Applications of hyperspectral ocean color data for aquaculture and fisheries management

NOAA National Marine Fisheries Service

Office of Science and Technology

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Introduction

The sun emits electromagnetic radiation that hits the Earth, and all of life on this planet depends on just a tiny portion of the electromagnetic spectrum - the colors of the rainbow ('visible' light). These are the specific wavelengths (400 -700 nm) by which plants on Earth photosynthesize and give us oxygen that we breathe. As this visible light hits the surface of the ocean and goes into the water, only one of two things can happen to that light - the light can either be scattered, or it can be absorbed by various constituents in the seawater. Pure water naturally absorbs more red light, leaving blue light to be scattered back to our eyes, and it is why the deep ocean appears blue. Conversely, other materials in the water – algae, dissolved organic material, dying or dead plant cells, floating seaweed, pollutants, suspended sediments from land, among other things - each uniquely absorb different amounts and types of light, creating a color pallet that we sense from discrete measurements of light from satellite sensors (Figure 1). How well we unravel the ocean composition from this signal largely depends on how well we can see these colors. Our heritage ocean color satellites detect anywhere from 5-10 wavelengths, which has limited our ability to distinguish some components from others. The launch of the **P**lankton, **A**erosol, **C**loud, and ocean **E**cosystem (PACE) mission on February 8, 2024 introduced the satellite community to global 'Hyper'-spectral measurements, meaning a spectrally continuous sampling of light. This has afforded the opportunity to sense the ocean through an entirely new lens by being able to resolve previously undetectable, subtle features unique to e.g. a particular phytoplankton class, or other ocean constituents. NOAA will be codifying these hyperspectral ocean color capabilities well into the 2050s with the launch of GeoXO, which will offer an even newer perspective from a geostationary orbit, where we can revisit the same area several times per day. This document is intended to familiarize readers with the capabilities and nuances of hyperspectral ocean color data to help guide use and implementation plans in NMFS.

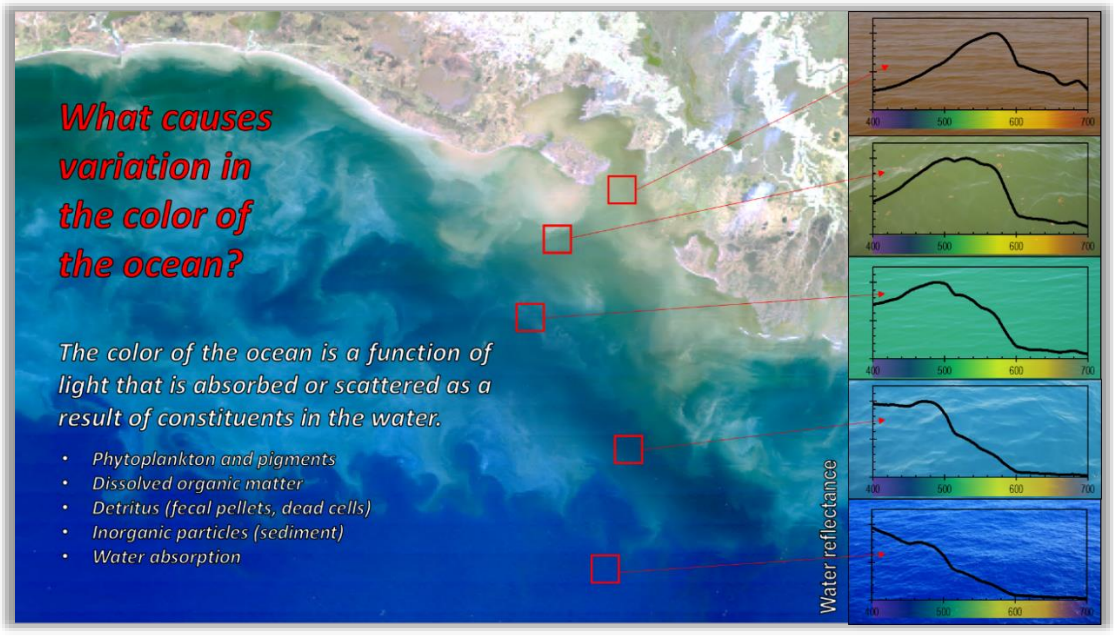


Figure 1: *The 5 panels (right) display the spectrum of light corresponding to the ocean color shown. The shape of the color intensity changes across the spectrum, providing a unique fingerprint imparted by the materials in the water.*

Section 1:

Hyperspectral products that are available now

Product 1: Chlorophyll-a (chlor_a)

What is it?

- Chlorophyll-a is a pigment contained within all phytoplankton and cyanobacteria cells. It is an estimate of algal biomass that is used for mapping the distribution of phytoplankton over time and space.

