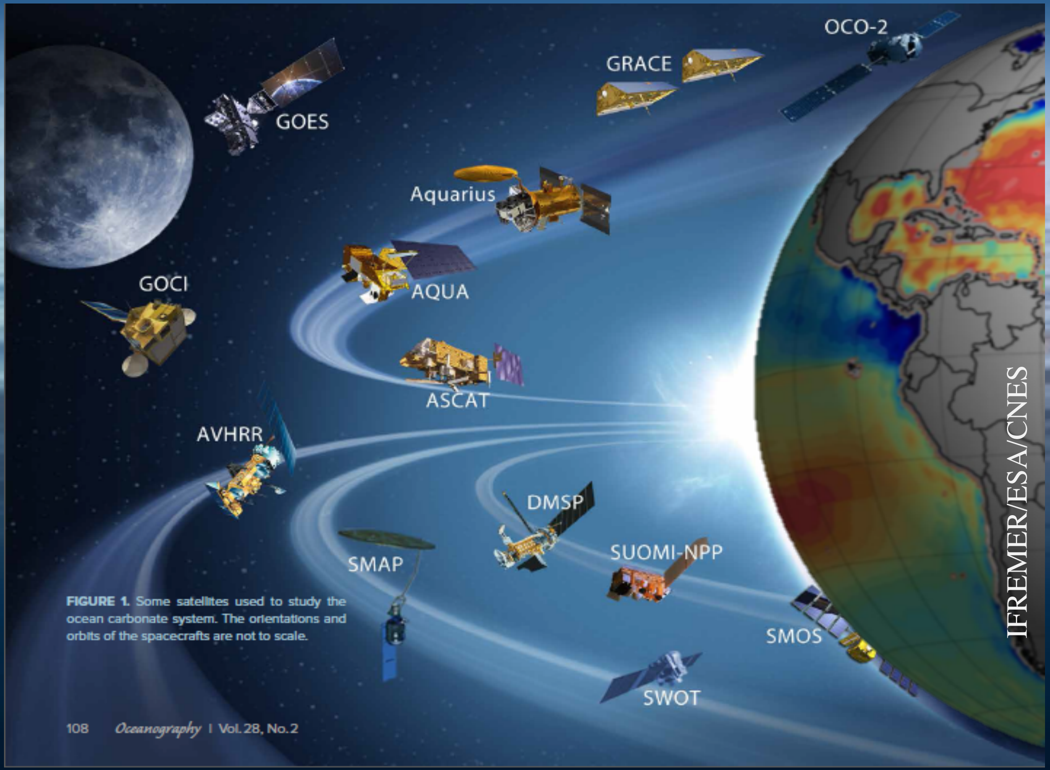
OCEAN ACIDIFICATION FROM SPACE

Presented for…
NASA Carbon Monitoring System
Policy Speaker Series

NASA Goddard Space Flight Center
2 June 2016



National Oceanic & Atmospheric Administration (NOAA)

Ocean Acidification Program Office

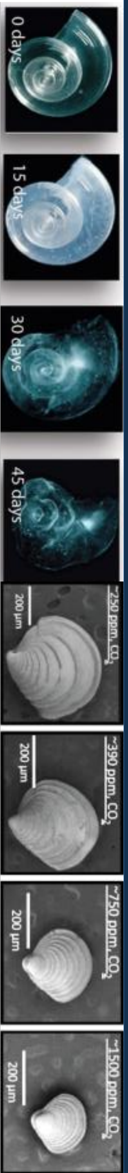
Dwight Gledhill, NOAA OAP
Deputy Director

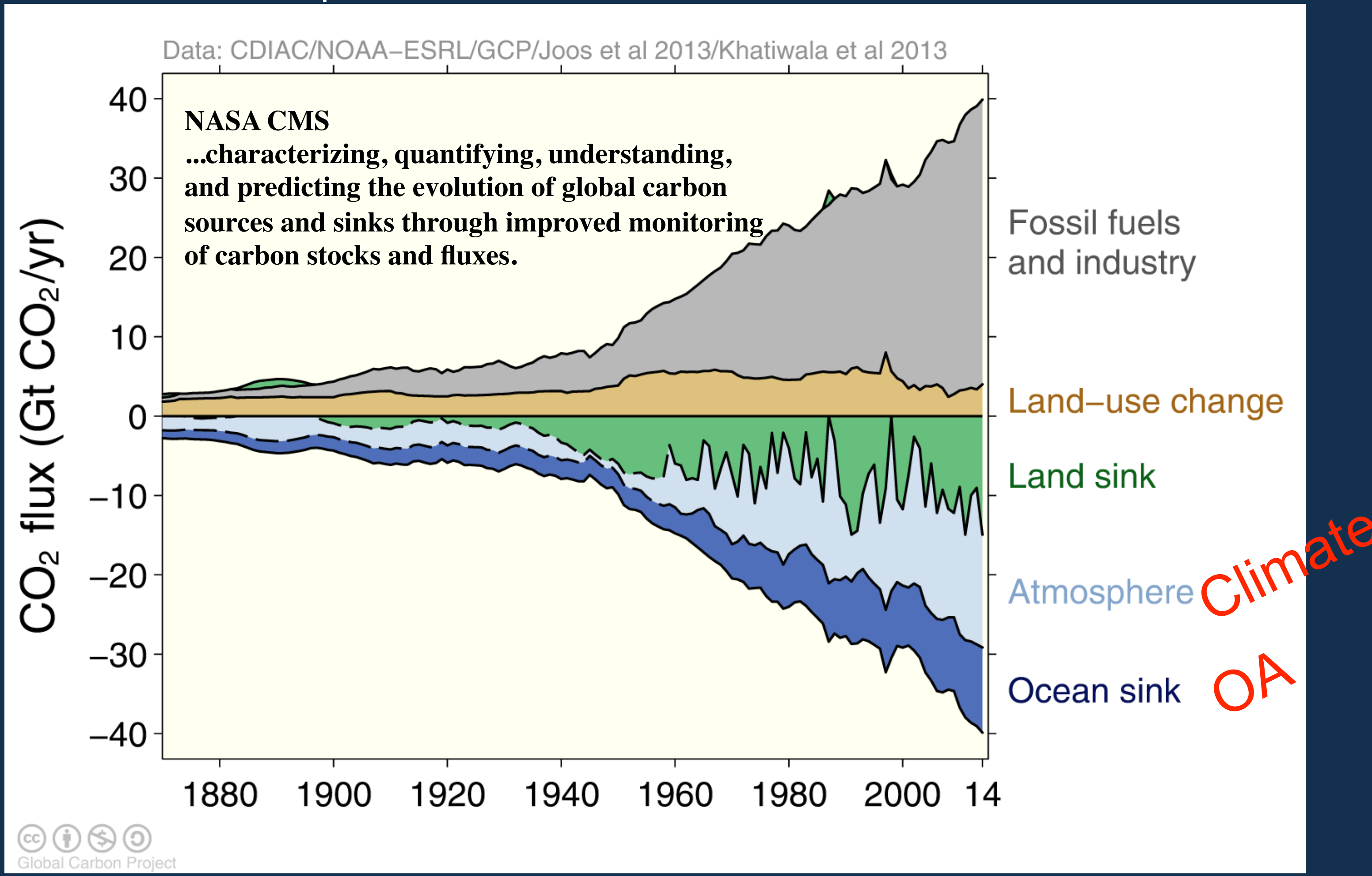
http://www.oceanacidification.noaa.gov/

NOAA OCEAN ACIDIFICATION PROGRAM

Global carbon budget

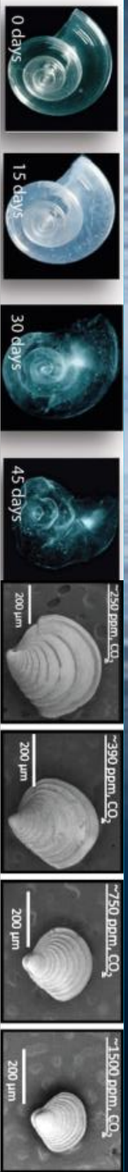
The carbon sources from fossil fuels, industry, and land use change emissions are balanced by the atmosphere and carbon sinks on land and in the ocean





Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2015; Global Carbon Budget 2015

Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009



- NOAA: …establish...[OAP] to conduct research, monitoring
- NASA: ...ensure space-based assets are applied
- NSF: ...competitive research

Defines ocean acidification as "the decrease in pH of the Earth's oceans and changes in ocean chemistry caused by chemical inputs from the atmosphere, including carbon dioxide."

Coordinate research, monitoring, and other activities consistent with the **Interagency Working Group on Ocean Acidification strategic research plan**.

U.S. Coordination on Ocean Acidification Science

Vision

"A nation, globally engaged and guided by science, sustaining healthy marine and coastal ecosystems, communities, and economies through informed response to ocean acidification"

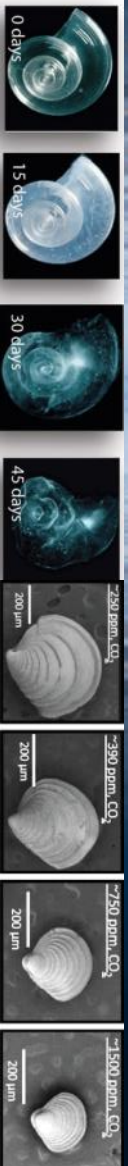
"...provide for an **assessment** of the impacts ...on marine ecosystems and the **development of adaption and mitigation strategies** to conserve marine organisms and marine ecosystems."

