

Development of innovative uses of CALIOP data

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Research Center

Outline

1. CALIPSO brief introduction
2. New Applications
 - Land (elevation, forest canopy)
 - Ocean (k_d , b_{bp} , bathymetry)
 - Cryosphere (snow/ice, melting)
3. Summary and Future work

1.CALIPSO brief introduction

CALIPSO Payload: Three Near Nadir Viewing instruments

Lidar

CALIOP

Cloud-Aerosol Lidar with Orthogonal Polarization

Vertical profiles of atmosphere

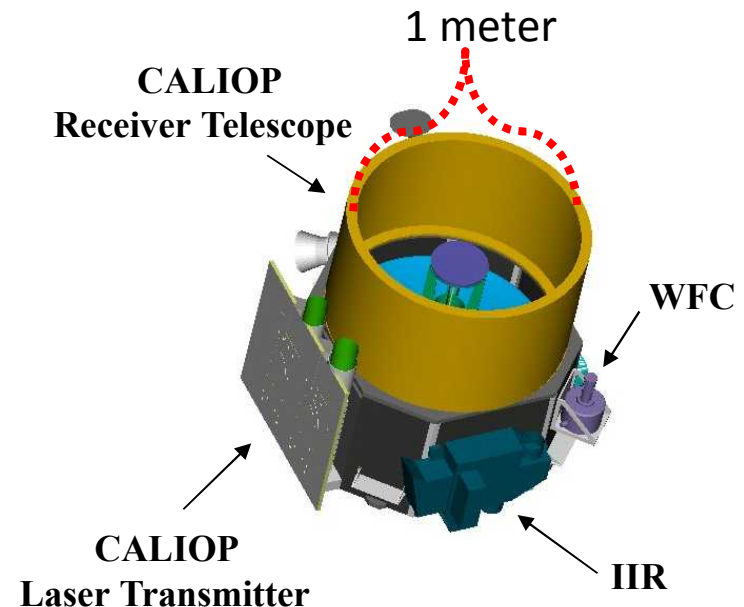
2 wavelength polarization sensitive lidar:
1064 nm, 532 nm (parallel and perpendicular)

Wide Field Camera (WFC)

High-resolution image (125m resolution)

Imaging Infrared Radiometer (IIR)

High-resolution image (swath product)



CALIOP lidar

Table 2.3 Spatial resolution of downlinked data

<u>Altitude Range (km)</u>	<u>Horizontal Resolution (km)</u>	<u>532 nm Vertical Resolution (m)</u>	<u>1064 nm Vertical Resolution (m)</u>
30.1 to 40.0	5.0	300	---
20.2 to 30.1	1.67	180	180
8.2 to 20.2	1.0	60	60
-0.5 to 8.2	0.33	30	60
-2.0 to -0.5	0.33	300	300

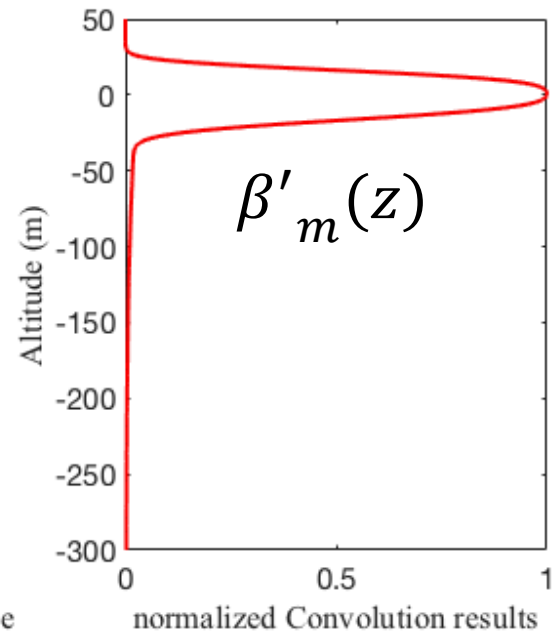
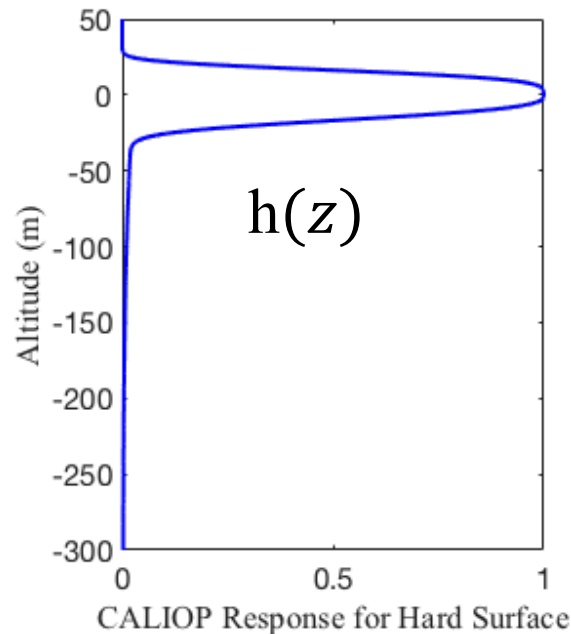
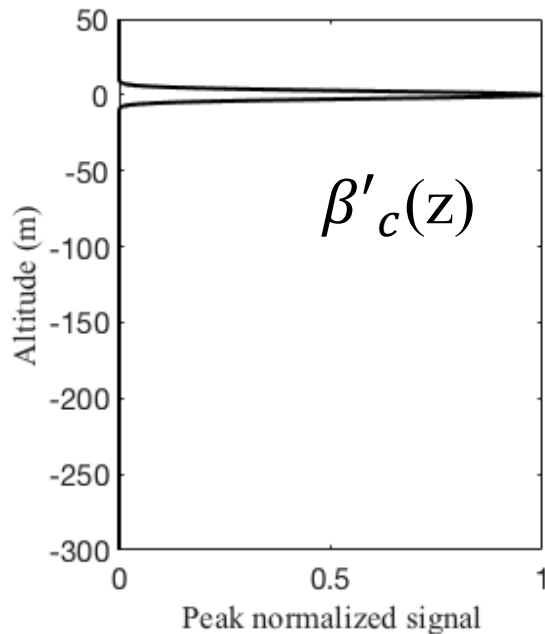
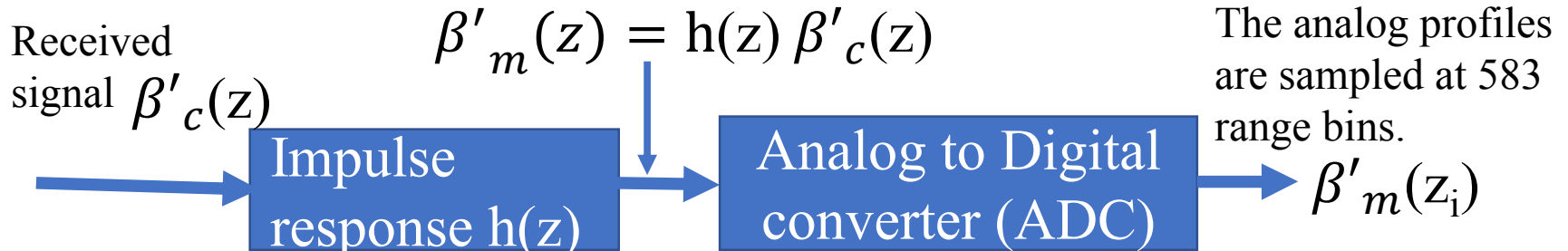
Questions:

- Can CALIOP give better surface vertical resolution
 - ❖ 1m vs. 30m
- Can CALIOP tell us deep water vs. shallow water?
 - ❖ K_d , b_{bp}
 - ❖ Water depth
- Can CALIOP tell us different surface types:
 - ❖ water,
 - ❖ bare ground,
 - ❖ Snow and sea ice cover,
 - ❖ Melting pond

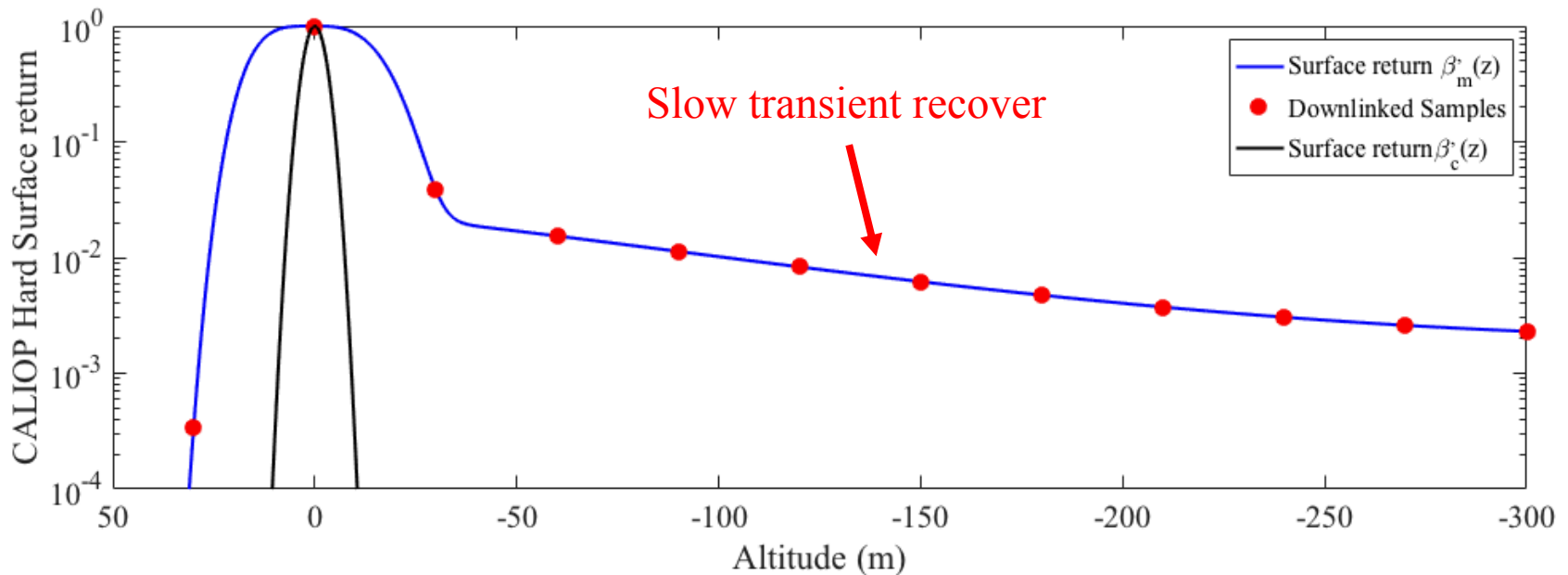
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CALIOP receiver model



CALIOP receiver model



Please Note:

- The downlinked samples near the surface are from one surface return.
- CALIOP impulse response exhibits a non-ideal recovery of the lidar signal after a strong backscattering target.

Slow transient recovery-example

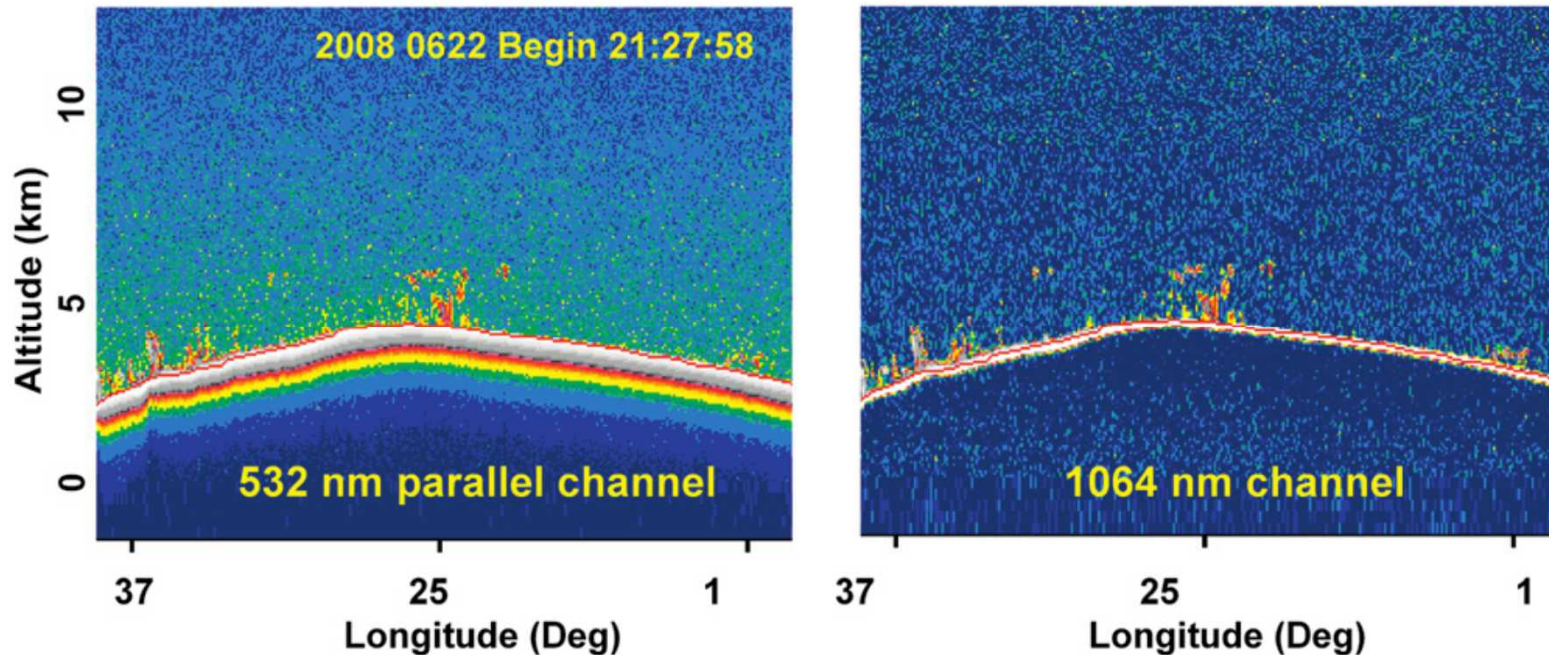
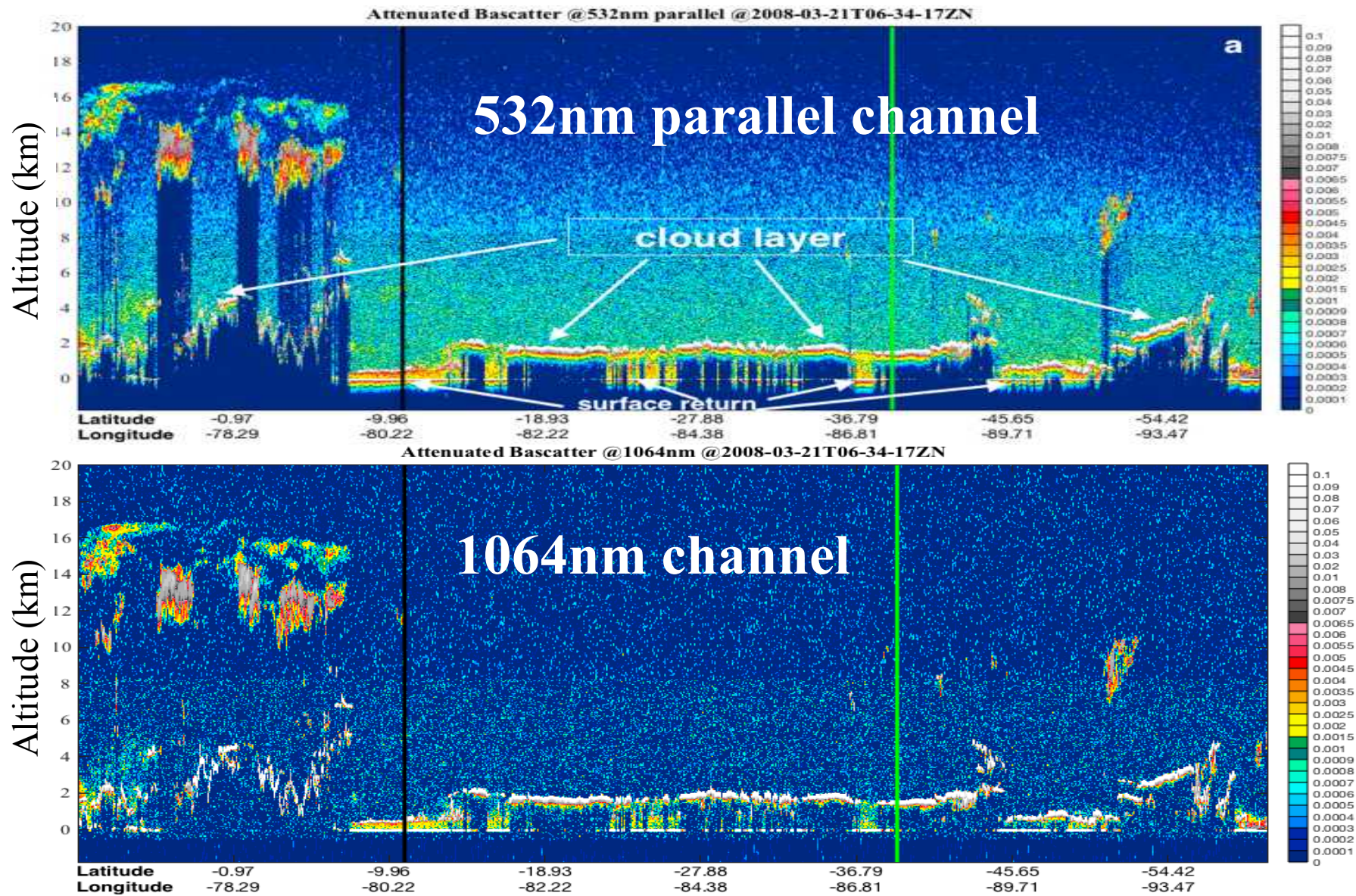
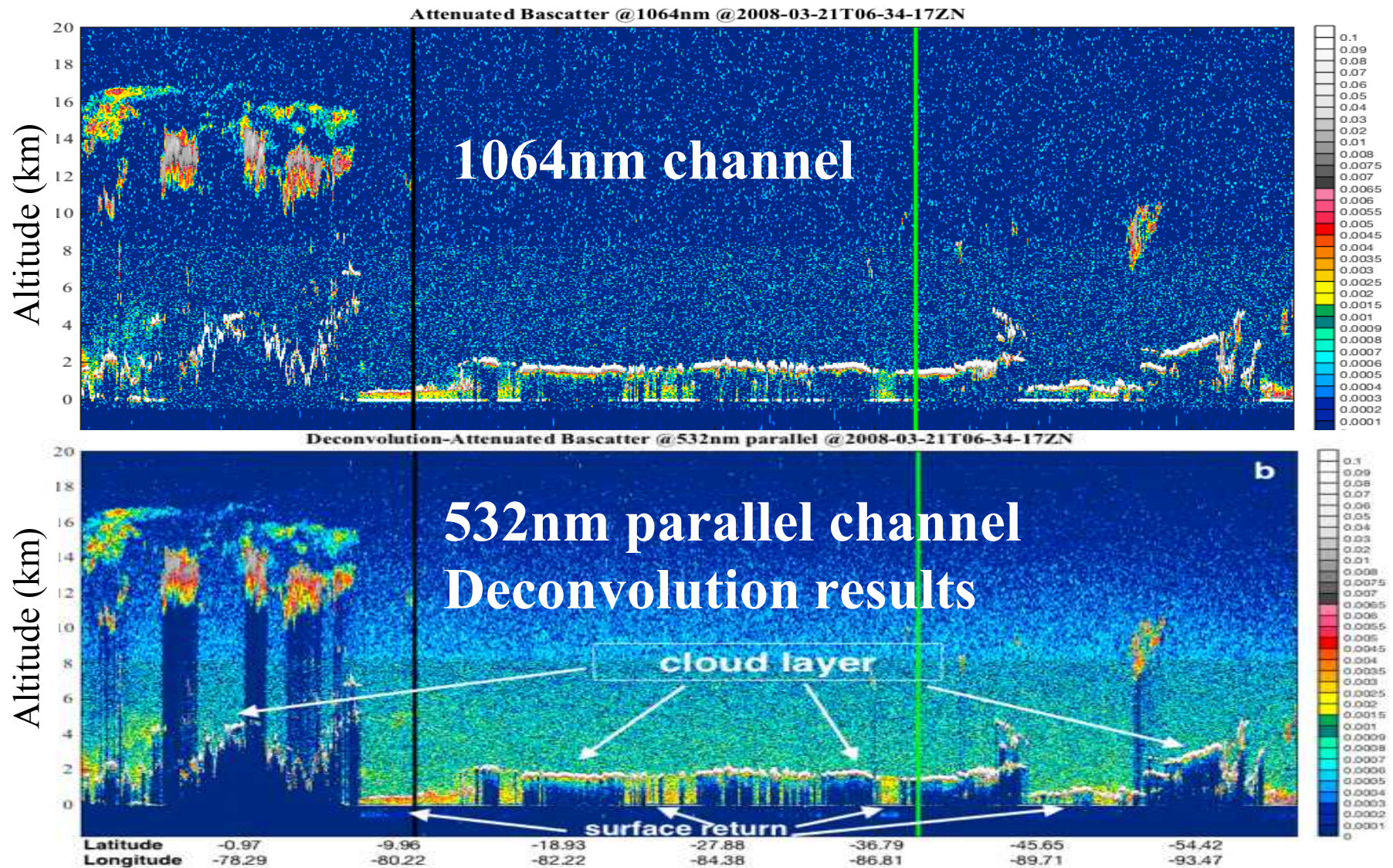


FIG. 17. Browse images of the 532- and 1064-nm backscatter signals from the ice-covered surface of Antarctica illustrating the slow transient recovery of the 532-nm channel PMT. The 532-nm channel signal shows a rainbow of colors below the surface as the PMT output goes slowly to zero after the surface return. The 1064-nm channel signal goes immediately to zero after the surface return. The location of the surface, as given by a digital surface elevation model, is shown by a red line in both images.

