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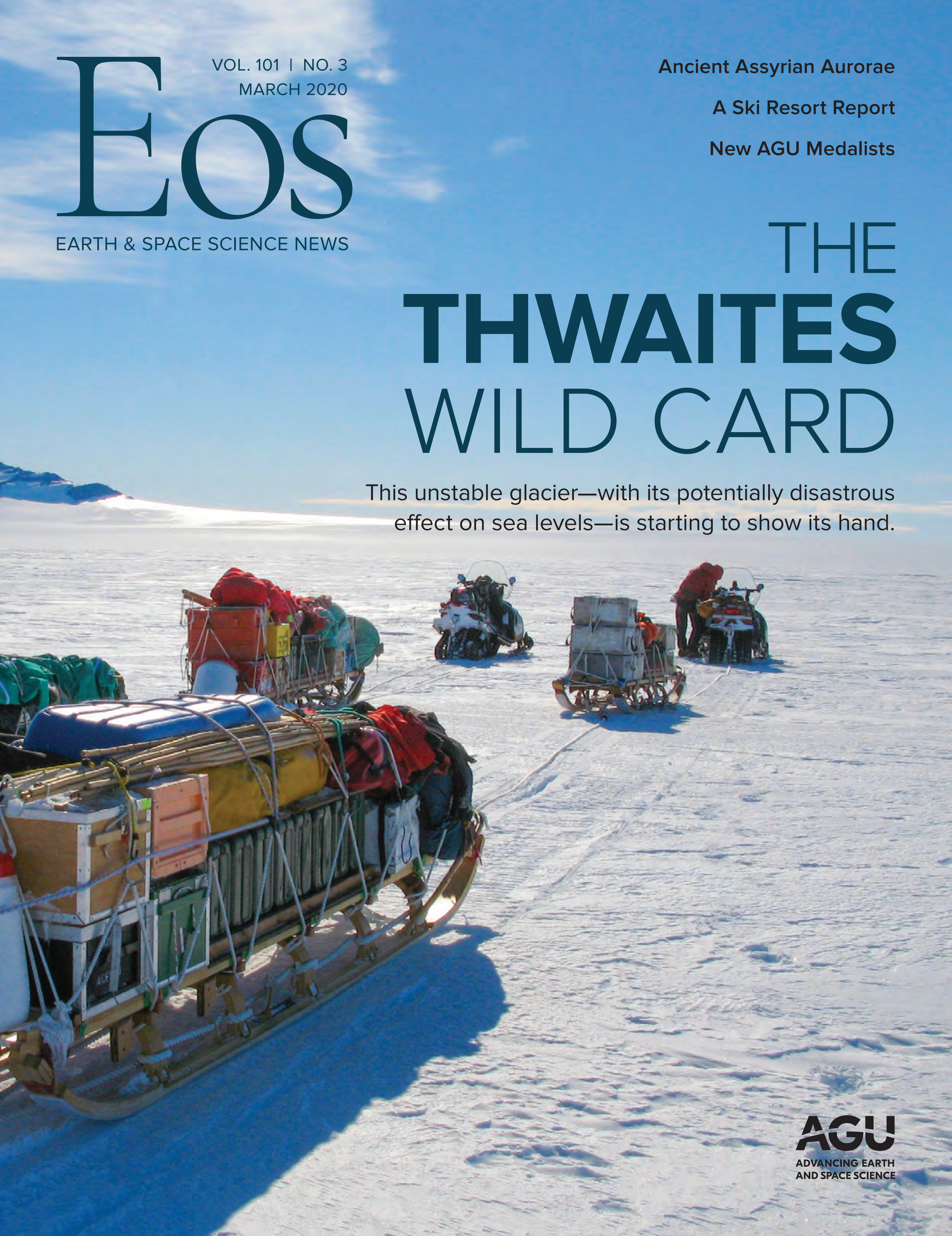