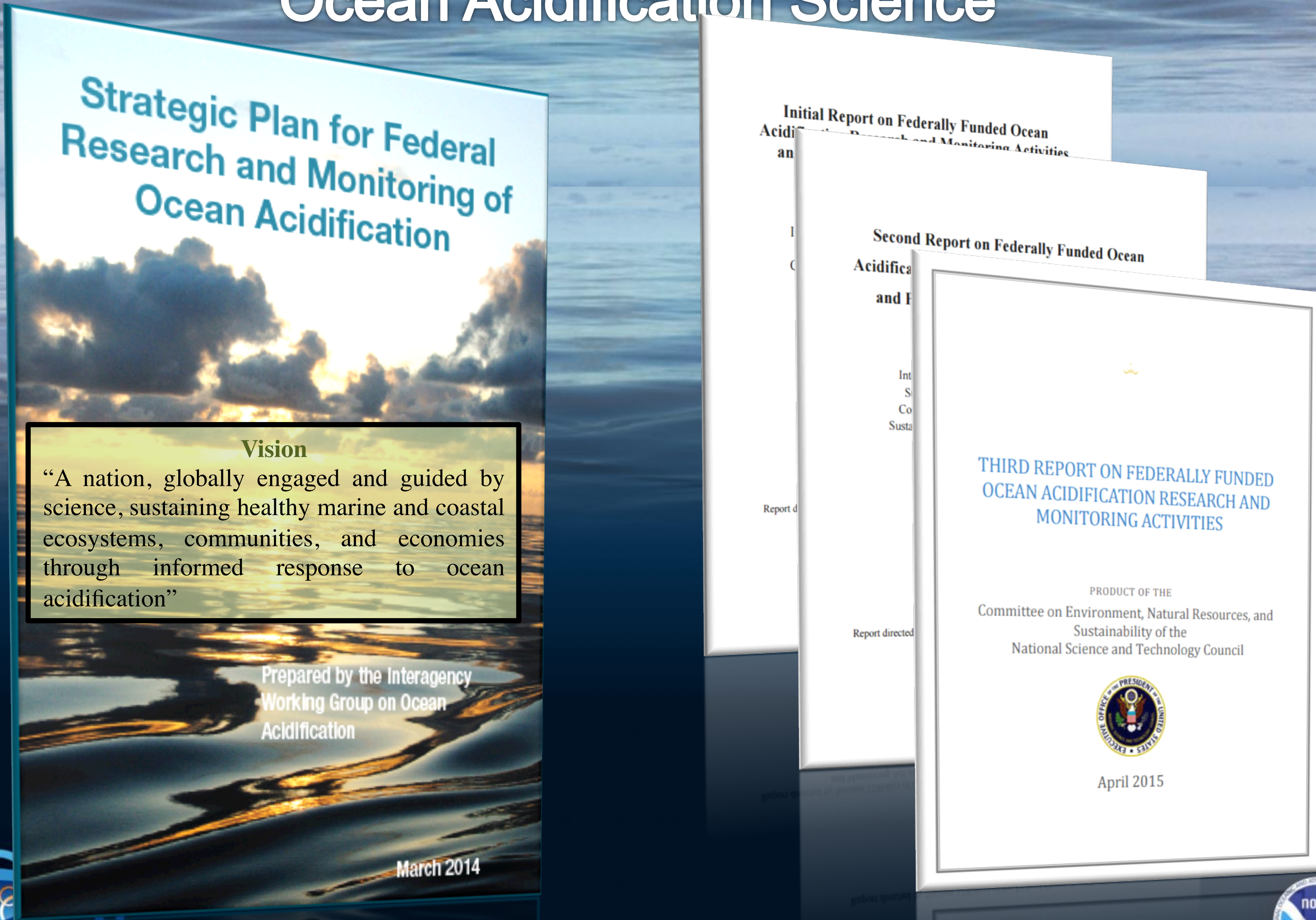
March 2014

Coastal and estuarine acidification, to the extent that the cause of the acidification can be traced back to anthropogenic atmospheric inputs to the ocean, are assumed to be covered

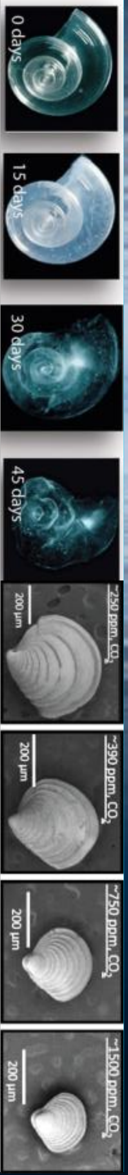
NOAA OCEAN ACIDIFICATION PROGRAM

U.S. Coordination on Ocean Acidification Science





NOAA OCEAN ACIDIFICATION PROGRAM



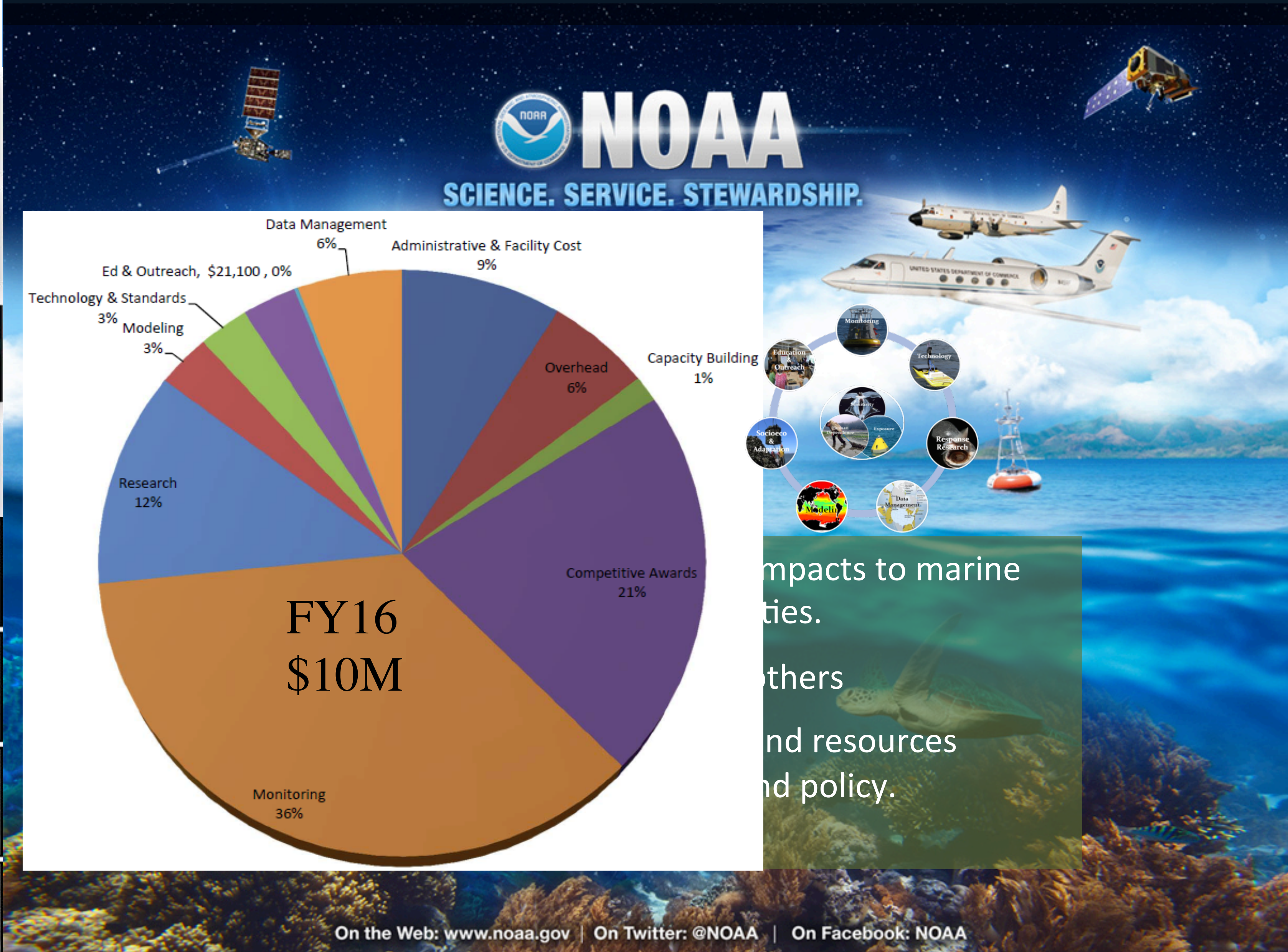
U.S. Coordination on Ocean Acidification Science

Highlighted Goals

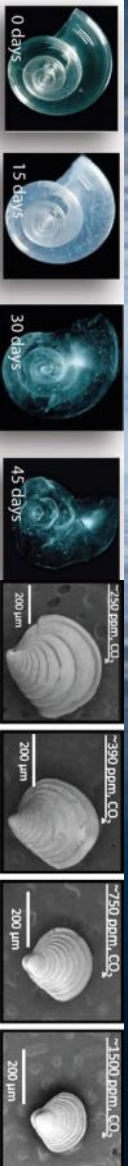
- Monitoring trends and conditions
- Research marine life response
- Predictive modeling
- Ensure data quality
- Link experimental to field
- Vulnerability assessments
- Advance technology
- Devise adaptation strategies
- Foster OA literacy
- Implement engagement strategies
- Translate science for policy
- Ensure integrated and managed data

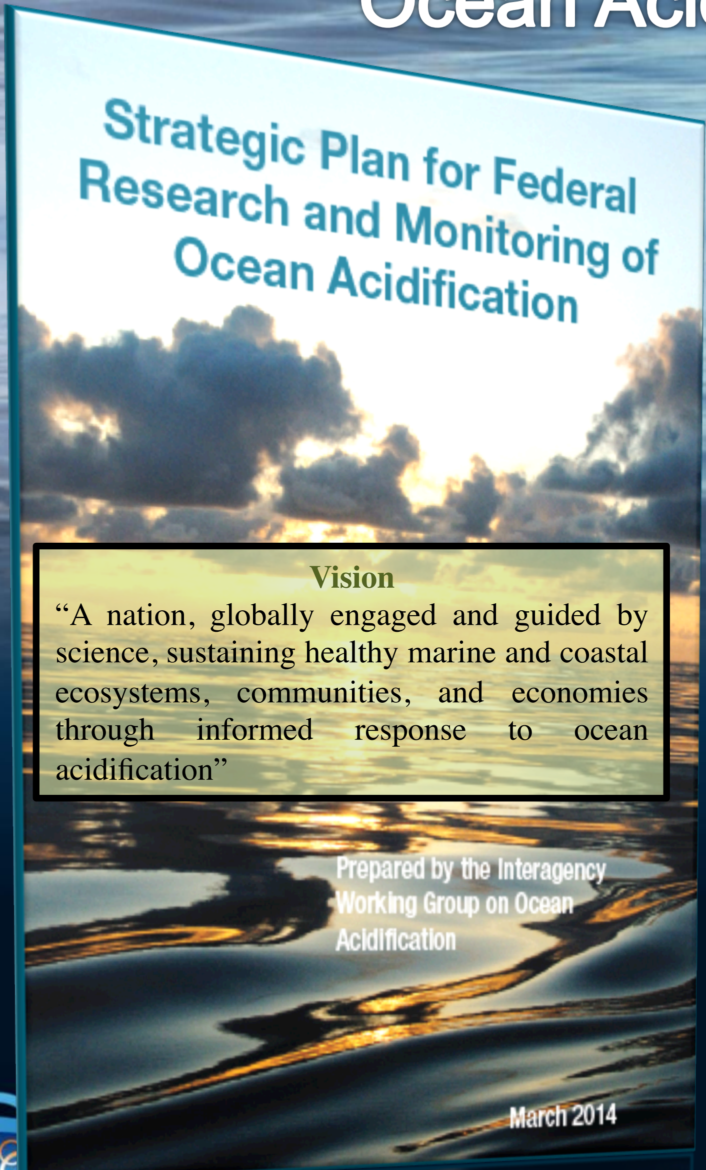
NOAA OCEAN ACIDIFICATION PROGRAM

NOAA's Ocean Acidification Program

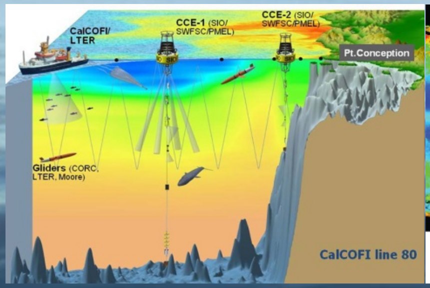


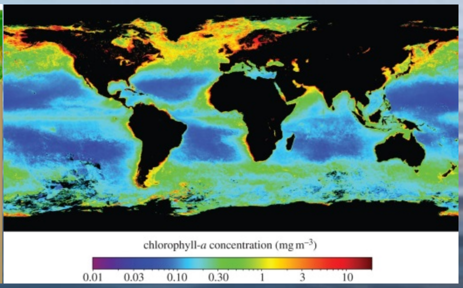
U.S. Coordination on Ocean Acidification Science





Theme 2. Monitoring of Ocean Chemistry and Biological Impacts





Goals - The National Ocean Acidification Program monitoring plan should be designed to rapidly characterize the magnitude and extent of acidification ... at global, regional, and local scales..[to enable] projections of future impacts of ocean acidification...

