

Unveiling PACE OCI's Hyperspectral Terrestrial Data Products

Skye Caplan^{1,2}, K. Fred Huemmrich^{1,3}

¹NASA Goddard Space Flight Center, Greenbelt, MD, USA; ²Science Systems and Applications, Inc., Lanham, MD, USA; ³University of Maryland, Baltimore County, MD, USA

Abstract

Imaging spectroscopy leverages narrow bandwidth radiance measurements to improve observations of Earth's ecosystems. The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission's Ocean Color Instrument (OCI) uses global, hyperspectral data to study not only the ocean, but also the land surface at ~1.2 km spatial resolution on a one- to two-day time scale. There are two PACE products immediately relevant to terrestrial science: the first is a suite of atmospherically corrected surface reflectances at 50+ OCI bands, resolving spectral properties of the Earth more finely than previous multispectral missions. The second is a suite of ten vegetation indices, six of which are well-known heritage indices requiring only broadband reflectances to be calculated. The remaining four indices depend on narrow-wavelength measurements and are being produced for the first time globally with PACE OCI. These indices have been shown to relate to green vegetation amount, foliar pigments (chlorophylls, carotenoids, and anthocyanins), water content, photosynthetic light use efficiency, and snow cover. Data from the early months of the mission show OCI's viability for terrestrial investigations – the instrument maintains and extends the historical multispectral data record while also generating novel hyperspectral results from which the mechanisms of Earth's land surface can be further unraveled.

1. Introduction

The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, launched on February 8th, 2024, aims to enhance understanding of Earth's ecosystems and atmosphere. The satellite's on-board instruments leverage hyperspectral observations to glean new information across the globe. Though land surface products were not included in the mission's initial requirements, the Ocean Color Instrument's (OCI) hyperspectral capabilities are applicable to observations of terrestrial environments. Since the public release of data on April 11th, 2024, OCI has been continuously generating two terrestrial product suites comprised of atmospherically corrected surface reflectances (SFREFL) and a set of spectral indices (LANDVI), respectively. These data enable in-depth analyses of the Earth's land surface and provide novel insights into vegetation dynamics which go beyond previous multispectral investigations. Results from the first few months of terrestrial PACE OCI data will be presented here, highlighting PACE's utility in ecosystem monitoring.

1.1 PACE and its Instruments

PACE has two major mission goals. The first is to continue and contribute to the robust data record of Earth observations from heritage missions like Moderate Resolution Imaging Spectroradiometer (MODIS), Visible Infrared Imaging Radiometer Suite (VIIRS), and others. This is especially relevant as MODIS reaches the end of its lifetime. The second is to enhance the understanding of various ecosystems through near-daily, global, hyperspectral measurements. These ambitions are to be met through PACE's three instruments: OCI, SPEXone (Spectropolarimeter for Planetary eXploration one), and HARP2 (Hyper Angular Research Polarimeter 2).

OCI is an imaging spectrometer built on lessons learned from previous ocean colour missions such as Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Coastal Zone Color Scanner (CZCS). It is hyperspectral from the ultraviolet (UV) into the near infrared (NIR) (340 –

Unveiling PACE OCI's Hyperspectral Terrestrial Data Products

895 nm) with 9 shortwave infrared (SWIR) bands. Table 1 provides further detail on OCI. HARP2 and SPEXone are polarimeters with hyperangular and hyperspectral capabilities. Terrestrial products for these polarimeters are yet to be determined; as such, only OCI will be addressed.

OCI Specifications	
Spectral Resolution	340 – 895 nm at 2.5 nm steps; 1.25 nm steps in certain regions 9 SWIR bands at 940, 1038, 1250, 1378, 1618, 2130, and 2260 nm 5 nm bandwidth
Spatial Resolution	1.2 km at nadir, up to $\sim 7 \times 3$ km across track $\times$ along track at swath edge
Swath Width	Approx. 2700 km, -56.0° to $+56.5^\circ$
Along-track tilt	19.9° to avoid sunglint
Temporal resolution	1 – 2 day coverage

Table 1: Summary of specifications for PACE's Ocean Color Instrument. Overlap between pixels does occur at extreme swath edges; Level 3 data masks these pixels at $\geq 60^\circ$ view zenith angle.

1.2 PACE Datasets

OCI data comes in many forms. Most importantly for terrestrial PACE data users are the Level 2 (L2) and Level 3 (L3) data. L2 data refers to georeferenced, geolocated, individual 5-minute granules that are in the instrument swath. These data have not been binned or geographically projected, and have the same spatial resolution as Level 1B (L1B) top-of-atmosphere (TOA) data. L3 refers to data that has been spatially and temporally aggregated into standard mapped images (SMIs). These data are global reprojections of binned data into the equirectangular Plate Carrée projection available at multiple spatial resolutions (OBPG, 2021).

The two product suites relevant to the terrestrial community are the surface reflectance suite, named SFREFL, and the spectral indices suite, named LANDVI. SFREFL (Section 2.1) contains 52 atmospherically corrected surface reflectance measurements. This subset of OCI's total band count was selected with each wavelength being relevant either for continuity with a heritage sensor or for terrestrial algorithm production. Future versions of SFREFL will include 122 spectral bands at 5 nm steps. Certain areas of the red edge will be provided at 2.5 nm steps.

The second of PACE's terrestrial products, LANDVI (Section 2.2), is a collection of 10 vegetation indices (VIs). Six of these are multi-band indices which will continue the heritage data record; the remaining four are hyperspectral VIs that, to the authors' knowledge, have not been produced on a daily global scale prior to the PACE mission.

