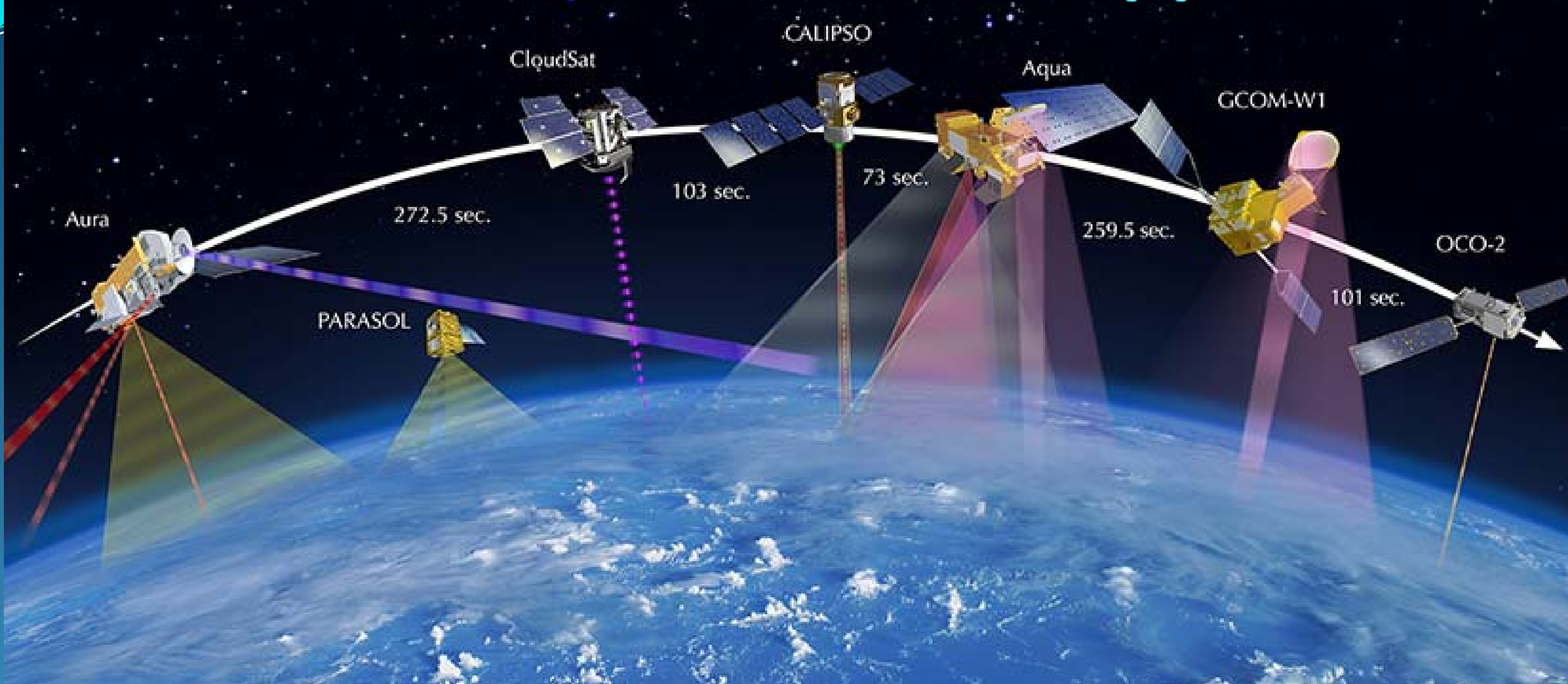
MET 611 – Satellite Data Applications



Aerosol Type from CALIOP

Jennifer D. S. Griswold

Aerosol Type

- Are more broadly characterized as anthropogenic (**urban/industrial pollution and biomass burning**) and natural (**desert dust, sea salt, biogenic, and volcanic**) aerosols

- **Original purpose was to estimate the lidar ratio used in the extinction retrieval**
  - But, it turned out aerosol type was interesting in its own right

- Each aerosol "**type**" is assumed to be a mixture of species
  - eg: "polluted cononental" = sulfate + nitrate + BC + dust

- Typing is performed **before** the extinction retrieval
  - Therefore, must be based on Level 1 profile data
  - In the future, we may retrieve for each type and select the best solution

Aerosol Properties from Space

- One of the challenges of satellite-based passive remote sensing of aerosol properties is the separation of the path radiance from the top-of-atmosphere (TOA) radiance.
  - **The path radiance is due to atmospheric reflection, whereas TOA radiance includes reflection by the surface.**

- For aerosol retrieval from passive instruments, once the path radiance is isolated, some methods use simulations of the top-of-atmosphere radiation to relate satellite-based observations to aerosol properties by using theoretical models.
  - These models are usually based on **measurements or established climatologies** (e.g., d'Almeida et al. 1991; WCRP 1986).

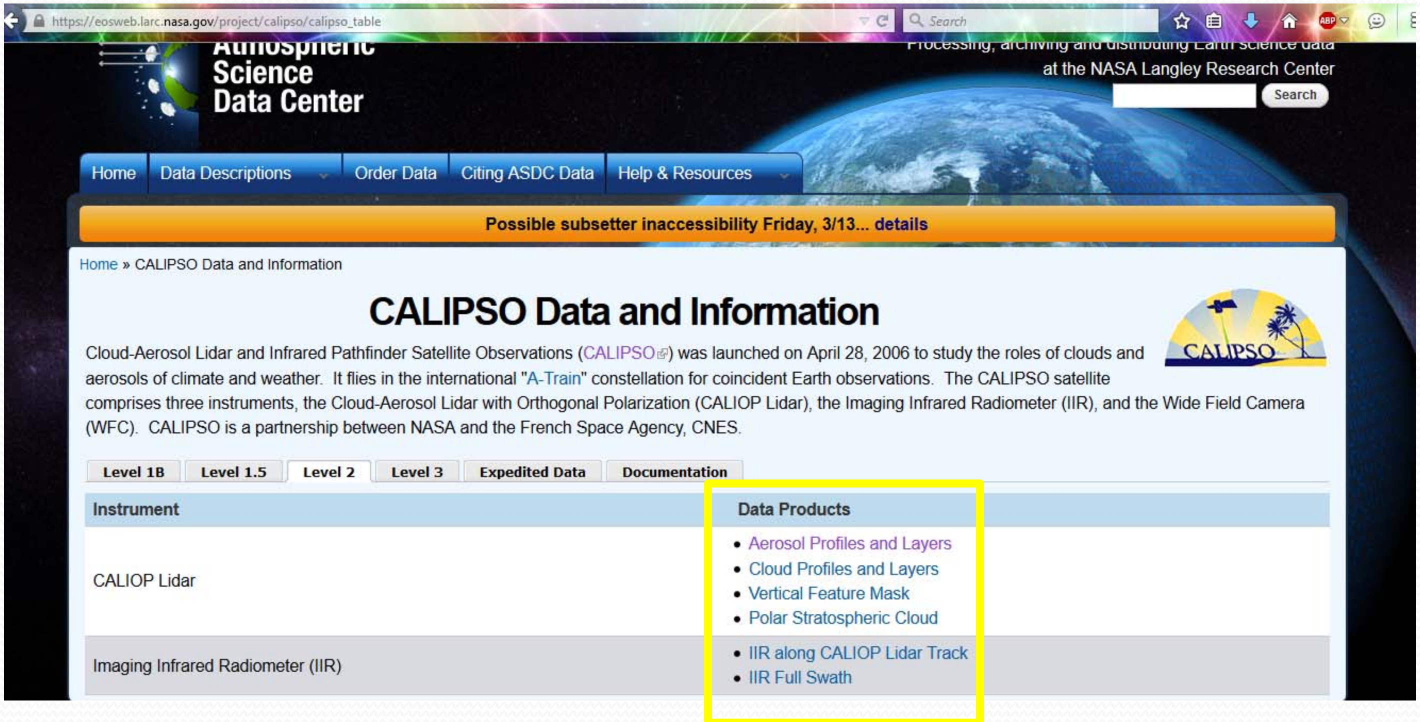
  - In most cases these algorithms make assumptions with significant contributions to TOA radiation including
    - vertical distribution of aerosols
    - surface reflectance

CALIPSO/CALIOP Aerosol

- CALIPSO (Winker et al. 2009, 2007) is an active sensor that makes range-resolved measurements of atmospheric constituents
  - it does not require the assumptions about vertical distribution and surface reflectance that are fundamental to most passive measurements.
- To determine aerosol type, these algorithms use:
  - the integrated attenuated backscatter measurements
  - the volume depolarization ratio measurements
  - surface type
  - layer altitude
- The algorithms do make a fundamental assumption for the extinction retrieval of most aerosol layers (discussed later).

CALIPSO/CALIOP Aerosol

- The aerosol subtyping products generated by the algorithms are available to the public at the **Langley Atmospheric Sciences Data Center (ASDC)** as part of the level 2 suite of products.



https://eosweb.larc.nasa.gov/project/calipso/calipso_table

Extinction-to-Backscatter (lidar) ratio

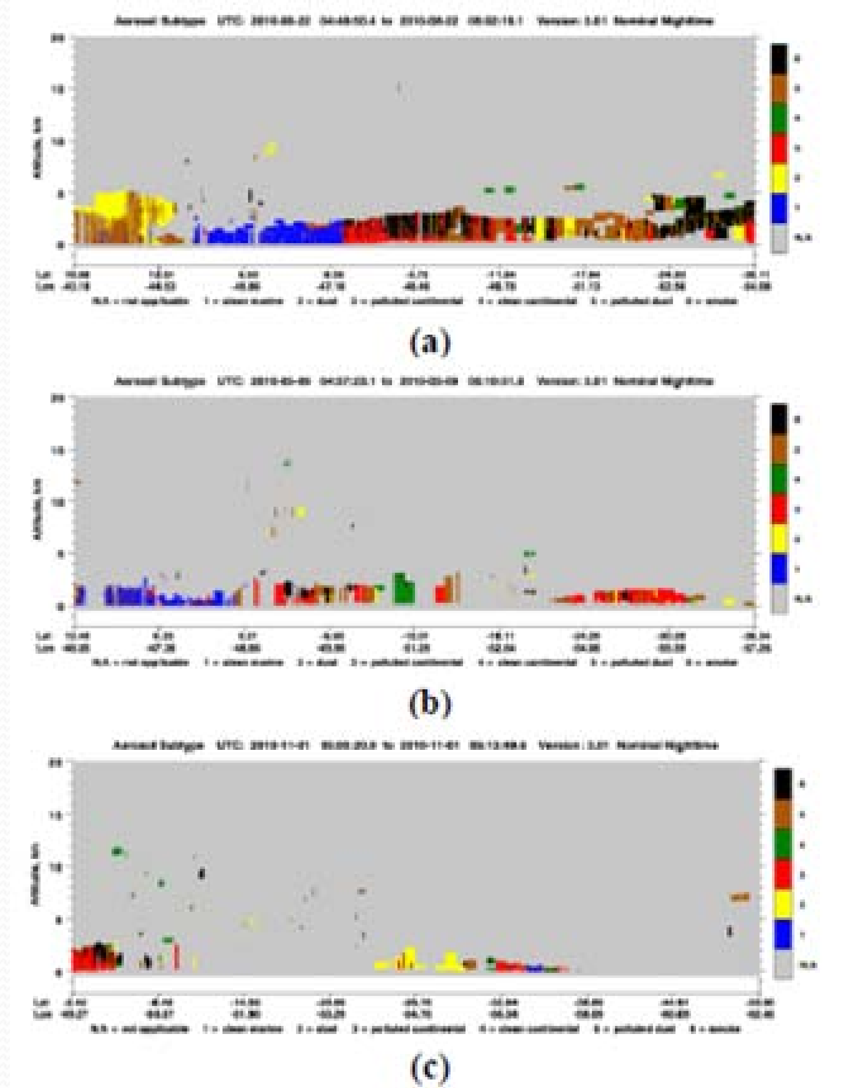
- Although backscatter lidar measurements such as CALIPSO are free from surface effects, they do suffer from a need to assume an aerosol extinction-to-backscatter ratio **Sa** (also referred to as the aerosol–lidar ratio) to enable, in most cases, the calculation of extinction from lidar backscatter signals.

