New Automated Methods for Detecting Volcanic Ash and Retrieving Its Properties from Infrared Radiances

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and
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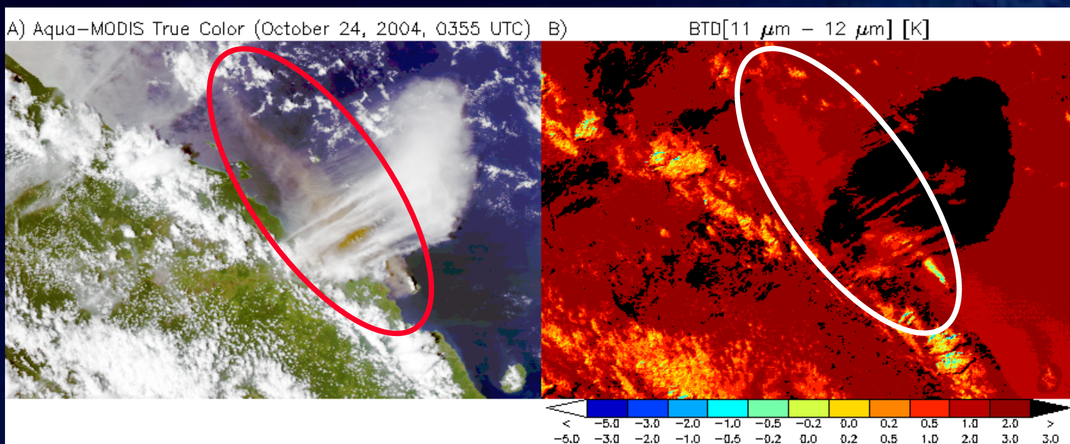
Introduction

- Suspended volcanic ash is a significant threat to aircraft as well as those on the ground where ash fallout occurs.
- Current satellite-based operational ash monitoring techniques are generally qualitative and require extensive manual analysis. Because of this timely detection is challenging. Quantitative products are needed to improve ash cloud monitoring.
- While future operational sensors such as the ABI, VIIRS, and CrIS will improve ash remote sensing capabilities, ash remote sensing techniques, too, must evolve to allow for reliable automated ash detection.
- *The goal of this talk is to present an automated approach, that takes advantage of advanced sensor capabilities, for detecting volcanic ash and retrieving its height and mass loading.*

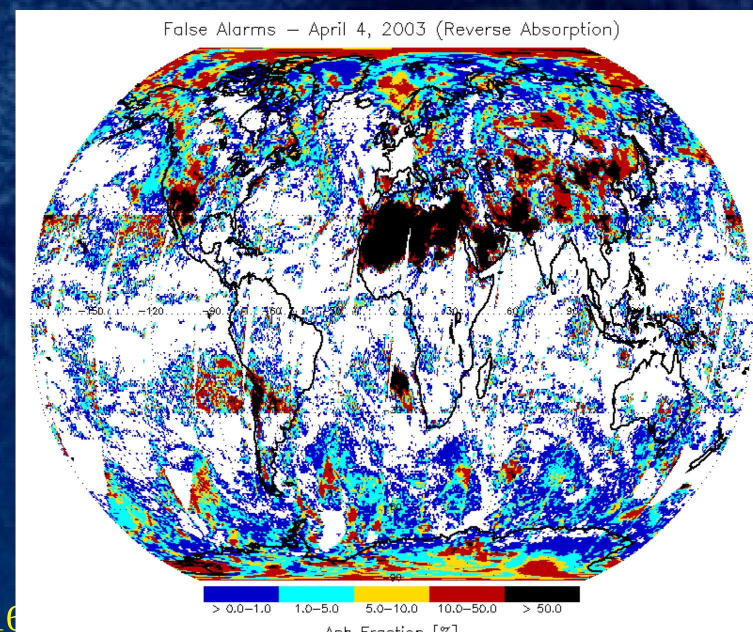
Improving Upon Established Ash Detection Techniques



The 11 - 12 μm "split-window" brightness temperature difference has traditionally be used to detect ash.

The split-window technique is not suitable for automated ash detection, though, because it is hampered by numerous false alarms (right) and missed detection due to water vapor absorption (top).

From Pavolonis et al. (2006)



Remote Sensing Philosophy

- Not only do we look to exploit channels such as the 8.5 and 10.3 μm channels that will be available on ABI, but we look to maximize the sensitivity of the measurements to cloud microphysics.
  - » Account for the background conditions on a pixel-by-pixel basis.
  - » The advent of more accurate fast RT models, higher quality NWP data, surface emissivity databases, and faster computers allows us to calculate a reasonable estimate of the clear sky radiance for each pixel.
  - » We also seek IR-only approached when possible.

Physical Relationships

$$\varepsilon(\lambda) = \frac{Rad(\lambda)_{observed} - Rad(\lambda)_{clear}}{[Rad(\lambda)_{ac} + t(\lambda)_{ac} * B(\lambda, T_{eff})] - Rad(\lambda)_{clear}}$$

After Van de Hulst (1980) and Parol at al. (1991)…

$$\beta_{observed} = \frac{\ln(1.0 - \varepsilon_{\lambda 1})}{\ln(1.0 - \varepsilon_{\lambda 2})}$$

$$\beta_{theoretical} = \frac{(1.0 - \omega_{\lambda 1} * g_{\lambda 1}) * \sigma_{ext\lambda 1}}{(1.0 - \omega_{\lambda 2} * g_{\lambda 2}) * \sigma_{ext\lambda 2}}$$

Effective absorption ratios (similar to ratio of scaled absorption cloud optical depth)

$$\beta_{theoretical} \approx \beta_{observed}$$

Physical Relationships

- The bottom line is that the cloud microphysical signal can be isolated from the surface and atmospheric contribution by converting the measured radiances to effective absorption optical depth and examining the spectral variation.

- This new data space allows us to largely avoid algorithm tuning and helps produce results that are much more spatially and temporally consistent.

- This is true even in the absence of cloud height information.

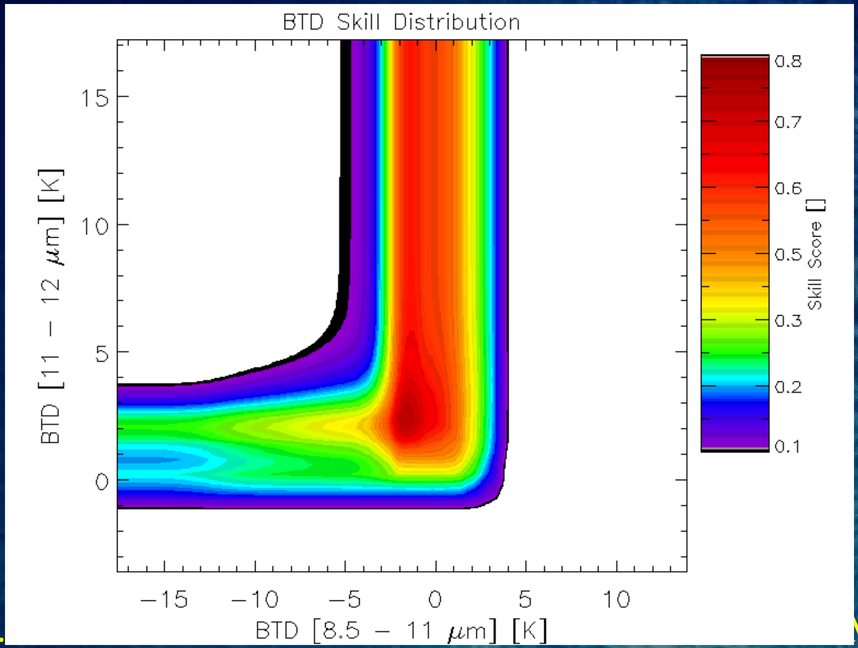
- This theory applies to both narrow band and hyperspectral measurements.

