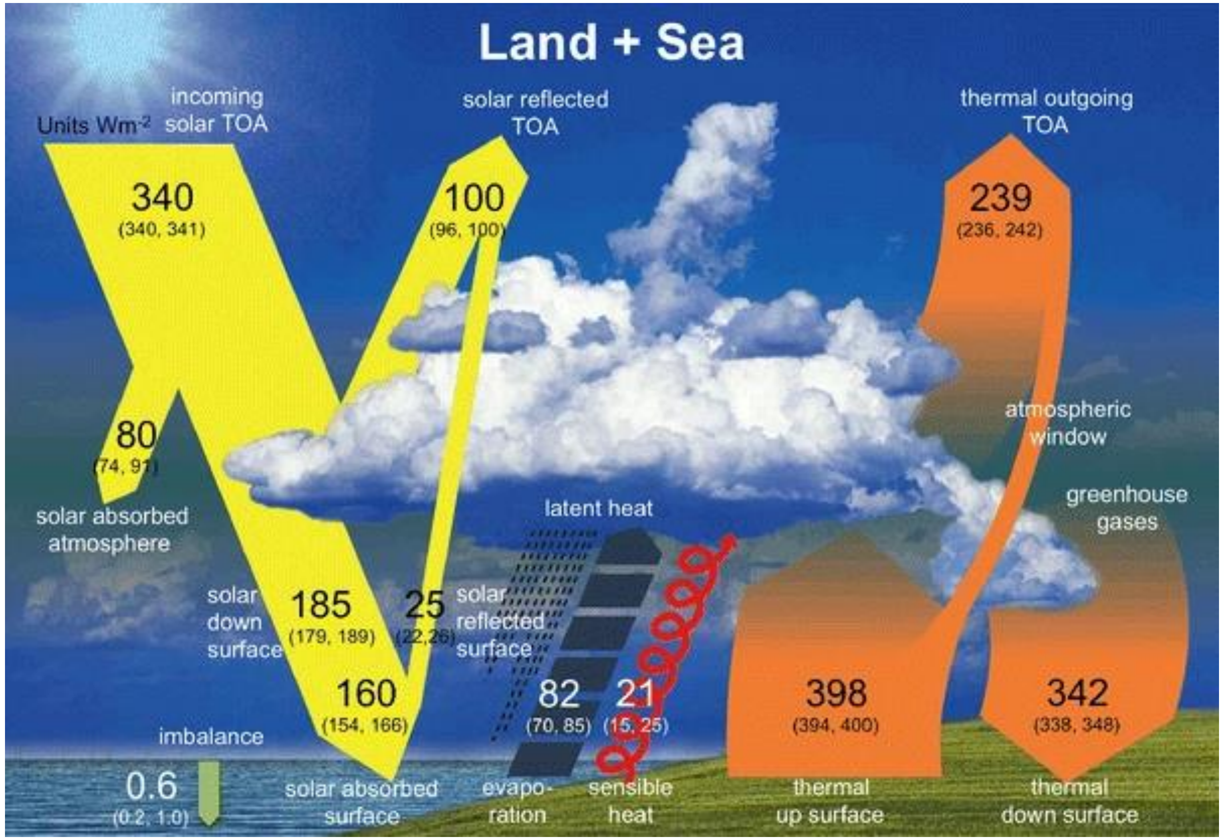
Global 3D Reconstruction of Clouds and Tropical Cyclones

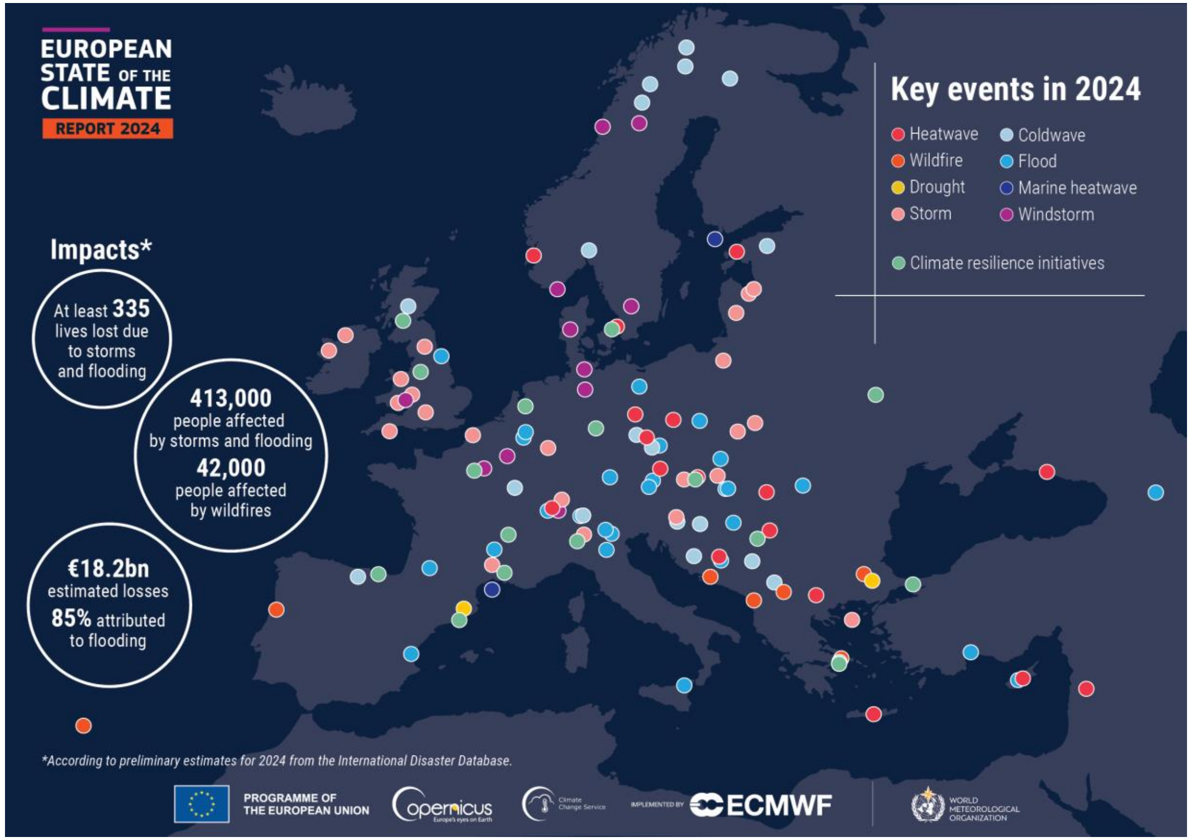
<u>William Jones</u>[1], Shirin Ermis[2], Cesar Aybar[3], Lilli Freischem[2], Stella Girtsou[4,5], Kyriaki-Margarita Bintsi[6,7], Emiliano Diaz Salas-Porras[3], Michael Eisinger[1], Anna Jungbluth[1], Benoit Tremblay[8]

1. European Space Agency, 2. University of Oxford, 3. Universitat de València, 4. National Observatory of Athens, 5. National Technical University of Athens, 6. Harvard Medical School, 7. Massachusetts General Hospital, 8. Environment & Climate Change Canada

