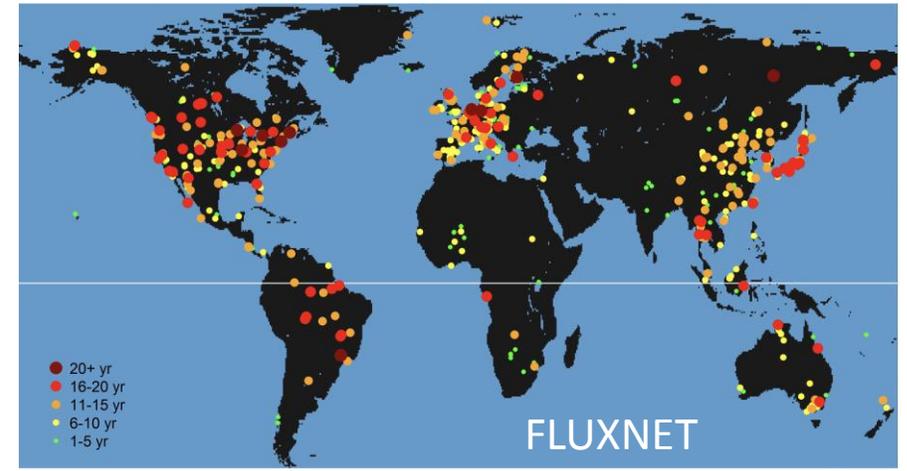


# Understanding Diurnal Cycles of Plant Water Use and Carbon Uptake with Existing and New Products Based on ECOSTRESS, MODIS, and FLUXNET



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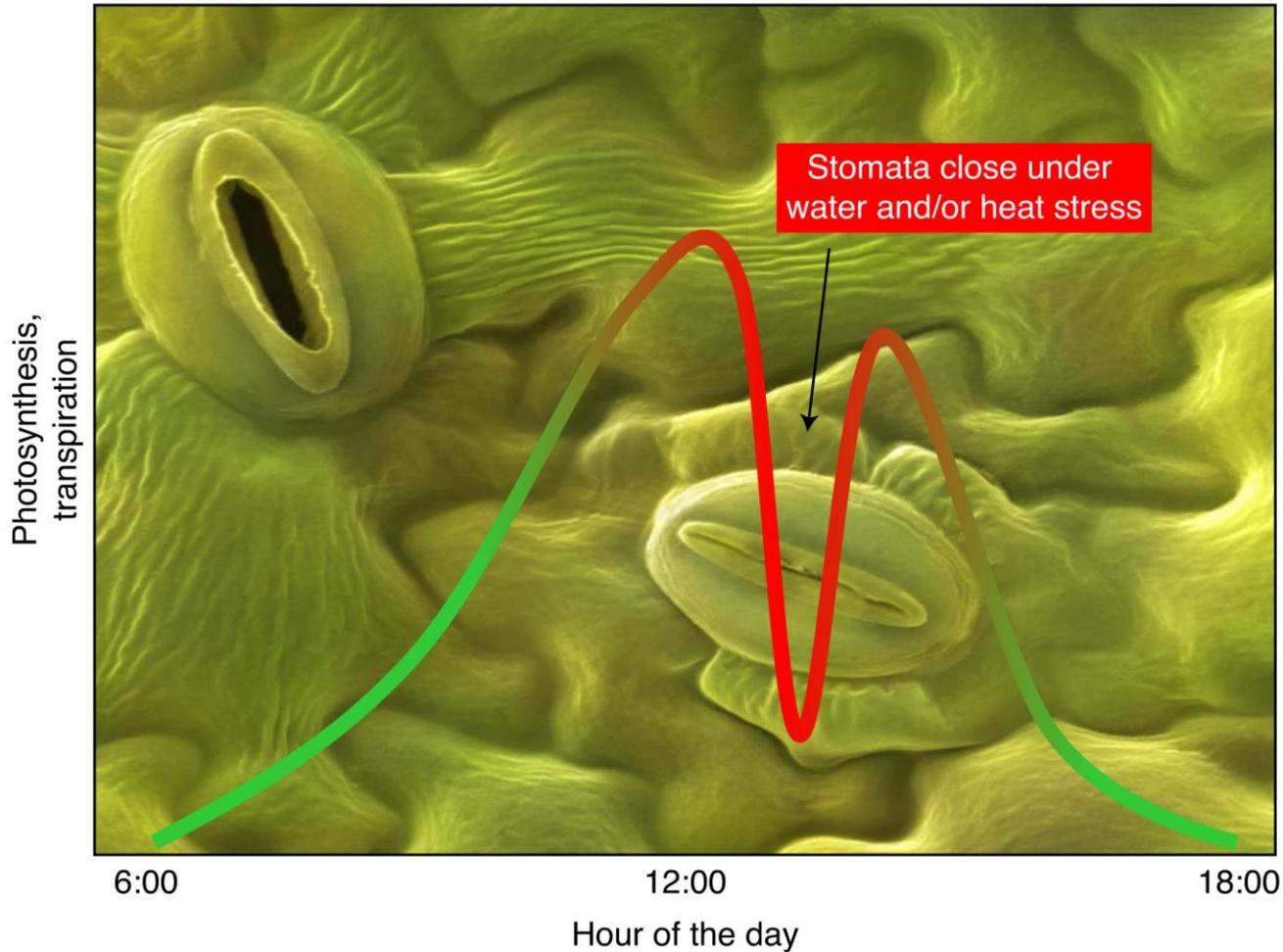
*ECOSTRESS Interim Science and Applications Team Meeting, August 17-19, 2021*



# Emerging satellite observations for diurnal cycling of ecosystem processes

Jingfeng Xiao <sup>1</sup> , Joshua B. Fisher<sup>2</sup>, Hirofumi Hashimoto <sup>3,4</sup>, Kazuhito Ichii<sup>5</sup> and Nicholas C. Parazoo<sup>2</sup>

Diurnal cycling of plant carbon uptake and water use, and their responses to water and heat stresses, provide direct insight into 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, photosynthesis and transpiration. Earth observations from polar-orbiting satellites are incapable of studying these diurnal variations. Here, 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, evapotranspiration (ET), gross primary production (GPP) and solar-induced chlorophyll fluorescence 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 land surface temperature, solar radiation, GPP and ET. Future satellite missions such as GeoCarb, TEMPO and Sentinel-4 are also planned to have diurnal sampling capability of solar-induced chlorophyll fluorescence. We explore the unprecedented opportunities for characterizing and understanding how GPP, ET and water use efficiency 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 improvements in Earth system models and climate projections.