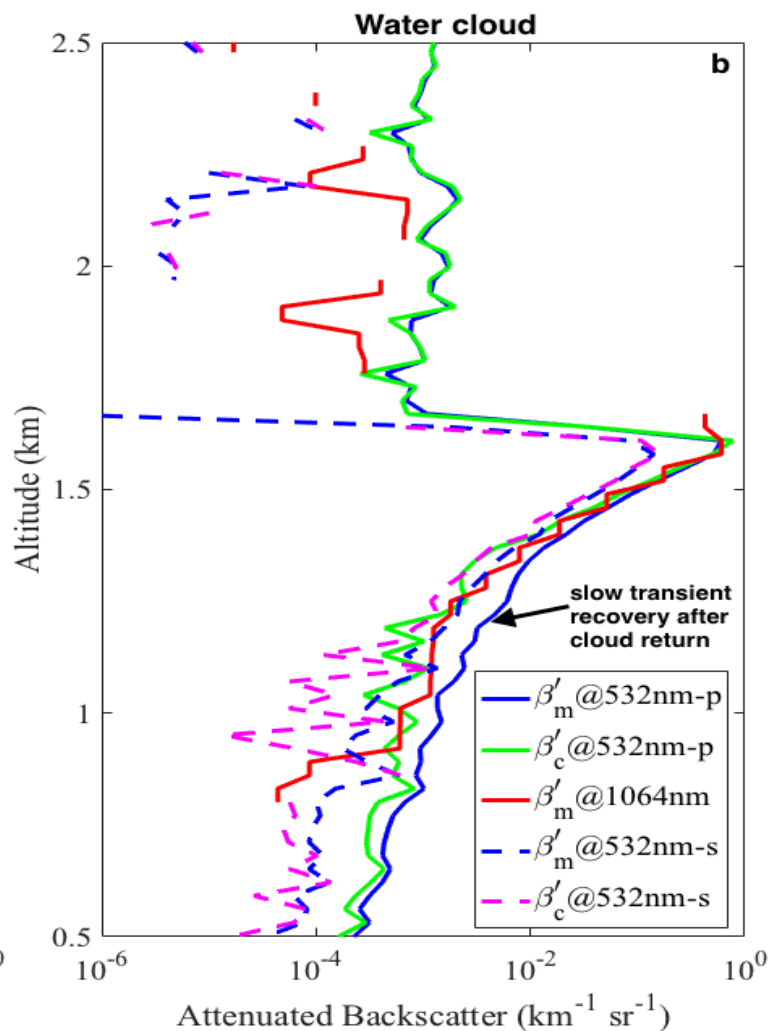
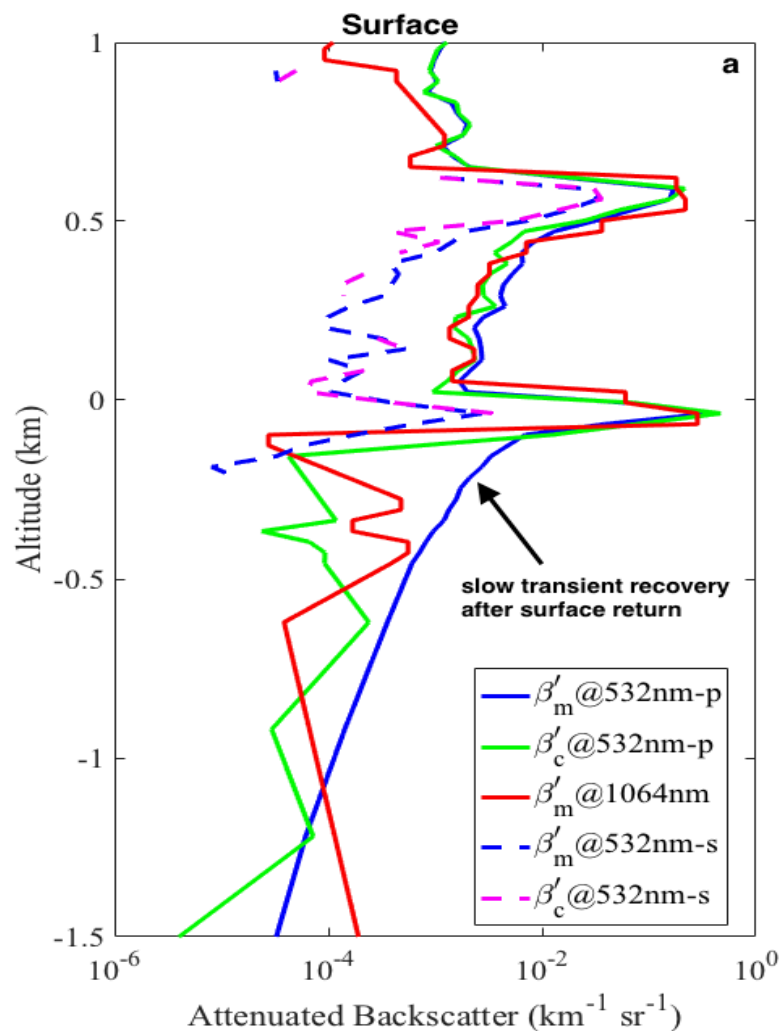
Slow transient recovery-example



Slow transient recovery-example

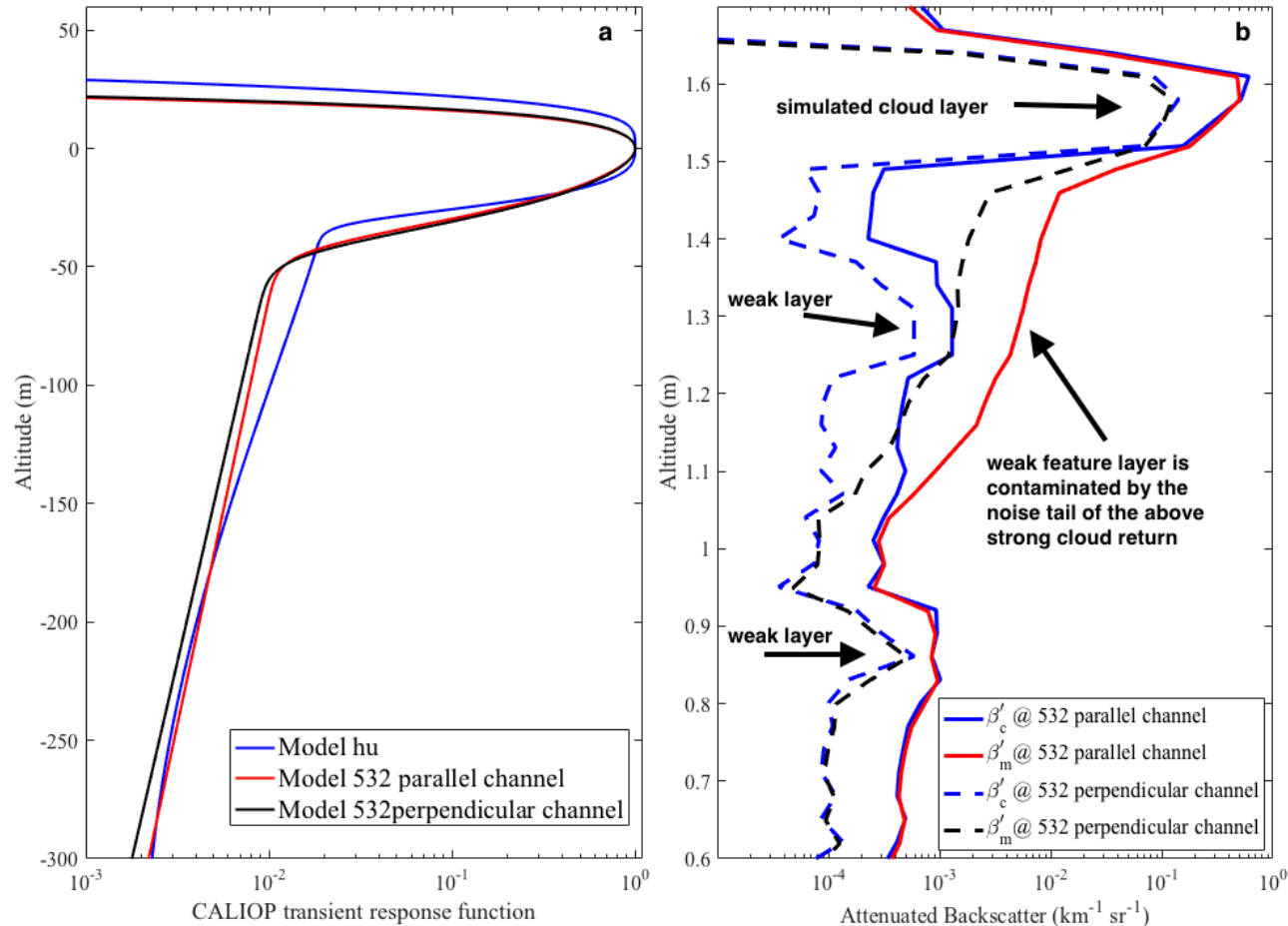


Examples

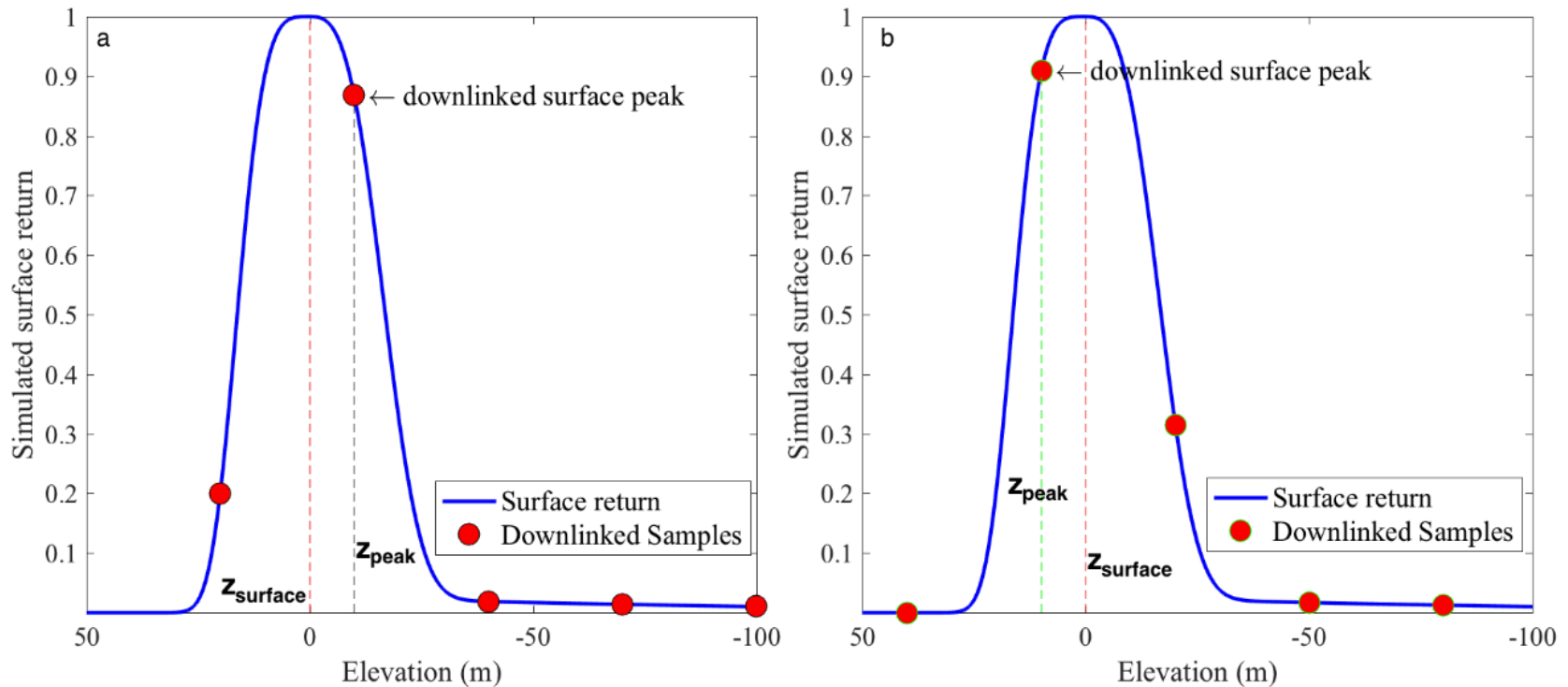


Simulated examples

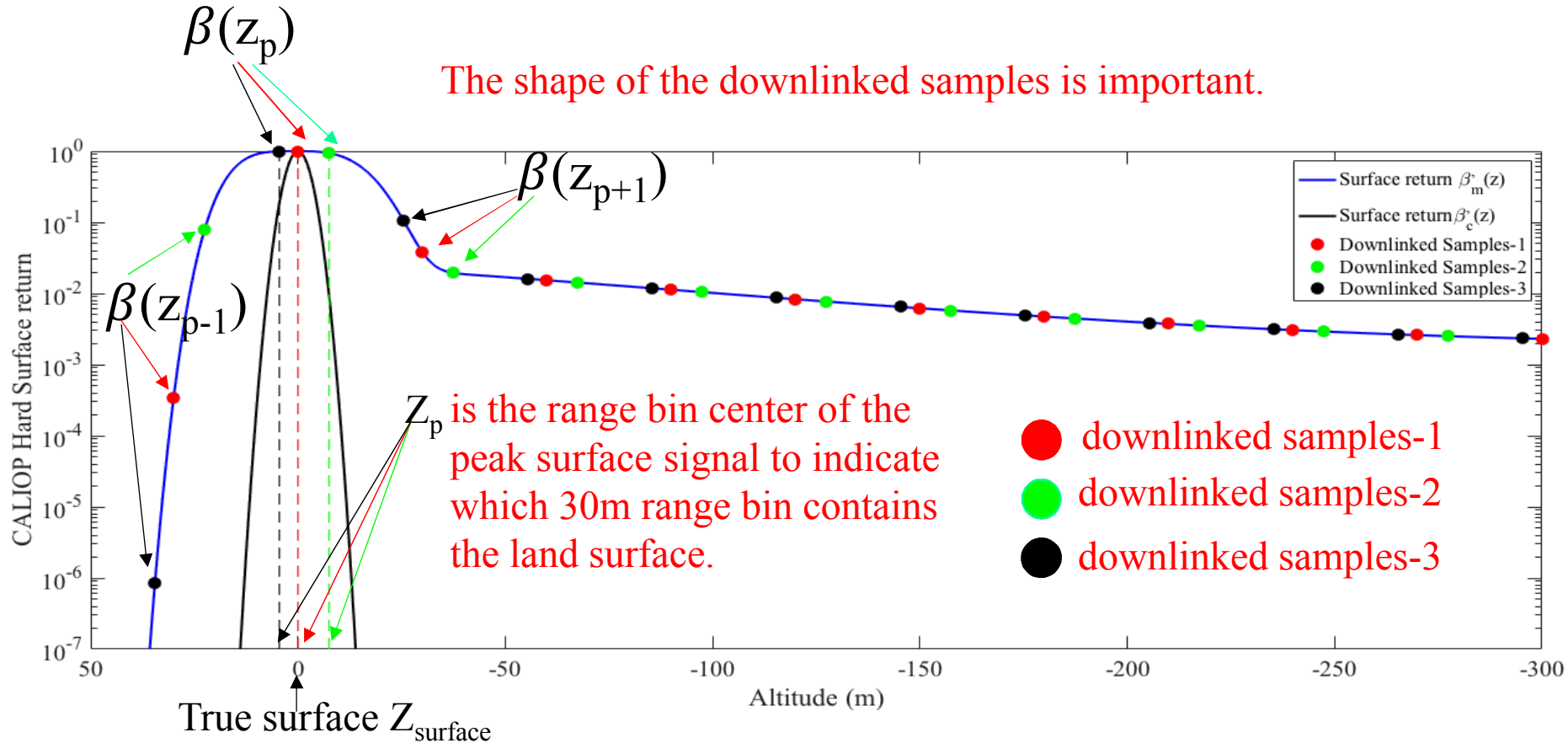
The lower altitude signal can be contaminated by the noise tail of the signals at higher altitude.



