# Satellite observation of dust

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


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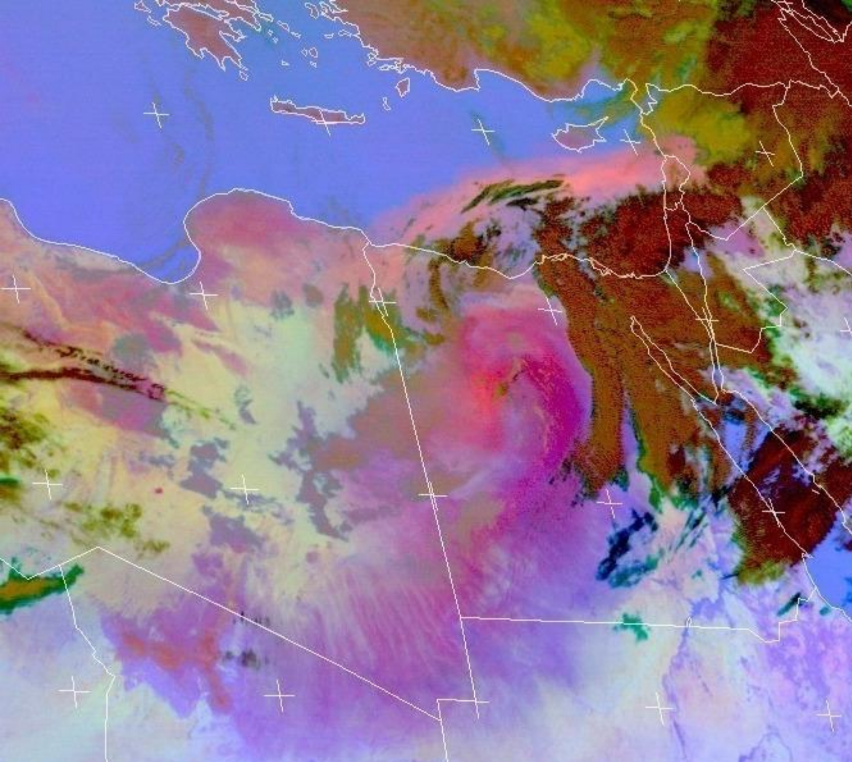
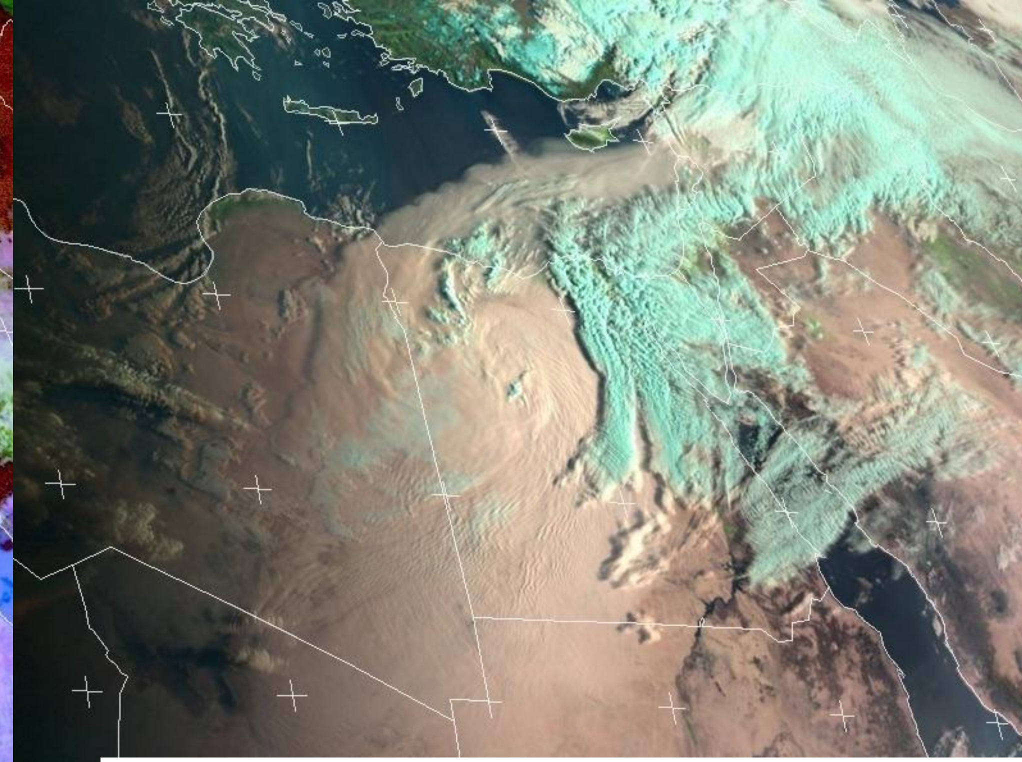
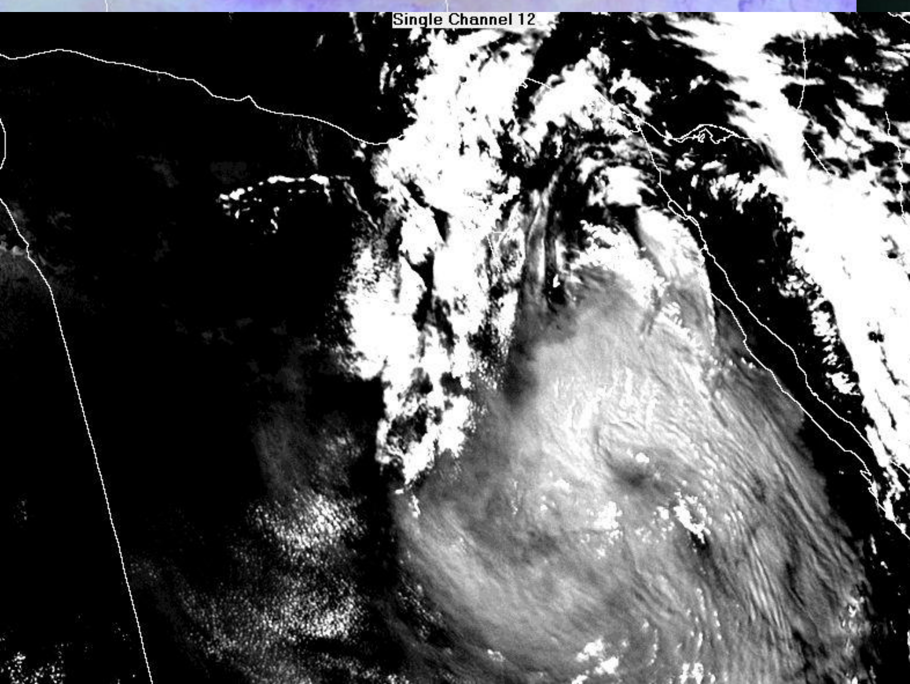
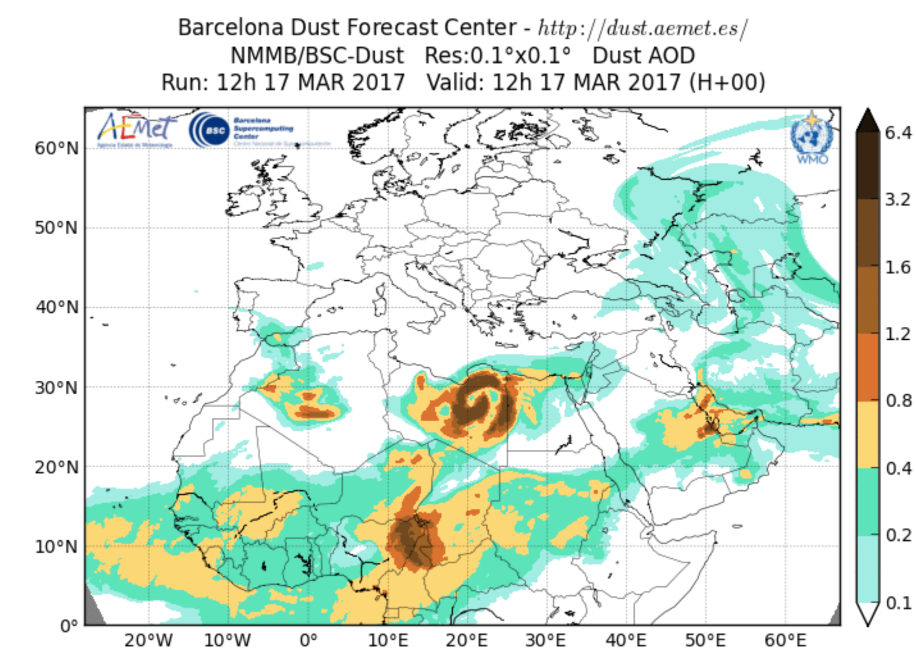
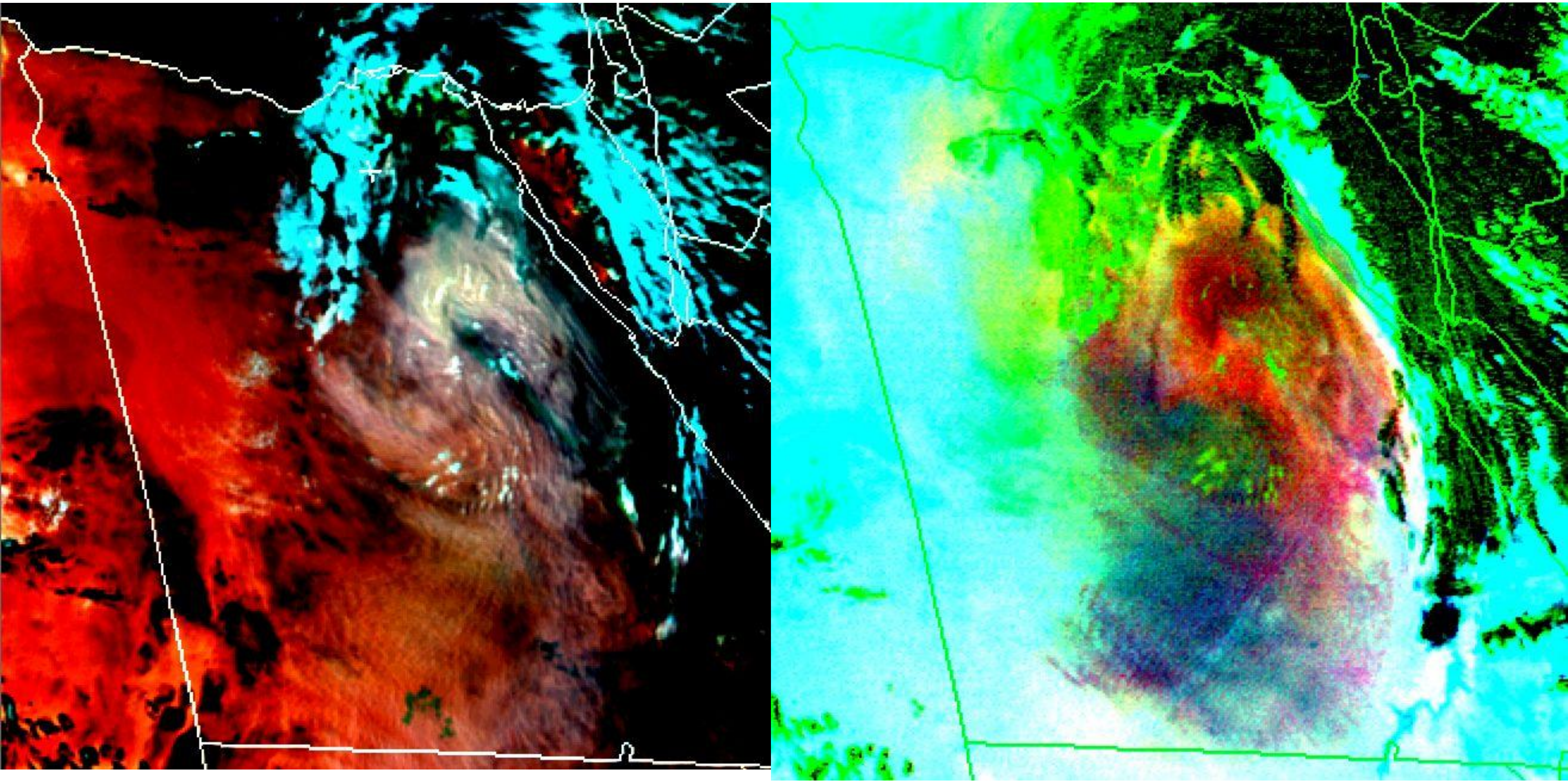