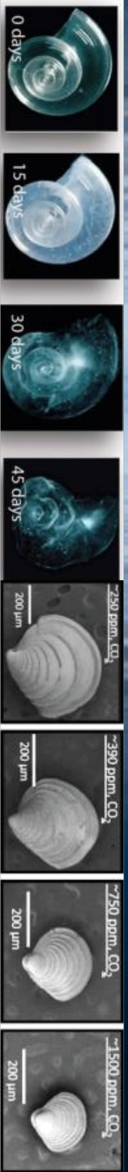
Remote Sensing- ...provide synoptic observations of a range of physical and optical parameters that allow us to **model changes in the distribution of carbonate chemistry** within the surface ocean where no in situ observations are available.

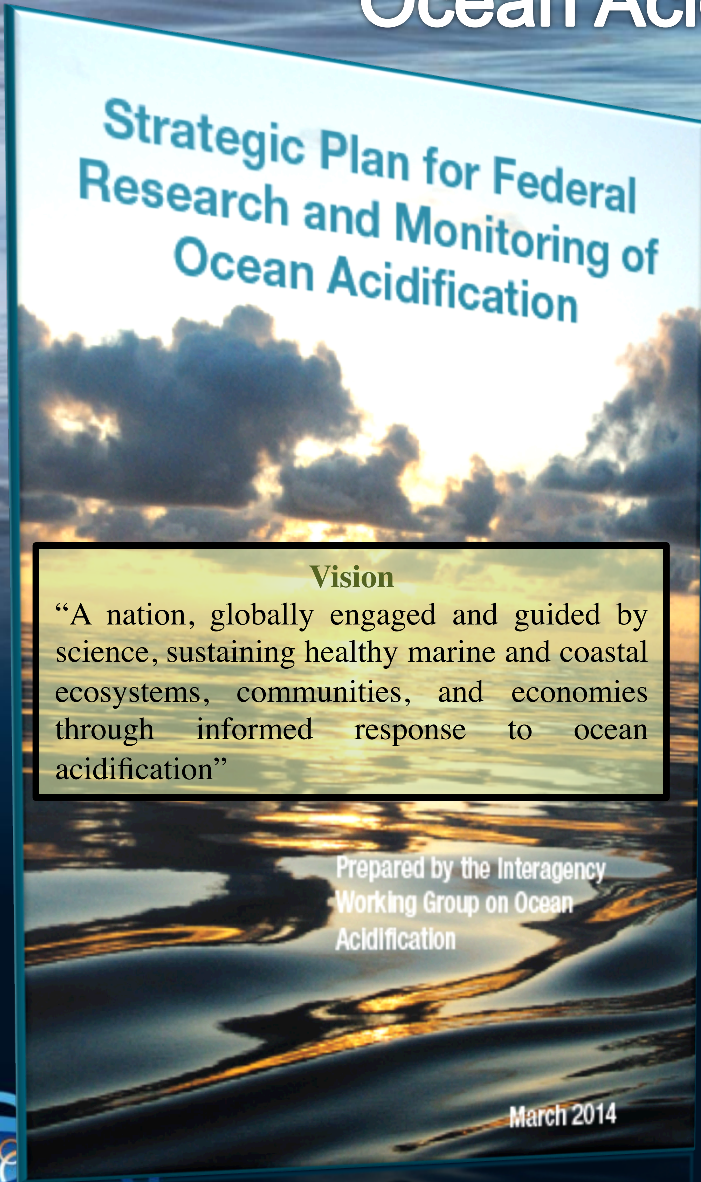
Short-term (3-5 yrs)

- Explore use of OSSEs for in situ and **remote/satellite** and aircraft-based ocean acidification observation network design.

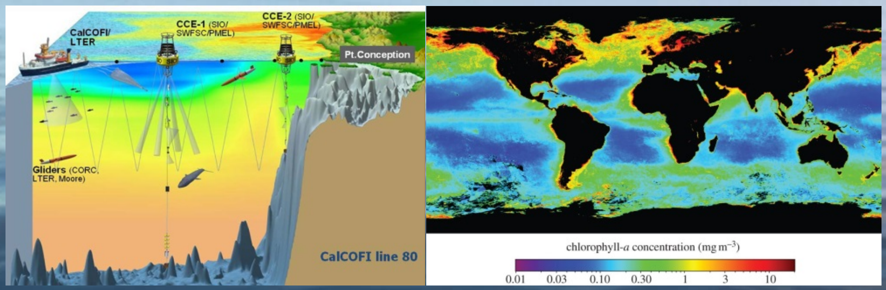
NOAA OCEAN ACIDIFICATION PROGRAM

U.S. Coordination on Ocean Acidification Science





Theme 4. Technology Development and Standardization of Measurements



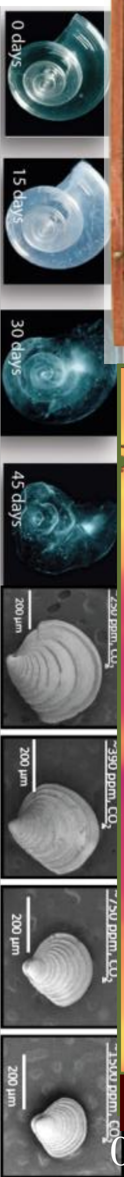
Goals - ... ensure that advancements in technology are developed systematically and quickly spread through the community.

Long-term (10 yrs)

- Develop and commercialize instrumentation **and techniques to improve capability to measure chemical** (with special focus on DIC and TA) **and biological variables over space and time**, including affordable autonomous sensors, more accessible and affordable high-quality instrumentation, **new remote sensing**, and in situ technologies..

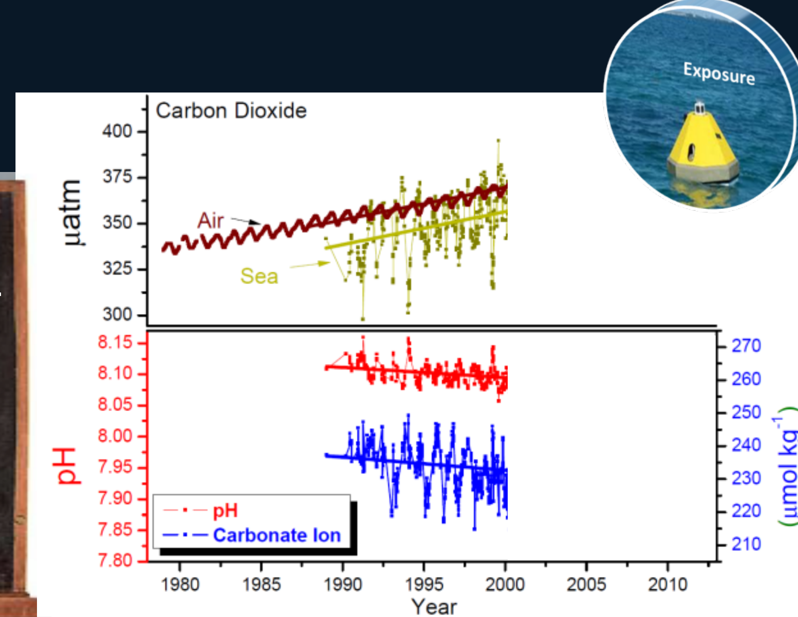
NOAA OCEAN ACIDIFICATION PROGRAM

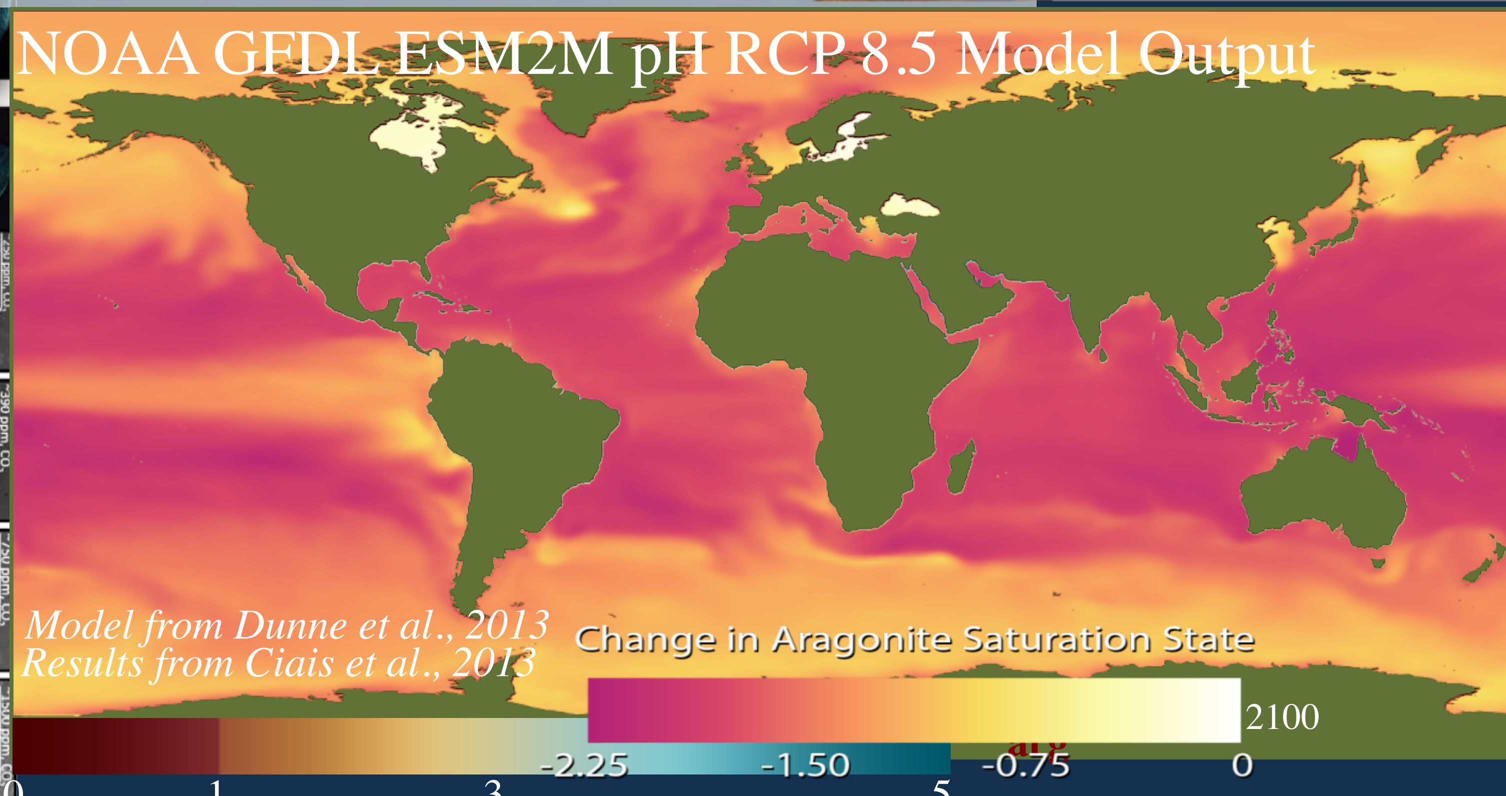
Ocean Acidification



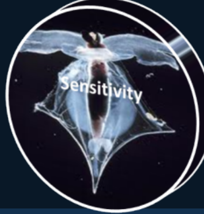
$$CO_{2,gas} + H_2O \rightarrow H^+ + HCO_3^-$$

