

Emerging satellite observations for diurnal cycling of ecosystem processes

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Abstract:

Diurnal cycling of plant carbon uptake and water use, and their responses to water and heat stresses, provide direct insight for assessing ecosystem productivity, agricultural production and management practices, carbon and water cycles, and feedbacks to the climate. Temperature, light, atmospheric water demand, soil moisture, and leaf water potential vary over the course of the day, leading to diurnal variations in stomatal conductance and ecosystem processes. Earth observations from polar-orbiting satellites are incapable of studying these diurnal variations. We review the emerging satellite observations that have the potential for studying how plant functioning and ecosystem processes vary over the course of the diurnal cycle. The recently launched ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and Orbiting Carbon Observatory-3 (OCO-3) provide land surface temperature (LST), evapotranspiration (ET), and solar-induced fluorescence (SIF) data at different times of day. New generation operational geostationary satellites such as Himawari-8 and the GOES-R series can provide continuous, high-frequency data of LST, solar radiation, and gross primary production (GPP). Future satellite missions such as GeoCarb, TEMPO, and Sentinel-4 are also planned to have diurnal SIF sampling capability. We explore the unprecedented opportunities for characterizing and understanding how GPP, ET, and water use efficiency (WUE) vary over the course of the day in response to temperature and water stresses and management practices. We also envision that these emerging observations will revolutionize studies of plant functioning and ecosystem processes in the context of climate change and that these observations and findings can inform agricultural and forest management and lead to improvement of Earth system models and climate projections.

Keywords: Plant functioning; photosynthesis; evapotranspiration; water use efficiency; circadian rhythms; stomatal conductance

Plant scientists and ecologists have been intrigued by the circadian rhythms (i.e., circadian clock) of plants for decades ^{1,2}. Many compelling science questions have arisen regarding the diurnal (i.e. diel) patterns of plant photosynthesis and transpiration. For example, how do plants use resources throughout the day? How does stomatal conductance change in response to environmental and internal factors (e.g., air temperature, light, atmospheric water demand, soil moisture, and leaf water potential/storage)? How do plant photosynthesis, transpiration, and water use efficiency (WUE) respond to these environmental factors? Addressing these questions is increasingly important in the context of climate change. Increasing water and heat stresses ^{3,4} can have large impacts on plant functioning and ecosystem processes, particularly during the midday period; plants may exhibit more frequent stomatal closure and midday depression, which can have significant impacts on plant growth, carbon uptake, and plant survival. Better understanding the responses of plants to water and heat stresses over the course of the day is critical for assessing the impacts of drought and heat waves on plant production and survival, food security, and terrestrial carbon dynamics and projecting carbon-climate feedbacks.

Elucidating diurnal cycling of plant water loss by transpiration and carbon gain by photosynthesis is of fundamental importance for understanding how plants interact with ambient and changing environmental conditions. Dissymmetric evolution of stomatal conductance and midday stomatal closure have been shown for different plant species, life stages, ecosystems ^{5,6,7}. As a result, photosynthesis can exhibit an afternoon decline and a midday depression (Fig. 1) ^{8,9}, ¹⁰, leading to a two-peaked and dissymmetric diurnal pattern ¹¹. The diurnal variations of stomatal conductance also shape the diurnal pattern of transpiration (Fig. 1). Water stress might result in a larger decrease in evapotranspiration (ET) than in gross primary production (GPP), leading to higher WUE ¹². Water stress may also decrease WUE and lead to less efficient carbon uptake.

Diurnal patterns of stomatal conductance, ET, and GPP may exhibit large differences among different plant and ecosystem types. Better understanding diurnal courses of plant water use and carbon uptake is essential for understanding the relations between water and productivity of natural and managed ecosystems ¹¹, providing insight into the vulnerability and resilience of different ecosystems to drought and/or heat stress ¹³, and informing management practices (e.g., irrigation).

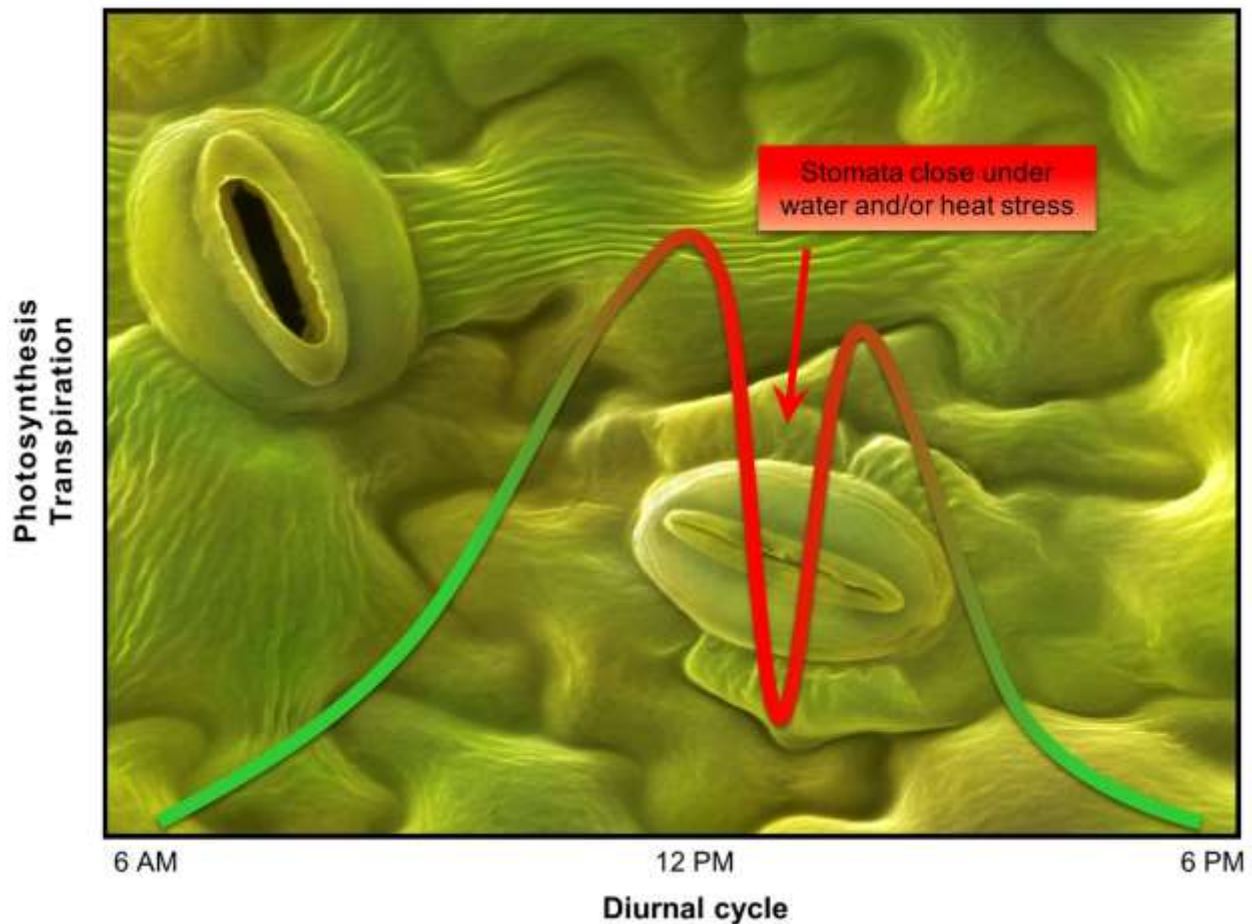


Fig. 1 Conceptual diagram of plant photosynthesis and transpiration over the course of a day. Both transpiration and photosynthesis may show mid-afternoon depressions due to stomatal closure under water and/or heat stresses. The background image shows open and closed stomata on a lavender leaf (*Lavandula dentata*), colored scanning electron micrograph (SEM) (Source: Science Photo Library; magnification $\times 2000$ at an image size of 10 cm wide). Stomata are pores on leaves that open and close to regulate the exchange of gases (carbon dioxide, water).