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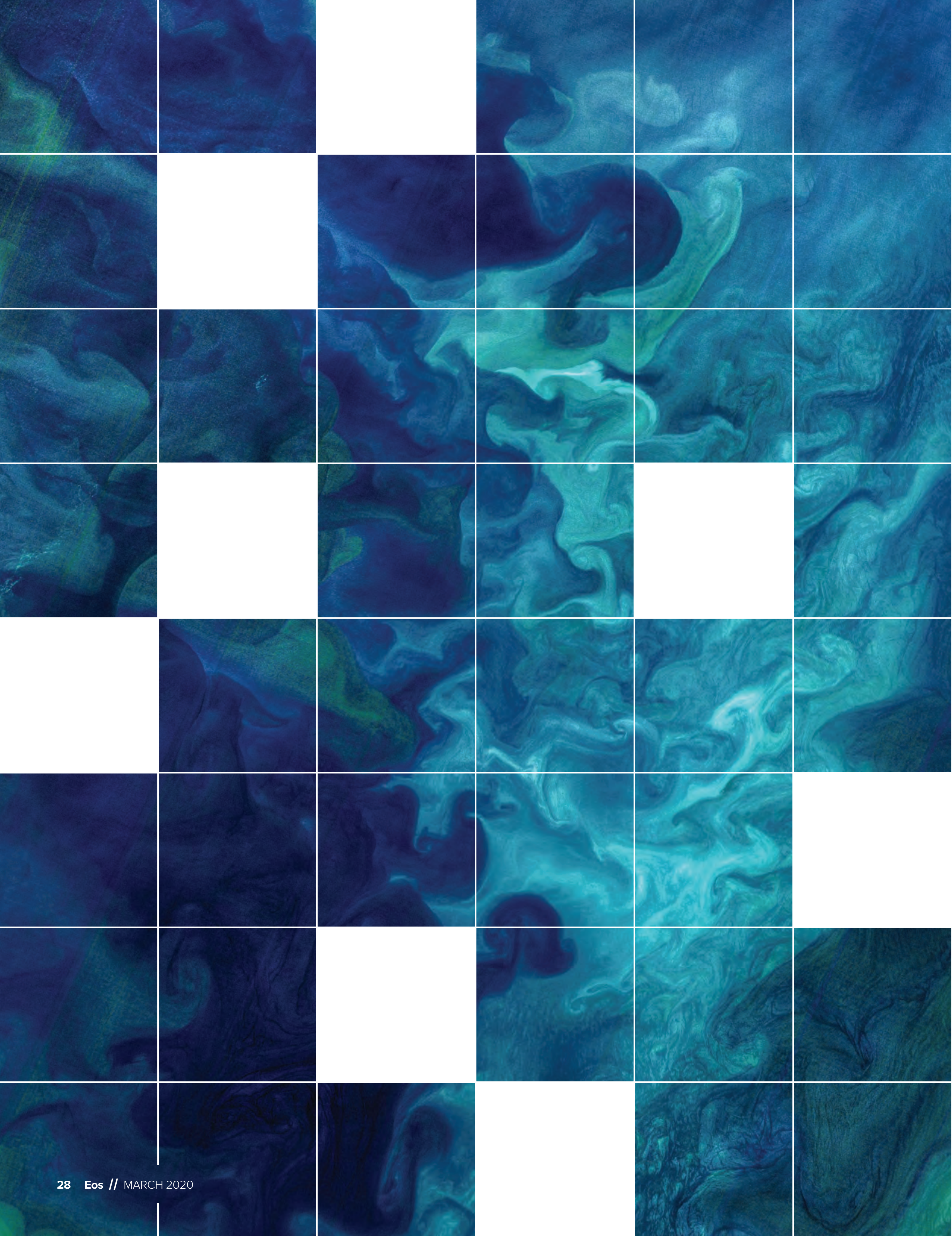
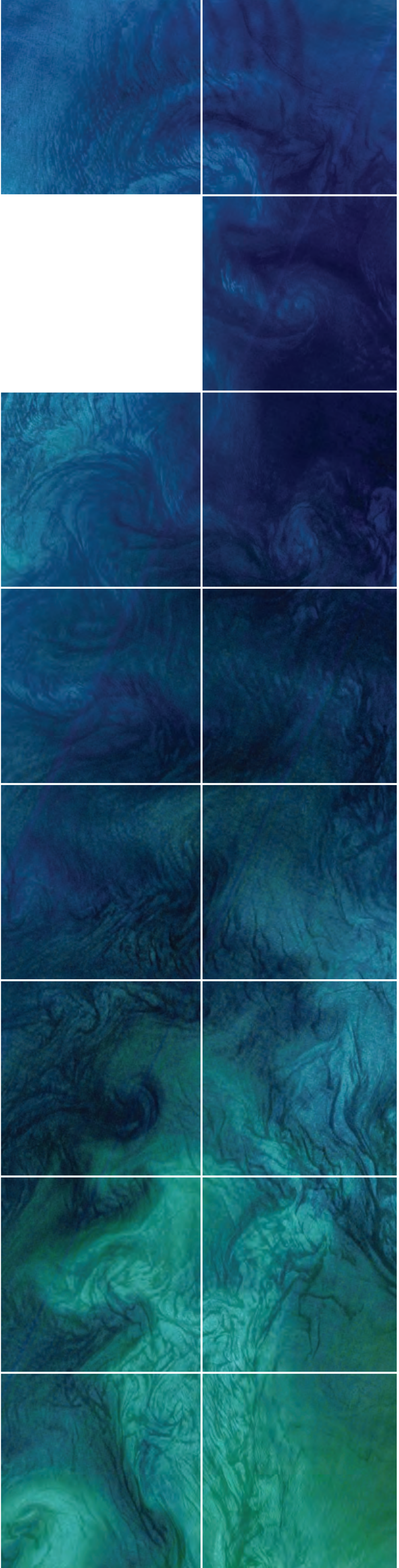