$$H^+ + CO_3^{2-} \rightarrow HCO_3^-$$

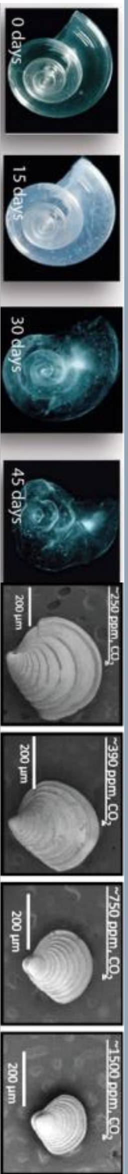




NOAA's OAP Species Response Research



Controls on Surface OA Variability

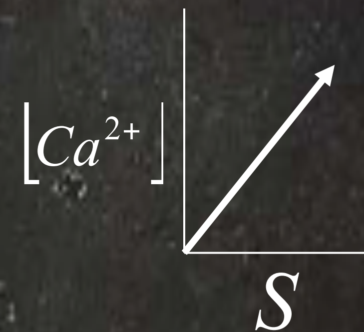


Saturation State

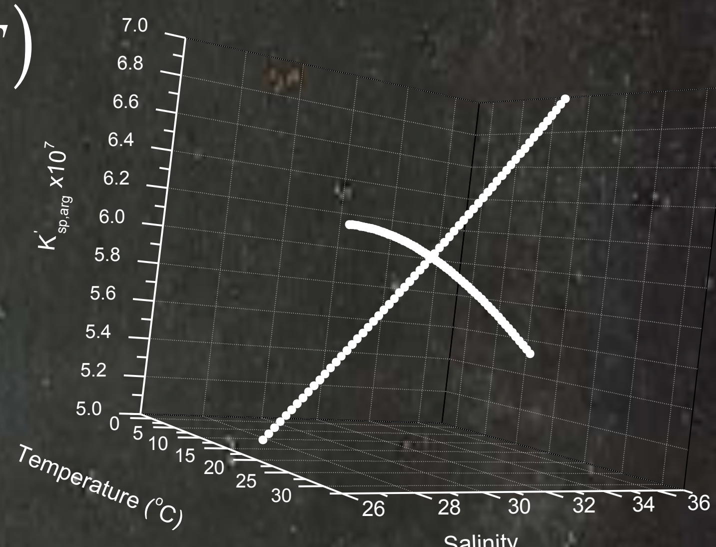
$$\Omega_{phase} = \frac{\left[Ca^{2+}\right]\left[CO_3^{2-}\right]}{K^*_{sp,phase}}$$

$$\Omega > 1 = precipitation$$
$$\Omega = 1 = equilibrium$$
$$\Omega < 1 = dissolution$$

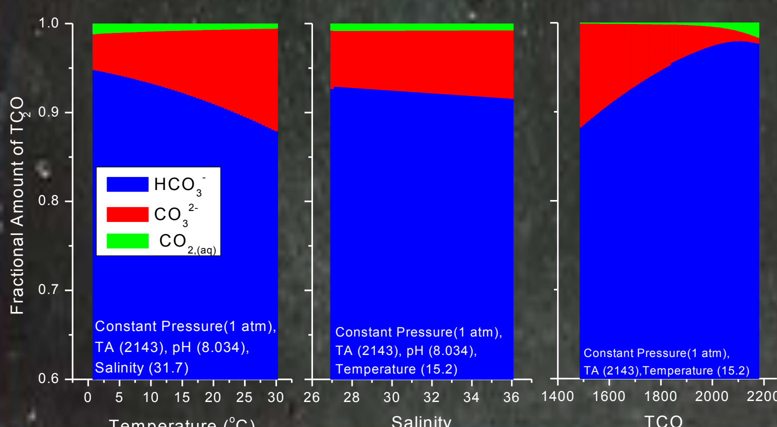
$$\left[Ca^{2+}\right] = f(S)$$



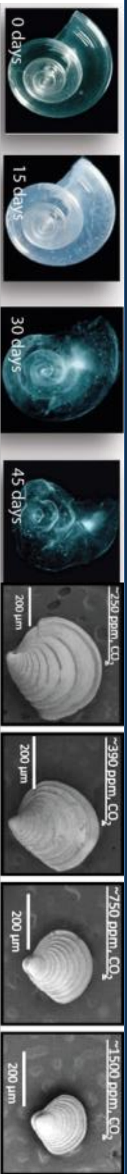
$$K^*_{sp,phase} = f(S,T)$$



$$\left[CO_3^{2-}\right] = f(S,T,TCO_2)$$

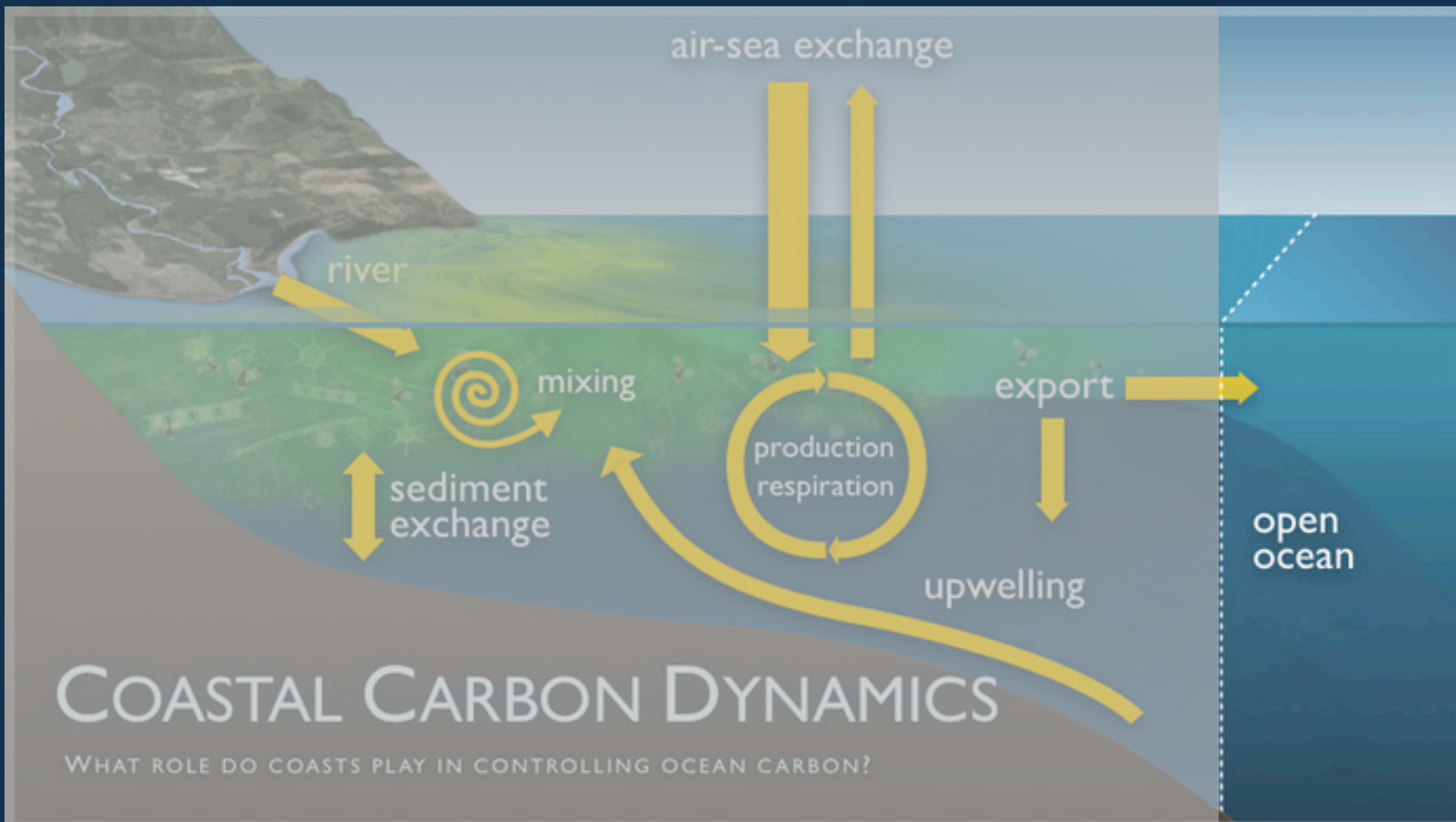


Ocean Acidification v1.0

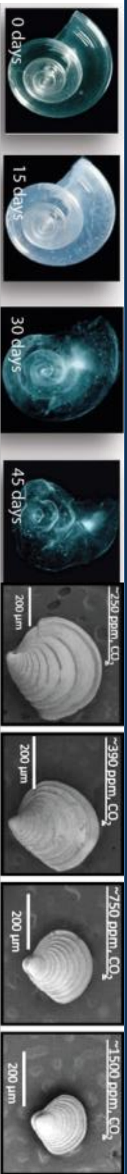


$\Omega = f$(temperature>>mixing>biology>salinity>>gas exchange)

v2.0 v1.0



Ocean Acidification v1.0



$\Omega = f$(temperature>>mixing>biology>salinity>>gas exchange)

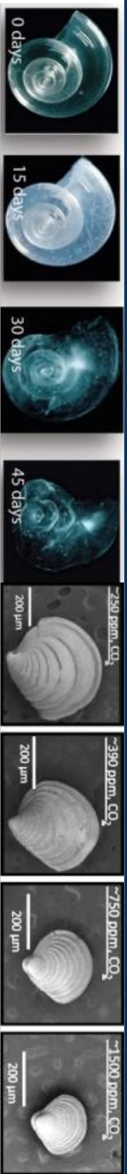
Application: temperature, solubility of carbon dioxide, mineral solubility

Satellite	Agency Name	Sensor	Wavelengths	Geophysical Measurement	Effective Repeat Interval	Product Spatial Resolution (km)	Orbit	Launch Date
Several since 1978	NOAA	Advanced Very High Resolution Radiometer (AVHRR)	Infrared (~12 µm)	IR radiance	Each ~daily	1.1	Polar	Several; 1978–present
Geostationary Operational Environmental Satellite (GOES)	NOAA	GOES Imagers	Infrared (~12 µm)	IR radiance	Each hourly	0.75	Geostationary	Several; 1975–present
Aqua and Terra	NASA	MODIS	Infrared (3.5 to 4.2 µm)	IR radiance	Each ~daily	1	Polar	1999 (Terra) 2002 (Aqua)
Meteosat Second Generation	ESA	Spinning Enhanced Visible and InfraRed Imager (SEVIRI)	Infrared	IR radiance	3-hourly	11.16 (at nadir)	Geostationary	Several; 2008–present
Tropical Rainfall Measuring Mission's (TRMM)	NASA and JAXA	Microwave Imager (TMI)	Microwave (10.7 GHz)	Passive microwave emissivity	3-day average	25	Polar	1997
Suomi-NPP	US National polar orbiting partnership	VIIRS	Infrared	IR radiance	~daily	0.75	Polar	2011

From: Salisbury et al., 2015. How can present and future satellite missions support scientific studies that address ocean acidification? *Oceanography* 28(2):108-121,http://dx.doi.org/10.5670/oceanog.2015.35.