- Drought and heatwaves are projected to be more frequent
- Observations at multiple times of the day are essential for understanding the diurnal cycles of plant water use and carbon uptake.

**Fig. 1 | Conceptual diagram of plant photosynthesis and transpiration over the course of a day.** Both transpiration and photosynthesis may show

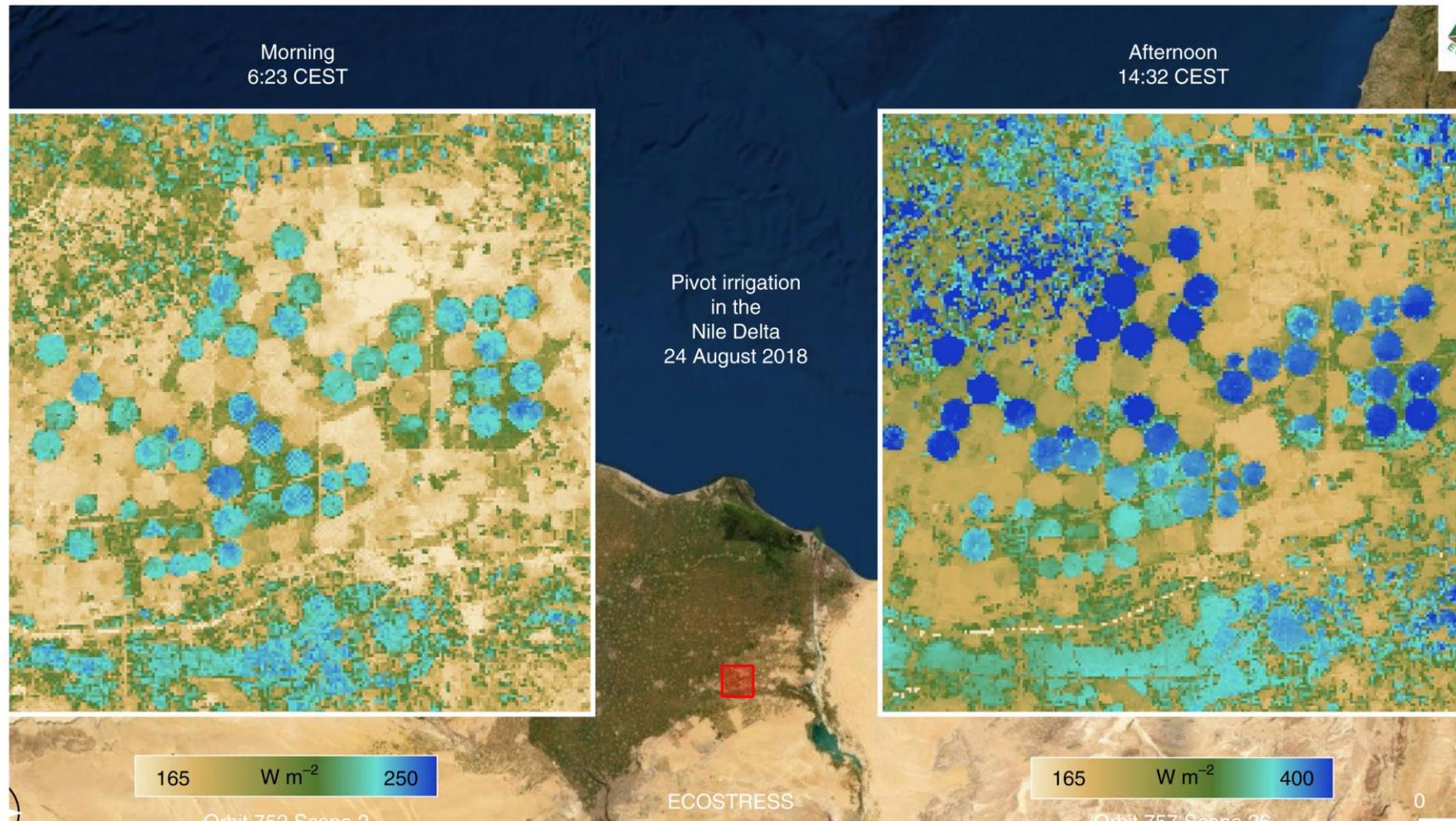
Xiao, Fisher, Hashimoto, Ichii, Parazoo, NP, 2021