Observations at multiple times of the day are essential for understanding the diurnal cycles of plant water use and carbon uptake. At canopy and ecosystem scales, in-situ measurements with portable instruments¹⁴ and the eddy covariance (EC) technique^{15, 16} have been widely used to examine the diurnal variations of plant functioning and ecosystem processes. In particular, the EC sites provide continuous, sub-hourly measurements of ecosystem carbon and water exchange, meteorological variables, and soil moisture¹⁷, allowing scientists to analyze how stomatal conductance, photosynthesis, and transpiration vary over the course of the diurnal cycle^{15, 16}. However, these in-situ measurements are spatially sparse, and the resulting findings do not necessarily apply elsewhere.

Compared with in-situ techniques, satellites can provide direct observations of plants over regions or the globe. Satellites measure plant status, canopy cover, plant productivity, vegetation structure, water stress, and other plant or environmental variables. Earth observations from polar-orbiting satellites such as Landsat, Sentinel, Terra, Aqua, and Orbiting Carbon Observatory-2 (OCO-2) have been widely used to examine ecosystem processes (e.g., GPP, ET, WUE) at regional to global scales^{18, 19, 20, 21}. However, polar-orbiting satellites typically acquire at best one or two snapshots of a given location during each day or a certain period (e.g., 16 days), at the same time of the day/night, and therefore are not designed to study diurnal variations of plant water use and carbon uptake. The carbon and water flux datasets based on these satellite data are available at daily or longer (e.g., 8-day) timescales (e.g., global GPP and ET products derived from the MODerate resolution Imaging Spectroradiometer or MODIS aboard Terra and Aqua^{18, 22}).

Several recently launched and forthcoming Earth-observing satellites have diurnal sampling capabilities. The recently launched ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and Orbiting Carbon Observatory-3 (OCO-3), both on board the

International Space Station (ISS), provide land surface temperature (LST), ET, and solar-induced chlorophyll fluorescence (SIF) data at different times of day. New generation geostationary satellites provide continuous observations throughout the day/night. Here we review these emerging satellite observations (Table 1) and explore the unprecedented opportunities for characterizing and understanding the diurnal cycling of plant functioning and ecosystem processes that have not yet been explored using measurements from space. We also envision how these emerging observations will revolutionize studies of plant functioning and ecosystem processes and how these observations and findings can inform agricultural management and improvement of Earth system models and climate projections.

Table 1. Specifications of the instruments/platforms that have diurnal sampling capability in studying plant functioning and ecosystem processes. NIR, SWIR, and TIR stand for near infrared, shortwave infrared, and thermal infrared wavelength, respectively.

Instrument	Platform	Launch date	Wavelength	Spatial resolution	Repeat cycle	Spatial extent
ECOSTRESS	ISS	June 29, 2018	TIR	70 m	1-5days	Global (52°N - 52°S)
OCO-3	ISS	May 4, 2019	Far red, SWIR	2 km	~5days	Global (52°N - 52°S)
AHI	Himawari-8	October 7, 2014	Visible, NIR, SWIR, TIR	0.5-2 km	10 mins ^a	Eastern Asia and Oceania
ABI	GOES-16	November 19, 2016	Visible, NIR, SWIR, TIR	0.5-2 km	10 mins ^b	Western Hemisphere
ABI	GOES-17	March 1, 2018	Visible, NIR, SWIR, TIR	0.5-2 km	10 mins ^b	Western Hemisphere
AGRI	Fengyun-4	December 10, 2016	Visible, NIR, SWIR, TIR	0.5-4 km	15 mins	Eastern Hemisphere
FCI	MTG	≥2022	Visible, NIR, SWIR, TIR	0.5-2 km	10 mins ^c	Europe and Africa
GeoCarb	TBD ^d	≥2022	Far red, SWIR	5-10 km	<1 day	Americas (52°N - 52°S)
TEMPO	TBD ^d	≥2022	Red, far red	2.1 km × 4.4 km	Hourly	North America
UVN	Sentinel-4	≥2022	Visible, NIR	8 km	Hourly	Europe and North Africa

^a Himawari-8: 10 minutes for full disk and 2.5 minutes for Japan.

^b GOES-16 and GOES-17: 10 minutes for full disk (with 15 minutes for full disk prior to April 2019), 5 minutes for the conterminous U.S., and 30 or 60 seconds at the mesoscale.
^c MTG: 10 minutes for full disk (Europe and Africa) and 2.5 minutes for Europe.
^d TBD stands for “to be determined”. Both GeoCarb and TEMPO will be deployed on commercial geostationary satellites.

ISS: ECOSTRESS

The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) was launched to the International Space Station (ISS) by the National Aeronautics and Space Administration (NASA) on 29 June 2018 ²³. ECOSTRESS measures thermal infrared radiation (TIR) in five bands from 8- to 12.5- μ m, plus an additional sixth band at 1.6 μ m for geolocation and cloud detection. ECOSTRESS covers the Earth continuously between $\sim 52^{\circ}$ N and $\sim 52^{\circ}$ S.

ECOSTRESS produces four levels of data products, with Levels 2-4 for primary science applications. The pixel size at nadir is 38 m x 69 m, which is resampled to 70 m x 70 m pixels for higher level data products. The ECOSTRESS science products consist of LST and emissivity (L2_LSTE) ^{24, 25}, ET including partitioning between canopy transpiration, soil evaporation, and interception evaporation (L3_ET_PT-JPL; L3_ET_ALEXI) ^{23, 26}, and the Evaporative Stress Index (ESI) and Water Use Efficiency (WUE) (Level 4) ^{27, 28}. LST is an instantaneous product, while ET includes both instantaneous and daily estimates. Both ESI and WUE are currently daily products. The daily WUE product is calculated from ECOSTRESS daily ET estimate and the MODIS GPP product ¹⁸. Instantaneous WUE can be derived from the instantaneous ET estimates (e.g., L3_ET_PT-JPL) ²³ and instantaneous GPP estimates ²⁹ based on ECOSTRESS LST data. Field validation based on dozens of land sites showed that the ECOSTRESS LST product met the accuracy requirement (daytime LST: bias = 0.1 K, RMSE = 1.1 K; nighttime LST: bias = -0.2 K; RMSE = 0.8 K) ³⁰. The ECOSTRESS ET product likewise performed well against in-situ measurements from 82 EC flux sites ($R^2=0.88$, overall bias = 8%; normalized RMSE = 6%) ²³.

Flying in the precessing orbit of the ISS, ECOSTRESS collects measurements at different times of day, thereby sampling the diurnal cycle. The ISS orbit characteristics, in conjunction with the large 384-km ECOSTRESS swath width, enables a return frequency every 1–5 days, depending on latitude. Higher latitudes, where the ISS orbital direction shifts, are measured multiple times in a single day. ECOSTRESS therefore provides the highest combination of spatial and temporal resolution diurnal sampling of surface properties associated with temperature and water. ECOSTRESS can sample a large portion of the diurnal cycle over a period of weeks.

