer.

[3]Cambio Consulting Group, LLC, contractor to the U.S. Geological Survey.

Introduction

East Timbalier Island was a flanking barrier island located along the south-central coast of Louisiana (La.) (fig. 1), west of Port Fourchon, La., which is a major staging point for the Gulf Coast oil and gas industry. Over the more than 100 years since the area was first mapped (USGS, 1894), East Timbalier Island underwent a massive transformation because of natural and human-induced environmental changes. Barrier islands along the Louisiana coast are rapidly degrading due to relative sea-level rise, land subsidence, diminishing sand-sediment resources, and an expanding tidal prism due to wetland loss. On average, coastal Louisiana loses 57 square kilometers (km^2) of land each year (Barras and others, 2008; Couvillion and others, 2017).

East Timbalier Island's land-loss rates were among the highest on the Gulf Coast at 6,500 square meters (m^2) per year (Thomas and others, 2011). In order to better understand the changes at East Timbalier Island, the U.S. Geological Survey (USGS) monitored these changes using remote sensing imagery products. Since the 1990s, the Global Fiducials Program (GFP) has provided high-resolution imagery of East Timbalier Island (Molnia and others, 2011; Thomas and others, 2011; Molnia, 2012; Molnia and others, 2019). These data allowed a consistent and scheduled look at changes. Additionally, the National Aerial Photography Program (NAPP), Louisiana State digital orthophoto quadrangle imagery, commercial aerial photography, satellite imagery, and declassified high-resolution HEXAGON imagery were used to closely monitor the changes that occurred since the early 1950s. This report describes and documents the dramatic landscape changes that occurred at East Timbalier Island between 1953 and 2021 and complements the paper "Using Remote Sensing and Imagery Exploitation to Monitor the Dynamics of East Timbalier Island, LA: 2000–2010" (Thomas and others, 2011). Figure 2 provides a historical topographic-map mosaic showing the Island as it appeared in 1953, when the earliest imagery used in this report was collected over this region.

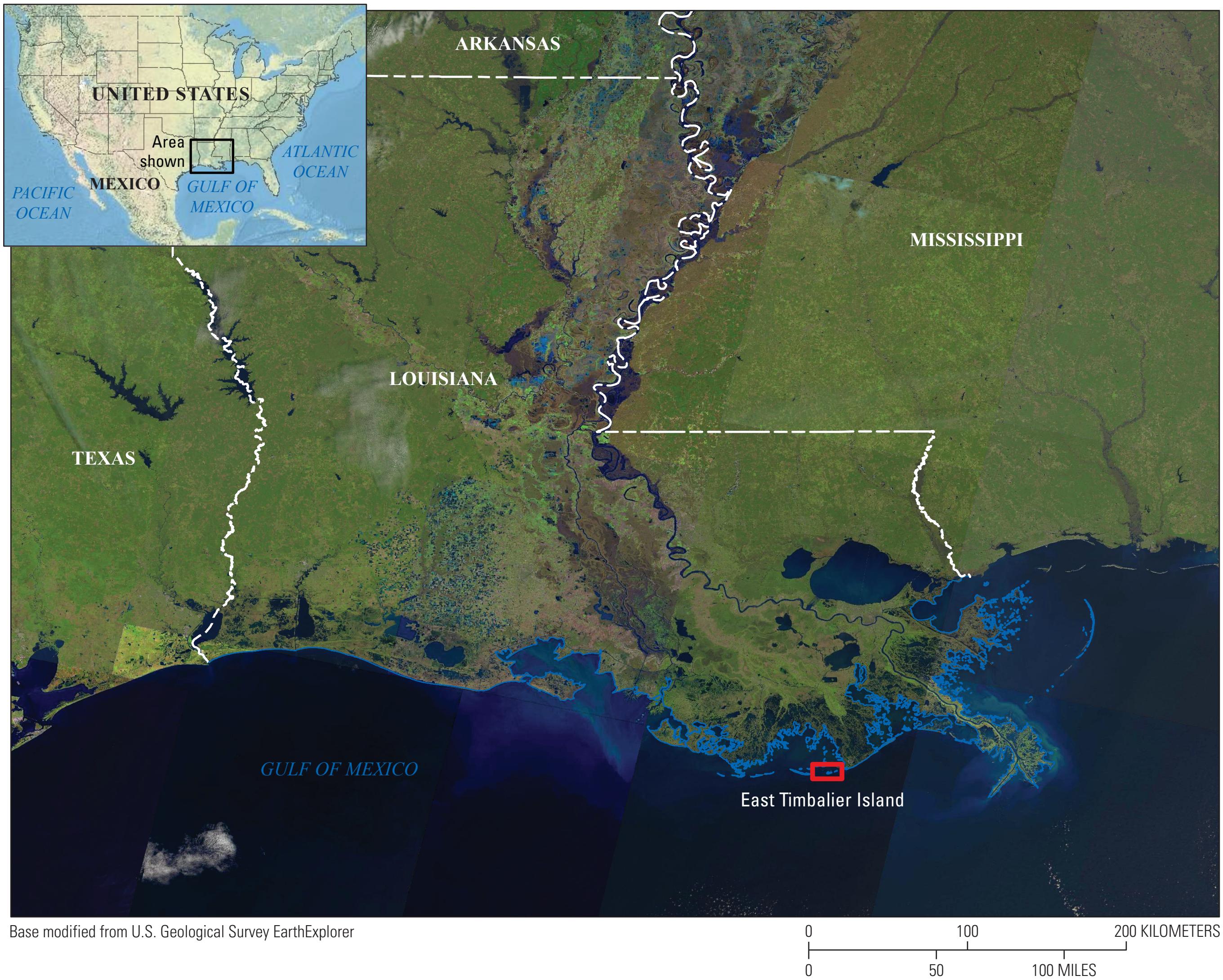

Figure 1. Map showing the location of the East Timbalier Island, Louisiana, study area.

Geologic and Early Historical Evolution of East Timbalier Island

Timbalier Island and East Timbalier Island formed approximately 1,000–3,000 years ago as part of the Lafourche delta complex (Morgan, 1974). This delta complex is a historical location for the Mississippi River as it migrated eastward during the past 5,000 years (Frazier, 1967). Bayou Lafourche was a historical pathway for the Mississippi River before it migrated east, and it provided abundant sediment for barrier island formation and growth. The Timbalier Islands developed from the reworking and erosion of the Lafourche delta complex as it left its former path (Penland and Ramsey, 1990; Penland and others, 1997). The complexities of this region allowed for frequent changes to the barrier islands within Timbalier Bay. East Timbalier Island experienced exceptional changes over the past 100 years. These changes were driven by the redistribution of sediment by waves and currents, ground subsidence, storms and storm-surges, and saltwater intrusion.

As this study shows, the resultant landscape is one of the most dynamic places on Earth. The first detailed maps of the region were drawn in the early 19th century and show frequent changes to the geomorphology of the barrier islands along the Gulf Coast (Burr, 1839). A review of early maps highlights the dynamic nature of this coast. By the turn of the 20th century, the changes at East Timbalier Island had become even more pronounced. Many maps created during this time show the Island in different shapes and sizes, and this may be because of imprecise mapping methods and the remote location of this area. Changes that have occurred since the 1950s were captured as remote sensing data became available, and this data helped describe the sensitivity of this environment to alterations in sediment supply, dynamic weather events, and human-induced changes resulting from oil and gas production in the region.

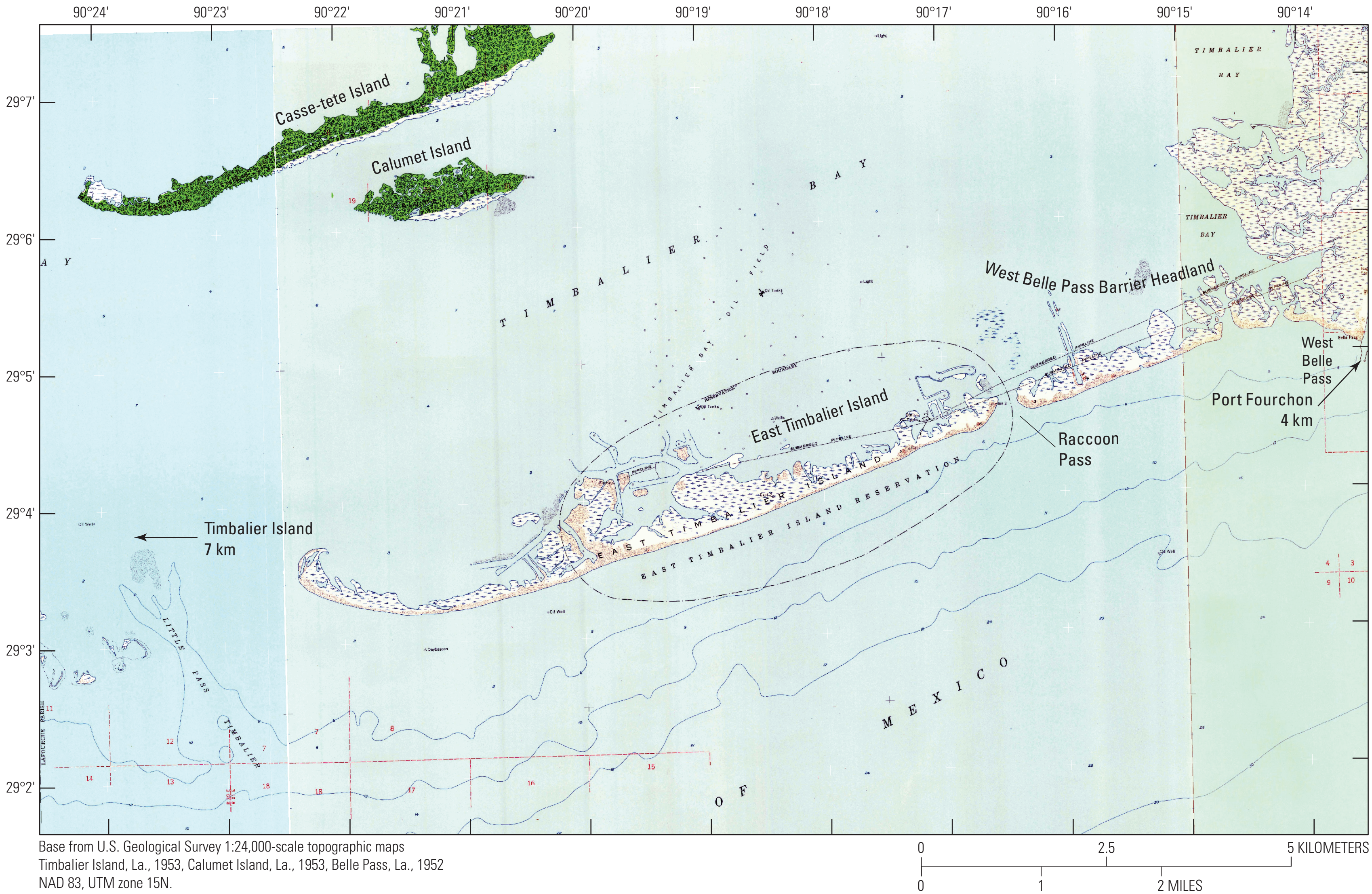

Figure 2. U.S. Geological Survey historical topographic map showing three Louisiana (La.) islands: East Timbalier Island, Casse-tete Island, and Calumet Island. km, kilometer; NAD 83, North American Datum of 1983; UTM zone 15N, Universal Transverse Mercator zone 15 north.

Extreme Erosion During the Past 70 Years

This report shows that East Timbalier Island experienced one of the most significant erosion rates of any area on Earth (Thomas and others, 2011). The earliest aerial photographs of the Island available for this report (app. 1, figs. 1.1, 1.2) were taken in the 1950s and show that East Timbalier Island had lost almost 50 percent of its land area by April 26, 1992, just prior to when Hurricane Andrew breached the Island on August 26, 1992 (app. 1, fig. 1.9). Additionally, the Island migrated northwestward, and the shape of the Island morphed from a straight-line barrier island into a crescent shape. Several remediation projects attempted to stabilize and rebuild the Island (Curole and others, 2012), but the Island continued to erode and was projected to disappear within a few years of 2011 (Thomas and others, 2011). Numerous factors caused these changes, including a disruption to the sediment supply from Bayou Lafourche, high-energy tropical storms in the region, and the susceptibility of the Island to accelerated erosion from the installation of oil and gas industry infrastructure (Miner and others, 2006).

Regional Subsidence Contributing to Island Erosion

Studies of subsidence and sea-level rise based on the analysis of tide gauge data by Penland and Ramsey (1990) conclude that “rapid relative sea level rise induced by delta-plain subsidence and a deficit of terrigenous wetland sedimentation are the primary factors driving the rapid deterioration of the Louisiana coastal zone.” Kolb and Van Lopik (1958) note that subsidence due to compaction is more rapid in recently abandoned delta regions than in areas abandoned several hundred years earlier, and local differences in delta sediment composition may result in consolidation and subsidence at higher rates than for the delta as a whole. Penland and Ramsey (1990) determined that the “relative sea level appears to rise faster in the Terrebonne Parish area than anywhere else in Louisiana.” They relate the rate of subsidence to the thickness of Holocene delta deposits and attribute the subsidence to compaction of the sediments. Relative sea-level rise coupled with diminished sediment supply contributed to extensive erosion. The Louisiana Barrier Island Comprehensive Monitoring (BICM) program analyzed data collected between 1880 and 2005 and determined that the Timbalier Islands and the adjacent Caminada Headland have some of the highest levels of erosion in the region, including to the lower shoreface and offshore areas. During the study period of this report, the Timbalier Islands had the highest rates of landward migration (Miner and others, 2009; Kindinger and others, 2013).

Hurricane and Tropical Storm Impacts

Tropical storms are a natural occurrence in the Gulf of Mexico. The Louisiana coast, according to the National Oceanic and Atmospheric Administration (NOAA), has one of the highest concentrations of hurricane landfalls of the entire U.S. coast (NOAA, 2020b) (fig. 3). Based on records maintained since the mid-1800s, the region around East Timbalier Island experienced more than 41 major hurricanes, tropical storms, and tropical depressions (table 1). On average, the region is hit by a major tropical storm every 4.5 years.[1] These storms greatly affected the stabilization of the Island and caused extensive reshaping and erosion.

Recent storms—during the 1992, 2002, 2005, 2008, 2020, and 2021 hurricane seasons—caused extensive changes to the Island, which never recovered. On June 7, 2020, Tropical Storm Cristobal passed 50 kilometers (km) east of the Island and caused substantial wash over and erosion. Tropical Storm Marco on August 24, 2020, and Hurricane Zeta on October 28, 2020, both caused extensive erosion to the Island, resulting in a significant loss of land and ground cover. Tropical Storm Claudette passed 67 km west of the Island on June 18, 2021, removing all remnants of the Island, leaving temporary sand and sediment bars to the north. Hurricane Ida, a Category 4 storm, passed directly over Port Fourchon, less than 10 km east of the Island, on August 29, 2021.

[1]Based on the data in table 1, the region around East Timbalier Island is hit by a major tropical storm every 4.5 years.

Table 1. Hurricanes (Category 1–5), tropical depressions, and tropical storms that potentially affected East Timbalier Island, Louisiana, from August 10, 1856, to August 29, 2021.

[Historical hurricane data for this table were obtained from the National Oceanic and Atmospheric Administration (NOAA) and are available at https://coast.noaa.gov/hurricanes/#map=4/32/-80 (NOAA, 2020a). E, east; km, kilometer; N, north; n/a, not applicable; S, south; TD, tropical depression; TS, tropical storm; W west; —, unnamed]

Date of landfall	Storm name	Hurricane category or storm type	Storm passage proximate to East Timbalier Island
August 10, 1856	—	[1]4	46 km SE
March 29–30, 1867	—	Winter storm[2]	n/a
October 04, 1867	—	2	12.5 km N
October 19, 1887	—	1	13.6 km NE
October 02, 1893	—	4	23 km SE
September 29, 1915	—	3	Direct landfall.
July 27, 1936	—	TS	31 km E
September 26, 1939	—	TS	34 km W
September 04, 1948	—	1	8.8 km W
September 24, 1956	Flossy	1	48 km SE
September 18, 1957	Esther	TS	63.5 km W
September 15, 1960	Ethel	5	135 km E
September 10, 1965	Betsy	4	12.7 km NE
August 17, 1969	Camille	5	125 km E
September 01, 1971	—	TD	15 km NE
September 06, 1971	Fern	TD	54 km W
September 08, 1974	Carmen	4	65 km W
October 25, 1977	—	TD	21 km NW
July 11, 1979	Bob	1	34 km W
September 04, 1980	Danielle	TS	90 km S
October 31, 1985	Juan	TS	18 km S
August 26, 1992	Andrew	4	61 km SW
July 17, 1997	Danny	TS	20.2 km E
August 05, 2002	Bertha	TS	81.5 km NE
September 26, 2002	Isidore	TS	Direct landfall.
October 03, 2002	Lili	4	150 km SE
June 30, 2003	Bill	TS	69 km W
October 10, 2004	Matthew	TS	67 km W
June 06, 2005	Cindy	1	13 km E
August 29, 2005	Katrina	4	66.5 km E
September 23, 2005	Rita	4	240 km SE
August 05, 2008	Edouard	TS	85 km SW
September 01, 2008	Gustav	2	20.5 km SW
September 03, 2011	Lee[3]	TS	160 km SW
August 29, 2012	Isaac[3]	1	5 km NE
July 13, 2019	Barry	1	69 km SW
June 07, 2020	Cristobal	TS	50 km E
August 24, 2020	Marco	TS	23 km S
October 28, 2020	Zeta	2	17 km W
June 18, 2021	Claudette	TS	67 km W
August 29, 2021	Ida	4	10 km E

[1]A Category 4 hurricane split Isle Dernière, Louisiana (Trickey, 2017).

[2]A “winter storm” destroyed Timbalier Bay Lighthouse on March 29–30, 1867 (USCG, 2015).

[3]These storms were relatively weak but slow-moving.

Figure 3. Map showing the paths of tropical depressions, tropical storms, and hurricanes that passed within 100 kilometers of East Timbalier Island, Louisiana, from 1856 to 2021. Dates are shown in year-month-day format. Refer to table 1 for specific dates, storm classifications, and storm locations proximate to East Timbalier Island.

Barrier Island Landforms

Barrier islands and back-barrier marshes are highly erodible sand-dune systems, of which many important landforms in many coastal areas—including in the Gulf of Mexico—are composed. Typically comprising flat areas of sand formed by wave and tidal action parallel to the mainland coast, barrier islands usually develop in chains that consist of anywhere from a few islands to more than a dozen and can stretch for hundreds of kilometers (List and others, 1994).

Barrier islands are critically important for protecting coastlines from potentially devastating ocean wave action, including swells and storms. Barrier islands are also critical for forming and preserving coastal wetland ecosystems such as lagoons, estuaries, and marshes. Without barrier islands, ecologically rich coastal wetland ecosystems might not exist (Merino and others, 2011). Barrier islands and their complex ecological functions are related to feedback loops among sediment supply (lithosphere), hydrology, the atmosphere, and ecology (biosphere). This recent view represents a departure from the traditional view of barrier islands resulting from variations in the sea level, sediment supply, and accommodation space (Barrineau and others, 2015).

The structure, length, and width of barriers and the overall morphology of barrier coasts are usually related to natural parameters such as tidal range, wave energy, sediment supply, and sea-level trends (Merino and others, 2011). However, barrier island absolute location is subject to gradual migration caused by natural forces. Historical bathymetric and shoreline data show that Bayou Lafourche eroded about 3 km since 1880 (List, 2004), and East Timbalier Island moved north at about 21 m per year since 1900 (McBride and others, 1992).

East Timbalier Island was subject to natural changes and anthropogenic influences; the latter were expected to reinforce coastal stability but effectively altered natural flows and currents. These natural and anthropogenic changes include the development of the overall oil and gas industry in the area; other coastal protection structures, such as levees and seawalls; sea-level rise; and land subsidence, all of which changed currents and flow patterns to effectively “starve” East Timbalier Island of needed sediment replacement (Solomon and others, 2007). In addition, because of the oil and gas facility established on the Island in the 1950s, several efforts were made to stabilize the Island, thereby protecting the oil and gas infrastructure (Thomas and others, 2011). These efforts, along with the effects of coastline stabilization projects, altered the sediment profile of East Timbalier Island.

Data and Methods

A search of commercial, government, and private sources of aerial photographic and cartographic records was undertaken to locate historical sources of photograph and map coverage of Timbalier and Terrebonne Bays along the southern coast of Louisiana. These data sources include the USGS, NOAA, the State of Louisiana, the National Archives and Records Administration, the U.S. Department of Agriculture, and the commercial mapping companies discussed in this report. Over 100 images were analyzed to determine the most suitable dates and data parameters for representing the conditions at the Island. The records accessed include written descriptions, graphic footprints, thumbnail images, aerial film negatives, film positives, and paper prints. Many coastal images were acquired at a relatively large scale, meaning that many images were needed to cover small geographic areas like East Timbalier Island.

When doing this type of research, requestors must search the available records and select the most suitable imagery frames. The selected records are then submitted to a photographic laboratory for reproduction or scanned for transformation into a digital product. Imagery and metadata sources include the date and time of acquisition, the camera and lens numbers, calibration reports (when available), the scale, the film or sensor type, and the flight direction. Appendixes 1–6 (see table 2) list the film, sources, and metadata for all imagery of acceptable scale and resolution that were acquired for this project. The formal metadata for other historical records used in this project can be found in Slonecker and others (2020).

When possible, the imagery was acquired as, or processed into, an orthorectified or geo-rectified format so that the cartographic qualities would be present to enable the accurate and consistent measurement of size, shape, distance, direction, and area. Tide levels were not assessed in the imagery due to the lack of metadata in earlier imagery (1950–1970). Currently, the tidal range is about 0.32 m, which may affect the amount of sand exposed on shallow, low-slope sand bars at low tide (NOAA 2021). There are several sources of aerial-photograph data in appendix 2 where this “orthorectification” was computed via automated methods derived by inertial navigation system and Global Positioning System data input. These images were initially provided by the original source program and later retrieved using online sources such as the USGS EarthExplorer website (USGS, 2021).

Several earlier aerial photographic missions that covered East Timbalier Island were not processed to correct the inherent cartographic distortions and exist as raw aerial photographs only. These images were scanned into a digital format and manually georegistered based on previous corrected data sources and key landscape “feature-identifiable control points” chosen by a trained imagery analyst. Because of the dynamic and changing landscape of East Timbalier Island, however, the accurate correction of some data was neither possible nor corrected to U.S. National Map Accuracy Standards (USGS, 1999). The oil and gas infrastructure that existed on the Island from the 1950s to the present (2021) allowed some cartographic control to be observable by way of small buildings and pipelines on the remnants of the Island, which greatly enabled the georectification of imagery of East Timbalier Island.

Historical declassified images from U.S. intelligence systems are also included in this list (app. 2). These U.S. National Imaging Systems (USNIS) images, which came from the Nation’s first photoreconnaissance satellites and included CORONA- and HEXAGON-series satellites, provided additional timestamps for changes in Timbalier Bay. Images from the CORONA program were declassified and released to the public in February 1995 (National Reconnaissance Office, 1995), and more information about the CORONA program can be found in Ruffner (1995). The HEXAGON suite of reconnaissance satellites was the last to use film, and selected images, which were declassified in 2011, are available online at the USGS Earth Resources Observation and Science Archive—Declassified Data—Declassified Satellite Imagery—3 (https://www.usgs.gov/centers/eros/science/usgs-eros-archive-declassified-data-declassified-satellite-imagery-3?qt-science_center_objects=0#qt-science_center_objects). The 0.61–1.22 m (2–4 foot) resolution of these images was extraordinary for satellites at that time.

Global Fiducials Library Imagery

The Global Fiducials Library (GFL) is a long-term archive of images from USNIS representing a long-term, periodic record for selected, scientifically important sites (https://www.usgs.gov/global-fiducials-library-data-access-portal), one of which is East Timbalier Island. The GFL was created to be the collection, archive, and data-management component of the Global Fiducials Program (GFP). The GFP (Baker and Zall, 2020) is a collaborative effort between Federal civil agencies, academia, and the intelligence community. At the time of its founding, the principal goal of the GFP was to build and maintain a long-term record of data to support scientists and policymakers involved in the GFP collaborative effort. The hope was that at some point—perhaps as much as 25 years into the future—the acquired data could be openly released to support future scientists and policymakers.

Since the early 1990s, the GFP has periodically collected images of environmentally important sites around the world. The GFL, which is the archive that maintains this long-term imagery record, is managed by the USGS under the National Civil Applications Center (NCAC) in partnership with the Civil Applications Committee. The GFL archive is dedicated to ensuring that the images are collected, maintained, and made available to scientists and policymakers to support scientific investigations into global dynamic systems and change. Since 2009, a goal of the GFP has been to systematically make parts of this extensive collection publicly available. This goal is accomplished through the creation of unrestricted imagery-derived products, which provide valuable, select imagery to the public. Several collections of aerial and satellite imagery were used to document the status and extent of East Timbalier Island. See the descriptions of appendixes 1–6 in table 2 of this report for examples of this information.

The GFL imagery in this report has been collected over East Timbalier Island since 1992 (app. 3). The purpose of collecting GFL data over East Timbalier Island was to monitor the extensive changes occurring there and maintain a detailed record of these changes. The environment of Timbalier Bay (fig. 2) and the barrier islands off the coast of south-central Louisiana constantly change. The GFL data provide insight through which scientists can observe, monitor, and measure the natural processes affecting the Island. The effects of those processes and their relation to human activity are provided through GFL data. The dates for GFL imagery used in this study are provided in appendix 3. GFL image-data products were either orthorectified using a digital elevation model or rectified to a plane (like mean sea level) and georeferenced into the Universal Transverse Mercator (UTM) projection. In most cases, the ground sample distance (GSD), or pixel size representation, is 1 meter. The area of interest for the individual GFL sites is a box that encompasses the site, which may cover anywhere from 2 km^2 to 1,000 km^2. The GFL imagery products may consist of one image or multiple images merged into a single-image mosaic, which is contained within that area-of-interest box. Each product is normally ascribed to a single date.