# Emerging satellite observations for diurnal cycling of ecosystem processes

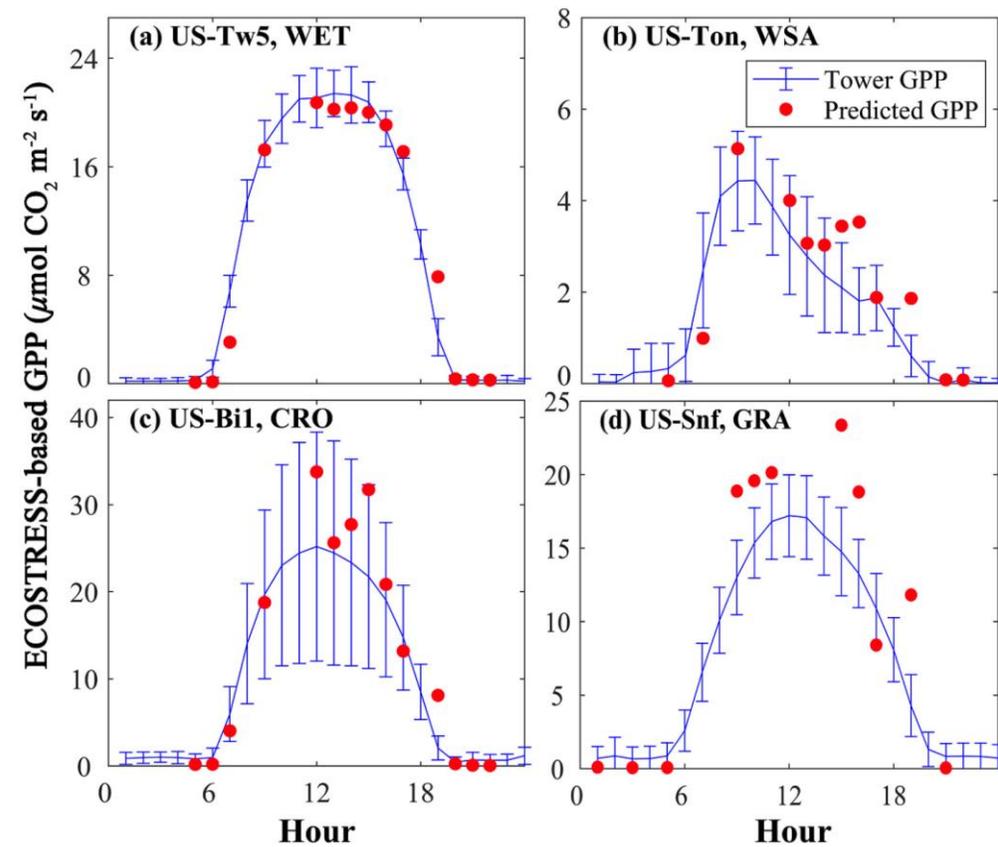
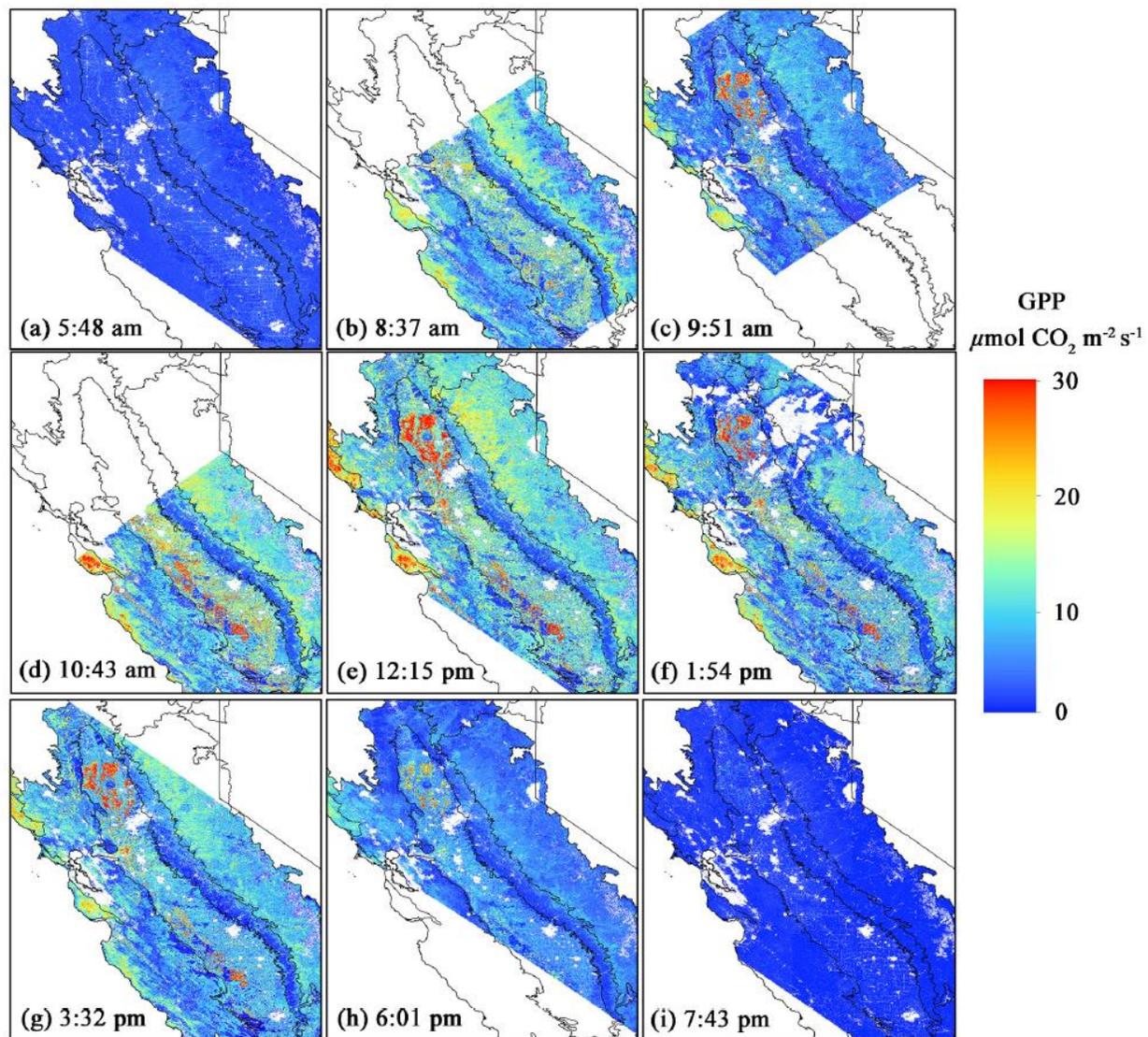
**Table 1 | Specifications of the instruments/platforms that have diurnal sampling capability in studying plant functioning and ecosystem processes**

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

<sup>a</sup>Himawari-8: 10 min for full disk and 2.5 min for Japan. <sup>b</sup>GOES-16 and GOES-17: 10 min for full disk (with 15 min for full disk before April 2019), 5 min for the conterminous United States and 30 or 60 s at the mesoscale. <sup>c</sup>MTG: 10 min for full disk (Europe and Africa) and 2.5 min for Europe. <sup>d</sup>TBD, to be determined. Both GeoCarb and TEMPO will be deployed on commercial geostationary satellites. NIR, near infrared; SWIR, shortwave infrared.