Diurnally, ECOSTRESS can provide transformative information about plant heat and water stress, and water use. While the diurnal sampling of geostationary satellites (e.g., Himawari-8, the GOES-R series) is more frequent, the coarse spatial resolution (e.g., 2 km for TIR bands) produces mixed pixels containing plant species or individuals with different diurnal cycles. The 70 m ECOSTRESS pixels are much closer to the scale of small ecosystem patches and individual agricultural fields. Further spatial downscaling is possible through fusion with other sensors³¹. It is therefore possible to detect from space, for example, individual fields drying out in the afternoon (Fig. 2) — this has never been possible in the history of remote sensing before ECOSTRESS. This type of information can be returned to farmers and water managers who may not know that individual fields could use more water. Similarly, it may be possible to see parts of a forest drying out before other parts (e.g., forest edges) — again, information that can be critically useful for forest and fire managers. While diurnal water stress is certainly not a new phenomenon, until ECOSTRESS we did not know where and when this was occurring globally. This type of science application requires that satellite instruments offer observations with <100 m pixel size, <10% relative uncertainty, and <weekly repeat cycle.

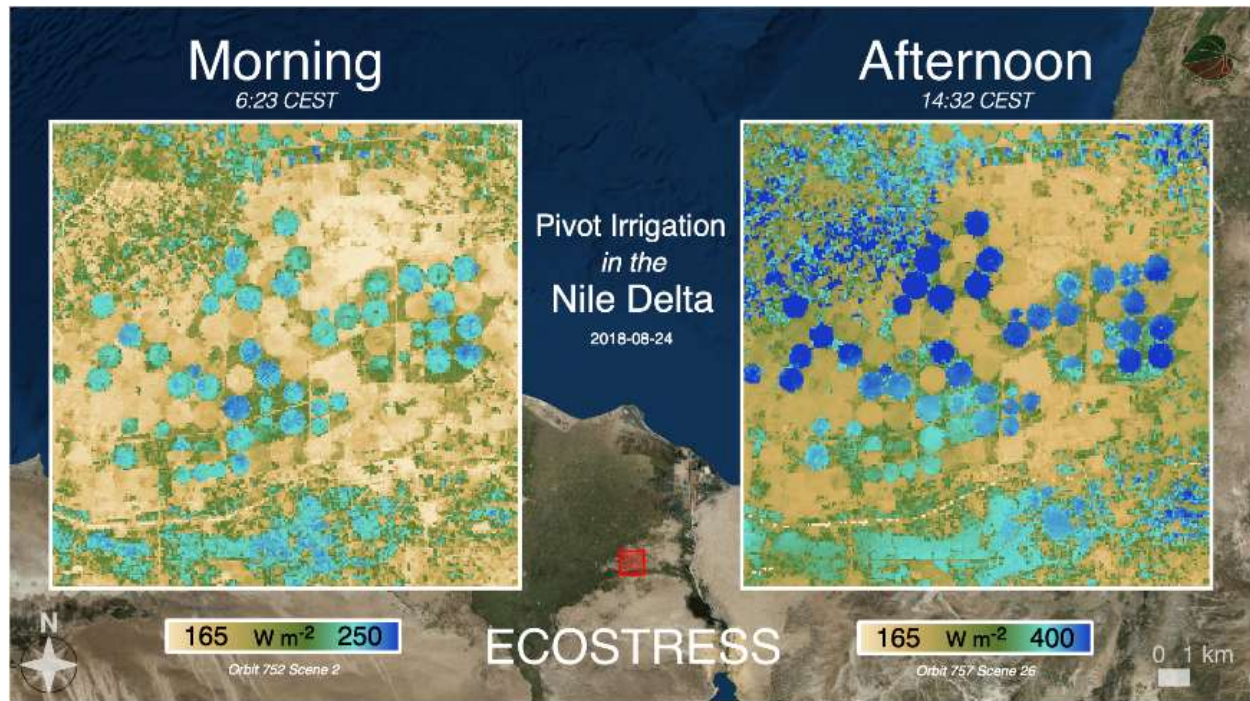


Fig. 2 NASA's ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) imaged the Nile Delta, Egypt from the International Space Station in the morning and afternoon on August 24, 2018. ECOSTRESS captured changes in evapotranspiration (ET) from agricultural fields within the same day. The image on the left is from 6:23 CEST, and the image on the right is from 14:32 CEST. Much more ET is shown in the afternoon image (blue colors), though there are larger differences between the fields than in the morning. The geographical coordinates of the center of the ECOSTRESS images (Orbit 752, Scene 2 and Orbit 757, Scene 26) are 30.54° N and 31.85° E. The scale bar applies to the background map; the pixel size of the inset maps is 70 m.

From a plant ecophysiological perspective, we are interested in water-, temperature-, and vapor pressure deficit (VPD)-induced stomatal closure³². We know well from local *in situ* measurements that some plants close stomata in response to these stressors³³. However, not all plants behave the same even within the same area or species, for example, due to variations in rooting depth, soil moisture, and/or water table; and/or due to differences in species, age, and/or

disturbance history³⁴. Although we know that these differences exist from local measurements, we do not know where these responses are occurring globally. That is where ECOSTRESS can advance plant ecophysiological science.

The suite of ECOSTRESS products can be used synergistically to understand diurnal cycle plant water and temperature responses. From the state-of-the-art number of TIR spectral bands and retrieval approach³⁵, the LST data can map with great precision both the instantaneous heat of the plant surface as well as the duration that heat might extend into the day and night²⁵. How that heat dissipates in time and space is related both to surface physical properties and water use (in the absence of exogenous factors). In turn, the ET data reveal how much water is used throughout the day, and how that water use deviates from expectations due to atmospheric demand alone³⁶. The canopy transpiration product can be used to isolate the plant contribution to total ET³⁷. The ESI product is useful for diagnosing attribution to ET responses, as well as lead-up prior to ET responses and drought impacts³⁸. GPP estimates based on ECOSTRESS LST data can reveal how plant photosynthesis varies throughout the day in response to variations in environmental and physiological factors and management practices (e.g., irrigation)²⁹. Finally, the WUE product can link water and temperature responses to carbon cycle processes²⁸, as well as to synergistic measurements from other sensors, such as SIF from OCO-3³⁹.

ISS: OCO-3

The Orbiting Carbon Observatory-3 (OCO-3) was deployed to the ISS in May 2019, and has been collecting joint measurements of atmospheric CO₂ and plant SIF since August 2019⁴⁰. Unlike its polar orbiting predecessor (OCO-2)⁴¹, OCO-3 samples reflected sunlight in the tropics and subtropics across the full range of daylight hours (dawn-to-dusk) with dense observations at northern and southern mid-latitudes (+/- 52°), like ECOSTRESS, due to the low-inclination ISS orbit. OCO-

3 also has a Snapshot Area Mode (SAM), and this technical innovation allows for localized mapping of SIF for the first time. By continuing the concurrent SIF observations of OCO-2 in time, expanding OCO-2 measurements in space, and focusing on ecosystem and urban hotspots, OCO-3 provides scientists a unique vantage of the processes that influence the global carbon cycle and plant behavior, thus increasing our understanding of how global climate patterns affect the terrestrial carbon cycle.

