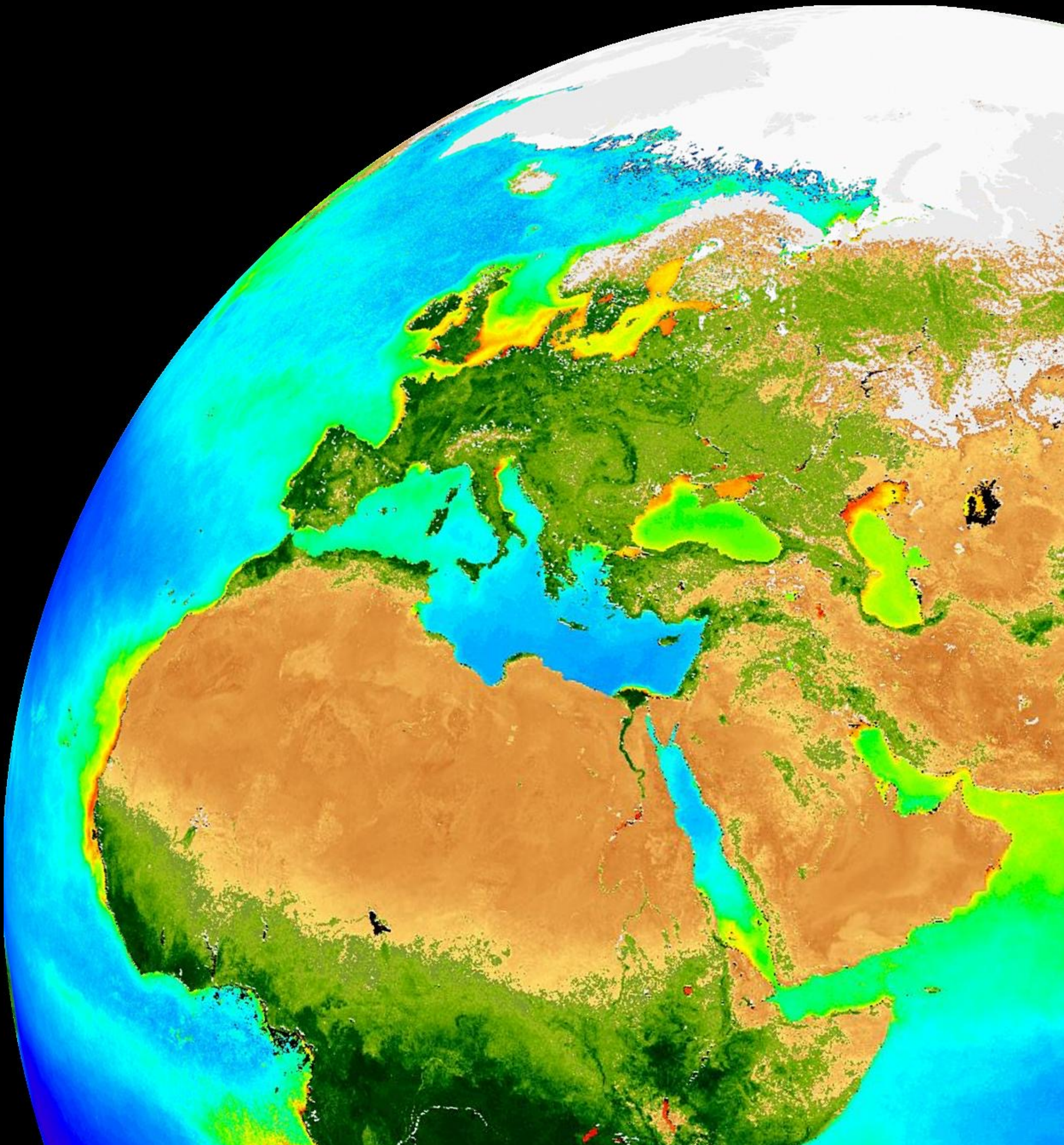
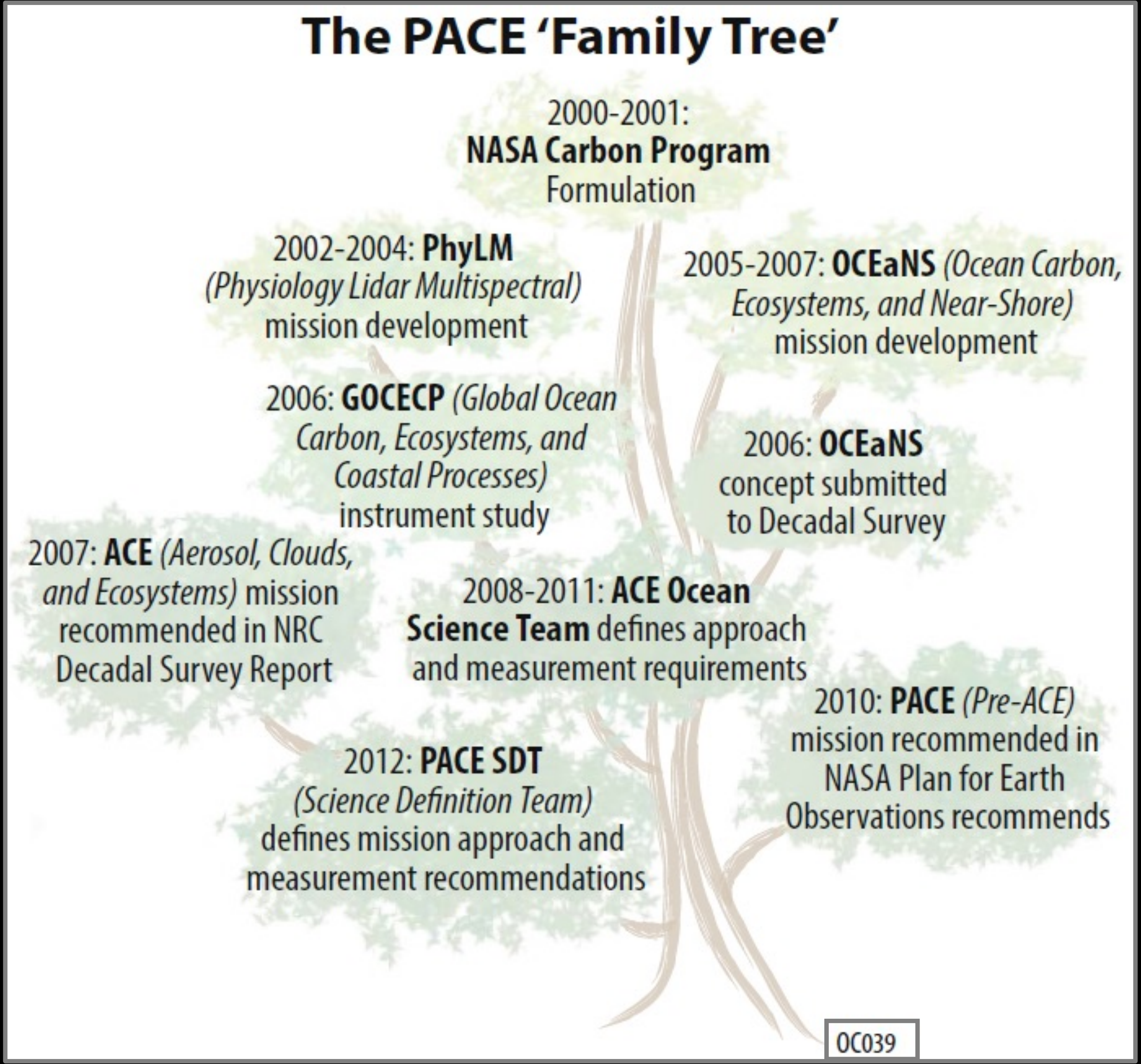
# There and back again: PACE version

Jeremy Werdell

PACE class @ UMBC
1-5 Aug 2022

GODDARD EARTH SCIENCES



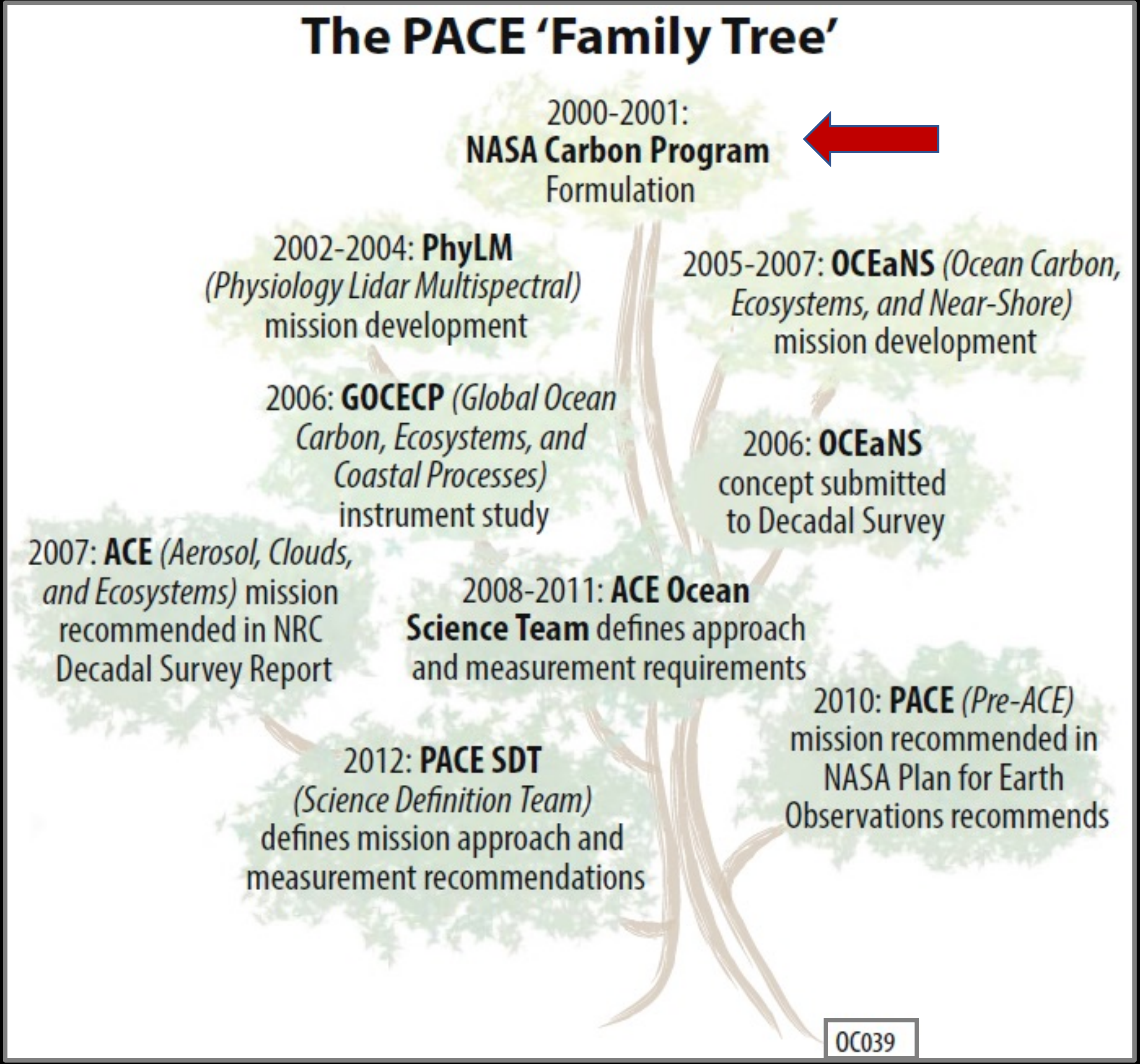



## 2000-2001 had:

- SeaWiFS
- MODIS-Terra
- MISR
- several others (MOS …)

