Dust estimation via the triple window IR technique (8.7µm, 10.8µm, 12.0µm)

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Satellite remote sensing of mineral dust

Dust estimation via infrared

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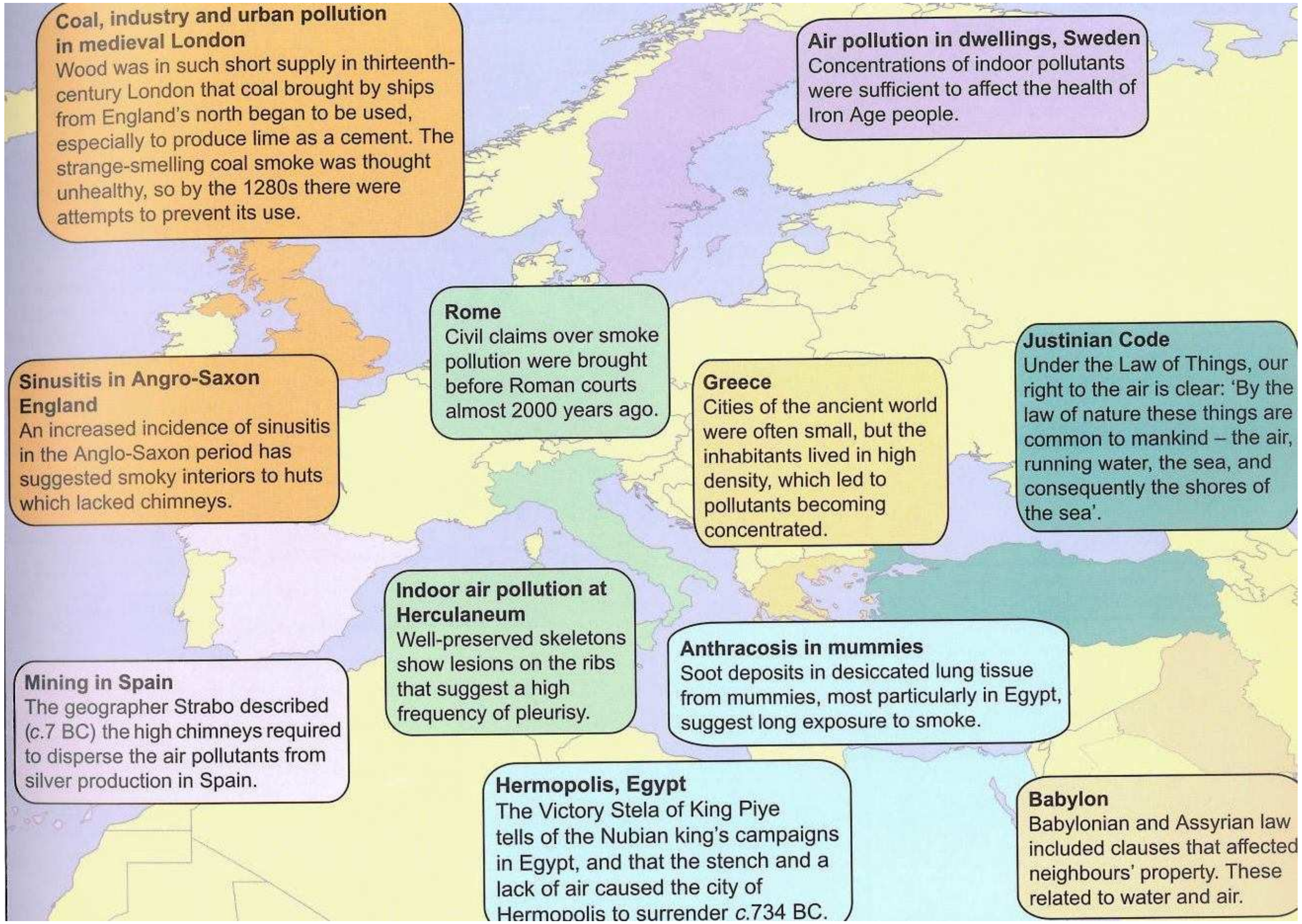
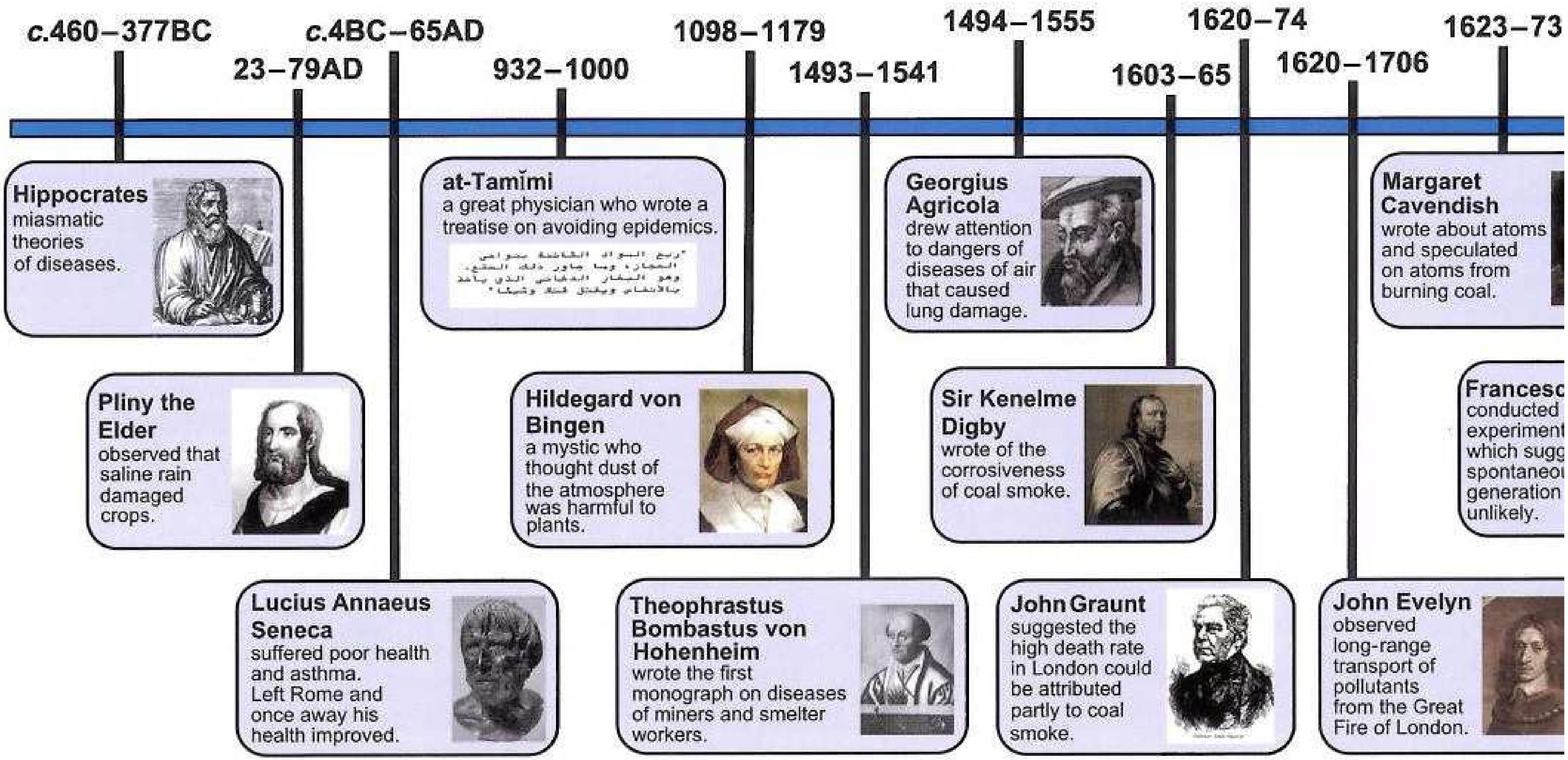
Early reports on dust



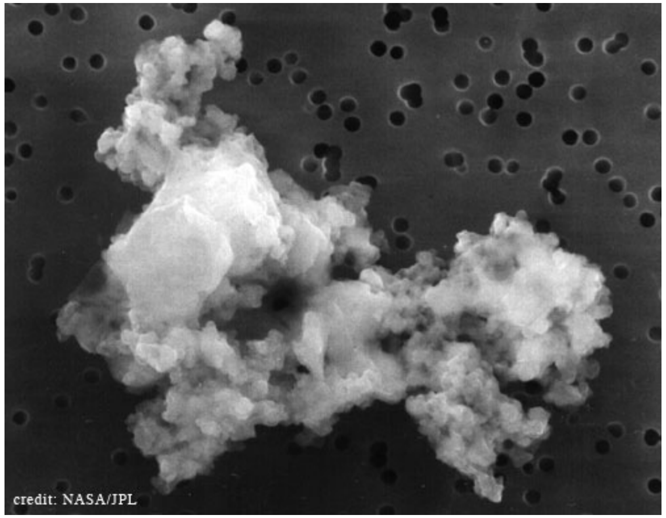
World Atlas of Atmospheric Pollution. Editor: R. S. Sokhi

... and on health



World Atlas of Atmospheric Pollution. Editor: R. S. Sokhi

Is air dust important?



← Dust particle 12 µm →

← Earth globe 12 Mm →

Connection:

-12 orders of magnitude difference in size
-10^12 kg in the atmosphere (10^-7 of atmospheric mass)
- Climate
- Atmospheric circulation
- Life ?
- Dostojewski: “Love both, small and big!”

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Optimal dust detection with the infrared?

Best contrast ?	DAY	NIGHT
IR		
VIS		

Click one of the four fields, the one with best contrast free-surface/dust-storm

Ocean	DAY	NIGHT
IR	good	good
VIS	good	A/N/A

Desert	DAY	NIGHT
IR	good	bad
VIS	bad	A/N/A

- On IR imagery, dusty air appears cool in contrast to the hot **daytime** land surface. At **night**, the thermal difference between the background and the dust lessens.
- On VIS imagery over **water**, dust is easy to note. Over **land**, however, the dust plume and the surface look similar

Consecutive days in Fuerteventura, January 2010

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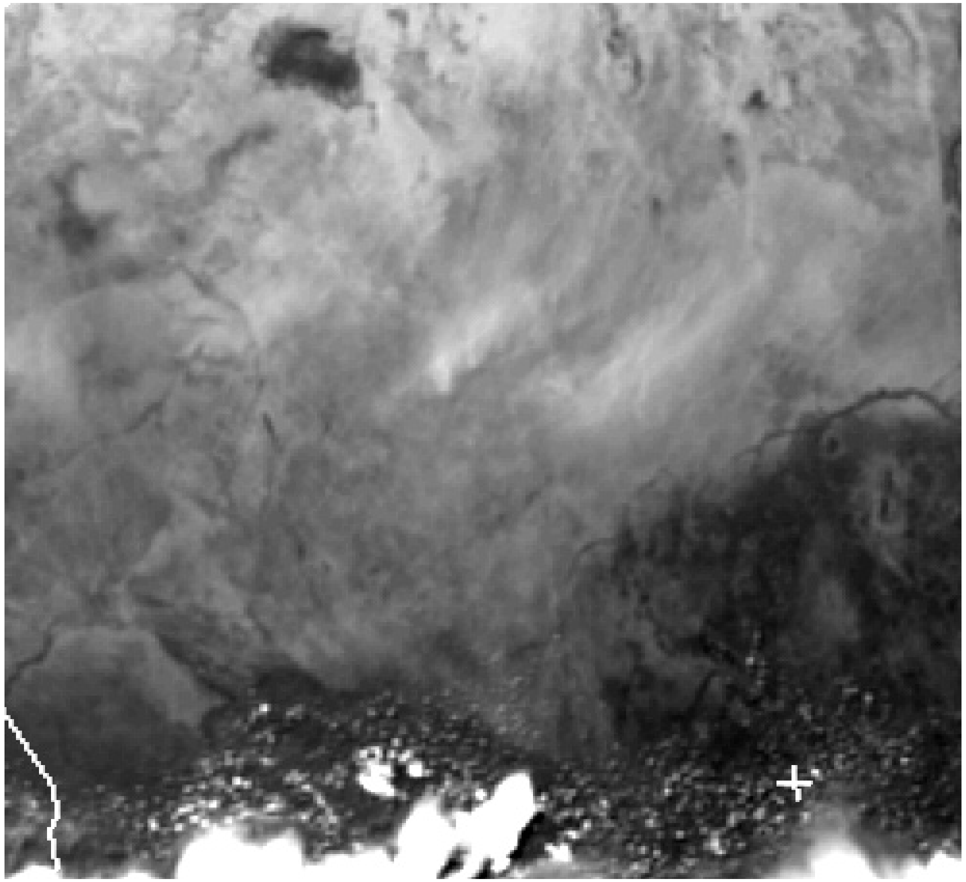
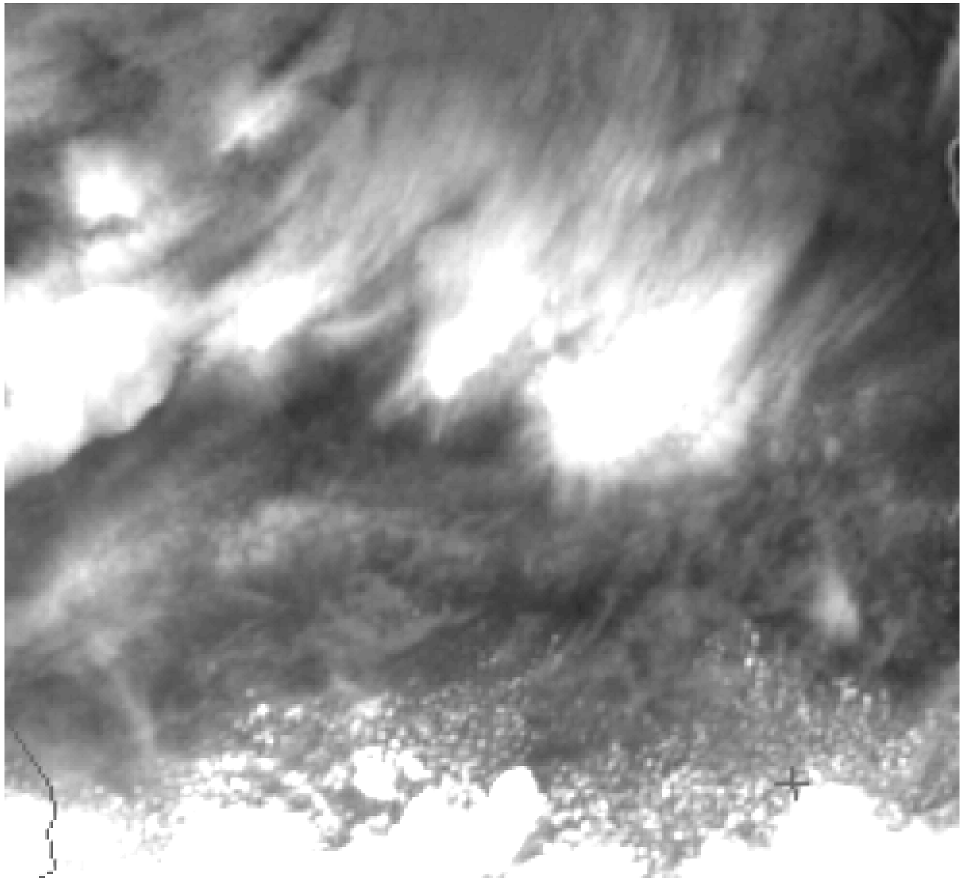
Dust on visible and infrared

•Disputed contribution to global cooling (S.K. Satheesh, 2006)



2004-05-13 13:00 UTC, 0.8 μm

•Dust **reflects** back solar energy to space



Same date-time, 10.8 μm

•Dusty air rises and **cools** down

Desert scene, Southern Sudan

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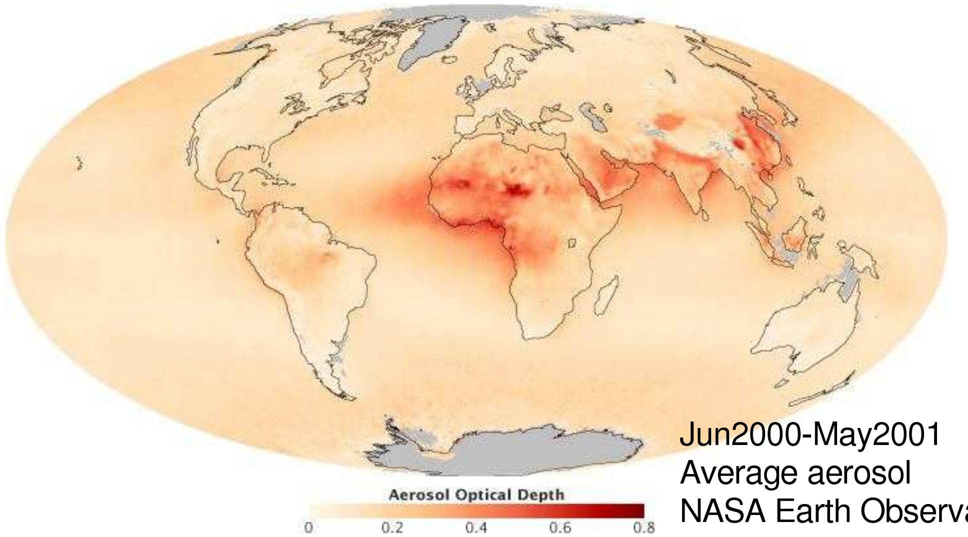
Contents

- Dust characteristics
- Display techniques
- Inter-channel comparisons: plots
- Radiation transfer concepts
- Graphical retrieval
- Value added by 8.7 µm
- Conclusions



Jun2000-May2001
Average aerosol
NASA Earth Observatory

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Characteristics

- Dust storms occasionally reach 5 km **height**, frequently thicker than 1km

- Dust optical depth around 0.5 (average on land) or 5 for storms, in the visible range. Optical **thickness** in the IR is about 40% of those values.