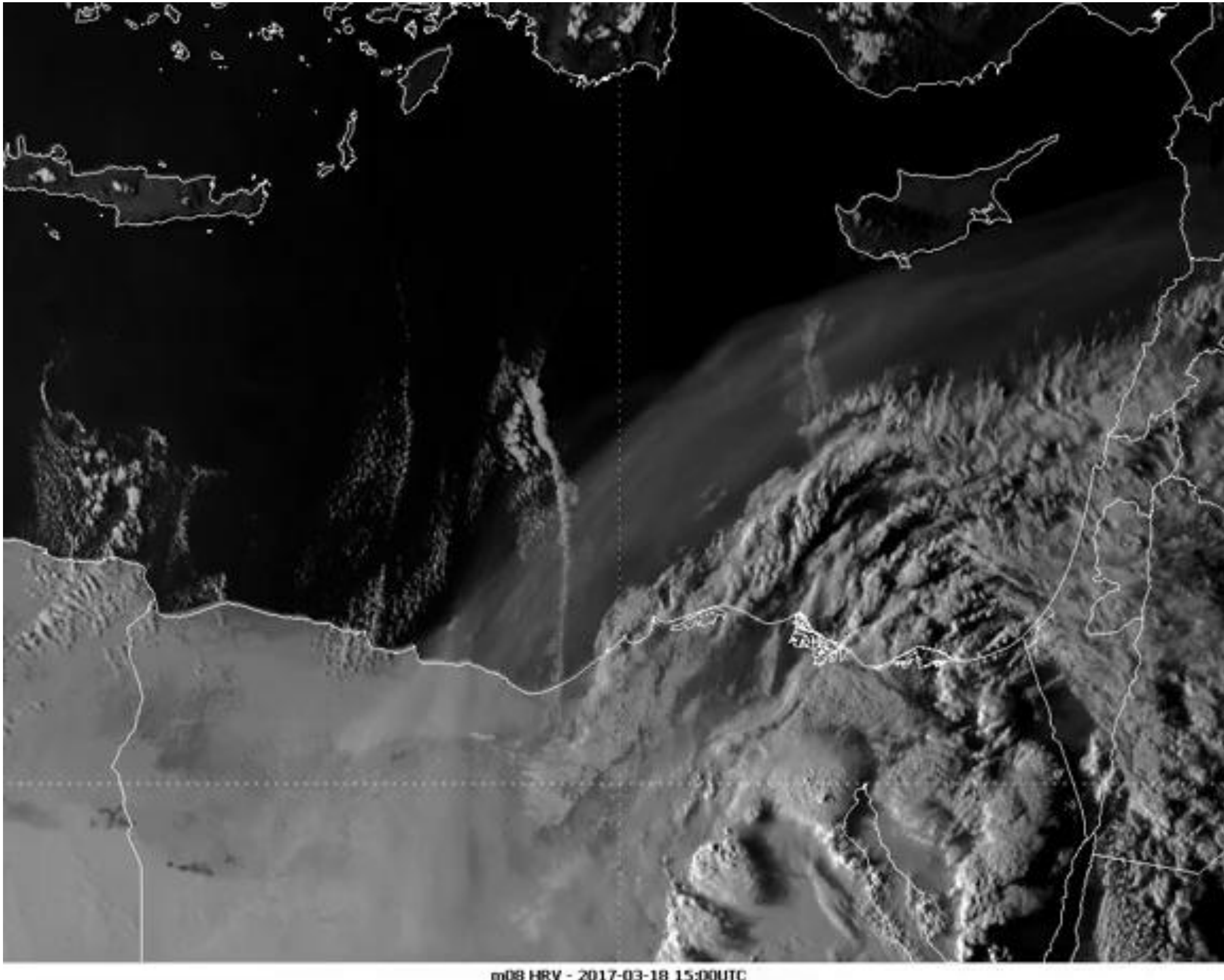

Single Channel 12


Barcelona Dust Forecast Center - http://dust.aemet.es/
NMMB/BSC-Dust Res:0.1°x0.1° Dust AOD
Run: 12h 17 MAR 2017 Valid: 12h 17 MAR 2017 (H+00)
60°N
50°N
40°N
30°N
20°N
10°N
0°
20°W
10°W
0°
10°E
20°E
30°E
40°E
50°E
60°E
6.4
3.2
1.6
1.2
0.8
0.4
0.2
0.1