## 2000-2001 did not yet have:

- MODIS-Aqua
- VIIRS
- POLDER-2
- MERIS, OLCI
- Landsat for oceans




NASA/TM—2002–210009

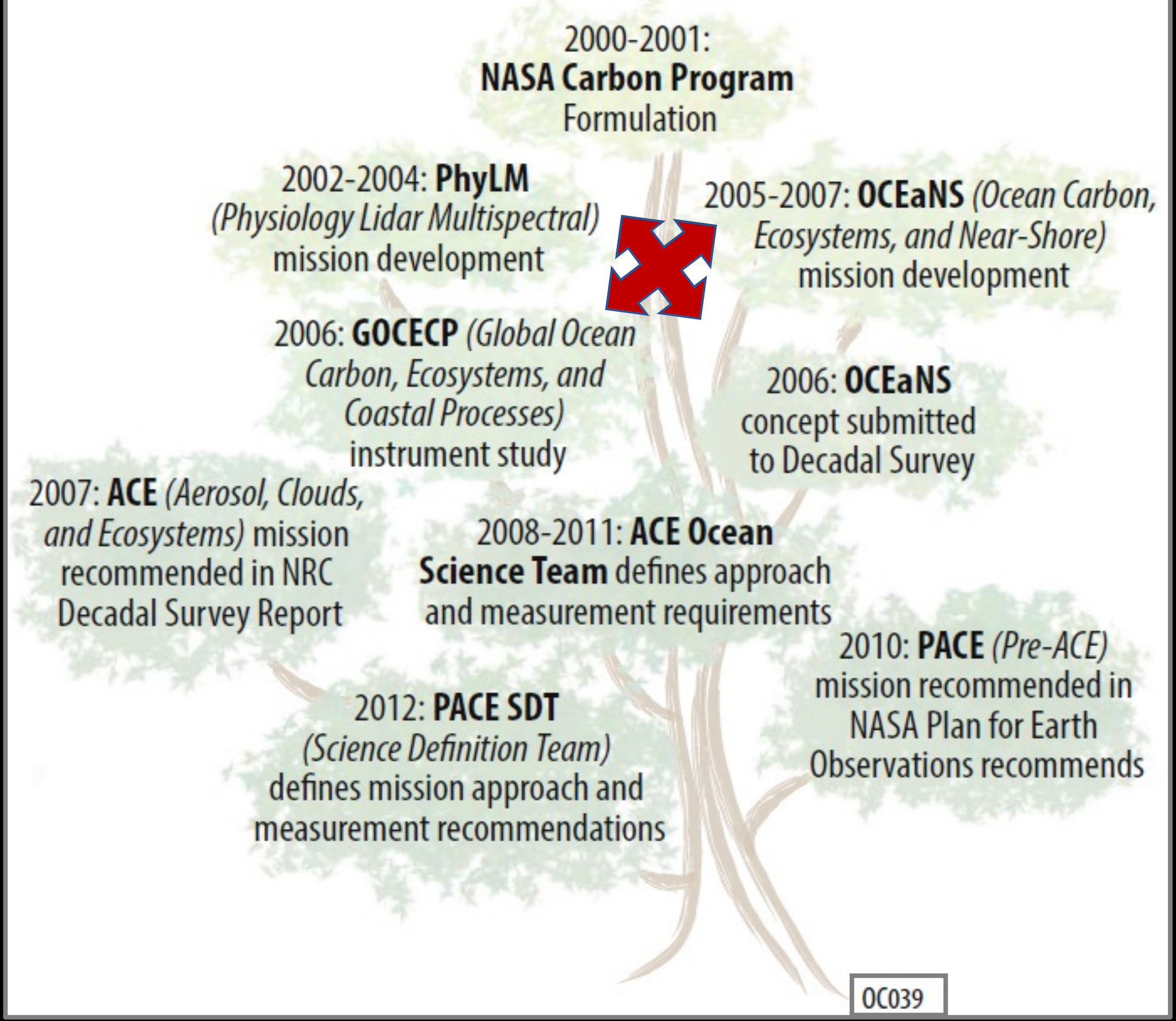
**Science and Observation Recommendations for Future NASA Carbon Cycle Research**

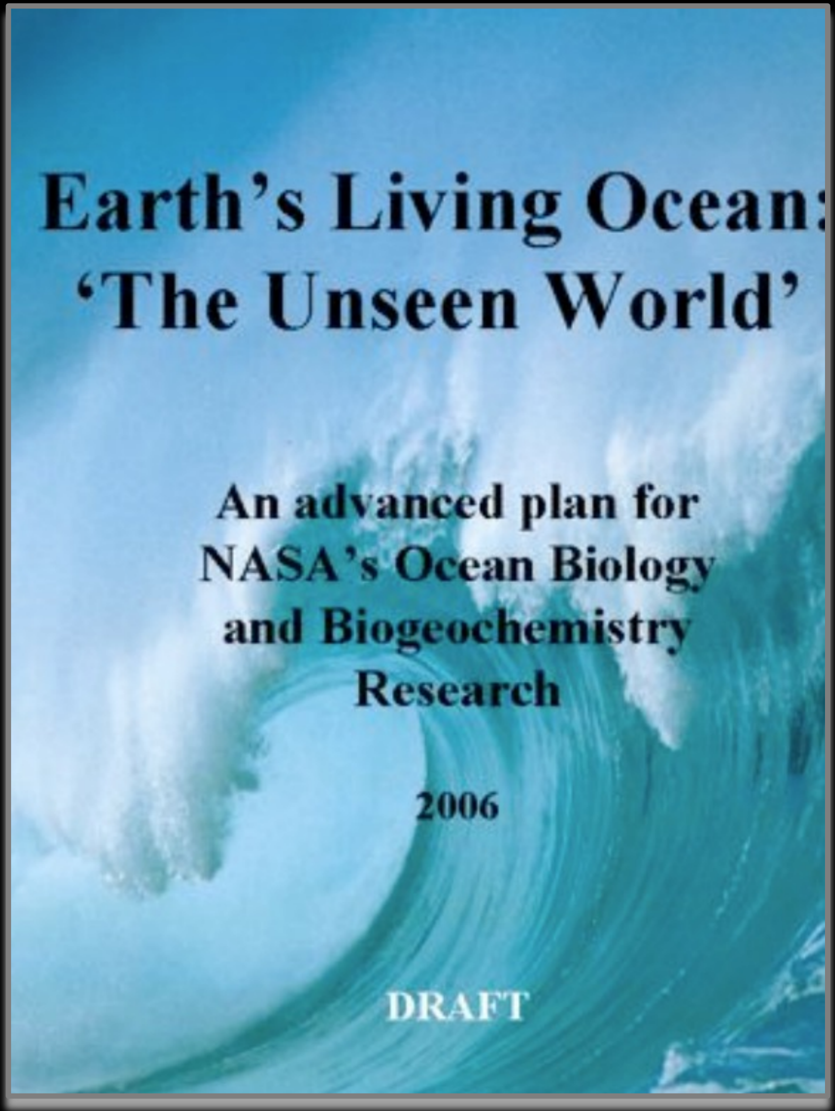
*C.R. McClain, F.G. Hall, G.J. Collatz, S.R. Kawa, W.W. Gregg, J.C. Gervin, J.B. Abshire, A.E. Andrews, C.D. Barnet, M.J. Behrenfeld, P.S. Caruso, A.M. Chekalyuk, L.D. Demaio, A.S. Denning, J.E. Hansen, F.E. Hoge, R.G. Knox, J.G. Masek, K.D. Mitchell, J.R. Moisan, T.A. Moisan, S. Pawson, M.M. Rienecker, S.R. Signorini, and C.J. Tucker*

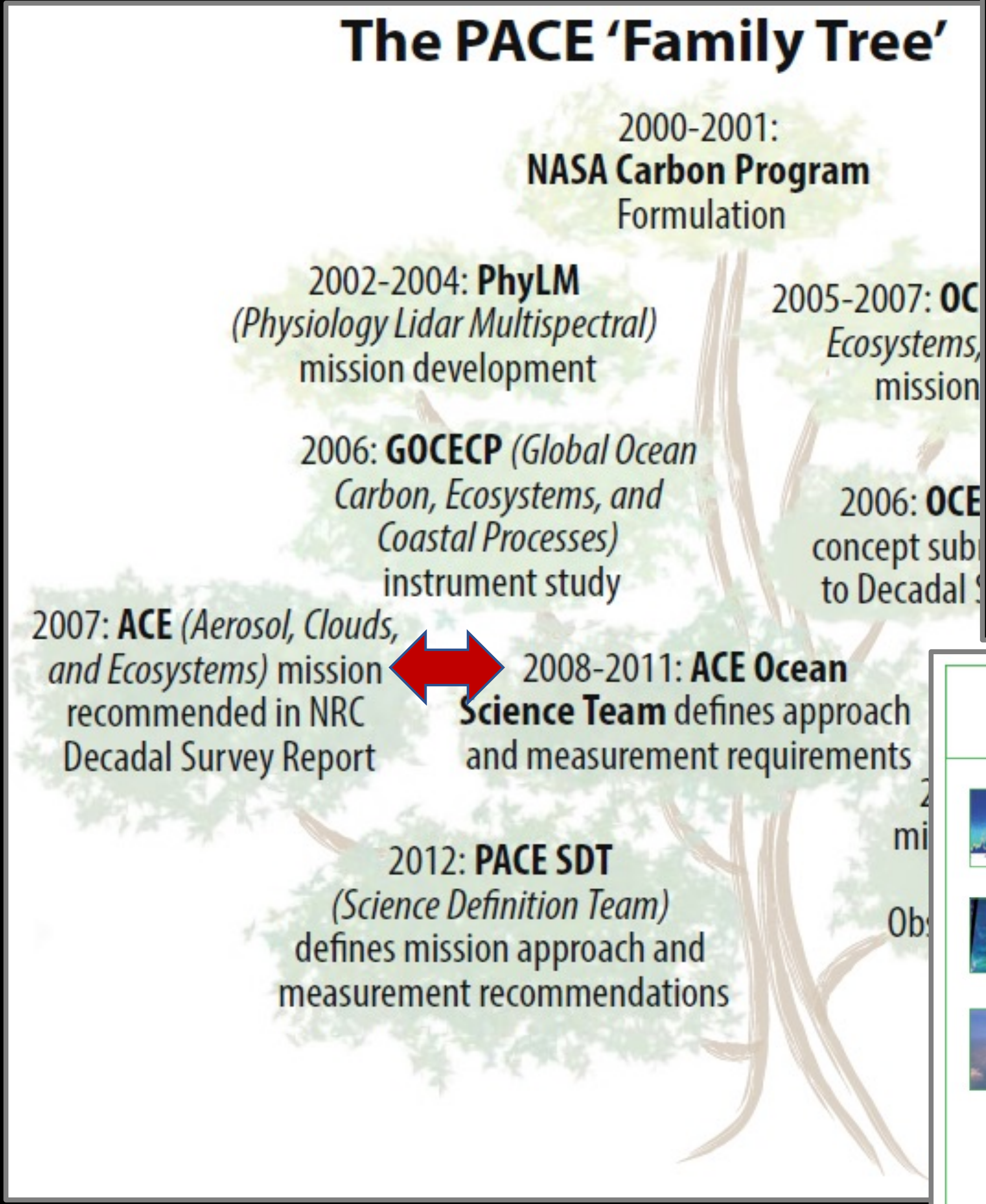
National Aeronautics and
Space Administration

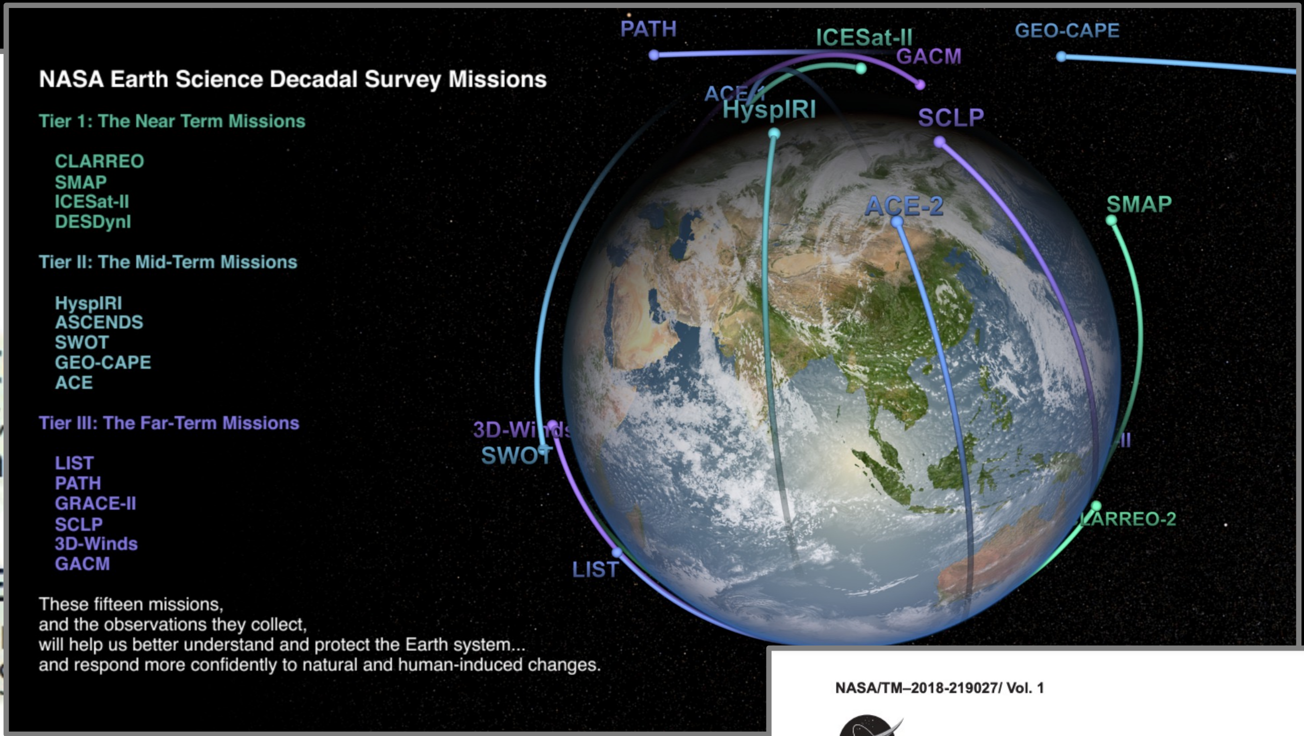
**Goddard Space Flight Center**
Greenbelt, Maryland 20771