Both LANDVI and SFREFL are being produced as L2 and L3 products. L3 data are available on a daily basis, and as 8-day or monthly averages. Annual averages will also be produced as the necessary data becomes available. L3 mapped files are produced both at 2.5 minutes (~ 4 km at the equator) and 0.1° (~ 11.1 km at the equator) spatial resolution.

As a relatively new mission, data are expected to be reprocessed frequently to incorporate the best quality calibration information for OCI. The algorithm descriptions and results (Section 3) provided below correspond to Version 2 (V2) of PACE data and may change as the mission matures. It should also be noted that neither the SFREFL nor LANDVI suites have yet been assigned 'standard' product status. Thus, these products are still under evaluation by algorithm developers and principal investigators. Additionally, neither product has been extensively validated, and all results should be viewed with appropriate caution.

2. Methods

Unveiling PACE OCI's Hyperspectral Terrestrial Data Products

2.1 Surface Reflectance

Crucial inputs to most terrestrial analyses are measurements of surface reflectance. In order to derive these values from the TOA reflectance measured by OCI, influences from scattering and absorbing gases in the atmosphere must be removed through atmospheric correction. As a non-standard product, the final algorithm for OCI's atmospheric correction has not yet been determined. The three methods under consideration are l2gen (a heritage ocean colour algorithm updated for land, Mobley et al., 2016), Imaging Spectrometer Optimal FITting (ISOFIT; optimal estimation atmosphere/surface retrievals, Thompson et al., 2018), and Multi-Angle Implementation of Atmospheric Correction (MAIAC; multi-temporal atmospheric correction, Lyapustin et al., 2011). Presently, V2 surface reflectances are calculated with l2gen due to the algorithm's implementation readiness and satisfactory performance over land surfaces.

L2gen is a broad codebase for L2 data processing that is part of the larger Ocean Color Science Software (OCSSW; OBPG, 2024) package distributed by the Ocean Biology Processing Group (OBPG). It is applied over land for each granule in near real time (NRT). Refined products are made available approximately 1 – 2 months after the NRT data is distributed, incorporating the best available ancillary data (OBPG, 2021).

L2gen's land processing code originally only corrected for Rayleigh scattering and influences of ozone. Upon the decision to include terrestrial products as OCI output, several additional absorbing gases were incorporated to make the atmospheric correction more robust. The gases now corrected for are ozone, carbon monoxide, nitrous oxide, methane, carbon dioxide, oxygen, and water vapor. A correction for nitrogen dioxide will be added in Version 3 (V3) of the data. Importantly, l2gen does not currently implement a terrestrial bidirectional reflectance distribution function (BRDF) correction. Therefore, owing to OCI's wide swath and $\sim 20^\circ$ tilt, angular effects will be present in SFREFL measurements and may propagate through to VI calculations. Further detail on l2gen surface reflectance calculations can be found in the Algorithm Theoretical Basis Document (OEL, 2024).

2.2 Vegetation Indices

Heritage VIs include those which can be computed with multiband missions like MODIS and Landsat. These VIs continue to be widely used throughout the terrestrial community to monitor ecosystem characteristics. Given their continued contributions to the field, they have value being produced by newer missions. OCI's 5 nm bandwidth also enables the calculation of hyperspectral-enabled VIs. These are indices that require surface reflectance measurements from narrow spectral regions to provide information on plant pigments beyond general vegetation health metrics. The reflectance signals occur in specific parts of the spectrum that are often not available from multispectral sensors. When the sensor does have a band that captures the relevant wavelength range, the features can get averaged out by their inherently broad bandwidths. OCI is able to resolve the nuances in surface reflectance to monitor these pigment dynamics.

2.2.1 Multispectral Vegetation Indices

Each of the six heritage VIs (Table 2) is a band ratio making use of OCI's broad spectral range. The Normalized Difference Vegetation Index (NDVI) is an empirical metric related to green vegetation abundance. The Enhanced Vegetation Index (EVI) is similar to NDVI, but incorporates additional resistance to atmospheric effects and effects of background reflectance. The inclusion of these two VIs specifically will extend MODIS's MOD13 data record.

Unveiling PACE OCI's Hyperspectral Terrestrial Data Products

Normalized Difference Water Index (NDWI) measurements are used to investigate water content and water stress in foliage. Normalized Difference Infrared Index (NDII) is similar to NDWI but uses a longer wavelength in the SWIR to quantify water stress. The Chlorophyll-Carotenoid Index (CCI) provides information on photosynthesis through chlorophyll/carotenoid relationship dynamics. Normalized Difference Snow Index (NDSI) is a metric for evaluating the presence of snow in any given pixel.

As an imaging spectrometer, OCI has much narrower bandwidths than heritage sensors like MODIS. In the interest of preserving continuity with such sensors, surface reflectance measurements from OCI are averaged to MODIS bandwidths before any of these multi-band indices are calculated. The aggregated surface reflectance measurements can be described as:

$$\rho_{\text{aggregated}} = \frac{\sum_i^n \rho_{i,\text{OCI}}}{N} \quad (1)$$

Where N is the number of OCI bands in the wavelength interval from i to n . The wavelengths defining each interval are: NIR, 847 – 877 nm; red, 620 – 671 nm; green(1), 526 – 537 nm; green(2), 545 – 566 nm; and blue, 459 – 479 nm. MODIS's spectral response is notably not included in the band aggregation – while weighting the averaged surface reflectances this way would likely further align OCI and MODIS VI results, the purpose of the aggregation is to use similar band data in the calculations, not to simulate MODIS's measurements.

