PACE OCI cloud algorithms

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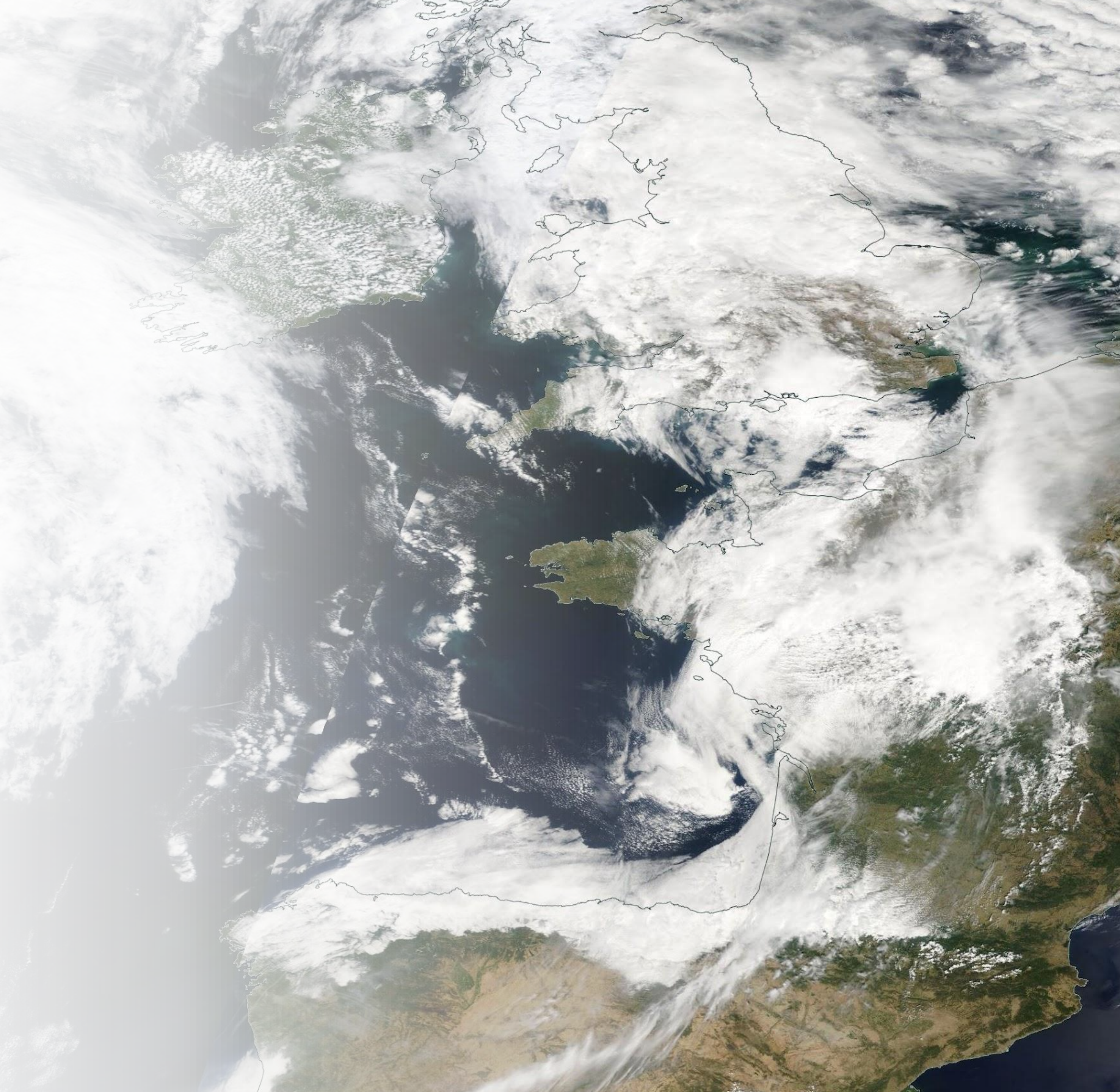
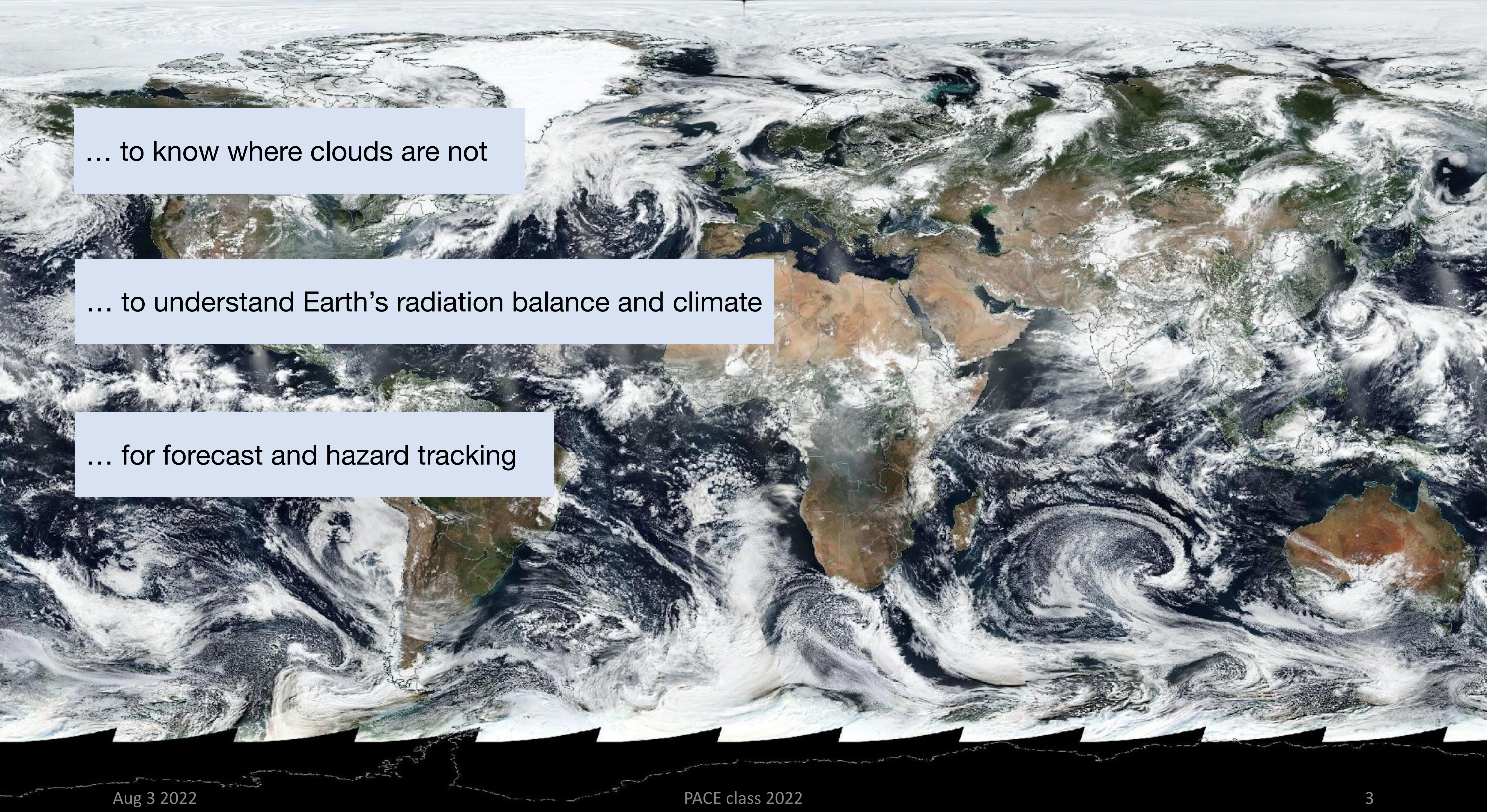
With thanks to decades of hard work
by the MODIS team and others



This lecture

- Why?
- OCI cloud products and processing flow
- Algorithms
  - Cloud mask
  - Cloud top pressure/height
  - Cloud optical properties