- TOMS Absorbing Aerosol Index (0-4) roughly equivalent of AOT (0-2)

- Aerosol **density** average in the atmosphere 10^-7 kg/m3 (equivalent of depth 0.1)

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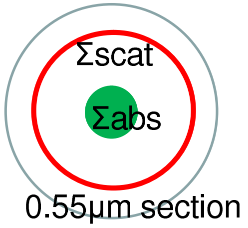
Characteristics

- Particle concentration for dust **storms** is about 5*10^8 /m3, similar to cloud
- Not understood transportation of sand particles (>60µm) beyond 1000km
- n=1.53 + i * 0.008 in the visible range (similar to droplets), **higher absorption** in the IR
- Dust **size** is tri-modal around 0.1 µm, 2 µm (marine salt), 40 µm (dust storm)
- Dust absorbs and scatters **infrared** radiation in the **Mie** range



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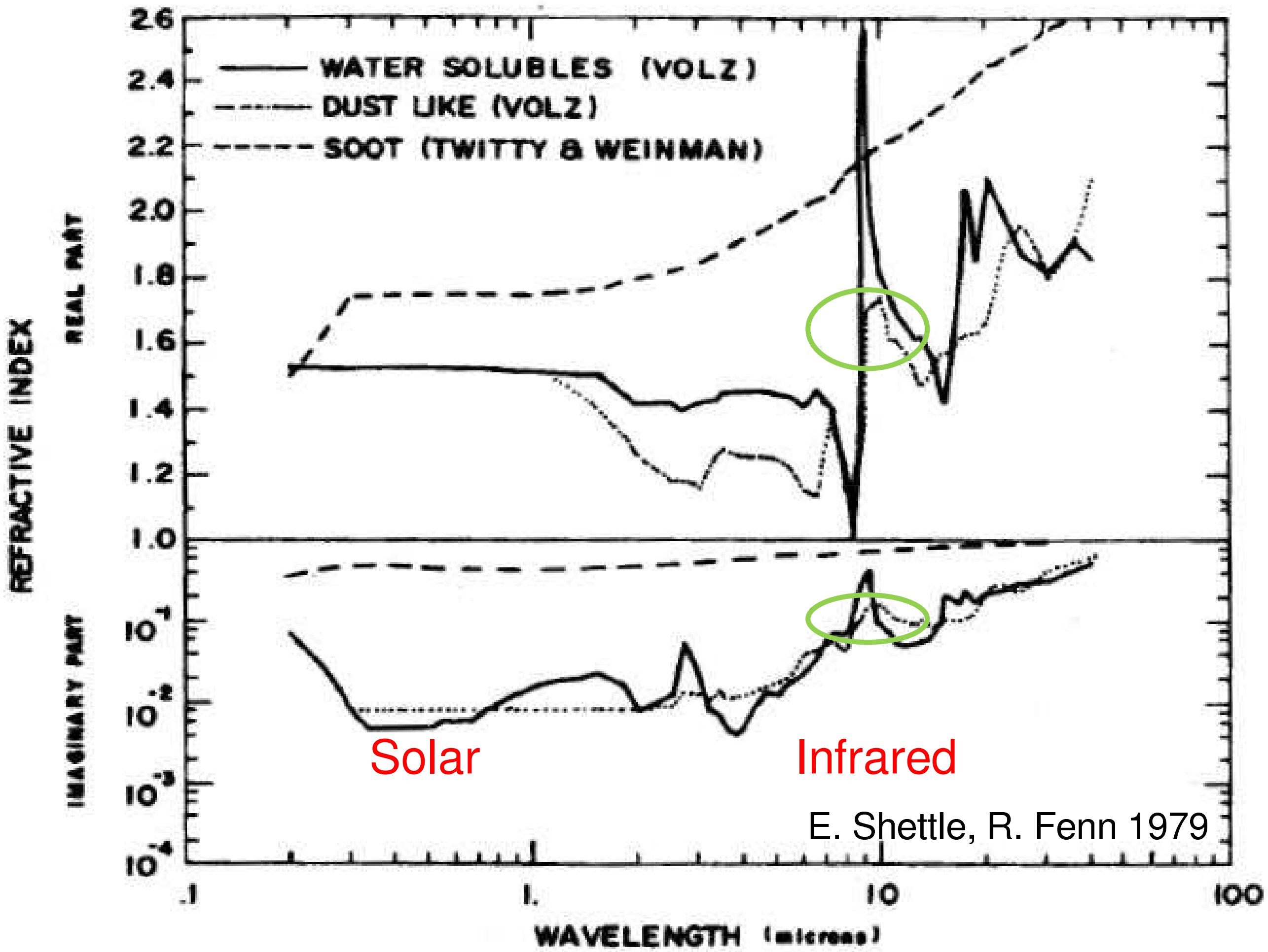
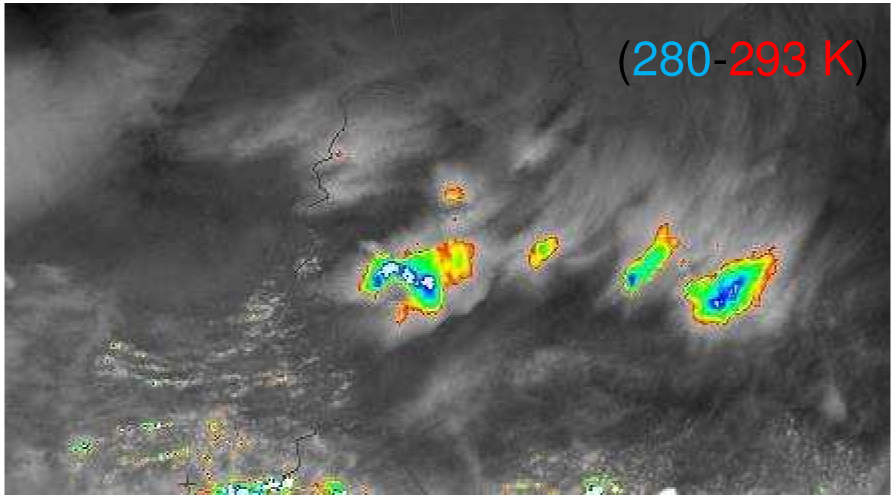
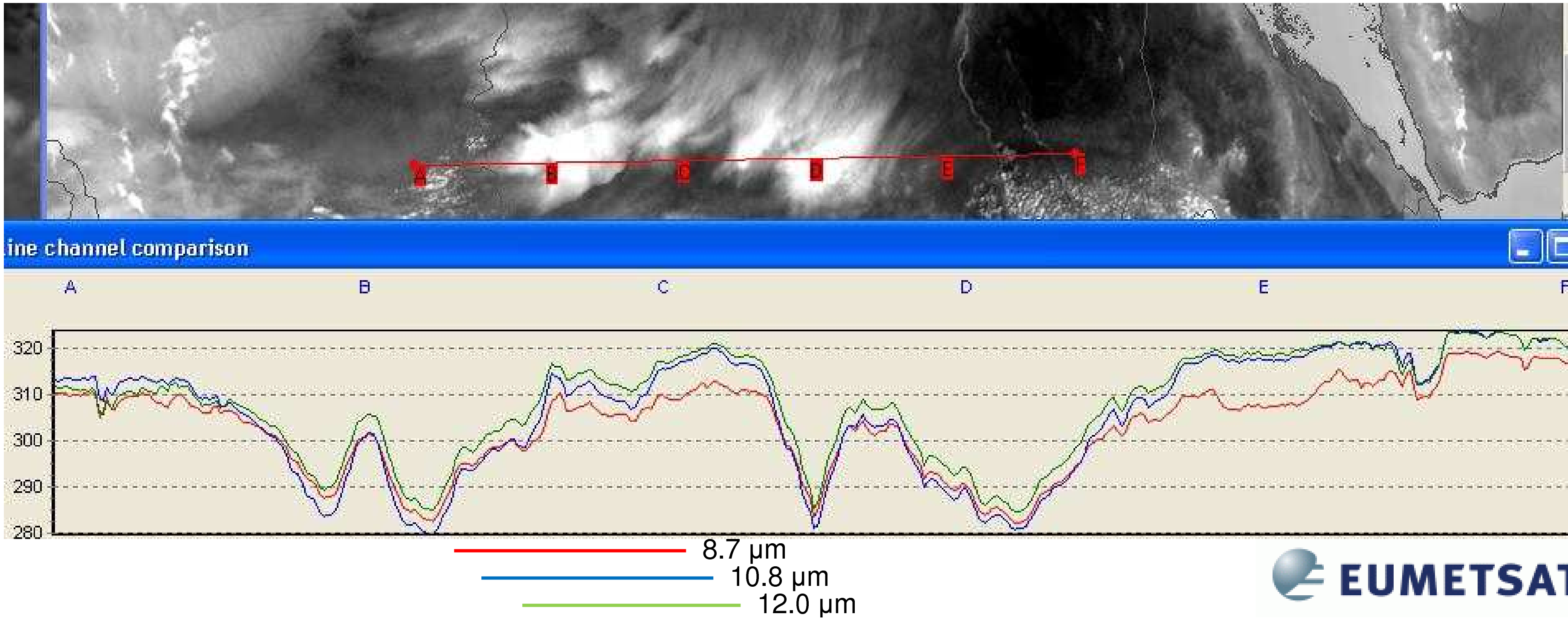
Characteristics

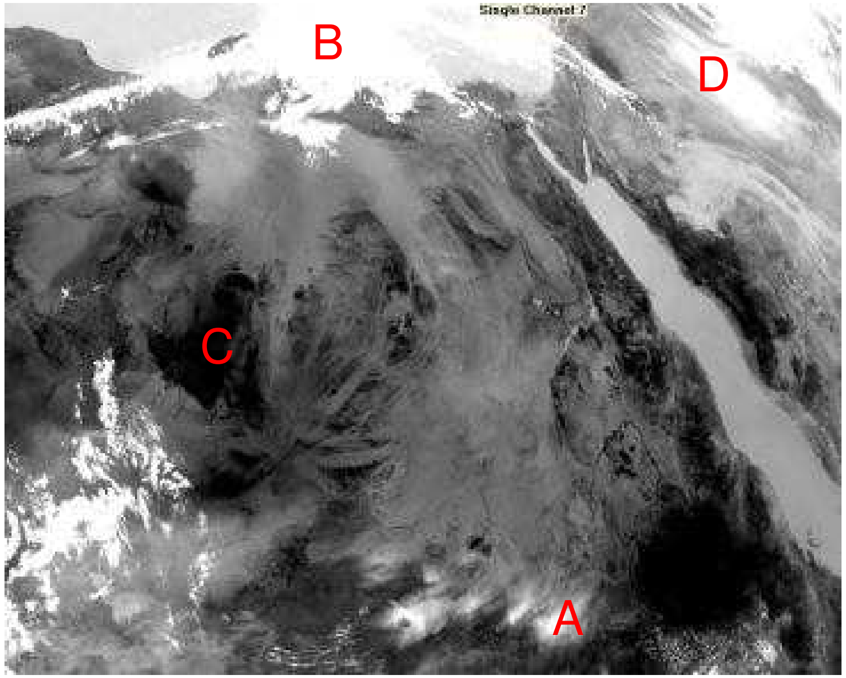


Dust enhancement in a single IR channel   !?



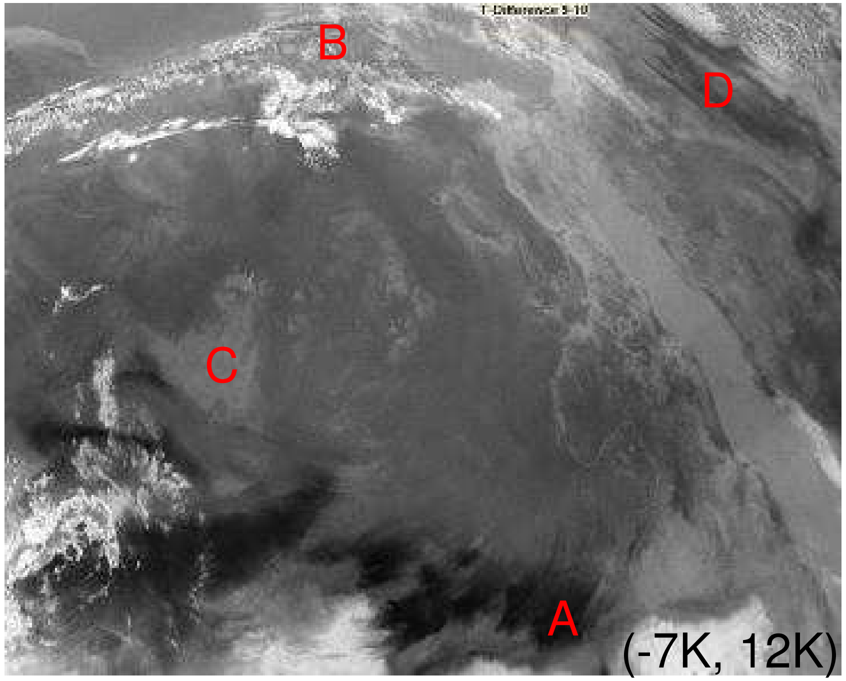
2004 May 13th 13:00 Meteosat **10.8µm**
colour-enhanced (left) and gray-enhanced (below)



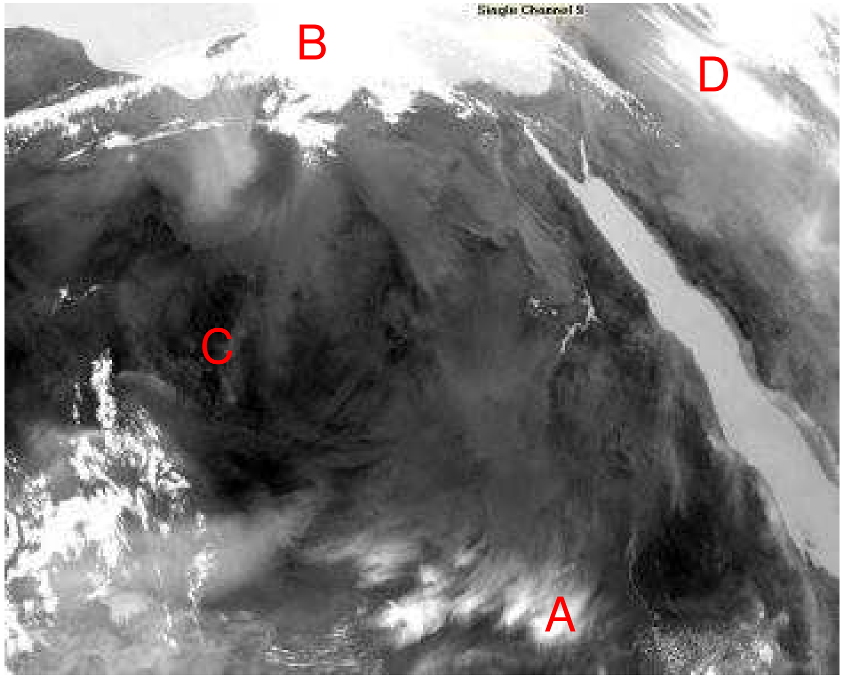


7

9-10

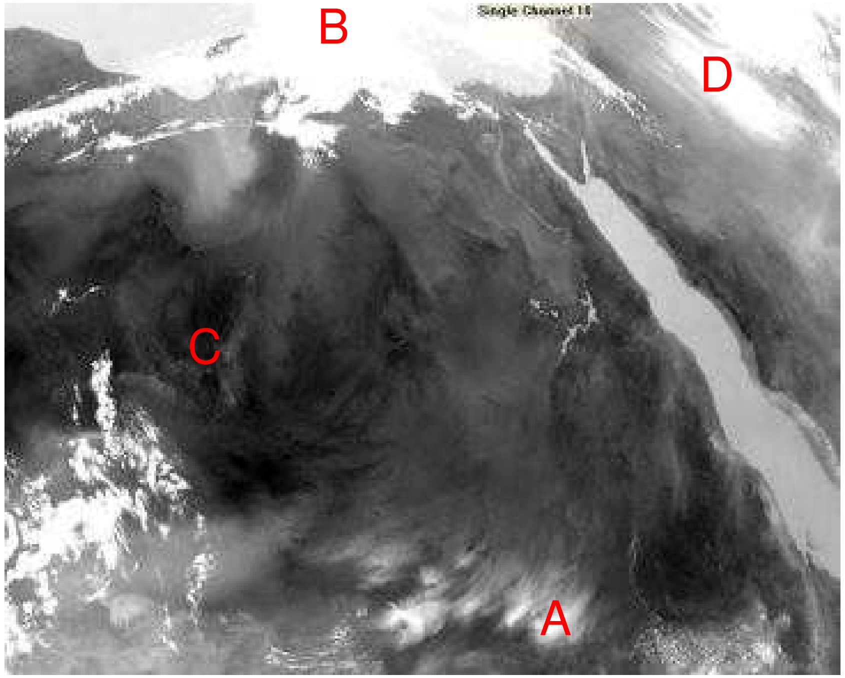


Single channel comparison and Ch9-Ch10 difference (*upper right*)

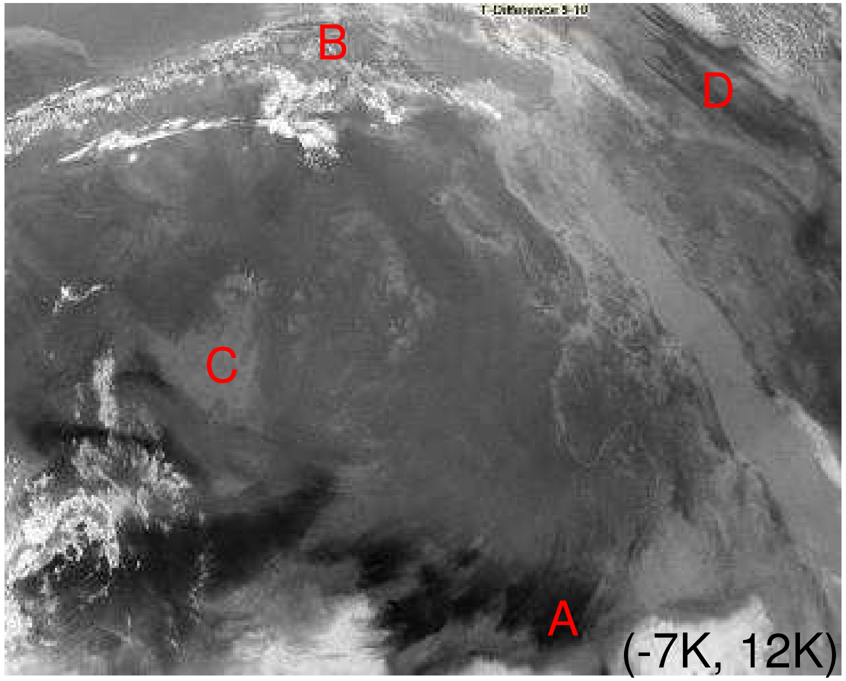


9

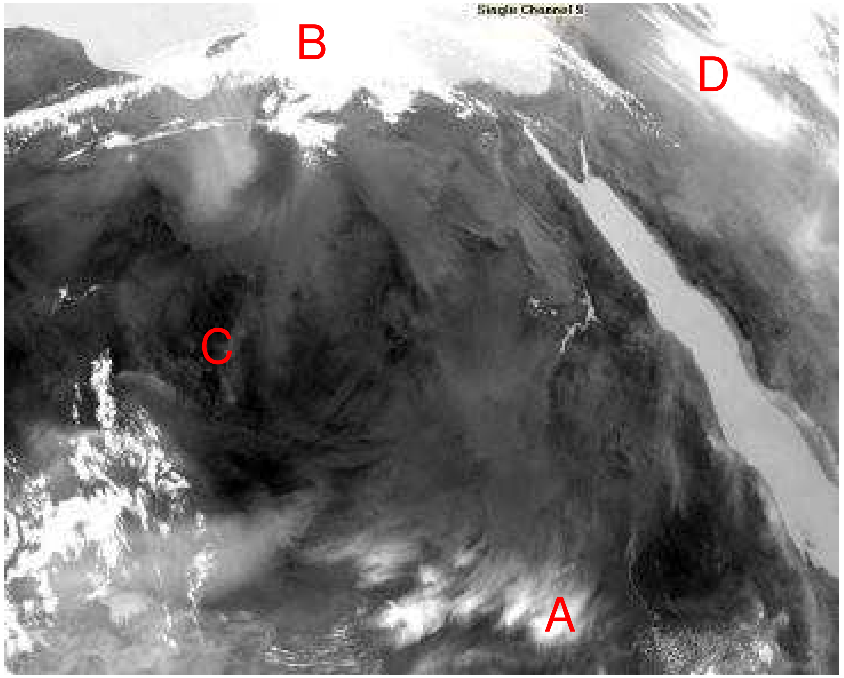
10



9-10

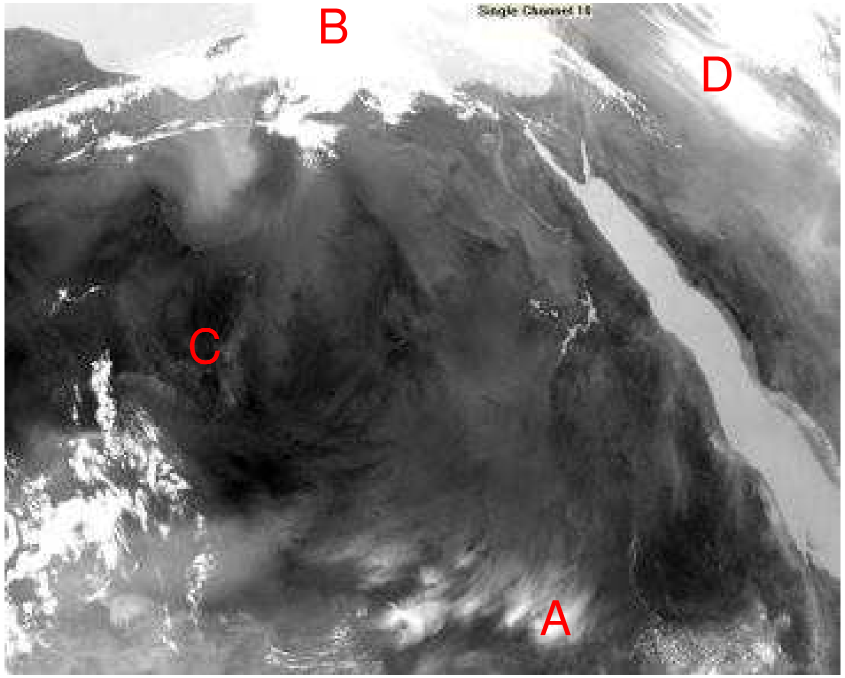


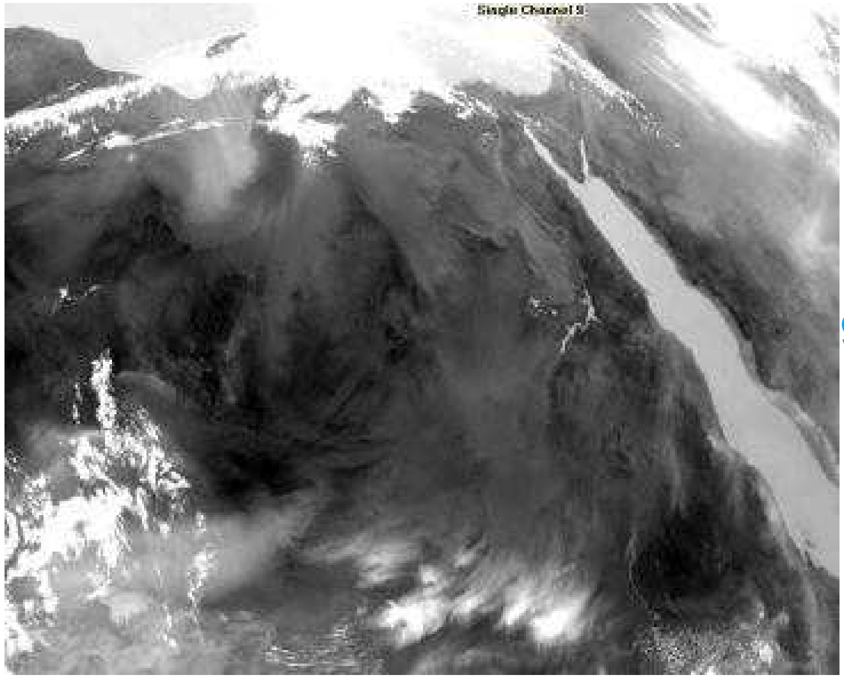
Single channel comparison and Ch9-Ch10 difference (*upper right*)