Commercial Satellite Imagery

Since the start of the new millennium, commercial satellite imagery has become available for more areas of the world. Many high-resolution images of East Timbalier Island are available. The NextView EULA_5749 end-user license agreement provides access to DigitalGlobe products (https://evwhs.digitalglobe.com/myDigitalGlobe/login) for the U.S. Government and its mission partners (National Geospatial Intelligence Agency, 2017). The DigitalGlobe imagery archive has a search tool for finding and viewing images at https://discover.maxar.com. Images of the remote area surrounding Timbalier Bay have traditionally been acquired by U.S. Government aerial photography and the USNIS satellite imagery described in the previous section. The new high-resolution commercial satellite systems can also provide a frequent look at isolated locations and enable accurate monitoring and mapping of dynamic landscapes. Although commercial imagery was not used for quantitative analysis in this study, it does provide an additional resource for further investigations into this dynamic coastal environment.

The DigitalGlobe[2] archive contains high-resolution (approximately 50 centimeters GSD) imagery over East Timbalier Island from September 2004 through September 2021

[2]DigitalGlobe was acquired by Maxar Technologies in 2017.

Table 2. List of appendixes in this report and the information types contained in these appendixes.

[The data in these appendixes are also available in Slonecker and others (2020)]

Report section	Title	Appendix content
Appendix 1	High-Resolution Imagery for East Timbalier Island, 1953–2021	Figures 1.1–1.27
Appendix 2	Historical Imagery Data	Table 2.1
Appendix 3	Global Fiducials Library Imagery Dates	Table 3.1
Appendix 4	DigitalGlobe Satellite Imagery Data	Table 4.1
[1]Appendix 5	Landsat Satellite Imagery Data	Table 5.1
[1]Appendix 6	Sentinel–2 Imagery Data	Table 6.1

[1]All images in this appendix are available on the U.S. Geological Survey (USGS) EarthExplorer website (USGS, 2021).

for 65 dates (app. 4). The imagery was collected from the GeoEye–1, QuickBird–1 and –2, and WorldView–1, –2, and –3 satellite systems and provides a wide area of coverage that enables the detailed analysis of features from high-resolution data. The collection frequency allows changes to the landscape to be detected and verified, which provides an effective set of additional imagery datasets to supplement periods that may be missing from GFL scheduled collections. The most recent satellite image over the study site was collected by WorldView–2 on September 11, 2021.

Landsat and Sentinel–2 Satellite Imagery

The jointly operated (NASA and USGS) Landsat satellite program has, since 1972, acquired over 1,200 images of East Timbalier Island that are at least partly clear of cloud cover. The average interval between coverage is about 18 days, weather permitting, with the resolution ranging from 60 m to 15 m. Landsat imagery provided a wealth of data about the Island, including nearshore bathymetry, vegetation classification, and soil moisture. To support the current research project, over 135 images acquired between 1972 and 2021 (app. 5) were used to create a time series to track changes in the size, shape, and position of East Timbalier Island and adjacent areas. By displaying the imagery in a rapid sequence (two frames per second), it is possible to detect, visualize, and track large-scale patterns of change to the Island and adjacent areas.

In addition to providing the longest available high-fidelity time series of multispectral images, Landsat also afforded unique insights by imaging areas of Timbalier Bay adjacent to Timbalier Island. The time-series images of the bay show land loss caused by both subsidence and erosion and by changes to the size of the islands adjacent to East Timbalier Island. Most importantly, the Landsat images give direct evidence that the changes affecting East Timbalier Island also affected adjacent areas to the east (the west end of Port Fourchon) and the west (the east end of Timbalier Island). The images also show that changes to these areas have accelerated since 2018 as East Timbalier Island decreased in size.

Satellite imagery from Sentinel–2, operated by the European Space Agency, supplemented other coverage. Over 250 Sentinel–2 images that are at least partly cloud-free are available for 2015–2021. Twenty-six clear Sentinel–2 images (app. 6), taken at approximately 3-month intervals since 2015, were used to provide a seasonal perspective and augment the Landsat coverage. The Sentinel–2 images have a higher revisit rate (sometimes as short as every 3–5 days) and higher resolution (20–10 m) than Landsat. Sentinel–2 imagery is an excellent gap-filler that provided initial information on significant changes, such as washover and thinning, that were more precisely documented with GFL and other higher resolution imagery.

Results and Discussion

Area Calculations and Cross-Sectional Measurements

Table 3 lists area measurements for selected dates of imagery from over East Timbalier Island. The NCAC created vector shorelines for selected images using manual digitizing techniques. Digitizing was done by the lead author using the commercially available Socet GXP geospatial intelligence software.[3] The purpose was to obtain a precise outline of the Island that followed the shoreline identified in the imagery. A consistent method for selecting images with like resolution and clarity was used to distinguish dry land from the surrounding water. Tidal effects on the imagery were considered and most likely influenced the visible location of the shoreline for selected dates, especially in areas of transitional sediment along the spits of land on the extreme east and west ends of the Island.

Calculations of vector files were performed using commercial geographic information system (GIS) software (ArcGIS[4]) to determine the aerial extent for all polygons created for each image date. The results were entered into a spreadsheet to provide a consolidated report of area changes for each date. These area measurements are a clear representation of the aerial extent of the Island for the selected observation dates. The purpose of creating these vector shoreline datasets was to provide an accurate assessment of the spatial changes that occurred on the Island between the 1953 aerial photograph and the 2020 National Oceanic and Atmospheric Administration Emergency Response Imagery (NOAA–ERI) (table 3).

Cross-sectional transects were measured across the axis of the Island using GFL data from 2011 through 2020. This period was selected to characterize changes that occurred since the previous study, by Thomas and others (2011), which used transects from 2001 to 2010. The movement of the Island before 2000 was so extensive that it is difficult to correlate precise locations on the landscape in newer imagery with that in images from before 2000. Transect lines were spaced at 100-m intervals, starting at the western end of the Island as it existed in September 2011 (fig. 4). The transect lines were measured diagonally across the Island, to include any land areas crossed, for determining the width of the Island for selected dates using available imagery from 2011 to 2020. Figure 5 is a graph showing the continual thinning of the Island as it eroded from 2011 to 2020. A few anomalies occurred during this period, most notably for 2017, 2018, and early 2020; however, the general trend is the extensive thinning of the Island over the past decade. The precise measurements for the data points used to calculate the mean and median distance for the transect lines in figure 5 are provided in table 4.

[3]SOCET GXP is geospatial intelligence software created by BAE Systems.

[4]ArcGIS is a geographic information system software suite created by the Esri company.

Table 3. Area calculations of East Timbalier Island, Louisiana, based on specified image source.

[B/W, black and white; CIR, color infrared image; DOQ, digital orthophoto quadrangle; GFL, Global Fiducials Library; NAPP, National Aerial Photography Program; NASA, National Aeronautics and Space Administration; NHAP, National High Altitude Photography program; NOAA–ERI, National Oceanic and Atmospheric Administration—Emergency Response Imagery; m^2, square meter; m^2/yr., square meters per year; USGS, U.S. Geological Survey; VNIR, visible and near-infrared; WV–3, DigitalGlobe WorldView–3; —, unavailable]

Image date	Land area (m^2)	Image source	Image descriptors	Area change (m^2/yr)	Area change (percentage)
July 19, 2021	0	WV–3	VNIR	–14,530	–100
October 29, 2020	14,530	NOAA–ERI	CIR	–58,765	–80
June 16, 2020	73,295	GFL	B/W	–112,915	–61
February 03, 2020	186,210	GFL	B/W	–5,740	–3
December 31, 2019	191,950	GFL	B/W	16,111	9
September 04, 2019	175,839	GFL	B/W	–44,290	–20
July 16, 2019	220,129	GFL	B/W	–5,459	–2
February 07, 2019	225,588	GFL	B/W	–17,959	–7
January 21, 2019	243,547	GFL	B/W	2,726	1
December 03, 2018	240,820	GFL	B/W	3,169	1
October 30, 2018	237,650	GFL	B/W	–54,609	–19
January 30, 2018	292,259	GFL	B/W	51,717	22
December 25, 2017	237,495	GFL	B/W	–2,705	–1
November 24, 2017	240,200	GFL	B/W	–343	–0
October 24, 2017	240,542	GFL	B/W	–130,799	–35
February 01, 2017	371,341	GFL	B/W	95,517	35
September 01, 2016	275,824	GFL	B/W	–95,646	–26
December 10, 2015	371,471	GFL	B/W	–14,602	–4
September 29, 2015	386,073	GFL	B/W	–158,011	–29
February 14, 2014	544,085	GFL	B/W	49,181	10
February 02, 2013	494,903	GFL	B/W	–185,386	–27
March 06, 2012	680,290	GFL	B/W	87,921	15
September 08, 2011	592,369	GFL	B/W	–527,312	–47
October 27, 2005	1,119,681	USGS	CIR, DOQ	–193,951	–15
January 10, 1998	1,313,633	GFL	B/W	–343,377	–21
January 21, 1994	1,657,010	NAPP	B/W	–490,547	–23
April 26, 1992	2,147,557	GFL	B/W	–14,276	1
November 03, 1989	2,133,281	NAPP	CIR	–237,968	–10
October 27, 1983	2,371,249	NHAP	B/W, CIR	–971,093	–29
April 01, 1978	3,342,343	NAPP	B/W	–26,410	–1
October 21, 1975	3,368,754	NASA	CIR	–747,014	–18
August 20, 1972	4,115,768	HEXAGON[1]	B/W	–1,393,293	–25
[2]1965	5,509,062	Tobin Aerial Surveys	B/W, orthophoto	–1,149,420	–17
January 07, 1954	6,658,482	Aerial	B/W	2,338,698	54
March 26, 1953	4,319,783	Aerial	B/W	—	—

[1]Declassified HEXAGON reconnaissance satellite imagery.

[2]A precise date is unavailable for this image.

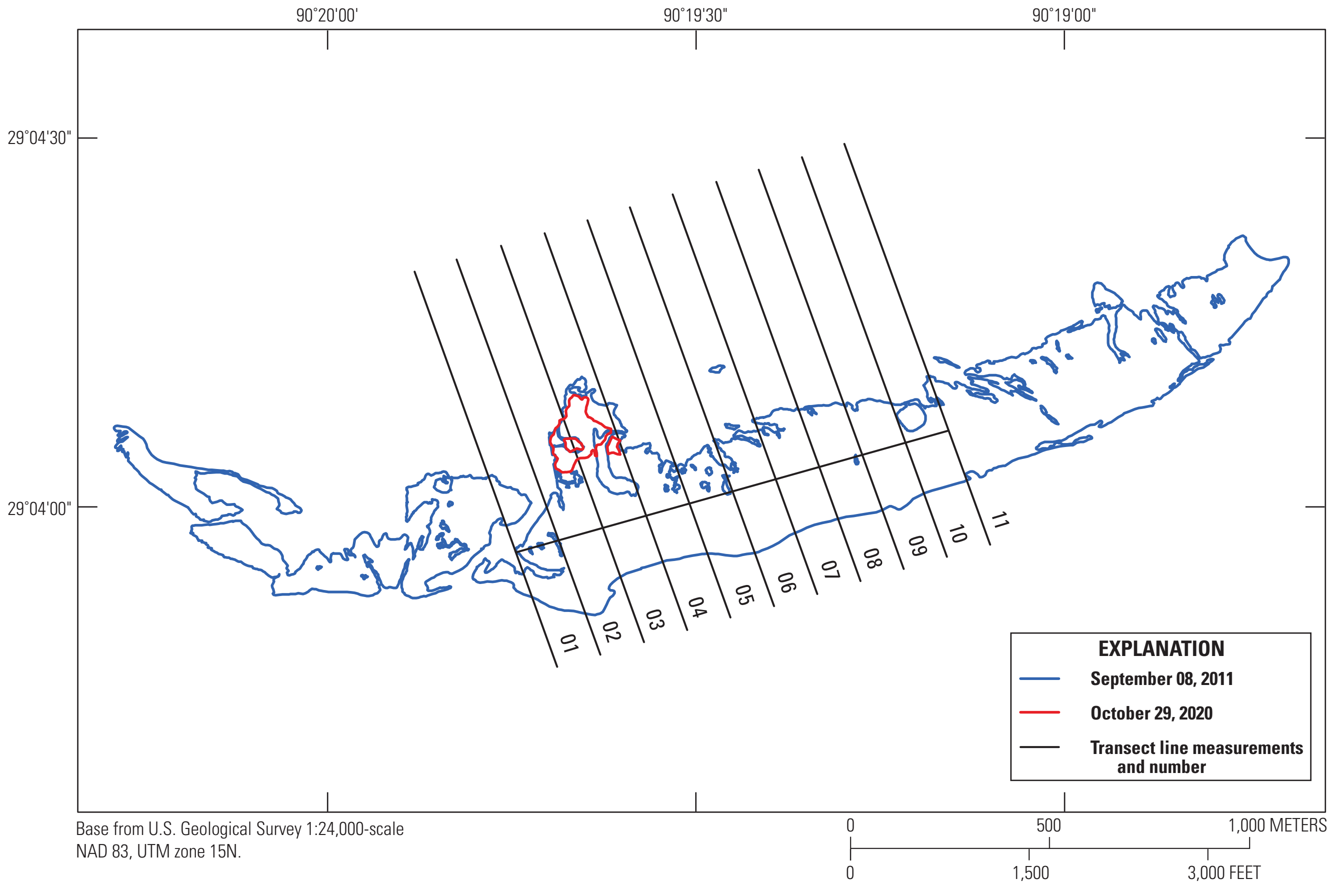

Figure 4. Map showing transect locations on East Timbalier Island, Louisiana, as it existed on September 8, 2011, and October 29, 2020. NAD 83, North American Datum of 1983; UTM zone 15N, Universal Transverse Mercator zone 15 north.

Table 4. Transect measurement lines (fig. 4), in meters, for width of East Timbalier Island using shoreline data, Louisiana, 2011–2021.

Image date	Transect 1	Transect 2	Transect 3	Transect 4	Transect 5	Transect 6	Transect 7	Transect 8	Transect 9	Transect 10	Transect 11	Mean	Median
July 19, 2021	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
October 29, 2020	0.0	0.0	84.0	23.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.7	0.0
June 16, 2020	76.4	89.5	117.3	58.8	15.2	10.8	24.2	0.0	0.0	0.0	0.0	35.7	15.2
February 03, 2020	115.7	247.7	198.8	92.8	27.7	32.7	50.2	92.6	75.4	91.4	0.0	93.2	91.4
December 31, 2019	106.7	139.9	215.3	122.5	37.7	0.0	61.3	63.5	114.2	14.3	0.0	79.6	63.5
September 04, 2019	135.3	59.0	233.0	142.1	50.4	64.5	67.4	64.2	97.3	0.0	0.0	83.0	64.5
July 16, 2019	179.0	59.0	235.2	131.8	47.3	58.4	86.9	69.6	213.4	0.0	0.0	98.2	69.6
February 07, 2019	140.3	88.0	247.6	183.0	66.1	57.6	99.9	107.3	72.5	7.2	0.0	97.2	88.0
January 21, 2019	179.1	118.2	250.9	179.1	78.0	55.6	111.1	100.9	135.1	0.0	0.0	109.8	111.1
December 03, 2018	285.3	87.5	256.8	141.5	80.3	51.3	111.1	104.1	110.0	0.0	0.0	111.6	104.1
October 30, 2018	182.8	107.2	260.3	179.4	91.4	76.1	125.7	128.6	117.9	9.9	0.0	116.3	117.9
January 30, 2018	321.1	129.4	302.5	194.3	124.6	92.9	156.5	162.7	203.5	30.1	0.0	156.2	156.5
December 25, 2017	254.3	135.2	291.2	179.1	113.1	84.6	144.4	161.5	171.9	55.5	0.0	144.6	144.4
November 24, 2017	255.0	135.2	291.4	179.4	113.2	84.9	144.9	161.3	159.0	55.5	0.0	143.6	144.9
October 24, 2017	251.1	137.2	297.6	182.4	111.3	83.9	146.6	160.6	141.5	54.6	0.0	142.4	141.5
February 01, 2017	316.4	171.1	356.8	227.6	164.0	134.2	192.7	207.4	186.4	155.5	120.7	203.0	186.4
September 01, 2016	98.8	163.7	312.4	236.5	156.8	137.4	185.5	138.3	180.6	158.0	117.3	171.4	158.0
December 10, 2015	156.1	221.3	382.0	275.3	193.9	150.1	214.9	212.6	199.1	223.4	160.6	217.2	212.6
September 29, 2015	154.3	240.4	377.8	263.8	198.8	165.8	222.7	241.7	226.5	232.1	188.6	228.4	226.5
February 14, 2014	287.9	247.3	418.1	317.1	226.6	188.0	245.0	257.1	244.4	242.5	188.7	260.2	245.0
February 02, 2013	174.5	255.6	412.5	325.7	230.5	216.3	264.0	272.6	260.5	228.9	199.5	258.2	255.6
March 06, 2012	199.0	280.8	416.7	367.7	231.2	238.3	280.1	303.3	315.1	240.3	208.2	280.1	280.1
September 08, 2011	190.7	281.6	381.8	359.7	226.4	52.5	277.0	285.4	274.3	236.7	263.2	257.2	274.3

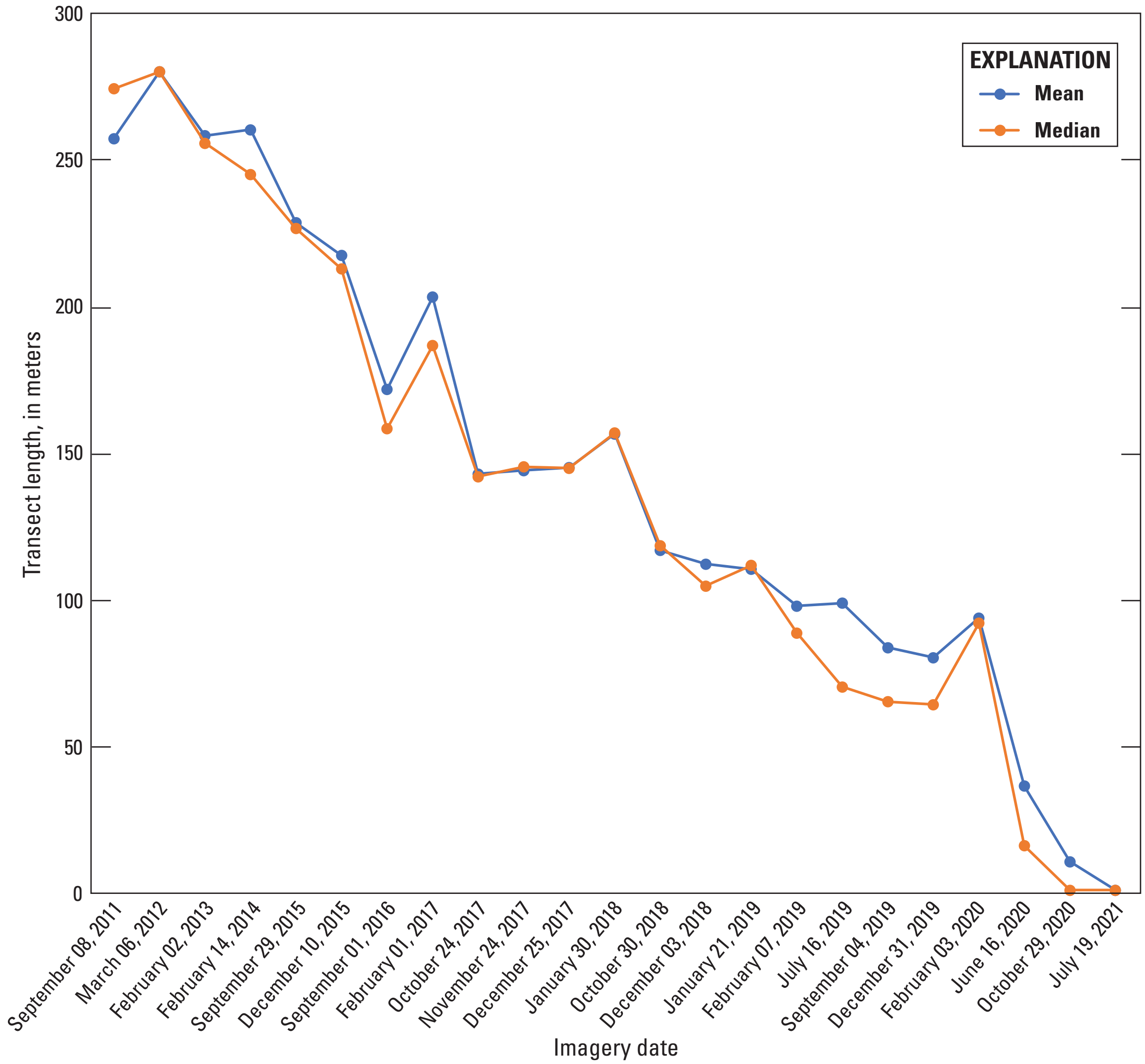

Figure 5. Line graph showing East Timbalier Island, Louisiana, cross-section transect measurements, in meters, for images on selected dates, from September 08, 2011, to July 19, 2021.

Migration of East Timbalier Island

The spatial composition of East Timbalier Island has drastically changed over the past 68 years. During most of this period, the Island repeatedly changed in size (table 3) and broke into smaller segments. The layout of the Island in the 1950s consisted of large segments that formed an almost continuous barrier between the Gulf of Mexico and Timbalier Bay (figs. 2, 1.1, and 1.2). Over the years, these segments divided into smaller segments, which allowed energy from the Gulf of Mexico to reshape the Island and move its core location to different areas. The centroid location of the Island for each date of the available imagery was calculated from polygon-outline vector files digitized to show the extent of the Island and better understand its migration. Figure 6 shows the outline of the Island, using shoreline vector data, for three selected dates (in 1953, 2011, and 2020) calculated in this study.

Each centroid point represents the geographic center of the Island based on the distance of the surrounding shoreline to the center of the Island. Where the Island is segmented, the polygon-outline vector files from the same date were merged to provide a contiguous outline of the Island. The geographic centroid could then be calculated using GIS software. These centroid points were plotted on an image map of the Island (fig. 7) to display the Island center location based on the dates for the imagery used in this report. Table 5 shows the geographic locations for each of these points. Table 6 lists the image dates and the distance that the Island centroid migrated between the two listed, consecutive dates. The mean distance for migration between dates is 155.6 m, which explains the frequent changes to the Island in size and location.

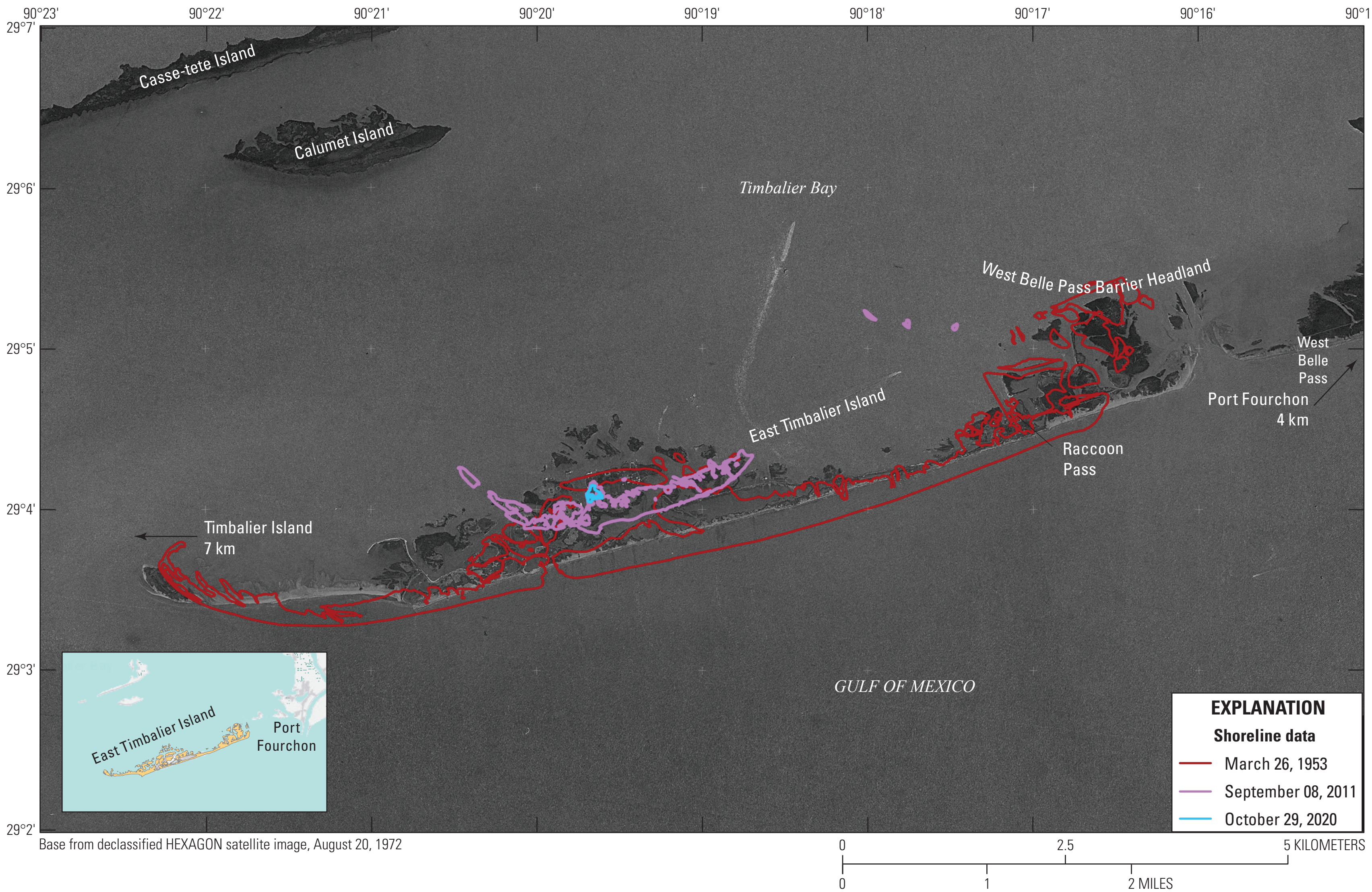

Figure 6. Map showing shorelines of East Timbalier Island, Louisiana, for the years 1953, 2011, and 2020. km, kilometer.