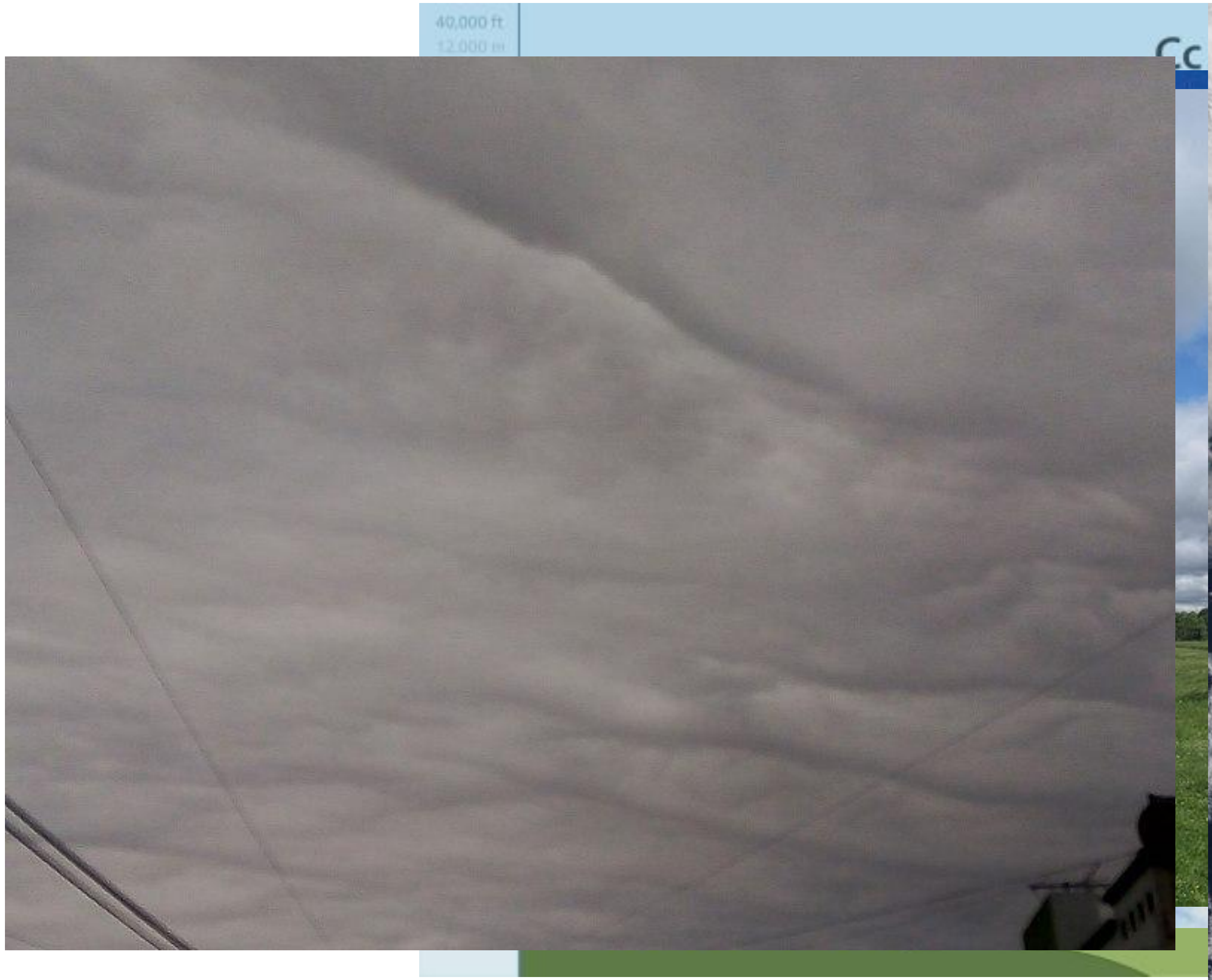


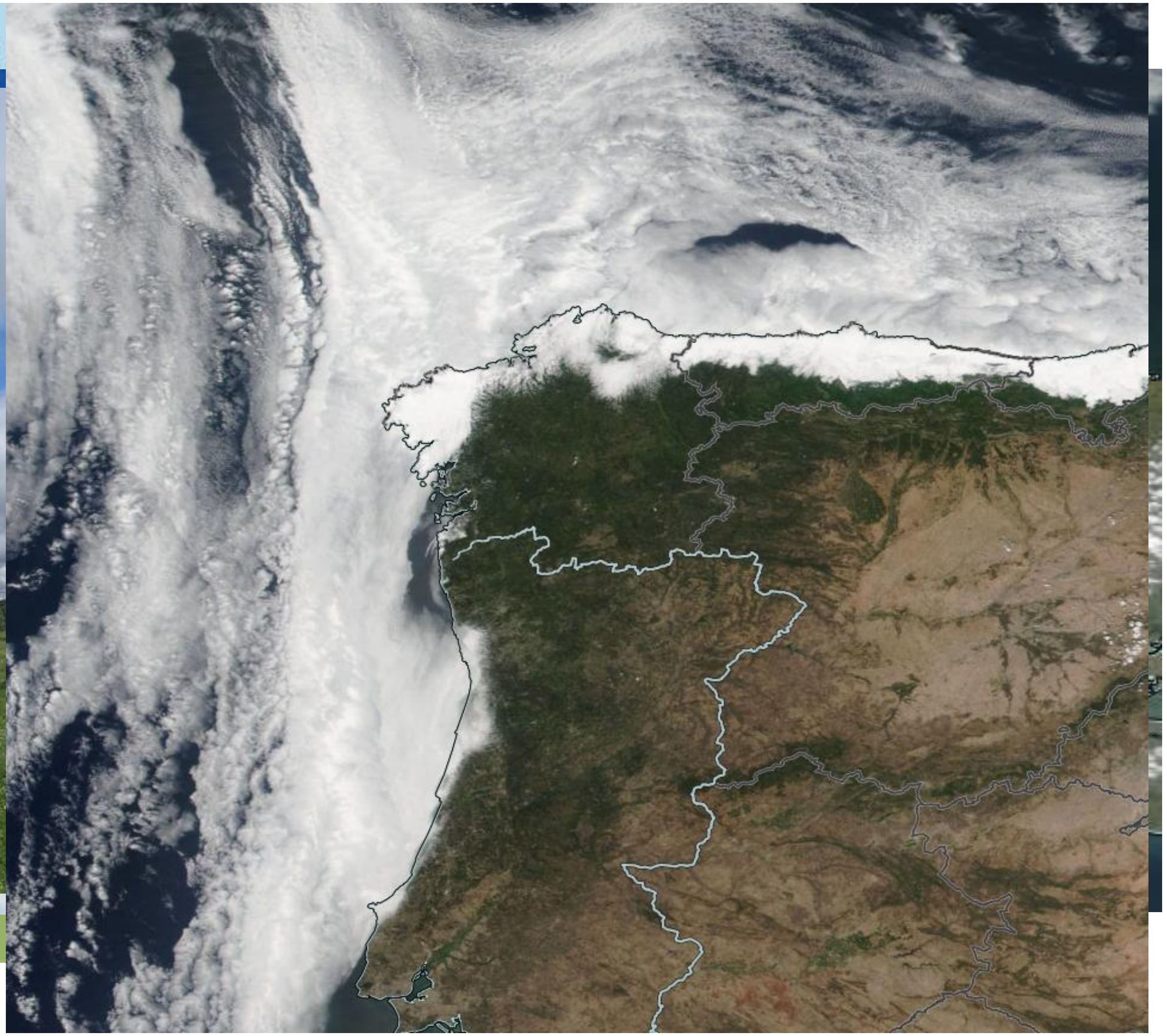
… to know where clouds are not

… to understand Earth’s radiation balance and climate

… for forecast and hazard tracking

Clouds don’t all look the same





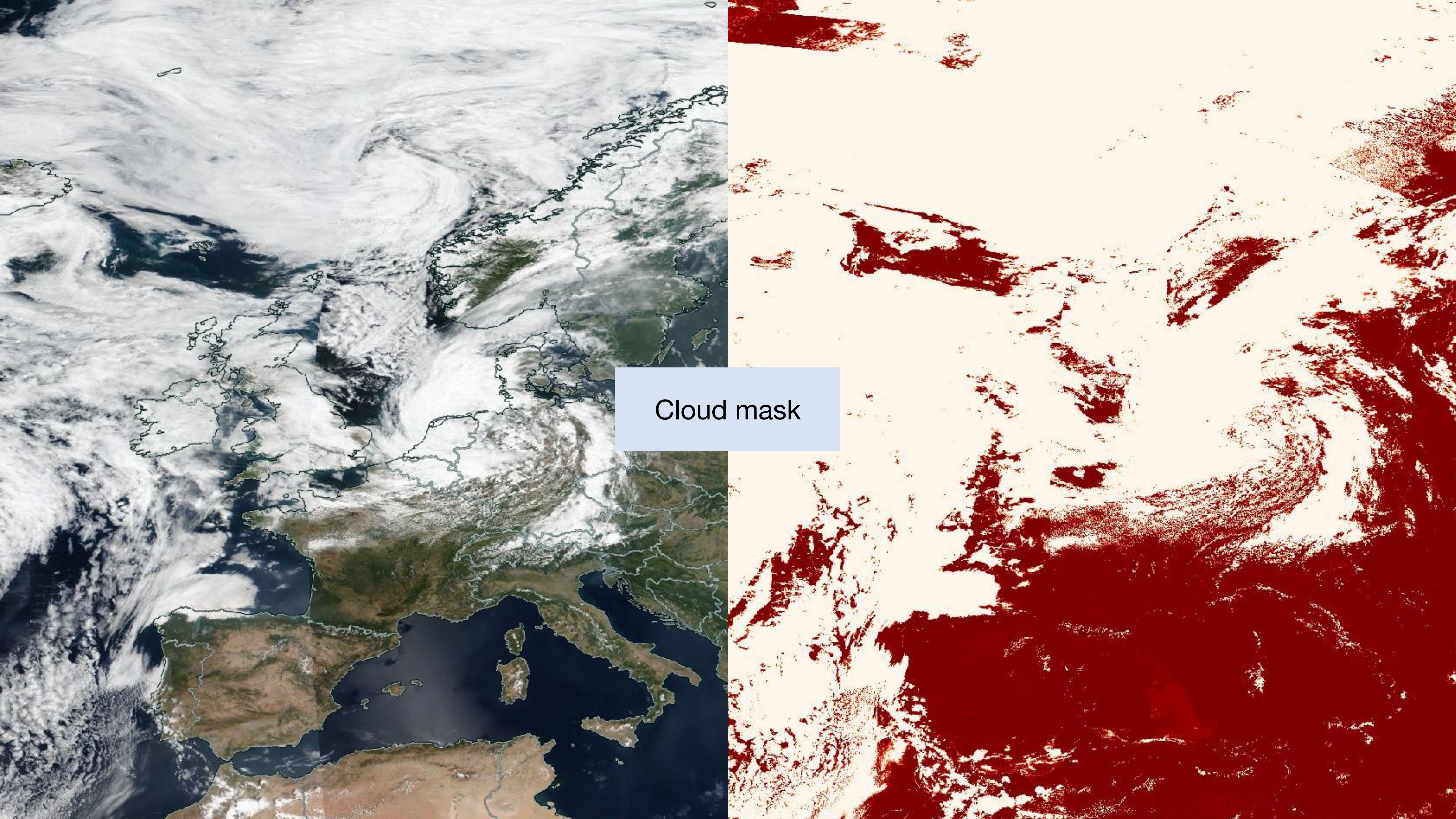
Non-satellite images from Wikipedia,
https://en.wikipedia.org/wiki/List_of_cloud_types

Plankton, Aerosol, Cloud, ocean Ecosystem

Geophysical product	Acronym	
Cloud mask	-	← **Where** are the clouds?
Cloud optical thickness at mid-visible wavelengths	COT	← **How strongly** do they scatter and absorb light?
Cloud droplet size distribution effective radius	CER	← **How large** are the droplets within the clouds?
Cloud top pressure, height, temperature	CTP, CTH, CTT	← **How high** up are the tops of the cloud?
Cloud phase	-	← Are they made of **liquid** or **ice**?
Liquid/ice water path	LWP/IWP (CWP)	← **How much water** is in them?