Ash Detection

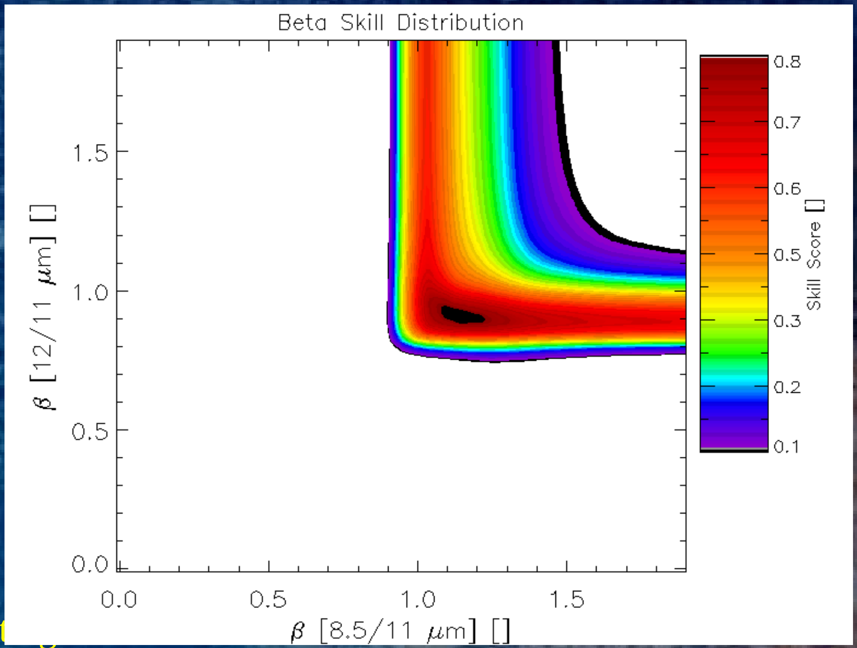
Why use β-ratios instead of brightness temperature differences(BTD's)?

•The skill score for a simple threshold based tri-spectral algorithm is shown as a function of threshold in each dimension for a BTD based approach and a β based approach.

BTD's



Beta Ratios



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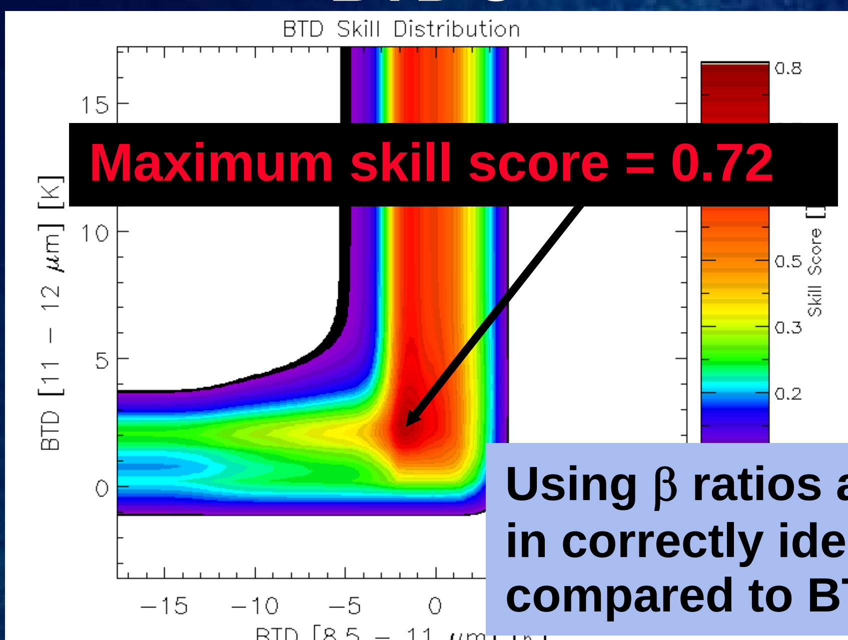
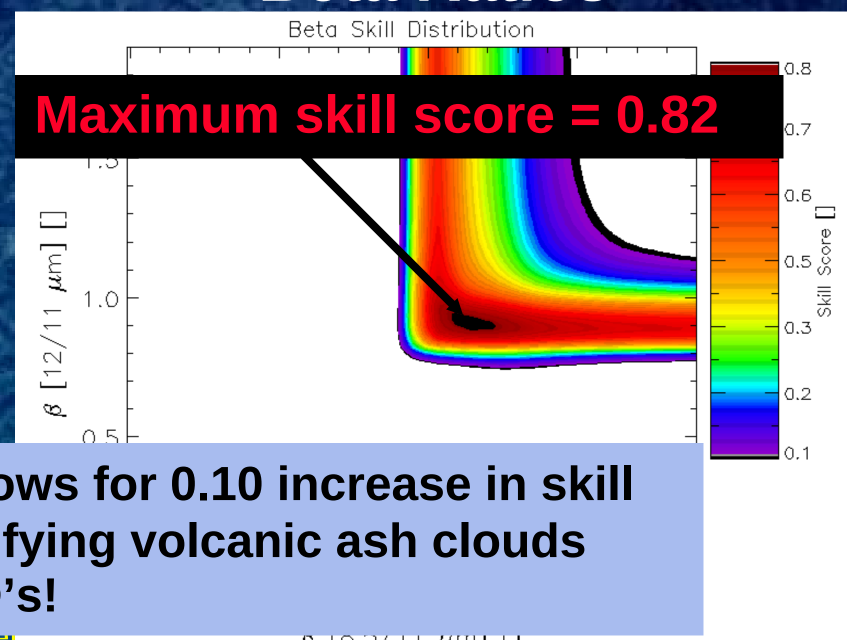
BTD's



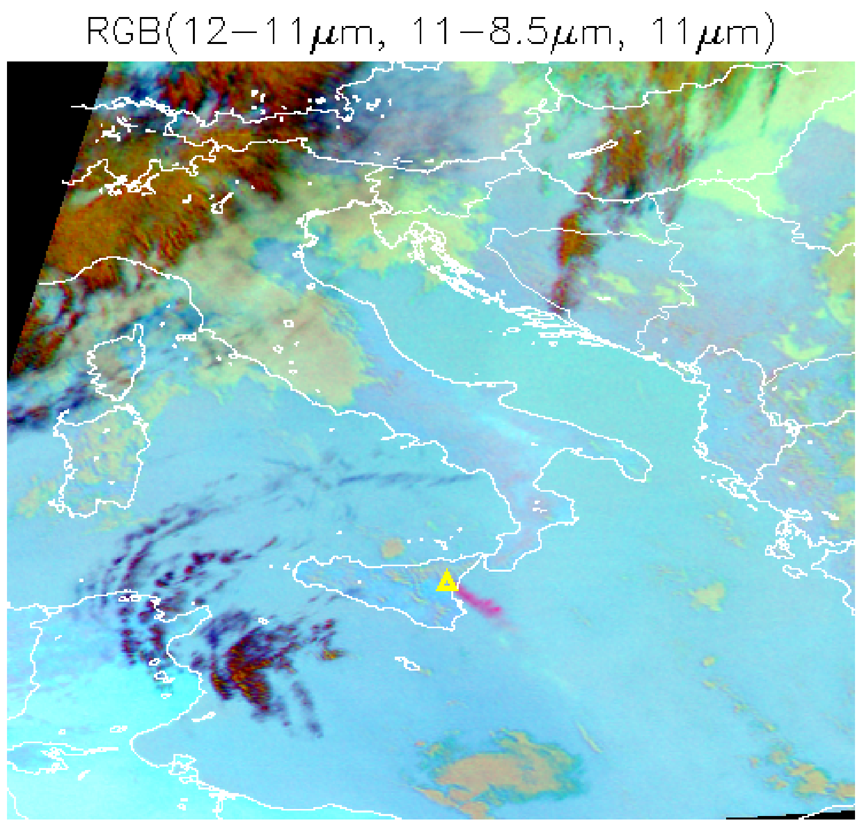
Beta Ratios

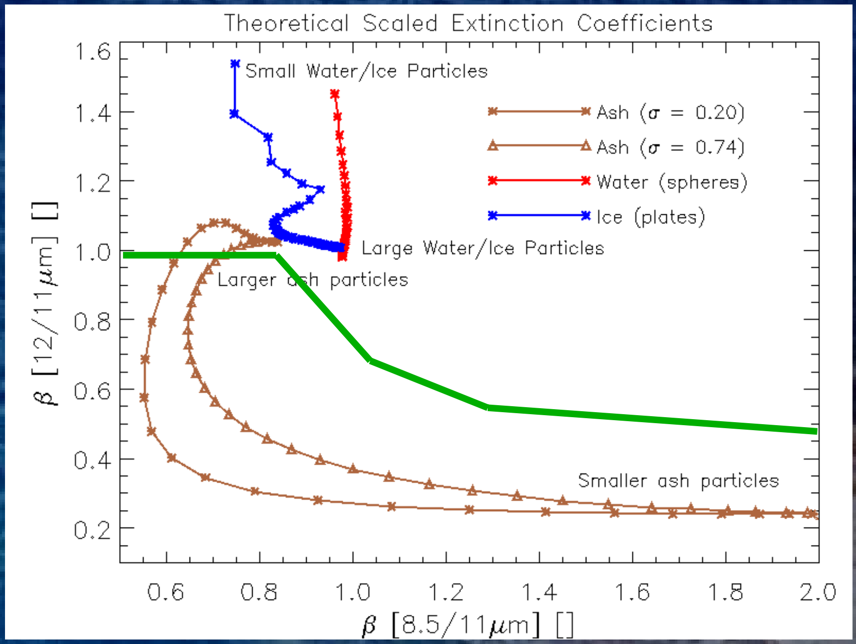


Using β ratios allows for 0.10 increase in skill in correctly identifying volcanic ash clouds compared to BTD's!