- Determining aerosol type is complex, we need aerosol models:
  - to determine the aerosol type
  - choose the appropriate aerosol model for the type,
  - determine the appropriate Sa.

  - The choice of Sa (the aerosol subtype product) is useful for developing global distributions of aerosol types for science studies, such as source attribution of aerosol forcing and pollution episodes.

Performance of Subtyping

- To determine performance of aerosol subtyping and Sa selection, qualitative measures are used, such as:
  - the distributions of optical depths
  - expected aerosol types both geographically and seasonally
  - convergence of the extinction calculation when model Sa values are used


(a) (b) (c)

CALIPSO Aerosol Models

- The CALIPSO aerosol models are based on the cluster analysis of multiyear (1993–2002) AERONET data
  - determine characteristic aerosol types grouped using nearly instantaneously observed physical and optical properties (see Omar et al. 2005).

- The cluster analysis identified six aerosol types representative of the aerosol mixtures most frequently observed at the AERONET sites.

CALIPSO Aerosol Models

- The CALIPSO models use some of the information derived from AERONET cluster analysis to determine Sa values.

- The typing and lidar ratio selection algorithm uses the lidar observables and surface-type information to aid in selecting values of Sa.
  - The goal is to constrain the uncertainty in Sa to no more than 30%.
  - The observed range of variability of Sa is between 10 and 110 sr (Anderson et al. 2000)
  - The modeled range is between 15 and 80 sr (Ackermann 1998).
  - Allowing for an uncertainty of 30%, our selected range of Sa values for this algorithm spans a range of 14–90 sr.

CALIPSO Aerosol Models

- For each aerosol model obtained from the cluster analysis of AERONET measurements, a lidar ratio was calculated and compared with field measurements of Sa for that aerosol type.

  - These measurements, primarily at 532 nm, come from a variety of techniques including:
    - 180° nephelometer (Anderson et al. 2000)
    - Raman lidar (Ackermann 1998),
    - slant path techniques
    - and transmittance methods (Young 1995)

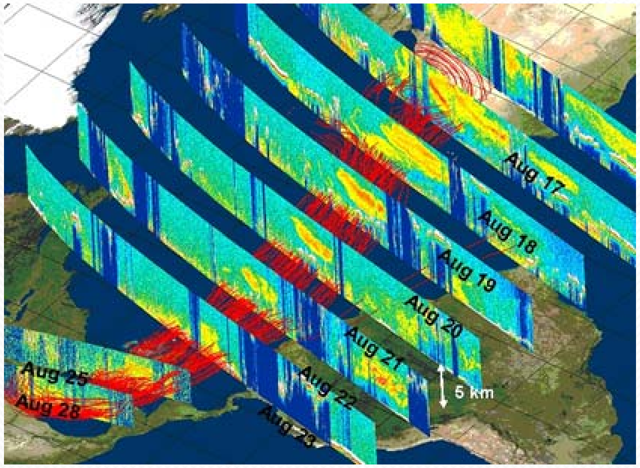
  - The AERONET derived model parameters were adjusted, when necessary, to bring the derived lidar ratio into better agreement with the measurements.

CALIPSO Aerosol Models

- Of the six AERONET clusters, three are adopted as CALIPSO aerosol models:
  - biomass burning
  - polluted continental
  - polluted dust (dust + smoke)

- Two models were built either directly from measurements of size distributions and complex refractive indices or by adjusting model parameters to general observed Sa values.
  - marine
  - background/clean continental

- The dust model is based on the work of Kalashnikova and Sokolik (2002).



CALIPSO Aerosol Models

Omar et al 2001

- The size distributions based on volume are shown in Fig. 1
- There are Dust, Smoke, Clean Continental, Polluted Continental, Polluted Dust and Clean Marine.

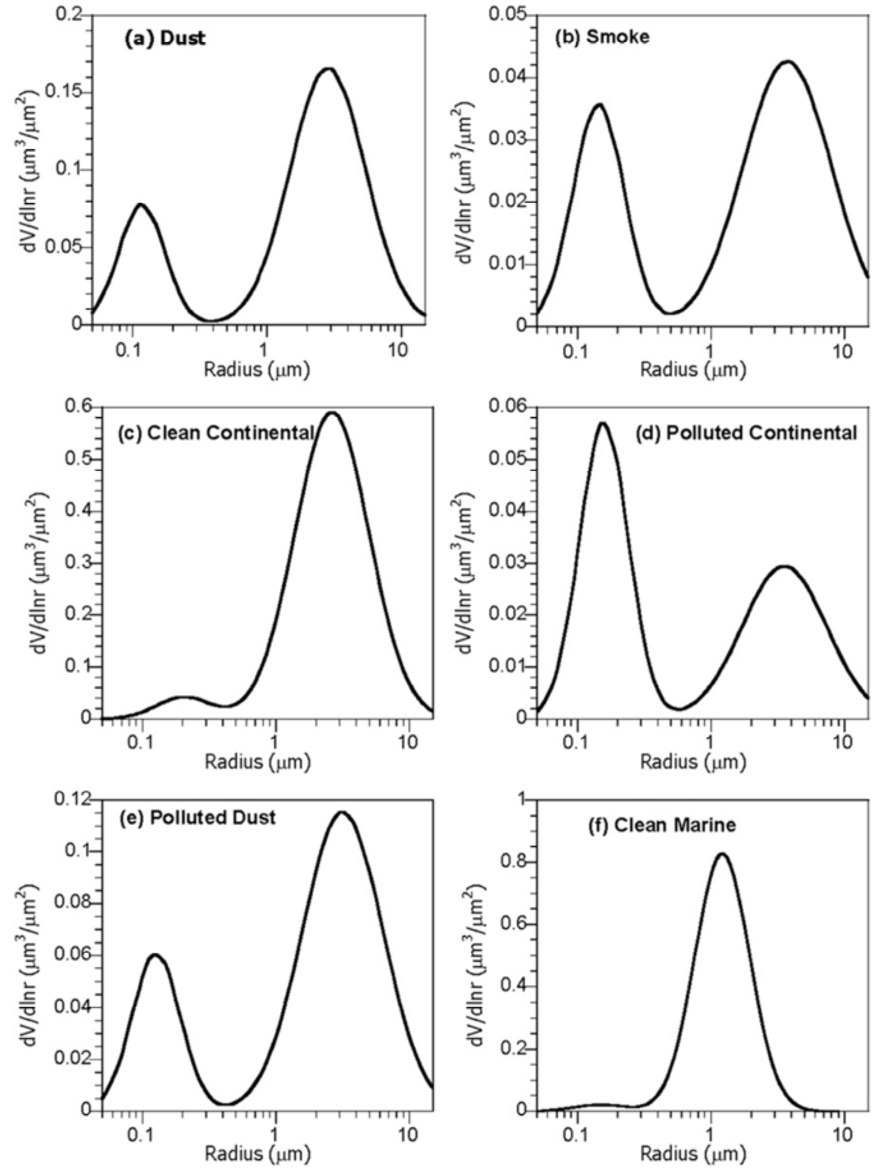


FIG. 1. The bimodal lognormal size distributions of the CALIPSO aerosol models.

CALIPSO Aerosol Model

Omar et al 2001

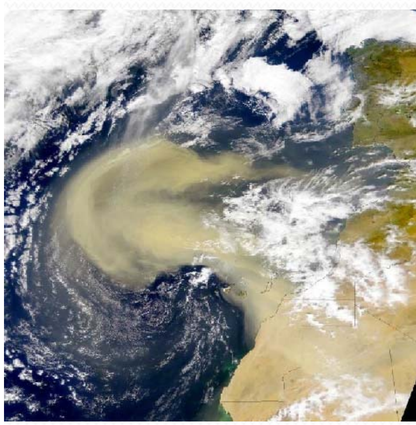
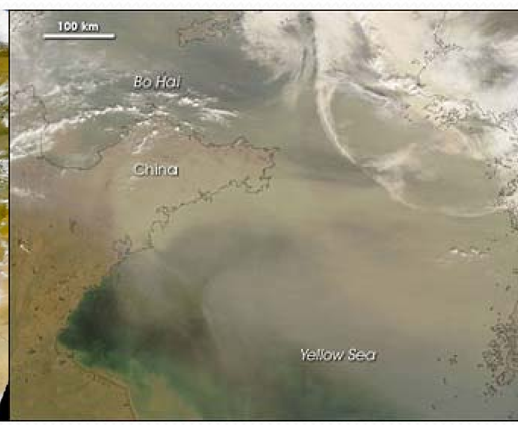
TABLE 1. Physical and optical characteristics of the CALIPSO aerosol models: $m_r(m_i)$ are complex real (imaginary) parts of the refractive index and particulate color ratio is the ratio of the particle backscatter at 1064 to 532 nm.

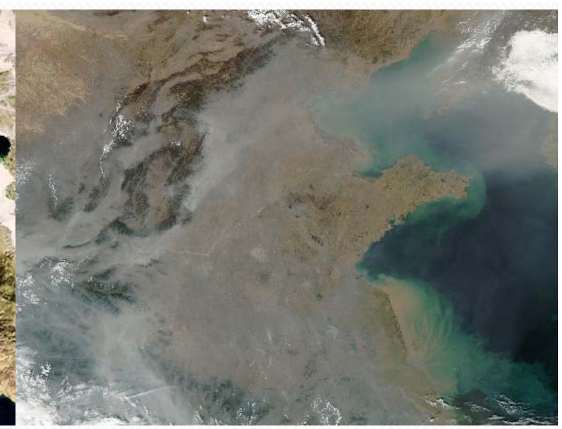
Optical/physical property	Dust	Smoke	Clean continental	Polluted continental	Clean marine	Polluted dust
m_r fine at 532 nm	1.414	1.517	1.380	1.404	1.400	1.452
m_i fine at 532 nm	0.0036	0.0234	0.0001	0.0063	0.0050	0.0109
m_r fine at 1064 nm	1.495	1.541	1.380	1.439	1.400	1.512
m_i fine at 1064 nm	0.0043	0.0298	0.0001	0.0073	0.0050	0.0137
m_r coarse 532 nm	1.414	1.517	1.455	1.404	1.400	1.452
m_i coarse 532 nm	0.0036	0.0234	0.0034	0.0063	0.0005	0.0109
m_r coarse 1064 nm	1.495	1.541	1.455	1.439	1.390	1.512
m_i coarse 1064 nm	0.0043	0.0298	0.0034	0.0073	0.0005	0.0137
Fine cut-off radius (μm)	1.00	1.00	1.00	1.00	0.60	1.00
Fine fraction by volume	0.223	0.329	0.050	0.531	0.025	0.241
Fine mean radius (μm)	0.1165	0.1436	0.205 56	0.1577	0.150	0.1265
Geometric std dev (GSD) fine	1.4813	1.5624	1.61	1.5257	1.600	1.5112
Coarse fraction by volume	0.777	0.671	0.950	0.469	0.975	0.759
Coarse mean radius (μm)	2.8329	3.726	2.6334	3.547	1.216	3.1617
GSD coarse	1.9078	2.1426	1.8987	2.065	1.600	1.9942
S_a at 532 nm (sr)	40	70	35	70	20	65
S_a at 1064 nm (sr)	55	40	30	30	45	30

- The table shows the microphysical and derived properties associated with each of the six CALIPSO aerosol models.