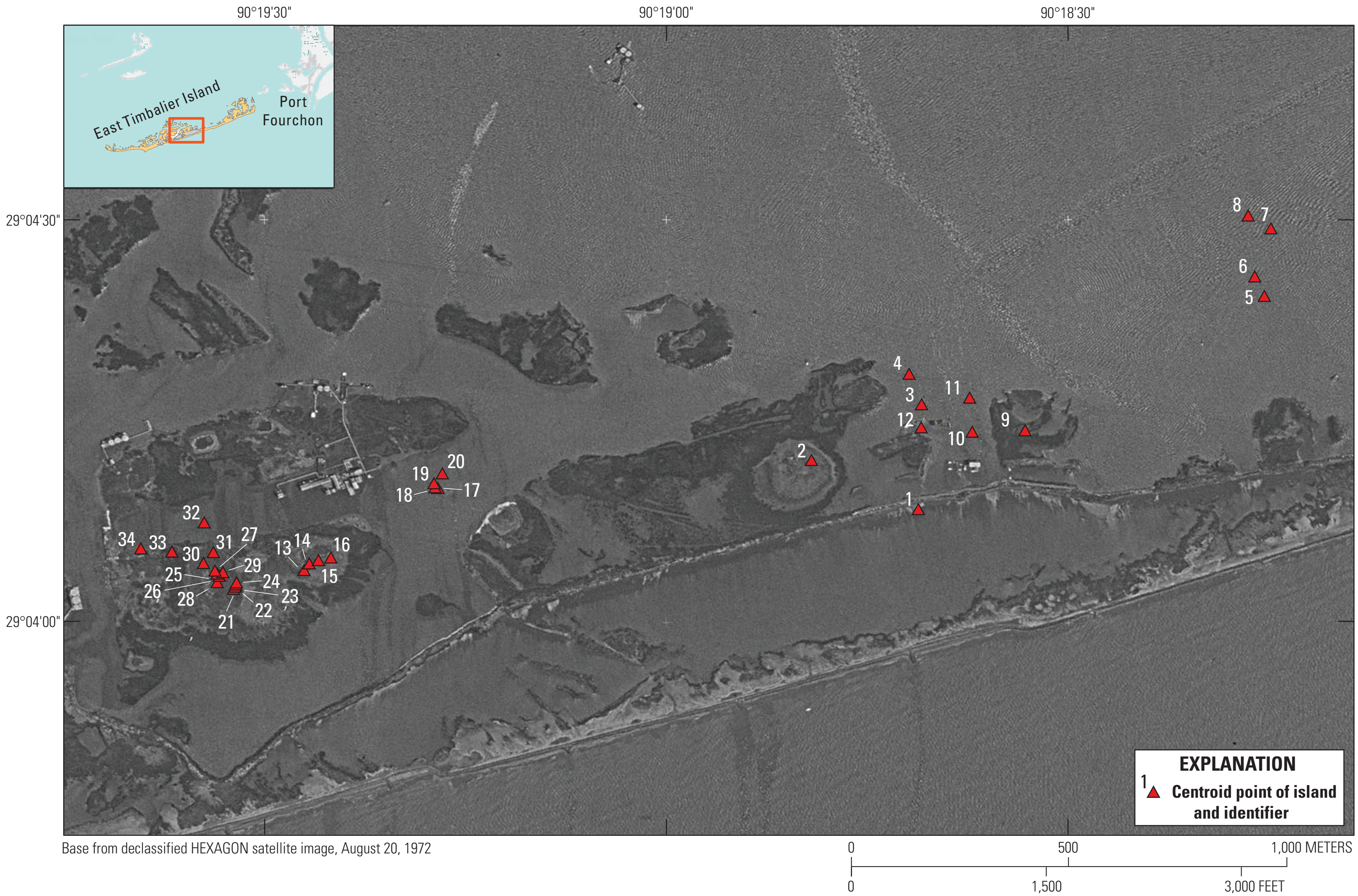

Figure 7. Map of East Timbalier Island, Louisiana, showing point identification numbers and locations of centroid points. Centroid point identification numbers and geographic coordinates are listed in tables 5 and 6.

Table 5. Point identification numbers and geographic coordinate locations of centroid points for East Timbalier Island, Louisiana.

[Point identification numbers and locations are shown in figure 7. Coordinate data in this table use decimal format due to the high precision of the image sources, therefore these data must be converted to the degree, minutes, and seconds coordinate format for correlation with figure 7]

Point identification no.	Image date	Latitude	Longitude	Point identification no.	Image date	Latitude	Longitude
1	March 26, 1953	29.06902	–90.31145	18	December 10, 2015	29.06948	–90.32146
2	January 07, 1954	29.07004	–90.31366	19	September 01, 2016	29.06956	–90.32148
3	[1]1965	29.07120	–90.31138	20	February 01, 2017	29.06976	–90.32131
4	August 20, 1972	29.07183	–90.31164	21	October 24, 2017	29.06738	–90.32561
5	October 21, 1975	29.07344	–90.30428	22	November 24, 2017	29.06743	–90.32558
6	April 01, 1978	29.07384	–90.30448	23	December 25, 2017	29.06743	–90.32558
7	October 27, 1983	29.07484	–90.30415	24	January 30, 2018	29.06747	–90.32557
8	November 03, 1989	29.07511	–90.30462	25	October 30, 2018	29.06762	–90.32593
9	April 26, 1992	29.07066	–90.30923	26	December 03, 2018	29.06773	–90.32598
10	January 21, 1994	29.07063	–90.31033	27	January 21, 2019	29.06775	–90.32601
11	January 10, 1998	29.07134	–90.31038	28	February 07, 2019	29.06750	–90.32596
12	October 27, 2005	29.07072	–90.31138	29	July 16, 2019	29.06767	–90.32584
13	September 08, 2011	29.06777	–90.32416	30	September 04, 2019	29.06791	–90.32624
14	March 06, 2012	29.06790	–90.32405	31	December 31, 2019	29.06815	–90.32606
15	February 02, 2013	29.06802	–90.32360	32	February 03, 2020	29.06876	–90.32625
16	February 14, 2014	29.06797	–90.32386	33	June 16, 2020	29.06813	–90.32692
17	September 29, 2015	29.06946	–90.32140	34	October 29, 2020	29.06824	–90.32756

[1]A precise date is unavailable for this image.

Table 6. Image dates and point identification numbers alongside associated migration distances and directions for centroid points of East Timbalier Island, Louisiana, 1953–2020.

[Point identification numbers are shown on figure 7. E, east; N, north; NA, not applicable; S, south; W, west]

Image dates	Point identification nos.	Migration distance (meters)	Migration direction
March 26, 1953, to January 07, 1954	1–2	243.6	NW
January 07, 1954, to 1965	2–3	256.7	NE
1965 to August 20, 1972	3–4	74.8	NNW
August 20, 1972, to October 21, 1975	4–5	738.0	ENE
October 21, 1975, to April 01, 1978	5–6	48.5	NNW
April 01, 1978, to October 27, 1983	6–7	115.8	NNE
October 27, 1983, to November 03, 1989	7–8	54.4	NW
November 03, 1989, to April 26, 1992	8–9	668.2	SW
April 26, 1992, to January 21, 1994	9–10	107.1	WSW
January 21, 1994, to January 10, 1998	10–11	77.5	NNW
January 10, 1998, to October 27, 2005	11–12	119.6	SW
October 27, 2005, to September 08, 2011	12–13	1,286.0	WSW
September 08, 2011, to March 06, 2012	13–14	18.0	NE
March 06, 2012, to February 02, 2013	14–15	46.0	ENE
February 02, 2013, to February 14, 2014	15–16	26.3	WSW
February 14, 2014, to September 29, 2015	16–17	291.2	NE
September 29, 2015, to December 10, 2015	17–18	6.0	WNW
December 10, 2015, to September 01, 2016	18–19	9.8	NNW
September 01, 2016, to February 01, 2017	19–20	27.7	NE
February 01, 2017, to October 24, 2017	20–21	495.5	SW
October 24, 2017, to November 24, 2017	21–22	7.0	NE
November 24, 2017, to December 25, 2017	22–23	0.4	SW
December 25, 2017, to January 30, 2018	23–24	4.5	NNE
January 30, 2018, to October 30, 2018	24–25	38.4	WNW
October 30, 2018, to December 03, 2018	25–26	13.9	NNW
December 03, 2018, to January 21, 2019	26–27	3.2	NW
January 21, 2019, to February 07, 2019	27–28	28.5	SSE
February 07, 2019, to July 16, 2019	28–29	19.7	NE
July 16, 2019, to September 04, 2019	29–30	47.2	NW
September 04, 2019, to December 31, 2019	30–31	32.2	NE
December 31, 2019, to February 03, 2020	31–32	70.5	NNW
February 03, 2020, to June 16, 2020	32–33	95.6	SW
June 16, 2020, to October 29, 2020	33–34	63.1	WNW
1953–2020	NA	[1]**155.6**	NA

[1]Mean distance of Island migration, 1953–2020.

Changes in Morphology and Migration

Calculations from the vector polygons in table 3 show that through mid-2020, the Island lost 95 percent of its land since measurements were first made using aerial photography in 1953. The dynamics of the Island are apparent, as it morphed in size and location over time. In 1953, the Island was over 4.3 million m^2. During the near seven decades of aerial observation after 1953, the Island underwent several stages of short-term growth and accelerated land loss. These changes are shown in the shoreline-outline graphics in figure 6. In 1954, the Island grew by 54 percent, possibly due to dredging fill for the oil and gas infrastructure. The difference in the size of the Island between 1953 and 1954 may also be attributed to tidal effects on the two dates that the imagery was collected. After 1954, the Island rapidly lost area across three decades until the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) restoration efforts in the late 1990s rebuilt large sections of the Island (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 2002). Since 2011, the Island has undergone several phases of short-term growth followed by rapid land loss, which is evinced by the large areas of sand and sediment surrounding the Island that frequently reform as sandbars and overwash areas on the Island.

The transect measurements shown in figure 5 indicate a decline in the width of the Island from 2011 to 2020. This trend correlates well with the area measurements in table 3 and shows a continual loss of size, excepting outliers in 2012, 2017, and 2020. These outliers may be partly attributed to tidal effects in the imagery or the redistribution of sediment along the backshore of the Island. The small sample size for the transects can be reliably represented by showing the median of the measurements. The median of the data (table 4) confirms the trend of land loss shown in the width of the Island, even when the outliers from 2012, 2017, and 2020 are included (fig. 5).

East Timbalier Island has changed continuously since aerial photographs were taken in the 1950s. The Island morphed in shape and size over the years, as illustrated in figure 6, and finally disappeared by early summer 2021. In 1953, the size of the Island was 4.3 million m^2; in February 2020, it measured 186,210 m^2. Across the period of the study, the size of the Island changed greatly over short intervals. Between 1953 and 1954, the Island grew 54 percent, from 4.3 million m^2 to 6.6 million m^2 (table 3). Much of the oil and gas infrastructure on the Island was under initial construction during this time. In 1954, the Gulf Oil Corporation constructed a dirt levee (between 2.4 and 6 m high) on the crest of East Timbalier Island, several hundred meters landward of the shoreline. This dirt became a sediment source that helped enlarge the Island in 1954 (van Beek and Meyer-Arendt, 1982). The redistribution of this sediment helped increase the Island's size.

The period between 1954 and 1989, however, saw a continual decrease in the size of the Island for each year that high-resolution aerial photography was available (app. 1). Several large storms also passed close to the Island during this time, which may have contributed to erosion and substantial land loss (table 1). Hurricane Flossy (Sep 24, 1956), Hurricane Betsy (September 10, 1965), Hurricane Carmen (September 8, 1974), Hurricane Bob (July 11, 1979), and Tropical Storm Juan (Oct 31, 1985) all had major impacts on the environment around East Timbalier Island. During this time, several shoreline-remediation projects took place near or at the Island to protect the port facilities at Port Fourchon, east of the Island.

In 1945, the jetties protecting Bayou Lafourche at Belle Pass were extended 90 m. The jetties were again extended by 300 m in 1969 (Kulp and others, 2003). These jetties affected the nearshore sediment supply that flows along the Gulf Coast from east to west at Timbalier Bay. In 1964, a new jetty was constructed at Belle Pass, which further affected the sediment supply to East Timbalier Island. In September 1965, Hurricane Betsy, a Category 4 storm, passed only 12 km northeast of the Island and caused substantial erosion and changes to the morphology of the Island. Four groins were installed in 1966 on the central and western parts of the Island to repair the breaches that occurred after Hurricane Betsy (Penland and Suter, 1985). A rock seawall was also erected alongshore, parallel to the shoreline, connecting the groins. Sections of this rock seawall were still visible in the GFL imagery collected in the mid-1990s.

In 1974, 16 km of rock seawall revetment were installed at East Timbalier Island, including 30-m groins spaced every 60 m across the Island (Kramer, 2016). This effort significantly interrupted the sediment supply to the Island. The original dirt levee on the center of the Island was reinforced with stone to protect the bayside of the Island from northwesterly driven waves. In September 1974, Hurricane Carmen passed 65 km to the west of the Island and caused major overwash and breaches across the Island. Between August 1972 and October 1975, the Island lost 747,000 m^2 of land or 18 percent of its land area (table 3). In 1980, several t-groins were added to the Gulf side of East Timbalier Island to protect the beach; however, these structures limited the sediment movement along the shoreline, resulting in a thinning of the Island. This installation considerably affected the shoreline's ability to withstand major storm overwash (Westphal, 2008).

On August 26, 1992, Hurricane Andrew passed 60 km west of East Timbalier Island, causing substantial erosion and a breach in the Island at a narrow spot on the east-central side of the shoreline, which resulted in profound changes to the morphology of the Island. The newly separated "eastern" section of the Island quickly migrated to the northeast, while the orientation of the "western" section of the Island morphed into a northeast to southwest strike. Before this event, the strike of East Timbalier Island was oriented with the strike of West Belle Pass Barrier Headland—the peninsula east of East Timbalier Island—in a general east-to-west orientation.

By August 1995, the eastern section of East Timbalier Island had migrated almost 2,000 m from the western section of the Island. This section of the Island continued to migrate northeast at an accelerating rate until 2008, when this section of the Island nearly disappeared. This change was reflected by a 1.2-km westward shift in the Island centroid over this period (fig. 7; table 6) (Kulp and others, 2015).

The Louisiana Coastal Wetlands Conservation and Restoration Task Force provided funding (through CWPPRA) to restore East Timbalier Island via projects TE–25 and TE–30 from 1999 to 2000 (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 2002). This restoration effort resulted in 2 million cubic meters of sediment dredged from nearby offshore areas being used to establish a 60-m-wide dune and a 180-m-wide marsh along the length of the Island (Byrnes and others, 2018). A 2,100-m-long rubble-mound revetment was also created to protect the shoreline of the Island. Project TE–25 funded the construction of 4,000 m of sand fences and the planting of 13,000 plugs of bitter panicum (*Panicum amarum*) and 6,500 plugs of marsh hay cordgrass (*Spartina patens*) along the Island's dunes to minimize wind-induced erosion (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 2002). However, the benefits of these extensive restoration efforts were short-lived. The 2005 hurricane season included some of the most destructive storms to ever hit the central Gulf Coast. Hurricanes Cindy, Katrina, and Rita all hit during 2005, resulting in a decrease of Island size by 15 percent between January 1998 and October 2005 (table 3). The 2008 hurricane season was another active period with two major storms passing close to East Timbalier Island: Tropical Storm Edouard and Hurricane Gustav. The land area of the Island decreased by 47 percent from October 2005 through September 2011 (table 3).

After 2010, the geomorphology of the Island changed at an accelerating rate (table 3). Several multi-year cycles of ocean-facing shore thinning, east-end erosion, breaching, and northward migration were identified. The latest cycle began in mid-2018 and continued into 2021. This cycle ended in 2021 with the disintegration of the Island into several small, elongated, northward-trending sand bars.

In 2011, the eastern and western ends of the Island began to migrate to the north, transforming the Island into a crescent shape. The tips of the east and west ends of the Island continued to grow and transform into narrow spits of land. By February 2014, the western spit had grown to over 1,800 m in length and then disappeared by September 2015. The eastern spit of land grew substantially from December 2015 to February 2017 and then disconnected from the main Island in October 2017. The growth and retreat in the size of this spit are reflected in the size-changes of the Island listed in table 3.

East Timbalier Island showed a 10-percent increase in growth when the image from February 14, 2014, was compared with the image from February 02, 2013 (table 3), and a 35 percent increase in growth was shown when the image from February 1, 2017, was compared with the image from September 01, 2016 (table 3). This growth correlates with the growth of the spits on either end of the Island during this period. Once the spits detached from the main Island, however, they quickly shrank. During a similar time period, 2011–2020, the width of the Island also grew and shrank relative to the periods of rapid growth and the disintegration of the spits. The mean width of the Island grew to 203.0 m by February 01, 2017 (table 4), which correlates with the increase in the size of the Island during that same period. Likewise, on January 30, 2018, the mean width of the Island was 156.2 m, having grown from 142.4 m in October 2017, which correlates with the increase in the size of the Island during that same period.

Hurricane Barry, which passed 69 km southwest of East Timbalier Island on July 13, 2019, was a relatively weak Category 1 hurricane but contributed to a 10-m change in the mean width of the Island between January 21, 2019, and July 16, 2019 (table 4). The change in the median width of the Island was over 40 m during this period. This substantial change in the width of East Timbalier Island demonstrates its vulnerability to coastal erosion and the rapid redistribution of sediment surrounding the Island.

The 2020–2021 hurricane seasons led to unprecedented tropical storm activity along the Louisiana coast. Five major storms struck the Louisiana coast in 2020, including three storms that heavily affected the Island. Tropical Storm Cristobal struck the Louisiana coast on June 7, 2020, passing 50 km east of East Timbalier Island and caused a land loss of 112,915 m^2 (table 3). Tropical Storm Marco passed 23 km south of the Island on August 24, 2020, resulting in extensive shoreline erosion. Hurricane Zeta passed 17 km west of the Island on October 28, 2020, and submerged the Island, leaving a 14,530 m^2 section of land near the oil infrastructure plant (fig. 1.24). By early 2021, this area was highly susceptible to erosion from tropical storms.

On June 18, 2021, Tropical Storm Claudette passed 67 km west of East Timbalier Island, causing erosion of the remaining land. While East Timbalier Island eroded from its original location, the shifting sand and sediment migrated northwest. With each passing storm, more sand and sediment was removed from the sand shoals and deposited further north into Timbalier Bay. This redistribution of sand is visible in the images in figure 8. The six images in figure 8 (*A*–*F*) show the central portion of the Island, with a focus on the remnants surrounding the oil and gas plant (fig. 8*C*). The resultant sand bars, which migrated to the north after Tropical Storm Claudette (fig. 8*D*), are also shown.

The rapid pace of Island erosion can be seen in the juxtaposition of the February 3, 2020, GFL image (fig. 8*A*) and the July 19, 2021, DigitalGlobe WorldView–3 image (fig. 8*D*). Each storm that passed the region during 2020 and 2021 caused significant erosion and the redistribution of sediment at the site of the Island. The site became completely submerged after Tropical Storm Claudette, and sand shoals emerged north of the site, although they are likely to dissipate. After Hurricane Ida passed over the site on August 29, 2021, the sand shoals north of the oil and gas plant disintegrated, and open water surrounded the site of the Island (figs. 1.26, 1.27).

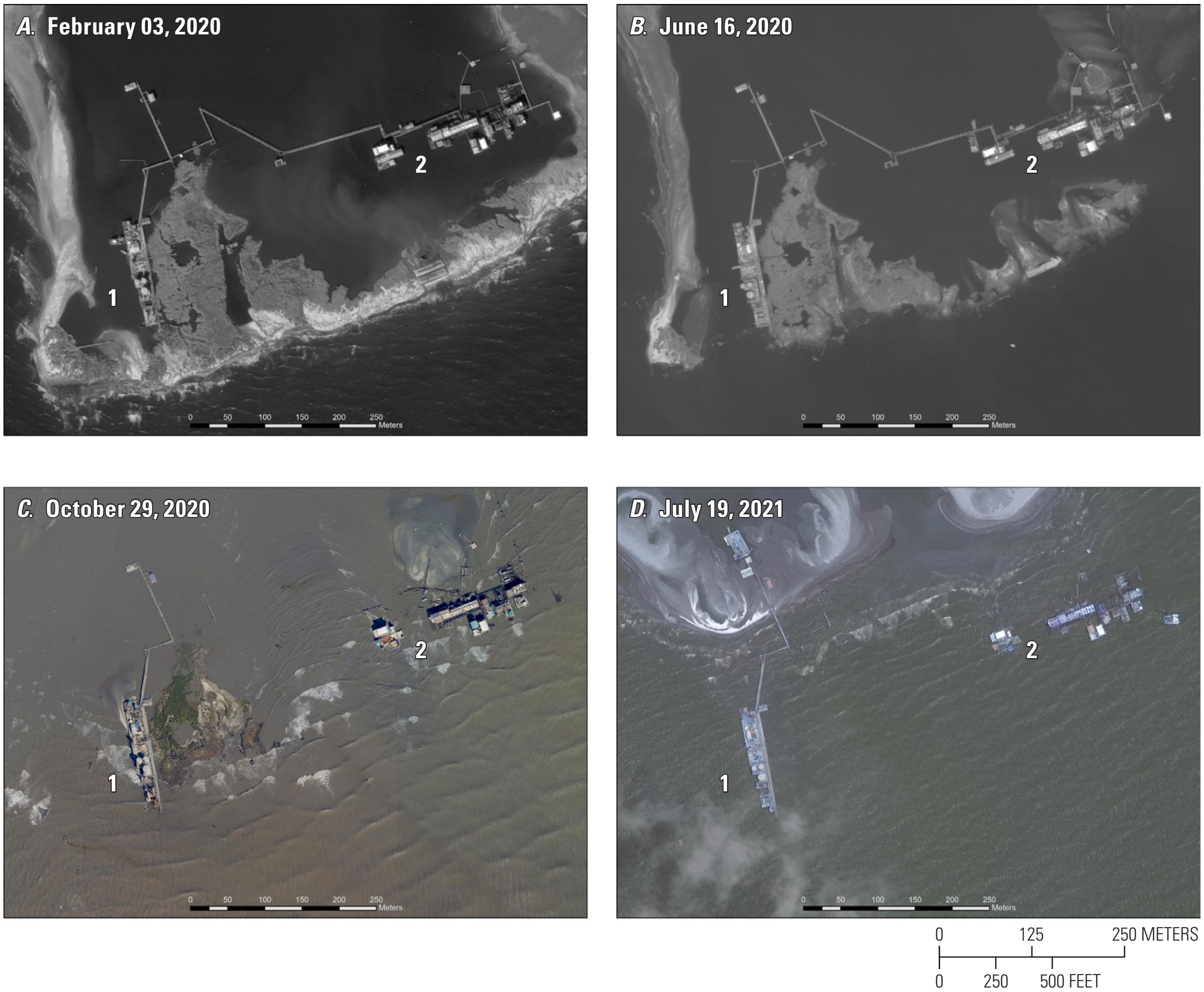

Figure 8. A collection of images (*A*–*F*) of East Timbalier Island, Louisiana (La.), captured between February 3, 2020, and September 4, 2021. Locations 1 and 2 in the images are sections of oil and gas infrastructure. *A*. Global Fiducials Library (GFL) image from February 3, 2020, shows the Island as a contiguous whole, although it has large sand- and sediment-filled sacks covering a washover from late 2019, just below location 2. *B*. Breaches seen in GFL image from June 16, 2020—south of location 1 and east of location 2—created direct openings to both segments of infrastructure after being hit by Tropical Storm (TS) Cristobal, leaving both exposed to western- and northern-moving Gulf wave action for the first time. *C*. Last land-surface Island remnant, just east of location 1, can be seen in the October 29, 2020, National Oceanic and Atmospheric Administration Emergency Response Imagery (NOAA–ERI) image collected a day after Hurricane Zeta passed. Some catwalks and infrastructure connecting location 1 to location 2 were damaged. *D*. DigitalGlobe WorldView–3 image from July 19, 2021, shows, after TS Claudette in June, the migrated sand-sediment created shoals and bars north of where East Timbalier Island was located. Hurricane Ida, a Category 4 hurricane, passed east of the Island on August 29, 2021, and was devastating to southern Louisiana and carried torrential rain and flooding into the northeastern United States. *E*. In the DigitalGlobe WorldView–1 image from September 2, 2021, the wave action continues from the south and east through locations 1 and 2, dissipating where the sand bars once were. Oil slicks appear to be coming from locations 1 and 2, drifting east into the Gulf of Mexico. In the complete WorldView–1 image, numerous oil leaks are visible in the Gulf, east of East Timbalier Island and south of Port Fourchon, La., some of which are visible in figure 1.26. *F*. DigitalGlobe GeoEye–1 image from September 4, 2021, in which the seas have calmed from the effects of Hurricane Ida. Locations 1 and 2 are surrounded by water, with only the shallow shoal present northwest of location 2. Infrastructure damage is visible, as are the oil slicks.

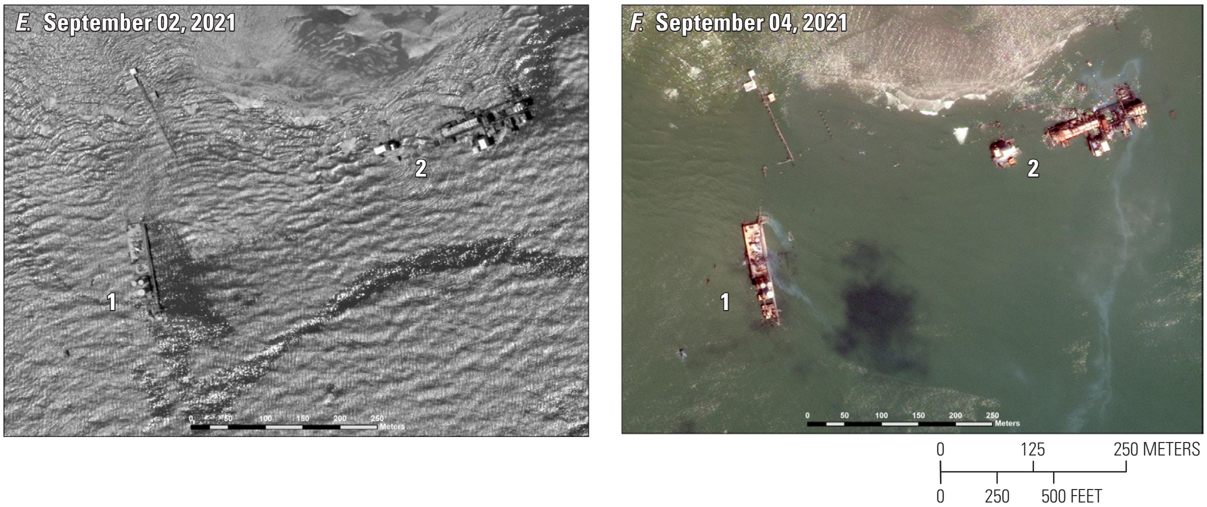

Figure 8.—Continued

Human-Induced Impacts

East Timbalier Island was a major transit location for the oil and gas industry operating in the central Gulf of Mexico. Approximately 150 active and abandoned oil and gas wells were constructed on the Island and in the surrounding waters. Dozens of pipelines crisscross the area and lead to a central processing plant on the north side of the Island. Before it became a major oil- and gas-transit hub, the Island was designated East Timbalier Island National Wildlife Refuge by President Theodore Roosevelt in 1907. The Island's protections were revoked in 1969 to further develop the oil and gas industry on the Island.