NOAA's OAP Funding Satellite-Based Projects

http://www.coral.noaa.gov/accrete/oaps.html



Ocean Acidification Product Suite for the Greater Caribbean Region, Gulf o Mexico, and US East Coast

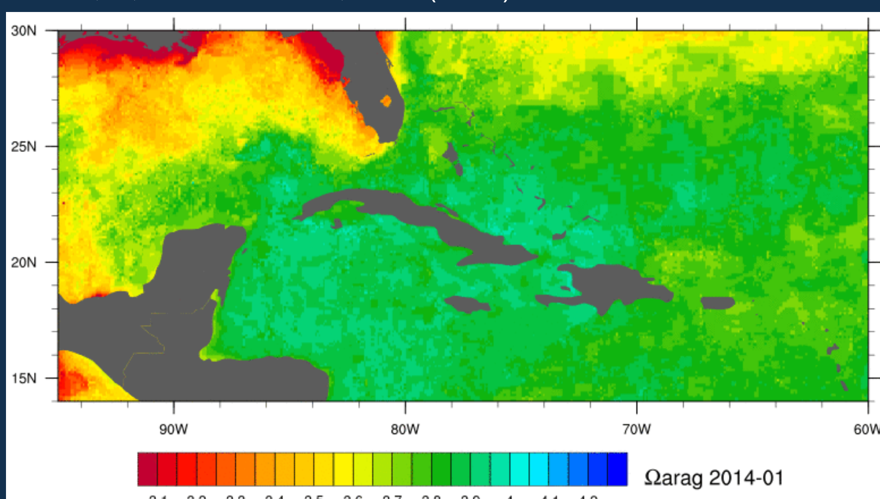
Van Hooidonik, Wanninkjof, Barbero (AOML)

$$A_T = a + b(SSS - 35) + c(SSS - 35)^2 + d(SST - 20) + e(SST - 20)^2$$

Lee, K., L. T. Tong, et al. (2006). "Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans." Geophysical Research Letters **33**.

$$pCO_{2,sw} = y_0 + A\, e^{(-K_0/B)} + pCO_{2,air}$$

Gledhill, D, R. Wanninkhof, et al. (2008). "Ocean Acidification of the Greater Caribbean 1996-2008." JGR **113**.



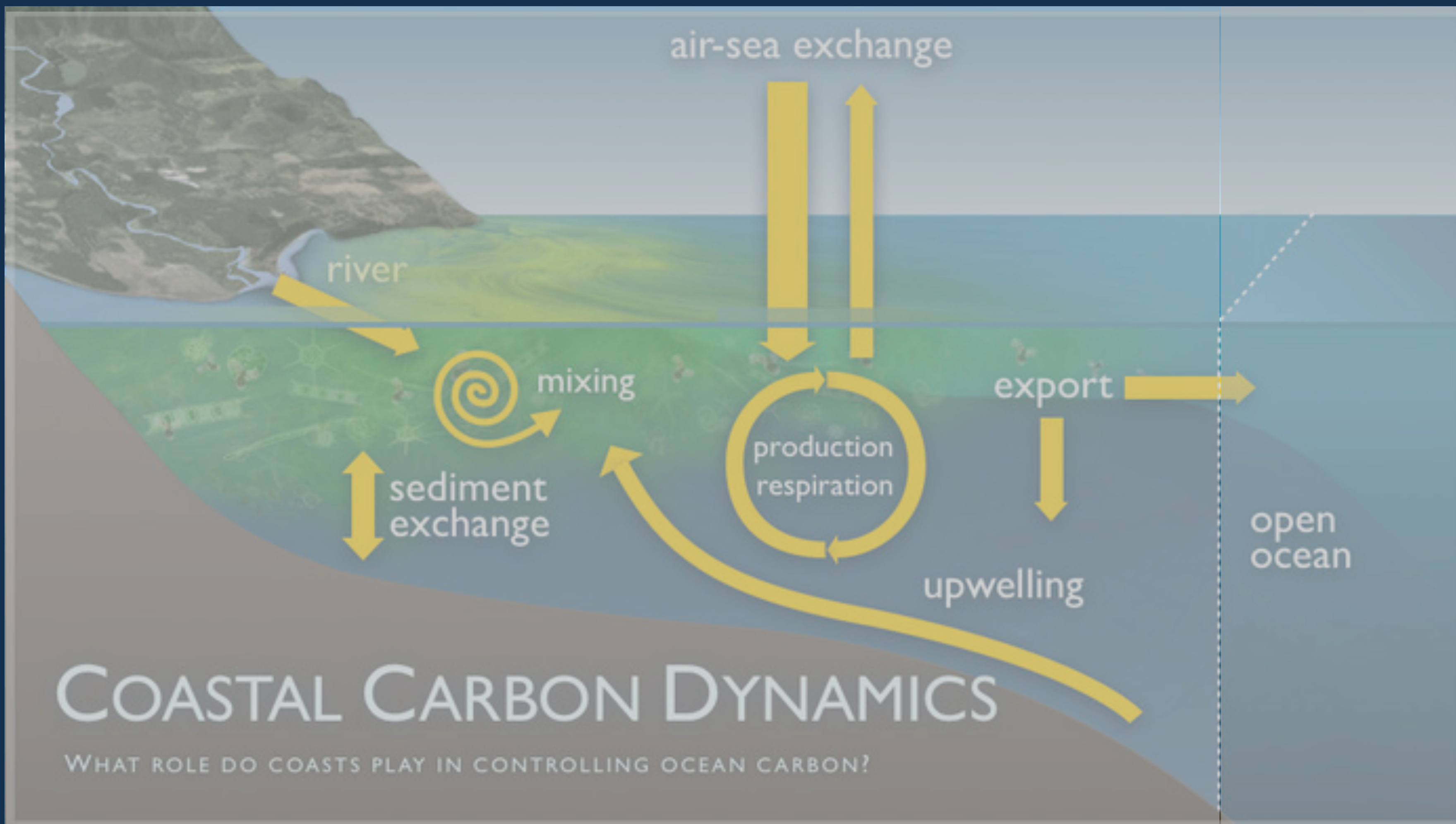
no single pCO2 algorithm applicable at the global scale

Ocean Acidification v1.0 / v2.0

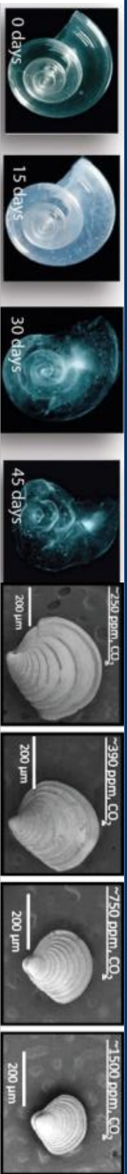
$\Omega = f$(temperature>salinity>biology>mixing>gas exchange)

$\Omega = f$(biology>mixing>temperature>salinity>gas exchange)

v2.0 v1.0



Ocean Acidification v2.0



$\Omega = f$(biology>>salinity>temperature>mixing>gas exchange)

Application: chlorophyll, particulate & dissolved colored carbon, particulate inorganic carbon, net primary & community productivity, ecological province designations

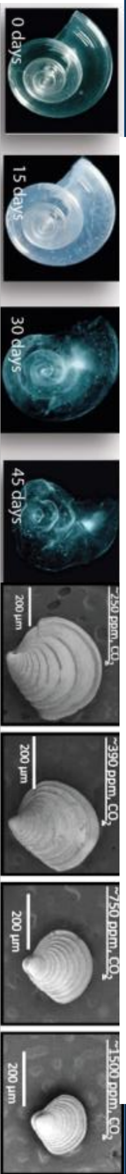
Satellite	Agency Name	Sensor	Wavelengths	Geophysical Measurement	Effective Repeat Interval	Product Spatial Resolution (km)	Orbit	Launch Date
Aqua and Terra	NASA	Moderate Resolution Imaging Spectroradiometer (MODIS)	Visible – near infrared	Water leaving radiance (λ)	~daily	0.25, 0.50, and 1.00	Polar	1999 (Terra) 2002 (Aqua)
Suomi-NPP	US National polar orbiting partnership	Visible Infrared Imaging Radiometer Suite (VIIRS)	Visible – near infrared	Water leaving radiance (λ)	~daily	0.75	Polar	2011
MERIS	European Space Agency	MEdium Resolution Imaging Spectrometer (MERIS)	Visible – near infrared	Water leaving radiance (λ)	~daily	0.3	Polar	2002
COMS	Korea Ocean Satellite Center	Geostationary Ocean Colour Imager (GOCI)	Visible – near infrared	Water leaving radiance (λ)	1 hour	0.5 (at nadir)	Geostationary	2009
OceanSat 2	Indian Space Research Organisation	Ocean Colour Monitor (OCM)	Visible – near infrared	Water leaving radiance (λ)	~daily	0.36	Polar	2009

PFT shifts: Satellite observations can be used to infer changes in the functional types that include calcifiers (coccolithophores), silicifiers (diatoms), and nitrogen fixers cyanobacteria)

Detection and quantification of coccolithophore PIC is invaluable providing spatiotemporal information about the conversion of TCO2 to PIC

From: Salisbury et al., 2015. How can present and future satellite missions support scientific studies that address ocean acidification? *Oceanography* 28(2):108-121,http://dx.doi.org/10.5670/oceanog.2015.35.

