Long Term Records of Dust Transport Over the Global Oceans: Past Results and Future Challenges to Understanding the Oceanic Dust Record

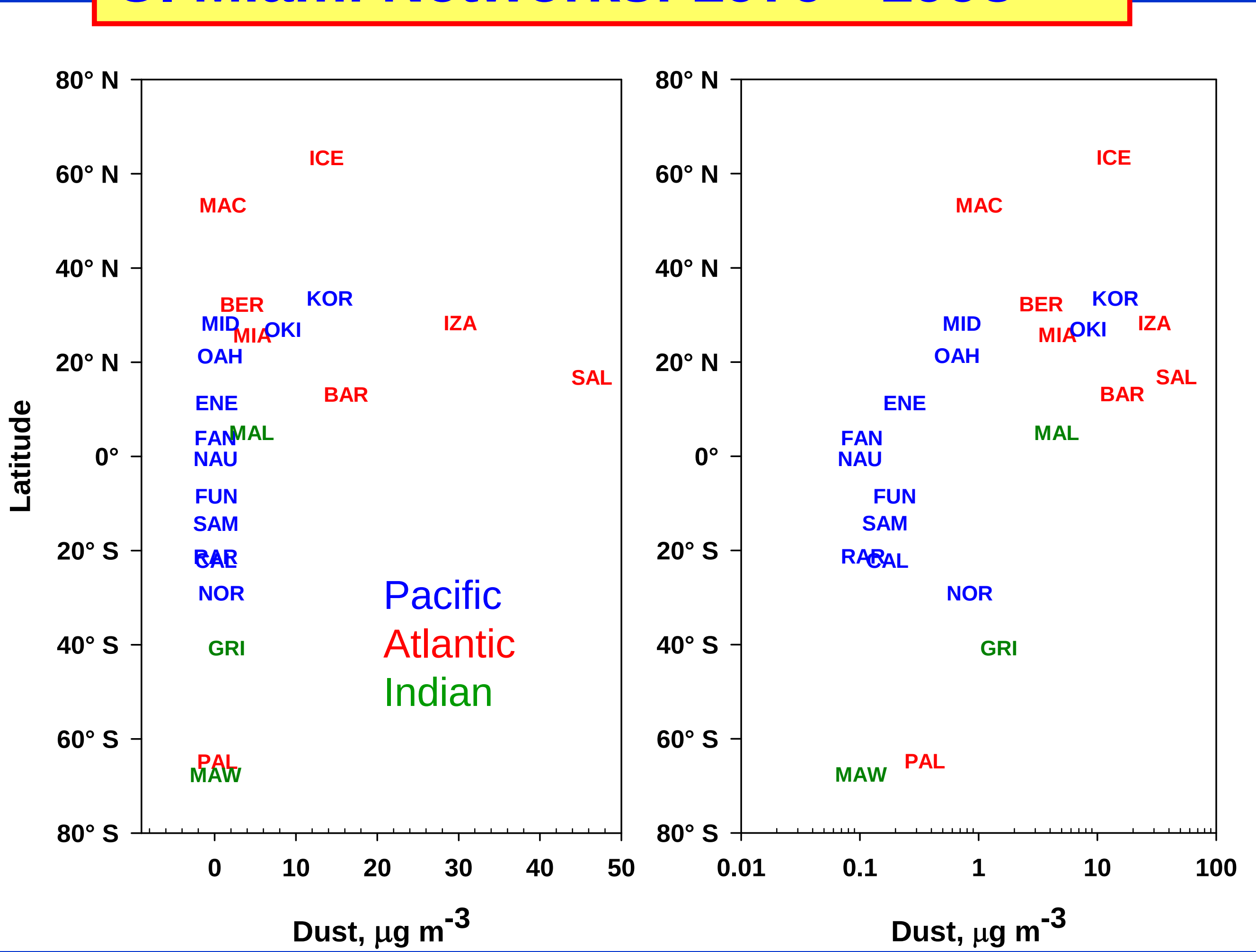
Joseph M. Prospero, University of Miami

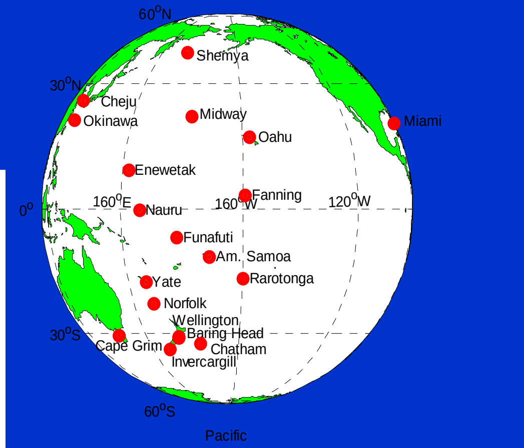
AEROCOM Workshop

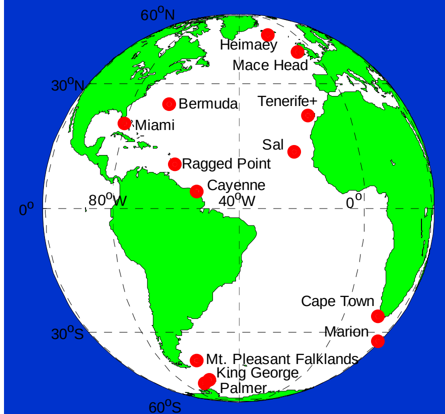
NOAA GFDL, Princeton

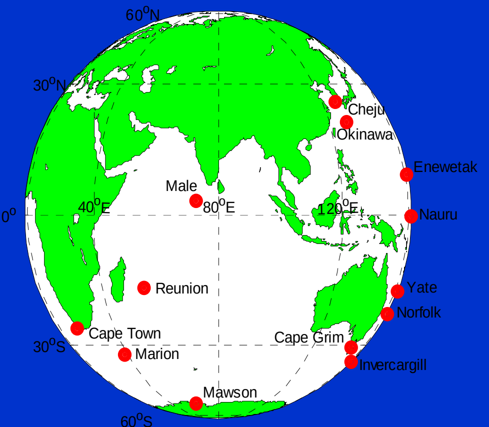
October 2009

Annual Mean Dust Concentrations
U. Miami Networks: 1979 - 1998









The North Atlantic is by far the ocean region most heavily and consistently impacted by dust.

Main Points

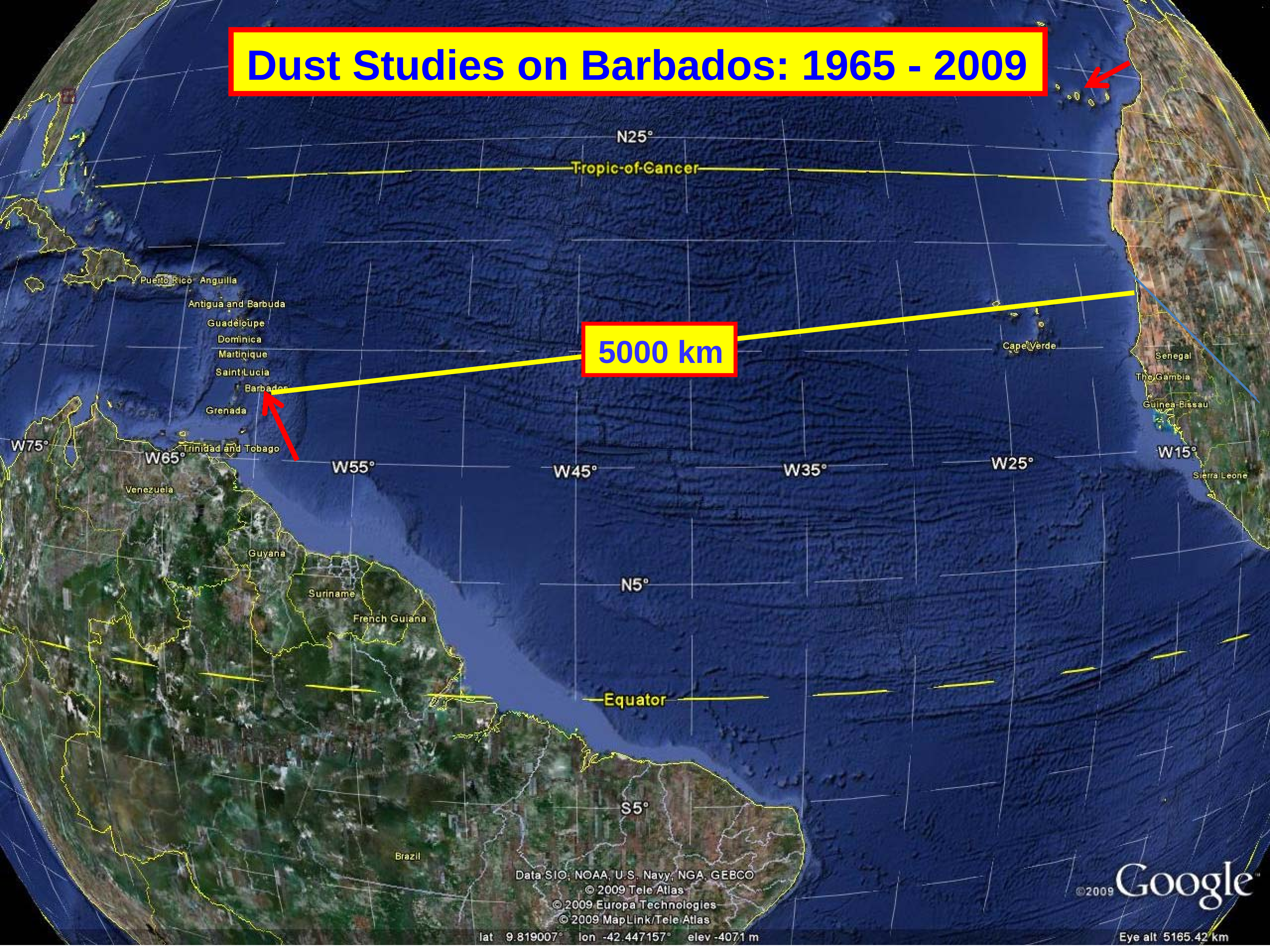
The North Atlantic is by far the ocean region that is most heavily and consistently impacted by dust.

Forty years after the “discovery” of the African dust phenomenon, we still know very little about the factors controlling its long range transport and deposition to the Atlantic

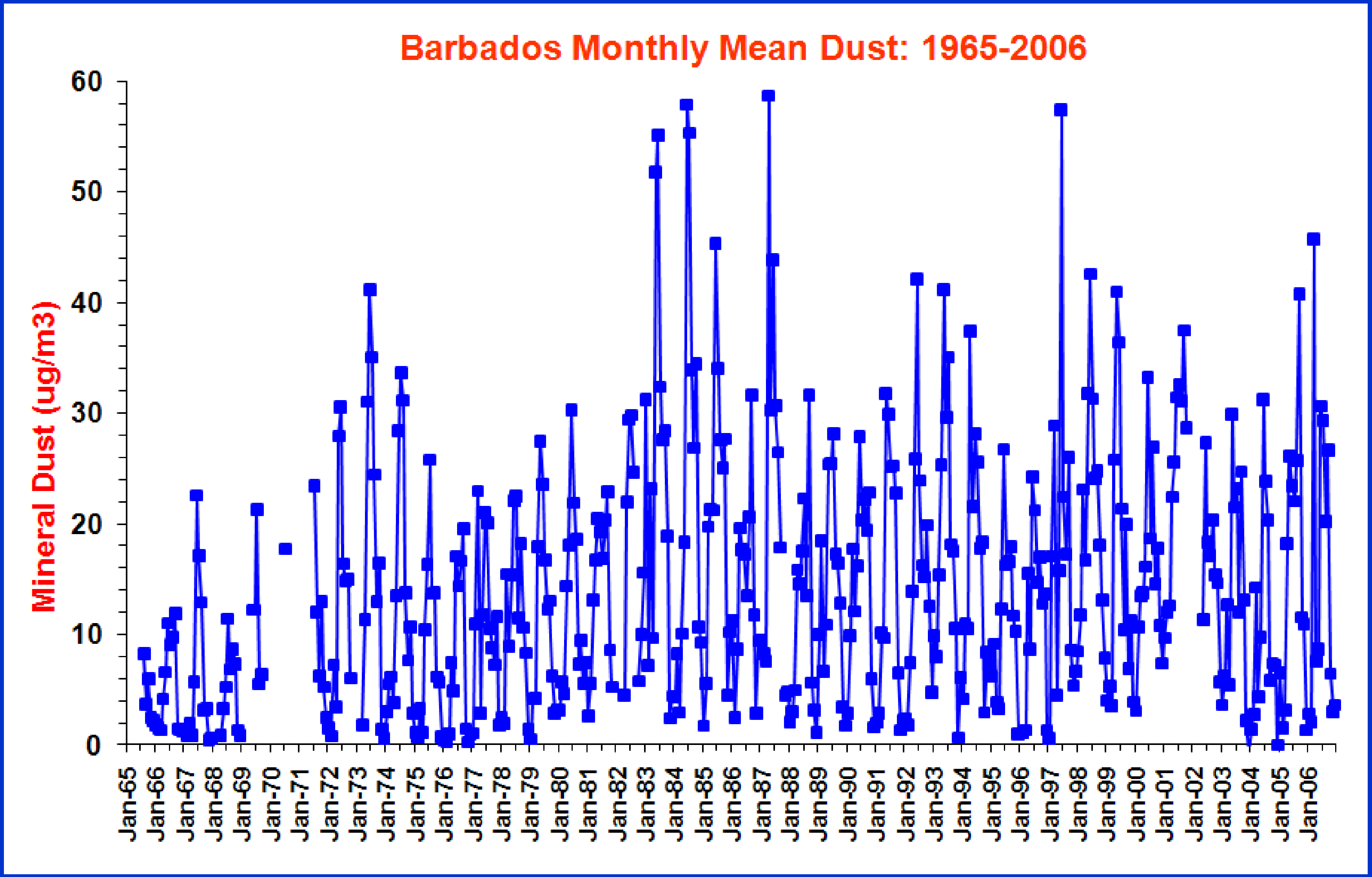
Some recent (and some old) research provides some insights on these processes.

Modelers: Please think about deposition!

Dust Studies on Barbados: 1965 - 2009



Forty Years of Dust Measurements on Barbados



Filter measurements of dust concentration in surface-level air at Barbados, West Indies.

A Brief History of Saharan Aerosol Layer (SAL) Studies
The two foundation papers: from BOMEX

VOL. 77, NO. 27 JOURNAL OF GEOPHYSICAL RESEARCH SEPTEMBER 20, 1972

Vertical and Areal Distribution of Saharan Dust over the Western Equatorial North Atlantic Ocean

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TOBY N. CARLSON

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Environmental Research Laboratories
National Oceanic and Atmospheric Administration, Miami, Florida 33124

MARCH 1972 JOURNAL OF APPLIED METEOROLOGY VOLUME 11

The Large-Scale Movement of Saharan Air Outbreaks over the Northern Equatorial Atlantic[1]

TOBY N. CARLSON

National Hurricane Research Laboratory, NOAA, Miami, Fla. 33124

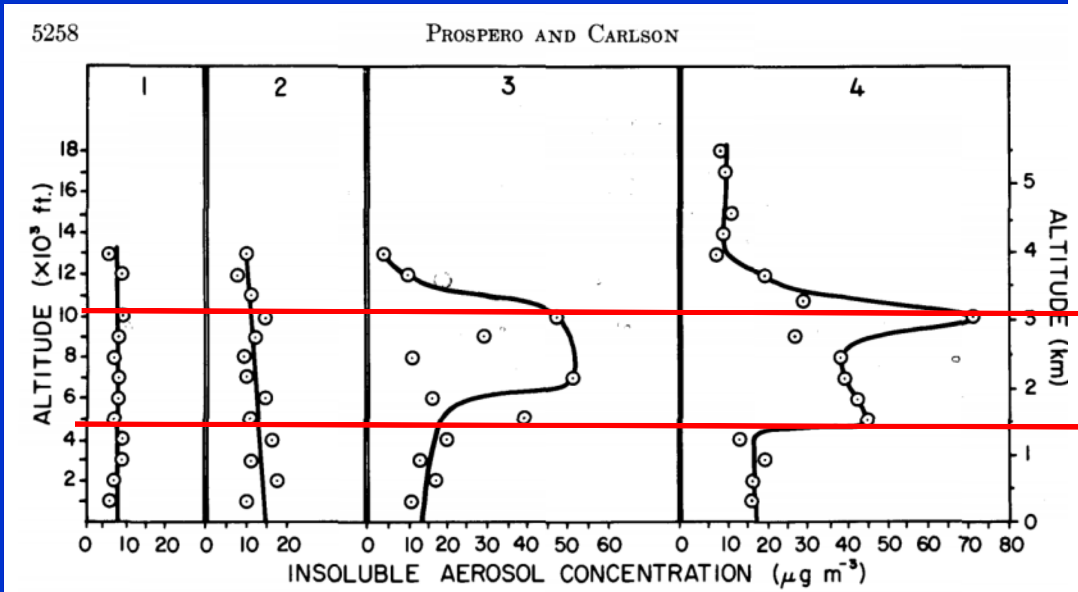
AND JOSEPH M. PROSPERO

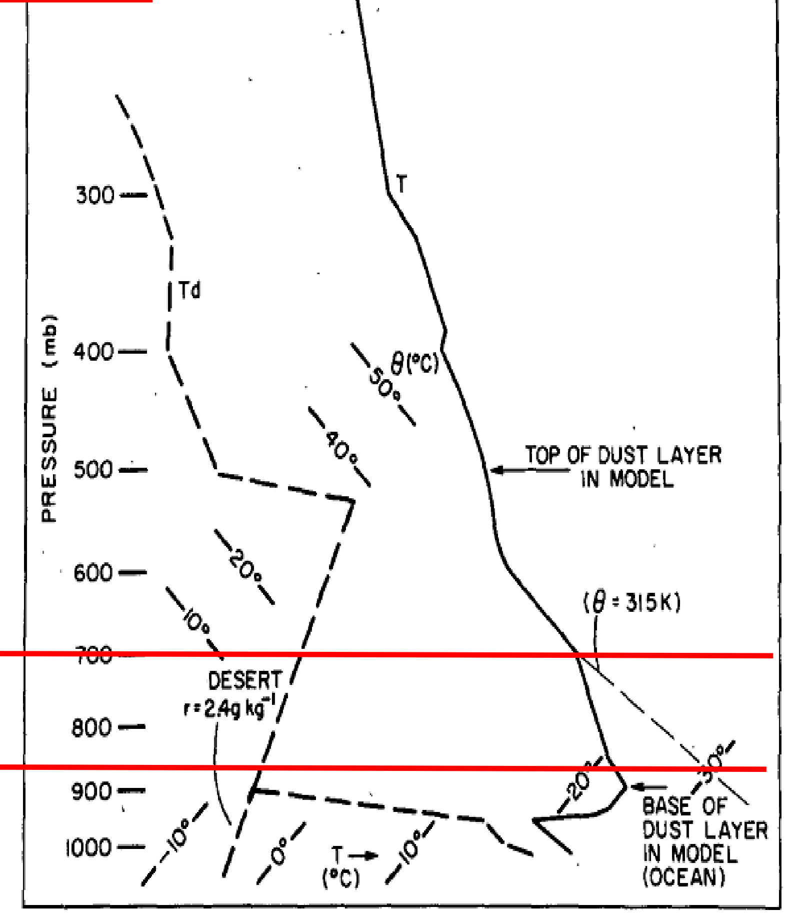
University of Miami, Rosenstiel School of Marine and Atmospheric Science, Miami, Fla. 33149