The earliest pipelines, which crossed the Island, can be seen in the 1950s imagery. The images show two lines following the length of the Island westward from Belle Pass. Appendix 1 contains imagery for all high-resolution images referenced in this report for 1953–2021. The 1950s imagery also shows several canals dug on the east side of the Island near Raccoon Pass (figs. 1.1, 1.2), as well as several canals and straightened shorelines on the west-central part of the Island where the main processing plant is located. In 1965, the canal dug into the western end of Belle Pass, east of Raccoon Pass inlet, quickly eroded and became a parallel inlet on the east side of Raccoon Pass (fig. 1.3). By 1972, the two inlets had merged into a single, 17-m-wide inlet that separated East Timbalier Island from the Belle Pass barrier spit (fig. 1.4).

Similarly, the land along the east-west traversing pipelines quickly eroded during this period, narrowing the Island width to less than 100 m at the east-central part of the Island. In 1992, erosion from Hurricane Andrew, which passed 60 km west of the Island, created a new inlet at this narrow location (fig. 1.10). The Island then segmented into two sections: an eastern section of approximately 500 ha and a western section of approximately 1,100 ha. By late 1992, both sections of the Island had numerous oil and gas facilities, including pipelines, buildings, radio towers, and containment ponds. This period saw the most significant changes to the Island, most notably the restoration efforts that were part of the CWPPRA project in the late 1990s.

The land area gained by the completion of the CWPPRA project in 2000 quickly eroded over the next decade, with a loss of more than 47 percent of the land area by September 8, 2011 (fig. 1.13). The eastern section of East Timbalier Island migrated northward during this time while also quickly eroding. By September 2011, this section had become a sand bar approximately 2 km north of its pre-2000 location (fig. 1.13). The north side of the main, western section of the Island includes onshore and offshore petroleum-associated facilities and a quay. The GFL images from September 2011 to February 2020 (figs. 1.13–1.22) show both the east and west ends of this section of the Island migrating northward in a crescent shape while eroding closer to the processing plant. The June 2020 GFL image shows that these sections eroded, offering little protection to the main part of the island, which surrounded the oil and gas infrastructure.

The spits of land that formed on the west and east sides of the Island broke off, respectively, in February 2013 and December 2015 (figs. 1.15, 1.17). These newly created islands quickly eroded and became sand bars that occasionally reemerged and then disintegrated with seasons and tides. On June 16, 2020 (fig. 1.23), the size of the Island was slightly over 73,000 m^2 and continuing to erode. The remaining section of the Island that was held in place by the oil and gas processing plant built in the 1960s (fig. 1.3) eroded until June 2021, when it disintegrated.

Hurricane Ida passed almost directly over the site of East Timbalier Island on August 29, 2021, causing significant destruction of the oil and gas plant. DigitalGlobe WorldView–1 and GeoEye–1 satellite imagery collected on September 2nd and 4th, respectively (figs 1.26 and 1.27), show two large oil spills south and east of the oil and gas plant. Several other oil spills were reported south and east of Port Fourchon (Biesecker, 2021; Singh and others, 2021), although the source of these spills is currently under investigation. Given the large concentration of petroleum infrastructure at the site of East Timbalier Island, environmental issues may be a continuing problem.

Implications for Timbalier Bay

Much of the change at East Timbalier Island was episodic, occurring during major storm events and seasonal high-water events when waves eroded vegetation and carried sand away from the Island. Ultimately, unmitigated erosion of the Island caused continued thinning and a shortening of the Island's east end. After the 2020 and 2021 storms, only a series of small, northward-migrating sand shoals remained. The consequences include a loss of local oil-production infrastructure; hazards to navigation that require new charts of the area; accelerated erosion to the eastern end of Timbalier Island; and an increased risk of erosion to the eastern portion of Timbalier Bay, including Calumet and Casse-tete Islands, La. (fig. 2), and the western approaches to Port Fourchon, La., through West Belle Pass. Over the longer term, Timbalier Bay is expected to continue to be shaped by regional subsidence of the Mississippi River Delta Plain, additional localized subsidence related to oil and gas extraction from the bay area, and continued efforts to mitigate wetland loss in the area.

Across the period covered by this report, oil-production-related infrastructure was affected by changes at East Timbalier Island. In early 2020, commercial satellite images showed that sediment from dredged areas around the oil facility was deposited at both recent and potential washover sites. By February 2020, additional mitigation efforts were underway, including the placement of several 20-m-long, sand-filled, anti-erosion barriers. These mitigation efforts ended shortly thereafter due to increased costs and the accelerated loss of the Island. With the Island sand and sediment redeposited north of the oil and gas infrastructure, there was no longer an Island to function as a barrier for storm-driven waves and surges.

During the 21st-century, erosion of the Island outpaced efforts to chart the changes in the area, increasing the risk to navigation. The version of NOAA Chart 11365 (NOAA, 2018) available at the time of this report includes corrections before June 1, 2021, but changes to the shape of the Island outpace even this recent chart. Continually changing bottom depths and shifting shoals and sandbars characterize the area around the Island. Submerged segments of a sea wall and piles of rip rap, along with a network of submerged operational and legacy pipelines and other infrastructure, pose potential hazards to fishing nets and boating.

The loss of East Timbalier Island opens a gap at the eastern end of Timbalier Bay, exposing the bay to the direct force of sea waves and storm surges. Over the longer term, Calumet and Casse-tete Islands may face increased erosion from more direct exposure to ocean waves, especially during tropical storms (figs. 1.22–1.24).

GFL imagery, commercial satellite imagery, Landsat and Sentinel–2 satellite imagery, and historical aerial photography provide a unique record of the changes to East Timbalier Island across the last seven decades, ultimately depicting its disappearance. Continued monitoring can help in assessing changes after the loss of the Island and the subsequent effects on Timbalier Bay.

Conclusion

East Timbalier Island experienced extreme erosion over the past 68 years, changing from an area of over 6.6 million m^2 in 1954, to less than 74,000 m^2 in mid-2020, to completely eroding away in early Summer 2021. Island width continued to shrink, decreasing from a mean average of 235.8 m in 2011, to a mean average of 49 m in mid-2020, to a value of 0 in early Summer 2021. The causes for this extreme erosion are complex and varied. These causes include exposure to frequent tropical storms that breached the Island and eroded the shoreline; dredging and channeling from the infrastructure built to support the oil and gas industry; and mitigation projects that occurred between 1998 and 2000. A project that started in 2020 led to sand berms and rock revetment walls designed to protect the Island from erosion, but they failed because they undermined the sediment that they were designed to protect.

Image collection over East Timbalier Island has been extensive and varied. High-resolution aerial photography captured the development of the oil and gas infrastructure on the Island during the 1950s and 1960s. Declassified CORONA and HEXAGON imagery collected in the 1960s and 1970s provide a detailed look at changes from that period. The GFL imagery collected over the Island since 1992 enabled the frequent observation of changes to the Island caused by tropical storm damage and catastrophic threats to the environment caused by the failed infrastructure and remediation projects. Additionally, moderate-resolution Landsat and Sentinel–2 satellite imagery provided continuous observation of the extensive changes that have happened since 1972 and 2015, respectively. Newer commercial satellite systems now provide additional observation platforms to help document changes along the Louisiana coast.

The unprecedented hurricane seasons of 2020 and 2021 resulted in the final erosion of the Island. Given the frequent shifts in the surrounding sediment and exposure to the open waters of the Gulf of Mexico, the Island became a drifting sand bar only exposed at low water. This extensive loss of land leaves an open gap to Timbalier Bay that was once protected by the over 10 km of barrier island provided by East Timbalier Island. Given the demise of this protection, the shoreline of the central Louisiana coast is now vulnerable to increased erosion and land loss.

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Appendix 1. High-Resolution Imagery for East Timbalier Island, 1953–2021

Appendix 1 contains high-resolution images covering the area around East Timbalier Island, Louisiana, from 1953 through 2021. These images include aerial photographs collected from various sources in the 1950s through the 2000s, satellite imagery collected by U.S. Government systems from the 1970s through 2020, and commercial satellite imagery collected in 2021.

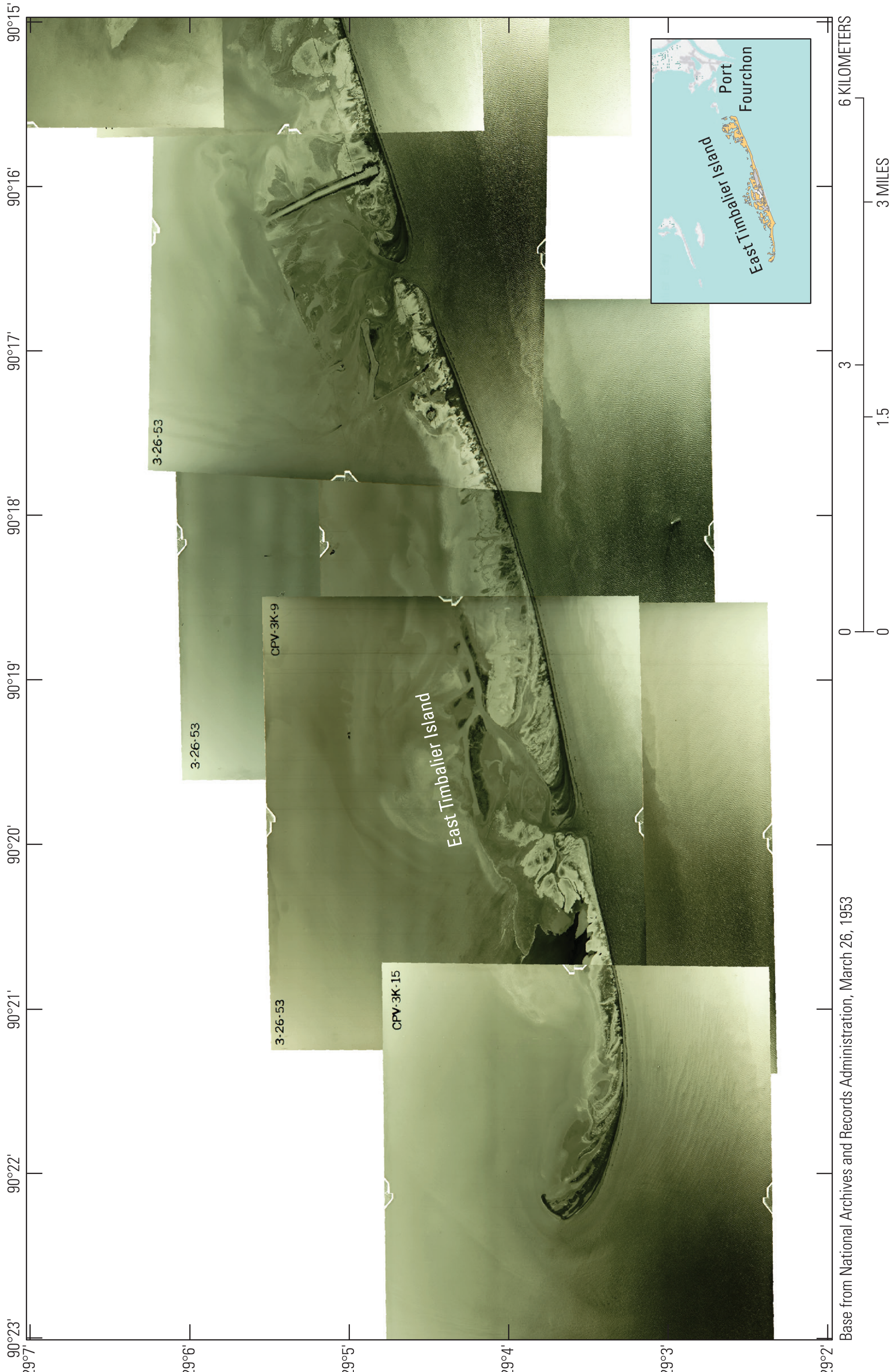

Figure 1.1. Historical aerial photograph of East Timbalier Island, Louisiana, March 26, 1953.

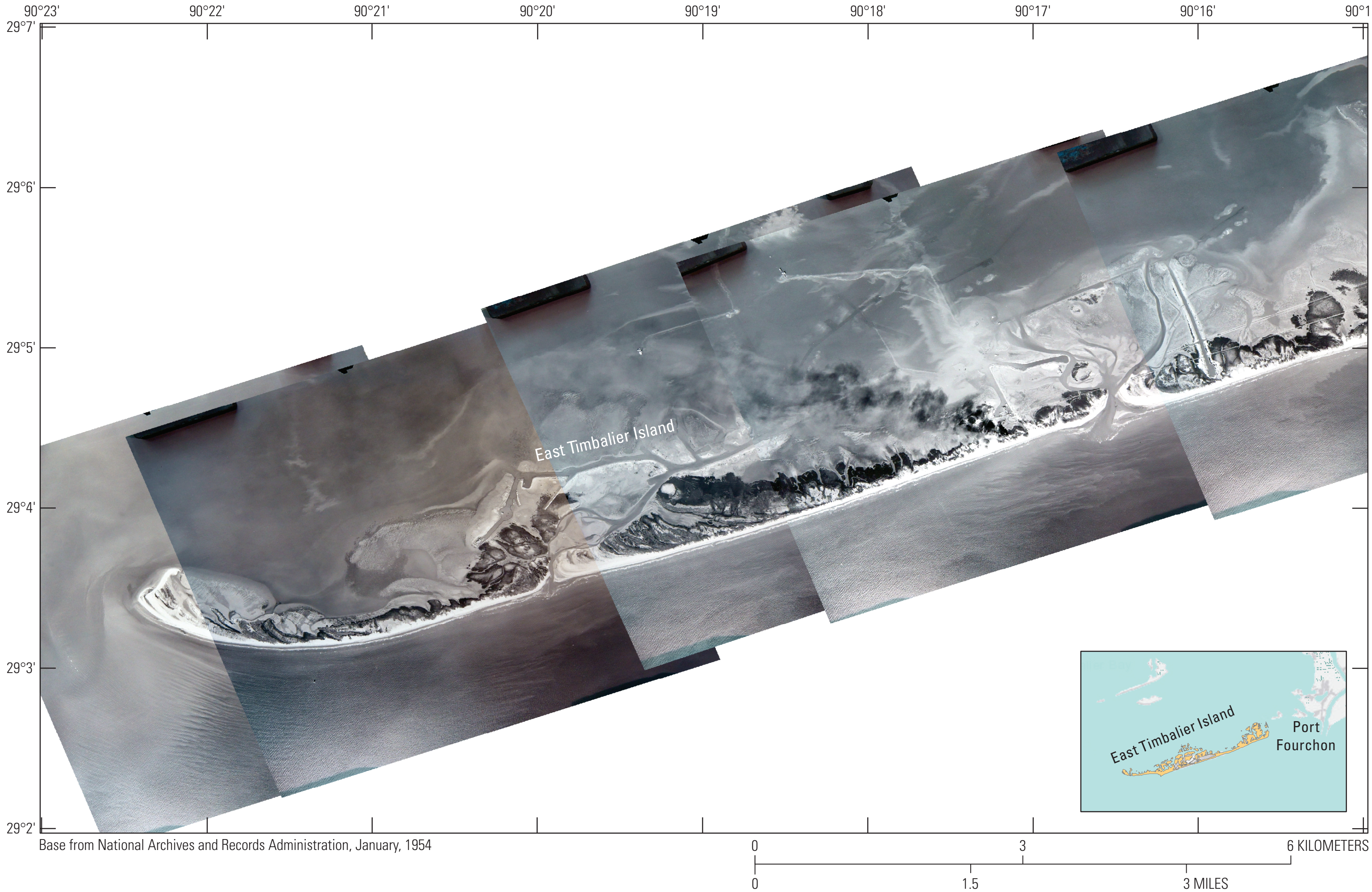

Figure 1.2. Historical aerial photograph of East Timbalier Island, Louisiana, January 07, 1954.

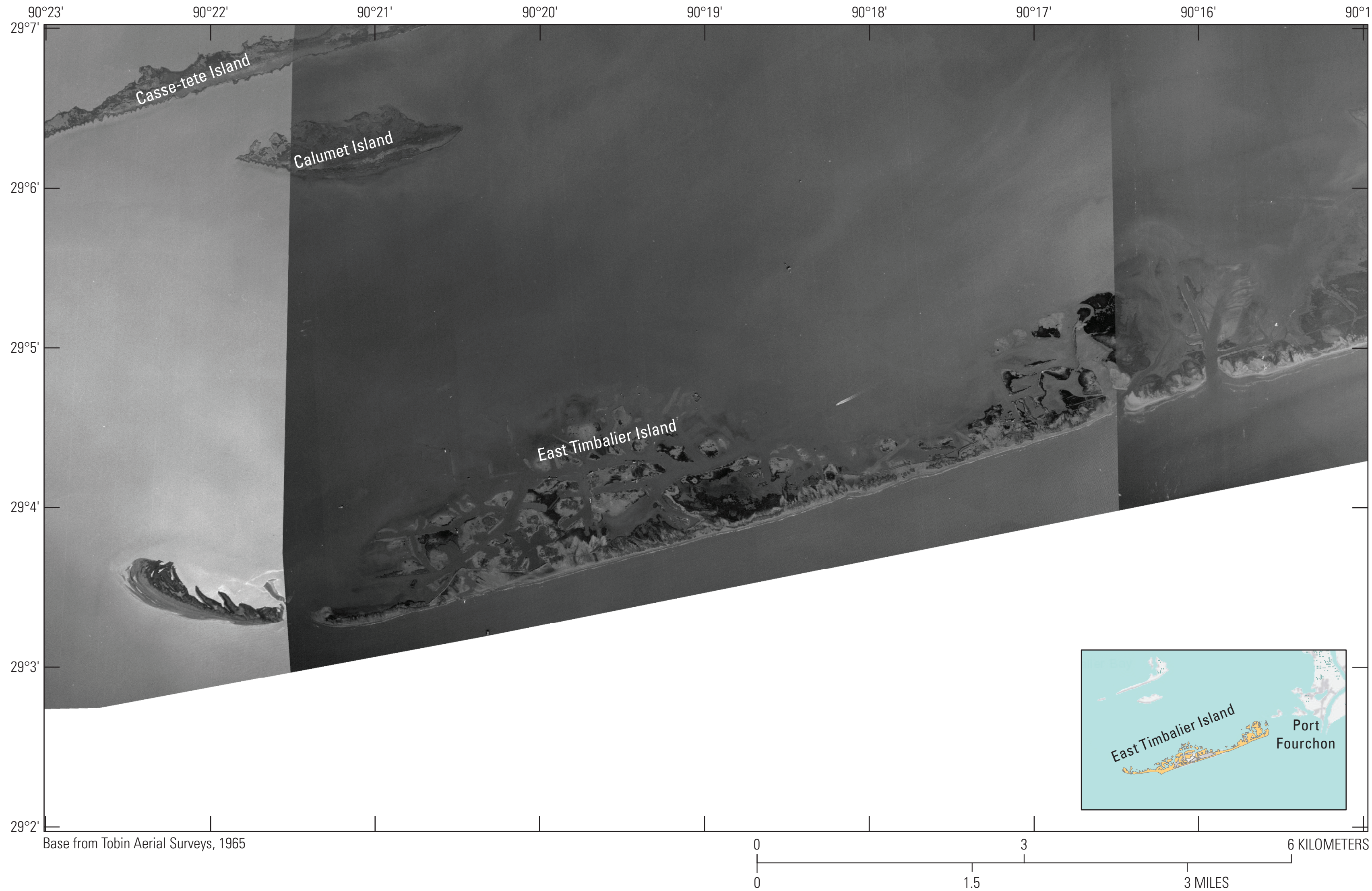

Figure 1.3. Tobin Aerial Surveys image of East Timbalier Island, Louisiana, 1965.

Figure 1.4. Declassified HEXAGON satellite image of East Timbalier Island, Louisiana, August 20, 1972.

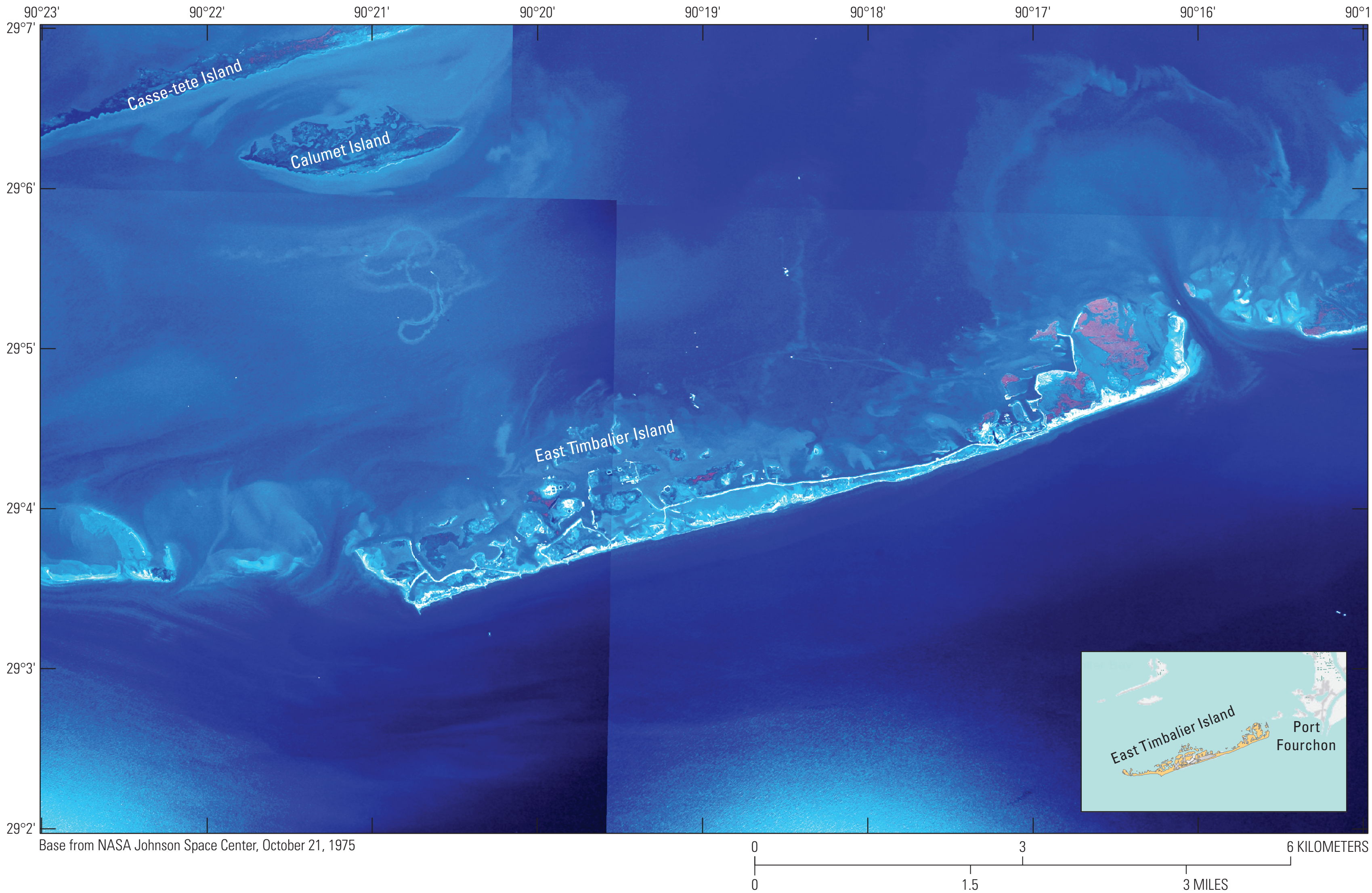

Figure 1.5. National Aeronautics and Space Administration aerial photograph of East Timbalier Island, Louisiana, October 21, 1975.

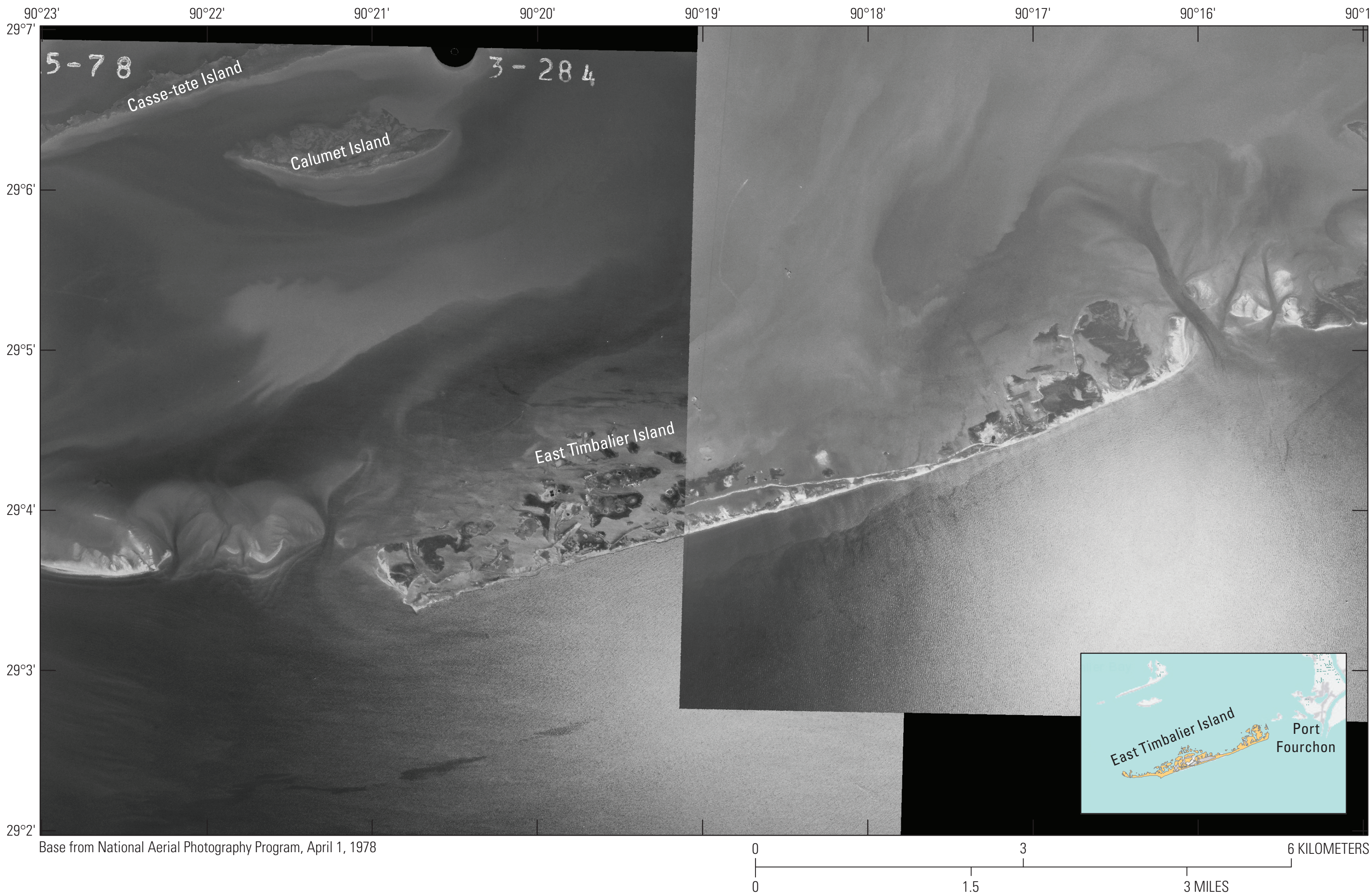

Figure 1.6. National Aerial Photography Program aerial photograph of East Timbalier Island, Louisiana, April 1, 1978.