CALIOP downlinked surface samples



CALIOP downlinked surface signal



$$M = \frac{\beta(z_{p+1}) - \beta(z_{p-1})}{\beta(z_p)} \quad \text{vs.} \quad \Delta R = Z_p - Z_{\text{surface}}$$

SRA Elevation Estimation Technique

- Peak signal ratio (M) is obtained from CALIPSO lidar measurement for land surface at three range bins (z_{p-1} , z_p and z_{p+1})

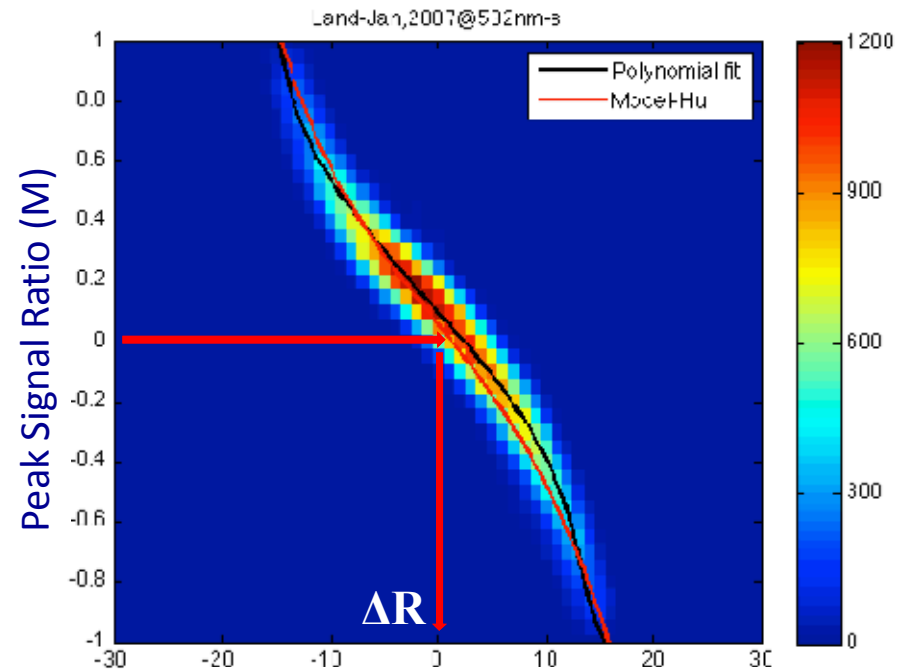
$$M = \frac{\beta(z_{p+1}) - \beta(z_{p-1})}{\beta(z_p)}$$

- Distance (ΔR) between peak signal range bin center z_p and surface is estimated from the left model with the value of M .
- Land surface elevation is retrieved as:

$$z_{surface} = z_p - \Delta R$$

References:

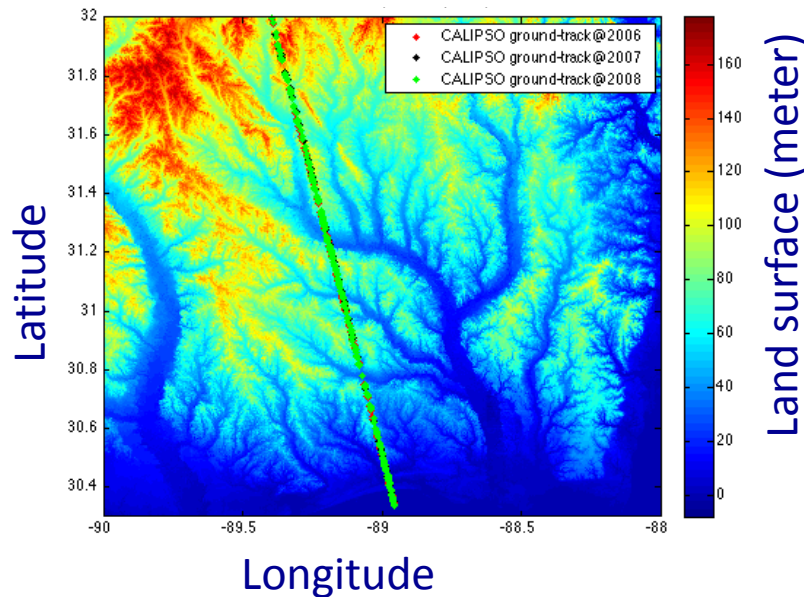
- X Lu, Y Hu, et al, "A super-resolution laser altimetry technique", IEEE Geoscience and Remote sensing letters, 2014
- Y Hu, et al, "Elevation information in tail (EIT) technique for lidar altimetry", Optics Express, 2007



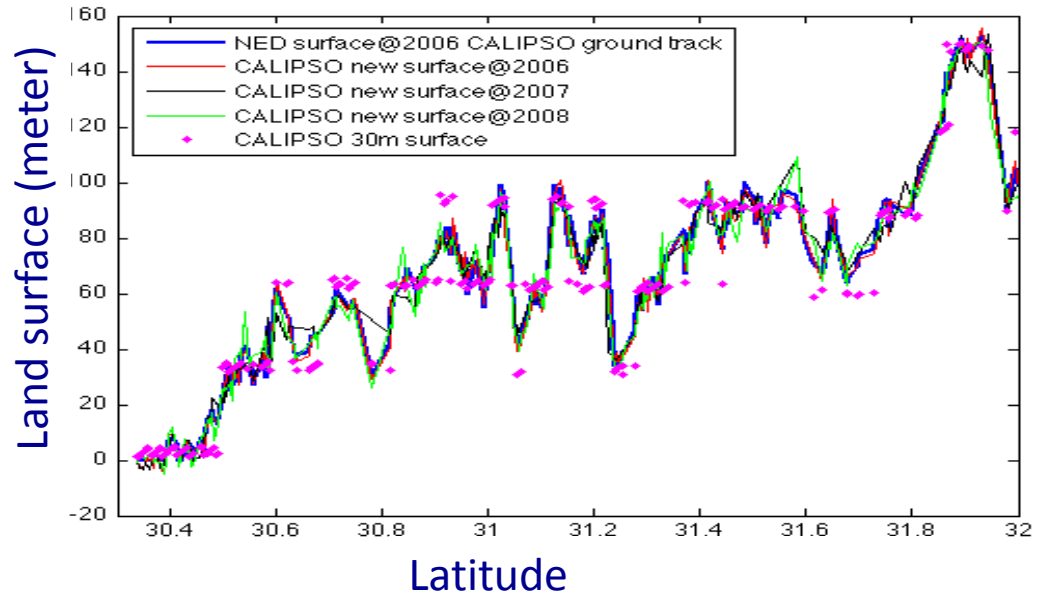
$$\Delta R = z_p - z_{USGS\ NED\ surface}$$

CALIPSO Land Surface Comparison

USGS NED 1 arc-second products



USGS National Elevation Database (NED) map and CALIPSO ground tracks for 2006, 2007, 2008

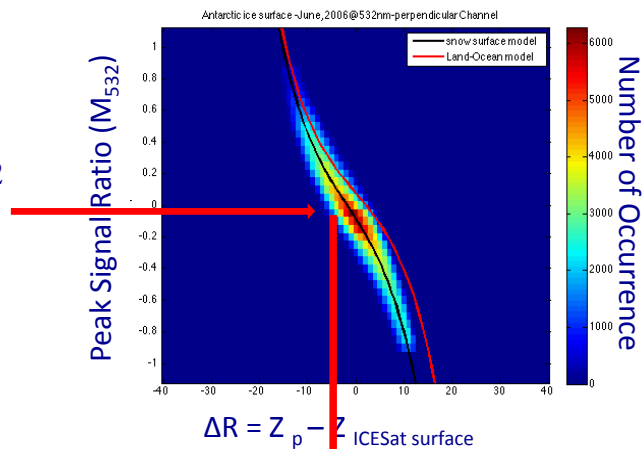


Surface elevation comparison among CALIPSO results and the USGS NED 1 arc-second products in 2006, 2007 and 2008.

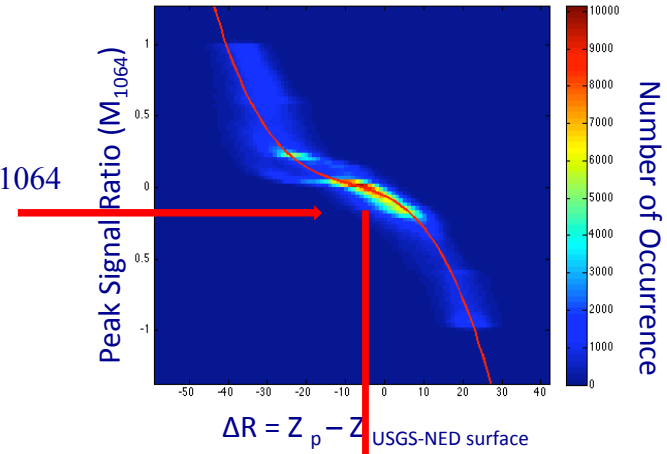
CALIOP Forest Canopy Height Estimation

1. $M_{532(1064)} = \frac{\beta(z_{p+1}) - \beta(z_{p-1})}{\beta(z_p)}$ obtained directly from CALIPSO level 1 attenuated backscatter coefficients at three range bins

2. M_{532}



M_{1064}

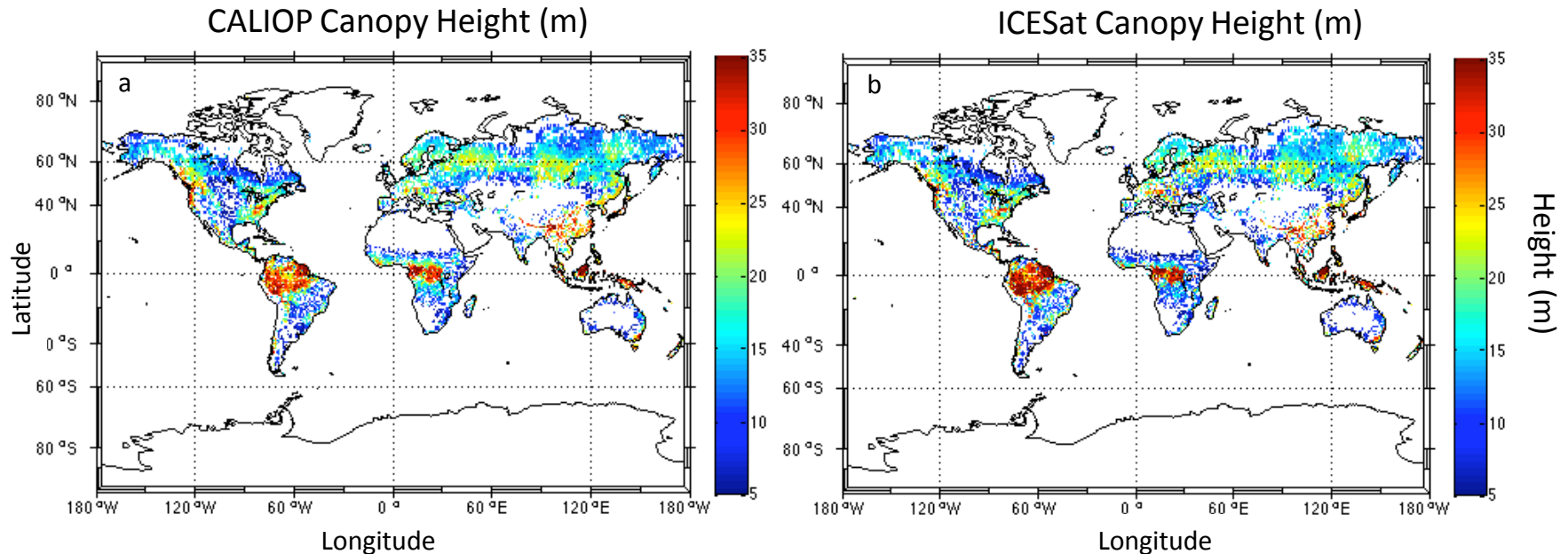


3. SRA method:
$$z_{532} = z_{p,532} - \Delta R_{532}$$
$$z_{1064} = z_{p,1064} - \Delta R_{1064}$$

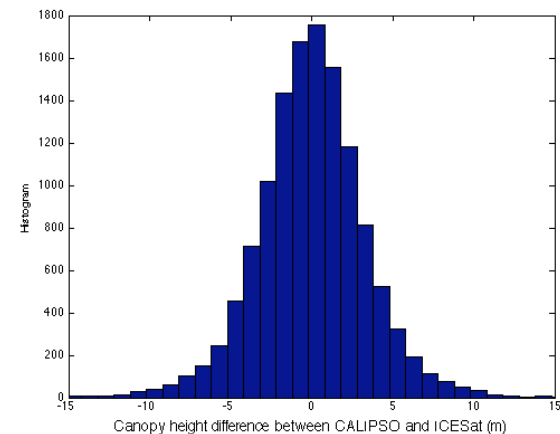
4. The altimetry signal from vegetation canopy is a combination of the tree top and the surface. At 1064nm, the signal is mostly from tree top as the vegetation canopy is highly reflective; At 532nm, surface backscatter is significantly more important due to relatively weaker backscatter from vegetation. The difference of the two channel comes primarily from vegetation canopy height,
$$x = z_{1064} - z_{532}$$

5. Finally, Forest canopy height was estimated based on this difference (x)-penetration depth difference

Comparison of Forest Canopy Height Estimation: CALIOP and ICESat



Comparison illustrates that little bias exists between measurements.



Take home message

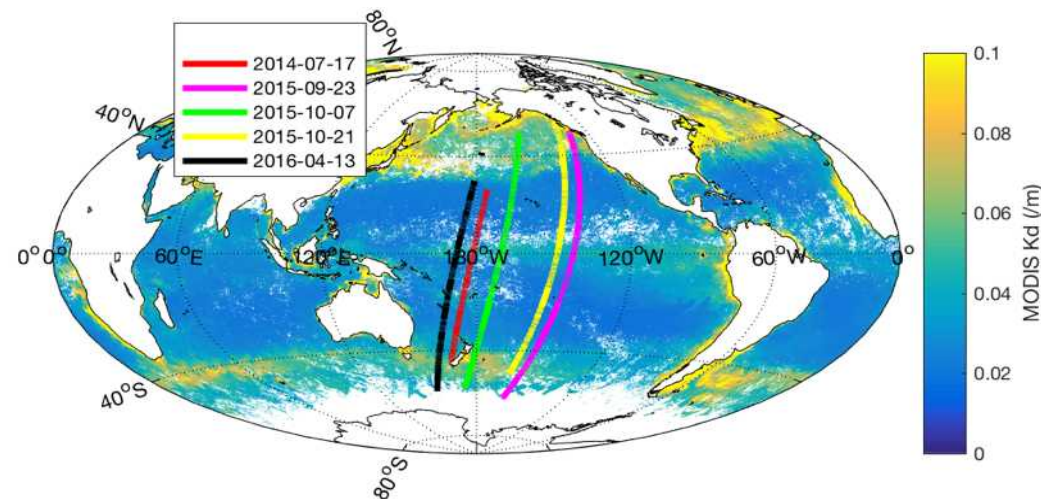
- The Super Resolution Altimetry technique provides improved CALIPSO surface elevation estimates with a precision of better than 1.4 m.
- Canopy penetration differences at 532 and 1064 nm indicate a moderately strong relationship for estimating forest canopy heights.
- Results indicate that CALIOP-derived canopy heights are well correlated with the ICESat derived canopy heights.

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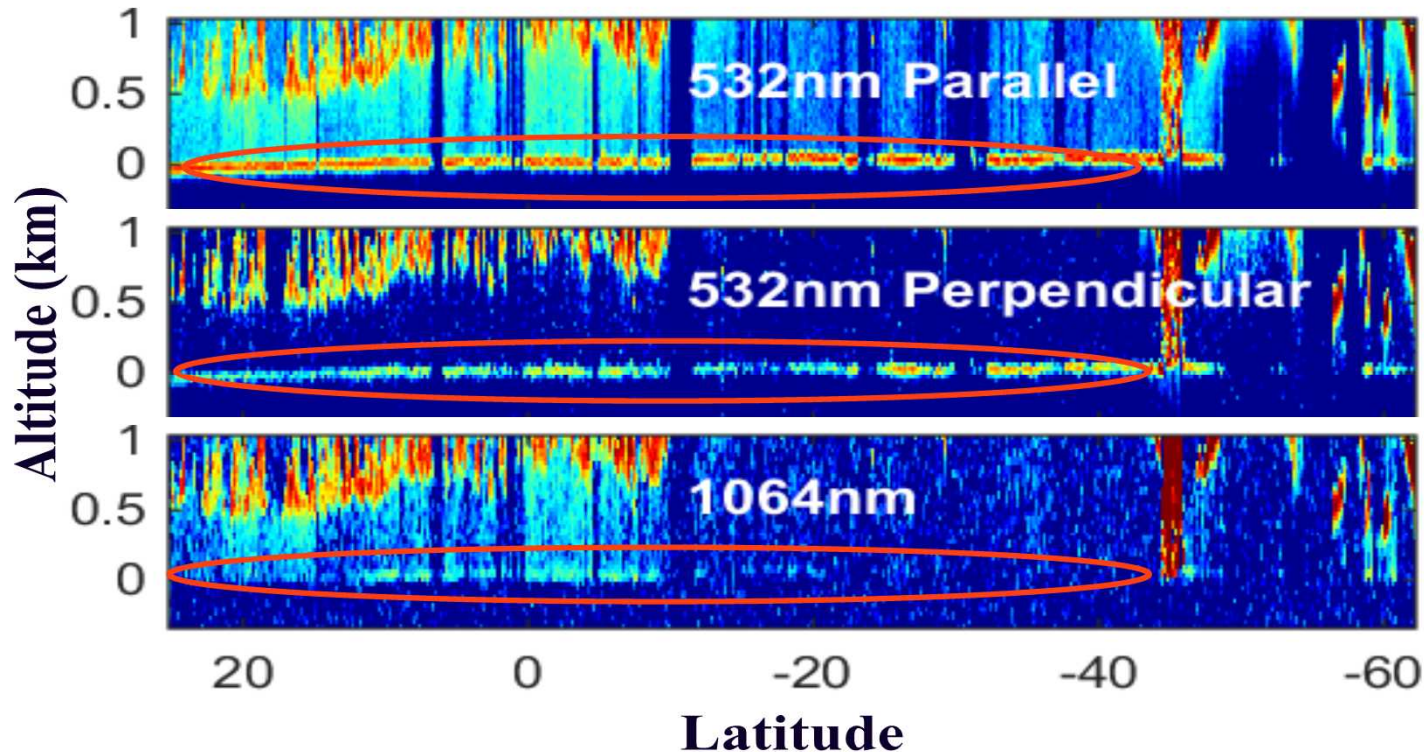
CALIOP 30° off-nadir measurement for ocean subsurface studies

Why pointing CALIOP 30 degree off-nadir:
avoid ocean surface backscatter



1. Direct demonstration of CALIOP ocean subsurface signals in both co-polarization and cross-polarization to convince the community that CALIOP can measure ocean subsurface particulate backscatter
2. Direct measurements of particulate depolarization ratio in water to improve CALIOP estimate of phytoplankton backscatter and biomass estimate.