Clouds, climate and extreme weather



Wild et al., 2015, Fig. 1

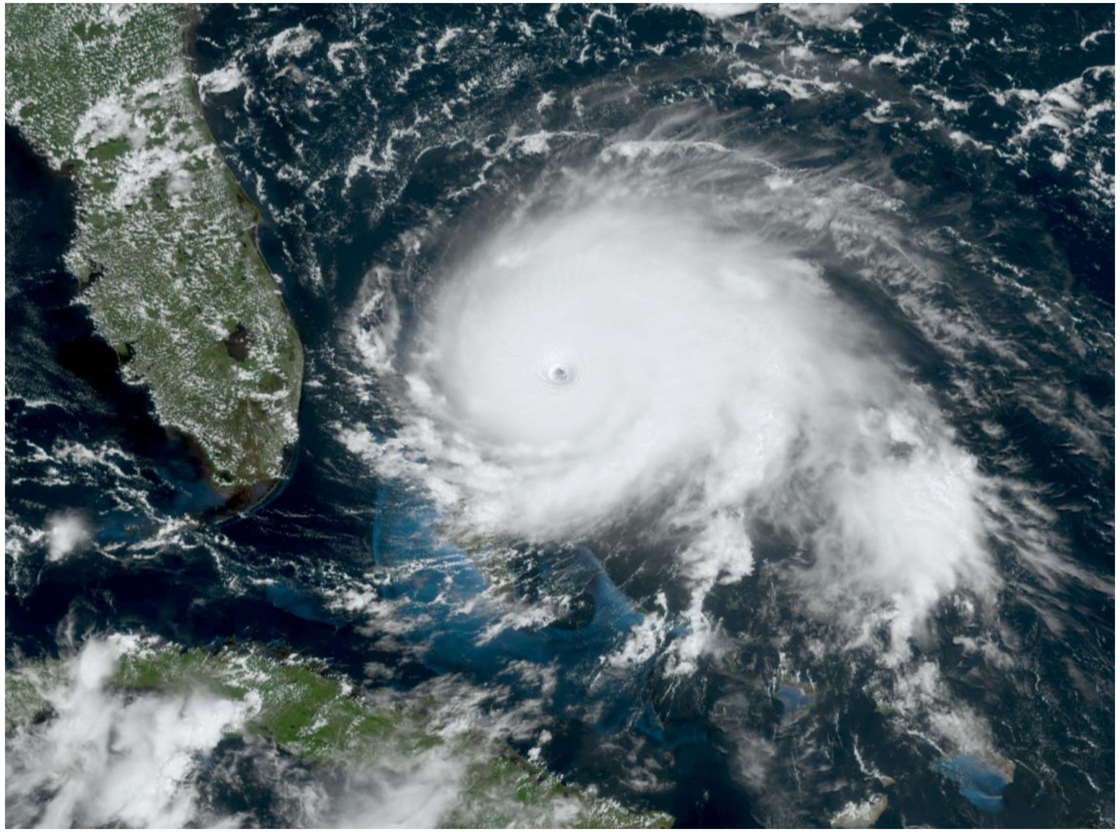


Copernicus Climate Change Service/WMO European State of the Climate 2024

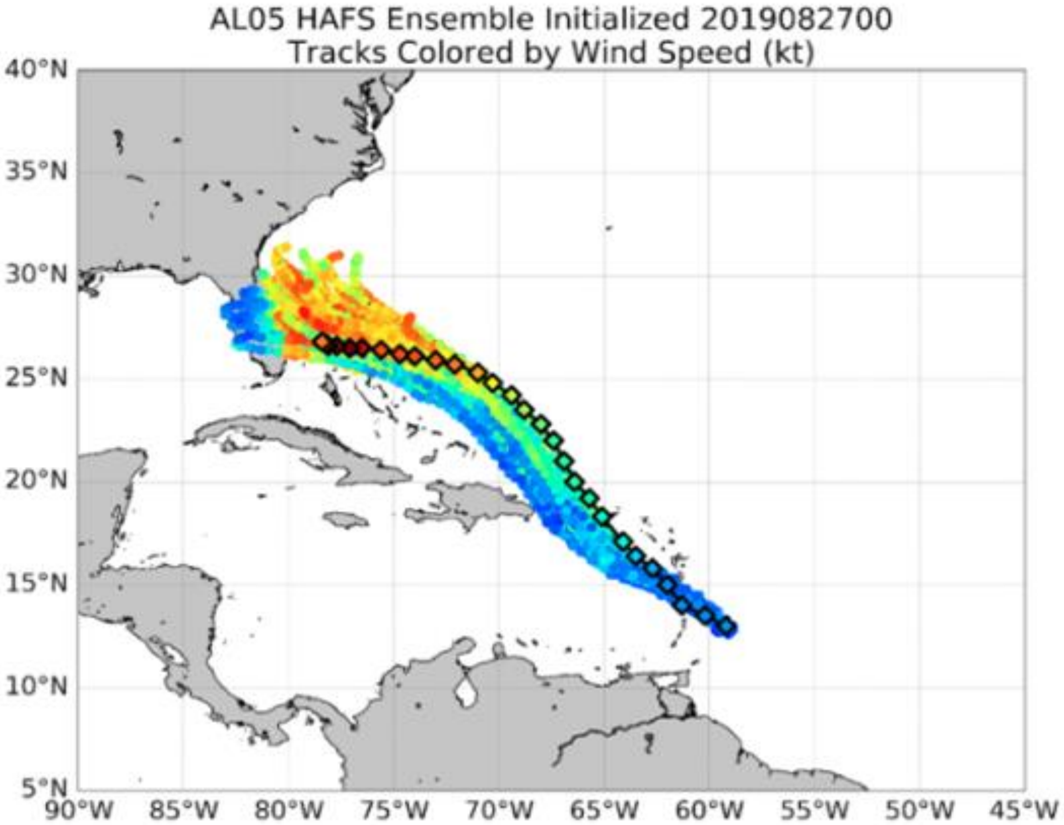
Clouds have a substantial influence on the Earth's energy budget through both the reflectance of sunlight and the absorption of outgoing longwave radiation

Convective storms contribute to the majority of damages from extreme weather, and storms are expected to become more intense with climate change

Tropical Cyclones: Hurricane Dorian



NOAA GOES-16 ABI/Wikimedia

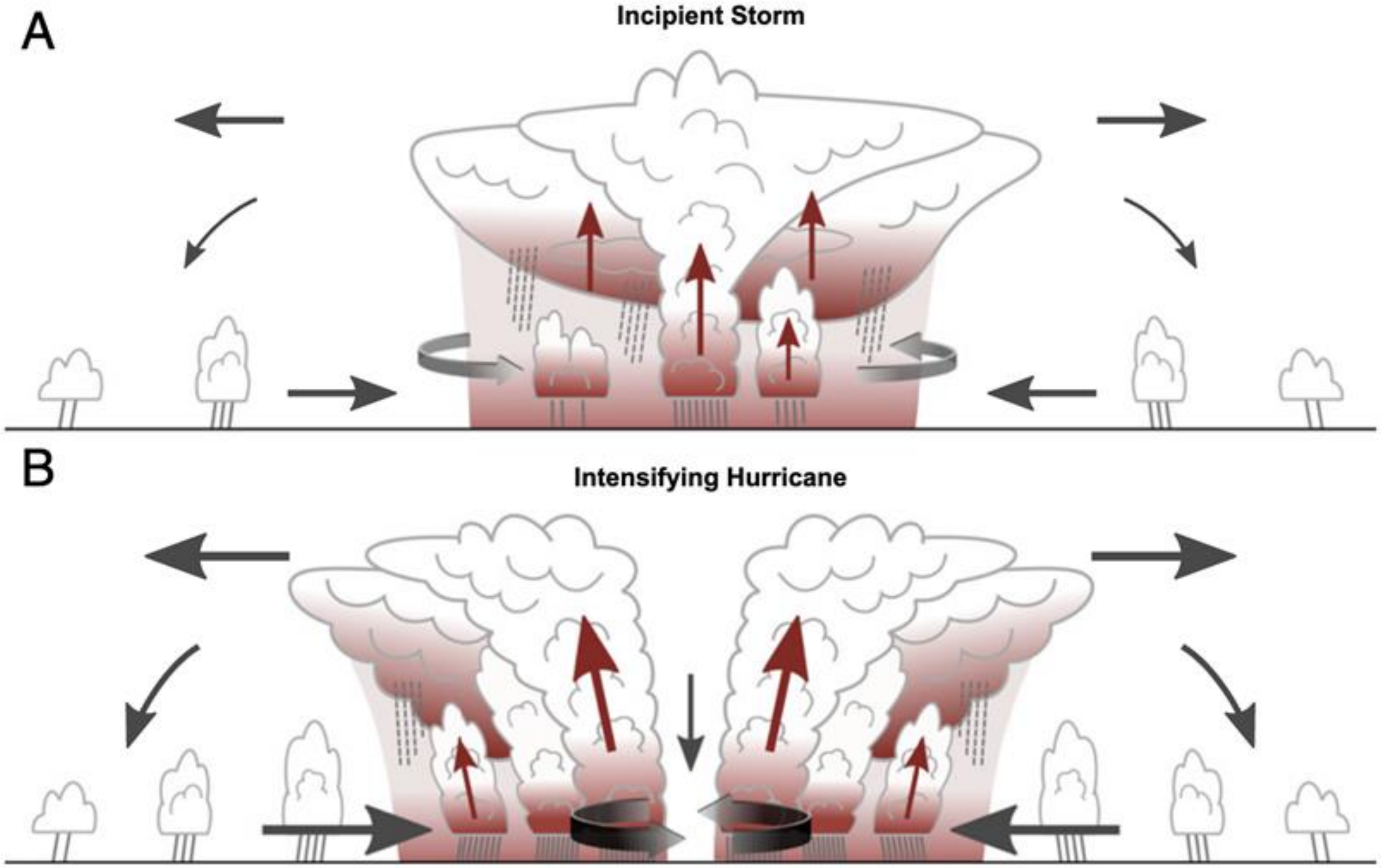


Hazelton et al., 2023. HAFS forecasts and best track

Hurricane Dorian struck the Bahamas on 1st September 2019, after undergoing rapid intensification.

Rapid intensification events remain difficult to predict, despite improvements in the forecasting of TCs

Rapid Intensification and CRH



Ruppert et al., 2020, fig. 1

Rapid intensification has remained a puzzle because it goes against the usual behaviour of storms

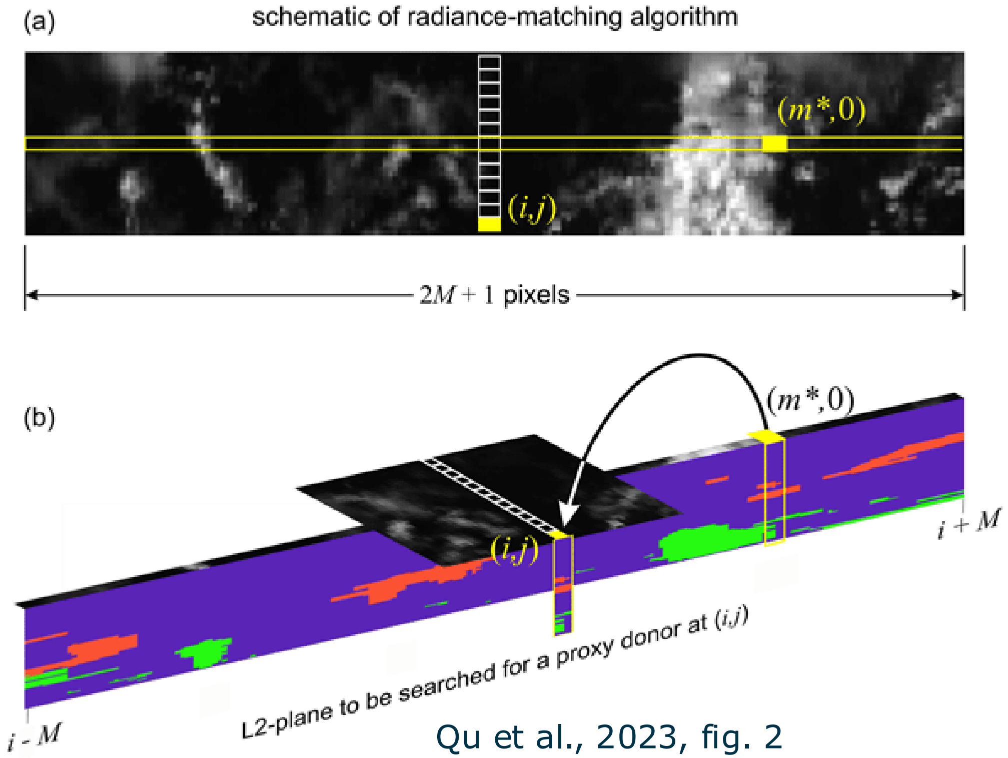
To sustain long term growth of the storm, a destabilising mechanism is required

Recent research has point to the radiative heating of clouds as a potential candidate for this process