Filling the Gaps in Ocean Maps

A new software application merges ocean color data from instruments aboard two satellites to provide gap-free, near-real-time monitoring of the global ocean environment.

By Xiaoming Liu and Menghua Wang

Color satellite images of the world's oceans are swirling, shifting works of art. They also provide vital information on sediment transport, plant life, and seasonal sea ice changes. As satellites orbit Earth, the instruments they carry collect detailed data on the amount of light at various wavelengths that is backscattered from ocean waters at a given location and time, and these data are compiled into color images.

The National Oceanic and Atmospheric Administration's (NOAA) Visible Infrared Imaging Radiometer Suite (VIIRS) instruments aboard the Suomi National Polar-orbiting Partnership (NPP) and NOAA-20 spacecraft provide ocean color images every day. However, cloud cover, high Sun glint, images taken from a less-than-optimal viewing angle, and other factors lead to significant data gaps in these daily images [*Mikelsons and Wang*, 2019].

Green is an important color in satellite ocean imagery. This color is related to the concentration of chlorophyll *a* (Chl *a*), a chemical produced by green plants, including phytoplankton, seaweed, and other algae. Therefore, coloration in satellite ocean images can be converted to Chl *a* concentration data, which are critical for monitoring and understanding ocean optical, biological, and ecological processes and phenomena. By merging and filling data gaps from the NPP and NOAA-20 VIIRS instruments, scientists at the NOAA Center for Satellite Applications and Research

Alaska's Chukchi Sea as observed by Landsat 8 in 2018. Credits: NASA image by Norman Kuring/NASA's Ocean Color Web, using Landsat data from the U.S. Geological Survey.