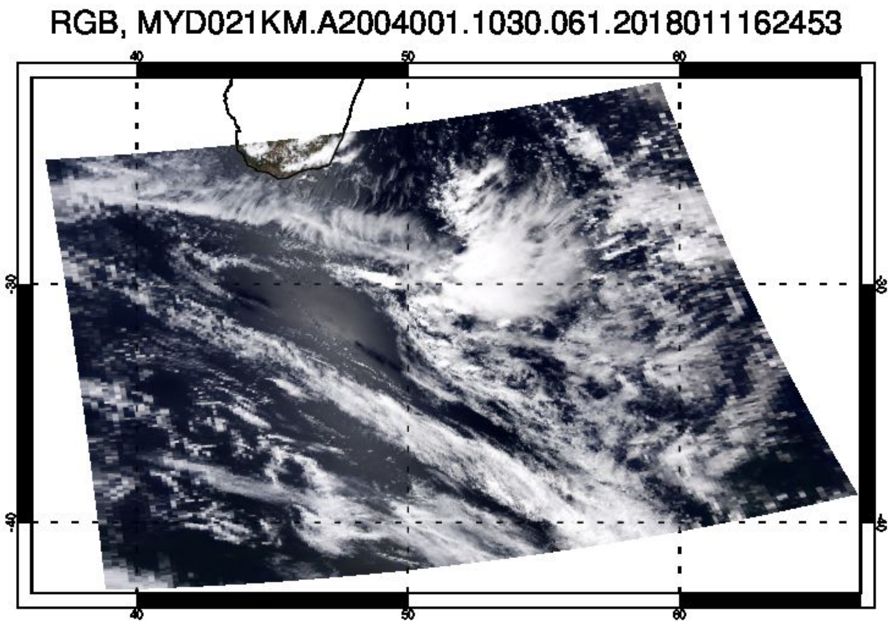
Overall processing flow is MODIS/VIIRS-like

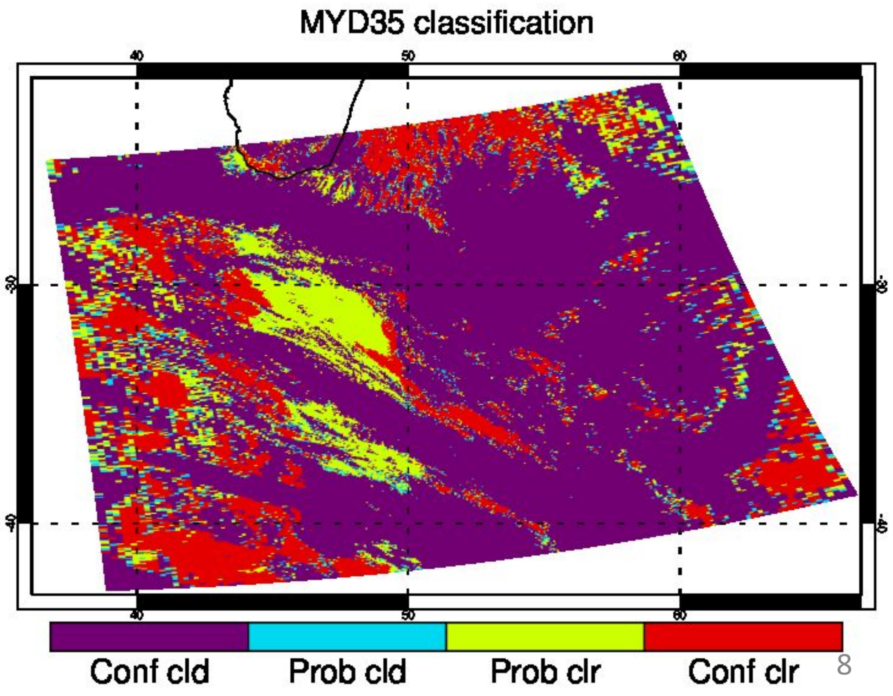
	MODIS/VIIRS heritage	PACE OCI at-launch approach
Cloud mask	Multispectral grouped threshold tests	Multispectral grouped threshold tests *or* neural network
Cloud altitude & phase	Thermal brightness temperatures & meteorological profile	O_2 A-band inversion & meteorological profile
COT, CER, phase	Bispectral retrieval (Nakajima-King) aka CHIMAERA code	
Water path	One-line calculation (with assumptions on vertical structure)	


Cloud mask

Obtain an estimate of whether a pixel is covered by clouds or not

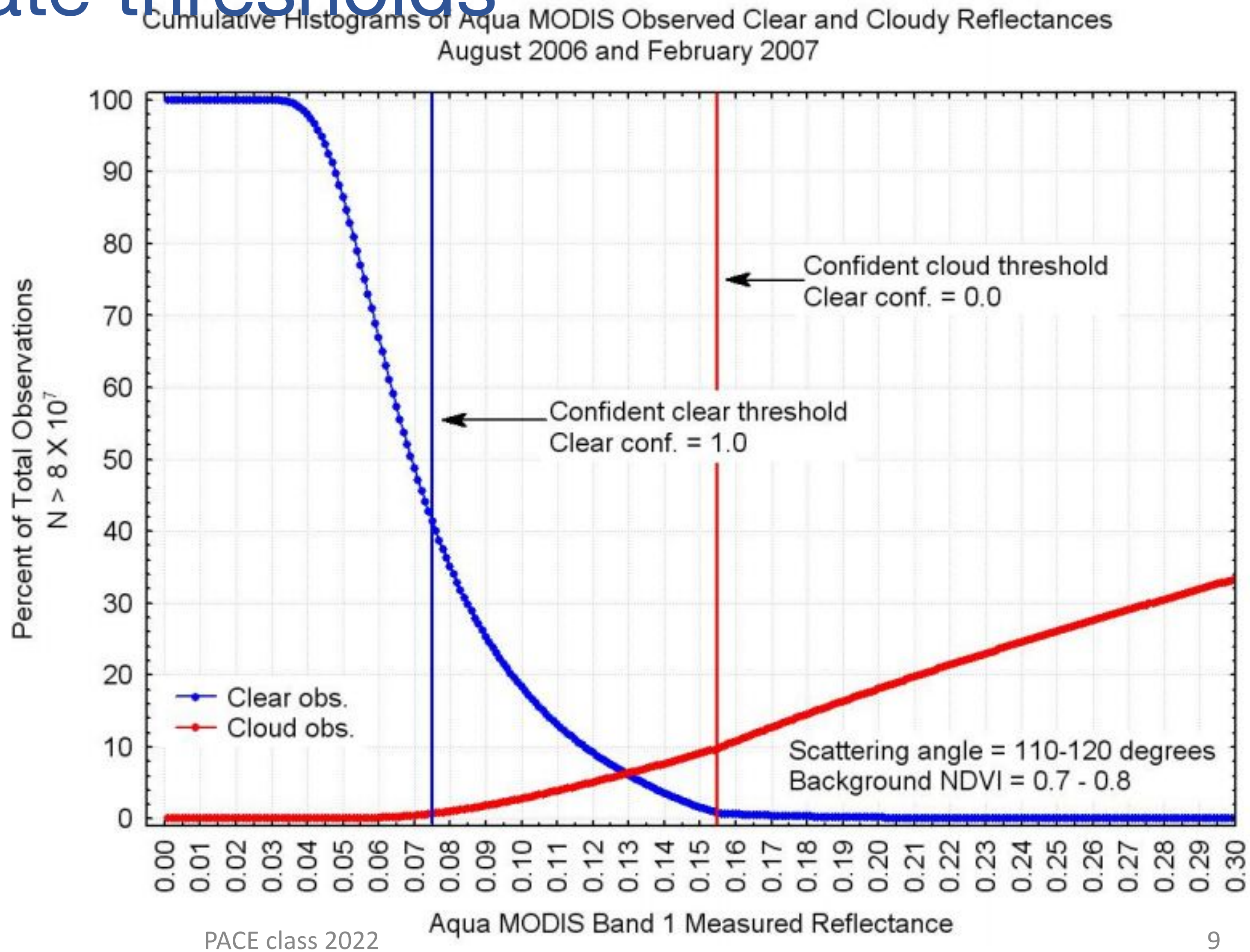
- A *categorical* cloud mask
  - Confidently cloudy
  - Probably cloudy
  - Probably clear
  - Confidently clear
- Further processing for some applications
  - Combine categories to give a *binary* mask
  - Add an *adjacency* barrier