9

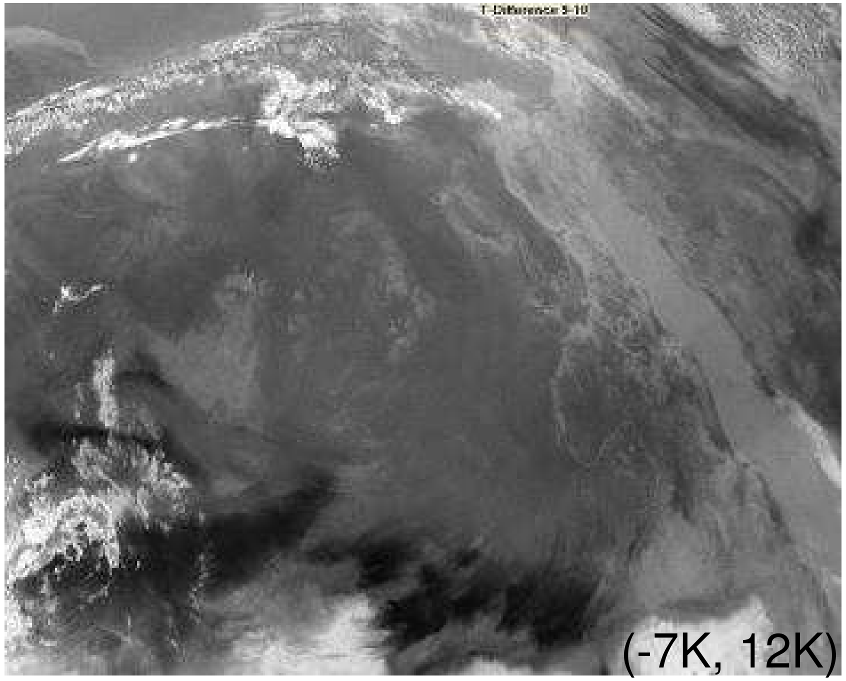
10



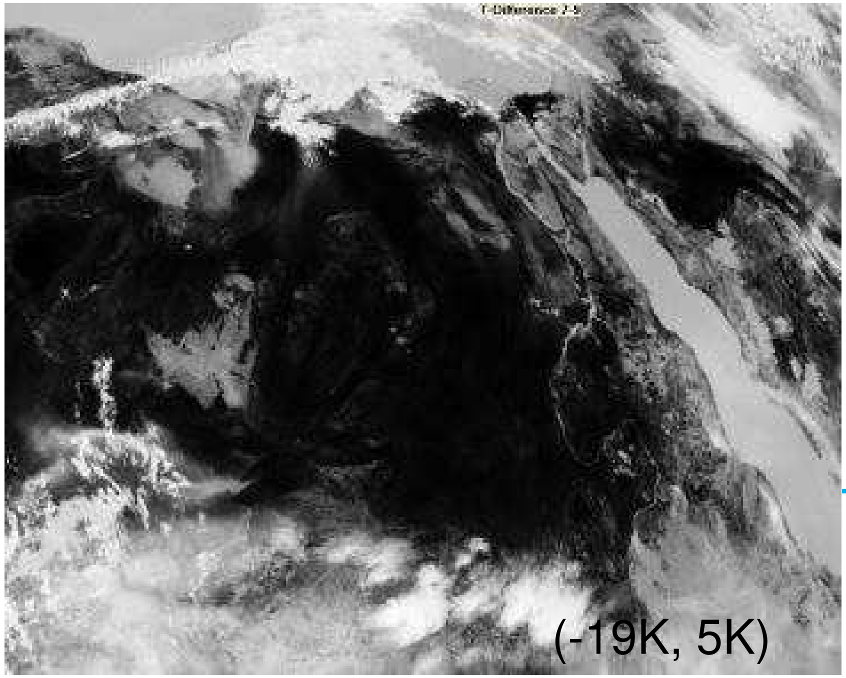


9

9-10

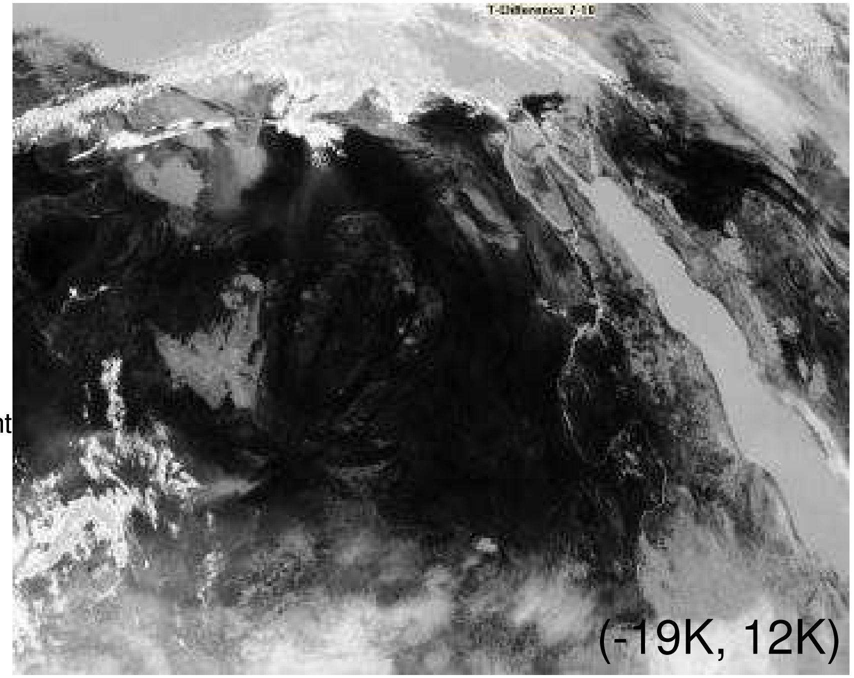


Ch9 (*upper left*) and three independent differences

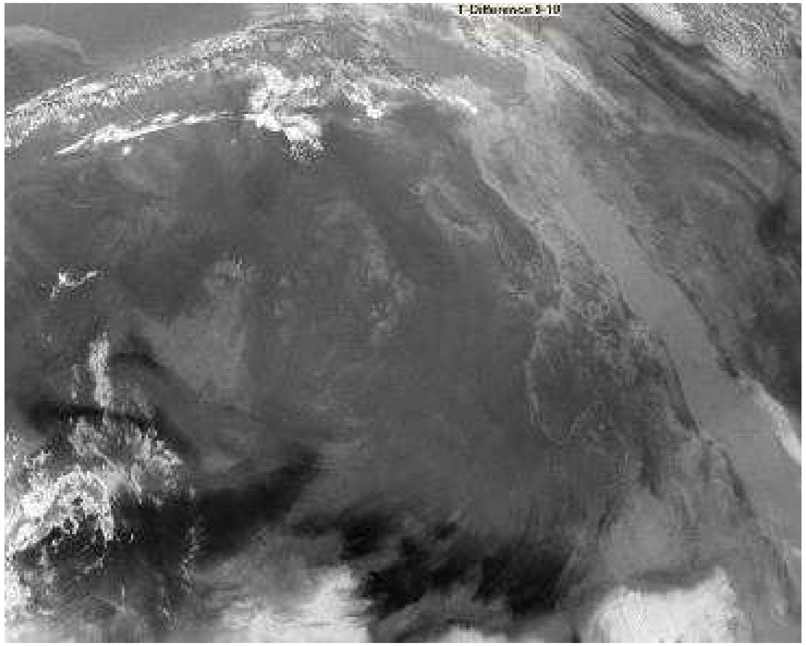


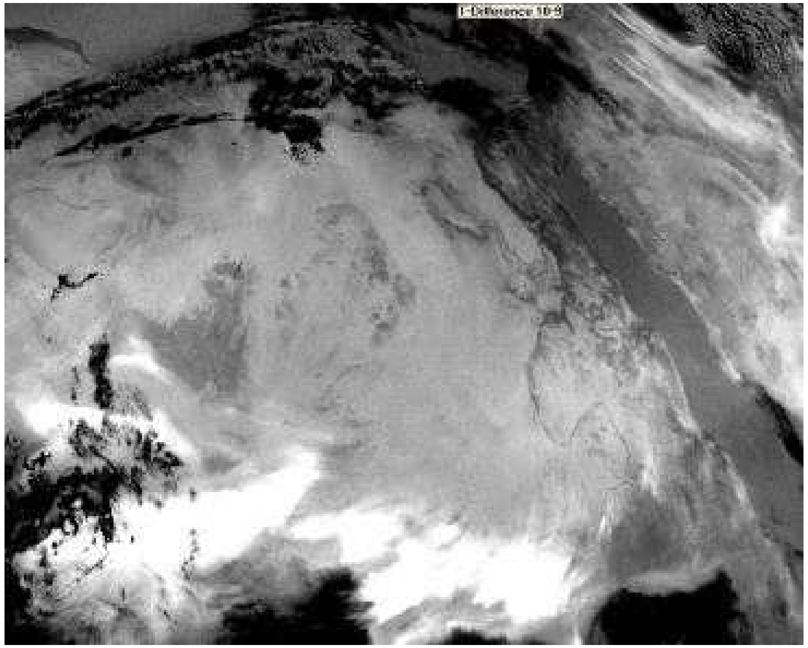
7-9

7-10
redundant



Difference image: Ch9-Ch10 or Ch10-Ch9 ?

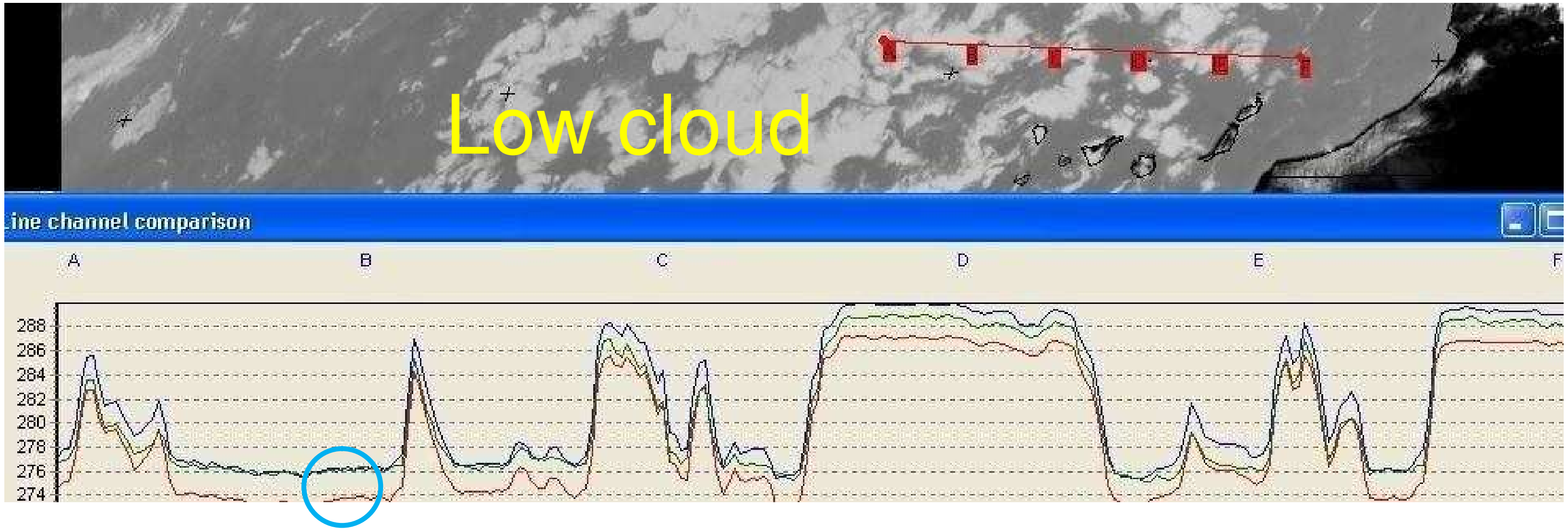


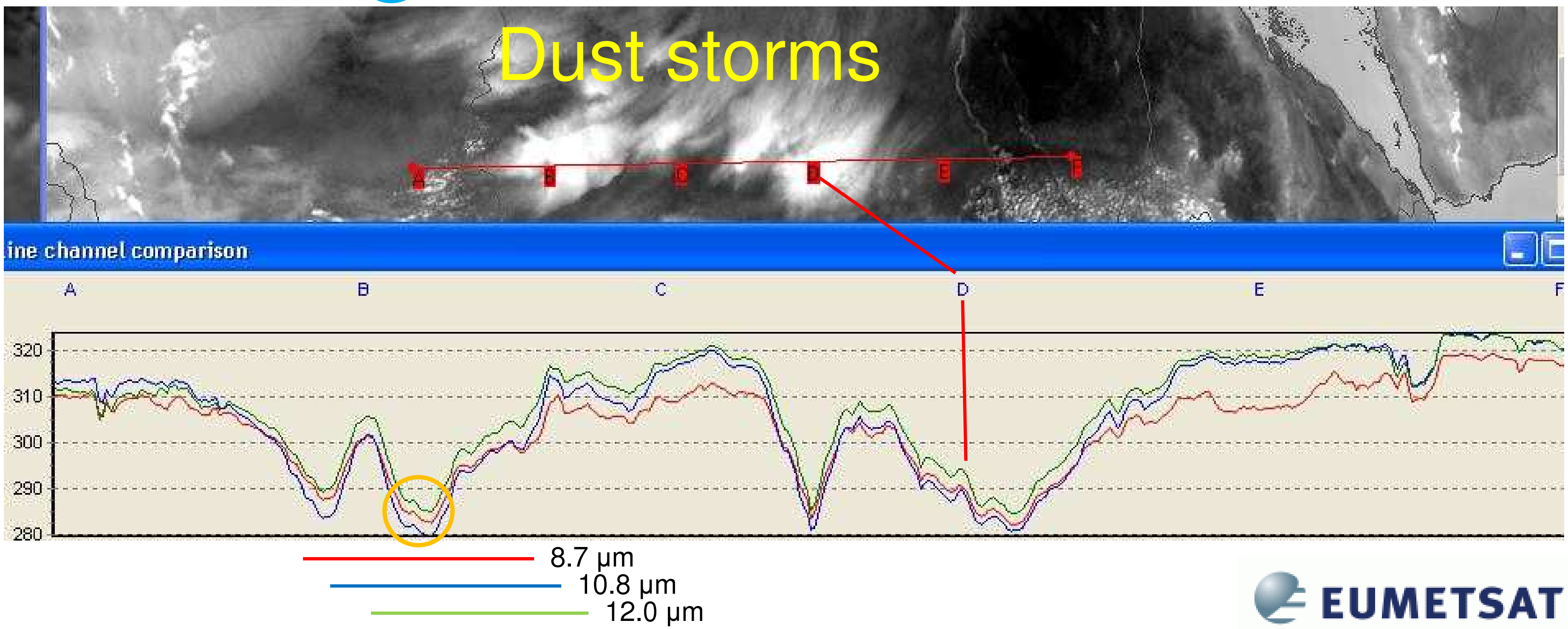


Direct Ch9-Ch10 versus reversed difference, Ch10-Ch9

- If dust is the target, reversed difference is more of an attention grabber
- For colour composites, this difference will show better reversed as colour

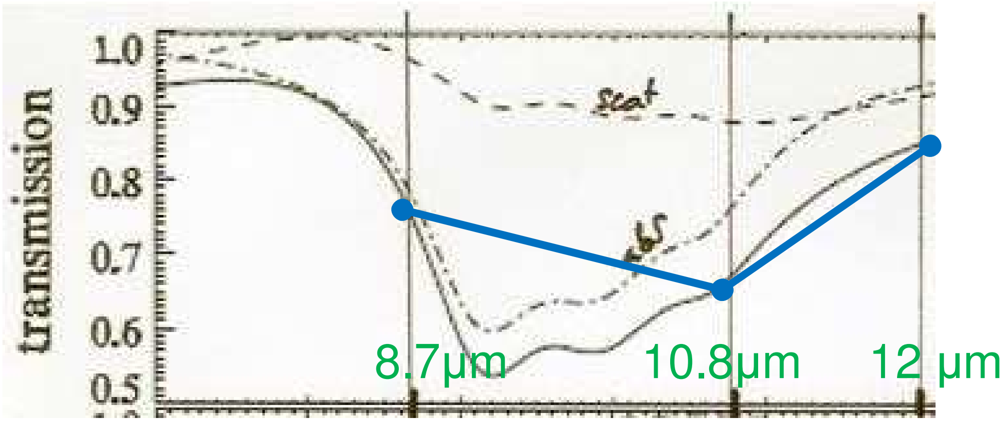
Comparison of water cloud and dust in the IR window





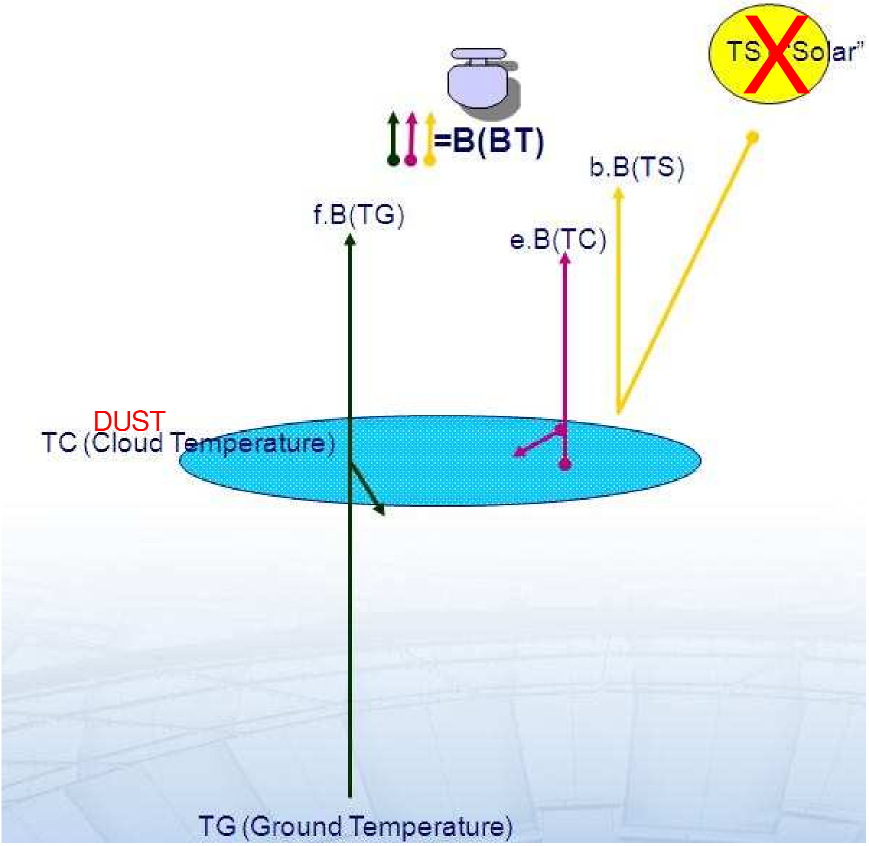
Signal reduction by dust storms (typical, dry atmosphere)

Signal reduction (K) at chan	8.7µm	10.8 µm	12.0 µm
Water vapour absorption	-2	0	-1
Dust absorption	-5	-6	-2
Dust scattering	-2	-4	-3
Dust extinction (abs + scat)	-7	-10	-5
Desert/clay emissivity	-10	-1	0
Ocean emissivity	0	0	0