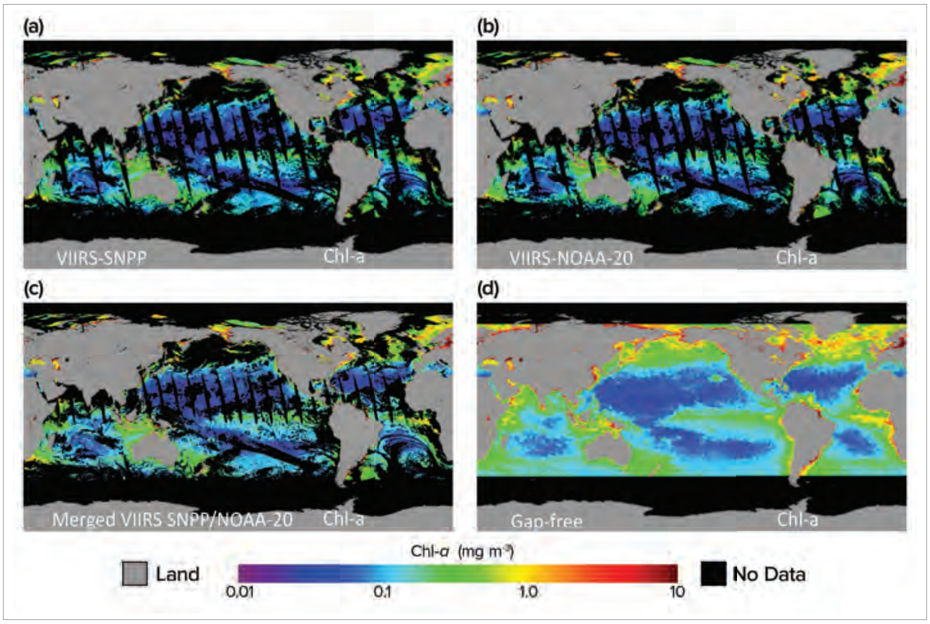


Fig. 1. This sequence of global maps shows VIIRS-measured Chl a *concentrations on 29 July 2019 from (a) Suomi National Polar-orbiting Partnership (NPP), (b) NOAA-20, (c) the merged Chl* a *image, and (d) the gap-free Chl* a *image. Chl* a *concentrations are in milligrams per cubic meter.*

(STAR) can now produce gap-free daily global ocean color Chl *a* maps that are accessible online in near-real time [*Liu and Wang,* 2019].

The gap-filling application uses a mathematical technique that exploits the coherency over location and time of the data from the two satellites to infer a value at the missing location.

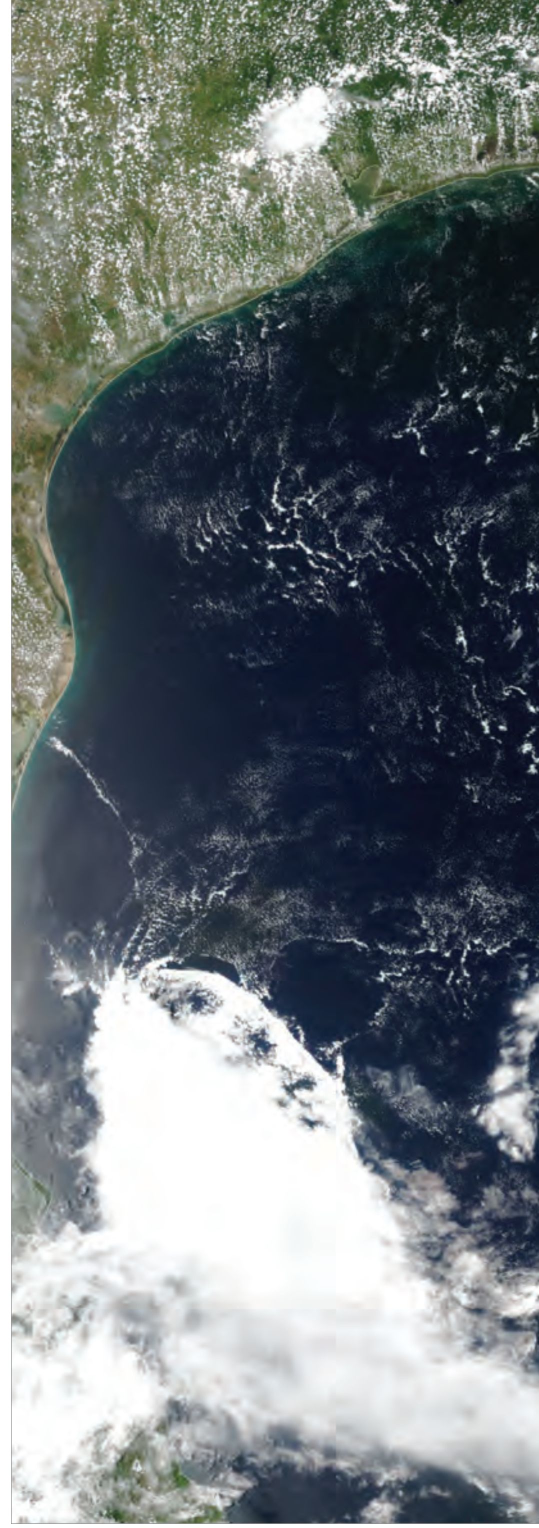
As examples, Figures 1a and 1b show global daily single-sensor Chl *a* images from NPP and NOAA-20 on 29 July 2019. About 60%–70% of the pixels in these single-sensor global daily images are missing (black streaks). These missing data make it difficult to capture dynamic ocean features in the images, so it's useful to fill these gaps before the data are used in various applications.