Ash Detection

How do the β's computed from the measurements compare to those computed from theoretical particle distributions?





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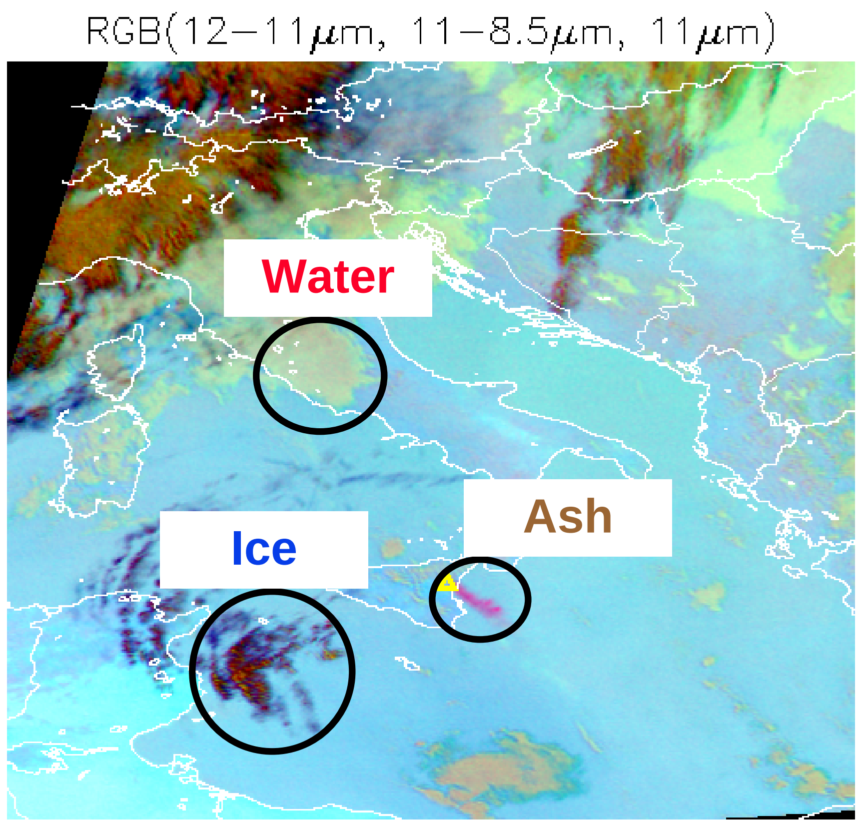