CALIOP Aerosol Type

Type	Criteria
Dust	High depolarization
Polluted Dust	Medium depolarization, assume dust is mixed with smoke
Smoke	Higher altitude, Low depolarization
Clean Continental	Overland, Low backscatter
Polluted Continental	Higher backscatter, low depolarization, near surface
Marine	Over ocean, in marine boundary layer

CALIPSO Aerosol Type Models

- **DUST**
  - The CALIPSO dust model is based on theoretical particle scattering calculations by using the **discrete dipole approximation (DDA) technique, with inputs of realistic compositions and irregular shapes** (Kalashnikova and Sokolik 2002).
  - The CALIPSO model Sa values for Dust are:
    - **40 sr at 532 nm**
    - **55 sr at 1064 nm**

- **POLLUTED CONTINENTAL**
  - The CALIPSO model for polluted continental is based on the **AERONET data**.
  - The CALIPSO model Sa values for Polluted Continental are:
    - **70 sr at 532 nm**
    - **30 sr at 1064 nm**

CALIPSO Aerosol Type Models

- **POLLUTED DUST**
  - This aerosol model is designed to account for episodes of **dust mixed with biomass burning smoke** (e.g. regions close to strong sources of both [West Africa and Asia]).
    - Also, dust mixed with urban pollution (e.g. Asia and Europe).
    - **A mixture of the AERONET desert dust (coarse mode) and biomass burning (fine mode) clusters.**
  - The CALIPSO model Sa values for Dust are:
    - **65 sr at 532 nm**
    - **30 sr at 1064 nm**

- **SMOKE (Biomass Burning)**
  - The **biomass burning cluster of AERONET measurements** is used to model the CALIPSO smoke aerosol.
  - The CALIPSO model Sa values for Smoke are:
    - **70 sr at 532 nm**
    - **40 sr at 1064 nm**

CALIPSO Aerosol Type Models

- **CLEAN CONTINENTAL**
  - This aerosol is also referred to as clean background.
  - The AERONET records of the background cluster from Omar et al. (2005) have low mean optical depths (<0.05 at 673 nm). The CALIPSO background aerosol model was derived by fitting size distributions and refractive indices to measurements of Sa of long-range continental transport (Anderson et al. 2000).
  - The CALIPSO model Sa values for Clean Continental are:
    - **35 sr at 532 nm**
    - **30 sr at 1064 nm**

- **CLEAN MARINE**
  - Derived from the parameters measured during the Shoreline Environmental Aerosol Study (SEAS) experiment (Masonis et al. 2003).
  - The CALIPSO model Sa values for Clean Marine are:
    - **20 sr at 532 nm**
    - **45 sr at 1064 nm**

Algorithm Design

- The goal of the aerosol typing algorithm is to identify the aerosol type closely enough to estimate the appropriate value of Sa to within 30% of the true value.
- These values are then passed on for use in the extinction retrieval algorithm (Young and Vaughan 2009).
- The selection scheme uses the observed backscatter strength, that is, the integrated attenuated backscatter at 532 nm (***γ'***), defined as:

$$\gamma' = \int_{\mathrm{top}}^{\mathrm{base}} \beta(z) T(z)\, dz,$$

Algorithm Design

- The integrated attenuated backscatter at 532 nm (γ'), defined as:

$$\gamma' = \int_{\text{top}}^{\text{base}} \beta(z) T(z) \, dz,$$

- β = the total (molecular m + particulate p backscatter)

- **T** = the atmospheric transmittance due to both molecules and particles.

Algorithm Design

- The sum of the perpendicular channel signal within a feature divided by the sum of the parallel channel (i.e., the volume depolarization ratio δ_v') is defined as

$$\delta'_v = \frac{\sum_{z_{\mathrm{base}}}^{z_{\mathrm{top}}} \beta'_{\perp}(z)}{\sum_{z_{\mathrm{base}}}^{z_{\mathrm{top}}} \beta'_{\mathrm{II}}(z)} = \frac{\sum_{z_{\mathrm{base}}}^{z_{\mathrm{top}}} [\beta'_{\perp,m}(z) + \beta'_{\perp,p}(z)]}{\sum_{z_{\mathrm{base}}}^{z_{\mathrm{top}}} [\beta'_{\mathrm{II},m}(z) + \beta'_{\mathrm{II},p}(z)]},$$

- where **z** is altitude and the subscripts "top" and "base" refer to the top and base of the feature as determined by the feature finder (Vaughan et al. 2009).

- The subscripts || and ⊥ refer to the polarized and depolarized attenuated backscatter *β'* signals, respectively

Algorithm Design

- In the algorithm, δ_v' has been corrected to account for the molecular contribution as follows:

$$\delta_v = \frac{\delta_v'[(R_{\mathrm{mas}} - 1)(1 + \delta_m) + 1] - \delta_m}{(R_{\mathrm{mas}} - 1)(1 + \delta_m) + \delta_m - \delta_v'},$$

  - where δ_v is the corrected depolarization ratio (or estimated particulate depolarization ratio)
  - R_{mas} is the mean attenuated scattering (mas) ratio (the ratio of the total attenuated backscatter to the molecular backscatter)
  - δ_m is the molecular depolarization ratio.
  - Because of this dependence on the layer R_{mas}, the distributions of the depolarization ratios will spread beyond the threshold values.

Algorithm Design

- Aerosol type is identified by using γ' and δ_v to the extent possible from among one of the six types.
- However, γ' and δ_v are not sufficient to fully constrain the model selection.
- Surface type is used to exploit differences in aerosol classes over the oceans, deserts, and snow/tundra regions.
- Information about **aerosol layer elevation** is also utilized to determine aerosol type, because conditions that favor lifting mechanisms for dust and smoke are more likely than for other aerosol types.

Algorithm Design

- There is a significant overlap between the distributions of the color ratio χ' (defined as the ratio of the attenuated 1064- and 532-nm backscatter).
- The overlap between χ' distributions for several aerosol types does not allow it to be used directly as an aerosol subtyping tool.

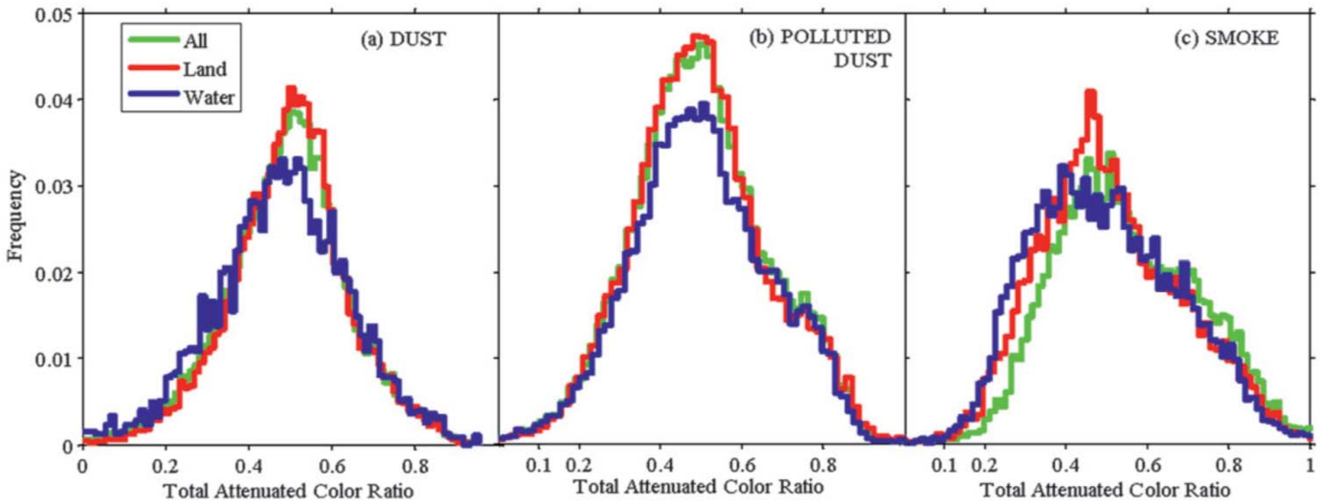


FIG. 11. PDFs of γ' of (a) dust, (b) polluted dust, and (c) smoke for one month (November 2006). The different colors denote layers found over land (red), water (blue), and both (green).