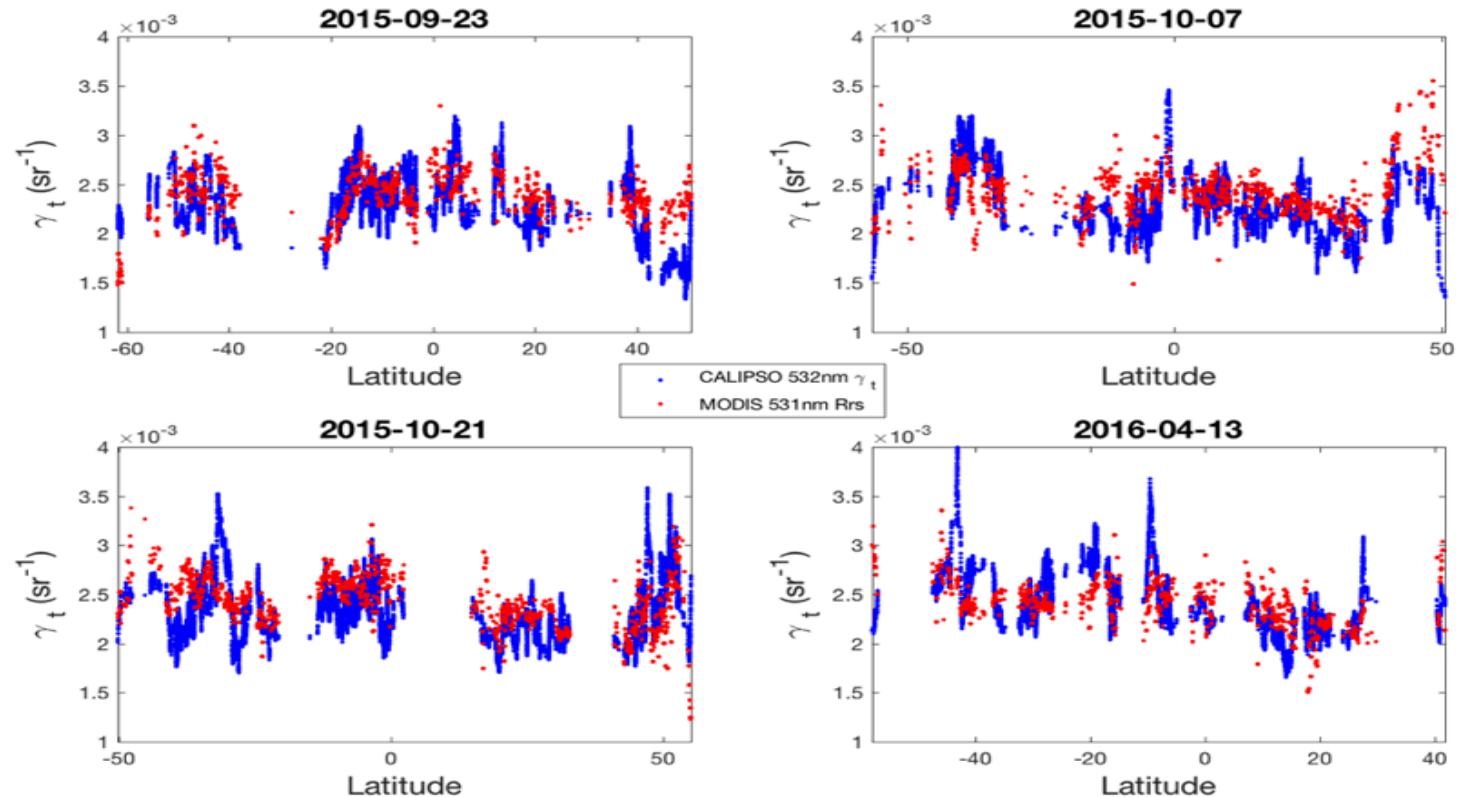
CALIOP ocean subsurface signals on July 17, 2014



Surface signals are much weaker than subsurface signals and can be corrected using 1064nm measurements. Observations suggest that ocean surface backscatter at 532 nm is about 30% less than ocean surface backscatter at 1064 nm.

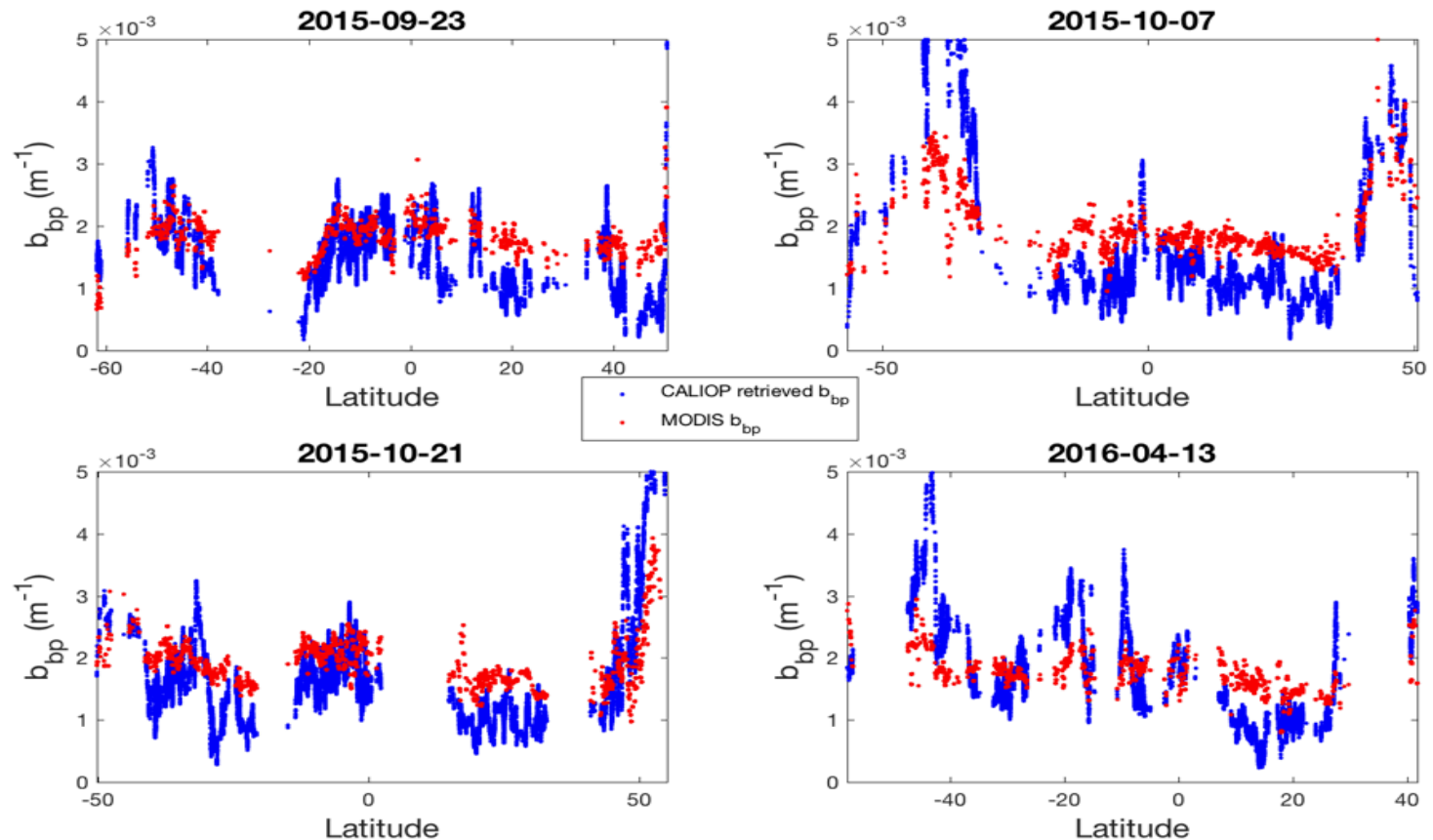
CALIOP subsurface lidar backscatter γ_t (/sr)

CALIOP γ_t (blue) vs. MODIS remote sensing reflectance R_{rs} (red)



CALIOP-retrieved particulate backscattering coefficient b_{bp} (/m)

CALIOP b_{bp} (blue) vs. MODIS b_{bp} (red)



CALIOP 3° off-nadir measurement for ocean subsurface studies

Information:

cross polarization backscatter profile (532nm perpendicular channel)

Calibration: ocean surface backscatter vs theory

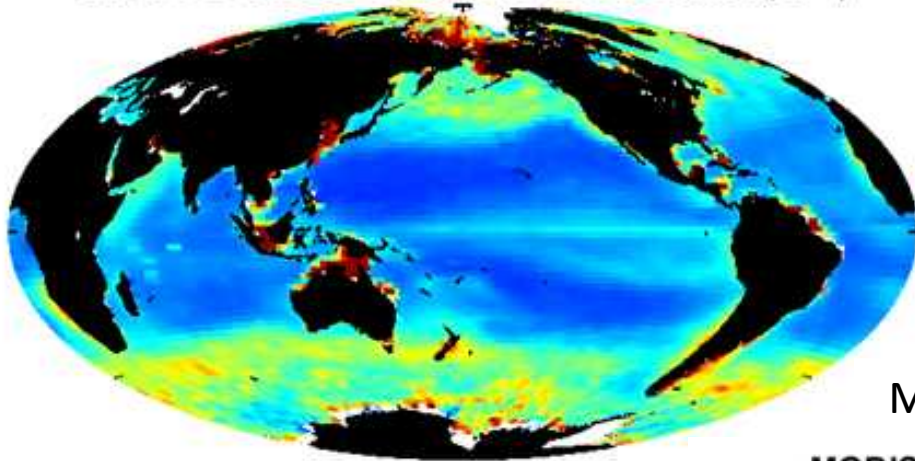
$$\left(\beta_s = \frac{0.0207}{4\pi \langle \sigma^2 \rangle} = \frac{0.0207}{4\pi [0.003 + 0.00512 * Wind]} \right) \quad (Hu \text{ et al. } 2008)$$

Advantage:

1. phytoplankton carbon biomass (Behrenfeld et al., 2013; Lu et al., 2014)
2. high latitude measurements (Behrenfeld et al., 2017)
3. day-night difference for studying zooplankton migration (Behrenfeld et al., 2018)

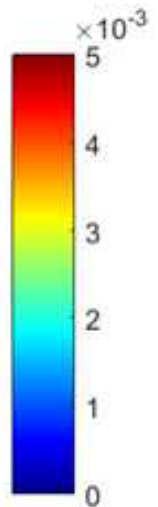
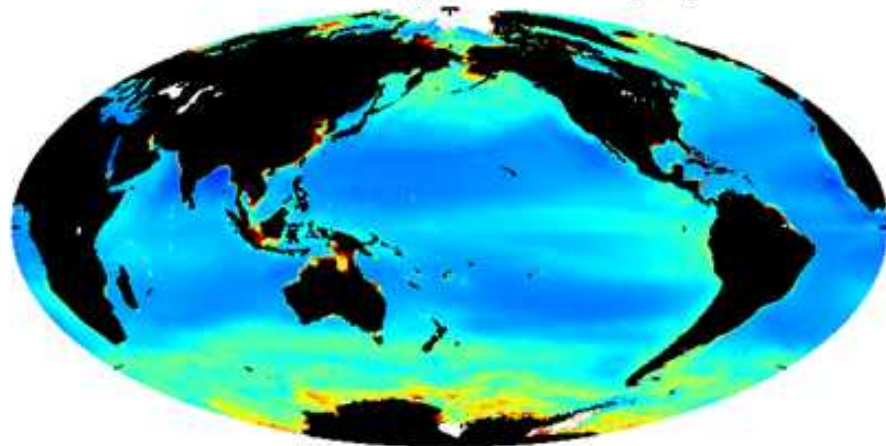
CALIOP cross polarization measurements of ocean subsurface backscatter: comparisons with MODIS

CALIPSO Cross Polarization Backscatter (Sr^{-1})

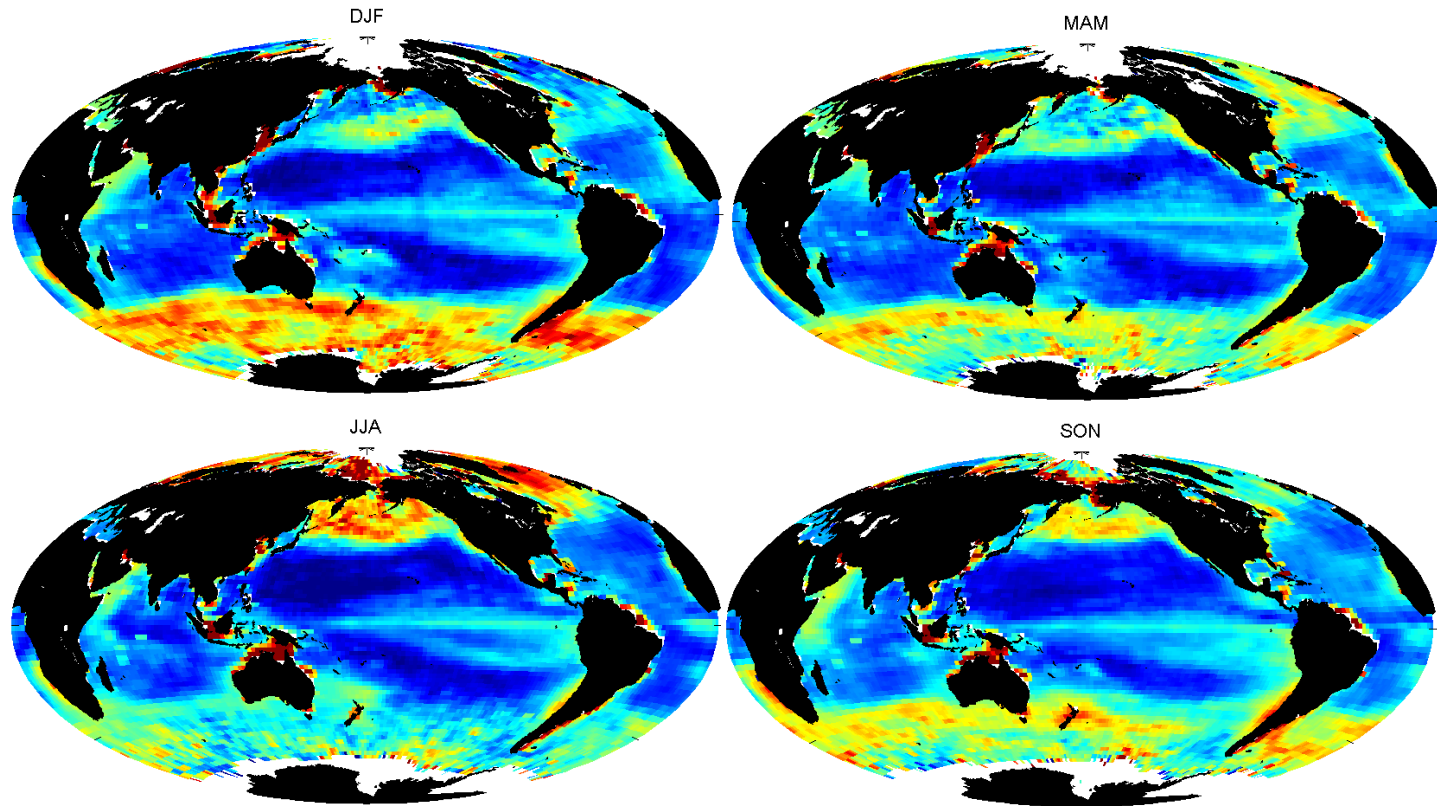


MODIS Backscatter from Phytoplankton /10

MODIS 531 $R_{rs} - bb_w / [2 * 2\pi * m_w^2 K_d] (\text{Sr}^{-1})$



Seasonal Variations of CALIPSO Ocean Cross Polarization Measurements of ocean subsurface Backscatter



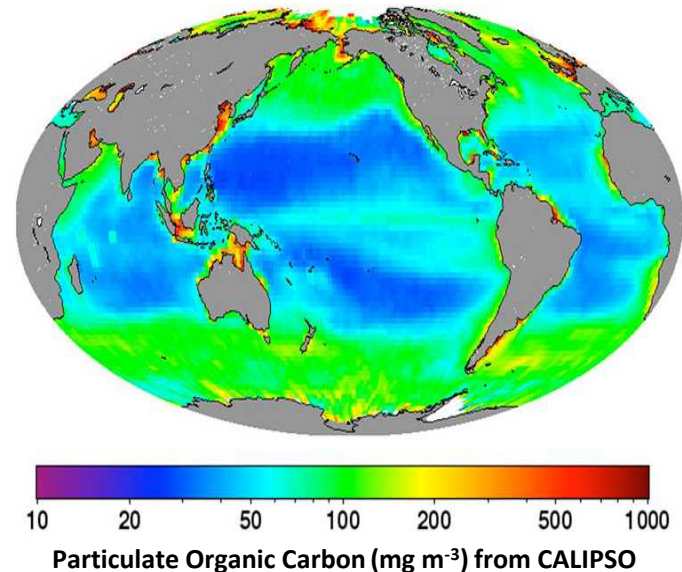
CALIOP measurements of ocean carbon biomass

EOS [*Earth & Space Science News*](#)

27 May 2015

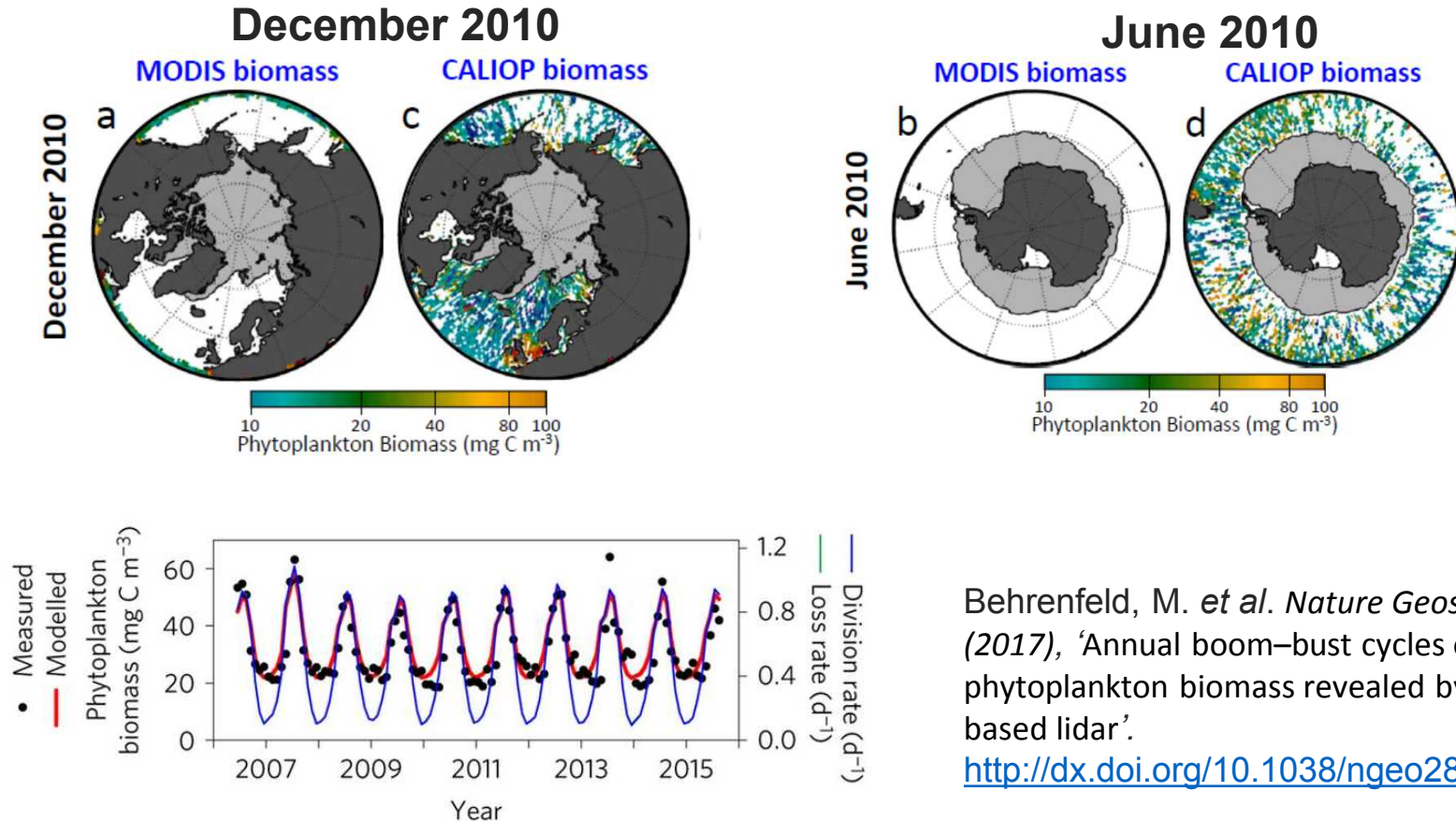
[Hacking a Climate Satellite to See Beneath the Ocean's Surface](#)

When NASA launched its CALIPSO spacecraft, the space agency did not intend to estimate phytoplankton populations.