How does it impact Aquaculture/Fisheries?

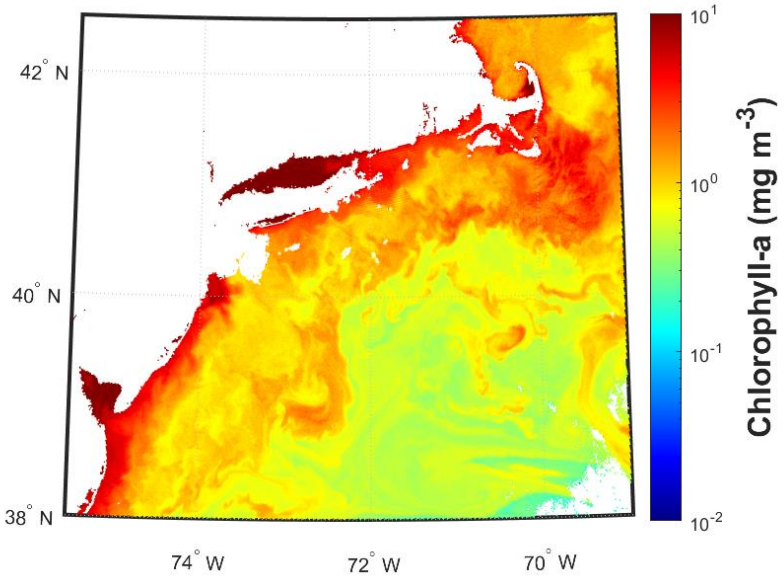
- Chlorophyll-a is a useful proxy of the biomass of phytoplankton in the water, the food source to filter feeding organisms and zooplankton. This parameter has been utilized for aquaculture siting, harmful algal bloom bulletins, species distribution models (fish, mammals, and top predators), end-to-end ecosystem models, and as a predictor of unregulated fishing activity.

What are the limitations/caveats?

- Currently, chlorophyll-a can be confused with other dissolved materials in the water, and it can be over-estimated in coastal regions, particularly in areas with river inputs or resuspension.

Does HYPERSPECTRAL directly improve/enable this product?

- Not operationally, but it will soon. Having more information about the other components of the water will help separate the living from non-living components, and will improve the performance chlorophyll-a product substantially. Some efforts at improving chlorophyll-a have been attempted using regional tuning methods, generalized additive models, or applying machine learning techniques, with no endorsed community convergence. Currently, NOAA/NASA are working on a dynamic tuning factor to make chlorophyll-a applicable across all water types and regions. Another chlorophyll-a product may soon be offered operationally from PACE that was built using hyperspectral reflectance data and a mixed density network approach; TBD.



Product 2: Phytoplankton carbon (carbon_phyto)

What is it?

- The phytoplankton carbon product expresses the concentration of phytoplankton in terms of carbon concentration, instead of chlorophyll-a. Contrasting from the chlorophyll-a product, phytoplankton carbon is derived from an empirical relationship to the particle backscattering properties (see Product 6) of the water.

How does it impact Aquaculture/Fisheries?

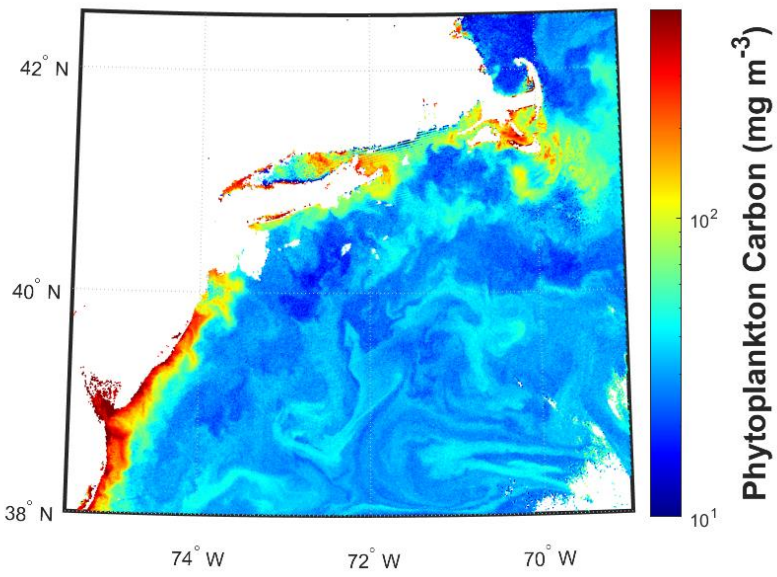
- Some fisheries applications may prefer to work in units of carbon biomass instead of pigment-based (i.e. chlorophyll-a) biomass. A constant chlorophyll-a value can represent a wide array of cell concentrations, due to environmental conditions and individual cell physiology/stress. For example, individual phytoplankton can produce more chlorophyll-a/cell in low-light conditions without changing the actual number of cells. The carbon product is not subject to these variations, and is a more direct indicator of phytoplankton biomass. Modelers may also be interested in computing the carbon to chlorophyll ratio, which can be obtained as carbon_phyto/chlor_a.

