remote sensing

MDPI

Review

Satellite Oceanography in NOAA: Research, Development, Applications, and Services Enabling Societal Benefits from Operational and Experimental Missions

Eric Bayler [1,*], Paul S. Chang [1], Jacqueline L. De La Cour [1,2], Sean R. Helfrich [1], Alexander Ignatov [1], Jeff Key [1], Veronica Lance [1], Eric W. Leuliette [1], Deirdre A. Byrne [1], Yinghui Liu [1], Xiaoming Liu [1,3], Menghua Wang [1], Jianwei Wei [1,4] and Paul M. DiGiacomo [1]

[1] National Oceanic and Atmospheric Administration (NOAA), National Environmental Satellite, Data, and Information Service (NESDIS), Center for Satellite Applications and Research (STAR), College Park, MD 20740, USA; paul.s.chang@noaa.gov (P.S.C.); jacqueline.shapo@noaa.gov (J.L.D.L.C.); sean.helfrich@noaa.gov (S.R.H.); jeff.key@noaa.gov (J.K.); veronica.lance@noaa.gov (V.L.); eric.leuliette@noaa.gov (E.W.L.); deirdre.byrne@noaa.gov (D.A.B.); yinghui.liu@noaa.gov (Y.L.); xiaoming.liu@noaa.gov (X.L.); menghua.wang@noaa.gov (M.W.); jianwei.wei@noaa.gov (J.W.); paul.digiacomo@noaa.gov (P.M.D.)
[2] Cooperative Institute for Satellite Earth System Studies, Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20740, USA
[3] Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University, Fort Collins, CO 80521, USA
[4] Global Science and Technology, Inc., Greenbelt, MD 20770, USA
* Correspondence: eric.bayler@noaa.gov; Tel.: +1-301-683-3519

check for updates

Citation: Bayler, E.; Chang, P.S.; De La Cour, J.L.; Helfrich, S.R.; Ignatov, A.; Key, J.; Lance, V.; Leuliette, E.W.; Byrne, D.A.; Liu, Y.; et al. Satellite Oceanography in NOAA: Research, Development, Applications, and Services Enabling Societal Benefits from Operational and Experimental Missions. *Remote Sens.* **2024**, *16*, 2656. https://doi.org/10.3390/rs16142656

Academic Editors: Chung-Ru Ho and Vittorio Barale

Received: 27 February 2024
Revised: 17 April 2024
Accepted: 27 June 2024
Published: 20 July 2024

Abstract: The National Oceanic and Atmospheric Administration's (NOAA) Center for Satellite Applications and Research (STAR) facilitates and enables societal benefits from satellite oceanography, supporting operational and experimental satellite missions, developing new and improved ocean observing capabilities, engaging users by developing and distributing fit-for-purpose data, applications, tools, and services, and curating, translating, and integrating diverse data products into information that supports informed decision making. STAR research, development, and application efforts span from passive visible, infrared, and microwave observations to active altimetry, scatterometry, and synthetic aperture radar (SAR) observations. These efforts directly support NOAA's operational geostationary (GEO) and low Earth orbit (LEO) missions with calibration/validation and retrieval algorithm development, implementation, maintenance, and anomaly resolution, as well as leverage the broader international constellation of environmental satellites for NOAA's benefit. STAR's satellite data products and services enable research, assessments, applications, and, ultimately, decision making for understanding, predicting, managing, and protecting ocean and coastal resources, as well as assessing impacts of change on the environment, ecosystems, and climate. STAR leads the NOAA Coral Reef Watch and CoastWatch/OceanWatch/PolarWatch Programs, helping people access and utilize global and regional satellite data for ocean, coastal, and ecosystem applications.

Keywords: satellite; oceanography; research; development; operational

1. Introduction

Satellite remote sensing observations of the ocean, including high-latitude regions and trans-boundary coastal zones, provide significant value through synoptic measurements of geophysical properties, with combined spatiotemporal resolution generally not available from in situ observations. Exploiting satellite ocean observations serves both situational awareness needs and prediction capabilities across short- and long-term time scales. Developing and providing tools and services for data science and informatics increases the utility of ocean satellite observations through enhanced discovery, access, visualization, and comprehension. User-driven ocean and coastal applications create and extract synergistic value from these satellite observations through integrated (e.g., with in situ measurements and/or modeling data) products and derived information, serving to inform decision making for society's benefit. This discussion highlights ongoing operational and experimental satellite oceanography activities within the United States (US), specifically within the US National Oceanic and Atmospheric Administration (NOAA).

The Center for Satellite Applications and Research (STAR), located within NOAA's National Environmental Satellite, Data and Information Service (NESDIS), performs extensive science-based satellite oceanography activities, spanning innovative research, algorithm developmental and sustainment efforts, calibration/validation, application development, transitions to routine and sustained use and operations, facilitating and enabling informed decision making for societal benefit. STAR engages with diverse users and stakeholders to understand and support their needs and missions, providing fit-for-purpose ocean data and derived products that are co-designed, co-developed, and co-produced. In addition to NOAA and other US domestic users, STAR actively supports the ongoing United Nations (U.N.) Decade of Ocean Science for Sustainable Development (U.N. Ocean Decade) and the broader global community of users, particularly within developing nations.

With NOAA being an operational agency, STAR's contributions encompass the user-driven value chain: supporting identification of user needs, developing new and improved observing capabilities, exploiting observations (remote and in situ), disseminating observations and derived information for societal benefit, and soliciting feedback to enhance existing and planned products and data streams. With the increasing volume and diversity of satellite data, STAR provides valuable support through curating, translating, and integrating multi-sensor, multi-platform, and multi-parameter data that enable improved societal outcomes. Increasingly, this support means coupling environmental and social science datasets across terrestrial, aquatic, atmospheric, and cryospheric domains.

Actively supporting and contributing to domestic and international missions and global fora, STAR aims to develop and provide satellite ocean observations foundational to addressing critical societal issues. These research and development (R&D) efforts support NOAA's operational satellite programs, in both geostationary (GEO) and low Earth orbit (LEO), as well as enable NOAA efforts to leverage the broader international constellation of operational and experimental satellite missions. This support includes extensive participation and engagement with the Committee on Earth Observation Satellites (CEOS), and the Coordination Group for Meteorological Satellites (CGMS), amongst other global entities and programs.

The R&D enterprise executed by STAR targets innovation, enhancement, and exploitation of satellite earth observations across the spectrum of sensing capabilities and applications, spanning radiances, imagery, and derived parameters. These efforts enhance understanding and representation of the ocean state, ocean dynamics, and surface conditions (sea surface height (SSH), sea surface salinity (SSS), sea surface temperature (SST), roughness, sea ice, ocean color, etc.), spanning near-real time to climate temporal scales. Active (scatterometry and synthetic aperture radar (SAR)) and passive technologies and techniques are used to measure and interpret ocean surface roughness, producing developmental and operational products that extract routine and extreme ocean surface vector winds (OSVWs), e.g., tropical cyclones. Additionally, SAR is exploited to provide the capability to assess inundation impact from storm surge, as well as ocean–atmosphere and ocean–atmosphere–sea ice fluxes, factors critical to improving coupled Earth system (ocean, atmosphere, cryosphere) predictions. Efforts also target satellite observations of cryospheric parameters, such as altimetric observations of sea ice thickness and SAR observations characterizing sea ice, aiming for new parameters and higher-resolution assessments to support higher-resolution modeling and prediction. Beyond physical parameters, STAR's developments in satellite ocean color radiometry (OCR) enable ocean biological and biogeochemical measurements that support ecosystem assessments and predictions. These efforts actively contribute to collaborative international scientific coordination groups, such as the Group for High-Resolution Sea Surface Temperature (GHRSST), the International Ocean Colour Coordinating Group (IOCCG), and the Ocean Surface Topography Science Team (OSTST).

Collectively, STAR science teams support user and stakeholder needs for ocean data and information across NOAA's diverse mission. Facilitating timely uptake and effective utilization of these satellite oceanography products, extensive user engagement, training, and support activities are provided by CoastWatch/OceanWatch/PolarWatch, a NOAA Program led and managed by STAR, commonly referred to collectively as "CoastWatch". CoastWatch's structural design facilitates collaboration across NOAA, with its programmatic structure including "Regional Nodes", comprising cross-NOAA teams dedicated to addressing the specific data product and information needs of a particular geographic region and/or specific thematic interests. The OceanWatch component provides global coverage and services for diverse users, leveraging the value proposition of satellite ocean data to address the common data and information needs shared by all nations and communities relative to the ocean. STAR also operates Coral Reef Watch for NOAA, which similarly bridges the gap between satellite data providers and users for these socio-economically and ecologically important ecosystems. Timely, accurate, and sustained data products and information are essential for these at-risk regions threatened by climate change and local anthropogenic impacts.

The paper's Abbreviations Section provides the definitions for the acronyms used.

2. Satellites, Sensors, and Calibration/Validation

2.1. Instruments and Sensors

Supporting satellite missions and sensors characterizes STAR's core role within NESDIS and NOAA. This role includes providing underpinning scientific R&D expertise for implementing NOAA's operational satellite missions, as well as for leveraging complementary and gap-filling partner satellite observations. Associated science efforts address the development and refinement of satellite ocean observations across the spectrum of instruments and phenomenology, aiming to exploit passive (visible, infrared, microwave) and active (altimetry, synthetic aperture radar (SAR), and scatterometry) capabilities to span physical, biological, and biogeochemical parameters for ocean-related applications, e.g., ecological forecasting.

Complementing development of satellite ocean observation retrieval algorithms, STAR performs critical developmental and operational calibration and validation support for NOAA's GEO and LEO missions. Current NOAA satellite missions with ocean-related sensors include the GOES-R series (specifically the GOES-R series Advanced Baseline Imager (ABI) [1]), the Joint Polar Satellite System (JPSS) series (Visual Infrared Imaging Radiometer Suite (VIIRS) [2], and the Jason/Sentinel-6 series altimeters [3].

Beyond NOAA's own satellite ocean observations, STAR leverages non-NOAA partner satellite observations for operational robustness, greater coverage and resolution, and for providing observations not available from NOAA's satellites. An aim is to exploit both operational and exploratory satellite missions of domestic and international partners, from LEO and GEO platforms for more intensive coverage of non-US waters. Examples include passive microwave observations from GCOM-W1 (AMSR2) [4] and SMAP [5], scatterometry from METOP (ASCAT) [6], and synthetic aperture radar (SAR) from the RADARSAT Constellation Mission [7] and the Sentinel-1 mission series [8]. Leveraged gap-filling capabilities include sea surface salinity, sea surface temperature, ocean surface vector winds, sea ice detection and characteristics through non-optical methods, oil spill detection and monitoring, and illegal, unreported, and unregulated (IUU) fishing detection and monitoring.

2.2. Technical Developments

STAR's satellite oceanography portfolio exploits passive and active capabilities across the electromagnetic spectrum. Representative examples follow, organized by the portion of the spectrum exploited and by passive/active sensing, noting that these highlights are not intended to be an exhaustive accounting of all related STAR ocean remote sensing activities, products, and services.

2.2.1. Visible Capabilities

Within the visible portion of the electromagnetic spectrum, STAR maintains a strong R&D program for retrievals and applications of ocean and freshwater parameters derived from "ocean color", which include chlorophyll-a (Chl-a) concentration, colored dissolved organic matter (CDOM), suspended particulate matter (SPM), water diffuse attenuation coefficient parameters, and various water classification products. These and other satellite ocean color data products are crucial for ocean/inland water environmental monitoring and biological, biogeochemical, and ecological research and applications (e.g., water quality and habitat assessments, aquaculture, and fishery management). With multi-sensor merged and global gap-free ocean color data, NOAA STAR continues to improve the surveillance and forecast of harmful algal blooms (HABs), coastal eutrophication, and changes in phytoplankton dynamics, food webs, and biological productivity due to climate change. This section highlights recent progress in ocean color remote sensing for generating routine global ocean color data, as well as new products for ocean, coastal, and inland water research and applications.

Global Ocean Color Product Data

Satellite ocean color products include normalized water-leaving radiance spectra ($nL_w(\lambda)$, i.e., ocean color) [9,10], Chl-a concentration [11], Chl-a anomaly products [12], water diffuse attenuation coefficient at 490 nm ($K_d(490)$) [13] and for photosynthetically available radiation (PAR) (K_d(PAR)), SPM concentration [14], and water class [15]. Satellite-derived Chl-a and consequently Chl-a anomaly (from Chl-a) data provide continuous global estimations of ocean phytoplankton concentration (biomass) and variations, which are used for monitoring HABs, ocean/water biological productivity, and other ocean/inland water environmental processes. Diffuse attenuation coefficient $K_d(490)$ data enable the monitoring of ocean water quality and the study of ocean processes, such as thermal dynamics and phytoplankton photosynthesis. SPM data contribute to quantifying water clarity across the world ocean and inland lakes, facilitating sediment transportation modeling and ocean circulation tracing, as well as land–ocean flux and global carbon cycle studies. These ocean color products are being routinely produced from VIIRS [16] onboard the Suomi National Polar-orbiting Partnership (SNPP), NOAA-20, and NOAA-21, the Ocean and Land Colour Instrument (OLCI) [17] on the Sentinel-3A (S3A) and Sentinel-3B (S3B) satellites, and the Second-Generation Global Imager (SGLI) on the Global Change Observation Mission-Climate (GCOM-C) satellite. The discussion below reviews ocean biological and biogeochemical products routinely produced in NOAA/STAR, highlighting some new ocean color products.

Chlorophyll-a Data

Satellite Chl-a data, derived using the ocean color index (OCI) method [11,18], employs satellite-derived $nL_w(\lambda)$ for the blue, green, and red bands. Satellite Chl-a accuracy over oligotrophic oceans (i.e., low Chl-a) can be significantly improved using the OCI-based approach, greatly reducing noise and bias errors [11], as STAR has shown, using in situ optics measurements from NOAA's Marine Optical Buoy (MOBY) [19]. Consequently, the OCI Chl-a algorithm has been implemented in the NOAA MSL12 enterprise ocean color data processing system to derive Chl-a data globally from all relevant satellite sensors [20,21]. Due to sensor spectral band differences from various satellite sensors, an algorithm makes appropriate adjustments for specific sensors to produce consistent Chl-a data across the different satellite sensors [22]. Consequently, Chl-a data from VIIRS, OLCI, and SGLI can be effectively merged, producing consistent multi-sensor global Chl-a data products. Additionally, global Chl-a anomaly products have been implemented in the

NOAA MSL12 ocean color data processing system and are being routinely generated [23] for various near-real-time applications, including global HAB monitoring.

Diffuse Attenuation Coefficient $K_d(490)$

The water diffuse attenuation coefficient at 490 nm, $K_d(490)$, an important water quality parameter, characterizes light penetration/dissipation with respect to depth in oceanic and aquatic systems, which significantly impacts primary productivity [24]. STAR developed satellite $K_d(490)$ observations using combined empirical (open oceans) and semi-analytical (turbid waters) approaches for deriving consistent $K_d(490)$ data [25]. The $K_d(490)$ algorithm uses $nL_w(\lambda)$ at the blue and green bands for open oceans, while employing $nL_w(\lambda)$ at the red band to relate the particle backscattering coefficient at 490 nm to $K_d(490)$ [26]. With proper accounting for sensor spectral band variations in the $K_d(490)$ algorithm, global $K_d(490)$ data derived from various sensors can be accurately merged [27].

New Global Suspended Particulate Matter Product

Suspended particulate matter (SPM) quantity, comprising organic and inorganic, living and nonliving particulates, is estimated as the total dry weight per unit volume of water. SPM assessments for the global ocean have been difficult due to the high spatiotemporal variability that spans a dynamic range of approximately 0.01–2000 mg L^{-1}. STAR's inversion model retrieves SPM from the remote sensing reflectance ($R_{rs}(\lambda)$ or $nL_w(\lambda)$) in the near-infrared (NIR), red, green, and blue bands (NIR-RGB) [28,29], employing algorithms separately developed for "turbid" and "clear" waters, demarcated by a threshold pertinent to $R_{rs}(671)$. Validation with in situ water filtration data shows a median absolute percentage difference of approximately 35–39% overall. NOAA employs original swath projection sensor radiance (Level-1) data to routinely generate a swath projection SPM (Level-2) data product (approximately 750 m resolution) from VIIRS observations, as well as gridded (Level-3) products (2 and 9 km, daily, 8 days, and monthly). Figure 1a depicts the VIIRS-derived SPM global climatology.

New Water Class Product

Satellite-based optical water classification can distinguish water bodies with different bio-optical and biogeochemical properties. Recently, STAR devised and implemented a new water classification model [15] based on a clustering analysis of hyperspectral $R_{rs}(\lambda)$ spectra. This model globally resolves oceanic, coastal, and inland waters into 23 contiguous classes, varying from purple-blue waters to green waters and yellow waters. Distinct bio-optical and biogeochemical properties separate these water classes, such as Chl-a, SPM, $K_d(490)$, light absorption coefficient of phytoplankton ($a_{ph}(443)$), light absorption coefficient of detritus and colored dissolved organic matter (CDOM) ($a_{dg}(443)$), and light backscattering coefficient of particles ($b_{bp}(443)$). Figure 1b depicts the VIIRS-derived water class climatology (2012–2023) for the global oceans and inland waters. For open oceans, the water classes predominantly comprise Classes 1–6, while the optically more complex coastal oceans and inland waters are characteristically dominated by Classes 7–23. This water classification data, a new addition to the satellite ocean color product list, can be exploited for many applications, such as water quality, ocean ecology, and ocean color uncertainty estimation.

Global Gap-Free Ocean Color Data

Satellite-derived daily ocean color product images can often have a significant number of missing pixels in a single-sensor daily image due to cloud cover, narrow swath width, high satellite viewing angle, high solar zenith angle, contamination by high sun glint, etc. Since these missing pixels often partially or completely obscure ocean features of interest, such as oceanic mesoscale/submesoscale eddies and fronts, STAR merges daily ocean color observations from multiple sensors to reduce the missing data, using a STAR-developed innovative method to completely fill data gaps, generating gap-free ocean color products. Discussion of STAR's routinely generated global gap-free ocean color products follows.