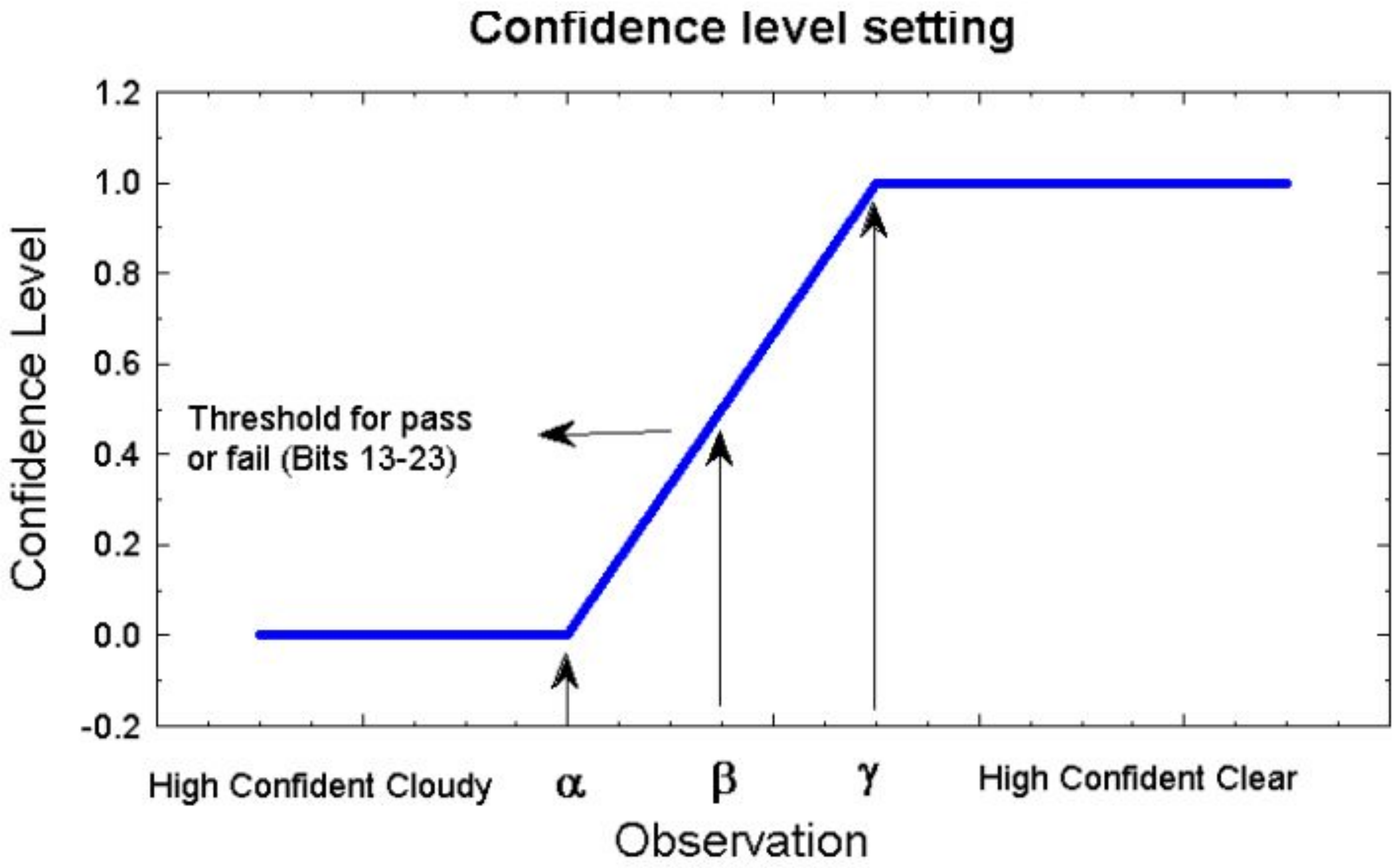
We need statistics of cloudy and cloud-free scenes
to inform appropriate thresholds

- Inputs could be *theoretical*, from *similar* sensors and algorithms, or from *human-labelled* data
- Overlapping distributions signal *ambiguity*
- We use published MODIS thresholds directly



From MOD35 ATBD here

Use thresholds as bounds to define a ‘probability of clear sky’ for each test



From MOD35 ATBD here

Combine result from similar tests to get an overall probability of cloudiness

Group I (Simple IR threshold test)

BT_{11}

$BT_{13.9}$

$BT_{6.7}$

Surface Temperature

Group II (Brightness temperature difference)

$BT_{8.6}$ - BT_{11}

BT_{11} - BT_{12}

$BT_{7.3}$ - BT_{11}

BT_{11} - $BT_{3.9}$

$BT_{8.6} - BT_{7.3}$

Group III (Solar reflectance tests)

$R_{0.65}$ or $R_{0.86}$

$R_{0.86}/R_{0.65}$

Group IV (NIR thin cirrus)

$R_{1.38}$

Group V (IR thin cirrus)

$BT_{3.9}$ - BT_{12}

From MOD35 ATBD here

- Determine the *lowest probability* of clear-sky conditions from tests in each group
- *Combine* results from multiple groups
- *Q* score determines pixel category

$$G_{i=1,5} = \min[F_i].$$

$$Q = \sqrt[N]{\prod_{i=1}^{N} G_i}$$

Lack of thermal bands means majority of MODIS/VIIRS heritage tests are inapplicable

Group I (Simple IR threshold test)

BT_{11}

Group II (B… …ture difference)

$BT_{7.3} - BT_{11}$

BT_{11} - $BT_{3.9}$

$BT_{8.6} - BT_{7.3}$

Group III (Solar reflectance tests)

$R_{0.65}$ or $R_{0.86}$

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From MOD35 ATBD here

Group IV (NIR thin cirrus)