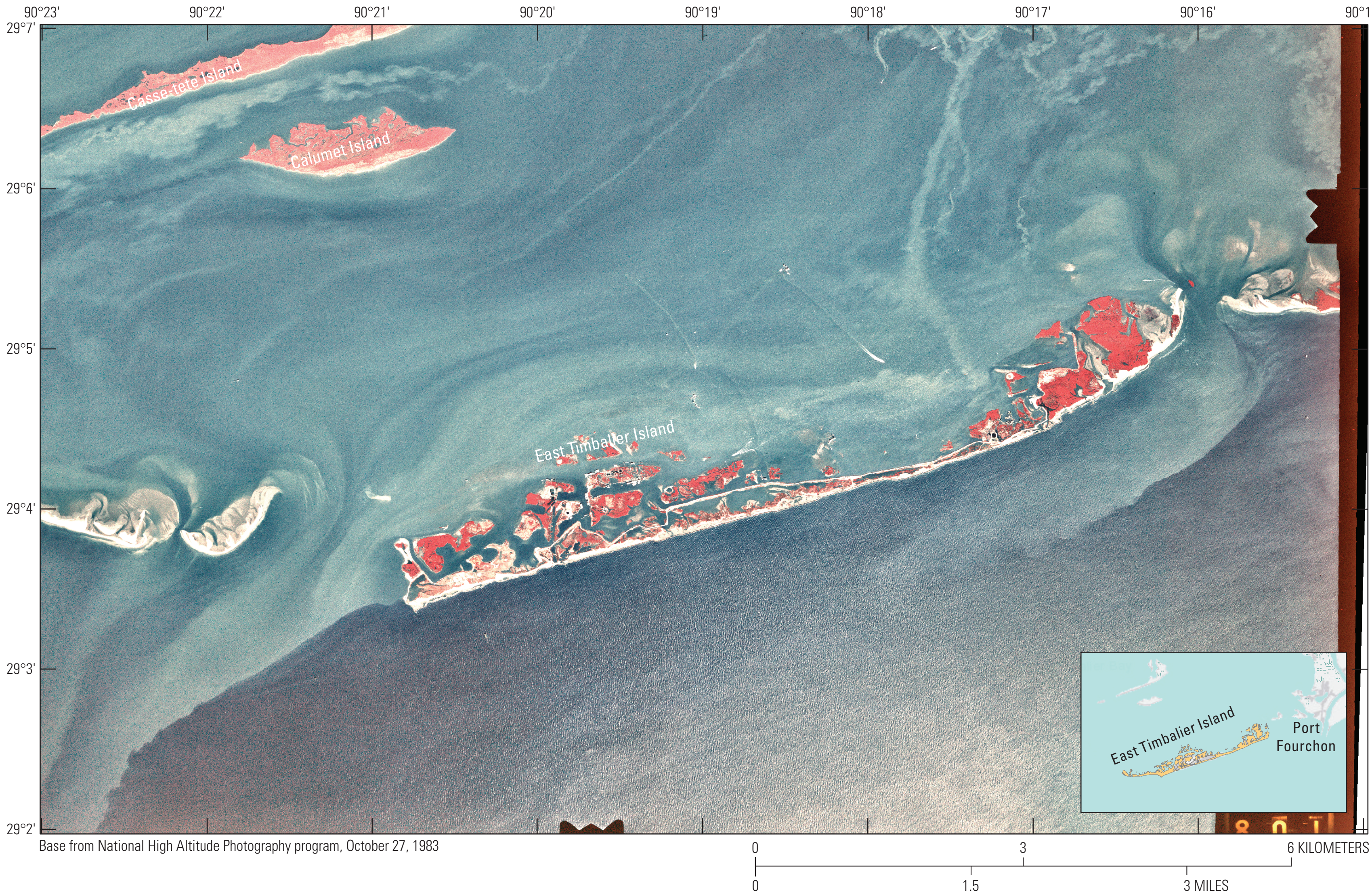

Figure 1.7. National High Altitude Photography program aerial photograph of East Timbalier Island, Louisiana, October 27, 1983.

Figure 1.8. National Aerial Photography Program aerial photograph of East Timbalier Island, Louisiana, November 3, 1989.

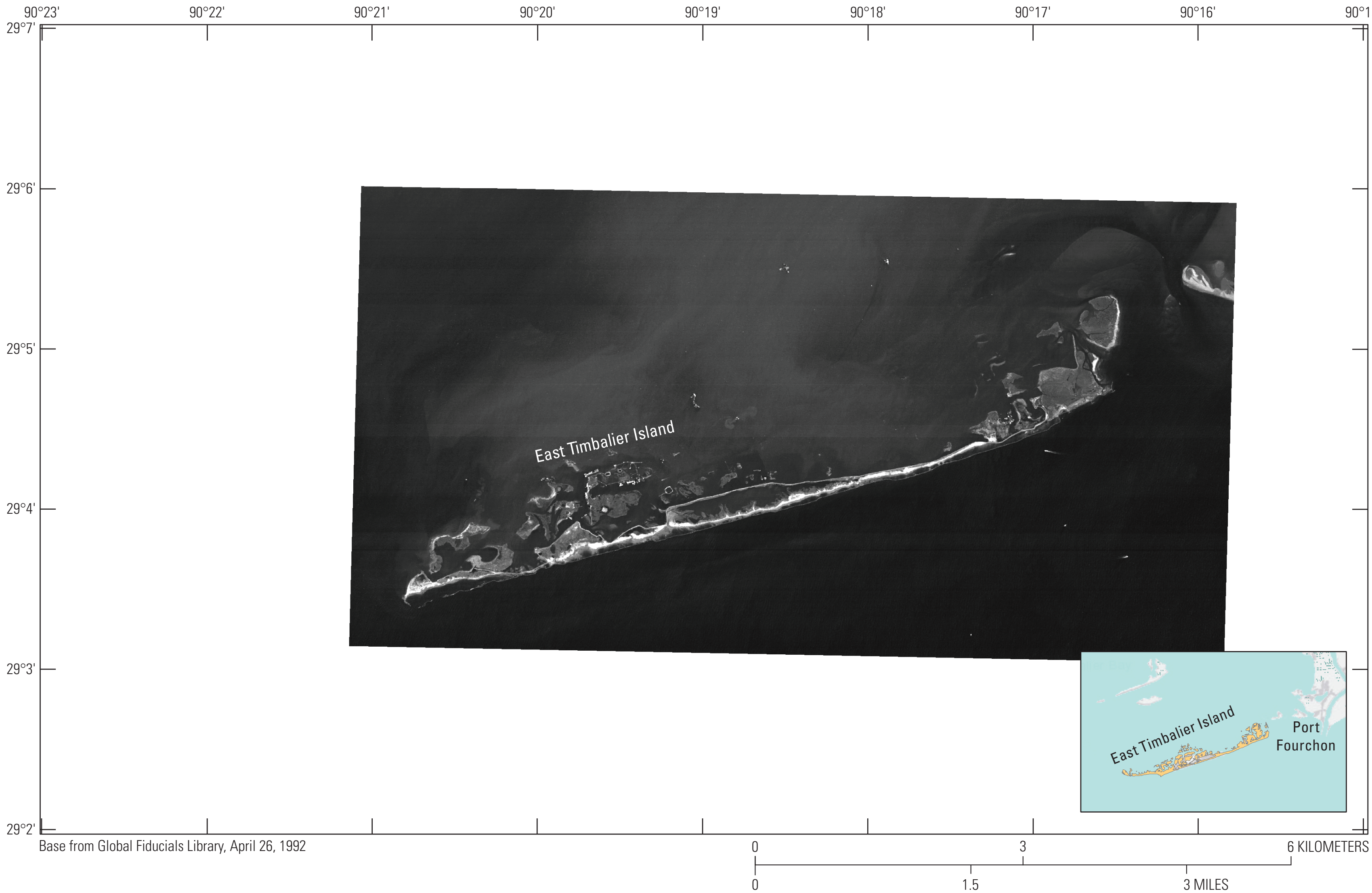

Figure 1.9. Global Fiducials Library image of East Timbalier Island, Louisiana, April 26, 1992.

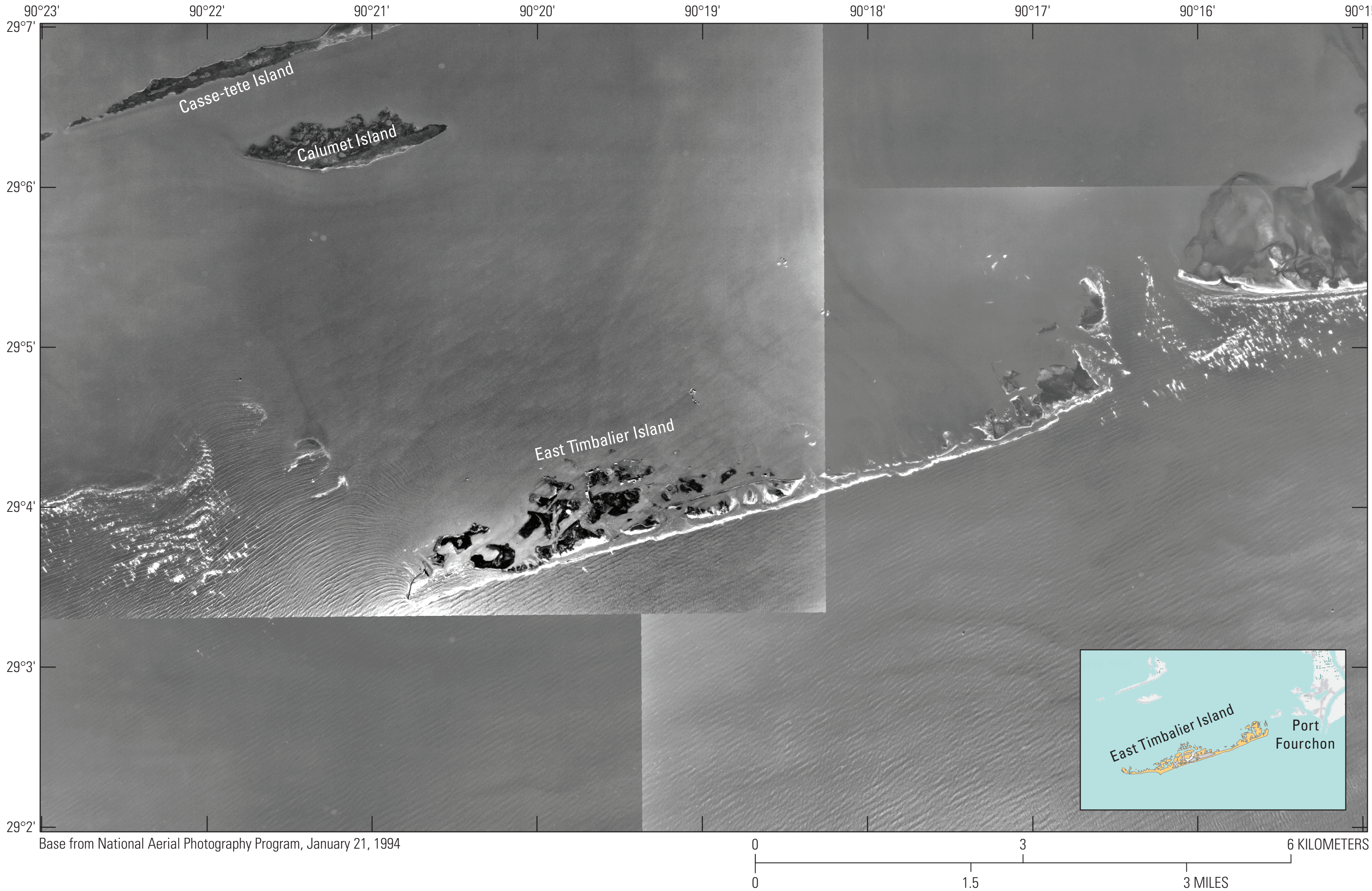

Figure 1.10. National Aerial Photography Program aerial photograph of East Timbalier Island, Louisiana, January 21, 1994.

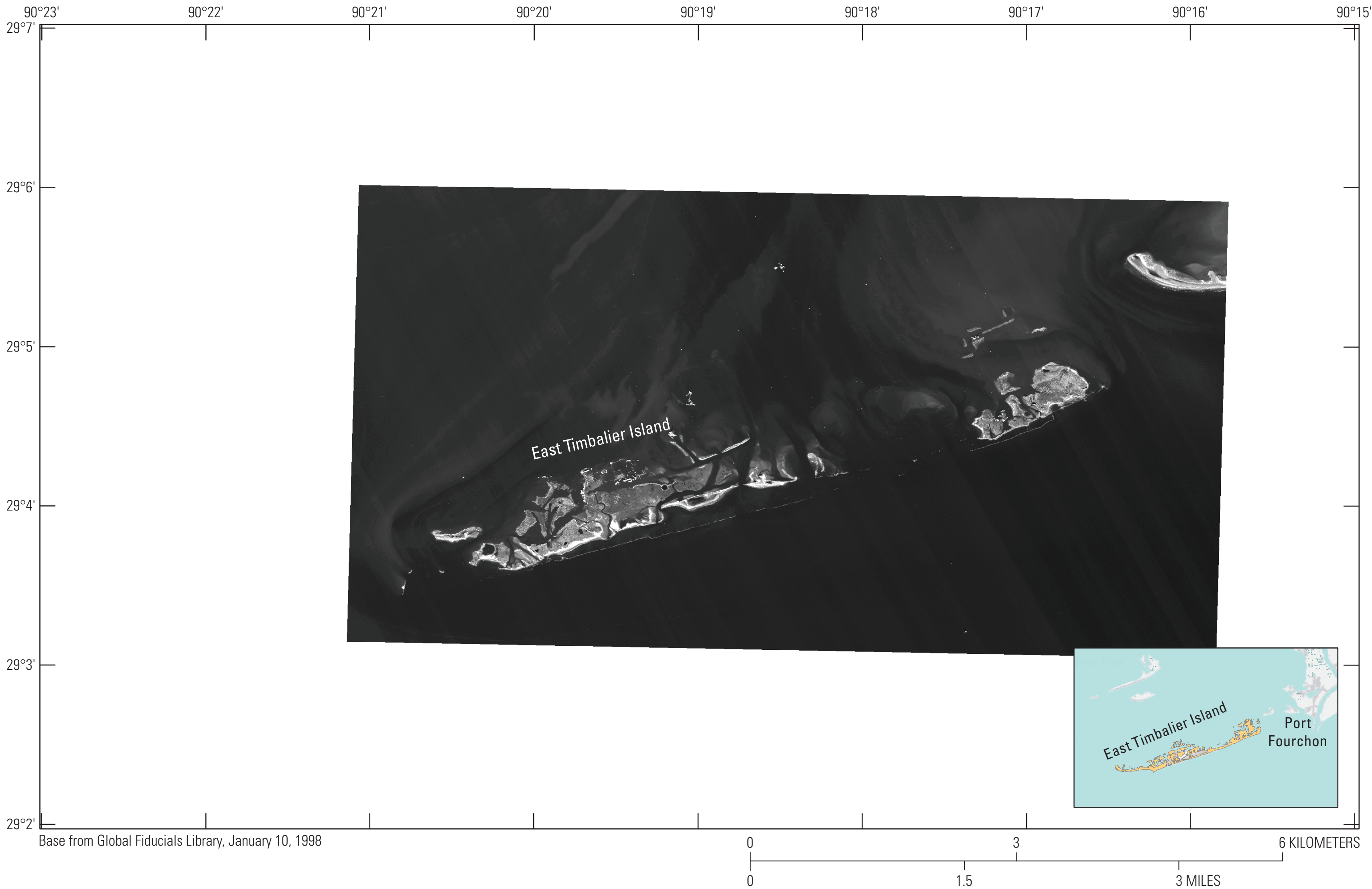

Figure 1.11. Global Fiducials Library image of East Timbalier Island, Louisiana, January 10, 1998.

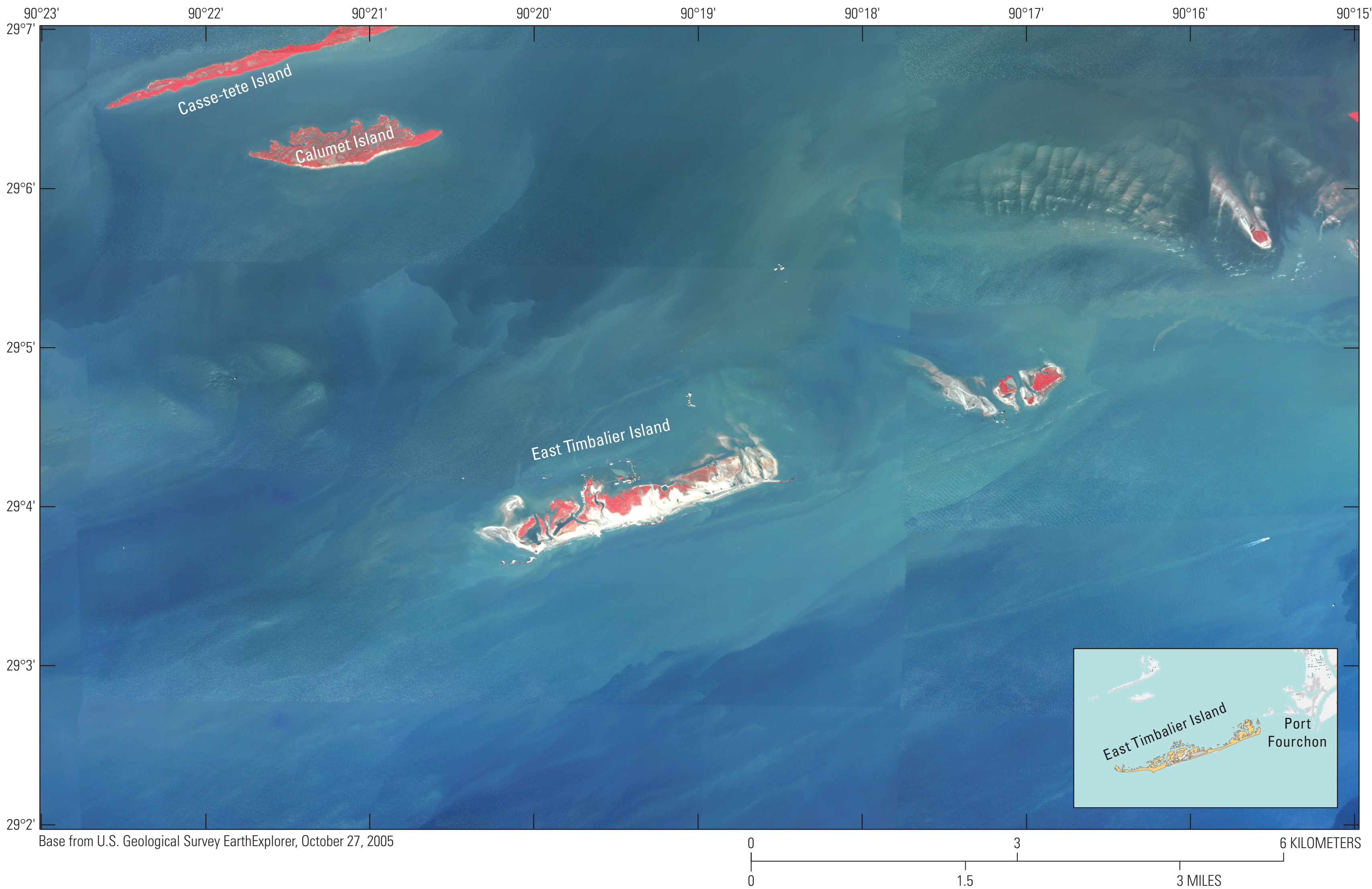

Figure 1.12. U.S. Army Corps of Engineers aerial photograph of East Timbalier Island, Louisiana, October 27, 2005.

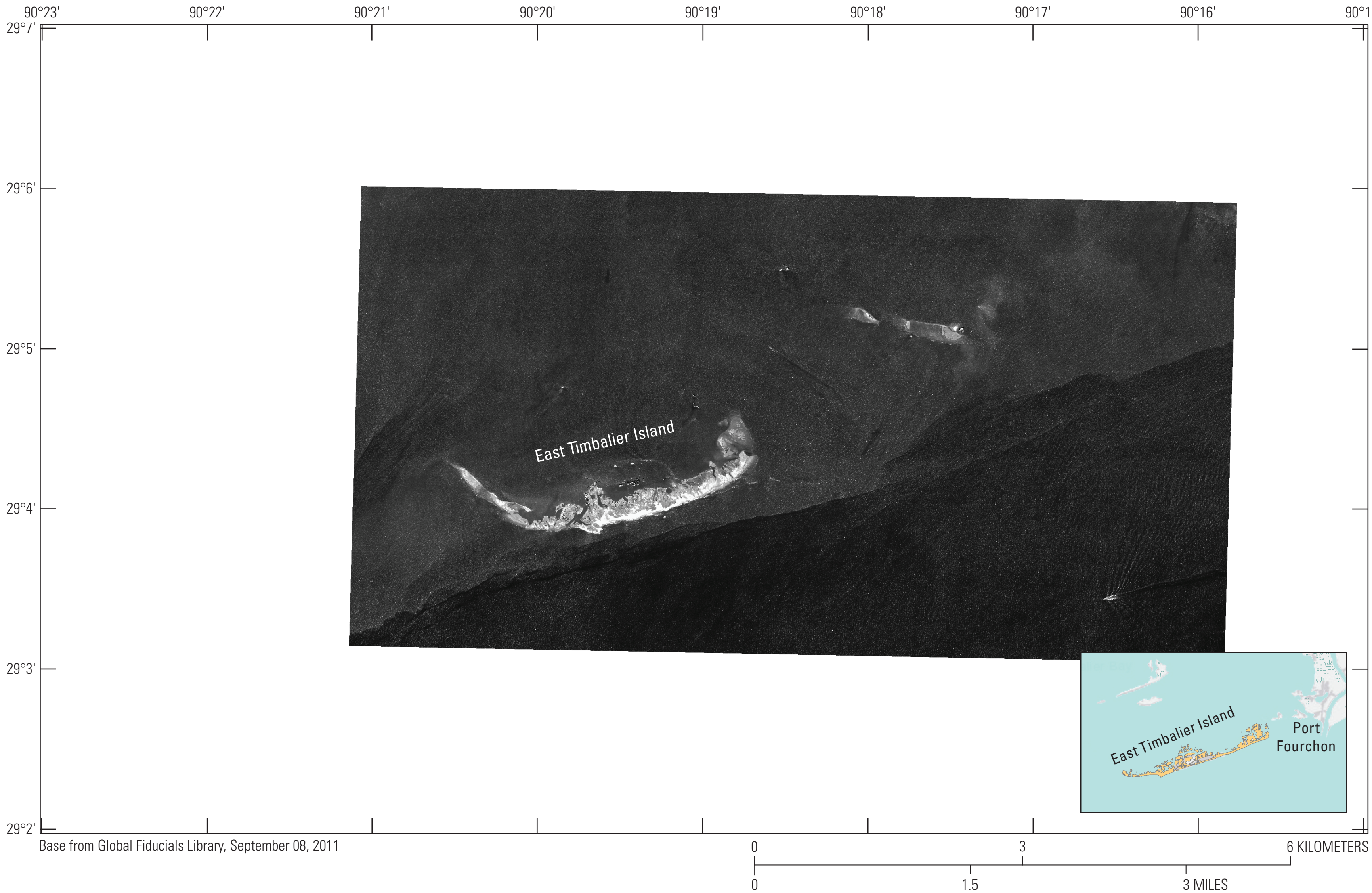

Figure 1.13. Global Fiducials Library image of East Timbalier Island, Louisiana, September 8, 2011.