(Manuscript received 20 July 1971)

BOMEX: The "Discovery" of the SAL

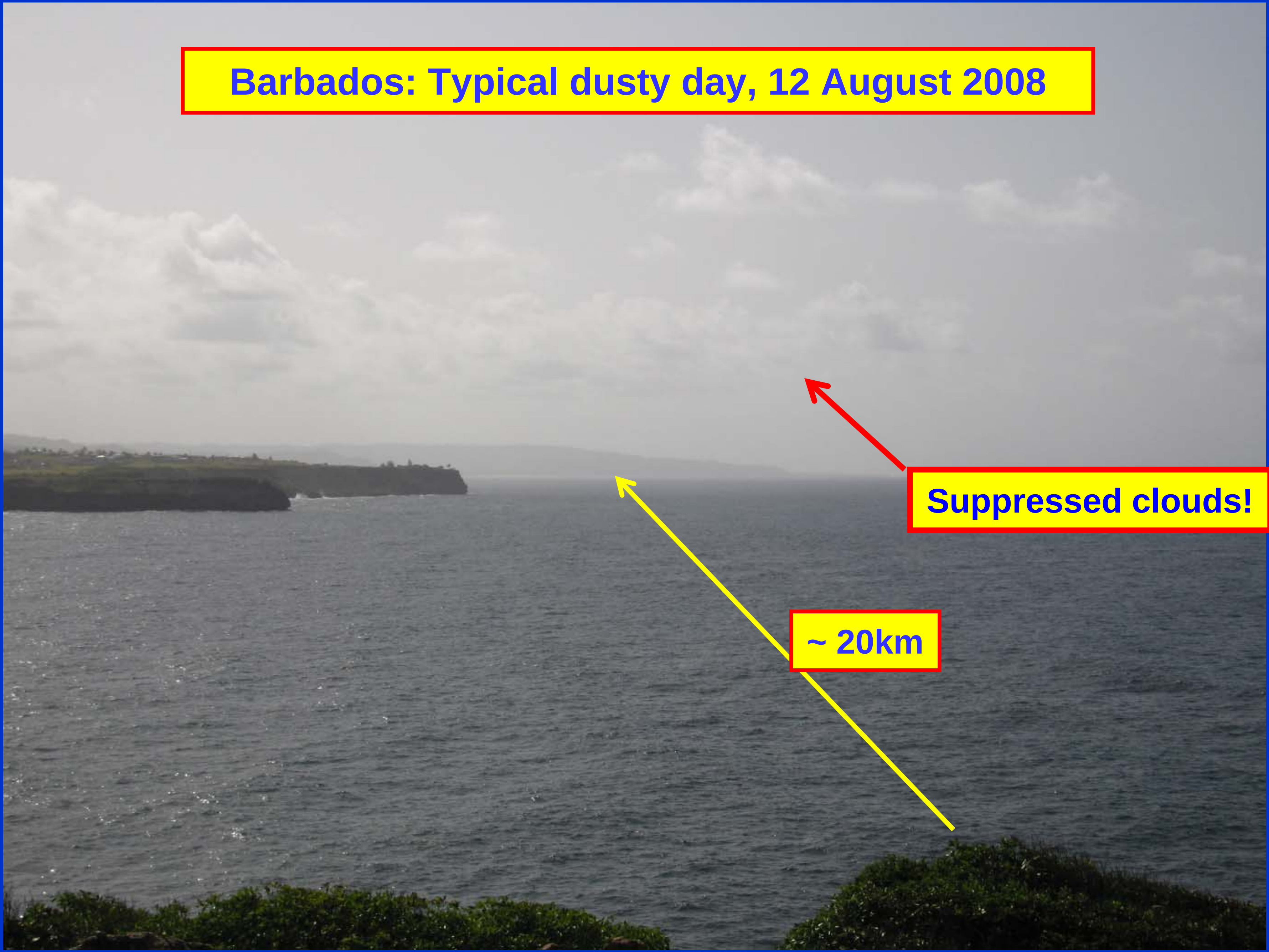
The SAL: a hot dry dust-laden elevated layer of air that originates over North Africa and often covers large areas of the tropical North Atlantic and Caribbean during the summer months.



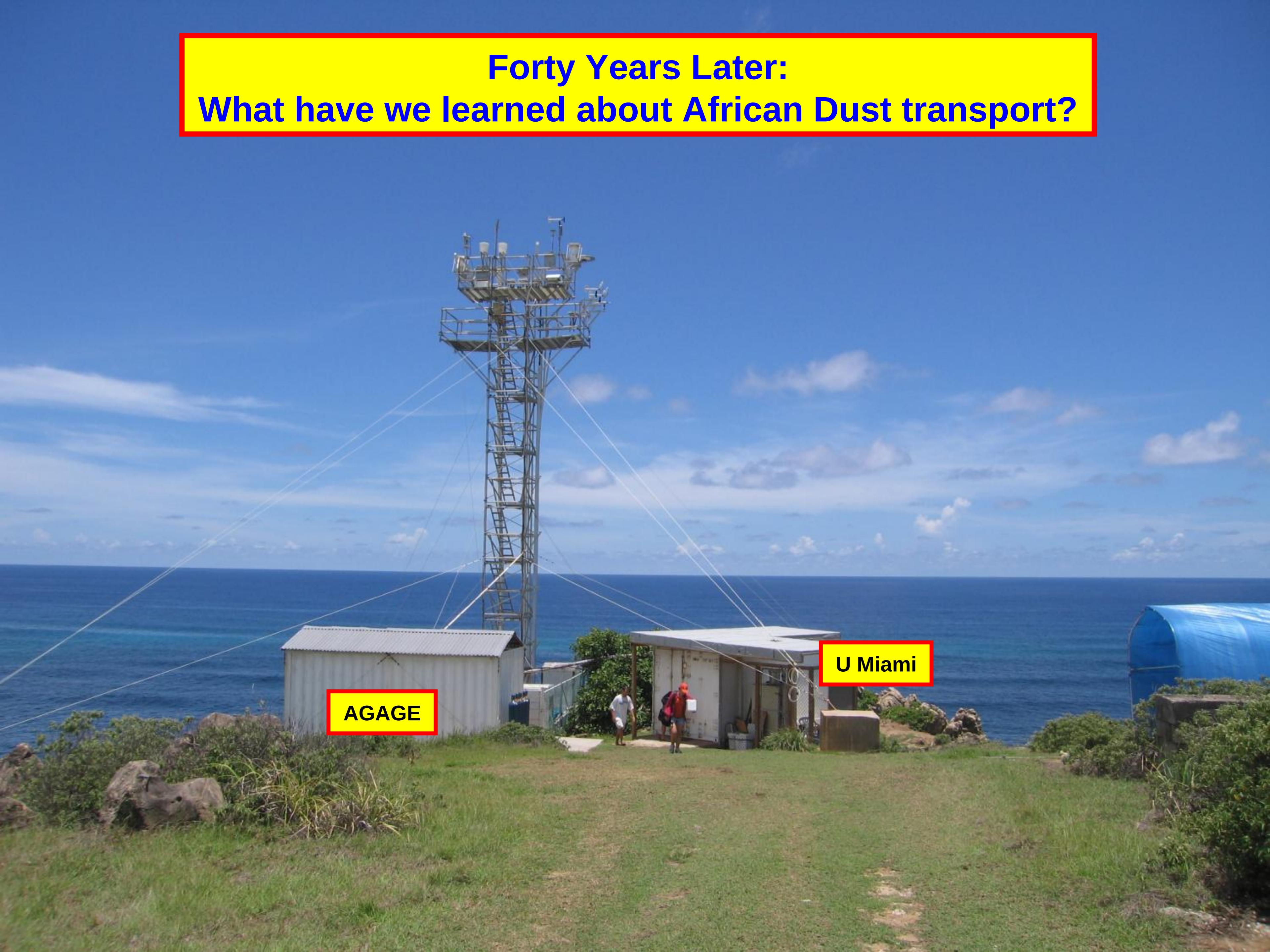


The vertical distribution of insoluble aerosol during each of the four Bomex periods. The total number of measurements in each period were 180, 411, 221, and 552, respectively. In all, 1360 filters were exposed continuously (15 - 30minutes per filter) on each of 32 flights (281 hours flying time).]

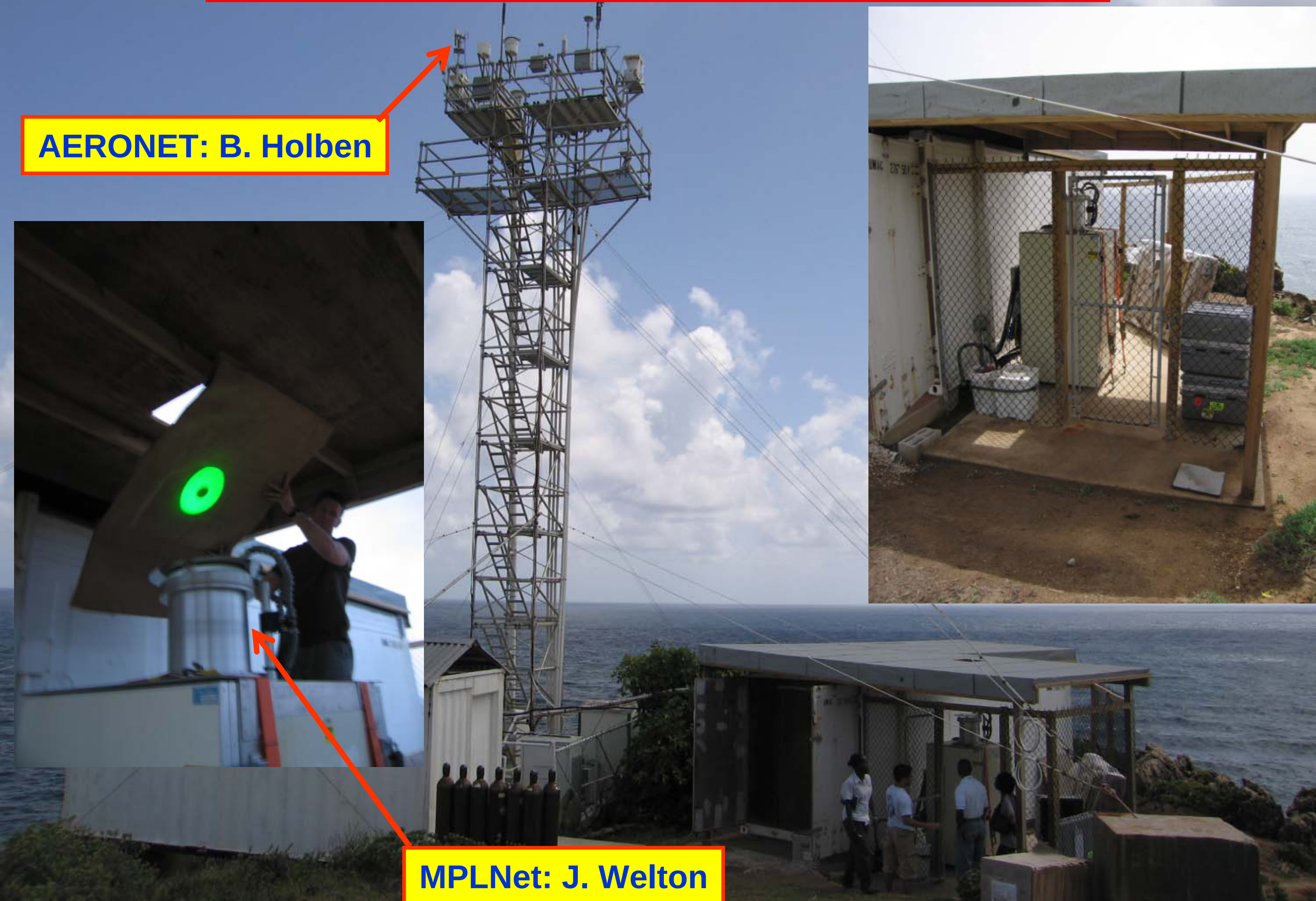
A typical meteorological sounding during a typical SAL episode.



Barbados: Typical dusty day, 12 August 2008
Suppressed clouds!
~ 20km

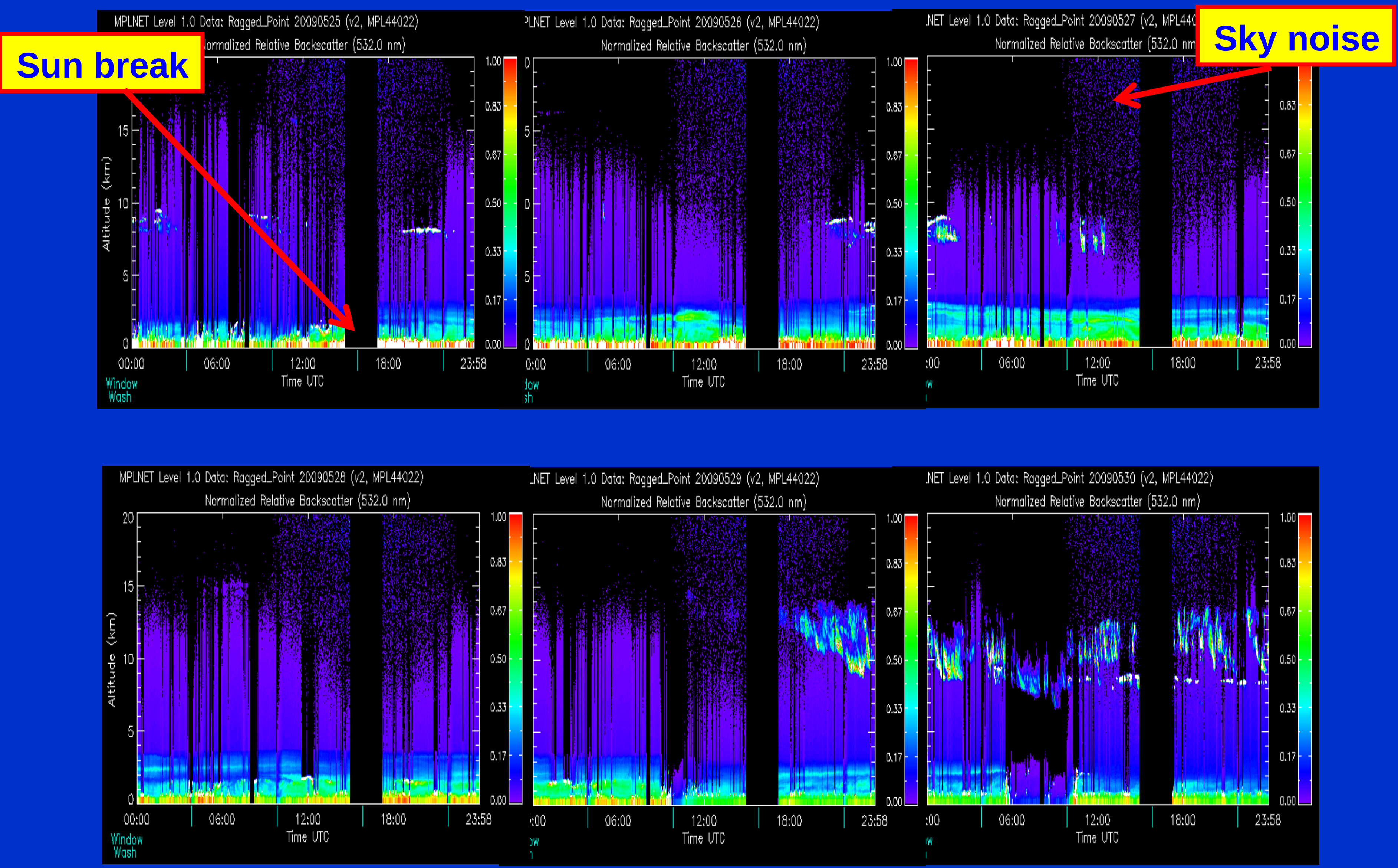

Forty Years Later:
What have we learned about African Dust transport?
U Miami
AGAGE