Merging Data from Two Satellites

NPP and NOAA-20 were launched in October 2011 and November 2017, respectively. The NOAA Ocean Color Team routinely produces global VIIRS ocean color products from both platforms using the Multi-Sensor Level 1 to Level 2 (MSL12) ocean color data processing system [*Wang et al.,* 2013].

NPP and NOAA-20 operate along the same Sun-synchronous polar orbit that crosses the equator at about 1:30 p.m. local time—both satellites travel around Earth from pole to pole in such a way that they observe the same areas at about the same time of day, no matter the season. There is about a 50-minute delay between the paths of NOAA-20 and NPP, so NOAA-20's path runs between two adjacent NPP orbital paths, and vice versa. Thus, the overlap of the spatial coverages of the two VIIRS sensors automatically fills each instrument's data gaps [*Mikelsons and Wang,* 2019]. In addition, ocean color data from both VIIRS instruments have the same spatial and temporal resolution, and these data are processed using the same algorithm and software package (i.e., MSL12). Therefore, the statistics of their ocean color products are very similar, and the data can be merged into a global 9-kilometer resolution data set directly without adjustment [*Liu and Wang,* 2019].

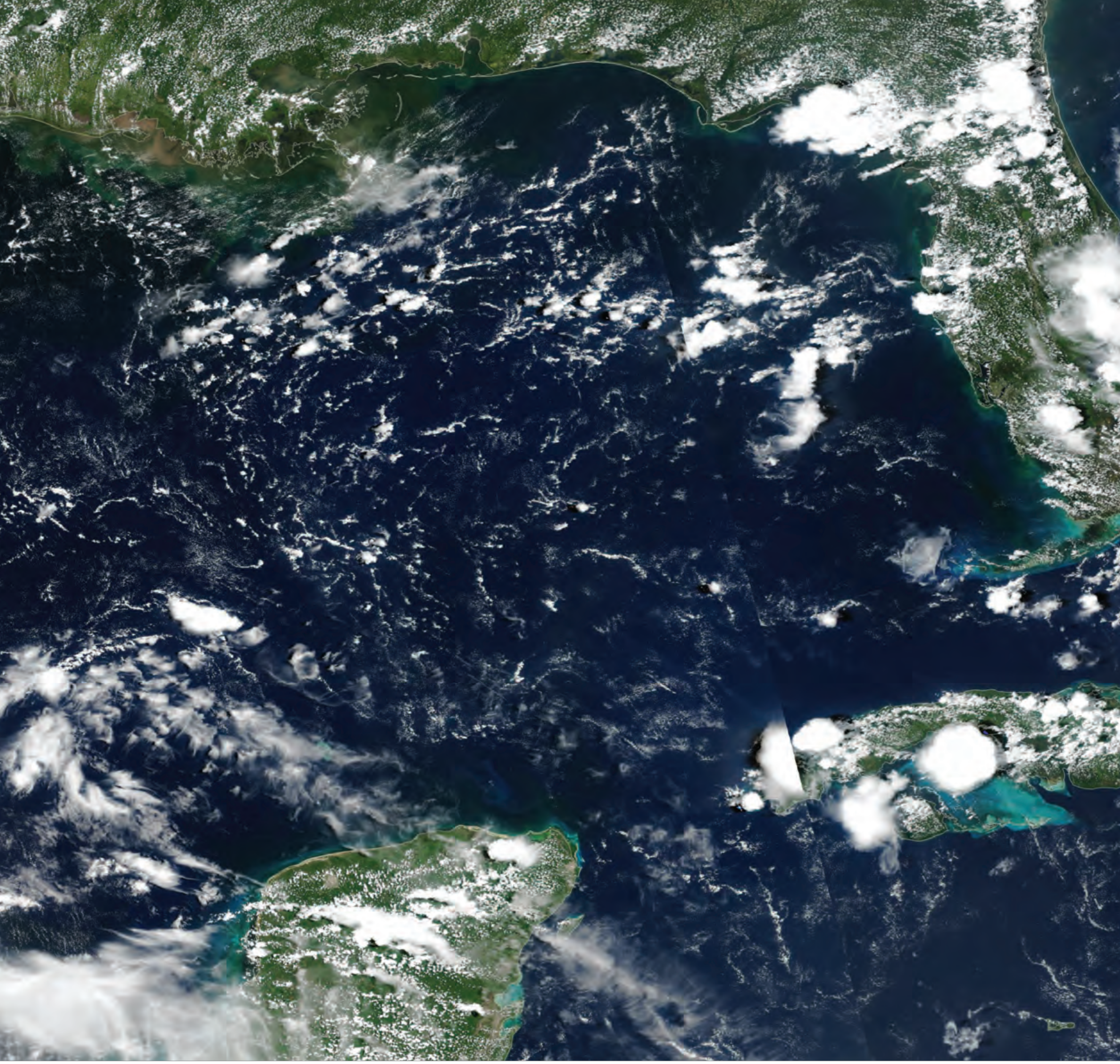
Figure 1c shows the merged Chl *a* image from 29 July 2019. In this image, the gaps of missing pixels caused by the high sensor zenith angle and high Sun glint contamination from both VIIRS sensors are almost filled. Overall, these merged data include about 38% more valid pixels than those from NPP or NOAA-20 alone.