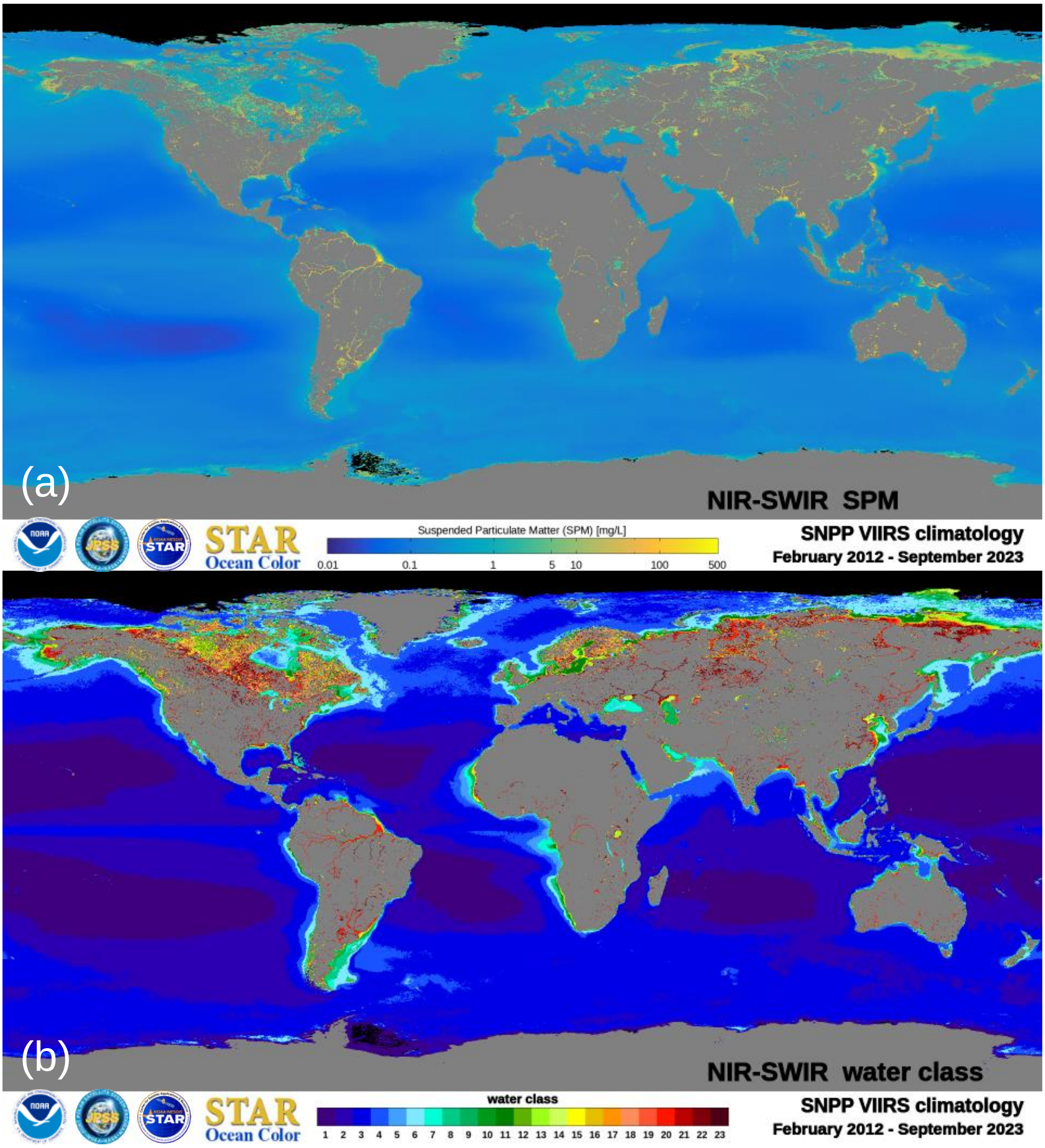

Figure 1. Climatology maps for 2012–2023 (SNPP VIIRS) for (**a**) suspended particulate matter and (**b**) water class product over global oceans and inland waters.

NOAA routinely produces global Level-3 (i.e., spatially and/or temporally aggregated from Level-2) ocean color data from multiple satellite missions, including VIIRS-SNPP, VIIRS-NOAA-20, OLCI-S3A, and OLCI-S3B. In general, a daily global image derived from VIIRS on SNPP or NOAA-20 comprises approximately 70 percent missing pixels and a daily global OLCI image from S3A or S3B comprises approximately 80 percent missing pixels [25–27]. Merging daily ocean color images from different sensors can significantly reduce the number of missing pixels. Currently, STAR routinely produces daily merged

Chl-a, $K_d(490)$, and SPM data, employing combinations of two, three, and four sensors (VIIRS and OLCI). A two-sensor merged daily image has approximately 38% more valid pixels than from a single VIIRS sensor for the same day, with three sensors adding about 12% more valid pixels and a four-sensor merged image adding approximately 8% more valid pixels beyond the three-sensor amount [26,27].

To completely fill missing pixel gaps in multi-sensor merged images, STAR employs the Data Interpolating Empirical Orthogonal Function (DINEOF) method [28,29] to reconstruct those missing pixels and generate a Level-4 product. The DINEOF method, based on Empirical Orthogonal Functions (EOFs), extracts the dominant spatial patterns (EOF modes) from a time series of satellite images to reconstruct the missing pixels. Currently, NOAA generates near-real-time daily global gap-free Chl-a, $K_d(490)$, and SPM data based on multi-sensor merged ocean color images [30], freely distributed via NOAA CoastWatch [31]. STAR provides global gap-free Chl-a, $K_d(490)$, and SPM data at 2 km and 9 km spatial resolutions. These daily gap-free ocean color data reveal large-scale and mesoscale ocean features, such as the equatorial current, the Gulf Stream, and mesoscale eddies, permitting smooth reconstruction of the evolution of mesoscale eddies, such as Loop Current rings, North Brazil Current rings, etc. [27]. Since enhanced (reduced) Chl-a values are often associated with cyclonic (anticyclonic) eddies, gap-free Chl-a data, along with satellite-observed sea level anomalies, facilitate tracking and globally studying mesoscale eddies [32]. Adding data from additional satellite sensors to merged images not only significantly increases the number of valid pixels, but also improves the quality of derived global gap-free images [27]. Notably, three-sensor gap-free images significantly enhance the definition of coastal features versus those assessed in two-sensor images [26].

To further resolve smaller-scale dynamic features, especially in coastal and inland lake regions, higher-resolution gap-free ocean color images are needed. VIIRS has a wide swath width of 3040 km, with spatial resolution gradually increasing from 0.75 km at nadir to approximately 1.5 km on the edge of the swath. Although OLCI's swath width (1270 km) is much narrower than VIIRS, OLCI has higher spatial resolution (0.3 km at nadir). Enabled by these sensor native spatial resolutions, four-sensor merged global and regional gap-free ocean color products at 2 km, 1 km, and 0.5 km spatial resolutions have been developed and tested [26]. These higher-resolution data capture more high-frequency variations in coastal oceans [26], e.g., the 2 km gap-free data images are capable of resolving fine ocean features, such as coastal eddies and filaments, with the 1 km and 0.5 km resolution images further enhancing the definition of such features [26]. Figure 2 provides examples for the ocean and inland waters of global daily 2 km gap-free Chl-a (Figure 2a), $K_d(490)$ (Figure 2b), and SPM (Figure 2c) for 1 July 2023. STAR routinely generates these gap-free ocean color products from three sensors (VIIRS-SNPP, VIIRS-NOAA-20, and OLCI-S3A). With ocean color data becoming available from more satellite sensors, more satellite data sources can be combined for higher-resolution daily global gap-free products. The community of users desiring gap-free ocean color products is large, spanning scientists "upstream" to decision-makers and "downstream" end-users across diverse research, application, management, and policy activities.

2.2.2. Infrared Capabilities

SST Data and Products

STAR has ongoing R&D efforts to develop experimental products within the infrared portion of the spectrum, with resulting significant refinement and exploitation of operational retrievals. These SST data enable NOAA and the broader community to assess ocean state and dynamics, inform ocean and weather predictions, and assess ecosystem/habitat conditions and associated implications on living marine resources.

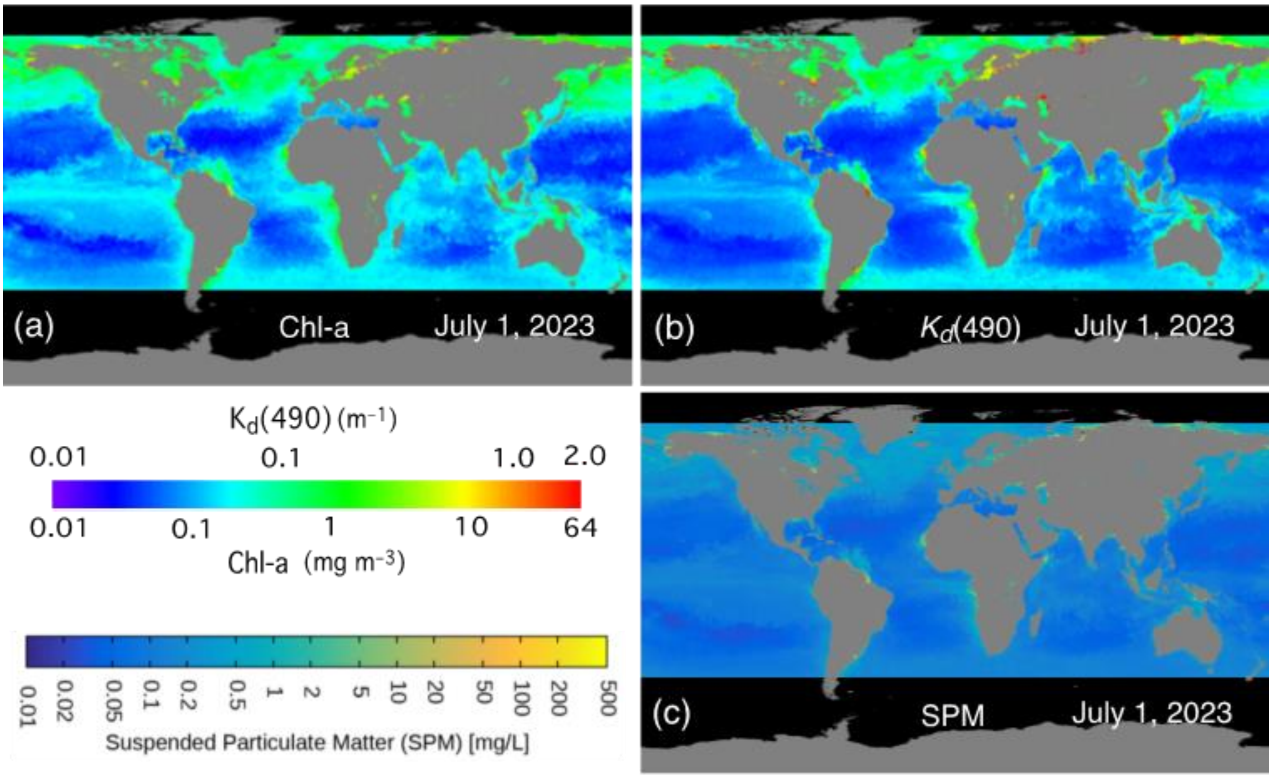

Figure 2. Three-sensor (VIIRS-SNPP, VIIRS-NOAA-20, and OLCI-S3A)-derived global daily gap-free 2 km ocean color products for (**a**) Chl-a, (**b**) K_d (490), and (**c**) SPM on 1 July 2023.

In the early 1980s, NOAA pioneered a global satellite SST product from 4 km-resolution data to produce Advanced Very High-Resolution Radiometer (AVHRR)/2 Global Area Coverage (GAC) onboard polar-orbiting NOAA-7 [33]. Over the next 20 years, NOAA's heritage LEO SST retrieval system has undergone multiple improvements [33–35]. In the 1990s, complementary SST retrievals from GEO data commenced [35,36]. In the 2000s, the scope of NOAA satellite SST capabilities significantly expanded, with changes largely driven by ongoing preparations for the next-generation US satellite systems, the JPSS, and GOES 'R' series, ultimately leading to the generation of a platform-agnostic, enterprise retrieval system for consistent SST products, the Advanced Clear Sky Processor for Ocean (ACSPO) [37–40] that supports the diverse fleet of SST sensors.

Currently, ACSPO processes data from eighteen LEO missions, including NOAA, EUMETSAT, and NASA satellites, and five GEO missions, including NOAA and Japanese Meteorological Agency (JMA) satellites (Table 1). Each of the satellites/sensors routinely provide data in several formats: original swath projection geophysical products (Level 2) and their gridded counterparts. All ACSPO products are currently provided at equal-grid 0.02° resolution. Following the GHRSST recommended standards, the Level 3 single-sensor products are available in two types: uncollated (L3U) or collated in time (L3C). ACSPO data can be accessed multiple ways, including via NOAA's Product Distribution and Access (PDA) system, NOAA CoastWatch, and NOAA's Centers for Environmental Information (NCEI), as well as EUMETSAT EUMETcast, and the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) [41–44].

NOAA, national, and international users extensively employ ACSPO products. Consistent feedback from users notes the challenge of ingesting and processing data from multiple platforms and sensors. Users commonly request that ACSPO L3U/C products be aggregated into sensor-agnostic products, where the large number of sensors and platforms offers greater potential for comprehensive SST consistency checks and quality assurance. Achieving this goal requires ingesting SST data from various individual sensors, reconciling and merging data, thereby enabling gridded super-collated (L3S) products that employ multiple sensors, with improved global coverage and improved spatiotemporal resolution.

Table 1. Sensor data sources processed by STAR's Advanced Clear Sky Processor for Ocean (ACSPO). Sources for data ingested into the current Level 3 Super-collated Daily LEO time series and data fusion product (L3S) are in italics. Sources for the planned GEO super-collated product are noted in the GEO section.

ACSPO Enterprise Processing	Heritage Sensors	Current Generation Sensors	Next Generation Sensors to Be Added
LEO	• NOAA AVHRR GAC, NOAA-7, 9, 11, 12, 14, 15, 16, 17, 18, and 19 • EUMETSAT MetOp First Generation A, B and C AVHRR FRAC • NASA MODIS, Terra and Aqua	• JPSS VIIRS, Suomi NPP, NOAA-20 and NOAA-21	• EUMETSAT MetOp Second Generation MetImage
GEO	• NOAA GOES Imager (list of several) • EUMETSAT Meteosat Second Generation, Spinning Enhanced Visible and InfraRed Imager	• NOAA GOES-R: GOES-16, 17, and 18 Advanced Baseline Imager • JMA Himawari-8 and Himawari-9 Advanced Himawari Imager	• EUMETSAT Meteosat-Third Generation Flexible Combined Imager

NOAA first pursued developing two L3S-LEO products, aggregating mid-morning (AM) data from the MetOp-First Generation-A, B, and C satellites and aggregating afternoon (PM) data from the JPSS Suomi NPP, NOAA-20, NOAA-21, and Aqua MODIS satellites, with each product comprising one nighttime file and one daytime file. Many NOAA users also want these four files aggregated into a single daily (DY) product. Global LEO satellite coverage of any given satellite sensor depends on the observation capability (orbit, swath, observation geometry, etc.) minus anything that is not ocean SST (clouds, ice, etc.). A single satellite typically provides "good" SST values for approximately 22–26% of the global ocean, with two satellites producing approximately 35–37% "good" coverage, and three satellites giving up to approximately 40% "good" coverage. The DY product (Figure 3), which aggregates data from up to five different satellites, provides "good" SST values for approximately 65% of the global ocean. The L3S-LEO time-series begins in February 2000.

Current work focuses on super-collating SSTs from six GEO satellites into a single L3S-GEO product (Table 1), which will result in near-global coverage at hourly temporal resolution, excluding the Indian Ocean, which is not presently covered by new-generation GEO SST observations from NOAA and its partners. Ultimately, the L3S-LEO and L3S-GEO will be combined into a single global L3S product having superior coverage, exploiting LEO's high spatial resolutions and GEO's high temporal resolutions.

All ACSPO SST products have three modes: (1) near-real time (2–3 h latency) for operational users; (2) science quality delayed mode (up to 2 months' latency) having improved sensor data (Level 1b) and ancillary data input; and (3) full mission reanalysis (RAN; several years latency) [41–44]. Before archiving at NOAA and NASA, all ACSPO products undergo extensive consistency checks and quality control, as well as calibration and validation against high-quality in situ data in multi-tier NOAA SST monitoring systems, notably the SST Quality Monitor (SQUAM) [45]; Monitor of Infrared Clear-sky Radiances over Ocean for SST (MICROS) [46]; and ACSPO Regional Monitor for SST (ARMS) [47]. STAR performs calibration and validation against high-quality in situ data captured in NOAA's in situ SST Quality Monitor (iQuam) [48]. STAR monitors additional information about sensors and platforms via the NOAA Sensor Stability for SST (3S) [49] system. All anomalies identified during monitoring are promptly addressed. Comprehensive monitoring of SST products, their source radiance data, and the health of contributing sensors and platforms ensures that STAR delivers the highest-quality ACSPO SST products to users.

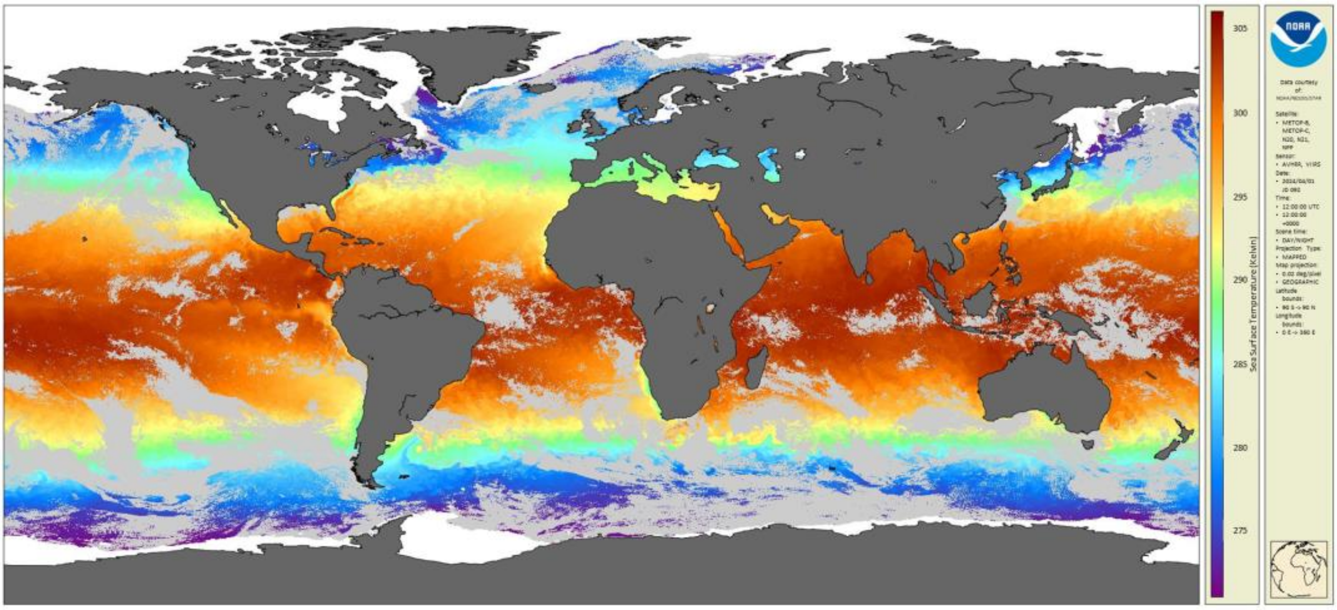

Figure 3. Global ocean LEO Level-3 super-collated (L3S-LEO) daily (DY) SST product for 1 April 2024 showing substantial global daily coverage of satellite observations (approximately 65% on average). The L3S-LEO DY time series begins in the year 2000. Gray areas indicate no SST data due to probable clouds or other quality flags and white areas represent no SST data due to probable ice.