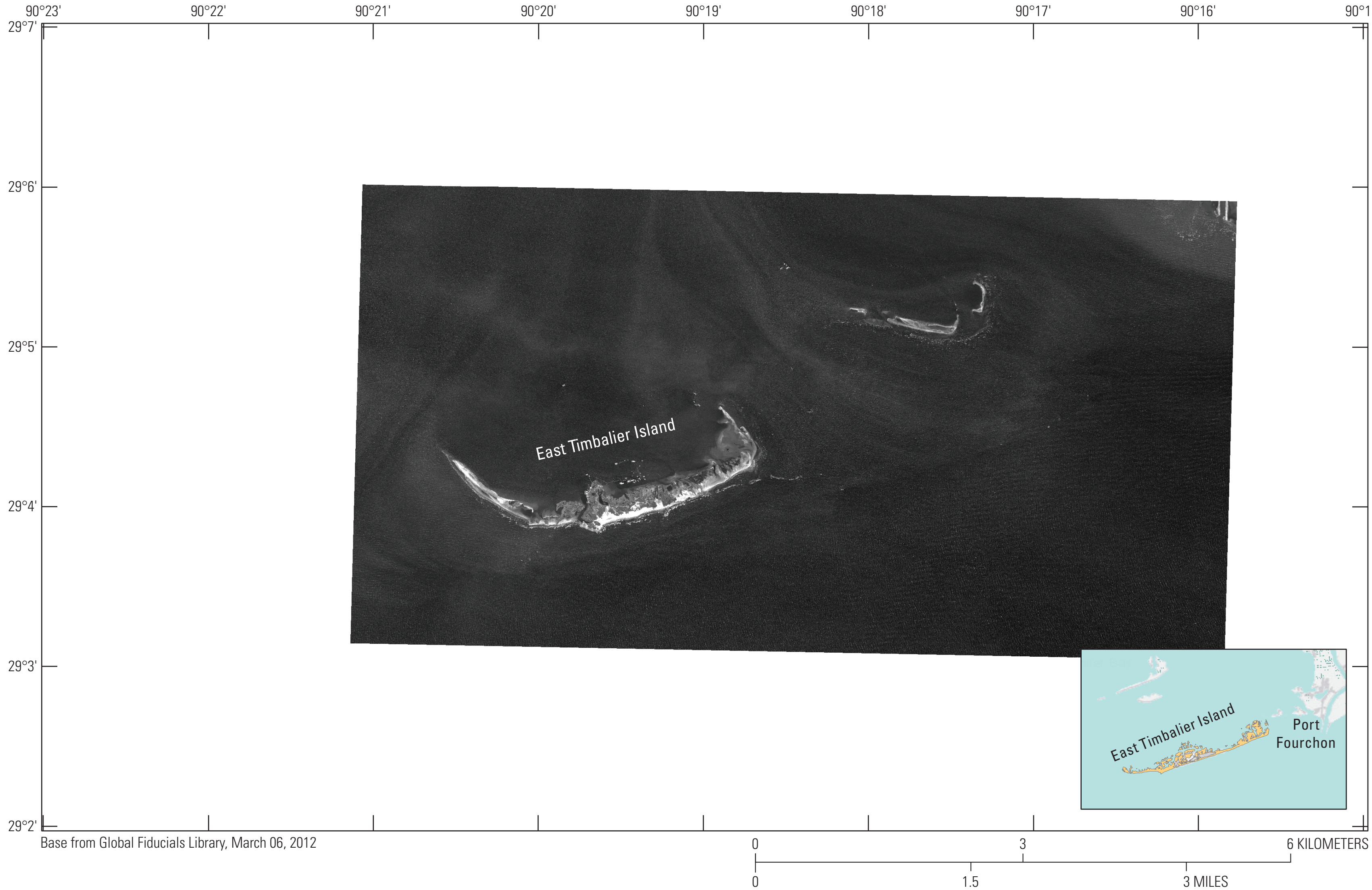

Figure 1.14. Global Fiducials Library image of East Timbalier Island, Louisiana, March 6, 2012.

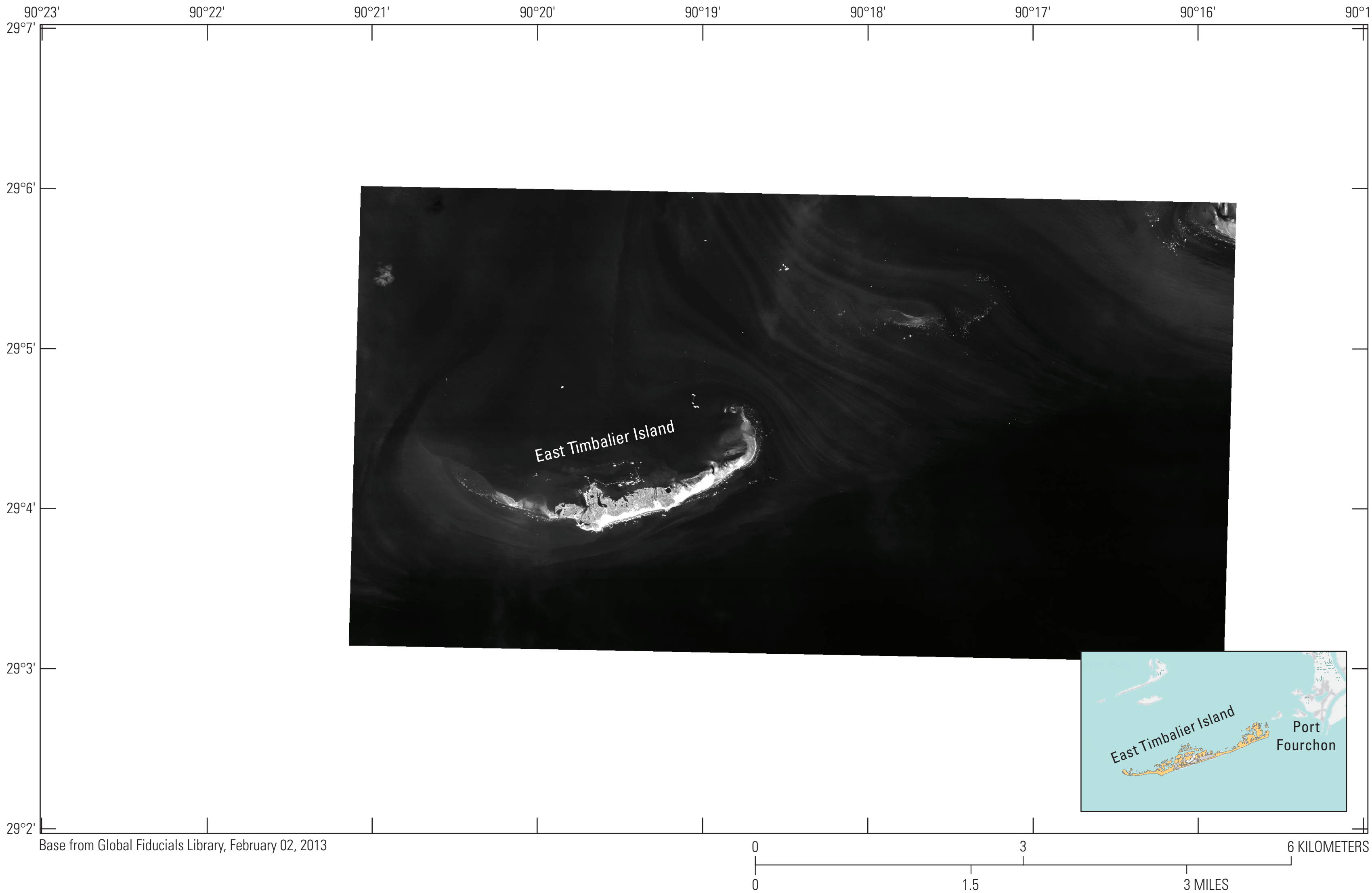

Figure 1.15. Global Fiducials Library image of East Timbalier Island, Louisiana, February 2, 2013.

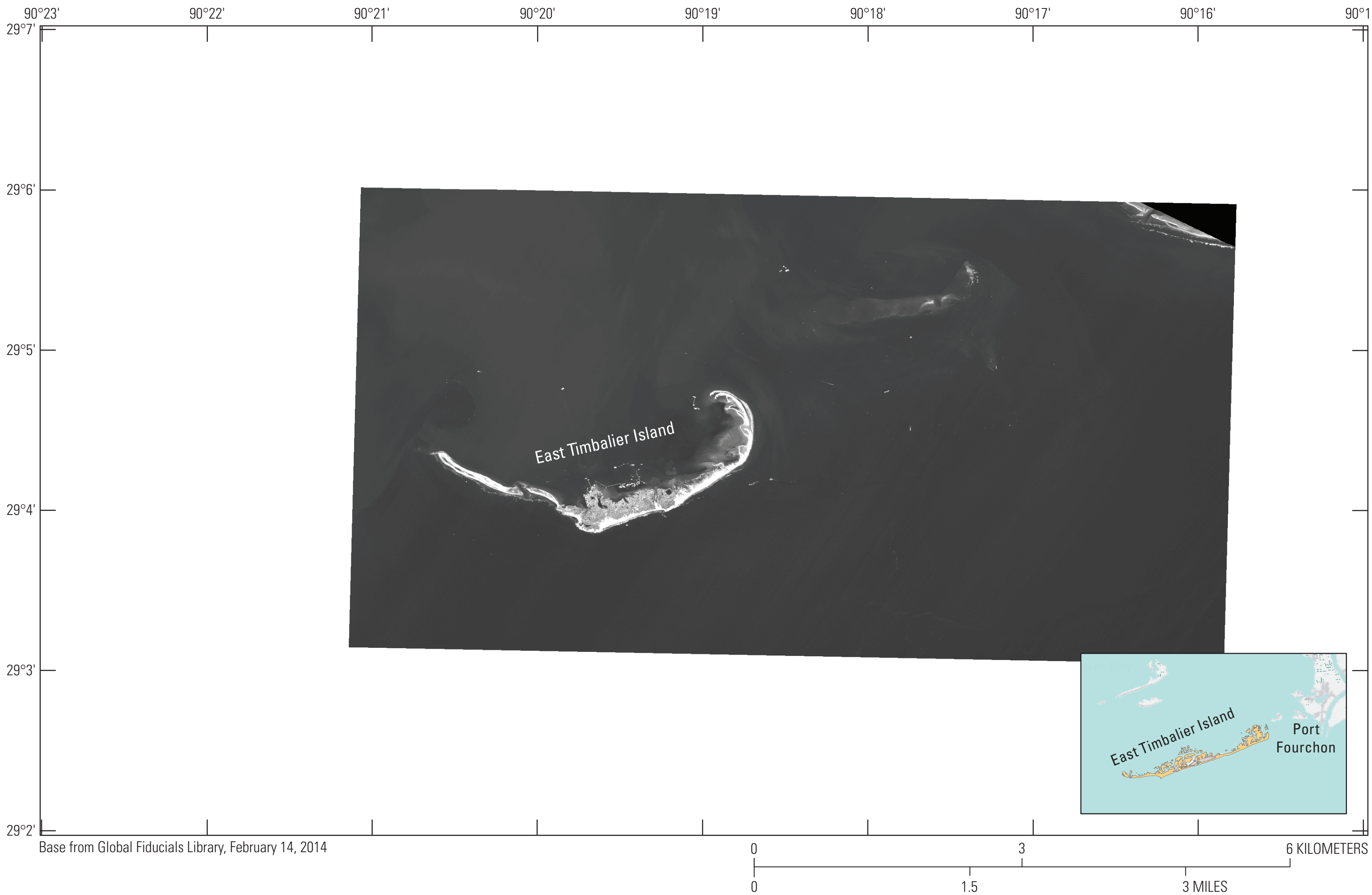

Figure 1.16. Global Fiducials Library image of East Timbalier Island, Louisiana, February 14, 2014.

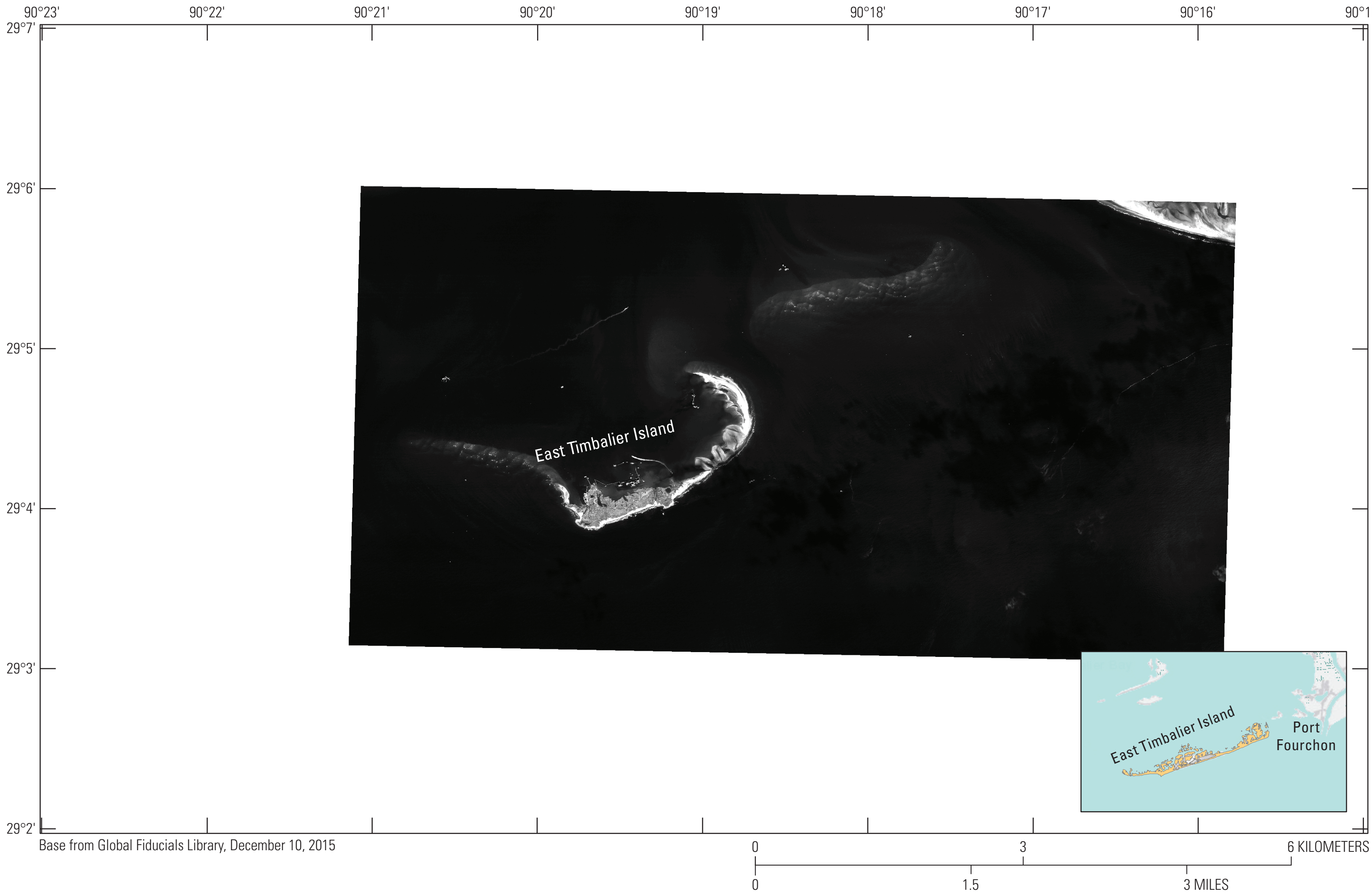

Figure 1.17. Global Fiducials Library image of East Timbalier Island, Louisiana, December 10, 2015.

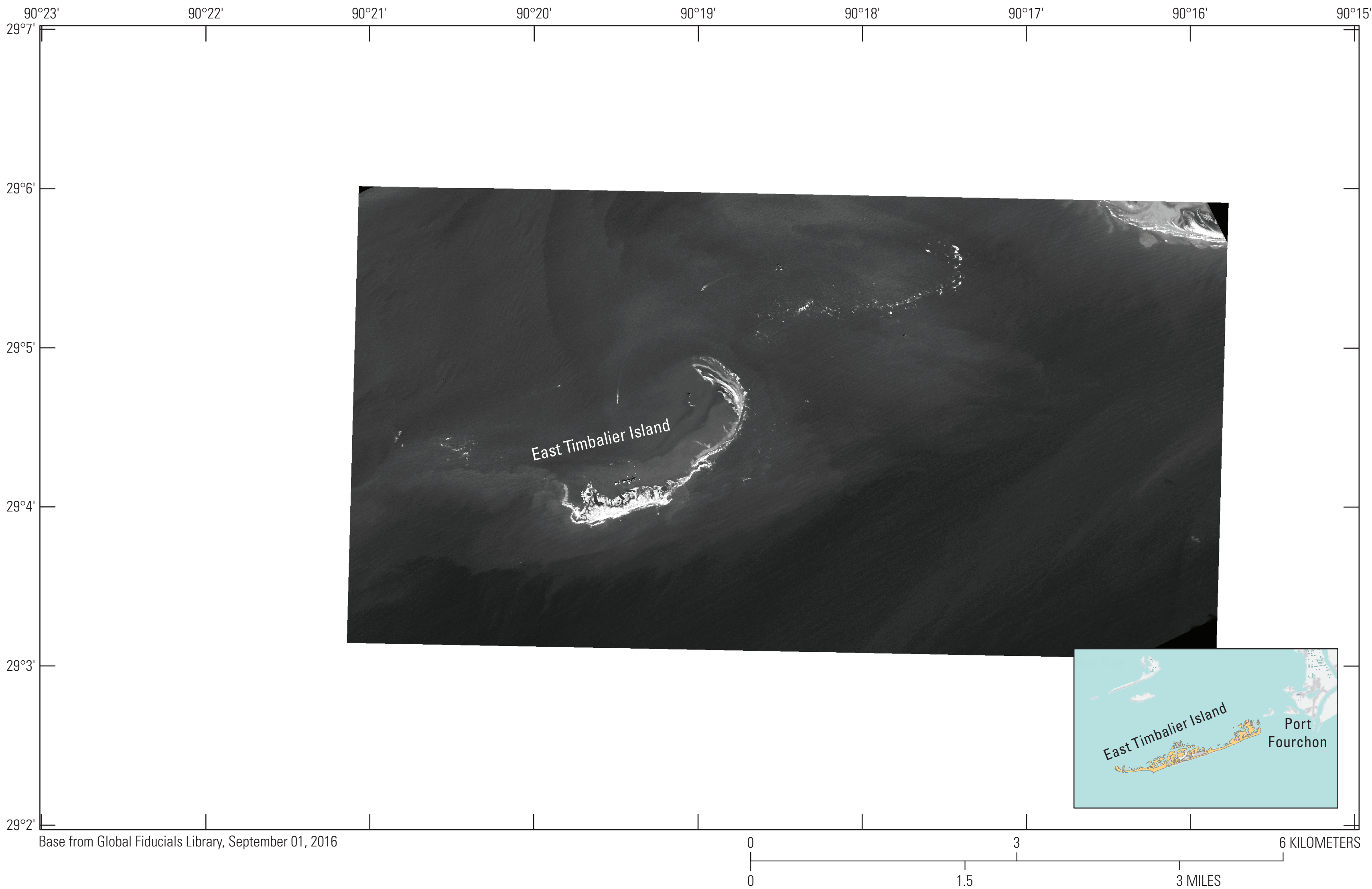

Figure 1.18. Global Fiducials Library image of East Timbalier Island, Louisiana, September 1, 2016.

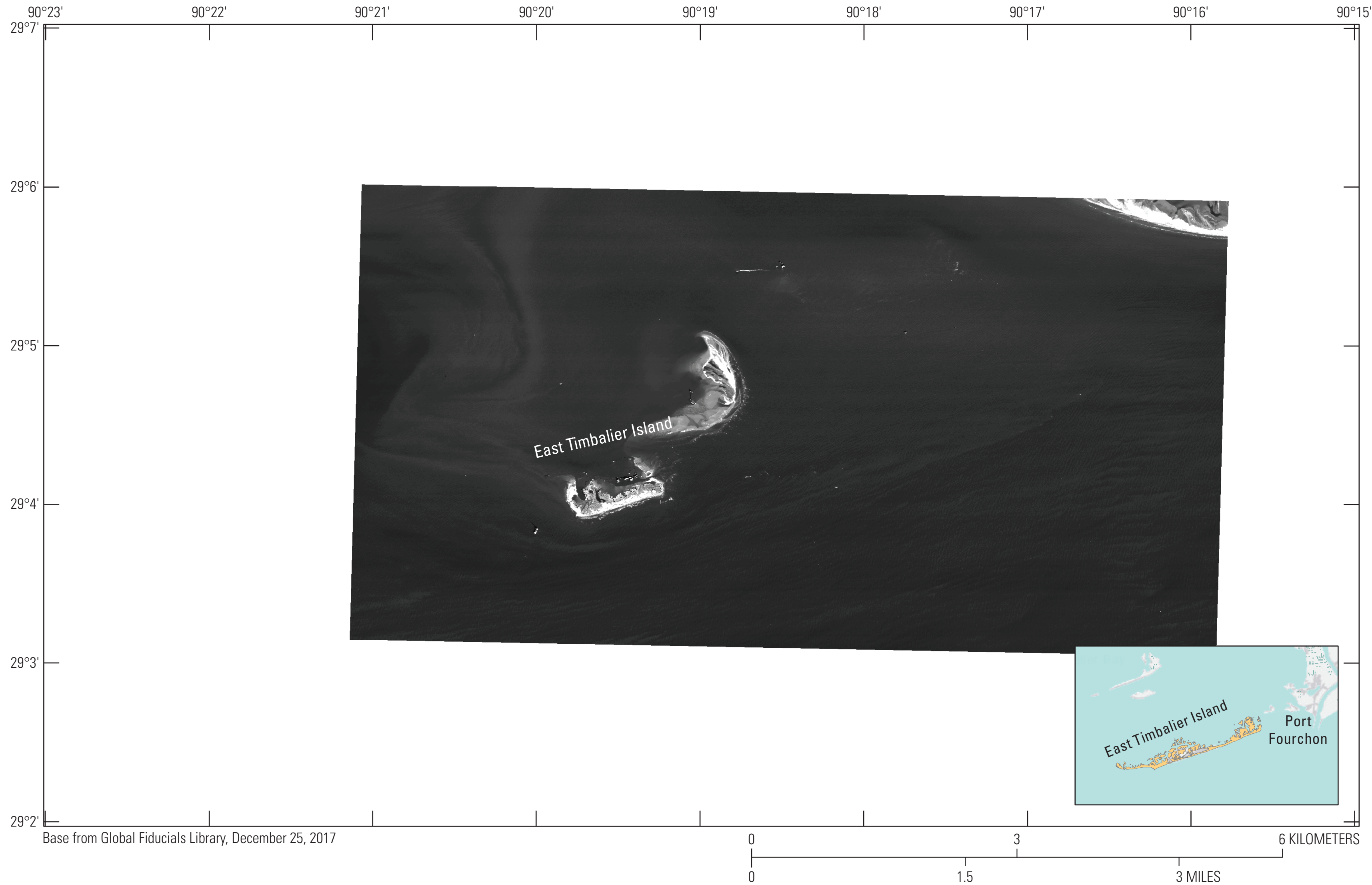

Figure 1.19. Global Fiducials Library image of East Timbalier Island, Louisiana, December 25, 2017.

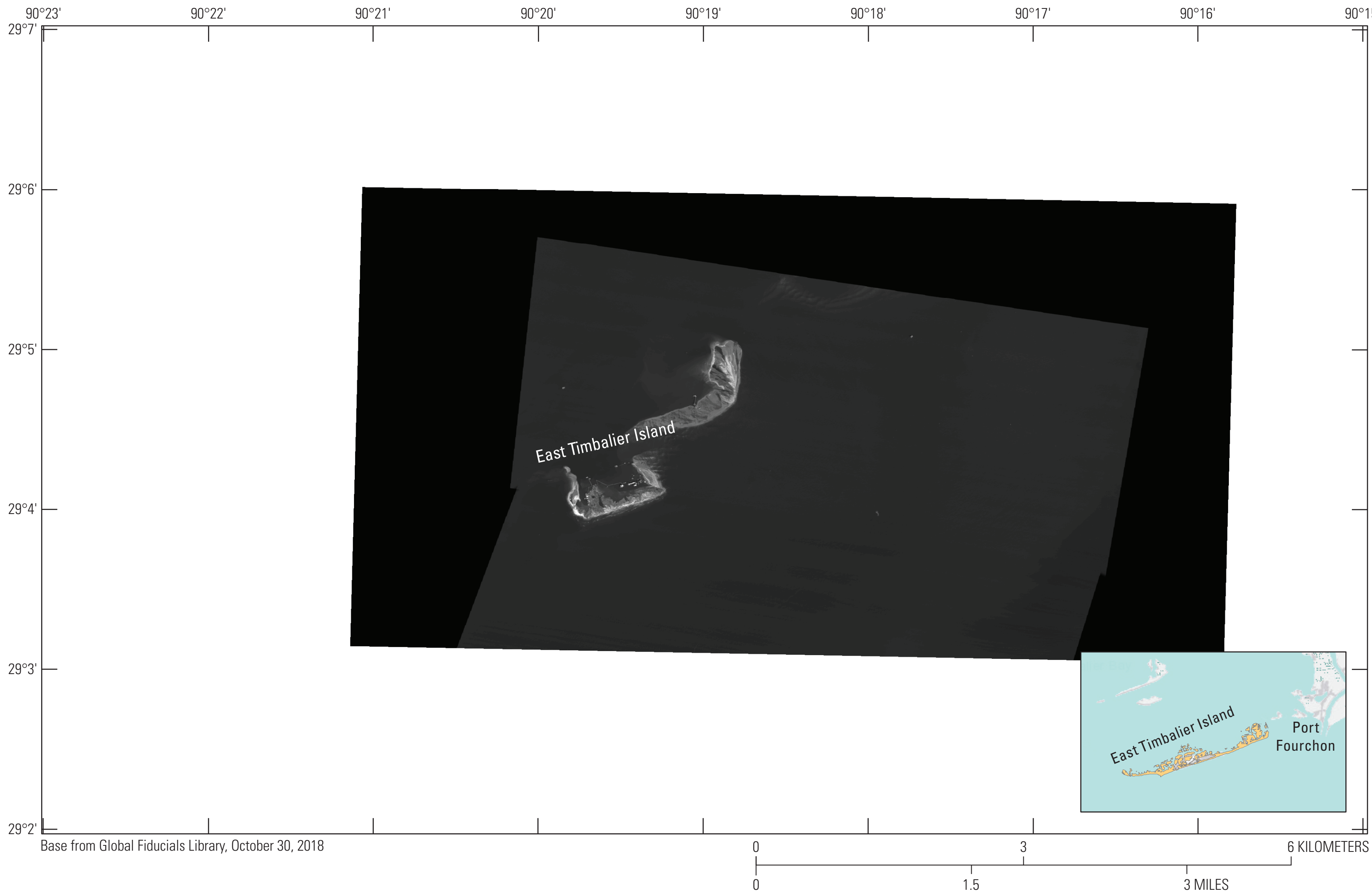

Figure 1.20. Global Fiducials Library image of East Timbalier Island, Louisiana, October 30, 2018.