**Fig. 2 | ECOSTRESS images from the Nile Delta within the same day.** NASA's ECOSTRESS captured changes in ET from agricultural fields of the Nile Delta, Egypt, from the ISS in the morning and afternoon on 24 August 2018. The image on the left is from 6:23 central European summer time (CEST) and the image on the right is from 14:32 CEST. There are larger differences in ET between the agricultural fields in the afternoon than in the morning. Some fields show much more ET while some fields are drying out in the afternoon. The geographical coordinates of the centre of the ECOSTRESS images Orbit 752, Scene 2 (left) and Orbit 757, Scene 26 (right) are 30.54°N and 31.85°E, respectively. The scale bar applies to the background map; the pixel size of the inset maps is 70 m.



Li, Xiao, et al., RSE, 2021

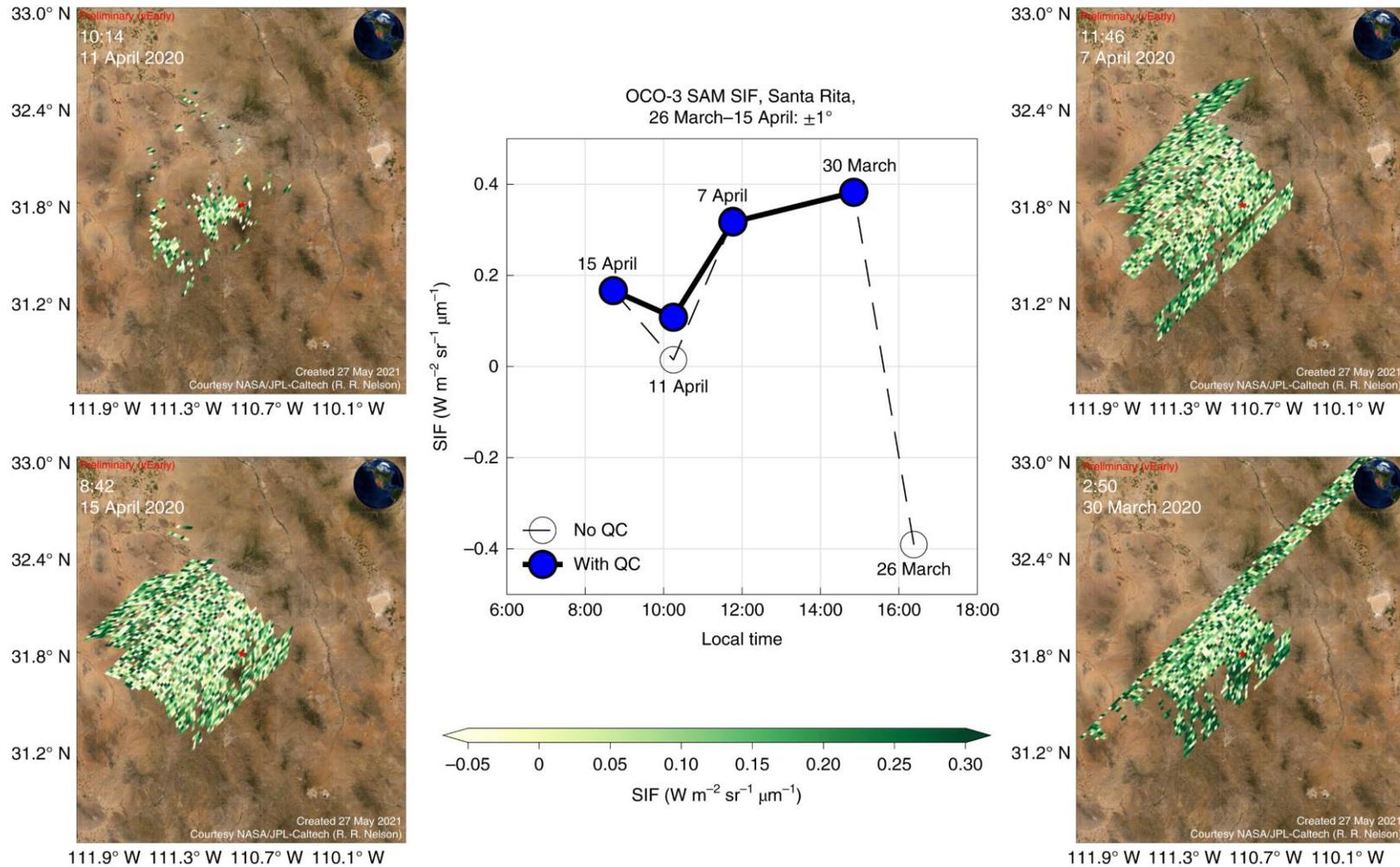
Fig. 5. Magnitude and spatial patterns of predicted ECOSTRESS GPP at different times of day in summer 2019 across the Central Foothills and Coastal Mountains, Central Valley, Sierra Nevada and Coast Range in California.

# Orbiting Carbon Observatory-3 (OCO-3)

- Launched in May 2019
- Solar-induced fluorescence (SIF)
- Different times of day
- Between  $\sim 52^{\circ}\text{N}$  and  $\sim 52^{\circ}\text{S}$
- 1-2 km footprints
- Also has a Snapshot Area Mode (SAM)



