3 ESD-developed EO missions launched since 2/2014
2 ISS-developed EO instruments launched (2014, 2015)
11+ more ESD EO launches before 2022

GPM 2/2014

CIARREO* 2019 for Pathfinders/ISS

SAGE-III (on ISS) mid-CY2016

Grace-FO Aug 2017

LIS (on ISS) 2016

RapidSCAT, CATS (on ISS) CY2014/15

NI-SAR 2021

SLI-TIR-FFD, L9 Formulation in 2015

SMAP Jan 2015

ICESat-2 June 2018

SWOT CY2020

PACE CY2022

GEDI/ISS ECOSTRESS /ISS

EVI-3 2022

EVI-2 2020

EVM-2 2021

TEMPO EVI-1, CY2018 LRD

EVI-2 2020

GEDI/ISS

EVM-2 2021

EVI-3 2022

JPSS-2 (NOAA)

TSIS-1

RBI OMPS-Limb

[[Future Altimetry]]

EVM-1, Oct 2016 LRD

[TSIS-2]

CYGNSS

✔

EVI-1

2020

✔

EVI-2

2020

✔
SLI-TBD Formulation in 2015

RBI OMPS-Limb

[[TSIS-2]]

[[Future Altimetry]]

JPSS-2 (NOAA)

TEMPO

PACE

SWOT

NI-SAR

SLI-TBD

CyGNSS

RapidScat, CATS, LIS, SAGE III (on ISS)

SMAP

RapidScat, CATS,

[[TCTE]]

Suomi NPP (NOAA)

Landsat-8 (USGS)

Landsat-7 (USGS)

Terra

Aqua

CloudSat

CALIPSO

Aura

GRACE (2)

OSTM/Jason 2 (NOAA)

GPM

OCO-2

FORMULATION

IMPLEMENTATION

PRIMARY OPS

EXTENDED OPS
Advanced Planning – Why?

- What have we accomplished since the last plan (2008)?
  - Are the existing questions still valid or do they need to evolve?
- What’s next scientifically?
- Systematic Observations – Suomi NPP to JPSS (?)
- New observations
  - Modeling, Technology, Applied Science, Data management, Cal/Val
<table>
<thead>
<tr>
<th>Category</th>
<th>Focused Questions*</th>
<th>Approach</th>
<th>Measurement Requirements</th>
<th>Instrument Requirements</th>
<th>Platform Requir’ts</th>
<th>Other Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean Biology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Global data sets from missions, models, or field observations:</td>
</tr>
<tr>
<td>1</td>
<td>What are the standing stocks, composition, &amp; productivity of ocean ecosystems? How and why are they changing? [OBB1]</td>
<td>Quantify phytoplankton biomass, pigments, optical properties, key (functional) phytoplankton groups, and productivity using bio-optical models and chlorophyll fluorescence</td>
<td>Water-leaving radiances in near-ultraviolet, visible, &amp; near-infrared for separation of absorbing &amp; scattering constituents and calculation of chlorophyll fluorescence</td>
<td>Ocean Radiometer • 5 nm resolution 350 to 750 nm • 1000 – 1500 SNR for 20 nm aggregate bands UV &amp; visible • 750 – 1000 SNR for 10 nm fluorescence bands (667, 678, 748 nm band centers) • 30 to 40 nm bandwidth atmospheric correction bands at 765, 865, 1245, 1640 nm with 180 – 750 SNR • 0.5% radiometric accuracy • 0.1% radiometric stability • 58.3o cross track scanning • Sensor tilt (20o) for glint avoidance • Polarization insensitive</td>
<td></td>
<td>(1) Ozone (2) Water vapor (3) Wind</td>
</tr>
<tr>
<td>2</td>
<td>How and why are ocean biogeochemical cycles changing? How do they influence the Earth system? [OBB2]</td>
<td>Measure particulate and dissolved carbon species, their characteristics and optical properties</td>
<td></td>
<td>sun synchronous orbit with crossing time between 10:30 a.m. &amp; 2:30 p.m.</td>
<td></td>
<td>Science Requirements (1) SST (2) SSH (3) PAR (4) UV (5) MLD (6) CO₂ (7) pH (8) Ocean circulation (9) Aerosol deposition (10) run-off loading in coastal zone (11) other…..</td>
</tr>
<tr>
<td>3</td>
<td>What are the material exchanges between land &amp; ocean? How do they influence coastal ecosystems, biogeochemistry &amp; habitats? How are they changing? [OBB1,2,3]</td>
<td>Assess ocean photobiochemical processes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>How do aerosols &amp; clouds influence ocean ecosystems &amp; biogeochemical cycles? How do ocean biological &amp; photochemical processes affect the atmosphere and Earth system? [OBB2]</td>
<td>Estimate particle abundance, size distribution, &amp; characteristics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>How do physical ocean processes affect ocean ecosystems &amp; biogeochemistry? How do ocean biological processes influence ocean physics? [OBB1,2]</td>
<td>Assimilate ACE observations in ocean biogeochemical model fields of key properties (cf., air-sea CO₂ fluxes, export, pH, etc.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>What is the distribution of algal blooms and their relation to harmful algal and eutrophication events? How are these events changing? [OBB1,4]</td>
<td>Compare ACE observations with ground-based and model data of biological properties, land-ocean exchange in the coastal zone, physical properties (e.g., winds, SST, SSH, etc), and circulation (ML dynamics, horizontal divergence, etc)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* ACE focused questions are traceable to the four overarching science questions of NASA’s Ocean Biology and Biogeochemistry Program [OBB1 to OBB4] as defined in the document: *Earth’s Living Ocean: A Strategic Vision for the NASA Ocean Biological and Biogeochemistry Program* (under NRC review)
Advance Plan: Earth’s Living Ocean: The Unseen World