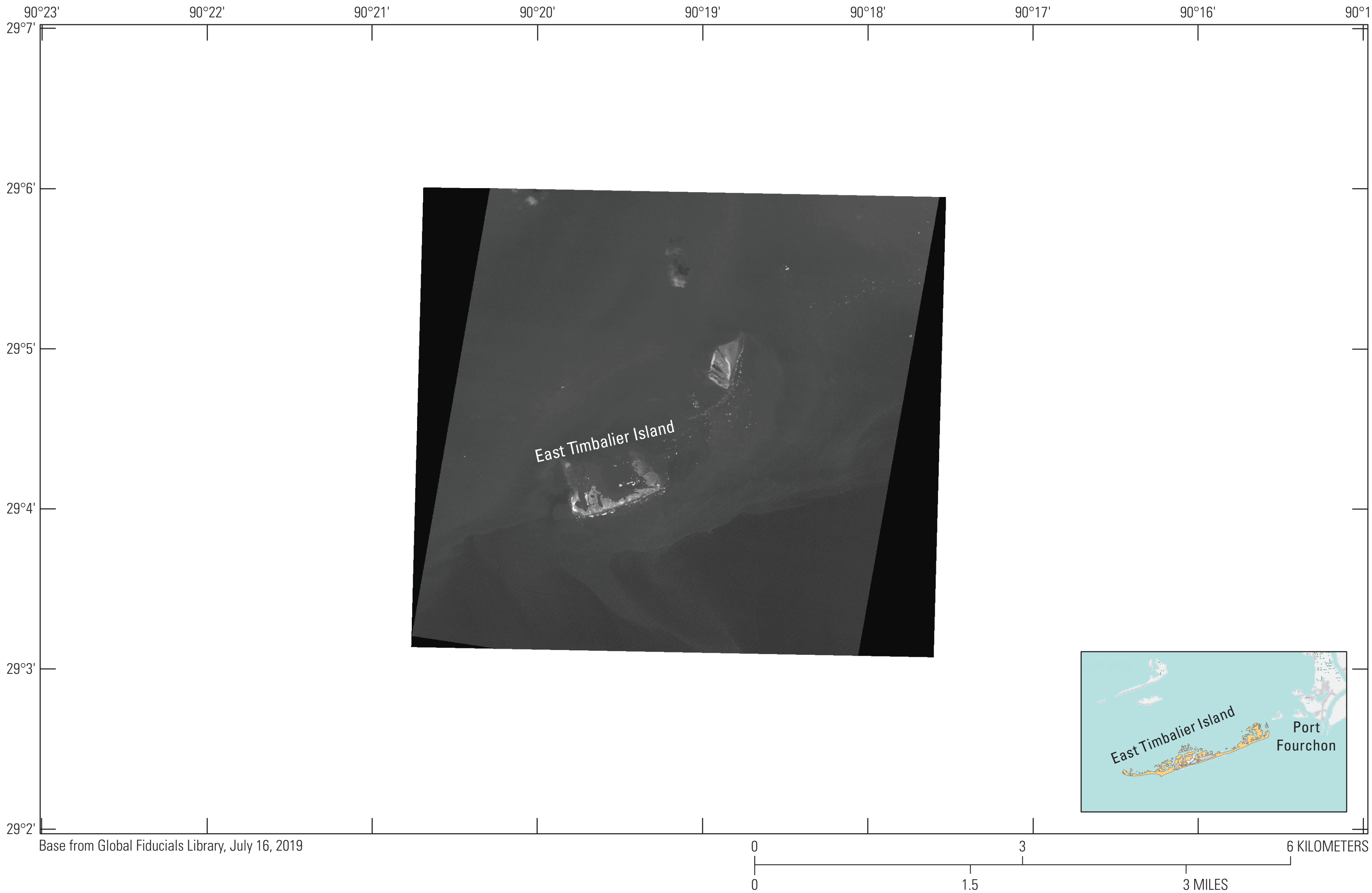

Figure 1.21. Global Fiducials Library image of East Timbalier Island, Louisiana, July 16, 2019.

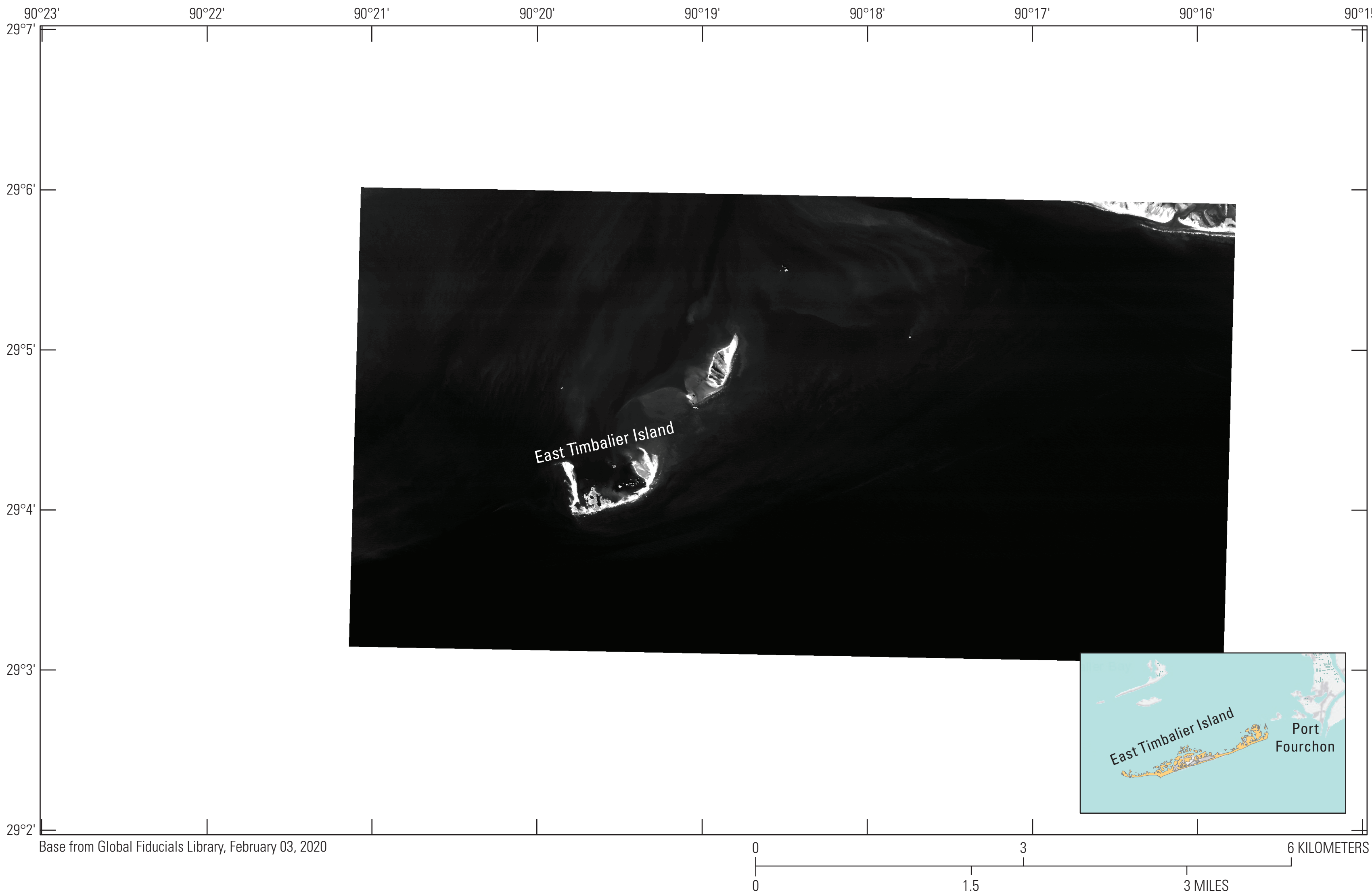

Figure 1.22. Global Fiducials Library image of East Timbalier Island, Louisiana, February 3, 2020.

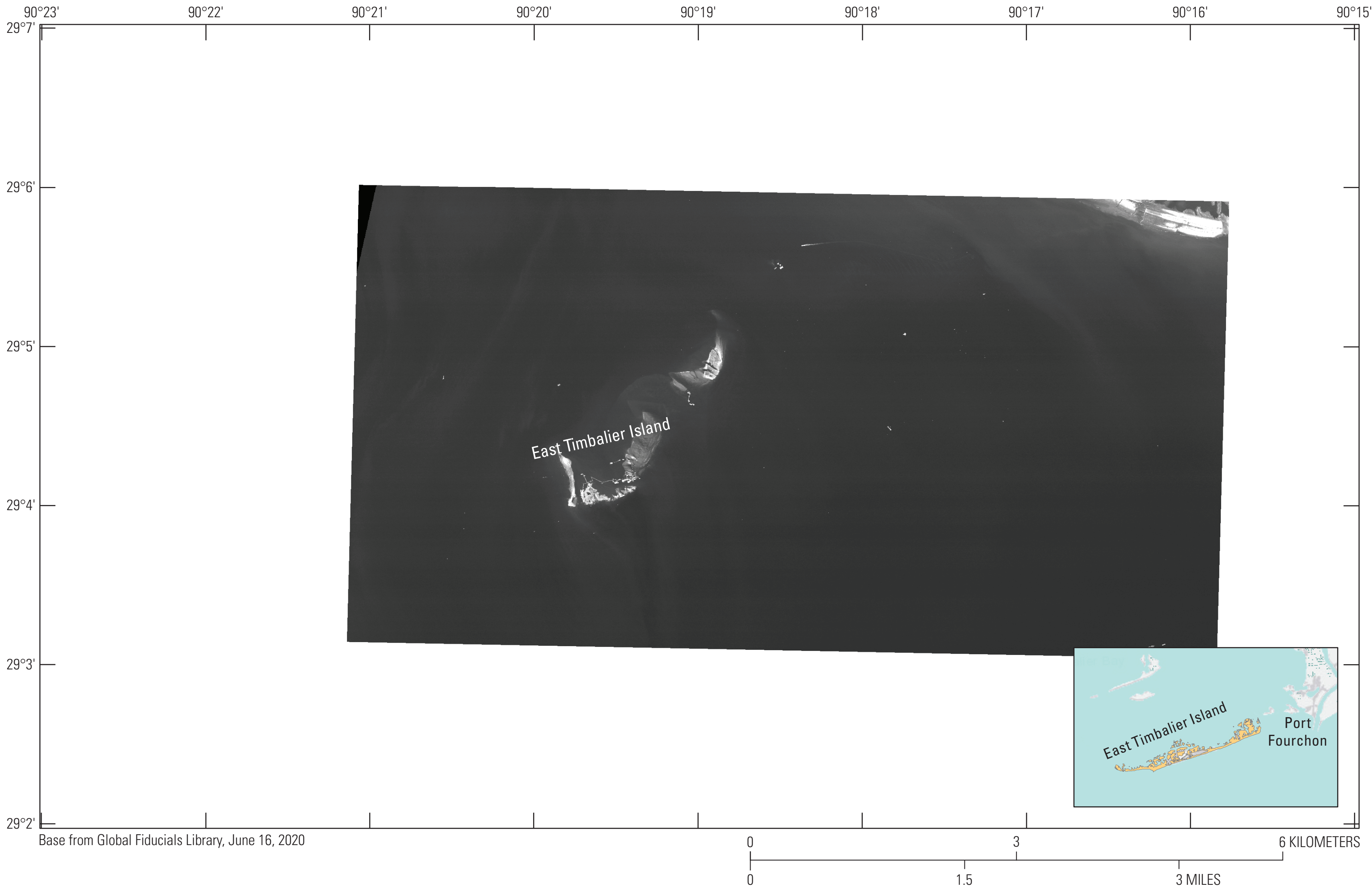

Figure 1.23. Global Fiducials Library image of East Timbalier Island, Louisiana, June 16, 2020.

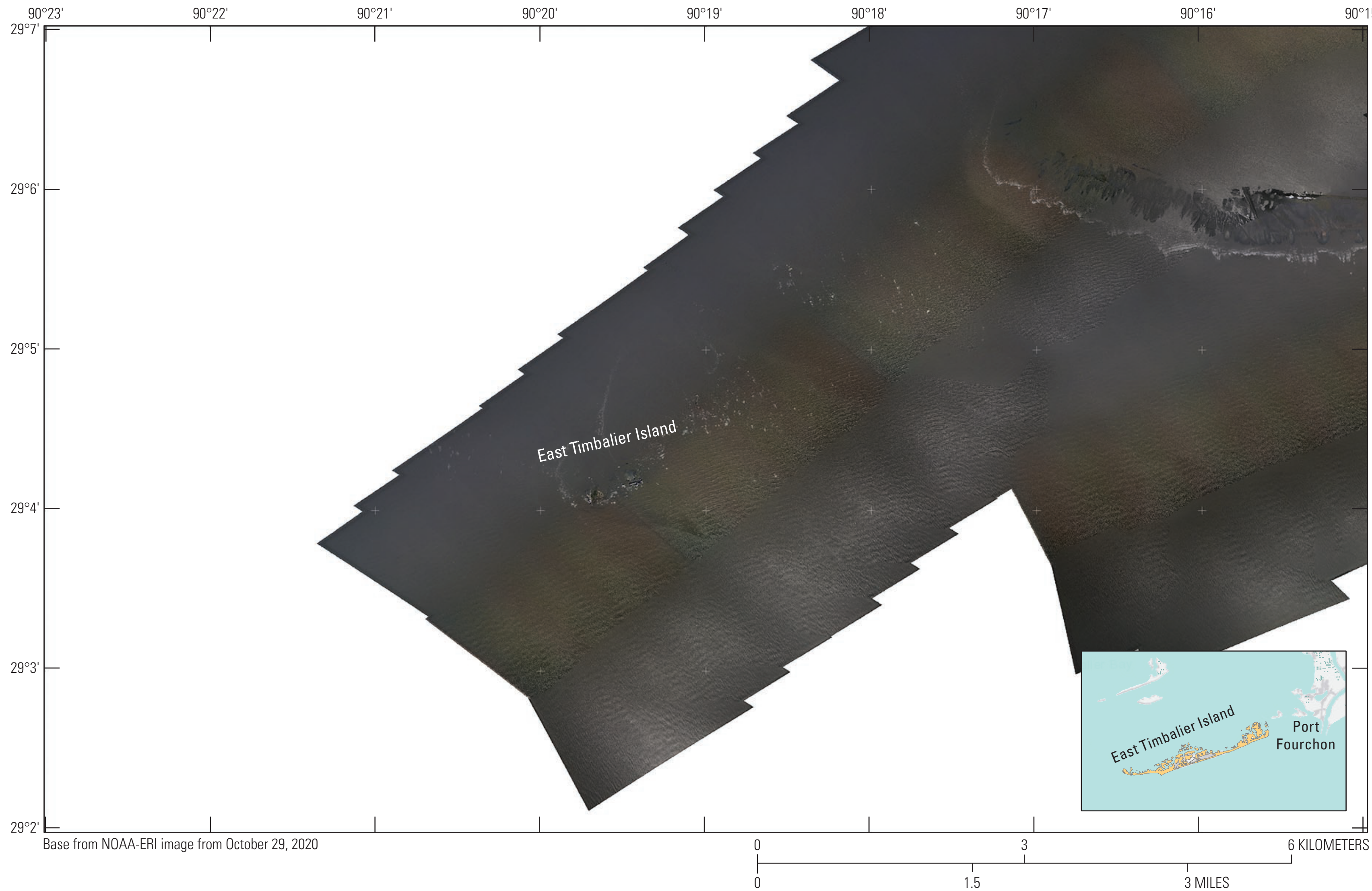

Figure 1.24. National Oceanic and Atmospheric Administration Emergency Response Imagery (NOAA–ERI) for Hurricane Zeta at East Timbalier Island, Louisiana, October 29, 2020.

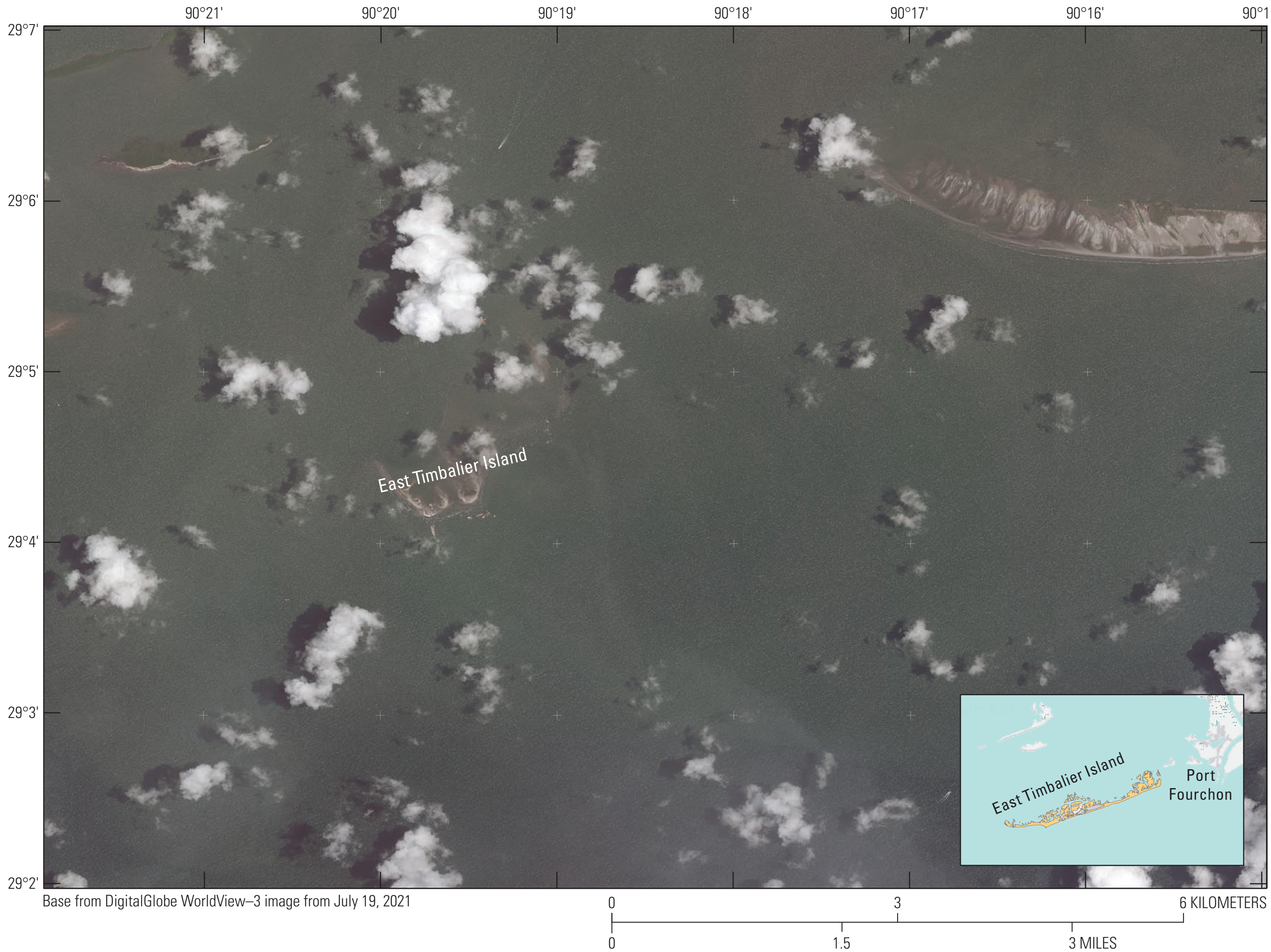

Figure 1.25. DigitalGlobe WorldView–3 image of the site of East Timbalier Island, Louisiana, July 19, 2021.

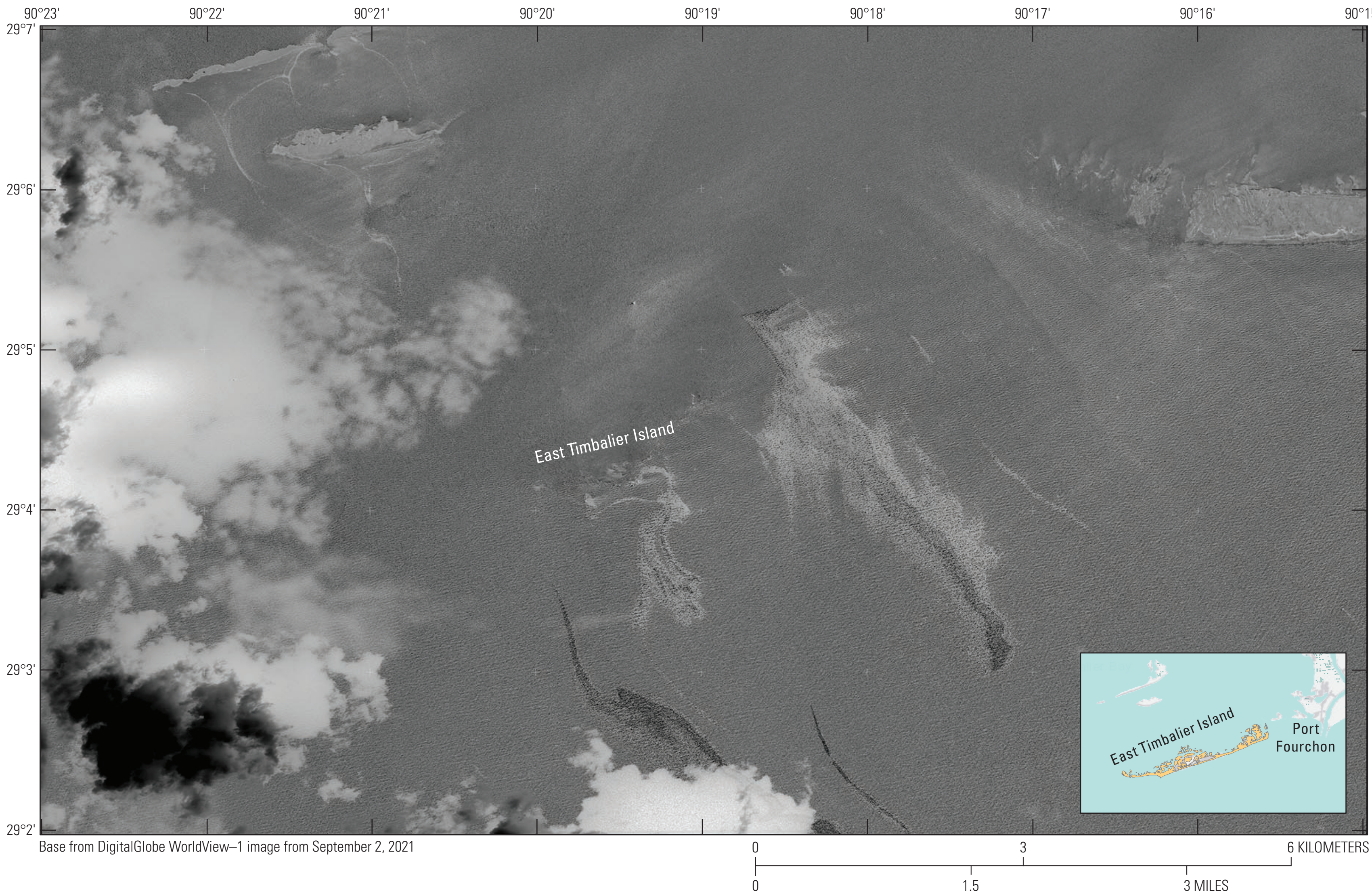

Figure 1.26. DigitalGlobe WorldView–1 image of the site of East Timbalier Island, Louisiana, September 2, 2021.

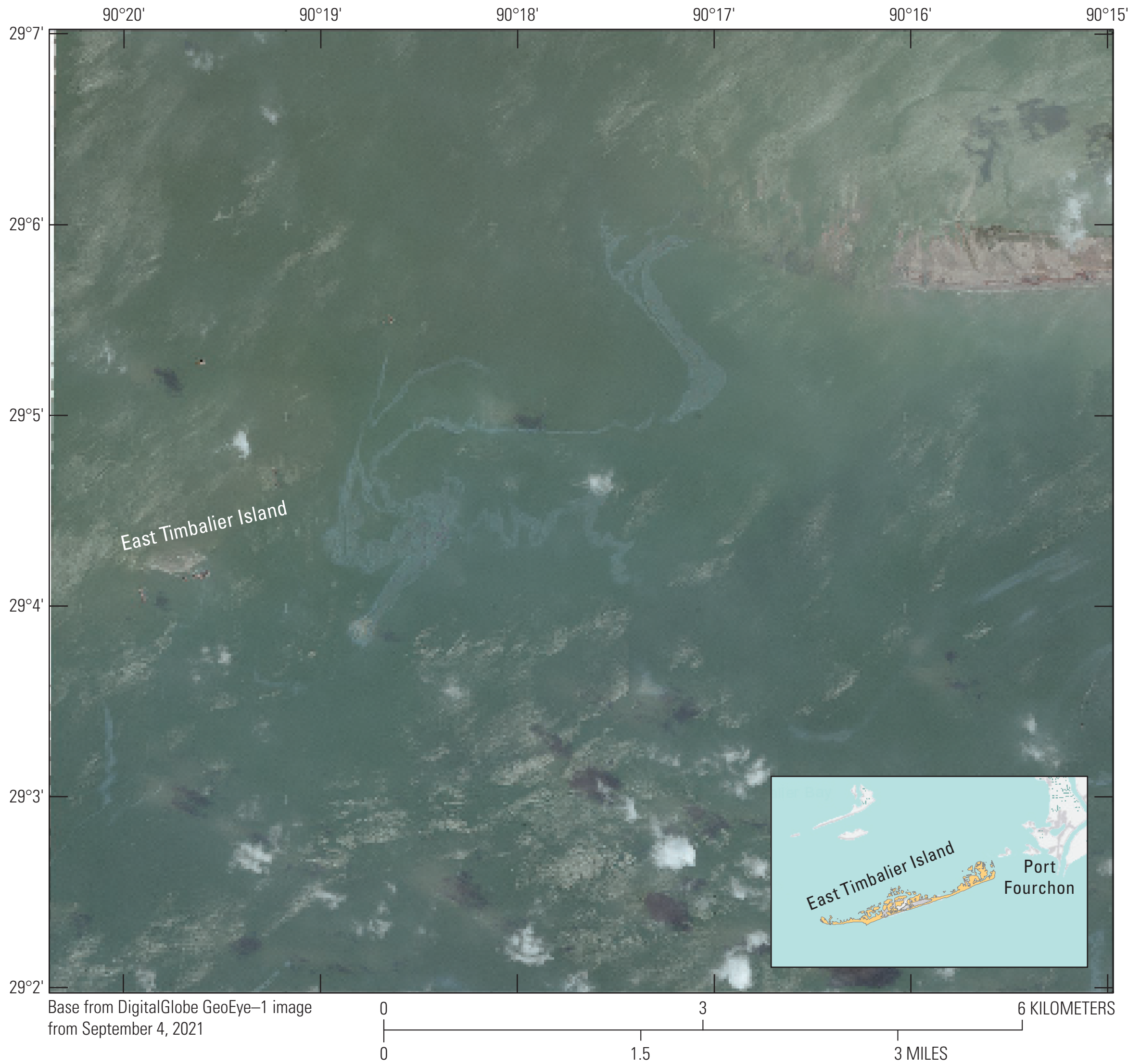

Figure 1.27. DigitalGlobe GeoEye–1 image of the site of East Timbalier Island, Louisiana, September 4, 2021.