Plant fluorescence has been studied in laboratories and the field for several decades focusing on plant-level photosynthesis⁴². When plants absorb solar energy for growth, they re-emit a small amount (~2%) of sunlight back to space. Although SIF exhibits a complex and varying relationship with photosynthesis at various scales (e.g., leaf, canopy, ecosystem)^{43, 44}, ecosystem resolving spaceborne sensors such as GOME-2, GOSAT, OCO-2, and TROPOMI found a simple linear relationship between fluorescence and rates of ecosystem-scale photosynthesis observed at towers, nearly independent of vegetation type^{21, 45, 46}. This allows scientists to use empirical relationships to estimate global rates of photosynthesis⁴⁷, its change over time and space, and study its climate sensitivity (e.g., the photosynthesis of tropical continents responded in different ways to warming and drying during the 2015-16 El Niño)⁴⁸. The intercomparison of SIF between OCO-3 and its predecessor (OCO-2) showed that OCO-3 SIF is of comparable quality as OCO-2 SIF⁴⁰, which shows strong seasonal agreement with tower and airborne SIF measurements at a sub-alpine evergreen forest⁴⁹, and correlates well with tower-based GPP across multiple biomes (with R^2 ranging from 0.73 to 0.81)^{21, 45}.

While OCO-2 offers the high spectral resolution needed to capture the downregulation of photosynthesis under increasing water limitation⁵⁰, it misses the full dynamic range of water stress responses due to fixed afternoon sampling during peak stress (~1:30 pm local). Moreover, attempts

to combine afternoon measurements from one polar-orbiting satellite (TROPOMI) with morning measurements from another satellite (GOME-2) reveal systematic orbital geometry-dependent variations which mask physiologically driven diurnal changes. A recent analysis of the FLUXNET2015 EC database shows that photosynthesis in most plant types typically peaks in late morning prior to peak potential shortwave incoming radiation, when water stress is low and boundary layer CO₂ is high, then decreases in the afternoon with lower light use efficiency⁵¹. ET, meanwhile, typically peaks in the afternoon with VPD, creating diurnal hysteresis between ecosystem fluxes that is typically and critically unresolved by polar-orbiting satellites.

OCO-3 provides the diurnal sampling and spatial resolution needed to advance our understanding of photosynthesis especially under heat and water stress. OCO-3 passes over any given location (at nadir) ~20 minutes earlier each time, eventually sampling all sunlit hours⁴⁰. Each time the instrument passes over, it collects SIF snapshots (1-2 km footprints) capable of resolving photosynthetic CO₂ uptake at the ecosystem. These measurements provide scientists with a new level of detail on the interaction between ecosystem scale photosynthetic processes and drought response.

OCO-3 target and SAM observations offer versatile alternatives to the narrow (~10 km) nadir and glint swaths for collection of dense, cloud-free, spatially resolved datasets at selected ecosystem hotspots and validation targets. OCO-3 scans a repeated swath over ~20 km x 20 km areas in the target mode and adjacent swaths over ~80 km x 80 km areas in the SAM mode. Target data are used primarily for CO₂ calibration and validation but offer high precision, diurnally and seasonally resolved SIF across a small subset of locations around the world. SAM data provide SIF across a wide variety of urban, volcanic, agricultural, and naturally vegetated locations to study biological exchange in managed and unmanaged landscapes. SAM locations can also be

reprogrammed for near-real time study of climate extremes (e.g., drought, flooding, fires), weather extremes (e.g., hurricane, derecho), and changes in management (e.g., irrigation, water-use restrictions).

The OCO-3 observations overlap in space and time with ECOSTRESS due to the shared ISS platform, although ECOSTRESS covers even more area due to its larger swath. A large percentage of SAM collection is coincident with ECOSTRESS priority EC validation sites. While the nature of the precessing ISS orbit can cause irregular spatial sampling, the extended spatial coverage enables more focused analyses of cloud-free subregions with overlapping coverage in time. For example, a series of SAMs collected at the Santa Rita Experimental Range in Arizona, USA demonstrate the impact of sporadic sampling and clouds on spatial maps (Fig. 3), but careful downsampling and quality control produces aggregated sounding and diurnal signature which resembles observations from ground-based measurements^{49, 52, 53}. OCO-3, in combination with ECOSTRESS, provides cutting-edge insight into ecosystem processes of SIF and ET, and ultimately can be combined as WUE, with high resolution sampling throughout the day. While certainly an advance over predecessor measurements, both instruments still do not continuously observe the diurnal cycle, and therefore synergy with geostationary instruments can help close that loop.

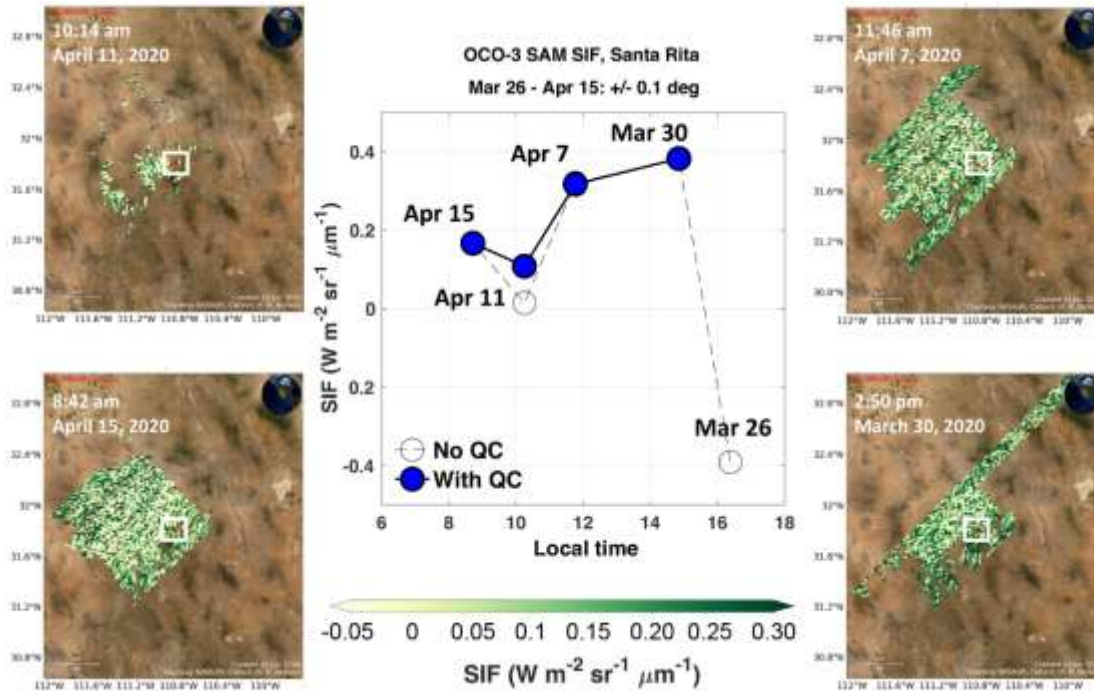


Fig. 3 Solar-induced chlorophyll fluorescence (SIF), a proxy of plant photosynthesis, at different times of day as measured by the Orbiting Carbon Observatory-3 (OCO-3) in the Snapshot Area Mapping (SAM) mode. The data were acquired surrounding the Santa Rita Experimental Range, Arizona (USA). The four maps show the spatial patterns of SIF at the landscape scale for different times of day in March and April, 2020. The center plot illustrates the diurnal variations of SIF spatially averaged within the 0.1 degree $\times$ 0.1 degree area surrounding the Santa Rita Experimental Range research site, and only good-quality data (solar zenith angle $< 70^\circ$, view zenith angle $< 40^\circ$, cloud fraction < 0.1) were used.