NOAA's OAP Funding Satellite-Based Projects



Multi-Scale Prediction of California Current Carbonate System Dynamics

Hales (OSU), Kavanaugh & Doney (WHOI)

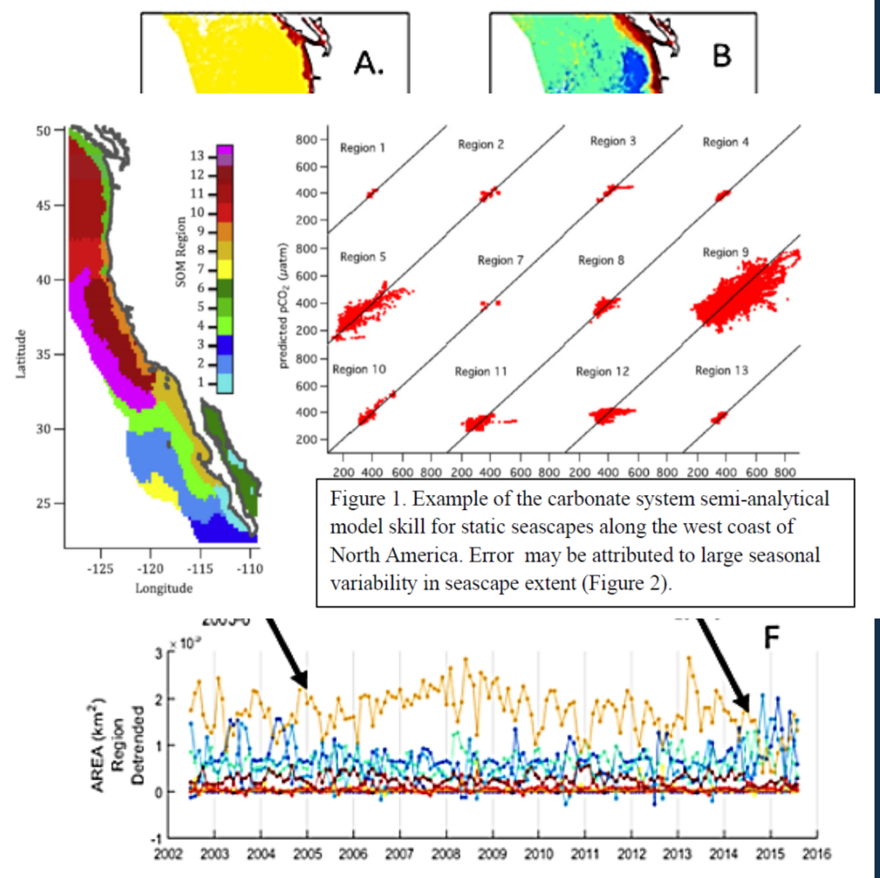
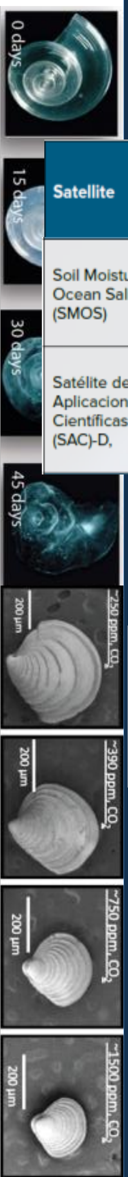


Figure 1. Example of the carbonate system semi-analytical model skill for static seascapes along the west coast of North America. Error may be attributed to large seasonal variability in seascape extent (Figure 2).

Objective: Embed semi-analytical OA prediction model within a dynamic classification of pelagic seascapes derived from satellite remotely sensed Variables (phytoplankton standing stock (chl-a), SST, and wind stress.

Application: Synoptic time series and nowcasts of surface OA conditions.

Salinity Sensors Application to OA



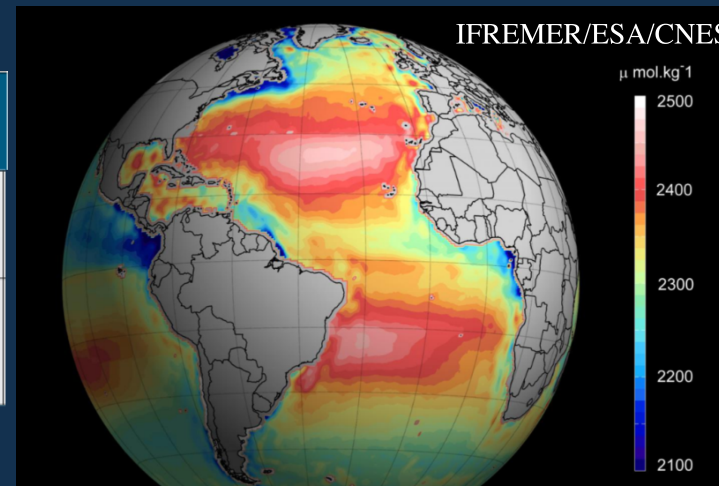
Application: salinity, total alkalinity, solubility of carbon dioxide, mineral solubility, mixing

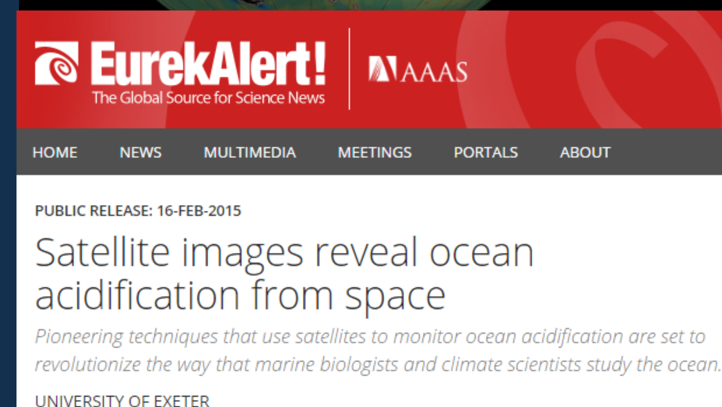
Satellite	Agency Name	Sensor	Wavelengths	Geophysical Measurement	Effective Repeat Interval	Product Spatial Resolution (km)	Orbit	Launch Date
Soil Moisture Ocean Salinity (SMOS)	ESA	Microwave Imaging Radiometer with Aperture Synthesis (MIRAS)	L-Band microwave (1.4 Ghz)	Passive microwave radiation	10–30 day average	~75	Polar	2009
Satélite de Aplicaciones Científicas (SAC)-D,	NASA/ Comisión Nacional de Actividades Espaciales (CONAE)	Aquarius	L-Band microwave (1.3 Ghz)	Passive microwave radiation	10–30 day average	~100	Polar	2011

From: Salisbury et al., 2015. How can present and future satellite missions support scientific studies that address ocean acidification? *Oceanography* 28(2):108-121,http://dx.doi.org/10.5670/oceanog.2015.35.

Close to the coast where pixel size limitations hamper salinity sensor capabilities, it is possible to retrieve salinity at higher resolution from established regional relationships between salinity and ocean color variables (Molleri al., 2010; Salisbury et al., 2011; Reul et al.,2013).

imprecision of ±0.2 in satellite-derived salinity translates to ±10–15 µMol kg–1 in Talk.

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PUBLIC RELEASE: 16-FEB-2015

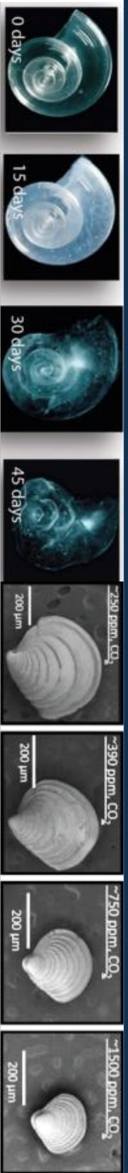
Satellite images reveal ocean acidification from space

Pioneering techniques that use satellites to monitor ocean acidification are set to revolutionize the way that marine biologists and climate scientists study the ocean.

UNIVERSITY OF EXETER

From: Land et al., 2015. Salinity from Space Unlocks Satellite-Based Assessment of Ocean Acidification. *Environmental Sci*. & *Tech*. 49(4):1987-1994, DOI: 10. 1021/es504849s.

Remote Sensing of Air-Sea CO_2 Exchange



Application: air-sea gas disequilibrium, secular changes in OA

Satellite	Agency Name	Sensor	Wavelengths	Geophysical Measurement	Effective Repeat Interval	Product Spatial Resolution (km)	Orbit	Launch Date
USAF F-16 through F-18	US Air Force (DMSP)	Special Sensor Microwave Imager/Sounder (SSM/IS)	Various microwave 19 to 183 GHz	Passive microwave radiation	Sub daily	17–74	Polar	2005
MetOp-B	European Space Agency	Advanced SCATterometer (ASCAT)	5.255 GHz (C-band)	Active radar	29 days	25–50	Polar	2012

Satellite	Agency Name	Sensor	Wavelengths	Geophysical Measurement	Effective Repeat Interval	Product Spatial Resolution (km)	Orbit	Launch Date
Orbiting Carbon Observatory-2 (OCO-2)	NASA	Triple spectrometers	NIR	Absorption (I)	16 days	1,000	Polar	2014

WHAT ROLE DO COASTS PLAY IN CONTROLLING OCEAN CARBON?

From: Salisbury et al., 2015. How can present and future satellite missions support scientific studies that address ocean acidification? *Oceanography* 28(2):108-121,http://dx.doi.org/10.5670/oceanog.2015.35.

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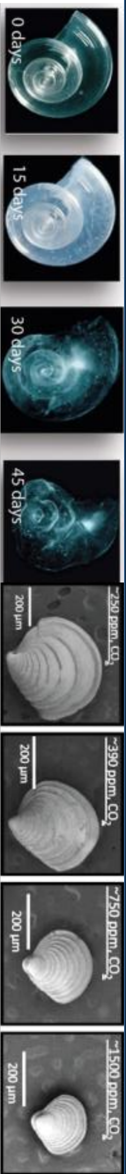
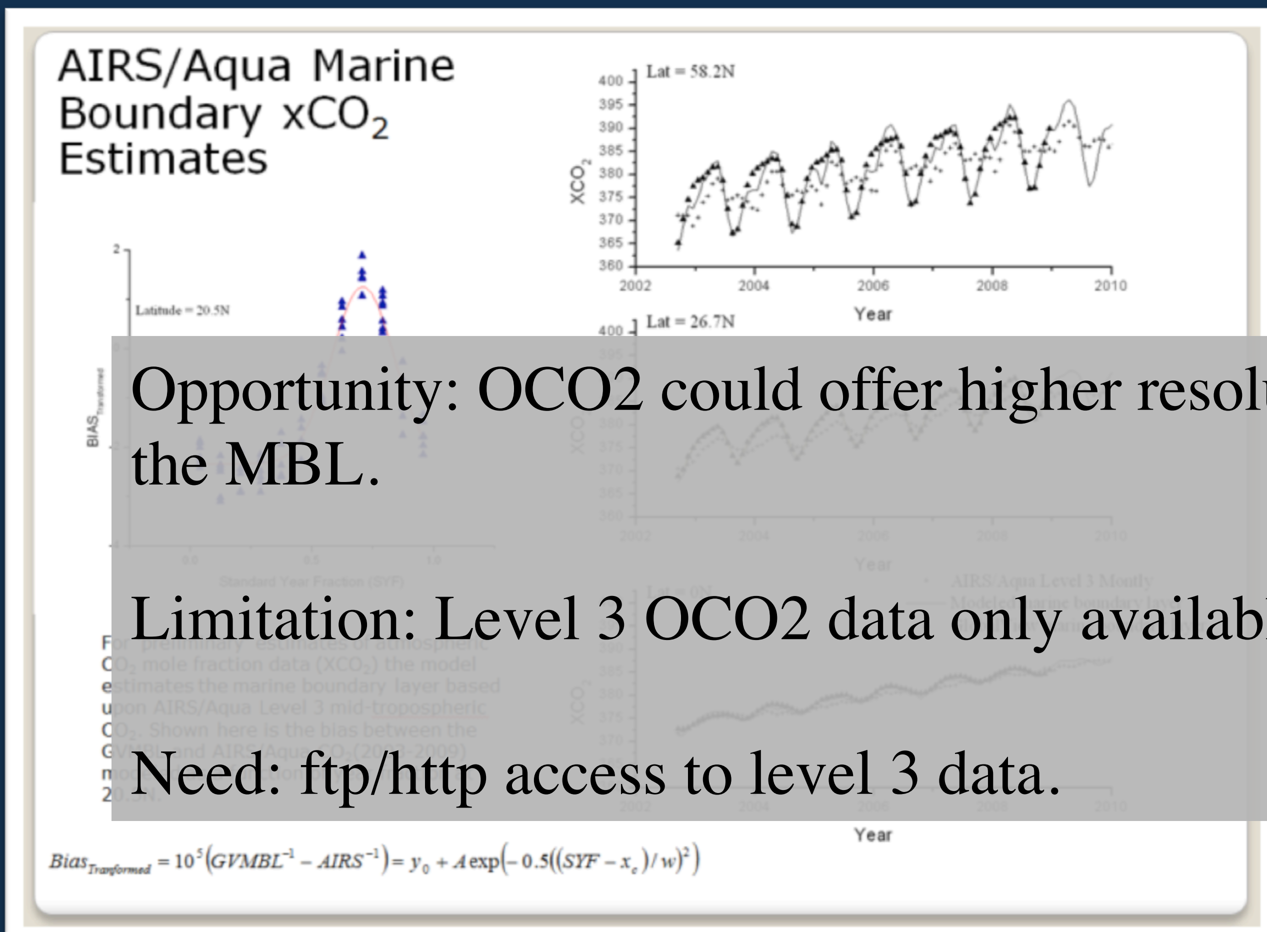