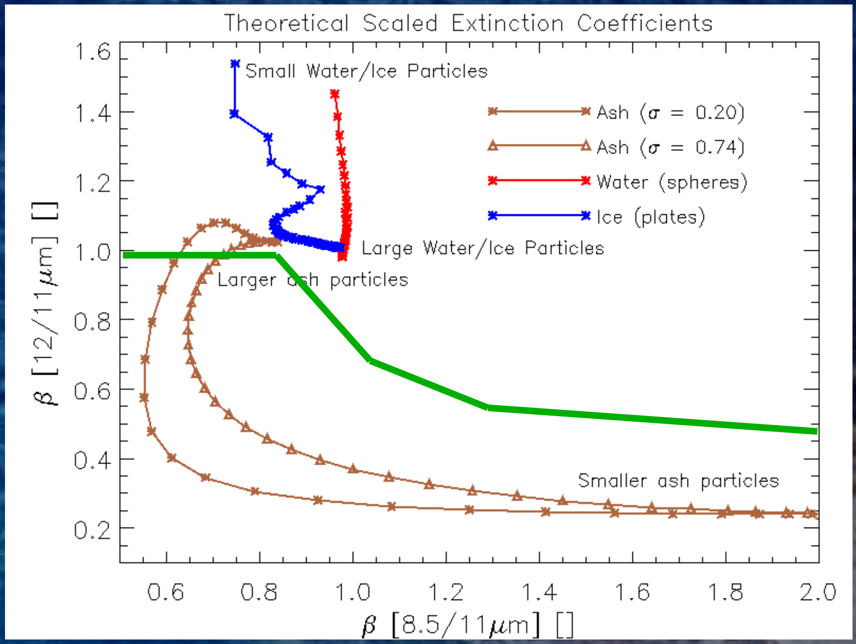

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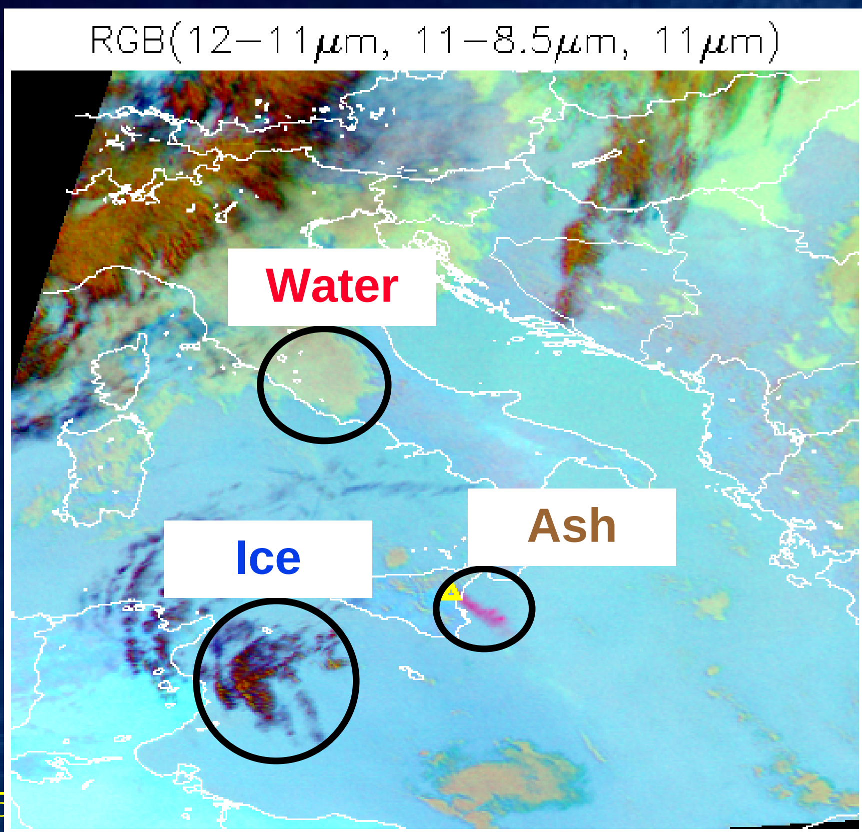
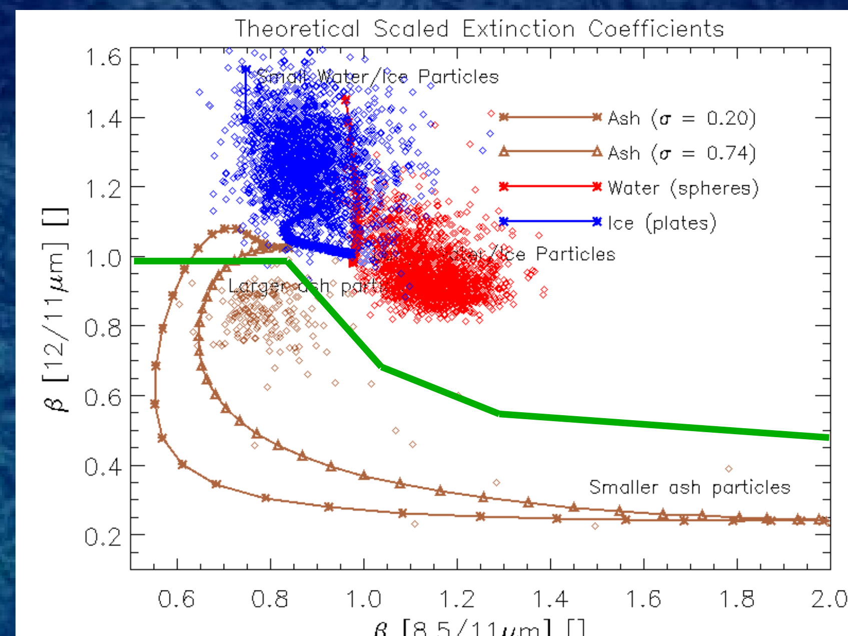
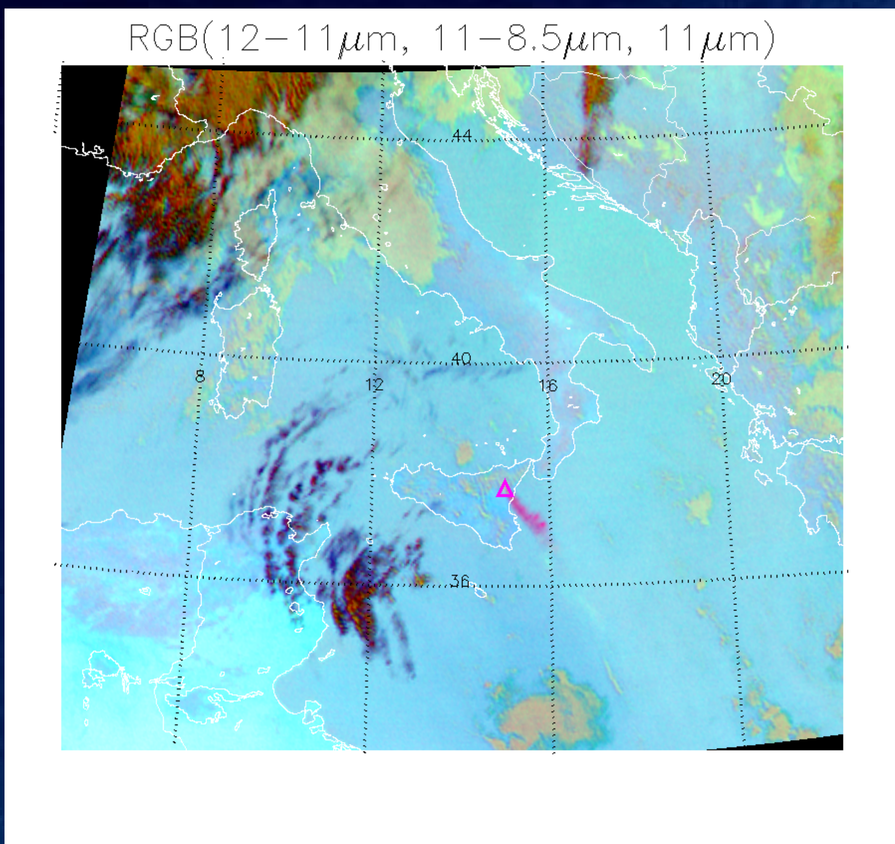
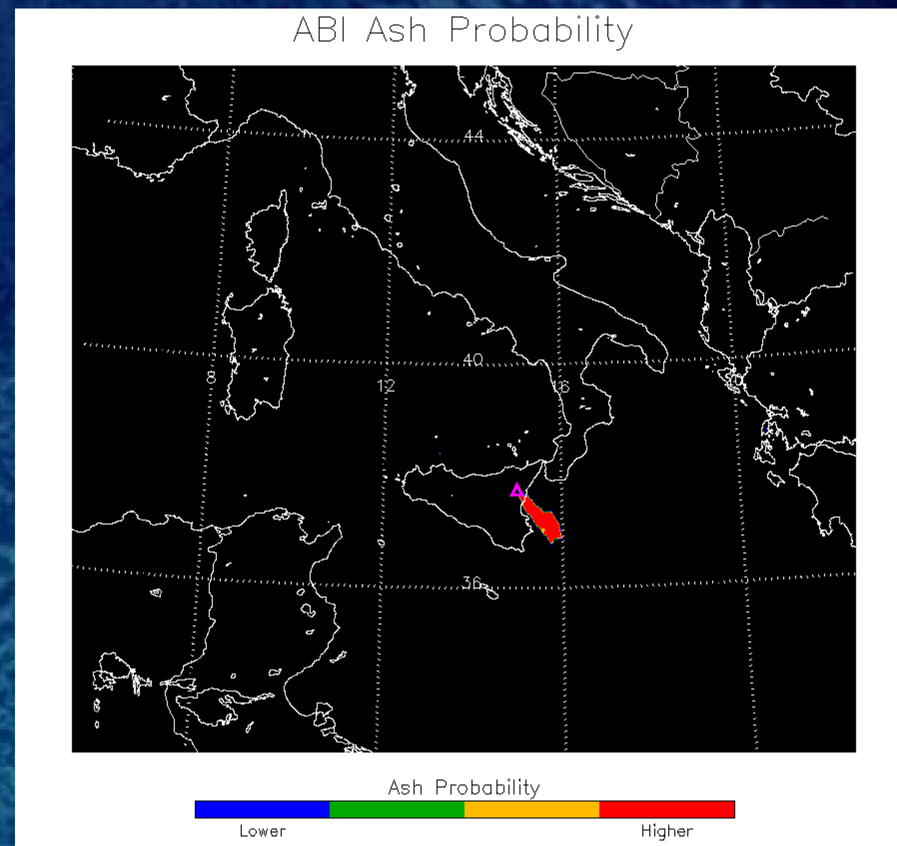




Ash Detection

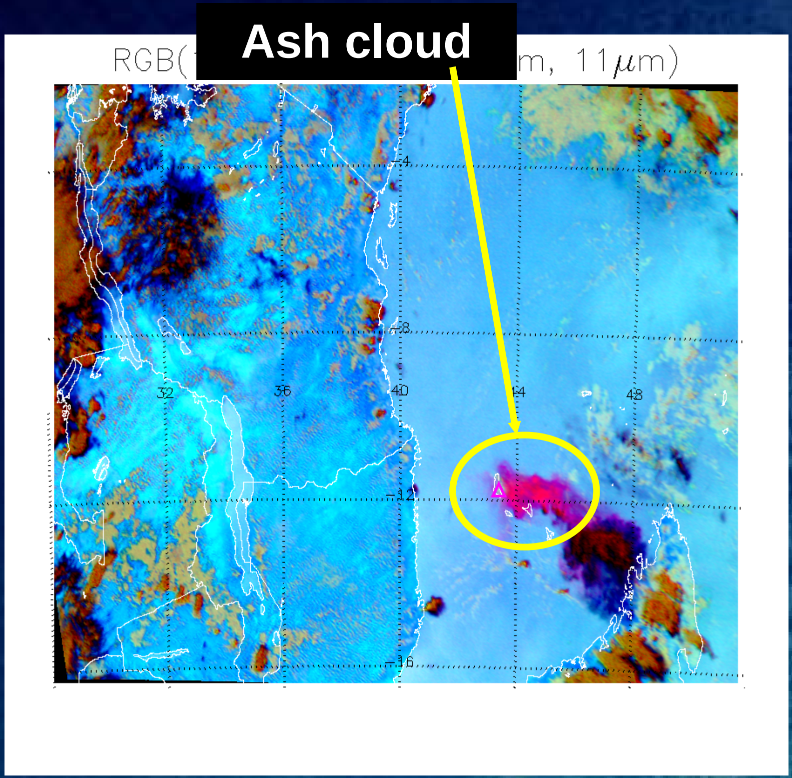
The ash detection results are expressed as a confidence value.