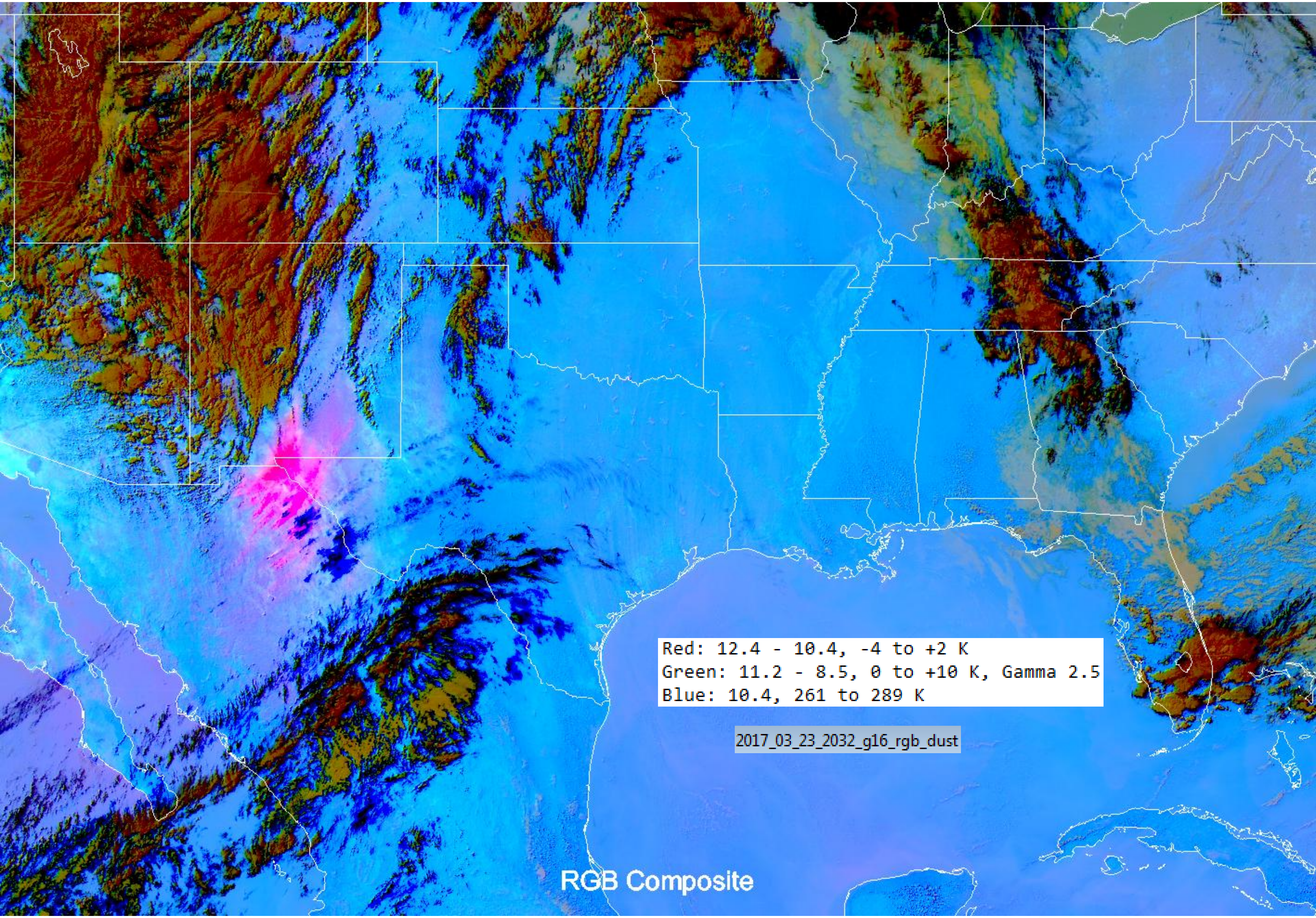
# Enhancing dust: solar and IR



# Is a solar image enough?




ETSAT




GOES-16

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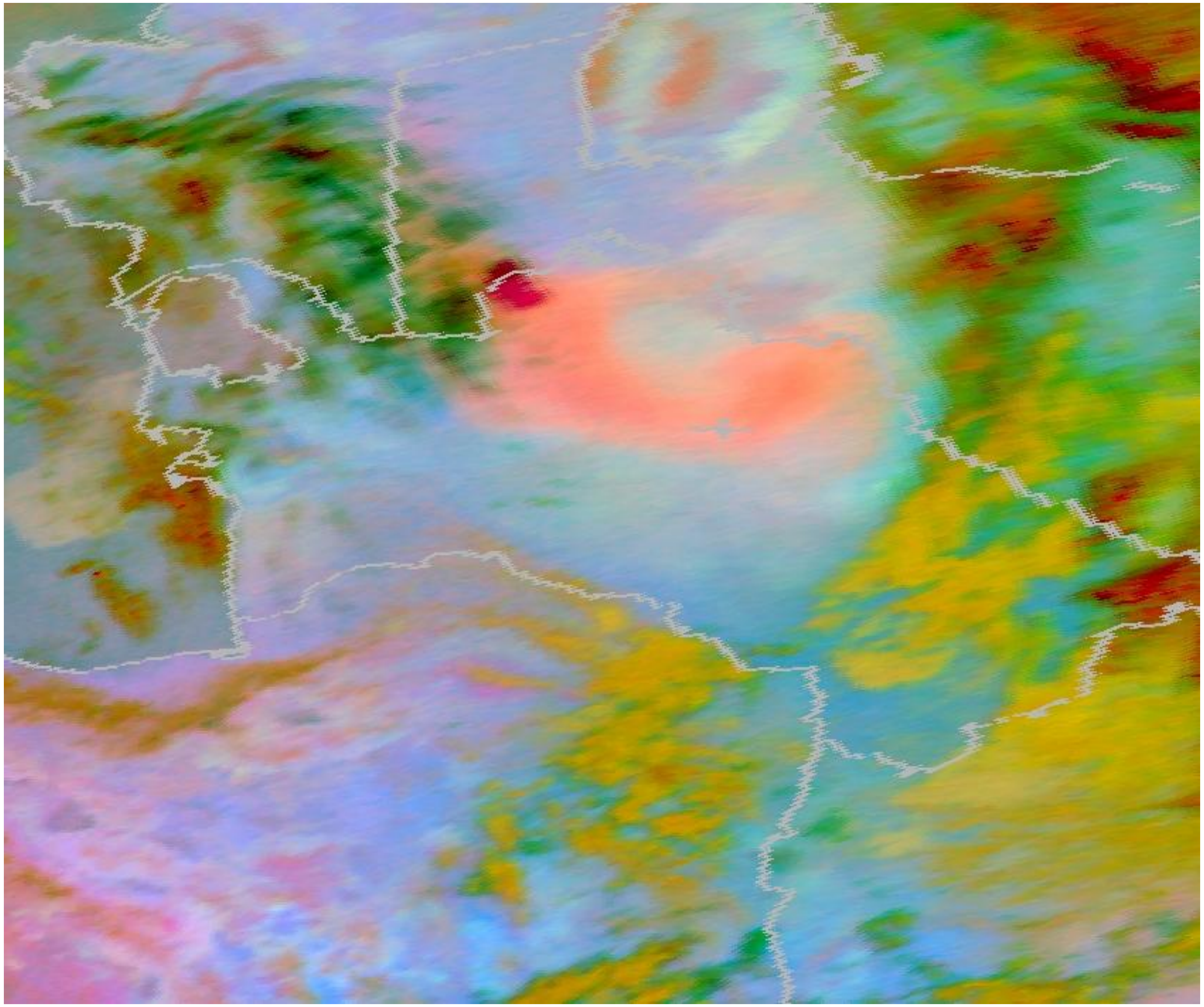
# “Peach” for big particle dust



Met-10 2009-04-02 06Z Infrared window composite

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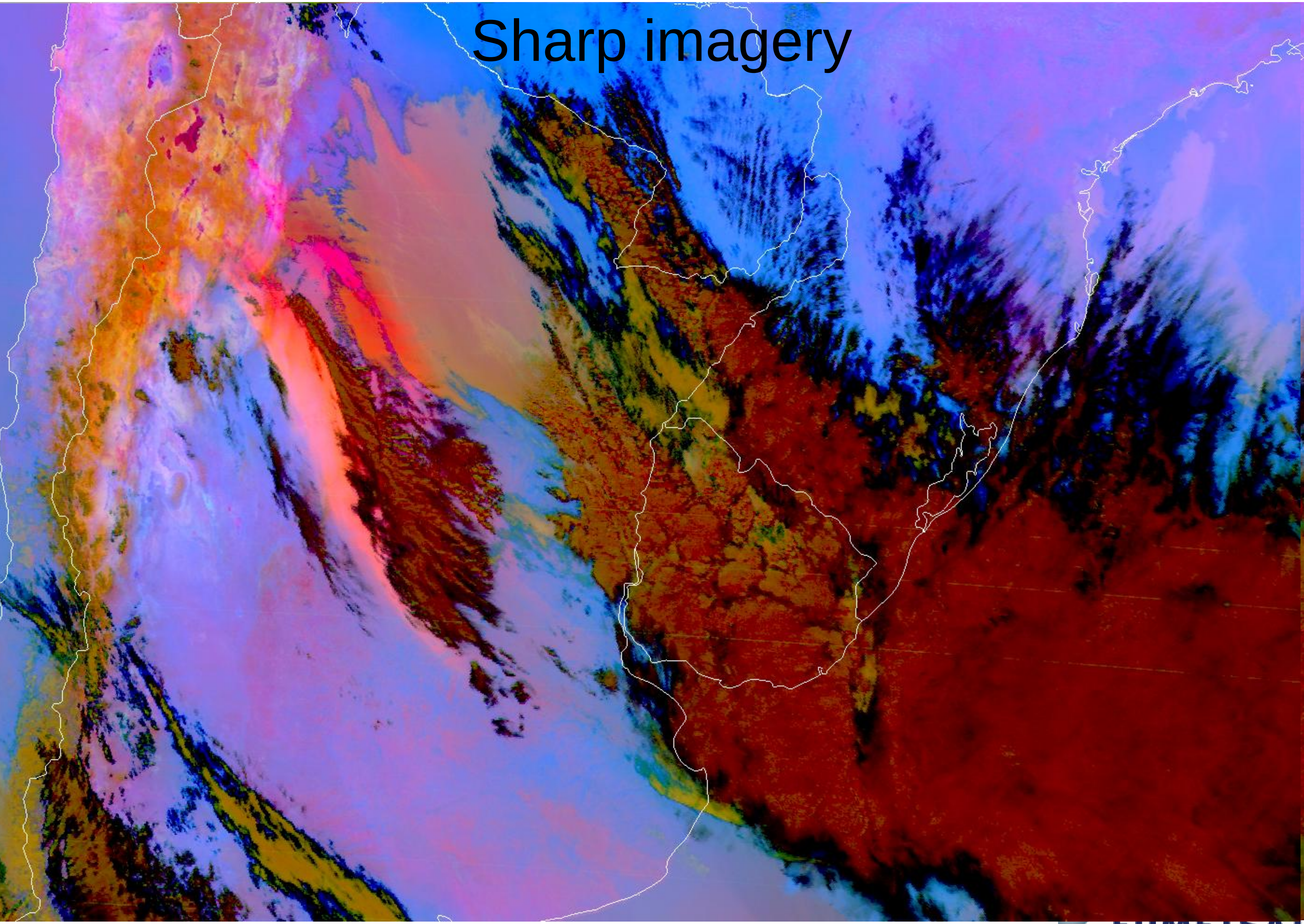
# Sharp imagery