What are the limitations/caveats?

- This product was empirically tuned with field data, but it is not currently representative of optically complex waters. The performance in coastal regions remains untested. This product relies on the "inherent optical property (IOP)" suite of ocean color products, and thus can sometimes fail to arrive at a solution (i.e. no data) in waters with extreme scattering or chromophoric dissolved organic matter (CDOM) concentrations.

Does HYPERSPECTRAL directly improve/enable this product?

- Indirectly through improvements to the IOP products. PACE is the first mission to offer phytoplankton carbon as a product under "provisional" status.



Product 3: Diffuse attenuation coefficients (K_d)

What is it?

- As light enters the water column, it is attenuated exponentially with depth until it has been absorbed completely. The light attenuation coefficient (K_d) is a measure of the exponential slope of this light extinction, providing an indicator of how deep light can penetrate into the water column. This enables the quantification of light intensity and quality at any depth.

How does it impact Aquaculture/Fisheries?

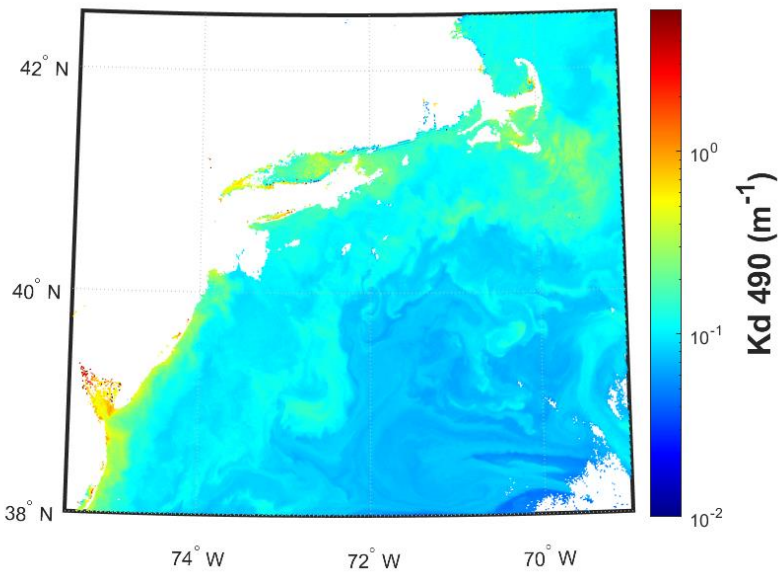
- Light influences all lifecycle stages of fish including egg and larvae survival, smolt timing, and maturation during the on-growing phase and broodstock spawning. Light attenuation changes can feasibly be used to effectively track aquaculture outflow, as well as incoming pollution sources. Light attenuation also impacts water visibility, and by extension fisheries catchability, foraging success, reproductive behavior, UV exposure, territoriality, and predation. K_d is also the term used to derive euphotic depth.

What are the limitations/caveats?

- K_d algorithms are among the more robust products offered in the ocean color suite, depending on how they are derived. Semi-analytical approaches reduce uncertainty in turbid, optically complex waters relative to more simple empirical approaches.

Does HYPERSPECTRAL directly improve/enable this product?

- It does, in that it offers a full suite of K_d coefficients across the visible spectrum. Historically, only the blue/green wavelength (490 nm) is utilized for most applications. With the full spectrum, the exact light quality can be determined at any depth, and also pinpoint the exact wavelength of light that penetrates the deepest into the water column, improving estimates of water visibility. Note, while computable, *water visibility* is not a standard operational product offering.



Product 4: Spectral phytoplankton absorption coefficients (a_{ph})

What is it?

- These absorption coefficients specifically define how light is absorbed by phytoplankton in the water column. This product partitions and isolates the phytoplankton component from the other absorbing materials in the water, like CDOM and other non-living components.

How does it impact Aquaculture/Fisheries?