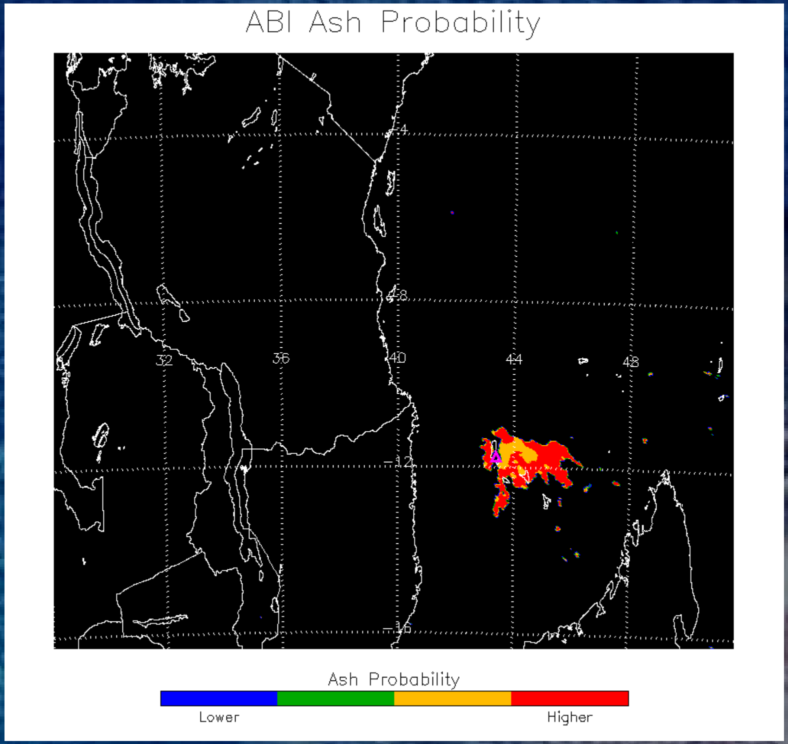




Ash Detection

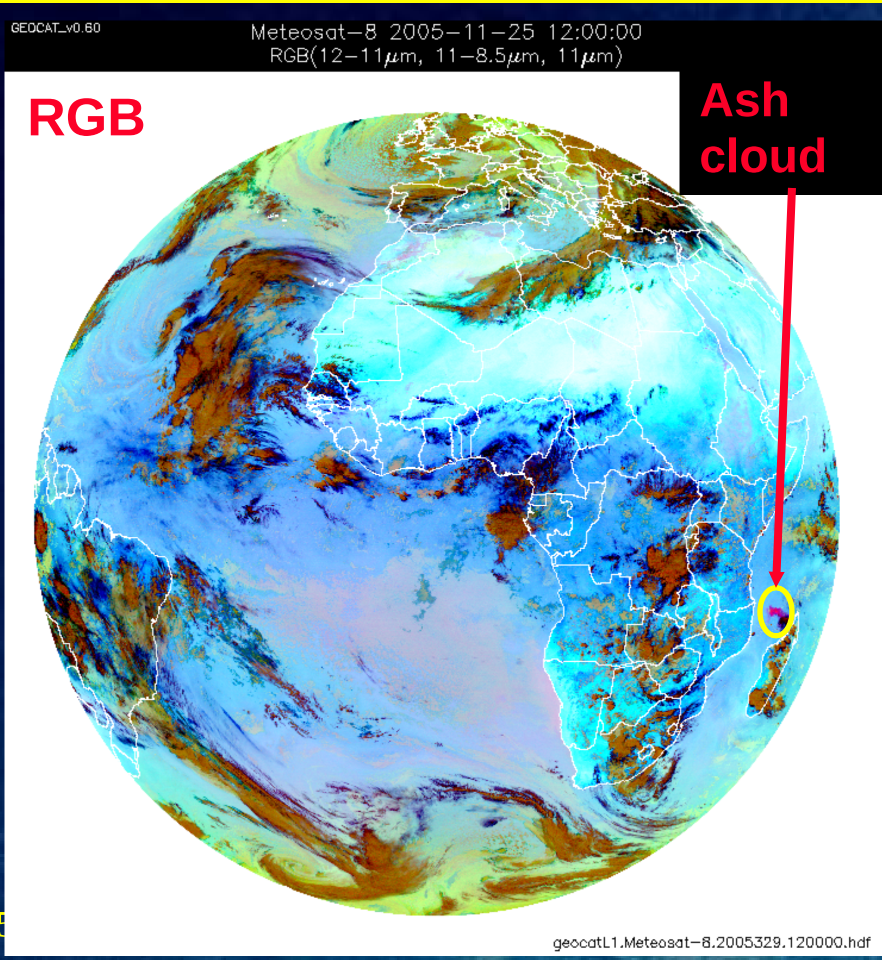
Eruption of Karthala (November 11/25/2005)

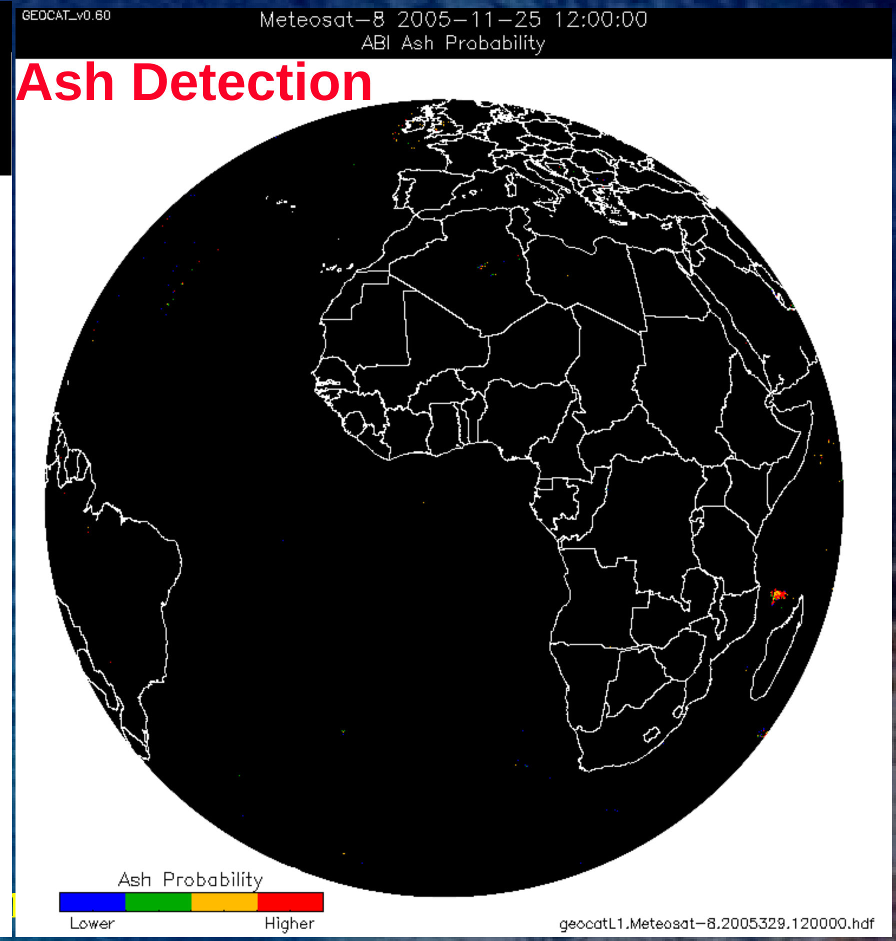




Ash Detection

Full disk results indicate that while the probability of detection is high for most ash clouds, while the probability of false alarm is low.



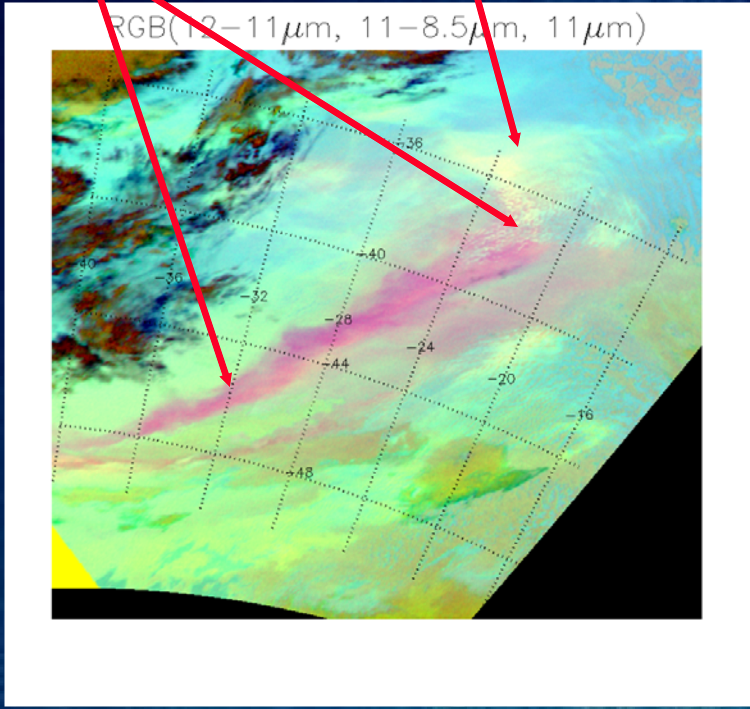


Ash Detection

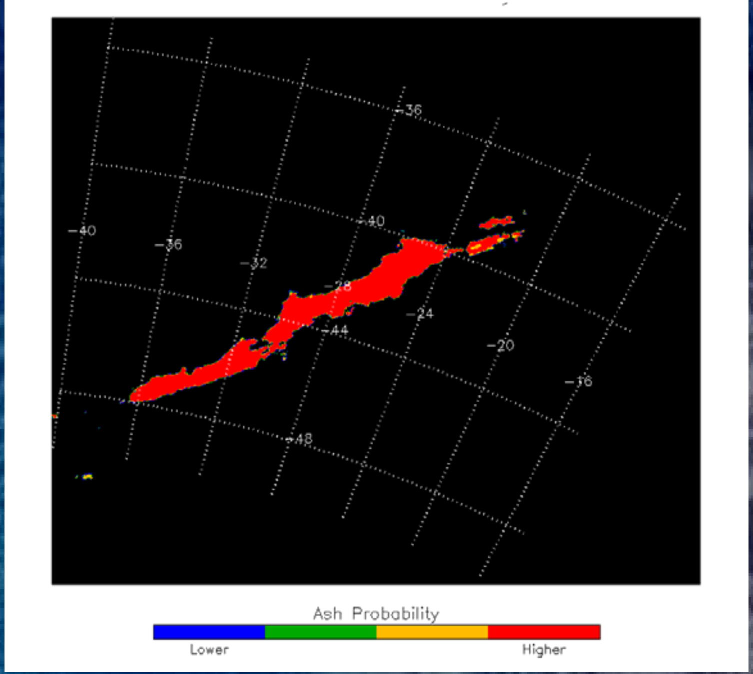
Ash detection under difficult multilayered conditions is improved when the low cloud layer is approximately accounted for.