Ocean Acidification Product Suite for the Greater Caribbean Region, Gulf o Mexico, and US East Coast

Van Hooidonik, Wanninkjof, Barbero (AOML)



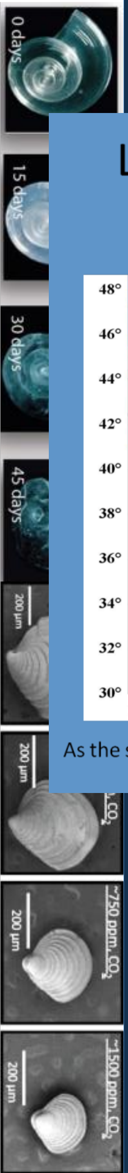
Opportunity: OCO2 could offer higher resolution data at the MBL.

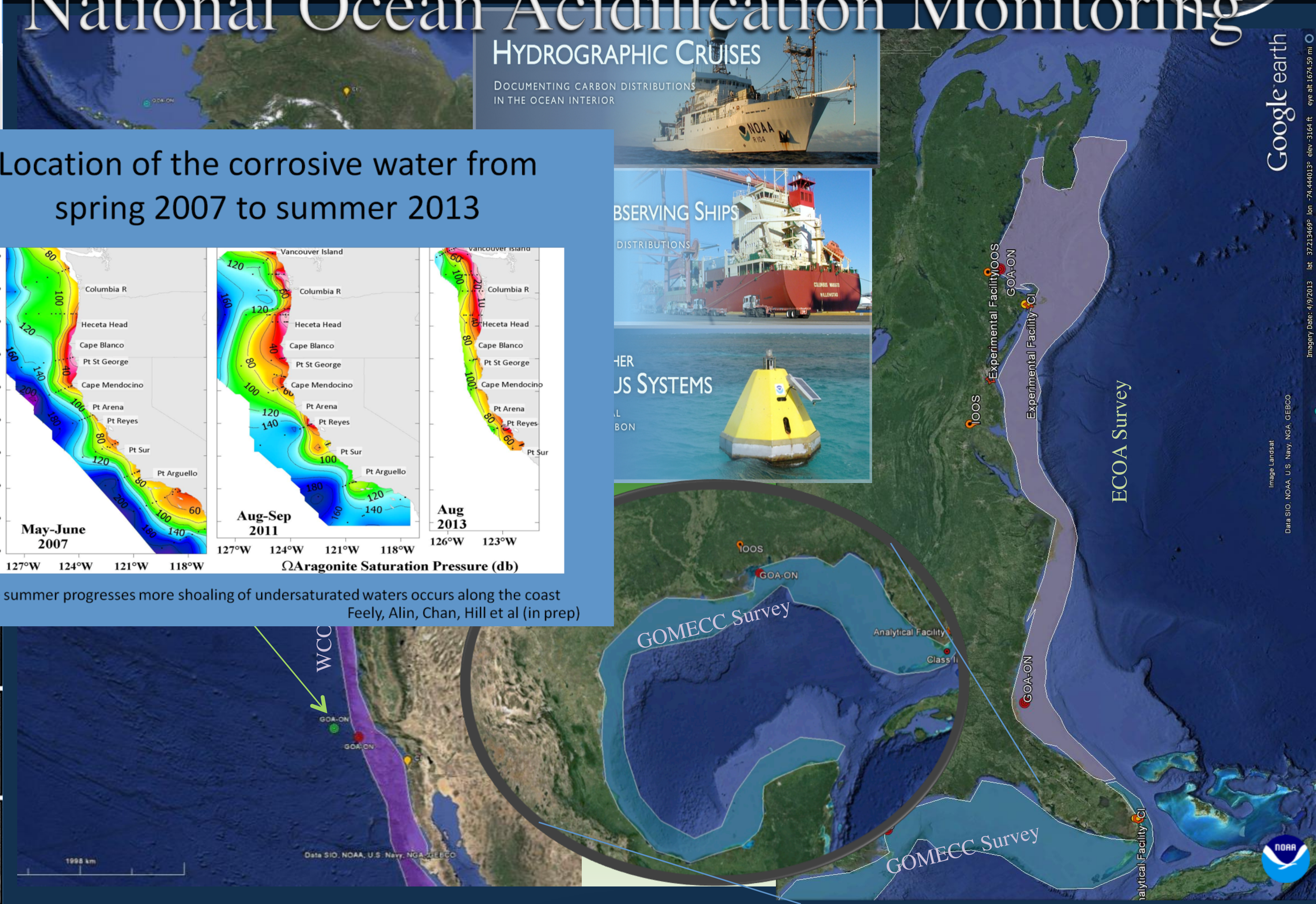
Limitation: Level 3 OCO2 data only available by request

Need: ftp/http access to level 3 data.

NOAA's OAP Other Related Efforts

National Ocean Acidification Monitoring

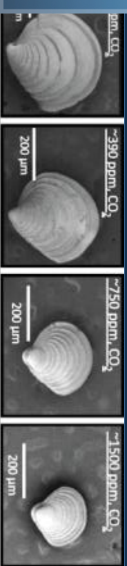


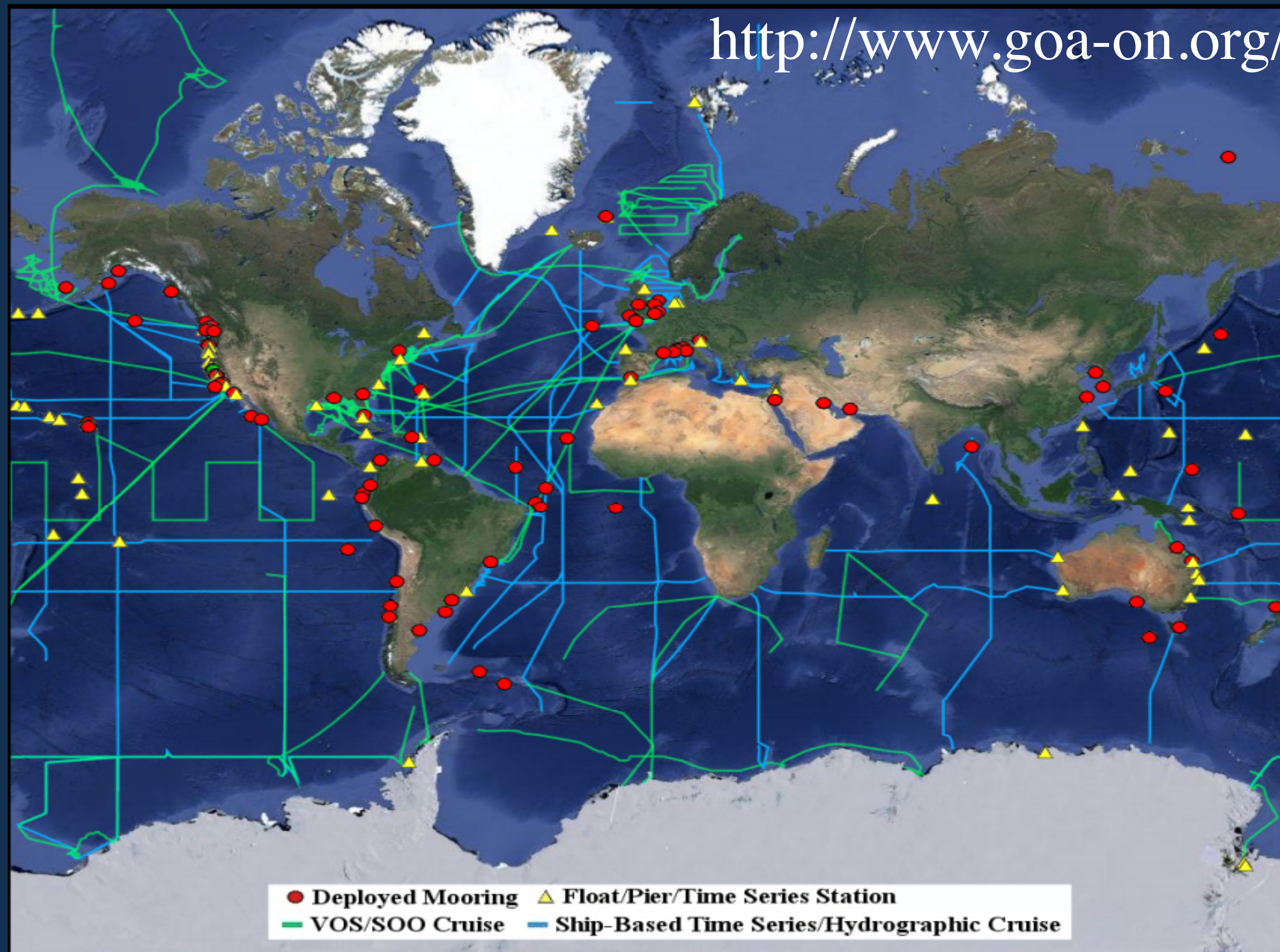


As the summer progresses more shoaling of undersaturated waters occurs along the coast
Feely, Alin, Chan, Hill et al (in prep)