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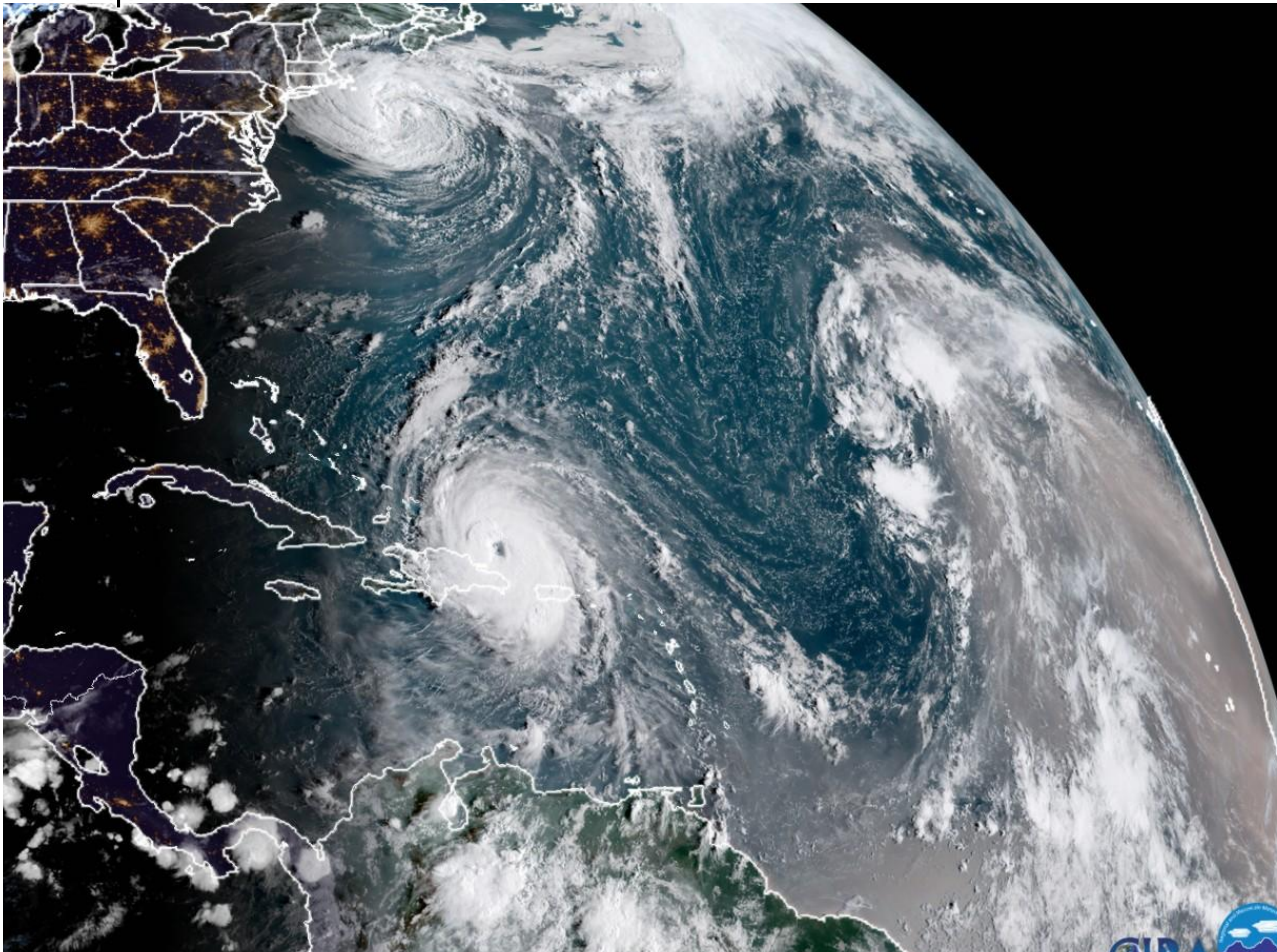
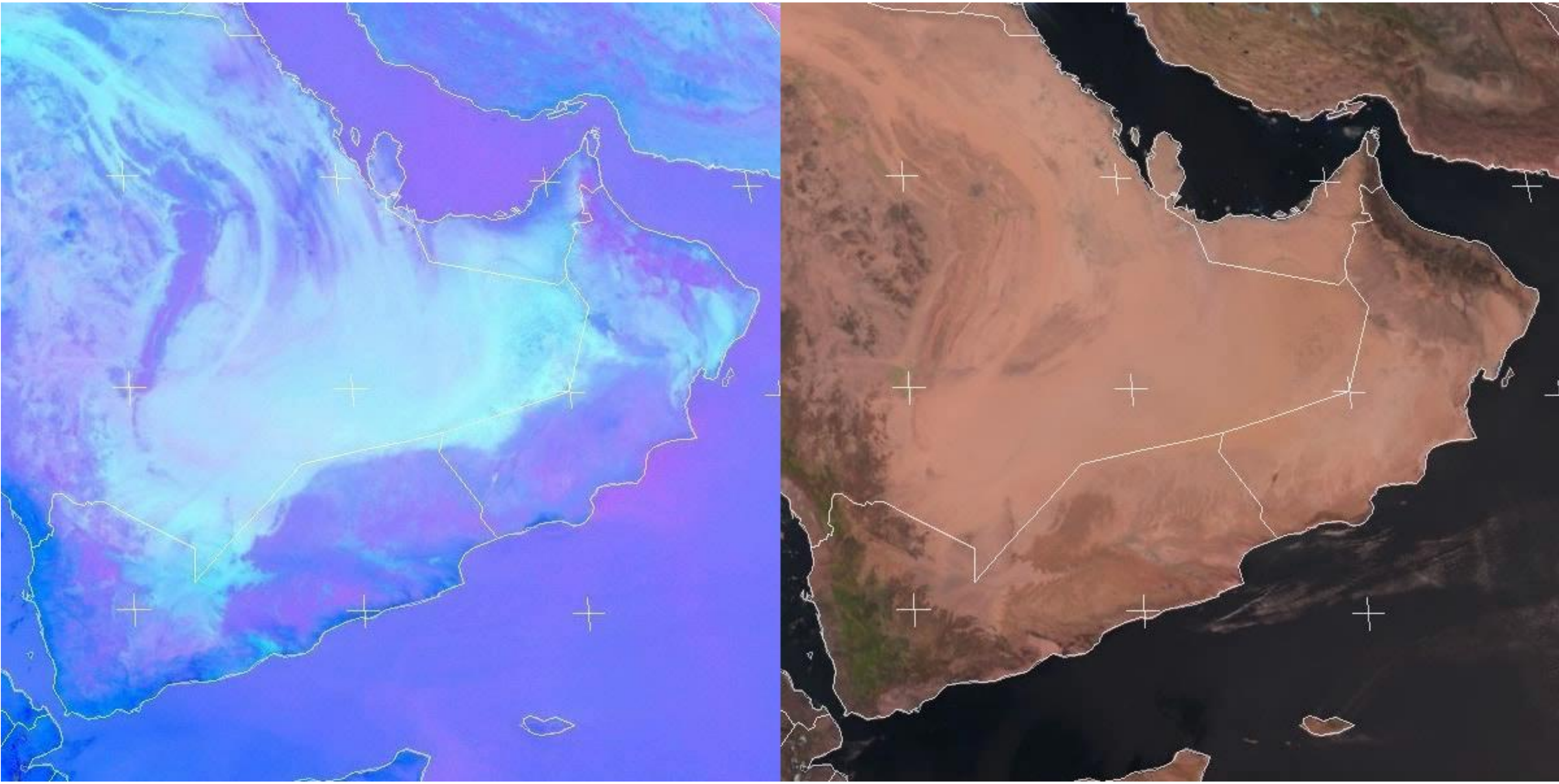
# Oblique  view GOES-16 sees Atlantic