Ash

Low Cloud



Ash detection *without* multilayered correction



Ash Detection

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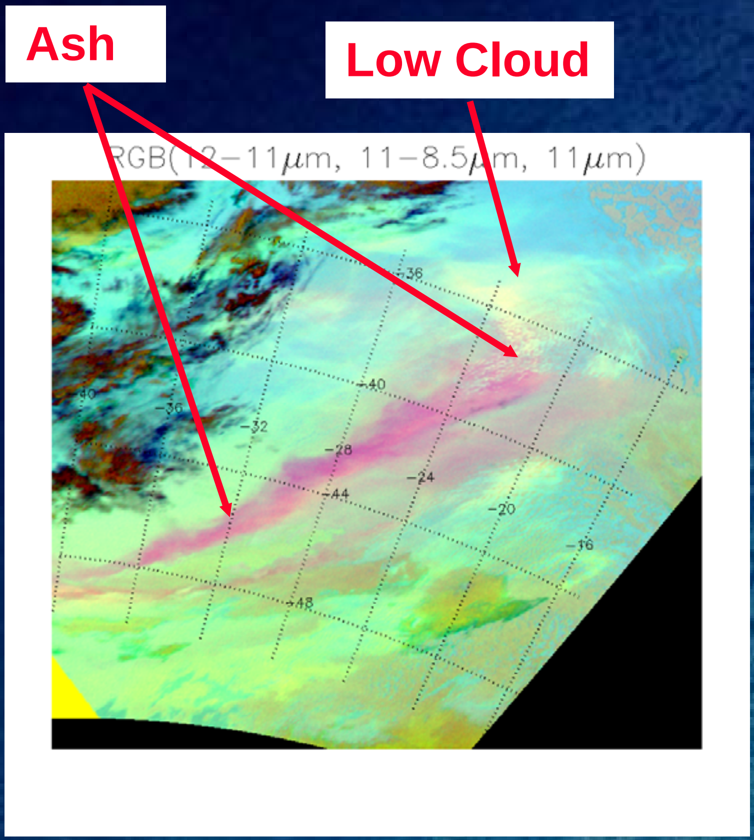
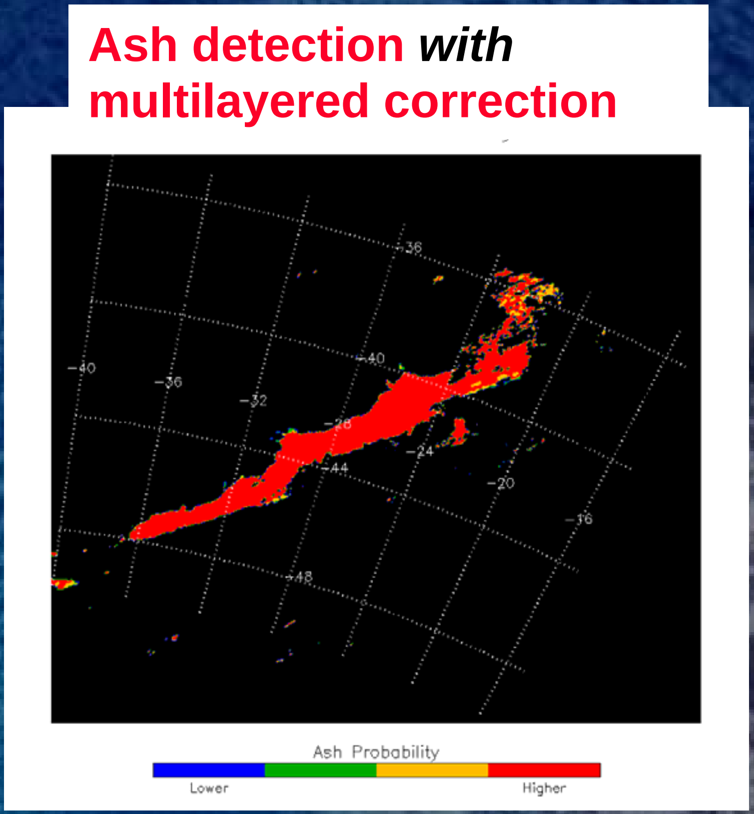
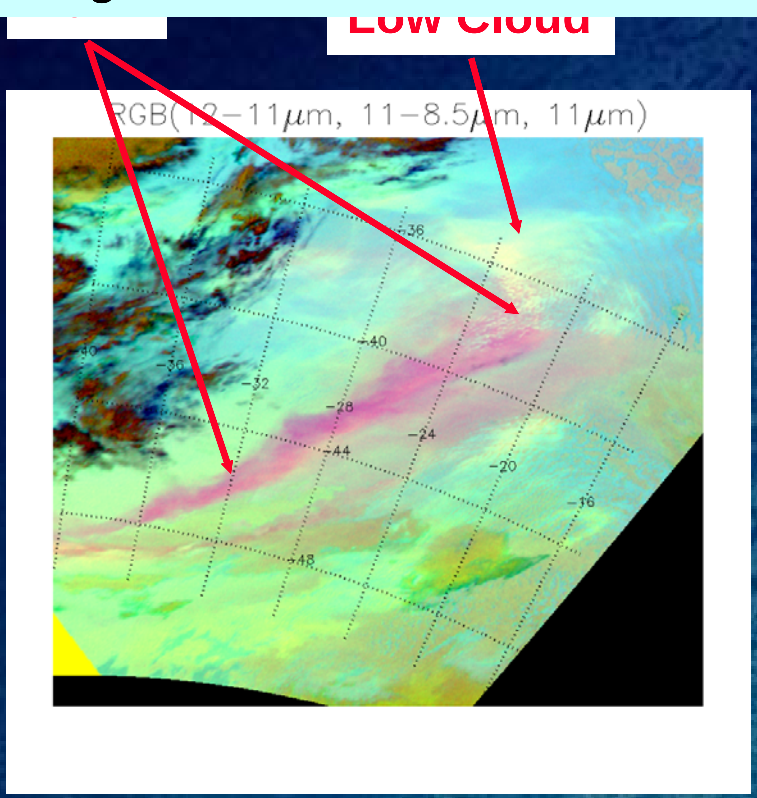


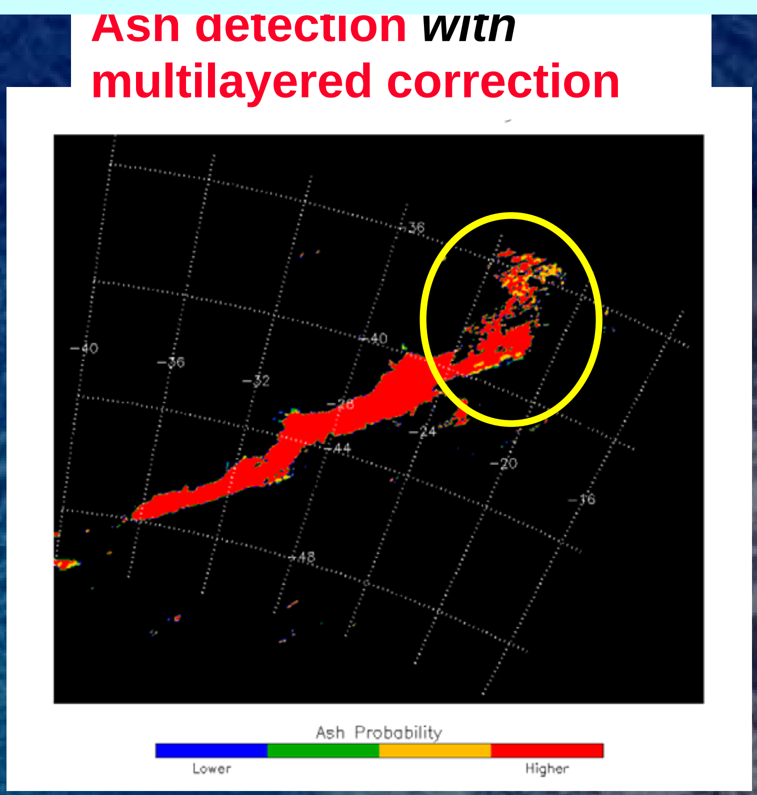


Ash Detection

•Significantly more ash is detected when the multilayered correction is applied.

•This correction is also taken into account when retrieving the height/mass loading.