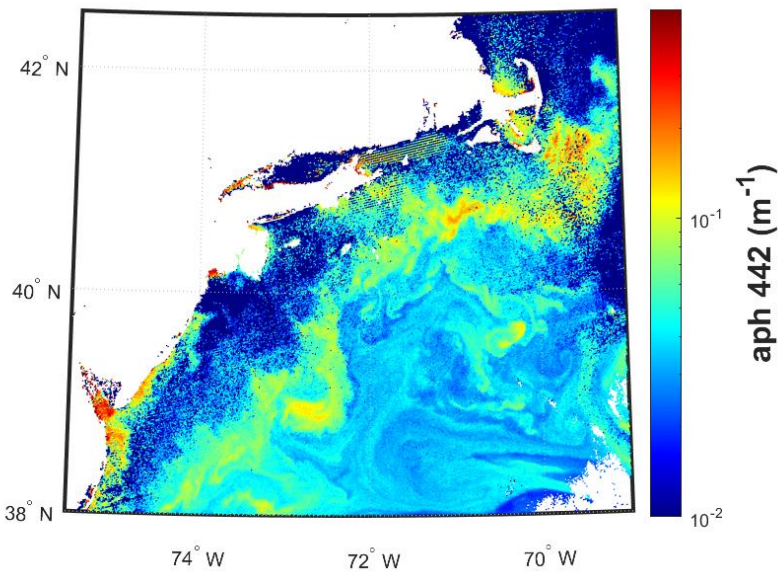
- The absorption of light by phytoplankton can vary by a factor of 4 or more at a constant chlorophyll-a value, so this parameter more accurately describes how much light has been utilized by living phytoplankton cells. This has implications for how much of this light energy will eventually be turned into biomass, and it is a central component of more advanced absorption-based primary productivity algorithms. As a standalone product, it partially helps mitigate the obscuring impact of other absorbing materials in the water, though not entirely.

What are the limitations/caveats?

- While the magnitude of absorption is dynamic, the absolute shape of spectral absorption is currently based on a global average, and thus offer no real insights to differentiating phytoplankton pigment absorption and should not be used for this purpose. Keep in mind that not all absorbed light is allocated to photosynthetic processes (i.e. some absorbed energy is lost to heat and fluorescence). The performance of this product can vary, and does not perform well in highly-scattering, or very high CDOM water-types.

Does HYPERSPECTRAL directly improve/enable this product?

- It does, in that it offers a full suite of a_{ph} coefficients across the visible spectrum. PACE Science and Applications Team members are working to improve this product using new approaches to radiative transfer as well as machine learning techniques. These improved products are TBD.



Product 5: Spectral non-algal particle plus dissolved organic matter absorption coefficients (a_{dg})

What is it?

- These absorption coefficients specifically define how light is absorbed by the combined effect of non-living particles (detrital) and dissolved optically-active materials i.e. CDOM.

How does it impact Aquaculture/Fisheries?

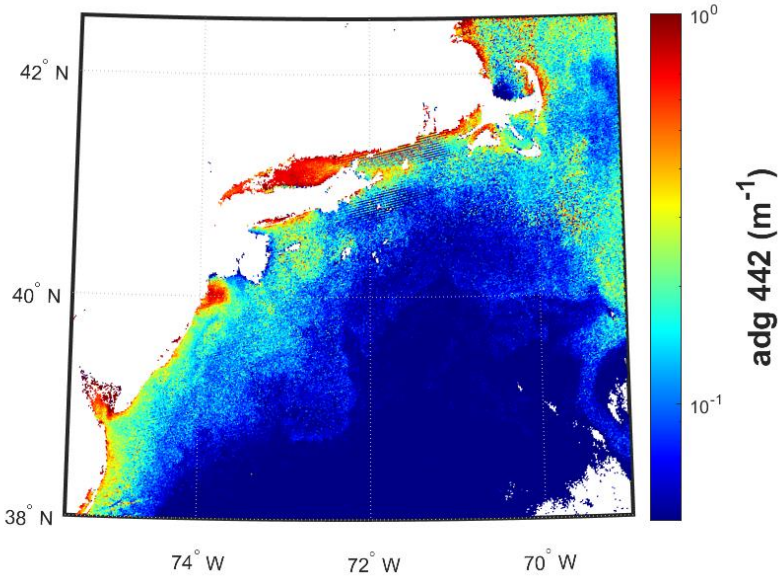
- The increased absorption of light by detritus+CDOM can indicate the presence of a declining phytoplankton bloom, or land-based detritus+CDOM from river input. In cases of known high river discharge events (e.g. after a storm event or heavy rainfall or ice melt), this product is a useful water mass tracer. CDOM has been found to be useful in source tracking of aquaculture as well as wastewater pollution.

What are the limitations/caveats?

- While the algorithm is tunable, its standard configuration defines a constant "shape" of detrital/CDOM absorption, so there is no information that can be derived about the origin of the materials other than through subjective spatial-temporal context. Note, this is a combined detrital matter + CDOM product, and not a standalone CDOM product (TBD).