2.2.2 Hyperspectral-Enabled Vegetation Indices

Four hyperspectral-enabled VIs comprise the rest of the LANDVI suite (Table 2). These indices rely on narrow bandwidths and thus do not require any band aggregation. The Photochemical Reflectance Index (PRI) captures shifts in xanthophyll cycle pigments associated with photosynthetic downregulation in response to stress. Chlorophyll Index Red Edge (CIRE) measurements are related to canopy chlorophyll content and are correlated with potential productivity in crops. The Carotenoid Content Index (Car) is related to canopy carotenoid content, which gives insight on photosynthesis and photoprotection. Modified Anthocyanin Reflectance Index (mARI) calculations describe anthocyanin content in vegetation, providing information on photoprotection and early indications of senescence.

Index	Equation	MODIS Equivalent	Reference
NDVI	$(\rho_{\text{NIR}} - \rho_{\text{red}}) / (\rho_{\text{NIR}} + \rho_{\text{red}})$	MOD13	Huete et al., 2002
EVI	$2.5 \times (\rho_{\text{NIR}} - \rho_{\text{red}}) / (\rho_{\text{NIR}} + 6.0 \times \rho_{\text{red}} - 7.5 \times \rho_{\text{blue}} + 1)$	MOD13	Huete et al., 2002; Jiang et al., 2008
NDWI	$(\rho_{\text{NIR}} - \rho_{1250}) / (\rho_{\text{NIR}} + \rho_{1250})$	P	Gao 1996
NDII	$(\rho_{\text{NIR}} - \rho_{1618}) / (\rho_{\text{NIR}} + \rho_{1618})$	P	Hardisky et al., 1983; Li et al. 2011
CCI	$(\rho_{\text{green}(1)} - \rho_{\text{red}}) / (\rho_{\text{green}(1)} + \rho_{\text{red}})$	P	Gamon et al., 2016; Middleton et al. 2016
NDSI	$(\rho_{\text{green}(2)} - \rho_{1618}) / (\rho_{\text{green}(2)} + \rho_{1618})$	MOD10	Hall and Riggs, 2011
PRI	$(\rho_{530} - \rho_{570}) / (\rho_{530} + \rho_{570})$	N	Grace et al., 2007; Coops et al., 2010
CIRE	$(\rho_{800} / \rho_{705}) - 1$	N	Gitelson et al., 2005 & 2017
Car	$[(1/\rho_{495}) - (1/\rho_{705})] \times \rho_{800}$	N	Gitelson et al., 2002
mARI	$[(1/\rho_{550}) - (1/\rho_{705})] \times \rho_{800}$	N	Gitelson et al., 2001

Table 2: Equations for each VI included in the LANDVI suite, with ρ_i representing the surface reflectance for wavelength or band i . Where colour ('red', 'green', 'blue') or spectral region ('NIR') is given, the surface reflectance follows the aggregation method described in Equation (1). Where a specific wavelength is given (e.g., 1250), single band measurements are used. The MODIS Equivalent column gives either the applicable MODIS product name, P for possible with MODIS bands, or N for not possible.

Unveiling PACE OCI's Hyperspectral Terrestrial Data Products

3. Results

3.1 Surface Reflectance

Surface reflectance spectra from an L2 SFREFL granule are provided in Figure 1. The OCI granule used here overlaps a MODIS MYD09 granule as much as possible to minimize angular effects on the comparison in Figure 2. Each spectrum represents atmospherically corrected reflectances at OCI's swath resolution. As such, they are not pure spectra of any one surface feature, though the spectral shapes are clearly influenced by majority land cover types of vegetation (top) and bare ground (bottom).

Several artifacts are visible in the SFREFL spectra due to both instrument and algorithm attributes. Although somewhat less evident in the vegetation-heavy spectra, small features occur around 680 nm, 720 nm, and 760 nm. These are regions with significant water vapor and oxygen absorption. Refinements to the l2gen algorithm are expected to improve reflectance retrievals in spectral regions influenced by these atmospheric constituents. Moreover, Figure 1 is drawn with NRT spectra. NRT data do not contain the most accurate climatology information, which further affects surface reflectance retrievals.

Surface reflectance values at 588, 601, 610, and 814 nm have been excluded from Figure 1 as well as in V2 SFREFL product files. The first three bands fall near or within the 590 nm to 610 nm range, where there is a transition between OCI's blue and red focal planes. A discontinuity occurs in radiance measurements due to differences in each focal plane that propagates through to surface reflectance calculations. As such, these bands are associated with high uncertainty measurements and should not be used. The 814 nm band exhibits a significant decrease in reflectance that has been attributed to the lower edge of the 820 nm water vapor absorption band. It is also associated with high uncertainty. In V3, several of these artifacts have been corrected – the V3 suite will include the ~814 nm range as part of its 122 bands, with exclusions only around spectral areas of high O₂ absorption (~690 nm and ~760 nm) and the focal plane transition (590 – 610 nm).