<https://www.jpl.nasa.gov>

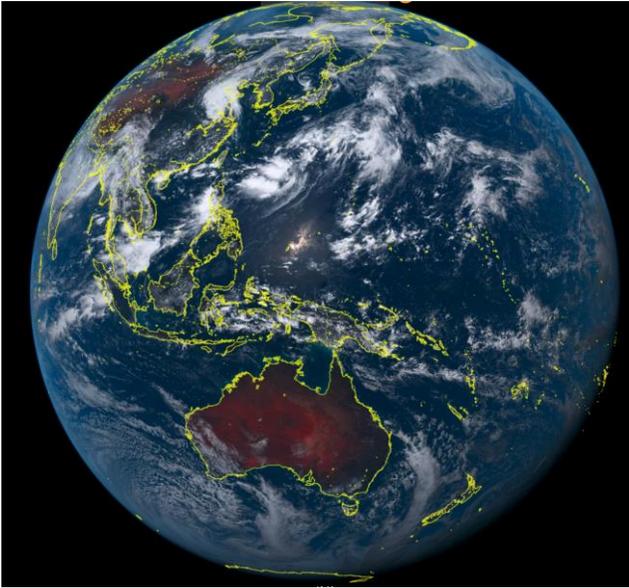


**Fig. 3 | SIF at different times of the day as measured by the OCO-3 in SAM mode.** The SIF data, a proxy of plant photosynthesis, were acquired surrounding the Santa Rita Experimental Range, Arizona. The four maps show the spatial patterns of SIF at the landscape scale for different times of day in March and April 2020. The centre plot illustrates the diurnal variations of SIF spatially averaged within the  $0.1 \times 0.1^\circ$  area surrounding the Santa Rita Experimental Range research site; the blue and white symbols indicate the uses of data with quality control (QC; solar zenith angle of  $<70^\circ$ , view zenith angle of  $<40^\circ$  and cloud fraction of  $<0.1$ ) and no QC, respectively.

# 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.
- Geostationary satellites carry sensors with high-frequency observation capability (10 to 15 minutes in full scan mode).
- New generation geostationary satellites offer observations with 0.5 – 2 km resolution
- With high temporal frequency and spectral features, these satellites are expected to improve diurnal monitoring of ecosystem processes