Does HYPERSPECTRAL directly improve/enable this product?

- It does, in that it offers a full suite of a_{dg} coefficients across the visible spectrum. PACE Science and Applications Team members are working to improve this product using new approaches to radiative transfer as well as machine learning techniques. These improved products, including the separation of a_d (detritus) from a_g (CDOM, or 'gelbstoff') are TBD.



Product 6: Spectral particle backscattering coefficients (b_{bp})

What is it?

- These backscatter coefficients specifically define how light is scattered in the backwards direction by particles in the water. This product provides an indicator of the concentration of particles in the ocean and a proxy indicator of particulate carbon concentrations.

How does it impact Aquaculture/Fisheries?

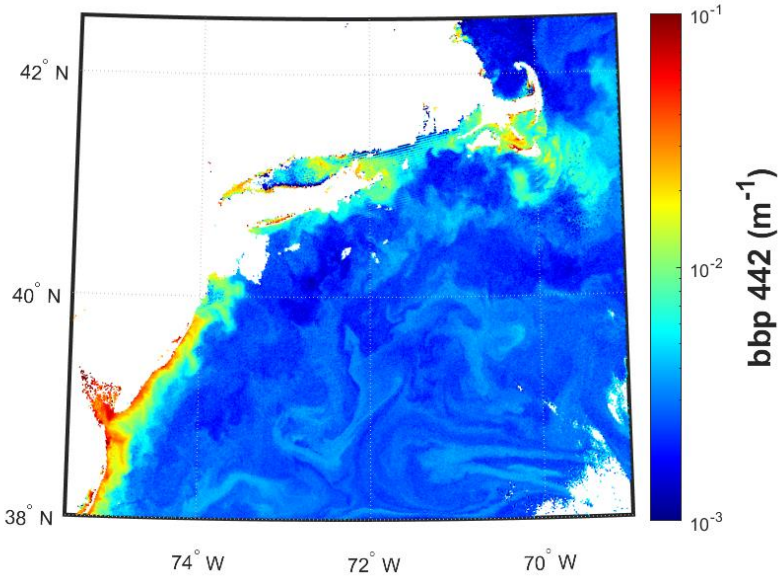
- Many phytoplankton exhibit unique backscattering characteristics, primarily as a function of cell size, and sometime composition (e.g. Coccolithophore blooms). Backscatter is also used to derive Particulate Inorganic Carbon (PIC) estimates from satellites. Particle backscatter is a particularly useful tool to determine high sediment loads in nearshore environments, which tends to heavily scatter light. High sediment loads can cause gill saturation in certain oyster species, and some fish species exhibit hypersensitivity to suspended sediment. While not a direct measurement of suspended particulate matter (SPM), it can be used to develop those products.

What are the limitations/caveats?

- The backscatter product is one of the most robust products offered in the "inherent optical property (IOP)" suite of ocean color products. The only caveat is that the IOP algorithms can sometimes fail to arrive at a solution (i.e. no data) in waters with extreme scattering or CDOM concentrations. Nearshore environments present challenges in disentangling phytoplankton backscatter from other optical constituents (re-suspended sediment, SPM, etc.).

Does HYPERSPECTRAL directly improve/enable this product?

- It does, in that it offers a full suite of b_{bp} coefficients across the visible spectrum. PACE Science and Applications Team members are working to improve this product using new approaches to radiative transfer as well as machine learning techniques. These improved products are TBD.



Product 7: Remote sensing reflectance (Rrs)

What is it?

- The remote sensing reflectance is the base unit by which most ocean color algorithms are built on. It is a direct measure of the water-leaving reflectance, after the atmosphere and surface reflectance effects have been removed. Each wavelength of color has its own reflectance value.

How does it impact Aquaculture/Fisheries?