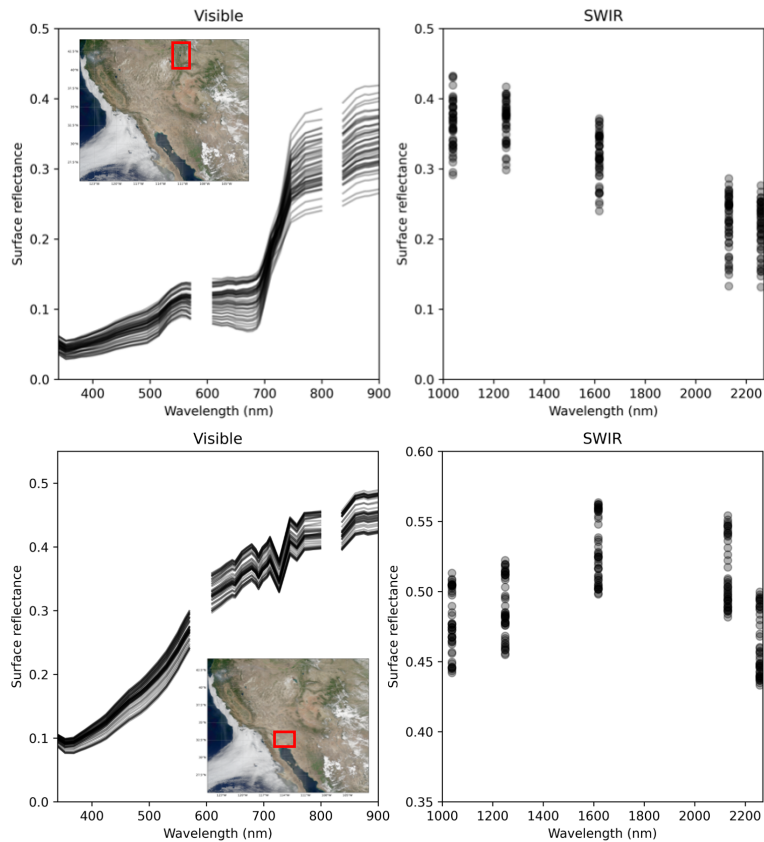


Figure 1: SFREFL spectra for two different locations in western North America on July 8th, 2024. Each graph contains 50 spectra from within the red bounding boxes in the RGB inset maps. Reflectance over clouds was excluded from the plots, and data at ~600 nm and 814 nm are masked out.

Unveiling PACE OCI's Hyperspectral Terrestrial Data Products

Of OCI's 9 SWIR bands, the SFREFL suite includes those at 1038 nm, 1249 nm, 1618 nm, 2131 nm, and 2258 nm. These bands occasionally show relatively large gradients across a scan line due to apparent band-to-band registration issues, which future reprocessings will correct.

The validation process for OCI and PACE as a whole is ongoing. The PACE-PAX field campaign (Knobelspiesse et al., 2023), for example, will provide an abundance of validation data which will help characterize the accuracy of all three PACE sensors. Figure 2 provides a preliminary evaluation of OCI's surface reflectances with respect to MODIS Aqua's MYD09 product. These results are not intended to comment on the accuracy of OCI, but instead to present the SFREFL product as a viable continuation of MODIS's land surface data record.

Figure 2 shows good correlation between SFREFL and MYD09, especially in the visible wavelength bands. These results do not show OCI as having a consistent bias in either direction compared to MYD09, although one could be expected given MODIS's correction for aerosols,