New generation geostationary satellites

Although ECOSTRESS and OCO-3 have diurnal sampling capabilities, these samples are not continuous throughout the day for a given location. By contrast, geostationary satellites carry optical sensors with high-frequency observation capability (10 to 15 minutes in full scan mode). With such high temporal frequency and spectral features, these satellites are expected to improve diurnal monitoring of ecosystem dynamics⁵⁴. Following the Himawari-8 (launched in 2014) with

the Advanced Himawari Imager (AHI) ⁵⁵, the subsequent geostationary satellites carry the same type of optical sensors: Advanced Baseline Imager (ABI) on the Geostationary Operational Environmental Satellite-R Series (GOES-R) (GOES-16 launched in 2016 and GOES-17 launched in 2018) ⁵⁶ and Advanced Meteorological Imager (AMI) on GEO-KOMPSAT-2A (GK-2A) (launched in 2018) ⁵⁷. These instruments collect high-frequency observations of radiance in both solar reflective and TIR wavelengths. New sensors with similar features are also aboard China's and Europe's new generation geostationary satellites: Advanced Geostationary Radiation Imager (AGRI) on Fengyun-4 (FY-4) series (FY-4A was launched in 2016) ⁵⁸ and Flexible Combined Imager (FCI) on Meteosat Third Generation (MTG) series ⁵⁹. The combination of the observations from those satellites (Table 1) can presumably cover the entire globe, and allow for the monitoring of any place on the Earth with such a high frequency. For example, the Copernicus Global Land Service (<https://land.copernicus.eu>) now provides LST data for a large portion of the Earth's land surface (Fig. S1 in the Supplementary Material). GeoNEX, a collaborative effort among NASA and agencies/organizations in other countries (e.g., Japan, Korea), is generating Earth monitoring products from the new generation geostationary satellites ⁶⁰.

TIR images with improved spectral, spatial, and temporal resolution can lead to more accurate and more frequent LST retrievals over previous geostationary measurements ⁶¹. For example, the GOES-16 LST had good agreement with in-situ measurements (overall bias of -0.84 K ⁶²), and the Himawari-8 LST was able to estimate LST with a RMSE ≤ 0.9 K ⁶¹. These observations can be used to understand how environmental stresses influence ET and GPP throughout the day. Furthermore, incoming solar radiation, which is a primary driver of photosynthesis, is available from geostationary satellites ⁶³. These geostationary satellite data can lead to high-frequency estimates of ecosystem processes throughout the day.

For example, we estimated hourly GPP over Australia at the hourly time step using the Himawari-8 AHI data and a light use efficiency model⁶⁴ (Fig. 4). The meteorological input data, including solar radiation, air temperature, and VPD, were estimated from AHI visible and thermal bands and ground meteorological data using machine learning techniques. The MODIS Fraction of Absorbed Photosynthetically Active Radiation (FPAR) product⁶⁵ was corrected using the normalized difference vegetation index (NDVI) time series derived from AHI. The comparison of the satellite-derived GPP to tower GPP from four EC flux sites showed consistent magnitude and diurnal patterns of hourly GPP (Figs. S2, S3). The resulting GPP product estimates gross carbon uptake of terrestrial ecosystems in Australia for each hour of the day. Fig. 4 illustrates how GPP varied over space for every two hours of the day and how GPP changed over the course of the day for each location across Northern Territory.

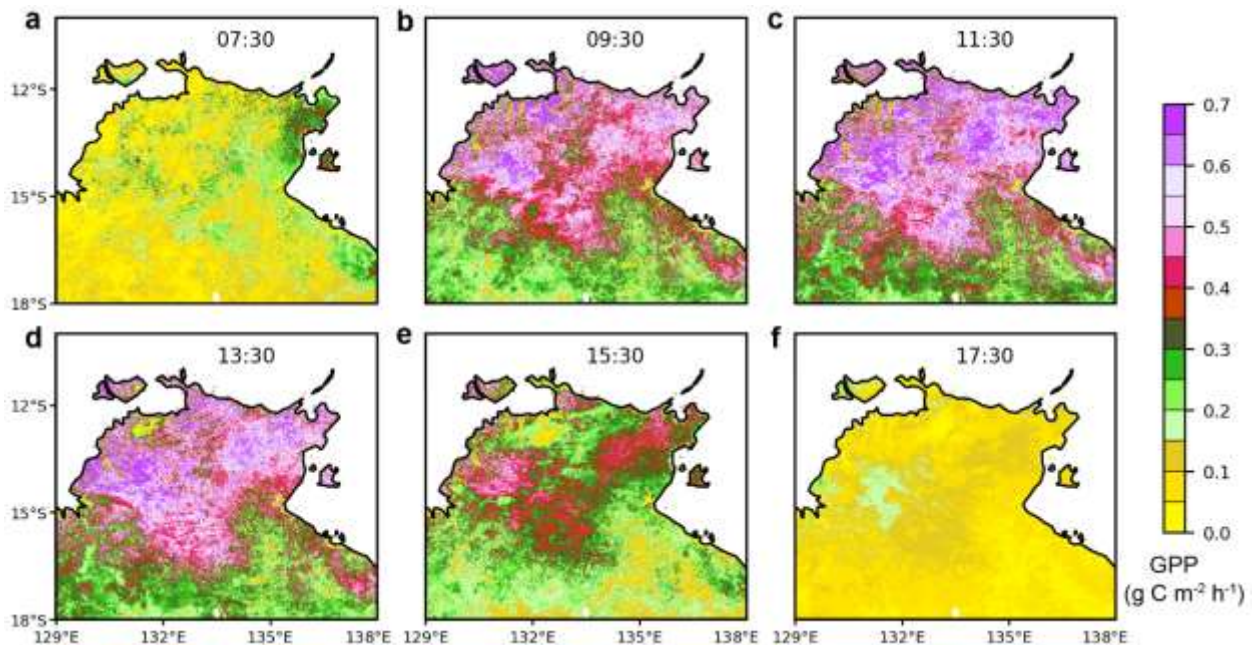


Fig. 4 Diurnal variations of plant photosynthesis (i.e., gross primary productivity, GPP) derived from geostationary satellite data (Himawari-8 AHI) and a light-use efficiency model. (a)-(f) show hourly GPP over Northern Territory, Australia every two hours from 7:30 to 17:30, Australian Central Time (ACT), on

February 1, 2018. The figure indicates that geostationary satellite data can be used to examine diurnal variations of ecosystem functioning.

Future missions

Some future missions also have planned diurnal sampling capabilities for ecosystem science (Table 1). The Geostationary Carbon Cycle Observatory (GeoCarb), a NASA mission with a currently planned launch as early as 2022, will measure CO₂, methane, carbon monoxide, and SIF⁶⁶. GeoCarb will be hosted in geostationary orbit at 85°W, and will measure SIF over North and South America at 5-10 km resolution. GeoCarb will use O₂ and CO₂ channels that are similar to those used for the OCO-2, and will also use the OCO-2 algorithm for SIF retrieval. Whereas other SIF sensors have narrow swaths, GeoCarb can measure every pixel in a scan block in a few hours. In the block scan mode, GeoCarb can measure SIF at the same place only once or twice a day, like a sampler as opposed to a continuous recorder, depending on scan blocks. However, the flexible scan strategy of GeoCarb allows for the measurement of SIF at the target area multiple times a day by the intensive scan mode. NASA will also install the Tropospheric Emissions: Monitoring of Pollution (TEMPO)⁶⁷ instrument on a commercial geostationary satellite in as early as 2022. TEMPO is mainly designed for monitoring air pollution but has the capability to measure SIF in both red and far-red wavelengths. TEMPO will cover North America with hourly frequency. However, the spectral resolution of TEMPO is coarse (0.6 nm), and therefore any SIF retrievals should be considered experimental. The European Space Agency (ESA) also has a planned similar geostationary mission, Sentinel-4, focusing on air pollution monitoring⁶⁸. Sentinel-4 will cover Europe hourly with the Ultra-violet Visible Near-infrared (UVN) imaging spectrometer at 8 km resolution. Compared to OCO-3 that collects measurements globally between ~52°N and ~52°S, these future missions (i.e., GeoCarb, TEMPO, Sentinel-4) will provide SIF observations at the

continental scale. These SIF observations, when combined, will be valuable for capturing the diurnal variations of photosynthesis. With high frequency, TEMPO and Sentinel-4 missions can lead to increased cloud-free SIF retrievals. Although the combined use of the SIF data from these sensors can cover larger spatial domains, these SIF data will be based on different wavelengths and have different quality. In addition, SIF measured by geostationary satellite sensors can have a large range in the view zenith angle, and therefore the effects of view angle on SIF should be considered in analyses.