Existing approaches

EarthCARE Scene Construction Algorithm

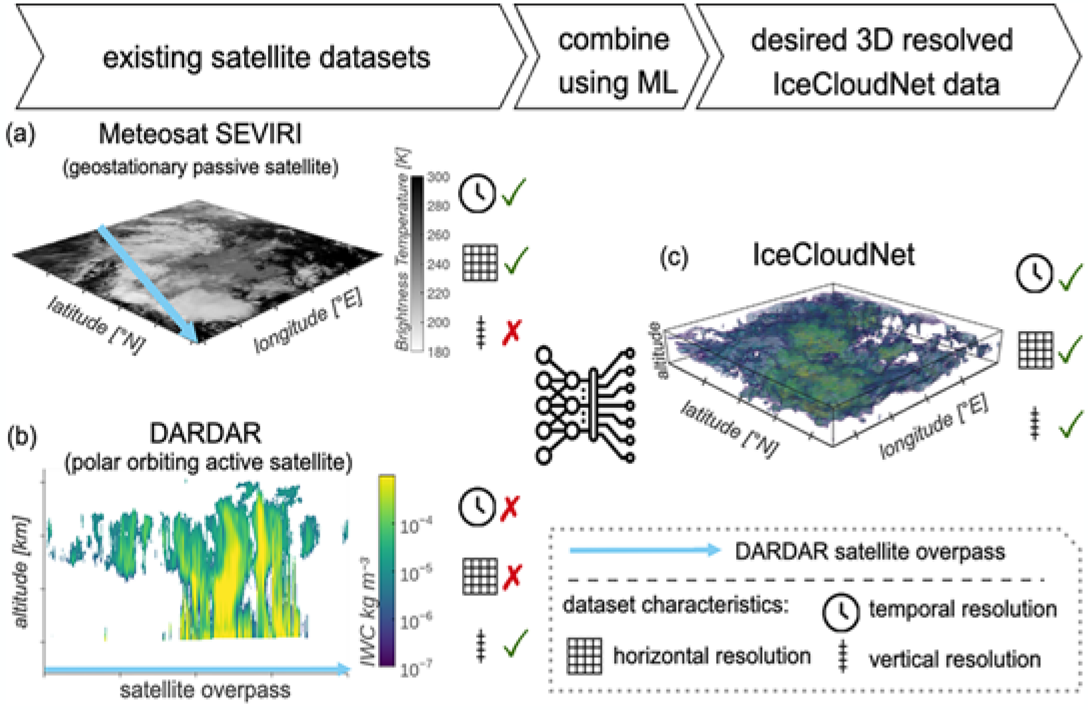
The SCA produces the 3D data required for radiative transfer calculations by duplicating radar/lidar profiles based on the nearest match found in MSI radiances.



Qu et al., 2023, fig. 2

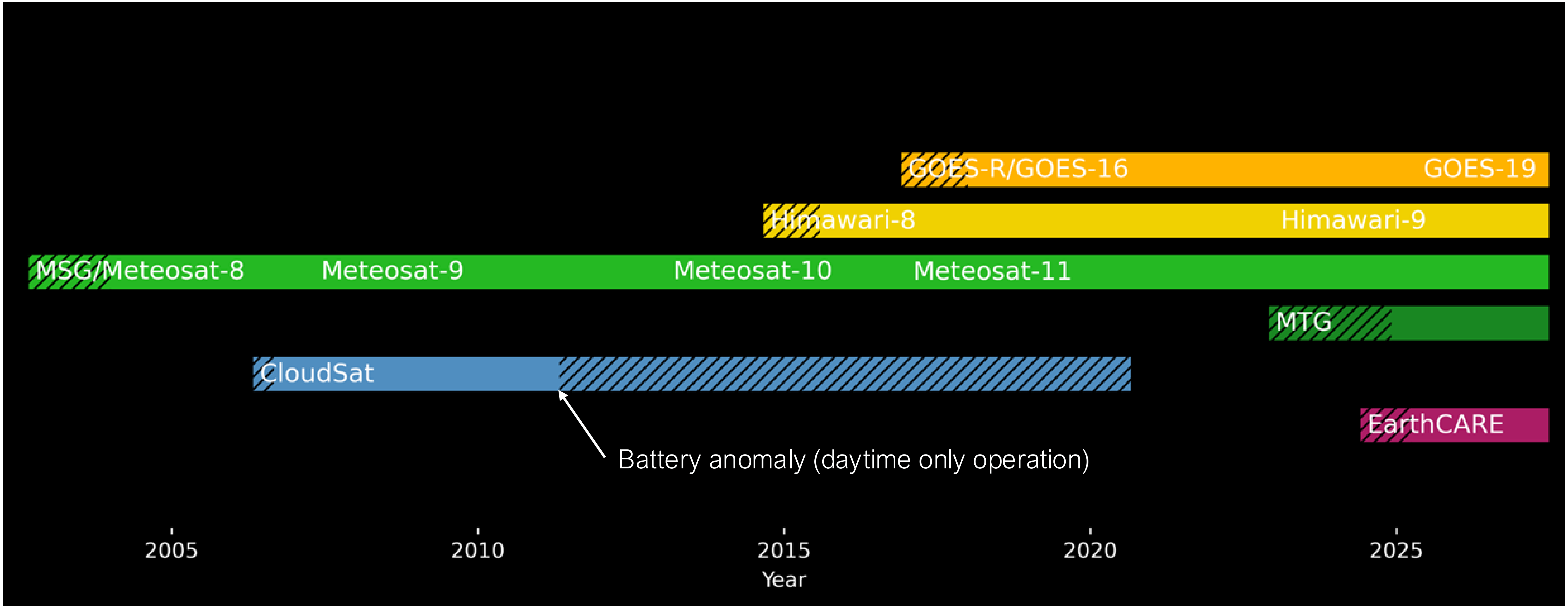
ML Approaches

3D cloud tomography (Brüning et al., 2024) and IceCloudNet, (Jeggle et al., 2025) predict CloudSat variables from MSG SEVIRI imagery using U-Net architectures.