Transmission through 3µm-ash
for wavelengths in the atmospheric window

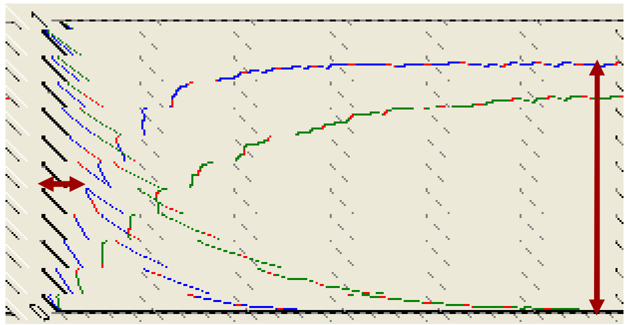
Scattering and absorption by a dust layer



- No solar contribution in the spectral range above 8µm
- But **scattering** !
- f + e < 1
- For thick dust layers e<1

•**Thick layer emissivity** dependent on absorption/scattering efficiencies **ratio**

•**Contributing layer** inversely to absorption+scattering (extinction) **sum**



optical depth →

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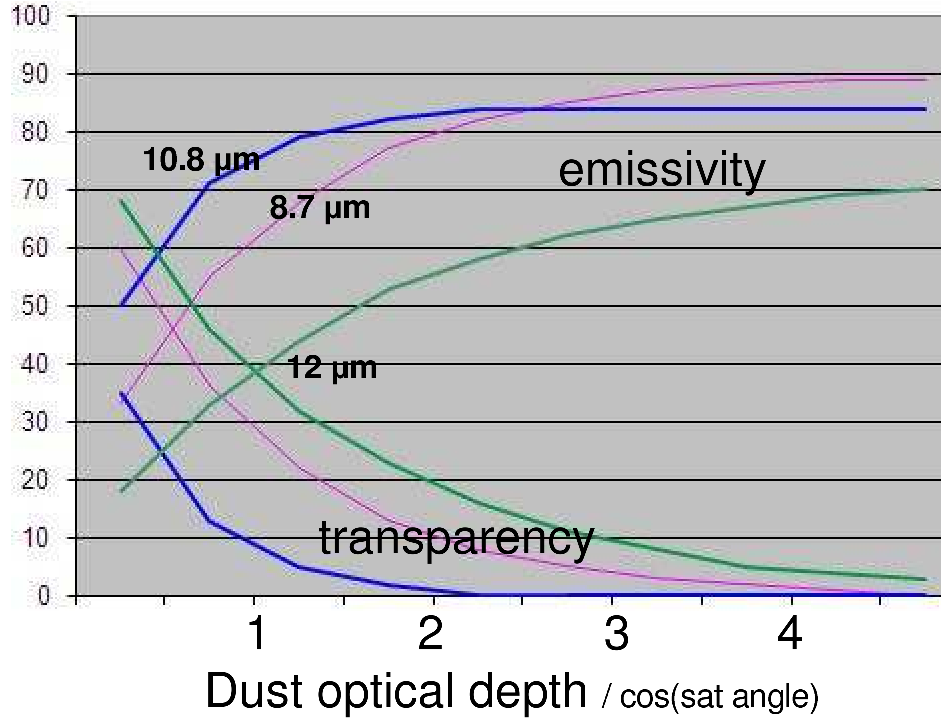
Emissivity and transparency



thin

➢EMISSIVITY: The emissivity of the dust layer grows with the dust optical depth up to a saturation value. It is higher for 10.8µm than for 12.0µm.

➢TRANSPARENCY: The transparency supplies warm signal from the ground, making the signal stronger at 12.0µm than at 10.8µm (opposite to warm bias)

thick

➢CONTRIBUTION LAYER: For deep dust (no ground contribution) the upper layer (supplying the signal) is thicker (and a few K warmer) at 12.0µm

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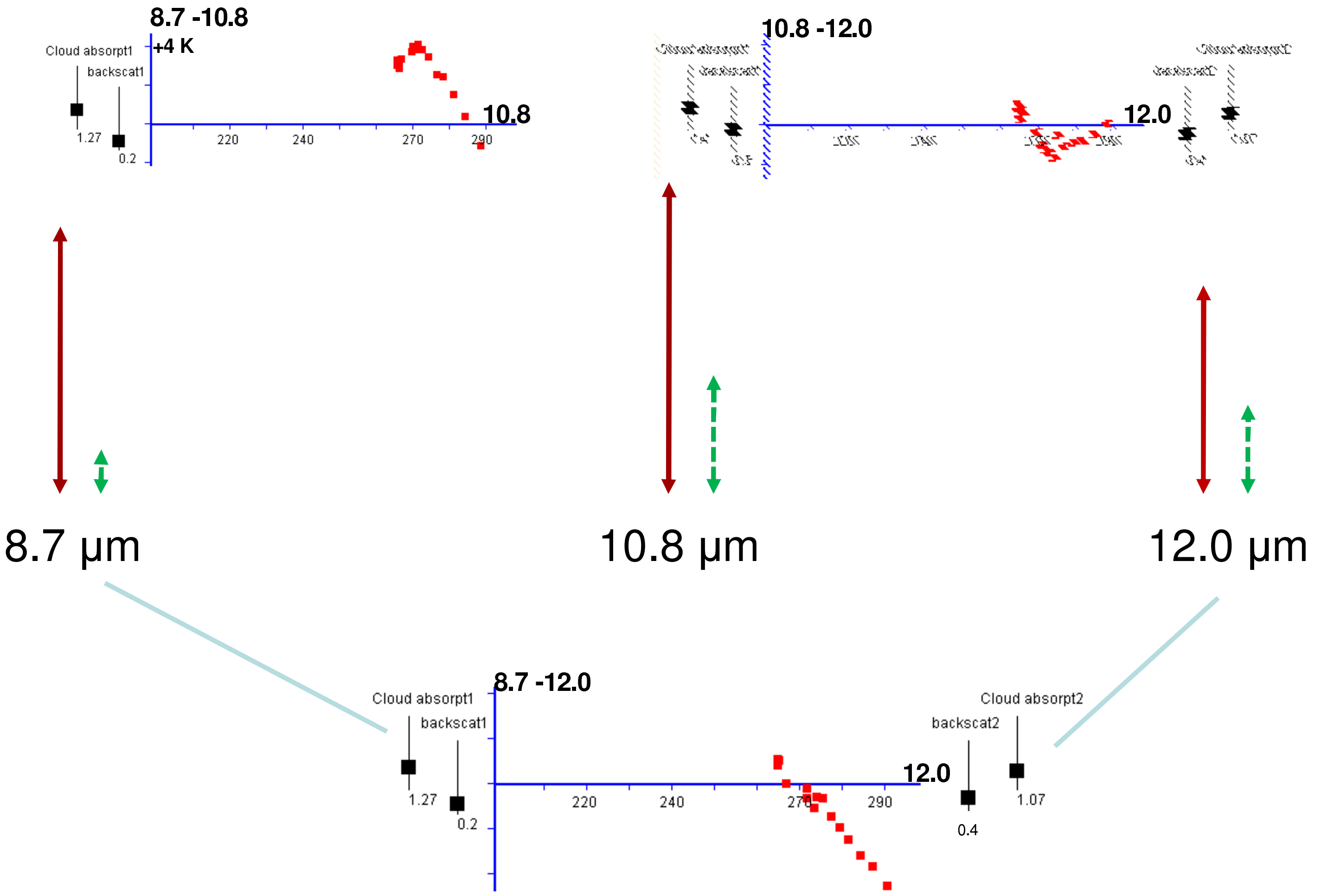
Absorption and scattering efficiencies



Red dots indicate dust optical depth in the range from 0 to 3 units

8.7µm is second in absorption, 12.0µm is second in scattering

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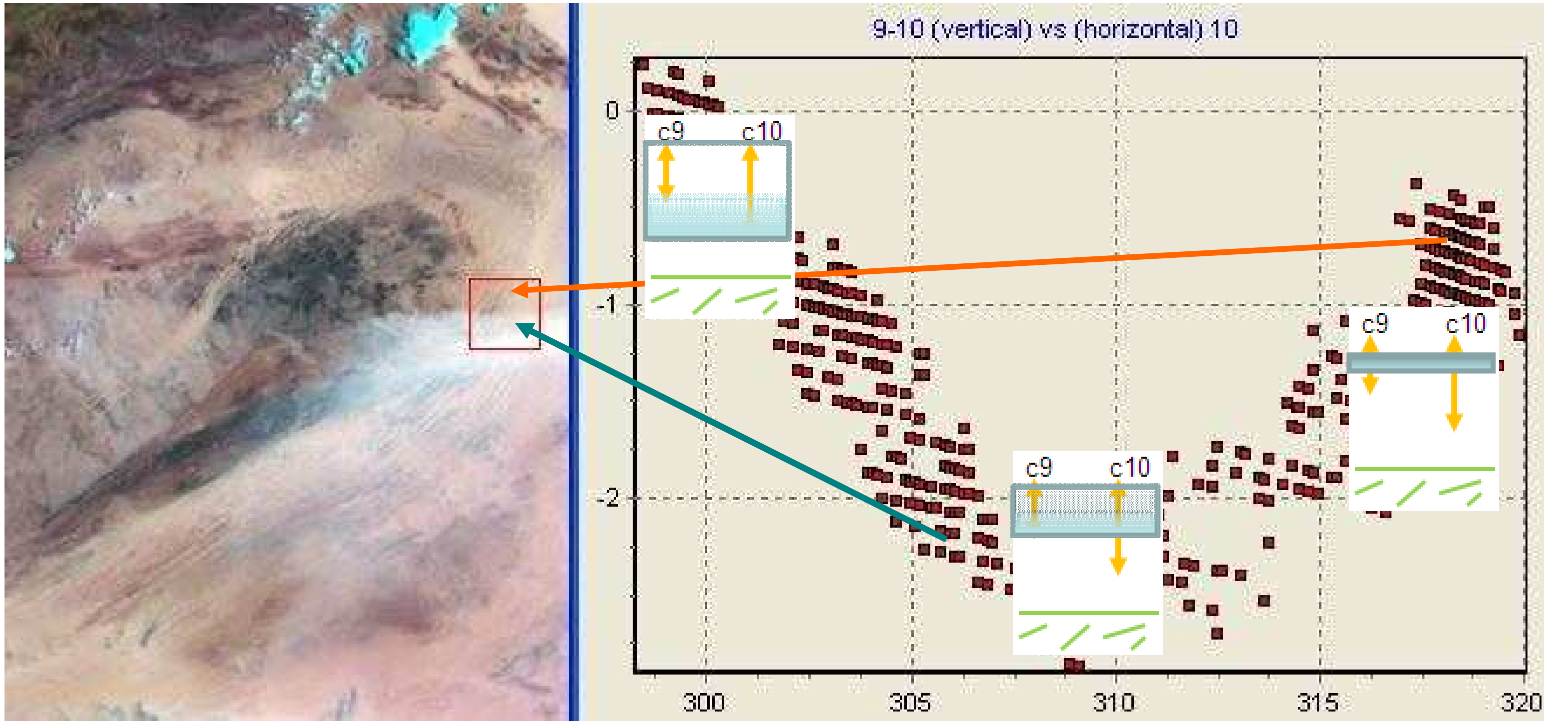
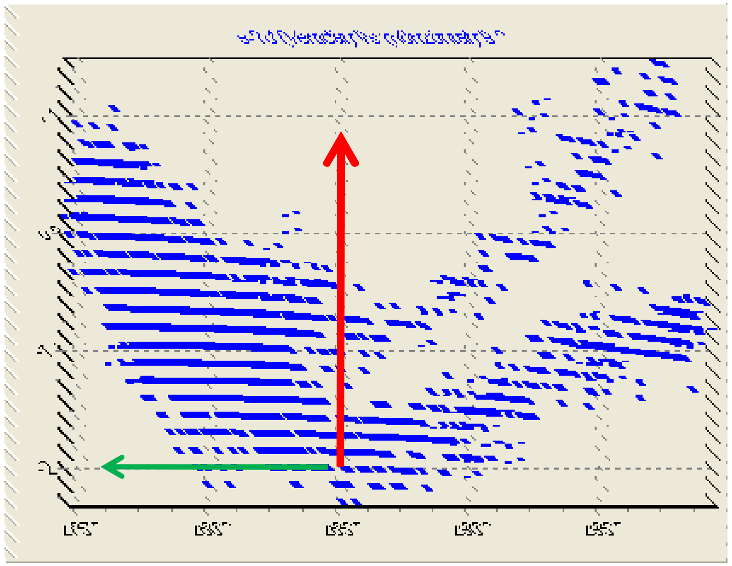
“Reversed arc” for dust scenes: Ch9-Ch10 versus Ch10



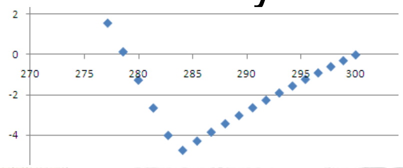
MSG Natural (solar) RGB composite 4-July-2003 10:00 UTC

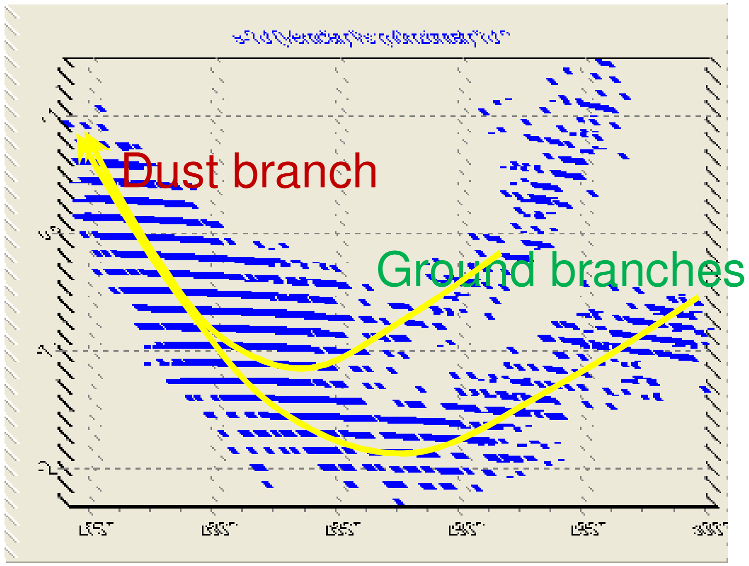
- 10.8µm radiation is more absorbed and more backscattered by dust than 12.0µm
- For dust or ash, arc is inverted due to the thinner contribution layer at 10.8µm
- 10.8µm channel shows higher BT for thick dust due to higher emissivity

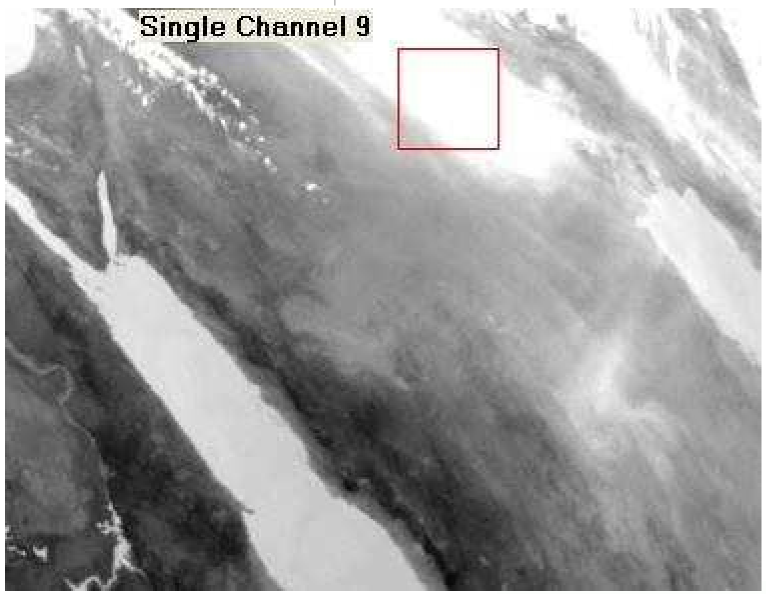
Positive Ch9-Ch10 for thick dust cloud



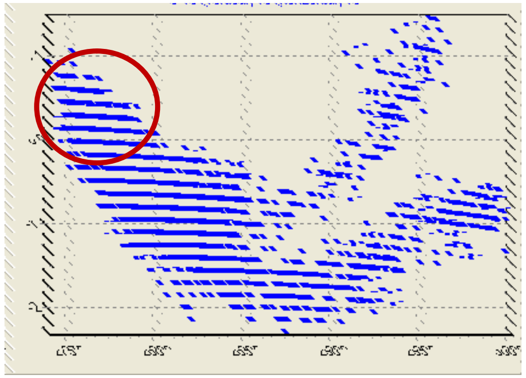
- Dust tends to higher levels far from the source, decreasing in **particle size**
- Higher dust directly correlates with thicker dust until the ground signal vanishes on Ch10
- 10K height ~ 3K 'thick' :classify dust storms
- Not really an arc:







Exercise: plots 9-10 versus 10



Why is the brightness temperature difference Ch9-Ch10 turning positive for very thick dust layers?

S E ❑ Dust shows a higher emissivity at Ch9 than at Ch10

S E ❑ Water vapour condenses on dust and favours Ch9 emissivity over Ch10 emissivity

S E ❑ Dust has a scattering component, higher at Ch9 than at Ch10

S E ❑ Dust Ch10 signal comes from a thicker (and therefore warmer) layer

S E ❑ Thicker layers normally reach higher in the atmosphere, and the signal decreases more on Ch10 for lower temperatures

Retrieval solutions: numerical and graphical

Pixel-based / numerical:

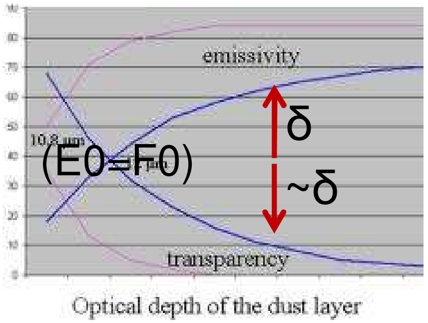
- Big errors in apriori information for variational assimilation
- Doubtful assumptions, gaussian-normal distribution for dust!