NASA Ocean Biology and Biogeochemistry Program

Team from April 2005: Michael Behrenfeld, Heidi Dierssen, Paul DiGiacomo, Steve Lohrenz, Chuck McClain, Frank Muller-Karger, Dave Siegel, (Paula Coble)
May 2006-October 2006: Posted for Public Comment
  Reviewers: Tony Freeman, Norm Nelson, Jim Yoder
March 2007: Briefed to NRC OSB
April 2007: Negotiations with NRC for review (OSB and SSB)
September 2007: Public comments incorporated
April 2008: Briefed to NRC SSB
April 2008: Letter drafted for NASA SMAC review
December 2008: plan to have joint SSB/OSB (NASA-NOAA) sponsored review
April 2009: Statement of Task for OSB, SSB finalized (NASA, NOAA, NSF, ONR)
**Timeline**

- **Immediate** (1 – 5 Years)
- **Near-Term** (5 - 10 Years)
- **Long-Term** (10 - 25 Years)

### Mission Themes

#### Global Separation of In-water Constituents & Advanced Atmospheric correction
- **Advanced radiometer & scattering lidar**
  - 5nm resolution from UV through visible
  - Ozone & extended NIR atmosphere bands
  - Atmosphere & subsurface particle scattering profiles

- **Ocean radiance and atmosphere aerosols**
  - Advanced radiometer
  - Scattering lidar for aerosol speciation
  - Polarimeter for global aerosol coverage
  - 500 m passive resolution

- **Radiometry, aerosols, and physiology lidar**
  - Global radiometry system
  - Aerosol height & species
  - Midnight/noon obs of variable stimulated fluorescence

#### High Spatial & Temporal Resolution Coastal
- **Coastal carbon – GEO Support analysis of current satellite data Landsat DCM partnership Development of suborbital sensor systems**

- **High-res coastal imager**
  - 20 bands from UV - NIR
  - 10 m res – 100 km swath

- **Constellation of imaging spectrometers**
  - High temporal res
  - LEO, MEO or GEO
  - Include SAR
  - Continued deployment of suborbital systems

#### Plant Physiology & Functional Composition
- **Support analysis of global passive data**
  - Assess functional groups using hyperspectral data
  - Estimate algal carbon & chlorophyll to characterize physiology

- **Support analysis of global & GEO data**

- **Variable fluorescence lidar constellation**
  - Map physiological provinces at different times of day
  - Dawn/dusk variable fluorescence lidar
  - Noon/midnight lidar

#### Mixed Layer Depth
- **Synthesis/analysis of observational forecast fields & on orbit remote sensing Mixed layer model development**

- **Prototype mixed layer sensor development**
  - Field testing of novel approaches for remote detection of mixed layer depth & light availability

- **Mixed layer depth mission**
  - Space-borne proof-of-concept mission for global mixed layer depth mapping

### Top Priority Science Questions

- **How are ocean ecosystems and the biodiversity they support influenced by climate or environmental variability and change, and how will these changes occur over time?**
  - Improved management of ecosystem goods and services

- **How do carbon and other elements transition between ocean pools and pass through the Earth System, and how do biogeochemical fluxes impact the ocean and Earth’s climate over time?**
  - Information-based policy on greenhouse gas emissions and nutrient loading

- **How (and why) is the diversity and geographical distribution of coastal marine habitats changing, and what are the implications for the well-being of human society?**
  - Mapping and assessment of coastal habitats for future development plans and tourism

- **How do hazards and pollutants impact the hydrography and biology of the coastal zone? How do they affect us, and can we mitigate their effects?**
  - National security and improved forecasting of natural and human-induced hazards

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**Bold Green Text Represents Satellite Missions**

**Bold Blue Text Represents Development Activities leading to Missions**

**Cross-hatch indicates secondary contribution to Mission Theme**
Science Questions

• How are ocean ecosystems and the biodiversity they support influenced by climate and environmental variability and change, and how will these changes occur over time?

• How do carbon and other elements transition between ocean pools and pass through the Earth System, and how do biogeochemical fluxes impact the ocean and Earth's climate over time?

• How (and why) is the diversity and geographical distribution of coastal marine habitats changing, and what are the implications for the well-being of human society?