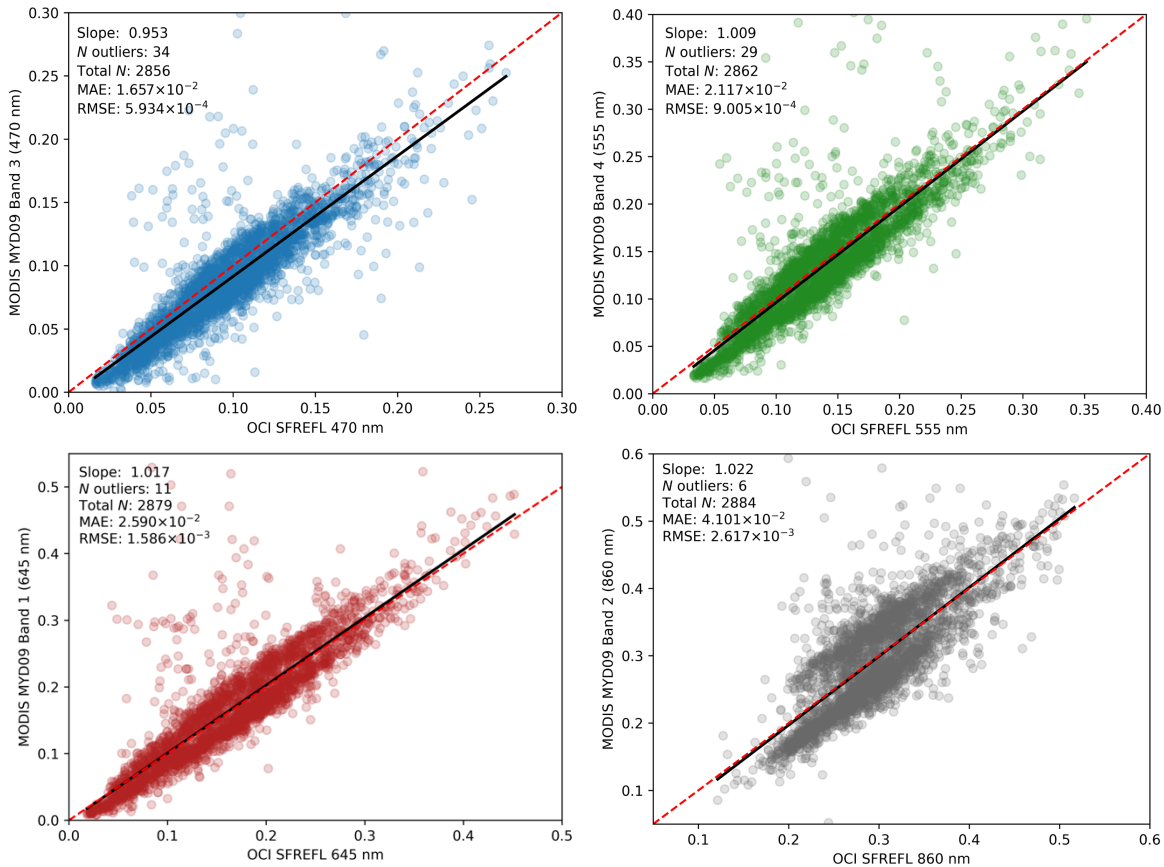


Figure 2: Comparison of MODIS MYD09 1 km surface reflectance with OCI SFREFL at wavelengths corresponding to the center of each applicable MODIS band. SFREFL measurements have not been aggregated to MODIS bandwidth as in the LANDVI suite. The black solid line is the regression line and the dashed red line is the 1:1 line. The coefficients of determination are: $R^2_{blue}=0.861$, $R^2_{green}=0.870$, $R^2_{red}=0.885$, $R^2_{NIR}=0.768$.

which OCI lacks (Vermote & Vermeulen, 1999). Aerosol correction would also account for the larger disagreement between the MODIS blue band (band 3) and OCI's 470 nm band, considering aerosol effects are stronger in the blue and UV. Moreover, the orbit and viewing geometry of PACE and MODIS Aqua are not the same. Neither of these datasets are corrected for angular effects, which contribute to the differences in measurements as well, especially in the NIR.

3.2 Vegetation Indices

Unveiling PACE OCI's Hyperspectral Terrestrial Data Products

Several of OCI's VIs are provided in Figure 3. The top row shows that the monthly averages for NDVI, NDWI, and CCI are reasonable – abundance of leaf cover in the northern hemisphere in June is clear from the high values of NDVI. The values of NDWI are consistent with humidity and higher water content in the northern hemisphere's summer as well. Values of CCI represent a relatively high ratio of chlorophyll to carotenoid in highly vegetated areas across the globe.

Subset of OCI's LANDVI Suite, June 2024

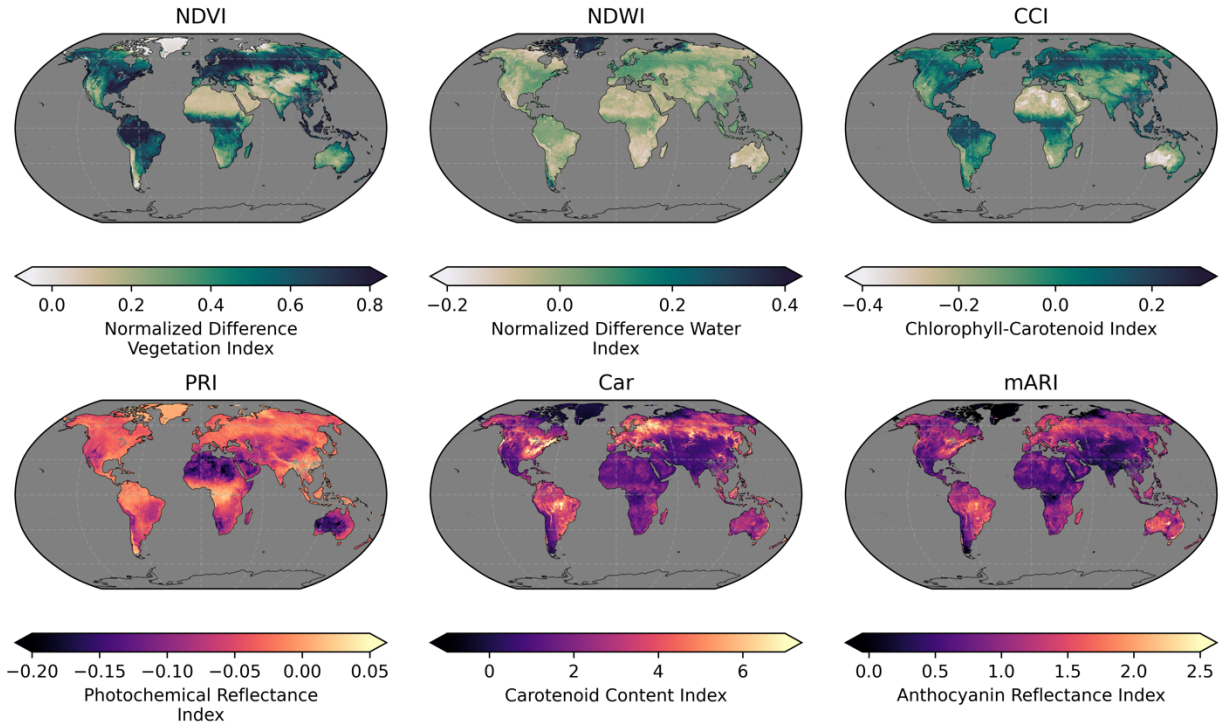


Figure 3: Global representations of 6 of OCI's 10 vegetation indices. Data in each map are monthly averages from June 2024. The top row displays the multiband VIs NDVI, NDWI, & CCI. The bottom row shows the novel narrowband indices PRI, Car, & mARI. Maps of NDII, NDSI, & EVI are not provided here. Maps of CIRE are included in Fig. 4.

Lower values of PRI tend to correspond to areas of high Car and low CIRE (Figure 4), although these signals can also be complicated by xanthophyll cycle activity. Relative carotenoid content from Car is much higher in places with presumably high leaf area and lower in regions where less vegetation is present, as expected. Values from mARI follow a similar pattern to Car, and are likely to develop and increase as the summer progresses to autumn.