Context-based / graphical:

- Even more assumptions (uniform dust type in area, height independence for size, uniform ground, ..)
- Intuitive
- Precise results

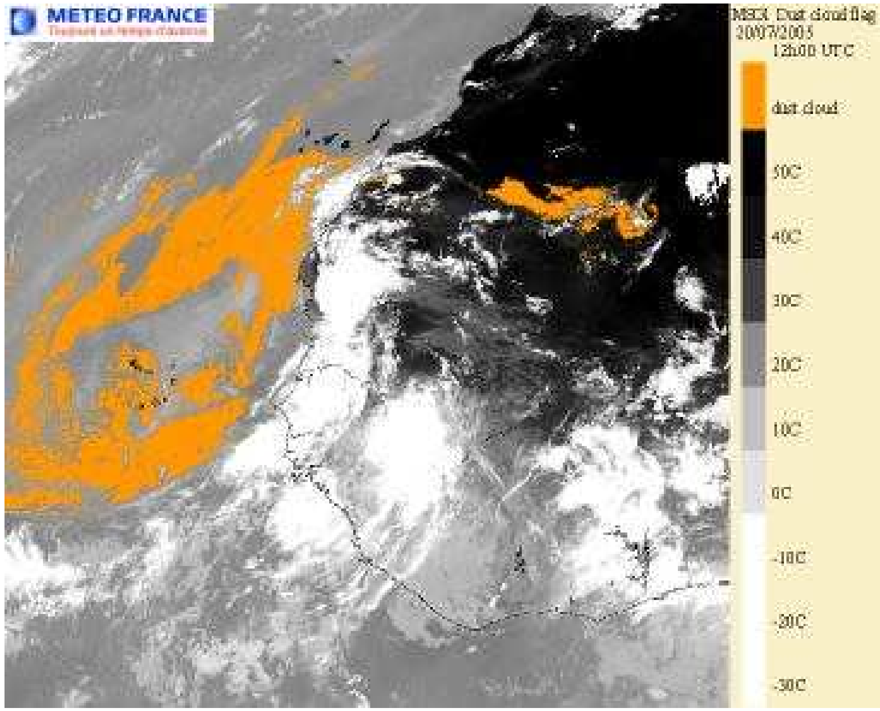
Numerical retrieval solutions

- Signal = Dust signal (T) + Ground signal (T0)
- B(BT) = (E0 + δ) B(T) + (F0 - δ) B (T0)
- δ can be translated to optical depth via E-F graph



Nowcasting SAF dust flag

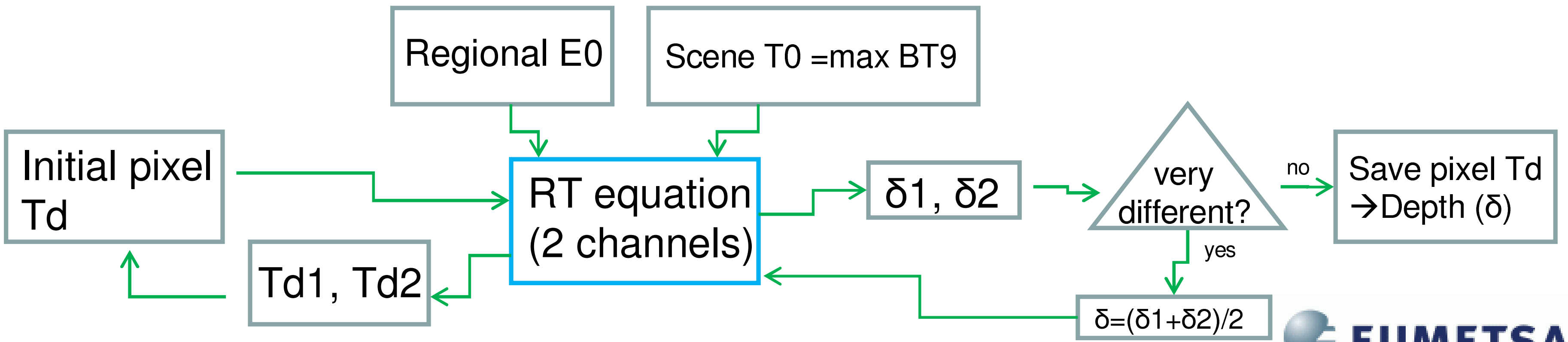
- *For the ocean, day time:* R1.6/R0.6 high, T12.0-T10.8 high, SD(T10.8-T3.9) smooth
- *For the ocean, night time:* same IR, T8.7-T10.8 high
- *For continental surfaces, day time:* not cold T10.8, smooth T10.8, filters for cloud



Numerical retrievals with two inputs

– For two channels (e.g.,10.8 and 12.0 µm):

- E0 and F0 are **adjusted** in advance for a **region** (same as efficiencies)
- **T0** is estimated for the whole **scene** as maximum value for BT9
- Initial dust T = BT9 in the pixel
- Calculate δ in the two equations, compare δ1 and δ2
- If δ1 and δ2 are very different, calculate T's for average δ in the 2 equations
- Iterate till differences get **smaller than** (2%, 2K)
- Save the pixel solutions



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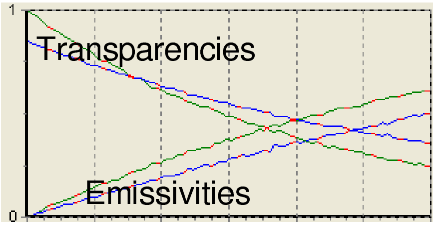
Numerical retrievals with three inputs

– For three channels (8.7, 10.8, 12.0 µm):

- Channel **8.7 adds** information and
- Provides scope for the retrieval of **three parameters**: (To, Td, optical depth)
- However, it introduces the **uncertainty** about **ground emissivity**
- And does **not** help with the depth retrieval for **thin dust** layers
- Still, improves retrieval for **thick dust**

Emissivities and transparencies
at 8.7µm and 10.8µm



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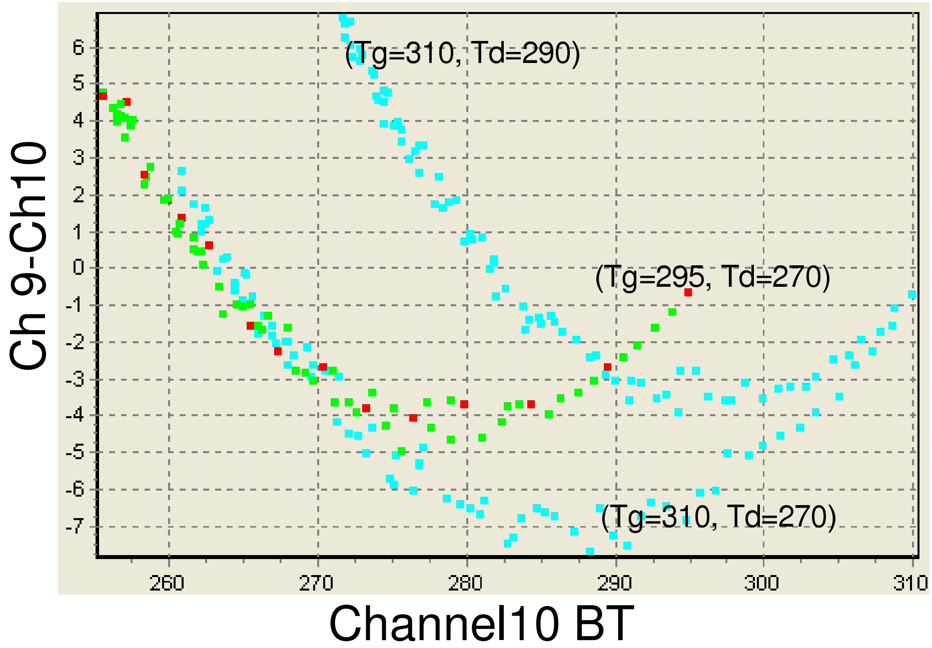
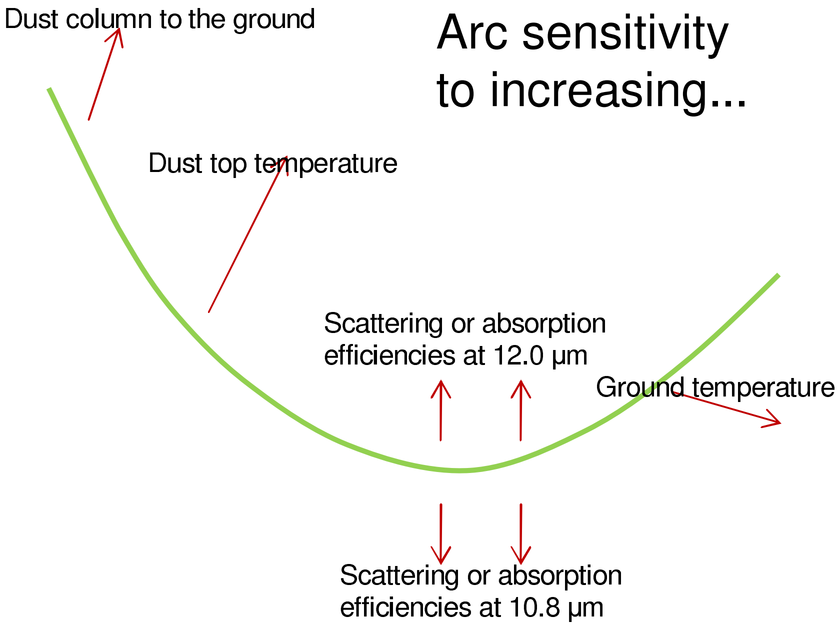
Graphical retrieval

- Thick dust cloud at low level can be confused with a thin layer high above
- Uncertain reduction of the ground temperature by dust ('thermal deficit')



Green-red dotted curve for (Tground=295, Tdust=270)
Cyan curves for Tg=310, and two values of Td=270 and 290



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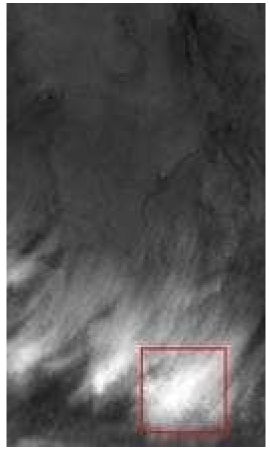
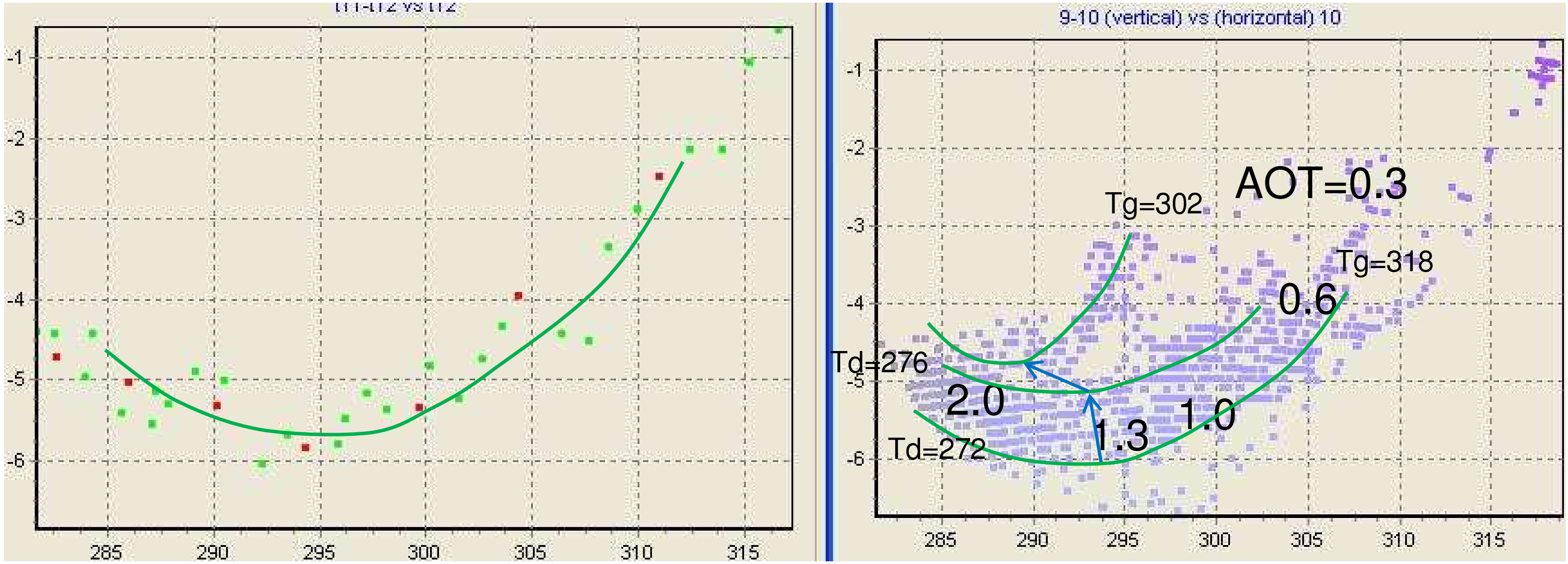
Dust (Td) and ground (Tg) temperatures estimates





Real (blue dots, right h.s.) compared with simulated (left h.s. and lines) scatterograms based on Tg=318 Td=272
Σ11=0.6, 0.3 Σ12=0.2, 0.25
The simulation (left h.s.) allows the thickness calibration (red dots for one-third depth units. Numbers are AOT units)
Ground thermal deficit: 30% of ground-dust difference, dust column down to 50% of that temperature difference
The upper pixels are the result of lower ground temperatures, acting as the blue arrows on the minimum.

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Low level dust forming a dust wall in Niamey (courtesy of E. Kploguede)

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Graphical-numerical retrieval: Td, Tg, AOT, Size

- Threshold in the box (32x32 surroundings): T10.8-T12.0 < *-1.3K*
- AOT estimate from location in the diagram: *0.14---1.3---3.5---4.8*
- Td estimate, max (T12.0) + 5*min(T10.8-T12.0)
- Forward model to simulate 10.8 and 12.0µm brightness temperatures
- Corrections to retrieved parameters based on sensitivity
- Distribute corrections in up to 32 steps
- Convergence criteria (too small changes in Td and AOT estimates)
- Four result categories:
  - Dust
  - Mixed with cloud
  - Only dust traces
  - Dust-free (or low-level only, or night-time, or dry ground)

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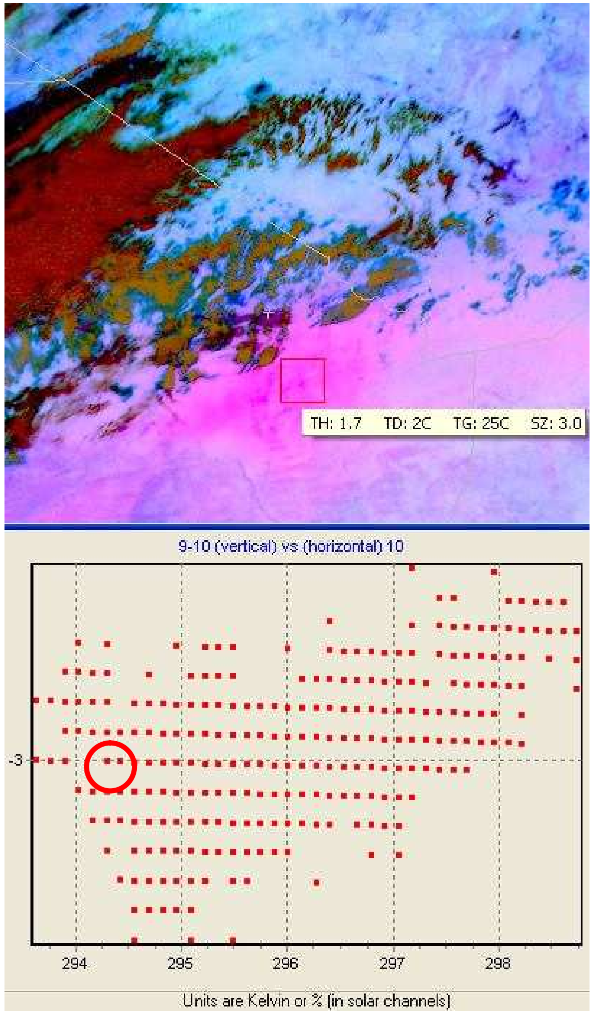
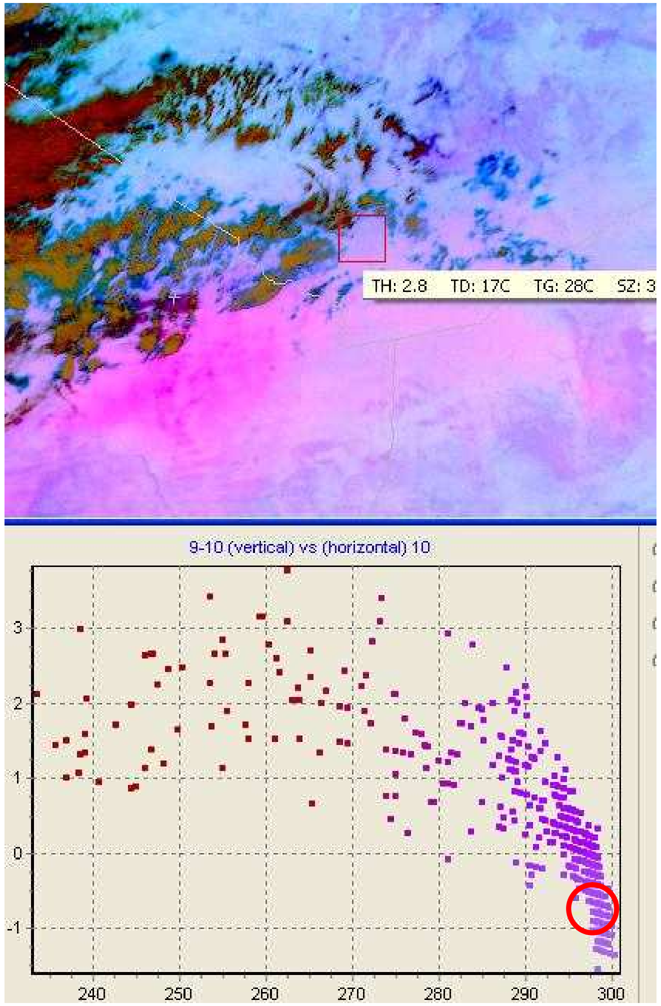
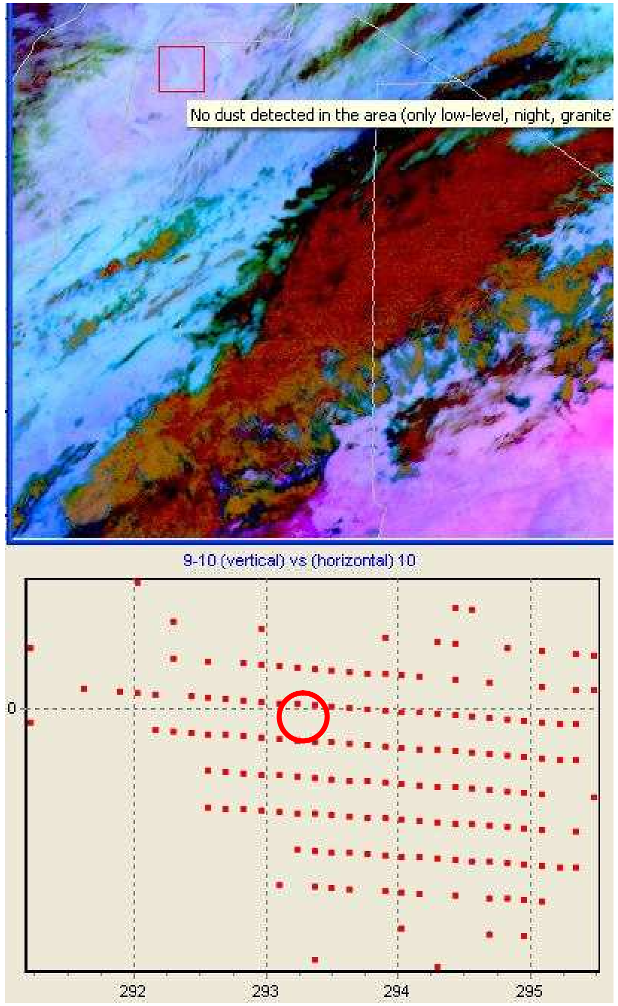
Graphical-numerical retrieval: scene determination