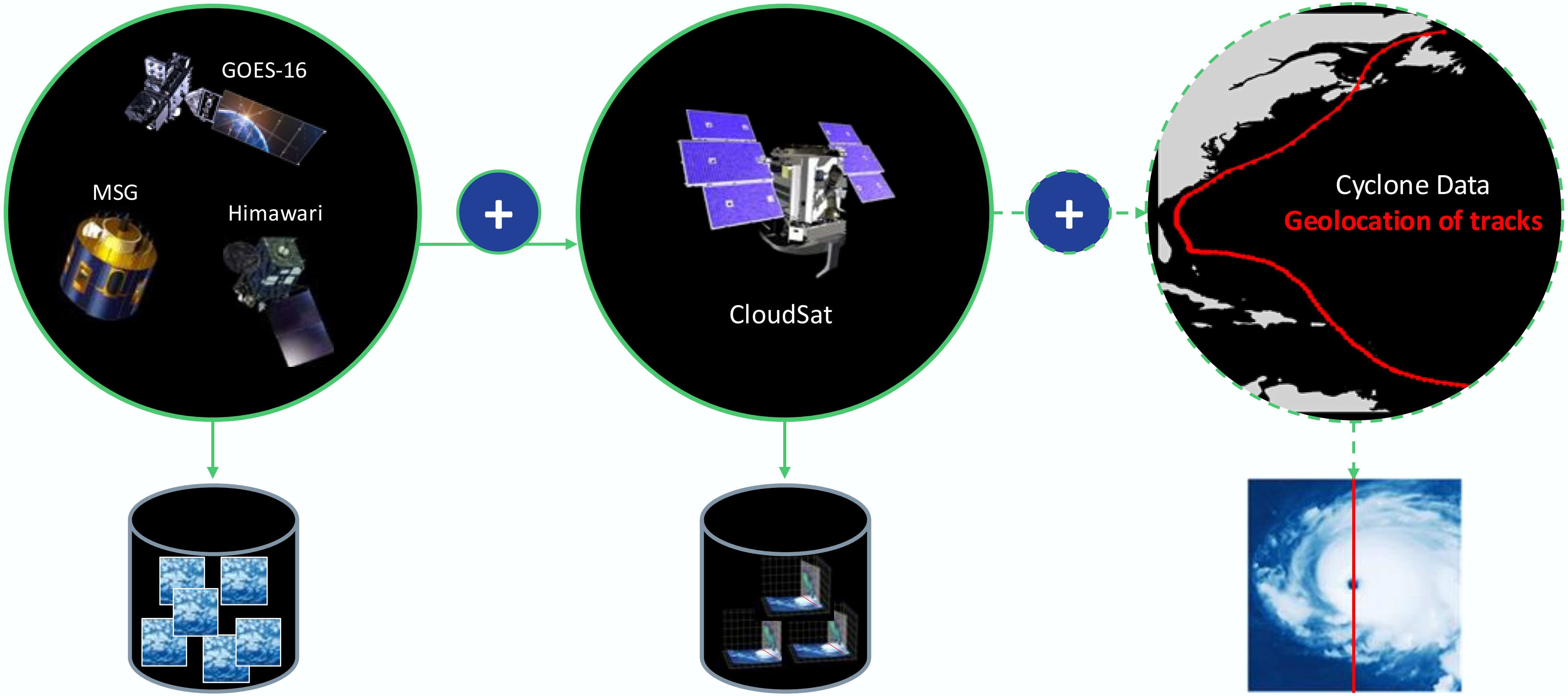


Jeggle et al., 2025

Overlap between geostationary and polar-orbiting satellites



ML-ready datasets: TC evaluation dataset

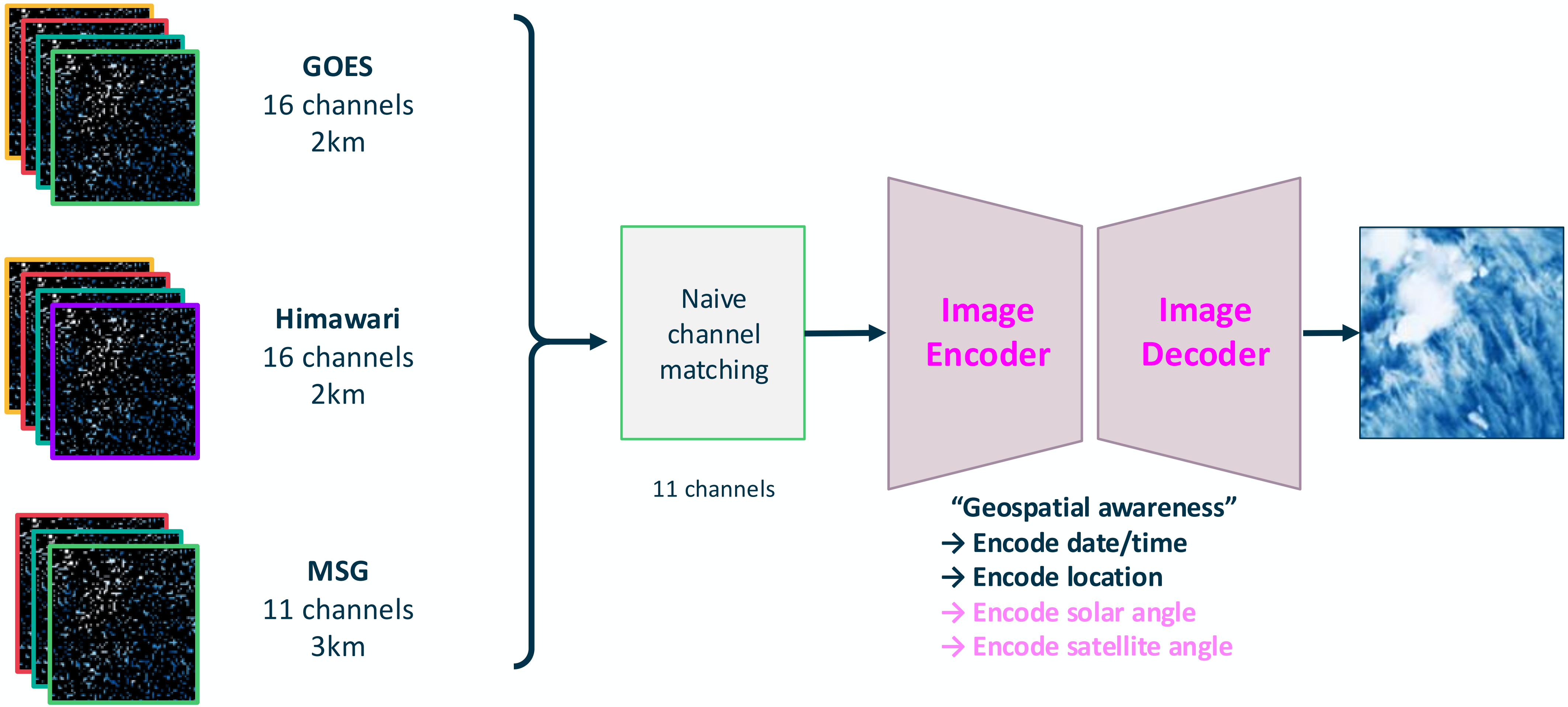


Geostationary Images
150k patches
2.4 TB

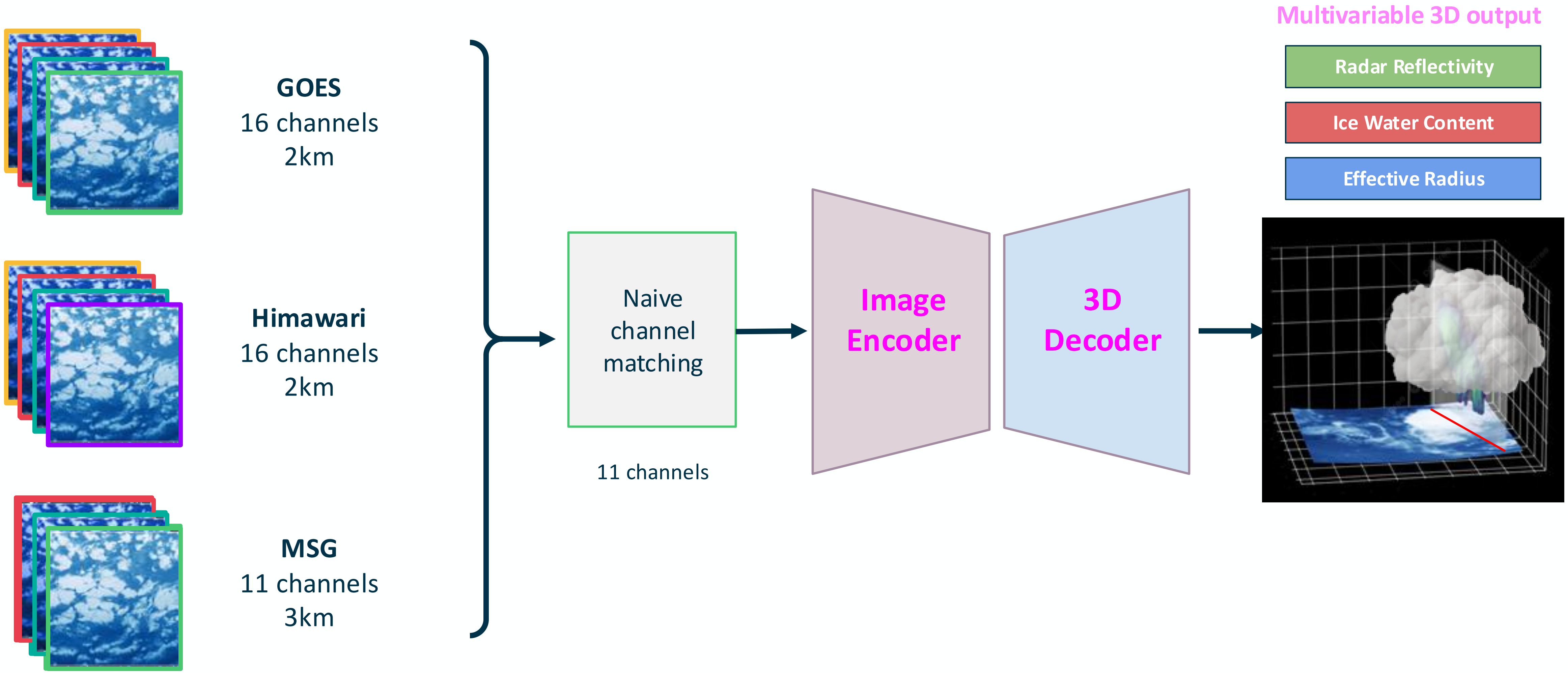
Image-Profile Pairs
270k patches
874 GB

Tropical cyclone tracks
703 patches (108 storms)
2 GB

Pre-training a multi-satellite model



Multivariable 3D reconstruction model



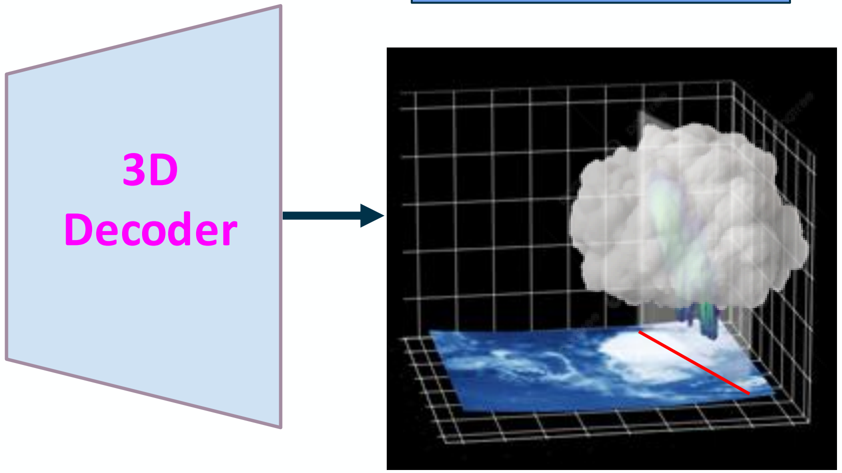
Multivariable 3D decoder(s)