Appendix 2. Historical Imagery Data

Appendix 2 contains a list of historical imagery that covers the area around East Timbalier Island from 1953 through 2012 and 2020. Table 2.1 provides a comprehensive list of historical imagery available for the area of study.

Table 2.1. Data on historical imagery of East Timbalier Island, Louisiana, used in this report.

[B/W, black and white panchromatic imagery; CIR, color infrared image; CRMS, Coastwide Reference Monitoring System; DOQ, digital orthophoto quadrangle; GOHSEP, Louisiana-Governor's Office of Homeland Security and Emergency Preparedness; NAPP, National Aerial Photography Program; NARA, National Archives and Records Administration; NASA–JSC, National Aeronautics and Space Administration, Johnson Space Center; NHAP, National High Altitude Photography program; NOAA–ERI, National Oceanic and Atmospheric Administration, Emergency Response Imagery; USACE, U.S. Army Corps of Engineers; USGS–EE, U.S. Geological Survey EarthExplorer. CORONA is the shortened name for the U.S. CORONA satellite program. HEXAGON is a shortened name for the U.S. KH–9 HEXAGON satellite system]

Date	Image source	Image-type descriptors	Original scale
March 26, 1953	NARA	B/W, single frame aerial	Variable
January 07, 1954	NARA	B/W, single frame aerial	Variable
[1]1958	Tobin Aerial Surveys	B/W	1:12,000
May 16, 1962	CORONA (declassified)	B/W	Variable
[1]1965	Tobin Aerial Surveys	B/W	1:24,000
February 13, 1971	NASA–JSC	B/W	1:119,190
May 05, 1972	NASA–JSC	CIR	1:34,722
August 20, 1972	HEXAGON (declassified)	B/W	Variable
December 01, 1972	HEXAGON (declassified)	B/W	Variable
October 02, 1974	NASA–JSC	CIR	1:40,000
October 21, 1975	NASA–JSC	CIR	1:41,000
December 09, 1975	HEXAGON (declassified)	B/W	Variable
April 01, 1978	NAPP	B/W	1:44,000
April 27, 1982	USGS	CIR, [2]LN140	1:12,161
November 13, 1982	NHAP	B/W, CIR	1:80,000
April 18, 1983	USGS–EE	CIR, [3]LN253	1:12,000
October 27, 1983	NHAP	B/W, CIR	1:80,000
November 16, 1983	NHAP	B/W, CIR	1:80,000
November 03, 1989	NAPP	CIR	1:40,000
November 09, 1989	NAPP	B/W	1:40,000
January 27, 1993	NAPP	CIR	1:24,000
January 21, 1994	NAPP	B/W	1:40,000
February 04, 1998	NAPP	CIR	Variable
January 22, 2004	NAPP	CIR	1:40,000
[4]September 2005	USACE	Natural color	Variable
October 27, 2005	USGS–EE	CIR, DOQ	Variable
[5]September 05, 2008	NOAA–ERI	Natural color	Variable[6]
October 01, 2008	CRMS, Atlas[7]	DOQ, natural color	Variable
[1]2010	GOHSEP	CIR, DOQ	Variable
[8]September 01, 2012	NOAA–ERI	Natural color	Variable[6]
October 20, 2012	USGS–EE	CIR, DOQ	Variable
[9]October 29, 2020	NOAA–ERI	Natural Color	Variable

[1]A precise date is unavailable for this image.

[2]LN140 is a "flight-line identifier."

[3]LN253 is a "flight-line identifier."

[4]This image was acquired during Hurricane Katrina.

[5]This image was acquired during Hurricane Gustav.

[6]This image was collected at a nominal altitude of 7,500 feet.

[7]Atlas is a data distribution system hosting a variety of publicly available geographic information system datasets for the State of Louisiana (https://atlas.ga.lsu.edu/).

[8]This image was acquired during Hurricane Isaac.

[9]This image was acquired during Hurricane Zeta.

Appendix 3. Global Fiducials Library Imagery Dates

Appendix 3 contains a list of all Global Fiducials Library (GFL) imagery that covers the area around East Timbalier Island from 1992 to 2020.

Table 3.1. Dates of Global Fiducials Library (GFL) images of East Timbalier Island, Louisiana, used in this report.

[These images are available through the Global Fiducials Library Data Access Portal (https://www.usgs.gov/global-fiducials-library-data-access-portal). All GFL images are black and white panchromatic]

Date (April 1992–August 2008)	Date (November 2008–December 2015)	Date (September 2016–June 2020)
April 26, 1992	November 04, 2008	September 01, 2016
January 10, 1998	February 04, 2009	February 01, 2017
September 22, 2001	August 28, 2009	October 24, 2017
October 15, 2002	September 30, 2009	November 24, 2017
October 05, 2003	November 03, 2009	December 25, 2017
October 13, 2004	February 02, 2010	January 30, 2018
September 09, 2005	March 19, 2010	October 30, 2018
September 30, 2005	May 12, 2010	December 03, 2018
February 15, 2006	June 16, 2010	January 21, 2019
March 14, 2006	September 08, 2011	February 07, 2019
June 19, 2006	March 06, 2012	July 16, 2019
October 03, 2006	February 02, 2013	September 04, 2019
November 17, 2006	February 14, 2014	December 31, 2019
October 28, 2007	September 29, 2015	February 03, 2020
August 23, 2008	December 10, 2015	June 16, 2020

Appendix 4. DigitalGlobe Satellite Imagery Data

Appendix 4 contains a list of high-resolution commercial satellite imagery collected over East Timbalier Island from 2004 through 2021.

Table 4.1. Dates of acquisition for satellite images of East Timbalier Island, Louisiana, and the DigitalGlobe sensor system used to acquire the images.

[Systems include GeoEye–1, QuickBird–1 and –2, and WorldView–1, –2, and –3. QB–1, QuickBird–1; QB–2, QuickBird–2]

Date	Sensor system	Date	Sensor system
September 23, 2004	QB–2	May 23, 2014	WorldView–2
November 06, 2004	QB–2	July 03, 2014	WorldView–2
November 11, 2004	QB–1	August 05, 2014	WorldView–1
January 25, 2006	QB–2	October 14, 2014	WorldView–2
October 12, 2006	QB–2	October 22, 2014	WorldView–2
November 12, 2007	QB–2	October 25, 2014	WorldView–2
September 08, 2008	WorldView–1	April 03, 2015	WorldView–2
October 30, 2009	WorldView–1	August 11, 2015	WorldView–2
January 06, 2010	WorldView–1	August 26, 2015	WorldView–3
January 10, 2010	WorldView–1	October 15, 2015	WorldView–2
May 27, 2010	WorldView–2	November 25, 2016	WorldView–2
June 10, 2010	GeoEye–1	December 16, 2016	WorldView–2
July 22, 2010	QB–2	February 21, 2017	WorldView–2
November 08, 2010	WorldView–2	June 24, 2017	WorldView–2
May 02, 2011	WorldView–1	July 10, 2017	WorldView–2
May 10, 2011	WorldView–1	July 27, 2017	WorldView–3
June 10, 2011	GeoEye–1	August 01, 2017	WorldView–1
June 18, 2011	GeoEye–1	August 08, 2017	WorldView–3
June 29, 2011	GeoEye–1	October 26, 2017	WorldView–1
September 06, 2011	WorldView–1	December 25, 2017	GeoEye–1
September 13, 2011	WorldView–2	April 24, 2018	WorldView–2
September 15, 2011	WorldView–1	May 10, 2018	WorldView–1
October 02, 2011	WorldView–1	December 03, 2018	WorldView–3
October 25, 2011	GeoEye–1	April 13, 2019	WorldView–3
January 04, 2012	WorldView–1	April 20, 2019	WorldView–2
March 13, 2012	GeoEye–1	June 23, 2019	WorldView–2
October 08, 2012	WorldView–2	August 08, 2019	WorldView–2
October 16, 2012	GeoEye–1	June 17, 2021	WorldView–1
December 18, 2012	WorldView–1	July 11, 2021	WorldView–2
February 07, 2013	WorldView–1	July 19, 2021	WorldView–3
August 30, 2013	WorldView–2	September 2, 2021	WorldView–1
September 10, 2013	WorldView–2	September 4, 2021	GeoEye–1
October 12, 2013	QB–2	September 11, 2021	WorldView–2

Appendix 5. Landsat Satellite Imagery Data

Appendix 5 contains of list of moderate-resolution satellite imagery collected from Landsat from 1972 through 2021 over East Timbalier Island. This includes data from Landsat 1, 2, 3, 4, 5, 7 and 8.

Table 5.1. Landsat satellite image data for listed acquisition dates.

[Images are available at the U.S. Geological Survey (USGS) EarthExplorer website (https://earthexplorer.usgs.gov) (USGS, 2021). For assistance using the table data to locate these images, refer to the USGS EarthExplorer Help Index (https://www.usgs.gov/centers/eros/science/earthexplorer-help-index)]

Date	Sensor system	Landsat product identifier[1]
August 07, 1972	Landsat 1	LM01_L1TP_023040_19720807_20180428_01_T2
February 03, 1973	Landsat 1	LM01_L1TP_023040_19730203_20180427_01_T2
November 13, 1974	Landsat 1	LM01_L1TP_023040_19741113_20180427_01_T2
October 03, 1975	Landsat 1	LM01_L1TP_023040_19751003_20180426_01_T2
October 21, 1975	Landsat 1	LM01_L1TP_023040_19751021_20180426_01_T2
November 17, 1975	Landsat 2	LM02_L1TP_023040_19751117_20180426_01_T2
December 23, 1975	Landsat 2	LM02_L1TP_023040_19751223_20180426_01_T2
February 24, 1976	Landsat 1	LM01_L1TP_023040_19760224_20180424_01_T2
April 09, 1976	Landsat 2	LM02_L1TP_023040_19760409_20180424_01_T2
April 18, 1976	Landsat 1	LM01_L1TP_023040_19760418_20180424_01_T2
December 17, 1976	Landsat 2	LM02_L1TP_023040_19761217_20180425_01_T2
June 03, 1977	Landsat 1	LM01_L1TP_023040_19770603_20180422_01_T2
October 19, 1977	Landsat 2	LM02_L1TP_023040_19771019_20180423_01_T2
November 06, 1977	Landsat 2	LM02_L1TP_023040_19771106_20180423_01_T2
November 12, 1977	Landsat 1	LM01_L1TP_023040_19771112_20180423_01_T2
May 05, 1978	Landsat 2	LM02_L1TP_023040_19780505_20180420_01_T2
May 14, 1978	Landsat 3	LM03_L1TP_023040_19780514_20180420_01_T2
December 16, 1978	Landsat 3	LM03_L1TP_023040_19781216_20180421_01_T2
March 07, 1979	Landsat 2	LM02_L1TP_023040_19790307_20180418_01_T2
May 18, 1979	Landsat 2	LM02_L1TP_023040_19790518_20180419_01_T2
October 27, 1979	Landsat 2	LM02_L1TP_023040_19791027_20180420_01_T2
September 15, 1980	Landsat 2	LM02_L1TP_023040_19800915_20180417_01_T2
November 08, 1980	Landsat 2	LM02_L1TP_023040_19801108_20180418_01_T2
December 14, 1980	Landsat 2	LM02_L1TP_023040_19801214_20180418_01_T2
February 24, 1981	Landsat 2	LM02_L1TP_023040_19810224_20180414_01_T2
October 16, 1981	Landsat 2	LM02_L1TP_023040_19811016_20180415_01_T2
November 21, 1981	Landsat 2	LM02_L1TP_023040_19811121_20180415_01_T2
December 09, 1981	Landsat 2	LM02_L1TP_023040_19811209_20180415_01_T2
October 18, 1982	Landsat 4	LM04_L1TP_022040_19821018_20180414_01_T2
April 12, 1983	Landsat 4	LM04_L1TP_022040_19830412_20180412_01_T2
December 08, 1983	Landsat 4	LM04_L1TP_022040_19831208_20180413_01_T2
February 10, 1984	Landsat 4	LM04_L1TP_022040_19840210_20180408_01_T2
May 24, 1984	Landsat 5	LM05_L1TP_022040_19840524_20180409_01_T2
December 02, 1984	Landsat 5	LM05_L1TP_022040_19841202_20180411_01_T2
December 18, 1984	Landsat 5	LM05_L1TP_022040_19841218_20180411_01_T2
March 24, 1985	Landsat 5	LM05_L1TP_022040_19850324_20180406_01_T2
August 31, 1985	Landsat 5	LM05_L1TP_022040_19850831_20180407_01_T2

Table 5.1. Landsat satellite image data for listed acquisition dates.—Continued

[Images are available at the U.S. Geological Survey (USGS) EarthExplorer website (https://earthexplorer.usgs.gov) (USGS, 2021). For assistance using the table data to locate these images, refer to the USGS EarthExplorer Help Index (https://www.usgs.gov/centers/eros/science/earthexplorer-help-index)]

Date	Sensor system	Landsat product identifier[1]
November 19, 1985	Landsat 4	LM04_L1TP_022040_19851111_20180407_01_T2
March 27, 1986	Landsat 5	LM05_L1TP_022040_19860327_20180331_01_T2
August 02, 1986	Landsat 5	LM05_L1TP_022040_19860802_20180401_01_T2
February 10, 1987	Landsat 5	LM05_L1TP_022040_19870210_20180328_01_T2
October 08, 1987	Landsat 5	LM05_L1TP_022040_19871008_20180330_01_T2
February 13, 1988	Landsat 5	LM05_L1TP_022040_19880213_20180326_01_T2
October 26, 1988	Landsat 5	LM05_L1TP_022040_19881026_20180327_01_T2
April 04, 1989	Landsat 5	LM05_L1TP_022040_19890404_20180324_01_T2
November 01, 1990	Landsat 5	LM05_L1TP_022040_19901101_20180324_01_T2
July 31, 1991	Landsat 5	LM05_L1TP_022040_19910731_20180322_01_T2
February 08, 1992	Landsat 5	LM05_L1TP_022040_19920208_20180318_01_T2
June 15, 1992	Landsat 5	LT05_L1TP_022040_19920615_20160929_01_T1
September 19, 1992	Landsat 5	LM05_L1TP_022040_19920919_20180319_01_T2
October 05, 1992	Landsat 5	LM05_L1TP_022040_19921005_20180319_01_T2
October 21, 1992	Landsat 5	LT05_L1TP_022040_19921021_20160928_01_T1
November 06, 1992	Landsat 5	LT05_L1TP_022040_19921106_20160929_01_T1
March 14, 1993	Landsat 5	LT05_L1TP_022040_19930314_20160928_01_T1
December 11, 1993	Landsat 5	LT05_L1TP_022040_19931211_20160927_01_T1
March 17, 1994	Landsat 5	LT05_L1TP_022040_19940317_20160928_01_T1
April 02, 1994	Landsat 5	LT05_L1TP_022040_19940402_20160927_01_T1
December 14, 1994	Landsat 5	LT05_L1TP_022040_19941214_20160926_01_T1
March 20, 1995	Landsat 5	LT05_L1TP_022040_19950320_20160926_01_T1
May 23, 1995	Landsat 5	LT05_L1TP_022040_19950523_20160927_01_T1
November 15, 1995	Landsat 5	LT05_L1TP_022040_19951115_20160926_01_T1
December 01, 1995	Landsat 5	LT05_L1TP_022040_19951201_20160925_01_T1
December 19, 1996	Landsat 5	LT05_L1TP_022040_19961219_20160924_01_T1
January 20, 1997	Landsat 5	LT05_L1TP_022040_19970120_20160924_01_T1
October 03, 1997	Landsat 5	LT05_L1TP_022040_19971003_20160924_01_T1
November 04, 1997	Landsat 5	LT05_L1TP_022040_19971104_20160924_01_T1
December 06, 1997	Landsat 5	LT05_L1TP_022040_19971206_20160923_01_T1
February 24, 1998	Landsat 5	LT05_L1TP_022040_19980224_20160923_01_T1
July 18, 1998	Landsat 5	LT05_L1TP_022040_19980718_20160924_01_T1
September 04, 1998	Landsat 5	LT05_L1TP_022040_19980904_20160922_01_T1
January 26, 1999	Landsat 5	LT05_L1TP_022040_19990126_20160923_01_T1
September 23, 1999	Landsat 5	LT05_L1TP_022040_19990923_20160919_01_T1
November 26, 1999	Landsat 5	LT05_L1TP_022040_19991126_20160923_01_T1
December 28, 1999	Landsat 5	LT05_L1TP_022040_19991228_20160919_01_T1
April 18, 2000	Landsat 5	LT05_L1TP_022040_20000418_20160919_01_T1
July 07, 2000	Landsat 5	LT05_L1TP_022040_20000707_20160918_01_T1
October 11, 2000	Landsat 5	LT05_L1TP_022040_20001011_20160918_01_T1
May 23, 2001	Landsat 5	LT05_L1TP_022040_20010523_20160919_01_T1
September 28, 2001	Landsat 5	LT05_L1TP_022040_20010928_20160917_01_T1

Table 5.1. Landsat satellite image data for listed acquisition dates.—Continued

[Images are available at the U.S. Geological Survey (USGS) EarthExplorer website (https://earthexplorer.usgs.gov) (USGS, 2021). For assistance using the table data to locate these images, refer to the USGS EarthExplorer Help Index (https://www.usgs.gov/centers/eros/science/earthexplorer-help-index)]

Date	Sensor system	Landsat product identifier[1]
December 01, 2001	Landsat 5	LT05_L1TP_022040_20011201_20160917_01_T1
December 20, 2002	Landsat 5	LT05_L1TP_022040_20021220_20160916_01_T1
January 05, 2003	Landsat 5	LT05_L1TP_022040_20030105_20160916_01_T1
October 20, 2003	Landsat 5	LT05_L1TP_022040_20031020_20160916_01_T1
March 12, 2004	Landsat 5	LT05_L1TP_022040_20040312_20160914_01_T1
May 31, 2004	Landsat 5	LT05_L1TP_022040_20040531_20160915_01_T1
November 07, 2004	Landsat 5	LT05_L1TP_022040_20041107_20160913_01_T1
February 11, 2005	Landsat 5	LT05_L1TP_022040_20050211_20160913_01_T1
October 09, 2005	Landsat 5	LT05_L1TP_022040_20051009_20160911_01_T1
February 14, 2006	Landsat 5	LT05_L1TP_022040_20060214_20160911_01_T1
March 02, 2006	Landsat 5	LT05_L1TP_022040_20060302_20160911_01_T1
September 26, 2006	Landsat 5	LT05_L1TP_022040_20060926_20160910_01_T1
February 17, 2007	Landsat 5	LT05_L1TP_022040_20070217_20160911_01_T1
April 06, 2007	Landsat 5	LT05_L1TP_022040_20070406_20160910_01_T1
June 09, 2007	Landsat 5	LT05_L1TP_022040_20070609_20160907_01_T1
February 04, 2008	Landsat 5	LT05_L1TP_022040_20080204_20160906_01_T1
November 02, 2008	Landsat 5	LT05_L1TP_022040_20081102_20160908_01_T1
November 18, 2008	Landsat 5	LT05_L1TP_022040_20081118_20160905_01_T1
January 05, 2009	Landsat 5	LT05_L1TP_022040_20090105_20160907_01_T1
October 20, 2009	Landsat 5	LT05_L1TP_022040_20091020_20160904_01_T1
February 25, 2010	Landsat 5	LT05_L1TP_022040_20100225_20160904_01_T1
October 07, 2010	Landsat 5	LT05_L1TP_022040_20101007_20160831_01_T1
November 24, 2010	Landsat 5	LT05_L1TP_022040_20101124_20160831_01_T1
February 12, 2011	Landsat 5	LT05_L1TP_022040_20110212_20160901_01_T1
November 11, 2011	Landsat 5	LT05_L1TP_022040_20111111_20160830_01_T1
March 26, 2012	Landsat 7	LE07_L1TP_022040_20120326_20160912_01_T1
August 01, 2012	Landsat 7	LE07_L1TP_022040_20120801_20160910_01_T1
March 29, 2013	Landsat 7	LE07_L1TP_022040_20130329_20160908_01_T1
December 18, 2013	Landsat 8	LC08_L1TP_022040_20131218_20170307_01_T1
April 09, 2014	Landsat 8	LC08_L1TP_022040_20140409_20170307_01_T1
November 19, 2014	Landsat 8	LC08_L1TP_022040_20141119_20170302_01_T1
March 27, 2015	Landsat 8	LC08_L1TP_022040_20150327_20170301_01_T1
September 19, 2015	Landsat 8	LC08_L1TP_022040_20150919_20170225_01_T1
February 26, 2016	Landsat 8	LC08_L1TP_022040_20160226_20170224_01_T1
March 13, 2016	Landsat 8	LC08_L1TP_022040_20160313_20170224_01_T1
December 10, 2016	Landsat 8	LC08_L1TP_022040_20161210_20170219_01_T1
April 01, 2017	Landsat 8	LC08_L1TP_022040_20170401_20170414_01_T1
May 19, 2017	Landsat 8	LC08_L1TP_022040_20170519_20170525_01_T1
September 08, 2017	Landsat 8	LC08_L1TP_022040_20170908_20170927_01_T1
November 27, 2017	Landsat 8	LC08_L1TP_022040_20171127_20171206_01_T1
December 13, 2017	Landsat 8	LC08_L1TP_022040_20171213_20171223_01_T1
January 14, 2018	Landsat 8	LC08_L1TP_022040_20180114_20180120_01_T1

Table 5.1. Landsat satellite image data for listed acquisition dates.—Continued

[Images are available at the U.S. Geological Survey (USGS) EarthExplorer website (https://earthexplorer.usgs.gov) (USGS, 2021). For assistance using the table data to locate these images, refer to the USGS EarthExplorer Help Index (https://www.usgs.gov/centers/eros/science/earthexplorer-help-index)]

Date	Sensor system	Landsat product identifier[1]
October 13, 2018	Landsat 8	LC08_L1TP_022040_20181013_20181030_01_T1
March 06, 2019	Landsat 8	LC08_L1TP_022040_20190306_20190324_01_T1
August 29, 2019	Landsat 8	LC08_L1TP_022040_20190829_20190903_01_T1
December 03, 2019	Landsat 8	LC08_L1TP_022040_20191203_20191217_01_T1
January 20, 2020	Landsat 8	LC08_L1TP_022040_20200120_20200128_01_T1
March 24, 2020	Landsat 8	LC08_L1TP_022040_20200324_20200409_01_T1
May 11, 2020	Landsat 8	LC08_L1TP_022040_20200511_20200511_01_RT
June 12, 2020	Landsat 8	LC08_L1TP_022040_20200612_20200824_02_T1
October 18, 2020	Landsat 8	LC08_L1TP_022040_20201018_20201105_02_T1
December 21, 2020	Landsat 8	LC08_L1TP_022040_20201221_20210310_02_T1
February 23, 2021	Landsat 8	LC08_L1TP_022040_20210223_20210303_02_T1
June 15, 2021	Landsat 8	LC08_L1TP_022040_20210615_20210622_02_T1
August 18, 2021	Landsat 8	LC08_L1TP_022040_20210818_20210818_02_RT

[1]The Landsat product identifier is a character string assigned to the image that is searchable on the U.S. Geological Survey EarthExplorer website.

Appendix 6. Sentinel–2 Imagery Data

Appendix 6 contains a list of moderate-resolution satellite imagery collected from Sentinel–2 from 2015 through 2021.

Table 6.1. Sentinel–2 satellite image data for listed acquisition dates.

[Images are available at the U.S. Geological Survey (USGS) EarthExplorer website (https://earthexplorer.usgs.gov) (USGS, 2021). USGS EarthExplorer stopped distributing Sentinel–2 satellite data. Sentinal–2 data are currently available at https://sentinel.esa.int/web/sentinel/sentinel-data-access]

Date	Vendor title ID[1]
December 08, 2015	L1C_T15RYN_A002411_20151208T165345
March 08, 2016	S2A_OPER_MSI_L1C_TL_SGS_20160304T221720_A003655_T15RYN_N02.01
May 23, 2016	S2A_OPER_MSI_L1C_TL_MTI_20160523T213255_A004799_T15RYN_N02.02
September 30, 2016	S2A_OPER_MSI_L1C_TL_MTI_20160930T213516_A006658_T15RYN_N02.04
December 12, 2016	L1C_T15RYN_A007702_20161212T165438
March 09, 2017	L1C_T15RYN_A008946_20170309T163651
July 02, 2017	L1C_T15RYN_A001682_20170702T163720
September 08, 2017	L1C_T15RYN_A011563_20170908T165451
December 09, 2017	L1C_T15RYN_A003970_20171209T163647
March 04, 2018	L1C_T15RYN_A014094_20180304T164359
June 07, 2018	L1C_T15RYN_A006544_20180607T164107
September 15. 2018	L1C_T15RYN_A007974_20180915T164300
December 04, 2018	L1C_T15RYN_A009118_20181204T164131
March 19, 2019	L1C_T15RYN_A019528_20190319T163452
May 28, 2019	L1C_T15RYN_A020529_20190528T163817
September 05, 2019	L1C_T15RYN_A021959_20190905T164153
December 02, 2019	L1C_T15RYN_A014309_20191202T164908
February 15, 2020	L1C_T15RYN_A024290_20200215T165047
May 02, 2020	L1C_T15RYN_A025391_20200502T164113
October 19, 2020	L1C_T15RYN_A027822_20201019T164334
October 29, 2020	L1C_T15RYN_A027965_20201029T163843
January 15, 2021	L1C_T15RYN_A020172_20210115T165517
April 2, 2021	L1C_T15RYN_A021273_20210402T164318
May 15, 2021	L1C_T15RYN_A021888_20210515T164437
May 27, 2021	L1C_T15RYN_A030968_20210527T164027
August 10, 2021	L1C_T15RYN_A023132_20210810T164444

[1]The vendor title ID is a character string assigned to the image that is searchable on the U.S. Geological Survey EarthExplorer website.

For more information, contact

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For additional information visit https://www.usgs.gov/programs/national-land-imaging-program

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