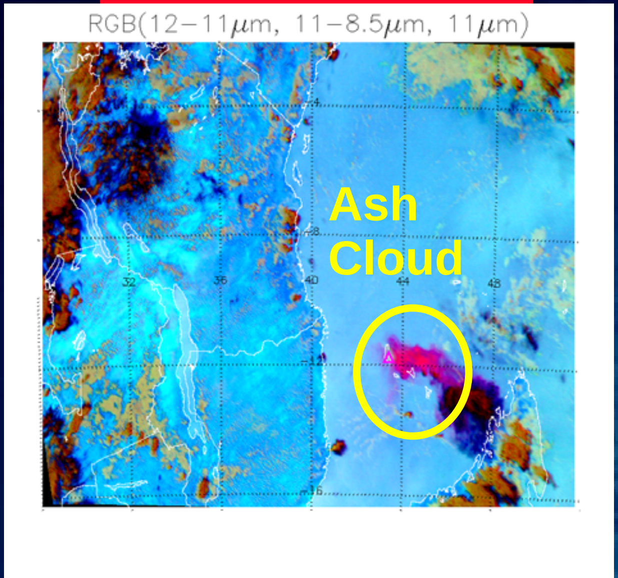


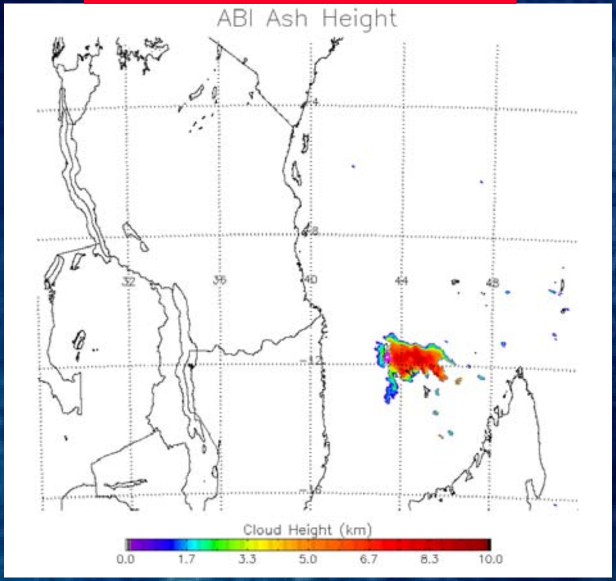


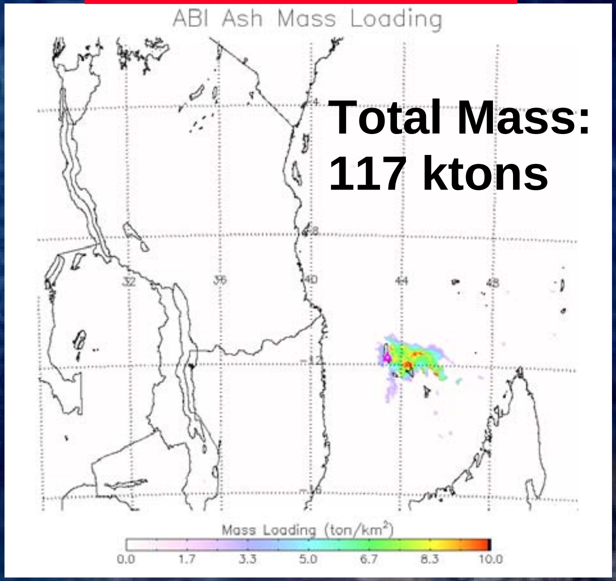
Ash Retrieval

- Retrievals of ash loading (optical depth and particle size) have been limited to case studies. Automated real-time capable retrieval algorithms are lacking both in operational and non-operational settings.
- An optimal estimation procedure (Heidinger and Pavolonis, 2009) is used to retrieve the ash cloud top temperature, emissivity, and microphysical parameter for pixels determined to contain ash by the detection algorithm.
- The results are used to compute a mass loading.
- Only infrared channels are used, so the results and day/night independent and the procedure is fully automated.
- It is hoped that these retrievals can be used to improve dispersion models.

Ash Retrieval



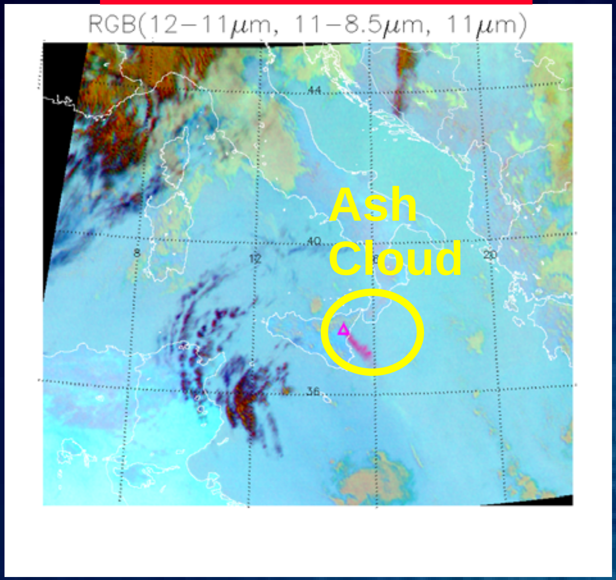




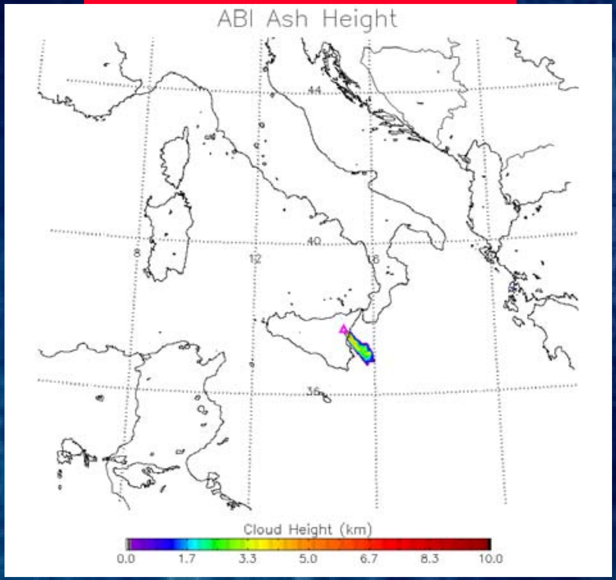
The height and mass loading products are free of visual artifacts and have reasonable spatial patterns for this *moderate* sized eruption.

Ash Retrieval

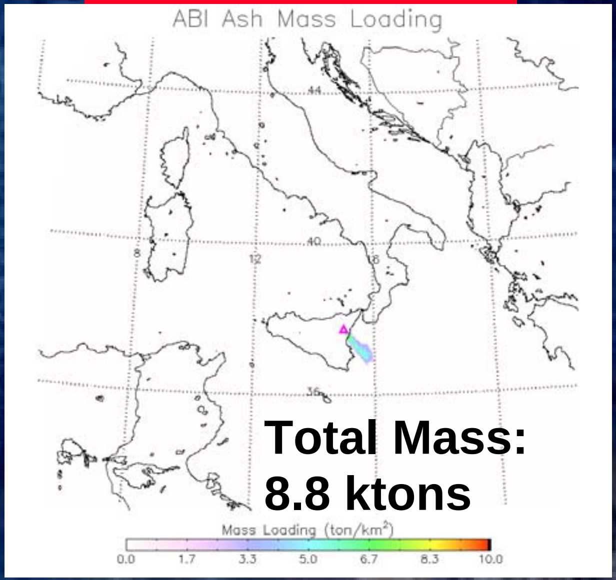
RGB Image



Ash Height



Ash Loading



The height and mass loading products are free of visual artifacts and have reasonable spatial patterns for this *light* sized eruption.

Summary

- Automated quantitative ash detection requires an advanced approach that can isolate the cloud microphysical signal from the background signal in order to be of operational quality (low false alarm rate).
- Retrievals of ash height and mass loading provide important additional information.
- We are applying similar detection and retrieval approaches to current operational sensors (e.g. GOES imager and AVHRR).