• How do hazards and pollutants impact the hydrography and biology of the coastal zone? How do they affect us, and can we mitigate their effects?
Mission Themes/Science Requirements

- Global separation of in-water constituents and advanced atmospheric corrections
- High temporal and spatial resolution coastal measurements
- Active assessments of plant physiology and functional composition
- Mixed layer depth
Science Requirements Lead to Observational Strategies

- Global Hyperspectral Imaging Radiometer
- Geostationary Hyperspectral Imaging Radiometer(s)
- Multi-Spectral High Spatial Resolution Imager
- Portable Sensors from Suborbital Platforms
- Variable Fluorescence Lidar
- Mixed Layer Depth and Illumination Sensor
- Ocean Particle Profiler and Aerosol Column Distributions
Science Requirements Lead to Observational Strategies

- Global Hyperspectral Imaging Radiometer
  - Aerosol-Ocean-Cloud (polarimeter, lidar, ocean radiometer, radar)
- Geostationary Hyperspectral Imaging Radiometer(s)
- Multi-Spectral High Spatial Resolution Imager
  - Plant Physiology and Functional Types
- Portable Sensors from Suborbital Platforms
- Variable Fluorescence Lidar
- Mixed Layer Depth and Illumination Sensor
- Ocean Particle Profiler and Aerosol Column Distributions
<table>
<thead>
<tr>
<th>Decadal Survey Mission</th>
<th>Mission Description</th>
<th>Orbit</th>
<th>Instruments</th>
<th>Rough Cost Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Timeframe 2010 – 2013, Missions listed by cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLARREO (NASA portion)</td>
<td>Solar and Earth radiation, spectrally resolved forcing and response of the climate system</td>
<td>LEO, Precessing</td>
<td>Absolute, spectrally-resolved interferometer</td>
<td>$200 M</td>
</tr>
<tr>
<td>SMAP</td>
<td>Soil moisture and freeze/thaw for weather and water cycle processes</td>
<td>LEO, SSO</td>
<td>L-band radar</td>
<td>$300 M</td>
</tr>
<tr>
<td>ICESat-II</td>
<td>Ice sheet height changes for climate change diagnosis</td>
<td>LEO, Non-SSO</td>
<td>Laser altimeter</td>
<td>$300 M</td>
</tr>
<tr>
<td>DESDynl</td>
<td>Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health</td>
<td>LEO, SSO</td>
<td>L-band InSAR Laser altimeter</td>
<td>$700 M</td>
</tr>
<tr>
<td><strong>Timeframe: 2013 – 2016, Missions listed by cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HyspIRI</td>
<td>Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health</td>
<td>LEO, SSO</td>
<td>Hyperspectral spectrometer</td>
<td>$300 M</td>
</tr>
<tr>
<td>ASCENDS</td>
<td>Day/night, all-altitude, all-season CO₂ column integrals for climate emissions</td>
<td>LEO, SSO</td>
<td>Multifrequency laser</td>
<td>$400 M</td>
</tr>
<tr>
<td>SWOT</td>
<td>Ocean, lake, and river water levels for ocean and inland water dynamics</td>
<td>LEO, SSO</td>
<td>Ka-band wide swath radar C-band radar</td>
<td>$450 M</td>
</tr>
<tr>
<td>GEO-CAPE</td>
<td>Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions</td>
<td>GEO</td>
<td>High and low spatial resolution hyperspectral imagers</td>
<td>$550 M</td>
</tr>
<tr>
<td>ACE</td>
<td>Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry</td>
<td>LEO, SSO</td>
<td>Backscatter lidar Multiangle polarimeter Doppler radar</td>
<td>$800 M</td>
</tr>
<tr>
<td><strong>Timeframe: 2016 -2020, Missions listed by cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LIST</td>
<td>Land surface topography for landslide hazards and water runoff*</td>
<td>LEO, SSO</td>
<td>Laser altimeter</td>
<td>$300 M</td>
</tr>
<tr>
<td>PATH</td>
<td>High frequency, all-weather temperature and humidity soundings for weather forecasting and SST*</td>
<td>GEO</td>
<td>MW array spectrometer</td>
<td>$450 M</td>
</tr>
<tr>
<td>GRACE-II</td>
<td>High temporal resolution gravity fields for tracking large-scale water movement</td>
<td>LEO, SSO</td>
<td>Microwave or laser ranging system</td>
<td>$450 M</td>
</tr>
<tr>
<td>SCLP</td>
<td>Snow accumulation for fresh water availability</td>
<td>LEO, SSO</td>
<td>Ku and X-band radars K and Ka-band radiometers</td>
<td>$500 M</td>
</tr>
<tr>
<td>GACM</td>
<td>Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction</td>
<td>LEO, SSO</td>
<td>UV spectrometer IR spectrometer Microwave limb sounder</td>
<td>$600 M</td>
</tr>
<tr>
<td>3D-Winds (Demo)</td>
<td>Tropospheric winds for weather forecasting and pollution transport</td>
<td>LEO, SSO</td>
<td>Doppler lidar</td>
<td>$650 M</td>
</tr>
</tbody>
</table>

* Cloud-independent, high temporal resolution, lower accuracy SST to complement, not replace, global operational forecasting systems.
Earth’s Living Ocean: The Unseen World

- NASA seeks to advance understanding of the Earth’s living ocean through global research, observations and predictive models

- Cal/Val

- Plan – Living Document