SST Gap-Filled Analysis

Responding to user interest and need for a gap-free Level-4 (L4) product, a global 0.05° resolution (approximately 5 km) gap-free Level-4 NOAA Geo-Polar Blended (GPB) daily analysis was created at STAR [50], separate from ACSPO heritage products [23], by combining Level 2 SST data from various US, Japanese, and European LEO and GEO instruments, including ACSPO data. A multi-scale optimum interpolation methodology, approximating a Kalman filter, is employed with a data-adaptive correlation length scale to ensure a good balance between spatial feature preservation and noise reduction. The time series for this analysis product begins in 2002. Temporal extension to earlier time periods is being researched. A key user of this analysis product is NOAA's Coral Reef Watch (CRW).

Next-Generation SST at NOAA/NESDIS

NOAA scientists with expertise in SST recognize the opportunity to improve NOAA's SST data product collection, especially with regard to addressing growing user demand for various decision-making applications; consequently, in an internal report (white paper), NESDIS/STAR presented a proposal for a next-generation SST product suite [51]. Applying new computing technologies, such as AI and machine learning, to the many robust, operational SST satellite sensor data openly shared amongst the international space agency community holds the promise of creating next-generation super-high-resolution observations that exceed the native sensor resolution. Higher-spatial-resolution SST products, both near-real-time data and reanalyzed longer-term time series, are highly desirable and in demand from multiple user sectors. The outlook is optimistic that relevant institutions will promote progress in this direction.

Infrared Ice Observations

Beyond SST, STAR develops infrared geophysical products for near-real-time monitoring of sea ice conditions, lake ice conditions, and longer-term climate studies. STAR provides ice information and services to aid marine navigation and security, weather and climate prediction, and climate monitoring and change detection. Near-real-time sea ice products, used or evaluated for sea-like ice operations in support of marine navigation and assimilation in numerical environmental prediction models, include sea ice concentration, temperature, thickness, and motion. The primary instruments for infrared-based ice surface temperature, ice thickness, and ice motion are VIIRS on S-NPP, NOAA-20, and NOAA-21, and ABI on the GOES-R series satellites [52]. Ice concentration is derived from the VIIRS and the ABI [53]. All except ice motion are generated operationally. These ice products will also be generated for the MetOp-SG series of satellites with the METImage instrument. While NOAA does have satellite products for land-based snow properties, there are currently no satellite products for snow on sea ice; however, an approach using active altimetry is under investigation. Figure 4 provides some examples of STAR's infrared-based sea ice products. Current research products include blended VIIRS+AMSR2 sea ice concentration [54], sea ice leads [55,56], ice surface temperature from a single VIIRS high-resolution band [57], blended ice motion, and sea ice dynamics and deformation.

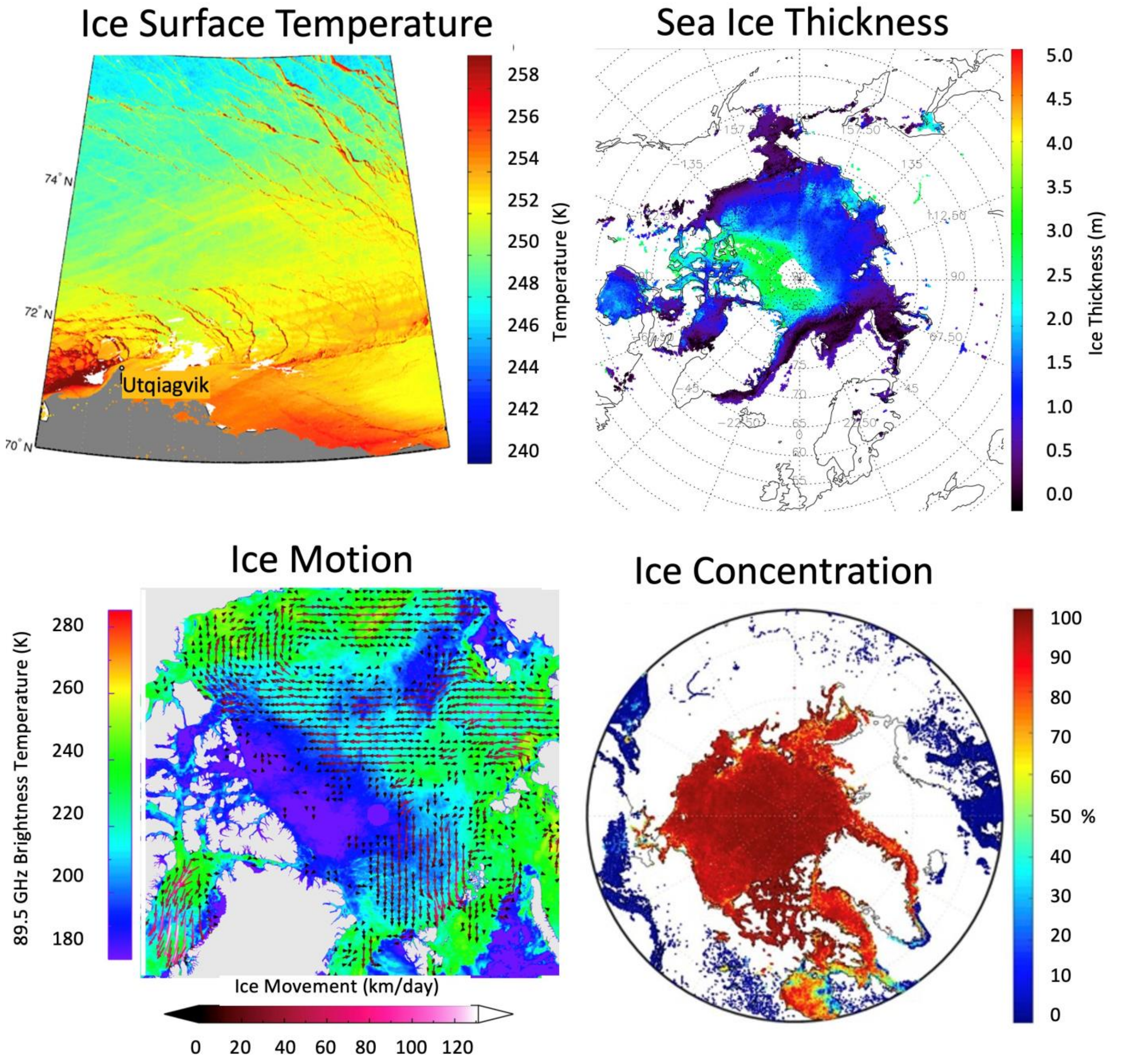

Figure 4. Near-real-time infrared-derived sea ice products. Clockwise from upper left: VIIRS sea ice surface temperature, VIIRS sea ice thickness, VIIRS + AMSR2 ice concentration, and VIIRS + AMSR2 ice motion, with the AMSR2 providing passive microwave data.

The scientific community uses sea ice climate data records (CDRs) for process studies and to better understand interactions and feedback in the climate system. STAR develops and enables robust climate data records that can be used for monitoring and assessing changes in Arctic and Antarctic climate. One NOAA CDR developed by STAR, the Extended Advanced Very High-Resolution Radiometer (AVHRR) Polar Pathfinder (APP-x), comprises a suite of 20 variables, including sea ice thickness, ice surface temperature, ice concentration, cloud properties, and radiative fluxes. APP-x covers both polar regions twice per day from 1982 to the present [58]. VIIRS data, added daily to APP-x, extends the CDR into the future. Another recently developed long-term dataset estimates ice thickness from ice age, where ice age is determined by tracking new ice parcels over a long period of time [59], a unique approach to deriving sea ice thickness that is very different from more direct altimetry-based observations.

2.2.3. Passive Microwave Capabilities

For passive microwave capabilities, STAR must leverage partner satellite observations. NOAA's formal partnership agreement with the Japan Aerospace Exploration Agency (JAXA) for timely access to data from the AMSR2 instrument on the GCOM-W1 satellite will extend to include continuity observations resulting from the launch of AMSR3 on JAXA's GOSAT-GW mission. The AMSR2 uniquely addresses several NOAA JPSS program observational requirements not met by NOAA satellites, notably microwave SST and microwave brightness temperature (MBT) imagery. STAR developed and validated several operationally generated and distributed AMSR2 ocean products, in particular sea surface wind speed (SSW), SST, total precipitable water (TPW), cloud liquid water (CLW), and MBT imagery for tropical cyclones. Recently, STAR developed an all-weather AMSR2 wind speed product, extending the utility of AMSR2 wind speed retrievals into the tropical and extratropical storm environments [60].

STAR pursues passive microwave sea ice retrievals (sea ice concentration, thickness, and motion) from AMSR2 [53] to provide observations complementary to infrared-based sea ice observations, targeting application in near-real-time monitoring of sea ice, and lake ice conditions, and for longer-term climate studies (Figure 4). Passive microwave sea ice concentration data, produced operationally from the AMSR2 and subsequent instruments, also will be generated for the Microwave Imager (MWI) instrument on the MetOp-SG series of satellites. Near-real-time passive microwave sea ice products directly support ice operations, marine navigation, assimilation in numerical ocean and atmosphere prediction models, as well as for climate data records used by the scientific community for process studies and better understanding of climate system interactions and feedback. Blended passive microwave (AMSR2) and infrared (VIIRS) products for sea ice motion and concentration have been developed but have not yet transitioned to operational production. The APP-x product suite includes a passive microwave ice concentration product. Sea ice thickness is derived from the retrieved snow–ice interface temperature and an ice growth model. Passive microwave satellite data (AMSR2) have been used to develop the first long-term basin-wide arctic climatology of dynamically and thermodynamically driven sea ice thickness effects at sub-seasonal temporal resolution [61]. Although over a decade long, this time series is not yet considered to be a CDR.

Beyond AMSR2 passive microwave observing capabilities, STAR also leverages the passive L-band observations of ESA's SMOS and NASA's SMAP missions for sea surface salinity (SSS) observations, a critical ocean state parameter. These SSS observations support NOAA operational efforts, including near-real-time global numerical modeling and seasonal-to-interannual prediction efforts [62]. STAR L-band SSS development efforts currently focus on enhancing exploitation of high-latitude SSS observations, where SSS observations are critical, but colder water impedes the geophysical retrieval. Another effort pursues exploiting satellite SSS observations as an artificial intelligence (AI) predictor for precipitation prediction at subseasonal to seasonal time scales.

2.2.4. Active Capabilities

Altimetry

STAR exploits satellite altimetry, notably for ocean surface topography efforts, which benefits numerical modeling and prediction of ocean dynamics; hurricane intensity forecasting through improved representation of ocean heat content; enhanced high wave warnings; ENSO forecasting and subsequent global water cycle implications; ocean surface current assessments that inform fishery management, fishing services, energy siting, habitat health, search and rescue, offshore operations, and incident responses; and understanding and mitigating global and regional sea level rise [63].

Routine calibration/validation activities of altimetry concentrate in two areas, near-real-time operational oceanography and the sea level climate record. The Near-Real-Time Altimeter Validation System (NRTAVS) produces comprehensive, running web-based statistical summaries of wind, wave, and sea surface height, as well as individual correction terms, which are used for rapid quality assurance. To ensure the integrity of STAR's regional and global sea level climate products, the previous tide gauge comparison system [64] was updated to detect system drifts and shifts. Additionally, a comprehensive radiometer comparison system looks for errors using atmospheric models, inter-satellite comparison, and vicarious methods [65]. Annually, STAR uses complementary sea level measurements from Argo array and the GRACE gravity missions to assess the altimetry-based sea level budget [66,67].

Through the international OSTST and in conjunction with NASA and other programs, the NOAA Jason/Sentinel-6 program supports research and development of altimetry applications, producing several innovative altimeter processing algorithms for improved sea level and sea state observations, altimetric bathymetry [68,69], inland water levels, and, for the cryosphere, sea ice thickness (freeboard). The Fully Focused Synthetic Aperture Radar (FF-SAR) algorithm [70] provides ultra-high-resolution altimetry at scales of up to 0.5 m, increasing the along-track resolution by 100 times over conventional processing methods. Widely applied, FF-SAR use includes improved altimeter range calibrations at dedicated transponders and new oceanographic observations, including swell [71]. Additionally, STAR has helped develop FF-SAR-based altimetry processors to monitor water levels of small inland water bodies, particularly for ungauged rivers and lakes in remote or undeveloped areas [72]. A more recent innovation, 2D retracking, introduces additional parameters to the processing of radar waveforms from Delay-Doppler (SAR) altimetry missions (e.g., Cryosat-2, Sentinel-3, Sentinel-6) [73,74]. This advanced algorithm provides two new ocean observations related to vertical wave motion and surface velocity. Including these parameters reconciles differences between conventional (i.e., TOPEX and Jason series) and SAR-Altimetry processing of sea level and waves, ensuring continuity in the ocean topography climate record from altimeters using these different technologies.

STAR, in conjunction with EUMETSAT and the Delft University of Technology, maintains the Radar Altimeter Database System (RADS), which provides multi-mission, consistent sea level anomalies, waves, and ocean surface wind speed products that NOAA operationally employs for ocean modeling and prediction [75]. Daily RADS gridded altimetry, a derived product, comprises a homogenized, high-resolution, gridded, gap-free sea level anomaly product, extending from 2017 to the present, with a major algorithm update slated for release in 2025 and a concomitant extension of the product time series to encompass 2000 onwards. In addition to sea level anomaly and absolute dynamic topography, this product also includes geostrophic surface velocity and eddy kinetic energy (EKE).

The NOAA Ocean Heat Content (OHC) Product Suite provides real-time, daily tropical cyclone heat potential (TCHP) and mixed-layer depth (MLD) estimates for hurricane prediction, using the Navy's ALtimeter Processing System-2 (ALPS2) and the Geopolar Blended 5 km SST [76] as inputs. The Next-Gen Enterprise OHC (in development at STAR), which employs RADS output, as well as Geopolar Blended 5 km SST, ocean surface salinity, and ocean winds, uses a dynamically consistent formulation to reduce error and increase the correlation of TCHP estimates for extremely warm waters [75,77], adding temperature and salinity estimates with 2 m vertical resolution for the upper ocean. The Blended Ocean Surface Currents (BOSC) product combines gridded altimetry with several other data sources to provide a near-real-time blended 1/6-degree gridded output, primarily depending on the RADS to provide accurate global daily surface current estimates. STAR's complementary new Multiparameter Eddy Significance Index (MESI) provides a blended-input estimate of an eddy's physical dynamics and biogeochemical impacts [32].

An innovative STAR algorithm for radar altimeter-based sea ice thickness, currently completing validation and preparations for operational production, exploits the FF-SAR Altimeter Processor [70] to dramatically increase (approximately 50 times) the spatial resolution of along-track altimetry-based sea ice thickness (freeboard) measurements. For more accurate estimates of surface elevation, a robust physical model helps account for ice properties in radar returns from sea ice surfaces, potentially producing more reliable and accurate estimates of sea ice thickness (freeboard), enabled by improved measurement of small sea ice leads (Figure 5) and being unaffected by cloud cover.

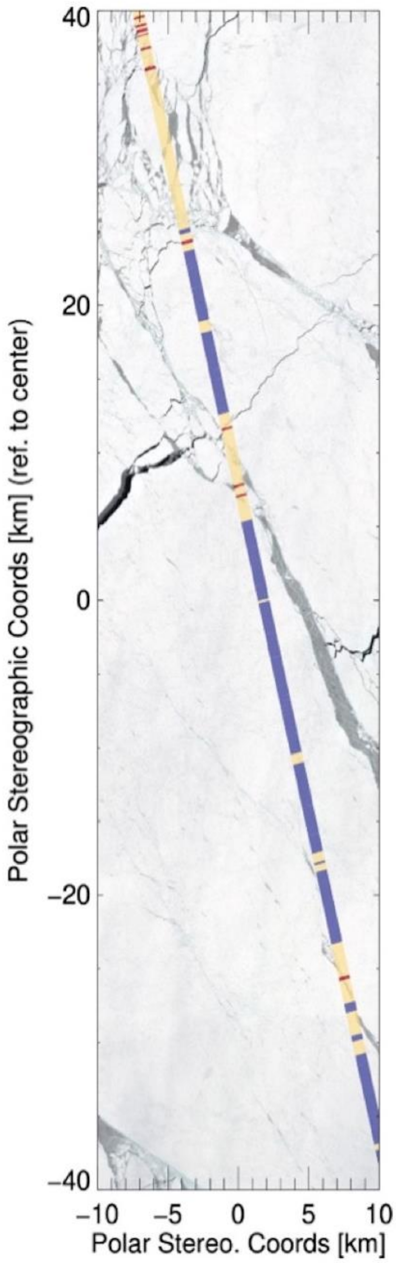

Figure 5. SAR altimeter processor lead detection: blue—floe, yellow—ambiguous, red—lead.

This new product will provide enhanced information for sea ice forecasting, modeling, and ice charting for navigation, maritime operations, and safety at sea. STAR is working with NOAA's National Weather Service (NWS) on implementing operational assimilation of the SAR-Altimeter Processor Sea Ice Thickness product into NOAA's United Forecast System Coupled Model (UFSCM). A new sea ice thickness product line under development aims to produce a sustained long-term time series using CryoSat-2 data, with continuity provided by data from the operational Sentinel-6/Jason-CS and Sentinel-3 missions, and the pending Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) mission.