- *Our goal is an automated combined LEO/GEO global volcanic ash monitoring system that will be a reliable tool for volcanic ash forecasters.*

Bonus Material

Volcano	Truth Yes	Truth Yes, Algo Yes	Truth No	Truth No, Algo Yes	POD	POF	PHK Skill
Etna							
1000 UTC	60	58	8983417	5777	0.9667	6.43×10^{-4}	0.9660
1200 UTC	204	194	8983243	4655	0.9510	5.18×10^{-4}	0.9505
Karthala							
0900 UTC	1189	1063	8982258	5083	0.8940	5.66×10^{-4}	0.8935
1200 UTC	2048	1749	8981399	4154	0.8540	4.63×10^{-4}	0.8535
1515 UTC	2728	2264	8980719	6751	0.8299	7.52×10^{-4}	0.8292
Chaiten							
0000 UTC	15037	7827	8989014	6189	0.5205	6.89×10^{-4}	0.5198
0600 UTC	34981	11679	8969070	3987	0.3339	4.44×10^{-4}	0.3334

Volcano	Truth Yes	Truth Yes, Algo Yes	Truth No	Truth No, Algo Yes	POD	POF	PHK Skill
Etna							
1000 UT	60	58	8983417	5777	0.9667	6.43×10^{-4}	0.9660
12 UT	[illegible]	[illegible]	[illegible]	[illegible]	0.9510	5.18×10^{-4}	0.9505
Ka							
09 UT	[illegible]	[illegible]	[illegible]	[illegible]	0.8940	5.66×10^{-4}	0.8935
12 UT	[illegible]	[illegible]	[illegible]	[illegible]	0.8540	4.63×10^{-4}	0.8535
15 UT	[illegible]	[illegible]	[illegible]	[illegible]	0.8299	7.52×10^{-4}	0.8292
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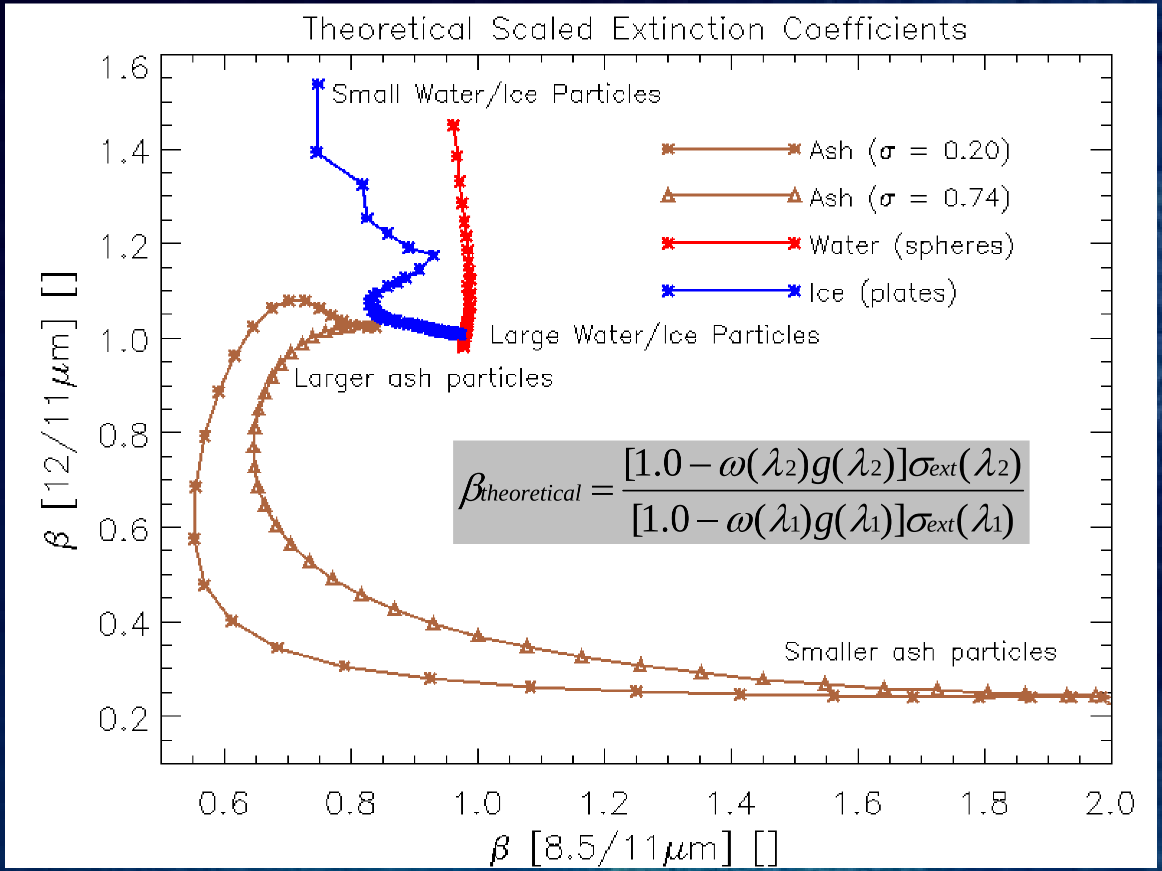
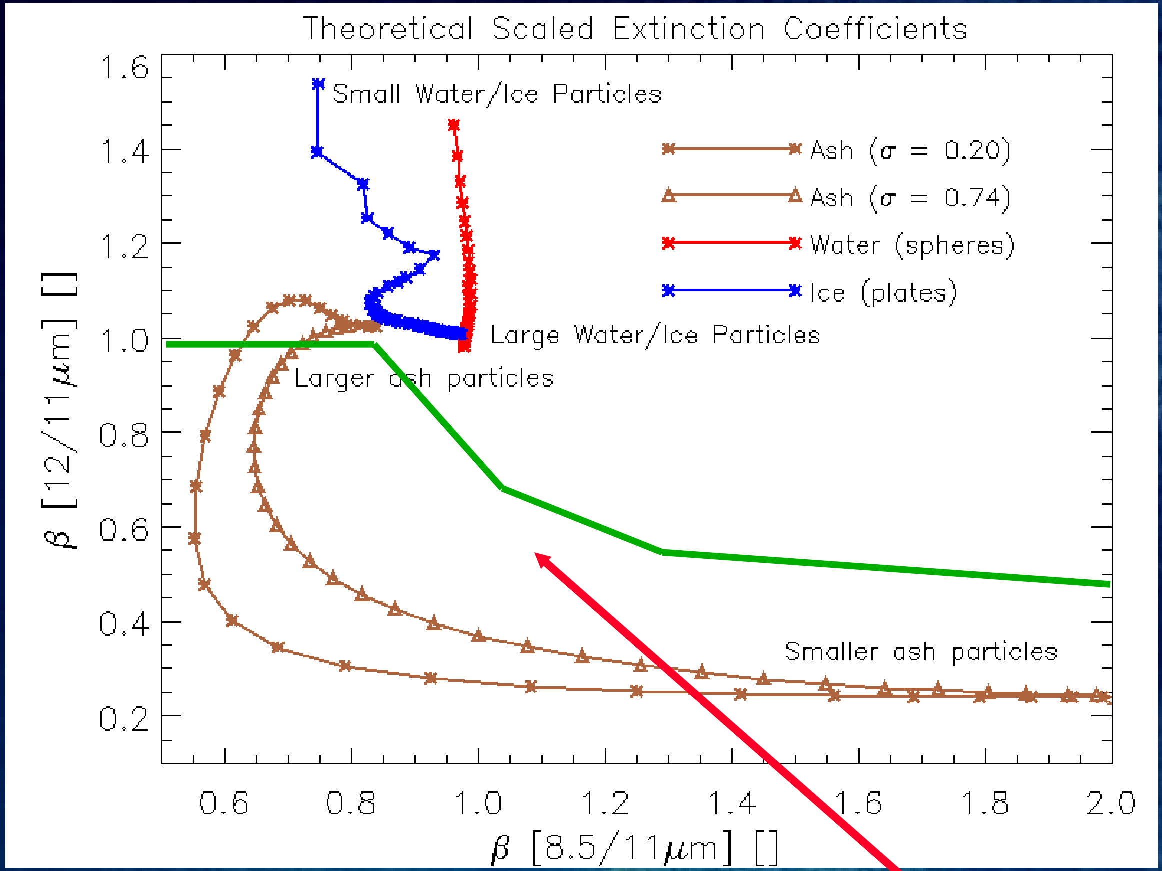
- **In most cases, the skill score exceeds 0.85.**
- **Detection capabilities decrease as ash cloud becomes more diffuse with time.**
- **Multilayered detection remains challenging.**

Ash Detection



Theoretical particle distributions are used to define the boundaries between meteorological clouds and volcanic ash clouds in a 2-dimensional β space, where β(12, 11) is shown as a function of β(8.5, 11).

Ash Detection



Pixels that have β(8.5, 11), β(12, 11) pairs that "closely" match the values predicted by theoretical ash size distributions are initially classified as volcanic ash.

"Volcanic ash β envelope"

The Advanced Baseline Imager:

	ABI	Current
Spectral Coverage		
	16 bands	5 bands
Spatial resolution		
0.64 μm Visible	0.5 km	Approx. 1 km
Other Visible/near-IR	1.0 km	n/a
Bands (>2 μm)	2 km	Approx. 4 km
Spatial coverage		
Full disk	4 per hour	Every 3 hours
CONUS	12 per hour	~4 per hour
Mesoscale	Every 30 sec	n/a
Visible (reflective bands)		
On-orbit calibration	Yes	No

Slide courtesy of Tim Schmit