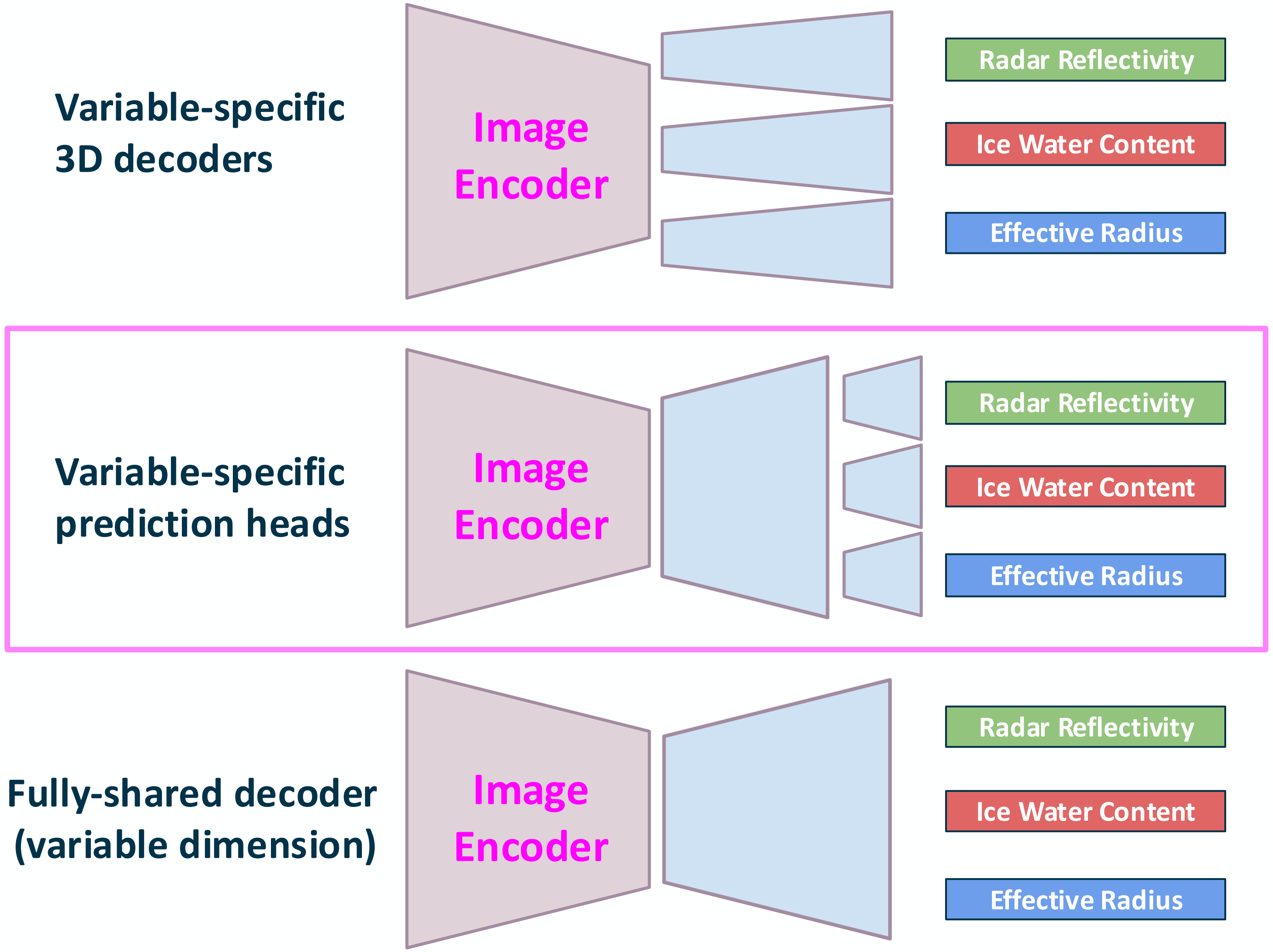
Multivariable 3D output

Radar Reflectivity

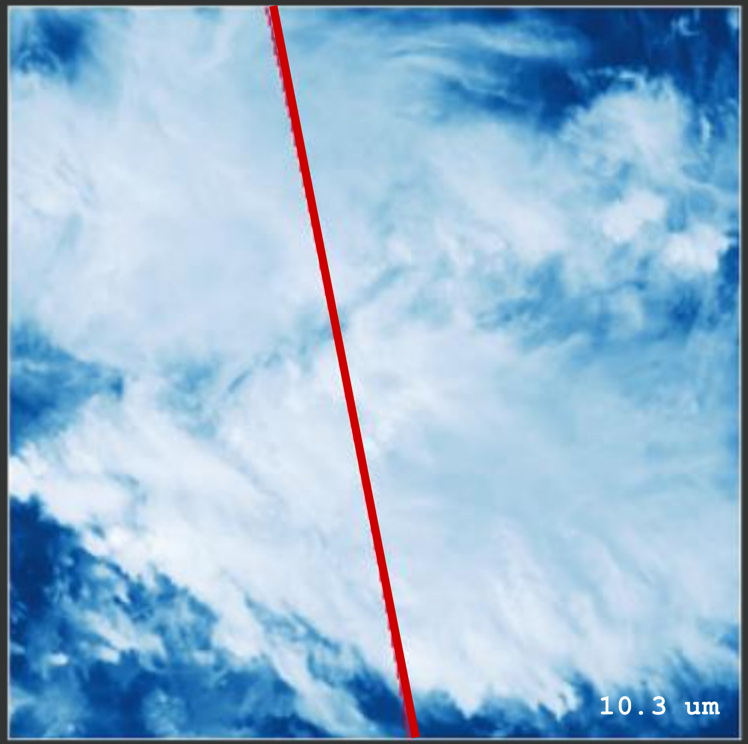
Ice Water Content

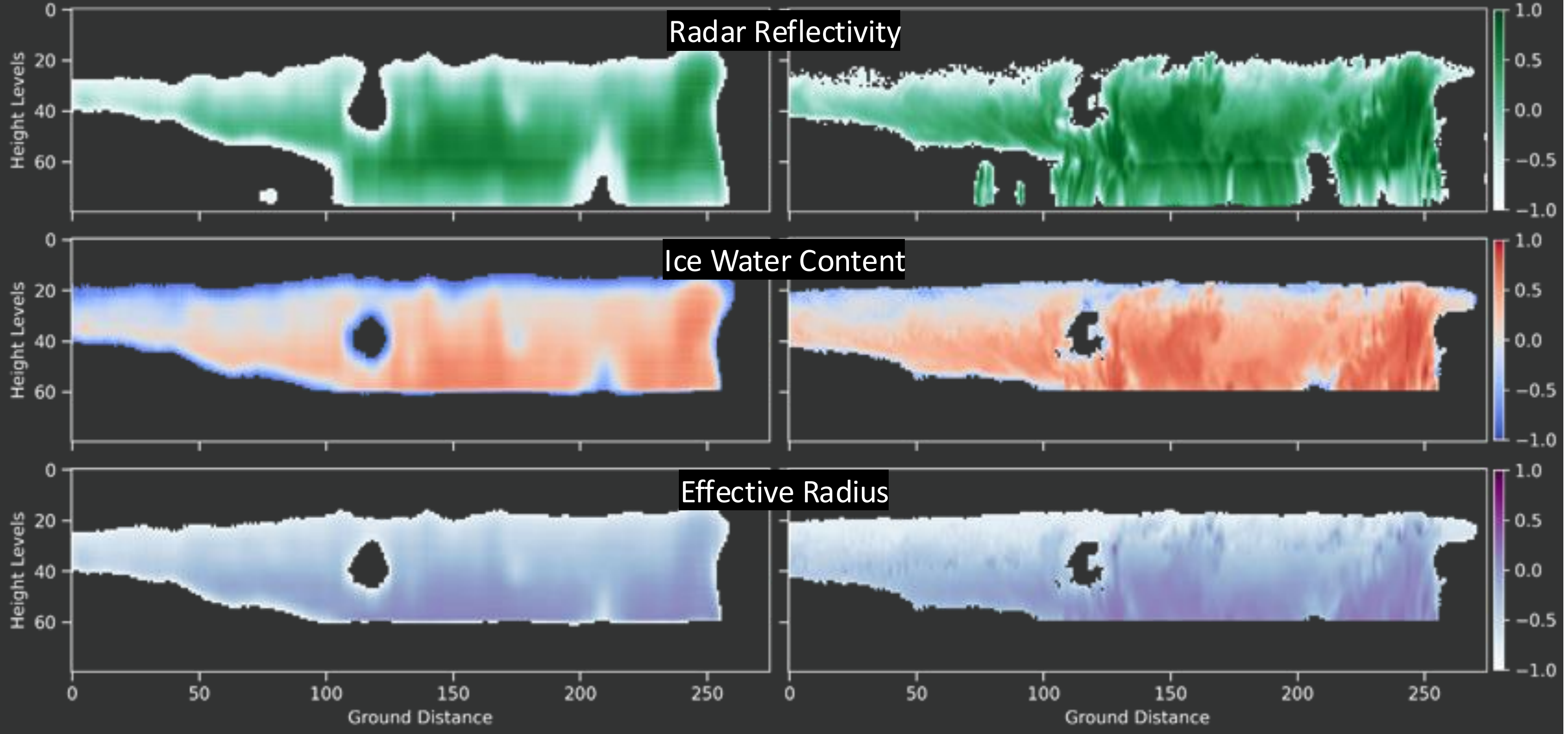
Effective Radius



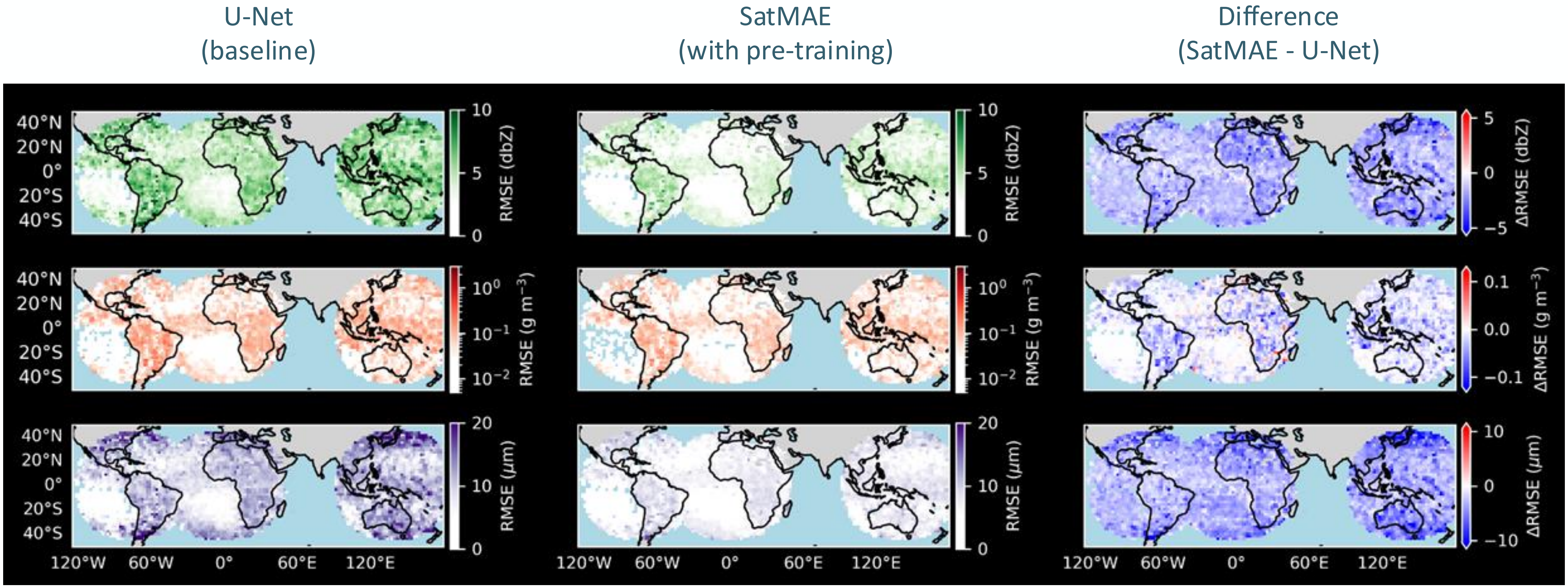


Multivariable 3D Reconstruction Model





Comparison to U-Net baseline

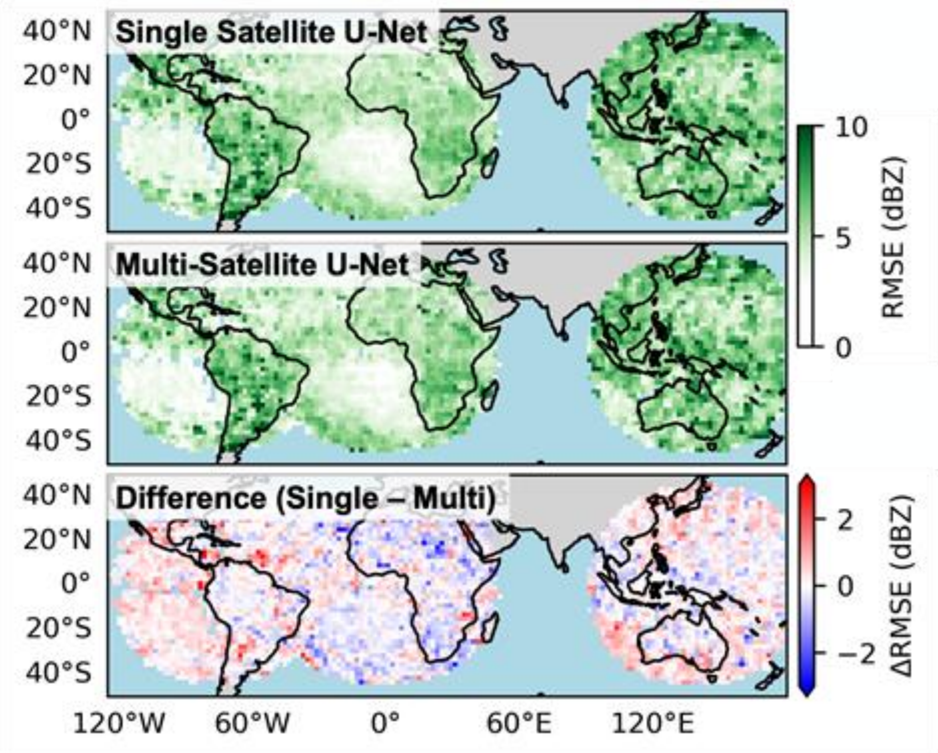


SatMAE approach improves metrics everywhere, but particularly at high viewing angles