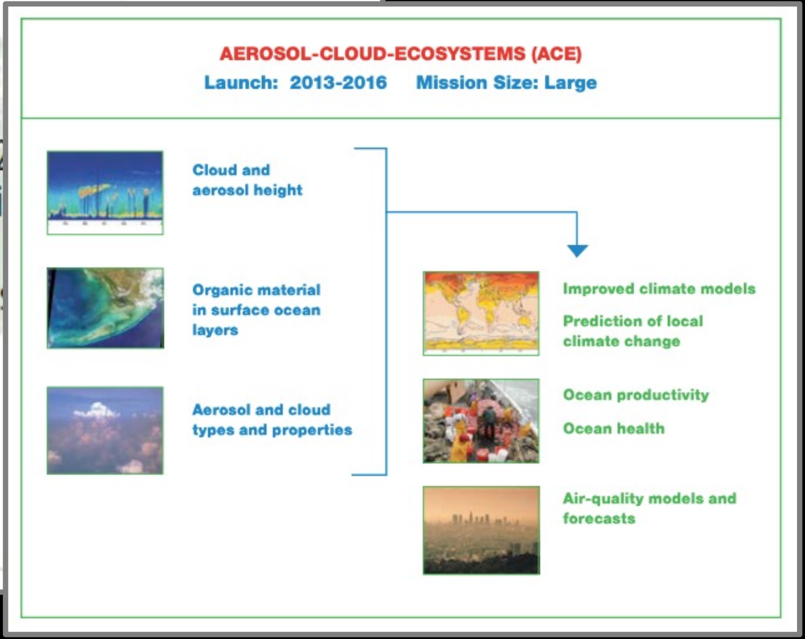
# The PACE 'Family Tree'

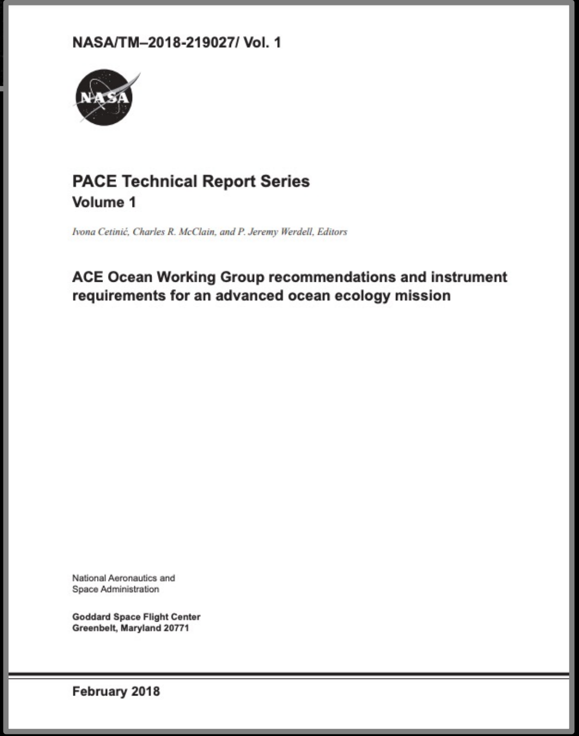






NASA/TM–2018-219027/ Vol. 1

PACE Technical Report Series
Volume 1

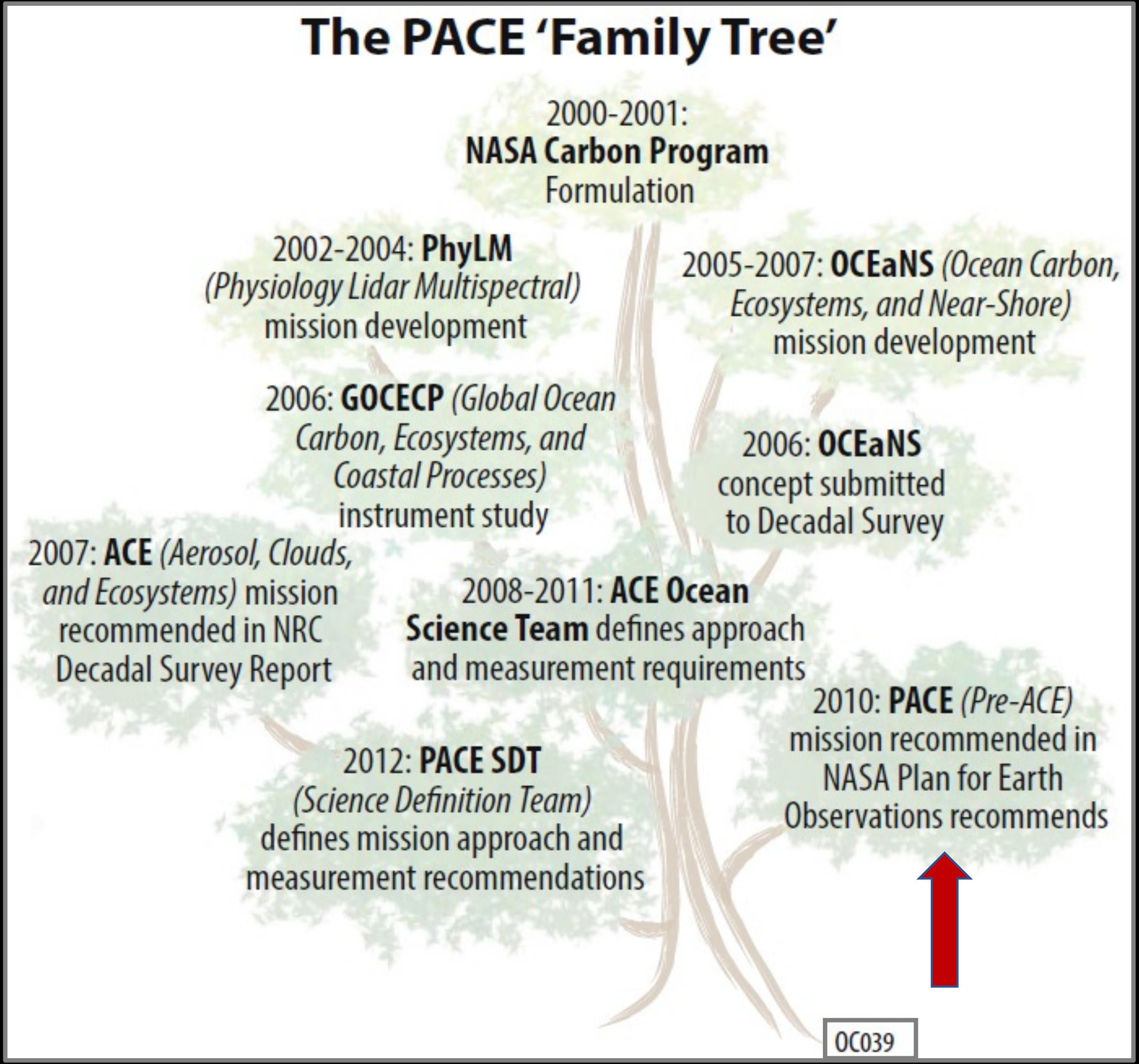
*Ivona Cetinić, Charles R. McClain, and P. Jeremy Werdell, Editors*

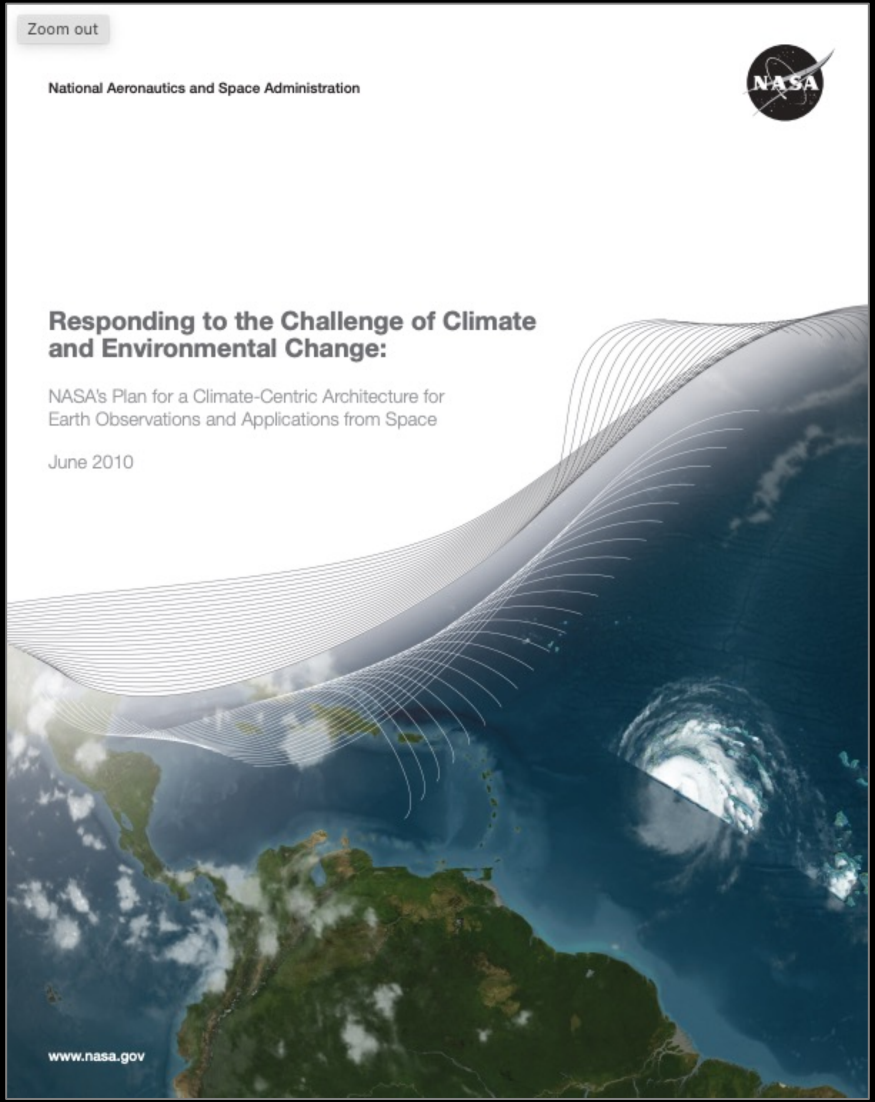
ACE Ocean Working Group recommendations and instrument requirements for an advanced ocean ecology mission

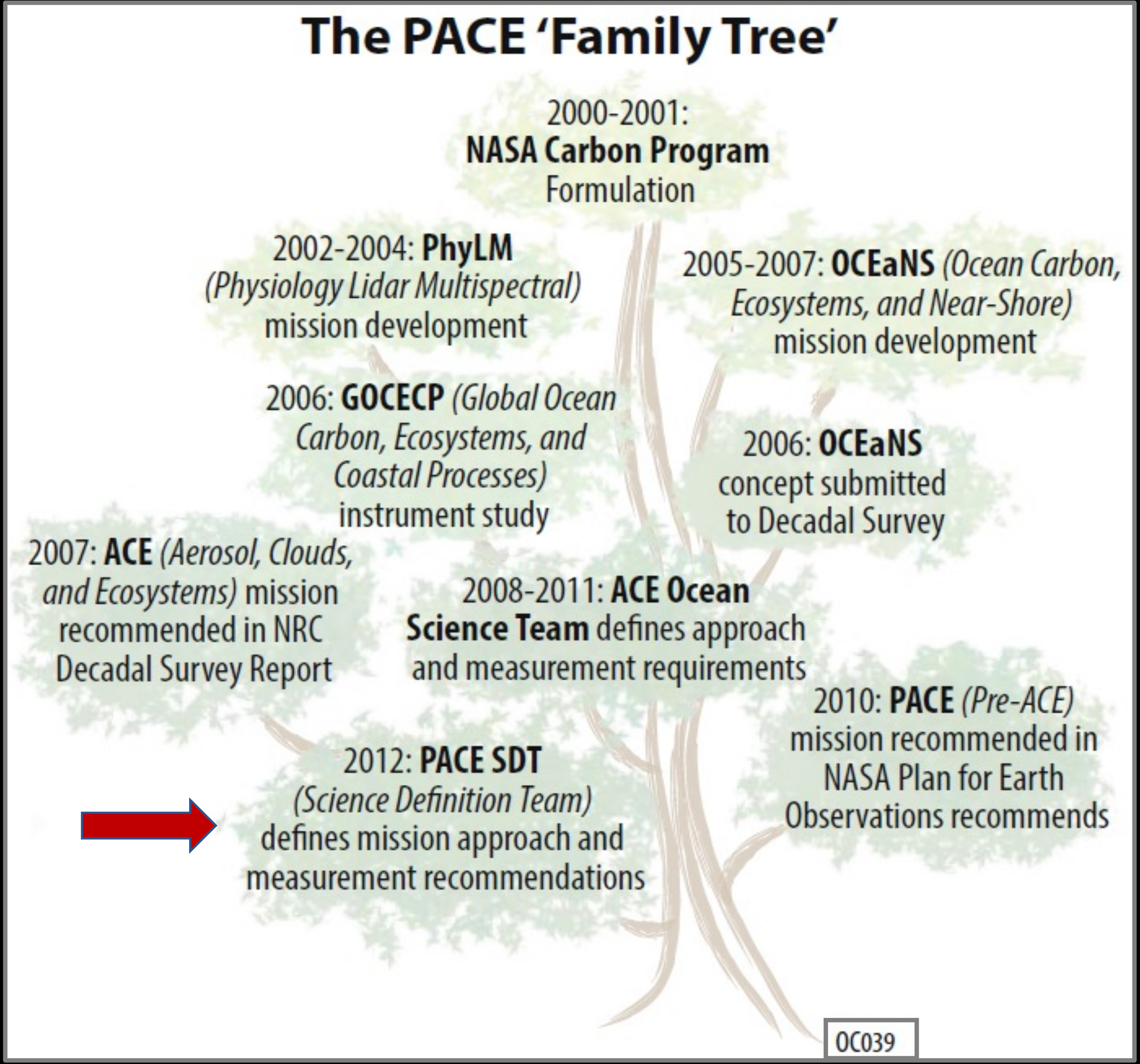
National Aeronautics and
Space Administration