threshold ch9-ch10 < -1.3K
AOT =1.7, strong depth



threshold ch9-ch10 < -1.3K
AOT =2.8, very strong depth
But suspicious of cloud



threshold NOT < -1.3K
AOT not calculated
Possible causes hinted

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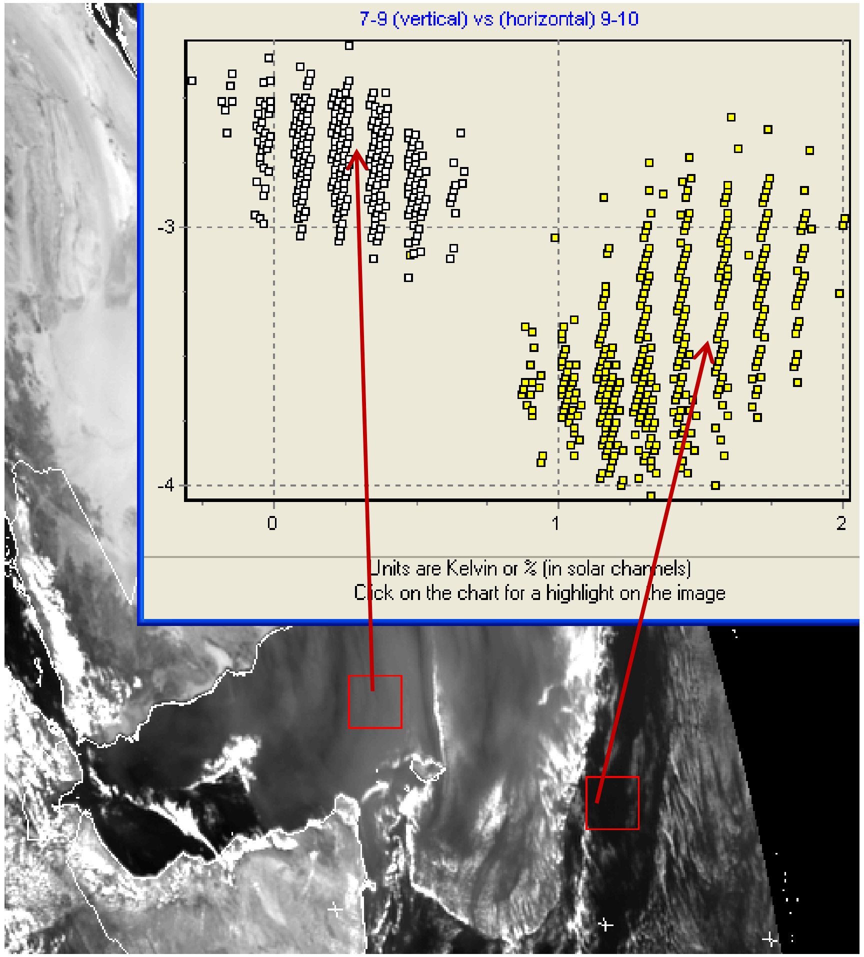
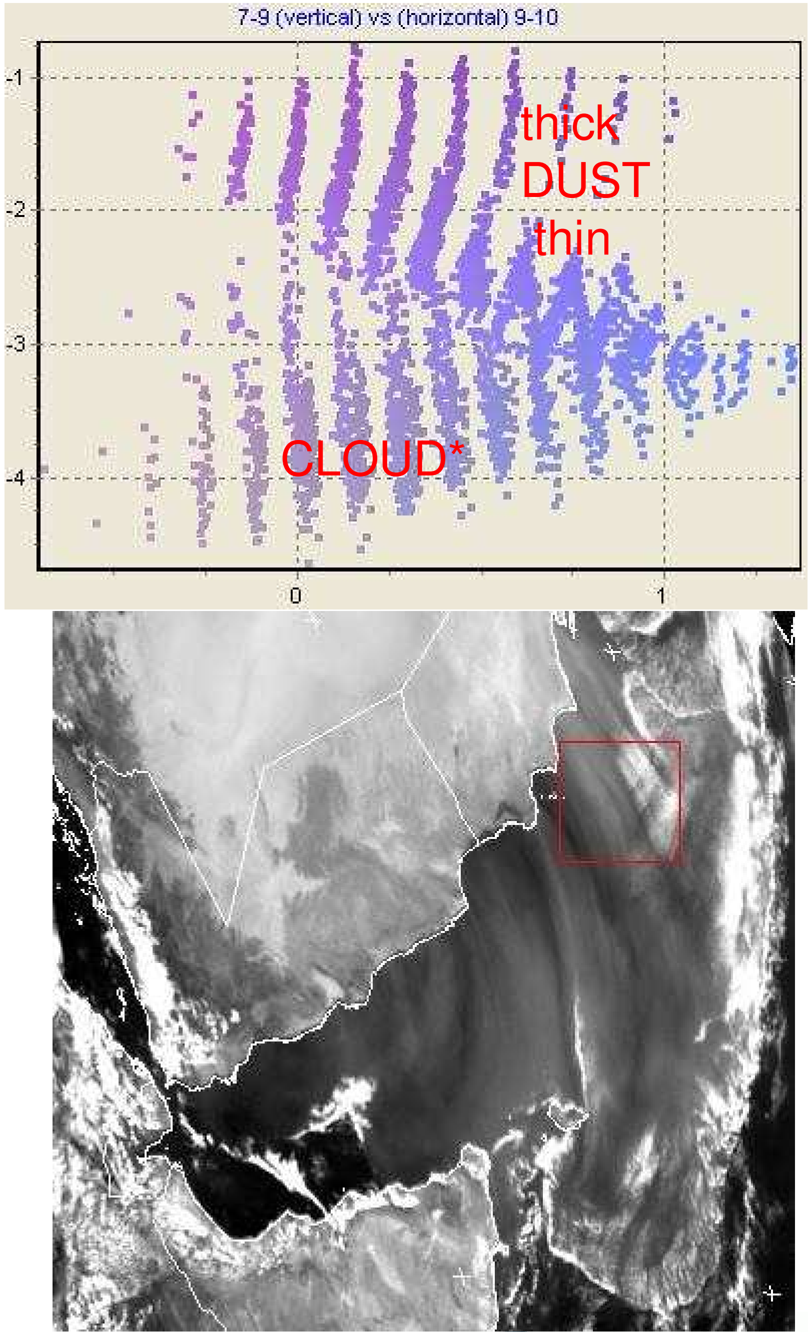
The oceans: double difference plot





Meteosat-9 **0.6µm** 2008-Feb-02 10:15 UTC

Hardly shows in IR channels

*Oblique path in the area enhances the negative 7-9 difference for cloud

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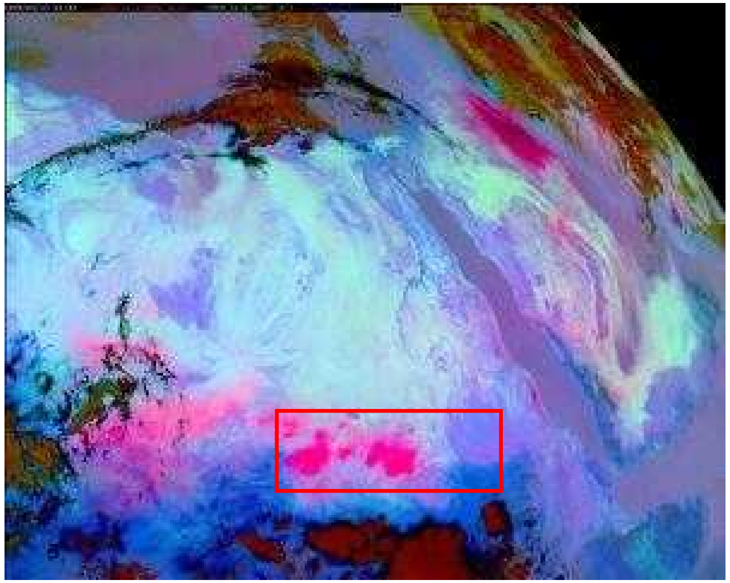
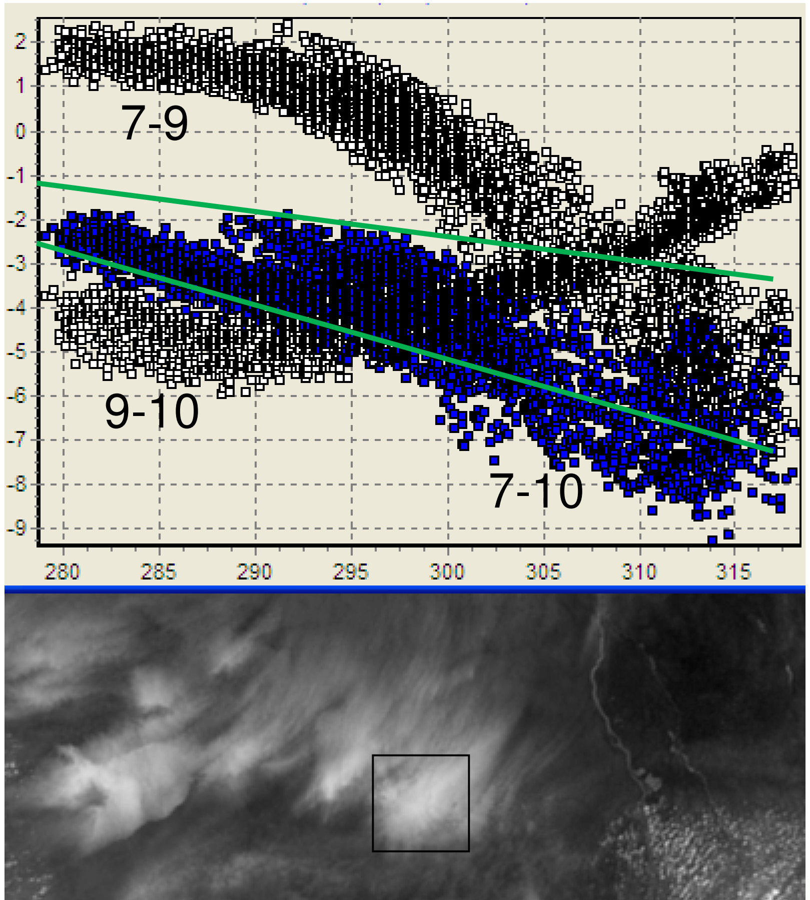
Single and double plot of differences



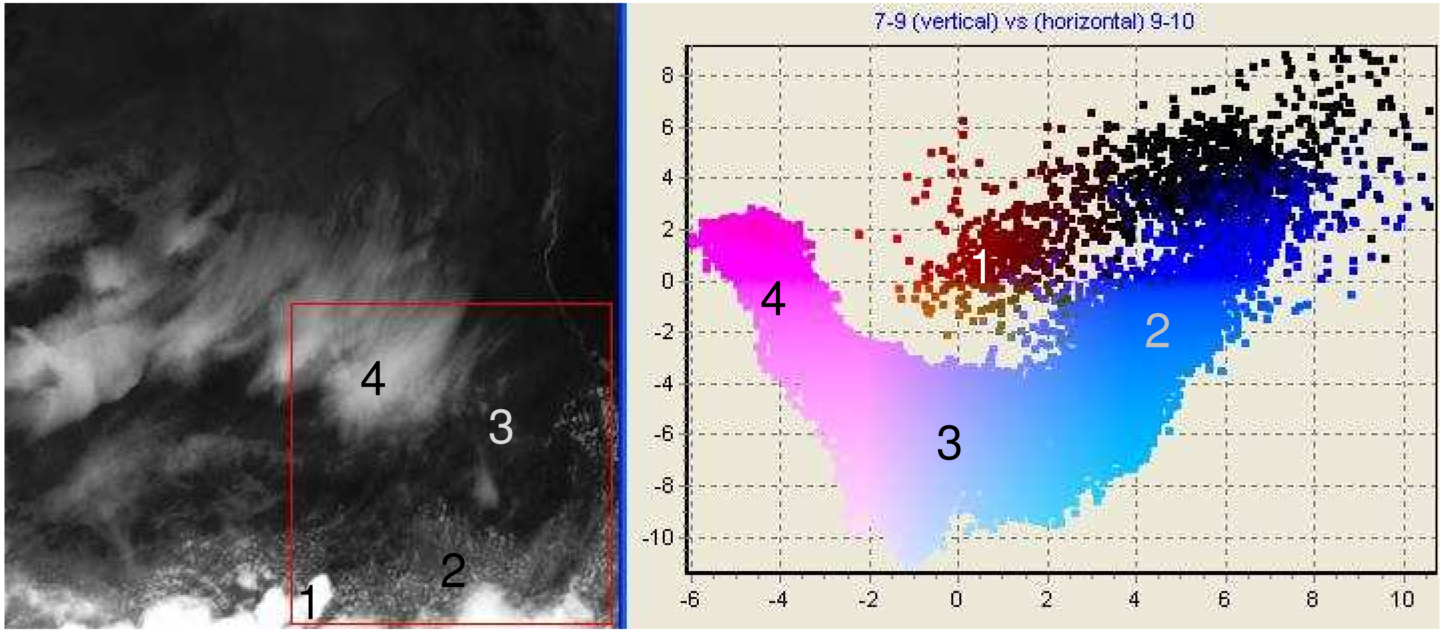
2004-05-13 13:00 UTC, 10.8 µm

•The difference 7-10 is twice the average of the others, and rather straight in single plots for dust

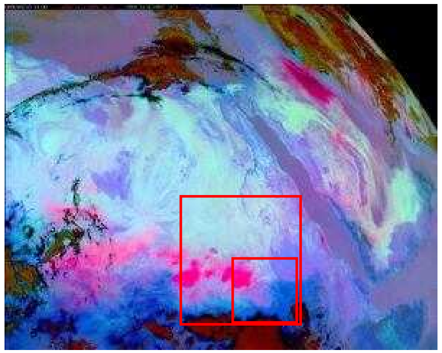
•The other two differences, 7-9 and 9-10, are usually preferred



The cloud-to-dust spiral in the differences graph



2004-05-13 13:00 UTC, 10.8 µm



1: Thick high cloud
2: Broken low cloud
3: Ground, drier air towards 4
4: Dust cloud

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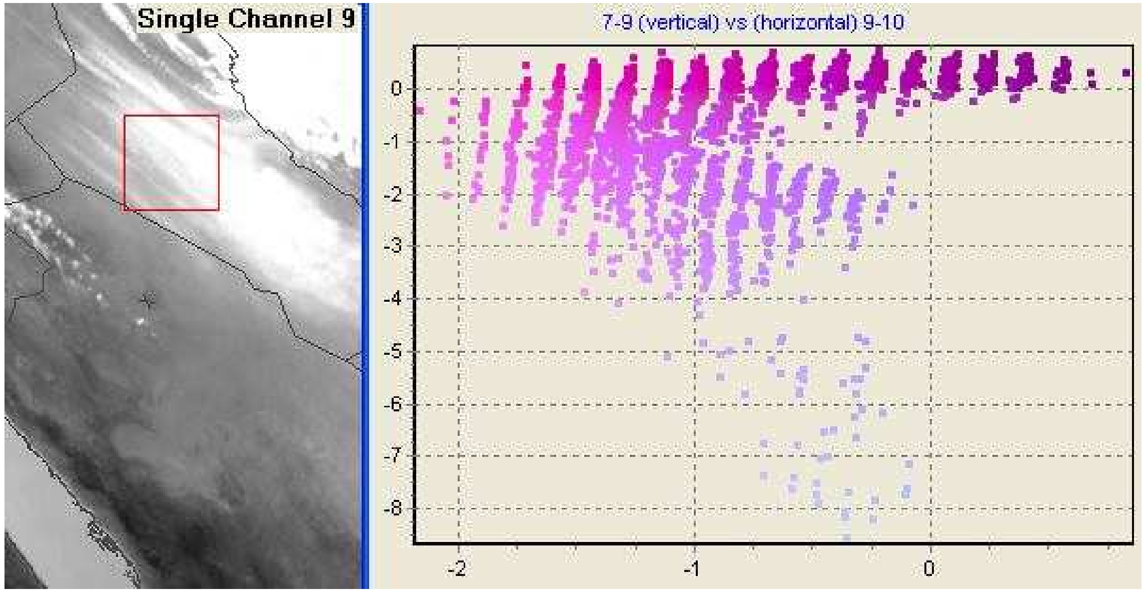
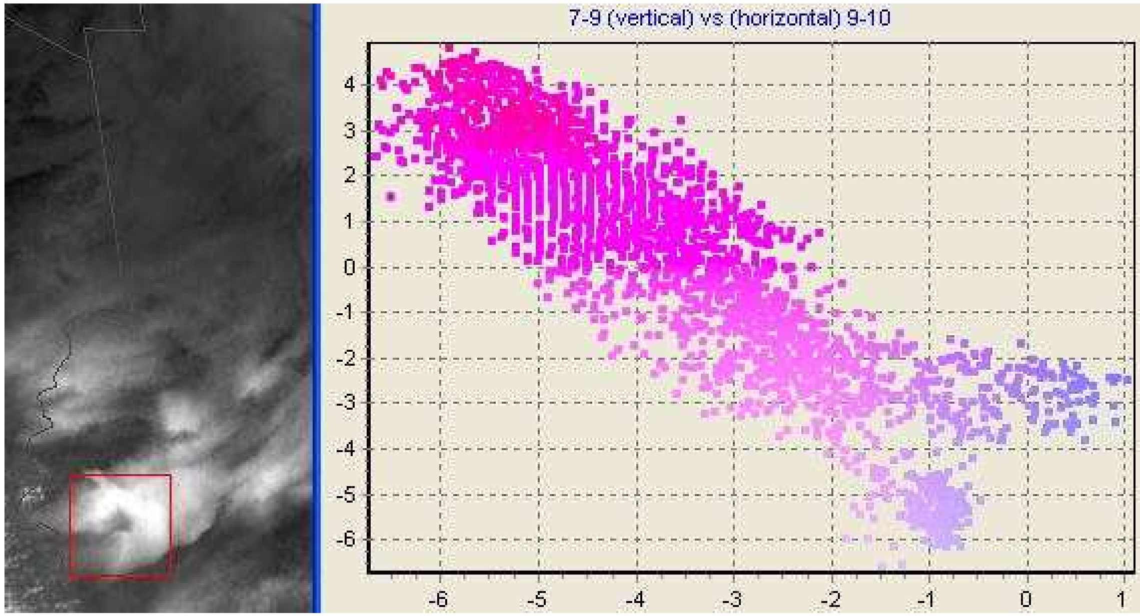
Dust branch often due to slant view of the dust storm (double diff)



Meteosat-8 10.8μm 2004 May 13th 13:00



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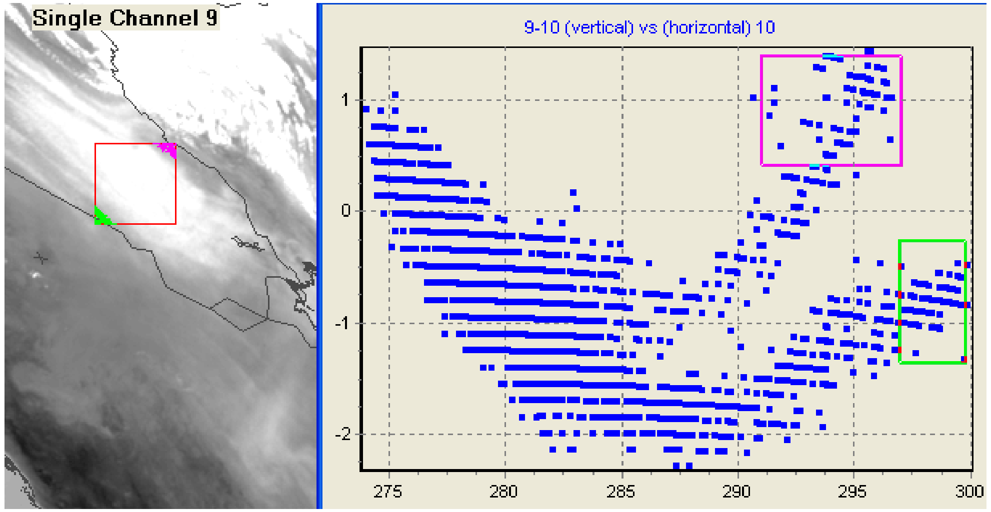
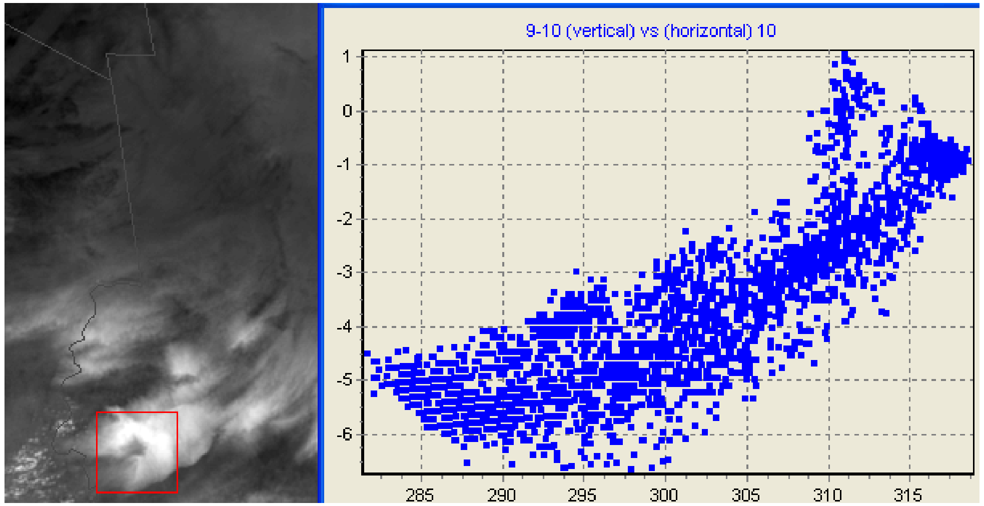
Dust branch only for intense dust storms or oblique views



- 2004 May 13 13:00
- 9-10 turns positive for thick dust (upper graph, Saudi Arabia) due to higher dust emissivity at channel 9
- Not thick enough (less slant view) in Sudan (graph on the right), far from reaching the zero difference on the dust branch