Filling the Remaining Data Gaps

Even after the data sets from the two satellites are merged, some gaps remain. To complete the picture, the gap-filling application uses a mathematical technique based on the data interpolating empirical orthogonal function (DINEOF) [*Alvera-Azcarate et al.,* 2005; *Beckers and Rixen,* 2003]. This technique exploits the coherency over location and time of the data from the two satellites to infer a value at the missing location.

However, applying DINEOF on global-scale data requires a large amount of com-



puting resources (time and processing units), and processing a large data set requires a significant amount of computer time. We developed a time-efficient procedure that uses the DINEOF method to fill in missing pixels on the daily global ocean color images [*Liu and Wang,* 2018]. To do this, we divided the global data set evenly into 16 sections, each covering a zone with a width of 10° latitude between 80°S and 80°N, and applied DINEOF to each of the zonal sections separately. Quantitative evaluation has shown that errors in the DINEOF reconstructed data are usually within 2% [*Liu and Wang,* 2019]. We found that we could improve the data processing efficiency still further by performing DINEOF analyses on the 16 zonal sections in parallel [*Liu and Wang,* 2018].

The goal of our near-real-time operation is to reconstruct the missing pixels of daily global images within 12–24 hours of when the images were acquired. DINEOF works on a time series of data, so in our daily operational setting, we fill the missing pixels in the image of the current day using

This true-color image, acquired by NOAA's Visible Infrared Imaging Radiometer Suite (VIIRS) instrument aboard the Suomi National Polar-orbiting Partnership (NPP) satellite, shows the Gulf of Mexico on 17 July 2019. Color images like this one are used to produce data for monitoring various ocean processes, but clouds, Sun glint, and other factors can leave gaps in these data. Measurements from VIIRS instruments aboard two satellites have been merged to derive gap-free data for chlorophyll a *(Chl* a*) concentration measurements, an indicator of plant life in the ocean. Credit: NOAA/STAR Ocean Color Team* global images from that day as well as the previous 29 days.

Normally, around 7:00 each morning, the previous day's gap-free global Chl *a* image is produced using the previous 30 days of global daily merged NPP/NOAA-20 VIIRS Chl *a* images. Figure 1d shows an example of one such image on 29 July 2019 in which gaps of missing pixels are all smoothly filled. The gap filling is also very smooth temporally. To view a video showing an animation of 180 days of gap-free global Chl *a* images visit bit.ly/Eos-maps-gaps.

Large and Medium Ocean Features

Gap-free global daily Chl *a* data reveal many large-scale and mesoscale ocean features. In Figure 1d and the video referenced on the previous page, the most obvious large-scale ocean features are the nutrient-poor (oligotrophic) waters in the centers of subtropical ocean gyres and the more Chl *a*–rich waters in the equatorial and coastal oceans.