AERONET and MPLNet on Barbados

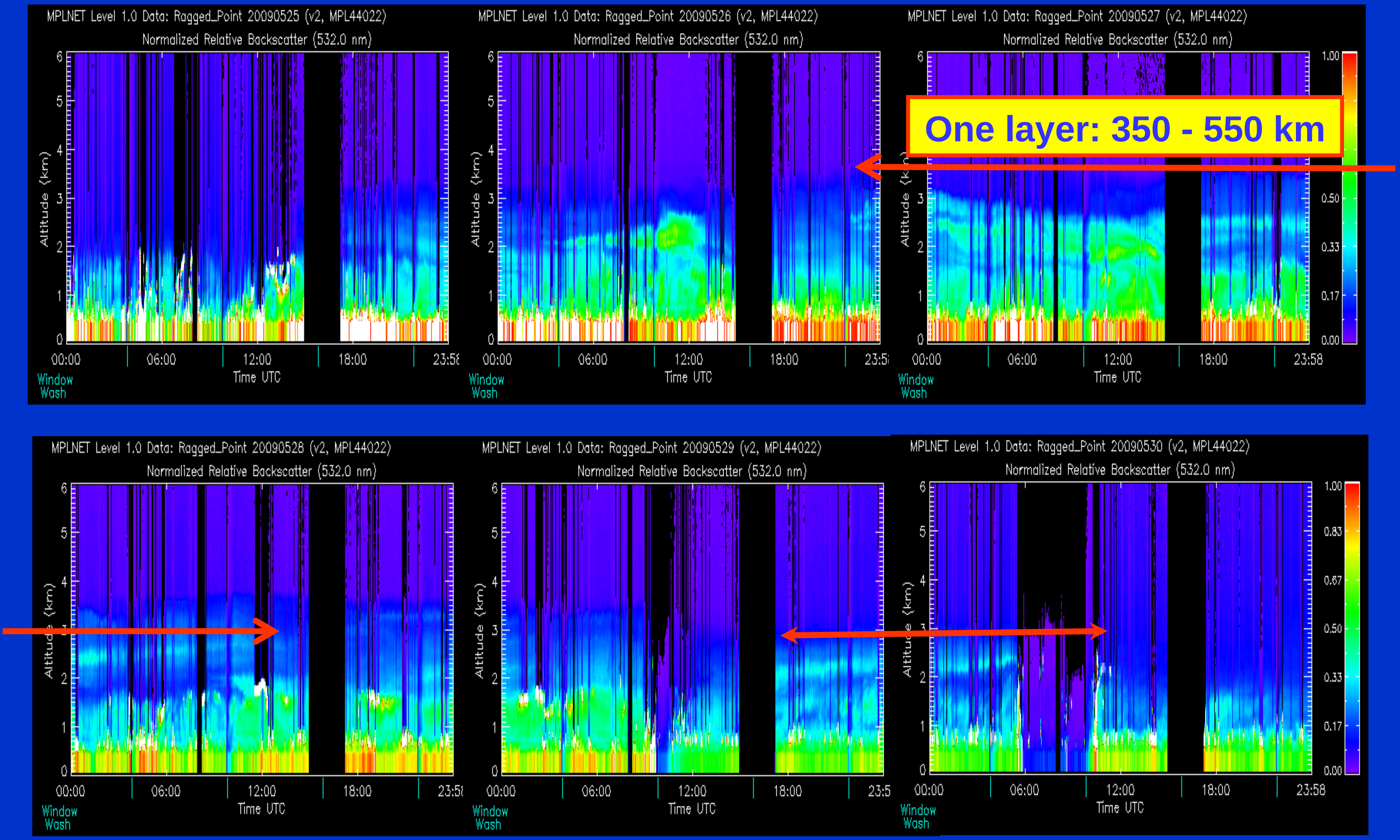


MPL Barbados: 25 - 30 May 2009

Range: Surface to 20km



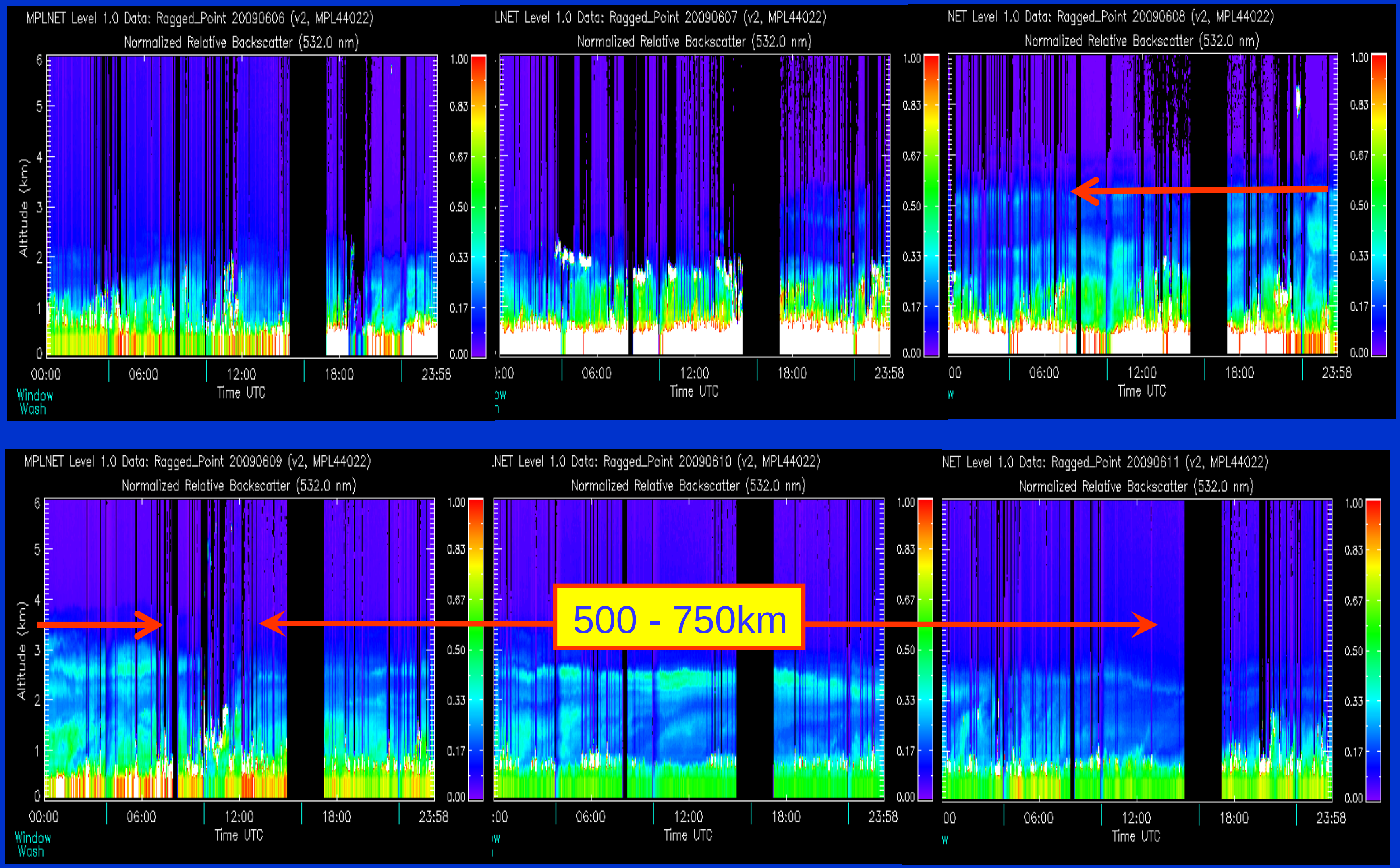
MPL Barbados: 25 - 30 May 2009 - Surface to 6km



NOTE: Data under about 500 meters difficult to interpret - instrument limitation and sea-salt.

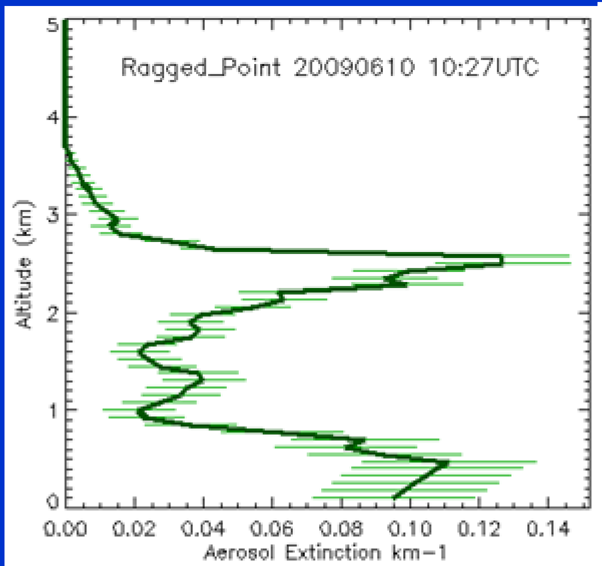
MPL Barbados: 6 - 11 June 2009

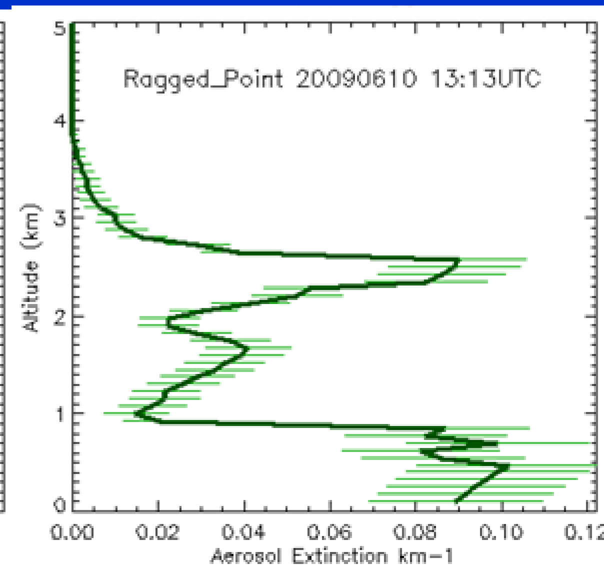
Range: Surface to 6 km

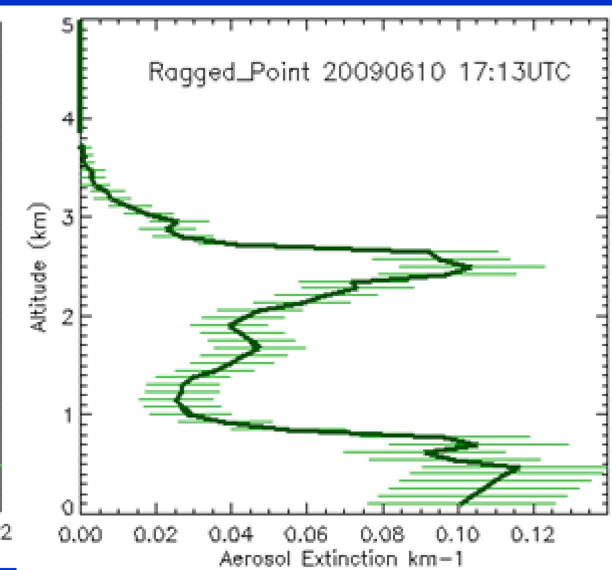


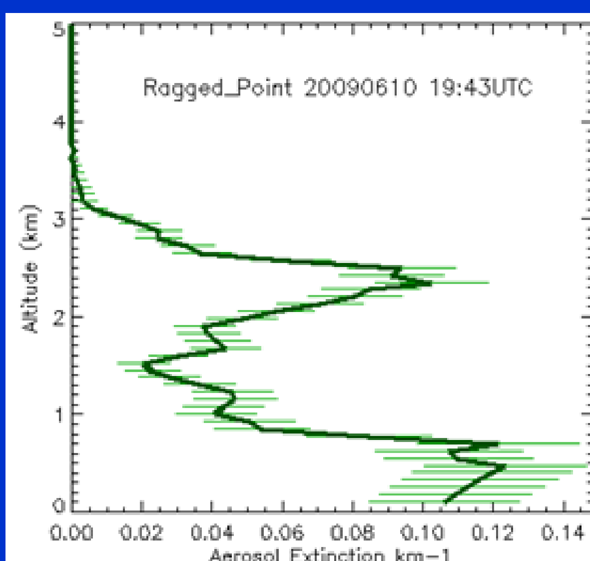
How can such thin layers persist for so long in a neutrally stable layer of air?
What about the effects of local heating due to solar absorption by the dust?

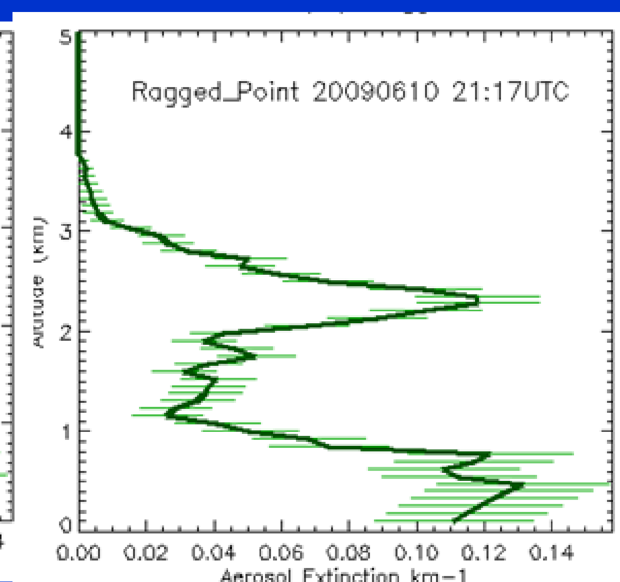
MPL: The Temporal and Spatial Persistence of Barbados Dust Layers







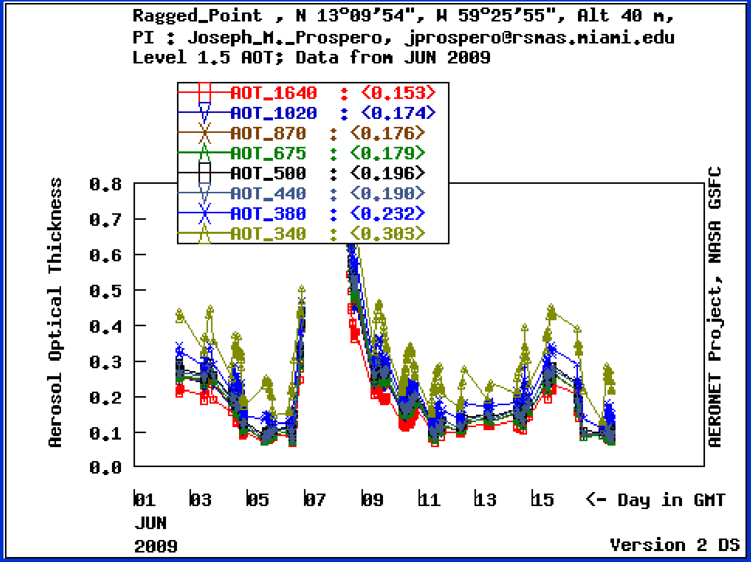


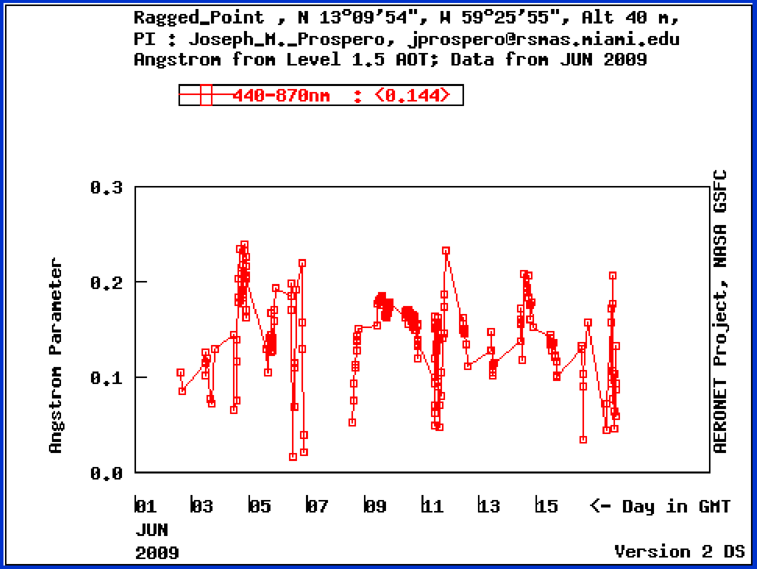


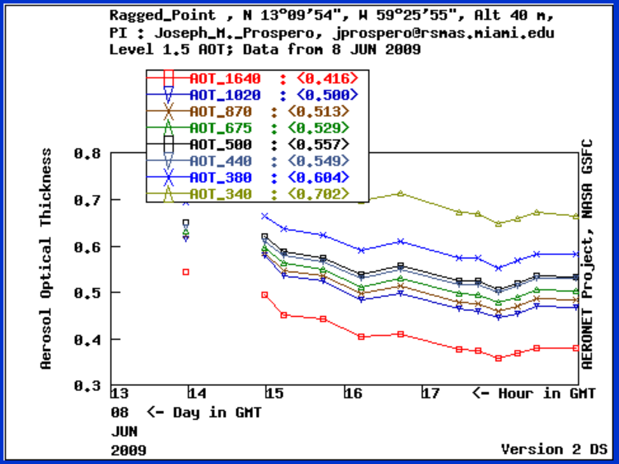
MPL profiles10 June 2009

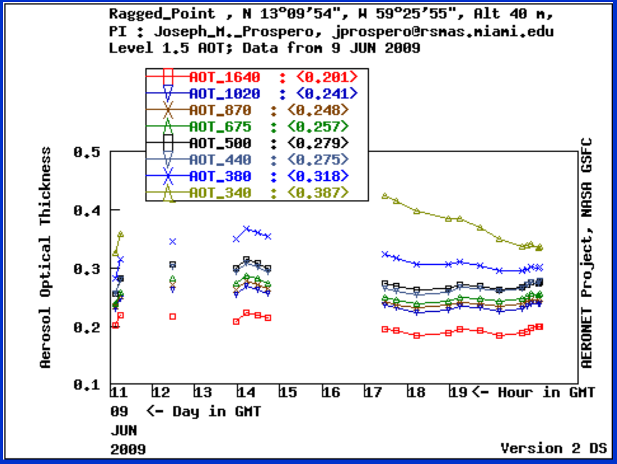
- **No substantial change in the dust layer over 10 hours**
- **Equivalent to a transport length of ca. 150km.**