Crucial for accurately and reliably estimating sea ice thickness and building upon previous experiences with both airborne and satellite altimetry data, STAR pursues exploiting dual-band satellite altimetry techniques to provide snow depth on arctic sea ice, subtracting IceSat-2 laser-based altimetry observations from radar-based altimetry observations to estimate snow thickness on sea ice. Quantifying and monitoring snow on sea ice provides critical information, constraining precipitation over the Arctic Ocean, thereby improving estimates of ocean–atmosphere heat flux, and enabling more accurate satellite-derived sea ice thickness retrievals through improved knowledge of hydrostatic snow loading. These innovations and associated infrastructure pave the way for exploiting future dual-band altimeter missions, such as CRISTAL, for enhanced sea ice products and their continuity.

Scatterometry

NOAA support for ocean surface wind vector (OSVW) product development and satellite scatterometer calibration/validation activities began in the early 1990s with the ERS-1 scatterometer. Lessons learned from the ERS scatterometer missions, combined with the large areal coverage (broad measurement swath) and consistent quality OSVW retrievals provided by NASA's QuikSCAT mission (launched in 1999), made routine use of scatterometer OSVW data by NWS possible, with the largest impact being direct use of OSVW observations by marine forecasters in their day-to-day jobs, notably for marine wind and wave analysis, warning, and prediction. STAR scientists, working closely with their peers in the NASA QuikSCAT science team and forecasters at the NWS Ocean Prediction Center (OPC) and National Hurricane Center (NHC), improved the near-real-time QuikSCAT OSVW products, thereby supporting NOAA's weather mission. This effort included improving and validating high-wind-speed retrievals in extratropical cyclones through the Ocean Winds flight experiment program described later.

Designed for a 3-year mission life, QuikSCAT lasted 10 years, during which its OSVW products drastically improved marine wind analyses, forecasts, and warnings by significantly extending the available observations beyond sparse buoy and ship reports and NWP model output. Actual observations now provide 12.5 km spatial resolution for an 1800 km wide swath for each QuikSCAT pass. The observed extent of gale, storm, and, sometimes, hurricane-force winds in tropical cyclones notably improved, allowing improved NWS wind warnings and resulting concomitant positive consequences for maritime commerce. In 2006, realizing the significant benefits of satellite scatterometer OSVW products and that NASA and NOAA had no follow-on mission planned for QuikSCAT, NOAA made a concerted effort to document the benefits and requirements for scatterometer OSVW data for operational weather forecasting and warnings [78–82], as well as the economic impact of satellite OSVW data [83,84]. To better address the impacts of satellite ocean observations, further studies of this type are crucially required, capturing not just the straightforward cost–benefit perspective, but also, more broadly, enabling improved societal outcomes. With no US follow-on scatterometer to QuikSCAT, STAR's focus shifted to exploiting observations from the Advanced Scatterometer (ASCAT) on EUMETSAT's Meteorological Operational satellites (MetOp-B/C). STAR, building upon previous experience with QuikSCAT and its flight experiment program, determined that ASCAT measurements had sensitivity to higher winds than currently being exploited [85]. Resulting updates to STAR's ASCAT processing improved detection of hurricane-force winds in extratropical cyclones, helping mitigate the loss of QuikSCAT for the NOAA forecasters. STAR continues extending the information extracted from ASCAT by notably employing different processing techniques to achieve a high-resolution ASCAT coastal wind and ice product [81]. This new technique enables ASCAT measurements within a few kilometers of the coast while also improving ASCAT's ability to measure winds in tropical cyclones (Figure 6). Efforts also focus on developing a near-real-time ice coverage product from this enhanced-resolution ASCAT product, with validation and refinement of this product being a component of STAR's winter flight experiments.

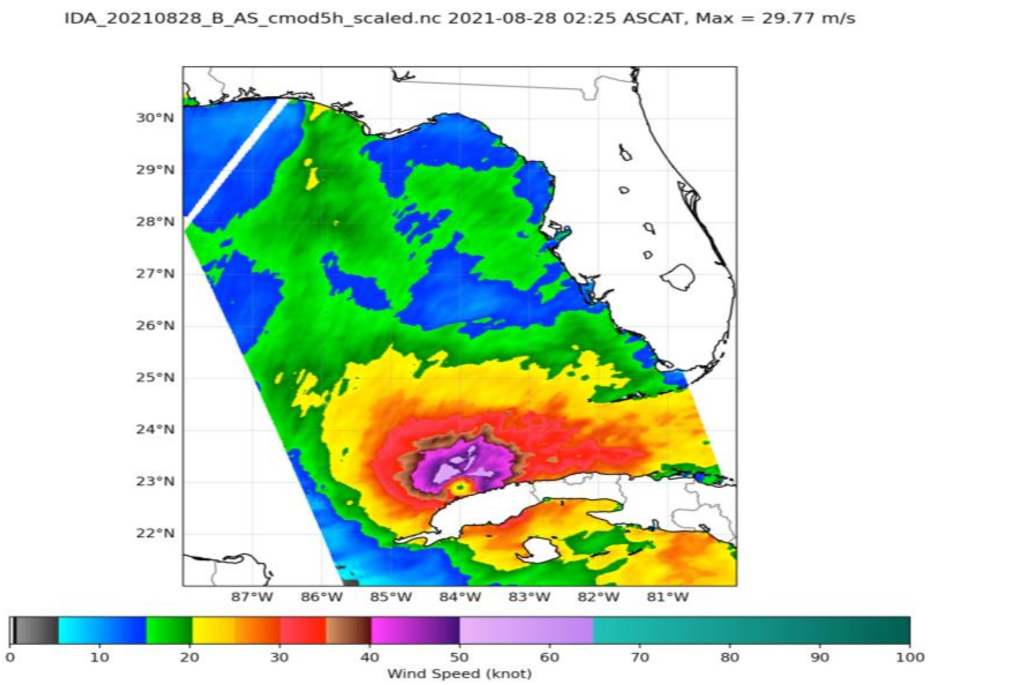

Figure 6. High-resolution ASCAT product utilizing the coastal and tropical cyclone wind speed retrieval improvements for Hurricane Ida on 28 August 2021.

Working closely with the Indian Space Research Organization (ISRO) on calibrating and validating the OSCAT instrument on the Oceansat-2 mission, a scatterometer similar to QuikSCAT in frequency and measurement geometry, STAR developed and produced its own OSCAT OSVW products in near-real time using NOAA's SCATSAT processing system. With both EUMETSAT and ISRO committed to follow-on scatterometer OSVW missions, STAR actively works with both agencies in support of satellite OSVW data for NOAA's weather mission. Currently, STAR OSVW efforts focus on calibrating, validating, and developing products for ISRO's Oceansat-3, as well as working with EUMETSAT in preparing for the launch of ASCAT's successor, the EPS-SG Scatterometer (SCA), in late 2025.

Satellite scatterometer-based products derived from ASCAT measurements help characterize sea ice properties, with spatial resolution enhanced through processing that exploits frequent swath overlap in the polar regions [86], including daily products for ice type, normalized radar cross-section (NRCS), and 10-day NRCS standard deviation. The frequency and resolution of these products provide metrics suitable for sea ice forecasting, input for sea ice thickness estimation, model input, and geophysical process studies.

Synthetic Aperture Radar (SAR)

Exploiting satellite Synthetic Aperture Radar (SAR) observations, STAR provides estimates of boundary layer conditions for the surface of oceans, lakes, rivers, and wetlands. The primary measurements, determined from spaceborne SAR imagery, map the surface microwave radar reflectivity at resolutions from the sub-meter scale to 100 m, depending on the particular SAR satellite and mode. At typical radar frequencies, SAR can image through clouds; consequently, SAR serves as an "all-weather" instrument, independent of time of day because the radar provides its own illumination. STAR currently derives several SAR-based geophysical parameters, enabling high-resolution monitoring of sea surface wind speed, tropical cyclones, sea and lake ice characteristics, flooding, marine oils and surfactants, and waves.

All STAR SAR products transform original SAR source data to NRCS imagery, with the associated backscatter of these NRCS data being proportional to surface roughness on the scale of the radar wavelength (from 3 to 30 cm). NOAA's principal sources for SAR data, C-Band imagery, come through partnerships with ESA (Sentinel 1) and the Canadian Space Agency (RadarSat Constellation Mission (RCM)), as well as commercial procurement for RadarSat-2 data.

For wind speed and direction estimates, STAR employs empirically determined geophysical model functions based on backscatter intensity from SAR NRCS imagery [87], with the same SAR polarization employed for transmission and reception: vertical (V), horizontal (H), co-polarization (VH or HV), or compact polarization (C). SAR fine-resolution estimates for cyclone winds, surface eye locations, and other cyclone characteristics provide tropical forecasters with a new tool [88]. When estimating tropical cyclone force wind speeds, SAR retrievals apply transmission backscatter cross-polarization (VH or HV) [89]. These SAR-derived tropical cyclone products (500 m, 3 km, and 12 km resolution) now routinely contribute to forecast products from the Joint Typhoon Warning Center (JTWC), National Hurricane Center (NHC), and the Central Pacific Hurricane Center (CPHC). Figure 7 depicts the SAR 500 m wind speed estimates for Cyclone Freddy on 16 Feb 2023.

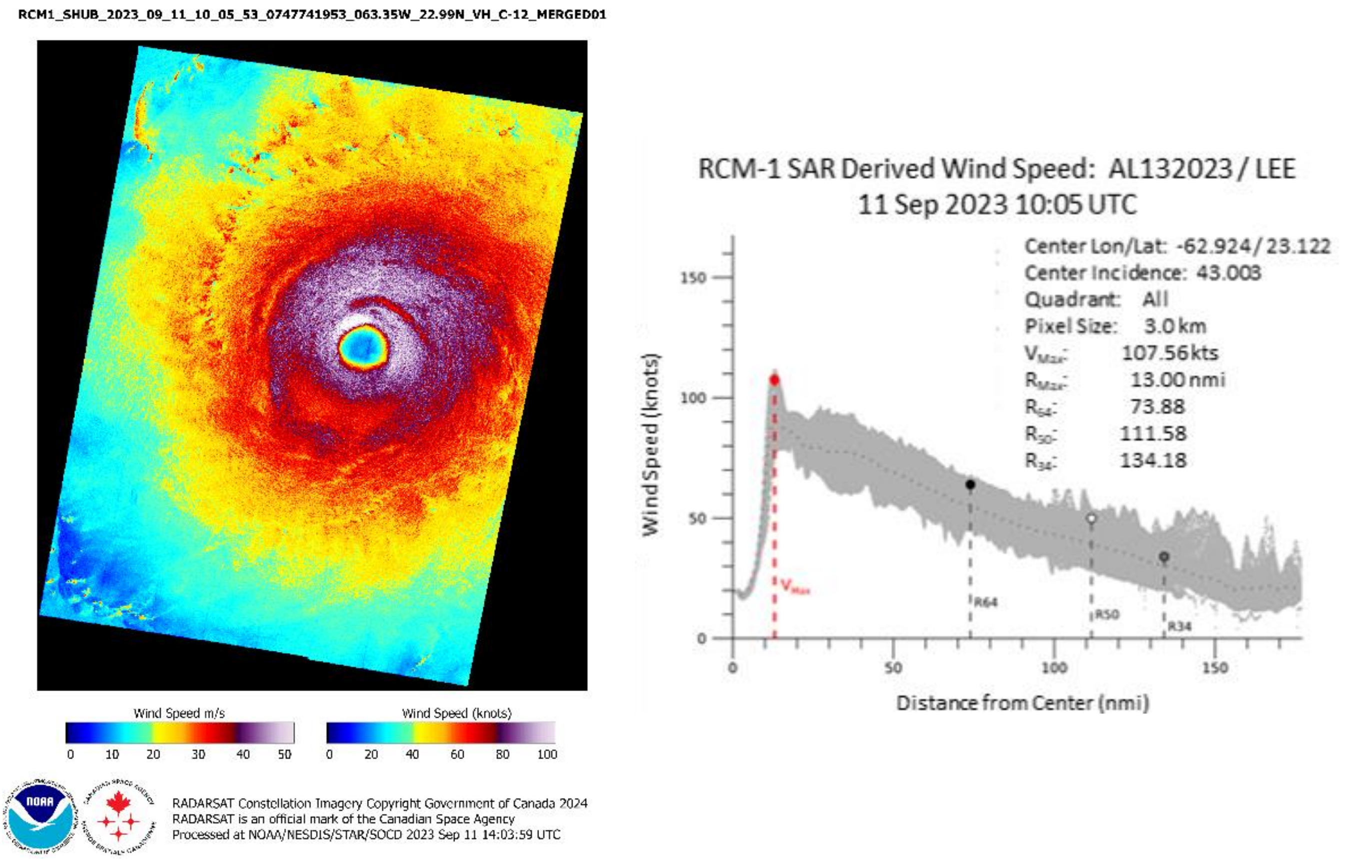

Figure 7. Synthetic Aperture Radar (SAR, Radarsat-2) data for Tropical Cyclone Freddy 11 September 2023 at 10:05 UTC: (**left**) 0.5 km resolution wind speed and (**right**) full storm radial profile, depicting that the 0.5 km processing extracts a maximum velocity (*VMax*) of 136.3 kts.

For most operational ice monitoring agencies, e.g., the US National Ice Center (USNIC) and the Alaskan Sea Ice Program (ASIP), SAR data serve as a primary source, recognizing that SAR data provide an ideal tool for ice observation, particularly due to persistent cloudy conditions, low solar illumination, SAR's high spatial resolution, and SAR's ability to track ice types. STAR provides NRCS, normalized mosaic imagery, ice motion, and ice extent products to USNIC and ASIP for ice charting. The ice motion products, using a customized algorithm, are generated on tailored resolutions and time intervals.

2.3. Suborbital and In Situ Data Collections Supporting Satellite Observations

2.3.1. Sea Ice

Validating satellite-based sea ice products with in situ observations presents notoriously difficult challenges due to the remote and harsh polar ocean environments. STAR pursues increased capacity for collecting airborne sea ice coverage measurements by leveraging NOAA's extensive expertise and resources in airborne operations. Using long-range NOAA aircraft, STAR observes remote regions of the arctic, collecting measurements over long transects (approximately 500–1500 km), thereby providing extensive data for validating satellite-based sea ice products over a variety of ice types, effectively bridging the gap between in situ point measurements and large-scale satellite measurements. STAR partnered with the European Space Agency (ESA) and NASA Goddard Space Flight Center (GSFC) during Operation IceBridge to perform long-transect, near-coincident under-flights of Envisat, ICESat, CryoSat-2, Sentinel 3A/B, and ICESat-2 for satellite sea ice product validation [90].

During the winters of 2021, 2022, and 2023, STAR conducted interdisciplinary airborne campaigns over the Beaufort Sea and Bering Sea regions using a WP-3D aircraft equipped with several advanced radar systems, collecting both wind and sea ice surface measurements (e.g., Figure 8), targeting near-coincident and coincident under-flights of multiple satellite altimeters, along with low-altitude surveys of the Sea Ice Dynamic Experiment (SIDEx) ice camp. STAR plans to add additional sea ice measurement instrumentation (e.g., lidar) for future field efforts and pursue using additional NOAA aircraft for product validation and sea ice monitoring, aiming to leverage emerging UAS platforms.

Through coordination with NOAA CoastWatch/PolarWatch and using NOAA's OceanView geophysical data visualization application, STAR has established a system designed to enhance and distribute scientific and monitoring information for the arctic and antarctic regions, aiming to provide access to data collected over a spectrum of spatial and temporal scales, along with active tools for analyzing and comparing multiple datasets. System capabilities include data mapping and visualization, on-the-fly statistical and time series analysis tools, and multivariable comparison tools. The system targets providing reliable polar in situ, airborne, and satellite-based measurements for satellite calibration/validation activities, as well as analysis capabilities for examining regional earth system processes; serving national and international cryospheric operational and science communities; and enabling downstream stakeholders through more useable satellite-based products serving fisheries, commercial efforts, security, navigation, arctic communities, etc.

2.3.2. Extreme Winds

STAR airborne field experiments employ several advanced radar systems, installed on the NOAA P-3 aircraft and routinely operated during flights into tropical cyclones and winter storms, to obtain measurements of extreme conditions. Over the past several years, STAR implemented inflight real-time processing for wind and wave products, enabling collected data to simultaneously inform critical National Hurricane Center (NHC) decision making. Targeting improvements to existing products and future mission instrumentation, these flight experiments, coordinated with satellite passes when possible, have multiple objectives: improve understanding of what microwave remote sensing instruments are really measuring at the extremes; advance the knowledge of processes at the air–sea interface in these extreme environments; test new remote sensing measurement instrumentation and techniques; and validate satellite products.