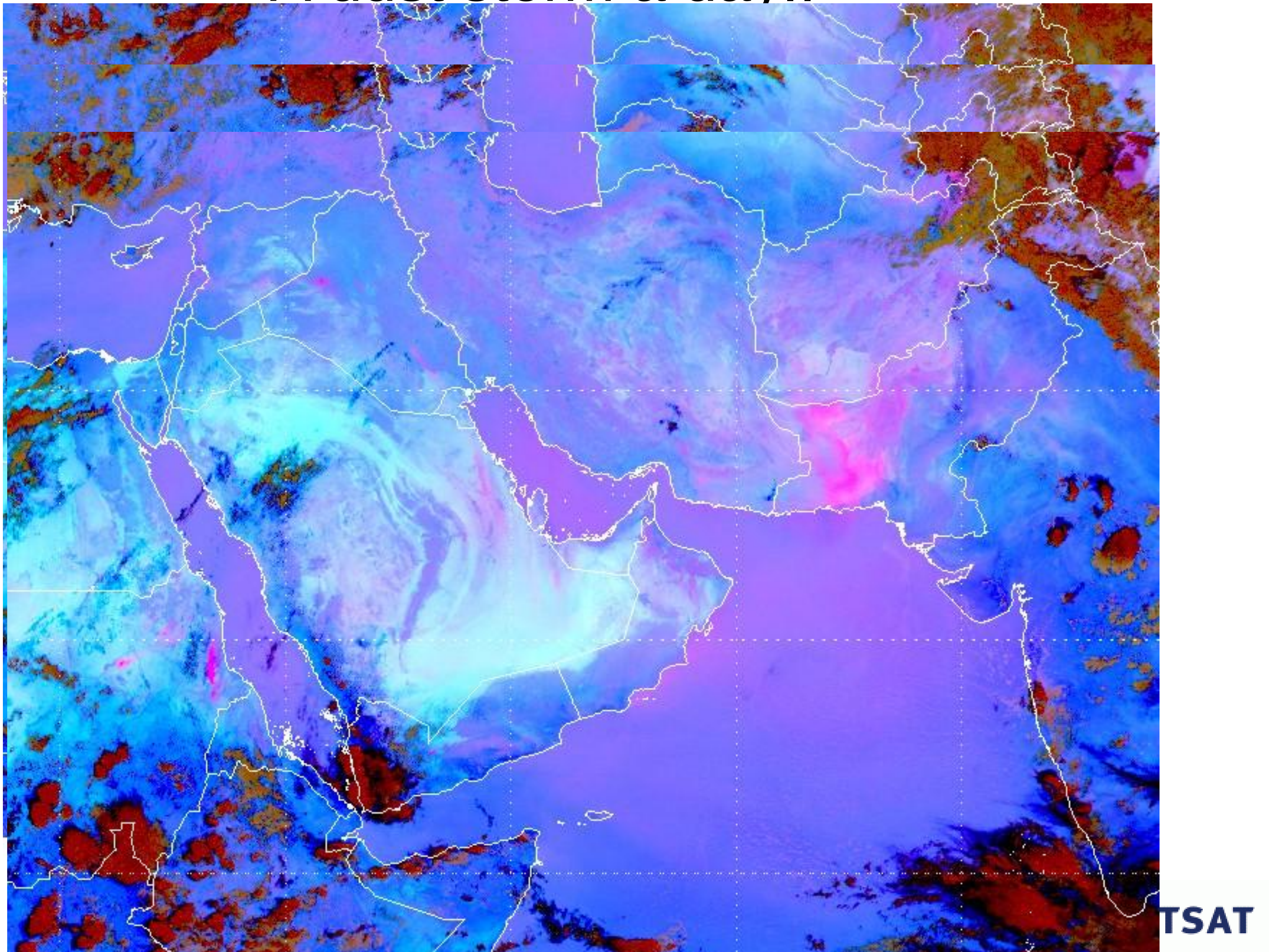


# Animation

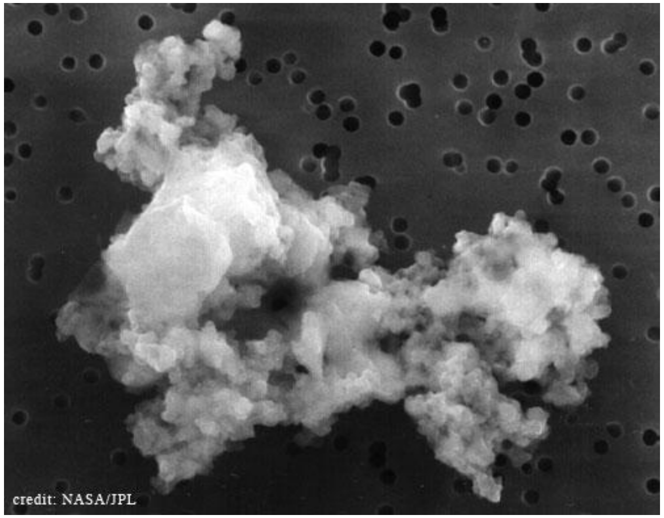


2017_05310600-06011100_m08

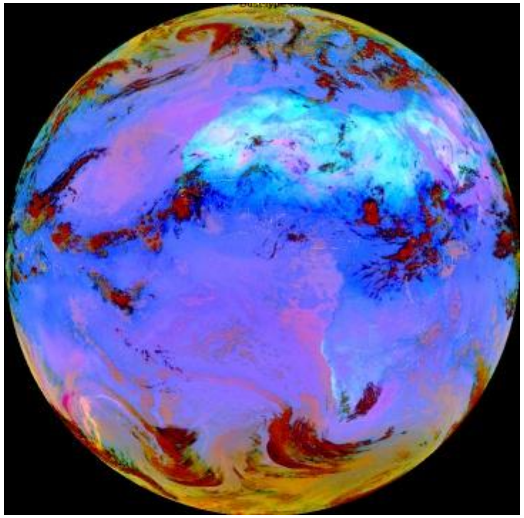
# A dust storm a day..



# Can a satellite see dust particles ?




← Dust particle 10 µm →



← Earth globe 10 Mm →

- From micro to mega, twelve orders of magnitude difference in size
- $10^{12}$ kg in the atmosphere ($10^{-7}$ of atmospheric mass) = fill all lorries!
- Disputed human contribution to global cooling (S.K. Satheesh, 2006)
- Inert tracer for atmospheric circulation
- Life vector (Saharan protozoa and bacteria to the Caribbean)

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# Better dust detection in the infrared?

| *Best contrast ?* | DAY | NIGHT |
|---|---|---|
| IR | | |
| VIS | | |

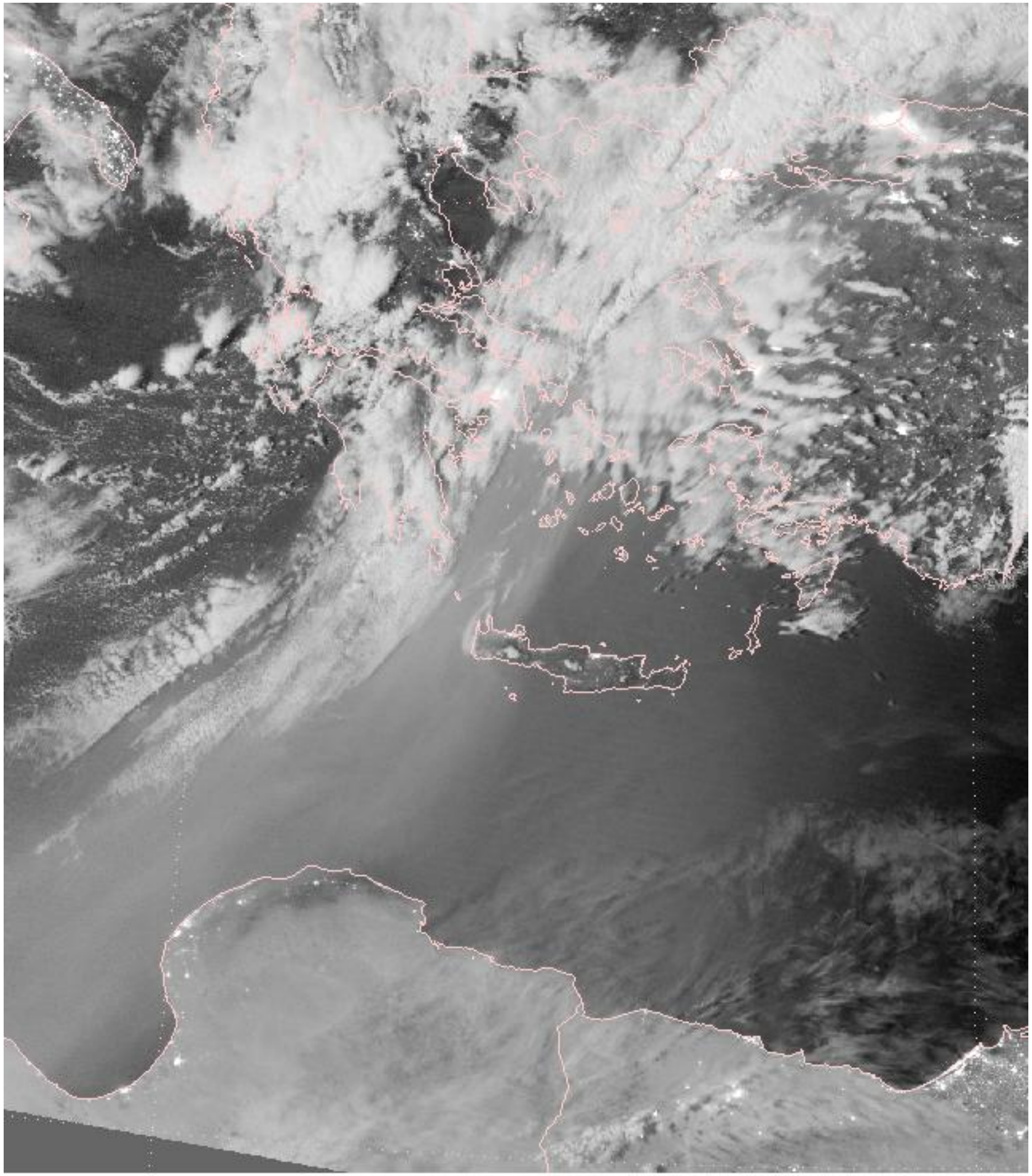
Choose one of the four fields, the one with best contrast between free-surfaces and dust areas

| *Ocean* | DAY | NIGHT |
|---|---|---|
| IR | strong | strong |
| VIS | very strong | A/N/A |

| *Desert* | DAY | NIGHT |
|---|---|---|
| IR | very strong | weak |
| VIS | weak | 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. Dust is not raised by thermals, too.
- On VIS imagery over **water**, dust is easy to note. Over **land**, however, the dust plume and dry surfaces look similar