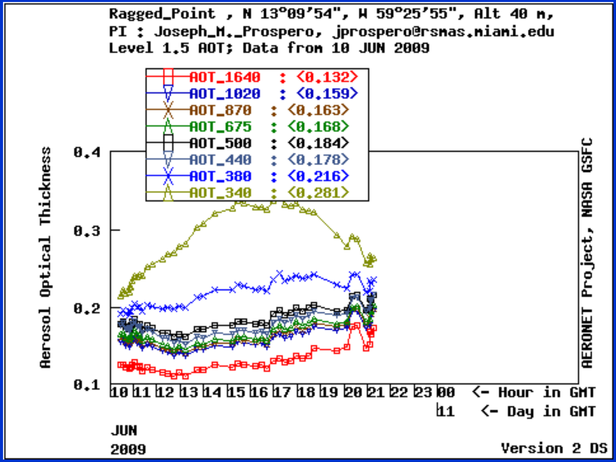
AERONET Aerosol Optical Thickness
Barbados 8 - 10 June 2009





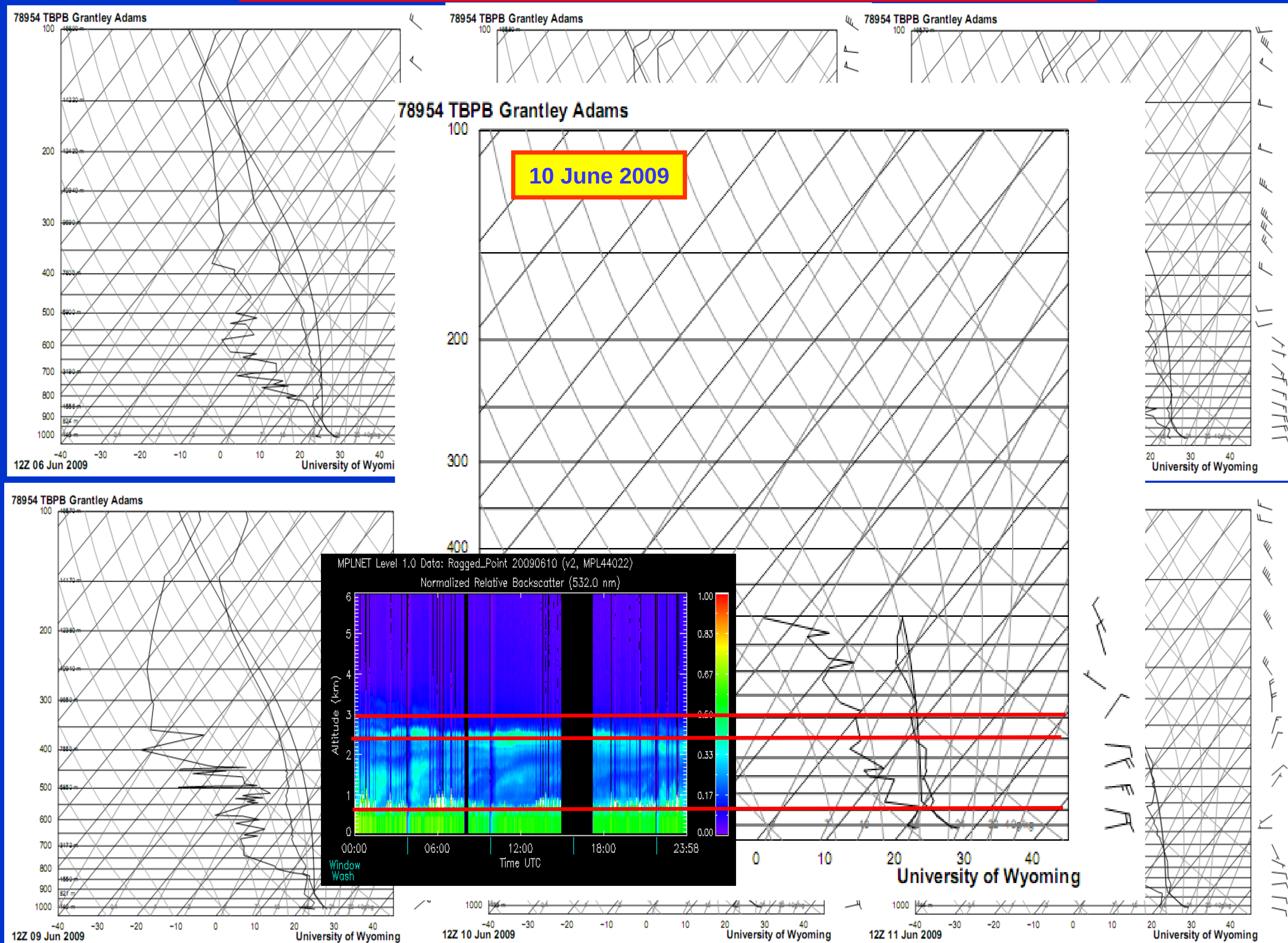


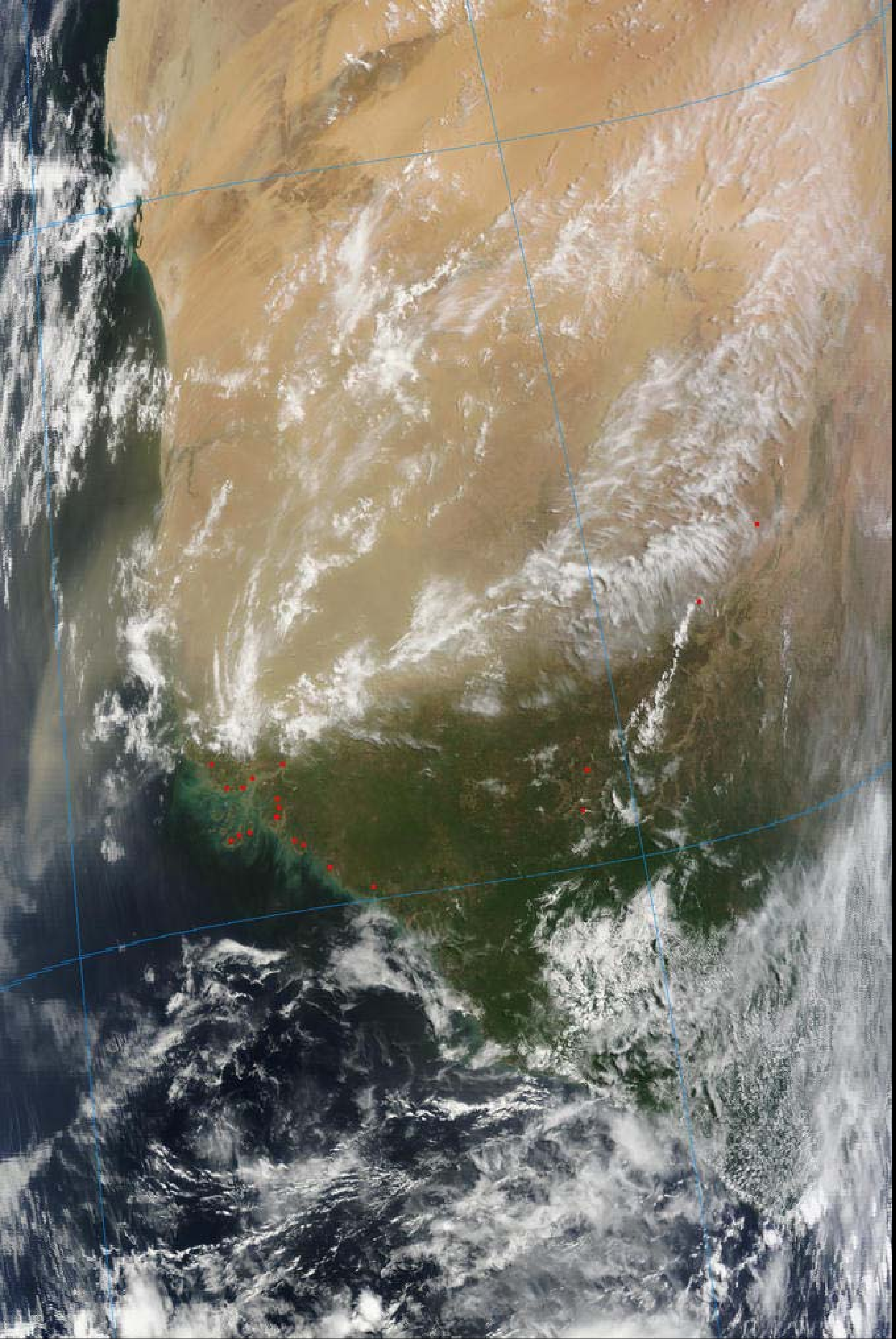




NOAA HRD GIV Flight, Barbados, 17Sep06

Rawinsondes 6 - 11 June 2009 : Barbados

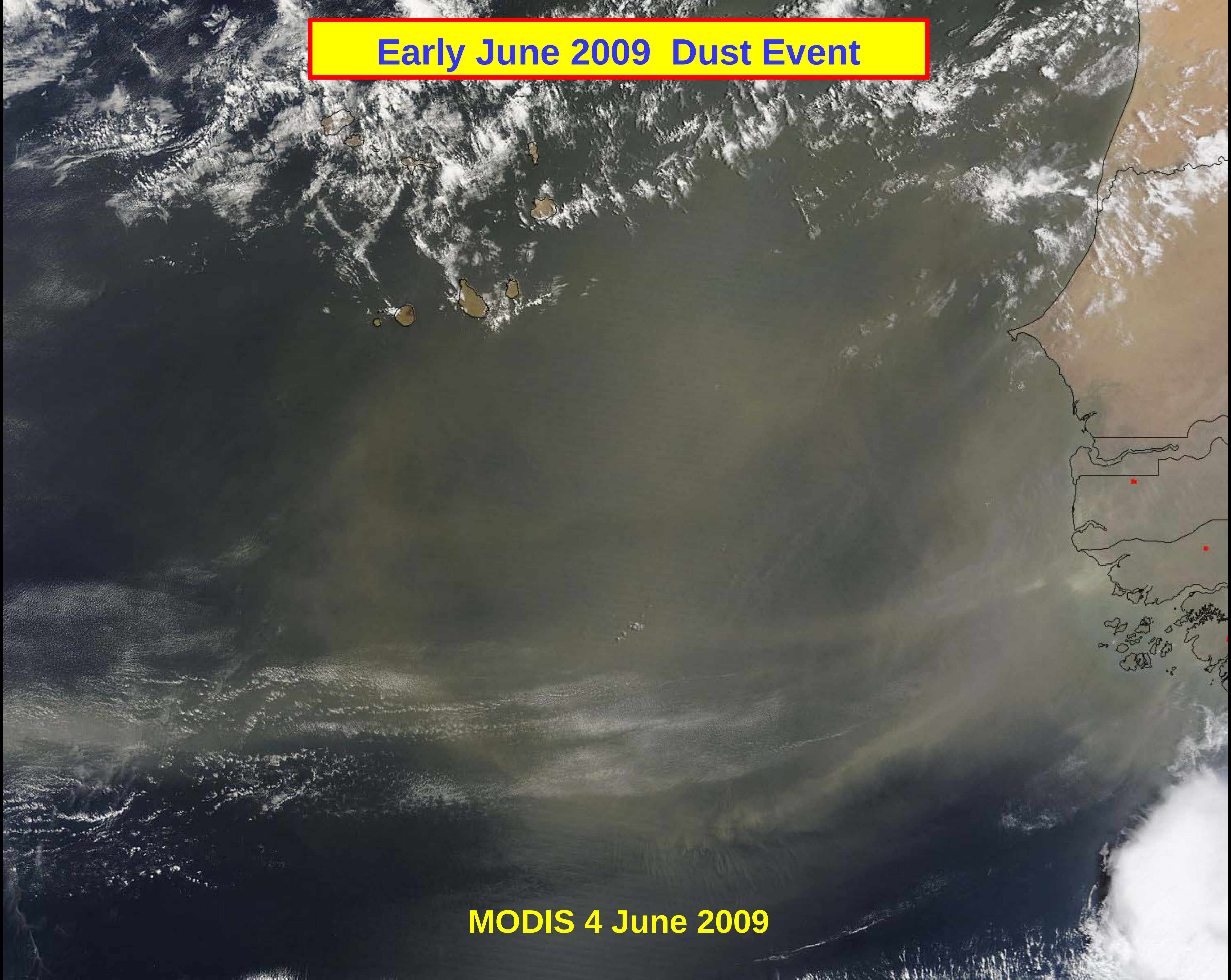




The Source of the Early June 2009 Dust Event

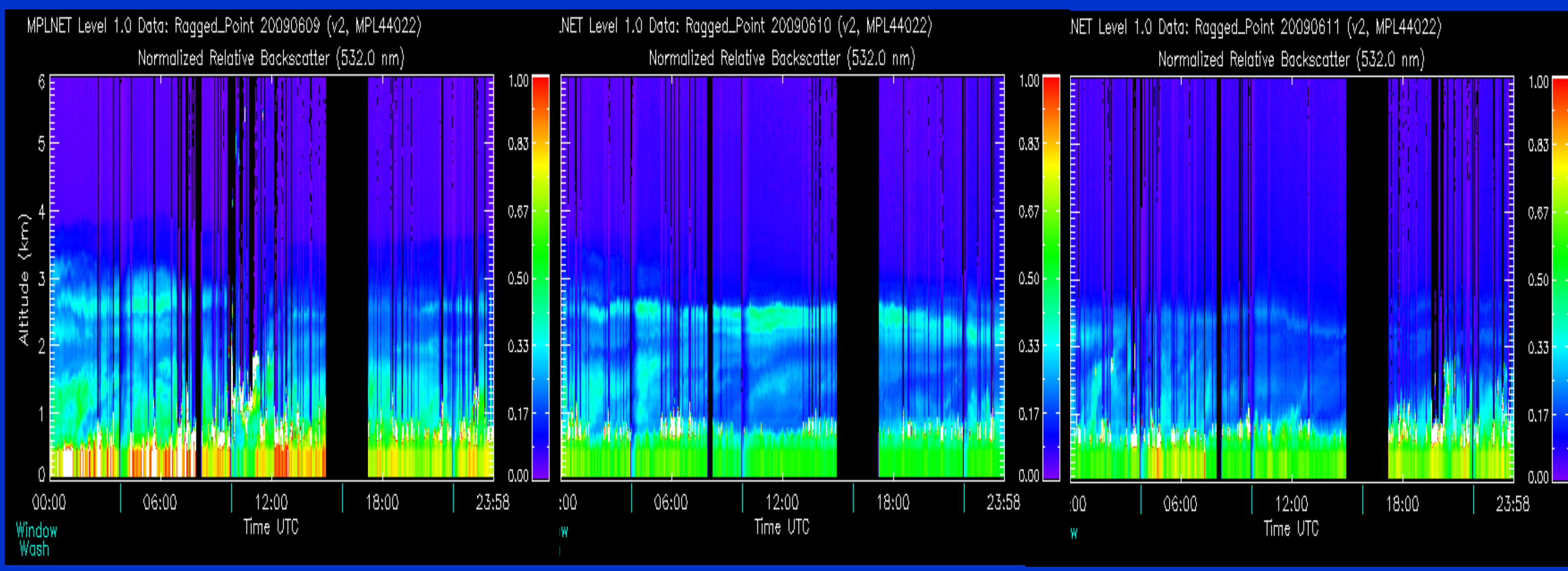
The dust arrived on Barbados 5 days later, on 8 June – a typical transit speed.