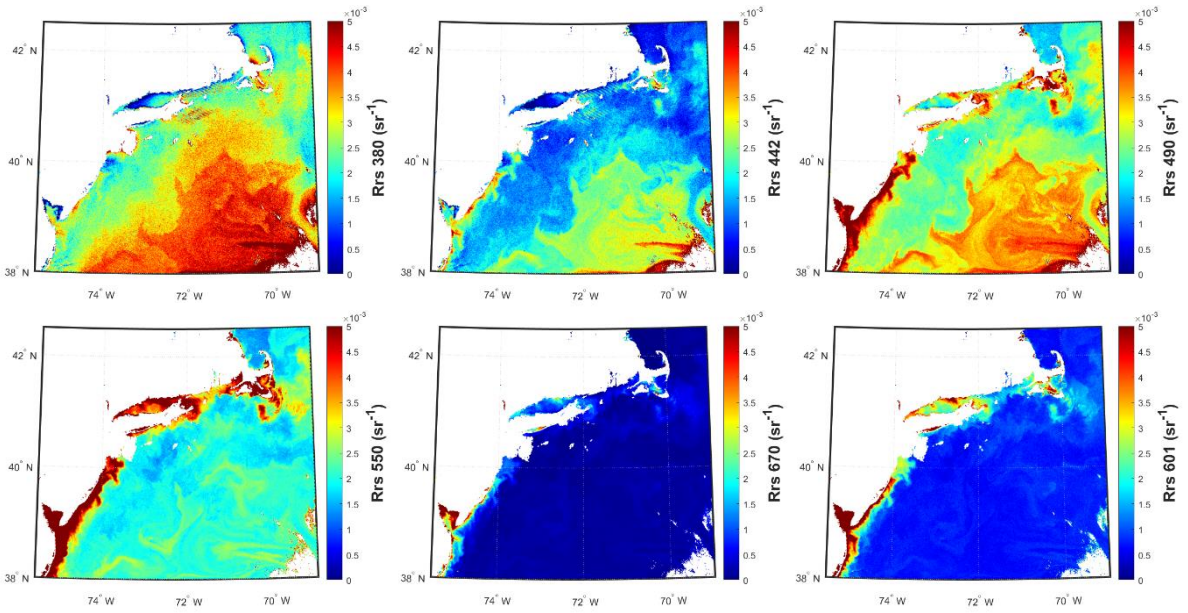
- These products may be preferred for advanced users who want to customize or build their own products for a regional/local application. This raw color information removes any the elements of uncertainty introduced by assumptions made during "product" development. If there are subtle features in the color reflectance spectrum that are unique to a phytoplankton species, this is currently the only set of products that will retain this information, though it is (currently) up to the user to determine what those features are. Some published algorithms for Harmful Algal Blooms can be reconstructed using the reflectance channels.

What are the limitations/caveats?

- The remote sensing reflectance is subject to uncertainties introduced in the removal of the atmospheric signal. These products may underperform, or be expressed as negative values, especially in areas with complex aerosol loadings (near urban areas), or in near-coastal regions.

Does HYPERSPECTRAL directly improve/enable this product?

- For context, relative to MODIS (10 color bands) or VIIRS (5 color bands), PACE offers 120 visible color bands (+ additional UV bands) by which to develop algorithms from. PACE Science and Applications Team members are working to improve the removal of the atmosphere, and thus improve the reflectance product. These improved products are TBD.



Product 8: Apparent Visible Wavelength (AVW)

What is it?

- The Apparent Visible Wavelength (AVW) is an optical water mass classification index that is sensitive to changes in the water's reflectance spectrum. Since the entire visible-range spectrum is utilized in the calculation of AVW, this product ensures that any diagnostic signals present in the reflectance signal are considered, and affords the opportunity to describe and analyze subtle shifts in color.

How does it impact Aquaculture/Fisheries?

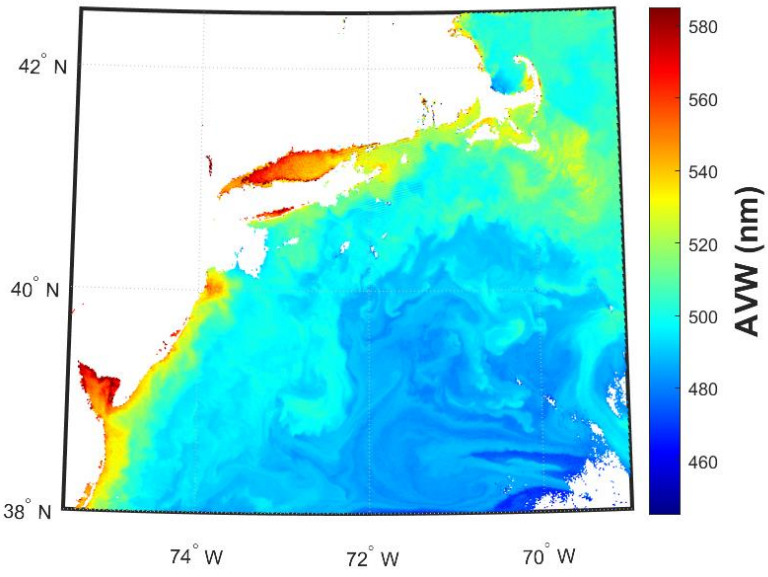
- Unlike other ocean color products, the AVW is not a derived geophysical variable, but instead an objective descriptor of the ocean's color. This makes it impervious to algorithm-induced biases, and thus useful and consistent across optically complex environments. This is a useful monitoring tool to assess if there are any changes to the color of the water, and if so, what direction the color is shifting (i.e. more red or more blue). While the attribution/cause of shifts in the water color are not elucidated with the product, it serves as an early indicator to detect changes in the optical water properties.