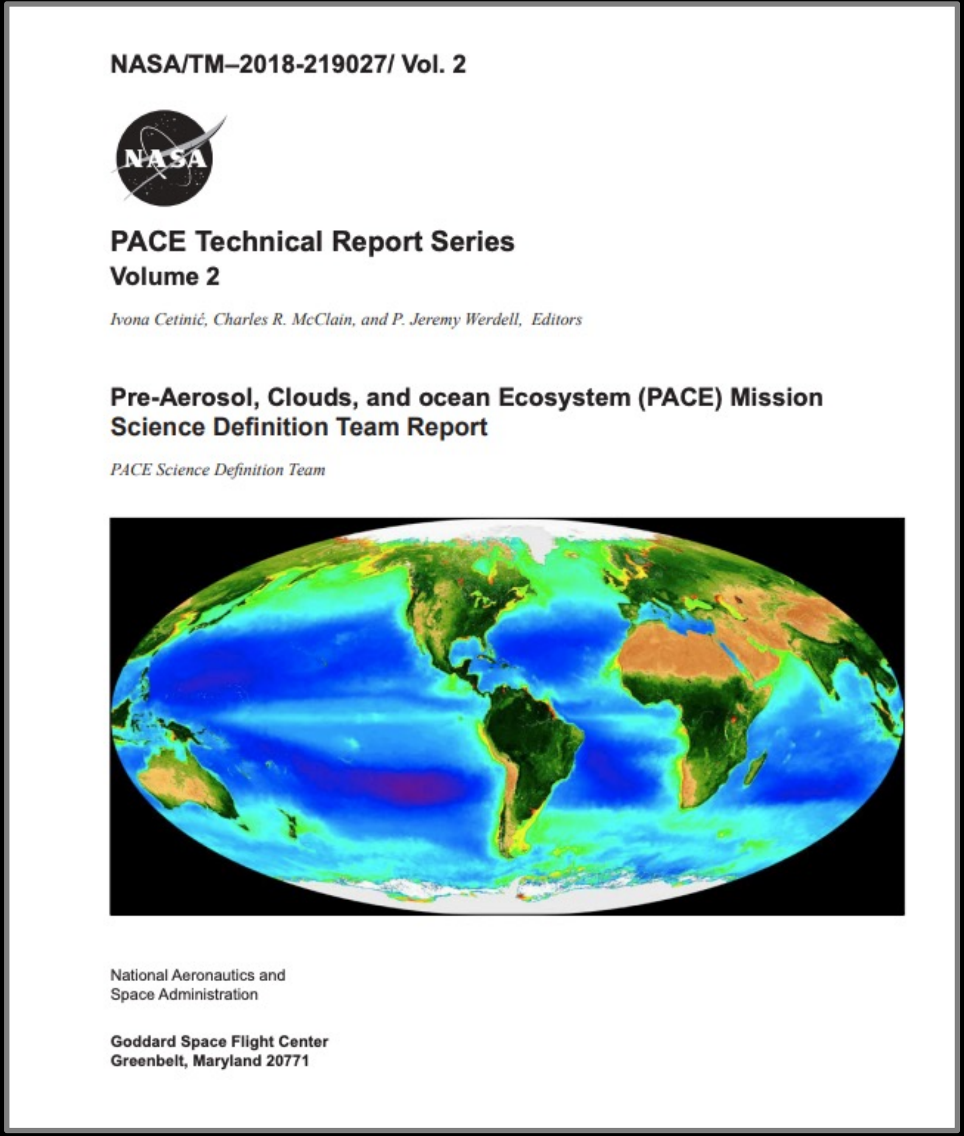
Goddard Space Flight Center
Greenbelt, Maryland 20771

February 2018


The PACE 'Family Tree'
2000-2001: NASA Carbon Program Formulation
2002-2004: PhyLM (Physiology Lidar Multispectral) mission development
2005-2007: OCEaNS (Ocean Carbon, Ecosystems, and Near-Shore) mission development
2006: GOCECP (Global Ocean Carbon, Ecosystems, and Coastal Processes) instrument study
2006: OCEaNS concept submitted to Decadal Survey
2007: ACE (Aerosol, Clouds, and Ecosystems) mission recommended in NRC Decadal Survey Report
2008-2011: ACE Ocean Science Team defines approach and measurement requirements
2010: PACE (Pre-ACE) mission recommended in NASA Plan for Earth Observations recommends
2012: PACE SDT (Science Definition Team) defines mission approach and measurement recommendations
OC039


Zoom out
National Aeronautics and Space Administration
NASA
Responding to the Challenge of Climate and Environmental Change:
NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space
June 2010
www.nasa.gov





NASA/TM–2018-219027/ Vol. 2

**PACE Technical Report Series**
**Volume 2**

*Ivona Cetinić, Charles R. McClain, and P. Jeremy Werdell, Editors*

**Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) Mission Science Definition Team Report**

*PACE Science Definition Team*

National Aeronautics and
Space Administration

**Goddard Space Flight Center**
**Greenbelt, Maryland 20771**

1. To address threshold PACE ocean science questions the PACE mission must include:

- An accurately calibrated and well characterized ocean color instrument covering a spectral range of 350 to 800 nm at ~5 nm resolution, and including a short wavelength near-UV band (approximately centered around 350 nm), two NIR bands (one of which should be centered at 865 nm), and three SWIR bands (1240 nm, 1640 nm, and 2130 nm) for atmospheric corrections. All measurement bands must have a spatial resolution of 1 $km^2$ (square pixel at nadir) with two-day global coverage. This instrument option is called OCI.

- A mission architecture that includes continual post-launch calibration (including lunar and vicarious calibration), frequent reprocessing of the entire data set, development and maintenance of algorithms, field validation, and process studies. The mission architecture should also include

product
NASA Oc

This OCI instrument ar
ocean science questio
ecology science questio

All the mission options
that would add value t
and cost. Adding these
meet all of its threshold ocean science mission requirements.

3. To address the threshold atmosphere science question and achieve threshold (heritage) imager-based aerosol data records and a subset of cloud data records initiated during the Earth Observing System (EOS) era with the Moderate Resolution Imaging Spectrora
Visible Infrared Imager Radio
augmented to include:

- The OCI with three add
nm) at 1 $km^2$ spatial re
OCI+.

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science questions regarding th
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## b.3. Threshold Atmosphere Science Question

This threshold atmosphere science question (ASQ) is addressed with the OCI+:

**ASQ-1** - In combination with data records that were begun with heritage/existing imagers, what are the long-term changes in aerosol and cloud properties that can be continued with PACE and how are these properties correlated with inter-annual climate oscillations?

## b.4. Goal Atmosphere Science Questions

### b.4.1 Goal Atmosphere (Ocean-Aerosol) Science Questions

These science questions are addressed by the OCI-3M:

**ASQ-4** - What are the magnitudes and trends of Direct Aerosol Radiative Forcing (DARF), and the anthropogenic component of DARF?

**ASQ-5** - How do aerosols influence ocean ecosystems and biogeochemical cycles?

## b.1. Threshold Ocean Science Questions

The threshold ocean science questions (SQ) addressed by the OCI option are listed below. The SQ are addressed by the ocean science instrument (OCI) and the mission requirements, as specified in Appendices I and II of this summary.

**SQ-1:** What are the standing stocks, compositions, and productivity of ocean ecosystems? How and why are they changing?





**SQ-2:** How and why are ocean biogeochemical cycles changing? How do they influence the Earth system?

**SQ-3:** What are the material exchanges between land and ocean? How do they influence coastal ecosystems and biogeochemistry? How are they changing?

**SQ-4:** How do aerosols influence ocean ecosystems and biogeochemical cycles? How do ocean biological and photochemical processes affect the atmosphere?

**SQ-5:** How do physical ocean processes affect ocean ecosystems and biogeochemistry? How do ocean biological processes influence ocean physics?

**SQ-6:** What is the distribution of both harmful and beneficial algal blooms and how is their appearance and demise related to environmental forcings? How are these events changing?

**SQ-7**: How do changes in critical ocean ecosystem services affect human health and welfare? How do human activities affect ocean ecosystems and the services they provide? What science-based management strategies need to be implemented to sustain our health and well-being?

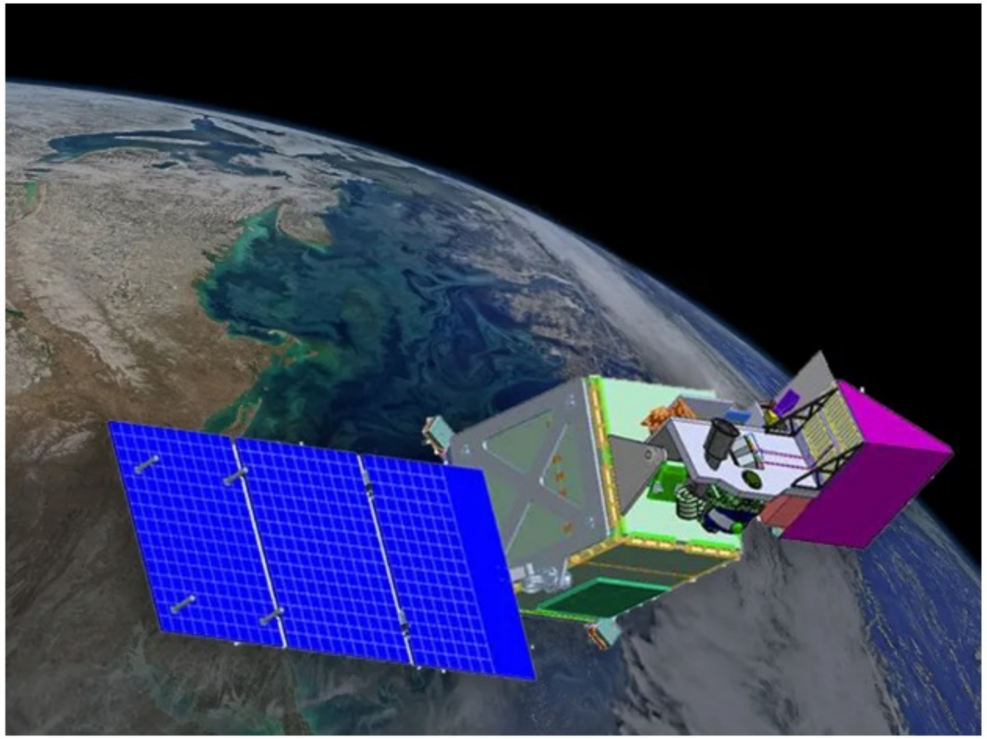
Early 2014 …

The 1st PACE Science Team

# A Novel Approach to a Satellite Mission's Science Team

*NASA's Plankton, Aerosol, Cloud, Ocean Ecosystem satellite mission, still in planning stages, operates with a framework that could serve as an example for science support of future missions.*

By **E. Boss** and **L. A. Remer** 12 February 2018



An artist's rendering of the proposed NASA PACE satellite. PACE is expected to significantly contribute to better understanding of the functioning of the atmosphere and oceans. Credit: G. V. Gasto, PACE Project, NASA GSFC

Late 2014 …

PACE becomes a real mission

Early 2015 …

The fun begins

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

December 10, 2014

Reply to Attn of: Science Mission Directorate/ Earth Science Division

TO: Distribution

FROM: NASA Earth Science Division Director

SUBJECT: Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) Mission Direction

On December 5, 2014, a pre-Acquisition Strategy Meeting (ASM) was held at NASA Headquarters, with participation from the Centers via teleconference. The purpose of the meeting was to discuss the path forward for the Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) mission. This memo serves to document the results of the meeting and to provide guidance to begin formulation for PACE. The charts presented by SMD at the meeting are enclosed.