Consecutive days in Fuerteventura, January 2010



snpp DNB - 2015-02-01 23:45UTC

Dust at the moonlight

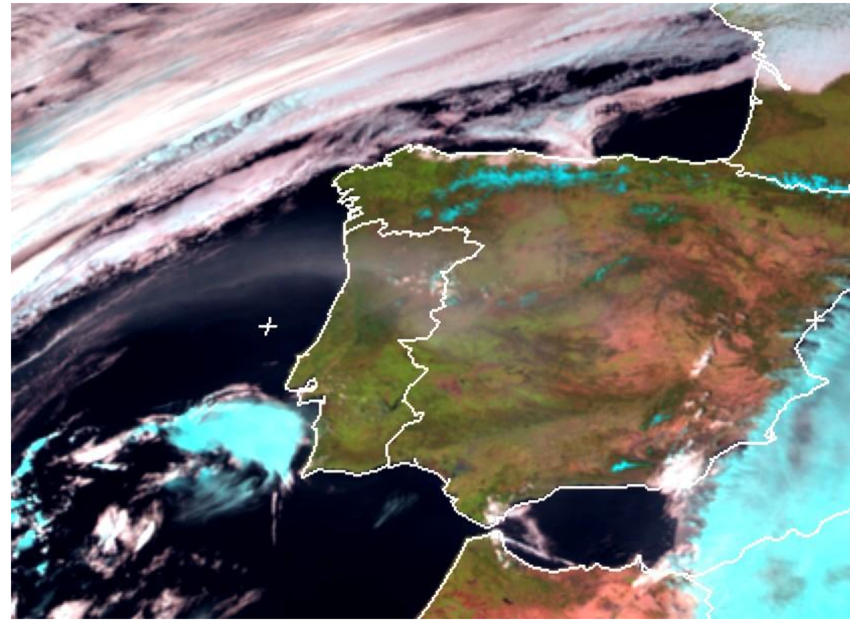
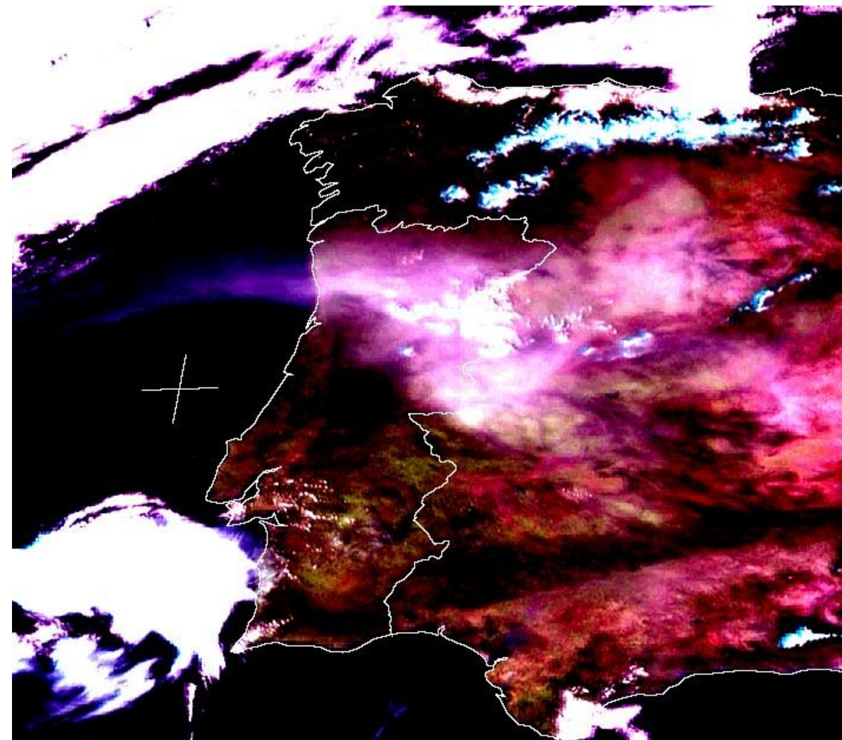
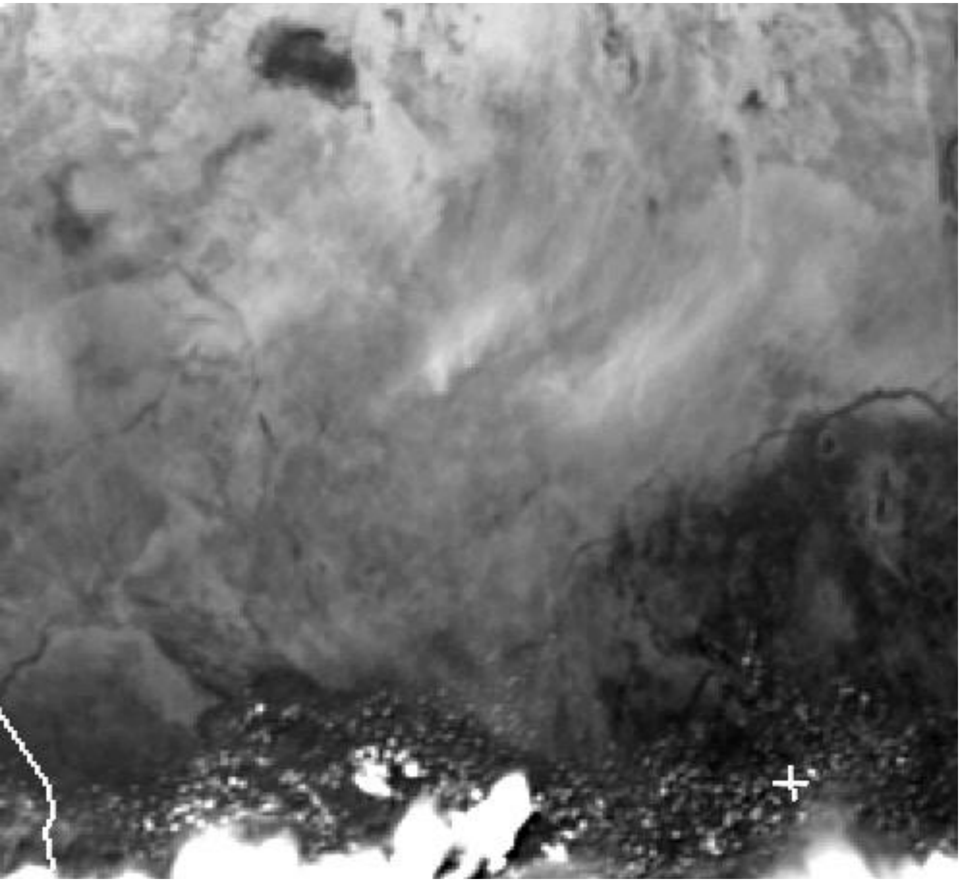


Fig. 1: immagine satellitare MODIS del 21.02.2016 alle 14:00 UTC (NASA'a Aqua- Earth)

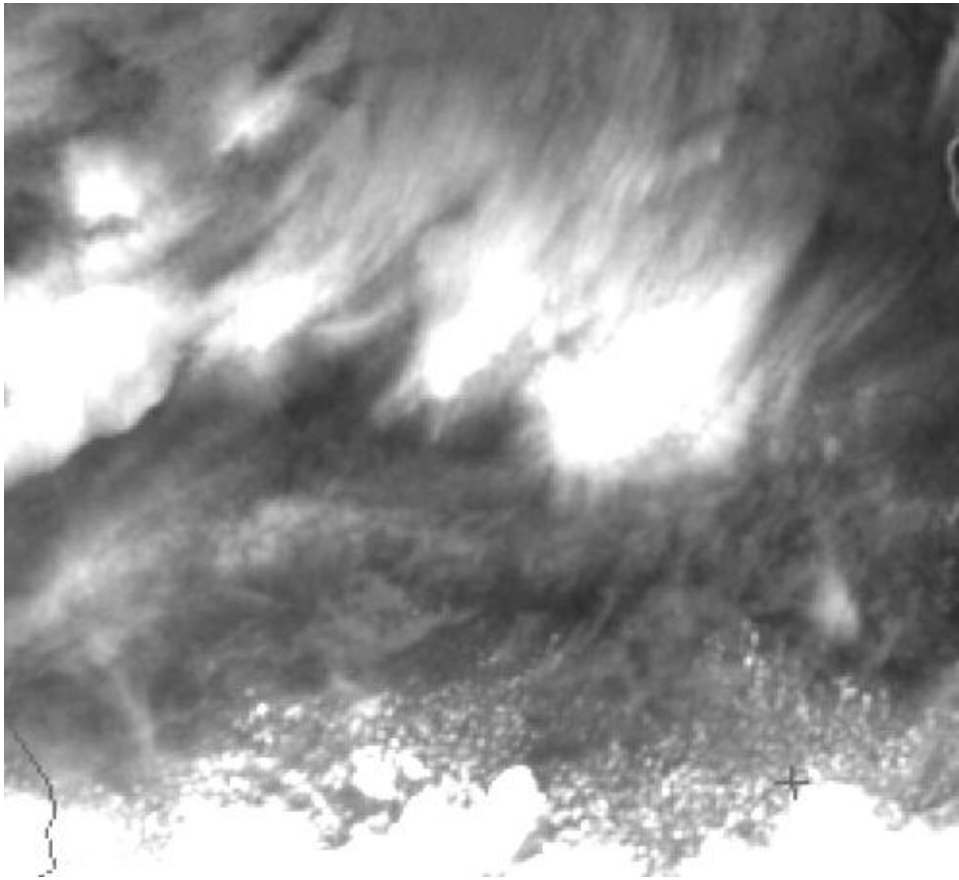


# Dust on solar and infrared images



2004-05-13 13:00 UTC, 0.8 µm

- Dust **reflects** back solar energy to space
- Midday, unfavourable reflection conditions



Same date and time, 10.8 µm

- Dusty air rises (**cools** down)