1. Behrenfeld, M., et al., (2013), Space-based lidar measurements of global ocean carbon stocks, *Geophys. Res. Lett.*, 40, 4355–4360, doi:10.1002/grl.50816.
2. Xiaomei Lu, et al., (2014) Ocean subsurface studies with the CALIPSO spaceborne lidar, *Journal of Geophysical Research: Oceans*, 119, 7, 4305.
3. Behrenfeld, M. *et al.* *Nature Geoscience* (2017), 'Annual boom–bust cycles of polar phytoplankton biomass revealed by space-based lidar'.
<http://dx.doi.org/10.1038/ngeo2861>.

CALIOP provides unique high latitude winter measurements for studying bloom cycle

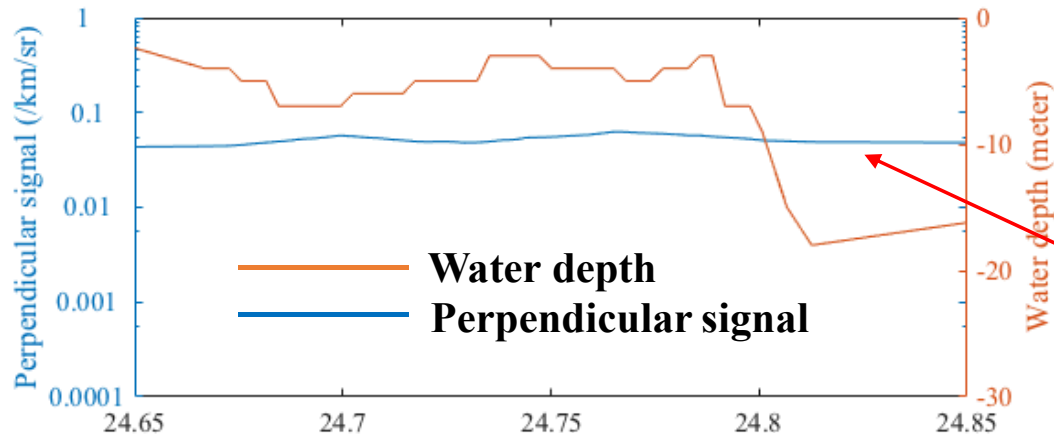


Behrenfeld, M. *et al. Nature Geoscience* (2017), 'Annual boom–bust cycles of polar phytoplankton biomass revealed by space-based lidar'.

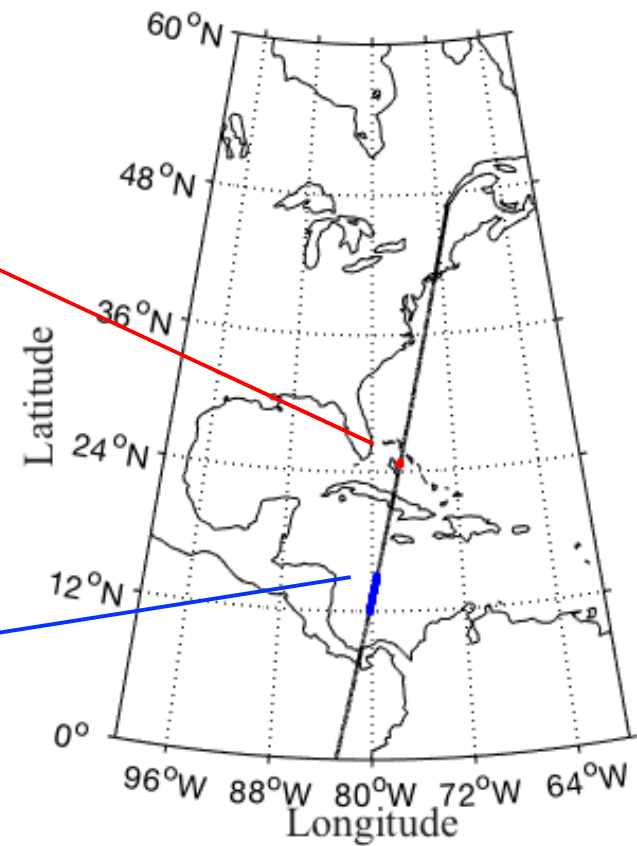
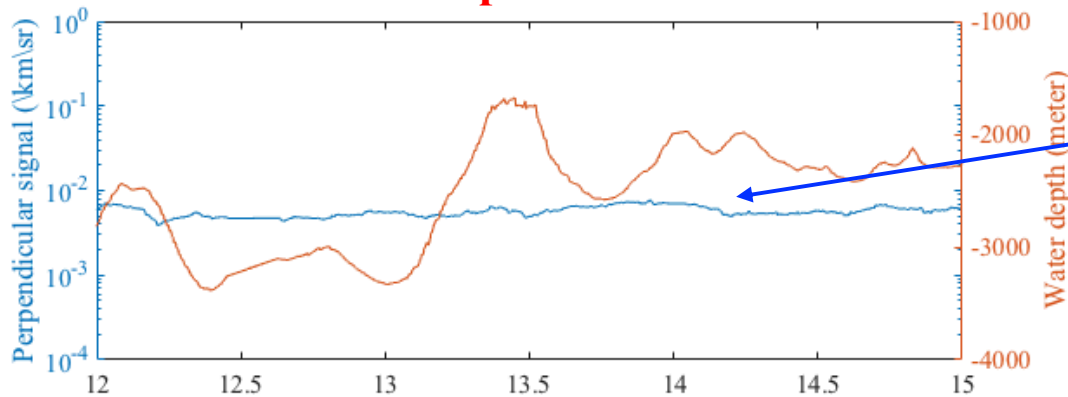
<http://dx.doi.org/10.1038/ngeo2861>.

Ocean study: shallow water vs. Deep water

Shallow water

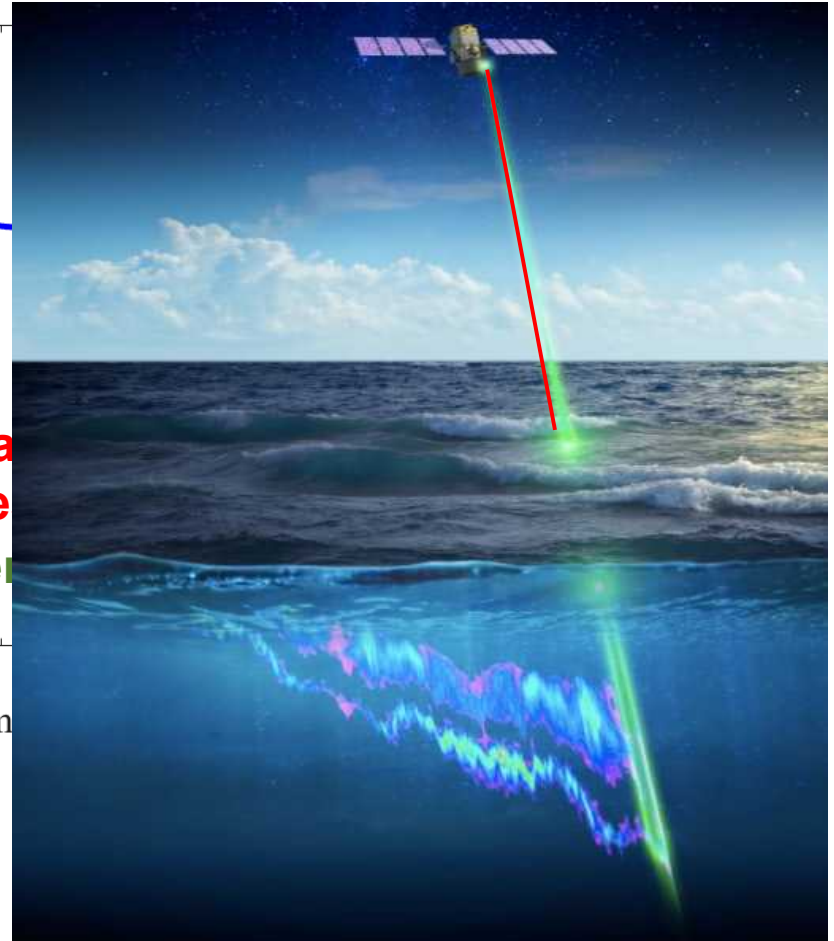
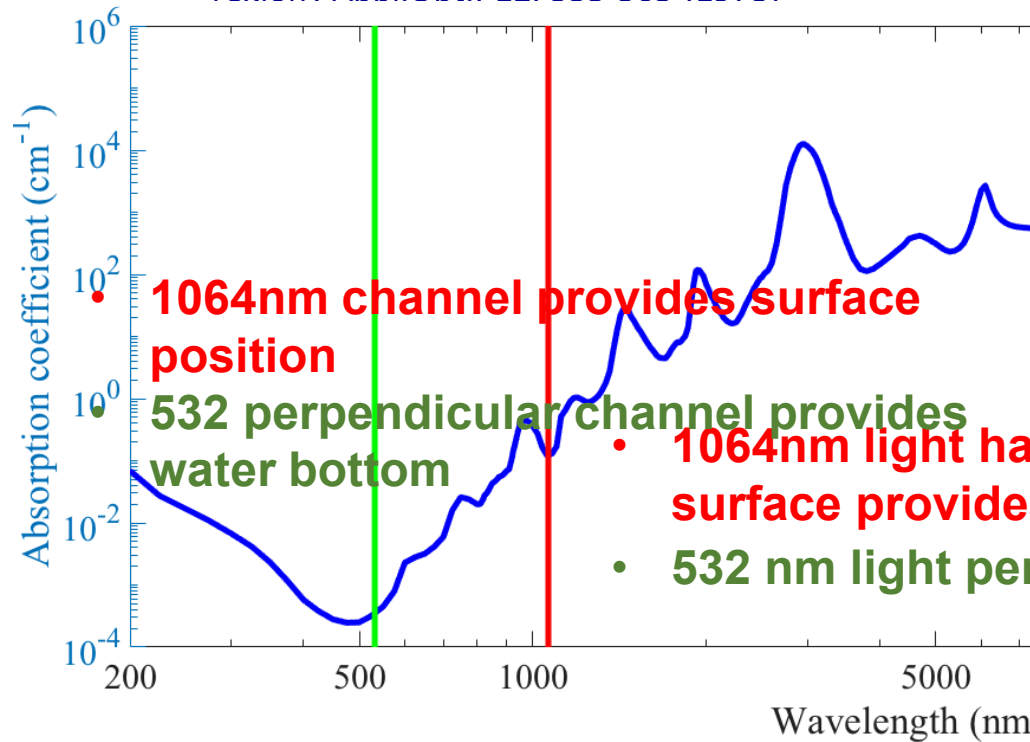


Deep water

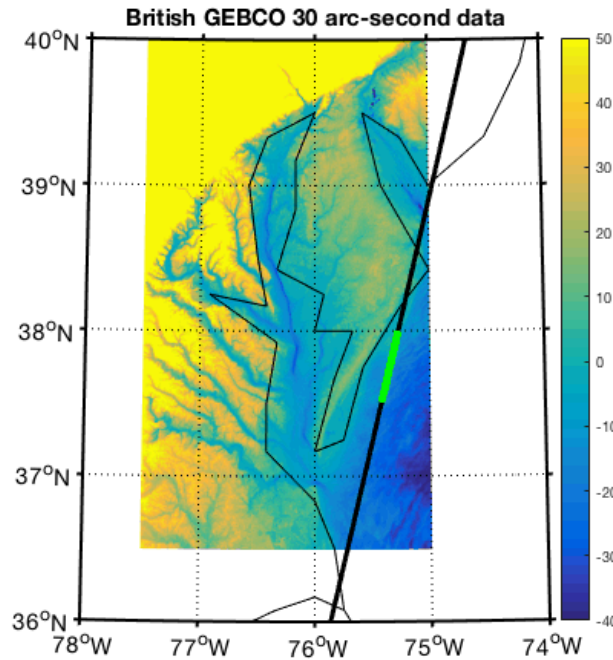


Ocean study: shallow water

G.M.Hale, M.R.Querry, 'Optical constants of water in the 200nm to 200um wavelength region'. Appl.Opt.. 12. 555-563 (1973)

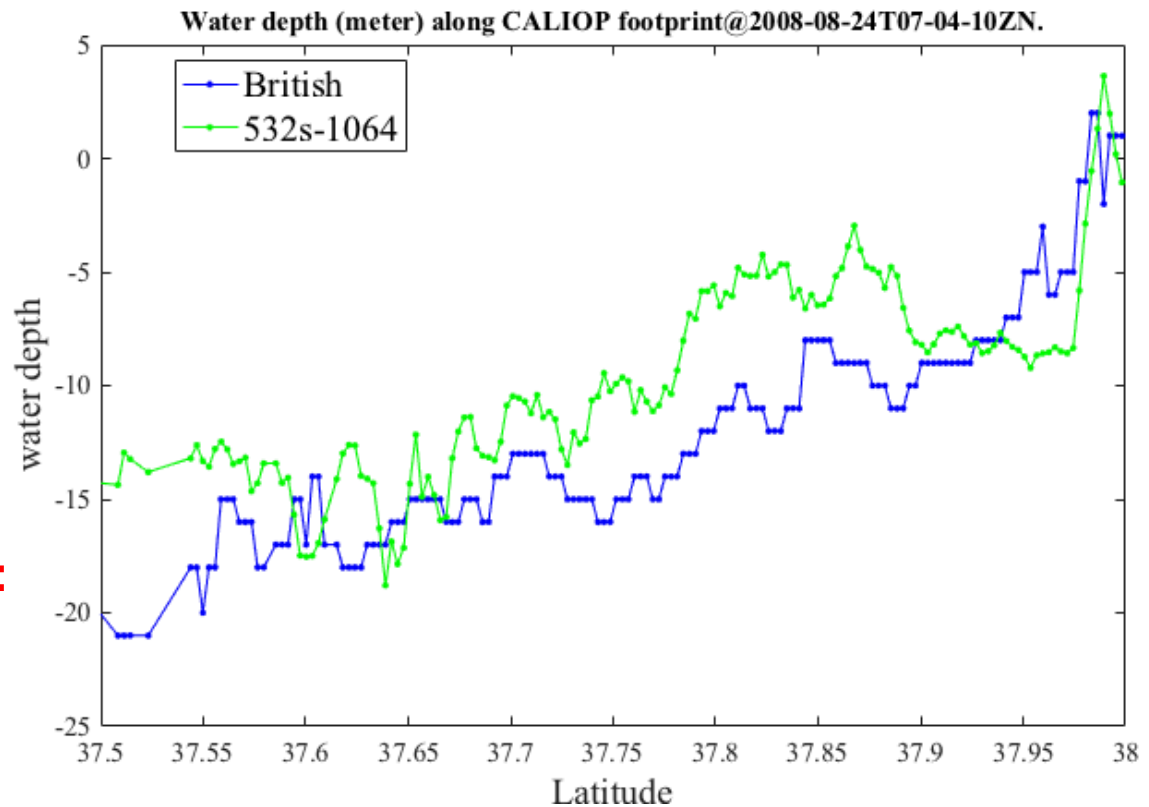


Ocean study: shallow water



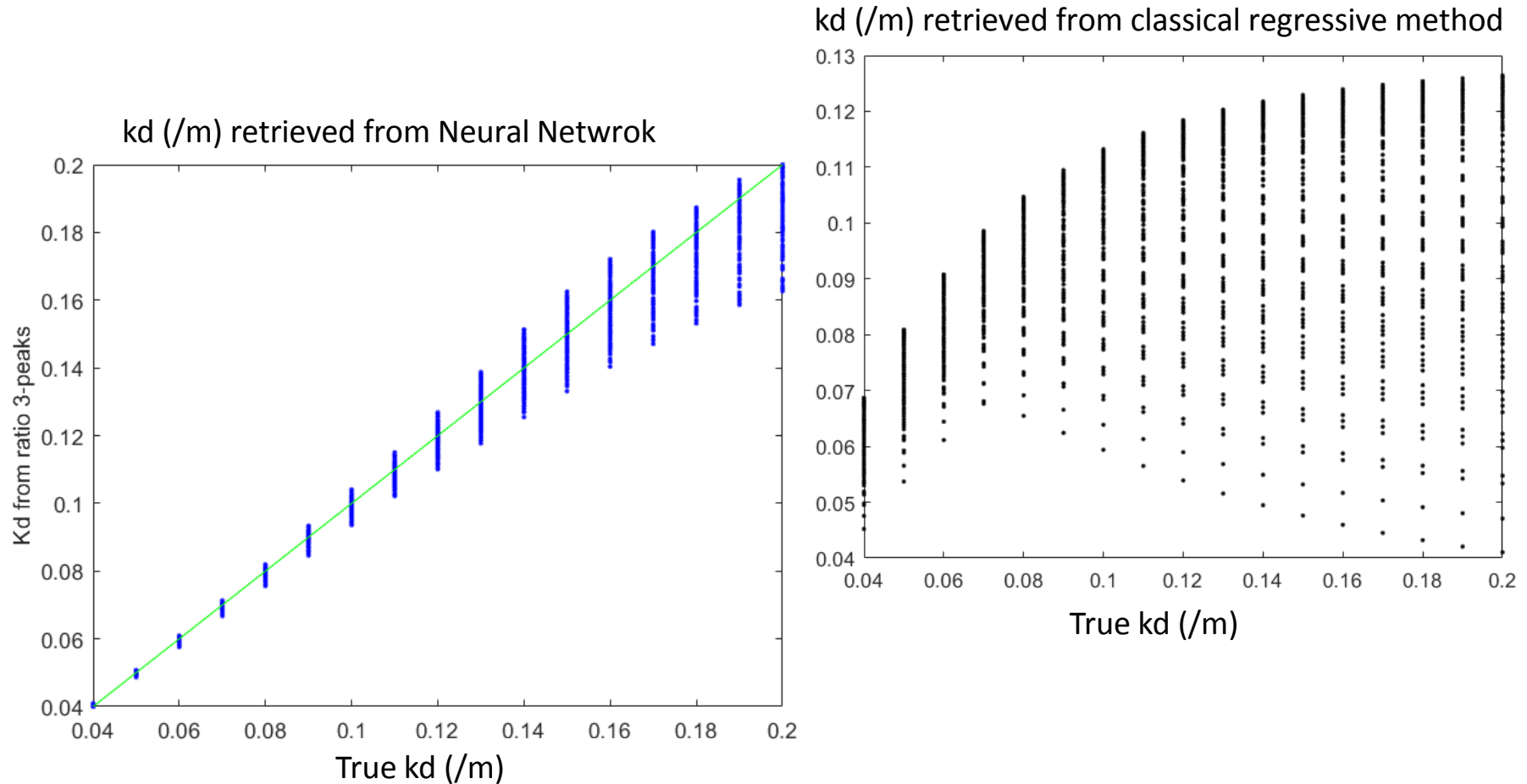
- **British 30 arc-second data: 1km resolution**
- **CALIOP 1/3km horizontal resolution**

1064nm channel provides surface position
532 perpendicular channel provides water bottom