MODIS Terra 3 June 2009


Early June 2009 Dust Event
MODIS 4 June 2009

Questions

- **How are these thin layers formed?**
- **How do they maintain their integrity over such time and distance?**
- **What can they tell us about the process of aerosol transport and deposition?**



Thirty Years After BOMEX
PRIDE: The Puerto Rico Dust Experiment

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D19, 8587, doi:10.1029/2002JD002544, 2003

Vertical distributions of dust and sea-salt aerosols over Puerto Rico during PRIDE measured from a light aircraft

H. Maring, D. L. Savioe, M. A. Izaguirre, and L. Custals
Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA

J. S. Reid[1]
SPAWAR Systems Center-San Diego, San Diego, California, USA

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D19, 8586, doi:10.1029/2002JD002493, 2003

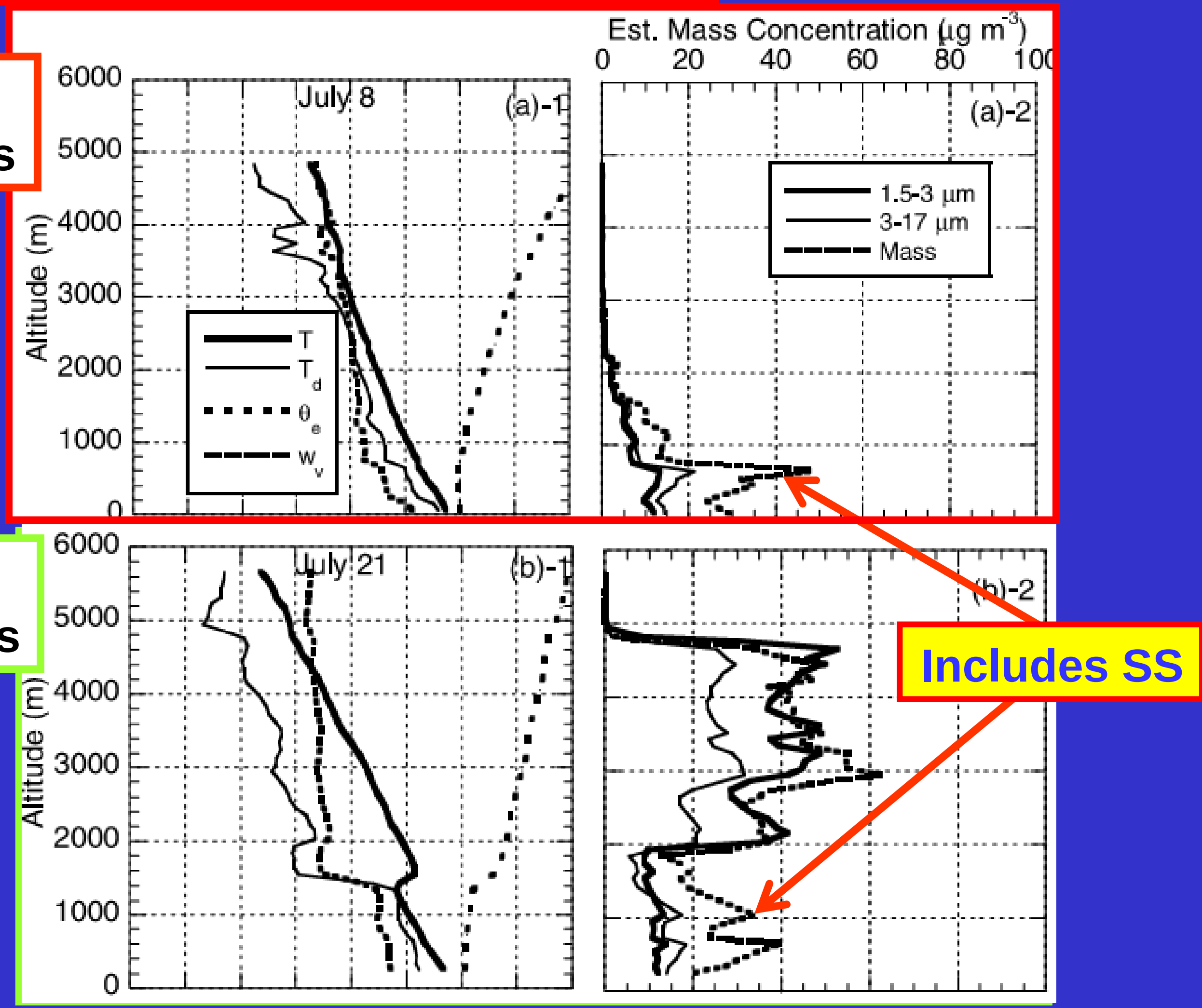
Analysis of measurements of Saharan dust by airborne and ground-based remote sensing methods during the Puerto Rico Dust Experiment (PRIDE)

Jeffrey S. Reid,[1,2] James E. Kinney,[1] Douglas L. Westphal,[2] Brent N. Holben,[3] Ellsworth J. Welton,[3] Si-Chee Tsay,[3] Daniel P. Eleuterio,[4] James R. Campbell,[5] Sundar A. Christopher,[7] P. R. Colarco,[8] Haflidi H. Jonsson,[4] John M. Livingston,[9] Hal B. Maring,[10] Michael L. Meier,[11] Peter Pilewskie,[12] Joseph M. Prospero,[10] Elizabeth A. Reid,[2] Lorraine A. Remer,[3] Philip B. Russell,[12] Dennis L. Savoie,[10] Alexander Smirnov,[6] and Didier Tanré[13]

PRIDE Aerosol Vertical Profiles

8 July 2000
clean marine conditions

21 July 2000
SAL Conditions



Atmospheric soundings and aircraft profiles for a day with: TOP clean marine conditions (8 July 2000); BOTTOM, SAL transport conditions (21 July 2000). First column, thermodynamic state variables. Second column, FSSP number concentration (1.5–3 um, thick solid lines; 3–17 um, thin solid lines), and estimated coarse mode particle mass concentration (dashed lines).

Does Stokes Settling Play a Discernable Role in Affecting Dust Vertical Distributions? (And dust deposition rates to the ocean?)

Part I: Over the Western Atlantic

Short Answer: Apparently Not.

Observation:

- **Compared concentration in the four larger-size bins (3–6, 6–11, 11–14, and 14–17 um) to that in the smallest, 1.5 - 3um.**

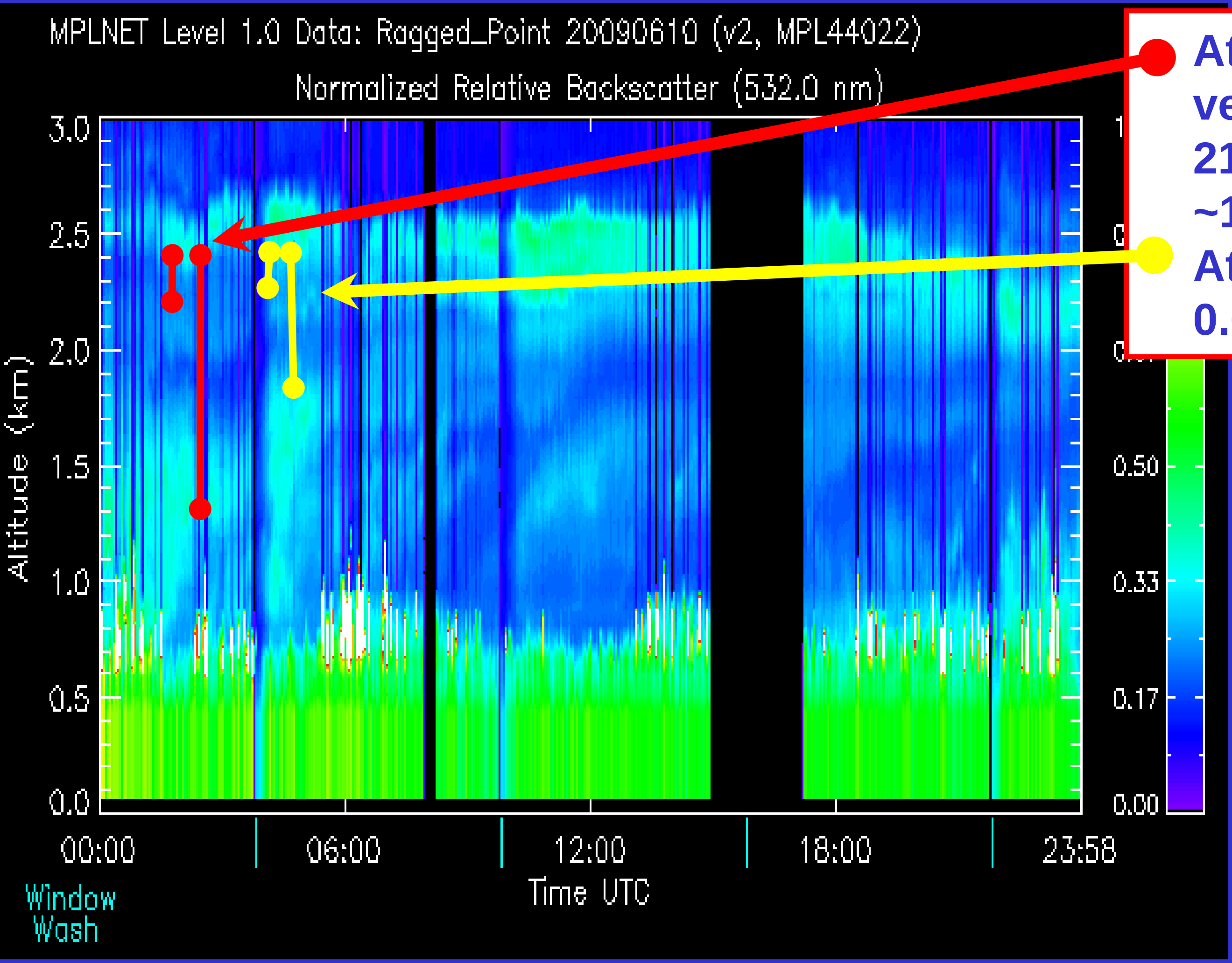
- **In general, observed no substantial and consistent changes in particle size ratios within the bulk of the dust layers and in the MBL under SAL conditions.**

Conclusion:

- **Stokes settling effects NOT evident in vertical distributions.**

- **Dust dry deposition processes to the ocean (which would be strongly size dependent) are NOT a dominant removal mechanism.**

Stokes Settling & Layers: Visualized



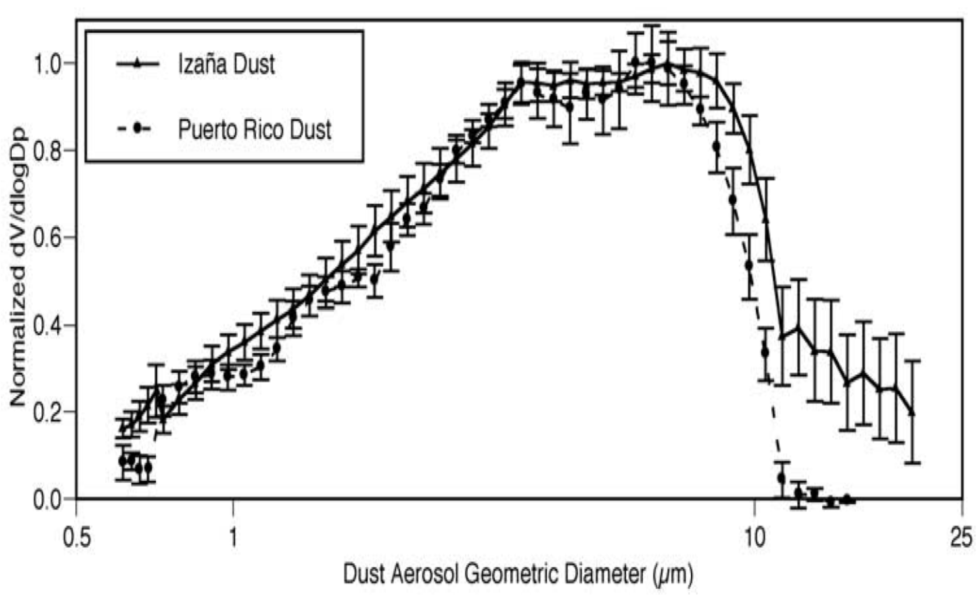
- At 8 um diam, settling velocity is 0.25 cm s^{-1}, 215 m day^{-1}. Over 6 days ~1.2 km.
- At 5 um, ~100 m day^{-1}, 0.6 km over 6 days.

So - how does dust get from the SAL to the MBL?

Does Stokes Settling Play a Discernable Role in Affecting Dust Size Distributions?

Part II: Across the entire Atlantic

Short Answer: Yes but not in a simple way



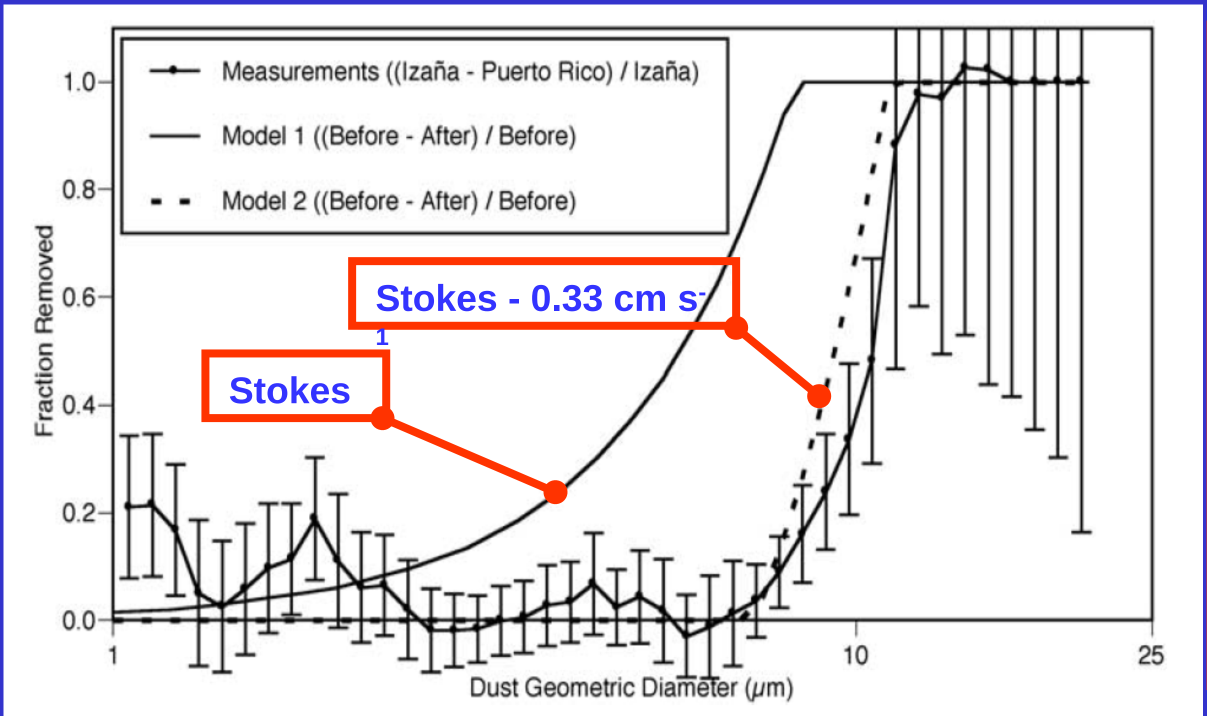
- **July 1995, Tenerife:**
Measurements made of aerosol size at a mountain top observatory on Tenerife during July 1995 using a TSI APS Model 3310 and a TSI SMPS Model 3934L .

- **July 2000 in PRIDE**
Same measurements made using the very same instruments.

Peak height normalized dust aerosol volume size distributions from the free troposphere at Izana, Tenerife, Canary Islands (solid line with solid triangles) and from the marine boundary layer at Puerto Rico (dashed line with solid circles). Error bars represent one standard deviation. [Maring et al., 2003]

Maring et al., (2003) Mineral dust aerosol size distribution change during atmospheric transport, J. Geophys. Res., 108

Does Stokes Play a Role in Dust Vertical Distributions Part II: Across the entire Atlantic (cont'd)



- **Assuming simple Stokes settling (Model 1), the particles in the upper size ranges are removed too rapidly.**
- **A good match is obtained if a uniform upward velocity is added to the calculated Stokes settling velocities.**

Fraction of dust particles removed from SAL during atmospheric transport as a function of particle size.

''Measurements'' - estimate of the change in dust size distribution that takes place between west coast of North Africa and 5000 km west at Puerto Rico (solid line with standard deviation).

''Model 1'' - particle removal by Stokes gravitational settling alone after 5.5 days of atmospheric transport (solid line).