A small satellite (SmallSat) constellation can also potentially monitor the diurnal variations of vegetation status. SmallSats constellations have been well developed by commercial companies⁶⁹, and some of them can be used for monitoring diurnal variations of ecosystem processes. For instance, Planet operates more than 100 SmallSats. Some of their satellite constellations, on an orbit similar to that of the ISS, can acquire observations for different times of day for each location with multiple optical bands and 0.5 - 3.7 m resolution⁷⁰. Planet's SmallSats can be used to retrieve ET using the same algorithm as ECOSTRESS, as well as a fused Planet-ECOSTRESS retrieval, for example⁷¹. Although these commercial satellite data are not free of charge, they provide increasing opportunities for studying ecosystem processes. A planned NASA SmallSats mission, Time-Resolved Observation of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS)⁷², will consist of 12 CubeSats, and provide high-frequency (21 minutes) observations of temperature profile, humidity profile, and precipitation. TROPICS is not designed to monitor ecosystems but can contribute to the diurnal cycling analyses of ecosystem processes given the high frequency of the observations.

Studies on diurnal cycling of ecosystem functioning will also be able to greatly benefit from new ideas for missions that can integrate the advantages of these existing and forthcoming

platforms. Ideally, such potential missions will be based on geostationary platforms but offer observations of LST with fine resolution equivalent to that of ECOSTRESS and observations of SIF with spatial resolution equivalent to that of OCO-3. While missions such as ECOSTRESS and OCO-3 are likely to continue well past their prime missions (e.g., ECOSTRESS is already an Extended Mission, having recently been approved for continuity in the NASA Senior Review), the shared platform of the ISS will perpetually introduce complex international negotiations over shared resources. So, new missions that can extend these types of measurements are still highly warranted. Still, the science and engineering communities must overcome current engineering limitations, costs, and tradeoffs associated with the high altitude geostationary orbits and the demand for high spatial, temporal, and spectral resolution.

Synergies

Emerging satellite diurnal observations can be synergistically used for new insights into plant functioning and ecosystem processes. ECOSTRESS and OCO-3, which normally would be unlikely pairs on the same mission platform, are now together afforded by the ISS. The combination of the data from these two instruments can allow us to examine plant transpiration and photosynthesis simultaneously and the coupling of these two processes for various types of ecosystems across the globe. Notably, the synergistic combination of OCO-3 SIF and ECOSTRESS ET can also provide a measure of WUE. Therefore, the synergistic use of ECOSTRESS and OCO-3 data can allow us to examine how plants use water and absorb carbon over the course of the diurnal cycle, and when, why, and how carbon and water uptake couple and decouple from one another. Fig. 5 illustrates the variations in SIF, ET, and WUE over a portion of the diurnal cycle at Santa Rita Experimental Range, Arizona (USA) based on ECOSTRESS and OCO-3 data acquired between March 26 – April 15, 2020. Although the coincident diurnal

391 measurements of ECOSTRESS and OCO-3 can directly provide diurnal measures of WUE that
392 likely have lower uncertainty, it should be noted that OCO-3 does not offer wall-to-wall SIF
393 coverage and also has coarse resolution, and that the combination of instantaneous ECOSTRESS
394 ET estimates ²³ with instantaneous ECOSTRESS GPP estimates ²⁹ can lead to wall-to-wall and
395 finer-resolution WUE estimates.

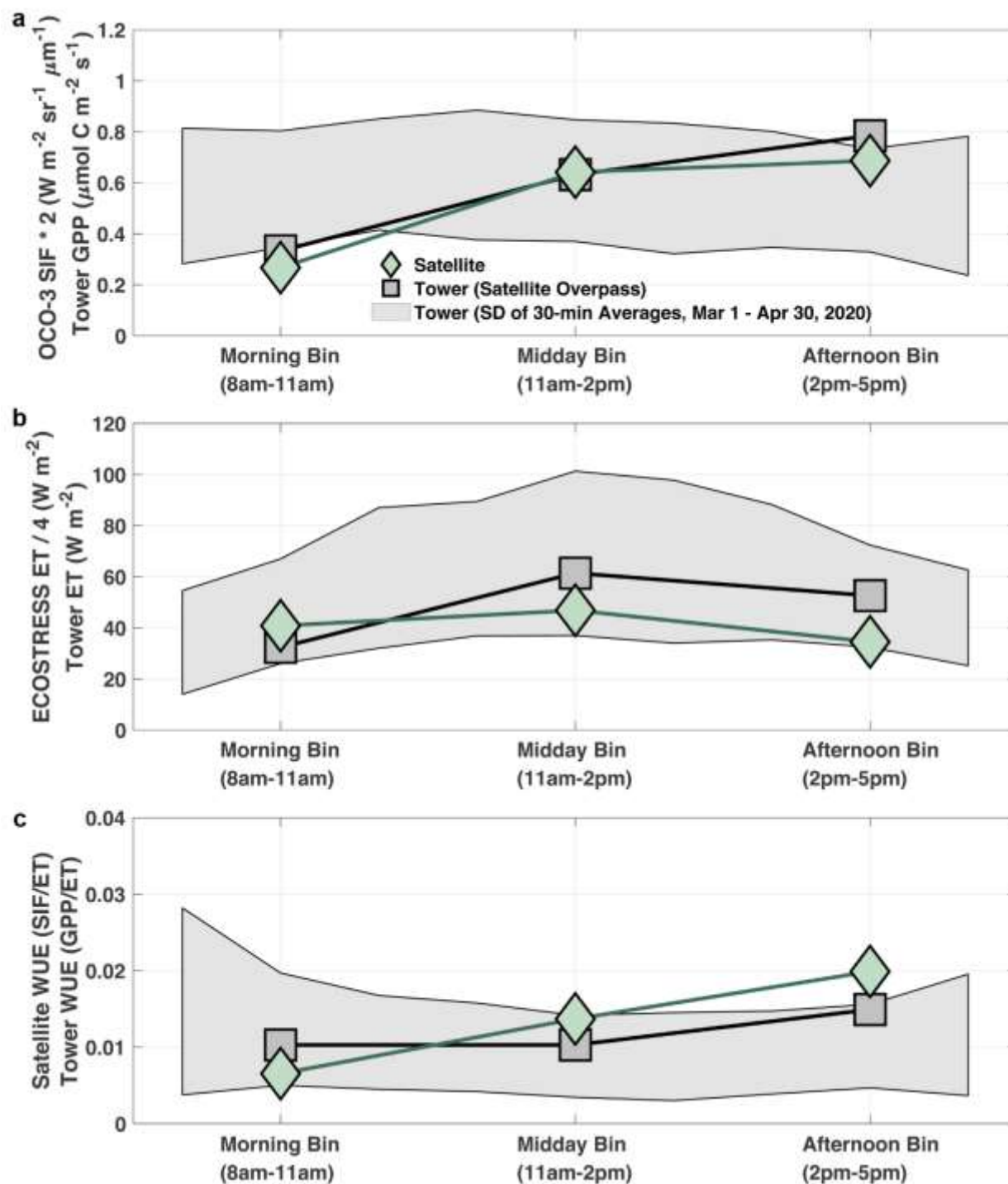


Fig. 5 The synergy between ECOSTRESS and OCO-3 data enables diurnal monitoring of water use efficiency (WUE) of terrestrial ecosystems. The ECOSTRESS ET, OCO-3 SIF (740 nm), and tower data at Santa Rita Experimental Range, Arizona, USA (31.82° E, 110.87° W) illustrate how OCO-3 SIF and