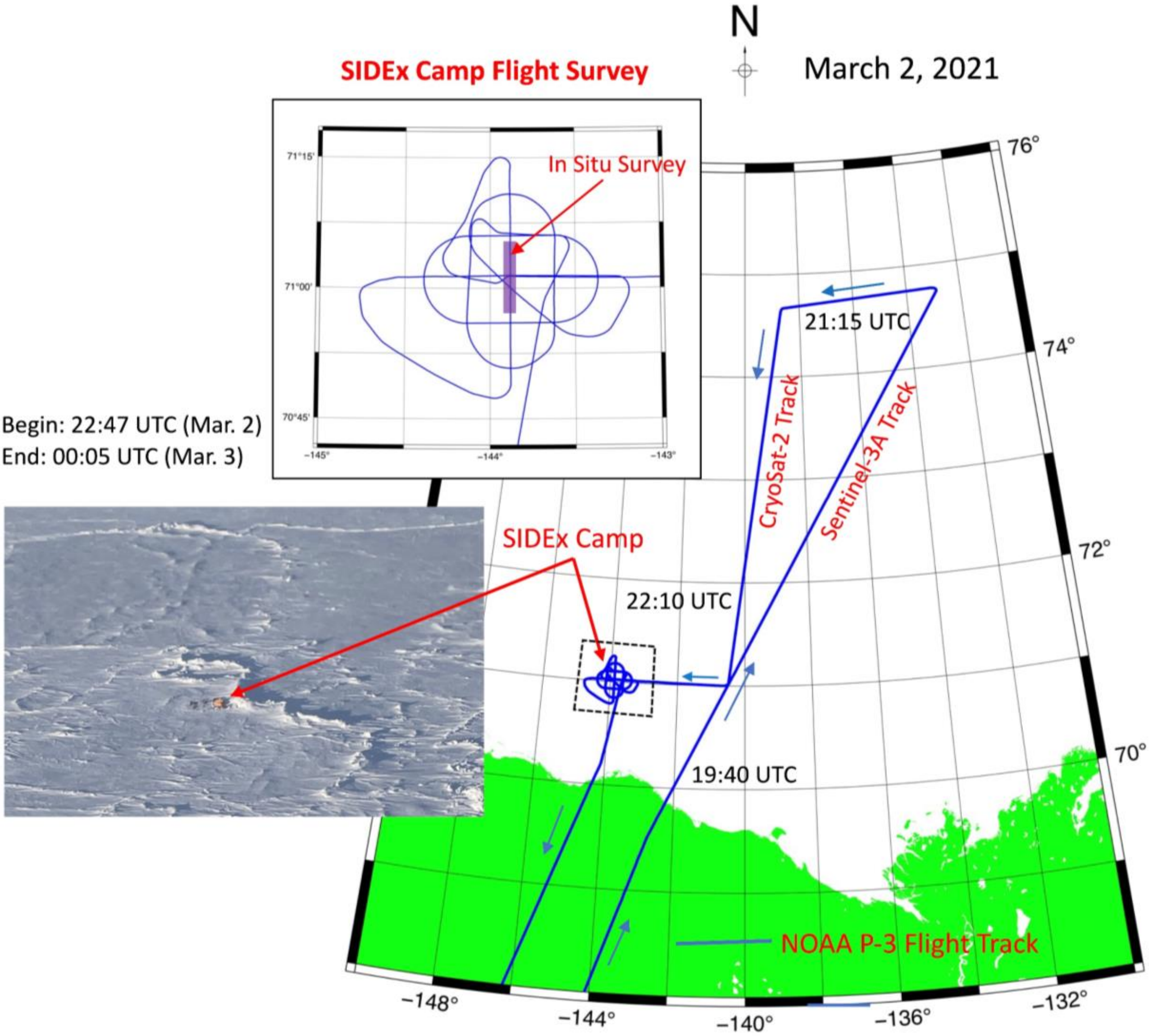

Figure 8. NOAA Ocean Winds and Sea Ice Winter field experiment—2 March 2021. Flight track included near-coincident under-flights of CryoSat-2 and Sentinel-3A satellites and a survey of the SIDEx ice camp.

While the extreme wind/wave conditions found in extratropical and tropical cyclones occupy a small fraction of the ocean surface at any moment, accurate knowledge and monitoring of these conditions are crucial for short-term and longer-term weather and climate applications. NOAA's unique heavy aircraft capability provides the platform with support for current remote sensing products while also enabling investigations targeting improvements in knowledge and future instrumentation. A current STAR priority targets using STAR airborne measurements to understand and address the issues being seen in the airborne Stepped Frequency Microwave Radiometer (SFMR) retrievals in high-wind/rain gradient areas. Hurricane specialists at the NHC question the accuracy of SFMR data in these regions; however, with STAR's suite of measurements, STAR aims to untangle what is happening at the surface and with the retrievals.

3. Models and Assimilation

3.1. General

The assimilation of satellite ocean observations into predictive modeling, namely NOAA's Unified Forecasting System, is the principal use, by volume and parameter type, of STAR's satellite ocean observations, supporting both NWS and NOS operational modeling. Operational assimilation of satellite ocean observation data requires careful calibration and validation to minimize the insertion of excess uncertainty into NOAA's operational forecasts.

Passive retrieval algorithm developments and improvements support the ongoing evolution of NOAA's Unified Forecast System to radiance-based assimilation, where feasible. The STAR-managed Community Surface Emissivity Model (CSEM) and Community Radiative Transfer Model (CRTM) implement STAR's passive retrieval algorithms for operationally translating between observed radiances and modeled geophysical parameters within the NOAA Unified Forecasting System. These passive retrieval algorithms enable the focus on radiance-based observation assimilation supporting the Joint Effort for Data assimilation Integration (JEDI), comprising US agencies and the United Kingdom (UK) Met Office.

3.2. Assimilation of Ocean Data into Models

For near-real-time and subseasonal–seasonal applications, NOAA employs satellite observations to assess the ocean state and its dynamics, as well as coupled ocean, atmosphere, and sea ice processes and fluxes of heat, moisture, and momentum for improved forecasts and outlooks. NOAA's operational global ocean model, the Real-Time Ocean Forecast System, currently assimilates SST, SSS, Absolute Dynamic Topography (ADT, similar to SSH), and sea ice concentration (passive microwave). Satellite ocean color observations inform predictive modeling on the absorption of solar radiance in the near-surface ocean, which has a biophysical feedback to ocean atmosphere heat and moisture fluxes. Developmental work is being carried out to assimilate satellite ocean color (chlorophyll) observations for initiating representation of the biological carbon cycle's photosynthetic base. Satellite sea surface roughness observations inform and constrain modeling of the surface wave state and sea ice extent, informing weather forecasting and subseasonal–seasonal outlooks. STAR recently brought satellite ocean data assimilation to the US NOS for operational regional/coastal ocean modeling, leading development of the US West Coast Operational Forecast System, which currently assimilates SST, ADT, and coastal high-frequency radar observations. Satellite SSS spatial resolution is an assimilation challenge due to finer scales of eastern boundary ocean dynamical features, notably eddies and filaments. STAR currently pursues better assimilation of high-latitude satellite SSS observations through an artificial intelligence approach to counter the impact of colder high-latitude waters on accurate satellite SSS retrievals.

4. Applications and User Support

Through leadership and satellite ocean observations, STAR works to address societal issues and develop relevant policies. Examples include co-leading the UN Ocean Decade Action titled "The Committee on Earth Observation Satellites–Coastal Observations, Applications, Services, and Tools (CEOS COAST)" [91], as well as the Group on Earth Observations' Blue Planet Initiative, which focuses on ocean and coastal observations for policy and decision making, aiming to bridge the gap between ocean and coastal observational data and societal needs for actionable information.

The STAR-led NOAA CoastWatch/OceanWatch [31], PolarWatch [92], and Coral Reef Watch [93] provide broad access to satellite-based ocean products, analyses, tools, and situational awareness applications that address the global oceans, focused regional and coastal ocean domains, and ocean cryosphere regions. The CoastWatch program, organized in four pillars (Regional or Thematic Nodes; Central Operations; Training, Communications and Outreach; and Innovation, Research and Applications), encompasses seven CoastWatch Nodes, each managed by a user-focused NOAA service, notably the National Ocean Service

(NOS), the National Weather Service (NWS), the National Marine Fisheries Service (NMFS), and NOAA Research. All CoastWatch Nodes share the same mission—connect people and applications to global and regional satellite data products for use in understanding, managing, and protecting ocean and coastal resources, and for assessing impacts of change in ecosystems, the environment, and climate. CoastWatch scientists lead research and co-design, co-develop new or enhanced exploitation of satellite ocean data for applications, and disseminate knowledge needed for informed decision making. For training, communications, and outreach, CoastWatch provides training courses, develops learning modules, and leads user engagement workshops. The CoastWatch Learning Portal [94], a collaboration with University of Maryland, hosts training modules for free and provides open access. The CoastWatch Data Portal [95] encompasses a browser-based one-stop-shop for finding, visualizing, and downloading oceanographic data, with over 150 near-real-time and science quality (delayed) products available for mapping. Through the integration of ArcGIS and CoastWatch Utilities Software (v 4.0.0), only a web browser is needed to access, visualize, and obtain the data available in the portal. CoastWatch performed over 35.8 million data transfers in 2022 alone. The OceanWatch Monitor [96] and OceanView [97] provide user-selected current and past analyses and visualizations of global and regional satellite ocean observations, spanning the available parameters.

4.1. Applications

A significant part of the ocean observation value chain entails extracting information from the data to provide actionable knowledge; consequently, the CoastWatch/OceanWatch Program develops and provides user-driven applications. Examples of successfully developed applications that have transitioned to use include fisheries and aquaculture, water quality assessment, ecosystem monitoring, ocean and coastal dynamics, transportation and safety, and climate and weather. Fisheries and aquaculture applications (SST, ocean color, currents, SSH) include nutrient assessments, bycatch minimization, favorable conditions for commercial fisheries, and ocean acidification. Water quality and habitat applications exploit SST, ocean color, optical imagery, and SAR data to assess estuary conditions, harmful algal blooms, ocean acidification, oil spills, etc. Ecosystem monitoring applications employ SST, SSH, ocean color, and SSS data for assessing habitats of temperature-sensitive species, as well as marine heat waves, currents, upwelling, distributions of ecologically important ecosystems, sediment plumes, freshwater influences in estuaries, and sea level rise impacts. Satellite SST, SSH, SSS, currents, and ocean color observations provide a basis for assessing ocean and coastal dynamics, including upwelling and mesoscale dynamic features, contributing to optimizing marine transportation and fishing efforts. Satellite ocean surface winds, sea surface roughness, and SSH data provide the marine transportation and safety sector information on dangerous conditions, surf and swell conditions, ice type and thickness, as well as improve tide and wave height forecasting for greater efficiency and safety. Optical imagery (e.g., from VIIRS) and SAR observations provide coastal inundation assessments for public safety and recovery. Additionally, STAR creates extended consistent satellite ocean observation datasets to address climate-scale questions and issues.

4.2. Polar Regions

Analysis tools and geophysical products developed by STAR enhance the understanding, monitoring, and situational awareness of Earth system environments and processes in the polar regions, notably remote sensing techniques and fit-for-purpose sea ice products supporting sea ice monitoring, numerical modeling, and prediction, advancing knowledge of the changing arctic sea ice cover across time scales. On the broader scale, to consolidate observing requirements and identify observing system gaps for properties of the cryosphere [98], STAR participates in the World Meteorological Organization (WMO) Rolling Review of Requirements (RRR) and Global Climate Observing System (GCOS) efforts.

Climate data records can enable better understanding of the relationships between various components of the climate system. For example, NOAA's satellite climate data records produced new information and insights on multi-decadal changes in arctic sea ice area, thickness, and volume. A recent STAR study [99] introduces a new perspective, based on ice longevity, for determining where ice is persistent and where it is disappearing (Figure 9). That research highlights the presence and persistence of sea ice in an area that directly influences arctic weather and climate, marine transportation, and ecosystems. These findings highlight that the arctic has become less ice-covered in all seasons, with summer and autumn having the most changes, with areal loss of perennial sea ice being the major factor in total sea ice loss in all seasons. Different mechanisms of the changing climate affect the thermodynamic and dynamic sea ice thickness processes.

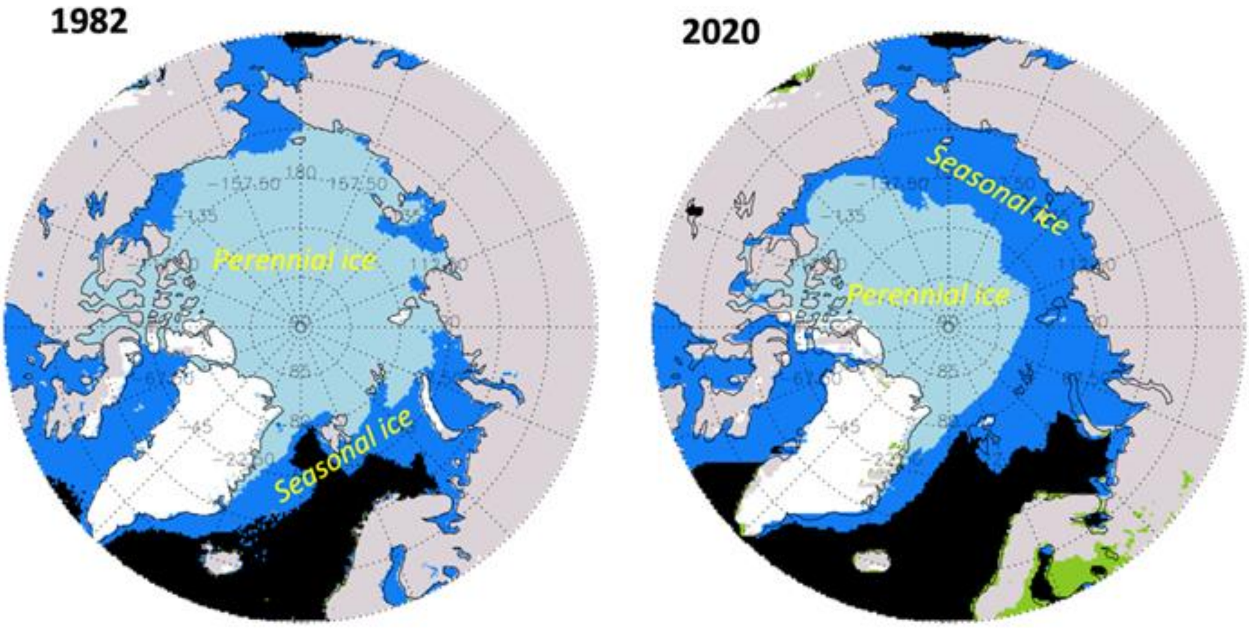

Figure 9. Spatial distribution of Arctic sea ice in 1982 (**left**) and 2020 (**right**) for perennial and seasonal sea ice and snow on land.

Results from passive microwave satellite data (AMSR2) show that Lagrangian dynamics account for almost half of ice thickness growth, depending on the region, providing critical new information for assessing ice processes in coupled models [61,100].

Recent work with satellite-derived cloud and sea ice products highlighted a somewhat surprising relationship between wintertime cloud anomalies and sea ice anomalies the following summer [101,102], with those summertime sea ice anomalies, in turn, driving an apparent positive feedback loop impacting cloud cover anomalies the subsequent winter [103]. The APP-x CDR enabled an assessment of the importance of arctic ice albedo feedback relative to snow albedo feedback [104]. Interestingly, in the arctic, the positive (increasing) trend of solar radiation absorption at the ocean surface due to sea ice decline is more than double the trend resulting from reductions in snow cover over land. Furthermore, in summer, the magnitude of the ice albedo feedback is four times larger than that of the snow albedo feedback; therefore, the dominant radiative feedback for the last few decades appears due to decreasing sea ice cover, not changes in terrestrial snow cover.

4.3. Ecosystem and Biogeochemical Applications

Actively targeting satellite remote sensing approaches for addressing marine ecosystem and biogeochemical data and information needs and challenges, STAR pursues enhancing and applying satellite ocean color measurements of chlorophyll, detritus, colored dissolved organic material (CDOM), and sediment to water quality applications, such as harmful algal bloom assessments and forecasting. The STAR-led CRW, employing SST observations to assess global SST anomalies, trends, hotspots, degree heating weeks, and coral bleaching alert areas, provides free, automated email alerts and critical decision support for coral reef ecosystem management and protection efforts. Additional relevant satellite-derived products address marine heatwaves, coral disease outbreak risk, light stress damage, and monitoring land-based sources of pollution, among other threats to the coral reef environment. Research efforts target projections of bleaching for coral reef areas.

4.3.1. Coral Reefs

The STAR-led NOAA CRW provides satellite and modeled products supporting conservation, restoration, and resilience-based research and management projects that aim to protect and/or restore coral reefs in a rapidly warming world. In times of low or no heat stress, users also apply CRW products to identify appropriate locations to implement conservation and restoration initiatives, for instance, to give transplanted corals or corals grown in situ the best chance at survival.

CRW satellite products, primarily based on SST measurements and updated in near-real time, aim to answer the question, "Is this coral reef currently at risk for bleaching?" These products (Figure 10) include operational daily global 5 km satellite coral bleaching heat stress products (including composites and animations), and daily 5 km satellite Virtual Stations (Regional Virtual Stations currently serving 214 coral reef regions and newly created single-pixel Virtual Stations for multiple US coral reefs). A free, automated Satellite Bleaching Alert email system alerts subscribers, twice per week, when heat stress conditions change on their reefs of interest. CRW also offers, among other tools, a daily global 5 km Marine Heatwave Watch (MHW) product (including new, regional MHW products); historical 5 km satellite Thermal History products; Coral Disease Outbreak Risk products (for Hawaii and the Great Barrier Reef, Australia); and Satellite Ocean Color Monitoring products (for Puerto Rico and Hawaii coral reefs). Additionally, CRW produces a modeled Four-Month Coral Bleaching Heat Stress Outlook (Figure 9) based on NOAA's Climate Forecast System version 2. The Outlook, updated weekly, provides information about potential future heat stress on reefs around the world, answering the question, "Will this reef be at risk for bleaching soon?".

In July 2023, responding to an exigent need, CRW developed single-pixel Virtual Stations [105] for key Florida reefs, consolidating critical CRW heat stress metrics for the individual 5 km $\times$ 5 km satellite pixels that overlay the reef sites. Stakeholders can now compare current heat stress levels across sites to assist with prioritization of current efforts by location; communication among stakeholders; subsequent relocation of coral colonies back into the water when the heat stress subsides; and monitoring and restoration activities. Working with local management partners, CRW also developed single-pixel Virtual Stations for key restoration and nursery reef sites in Puerto Rico and the US Virgin Islands. Going forward, CRW will develop additional single-pixel Virtual Stations for all remaining US coral reef areas and for selected key international coral reef sites.

4.3.2. Coastal Zones

Exploiting satellite ocean color observations, NOAA CoastWatch supports risk assessments in coastal zones, including the California-Harmful Algae Risk Mapping (C-HARM) system [106], developed in partnership with the Southern California Coastal Ocean Observing System (SCCOOS). C-HARM HAB products provide probability predictions of high levels of *Pseudo nitzschia* and their harmful neurotoxin, domoic acid. Human and wildlife consumers of shellfish contaminated with domoic acid are at risk of contracting Amnesic Shellfish Poisoning, which can be fatal, if not treated properly. Fisheries, aquaculture, and marine mammal rescue groups, including the West Coast Marine Mammal Stranding Network, need accurate information on a daily basis for making public health decisions and aiding preparations; consequently, C-HARM products serve a vital role in this regard.

