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ICESat-2 Atmospheric Layer Feature Subtyping Using MERRA-2 Model Reanalysis

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Abstract As a complement to its detailed altimetry products, basic atmospheric products, including calibrated backscatter profiles and cloud and aerosol layer detection, have also been developed for the Ice, Cloud, and Land Elevation Satellite 2 (ICESat-2). With the limitations of having a single 532nm wavelength without depolarization, feature subtyping is not feasible using heritage space-based lidar algorithms. To allow for further subtyping of these features, we sample Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis along the ICESat-2 orbit to allow for cloud phase and aerosol types to be assigned for detected layers. Using coincident points from intersecting orbits, we show that these model-assisted feature subtypes compare well to those determined by Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). Expanding the atmospheric products from ICESat-2 to include cloud phase and aerosol type will allow for lidar ratios to be assigned, facilitating the future development of layer optical depths.

1. Introduction

Space-based lidar is unmatched in providing profiles of clouds and aerosols. The altitudes of these atmospheric features can be accurately determined which is a benefit both in operational forecasting and in answering research questions pertaining to the radiative balance of the planet. In recognition of the value of these observations NASA has launched multiple atmosphere-focused space-based lidar missions including CALIOP and Cloud Aerosol Transport System (CATS). Unfortunately, as of today, both missions have ceased data collection (2023 for CALIOP and 2017 for CATS) leaving a gap before the next generation of NASA space-based lidars are launched to orbit.

While not specifically designed for atmospheric observations, the ICESat-2 mission and its Advanced Topographic Laser Altimeter System (ATLAS) lidar provide basic atmospheric products including calibrated backscatter curtains and cloud and aerosol layer detection. Compared to CALIOP and CATS, the ATLAS instrument is limited in its hardware, only providing observations in one 532 nm wavelength without depolarization. This limitation makes aerosol type and cloud phase determinations difficult through heritage algorithms.

To make this typing possible, we use MERRA-2 model reanalysis data, sampled along the ICESat-2 orbit. We use meteorological data and model aerosol fields in new cloud phase and aerosol typing algorithms to predict aerosol type and cloud phase for ICESat-2 detected layers. The subtyping of these layers may allow for the future development of layer optical depth and extinction profiles.

2. Methods

The ICESat-2 satellite was launched into a 92° inclination orbit in September of 2018 and has been in continuous operation since October of that year [1, 2]. Though specifically designed and optimized to obtain high resolution altimetry measurements of the Earth’s surface, ICESat-2 also has an atmospheric channel to record backscatter from clouds and aerosols from 14 km altitude to the surface. ICESat-2 carries only one instrument – the ATLAS lidar that utilizes a high repetition rate (10 KHz), low per pulse energy (500 μJ), 532 nm laser and photon counting detectors. On board the satellite, 400 shots are summed and then downlinked resulting in 25 Hz profiles (280 m horizontal and 30 m vertical resolution). ATLAS employs a diffractive optical element (DOE) to split the laser pulse into 6 individual beams that are simultaneously emitted from the satellite. Three of the beams have nominal energies of about 25 μJ per pulse (weak beams) and the other 3 have energies roughly 4 times the weak beams (strong beams). The altimetry measurements utilize all 6 laser beams while for the atmospheric measurements, backscatter data are captured only from the 3 strong beams (known as profile1, profile2 and profile3 on the ATL04 and ATL09 data products). Each strong/weak beam pair is separated by about 3 km on the ground (across track).

The ICESat-2 atmospheric data products include level 2A (ATL04), 3A (ATL09) and 3B (ATL16/17). ATL04 and ATL09 are along-track products that contain among other things normalized relative backscatter profiles (ATL04) and calibrated, attenuated backscatter profiles (ATL09). ATL16 and ATL17 are weekly and monthly gridded fields of various parameters on the ATL09 product. In addition to the calibrated, attenuated backscatter profiles, ATL09 contains the top and bottom height of all atmospheric layers detected in the data and a flag to indicate whether each layer is a cloud, aerosol or unknown [4].

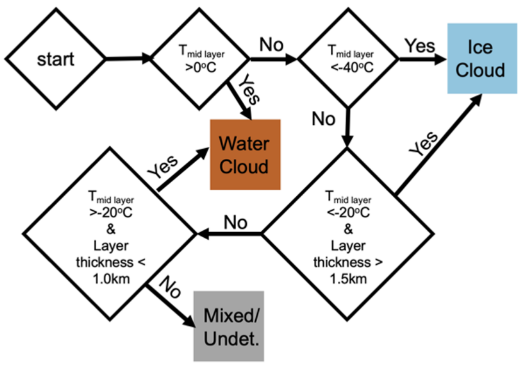

Figure 1. Flow chart of cloud typing algorithm

The cloud and aerosol typing algorithms for ICESat-2 atmospheric features use the MERRA-2 reanalysis to distinguish aerosol and cloud layers (Figures 1 & 2). This is similar to the scheme utilized by the CATS lidar after it moved to single, 1064 nm wavelength operations on the International Space Station (ISS) [3]. Roughly following the CALIOP/CATS convention, we distinguish cloud phase (ice or liquid water) (Figure 1) and 6 aerosol feature types following CALIOP/CATS conventions: marine, dust, clean background, polluted continental, smoke, and UTLS (upper tropospheric/lower stratospheric) (Figure 2).