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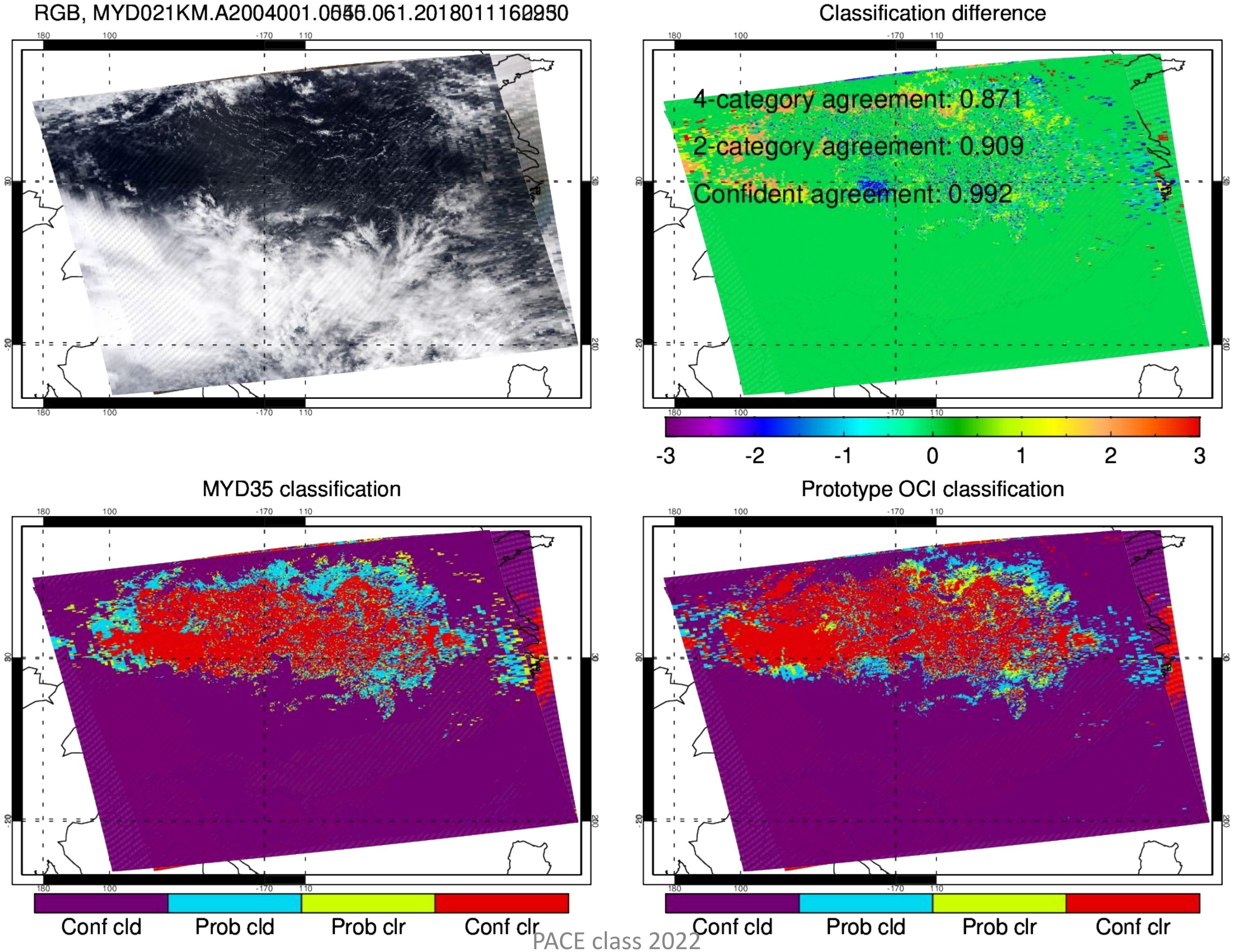
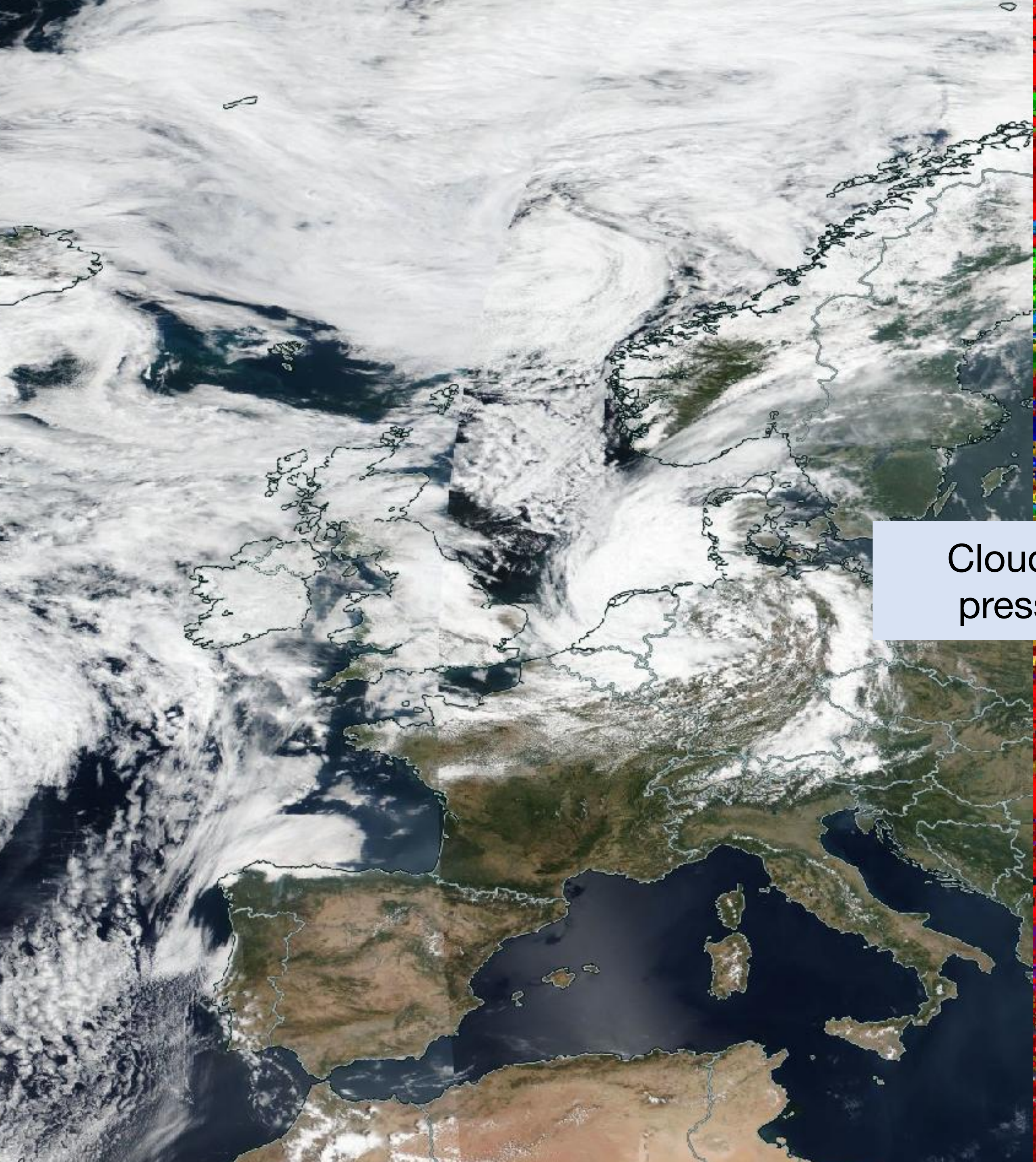
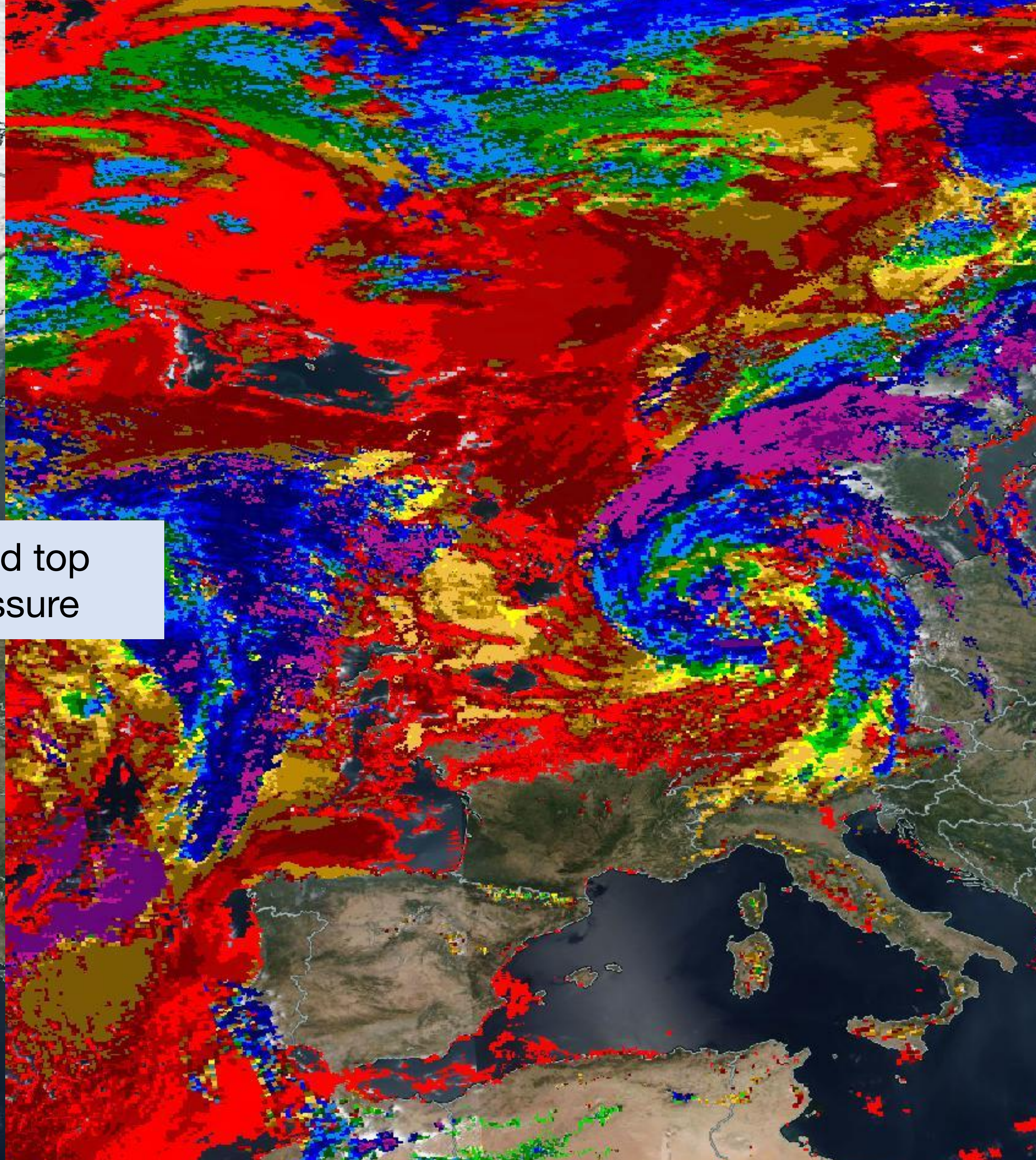
Solar-only works quite well over water, less over land