Single Satellite vs. Multi-Satellite

	Single satellite			Multi-satellite		
Metrics	**GOES**	**MSG**	**HIMAWARI**	**GOES**	**MSG**	**HIMAWARI**
RMSE (dBZ)	5.44 ± 2.61	**4.81 ± 2.21**	6.14 ± 2.99	**5.22 ± 2.65**	4.95 ± 2.17	**6.03 ± 3.05**
SSIM	0.75 ± 0.13	**0.78 ± 0.11**	0.71 ± 0.14	**0.76 ± 0.13**	0.77 ± 0.11	**0.72 ± 0.15**

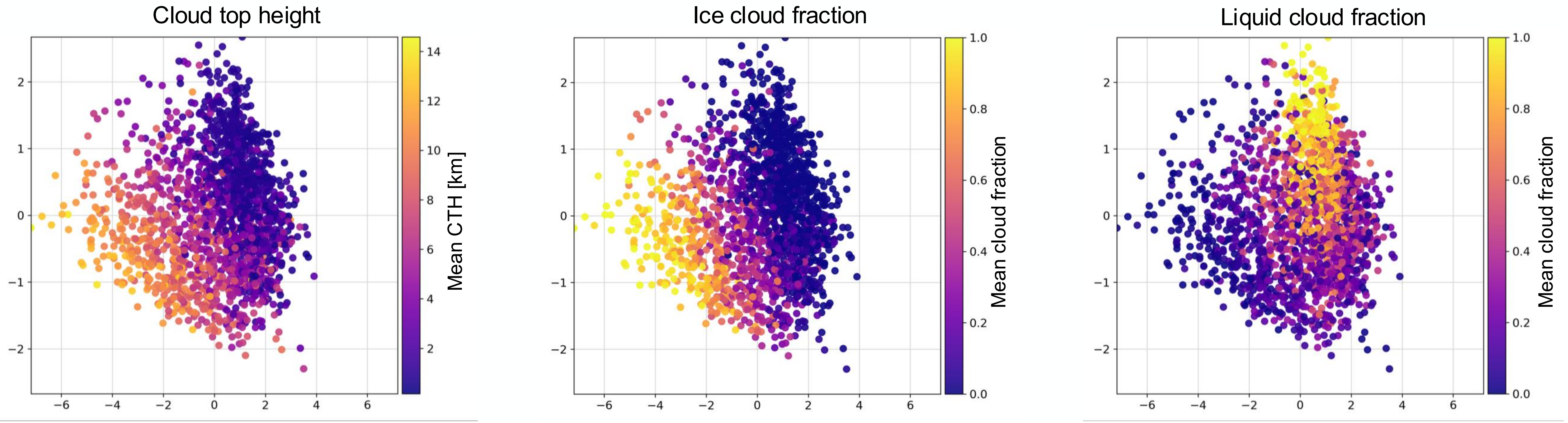
Average RMSE / SSIM hides spatial variability of model performance



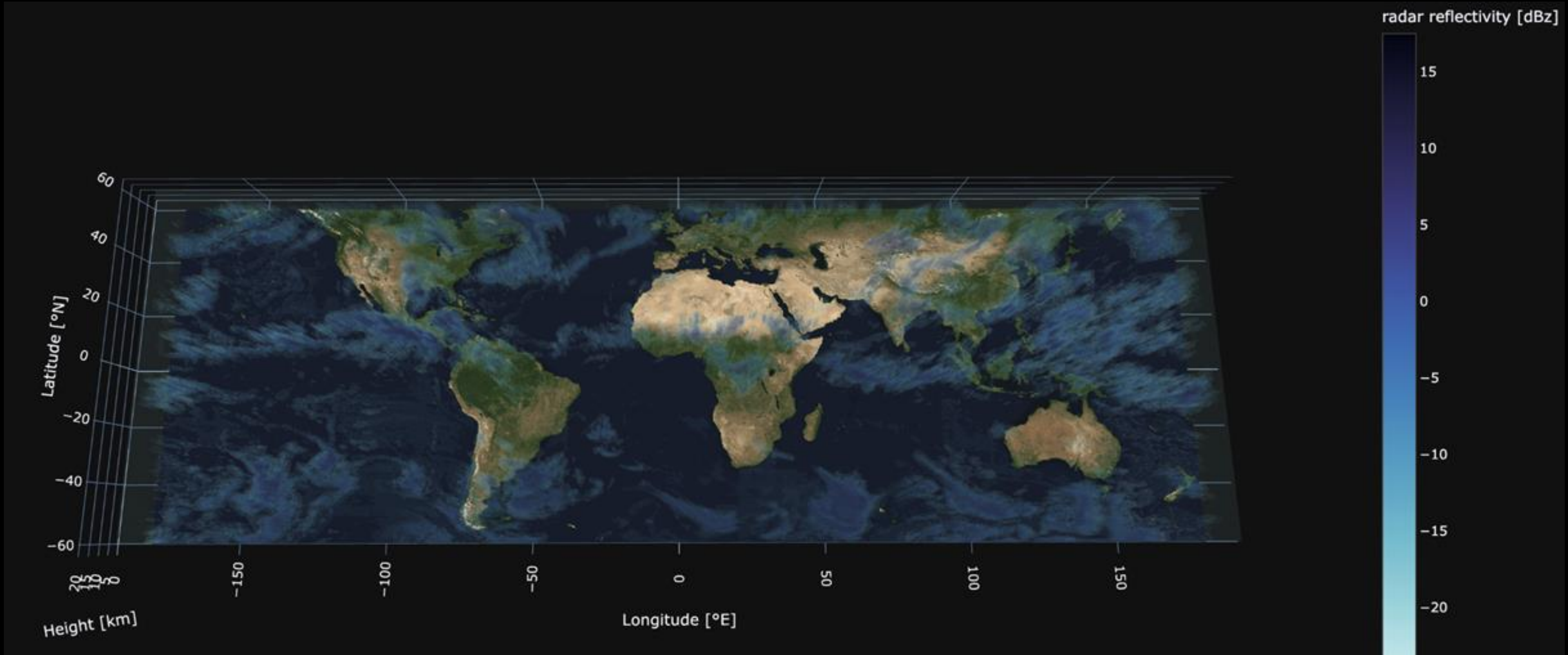
Takeaway: Naively combining different satellites (and increasing the dataset size) often improves model results.
! Our *end goal* is to study TCs, which appear in GOES and Himawari's field-of-view, so slightly worse results for MSG are not an issue.

What do the embeddings learn?

PCA used to investigate how the model's learned embeddings correspond to retrieved cloud properties