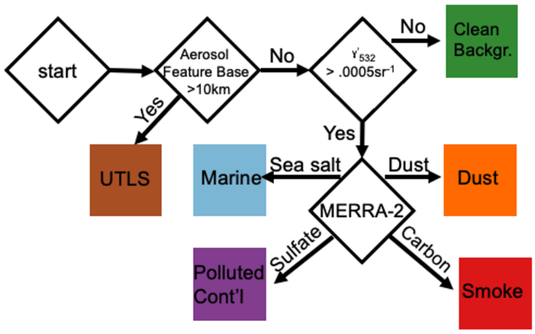

Figure 2. Flow chart of aerosol typing algorithm

In the initial aerosol typing algorithm, after aerosols layers are identified, aerosol features higher than 10 km will be categorized as UTLS. Any layer lower than 10 km and featuring an integrated backscatter (γ'532) less than 0.0005 sr^{-1} is categorized as a clean, background aerosol layer like CALIOP [5]. Aerosol layers with integrated backscatters greater than 0.0005 sr^{-1} will be classified based on the model predicted aerosol types with profiles containing predominantly (by extinction) sea salt aerosols being classified as marine, sulfate aerosol layers as polluted continental, dust as dust, and carbonaceous aerosols as smoke [6,3]. Because of its incorporation in MERRA-2 to calculate sea salt emissions, surface types are not used to type marine aerosols.

3. Results

Coincidences between the orbits of ICESat-2 and CALIOP provide unique opportunities to compare the cloud phase and aerosol typing of ICESat-2 using the MERRA-2 reanalysis and the those determined by CALIOP. We have illustrated two of these cases: one where the orbits crossed on July 20, 2019 over Iran (Figure 3) and on August 1, 2019 over the Coral Sea in the Southwest Pacific Ocean (Figure 4).

In both of these cases, we see the utility of MERRA-2 in accurately typing the primary layers present in the scenes. For the Iranian case, the aerosol layer is typed as dust which agrees with CALIOP 4.51 layer data. Further away from the coincident point (middle of the figure), there is more disagreement in the extent of the dust aerosol layer but this is due to differences in the layer identification techniques and algorithms of ICESat-2 and CALIOP and the horizontal data averaging in CALIOP, not the feature typing performed here [4, 7].

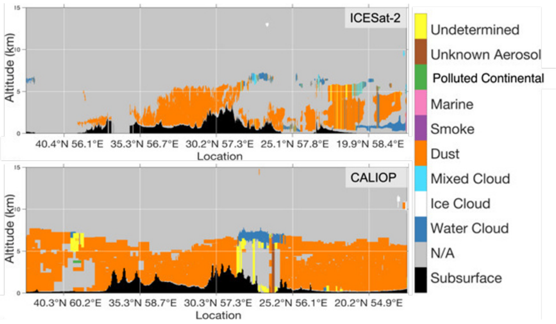

Figure 3: Aerosol typing and cloud phase prediction of a July 20, 2019 orbit coincidence of ICESat-2 (top) and CALIOP (bottom) (22:20 UTC). The coincident point is in the middle.

For the cloudier marine case (August 1, 2019), we also find general agreement between ICESat-2 and CALIOP feature types (Figure 4). The cloud between 10 and 15km is identified as ice in both CALIOP and ICESat-2 and the layers near the surface are likewise categorized as either marine aerosol or water cloud.

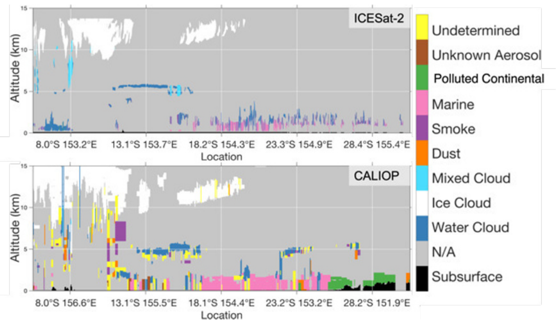

Figure 4: Aerosol typing and cloud phase prediction of an August 1, 2019 orbit coincidence of ICESat-2 (top) and CALIOP (bottom) (15:22 UTC). The coincident point is in the middle.

4. Discussion and Conclusion

Because of the hardware limitations of the ATLAS lidar, accurate feature subtyping of ICESat-2 atmospheric products requires the incorporation of supplemental data, such as model reanalysis. Here we showed that for cases where aerosol types are accurately modeled and predictable, model reanalysis data can allow for aerosol types and cloud phases to be accurately assigned for ICESat-2 identified layers. Because this method relies on both accurate ICESat-2 layer identification and accurate modeled representation of the meteorological and aerosol conditions, it is limited and can be prone to errors where ICESat-2 layer detection is weaker, such as during daytime, where the model reanalysis is inaccurate, or where aerosol types are ambiguous. In the future, these accurately assigned layer subtypes will facilitate the selection of lidar ratios and the determination of layer optical depths from ICESat-2 data.

5. References

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