While the static images in Figure 3 are useful snapshots of these indices, a more valuable way to analyze trends in vegetation would be at multiple time steps. Figure 4 presents a 2.5 minute map of CIRE over the course of spring and into summer. As the months advance from April to July and leaf area increases in the northern hemisphere, CIRE also increases. This is especially evident at higher latitudes. Conversely, in the southern hemisphere, CIRE decreases as expected with the onset of winter. This pattern is similar to what would be seen with NDVI as leaf-out occurs.

Unveiling PACE OCI's Hyperspectral Terrestrial Data Products

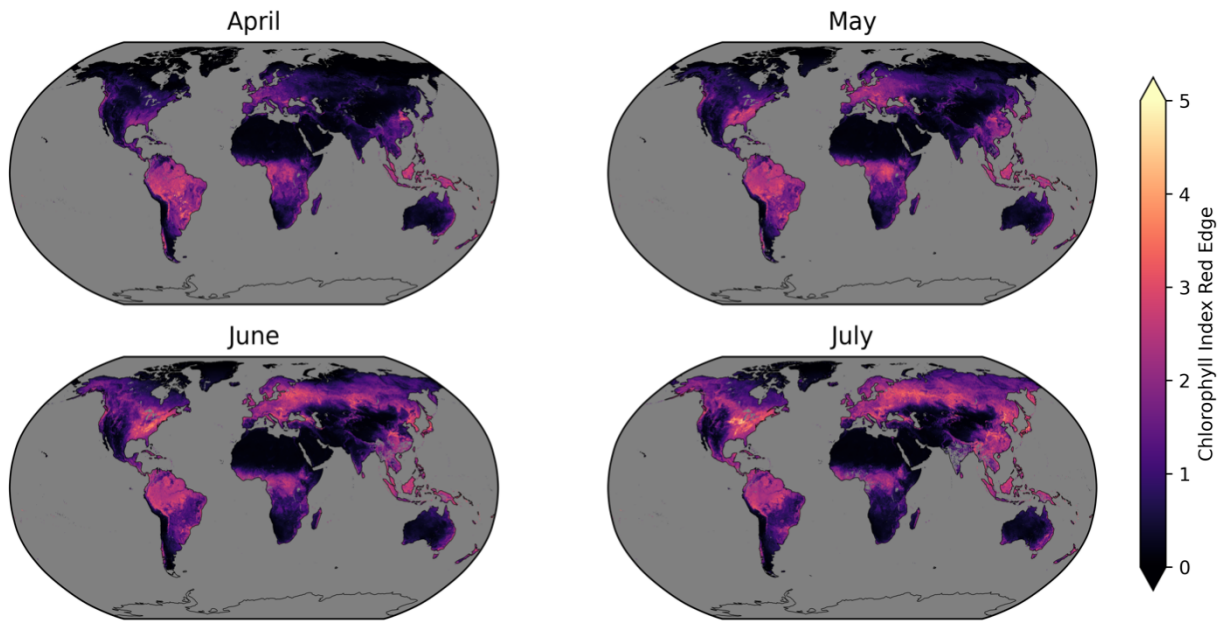


Figure 4: Global maps of CIRE for April, May, June, & July, showing the shifting dynamics of relative chlorophyll content across the globe. Missing data is due to cloud cover or other quality control over the course of the month. No data is available for Antarctica for this period due to polar night.

The 8-day OCI LANDVI data provide more detail on relative amounts of chlorophyll through time. Figure 5 provides a time series for several different vegetation types, showing CIRE signals change on finer time scales than Figure 4. For middle latitudes, an increase in CIRE begins around the end of March or beginning of April. For those points at higher latitudes, the increase begins

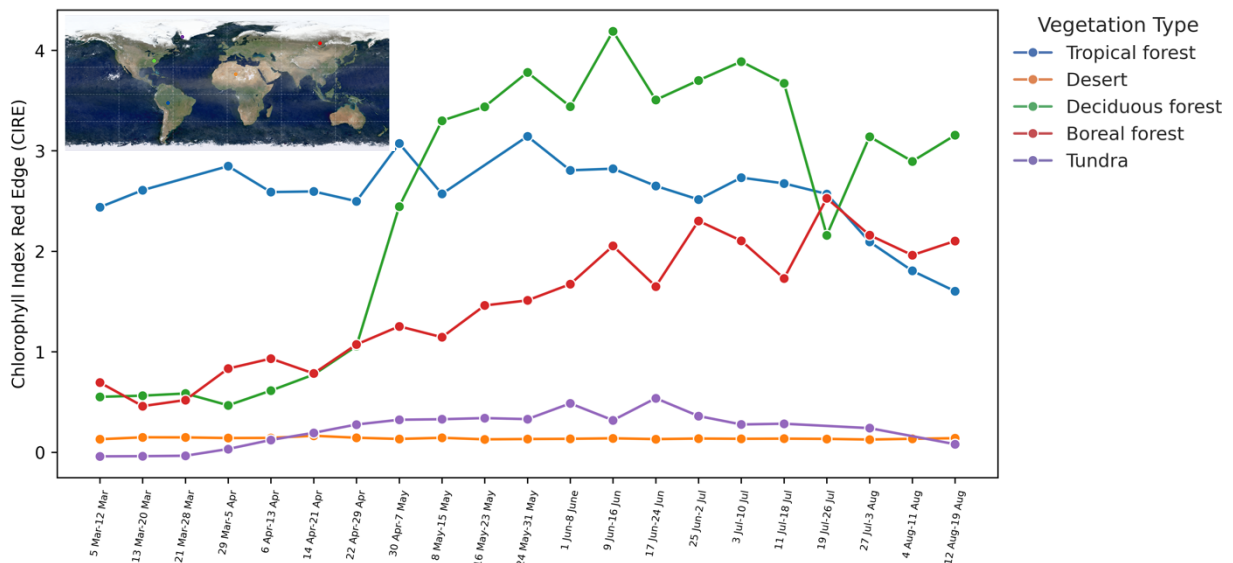


Figure 5: Time series of CIRE values from 5 different majority vegetation types. Values at each time step represent 8-day averages for the time period on the x-axis. All dates are from 2024. The map in the top left shows the location for each time series by colour. Missing data points occur where no cloud-free data existed, or where other flags excluded data from the product.