Desert scene, Sudan

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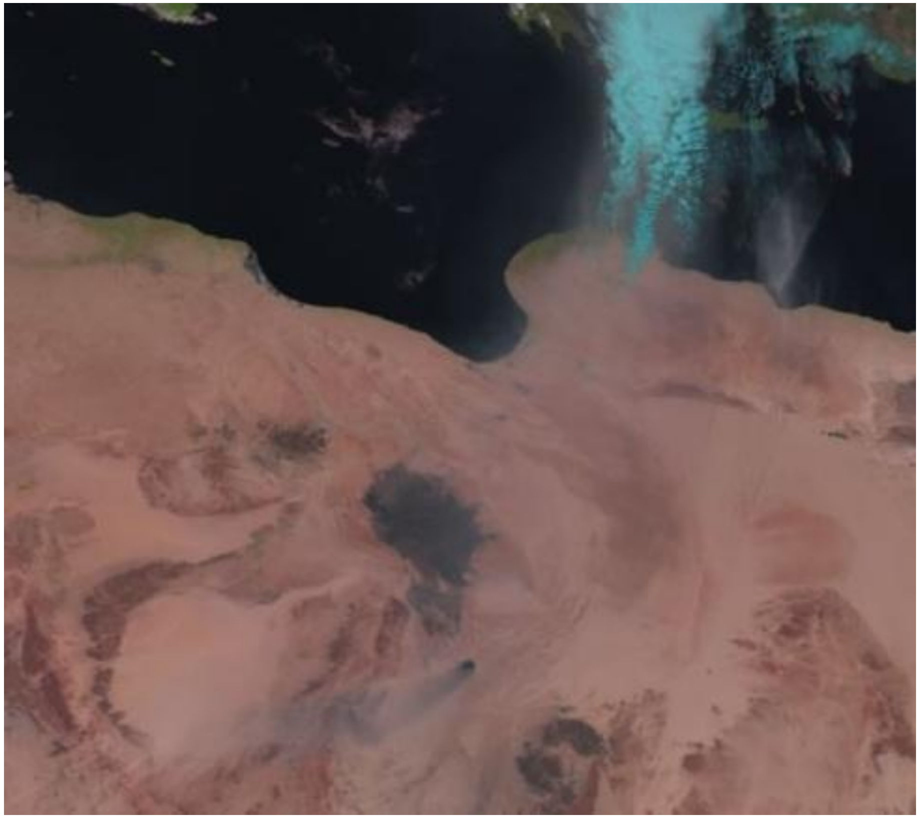
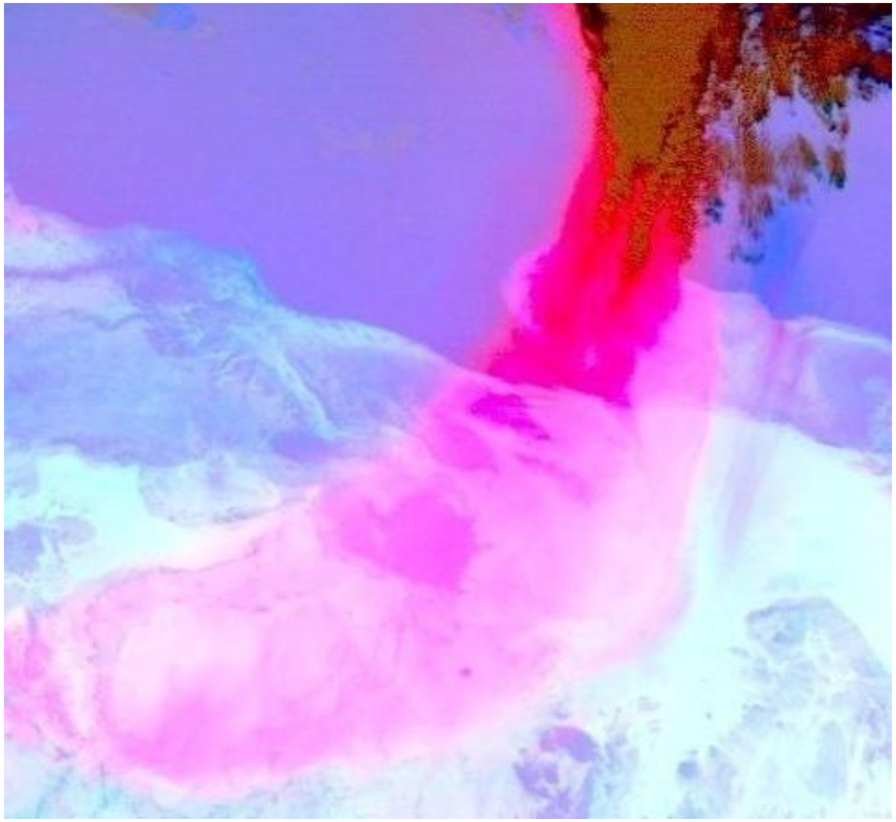
# DUST RGB composite:
# the strength of infrared for dust detection



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



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

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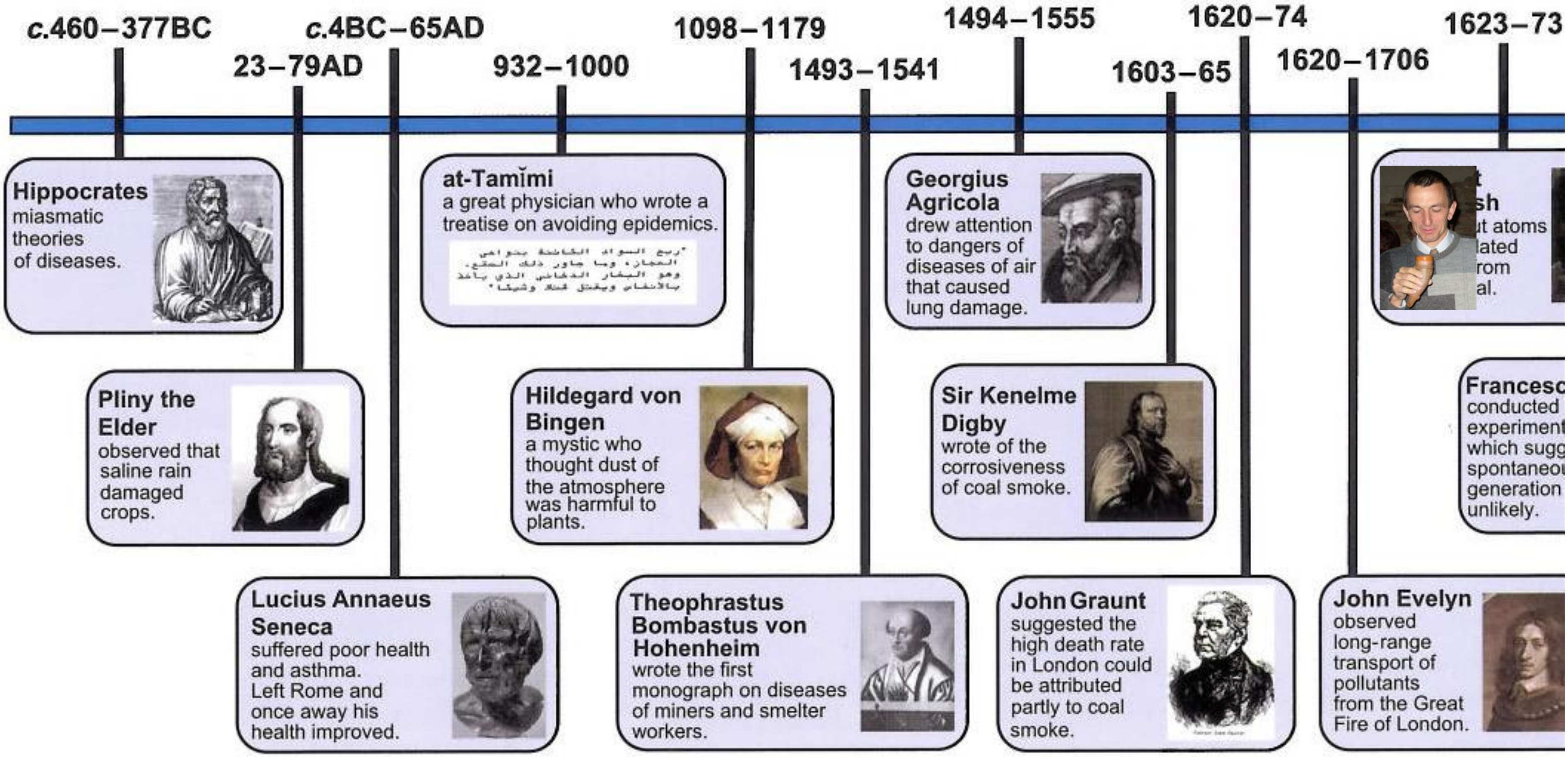
# Aerosol and health




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

Impact on: agriculture (fertile fields), climate (radiative balance), aviation (ash in routes)