NOAA's OAP Other Related Efforts

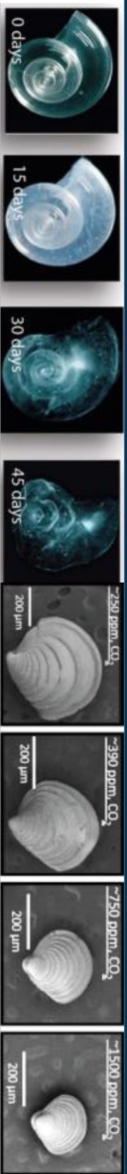
Global Ocean Acidification Monitoring

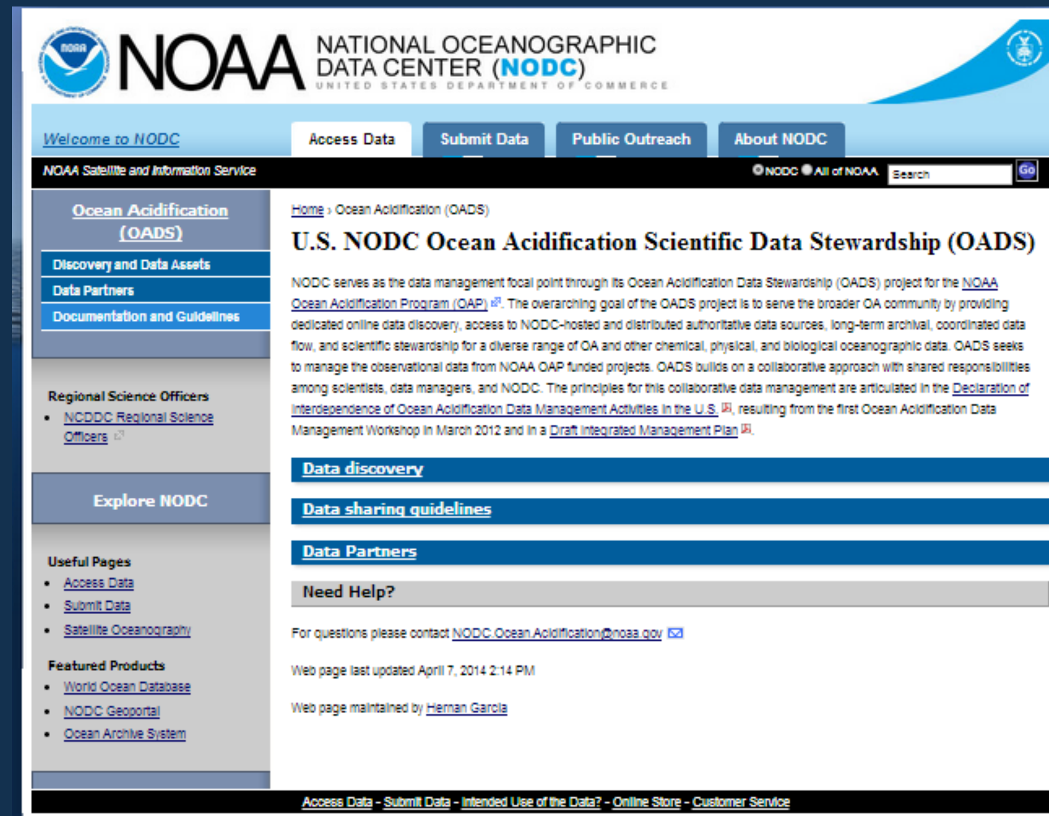




>30 Nation's currently participating in GOA-ON

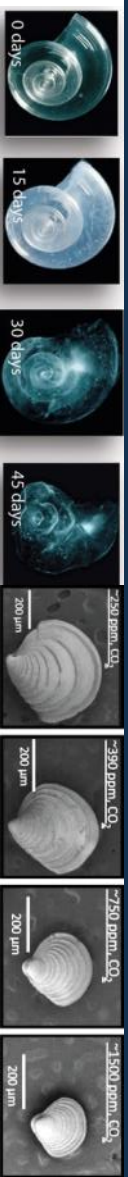
More information and data access





http://www.oceanacidification.noaa.gov/

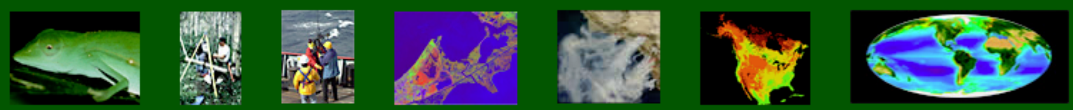
NOAA's Ocean Acidification Program



National Aeronautics and Space Administration

› Visit NASA.gov

Carbon Cycle & Ecosystems



Science Mission Directorate

NASA Research Announcement

Carbon Cycle Science

Solicitation: NNH16ZDA001N-CARBON

Dates	
Release	Feb 19, 2016
CARBON16 NOIs Due	Apr 01, 2016
CARBON16 Proposals Due	Jun 15, 2016

3.6.3.1 *Improved Observations*

. . .studies which involve improved measurement of the carbonic acid system within poikilohaline environments may be considered, if proposed as a means to improving quantification of coastal carbon fluxes and achieving better constraint of coastal acidification processes.

http://cce.nasa.gov/cce/opportunities.htm

Concluding Thoughts

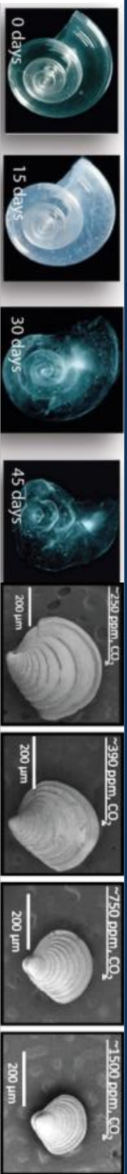
- The vulnerability of society to the impacts of ocean acidification differs regionally due to local chemistry, biology, and economic dependence. This heterogeneity creates an opportunity for information product needs.
- Most of the user needs for OA data products emerge from the marine resource management and industry community in the form of synthesis assessments. Not necessarily nRT.
- Satellite Ocean Color products are particularly of aid in improving synoptic mapping of OA with the coastal domain where biological forcing imparts a first-order effect to carbonate system dynamics.
- The primary utility of remote-sensing algorithms is presently in the ability to parameterize hydrographic linkages to natural variability and to bolster our understanding of baseline conditions.
- Limitations include resolution (i.e. SSS), land-masking, limited information on process rates. Algorithms have an expiration date requiring constant *in situ* verification and correction.
- Opportunities exist to further improve coastal/shelf algorithms by leveraging OAP supported geochemical surveys and other in-situ monitoring in support of the NOA-ON.

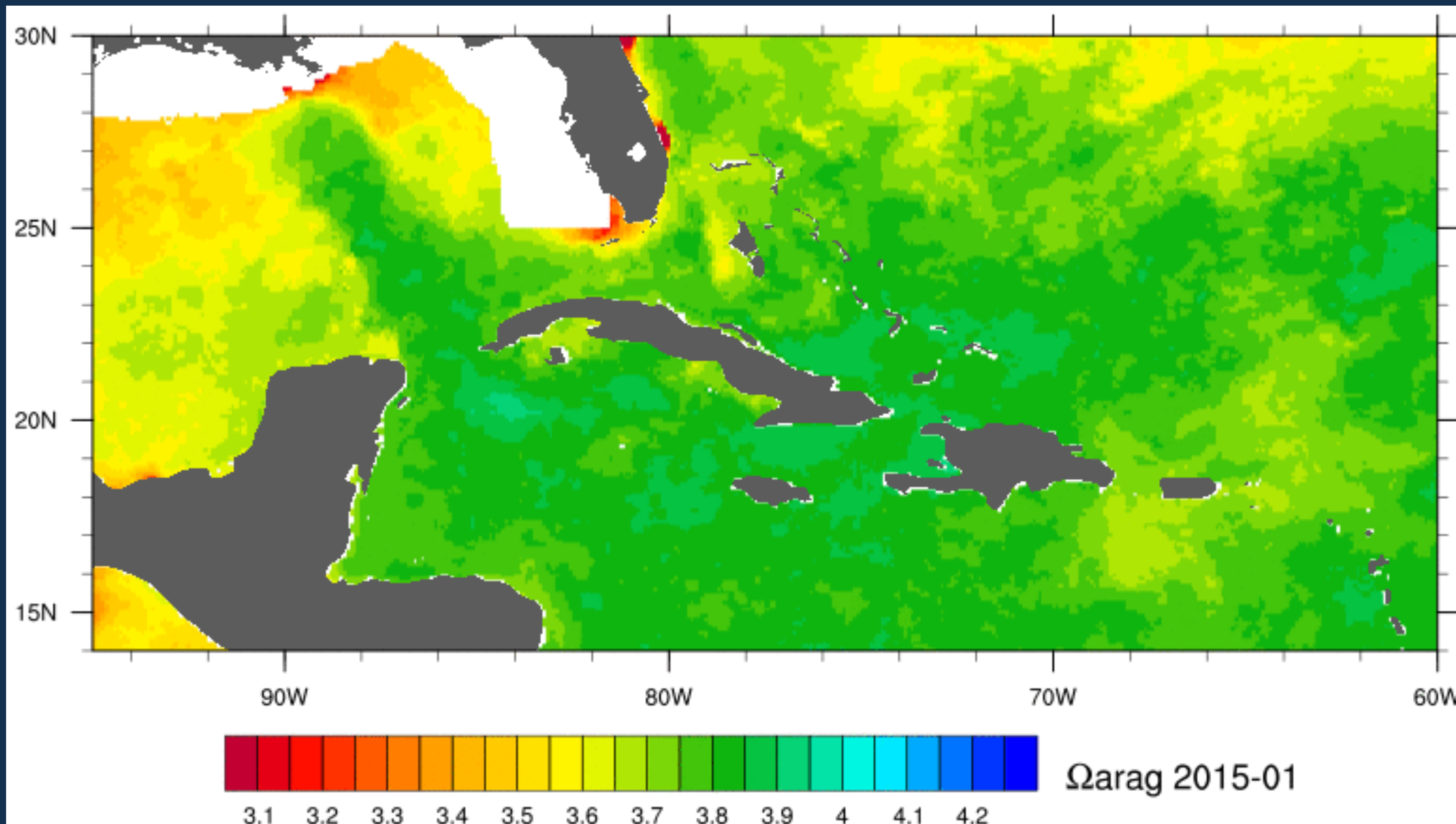
Discussion Points

- There isn't a direct remote-sensing proxy for essentially any of the carbonate parameters (maybe regional low-precision TA based on the current S products).
- The regression-based approaches that link directly to the individual parameters of interest (IPOIs) like pH, pCO_2, Ω are a-mechanistic, given IPOIs' non-linear dependence on TA, DIC.
- TA and DIC are the most mechanistically-linked to remotely-observable parameters, but those linkages require meta-modeling to approximate mixing and biological processes.
- Particle-based standing-stock observables have a rate and transport decoupling from the DIC and TA fields.
- The empirical relationships that allow the linkages between 3 and 4 are region-specific, which limits transferability of region-specific algorithms

- Burke Hales endorsed by Joe Salisbury

Thanks for listening





Let us not be too particular; it is better to have old secondhand diamonds than none at all.
- Mark Twain