Ocean study: Deep water

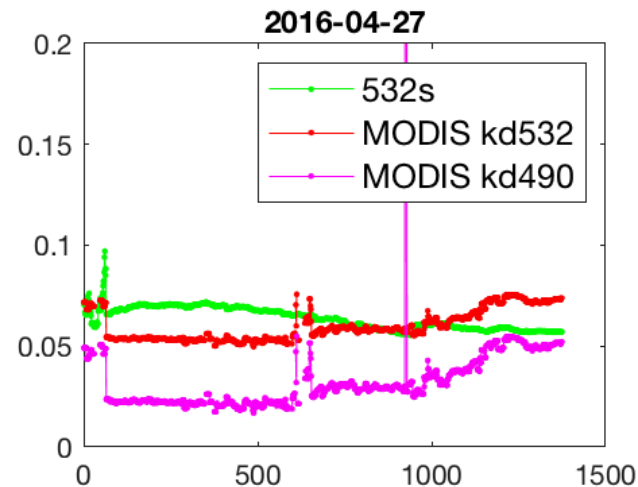
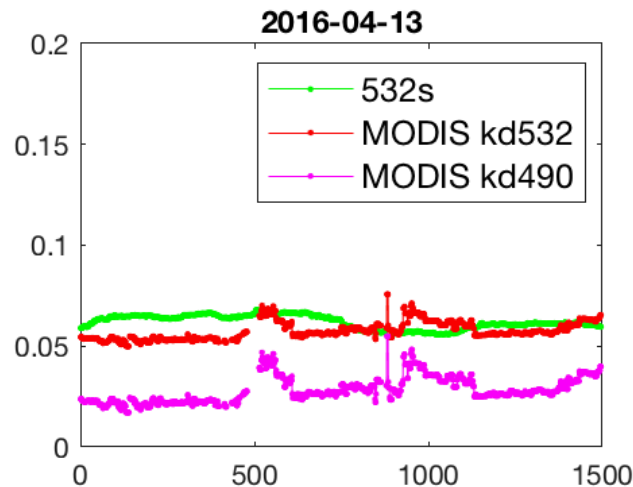
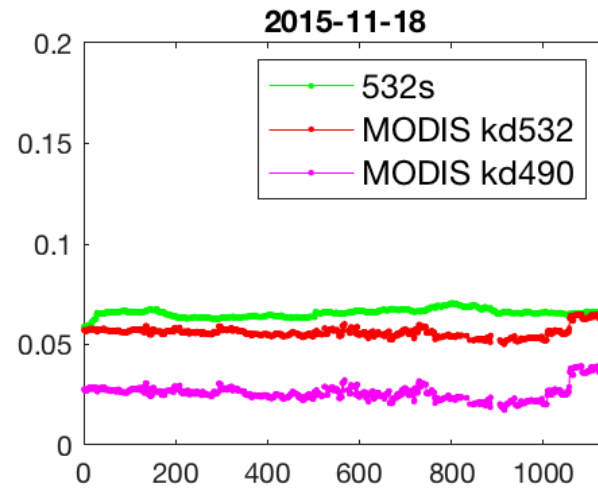
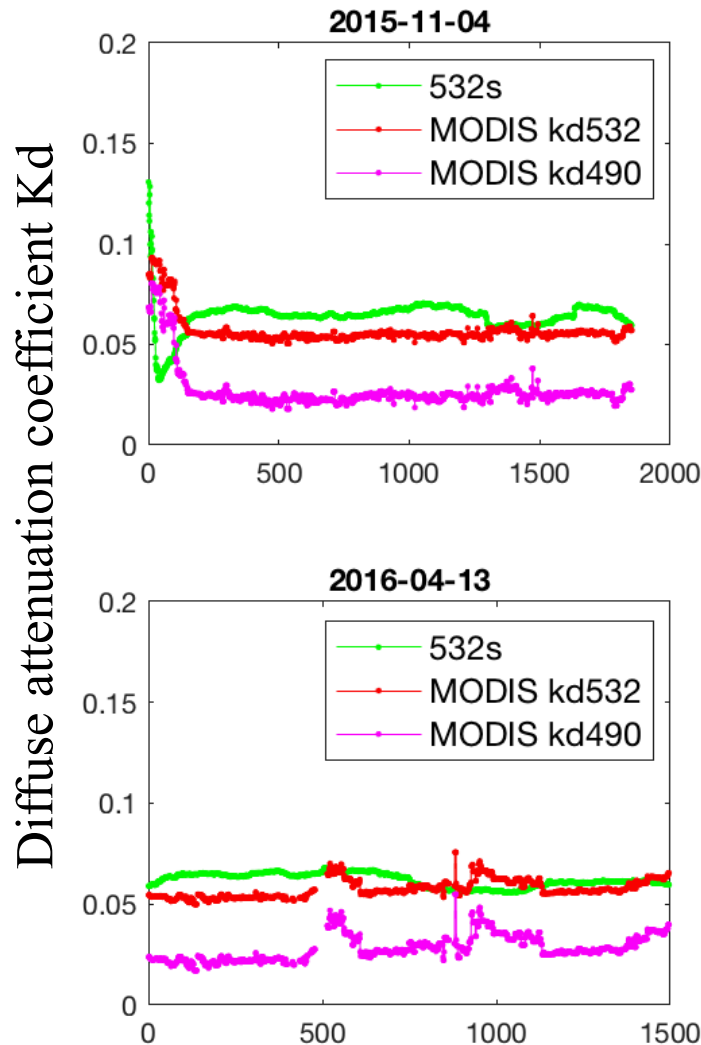
Neural Network is used to estimate Diffuse attenuation coefficient, K_d (/m)



Ocean study: Deep water

Diffuse attenuation coefficient, K_d (/m) are retrieved from 532nm perpendicular channel by Neural Network.

Note:
CALIOP: single shot
MODIS: Monthly



Take home message

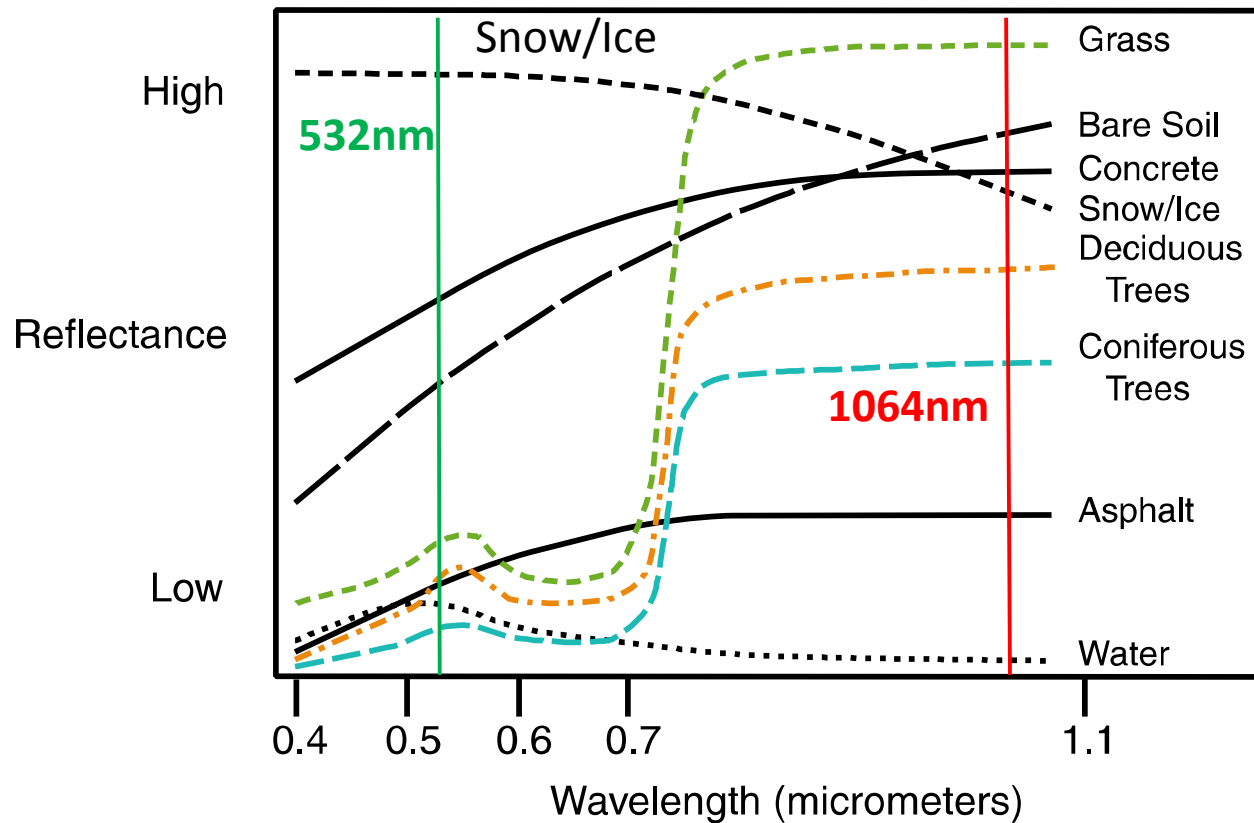
- CALIOP 532nm perpendicular channel can provide information about the water diffuse attenuation coefficient (K_d), particulate backscattering coefficient bbp (/m), and ocean subsurface backscatter. Results are in good agreement with MODIS results.
- CALIOP 532nm perpendicular channel and 1064nm channel can provide bathymetry study. Preliminary results indicate that CALIOP-derived water depth are well correlated with the British oceanographic water depth.
- CALIOP provides unique high latitude winter measurements for studying bloom cycle, and ocean par.

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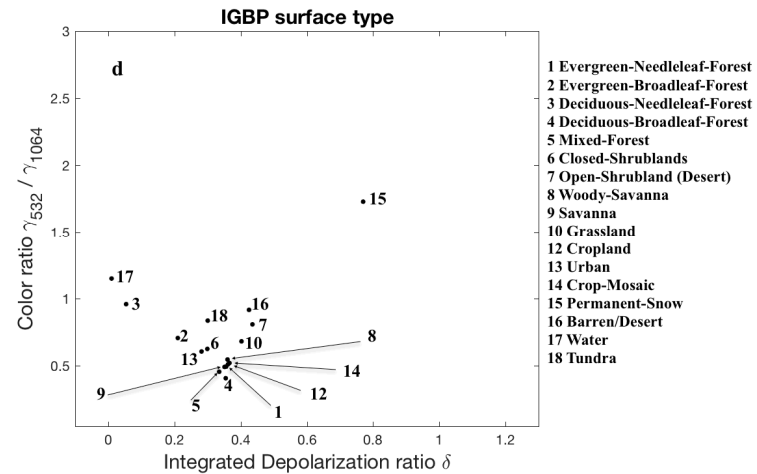
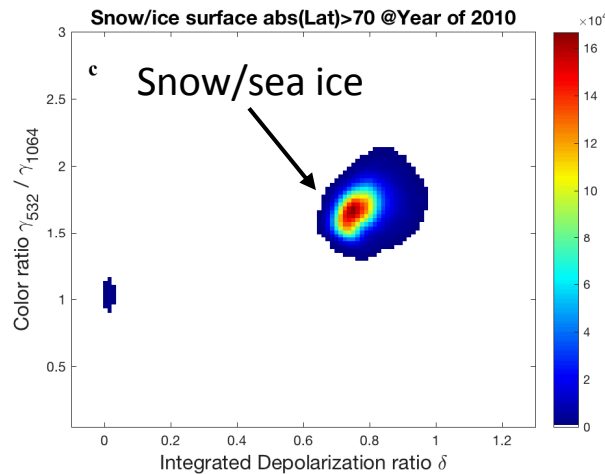
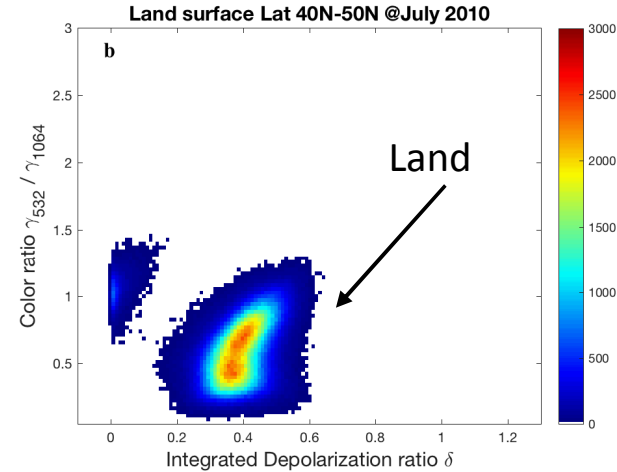
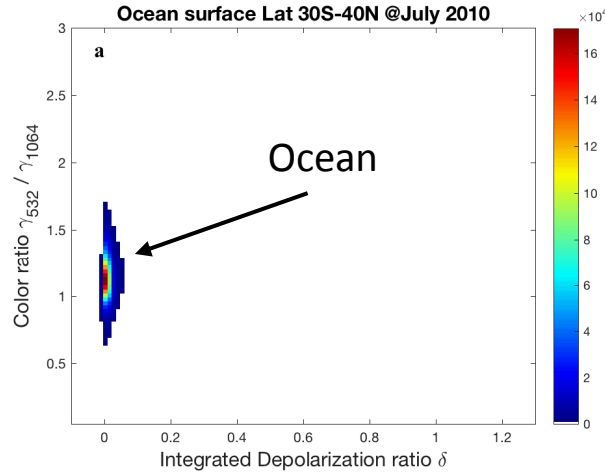
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Surface type identification

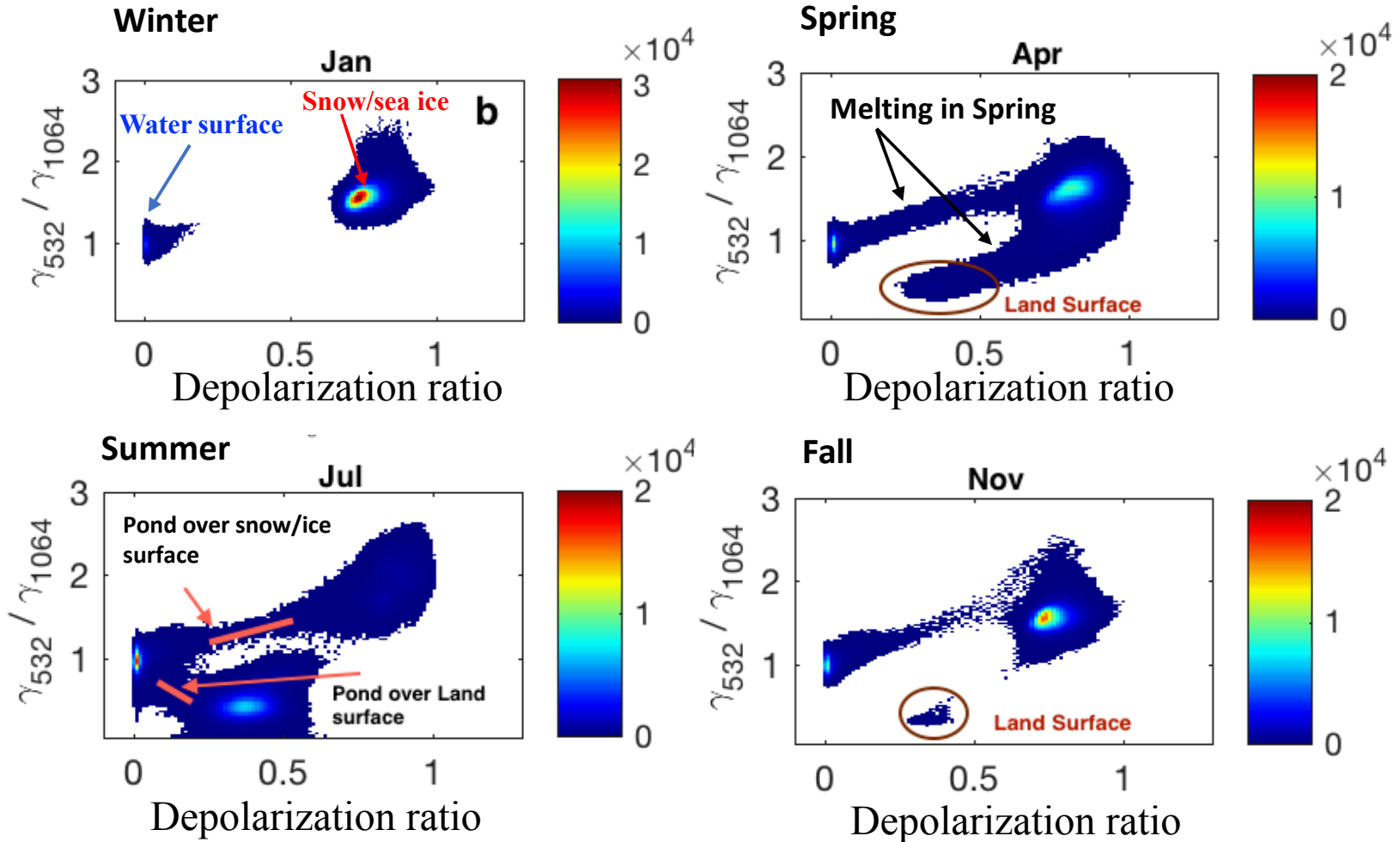
Spectral reflectance for different land surface covers