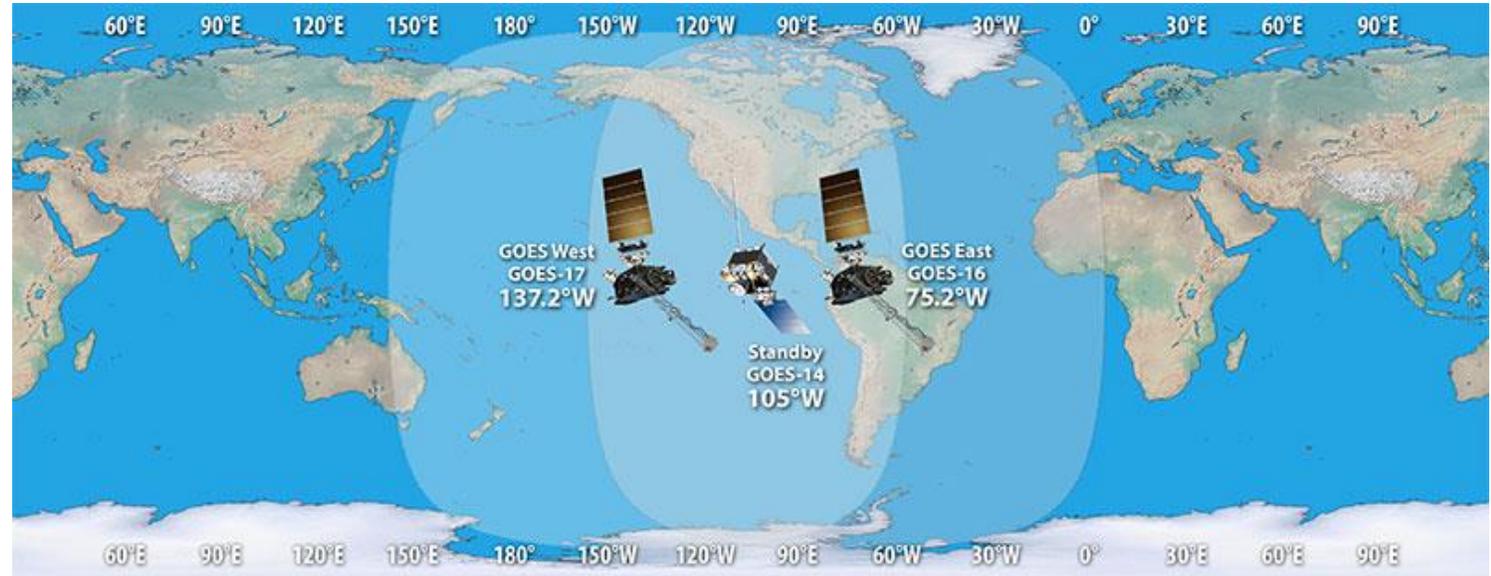
# Himawari-8



<https://himawari8.nict.go.jp>

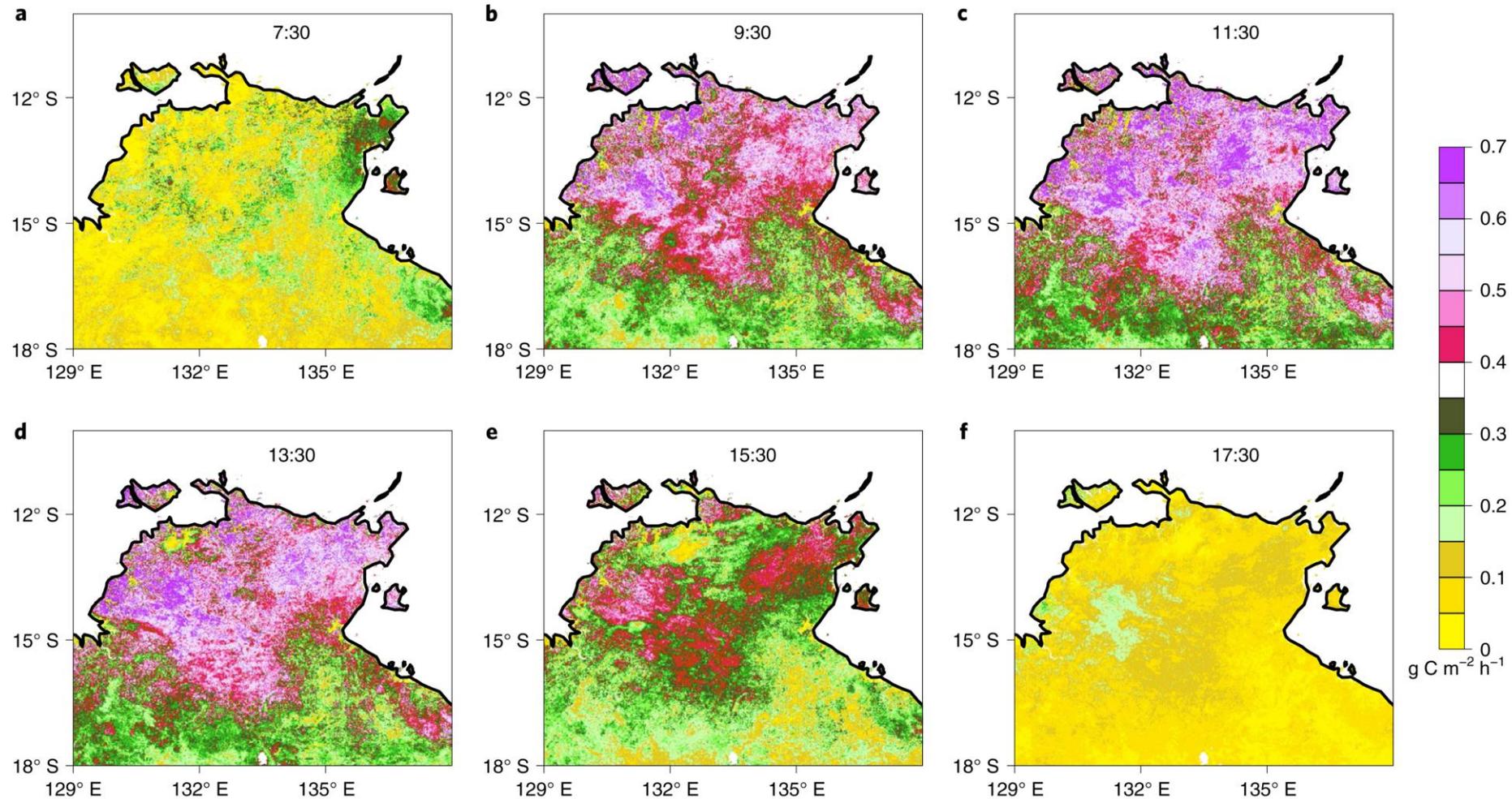
- Launched in 2014
- Advanced Himawari Imager (AHI)
- 0.5-2 km resolution
- 10 min repeat cycle

# GOES-R Series



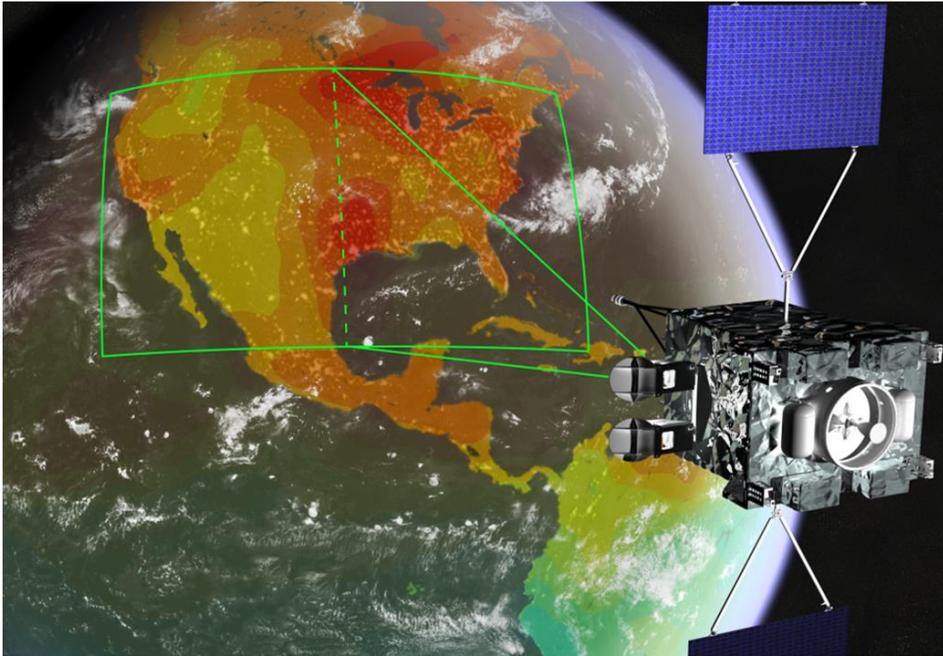
<https://www.goes-r.gov/mission/mission.html>

- GOES-16 (2016) & GOES-17 (2018)
- Advanced Baseline Imager (ABI)
- 0.5-2 km resolution
- 10 m repeat cycle



**Fig. 4 | Diurnal variations in plant photosynthesis derived from geostationary satellite data and a light-use efficiency model. a-f**, The Himawari-8 AHI captured hourly variations in plant photosynthesis (that is, GPP) over the Northern Territory, Australia, every 2 h from 7:30 to 17:30 (Australian central time) on 1 February 2018. The figure indicates that geostationary satellite data can be used to examine diurnal variations of ecosystem functioning.

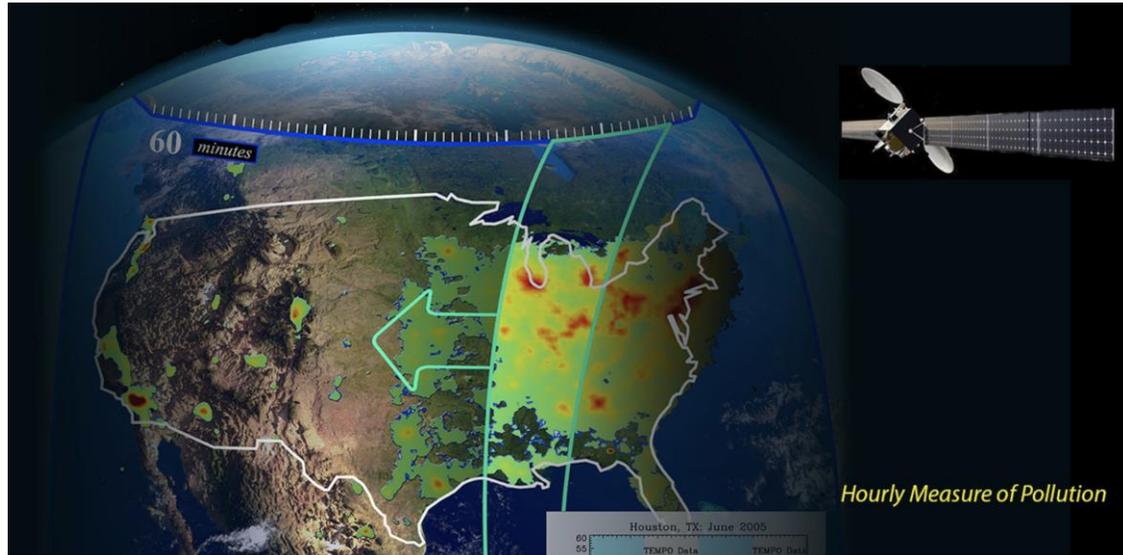
# Geostationary Carbon Cycle Observatory (GeoCarb)