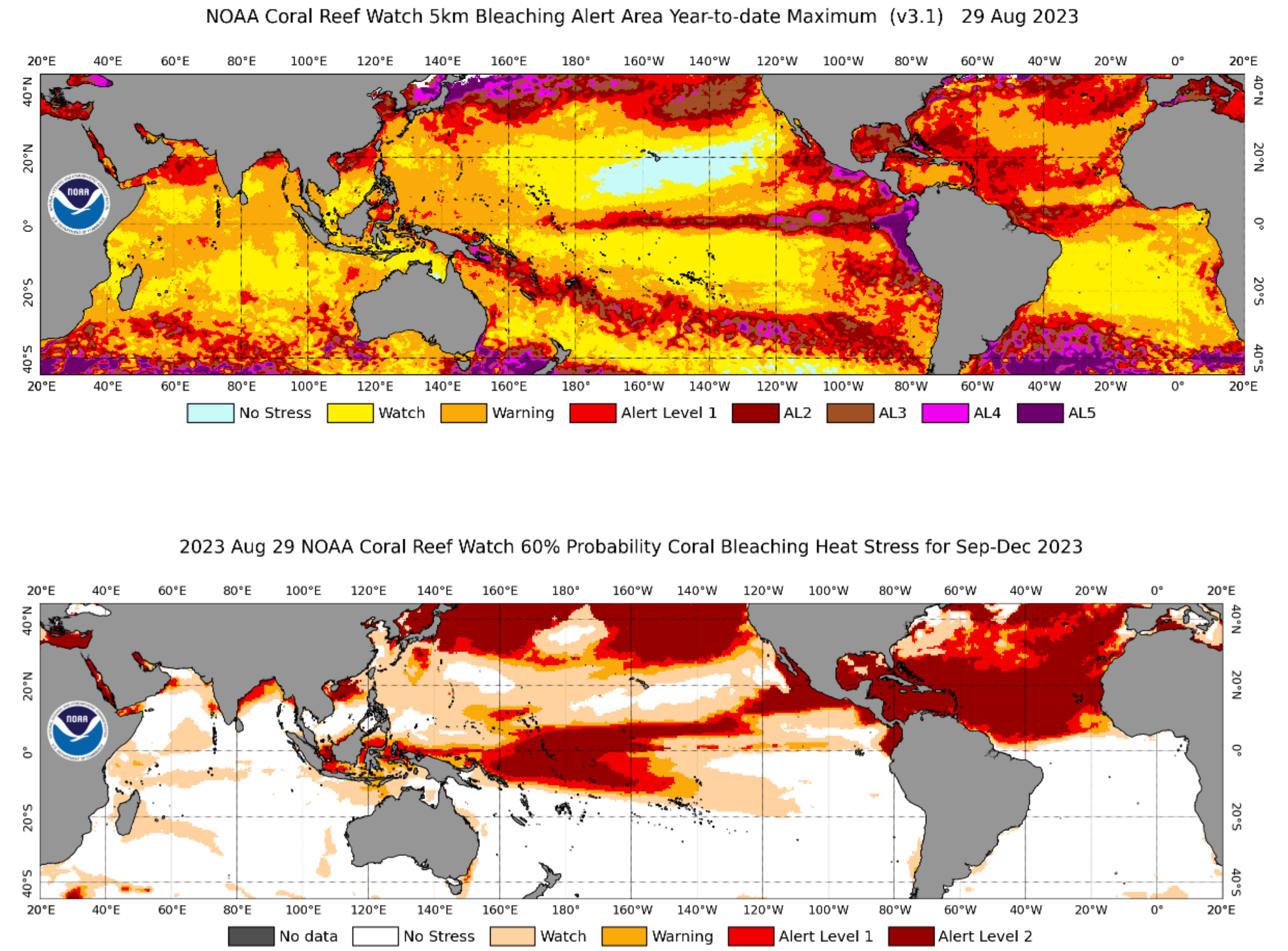

Figure 10. (**Top**) NOAA Coral Reef Watch composite 5 km Satellite Bleaching Alert Area 2023 Year-to-Date Maximum map, depicting the highest bleaching alert levels experienced by tropical coral reefs as of 29 August 2023. In 2023, severe marine heat stress (Bleaching Alert Levels 1 and 2) associated with mass coral bleaching and mortality occurred along Florida, in the Caribbean and Gulf of Mexico, throughout the eastern Tropical Pacific, and in swaths extending from the Sea of Japan to the South China Sea, and from eastern Papua New Guinea to the Cook Islands. (**Bottom**) NOAA Coral Reef Watch modeled Four-Month Coral Bleaching Heat Stress Outlook for 29 August 2023, showing predicted ocean heat stress (and corresponding bleaching alert levels) from September to December 2023.

Timely, accurate, and sustained observations for global coastal zones are essential for addressing existing and emerging societal issues, needs, and concerns, from coastal resiliency, flood forecasting, and disaster recovery to habitat monitoring, eutrophication, water quality, challenges of continued growth in coastal regions, and assessment of climate change impacts. The NOAA co-led CEOS COAST provides new and improved scientific/technical capabilities and continues to build global capacity for a more robust, end-to-end value chain supporting coastal stakeholders and global sustainable development [107,108].

COAST's user-driven efforts encourage broader utilization of Earth observations and other CEOS capabilities for societal benefits within coastal zones (e.g., Blue Economy; Sustainable Development Goals) [109]. User co-design and co-development are key to implementing COAST solutions [109]. High-impact regional pilot projects implemented by CEOS-COAST leverage the CEOS Analysis Ready Data (ARD) framework, employing higher-resolution datasets for the development of shoreline change assessments within Chesapeake Bay [110]. The CEOS-COAST team has additional products and applications in development.

Many global and regional partners seek such scientific and technical (e.g., geospatial and computational) support, affording specific opportunities for CEOS engagement, particularly through the Group on Earth Observations (GEO) Blue Planet and AquaWatch Initiatives, which are actively led and supported by NOAA/STAR and external stakeholders, including the Intergovernmental Oceanographic Commission (IOC)/Global Ocean Observing System (GOOS), United Nations (UN) Environment, the World Meteorological Organization, and the UN Decade of Ocean Science for Sustainable Development (2021–2030). In June 2021, the IOC endorsed CEOS COAST as an official UN Ocean Decade Contribution [91].

4.4. User Engagement and Decision-Making Support

In addition to employing regional nodes for user engagement, NOAA CoastWatch provides training on exploiting satellite ocean observations. Navigating vast amounts of satellite data can be overwhelming; consequently, CoastWatch offers structured courses to introduce users to oceanographic satellite products, the software and tools commonly used to analyze them, and ways to effectively use the data. CoastWatch/OceanWatch resources are free and accessible to all, regardless of class enrollment. An online Learning Portal, launched in 2023 in partnership with the University of Maryland, provides organization for the CoastWatch lectures, guides, and tutorials, receiving positive feedback.

An extensive and diverse user community worldwide regularly employs NOAA CRW's online global decision support system, employing its satellite and modeled products for coral reef management, monitoring, research, and protection of coral reef ecosystems in a rapidly warming world. CRW's broad engagement in research, development, and operations, and its extensive communication and outreach with its users and partners, addresses a critical global need for coral health remote prediction, monitoring, and assessment and allows NOAA to meet user needs and established NOAA missions, goals, and objectives.

Marine resource managers, scientists, decision makers (including political officials), in-water coral reef monitoring networks, and other worldwide coral reef ecosystem stakeholders rely on NOAA's coral reef satellite and modeled products and alerts to predict and monitor in near-real time changes in thermal stress in the coral reef environment; prepare and prioritize resources for events (e.g., mass coral bleaching or disease) that have long-term, ecologically significant impacts on coral and reef health and function; communicate, quickly and broadly, among agencies, the press, and the public, changes in the status of local reefs; implement timely, protective responses and adaptation actions; analyze climate change impacts (e.g., bleaching, disease, and mortality) on coral reefs; and assess when specific reefs are vulnerable or resilient to anthropogenic climate change and its impacts. Using information that the CRW team and its products provide, users have activated local coral bleaching and disease response plans, incident action plans, and associated in-water monitoring networks; rescued native and rare corals; and shaded/cooled key nursery reefs. Stakeholders have also worked to reduce local stressors, such as by closing scuba diving and fishing areas during times of high-bleaching-level heat stress. For example, in May 2016, following CRW's alerts and communications, Thailand's Government closed multiple key reef sites to scuba diving and other activities. In June 2022, the Nha Trang Bay Management Authority closed popular scuba diving areas off of Hon Mun Island, Vietnam. Critical product and data updates are quickly and broadly communicated to the user community and partners worldwide, along with significant contributions to quarterly and monthly climate reports and "Current Conditions Reports" issued by major partners to their in-water monitoring networks, including the Southeast Florida Action Network BleachWatch Program, Mote Marine Laboratory/Florida Keys National Marine Sanctuary BleachWatch Program, Hawaii Eyes of the Reef, the Caribbean Regional Climate Centre/Caribbean Institute for Meteorology and Hydrology, and the Coastal Oceans Research and Development Indian Ocean–East Africa (CORDIO) network, among others. CRW efforts inform many national and international assessments of coral reef conditions, with staff regularly publishing in the scientific literature. User engagement efforts include responding to frequent requests for information about the coral reef products and datasets; consequently, CRW maintains an online tutorial and detailed methodology page about its daily global 5 km satellite products and conducts other outreach and educational activities to enhance understanding and ensure appropriate application of the decision support products and data.

With the developing El Niño of 2023–2024, NOAA CRW directly supports in-water monitoring, conservation, rescue, restoration, and communication efforts, working closely with partners and decision makers in areas impacted by coral reef heat stress. In Florida, where a severe marine heatwave and mass bleaching event continues (as of this writing), CRW continues its extensive communication with in-water partners, guiding the application of CRW products (including newly developed [105] single-pixel satellite Virtual Stations) to guide monitoring, mitigation, and triage efforts, including relocating and protecting thousands of corals in onshore or deeper-water nurseries. Such efforts extend to communicating with global partners that are experiencing heat stress events and documented mass coral bleaching, as well as providing guidance on the strong El Niño as it relates to current/projected heat stress on their reefs. In direct collaboration with the Australian Government and other local stakeholders coordinating information sharing and messaging to global media outlets, as in 2016, 2017, 2020, and 2021, CRW provided advance warning and near-real-time satellite monitoring for the 2022–2023 heat stress and subsequent mass coral bleaching event on the Great Barrier Reef. Leading up to and during severe heat stress and mass bleaching events around the world, CRW frequently provides interviews for US and international press articles, with its products featured across press and social media, notably the daily global 5 km satellite coral bleaching heat stress products and modeled Four-Month Coral Bleaching Heat Stress Outlook.

Through leadership and satellite ocean observations, STAR works to address societal issues and support relevant policies. Examples include co-leading the UN Ocean Decade Action CEOS-COAST, as well as the Group on Earth Observations' Blue Planet Initiative, focusing on ocean and coastal observations for policy and decision making, aiming to bridge the gap between ocean and coastal observations and delivering actionable information for societal needs.

5. Discussion

Fulfilling its crucial role in NOAA, STAR continues to support and advance satellite oceanography from the R&D and operational perspectives, with these inherently coupled domains furthered through extensive internal and external collaborations and partnerships. From the R&D perspective, key foci and activity areas by STAR and the broader Earth observing community over the next decade and beyond follow.

STAR will actively facilitate development and exploitation of new missions in the domains of ocean, coastal, and inland waters. The implementation of geostationary ocean color, as part of the forthcoming GEO-XO satellite system, represents an extremely exciting development that will significantly advance ecosystem monitoring and forecasting for US waters, significantly expanding capabilities for research, applications, and operations. NOAA will also continue to rely on leveraging non-NOAA satellite data streams for its ocean and aquatic observations. Recent and upcoming agency launches, including those of SWOT, PACE, and NISAR, will provide important new experimental and operational data streams for NESDIS to develop and exploit in support of NOAA and non-NOAA stakeholders. Greater utilization of data from commercial platforms likewise will be essential as complementary to the observations from agency platforms.

Developing new and improved products for ocean basins, coastal zones, and inland waters continues to be a high-priority need, particularly for the rapidly changing polar regions (Arctic and Antarctic). In particular, pursuing and exploiting hyperspectral (e.g., PACE), higher spatial, temporal, and spectral resolution capabilities of existing and planned satellite sensors is a crucial need and priority; notably, in this regard, new PACE hyperspectral data for ocean color research and applications, as well as commercial data, will be invaluable, especially high-resolution optical and SAR imagery, notably enabling efforts in critical coastal regimes. Required efforts include continued development of fully focused SAR altimetry approaches for various aquatic applications. Identifying, tracking, and extracting dynamic processes, events, and features from multi-sensor and multi-parameter satellite imagery (e.g., MESI [32]) present compelling capabilities supporting diverse users and applications, e.g., plumes, blooms, habitat assessments for fisheries and aquaculture management, marine carbon dioxide removal (MCDR), and coastal blue carbon for climate assessments.

Users need further development of gap-reduced or gap-filled products, including multi-mission merged/fused Level-3 products, as well as gap-filled blended Level-4 analyses, with spatial and temporal feature resolution maximally preserved. Many users indicate a strong preference for these types of products to facilitate exploiting increasing information content while reducing data volumes, number of files, cloud impacts, etc. Additionally, long-identified requirements across diverse NOAA users exist for developing consistent, long-term, multi-mission times series for complementary physical, biological, and biogeochemical ocean parameters and their anomalies. Within NOAA, addressing the wide range of relevant climate research and other longer-term applications requires using STAR enterprise algorithm systems. Ocean color radiometry, ocean surface vector winds, sea surface height, and sea surface temperature time series currently are high priorities within NESDIS that will leverage and integrate both NOAA and non-NOAA data streams.

Significant advances in data science and informatics for ocean research and applications need to complement developments in new and improved data and derived products. The broader community progresses with exciting ongoing transitions into cloud-based solutions, as well as broader exploitation of Artificial Intelligence (AI) and Machine Learning (ML) approaches for data processing, product development, forecasting, etc. STAR research and development activities support and advance these trends, which are expected to provide more equitable access to data and derived information. Emerging ecosystem applications include using AI approaches for identifying and forecasting eutrophication and hypoxia in coastal waters, which will be particularly important for developing nations and transitioning economies as they strive for sustainable development in a rapidly changing environment.

Curation and translation of ocean, coastal, and inland water data products to provide better information and greater knowledge for users proves to be increasingly important. Given petabytes of data and hundreds of products, STAR scientists, as part of broader global community efforts, increasingly play the role of trusted advisor and curator to users, identifying fit-for-purpose products for their particular needs and applications within their domain. Immediate priorities include advancing the use of satellite products in ocean and ecological forecasting, aiming to address underutilization of observation data in marine modeling. This underutilization can be attributed to challenges in modeling complex interrelationships between observed parameters; data latency, accuracy, and uncertainties in what is measured and inferred; and spatial resolution. With respect to spatial resolution challenges, data thinning may be required to align with model resolution, as well as the data may be non-representative when pixel resolution exceeds the resolution of targeted modeled features and processes. Numerical ocean forecasting and prediction have predominantly focused on representing physical states and processes, for which STAR has recently brought new data streams into operational assimilation, notably sea surface salinity and absolute dynamic topography derived from satellite altimetry. Developmental efforts include exploiting satellite chlorophyll-a observations for both biophysical feedback processes and ecosystem modeling, as well as new satellite sea ice observations, notably sea ice thickness from satellite infrared observations. New sea ice observation capabilities from altimetry, synthetic aperture radar, and passive microwave are currently in progress.

A significant focus on exploiting satellite observations of sea ice aims to enable and support NOAA's pending new operational coupled (ocean, atmosphere, and sea ice) model. Integration of data across missions (NOAA and non-NOAA), parameters (e.g., physical, optical, biological, and biogeochemical), domains (e.g., land-sea, ocean-atmosphere), and disciplines (e.g., natural sciences and social sciences) needs to provide a foundation for augmenting the development of new and improved satellite-based indicators that measure both outputs and outcomes, as well as enhanced scientific support and service delivery.

6. Conclusions

The NOAA Center for Satellite Applications and Research (STAR) broadly engages in research, development, and operational support to improve formulation, availability, and utilization of ocean and coastal observations from space; keep NOAA on the leading edge of monitoring and predicting the global environment; and provide, for the benefit of society, critical, timely, and fit-for-purpose information for global stakeholders about changing ocean conditions and associated impacts.

The complexity and criticality of these scientific and technical challenges and efforts and, more so, desired societal impacts, require a global partnership. In advancing the routine and sustained use of satellite oceanography data, NOAA actively coordinates with EUMETSAT and other global and regional partners to develop and implement the collaborative international operational satellite oceanography (OSO) initiative. The OSO initiative, started in 2018, has, to date, held three related international community symposia. The most recent symposium (2023), held in Busan, South Korea, was recognized as an official event of the U.N. Decade of Ocean Science for Sustainable Development. Further details of these events are available in the respective OSO Symposia (OSOS) Reports [111,112]. Working together as a community of EO data providers, the collective ability to positively impact the future is very promising.

Author Contributions: Conceptualization, E.B.; Writing–Original Draft Preparation, E.B., P.S.C., J.L.D.L.C., S.R.H., A.I., J.K., V.L., E.W.L., D.A.B., Y.L., X.L., M.W., J.W. and P.M.D.; Writing–Review and Editing, E.B. and P.M.D. All authors have read and agreed to the published version of the manuscript.

Funding: This NOAA effort was funded by the NOAA Product Development, Readiness, and Application (PDRA) Ocean Re-mote Sensing (ORS) and Jason/Sentinel-6 Programs. The NOAA Coral Reef Conservation Program provided co-author Jacqueline De La Cour's funding support via NOAA grant NA19NES4320002 (Cooperative Institute for Satellite Earth System Studies) at the University of Maryland/ESSIC.