Algorithm Design

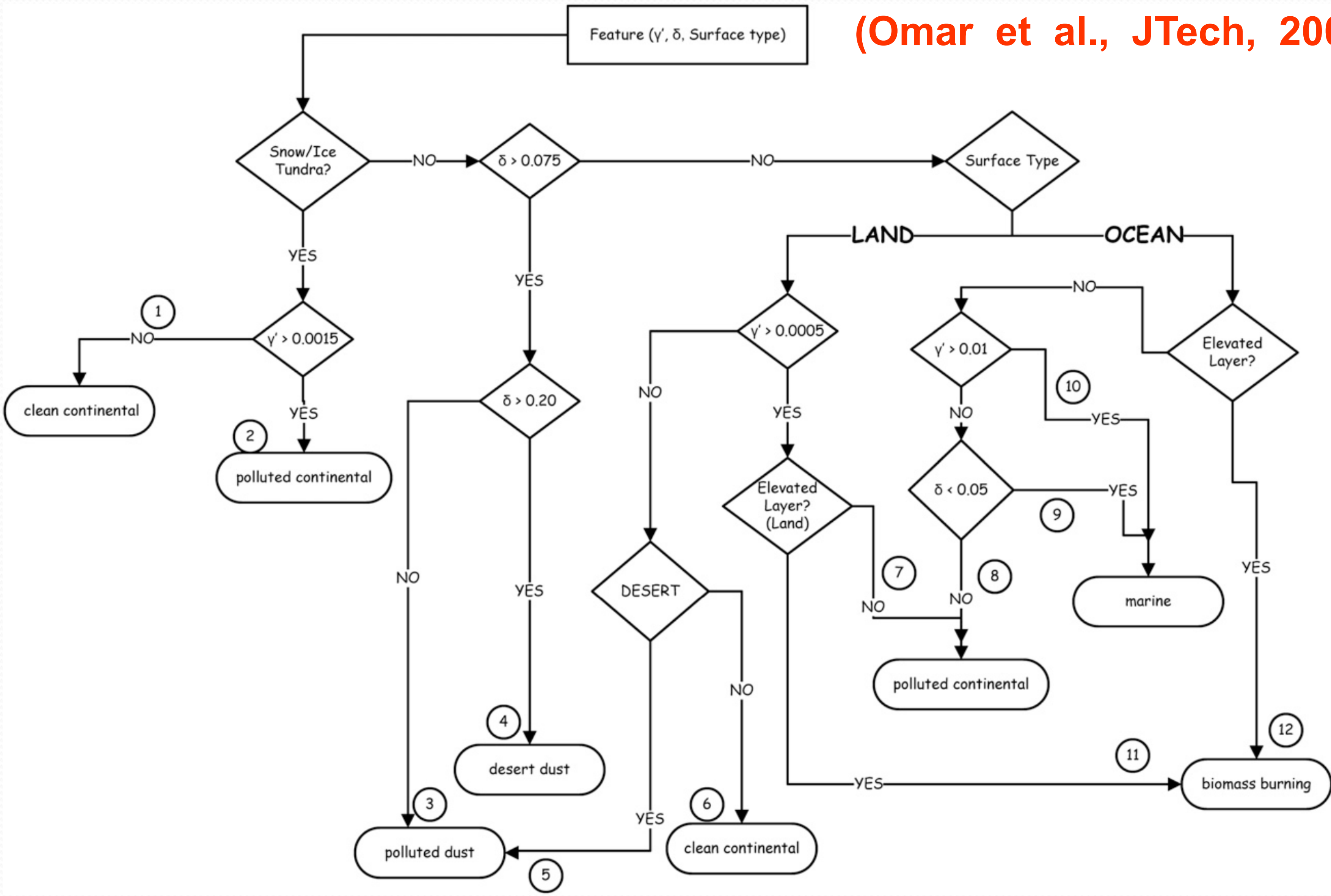
- **To identify the type** (following one of 12 pathways in the Algorithm Flowchart (see next slide) input parameters are used:
  - altitude
  - location
  - surface type
  - volume depolarization ratio
  - integrated attenuated backscatter measurements

- The surface types are from the International Geosphere-Biosphere Programme (IGBP).

- The threshold values of δ_v and γ' in the Algorithm Flow chart are estimates based on Lidar In-space Technology Experiment (LITE) measurements
  - in the case of depolarization, they are based on a limited set of observations and models (Barnaba and Gobbi 2004; Gobbi et al. 2000; Murayama et al. 1999; Reagan et al. 2001; Sakai et al. 2003).

Algorithm Flowchart

(Omar et al., JTech, 2009)



Algorithm Design

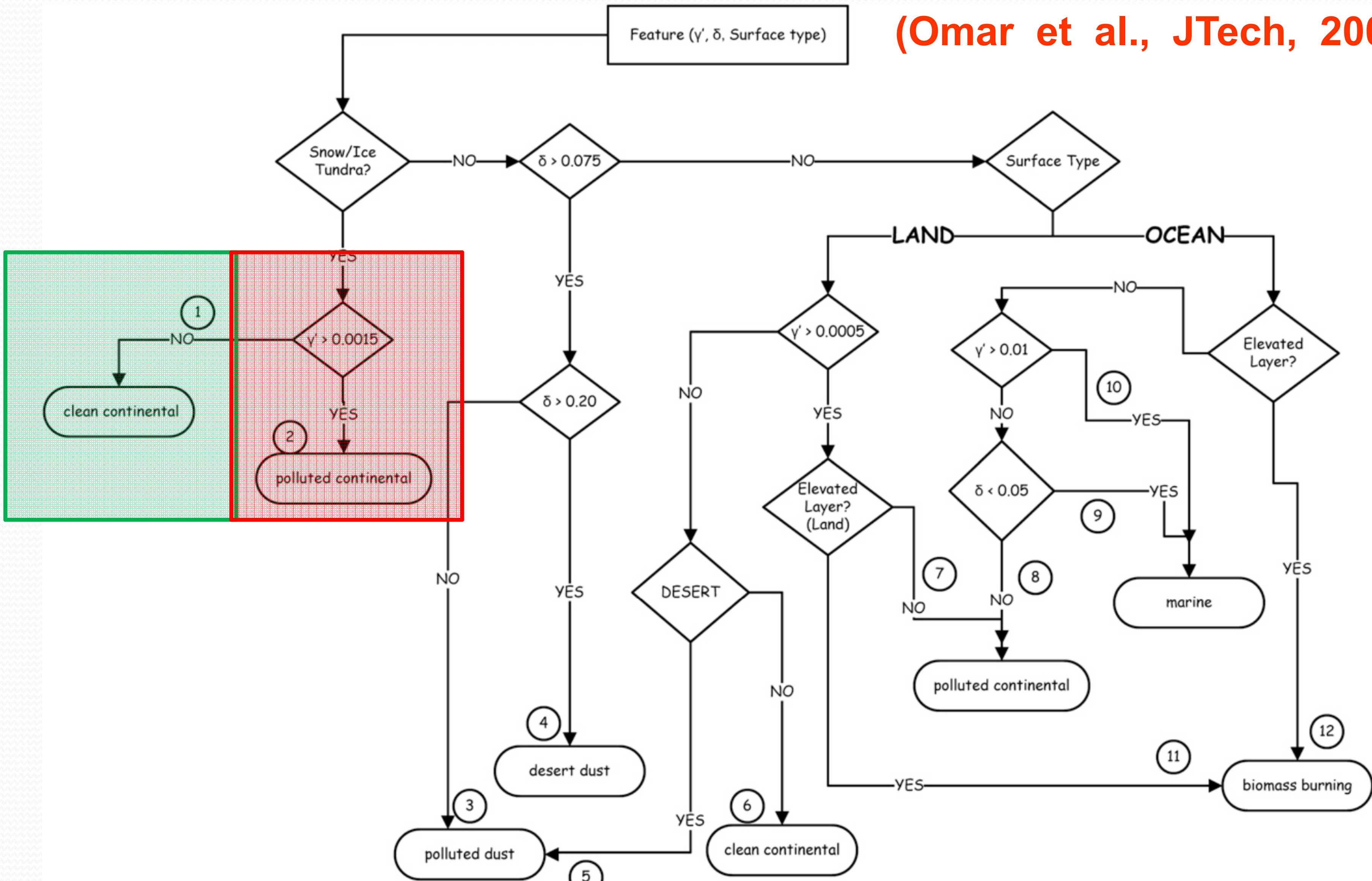
- **Aerosol layers over polar regions** can either be **clean continental** or **arctic haze**, depending on the magnitude of ***γ'*** (see pathways 1 and 2 in in the Flowchart).

- **Arctic haze** is similar to continental pollution and, in some cases, it is continental pollution transported to the Arctic region.
  - **Arctic haze** has a low depolarization ratio ~2% (Ishii et al. 1999), and it **is modeled as polluted continental**.

- As currently written, the algorithm **does not allow dust and smoke types in polar regions**.

Algorithm Flowchart

(Omar et al., JTech, 2009)



Algorithm Design

- δ_v is used to identify aerosol types that have a **substantial mass fraction of non-spherical particles** (e.g., a mixture of smoke and dust in pathways 3 and 5).

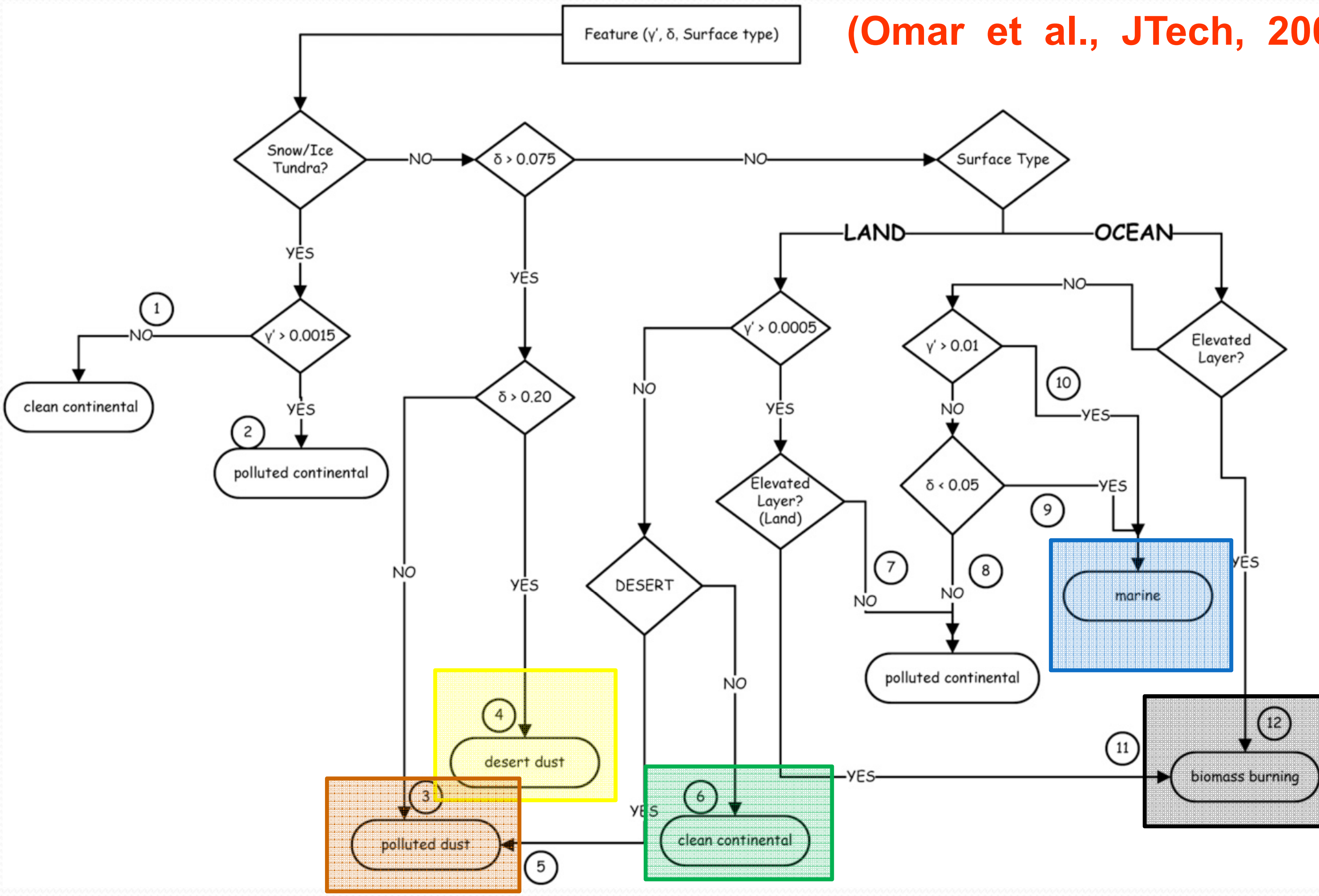
- γ' is used to discern instances of **transient high aerosol loading over surfaces where this is not usually expected** (e.g., a smoke or dust layer over land or the ocean in pathways 10 and 11, respectively).