Source: NASA

- A NASA mission as early as 2022
- Measure CO<sub>2</sub>, methane, carbon monoxide, and SIF
- Geostationary orbit
- Measure SIF over North and South America
- 5-10 km resolution

# Tropospheric Emissions: Monitoring of Pollution (TEMPO)

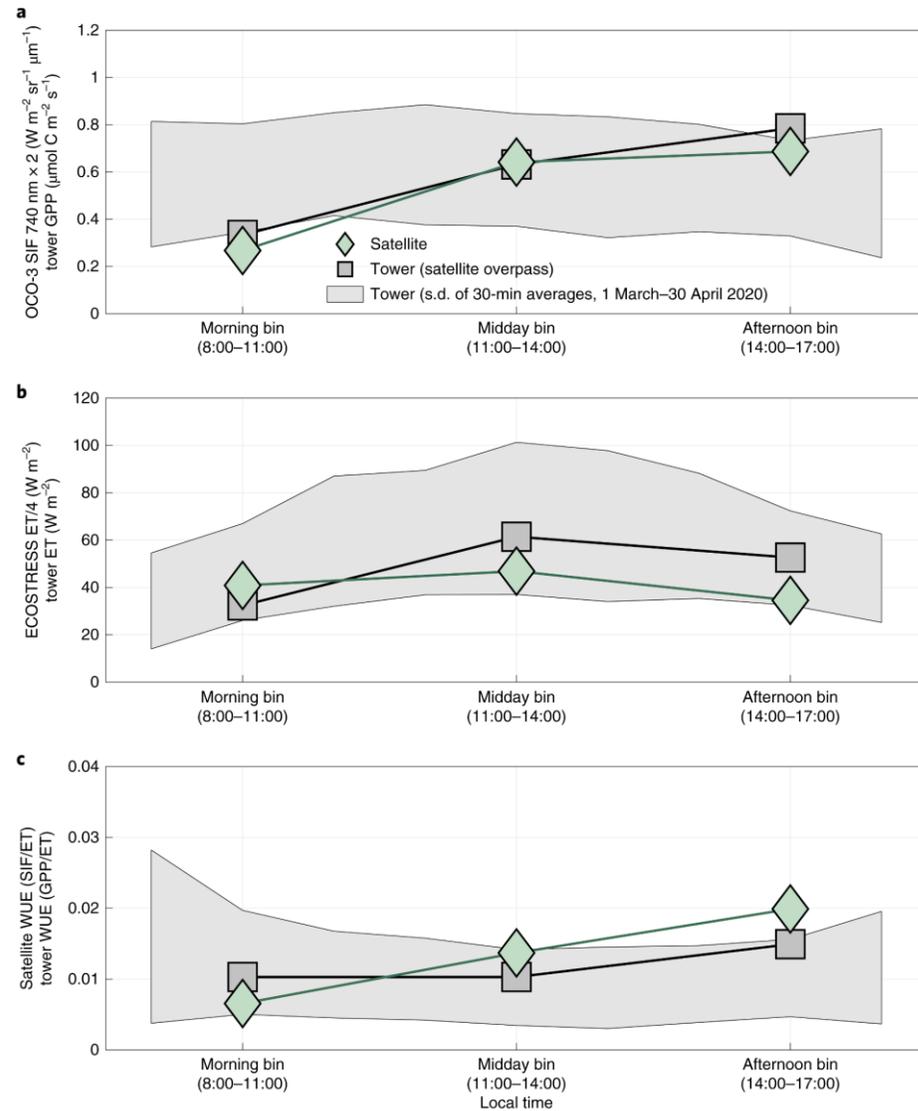


<http://tempo.si.edu>

- Another NASA mission as early as 2022
- Geostationary orbit
- Mainly designed for monitoring air pollution
- Measure SIF in red and far-red wavelengths
- North America with hourly frequency
- Spectral resolution is coarse (0.6 nm)

# Synergies

- Combination of ECOSTRESS and OCO-3 data can allow us to examine plant transpiration and photosynthesis simultaneously and their coupling.
- Synergistic combination of OCO-3 SIF and ECOSTRESS ET can provide a measure of WUE.
- Observations from ECOSTRESS and OCO-3 can also be synergistically used with data from geostationary satellites.
- ECOSTRESS, OCO-3, and geostationary satellite data also have anticipated synergies with those from the forthcoming missions.
- These data can also be used in combination with data from polar-orbiting satellites and in-situ measurements.