tower GPP (a), ECOSTRESS ET and tower ET (b), and satellite and tower WUE (c) vary over a portion of the diurnal cycle spanning morning, midday, and afternoon hours. Here satellite-derived WUE ($\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1} / \text{W m}^{-2}$) is defined as the ratio of SIF to ET, while tower-based WUE ($\mu\text{mol C m}^{-2} \text{s}^{-1} / \text{W m}^{-2}$) is defined as the ratio of GPP to ET. The data were acquired between March 1 – April 30, 2020. The SIF and ET data were grouped into 3-hour bins (8-11 am, 11 am–2 pm, and 2-5 pm, local time) for the calculation of WUE.

Observations from ECOSTRESS and OCO-3 can also be synergistically used with data from geostationary satellites. ECOSTRESS and OCO-3 provide broader global-scale spatial coverage than any geostationary satellite, and therefore consistent studies of this scale are more straightforward from a single ISS platform than piecing together multiple satellites from different geostationary platforms. Despite the diurnal sampling capability, ECOSTRESS and OCO-3 provides only one or few (or no) observations for each location during a given day, and therefore capturing a large portion of the diurnal cycle will require ISS overpasses over a relatively long period (e.g., weeks). Over such a period of time, the variations in instantaneous LST, ET, or SIF are caused by not only diurnal variations in meteorological conditions and water/heat stress but also the day-to-day variations in these factors, vegetation structure (e.g., leaf area index or LAI), and/or phenology, which can complicate diurnal cycle analyses to a certain extent. Compared to these instruments, new-generation geostationary satellites (e.g., Himawari-8, the GOES-R series) provide continuous observations throughout the day. On the other hand, ECOSTRESS has much finer spatial resolution (70 m) than geostationary satellites (e.g., 2 km) and allows the identification of ecosystem patches or individual fields of croplands. The observations from these instruments can be synergistically used to study the diurnal variations of ecosystem processes by taking advantage of the temporally continuous nature of the geostationary satellite observations

throughout the day and the much finer spatial resolution of the ECOSTRESS data. With data fusion techniques e.g., ⁷³, the observations from these satellites/instruments can also potentially be merged to generate new data that are temporally continuous over the course of the day and also have fine spatial resolution.

As an illustration, the combined use of the data based on Himawari-8 AHI, ECOSTRESS, and OCO-3 allowed us to examine how plant photosynthesis and transpiration changed over the course of the day in response to heat and/or water stress in southern Australia (2018-2019 and 2019-2020) (Fig. 6). The AHI LST data covers the entire region (Fig. 6a) and beyond (Australia and eastern Asia). Compared with AHI, ECOSTRESS acquired a limited number of observations but offered much more spatial detail (Fig. 6b, c). The instantaneous ET estimates based on ECOSTRESS showed that with heat and water stress, grasslands and croplands (light green and brown areas) exhibited much lower ET in the early afternoon than in the early morning (~9 am); forests (bright green areas), with much higher elevation and deeper roots, had only slightly higher ET in the early afternoon than in the early morning (Fig. 6d, e). Meanwhile, SIF data from OCO-3 revealed differences in photosynthesis among different times of day and indicated that plants (in the area highlighted by the ellipse) had high photosynthesis in the early morning but had low values around 4:30 pm (Fig. 6f, g). Compared with the ISS instruments, AHI provides high-frequency observations throughout the day and makes it feasible to examine the full diurnal cycles of LST and GPP (Fig. 6h, i). The LST on the heatwave day exceeded 40 °C from ~9 am to ~6 pm and 60 °C from ~11 am to ~4 pm, and the stomatal closure due to water and heat stresses led to a substantial decline in transpiration and a large increase in canopy temperature (Fig. 6h). The hourly GPP based on AHI and the in-situ GPP based on an EC flux site showed large and rapid declines from late morning to the middle afternoon with the onset of heat stress over a four-day period

(December 22-26, 2018) and exhibited mid-day depression (Fig. 6i). The AHI GPP captured the diurnal variations in EC GPP for both normal ($R^2=0.93$, $p<0.0001$) and heatwave ($R^2=0.60$, $p<0.0001$) days. This example indicates that we can explore diurnal cycling of ecosystem processes from space using these unique datasets together.