- In pathway 4, aerosol layers that have $\delta_v > 0.2$ are identified as dust everywhere but at the poles.

- **Thin aerosol layers over land** (other than dust) are identified as **clean continental** (pathway 6) unless these layers are elevated, in which case they are identified as smoke (pathway 11).

Algorithm Flowchart

(Omar et al., JTech, 2009)



Algorithm Design

- If, however, they are **not elevated but still scatter more strongly than the clean continental threshold** ($\boldsymbol{\gamma'}$ = 0.0005), then we identify them as **polluted continental** (pathway 7).

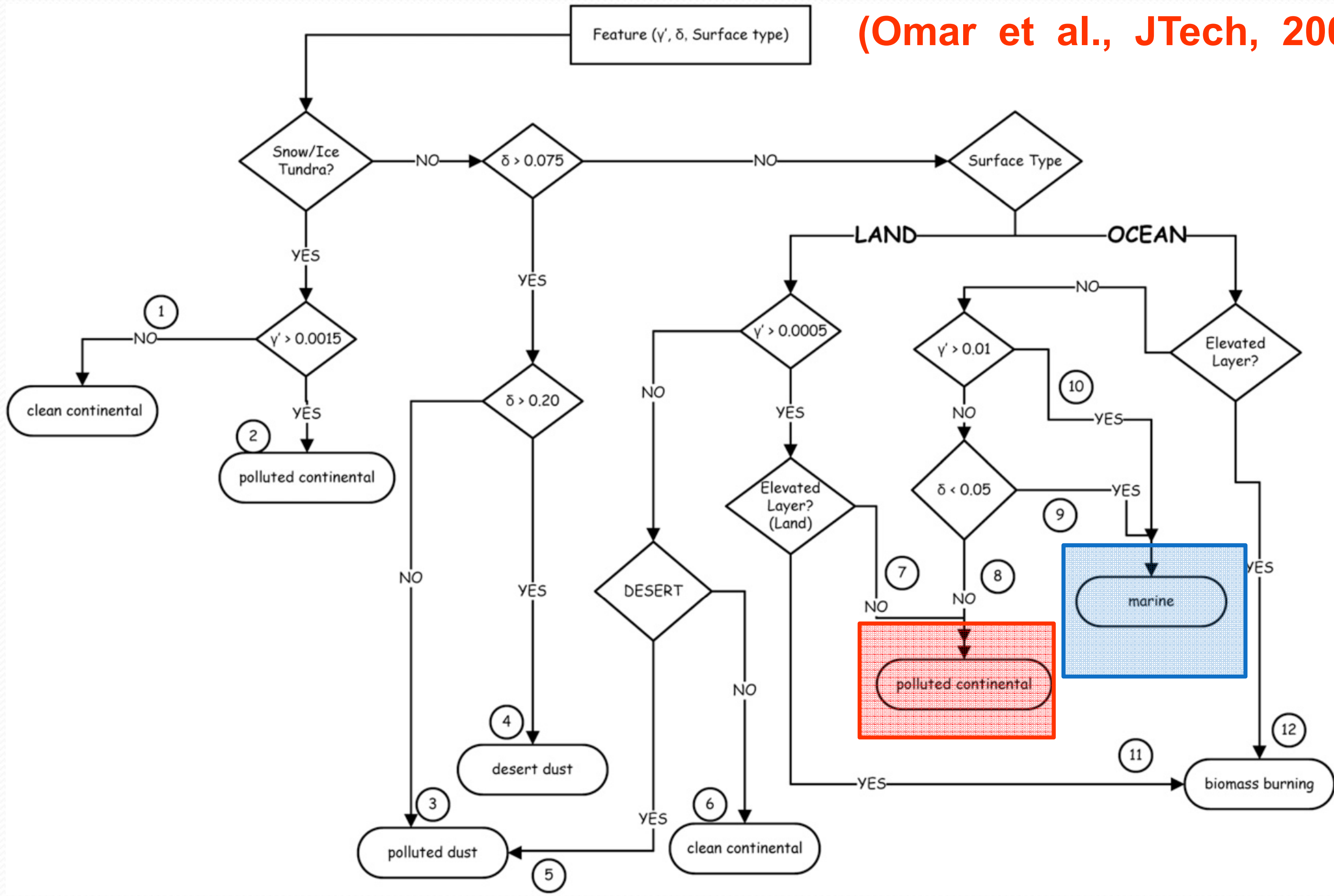
- Over the ocean, **all elevated non-dust aerosol layers** are identified as **smoke**.

- In the marine boundary layer (MBL), aerosol layers can either be **clean marine** characterized by optically thick layers consisting of spherical particles (pathways 9 and 10) or optically thin layers with some non-spherical particles, as would be found near coastal regions and classified as **polluted continental** (pathway 8).

- **Once the type is identified**, Sa is chosen from a lookup table that currently consists of the six pairs of 532- and 1064-nm values shown in Table 1.

Algorithm Flowchart

(Omar et al., JTech, 2009)



Case Studies

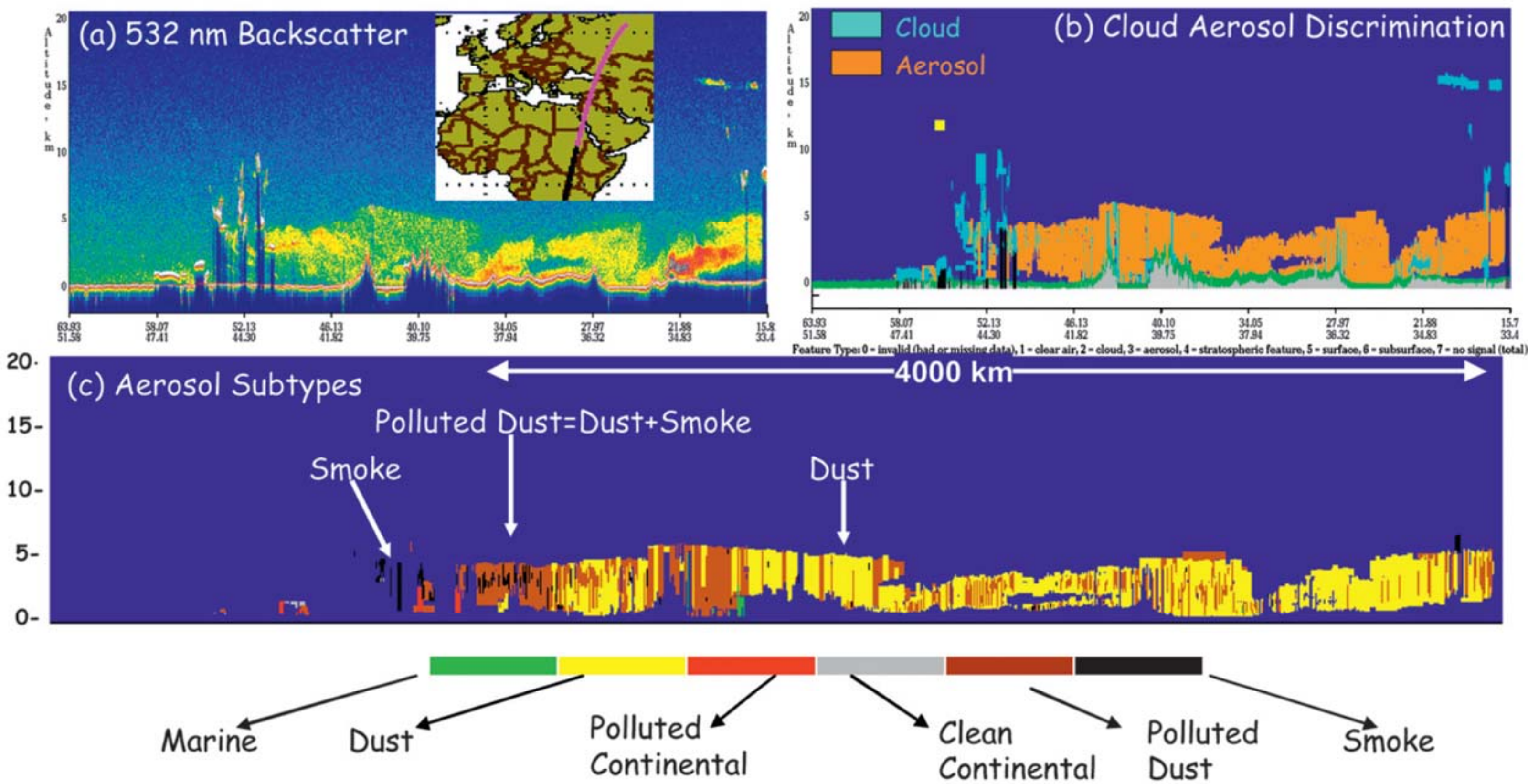


FIG. 3. A Saharan dust and pollution layer extending from continental Europe to central Africa (4000 km) observed on 8 Aug 2006. The images are (a) backscatter browse image, (b) cloud–aerosol mask, and (c) classification of the aerosol found by the aerosol subtyping algorithm. Note that although the scales of (a),(b) are the same, the aerosol subtype plots (c) are at twice the horizontal scale of (a),(b).

The subtyping algorithm captures the evolution of the aerosol from smoke and polluted dust to pure dust in the Sahara.