OCO-3 SIF  
Tower GPP

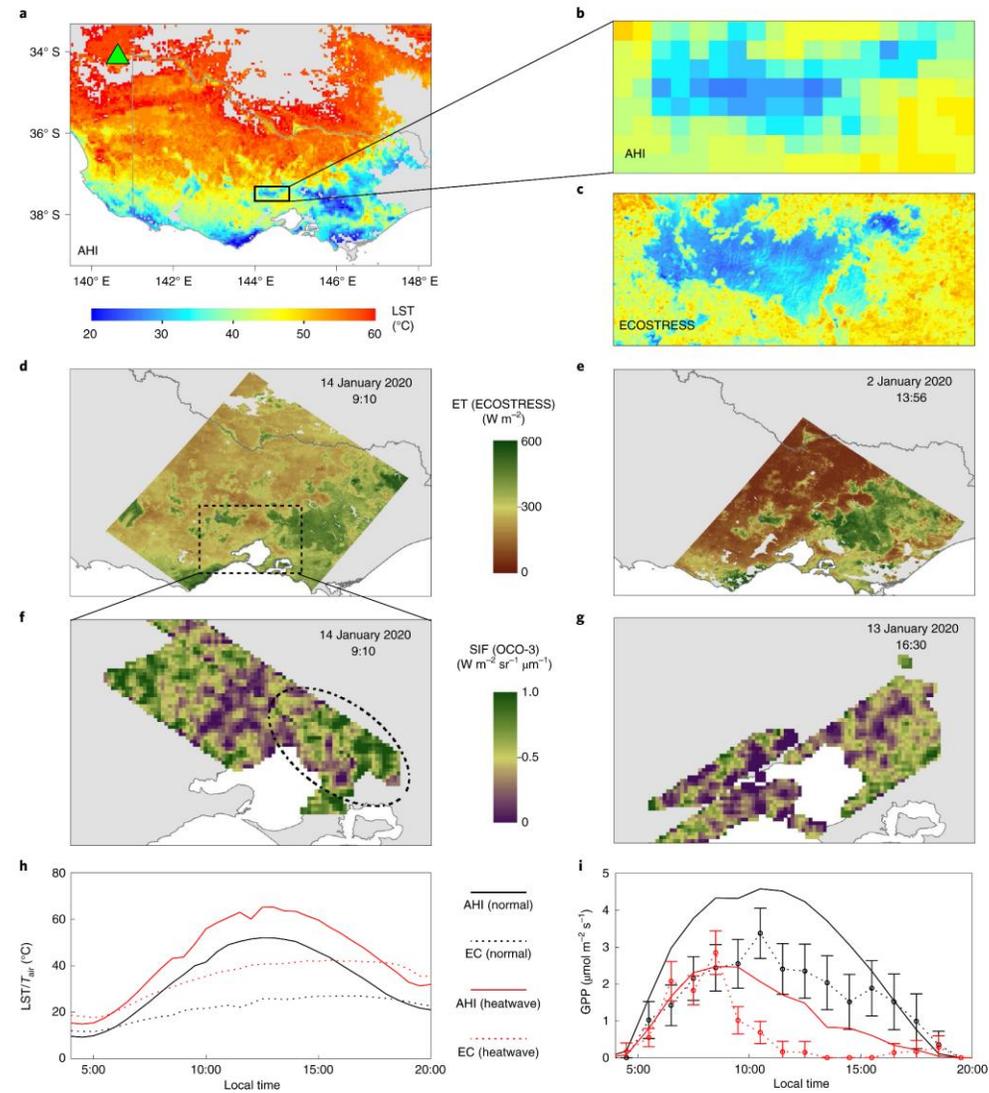
ECOSTRESS ET  
Tower ET

OCO-3/ECOSTRESS WUE: SIF/ET  
Tower WUE: GPP/ET

**Fig. 5 | The synergy between ECOSTRESS and OCO-3 data enables diurnal monitoring of WUE of terrestrial ecosystems. a-c.** The ECOSTRESS ET, OCO-3 SIF (740 nm) and tower data at the Santa Rita Experimental Range, Arizona (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 ( $W m^{-2} sr^{-1} \mu m^{-1} / W m^{-2}$ ) is defined as the ratio of SIF to ET, while tower-based WUE ( $\mu mol C m^{-2} s^{-1} / W m^{-2}$ ) is defined as the ratio of GPP to ET. The data were acquired between 1 March and 30 April 2020. The SIF and ET data were grouped into 3-h bins (8:00–11:00, 11:00–14:00 and 14:00–17:00, local time) for the calculation of WUE.

# Synergies

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- ECOSTRESS, OCO-3, and geostationary satellite data also have anticipated synergies with those from the forthcoming missions.
- These data can also be used in combination with data from polar-orbiting satellites and in-situ measurements.



**Fig. 6 | Synergistic use of observations from a geostationary satellite and two ISS instruments for studying diurnal cycling of ecosystem processes.** Two heatwaves in Australia (2018 and 2020) were studied. **a**, Himawari-8 AHI LST at 13:30 on 2 January 2020 for southern Australia and the location of the EC flux site (Calperum Chowilla, location indicated by the green triangle). **b, c**, The coarse-resolution AHI LST (**b**) and fine-resolution (**c**) ECOSTRESS LST (13:55 on 2 January 2020) for the small area highlighted by the rectangle in **a**. **d, e**, Instantaneous ECOSTRESS ET for different times of the day. **f, g**, Instantaneous OCO-3 SIF for different times of the day. The highlighted area with an ellipse exhibits relatively high SIF in the early morning but low values in the late afternoon. **h**, Diurnal variations in LST (AHI) and air temperature ( $T_{air}$ ) for a normal day (22 December 2018) and a heatwave day (26 December 2018) at the EC site. **i**, 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.

# Summary

- We envision that the emerging satellite observations will trigger numerous research efforts aimed at understanding how plant carbon uptake and water use vary over the course of the diurnal cycle.
- Data from ECOSTRESS, OCO-3, geostationary satellites, and future missions with diurnal sampling capability are anticipated to be used both individually and synergistically.
- These observations will likely revolutionize the study of plant functioning and ecosystem processes to a certain extent.



## New missions?

- Studies of 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 GEO platforms but will offer LST observations with fine resolutions equivalent to that of ECOSTRESS and observations of SIF with resolutions equivalent to that of OCO-3.
- Still, the science and engineering communities must overcome current engineering limitations, costs and trade-offs associated with the high-altitude geostationary orbits and the demand for high spatial, temporal and spectral resolution.

## Ongoing and future work

- Assess diurnal variations of ecosystem WUE and responses to environmental factors for different vegetation types with ECOSTRESS and in-situ data
- Explore the possibility of including another instantaneous GPP dataset into the ECOSTRESS WUE product