''Model 2''- particle removal by gravitational settling minus an upward velocity of 0.33 cm s^{-1} after 5.5 days of atmospheric transport (dashed line). [Maring et al., 2003]

Conclusions

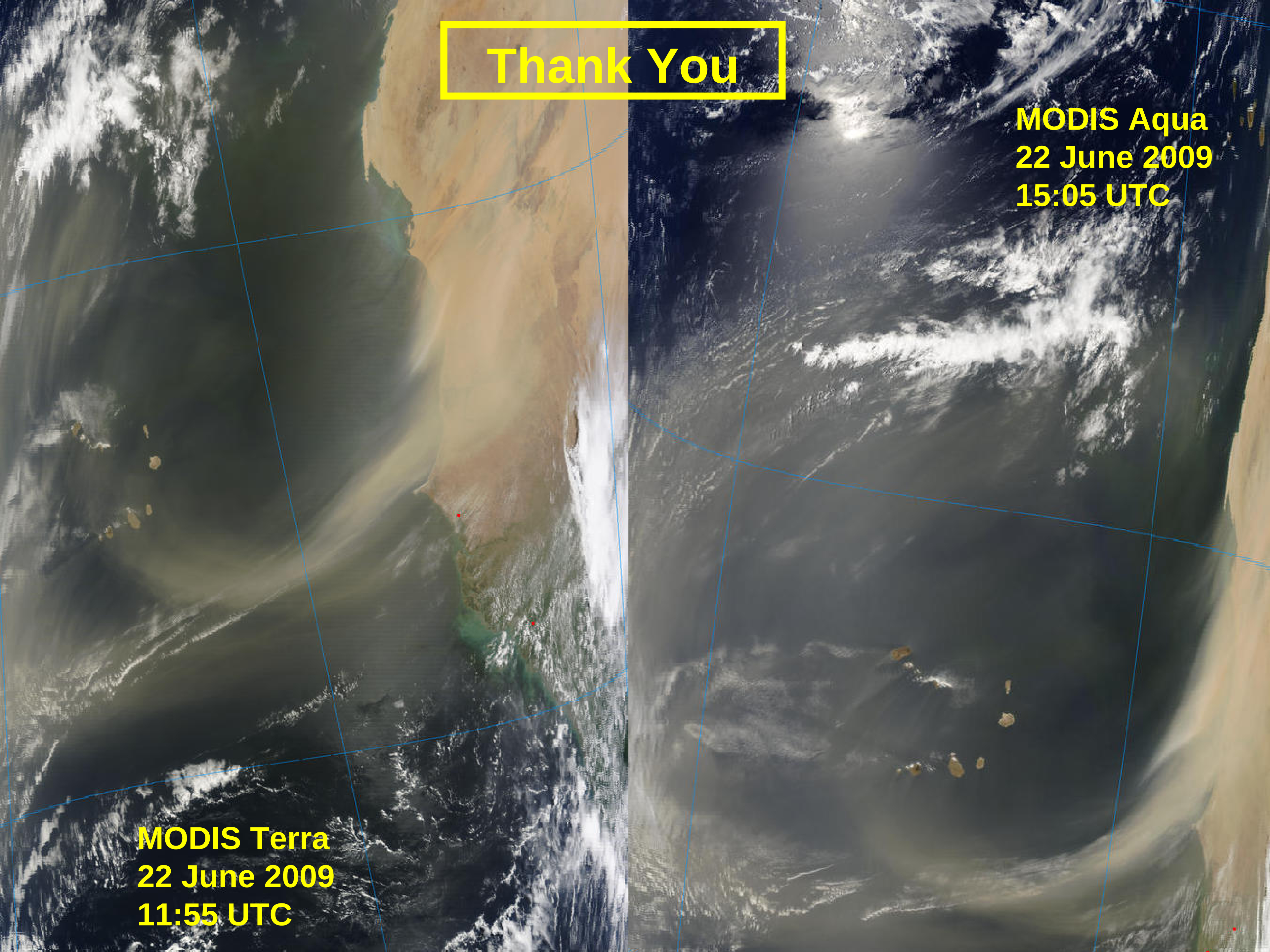
We need more research on the processes that control dust (and other aerosol) transport over the central and western North Atlantic – especially on the relative importance of wet and dry removal processes.

Dust models should focus on particle size ranges that would be sensitive to size changes observed (or not observed) here.

We need greater cooperation between the ocean and atmospheric communities if we are to understand the processes that affect dust transport and deposition to the ocean and how these processes might change in the future with changing climate.

Caveat! All measurements presented here were made in summer in the tropical North Atlantic! There is essentially no data from the South Atlantic where we know huge amounts of dust and smoke are transported in boreal winter.

Thank You


MODIS Aqua
22 June 2009
15:05 UTC
MODIS Terra
22 June 2009
11:55 UTC

Summary: Particle Physical Properties and Long Range Transport

The physical properties of dust transported across the Atlantic are remarkably uniform.

The uniformity of size distribution in the vertical suggests that Stokes settling is not a major factor in redistributing dust.

The uniformity of size across the Atlantic suggests that that the removal processes acting on the dust are NOT strongly size dependent. Suggests that wet deposition is dominant over dry.

The uniformity of size from event-to-event suggests that dust events do not carry a strong signal of source soil particle size properties or dust generating/transport processes that might affect size distributions. (Caveats!)

The presence of persistent (long-lived, long-traveled) dust layers presents a challenge to our understanding of long range transport.

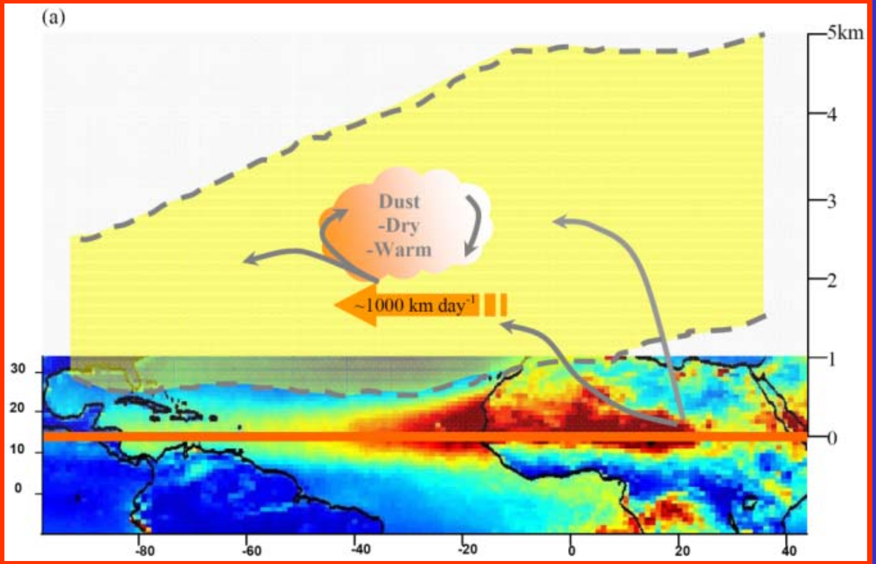

Thank You

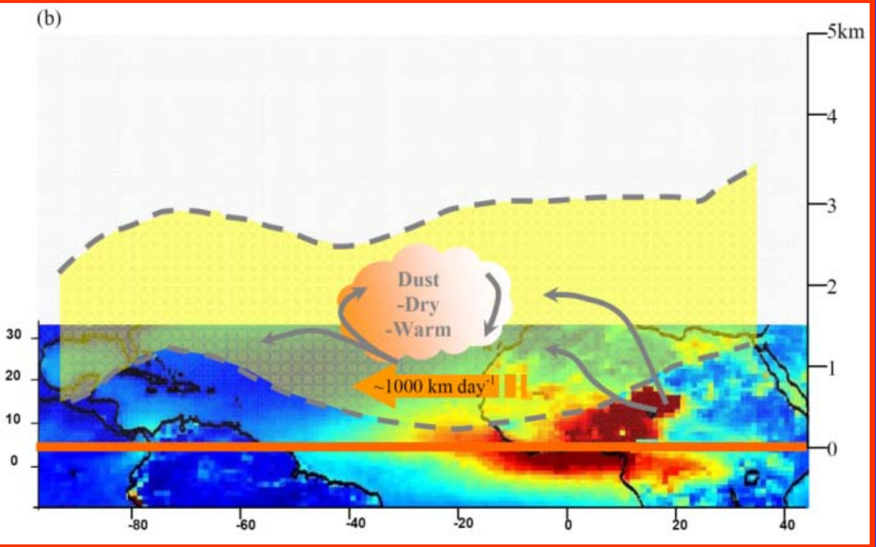
What About Winter - Spring Dust?

A huge quantity of dust and biomass burning products is transported across the equatorial Atlantic from Africa during boreal winter and spring.

There are no aerosol-focused measurements from this region except for an occasional ship cruise.

The source processes over Africa and the transport dynamics over the Atlantic are markedly different in Winter compared to Summer.





African Dust Outbreaks: Temporal and Spatial Variability over the Tropical Atlantic Ocean

J. Huang, C. Zhang, J. M. Prospero. Submitted JGR May 09

Deposition Processes

What do we know about atmospheric dust deposition processes and how can we improve our knowledge about them?

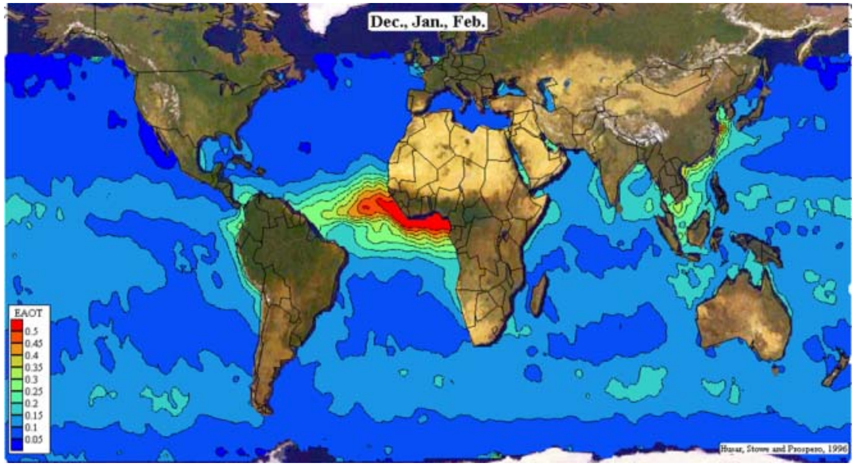
Given the importance of Fe in ocean biogeochemistry, what aerosol properties should we measure and where should we measure them?

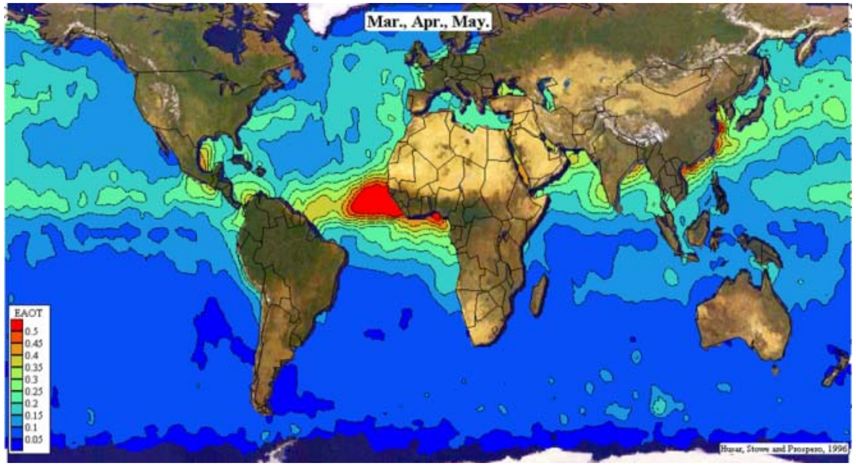
I make the case that greater cooperation is needed between the ocean communities and the atmospheric communities if we are to understand the processes that affect ocean deposition and how this might change in the future with changing climate.

Finally

A huge quantity of dust and biomass burning products is transported across the equatorial Atlantic from Africa during boreal winter and spring.

There are no aerosol-focused measurements from this region except for an occasional ship cruise.





Is African Dust Hygroscopic?
If so, How Does it Respond to RH Changes?

Answer: 1. Very little and 2. Not much.

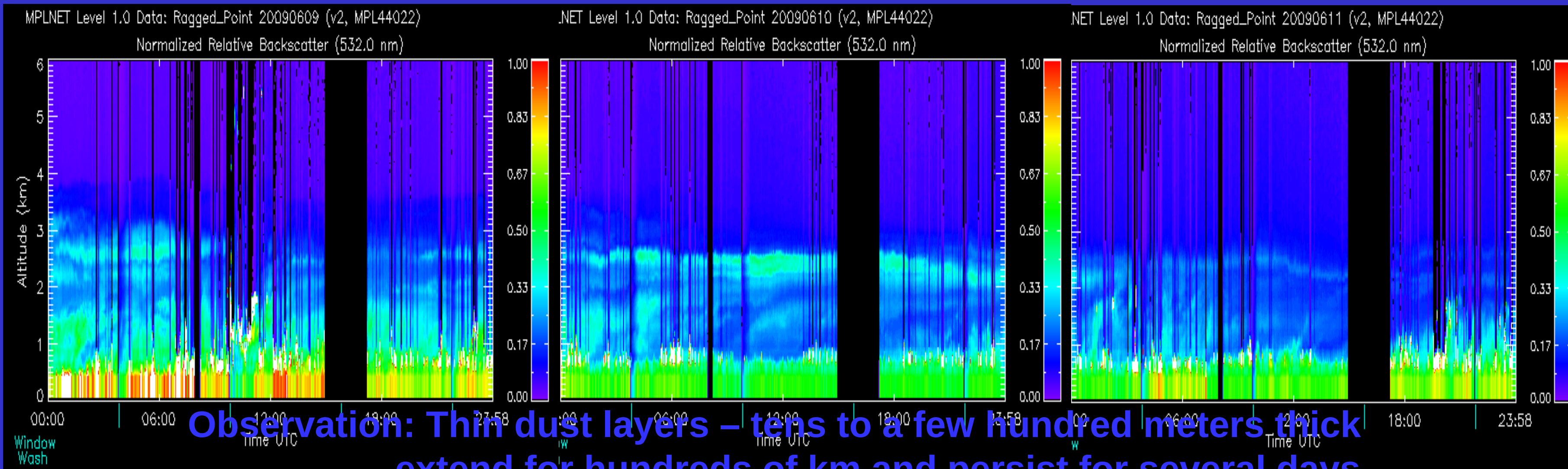
PRIDE: the Volume Median Diameters (VMDs) of dust aerosols at high relative humidity in the MBL were statistically indistinguishable from the VMDs of dust particles at low relative humidity in the SAL. Thus it appears that dust particles over the TNAO and Caribbean do not change size significantly due to the absorption of water up to a relative humidity of 97%. [Maring et al. 2003]

- Has implications for aerosol chemistry re surface processes

Barbados: We obtained the same result in a surface-level field experiment at our tower site in 1994

Li, X., et al. (1996), *Dominance of mineral dust in aerosol light-scattering in the North Atlantic trade winds, Nature*, 380(6573), 416-419.

How can we explain the existence and persistence of thin dust layers in the SAL over the Western Atlantic?



Observation: Thin dust layers – tens to a few hundred meters thick – extend for hundreds of km and persist for several days.

Convection would quickly dissipate any such layering.

What about aerosol heating? The SAL is neutrally stable.
- Any significant heating would lead to internal mixing.

Suppressed condition under SAL dust events. Only small Cu.

What is the role of mixing in Easterly Waves and Tropical Cyclones?

For the most part, isolated clouds are not mixing dust from deep within the SAL to the surface.

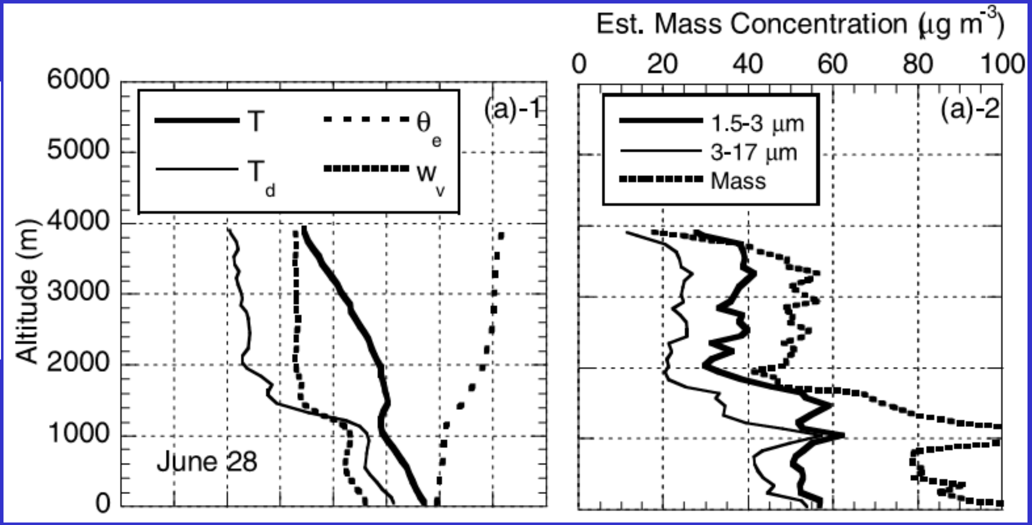
AERONET Sun Photometer at Barbados

Few towers penetrate the SAL

SAL suppresses convection

What is the origin of the dust in the MBL over the Western Atlantic?

Observation: In summer in the presence of the SAL, there is always some dust in the MBL. On some days there is more dust in the MBL than in the SAL (example at right).