The goal of PACE is to deliver a scientifically relevant mission that will make high-quality, global measurements of ocean color and atmospheric aerosol properties to advance Earth system science and applications, while also setting a precedent for cost control and capability maximization for directed missions. Sustained attention and dedication on the parts of the implementation teams, with continual involvement of senior levels of management at Centers and NASA HQ, will be necessary to ensure that the decisions and direction documented herein are maintained over the lifetime of the mission.

The decisions reached during the December 5, 2014 pre-ASM meeting for PACE

NEWS | March 15, 2015

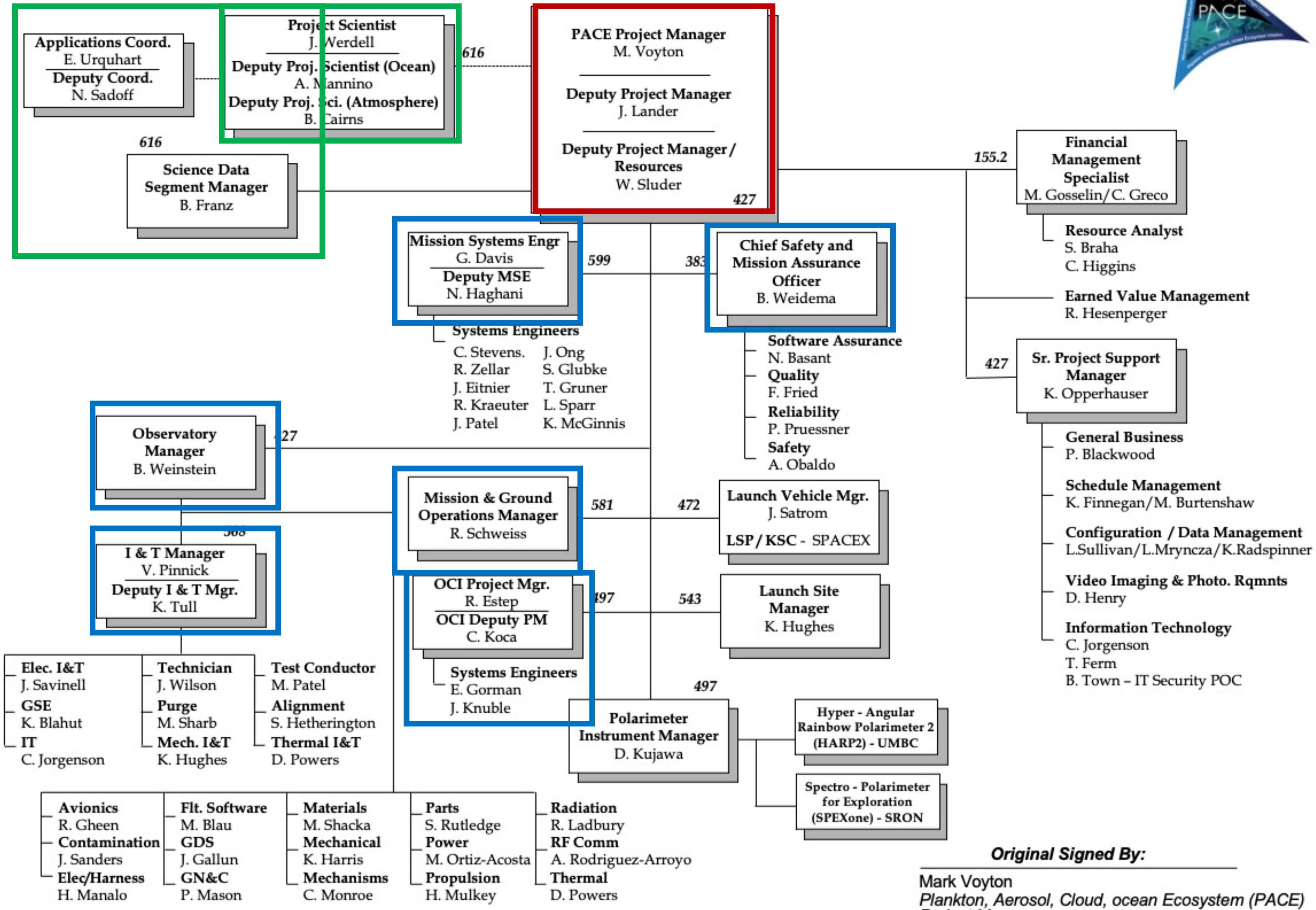
## New mission to study ocean color, airborne particles and clouds

By Steve Cole, NASA Headquarters,
and Rani Gran, NASA's Goddard Space Flight Center

appropriate capabilities and risk. Successful passage through the KDP-B and

3. A design-to-cost approach will be employed. It is expected that the LCC cap will enable development and flight of PACE with a payload including both the primary ocean color instrument and the secondary polarimeter instrument, with appropriate capabilities and risk. Successful passage through the KDP-B and KDP-C gates will require explicit demonstration of the iterative design-to-cost approaches utilized during formulation.
4. An Acquisition Strategy Meeting (ASM) will be held at NASA HQ during Phase A to consider PACE Project recommendations for (1) the spacecraft procurement approach and (2) the approach for providing the secondary polarimeter instrument under the cost cap. Options for the polarimeter are:
    a. No polarimeter (hopefully unlikely recommendation);
    b. The polarimeter directed to the Jet Propulsion Laboratory (JPL);
    c. The polarimeter competed (GSFC excluded).

# Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Project




***Original Signed By:***

Mark Voyton
*Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Project Manager*

**05/31/2022**

# PACE Science Organization

+ Pengwang!

**PACE Science Team**
Lead: Heidi Dierssen (UConn)
Deputy Lead: Lorraine Remer (UMBC)

**Program Science**
Program Scientist: Laura Lorenzoni
Deputy Program Scientist: Hal Maring
Applications Lead: Woody Turner
Dep. Prog. Applications (Oceans): Maria Tzortziou
Dep. Prog. Applications (Atmospheres): Ali Omar

**Project Science Management**
Project Scientist: Jeremy Werdell
Deputy Project Scientist (Oceans): Antonio Mannino
Deputy Project Scientist (Atmospheres): Brian Cairns

**System Vicarious Calibration**
MarONet: Ken Voss (UMiami)
HyperNAV: Andrew Barnard (Sea-bird)

**Science Data Segment (SDS)**
SDS Manager: Bryan Franz
Operations Manager: Fred Patt
OB.DAAC: Sean Bailey

**Project Science Leads**
Atmospheric Correction: Amir Ibrahim
Bio-optics: Lachlan McKinna
Biogeochemical Stocks: Ivona Cetinic
OCI Clouds/Aerosols: Andy Sayer
Polarimetry: Kirk Knobelspiesse

**Calibration & Validation Leads**
System Vicarious Cal: Susanne Craig
Operations: Chris Proctor
Datasets: Violeta San Juan Calzado
Protocols: Antonio Mannino

**Project Communications Team**
Coordinator: Sara Blumberg
Web: Annette deCharon
Production: Michael Starobin

**Project Applications Team**
Coordinator: Erin Urquhart Jephson
Deputy Coordinator: Natasha Sadoff

**Instrument Science**
OCI Instrument Scientist for Calibration: Gerhard Meister
OCI Instrument Scientist for Engineering: Bill Cook (551)
Polarimeter Instrument Scientist (HARP2)
Polarimeter Instrument Scientist (SPEXone)

GSFC | HQ | external

**last updated: 3 Nov 2021**

NASA/TM–2018-219027/ Vol. 5

# PACE Technical Report Series, Volume 5

*Ivona Cetinić, Charles R. McClain, and P. Jeremy Werdell, Editors*

## Mission Formulation Studies

*Paula Bontempi, Brian Cairns, Susanne E. Craig, André Dress, Bryan Franz, Robert Lossing, Antonio Mannino, Lachlan I. W. McKinna, Nima Pahlevan, Frederick S. Patt, Robert Schweiss, and Jeremy Werdell*



National Aeronautics and
Space Administration

**Goddard Space Flight Center**
**Greenbelt, Maryland 20771**

**December 2018**

NASA/TM–2018-219027/ Vol. 7

# PACE Technical Report Series, Volume 7

*Ivona Cetinić, Charles R. McClain, and P. Jeremy Werdell, Editors*

## Ocean Color Instrument (OCI) Concept Design Studies

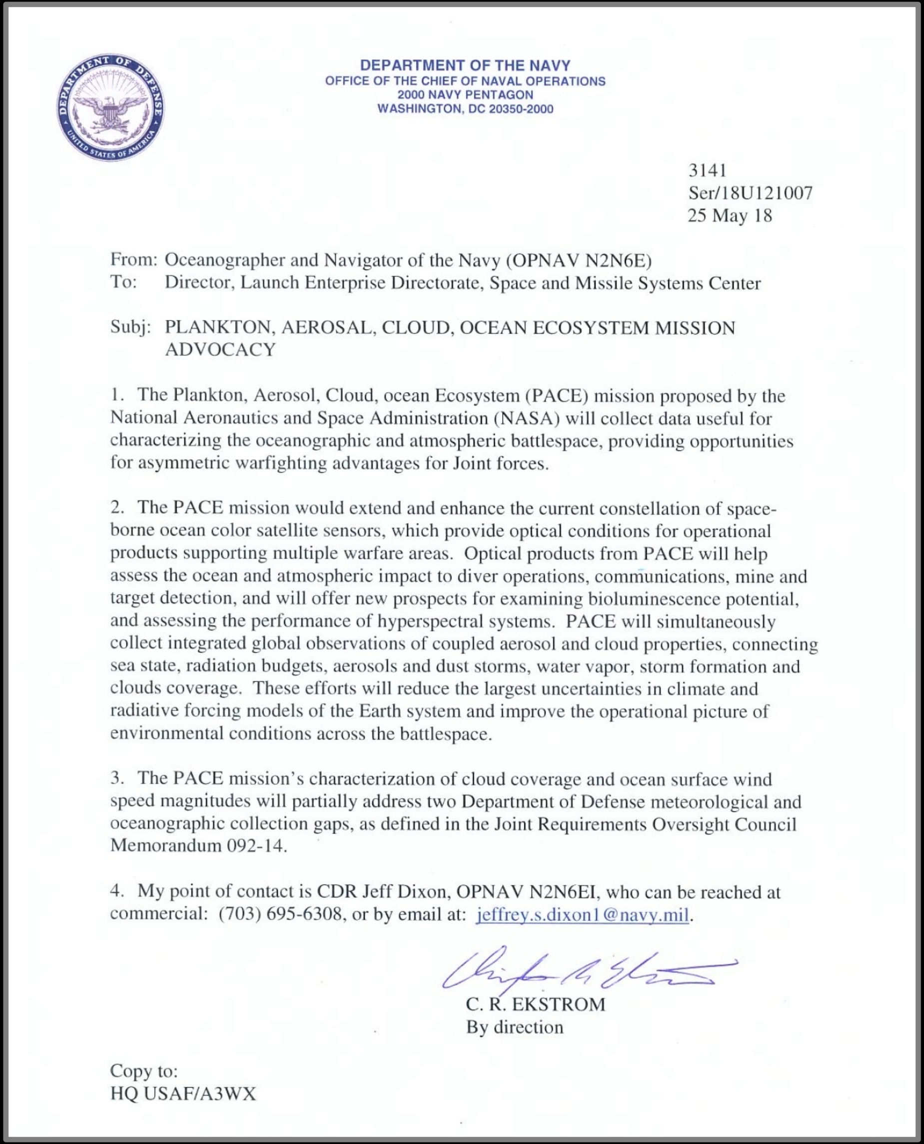
*Ziauddin Ahmad, Robert Arnone, Michael J. Behrenfeld, Brian Cairns, Ivona Cetinić, Robert E. Eplee, Bryan Franz, David Haffner, Amir Ibrahim, Antonio Mannino, Lachlan I. W. McKinna, Gerhard Meister, Aimee Neeley, Nima Pahlevan, Frederick S. Patt, Wayne Robinson, Sergio R. Signorini, Ryan Vandermeulen, Toby Westberry, and Jeremy Werdell*



National Aeronautics and
Space Administration

**Goddard Space Flight Center**
**Greenbelt, Maryland 20771**

**December 2018**


DEPARTMENT OF THE NAVY
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
2000 NAVY PENTAGON
WASHINGTON, DC 20350-2000

3141
Ser/18U121007
25 May 18

From: Oceanographer and Navigator of the Navy (OPNAV N2N6E)
To: Director, Launch Enterprise Directorate, Space and Missile Systems Center

Subj: PLANKTON, AEROSAL, CLOUD, OCEAN ECOSYSTEM MISSION ADVOCACY

1. The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission proposed by the National Aeronautics and Space Administration (NASA) will collect data useful for characterizing the oceanographic and atmospheric battlespace, providing opportunities for asymmetric warfighting advantages for Joint forces.