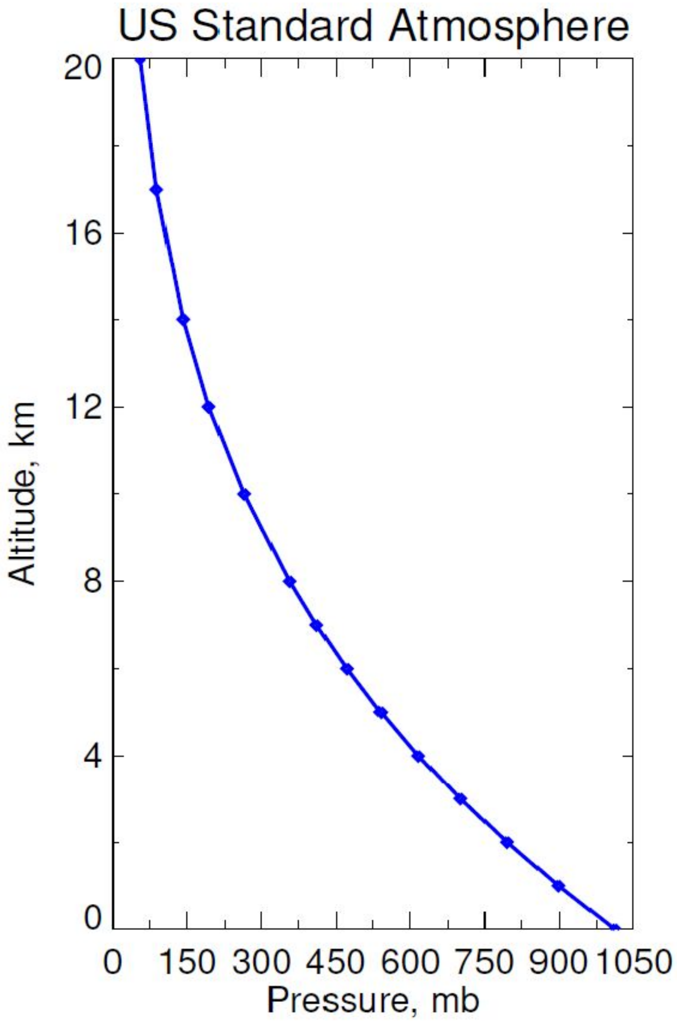


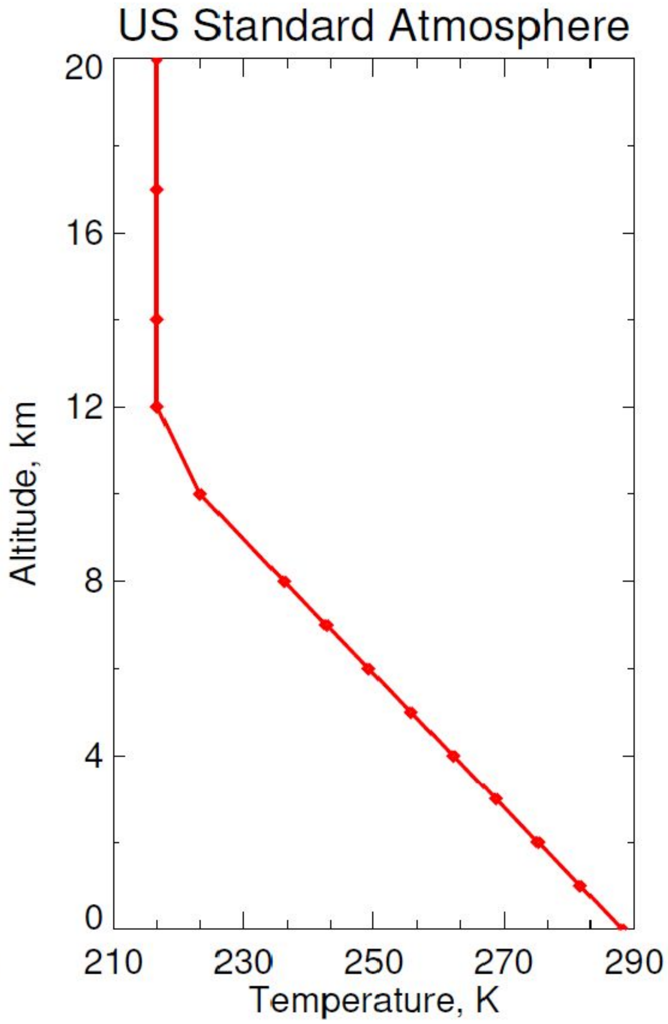
Cloud top pressure



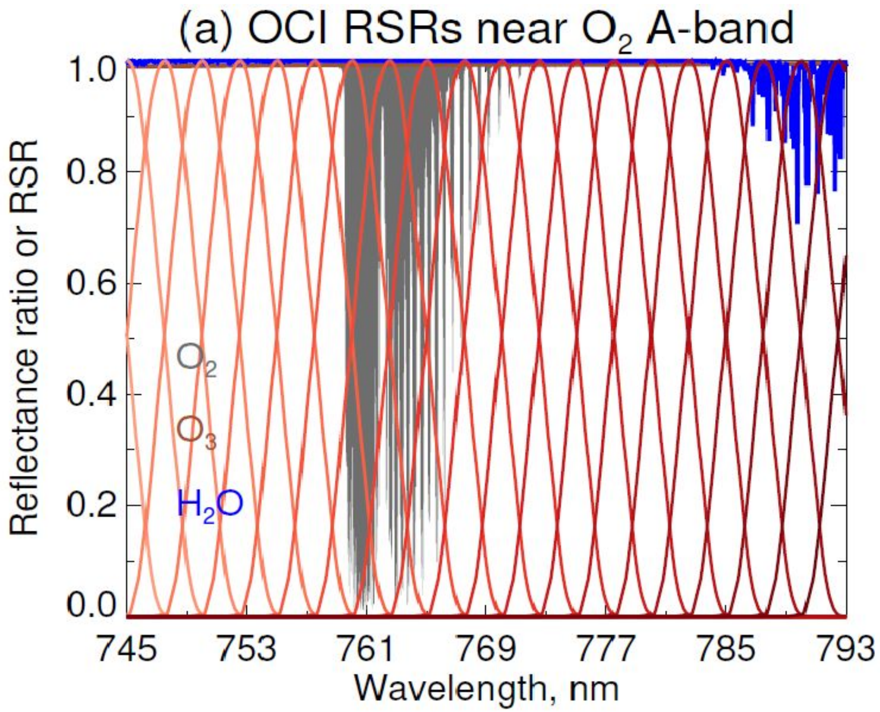
Obtain an estimate of the altitude of the top of the cloud

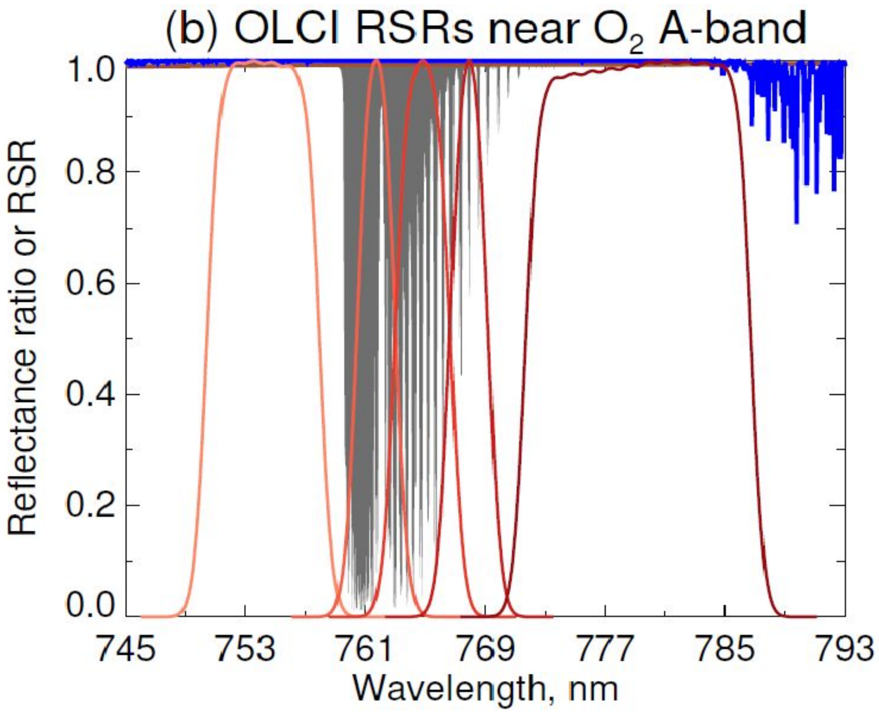
- OCI is sensitive to *pressure* (CTP)
  - Coordinate transform to *height* (CTH) and *temperature* (CTT) with meteorological profiles
- New algorithm based on O_2 A-band absorption





OCI samples strong O_2 absorption features

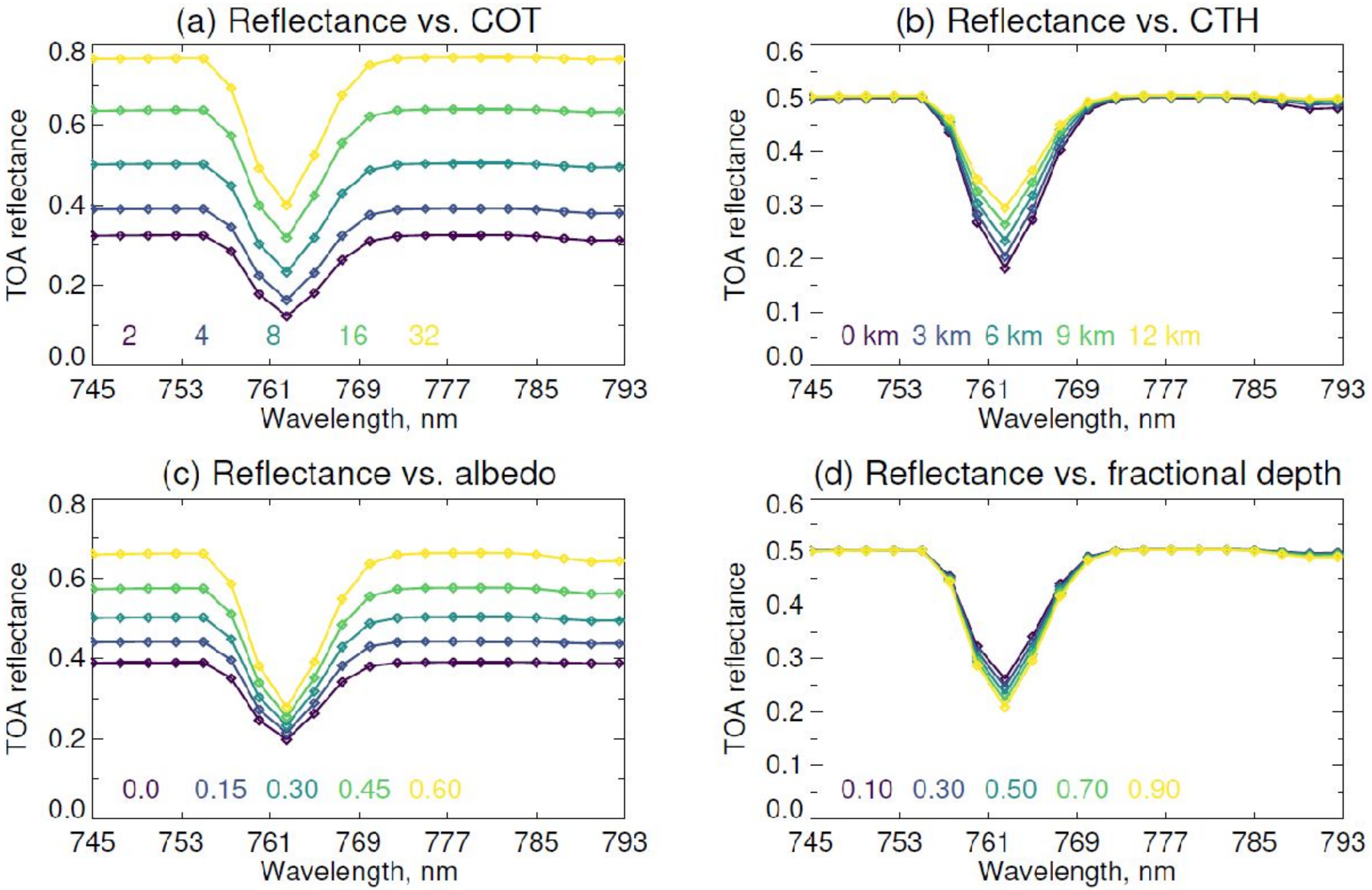




- Combine *window* channels near O_2 absorption band with channels *inside* it
  - O_3 absorption is weak; need to avoid H_2O features
  - Short spectral range means cloud, aerosol, surface properties are fairly flat