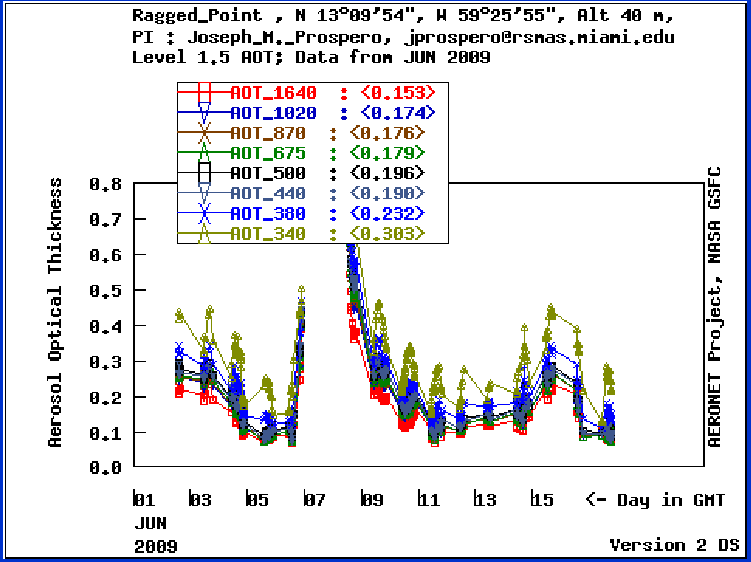
The particle size measurements argue that Stokes settling is not significant.

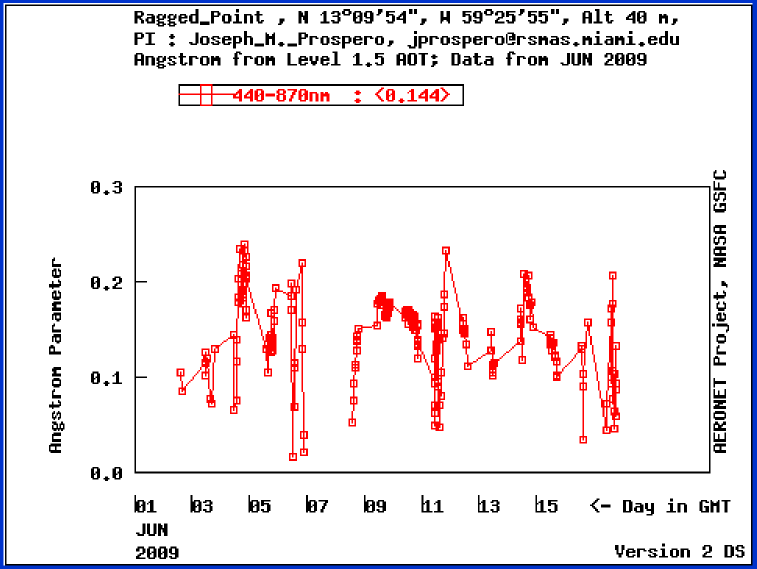
Deep clouds are not mixing dust from deep within the SAL to the surface. If they were, we would see moistening of the SAL.

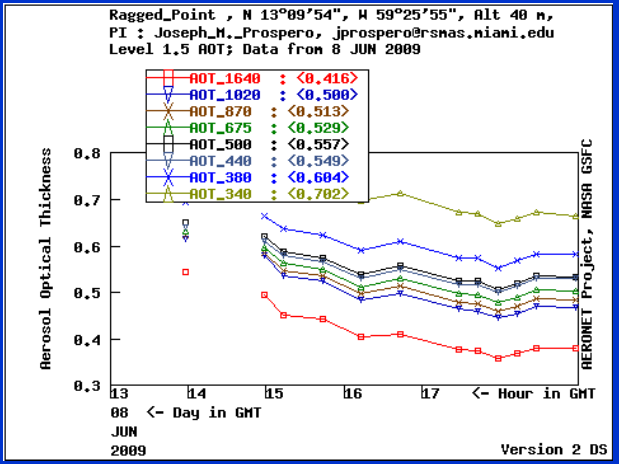
But smaller Isolated clouds could be playing a role along with entrainment at the base of the SAL.

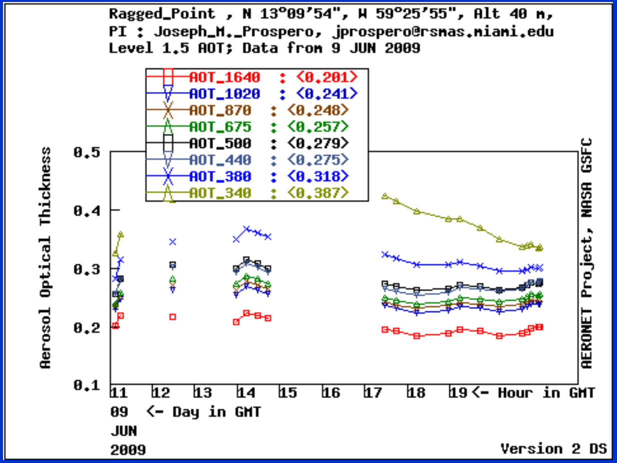
If dust passes through the trade inversion into the CBL, clouds would mix the dust and transport it into the MBL much more rapidly than gravitational settling.

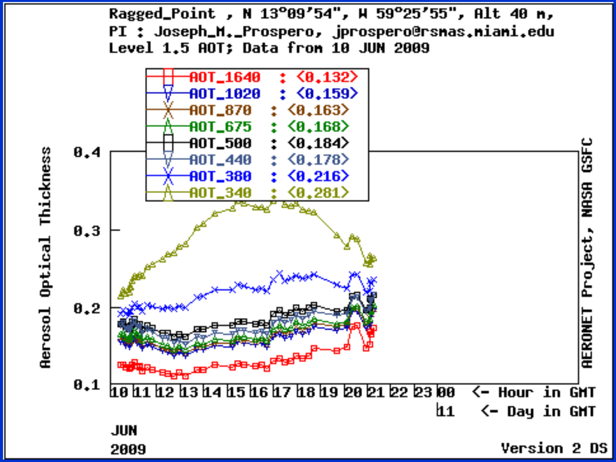
AERONET Aerosol Optical Thickness Barbados 8 - 10 June 2009











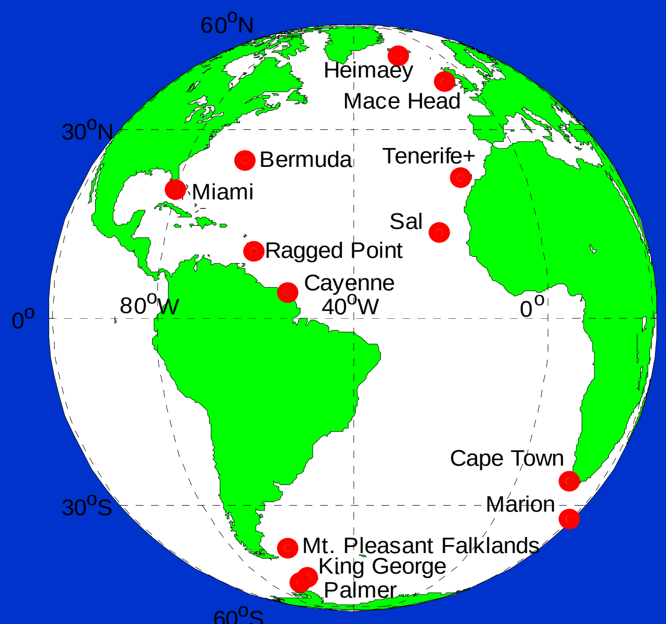
NOAA SAL Flight: Sept. 27, 2005

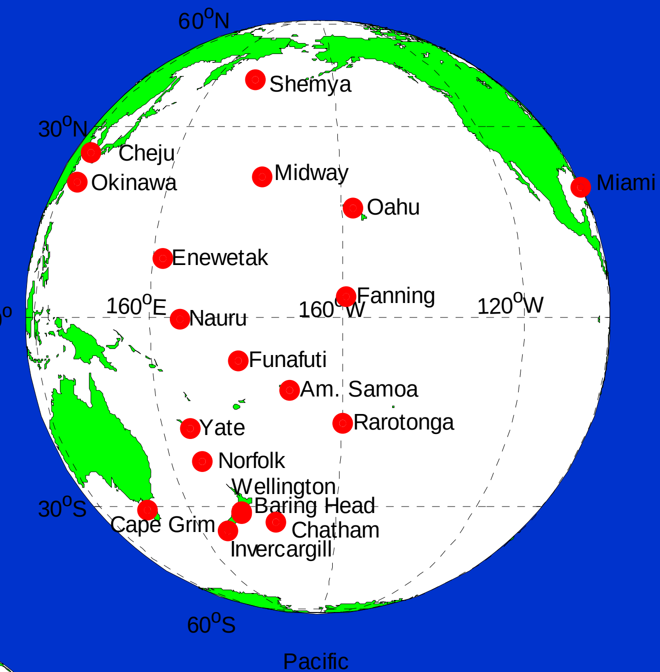
- **Photos taken from the NOAA G-IV jet on 27 September 2005 from ~45,000 ft in the central Atlantic at ~14°N 35°W [Dason Dunion, NOAA HRD]**

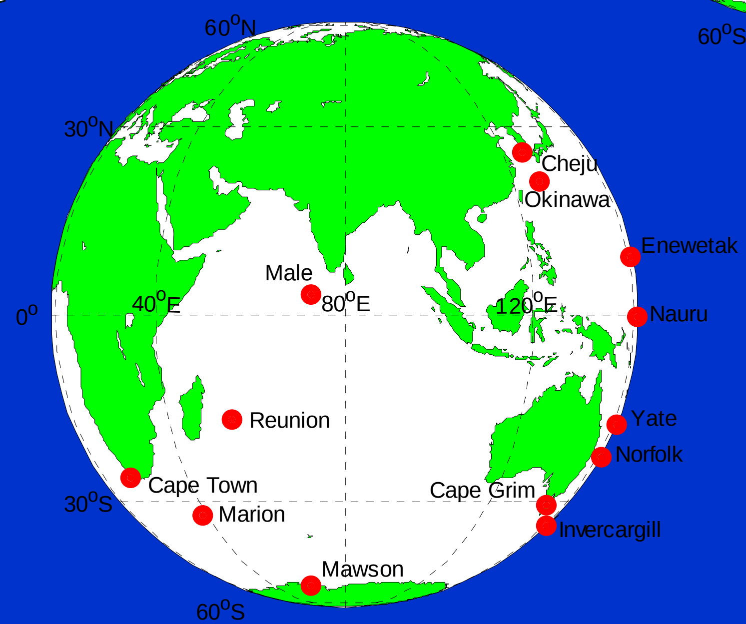
- http://www.aoml.noaa.gov/hrd/Storm_pages/salex2005/20050927N1.html

J.M.Prospero/U.Miami

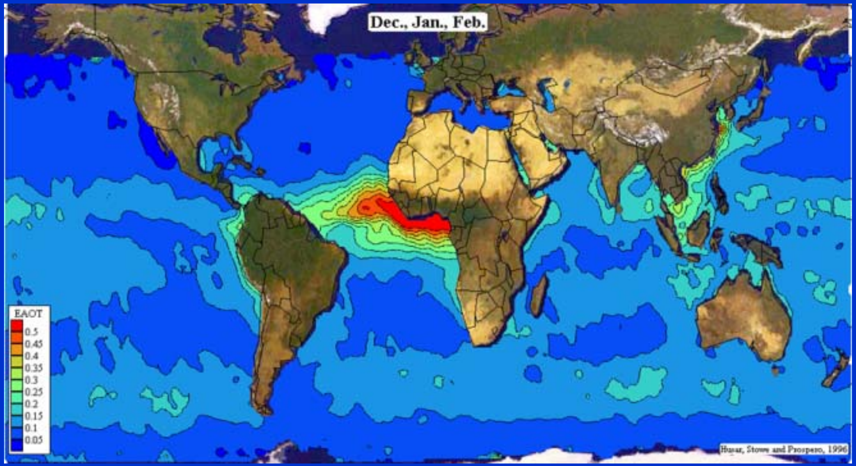
University of Miami Global Ocean Networks: Early 1980s - Late 1990s



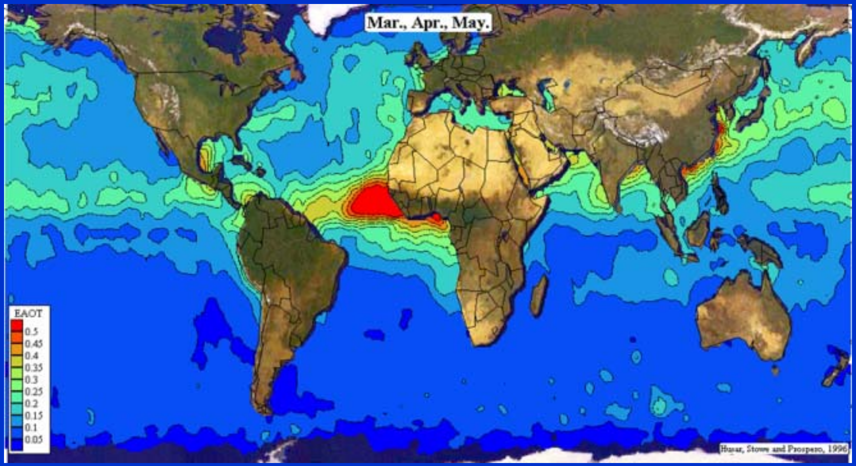




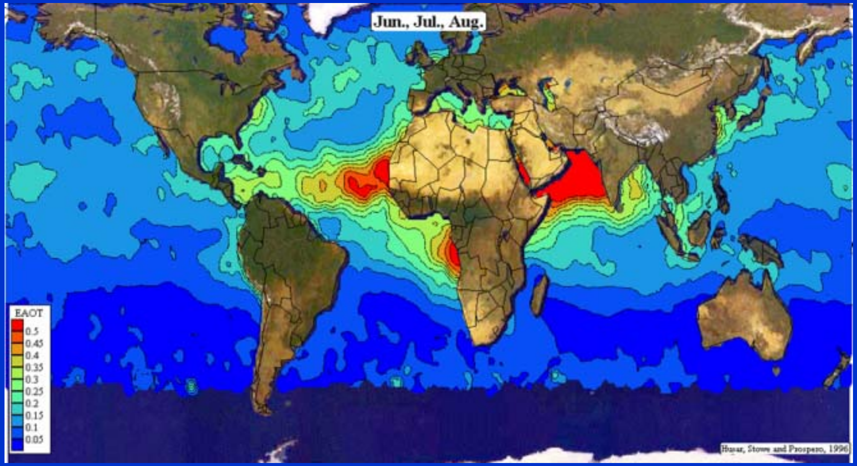
TEXT



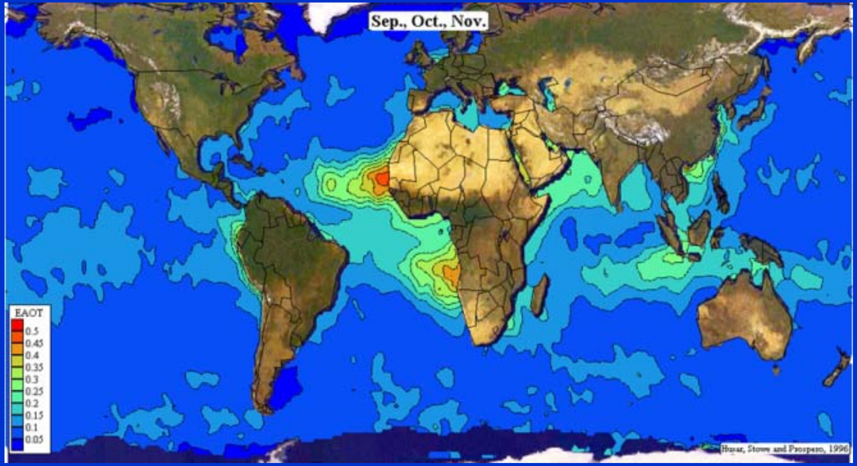
Dec., Jan., Feb.
EAOT
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Husar, Stowe and Prospero, 1996



Mar., Apr., May.
EAOT
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Husar, Stowe and Prospero, 1996



Jun., Jul., Aug.
EAOT
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Husar, Stowe and Prospero, 1996



Sep., Oct., Nov.
EAOT
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Husar, Stowe and Prospero, 1996

The Intercontinental Tracking of a Dust Outbreak Relationship to Easterly Waves & Dust Model

Movement of Wave Axis, Dust Pulse, Warm Center and Axis of Mid-Level Jet: 1 to 13 July 1979

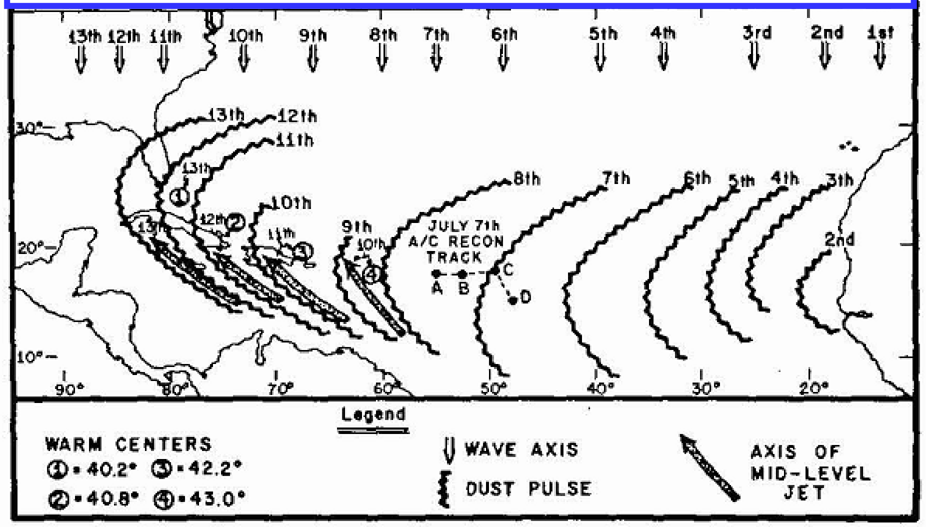


FIG. 14. Continuity chart showing the progress of the axis of an African wave disturbance and the leading edge of the dust plume over the period 1-13 July 1970. The positions of the easterly wind maximum in the Saharan air and the centers of maximum potential temperature are shown for the period 10-14 July. The location of the leading edge of the dust plume during the period 8-13 July was determined on the basis of where Saharan air could be found on the temperature soundings.