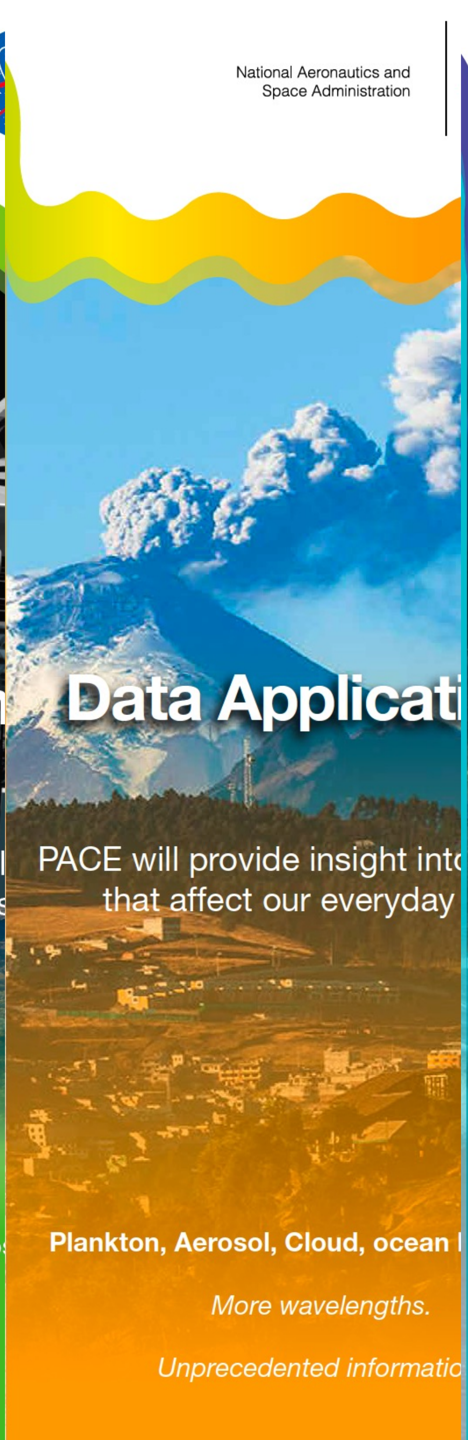
2. The PACE mission would extend and enhance the current constellation of space-borne ocean color satellite sensors, which provide optical conditions for operational products supporting multiple warfare areas. Optical products from PACE will help assess the ocean and atmospheric impact to diver operations, communications, mine and target detection, and will offer new prospects for examining bioluminescence potential, and assessing the performance of hyperspectral systems. PACE will simultaneously collect integrated global observations of coupled aerosol and cloud properties, connecting sea state, radiation budgets, aerosols and dust storms, water vapor, storm formation and clouds coverage. These efforts will reduce the largest uncertainties in climate and radiative forcing models of the Earth system and improve the operational picture of environmental conditions across the battlespace.

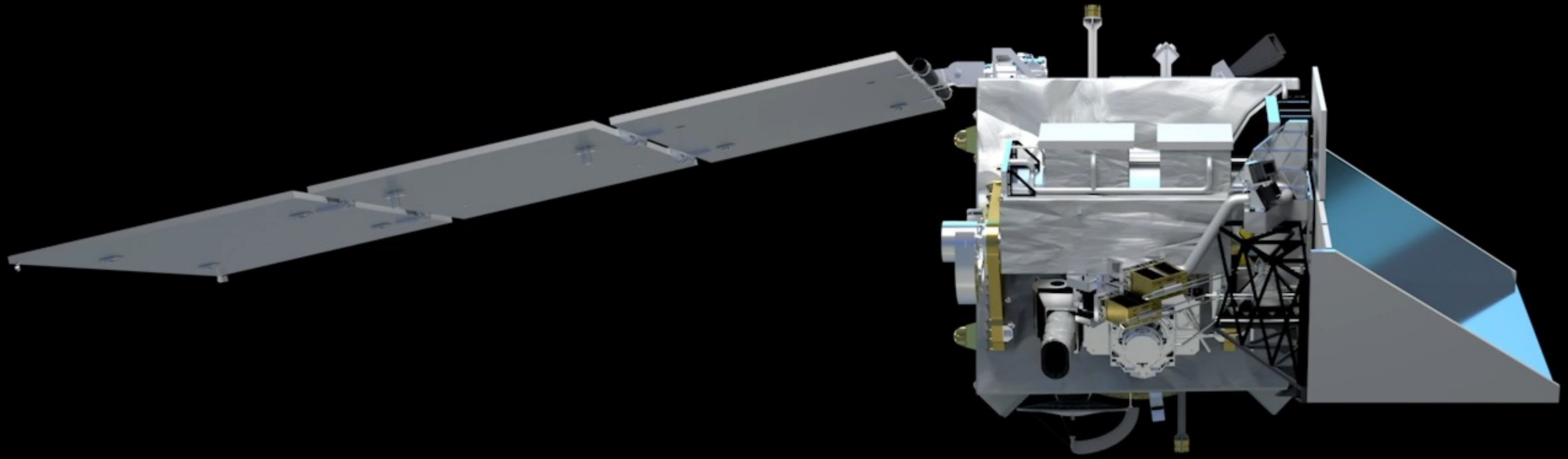
3. The PACE mission's characterization of cloud coverage and ocean surface wind speed magnitudes will partially address two Department of Defense meteorological and oceanographic collection gaps, as defined in the Joint Requirements Oversight Council Memorandum 092-14.

4. My point of contact is CDR Jeff Dixon, OPNAV N2N6EI, who can be reached at commercial: (703) 695-6308, or by email at: jeffrey.s.dixon1@navy.mil.

C. R. EKSTROM
By direction

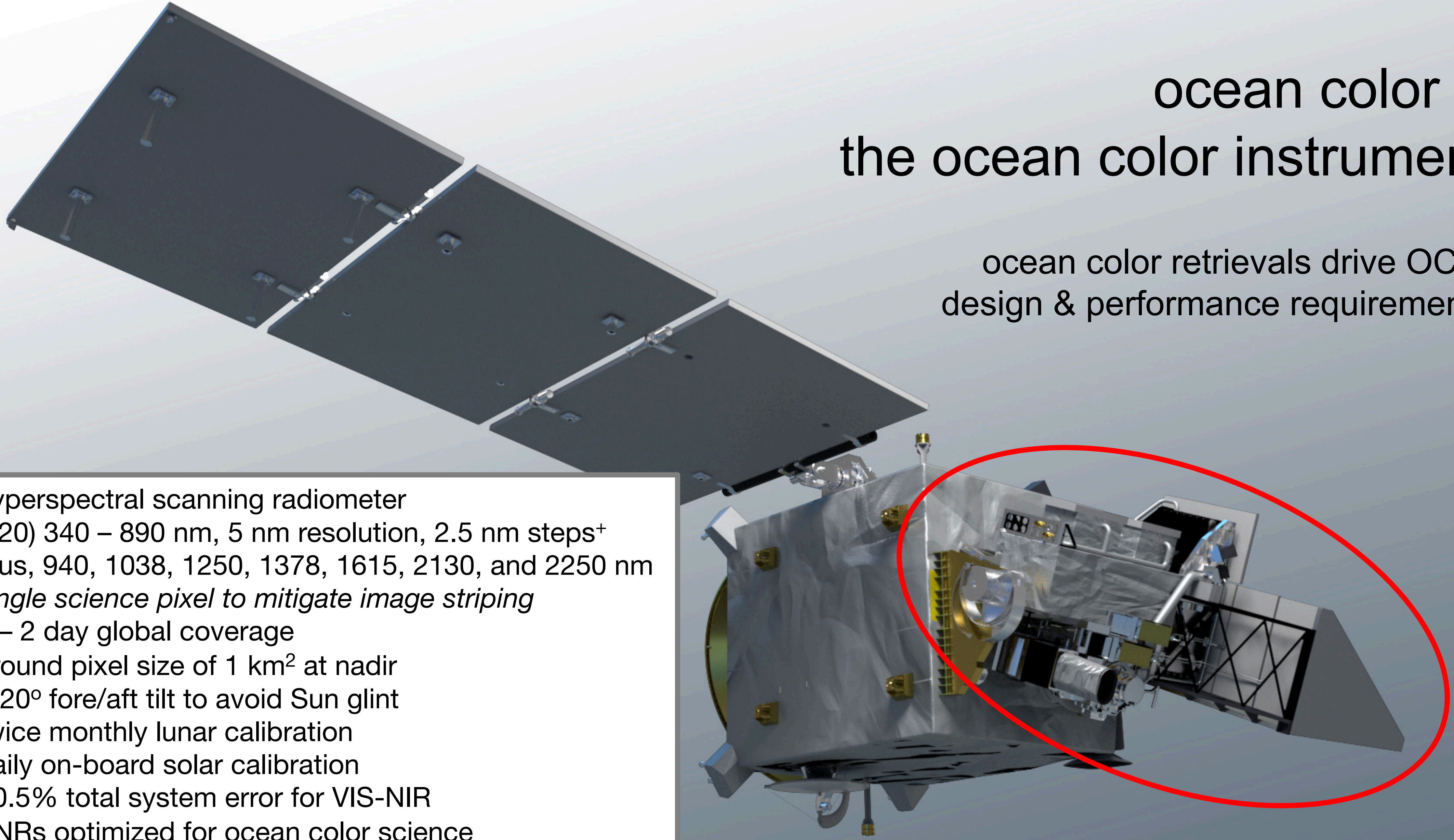
Copy to:
HQ USAF/A3WX

# ocean color &
# the ocean color instrument

ocean color retrievals drive OCI's
design & performance requirements



- hyperspectral scanning radiometer
- (320) 340 – 890 nm, 5 nm resolution, 2.5 nm steps$^{+}$
- plus, 940, 1038, 1250, 1378, 1615, 2130, and 2250 nm
- *single science pixel to mitigate image striping*
- 1 – 2 day global coverage
- ground pixel size of 1 km$^2$ at nadir
- ± 20º fore/aft tilt to avoid Sun glint
- twice monthly lunar calibration
- daily on-board solar calibration
- <0.5% total system error for VIS-NIR
- SNRs optimized for ocean color science
- simulated top-of-atmosphere data available

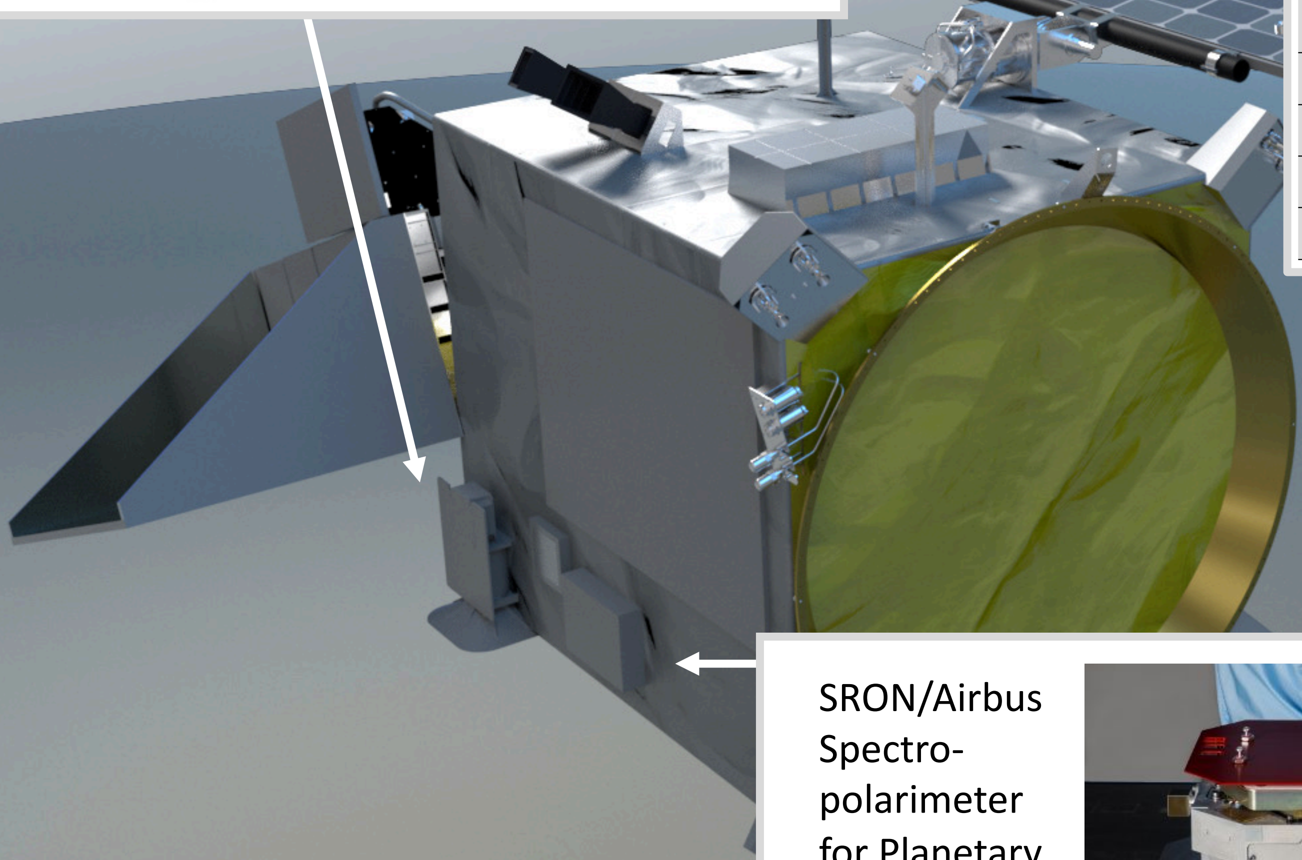
+ with 1.25 nm steps in several spectral regions