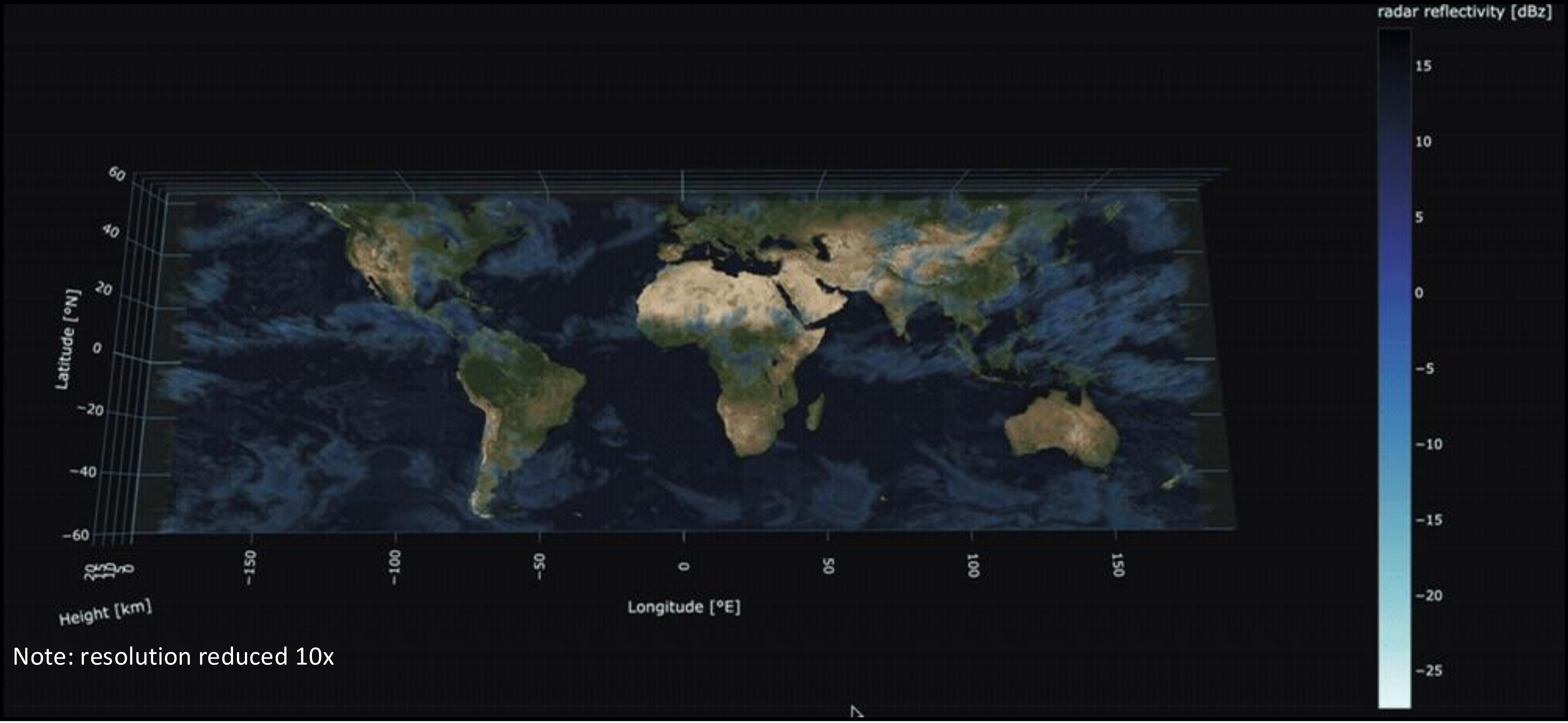


Global 3D Cloud Reconstructions



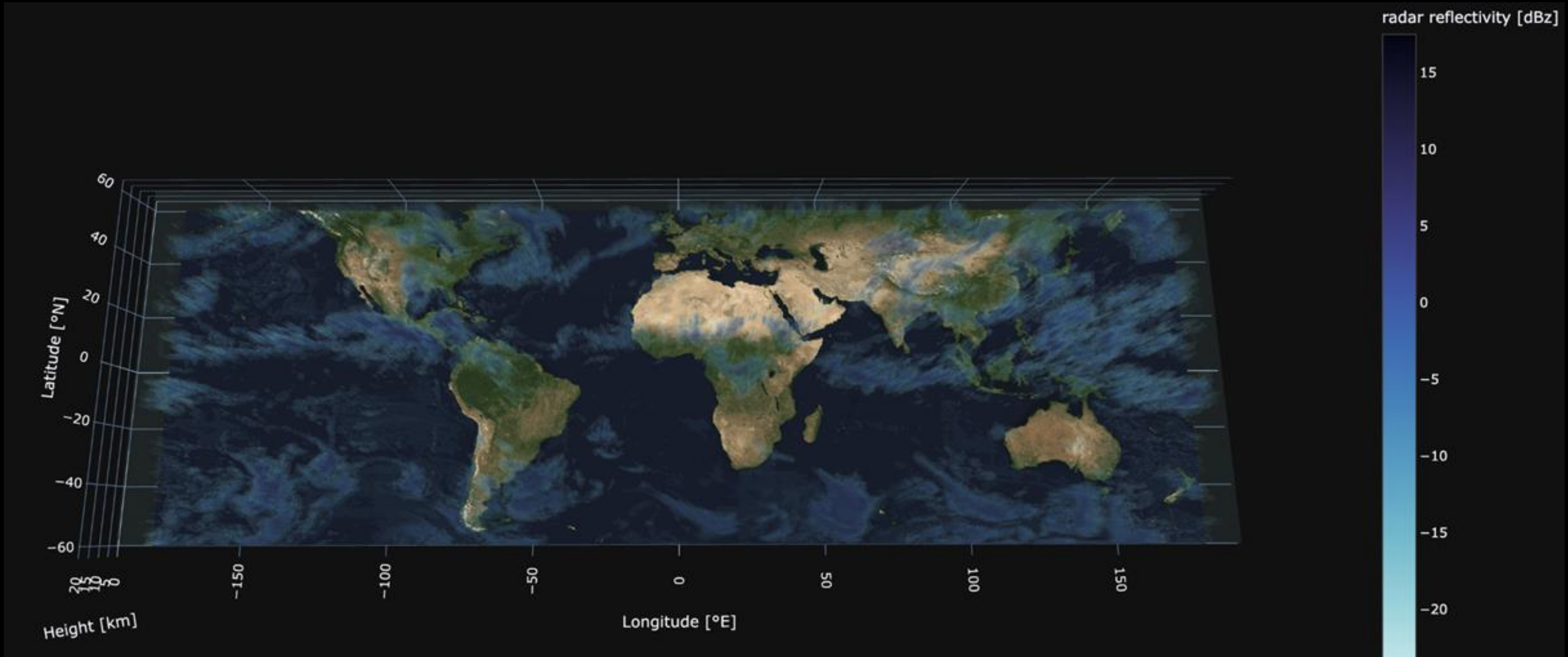
Note: resolution reduced 10x

Global 3D Cloud Reconstructions



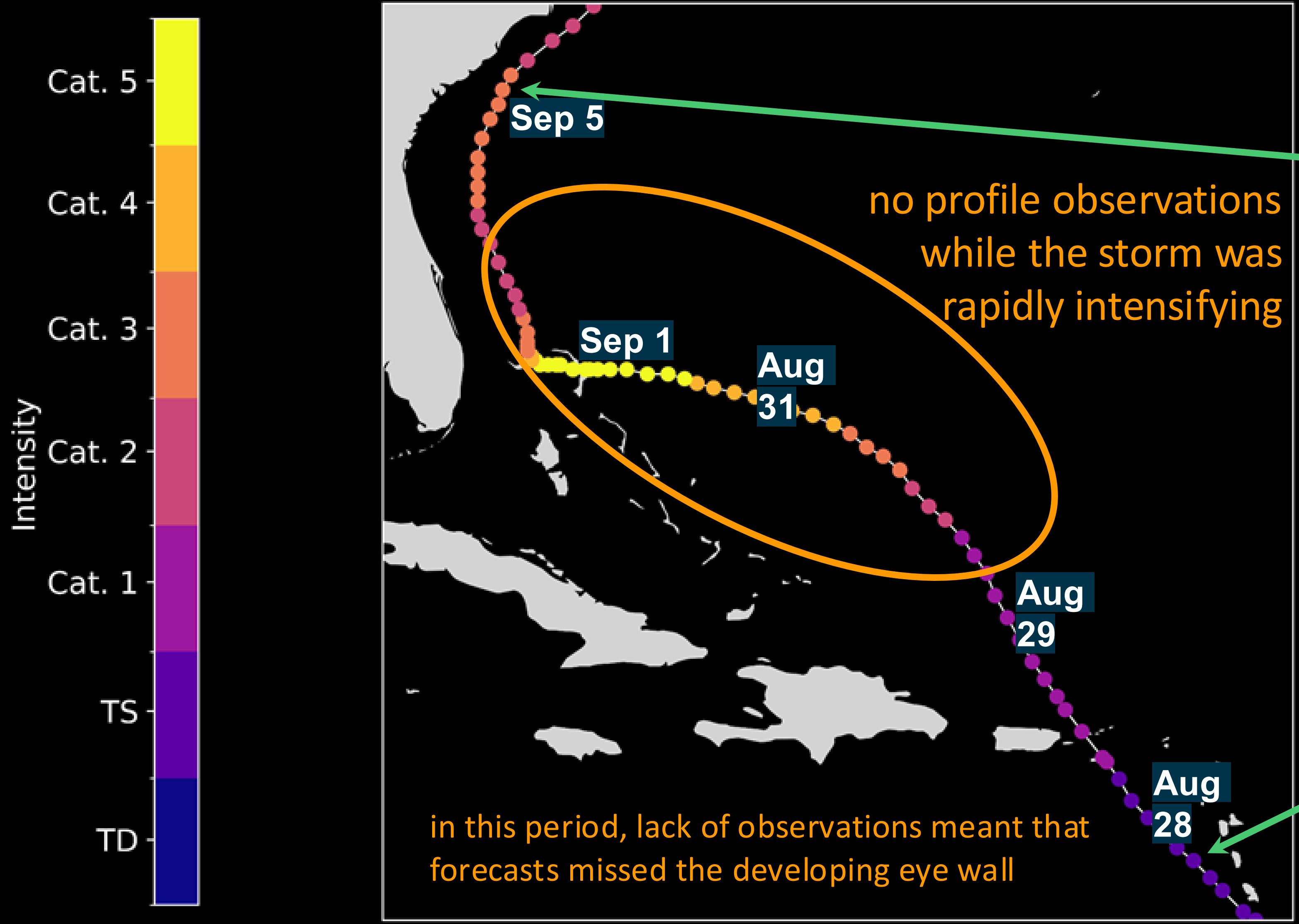
Note: resolution reduced 10x

Global 3D Cloud Reconstructions

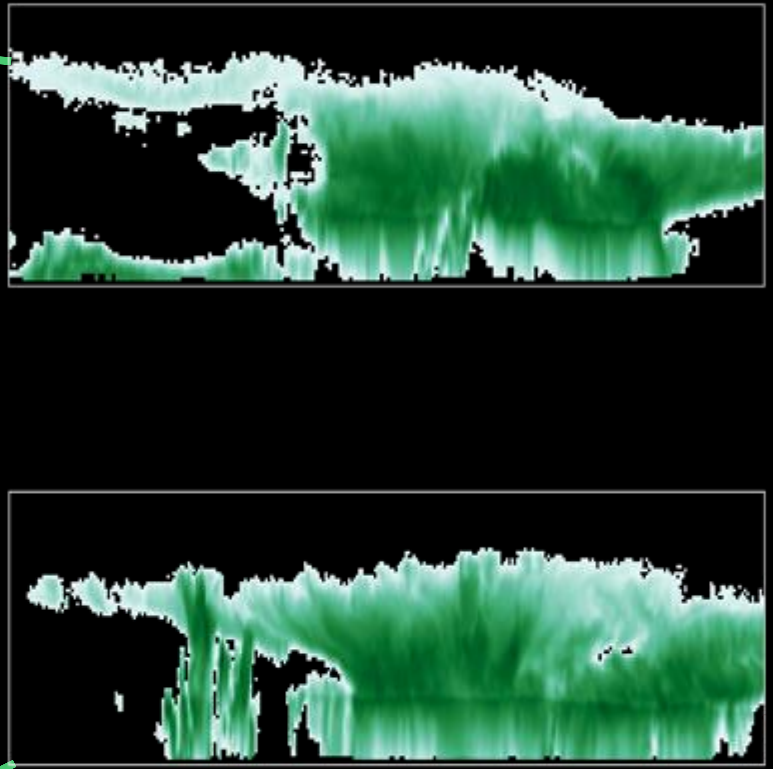


Note: resolution reduced 10x

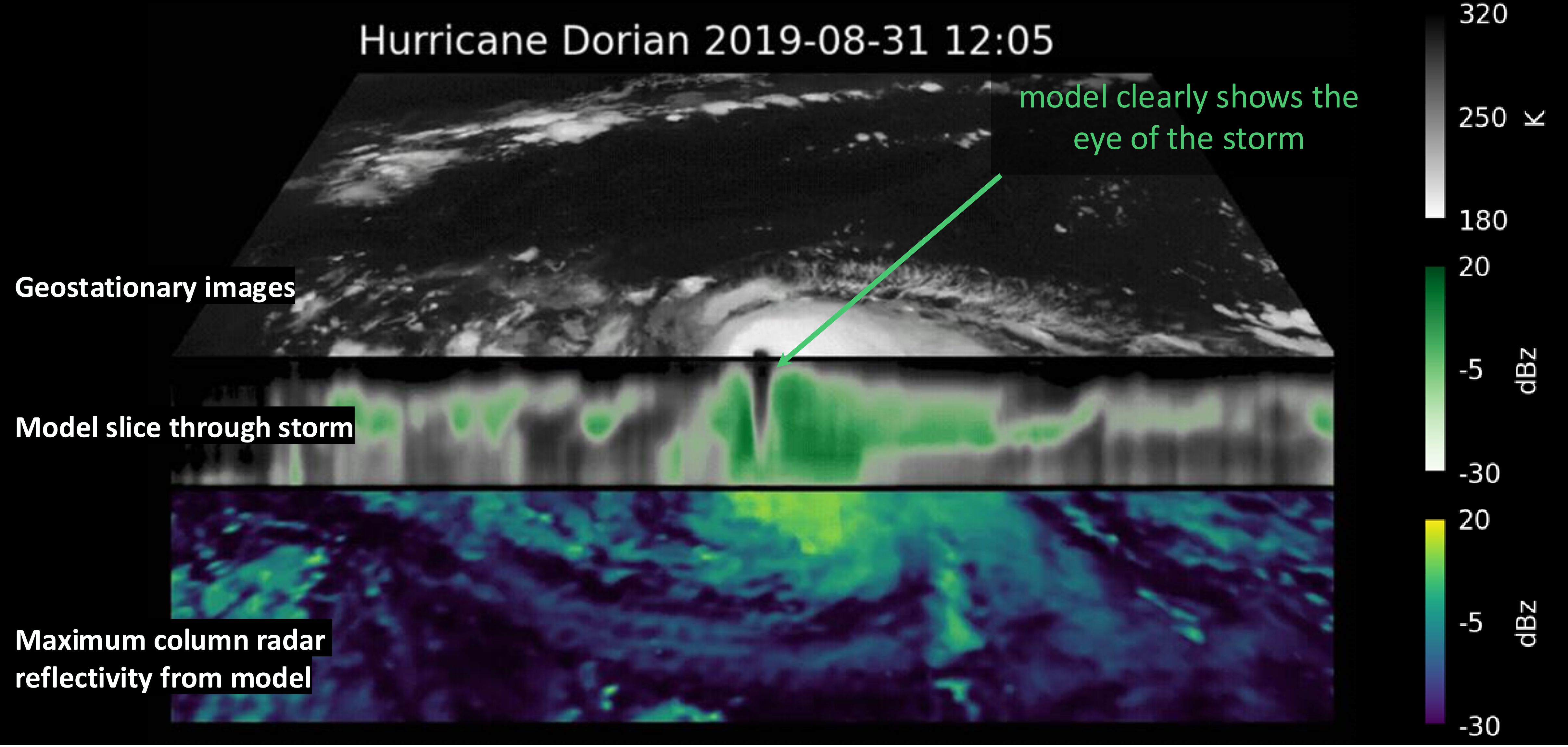
Hurricane Dorian Reconstruction



two CloudSat overpasses

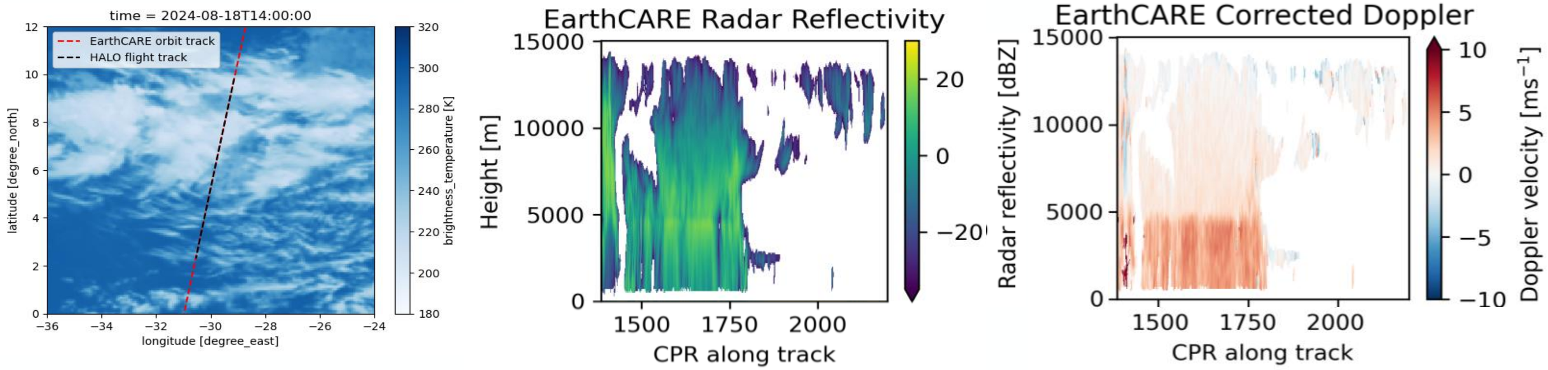


Hurricane Dorian Reconstruction

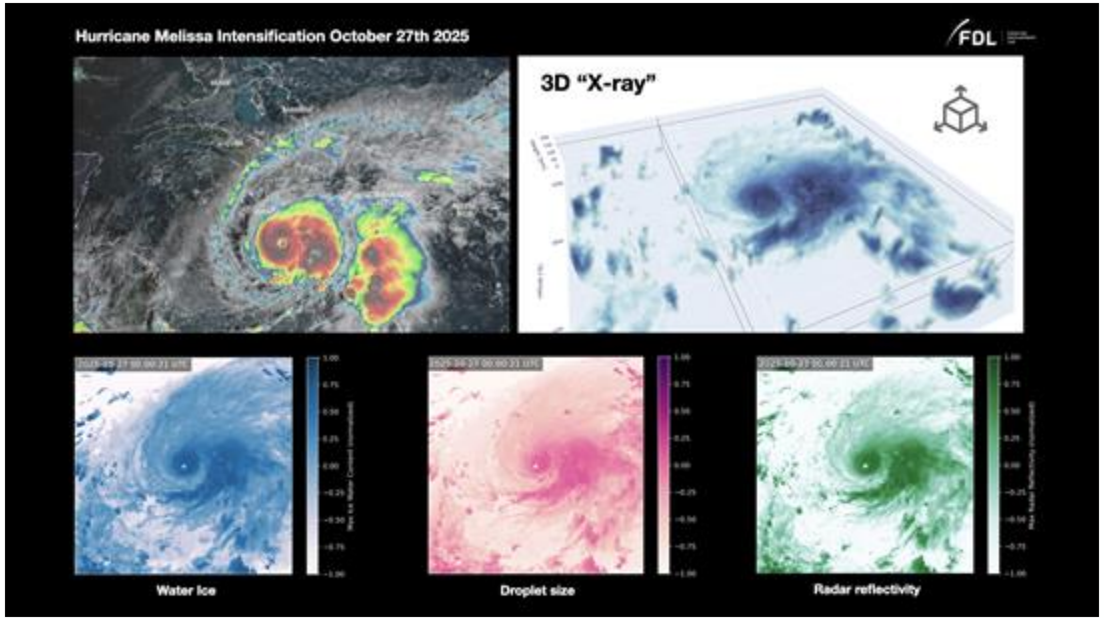


Next Steps

- Model improvements: optimising the ViT and geospatial encoding
- Application to EarthCARE data
- Validation against independent observations
- Scientific studies: how does cloud ice affect TC intensification?