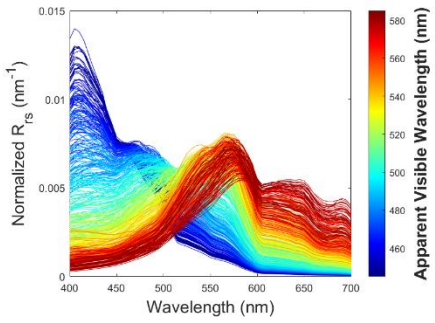
What are the limitations/caveats?

- This product relies on the accuracy of remote sensing reflectance products, which are subject to uncertainties introduced in the removal of the atmospheric signal.

Does HYPERSPECTRAL directly improve/enable this product?

- This product was developed specifically for hyperspectral applications, but can be "calibrated" for multi-spectral sensors to provide time-series continuity. PACE is the first mission to offer AVW as a product under "provisional" status.





The spectral reflectance spectra (above) are color-coded as a function of the mapped AVW (left).

Section 2:

Hyperspectral products coming soon

Product(s) 1: Phytoplankton community composition (PCC)

What is it?

- Phytoplankton absorb and scatter different colors, depending on their internal pigmentation and cellular composition/size. While all contain chlorophyll-a, several additional 'accessory' pigments may be present, which is one means of helping distinguish different phytoplankton classes (e.g. diatoms, cyanobacteria, dinoflagellates, etc.). There are also unique backscattering properties of phytoplankton based on cell size, chemical composition, and taxonomy. There are several PACE products that will address phytoplankton community composition. The known algorithms in the NASA pipeline are as follows:

    - **MOANA (Lange):** Resolves the concentration of smaller oceanic phytoplankton: Synechococcus, Prochlorococcus, and picoeucaryotes.
    - **TBD Pigments (Chase):** Phytoplankton pigments Chlorophyll-a, b, and c along with photoprotective and photosynthetic carotenoids.
    - **TBD Taxonomic groups (Kramer):** Diatoms, Dinoflagellates, Nanoplankton, Haptophytes, Picoplanktom, based on phytoplankton pigment estimates.
    - **TBD Particle size class (Kostadinov):** Size classes of cells (pico-, nano-, micro-plankton).

- Note, there are many more approaches to derive phytoplankton community composition described in literature, but are not slated for operational production.

How does it impact Aquaculture/Fisheries?

- Not all phytoplankton are equally utilized in the food web. As one example for aquaculture, smaller phytoplankton are often not efficiently retained as food and therefore phytoplankton size can affect bivalve growth and condition. For fisheries, NPZ and ecosystem models consider phytoplankton community composition as a variable to allocate trophic inputs and efficiency terms. These approaches may also help detect and distinguish harmful algal blooms.

What are the limitations/caveats?

- These algorithms will be classified as "provisional" until the PACE validation and science team is able to validate these products. Each approach comes with its own set of unique uncertainties, and should be verified on a regional basis before using operationally.

Does HYPERSPECTRAL directly improve/enable this product?

- Many PCC algorithms do exist with multispectral data, but hyperspectral is making a new class of algorithms possible by exploiting color bands not previously available. PACE will be the first mission to operationally offer phytoplankton community composition products under "provisional" status.

Product 2: Fluorescence line height (FLH)

What is it?

- Light leaving the surface ocean due to the sun induced chlorophyll fluorescence. This provides an indicator of phytoplankton physiology/nutrient stress, and is utilized as an input to some chlorophyll-a and harmful algal bloom algorithms.

How does it impact Aquaculture/Fisheries?

- Mitigating/preparing for HAB closures and assessing health status of a phytoplankton bloom.

What are the limitations/caveats?

- This algorithms will be classified as "provisional" until the PACE validation and science team is able to validate these products.

Does HYPERSPECTRAL directly improve/enable this product?

- A multispectral version of this product exists which uses a static set of wavelengths. Note, these particular wavelengths are not available on the VIIRS series (MODIS or OLCI are used instead). PACE will improve the FLH approach by optimizing the choice of wavelengths, which is not possible with multispectral (e.g. MODIS, VIIRS) approaches. This will enhance the reliability and accuracy of the product.

Product 3: Absorption-based Net Primary Production (NPP)

What is it?