Unveiling PACE OCI's Hyperspectral Terrestrial Data Products

later, around May, accounted for by the later onset of spring and delayed growth of new leaves. Greenland's tundra, for example, sees a slight increase in CIRE from April to May, where values then level off and begin to decrease in June. In a tropical setting, the value of CIRE is high and relatively stable, with fluctuations over the course of the season and a sustained dip toward the end of July and beginning of August. In the Sahara, CIRE values are extremely stable and low throughout this 5-month period, staying at approximately 0.13 for the duration of the analysis.

The patterns in these data are consistent with the dynamics of vegetation growth for each land cover type provided, seeing low values where little vegetation exists and higher values for areas with presumptively higher leaf area. However, fluctuations on finer timescales, i.e., the decrease in CIRE in both deciduous and boreal forests several times during the months of June and July, are curious. Given these are average values for several kilometers of forests, sub-pixel scale events during the 8-day periods could have significant effect on the CIRE values, especially if the number of valid observations also varies from time step to time step.

4. Summary & Future work

In this letter, the terrestrial product suites from PACE OCI are introduced. Though outside of the primary focus of the PACE mission, they are already providing previously unseen global insights on ecosystem dynamics through frequent repeat hyperspectral reflectance measurements. The agreement between PACE's hyperspectral surface reflectances with MODIS multiband measurements bode well for collaboration with current and future missions like Earth Surface Mineral Dust Source Investigation (EMIT) (Thompson et al. 2024), Landsat Next (USGS, 2024), and Surface Biology and Geology (SBG) (Stavros et al. 2023). OCI's vegetation indices are also extending the multispectral data record and delivering novel results with hyperspectral vegetation indices.

The immediate future for PACE terrestrial products will be to move toward standard product status, involving the determination of a final surface reflectance algorithm as well as extensive validation of both SFREFL and LANDVI. Field campaigns such as PACE-PAX and field data from the National Ecological Observation Network (NEON) and Radiometric Calibration Network (RadCalNet) sites will greatly assist the validation effort. In the longer term, a nadir BRDF adjusted surface reflectance product is essential both for continuity with heritage missions and to ease collaboration with current and future hyperspectral sensors. Along with those from OCI, terrestrial products are also being considered for HARP2 and SPEXone. As the PACE mission matures, these initiatives will foster a deeper understanding of Earth ecosystems and contribute to informed decision-making in environmental policies and practices.

Disclosure Statement

No potential conflict of interest was reported by the authors.

Data Availability Statement

The data that support the findings of this study are openly available on the NASA Ocean Color Website at https://oceandata.sci.gsfc.nasa.gov/api/file_search/.

References

- Coops, Nicholas C., Thomas Hilker, Forrest G. Hall, Caroline J. Nichol, and Guillaume G. Drolet. "Estimation of Light-Use Efficiency of Terrestrial Ecosystems from Space: A Status Report." *BioScience* 60, no. 10 (November 2010): 788–97. <https://doi.org/10.1525/bio.2010.60.10.5>.
- Gamon, John A., K. Fred Huemmrich, Christopher Y. S. Wong, Ingo Ensminger, Steven Garrity, David Y. Hollinger, Asko Noormets, and Josep Peñuelas. "A Remotely Sensed Pigment Index Reveals Photosynthetic Phenology in Evergreen