EarthCARE overpass during ORCESTRA field campaign, Aug 2024



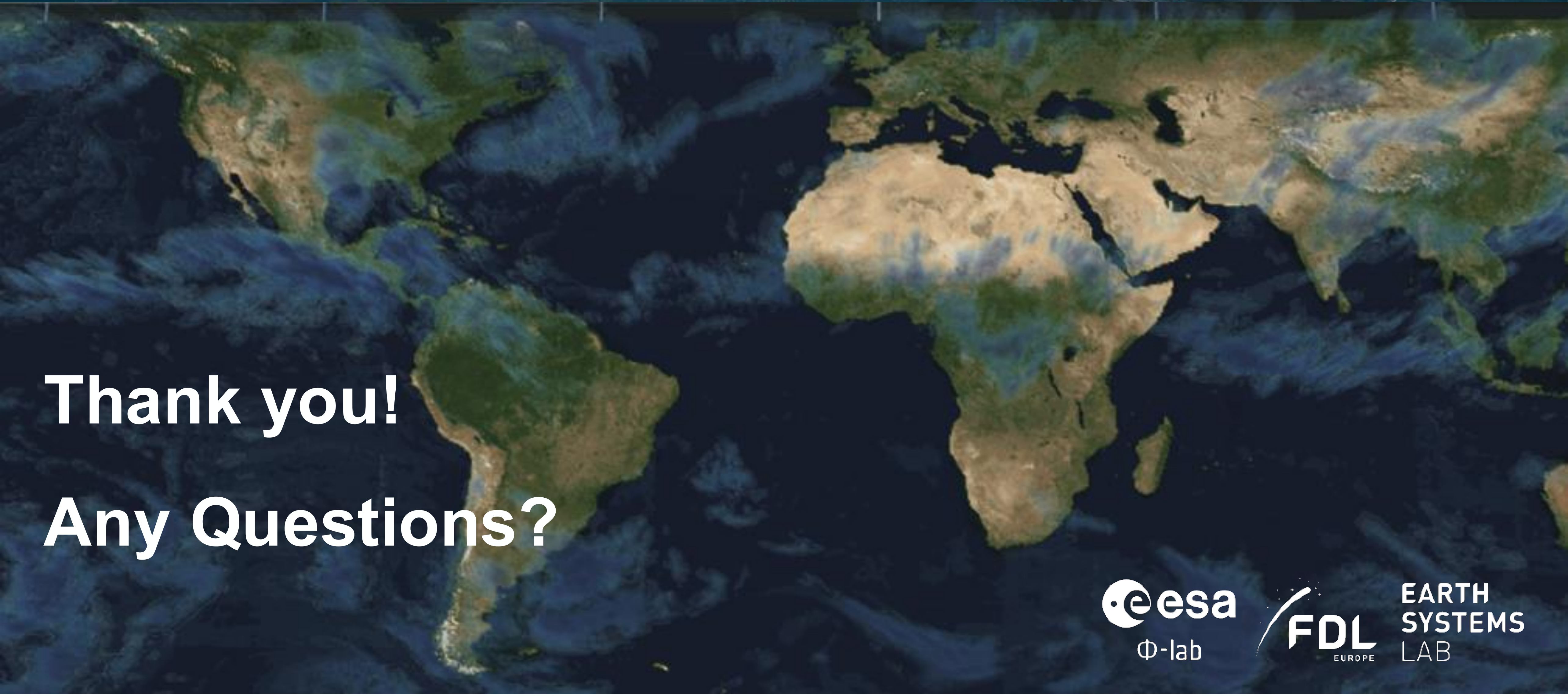
Hurricane Melissa case study

Summary

3D cloud properties are desirable for a range of scientific studies, including constraints on cloud condensate profiles, response of clouds to climate change, and behaviour of extreme weather events

3D cloud reconstruction models, using novel ML techniques, show promise in producing 3D cloud properties globally using multi-sensor input and multi-variable prediction

But, these new methods need more thorough validation to prove their worth for scientific and technical studies. Furthermore, there are many opportunities to extend these approaches, including to EarthCARE observations



Thank you!

Any Questions?