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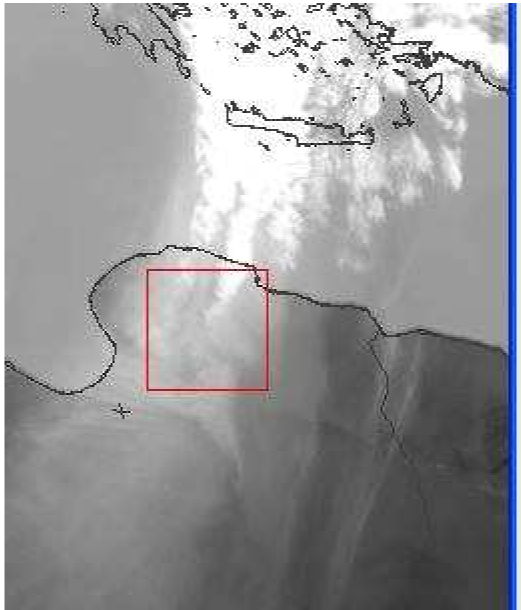
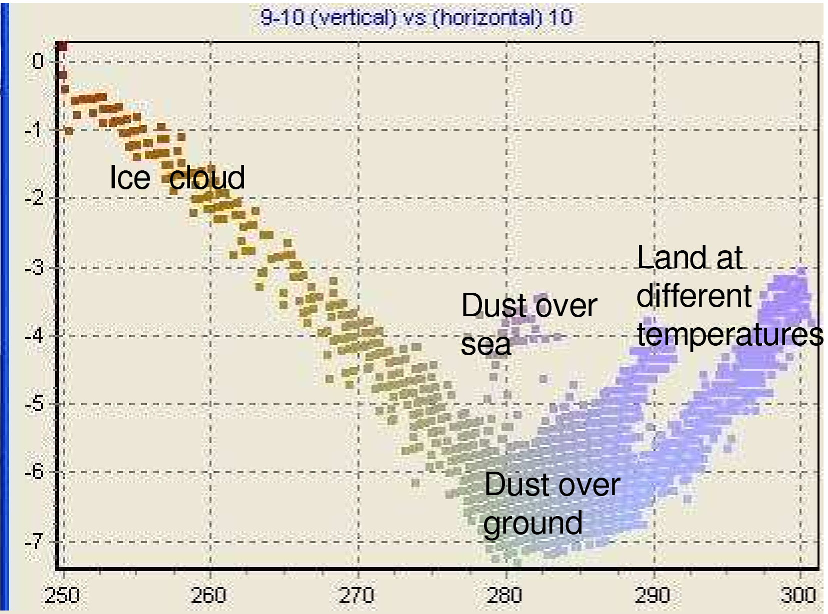
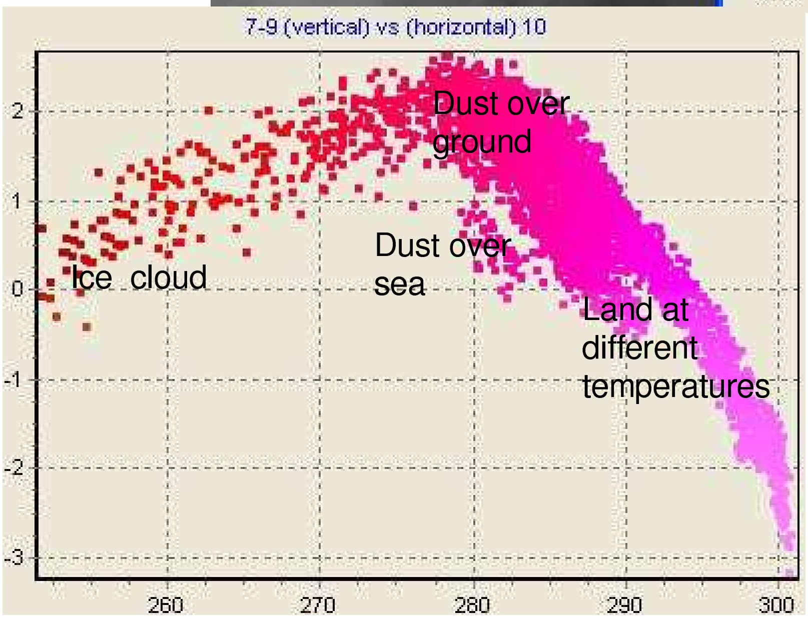
Single plot: Ch9-Ch10 vertical, Ch10 horizontal

2008-03-23 11:30 UTC Meteosat Ch9



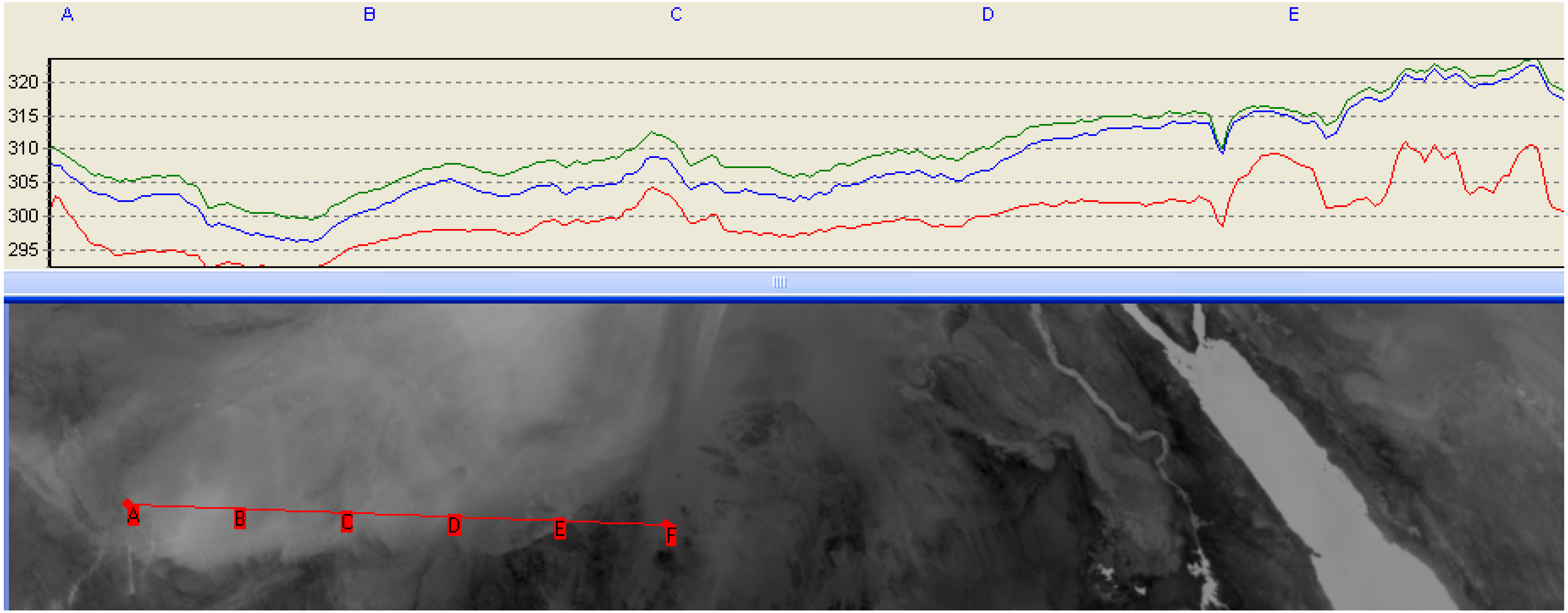




At which temperature is the cloud boundary?

- 265 K
- 275 K
- 285 K

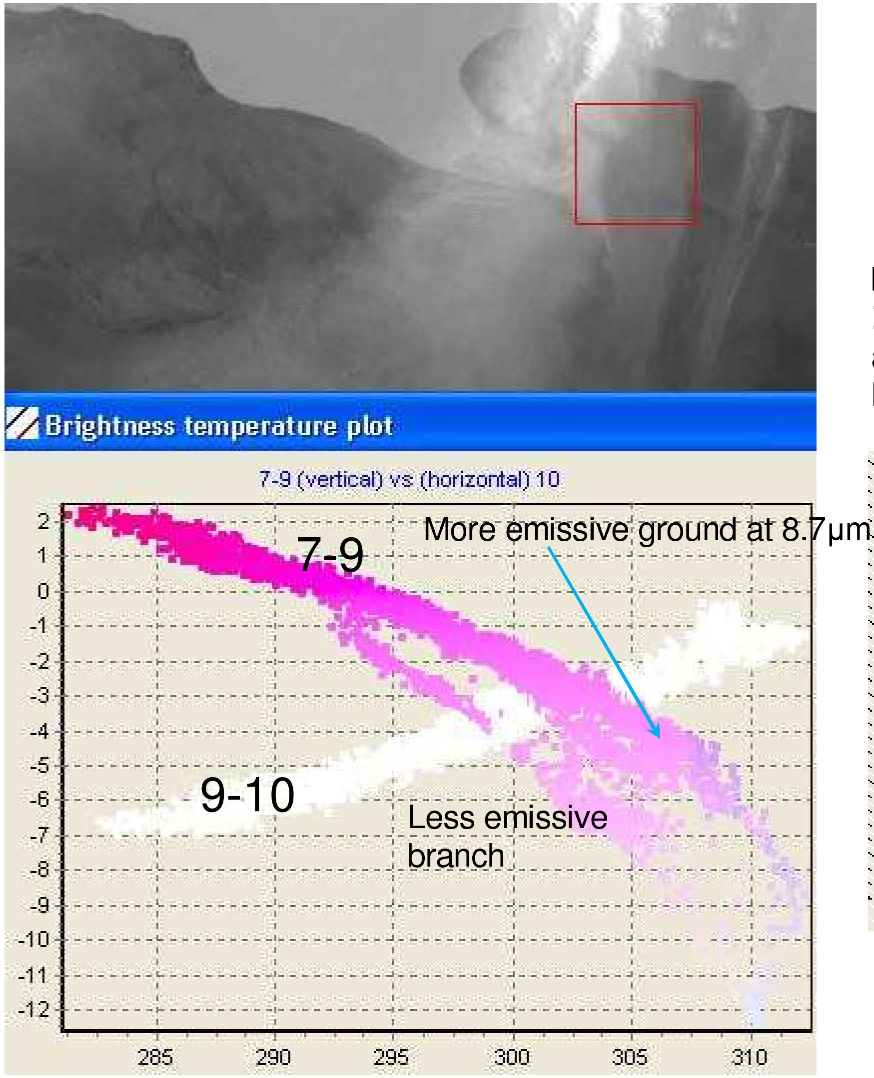
The value added by the channel 7 (at 8.7µm)



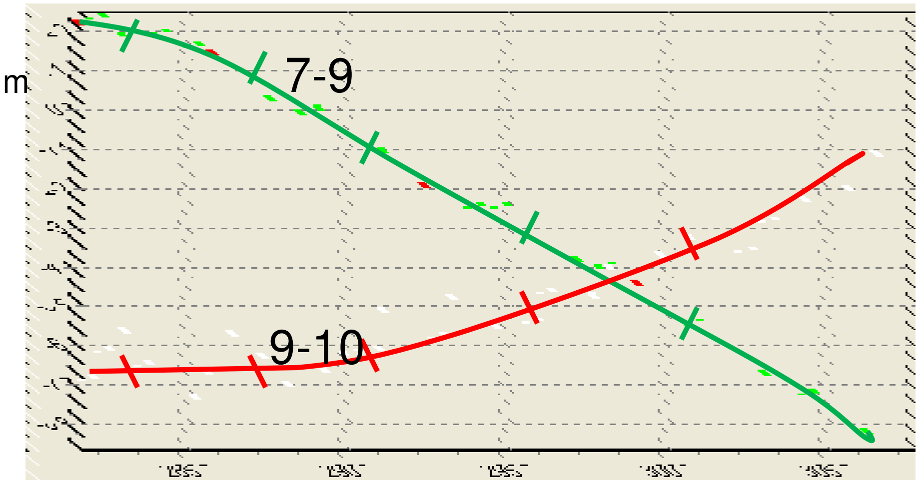
2008-March-23 11:30 UTC, Meteosat-9

- Difference 7-9 depends on dust concentration, humidity and ground emissivity
- Difference 9-10 depends on dust concentration and humidity

The value added by the channel 7 (at 8.7µm)



Real (left h.s.) compared with simulated (right h.s.) scatterograms
based on Tg=308 Td=266
Σ8.7=0.35, 0.2 Σ11=0.6, 0.3 Σ12=0.2, 0.25
and ground emissivity 85% at 8.7µm
Marks at optical-thickness third-units from the right ends



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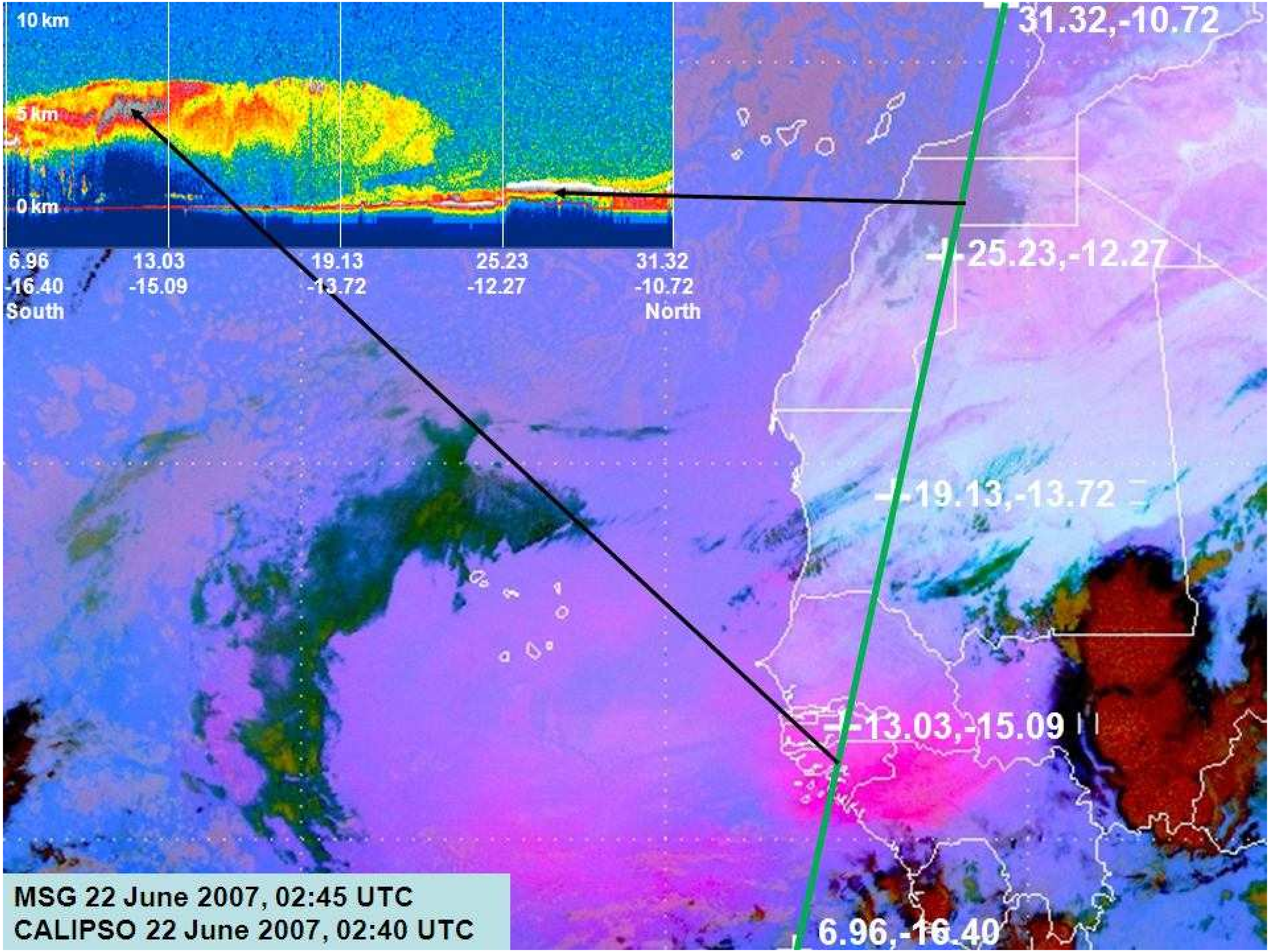

10 km
5 km
0 km
6.96
-16.40
South
13.03
-15.09
19.13
-13.72
25.23
-12.27
31.32
-10.72
North
31.32,-10.72
25.23,-12.27
19.13,-13.72
13.03,-15.09
6.96,-16.40
MSG 22 June 2007, 02:45 UTC
CALIPSO 22 June 2007, 02:40 UTC

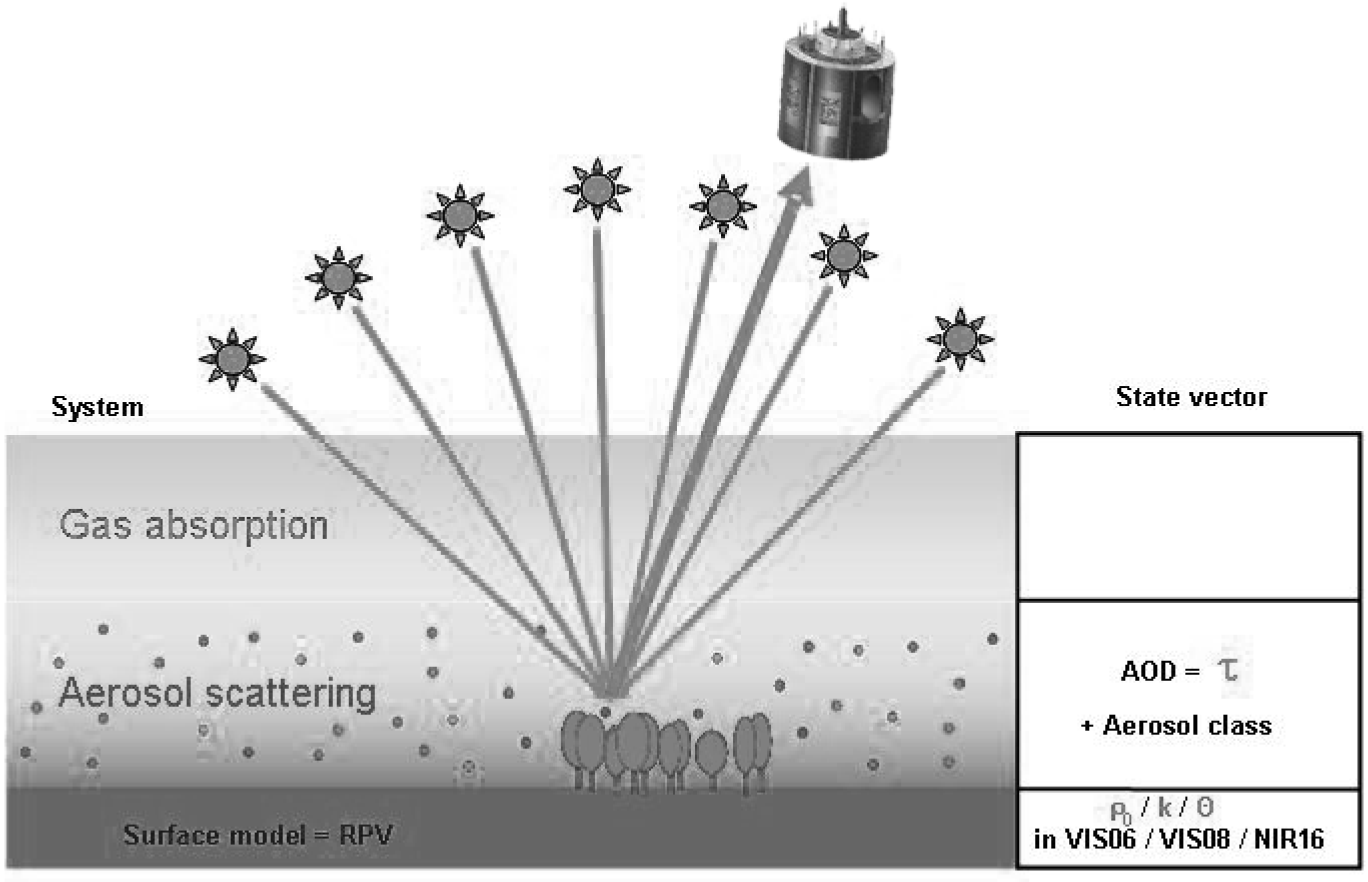
Conclusions

- Graph adjustment is more **subjective** than numerical retrieval, but it facilitates **understanding** of the radiative transfer and provides the parameters for dust storm **classification**

- Channel at **8.7µm** provides **refinement** for *Tdust* and *Depth* values at the thick end of the curves

- An operational detection algorithm can be based alternatively on **thresholds** of the type: Ch9-Ch10 < -1.3K for pixels, plus texture indices in the area. However those thresholds are not necessary for dust

Land daily aerosol algorithm



Outlook

•A model for **dust cooling** and **height-thickness** modelling will improve the simulation of the observed radiances

•A study of the **particle size** effect on channel emissivities will improve the match between expected and real radiances

•Looking into the BT's for **dust mixed with water** will clarify the role of aerosols in cooling the atmosphere

•Coupling IR technique with existing methods for solar channel simultaneous retrieval of surface **albedo** and **aerosol optical depth**

•A comparison with results from the **visible techniques** for dust estimation will provide calibration and skill for the IR estimates, obtainable during night too

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DUST RGB composite:
the strength of infrared for dust detection

IR RGB composite based on channels at 8.7, 10.8 and 12.0 μm

Solar RGB composite based on channels at 1.6, 0.8 and 0.6 μm

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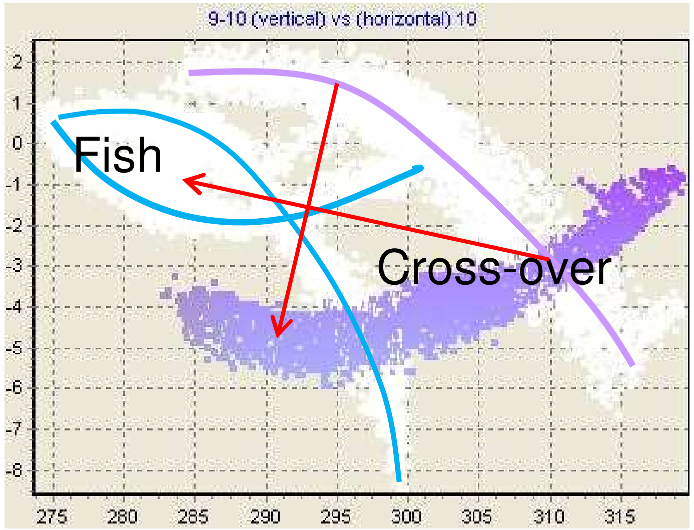
THANKS FOR YOUR ATTENTION !