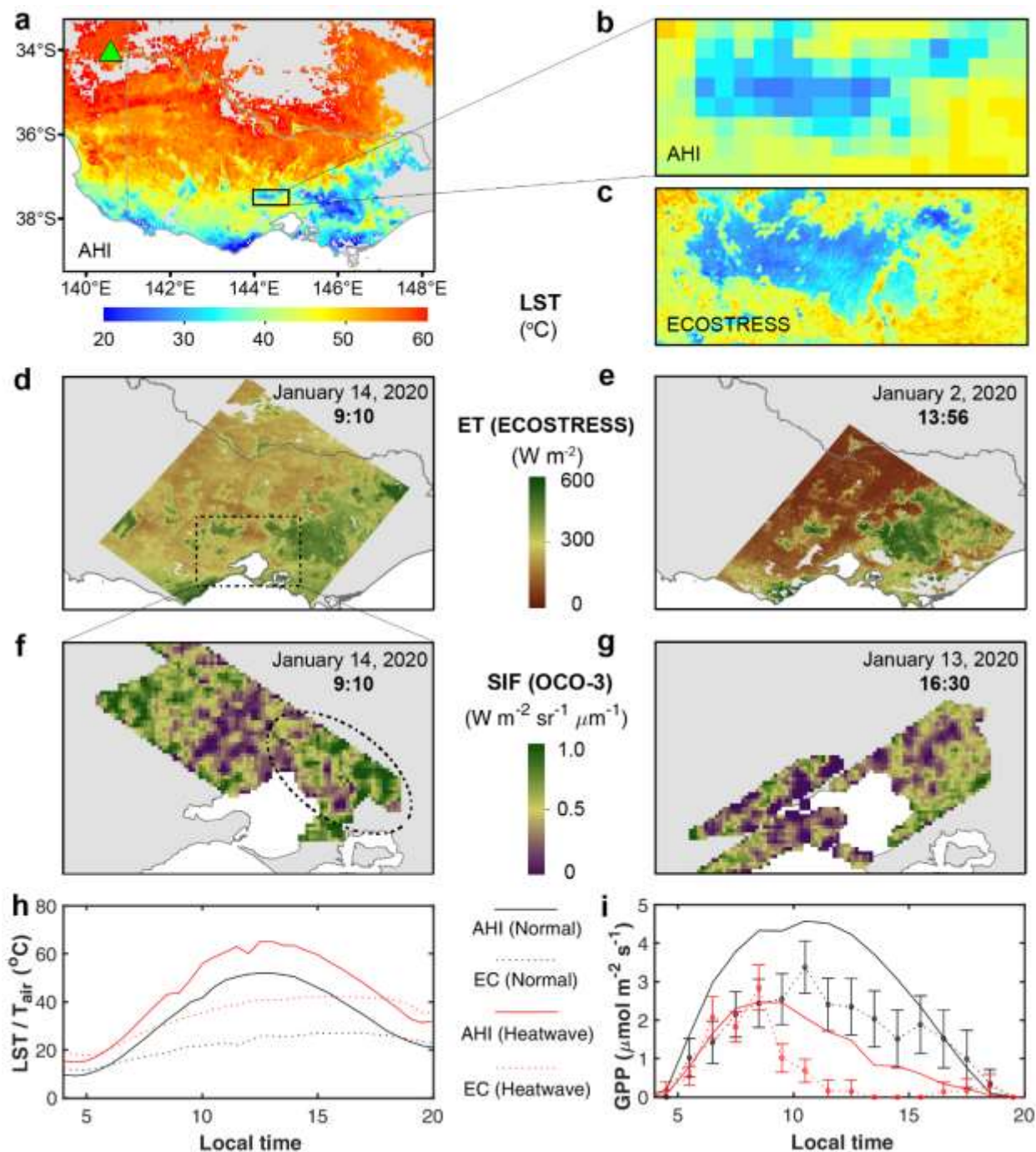


Fig. 6 Synergistic use of observations from a geostationary satellite instrument (Himawari-8 AHI) and two instruments from the International Space Station (ECOSTRESS and OCO-3) for studying diurnal cycling of ecosystem processes during heatwaves over Australia's summers (2018 and 2020). (a) shows AHI LST at 13:30, January 2, 2020 for southern Australia and the location of the eddy covariance (EC) flux site (Calperum Chowilla, location indicated by the green symbol in a), while (b) and (c) show the coarse-resolution AHI LST and fine-resolution ECOSTRESS LST (13:55, January 2, 2020) for the small area as highlighted by the rectangle in (a). (d) and (e) are instantaneous ECOSTRESS ET for different times of day. (f) and (g) are instantaneous OCO-3 SIF for different times of day, and the highlighted area with an ellipse exhibits relatively high SIF in the early morning but low values in the late afternoon. (h) illustrates diurnal variations in LST (AHI) and air temperature (T_{air}) for a normal day (December 22, 2018) and a heatwave day (December 26, 2018) at the EC site, and (i) shows diurnal variations in AHI-based GPP estimates and flux tower GPP for both the normal and heatwave days at the EC site; the error bars indicate the uncertainty associated with flux partitioning. All times are local time.

The observations from ECOSTRESS, OCO-3, and new generation geostationary satellites also have anticipated synergies with those from the forthcoming missions. For example, the SIF data from OCO-3 and GeoCarb can be directly integrated for ecosystem studies over the Americas. Taken together, the observations from these two missions will cover a 13-18 year period starting from 2019, allowing continued exploration of diurnal photosynthesis at interannual and decadal scales. For example, this will make it possible to examine how the increasing atmospheric CO_2 concentrations influence stomatal behavior and plant photosynthesis. The SIF data from OCO-3, GeoCarb, and TEMPO can also be synergistically used by taking advantage of the higher-quality data from OCO-3 and GeoCarb and high-frequency measurements from TEMPO.

Besides the synergies among these emerging observations, these data can also be used in combination with data from polar-orbiting satellites (e.g., Terra, Aqua, Suomi NPP, JPSS, Landsat,

Sentinel, OCO-2, SmallSats) and in-situ measurements. Polar-orbiting satellites provide observations of vegetation for the globe over multiple decades. These data products (e.g., vegetation indices, LAI) can be used to provide additional essential variables or extend spatial or temporal domains for the diurnal cycle analyses based on the emerging observations with diurnal sampling capability. Moreover, because of the polar orbit, the Terra and Aqua have significant swath overlap at the high latitudes (e.g., the Arctic), and the resulting larger number of observations can potentially be used for diurnal cycling studies.

In-situ measurements have been traditionally used to study diurnal cycling of ecological and physiological processes. For example, previous studies used leaf-level measurements to understand the responses of stomata, leaf photosynthesis, and transpiration to soil water content, leaf water potential, and VPD^{5, 33} and midday depression of photosynthesis⁷⁴. Ground measurement networks for water, carbon, and energy fluxes such as FLUXNET¹⁷ and the National Ecological Observatory Network (NEON)⁷⁵ provide continuous half-hourly measurements and ancillary ecological and environmental data. These data have been used to examine the diurnal cycling of ecological and physiological processes, such as the influences of heat and water stresses on canopy conductance, ET, GPP, and WUE¹⁶, physiological responses of carbon-water coupling to hydraulic and non-stomatal limitations¹⁵, and hysteresis patterns of ET and GPP⁵¹. The emerging satellite observations for diurnal cycling of ecosystem processes make it feasible to explore these ecophysiological processes and phenomena at expanded spatial scales (e.g., ecosystems, regions, the globe) from space. Ecophysiological understanding based on in-situ measurements will inform and facilitate the exploration of plant water stress and carbon uptake at the regional to global scales using the measurements from space. Data from ECOSTRESS, OCO-

3, and the new generation geostationary satellites can be directly linked with half-hourly or hourly flux data to quantify GPP, ET, and/or WUE over regions or the globe for different times of day.

Conclusions

Diurnal cycling of ecosystem processes is of significant scientific importance for understanding plant water use and carbon uptake in response to water and heat stress, changing climate, rising atmospheric CO₂, and management practices. We envision that the emerging satellite observations outlined in this article will trigger numerous research efforts aimed at understanding how plant carbon uptake and water use vary over the course of the diurnal cycle from ecosystem to the globe. Data from ECOSTRESS, OCO-3, geostationary satellites, and future missions with diurnal sampling capability (e.g., GeoCarb, TEMPO, Sentinel-4) are anticipated to be used both individually and synergistically. These observations will likely revolutionize studies of ecosystem processes and carbon and water cycling to a certain extent. The resulting analyses can help us better understand the resilience and vulnerability of different ecosystem types to drought and heat waves. For croplands, these data can reveal how plant water use varies throughout the day and how irrigation influences ET, water stress, and photosynthesis, and the findings can inform agricultural management (e.g., irrigation strategies). The instantaneous estimates of ecosystem processes at regional to global scales over the course of the diurnal cycle will be useful for calibrating and validating Earth system models. Better understanding how ecosystem processes respond to water and heat stress, changing climate, and rising atmospheric CO₂ with the emerging satellite observations can also guide the improvement of Earth system models and projections of carbon/water dynamics and carbon-climate feedbacks.

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811 **Authors contributions**

812 J.X. conceived the idea. J.X., J.B.F., H.H., K.I., and N.C.P. designed the research, conducted the
813 analyses, interpreted the data, and wrote the paper.

814

815 **Competing interests**

816 The authors declare no competing interests.

817

818 **Data availability statement**

819 The data that support the findings of this study are available from <https://earthdata.nasa.gov>
820 (ECOSTRESS), <https://lpdaacsvc.cr.usgs.gov/appears/> (ECOSTRESS),
821 <https://ocov3.jpl.nasa.gov/oco-3-data-center/> (OCO-3), <http://data.ozflux.org.au> (flux tower data),
822 <https://data.nas.nasa.gov/geonex/> (Himawari-8), [ftp://hmwr829gr.cr.chiba-](ftp://hmwr829gr.cr.chiba-u.ac.jp/gridded/FD/V20151105/)
823 <u.ac.jp/gridded/FD/V20151105/> (Himawari-8), and <https://land.copernicus.eu/global/products/>
824 (global geostationary satellite LST data).