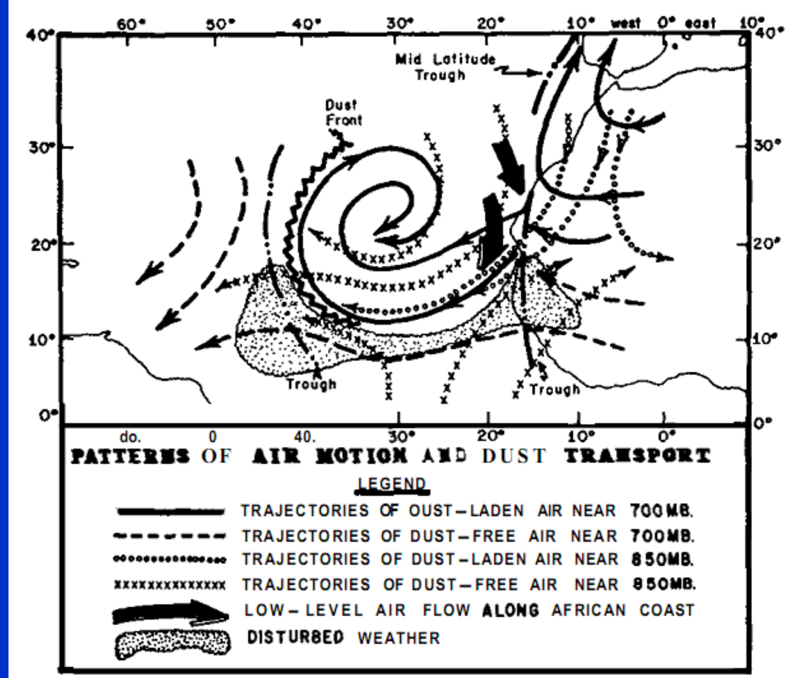


Fig. 20. Schematic model of air motions accompanying the movement of African disturbances and the associated dust pulses from Africa.

Schematic "model" of the Saharan Air Layer (SAL)

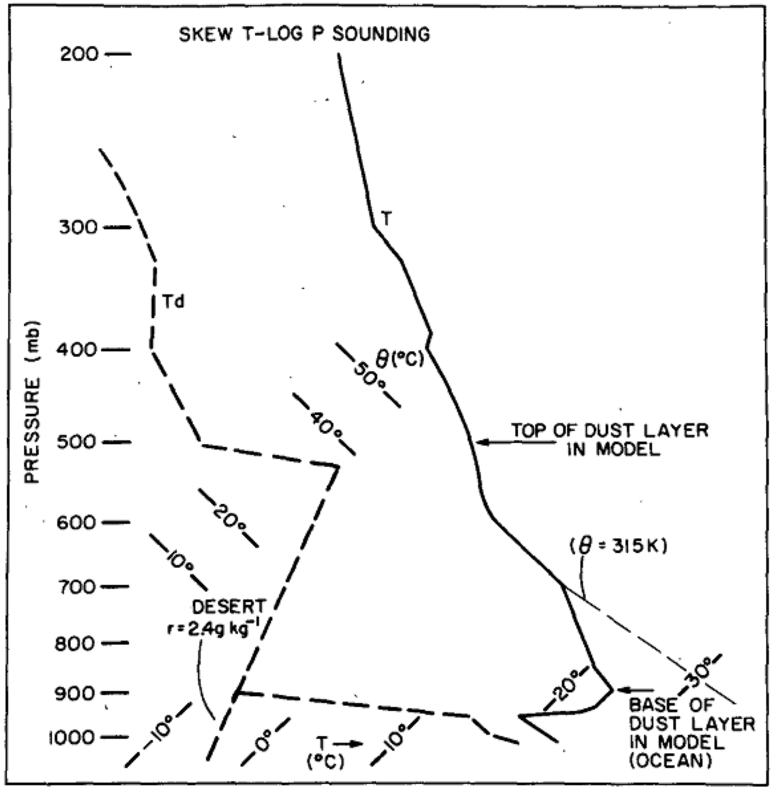


FIG. 2. Vertical temperature (T) and dew point (T_d) sounding on skew $T-\log P$ diagram for Saharan air layer sounding over ocean (heavy solid and dashed lines) and over the desert (thin solid and dashed lines, where different from ocean). The top of the dust layer is considered to be at 500 mb. The dashed lines $\theta = 315$ K and $r = 2.4$ g kg^{-1} represent the constant potential temperature (θ) and mixing ratio (r) for the desert case.

Carlson, T. N., and J. M. Prospero (1972), The Large-Scale Movement of Saharan Air Outbreaks over the Northern Equatorial Atlantic, *Journal of Applied Meteorology, 11(2), 283-297.*

A Model for African Dust Outbreaks

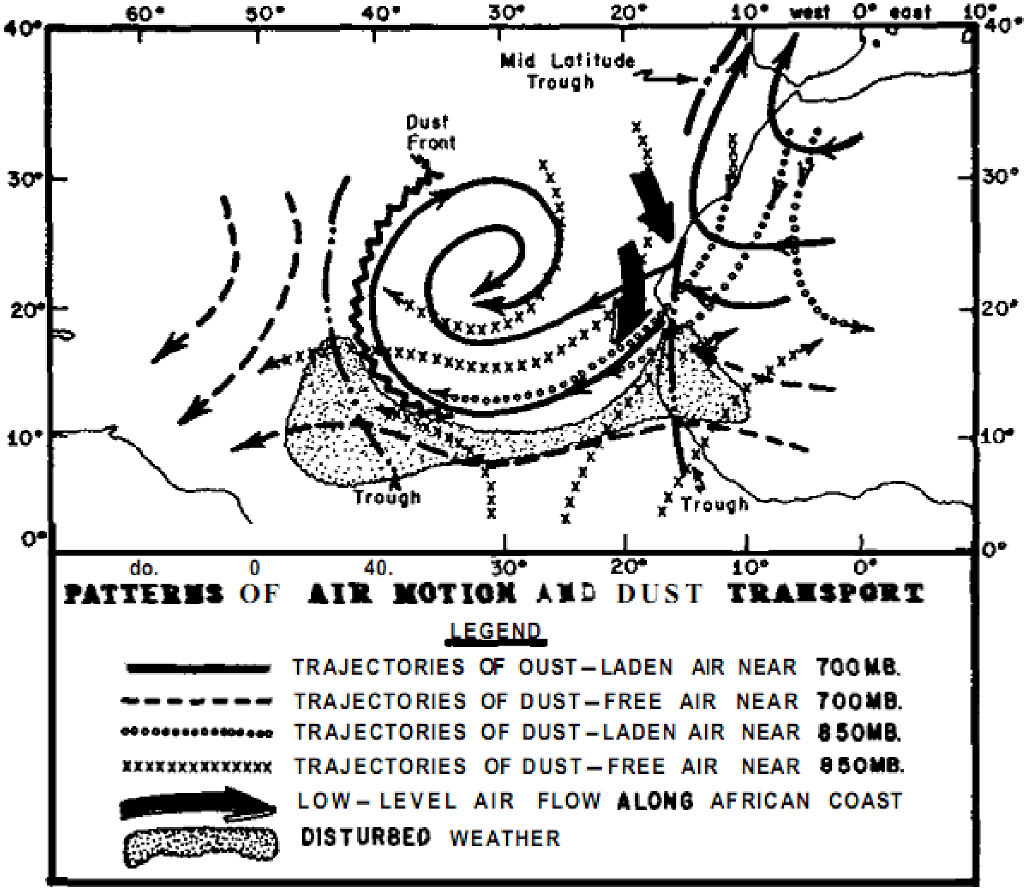
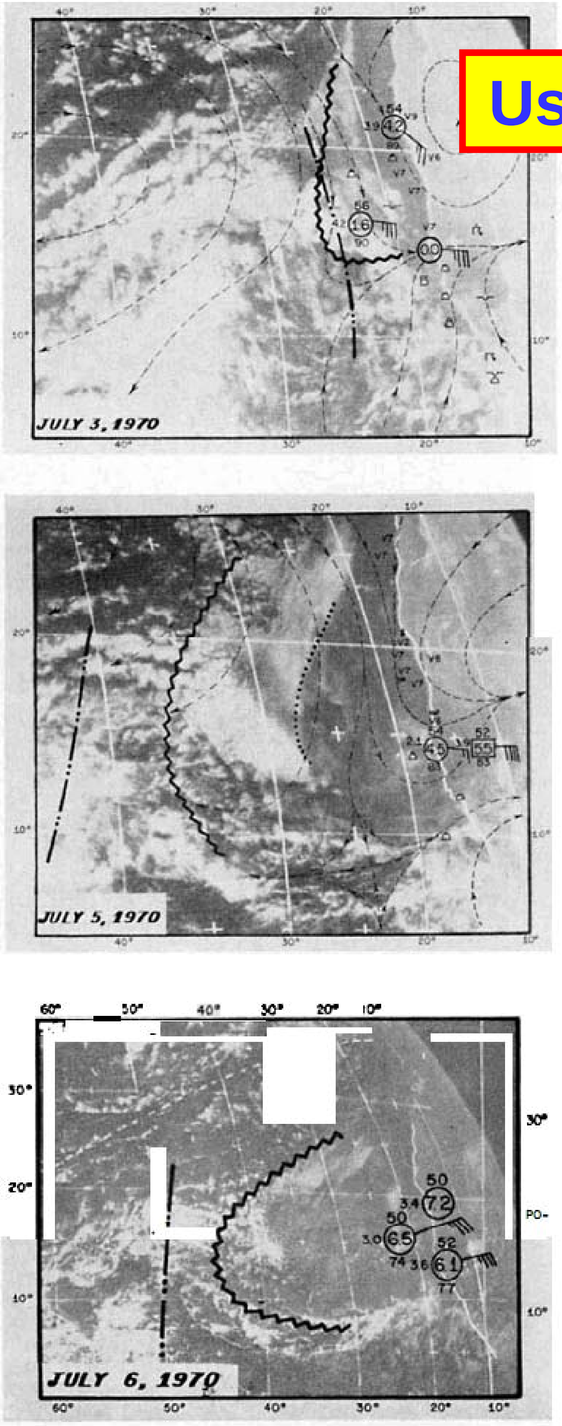


Fig. 20. Schematic model of air motions accompanying the movement of African disturbances and the associated dust pulses from Africa.

Carlson, T. N., and J. M. Prospero (1972), The Large-Scale Movement of Saharan Air Outbreaks over the Northern Equatorial Atlantic, *Journal of Applied Meteorology, 11(2), 283-297.*

Using Satellite Images to Study Dust Events

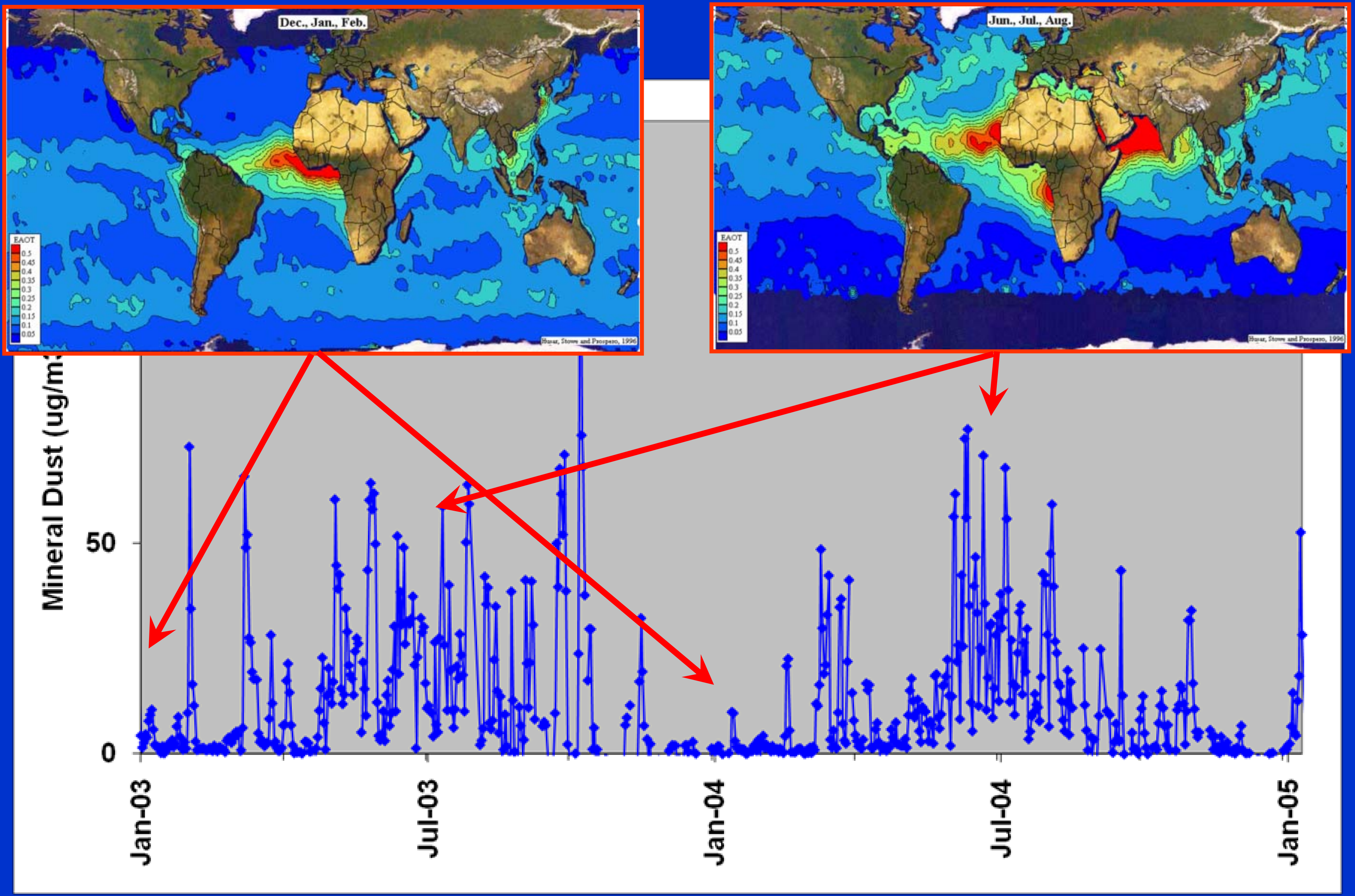
Carlson, T. N., and J. M. Prospero (1972) ***The Large-Scale Movement of Saharan Air Outbreaks over the Northern Equatorial Atlantic, Journal of Applied Meteorology, 11(2), 283-297.***



One of the first papers to attempt to use satellite images to understand the long-range transport of aerosols and the relationship to metrological features.

FIG. 13. ATS-111 satellite photographs of the equatorial Atlantic for 3 (a), 5 (b) and 6 (c) July 1970. In 13b the serrated edge marks the leading edge of the cloud discontinuity and the dotted line indicates the edge of the clear area, while 13c shows the larger view of the advancing cloud discontinuity.

Barbados Daily Dust Concentrations: 2003 - 2004



Yet there has been remarkably little research of dust transport over this ocean region in the sense of physical measurements of dust aerosols and the meteorological processes associated with the dust transport.

But there has been nothing over the central Atlantic.

Over the western Atlantic, the history can be briefly summarized.

The absence of research is remarkable considering all the papers that have been written on the dust impact on radiation, precipitation, ocean deposition.

Dust suppressing TC development.

Dust through radiative processes increasing atmospheric stability, suppressing convection.

Reduction of insolation at ocean surface.

Proposal to modify hurricanes by seeding TCs - based on model studies in the absence of ANY aerosol measurement in TC environments.

The North Atlantic is ocean region that is most heavily and persistently impacted by dust transport.

There are many satellite products that show this.

Models show this.

Yet there has been remarkably little research of dust transport over this ocean region in the sense of physical measurements of dust aerosols and the meteorological processes associated with the dust transport.

There has been extensive research on dust and other aerosols over the eastern Atlantic in ACE-2 (although dust was NOT a focus) and more recently, and much more intensively in the AMMA program.

But there has been nothing over the central Atlantic (except Albrecht-Huebert which was not dust focused).

Over the western Atlantic, the history can be briefly summarized.

BOMEX in 1969 (papers by Carlson and Prospero.

Then a thirty year gap to PRIDE.

The absence of research is remarkable considering all the papers that have been written on the dust impact on radiation, precipitation, ocean deposition. Dust suppressing TC development. Dust through radiative processes increasing atmospheric stability, suppressing convection. Reduction of insolation at ocean surface. Proposal to modify hurricanes by seeding TCs - based on model studies in the absence of ANY aerosol measurement in TC environments.