Case Studies

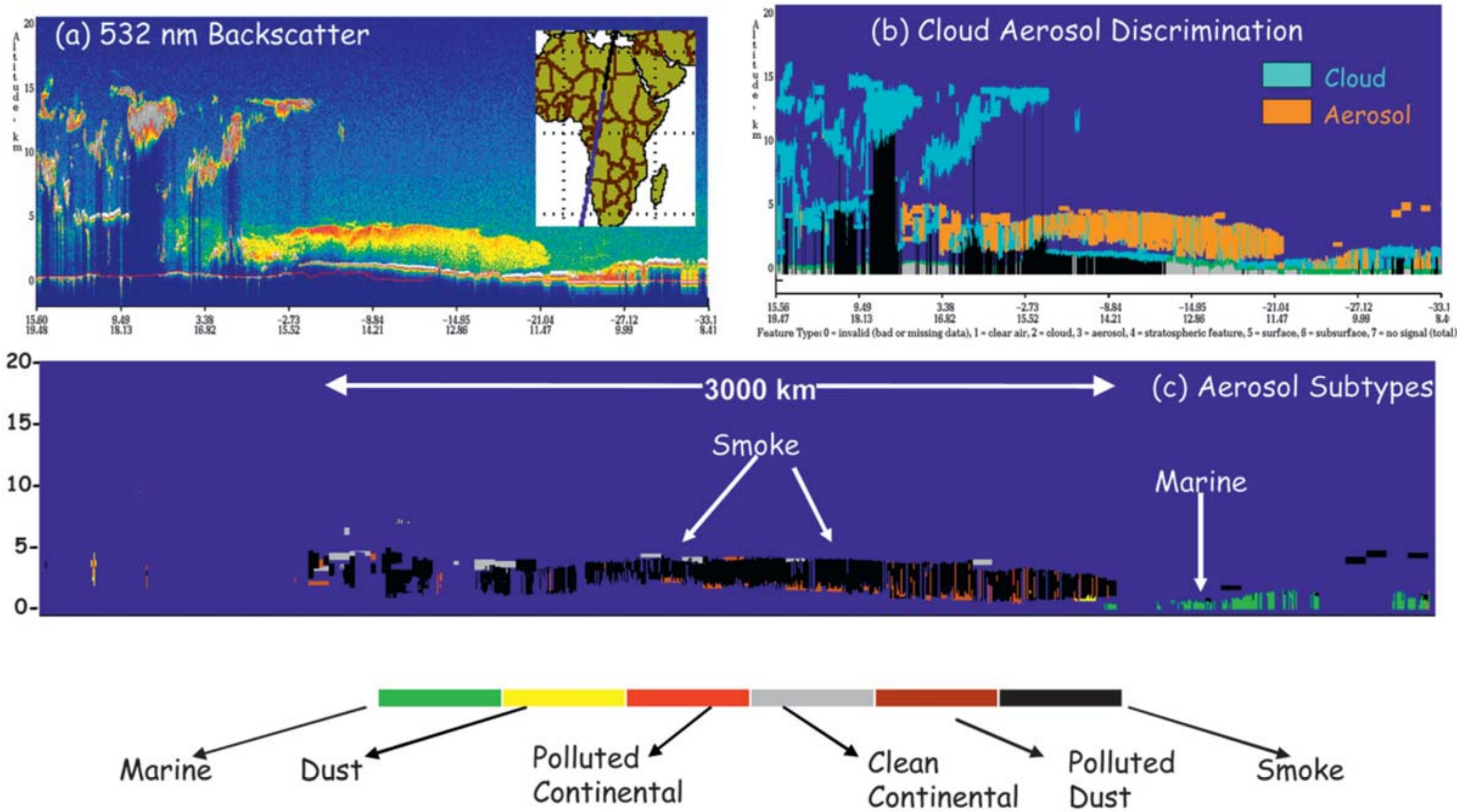


FIG. 4. (a) A 532-nm backscatter browse image, (b) cloud–aerosol mask, and (c) the corresponding aerosol subtyping plot showing vast smoke layer in southwestern Africa during the peak of the burning season, observed on 8 Aug 2006 and stretching across land into the South Atlantic. The relative scales are as in Fig. 3.

Figure 4 is another example of the subtyping result showing an aerosol layer that has been classified as predominantly smoke extending from land to the deep ocean. Note that the aerosol type on the ocean surface is classified as marine aerosol.

Case Studies

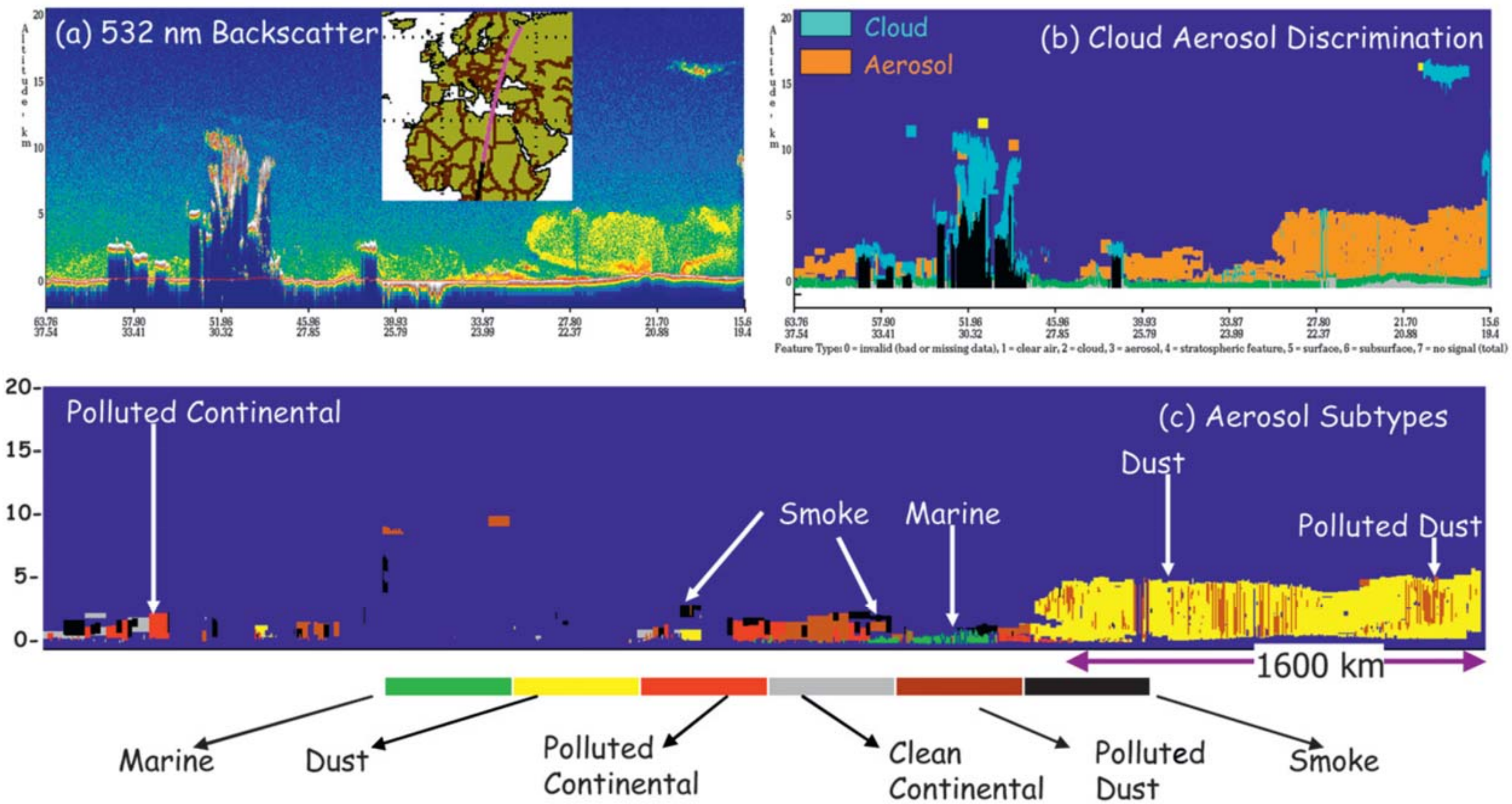
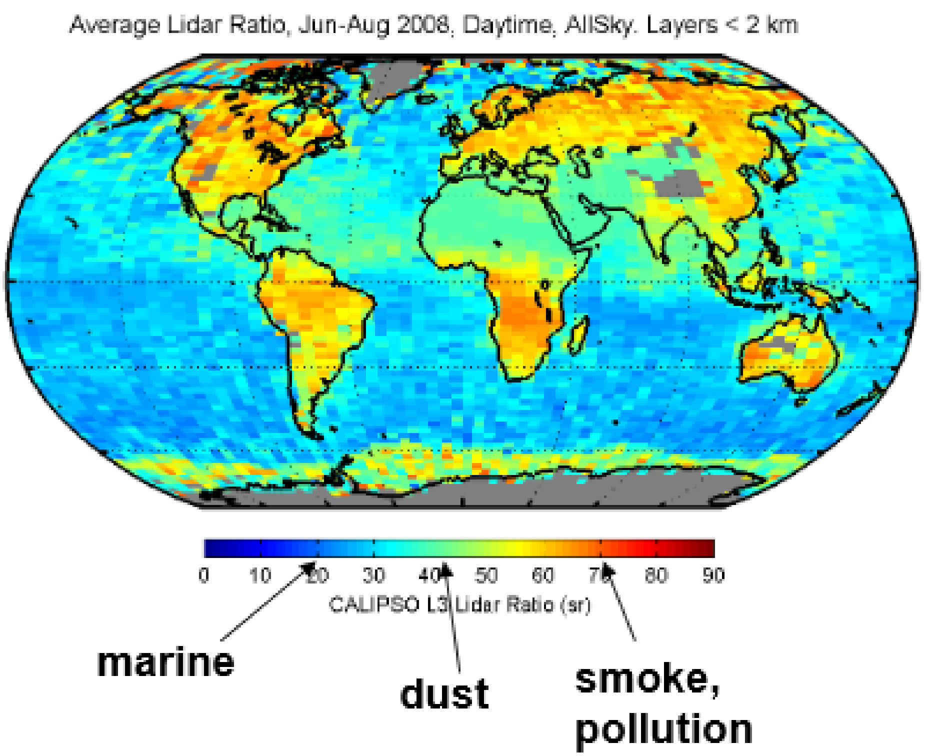
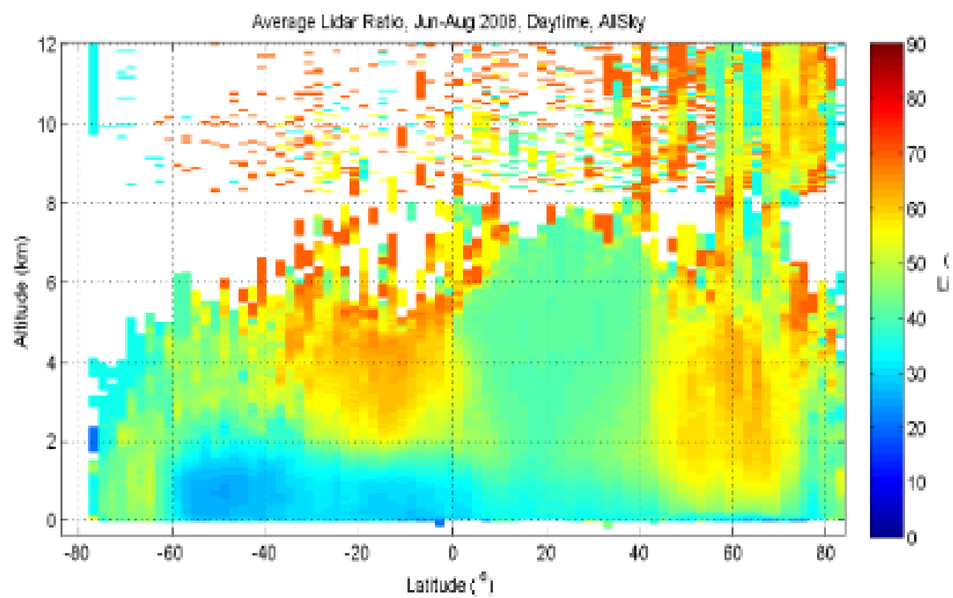


FIG. 5. (a) A 532-nm backscatter browse image, (b) a cloud–aerosol feature mask, and (c) the aerosol subtyping plot of the same scene showing all six aerosol types for this orbit section observed on 8 Aug 2006. The relative scales of the three figures are as in Fig. 3.