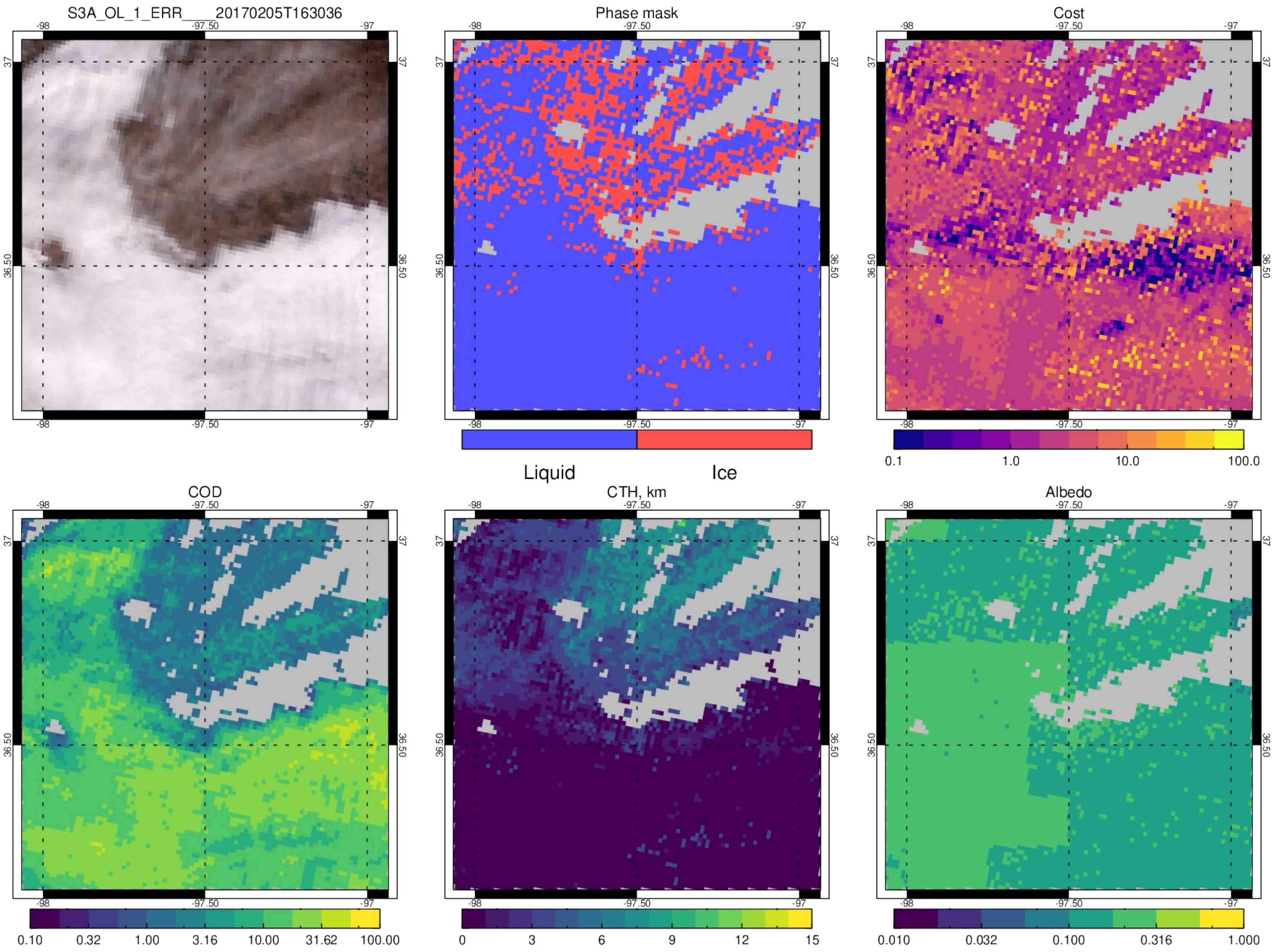
The A-band signal is sensitive to COT, surface albedo, and cloud vertical structure

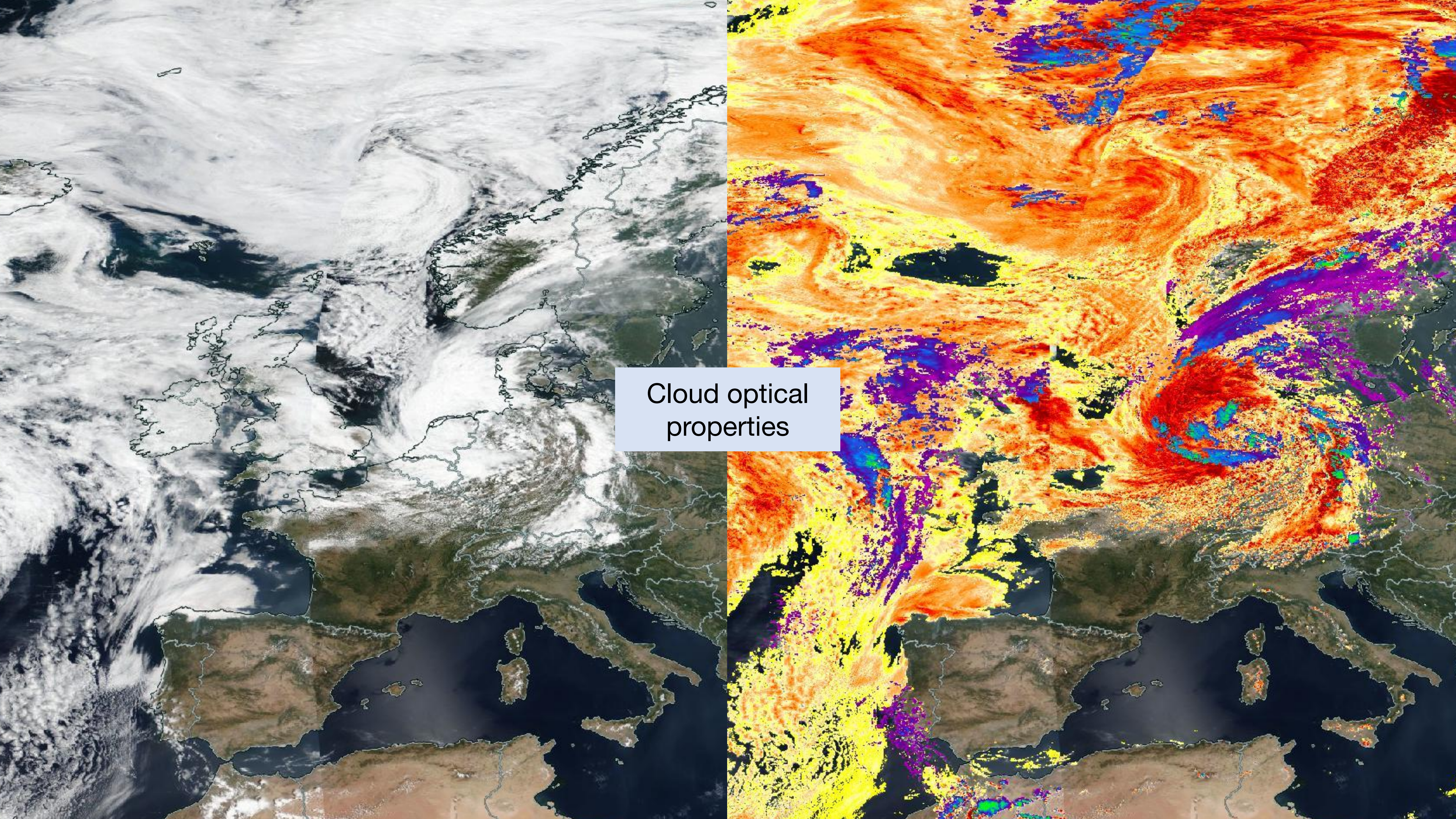
- *Simultaneously* retrieve COT, CTH, and surface albedo
  - Strong albedo prior constraint
- Assume other quantities
  - Cloud vertical structure, aerosol, etc
- Estimate cloud phase by running retrieval for *both liquid and ice* and see what fits best



Sentinel-3 OLCI is a useful OCI proxy for this algorithm

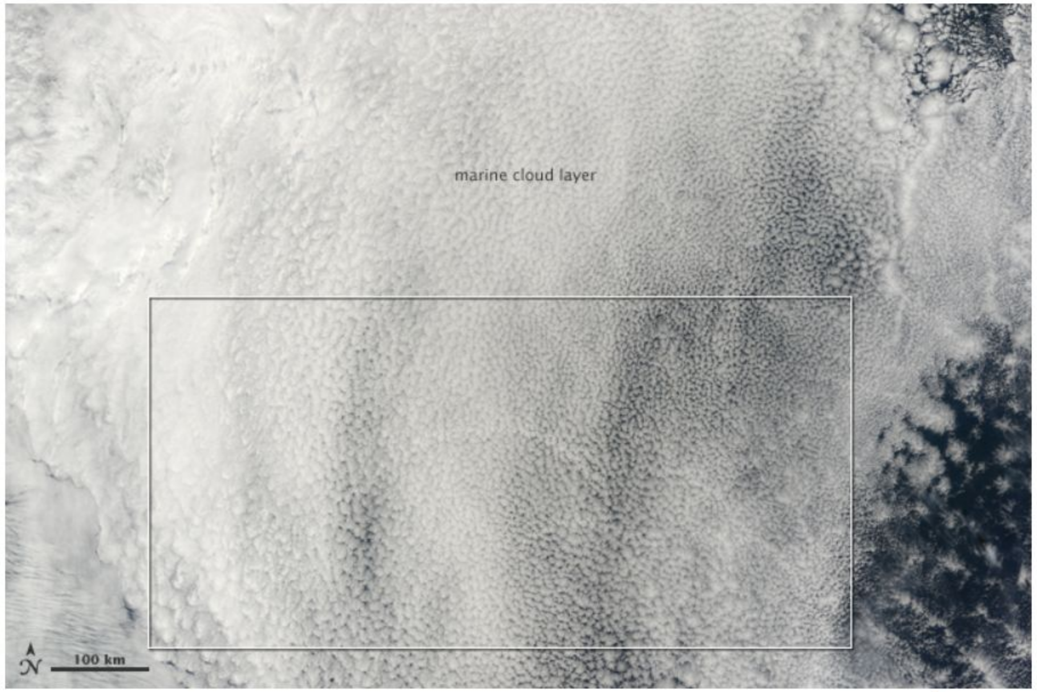
- Similar capabilities within the A-band
- Similar pixel size
- Can evaluate algorithm prior to launch