Unveiling PACE OCI's Hyperspectral Terrestrial Data Products

- Conifers.” *Proceedings of the National Academy of Sciences* 113, no. 46 (November 15, 2016): 13087–92. <https://doi.org/10.1073/pnas.1606162113>.
- Gao, Bo-cai. “NDWI—A Normalized Difference Water Index for Remote Sensing of Vegetation Liquid Water from Space.” *Remote Sensing of Environment* 58, no. 3 (December 1996): 257–66. [https://doi.org/10.1016/S0034-4257\(96\)00067-3](https://doi.org/10.1016/S0034-4257(96)00067-3).
- Gitelson, Anatoly A., Mark N. Merzlyak, and Olga B. Chivkunova. “Optical Properties and Nondestructive Estimation of Anthocyanin Content in Plant Leaves.” *Photochemistry and Photobiology* 74, no. 1 (May 1, 2007): 38–45. [https://doi.org/10.1562/0031-8655\(2001\)0740038OPANEO2.0.CO2](https://doi.org/10.1562/0031-8655(2001)0740038OPANEO2.0.CO2).
- Gitelson, Anatoly A., Andrés Viña, Verónica Ciganda, Donald C. Rundquist, and Timothy J. Arkebauer. “Remote Estimation of Canopy Chlorophyll Content in Crops.” *Geophysical Research Letters* 32, no. 8 (April 2005): 2005GL022688. <https://doi.org/10.1029/2005GL022688>.
- Gitelson, Anatoly A., Yoav Zur, Olga B. Chivkunova, and Mark N. Merzlyak. “Assessing Carotenoid Content in Plant Leaves with Reflectance Spectroscopy,” n.d.
- Gitelson, Anatoly, and Alexei Solovchenko. “Generic Algorithms for Estimating Foliar Pigment Content.” *Geophysical Research Letters* 44, no. 18 (September 28, 2017): 9293–98. <https://doi.org/10.1002/2017GL074799>.
- Grace, J., C. Nichol, M. Disney, P. Lewis, T. Quaife, and P. Bowyer. “Can We Measure Terrestrial Photosynthesis from Space Directly, Using Spectral Reflectance and Fluorescence?” *Global Change Biology* 13, no. 7 (July 2007): 1484–97. <https://doi.org/10.1111/j.1365-2486.2007.01352.x>.
- Hall, Dorothy K., George A. Riggs, and Vincent V. Salomonson. “Algorithm Theoretical Basis Document (ATBD) for the MODIS Snow and Sea Ice-Mapping Algorithms,” n.d.
- Hardisky, Michael A., Victor Klemas, and R. M. Smart. “The influence of soil-salinity, growth form, and leaf moisture on the spectral radiance of *Spartina alterniflora* canopies.” *Photogrammetric Engineering & Remote Sensing* 48, no. 1 (January 1983): 77–83.
- Huete, A., K. Didan, T. Miura, E. P. Rodriguez, X. Gao, and L. G. Ferreira. “Overview of the Radiometric and Biophysical Performance of the MODIS Vegetation Indices.” *Remote Sensing of Environment* 83, no. 1–2 (November 2002): 195–213. [https://doi.org/10.1016/S0034-4257\(02\)00096-2](https://doi.org/10.1016/S0034-4257(02)00096-2).
- Ji, Lei, Li Zhang, Bruce K. Wylie, and Jennifer Rover. “On the Terminology of the Spectral Vegetation Index (NIR – SWIR)/(NIR + SWIR).” *International Journal of Remote Sensing* 32, no. 21 (November 10, 2011): 6901–9. <https://doi.org/10.1080/01431161.2010.510811>.
- Jiang, Z., A. Huete, K. Didan, and T. Miura. “Development of a Two-Band Enhanced Vegetation Index without a Blue Band.” *Remote Sensing of Environment* 112, no. 10 (October 15, 2008): 3833–45. <https://doi.org/10.1016/j.rse.2008.06.006>.
- Knobelspiesse, K. D., B. Cairns, I. Cetinić, S. Craig, B. A. Franz, M. Gao, A. Ibrahim, A. Mannino, A. M. Sayer, and P. J. Werdell. “PACE Technical Report Series, Volume 11: The PACE Postlaunch Airborne eXperiment (PACE-PAX).” *NASA Technical Reports Server*, (June 2023).
- Lyapustin, Alexei, John Martonchik, Yujie Wang, Istvan Laszlo, and Sergey Korkin. “Multiangle Implementation of Atmospheric Correction (MAIAC): 1. Radiative Transfer Basis and Look-up Tables.” *Journal of Geophysical Research* 116, no. D3 (February 11, 2011): D03210. <https://doi.org/10.1029/2010JD014985>.
- Middleton, E. M., K. F. Huemmrich, D. R. Landis, T. A. Black, A. G. Barr, and J. H. McCaughey. “Photosynthetic Efficiency of Northern Forest Ecosystems Using a MODIS-Derived Photochemical Reflectance Index (PRI).” *Remote Sensing of Environment* 187 (December 2016): 345–66. <https://doi.org/10.1016/j.rse.2016.10.021>.
- Mobley, Curtis D., Jeremy Werdell, Bryan Franz, Ziauddin Ahmad, Sean Bailey. “Atmospheric Correction for Satellite Ocean Color Radiometry” *NASA Technical Reports Server*, (June 2016).
- OBPG (Ocean Biology Processing Group). 2021. *NASA Goddard Space Flight Center Ocean Biology Processing Group Data Management Plan*. Greenbelt, MD: U.S. National Aeronautics and Space Administration.
- OBPG (Ocean Biology Processing Group). 2024. “Ocean Color Science Software” V. V2024.6. NASA Goddard Space Flight Center Ocean Biology Processing Group <https://oceancolor.gsfc.nasa.gov/docs/ocssw/>
- OEL (Ocean Ecology Laboratory). 2024. “Algorithm Theoretical Basis Document for OCI Surface Reflectance (SFREFL)” Algorithm Publication Tool Working Document. NASA Goddard Space Flight Center Ocean Ecology Laboratory, Greenbelt, MD.
- Stavros, E. Natasha., Jon Chrone, K. Cawse-Nicholson, A. Freeman, N. F. Glenn, L. Guild, ... & D. Schimel. “Designing an Observing System to Study the Surface Biology and Geology (SBG) of the Earth in the 2020s”. *Journal of Geophysical Research: Biogeosciences* (June 5 2023), 128(1), e2021JG006471. <https://doi.org/10.1029/2021JG006471>
- Thompson, David. R., R. O. Green, C. Bradley, P. G. Brodrick, N. Mahowald, E. B. Dor, ... & S. Zandbergen, S. “On-orbit calibration and performance of the EMIT imaging spectrometer.” *Remote Sensing of Environment* 303 (March 15, 2024), 113986. <https://doi.org/10.1016/j.rse.2023.113986>
- Vermote, Eric. F., and Vermeulen, Anne. “Atmospheric Correction Algorithm: Spectral Reflectances (MOD09)” Version 4.0 (April 1999). <http://doi.org/10.5067/MODIS/MYD09A1.006>
- U.S. Geological Survey, 2024, Landsat Next (ver. 1.1, March 25, 2024): U.S. Geological Survey Fact Sheet 2024–3005, 2 p., <https://doi.org/10.3133/fs20243005>.