Conflicts of Interest: Author Jianwei Wei was employed by the company Global Science and Technology, Inc. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

Acronyms (alphabetical order)

ABI	Advanced Baseline Imager
ACSPO	Advanced Clear Sky Processor for Ocean
$a_{dg}(443)$	absorption coefficient of detritus and colored dissolved organic matter at 443 nm
ADT	Absolute Dynamic Topography
AHI	Advanced Himawari Imager
AI	artificial intelligence
AM	aggregated mid-morning data from the MetOp-FG-A/B/C satellites
AMSR2	Advanced Microwave Scanning Radiometer 2
AMSR3	Advanced Microwave Scanning Radiometer 3
$a_{ph}(443)$	light absorption coefficient of phytoplankton at 443 nm
APP-x	Polar Pathfinder

ArcGIS	a family of client, server and online geographic information system software developed and maintained by Esri.
ARMS	ACSPO Regional Monitor for SST
ASIP	Alaskan Sea Ice Program
AVHR	Advanced Very High-Resolution Radiometer
$b_{bp}(443)$	light backscattering coefficient of particles at 443 nm
BOSC	Blended Ocean Surface Currents
Cal/Val	calibration/validation
CDOM	colored dissolved organic matter
CDR	climate data records
CEOS	Committee on Earth Observation Satellites
CEOS-COAST	Committee on Earth Observation Satellite's Coastal Observations, Applications, Services and Tools team
CGMS	Coordination Group for Meteorological Satellites
C-HARM	California-Harmful Algae Risk Mapping
Chl-a	chlorophyll-a
CLW	cloud liquid water
CORDIO	Coastal Oceans Research and Development Indian Ocean–East Africa
CPHC	Central Pacific Hurricane Center
CRISTAL	Copernicus Polar Ice and Snow Topography Altimeter
CRTM	Community Radiative Transfer Model
CRW	Coral Reef Watch
CryoSat-2	a European Space Agency Earth Explorer Mission dedicated to measuring polar sea ice thickness and monitoring changes in ice sheets
CSEM	Community Surface Emissivity Model
CW Utilities	NOAA CoastWatch Utilities data acquisition tool
DINEOF	Data Interpolating Empirical Orthogonal Function
DM	delayed mode
DY	a single daily product
EKE	eddy kinetic Energy
ENSO	El Nino Southern Oscillation
EOF	Empirical Orthogonal Functions
EPS-SG	EUMETSAT Polar System–Second Generation
ERS-1	European Remote-Sensing Satellite-1
ESA	European Space Agency
EUMETCast	a method of disseminating various (mainly satellite based) meteorological data operated by the European Organisation for the Exploitation of Meteorological Satellites
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FEMA	Federal Emergency Management Agency
FRAC	Full Resolution Area Coverage
GAC	Global Area Coverage
GCOM-C	Global Change Observation Mission-Climate
GCOM-W1	Global Change Observation Mission–Water 1
GEO	geostationary
GHRSST	Group for High Resolution Sea Surface Temperature
GOES-R	Geostationary Operational Environmental Satellites R-series
GOSAT-GW	Global Observing SATellite for Greenhouse gases and Water cycle
GPB	Geo-Polar Blended
GSFC	Goddard Space Flight Center
HAB	harmful algal bloom
ICESat-2	Ice, Cloud and land Elevation Satellite 2
IOCCG	International Ocean Colour Coordinating Group
iQuam	NOAAs in situ SST Quality Monitor
ISRO	Indian Space Research Organization
IUU	illegal, unreported, and unregulated fishing
JAXA	Japan Aerospace Exploration Agency
JEDI	Joint Effort for Data assimilation Integration

JPSS	Joint Polar Satellite System
JTWC	Joint Typhoon Warning Center
K_d	diffuse attenuation coefficient
L3C	Level three collated
L3S	Level three super-collated
L3U	level three uncollated
L4	Level-4
LEO	low Earth orbit
Lidar	Light Detection and Ranging
MBT	microwave brightness temperature
MDA	an international space mission partner based in Canada
MESI	Multiparameter Eddy Significance Index
FCI	Flexible Combined Imager on the Meteosat Third Generation Satellite
METImage	Meteorological Imager
METOP	(ASCAT) Meteorological Operational satellites advanced scatterometer
MetOp SG	MetOp Second Generation
MICROS	Monitor of IR Clear-sky Radiances over Ocean for SST
MLD	Mixed Layer Depth
MOBY	Marine Optical BuoY
MODIS	Moderate Resolution Imaging Spectroradiometer
MSG SEVIRI	Meteosat Second Generation Spinning Enhanced Visible Infra-Red Imager
MSL12	Multi-Sensor Level-1 to Level-2
MWI	Microwave Imager
NASA	National Aviation and Space Administration
NESDIS	National Environmental Satellite, Data and Information Service
NHC	National Hurricane Center
NIR	near-infrared
NIR	RBG-red, green, and blue bands
$nL_w(\lambda)$	Normalized water-leaving radiance
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOAA-20	the first of NOAA’s latest generation of US JPSS polar-orbiting satellites
NOAA-21	the second of NOAA’s latest generation of US JPSS polar-orbiting satellites
NOS	National Ocean Service
NRCS	normalized radar cross section
NRT	near-real-time
NRTAVS	Near Real-Time Altimeter Validation System
NWS	National Weather Service
OCI	ocean color index
OCR	ocean color radiometry
OHC	operational ocean heat content
OLCI	Ocean and Land Colour Instrument
OPC	Ocean Prediction Center
OSCAT	OceanSat 2 Scatterometer
OSTST	Ocean Surface Topography Science Team
OSVW	ocean surface vector winds
P-3	a type of military aircraft
PADI	Professional Association of Diving Instructors
PAR	photosynthetically available radiation
PM	aggregated afternoon data from the JPSS NPP/N20/N21 and Aqua MODIS satellites
PO.DAAC	NASA Physical Oceanography Distributed Active Archive Center
QuikSCAT	Quick Scatterometer
R&D	research and development
RADARSAT RCM	Canadian Space agency’s RadarSat Constellation Mission
RADS	Radar Altimeter Database System
RAN	reanalysis
R_{rs}	Remote sensing reflectance

RTOFS	Real-Time Ocean Forecast System
S3A	Sentinel-3A
S3B	Sentinel-3B
SAR	synthetic aperture radar
SCA	Scatterometer
SCCOOS	Southern California Coastal Ocean Observing System
SFMR	Stepped Frequency Microwave Radiometer
SGLI	Second-Generation Global Imager
SIDEx	Sea Ice Dynamic Experiment
SIR	Sargassum Inundation Reports
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity
SNPP	Suomi National Polar-orbiting Partnership
SPM	suspended particulate matter
SQUAM	SST Quality Monitor
SSH	sea-surface height
SSS	sea-surface salinity
SST	sea-surface temperature
SSW	sea surface wind speed
STAR	Center for Satellite Applications and Research
TC	Tropical cyclone
TCHP	tropical cyclone heat potential
TPW	total precipitable water
UAS	unmanned aircraft system
UFSCM	NOAA's United Forecast System Coupled Model
UK	United Kingdom
UN	United Nations
UN Ocean Decade	United Nations Decade of Ocean Science for Sustainable Development
US	United States
USNIC	US National Ice Center
VIIRS	Visual Infrared Imaging Radiometer Suite
VMax	Vertical Maximum
WP-3D	a type of Lockheed Orion plane used to take measurements in storms
WSC	water surface conditions

References

1. Schmit, T.J.; Griffith, P.; Gunshor, M.M.; Daniels, J.M.; Goodman, S.J.; Lebair, W.J. A Closer Look at the ABI on the GOES-R Series. *Bull. Am. Meteorol. Soc.* **2017**, *98*, 681–698. [CrossRef]
2. Chen, H.; Xiong, X.; Link, D.O.; Sun, C.; Chiang, K. V NOAA-20 Visible Infrared Imaging Radiometer Suite Day–Night Band on-Orbit Calibration and Performance. *J. Appl. Remote Sens.* **2020**, *14*, 34516. [CrossRef]
3. Eldardiry, H.; Hossain, F.; Srinivasan, M.; Tsontos, V.M. Success Stories of Satellite Radar Altimeter Applications. *Bull. Am. Meteorol. Soc.* **2022**, *103*, E33–E53. [CrossRef]
4. AMSRs Advanced Microwave Scanning Radiometer Series. Available online: https://www.eorc.jaxa.jp/AMSR/index_en.html (accessed on 12 April 2024).
5. Entekhabi, D.; Yueh, S.H.; Bindlish, R.; Entin, J.K.; Garcia, M. SMAP Science and Application Results. In Proceedings of the IGARSS 2022–2022 IEEE International Geoscience and Remote Sensing Symposium, Kuala Lumpur, Malaysia, 17–22 July 2022; pp. 4224–4227.
6. Ricciardulli, L.; Manaster, A. Intercalibration of ASCAT Scatterometer Winds from MetOp-A,-B, and-C, for a Stable Climate Data Record. *Remote Sens.* **2021**, *13*, 3678. [CrossRef]
7. Dabboor, M.; Olthof, I.; Mahdianpari, M.; Mohammadimanesh, F.; Shokr, M.; Brisco, B.; Homayouni, S. The RADARSAT Constellation Mission Core Applications: First Results. *Remote Sens.* **2022**, *14*, 301. [CrossRef]
8. Potin, P.; Rosich, B.; Miranda, N.; Grimont, P. Sentinel-1 Mission Status. *Procedia Comput. Sci.* **2016**, *100*, 1297–1304. [CrossRef]
9. Gordon, H.R.; Wang, M. Retrieval of Water-Leaving Radiance and Aerosol Optical Thickness over the Oceans with SeaWiFS: A Preliminary Algorithm. *Appl. Opt.* **1994**, *33*, 443–452. [CrossRef] [PubMed]
10. Wang, M. Remote Sensing of the Ocean Contributions from Ultraviolet to Near-Infrared Using the Shortwave Infrared Bands: Simulations. *Appl. Opt.* **2007**, *46*, 1535–1547. [CrossRef]
11. Wang, M.; Son, S.H. VIIRS-Derived Chlorophyll-a Using the Ocean Color Index Method. *Remote Sens. Environ.* **2016**, *182*, 141–149. [CrossRef]

12. Wang, M.; Jiang, L.; Mikelsons, K.; Liu, X. Satellite-Derived Global Chlorophyll-a Anomaly Products. *Int. J. Appl. Earth Obs. Geoinf.* **2021**, *97*, 102288. [CrossRef]
13. Wang, M.; Son, S.H.; Harding, L.W. Retrieval of Diffuse Attenuation Coefficient in the Chesapeake Bay and Turbid Ocean Regions for Satellite Ocean Color Applications. *J. Geophys. Res. Ocean.* **2009**, *114*, C10011. [CrossRef]
14. Wei, J.; Wang, M.; Jiang, L.; Yu, X.; Mikelsons, K.; Shen, F. Global Estimation of Suspended Particulate Matter from Satellite Ocean Color Imagery. *J. Geophys. Res. Ocean.* **2021**, *126*, e2021JC017303. [CrossRef] [PubMed]
15. Wei, J.; Wang, M.; Mikelsons, K.; Jiang, L.; Kratzer, S.; Lee, Z.; Moore, T.; Sosik, H.M.; Van der Zande, D. Global Satellite Water Classification Data Products over Oceanic, Coastal, and Inland Waters. *Remote Sens. Environ.* **2022**, *282*, 113233. [CrossRef]
16. Goldberg, M.D.; Kilcoyne, H.; Cikanek, H.; Mehta, A. Joint Polar Satellite System: The United States next Generation Civilian Polar-Orbiting Environmental Satellite System. *J. Geophys. Res. Atmos.* **2013**, *118*, 13463–13475. [CrossRef]
17. Donlon, C.; Berruti, B.; Buongiorno, A.; Ferreira, M.H.; Féménias, P.; Frerick, J.; Goryl, P.; Klein, U.; Laur, H.; Mavrocordatos, C.; et al. The Global Monitoring for Environment and Security (GMES) Sentinel-3 Mission. *Remote Sens. Environ.* **2012**, *120*, 37–57. [CrossRef]
18. Hu, C.; Lee, Z.; Franz, B. Chlorophyll a Algorithms for Oligotrophic Oceans: A Novel Approach Based on Three-Band Reflectance Difference. *J. Geophys. Res. Ocean.* **2012**, *117*, C01011. [CrossRef]
19. Clark, D.K.; Gordon, H.R.; Voss, K.J.; Ge, Y.; Broenkow, W.; Treess, C. Validation of Atmospheric Correction over the Oceans. *J. Geophys. Res. Atmos.* **1997**, *102*, 17209–17217. [CrossRef]
20. Wang, M.; Liu, X.; Tan, L.; Jiang, L.; Son, S.; Shi, W.; Rausch, K.; Voss, K. Impacts of VIIRS SDR Performance on Ocean Color Products. *J. Geophys. Res. Atmos.* **2013**, *118*, 10347–10360. [CrossRef]
21. Wang, M.; Liu, X.; Jiang, L.; Son, S. Visible Infrared Imaging Radiometer Suite Ocean Color Products. *VIIRS Ocean Color Algorithm Theoretical Basis Document (ATBD)*, 68 pp., NOAA/NESDIS/STAR, On-Line Version 1.0 NOAA, June 2017. Available online: https://www.star.nesdis.noaa.gov/jpss/documents/ATBD/ATBD_OceanColor_v1.0.pdf (accessed on 26 June 2024).
22. Wang, M.; Jiang, L.; Son, S.; Liu, X.; Voss, K.J. Deriving Consistent Ocean Biological and Biogeochemical Products from Multiple Satellite Ocean Color Sensors. *Opt. Express* **2020**, *28*, 2661. [CrossRef]
23. Platt, T.; Sathyendranath, S.; Caverhill, C.M.; Lewis, M.R. Ocean Primary Production and Available Light: Further Algorithms for Remote Sensing. *Deep Sea Res. Part A Oceanogr. Res. Pap.* **1988**, *35*, 855–879. [CrossRef]
24. Yu, X.; Lee, Z.; Shen, F.; Wang, M.; Wei, J.; Jiang, L.; Shang, Z. An Empirical Algorithm to Seamlessly Retrieve the Concentration of Suspended Particulate Matter from Water Color across Ocean to Turbid River Mouths. *Remote Sens. Environ.* **2019**, *235*, 111491. [CrossRef]
25. Liu, X.; Wang, M. Gap Filling of Missing Data for VIIRS Global Ocean Color Products Using the DINEOF Method. *IEEE Trans. Geosci. Remote Sens.* **2018**, *56*, 4464–4476. [CrossRef]
26. Liu, X.; Wang, M. High Spatial Resolution Gap-Free Global and Regional Ocean Color Products. *IEEE Trans. Geosci. Remote Sens.* **2023**, *61*, 3271465. [CrossRef]
27. Liu, X.; Wang, M. Global Daily Gap-Free Ocean Color Products from Multi-Satellite Measurements. *Int. J. Appl. Earth Obs. Geoinf.* **2022**, *108*, 102714. [CrossRef]
28. Alvera-Azcárate, A.; Barth, A.; Rixen, M.; Beckers, J.M. Reconstruction of Incomplete Oceanographic Data Sets Using Empirical Orthogonal Functions: Application to the Adriatic Sea Surface Temperature. *Ocean Model.* **2005**, *9*, 325–346. [CrossRef]
29. Beckers, J.M.; Rixen, M. EOF Calculations and Data Filling from Incomplete Oceanographic Datasets. *J. Atmos. Ocean. Technol.* **2003**, *20*, 1839–1856. [CrossRef]
30. NOAA STAR NOAA STAR Ocean Color Science Team. Available online: https://www.star.nesdis.noaa.gov/socd/mecb/color/index.php (accessed on 19 February 2024).
31. NOAA CoastWatch. Available online: https://coastwatch.noaa.gov/cwn/index.html (accessed on 19 February 2024).
32. Roman-Stork, H.L.; Byrne, D.A.; Leuliette, E.W. MESI: A Multiparameter Eddy Significance Index. *Earth Sp. Sci.* **2023**, *10*, e2022EA002583. [CrossRef]
33. Walton, C.C.; Pichel, W.G.; Sapper, J.F.; May, D.A. The Development and Operational Application of Nonlinear Algorithms for the Measurement of Sea Surface Temperatures with the NOAA Polar-Orbiting Environmental Satellites. *J. Geophys. Res. Oceans* **1998**, *103*, 27999–28012. [CrossRef]
34. McClain, E.P.; Pichel, W.G.; Walton, C.C. Comparative Performance of AVHRR-Based Multichannel Sea Surface Temperatures. *J. Geophys. Res. Ocean.* **1985**, *90*, 11587–11601. [CrossRef]
35. Wu, X.; Menzel, W.P.; Wade, G.S. Estimation of Sea Surface Temperatures Using GOES-8/9 Radiance Measurements. *Bull. Am. Meteorol. Soc.* **1999**, *80*, 1127–1138. [CrossRef]
36. Maturi, E.; Harris, A.; Merchant, C.; Mittaz, J.; Potash, B.; Meng, W.; Sapper, J. NOAA's Sea Surface Temperature Products from Operational Geostationary Satellites. *Bull. Am. Meteorol. Soc.* **2008**, *89*, 1877–1888. [CrossRef]
37. Petrenko, B.; Ignatov, A.; Kihai, Y.; Heidinger, A. Clear-Sky Mask for the Advanced Clear-Sky Processor for Oceans. *J. Atmos. Ocean. Technol.* **2010**, *27*, 1609–1623. [CrossRef]
38. Petrenko, B.; Ignatov, A.; Kihai, Y.; Stroup, J.; Dash, P. Evaluation and Selection of SST Regression Algorithms for JPSS VIIRS. *J. Geophys. Res.* **2014**, *119*, 4580–4599. [CrossRef]
39. Petrenko, B.; Ignatov, A.; Kihai, Y.; Dash, P. Full Access Sensor-Specific Error Statistics for SST in the Advanced Clear-Sky Processor for Oceans. *J. Atmos. Ocean. Technol.* **2016**, *33*, 345–359. [CrossRef]