* developed primarily for mechanical processing assessments

UMBC Hyper Angular Rainbow Polarimeter (HARP-2)

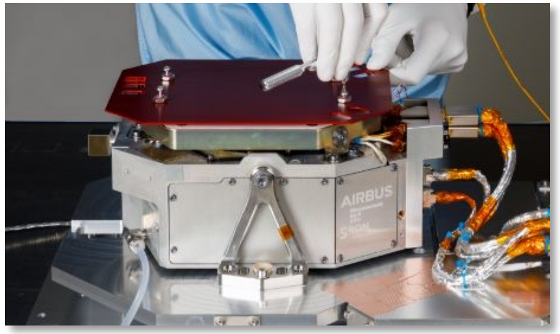
## Update

- Flight unit rebuild underway at UMBC
- Delivery to GSFC for I&T in Fall 2022



| | HARP-2 | SPEXone |
|---|---|---|
| UV-NIR range | 440, 550, 670, 870 nm | Continuous from 385-770 nm in 5 nm steps |
| SWIR range | None | None |
| Polarized bands | All | Continuous from 385-770 nm in 15-45 nm steps |
| Number of viewing angles [degrees] | 10 for 440, 550, 870 nm; 60 for 670 nm [spaced over 114°] | 5 [-57°, -20°, 0°, 20°, 57°] |
| Swath width | ±47° [1556 km at nadir] | ±4.5° [106 km at nadir] |
| Global coverage | 2 days | 30+ days |
| Ground pixel | 3 km | 2.5 km |
| Heritage | AirHARP, Cubesat | AirSPEX |

SRON/Airbus Spectro-polarimeter for Planetary Exploration (SPEXone)



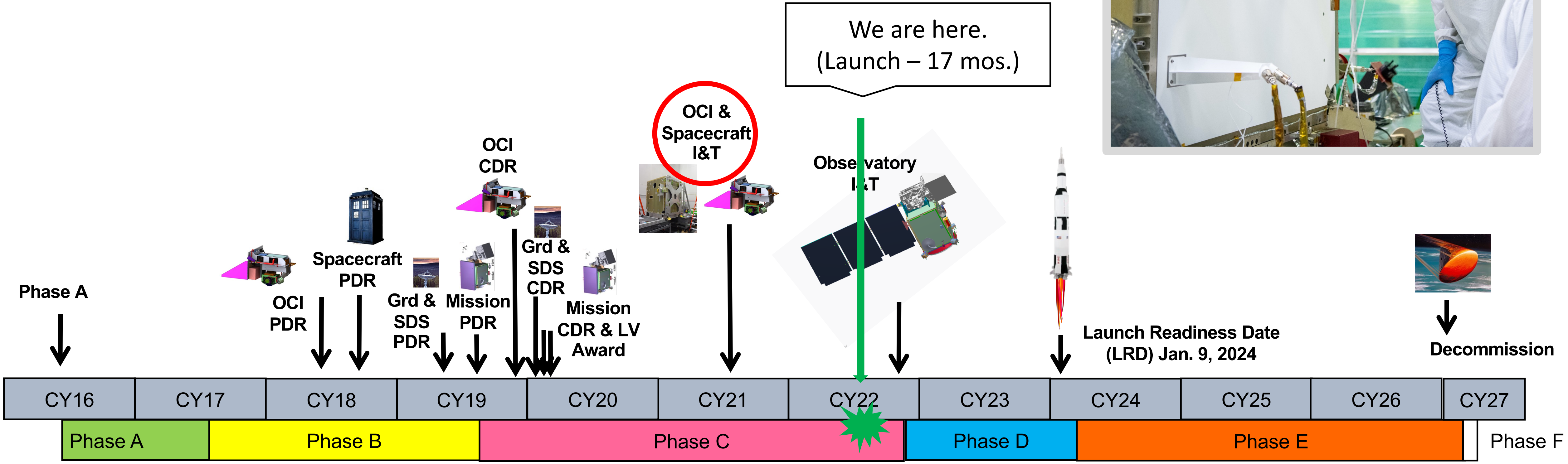

## Update

- SPEXone fully integrated onto the spacecraft in June 2022
- 16 orbits of simulated data available online

# PACE mission update: where are we?

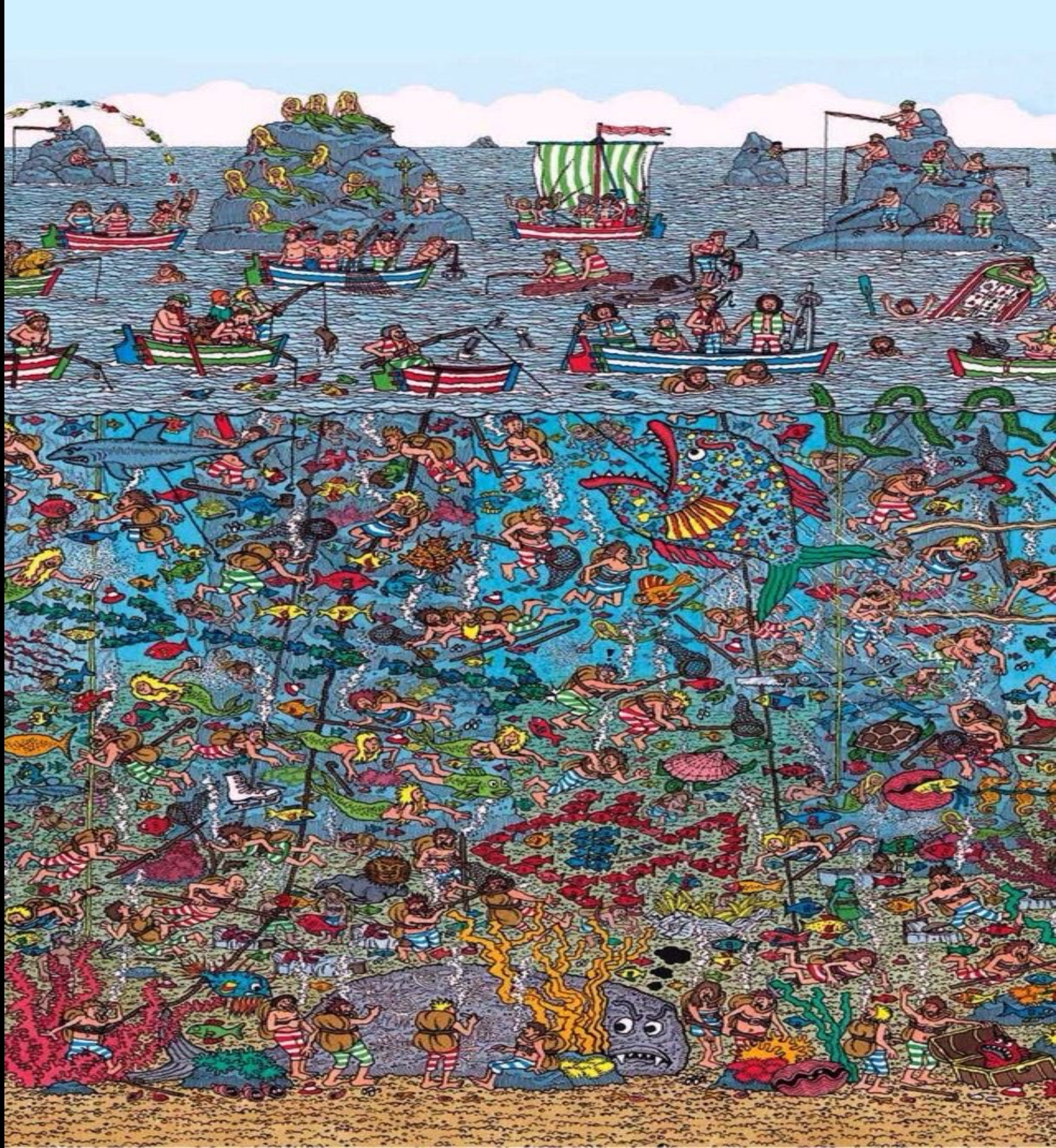
**Phase C – final design & fabrication**

- all mission elements have passed Critical Design Reviews (CDRs)
- all mission elements will have System Integration Reviews (SIRs)
- engineering test units characterized; flight builds nearing completion
- Project & HQ science implementing science capabilities



# science community engagement:

- Science & Applications Team #2 (competed; Jun 2020)
- System Vicarious Calibration teams (competed; Jul 2020)
- Post-launch validation team (to be competed; TBD)
- Applications Program



# Science & Applications Team #2 (”the SAT”)

3 year competitive award that began in July 2020

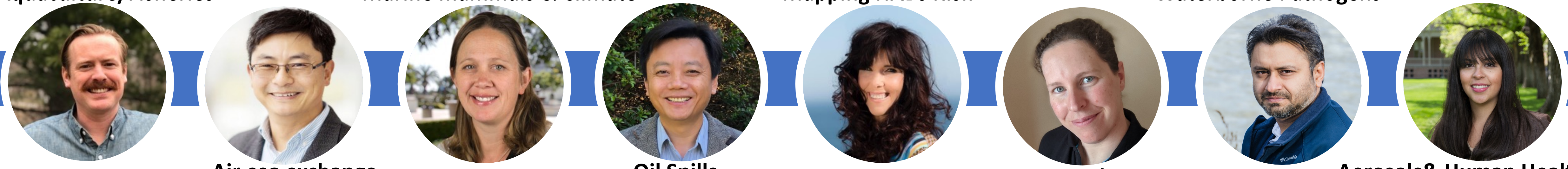
24 teams (>100 people) with researchers spanning U.S. & international collaborations

contribute algorithms & approaches for OCI & polarimeter science products


Locations of SAT PIs and Co-Is

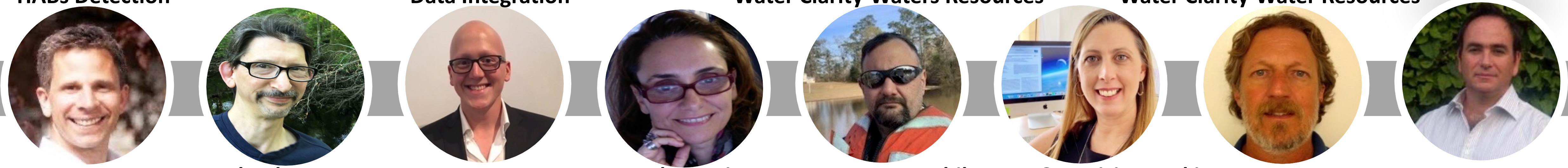
# PACE Early Adopters (*PACE's Application Developers*)

Aquaculture/Fisheries
Marine mammals & Climate
Mapping HABs Risk
Waterborne Pathogens



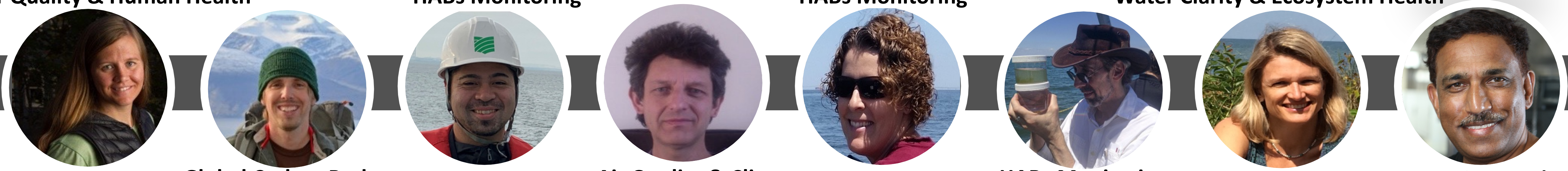
Air-sea exchange
Oil Spills
Aquaculture/Fisheries
Aerosols& Human Health