All six aerosol types: Europe is primarily polluted continental in the north and smoke and polluted dust in the south near the Mediterranean Sea. Cean marine aerosol near the surface of the sea and a 5-km-deep dust layer stretching across the Sahara.

Aerosol Type JJA 2008





- You can clearly see the difference between marine, dust and smoke.

Optical Depth by Aerosol Type

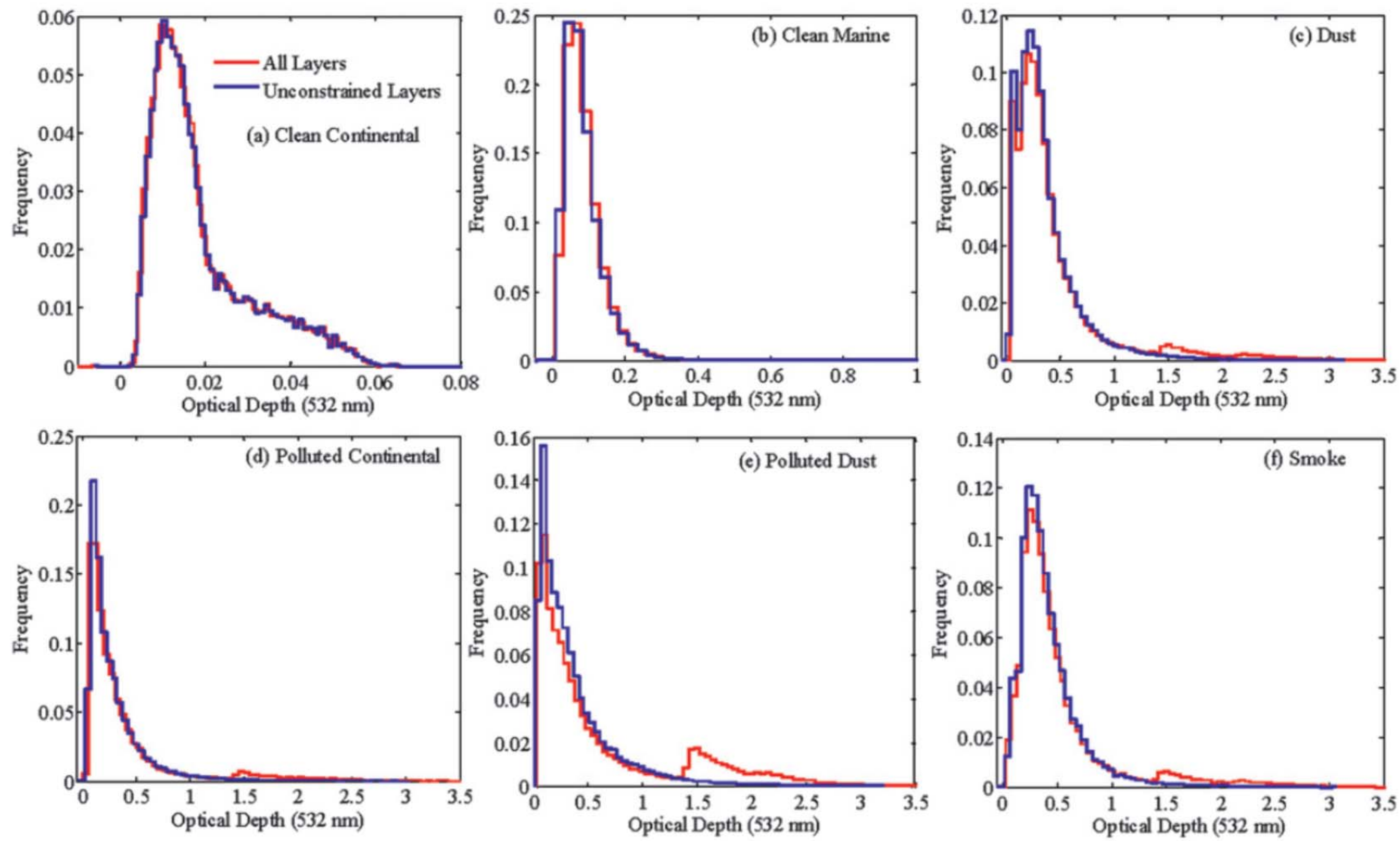


FIG. 9. PDFs of the optical depths by aerosol type. The two histograms show the two cases where the optical depth is retrieved using the initial lidar ratio (unconstrained layers; shown in blue) and all other cases (shown in red), which includes cases where the initial lidar ratio may have been reduced or increased to obtain a solution during the retrieval of the optical depth.

Optical Depth by Season and Type

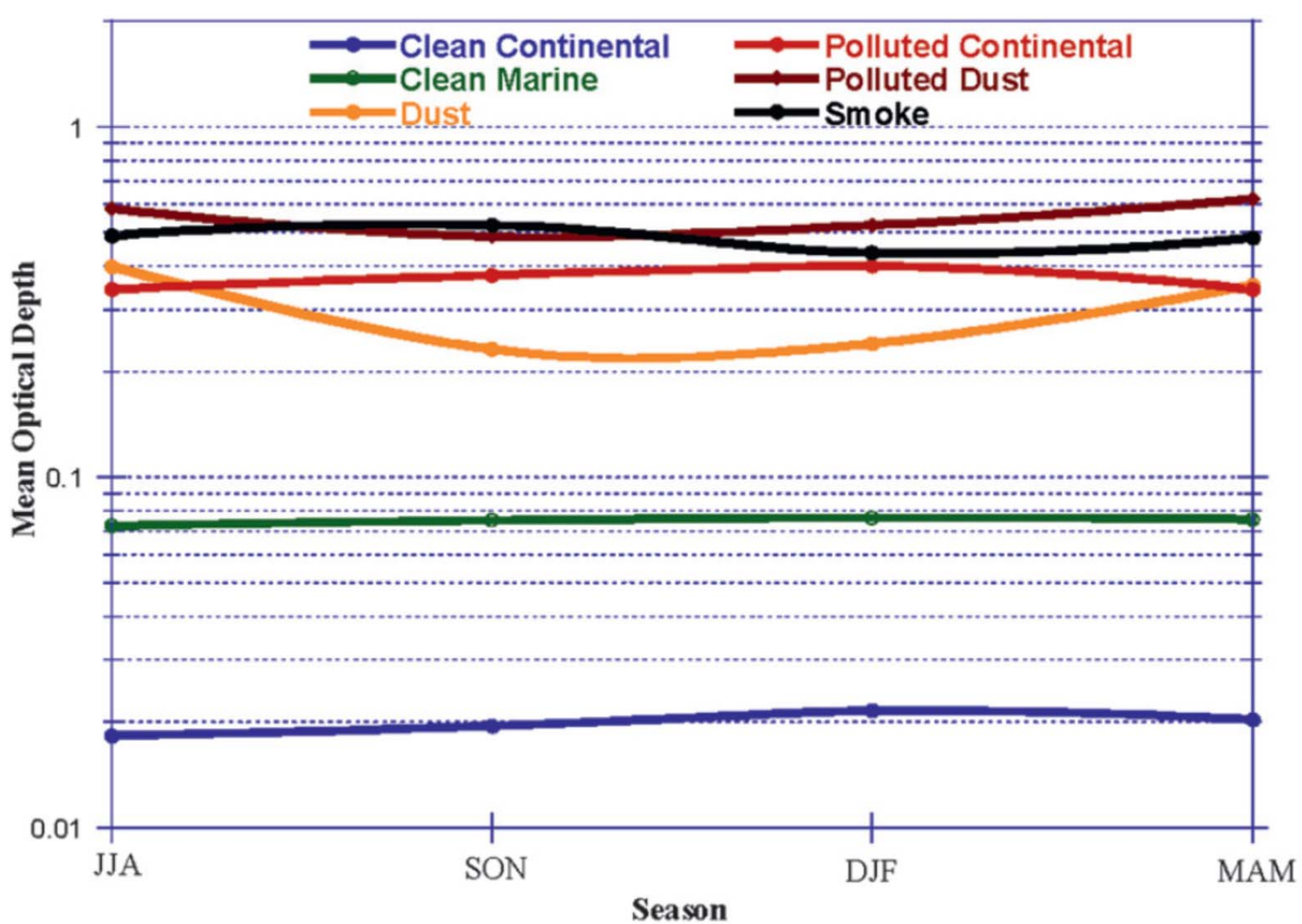
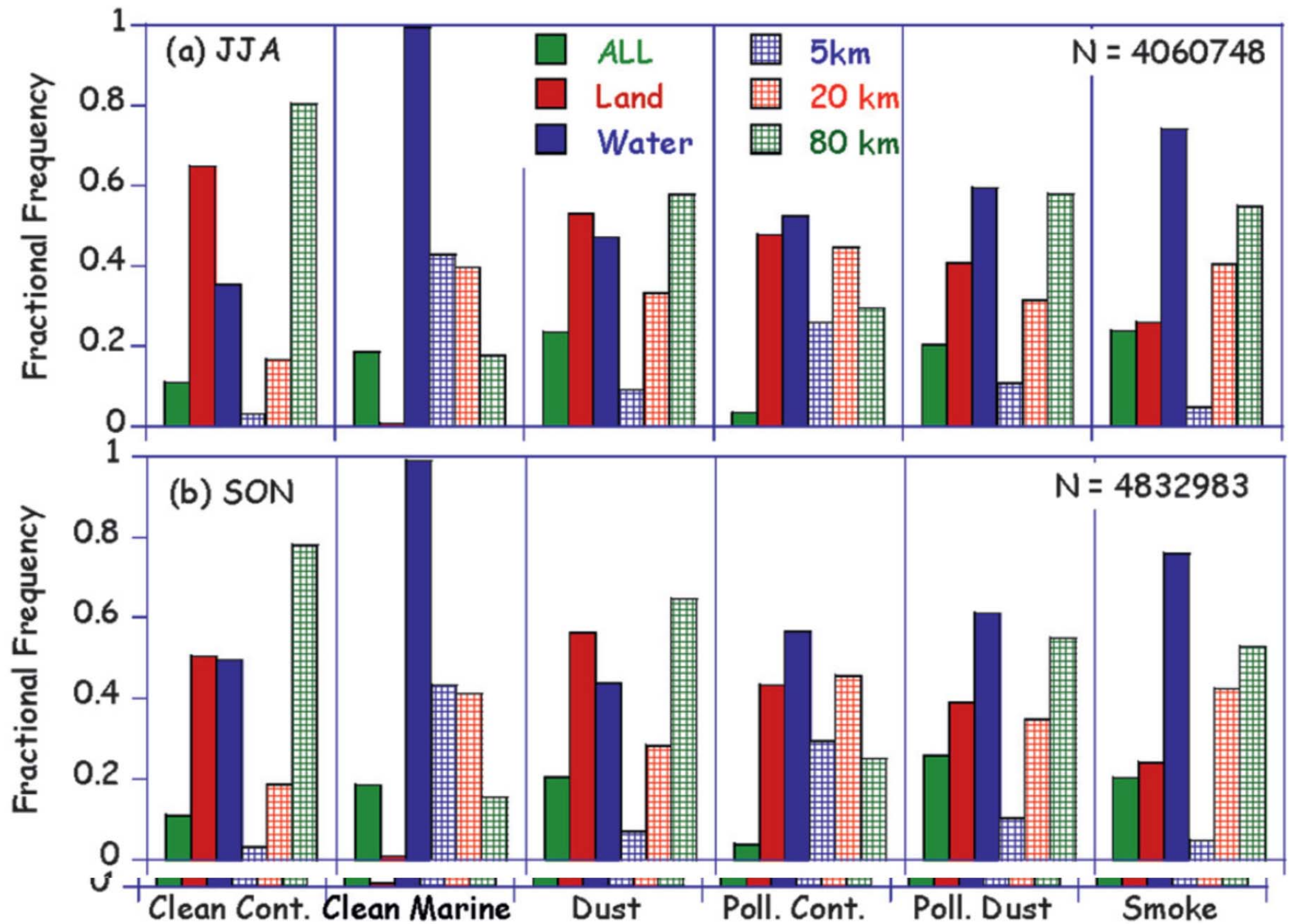
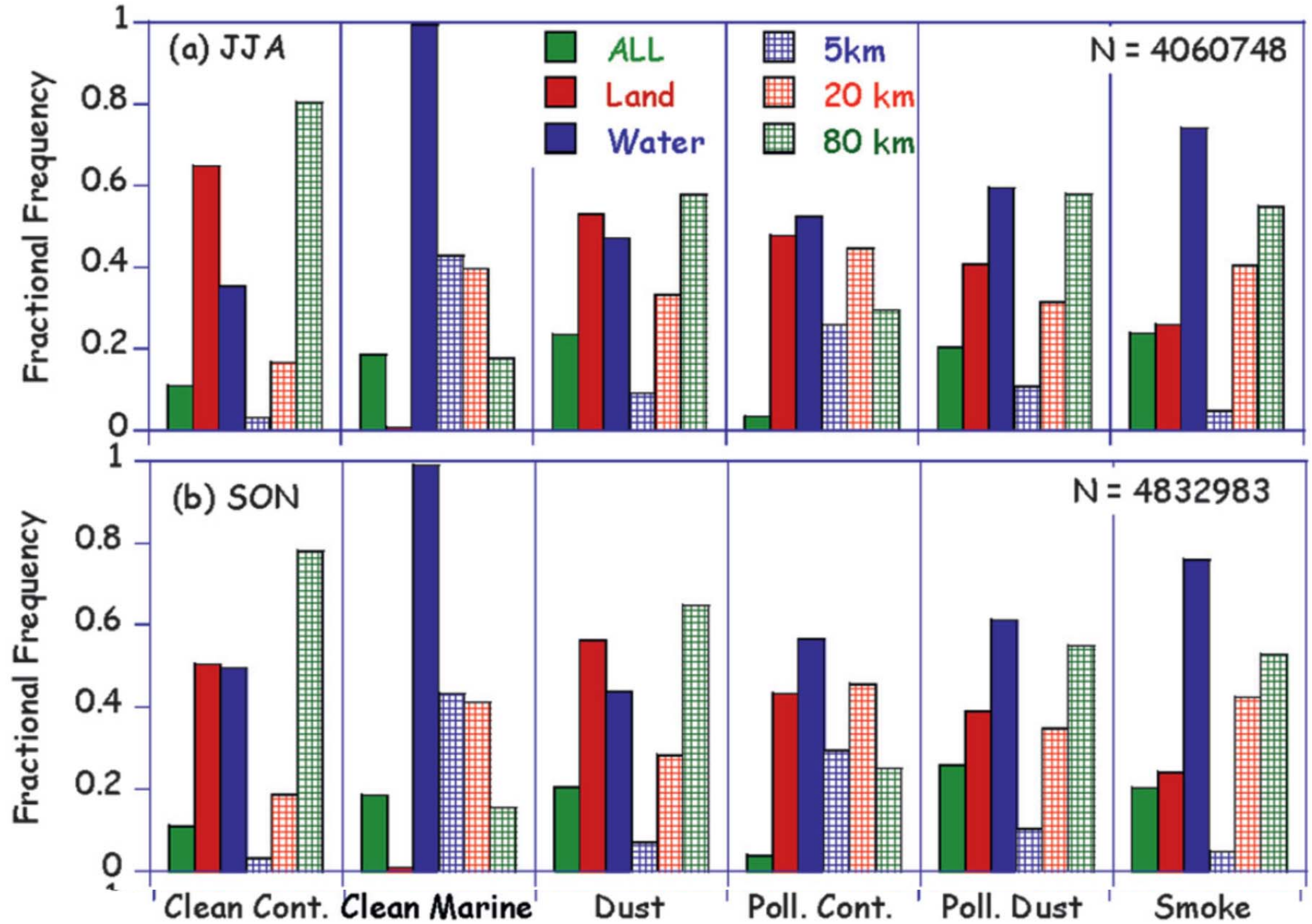