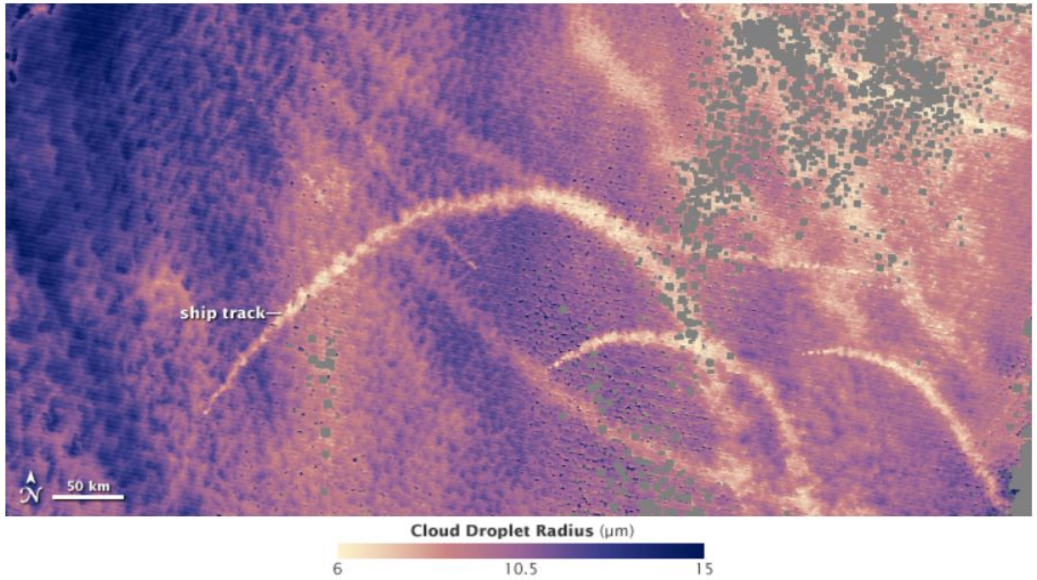



Cloud optical
properties

Obtain estimates of cloud light extinction, cloud droplet particle size, and total amount of water

- Use CHIMAERA code from MODIS/VIIRS group
  - Retrieve COT, CER, and phase estimate
  - Derive LWP/IWP
- Last in processing chain:
  - Needs cloud mask to *identify pixels*
  - Needs CTH for *trace gas correction*
  - Benefits from altitude *phase estimate*

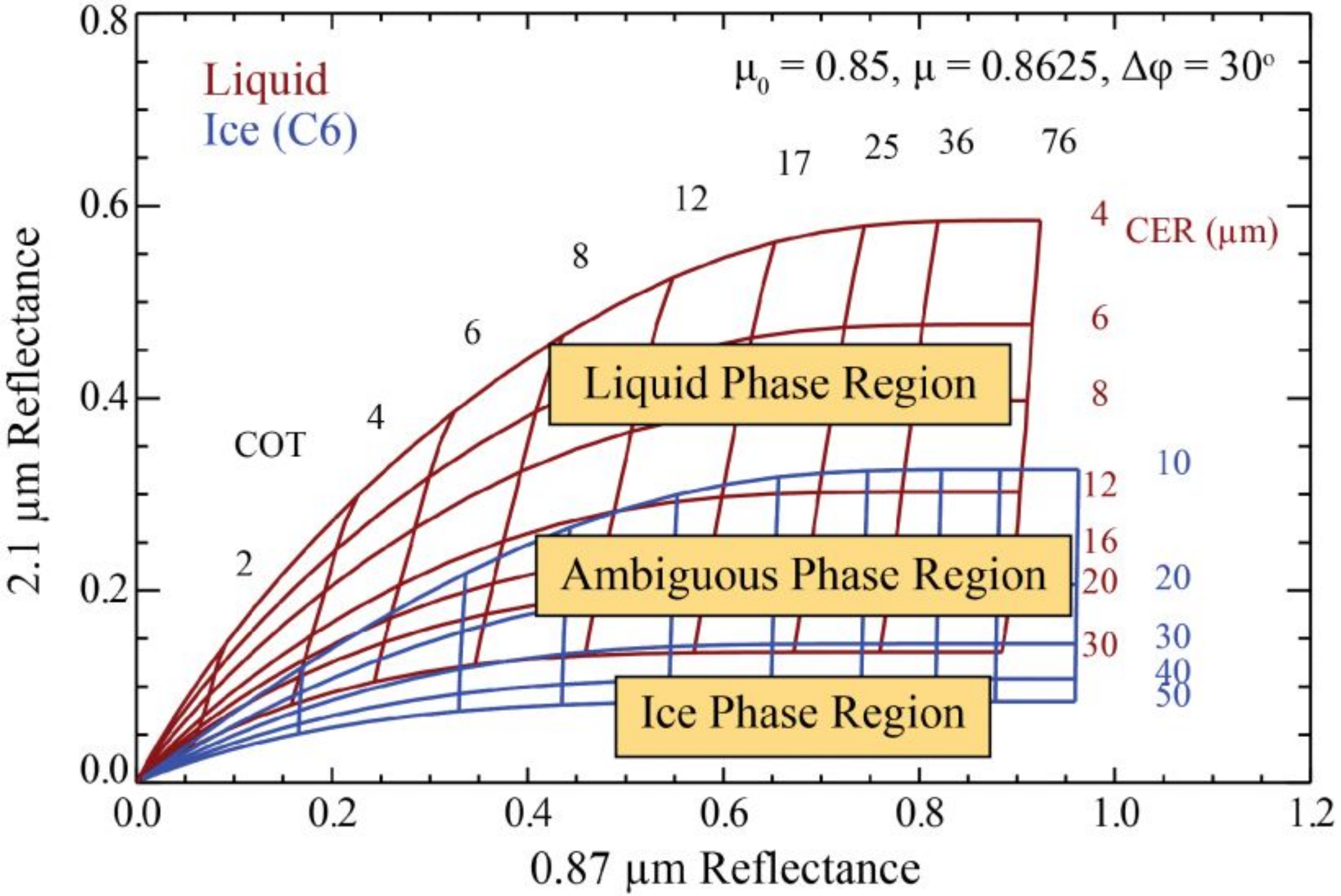




From https://earthobservatory.nasa.gov/images/44517/ship-tracks-in-the-north-pacific

The bispectral approach has >30 years heritage

- Bispectral approach (Nakajima-King)
  - 650 or 865 nm where cloud absorption is negligible
  - 1.6, 2.1, or 2.2 µm where cloud absorption is significant
- Assume surface albedo known



From Platnick et al., *IEEE* (2017)

Different swIR bands have different penetration depths

- Photon penetration depth depends on cloud water absorption
- Multiple retrievals inform on cloud *vertical structure*
  - PACE OCI is first time we'll have 2.1 and 2.2 μm together
  - Won't have 3.7 μm

From Platnick *JGR* (2000)

Summary

- Cloud remote sensing from passive multispectral imaging has a long history
- PACE OCI will mostly rely on MODIS/VIIRS heritage approach at launch
  - Threshold-based cloud masking
    - Neural network in development as an alternative
  - Cloud top pressure is a new retrieval using absorption in O_2 A-band channels
    - Necessary because no thermal infrared bands on OCI
    - Heritage on European sensors and EPIC
  - Running the CHIMAERA code for optical properties
- All processed on single pixels at a time

References and resources

- Satellite imagery (true-colour and level 2) is MODIS and VIIRS on July 21 2022, mostly from https://worldview.earthdata.nasa.gov
- MODIS/VIIRS heritage cloud mask
  - MODIS ATBD at https://modis-atmosphere.gsfc.nasa.gov/sites/default/files/ModAtmo/MOD35_ATBD_Collection6_1.pdf
  - MODIS-VIIRS continuity ATBD at https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/viirs/MODIS_VIIRS_Cloud-Mask_UG_04162020.pdf
- CHIMAERA code and related papers

  - Nakajima, T., & King, M. D. (1990), Determination of the Optical Thickness and Effective Particle Radius of Clouds from Reflected Solar Radiation Measurements. Part I: Theory, Journal of Atmospheric Sciences, 47(15), 1878-1893, https://doi.org/10.1175/1520-0469(1990)047%3C1878:DOTOTA%3E2.0.CO;2
  - Platnick, S. (2000), Vertical photon transport in cloud remote sensing problems, *J. Geophys. Res.*, 105(D18), 22919– 22935, https://doi.org/10.1029/2000JD900333
  - Platnick, S., K. G. Meyer, M. D. King, G. Wind, N. Amarasinghe, B. Marchant, G. T. Arnold, Z. Zhang, P. A. Hubanks, R. E. Holz, P. Yang, W. L. Ridgway, and J. Riedi (2017), The MODIS cloud optical and microphysical products: Collection 6 updates and examples from Terra and Aqua, *IEEE Trans Geosci Remote Sens*, 55(1), 502–525, https://doi.org/10.1109/TGRS.2016.2610522
  - Wind, G., S. Platnick, K. Meter, T. Arnold, N. Amarasinghe, B. Marchant, and C. Wang (2021), The CHIMAERA system for retrievals of cloud top, optical and microphysical properties from imaging sensors, *Computers & Geosciences*, 149, 104710, https://doi.org/10.1016/j.cageo.2021.104710

- Cloud top pressure

  - Sayer, A. M., L, Lelli, B. Cairns, B. van Diedenhoven, A. Ibrahim, K. Knobelspiesse, S. Korkin, and P. J. Werdell, The CHROMA cloud top pressure/height retrieval algorithm for the forthcoming NASA PACE OCI, *Atmos. Meas. Tech.*, submitted