- List of referred events:
  - 2004-05-13 12:00, Sudan and Saudi Arabia
  - 2008-02-02 06:00, Saudi Arabia
  - 2008-03-23 12:00, Libya
  - 2009-03-28 18:00, Argentina



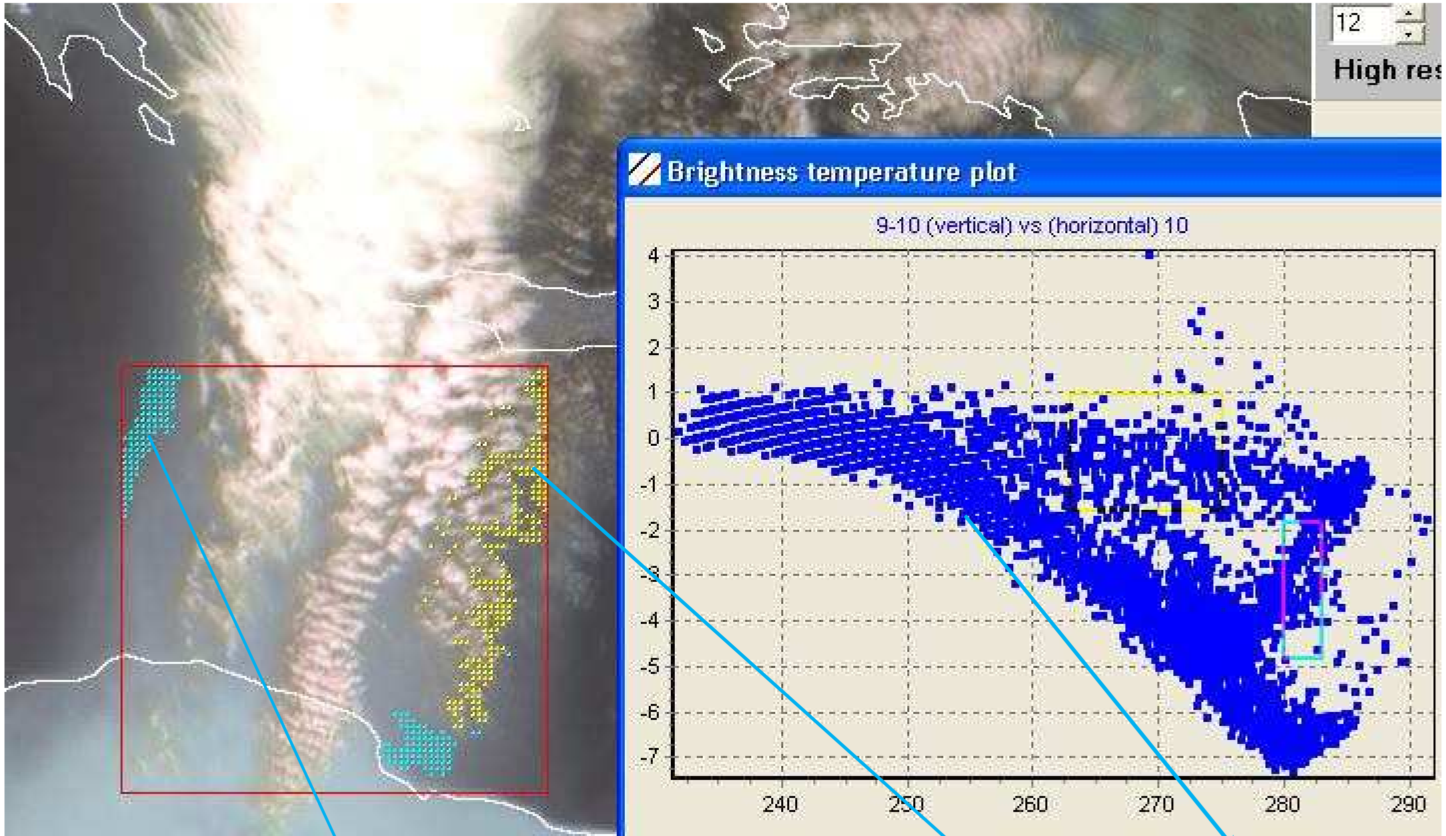
Size behaviour

Dust Ø 2 µm	Σa=0.1	Σs=0.05
Dust Ø 20 µm	Σa=1.2	Σs=0.06
Cross-section	x1200	x120
Mass (20/2)	x1000	
Section (20/2)	/100	

Absorption is proportional to particle mass, not dependent on particulation
Scattering is under-proportional to mass

	Σa	Σs	
Dust Ø 2 µm	0.1	0.05	
Dust Ø 20 µm	1.2	0.06	
CrossSect 20/2	1200		120
Sect/mass	10		

Dust and water vapour in competition



Dust predominance

Water vapour predominance

Semitransparency arc

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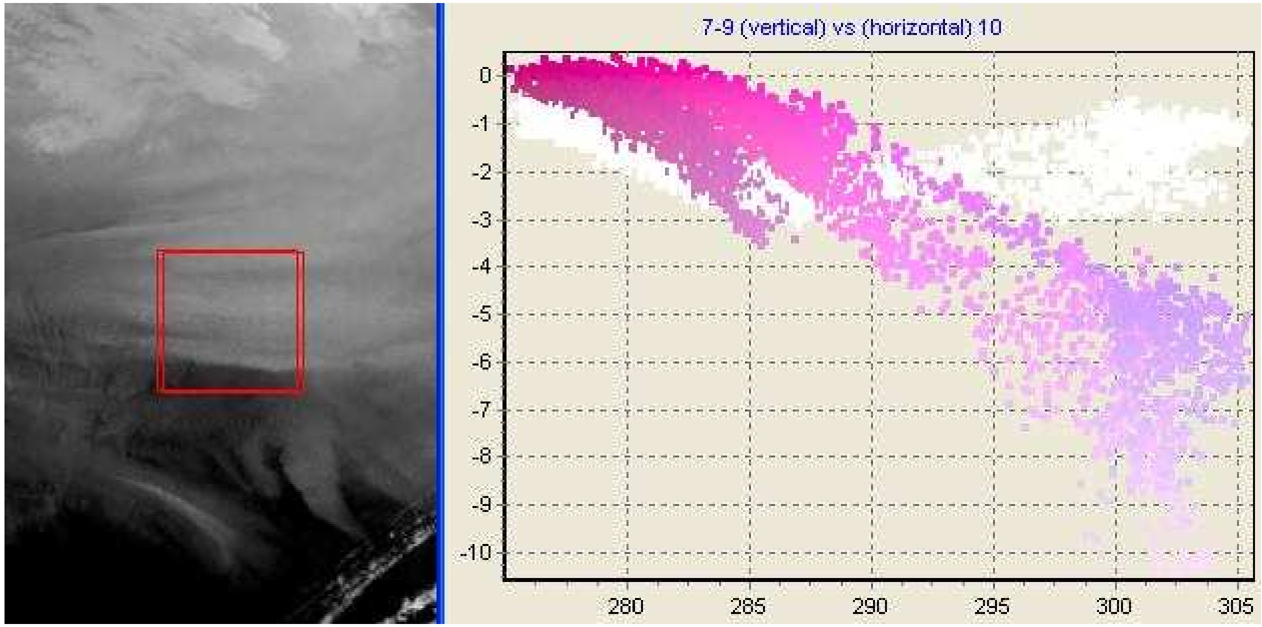
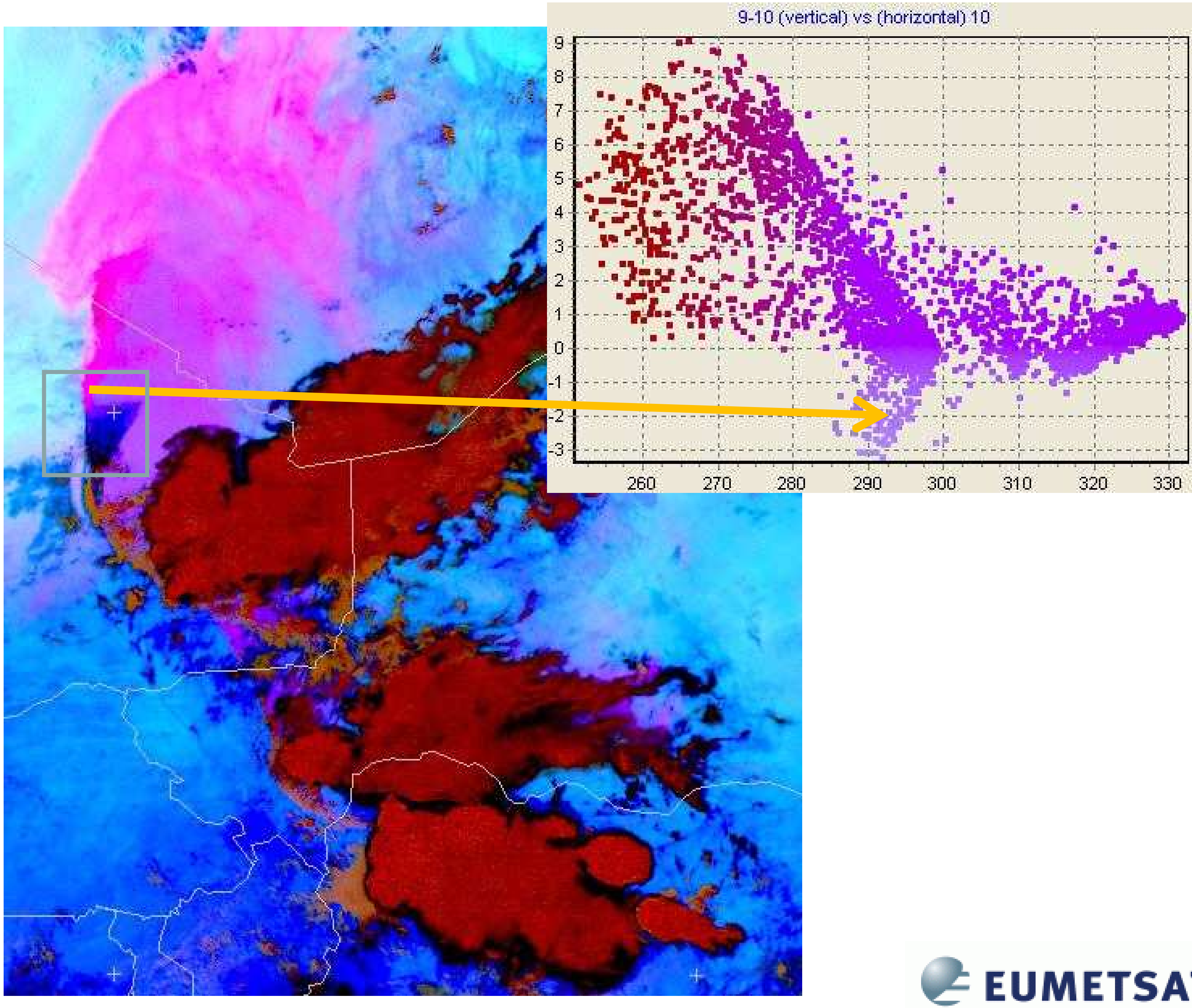
2006-Feb-23 12:00 Sahara desert, 10E, 27N





2010 Jun 09 12:30 UTC
Dust (and convection) over
the Sahara desert
DUST RGB

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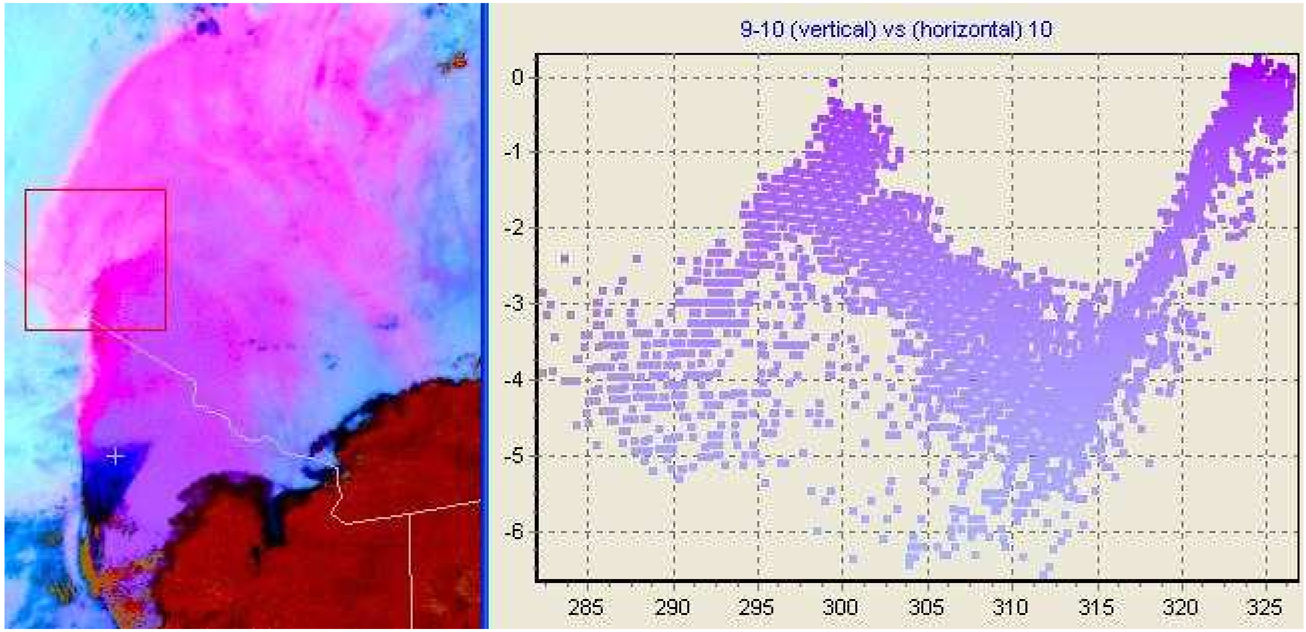
9-10 (vertical) vs (horizontal) 10
0
-1
-2
-3
-4
-5
-6
285
290
295
300
305
310
315
320
325

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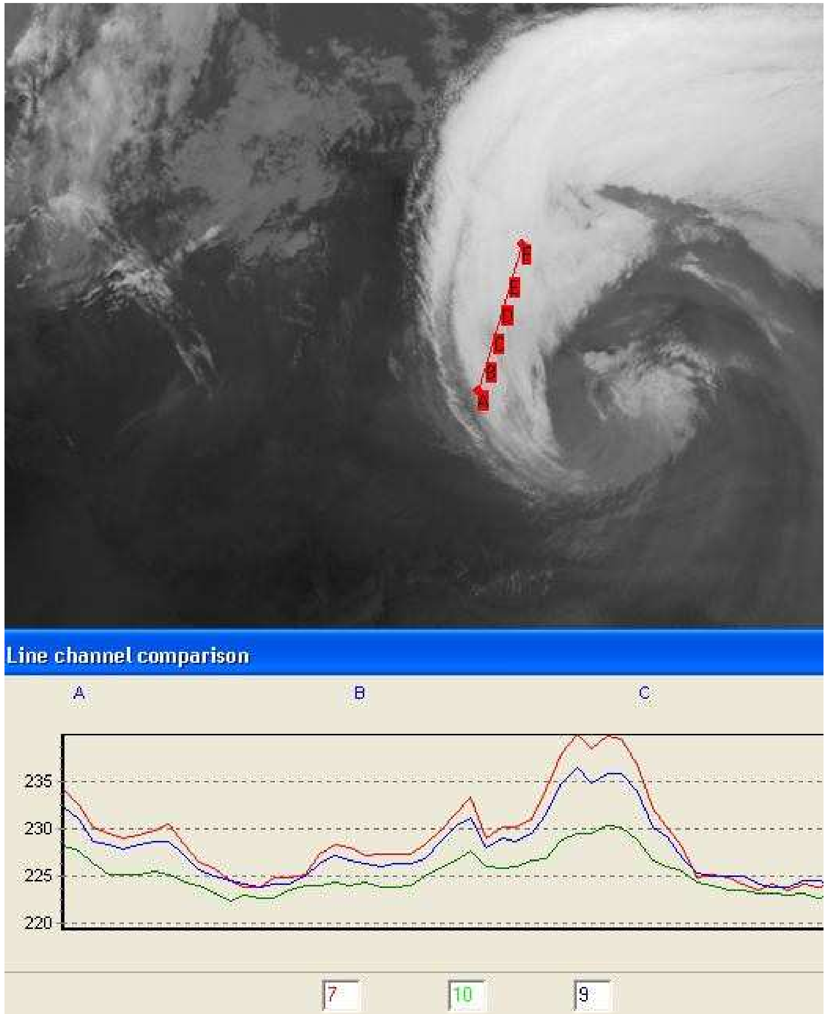
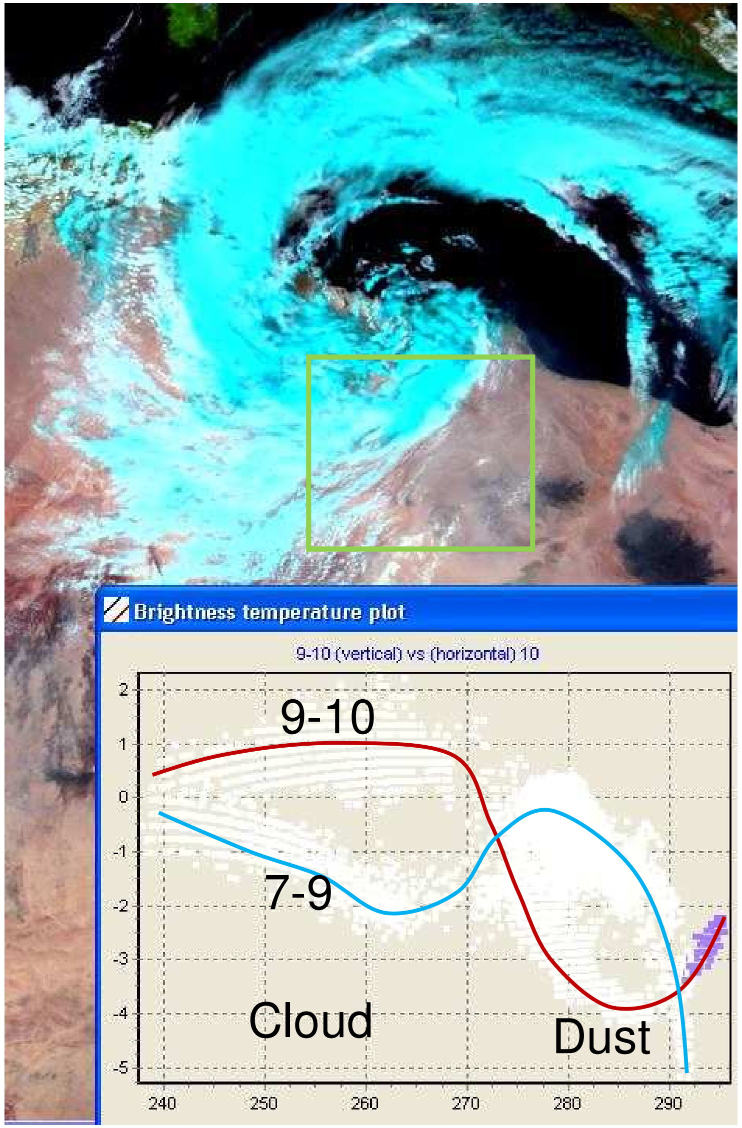
Cloud with dust shows 7-9-10 big differences

2007-Feb-22 12:00 Sahara desert, 7E, 32N



Cloud with dust shows 7-9-10 big differences

2007-March-09 12:00 Sahara desert, 14E, 29N



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•Models of the Aerosols of the Lower Atmosphere and the Effects of Humidity variations on their optical properties. P. Shettle, R W Fenn. Sept.1979

•Absorption of sunlight by dust as inferred from satellite and ground-based remote sensing. Y J Kaufman et al.

•Geophysical Research Letters, vol.28, no.8 1497-82, April 2001

•Desert Dust in the global system. Springer. A S Goodie, N J Middleton

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