FIG. 10. The seasonal variation of the type attributed optical depth for June 2006–May 2007.

Fractional Frequency by Season



Fractional Frequency by Season



Seasonal Distributions of Dust

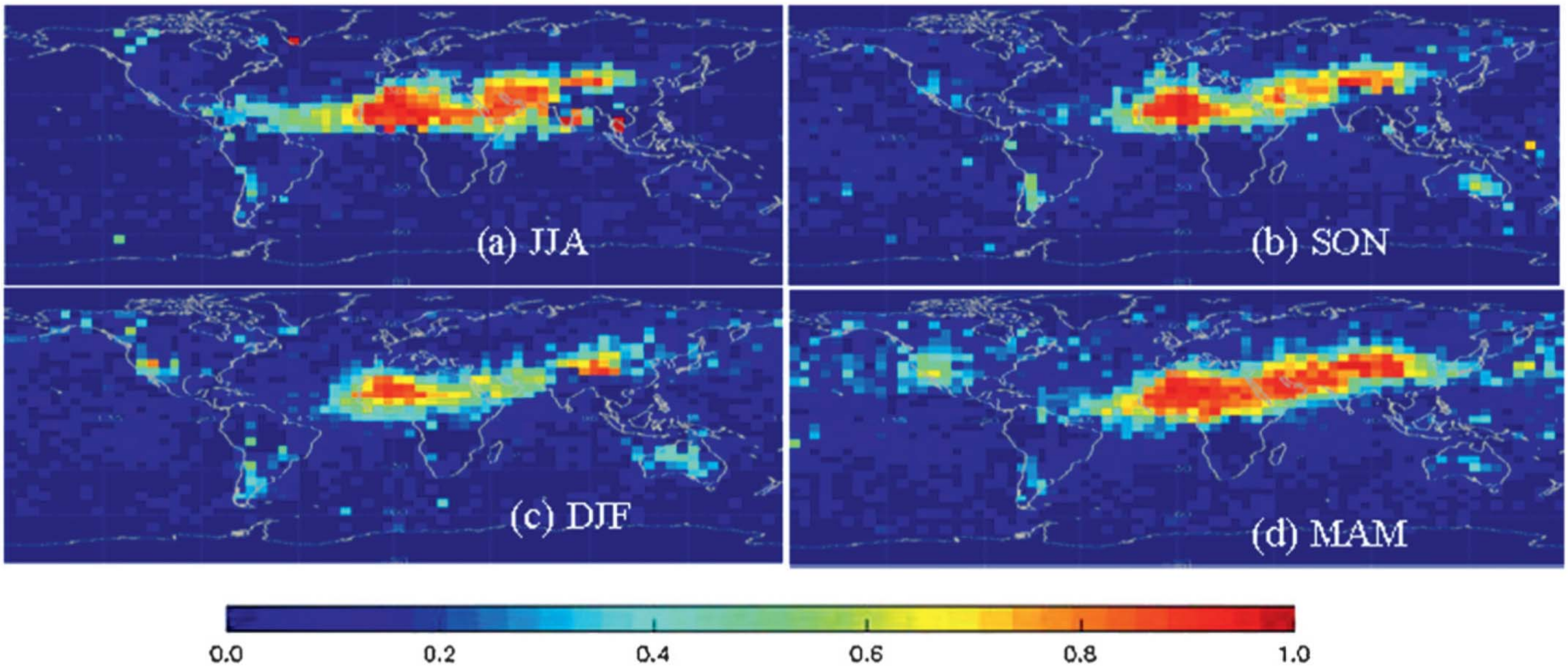


FIG. 15. Seasonal distributions of dust fractions of the aerosol layers in 5° × 5° grid boxes.

Polluted Dust Inter-annual Distribution

- The figure is a plot of the number of layers of polluted dust found in 5°x 5° grid boxes in JJA 2006 and 2007.

- Notwithstanding slight differences in the number of sampling days for these two periods, distributions are remarkably similar, an expected outcome for these aerosols.

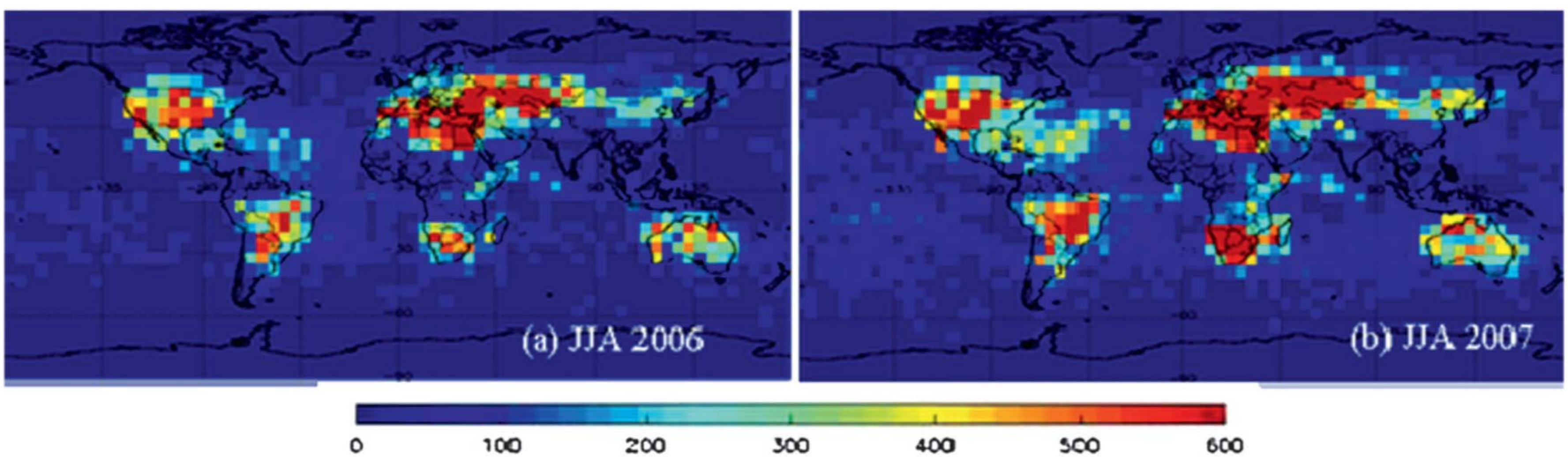


FIG. 16. Number of polluted dust layers found in 5° × 5° grid boxes for June, July, and August of (a) 2006 and (b) 2007.