HABs Detection
Data Integration
Water Clarity-Waters Resources
Water Clarity-Water Resources



Wetland Ecosystems
Food Security
Mobile Apps & Decision Making
Data management

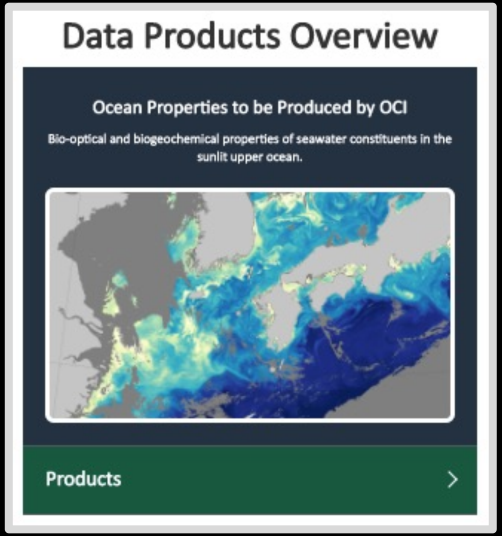
Air Quality & Human Health
HABs Monitoring
HABs Monitoring
Water Clarity & Ecosystem Health



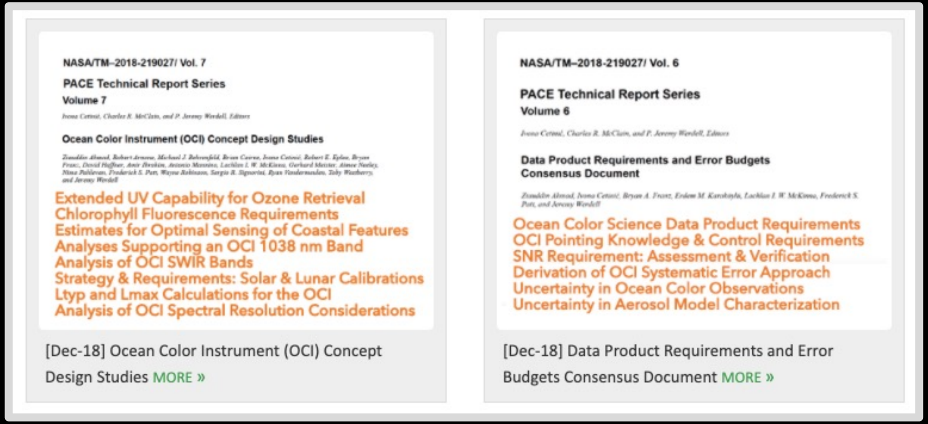
Global Carbon Budget
Air Quality & Climate
HABs Monitoring
Data Integration

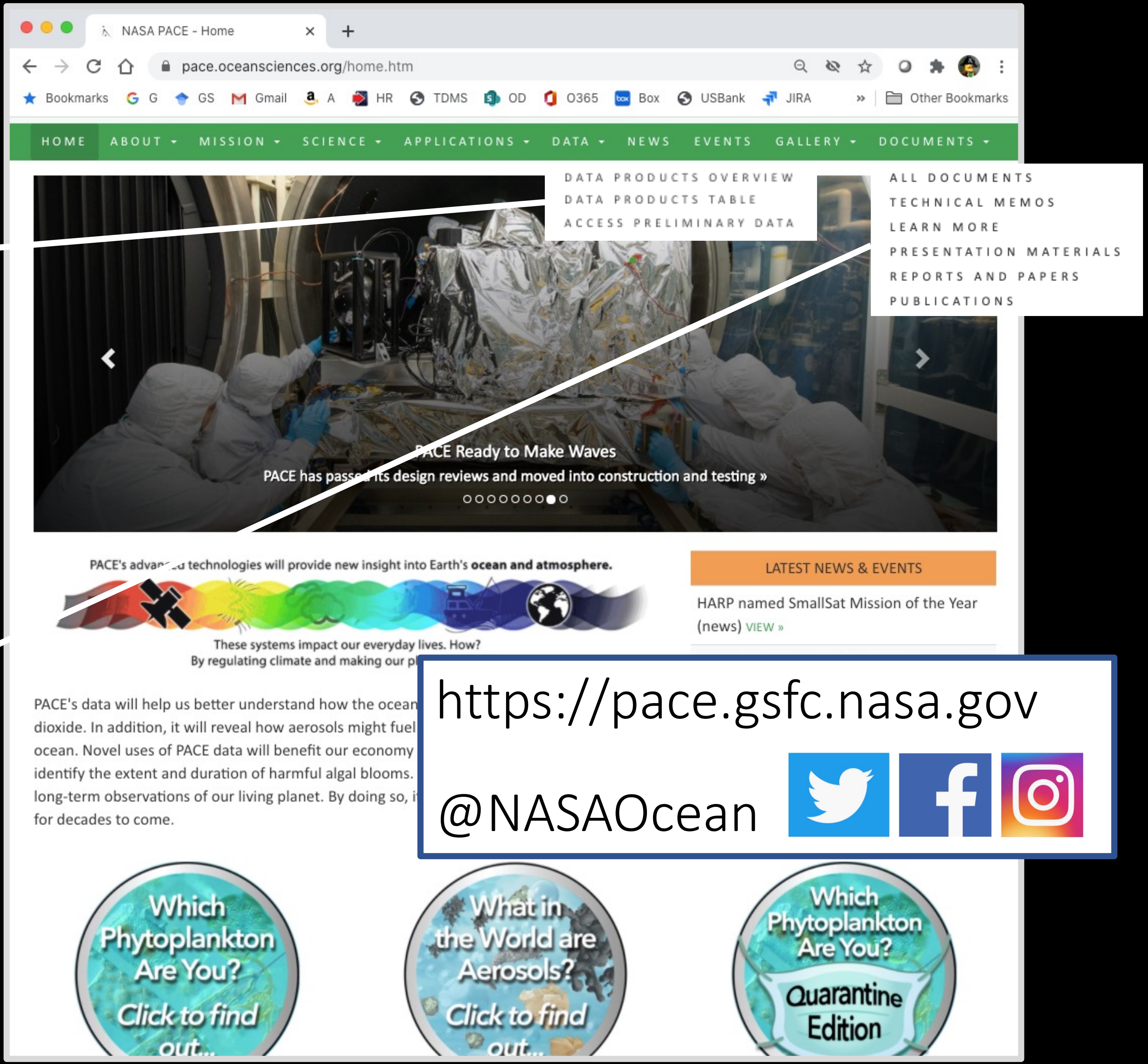
# resources & useful info

data product descriptions + access to simulated data & characterizations




PACE technical memos & other documents




https://pace.gsfc.nasa.gov

@NASAOcean

# THE PLANKTON, AEROSOL, CLOUD, OCEAN ECOSYSTEM MISSION

## Status, Science, Advances

P. Jeremy Werdell, Michael J. Behrenfeld, Paula S. Bontempi, Emmanuel Boss, Brian Cairns, Gary T. Davis, Bryan A. Franz, Ulrik B. Gliese, Eric T. Gorman, Otto Hasekamp, Kirk D. Knobelspiesse, Antonio Mannino, J. Vanderlei Martins, Charles R. McClain, Gerhard Meister, and Lorraine A. Remer

The PACE mission represents NASA's next investment in ocean color, cloud, and aerosol data records to enable continued and advanced insight into oceanographic and atmospheric responses to Earth's changing climate.

The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE; https://pace.gsfc.nasa.gov) mission represents the National Aeronautics and Space Administration's (NASA) next advance in satellite ocean color and polarimetry for the combined study of Earth's ocean–atmosphere–land system. Its multidisciplinary observations will serve the oceanographic, atmospheric, and terrestrial science communities, building upon a recognition that significant synergies exist between measurement requirements for atmospheric and aquatic ecosystem remote sensing retrievals of geophysical properties. PACE observations will enable continuation of climate research-quality long-term data records established by a diversity of heritage U.S. and international Earth-observing satellite missions. The underlying motivation for the mission, however, has long been to provide advanced observational capabilities enabling a leap forward in

**AFFILIATIONS:** Werdell, Franz, Knobelspiesse, Mannino, Meister, and McClain*—Ocean Ecology Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland; Behrenfeld—Department of Botany and Plant Pathology, Oregon State University, Corvallis, Oregon; Bontempi—Earth Sciences Division, NASA Headquarters, Washington, D.C.; Boss—School of Marine Sciences, University of Maine, Orono, Maine; Cairns—Goddard Institute of Space Sciences, NASA Goddard Space Flight Center, New York, New York; Davis—Mission Systems Engineering Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland; Gliese—Instrument Projects Division, NASA Goddard Space Flight Center, Greenbelt, Maryland; Gorman—Systems Engineering Services and Advanced Concepts Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland; Hasekamp—SRON, Netherlands Institute of Space Research, Utrecht, Netherlands; Martins and Remer—Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, Maryland
* Retired
**CORRESPONDING AUTHOR:** P. Jeremy Werdell, jeremy.werdell@nasa.gov

*The abstract for this article can be found in this issue, following the table of contents.*

DOI:10.1175/BAMS-D-18-0056.1

In final form 18 April 2019




frontiers | Frontiers in Remote Sensing

REVIEW
published: 05 July 2022
doi: 10.3389/frsen.2022.938006

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# Genesis and Evolution of NASA's Satellite Ocean Color Program

*Charles R. McClain*[1]*, *Bryan A. Franz*[2] *and P. Jeremy Werdell*[2]

[1]*Former Member of the Ocean Ecology Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, United States,* [2]*Ocean Ecology Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, United States*

We recount, based on our involvements in NASA ocean color flight projects, the chronology of technical challenges, lessons learned, and key developments over the past 40 + years of NASA satellite ocean color, beginning with the Nimbus-7/Coastal Zone Color Scanner, that have led to the upcoming Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission. Topics include the evolution of 1) satellite ocean color and field bio-optical data access, 2) satellite sensor capabilities, i.e., CZCS to PACE's hyperspectral Ocean Color Imager, OCI, 3) atmospheric corrections, 4) pre- and post-launch sensor characterization and calibration, 5) bio-optical algorithms, 6) in situ-derived radiometry and photosynthetic pigment data measurement quality, and 7) applications of hyperspectral satellite observations.

**Keywords: NASA satellite ocean color missions, bio-optical algorithms, atmospheric correction, satellite sensor calibration, global ocean chlorophyll-a time series, hyperspectral remote sensing**

OPEN ACCESS

***Edited by:***
*Soo Chin Liew, National University of Singapore, Singapore*

***Reviewed by:***
*Joji Ishizaka, Nagoya University, Japan*
*Bo-Cai Gao, United States Naval Research Laboratory, United States*

***Correspondence:**
*Charles R. McClain*
*chuckmcclain@verizon.net*

***Specialty section:***
*This article was submitted to Multi- and Hyper-Spectral Imaging, a section of the journal Frontiers in Remote Sensing*

***Received:*** *06 May 2022*
***Accepted:*** *14 June 2022*
***Published:*** *05 July 2022*

***Citation:***
*McClain CR, Franz BA and Werdell PJ (2022) Genesis and Evolution of NASA's Satellite Ocean Color Program. Front. Remote Sens. 3:938006. doi: 10.3389/frsen.2022.938006*

## INTRODUCTION

This article was submitted at the request of the guest editor of this special issue of *Frontiers in Remote Sensing*, Dr. Robert Frouin, who thought it would be useful to the community for us to document our experiences and perspectives per our involvements in NASA's ocean color missions beginning with the Nimbus-7 Coastal Zone Color Scanner (CZCS) launched in October 1978 and extending through the upcoming Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission scheduled to launch in January 2024. Thus, our account will be limited primarily to activities conducted at NASA Goddard Space Flight Center, e.g., experiences with the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) and preparation for PACE, and intentionally reads much like a memoir. Over the past 40 + years, there have been numerous advances and refinements in the technologies, methodologies and algorithms and we will highlight many. Acker (2015) also provides a detailed description of the NASA ocean color program up through the initial phases of the National Polar-orbiting Environmental Satellite System (NPOESS) Preparatory Project (later renamed to the Suomi National Polar-orbiting Partnership (SNPP)) that incorporated the first Visible-Infrared Imaging Radiometer Suite (VIIRS). In addition, the basic concepts of ocean color are discussed by a number of chapter authors in Zibordi et al. (2014), as well as in Werdell and McClain (2019). Mobley et al. (2016) provides a useful accompanying reference for the atmospheric correction processes and terminology we will discuss. Finally, there have been complementary and useful airborne sensors that we will not discuss, but one of note is the Airborne Oceanic Lidar (AOL, e.g., Hoge et al., 1988) that operated out of the NASA Wallops Flight Facility (WFF) for many years. We will not endeavor to recount the multitude of advances in ocean science that have resulted from these missions. In our reflections, being somewhat personal, we will refer to ourselves in the text as CM, BF, and JW, for Charles "Chuck" McClain, Bryan Franz, and Jeremy Werdell.

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