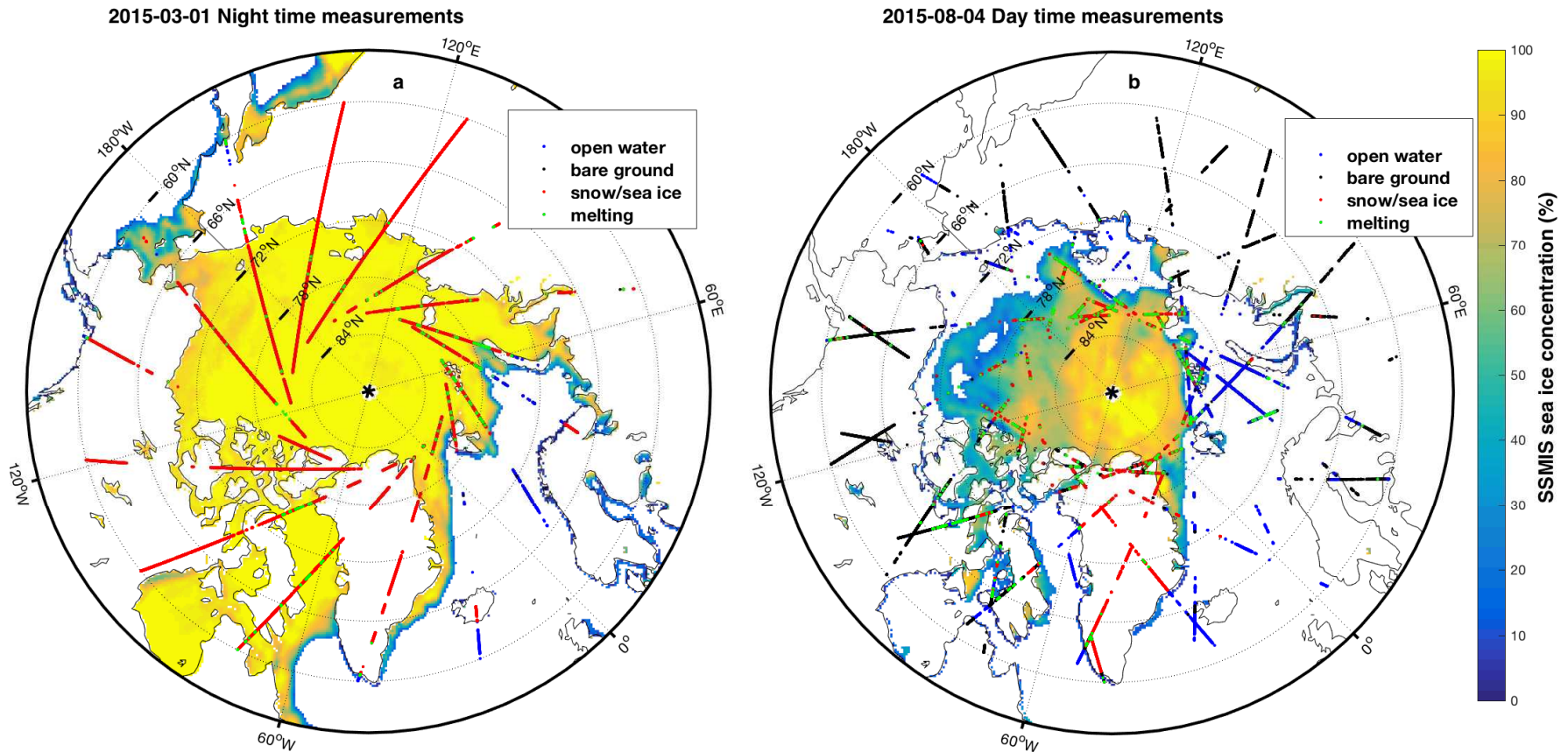
Surface type identification



Surface type identification-Arctic region



Surface type identification



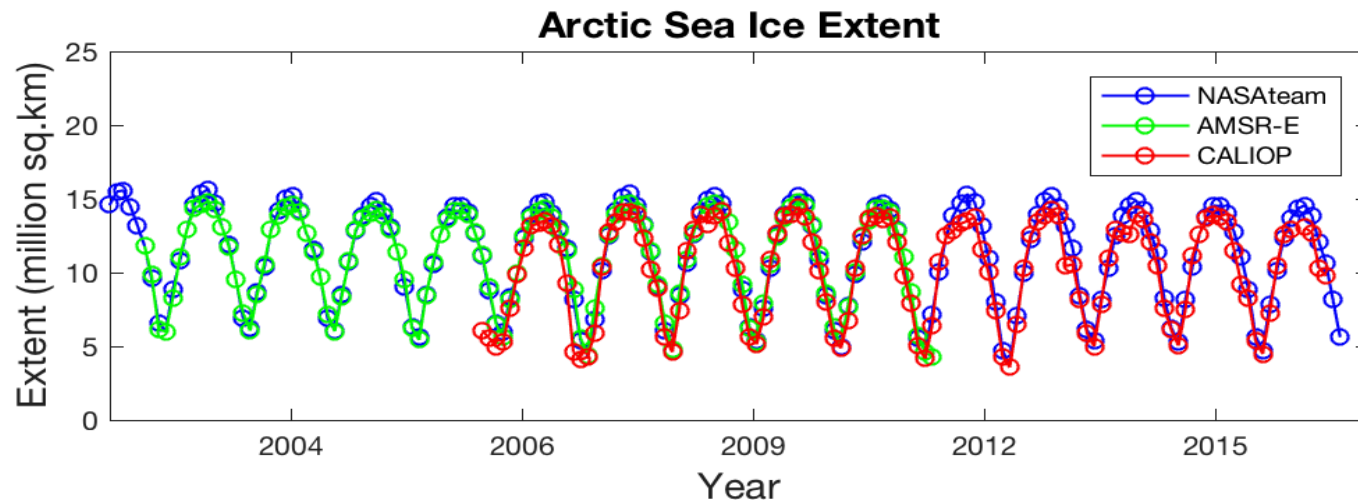
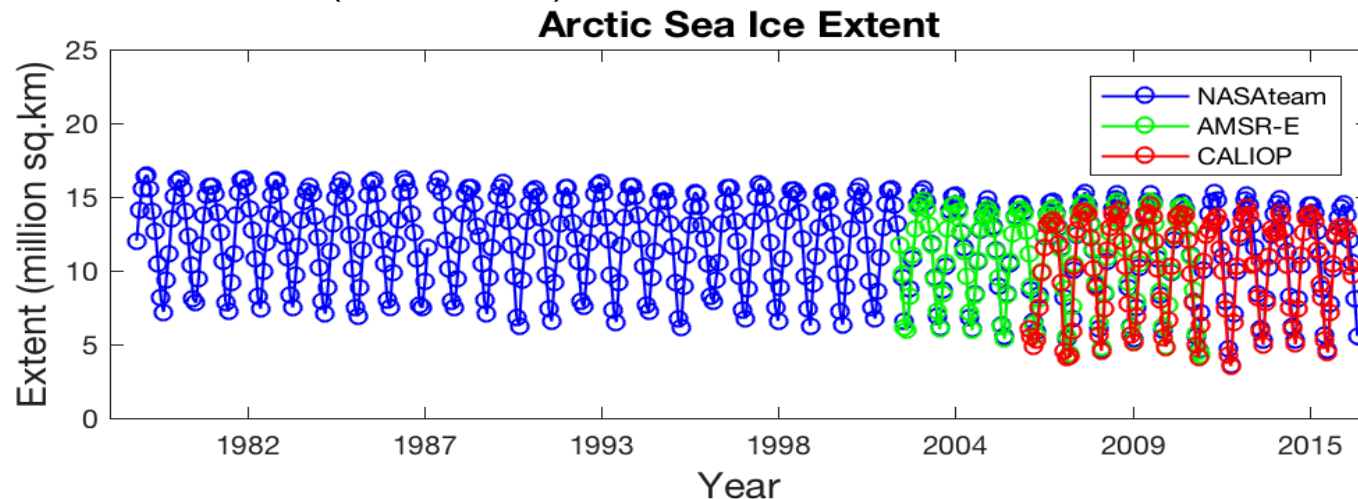
Background color is the SSMIS sea ice concentration (%) on March 1st, 2015 (left panel) and Aug 4th, 2015 (right panel).

Arctic sea ice area and extent

Monthly time-series plot of the Arctic sea ice extent (10^6 km^2) from 1978 to 2016:

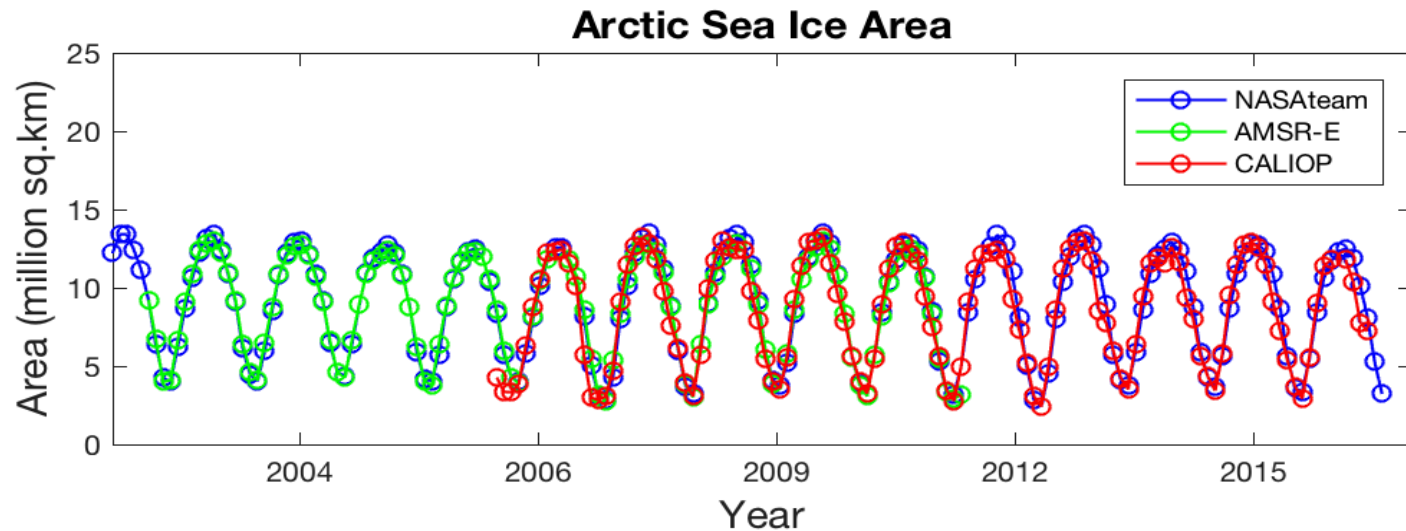
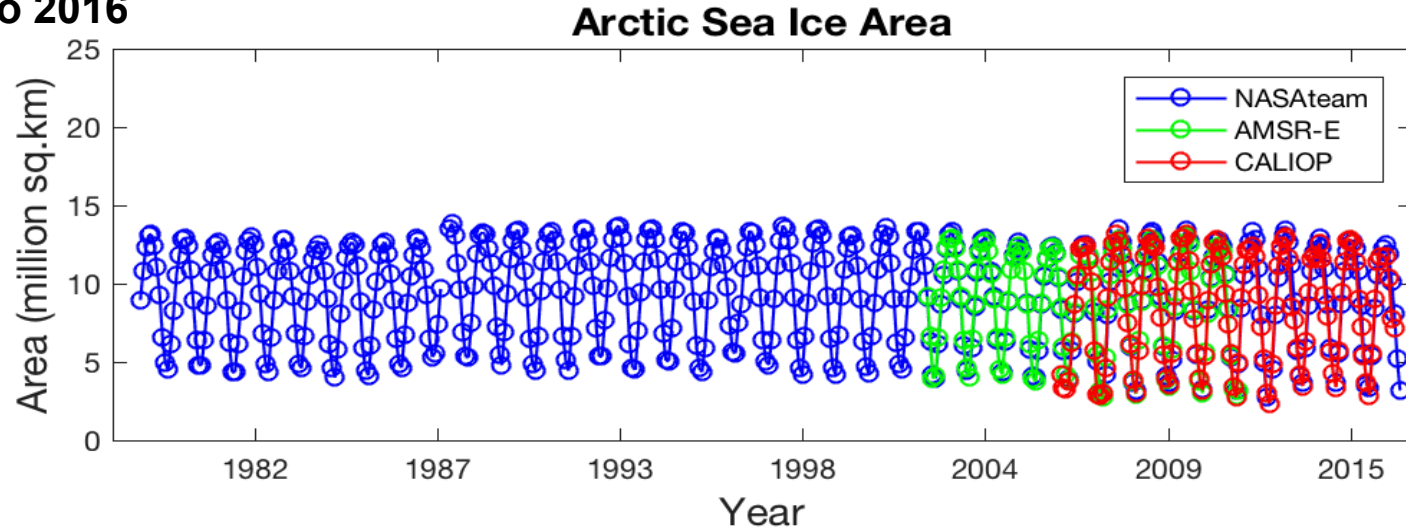
2016: CALIOP (2006–2016). Blue: NASA team algorithm data (1978–2016).

Green: AMSR-E dataset (2002–2011).

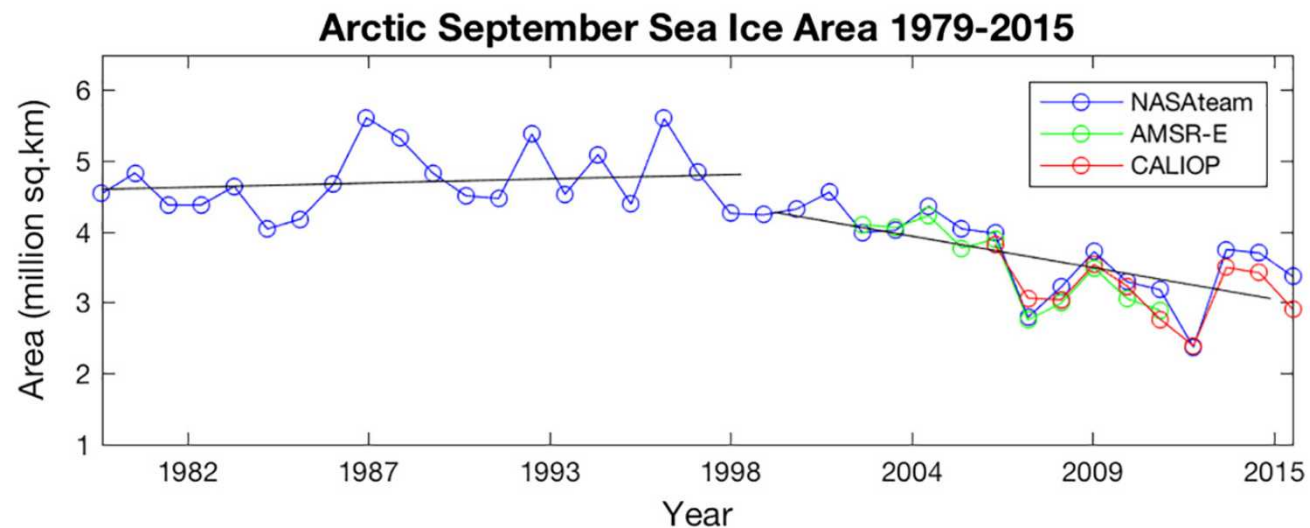
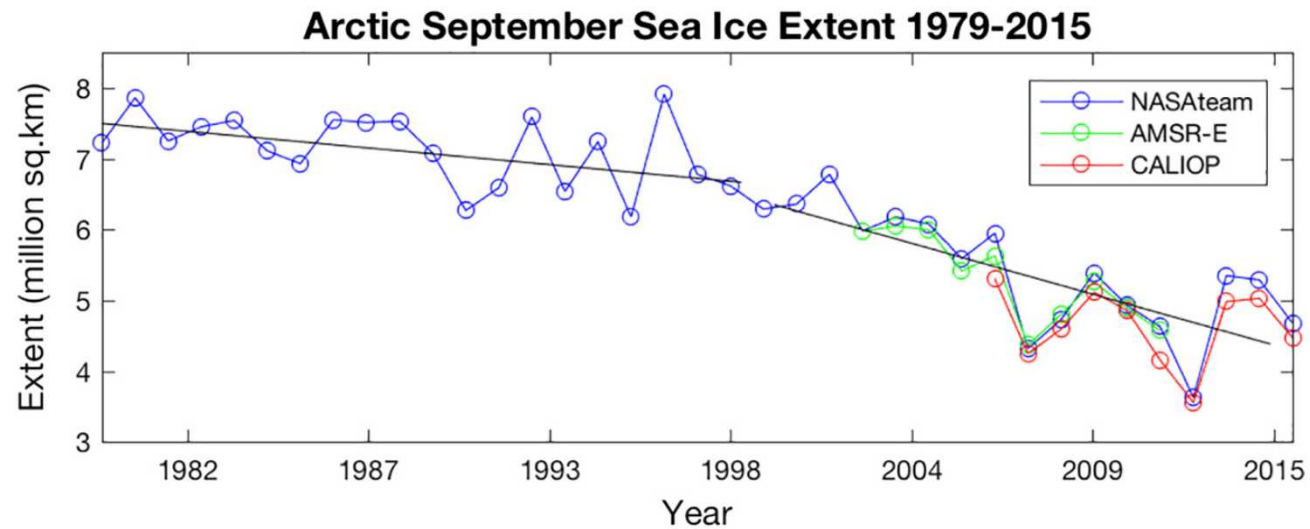


Arctic sea ice area and extent

Monthly time-series plot of the Arctic sea ice area (10^6 km^2) during the period of 1978 to 2016

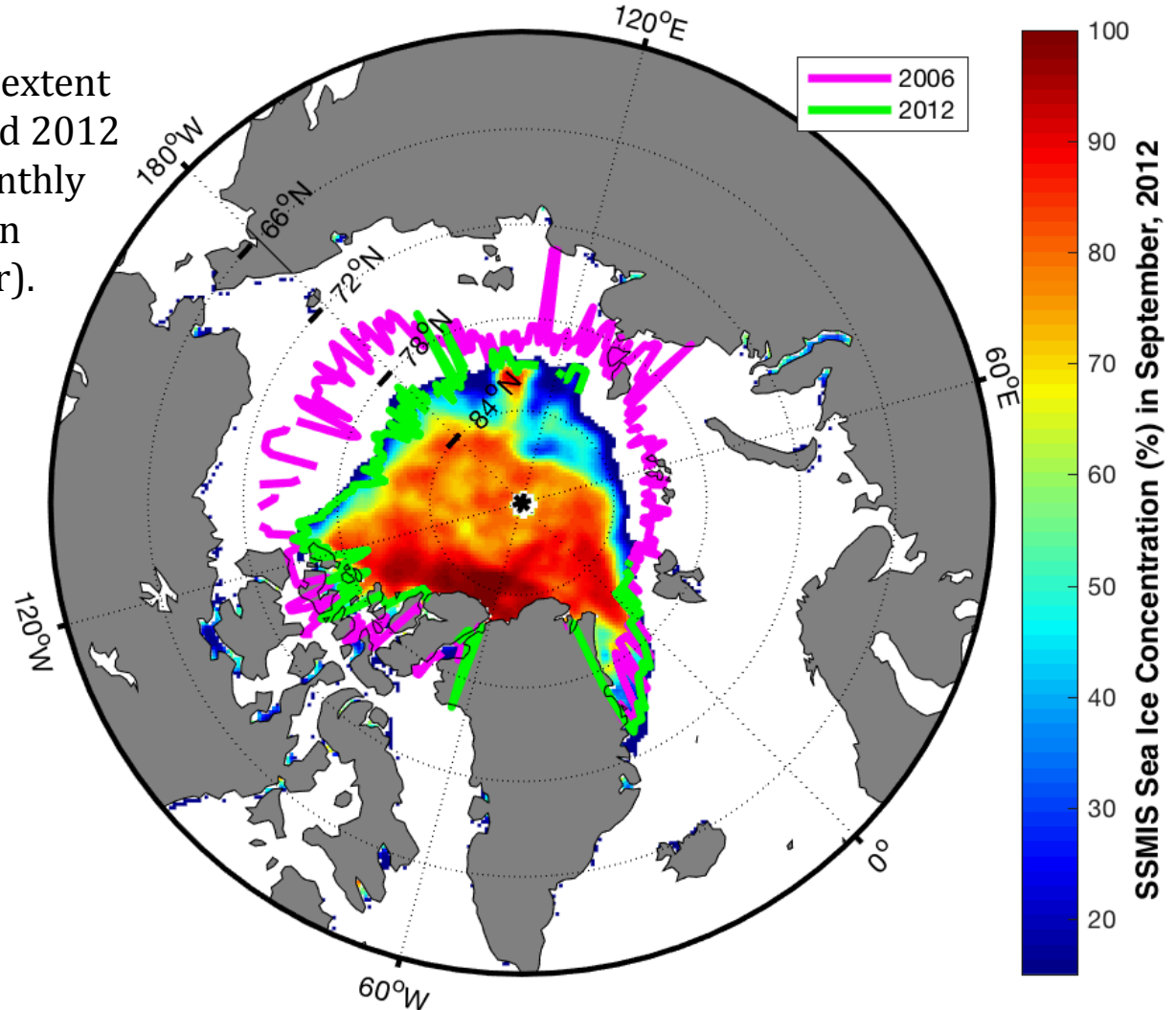


Arctic sea ice area and extent-September

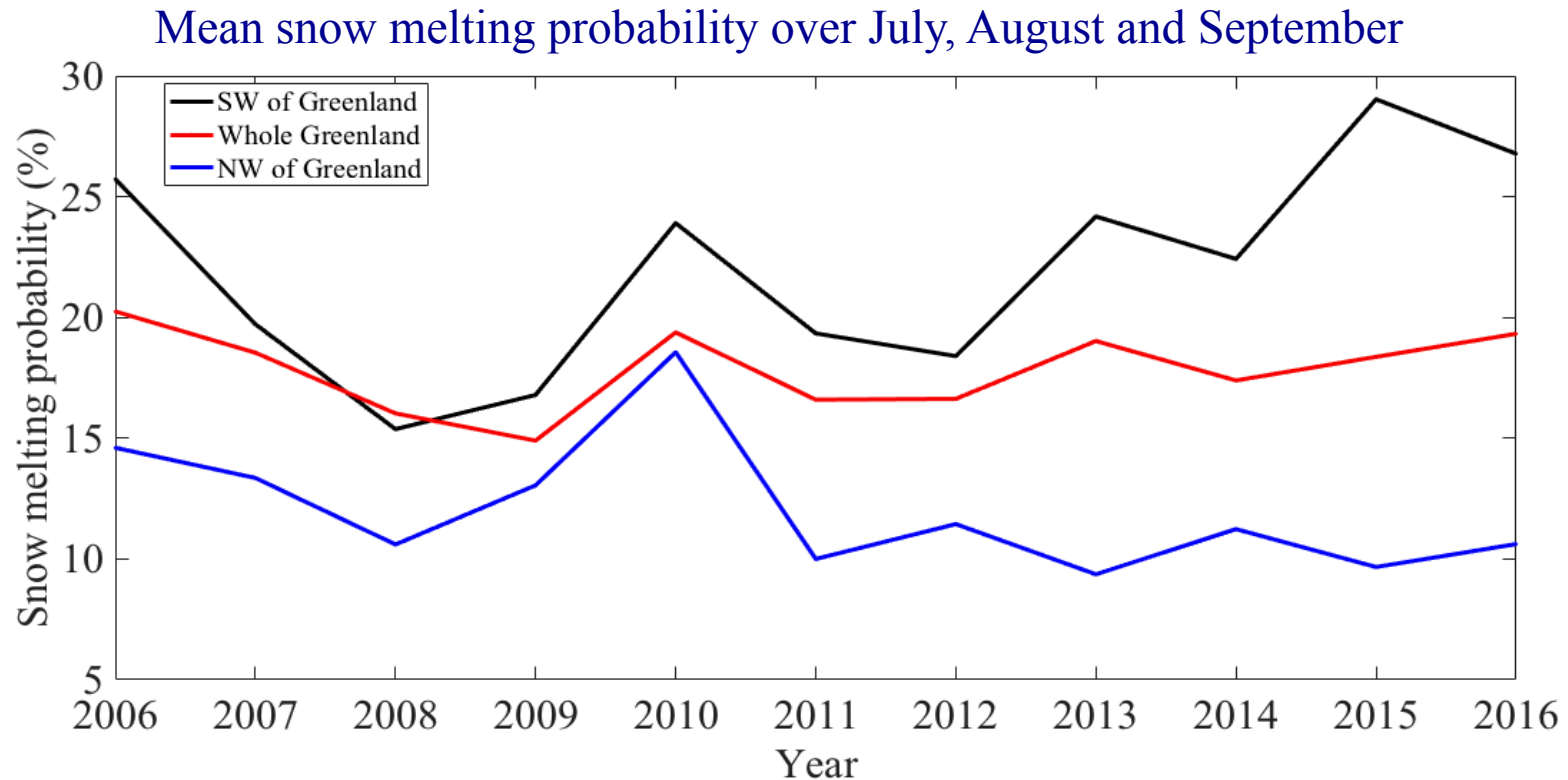


Arctic sea ice extent

CALIOP September sea ice extent at year 2006 (pink line) and 2012 (green line) and SSMIS monthly sea ice concentration (%) in September, 2012 (color bar).