As an example of a mesoscale ocean feature, Figure 2 shows the transformation of the Loop Current and its associated eddies in the Gulf of Mexico. A Loop Current eddy, the dark blue area marked "A" in Figure 2c, spun off the Loop Current from 2 July to 12 July 2019. From 17 July to 11 August, the eddy continued to move westward while changing its shape and orientation. The transitions of these mesoscale ocean features were very smooth and can be clearly observed through the gap-free Chl *a* daily images.

The global daily gap-free VIIRS Chl *a* images can be accessed online via our state-of-the-art web application, Ocean Color Viewer (OCView) [*Mikelsons and Wang,* 2018]. The gap-free global Chl *a* data (Level-3 binned files in NetCDF-4 format) used to produce the images seen in OCView are also available upon request.

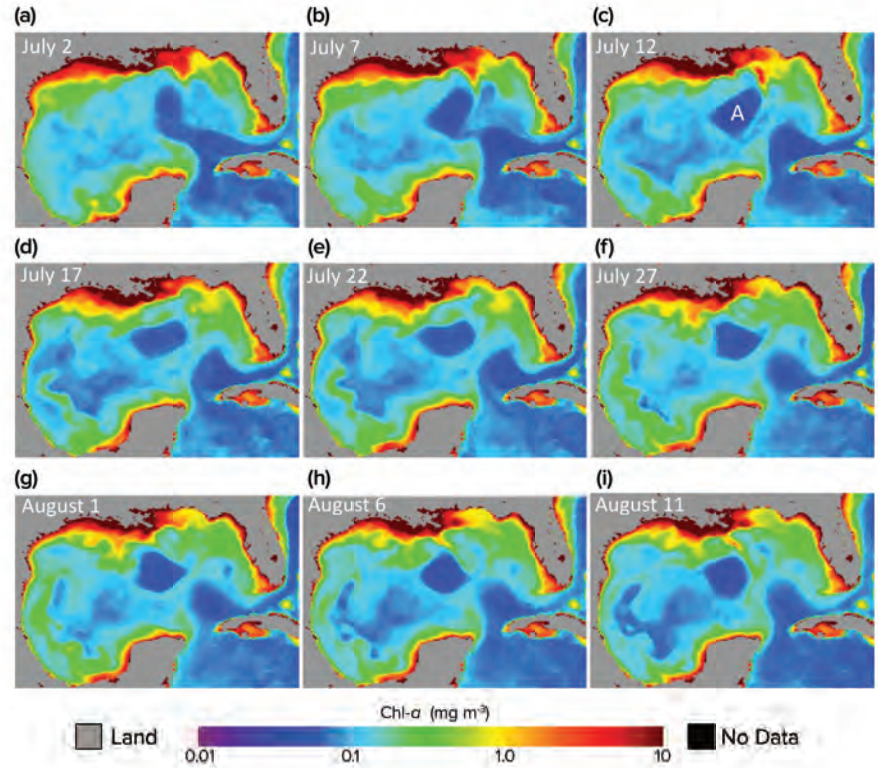


Fig. 2. This sequence of images shows daily Chl a *concentration data for the Gulf of Mexico from 2 July to 11 August 2019 with the Loop Current and a Loop Current eddy (dark blue region marked "A" in Figure 2c). Chl* a *concentrations are in milligrams per cubic meter.*

Adding More Satellite Sources in the Future

The gap-free data based on the NPP/NOAA-20 VIIRS merged products show more details in ocean features than those based on single sensors alone [*Liu and Wang,* 2019]. This result indicates that adding even more sensors into the merged products could significantly improve the quality of gap-free global ocean color data.

Currently, in addition to VIIRS on NPP and NOAA-20, the Ocean and Land Colour Instruments on the European Space Agency/European Organisation for the Exploitation of Meteorological Satellites Sentinel-3A (2016 to present) and Sentinel-3B (2018 to present) satellites and the Japan Aerospace Exploration Agency's Second-Generation Global Imager on the Global Change Observation Mission–Climate (2017 to present) are each providing unprecedented global views of ocean optical, biological, and biogeochemical properties. We are working to add these sensors into the data-merging process in the near future, which we anticipate will further improve data quality and reduce gaps in global ocean color data.

Acknowledgments

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