- Rate of conversion of dissolved carbon dioxide to organic carbon through photosynthesis minus the carbon used for respiration. NPP is an important part of the carbon cycle and these products are used in local models (estimating food availability to fish populations) all the way up to global climate and Earth System models (to predict information about the oceans of today and tomorrow). Using an absorption-based approach to NPP holds several advantages over the traditional chlorophyll-a based approaches (e.g. frequently used VGPM model):

    - Absorption is directly related to satellite measurements of radiance.
    - Absorption-based models encapsulate accessory pigment composition
    - A spectral correction factor accounts for changes in spectral quality with depth.
    - Quantifies NPP below the mixed layer depth.
    - Corrects for iron-stress using fluorescence quantum yield estimates.
    - Due to the "package effect," chlorophyll-specific phytoplankton absorption can vary over a factor of 4 or more for the same chlorophyll value. Light driven decreases in chlorophyll can be associated with constant or even increased photosynthesis

How does it impact Aquaculture/Fisheries?

- For aquaculture, NPP can be used in siting as well as harvesting decision making, assessing the impact of marine cages on the environment, and constructing dynamic energy budgets for shellfish growth models. More broadly for fisheries, NPP is an important component to assess total trophic energy potential, recruitment in relation to phytoplankton phenology, zooplankton productivity, ecosystem overfishing, species distribution models, ecosystem status reports, and fisheries economic performance, among other applications.

What are the limitations/caveats?

- NPP is extremely challenging to validate, even under the best of circumstances. On long time scales, NPP is a very useful metric, but instantaneous/daily values derived from satellites may require some additional caution in interpretation.

Does HYPERSPECTRAL directly improve/enable this product?

- PACE will offer an absorption-based approach to modeling net primary productivity. This approach addresses several inefficiencies and uncertainties present in the more ubiquitous chlorophyll-a and carbon based approaches. While a multi-spectral version of this product exists, several upgrades are being made using the hyperspectral nature of PACE (TBD).

Product 4: Suspended Particulate Matter

What is it?

- Near surface concentration of particles both living (phytoplankton, zooplankton, bacteria) and non-living (detritus, sediments).

How does it impact Aquaculture/Fisheries?

- Suspended particulate matter is a parameter likely recognized in the aquaculture community. It is a useful product for detecting high sediment loads, which compromise water quality and growth conditions for many shellfish species, as well as adversely impact shellfish burial rates. Offshore fisheries can also produce significant amounts of suspended particulate waste. Suspended particles also can transport toxic heavy metals and organic compounds that accumulate in fish tissues.

What are the limitations/caveats?

- This algorithm will be classified as "provisional" until the PACE validation and science team is able to validate this product. Depending on the absorption/scattering properties of the water mass, some regional tuning should be anticipated.

Does HYPERSPECTRAL directly improve/enable this product?

- PACE will be the first mission to operationally offer an operational suspended particulate matter product derived from *hyperspectral* measurements. The approach relies on hyperspectral reflectance and machine learning techniques. A multi-spectral approach to deriving SPM, as well as Particulate Organic Carbon (POC) in the presence of SPM is being implemented for MODIS, SNPP-VIIRS, NOAA-20, and OLCI through NOAA CoastWacth.

Section 3:

Unique NOAA STAR products

Additional Products that NOAA STAR can generate/provide

What are they?

- **Anomalies**: Anomaly products track the average conditions of a product (e.g. chlorophyll-a) for the past 60 days, and ratio that against the latest image. (+) Anomalies are depicted as red while (–) anomalies are depicted as blue. This is particularly useful to demonstrate and detect early changes to environmental conditions. These can be generated for any satellite product and are highly recommended for monitoring applications.

- **Optical Water Mass Classification**: Based on Wei et al. (2022), NOAA produces a reflectance shape-based algorithm used to resolve the global water classes into one of 23 distinct water types.

- **QA Score**: The Quality Assurance (QA) score is a metric used to estimate and map the relative quality of ocean color data on a scale of 0 (not good) to 1 (excellent). Details provided in Wei et al. (2016).

- **Gap-filled products:** Using a gap-filling procedure by combining multiple sensors with a Data Interpolating Empirical Orthogonal Functions (DINEOF), NOAA can provide daily gap-filled data products at 2-km resolution for models that cannot tolerate data gaps.

- **Seascape Pelagic Habitat Classification:** Seascapes identify spatially explicit water masses with particular biogeochemical features using a model and satellite-derived measurements. Dynamic seascapes are derived by combining satellite time series of sea surface temperature, salinity, sea surface height, sea ice, chlorophyll-a concentration, chromophoric dissolved organic matter (CDOM), and normalized fluorescent line height using a supervised thematic classification. The seascape product is generated as monthly and 8-day composites at 5 km spatial resolution.

- **Other satellite data streams**: Including sea surface temperature, salinity, sea surface height (i.e. sea level), ocean winds, synthetic aperture radar, sea ice, and true color imagery.

For questions, contact the NMFS Satellite Coordinator
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