Greenland Snow melting probability



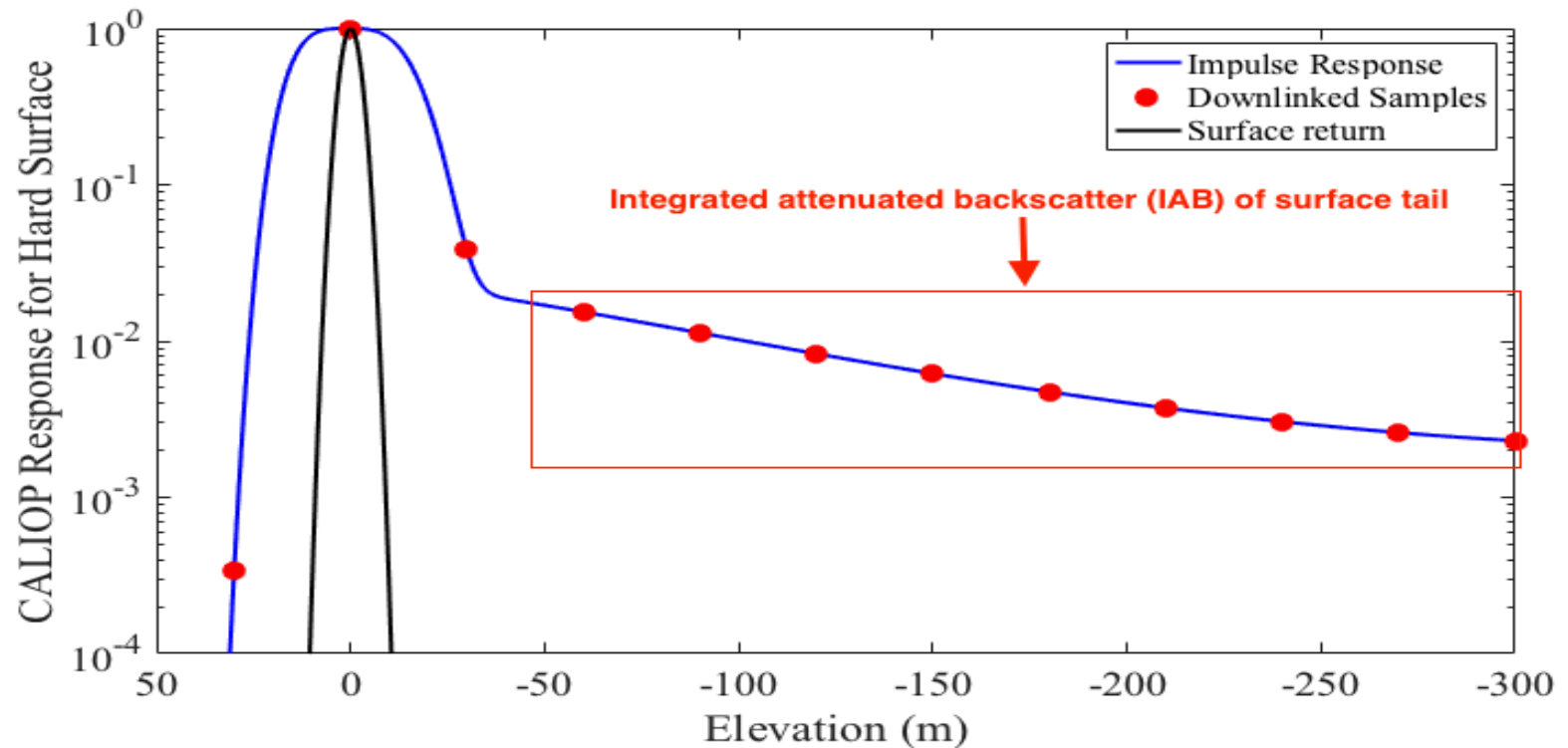
$$\text{Snow melting probability} = \frac{\text{Number of melting}}{\text{Number of total CALIOP observations}} \times 100\%$$

SW: South west region: latitude $60^{\circ} \sim 64^{\circ}\text{N}$; longitude $< -40^{\circ}\text{W}$

NW: North west region: latitude $>78^{\circ}\text{N}$; longitude $-72^{\circ} \sim -45^{\circ}\text{W}$

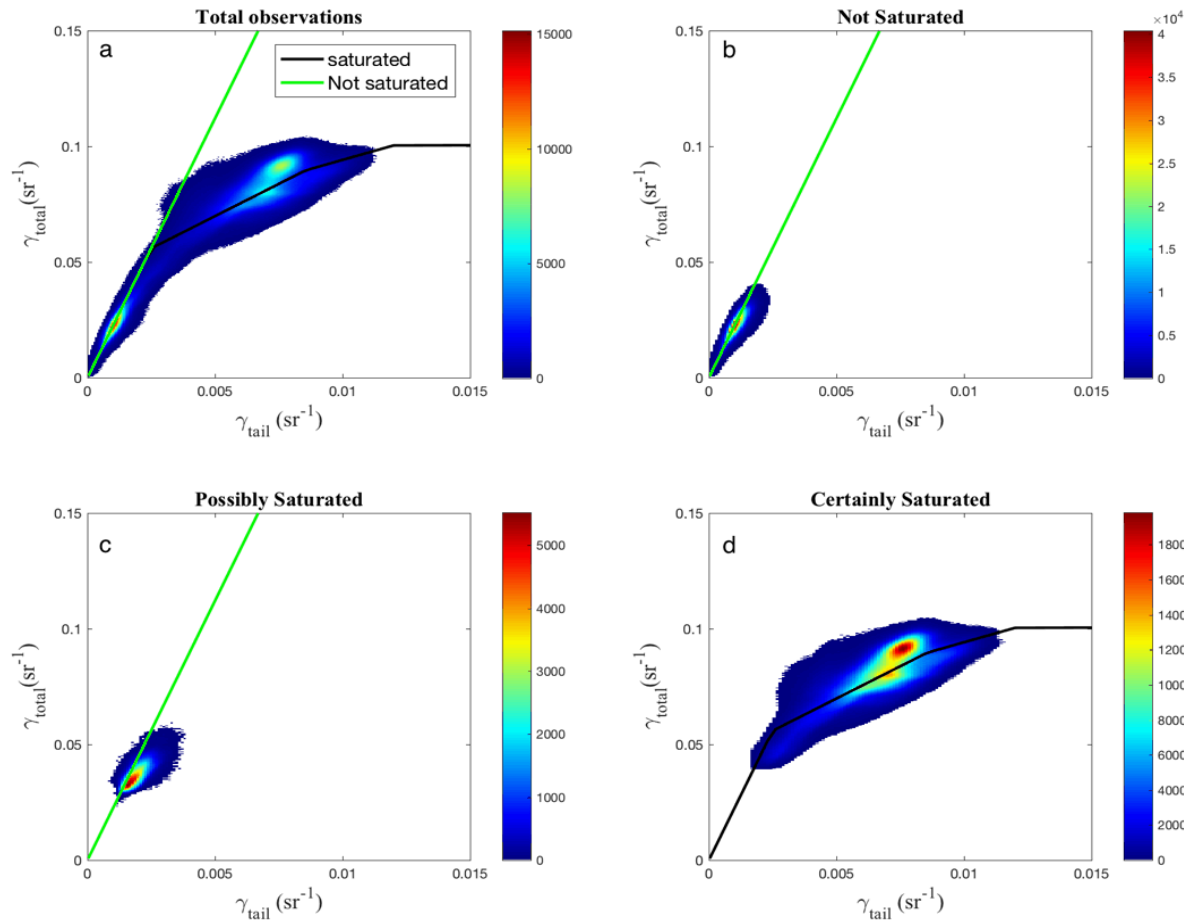
Laser pulse bidirectional reflectance

$$\gamma'_{\text{total}} = \int_{\text{surface}-300\text{ m}}^{\text{surface}+30\text{ m}} \beta'(z) dz, \quad \gamma'_{\text{tail}} = \int_{\text{surface}-300\text{ m}}^{\text{surface}-60\text{ m}} \beta'(z) dz.$$



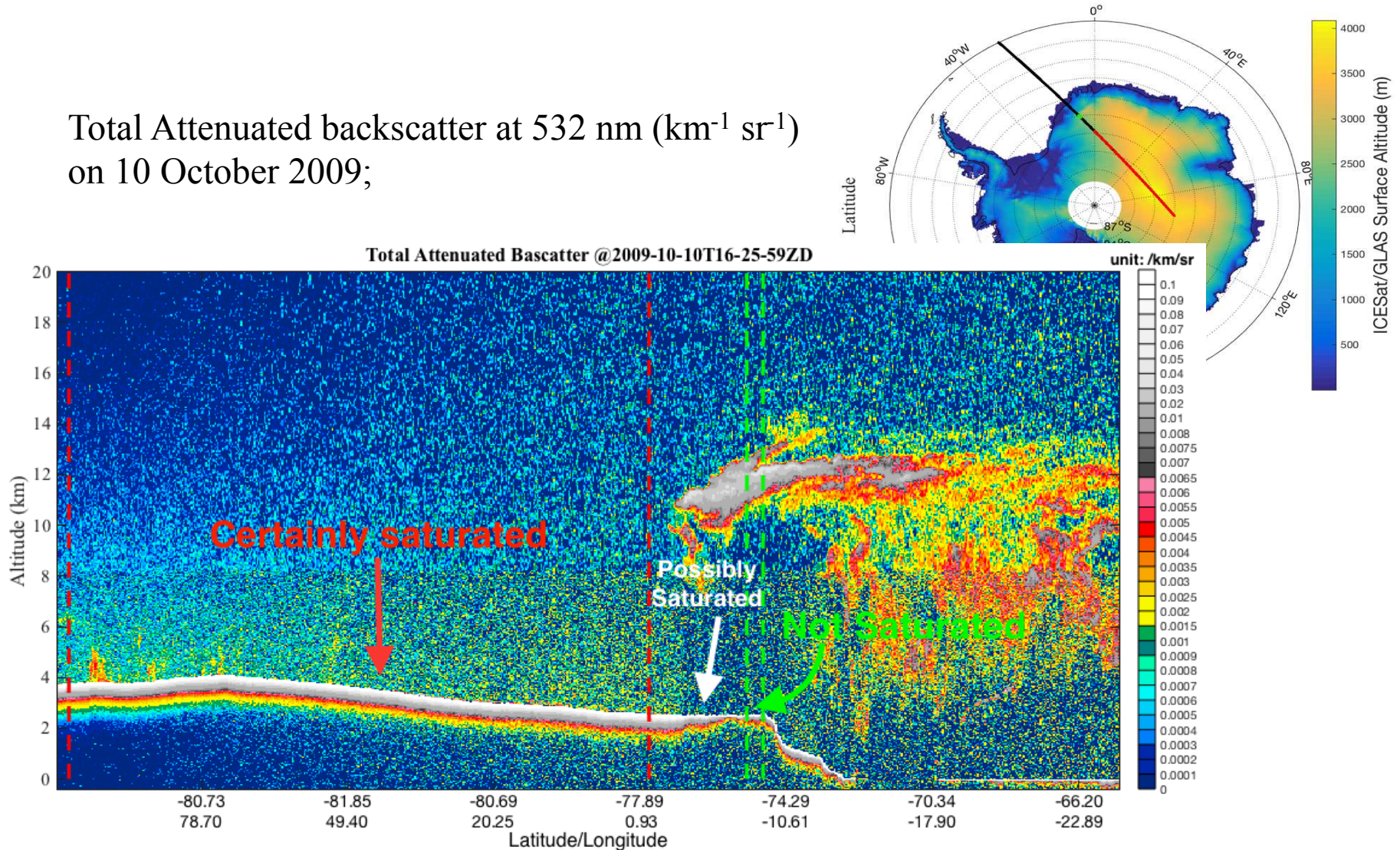
Laser pulse bidirectional reflectance

For the saturated signals, the total integrated attenuated backscatter (γ'_{total}) can be estimated from the surface tail γ'_{tail} as $\gamma'_{total} = c\gamma'_{tail}$. The value of c is about 19.6 ± 3.5 from fitting the not-saturated signals.



Laser pulse bidirectional reflectance

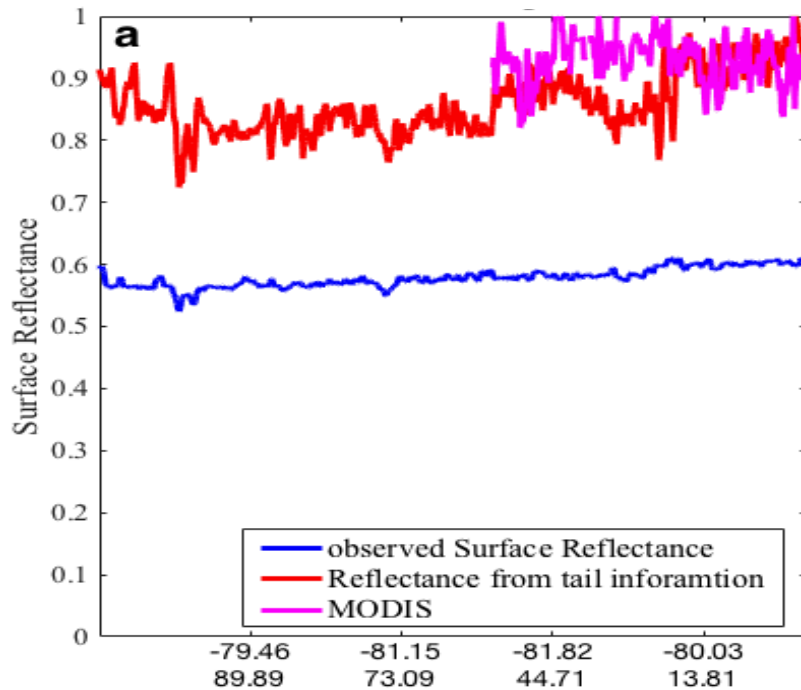
Total Attenuated backscatter at 532 nm ($\text{km}^{-1} \text{sr}^{-1}$)
on 10 October 2009;



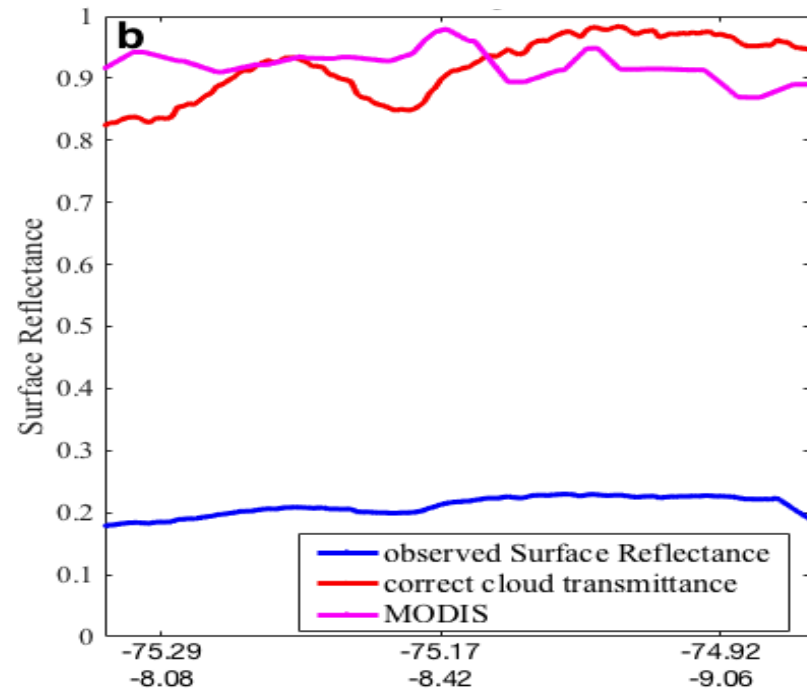
Laser pulse bidirectional reflectance

CALIOP observations on 10 October 2009;

Saturation region



Cloud region



Take home message

- CALIOP measurements at 532nm and 1064nm channels tell us different surface types: including open water, snow/sea ice, melting.
- CALIOP sea ice area and extent results compared well with microwave sea ice results.
- CALIOP lidar measurements can be used to estimate the snow/sea ice melting probability, and laser pulse bidirectional reflectance.

Outline

1. CALIPSO brief introduction
2. New Applications
 - Land (elevation, forest canopy)
 - Ocean (k_d , b_{bp} , bathymetry)
 - Cryosphere (snow/ice, melting)
- 3. Summary and Future work**

Summary and Future work

Operational Achievements:

- Long term measurements: CALIOP collected more than 12 years of measurements so far;
- Observations during day/night and for all seasons
- Data publicly available
- **Other applications:**

Altimetry; (*Hu et. al., 2007; Lu et.al,2014*)

Surface type distinguish, Arctic sea ice trend; (*Lu et.al, 2016, 2017*)

Ocean subsurface; (*Behrenfeld et. al., 2013, 2016; Lu et.al, 2014, 2016*)

Ocean surface-wind speed (*Hu et.al, 2007*)

Future work:

- *Global diffuse attenuation coefficient study, especially in polar region, where MODIS has limited results. Day and night difference.*
- *Bathymetry of shallow water, Pond depths study over Greenland, melting water mass, and its relation with Greenland glacier loss*
- *Snow grain size retrieval from CALIOP surface reflectance at 532nm and 1064nm*