40. Ignatov, A.; Gladkova, I.; Ding, Y.; Shahriar, F.; Kihai, Y.; Zhou, X. JPSS VIIRS Level 3 Uncollated Sea Surface Temperature Product at NOAA. *J. Appl. Remote Sens.* **2017**, *11*, 32405. [CrossRef]
41. Petrenko, B.; Pryamitsyn, V.; Ignatov, A.; Jonasson, O.; Kihai, Y. AVHRR GAC Sea Surface Temperature Reanalysis Version 2. *Remote Sens.* **2022**, *14*, 3165. [CrossRef]
42. Jonasson, O.; Ignatov, A.; Pryamitsyn, V.; Petrenko, B.; Kihai, Y. JPSS VIIRS SST Reanalysis Version 3. *Remote Sens.* **2022**, *14*, 3476. [CrossRef]
43. Pryamitsyn, V.; Petrenko, B.; Ignatov, A.; Kihai, Y. Metop First Generation AVHRR FRAC SST Reanalysis Version 1. *Remote. Sens.* **2021**, *13*, 4046. [CrossRef]
44. Jonasson, O.; Ignatov, A.; Petrenko, B.; Pryamitsyn, V.; Kihai, Y. NOAA MODIS SST Reanalysis Version 1. *Remote Sens.* **2023**, *15*, 5589. [CrossRef]
45. Dash, P.; Ignatov, A.; Kihai, Y.; Sapper, J. The SST Quality Monitor (SQUAM). *J. Atmos. Ocean. Technol.* **2010**, *27*, 1899–1917. [CrossRef]
46. Liang, X.; Ignatov, A. Monitoring of IR Clear-Sky Radiances over Oceans for SST (MICROS). *J. Atmos. Ocean. Technol.* **2011**, *28*, 1228–1242. [CrossRef]
47. Ding, Y.; Ignatov, A.; He, K.; Gladkova, I. ACSPO Regional Monitor for SST (ARMS). In Proceedings of the GHRSTT XIX: Science Team Meeting, Darmstadt, Germany, 4–8 June 2018.
48. Xu, F.; Ignatov, A. In Situ SST Quality Monitor (IQuam). *J. Atmos. Ocean. Technol.* **2014**, *31*, 164–180. [CrossRef]
49. He, K.; Ignatov, A.; Kihai, Y.; Cao, C.; Stroup, J. Sensor Stability for SST (3s): Toward Improved Long-Term Characterization of AVHRR Thermal Bands. *Remote Sens.* **2016**, *8*, 346. [CrossRef]
50. Maturi, E.; Harris, A.; Mittaz, J.; Sapper, J.; Wick, G.; Zhu, X.; Dash, P.; Koner, P. A New High-Resolution Sea Surface Temperature Blended Analysis. *Bull. Am. Meteorol. Soc.* **2017**, *98*, 1015–1026. [CrossRef]
51. Lance, V.P. (NOAA) First Report of the NESDIS SST Working Group August 2021 Advancing NESDIS Sea Surface Temperature to Fulfill NOAA Requirements and; 2021.
52. Key, J.R.; Mahoney, R.; Liu, Y.; Romanov, P.; Tschudi, M.; Appel, I.; Maslanik, J.; Baldwin, D.; Wang, X.; Meade, P. Snow and Ice Products from Suomi NPP VIIRS. *J. Geophys. Res. Atmos.* **2013**, *118*, 12816–12830. [CrossRef]
53. Meier, W.N.; Stewart, J.S.; Liu, Y.; Key, J.; Miller, J.A. Operational Implementation of Sea Ice Concentration Estimates from the AMSR2 Sensor. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2017**, *10*, 3904–3911. [CrossRef]
54. Dworak, R.; Liu, Y.; Key, J.; Meier, W.N. A Blended Sea Ice Concentration Product from Amsr2 and Viirs. *Remote Sens.* **2021**, *13*, 2982. [CrossRef]
55. Hoffman, J.P.; Ackerman, S.A.; Liu, Y.; Key, J.R. A 20-Year Climatology of Sea Ice Leads Detected in Infrared Satellite Imagery Using a Convolutional Neural Network. *Remote Sens.* **2022**, *14*, 5763. [CrossRef]
56. Hoffman, J.P.; Ackerman, S.A.; Liu, Y.; Key, J.R.; McConnell, I.L. Application of a Convolutional Neural Network for the Detection of Sea Ice Leads. *Remote Sens.* **2021**, *13*, 4571. [CrossRef]
57. Liu, Y.; Dworak, R.; Key, J. Ice Surface Temperature Retrieval from a Single Satellite Imager Band. *Remote Sens.* **2018**, *10*, 1909. [CrossRef]
58. Key, J.; Wang, X.; Liu, Y.; Dworak, R.; Letterly, A. The AVHRR Polar Pathfinder Climate Data Records. *Remote Sens.* **2016**, *8*, 167. [CrossRef]
59. Liu, Y.; Key, J.R.; Wang, X.; Tschudi, M. Multidecadal Arctic Sea Ice Thickness and Volume Derived from Ice Age. *Cryosphere* **2020**, *14*, 1325–1345. [CrossRef]
60. Alsweiss, S.; Jelenak, Z.; Chang, P.S. Extending the Usability of Radiometer Ocean Surface Wind Measurements to All-Weather Conditions for NOAA Operations: Application to AMSR2. *IEEE Trans. Geosci. Remote Sens.* **2023**, *61*, 5301112. [CrossRef]
61. Anheuser, J.; Liu, Y.; Key, J.R. A Climatology of Thermodynamic vs. Dynamic Arctic Wintertime Sea Ice Thickness Effects during the CryoSat-2 Era. *Cryosphere* **2023**, *17*, 2871–2889. [CrossRef]
62. Xie, P.; Boyer, T.; Bayler, E.; Xue, Y.; Byrne, D.; Reagan, J.; Locarnini, R.; Sun, F.; Joyce, R.; Kumar, A. An in Situ-Satellite Blended Analysis of Global Sea Surface Salinity. *J. Geophys. Res. Ocean.* **2014**, *119*, 6140–6160. [CrossRef]
63. Abdalla, S.; Abdeh Kolahchi, A.; Ablain, M.; Adusumilli, S.; Aich Bhowmick, S.; Alou-Font, E.; Amarouche, L.; Andersen, O.B.; Antich, H.; Aouf, L.; et al. Altimetry for the Future: Building on 25 Years of Progress. *Adv. Sp. Res.* **2021**, *68*, 319–363. [CrossRef]
64. Mitchum, G.T. An Improved Calibration of Satellite Altimetric Heights Using Tide Gauge Sea Levels with Adjustment for Land Motion. *Mar. Geod.* **2000**, *23*, 145–166. [CrossRef]
65. Zhang, B.; Cao, C.; Lillibridge, J.L.; Miller, L. Assessing the Measurement Consistency Between the Jason-2/AMR and SARAL/AltiKa/DFMR Microwave Radiometers Using Simultaneous Nadir Observations. *Mar. Geod.* **2015**, *38*, 143–155. [CrossRef]
66. Leuliette, E.W.; Willis, J.K. Balancing the Sea Level Budget. *Oceanography* **2011**, *24*, 122–129. [CrossRef]
67. Merrifield, M.A.; Thompson, P.R.; Chambers, D.P.; Mitchum, G.T.; Menéndez, M.; Nerem, R.S.; Leuliette, E.W.; Miller, L.; Holgate, S.J.; Marra, J.J.; et al. Sea Level Variability and Change. *Bull. Am. Meteorol. Soc.* **2017**, *93*, S81–S84.
68. Sandwell, D.T.; Goff, J.A.; Gevorgian, J.; Harper, H.; Kim, S.; Yu, Y.; Tozer, B.; Wessel, P.; Smith, W.H.F. Improved Bathymetric Prediction Using Geological Information: SYNBATH. *Earth Sp. Sci.* **2022**, *9*, e2021EA002069. [CrossRef]
69. Marks, K.M.; Smith, W.H.F. Comparison of Stacked Sentinel-3 A&B and AltiKa Repeat Cycle Data. *Earth Sp. Sci.* **2022**, *9*, e2021EA001892. [CrossRef]

70. Egido, A.; Smith, W.H.F. Fully Focused SAR Altimetry: Theory and Applications. *IEEE Trans. Geosci. Remote Sens.* **2017**, *55*, 392–406. [CrossRef]
71. Altiparmaki, O.; Kleinherenbrink, M.; Naeije, M.; Slobbe, C.; Visser, P. SAR Altimetry Data as a New Source for Swell Monitoring. *Geophys. Res. Lett.* **2022**, *49*, e2021GL096224. [CrossRef]
72. Kleinherenbrink, M.; Naeije, M.; Slobbe, C.; Egido, A.; Smith, W.H.F. The Performance of CryoSat-2 Fully-Focussed SAR for Inland Water-Level Estimation. *Remote Sens. Environ.* **2020**, *237*, 111589. [CrossRef]
73. Buchhaupt, C.K.; Egido, A.; Smith, W.H.F.; Fenoglio, L. Conditional Sea Surface Statistics and Their Impact on Geophysical Sea Surface Parameters Retrieved from SAR Altimetry Signals. *Adv. Sp. Res.* **2023**, *71*, 2332–2347. [CrossRef]
74. Buchhaupt, C.K.; Egido, A.; Vandemark, D.; Smith, W.H.F.; Fenoglio, L.; Leuliette, E. Towards the Mitigation of Discrepancies in Sea Surface Parameters Estimated from Low- and High-Resolution Satellite Altimetry. *Remote Sens.* **2023**, *15*, 4206. [CrossRef]
75. Scharroo, R.; Lillibridge, J.; Byrne, D.; Naeije, M. RADS: Consistent Multi-Mission Products RADS: CONSISTENT MULTI-MISSION PRODUCTS. In Proceedings of the Symposium on 20 Years of Progress in Radar Altimetry, Venice, Italy, 20–28 September 2012; European Space Agency European Space Agency Special Publication: Paris, France, 2013; p. 4.
76. Maturi, E.; Shay, L.; Donahue, D.; Byrne, D. NOAA's Operational Satellite Ocean Heat Content Products. *J. Oper. Oceanogr.* **2022**, *17*, 93–102. [CrossRef]
77. Byrne, D.A.; Maturi, E.M.; Burns, J.; Leuliette, E.W. New Developments for NOAA's Operational Upper Ocean Heat Content Product Suite. In Proceedings of the Ocean Surface Topography Science Team (OSTST) Meeting, Chicago, IL, USA, 21–25 October 2019. Available online: https://ostst.aviso.altimetry.fr/fileadmin/user_upload/Poster-APOP2019-Byrne.pdf (accessed on 26 June 2024).
78. Chang, P.; Jelenak, Z. NOAA Operational Satellite Ocean Surface Vector Winds Requirements Workshop Report; 2006. Available online: https://manati.star.nesdis.noaa.gov/SVW_nextgen/SVW_workshop_report_final.pdf (accessed on 26 June 2024).
79. Chang, P.S.; Jelenak, Z.; Sienkiewicz, J.M.; Knabb, R.; Brennan, M.J.; Long, D.G.; Freeberg, M. Operational Use and Impact of Satellite Remotely Sensed Ocean Surface Vector Winds in the Marine Warning and Forecasting Environment. *Oceanography* **2009**, *22*, 194–207. [CrossRef]
80. Jelenak, Z.; Chang, P.S.; Sienkiewicz, J.; Brennan, M.; Knabb, R.; Ward, B.; Edson, R.; Hufford, G.; Scott, C.; Lorens, J.; et al. *Dual Frequency Scatterometer (DFS) on GCOM-W2 Satellite: Instrument Design, Expected Performance and User Impact Addendum to QuikSCAT Follow-On User Impact Study*; NESDIS: Silver Spring, MD, USA, 2009. Available online: https://manati.star.nesdis.noaa.gov/SVW_nextgen/DFS_design_performance_and_user_impact_rev3.pdf (accessed on 26 June 2024).
81. Soisuvarn, S.; Jelenak, Z.; Chang, P.S.; Zhu, Q.; Shoup, C.G. High-Resolution Coastal Winds from the NOAA Near Real-Time ASCAT Processor. *IEEE Trans. Geosci. Remote Sens.* **2023**, *61*, 5500212. [CrossRef]
82. Jelenak, Z.; Chang, P.S.; Sienkiewicz, J.; Knabb, R.; Ward, B.; Edson, R.; Hufford, G.; Lorens, J.; Murphy, V.; Johnson, K.; et al. QuikSCAT Follow−On Mission: User Impact Study Report NOAA Operational Satellite Ocean Surface Vector Winds; 2008. Available online: https://manati.star.nesdis.noaa.gov/SVW_nextgen/QFO_user_impact_study_final.pdf (accessed on 26 June 2024).
83. Kite-Powell, H. The Value of Ocean Surface Wind Information for Maritime Commerce. *Mar. Technol. Soc. J.* **2011**, *45*, 75–84. [CrossRef]
84. Powell, H.K. Economic Benefits from Ocean Surface Vector Wind Observations and Forecasts Cumulative Activity by Distance from Shore. 2009, 1–5. Available online: https://manati.star.nesdis.noaa.gov/SVW_nextgen/ocean_surface_wind_obs_benefits_study_09SEPT2009.pdf (accessed on 26 June 2024).
85. Soisuvarn, S.; Jelenak, Z.; Chang, P.S.; Alsweiss, S.O.; Zhu, Q. CMOD5.H-A High Wind Geophysical Model Function for C-Band Vertically Polarized Satellite Scatterometer Measurements. *IEEE Trans. Geosci. Remote Sens.* **2013**, *51*, 3744–3760. [CrossRef]
86. Long, D.G.; Hardin, P.J.; Whiting, P.T. Resolution Enhancement of Spaceborne Scatterometer Data. *IEEE Trans. Geosci. Remote Sens.* **1993**, *31*, 700–715. [CrossRef]
87. Monaldo, F.; Jackson, C.; Pichel, W. Seasat to Radarsat-2: Research to Operations. *Oceanography* **2013**, *26*, 34–45. [CrossRef]
88. Jackson, C.R.; Ruff, T.W.; Knaff, J.A.; Mouche, A.; Sampson, C.R. Chasing Cyclones from Space. *EOS Earth Space Sci. News* **2021**, *102*. [CrossRef]
89. Mouche, A.; Chapron, B.; Knaff, J.; Zhao, Y.; Zhang, B.; Combot, C. Copolarized and Cross-Polarized SAR Measurements for High-Resolution Description of Major Hurricane Wind Structures: Application to Irma Category 5 Hurricane. *J. Geophys. Res. Ocean.* **2019**, *124*, 3905–3922. [CrossRef]
90. Duncan, K.; Farrell, S.L.; Richter-Menge, J.; Casal, T.; Connor, L.; Forsberg, R.; Haas, C.; Hendricks, S.; Leuliette, E.; McAdoo, D.C.; et al. Dedicated Airborne Experiments to Validate Satellite Altimetry over Arctic Sea Ice: A Review. In Proceedings of the Poster, CryoSat 10th Anniversary Science Conference, Virtual Event, 14–17 June 2021.
91. CEOS COAST UN Ocean Decade Contribution. Available online: https://oceandecade.org/actions/committee-on-earth-observation-satellites-coastal-observations-applications-services-and-tools-ceos-coast/ (accessed on 19 February 2024).
92. NOAA PolarWatch. Available online: https://polarwatch.noaa.gov/ (accessed on 19 February 2024).
93. NOAA Coral Reef Watch. Available online: https://coralreefwatch.noaa.gov/ (accessed on 19 February 2024).
94. NOAA CoastWatch Learning Portal. Available online: https://umd.instructure.com/courses/1336575 (accessed on 19 February 2024).

95. NOAA CoastWatch Data Portal. Available online: https://coastwatch.noaa.gov/cw_html/cwViewer.html (accessed on 19 February 2024).
96. NOAA OceanWatch Monitor. Available online: https://www.star.nesdis.noaa.gov/socd/om/ (accessed on 19 February 2024).
97. NOAA Ocean Viewer. Available online: https://www.star.nesdis.noaa.gov/socd/ov/ (accessed on 19 February 2024).
98. Lavergne, T.; Kern, S.; Aaboe, S.; Derby, L.; Dybkjaer, G.; Garric, G.; Heil, P.; Hendricks, S.; Holfort, J.; Howell, S.; et al. A New Structure for the Sea Ice Essential Climate Variables of the Global Climate Observing System. *Bull. Am. Meteorol. Soc.* **2022**, *103*, E1502–E1521. [CrossRef]
99. Wang, X.; Liu, Y.; Key, J.R.; Dworak, R. A New Perspective on Four Decades of Changes in Arctic Sea Ice from Satellite Observations. *Remote Sens.* **2022**, *14*, 1846. [CrossRef]
100. Anheuser, J.; Liu, Y.; Key, J.R. A Simple Model for Daily Basin-Wide Thermodynamic Sea Ice Thickness Growth Retrieval. *Cryosphere* **2022**, *16*, 4403–4421. [CrossRef]
101. Letterly, A.; Key, J.; Liu, Y. The Influence of Winter Cloud on Summer Sea Ice in the Arctic, 1983–2013. *J. Geophys. Res.* **2016**, *121*, 2178–2187. [CrossRef]
102. Liu, Y.; Key, J.R. Less Winter Cloud Aids Summer 2013 Arctic Sea Ice Return from 2012 Minimum. *Environ. Res. Lett.* **2014**, *9*, 44002. [CrossRef]
103. Liu, Y.; Key, J. Cold Season Cloud Response to Sea Ice Loss in the Arctic. *J. Climate* **2024**. *submitted*.
104. Letterly, A.; Key, J.; Liu, Y. Arctic Climate: Changes in Sea Ice Extent Outweigh Changes in Snow Cover. *Cryosphere* **2018**, *12*, 3373–3382. [CrossRef]
105. NOAA Coral Reef Watch Virtual Stations. Available online: https://coralreefwatch.noaa.gov/product/vs_single_pixel_exp/florida_keys.php (accessed on 19 February 2024).
106. Anderson, C.R.; Kudela, R.M.; Kahru, M.; Chao, Y.; Rosenfeld, L.K.; Bahr, F.L.; Anderson, D.M.; Norris, T.A. Initial Skill Assessment of the California Harmful Algae Risk Mapping (C-HARM) System. *Harmful Algae* **2016**, *59*, 1–18. [CrossRef]
107. Introduction to CEOS COAST. Available online: https://www.star.nesdis.noaa.gov/socd/coast/ (accessed on 19 February 2024).
108. CEOS COAST Ad Hoc Team Implementation Plan. Available online: https://ceos.org/document_management/Ad_Hoc_Teams/COAST/Documents/CEOS-COAST%20Implementation%20Plan%20Final%20Vers_1.2.pdf (accessed on 19 February 2024).
109. Neely, M.B.; Nezlin, N.; Lazzaro, R.; Bishop-Taylor, R.; Saga, S.; DiGiacomo, P.M.; Sharma, R. CEOS COAST: Progress on the Chesapeake Bay Pilot and Future Work. In Proceedings of the OCEANS 2022 Hampton Roads, Virginia Beach, VA, USA, 17–20 October 2022; pp. 1–5.
110. Nezlin, N.P.; Herman, J.D.; Hodge, J.; Sagar, S.; Bishop-Taylor, R.; Zheng, G.; DiGiacomo, P.M. Assessment of Changes of Complex Shoreline from Medium-Resolution Satellite Imagery. *Estuaries Coasts* **2023**, *46*, 1723–1739. [CrossRef]
111. Davies, G.; Digiacomo, P.; Lance, V.; Obligis, E.; Carroll, A.O. *Report of the Second International Operational Satellite Oceanography Symposium*, Virtual Meeting Held 25–27 May 2021, 2022; EUMETSAT, Darmstadt, Germany. Available online: https://cdn.eventsforce.net/files/ef-xnn67yq56ylu/website/18/osos-2_final_report_released_31_march_2022.pdf (accessed on 26 June 2024).
112. Brown, C.; Digiacomo, P.; Foli, B.; Lance, V.; Levy, G.; Montagner, F.; Neely, M.B.; Rayner, R.; Reppucci, A.; Wilson, C. Report of the First International Operational Satellite Oceanography; 2019; NOAA, College Park, MD, USA. Available online: https://www.geoaquawatch.org/wp-content/uploads/2020/06/Final-2019-OSOS-Summary_Final_vers2.1.pdf (accessed on 26 June 2024).