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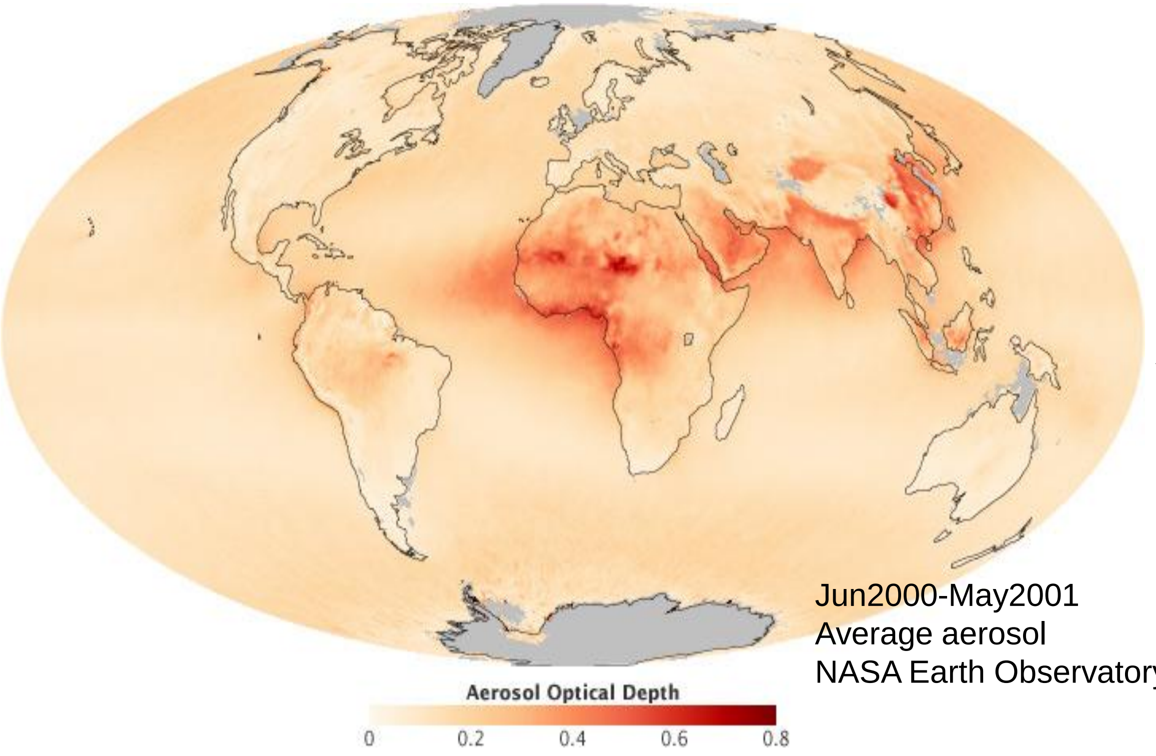
# Aerosol is more than dust




Jun2000-May2001
Average aerosol
NASA Earth Observatory

Dust
Marine salt
Smoke
(biomass burn,
industrial carbon)
Ash
Pollen
Ice crystals
?

HUMAN

Forward fraction=exp(-AOD)

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# Contents

# Dust characteristics

- Dust storms occasionally reach up to 1km | 5km | 10km **height**, and are as thick as 100m | 2km | 5km

- Over land, dust optical depth is typically around 0.1 | 0.5 | 1 or 2 | 10 | 50 for storms, in the visible range. Efficient **thickness** in the IR is about 40% of those values.

- Dust absorbs and scatters **infrared** radiation in the **Mie | Rayleigh | optical** region

- Aerosol **density** average in the atmosphere $10^{-7}$ kg/m3 ( equivalent optical depth 0.1 | 1 | 3 )

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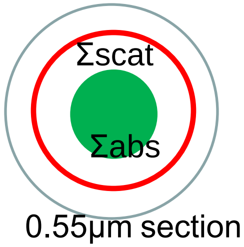
# Dust characteristics

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

- Over land, dust optical depth is typically around 0.5 or 2 for storms, in the visible range. Efficient **thickness** in the IR is about 40% of those values.

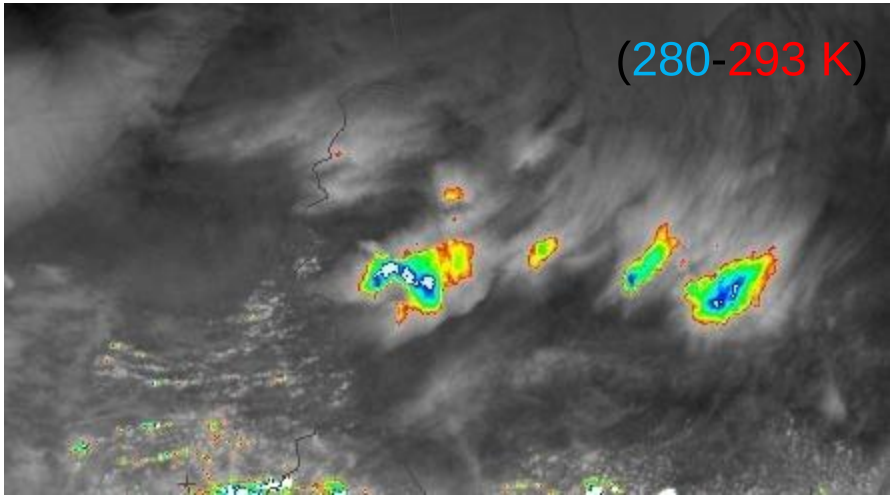
- Dust absorbs and scatters **infrared** radiation in the **Mie** region

- Aerosol **density** average in the atmosphere $10^{-7}$ kg/m3 ( optical depth 0.1)

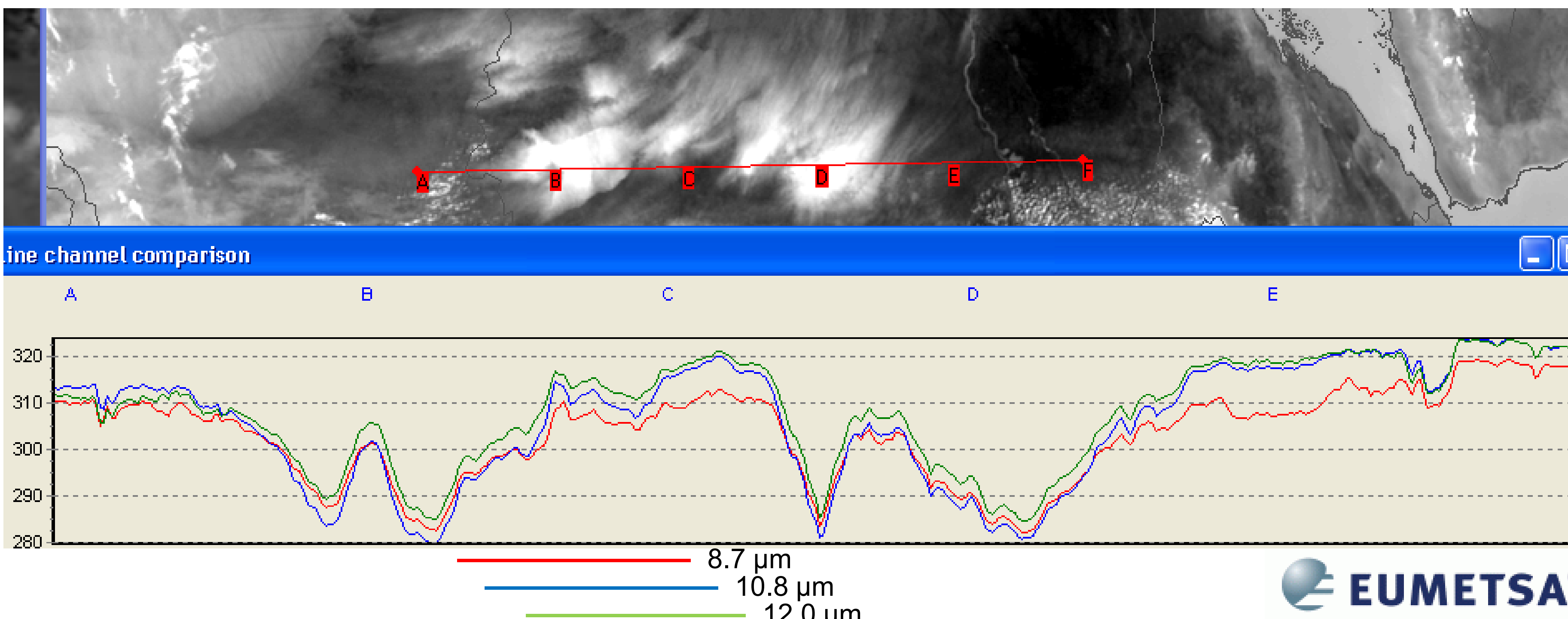

- Dusty air ~ AOD=1 ~ 1 mg/m$^3$ ~ 1 g/m$^2$

# Dust seen at a single IR channel




- -Variable limits for colour enhancement
- -Uncertain nature of the cold area (cloud?)
- -Possible mixture of cloud and dust

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

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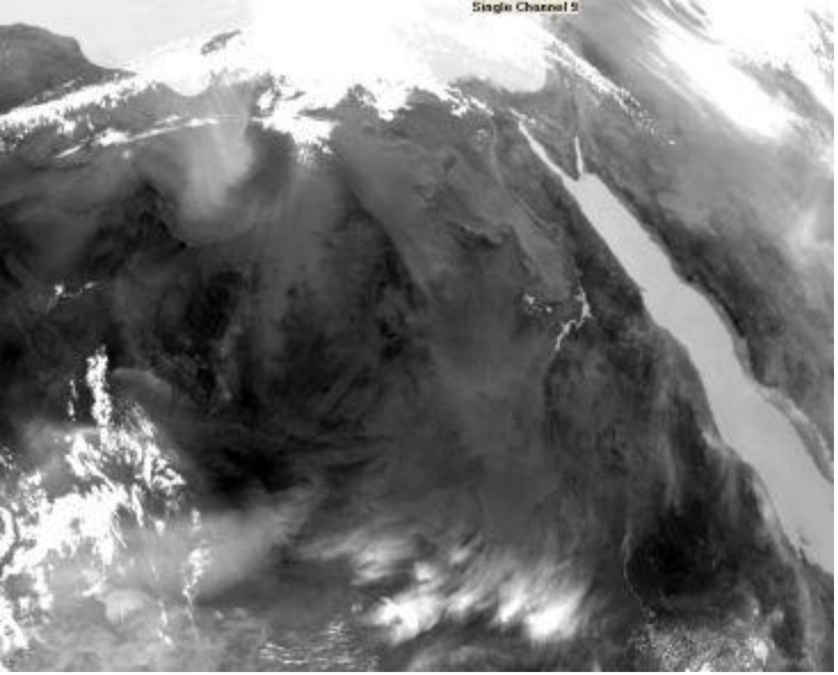
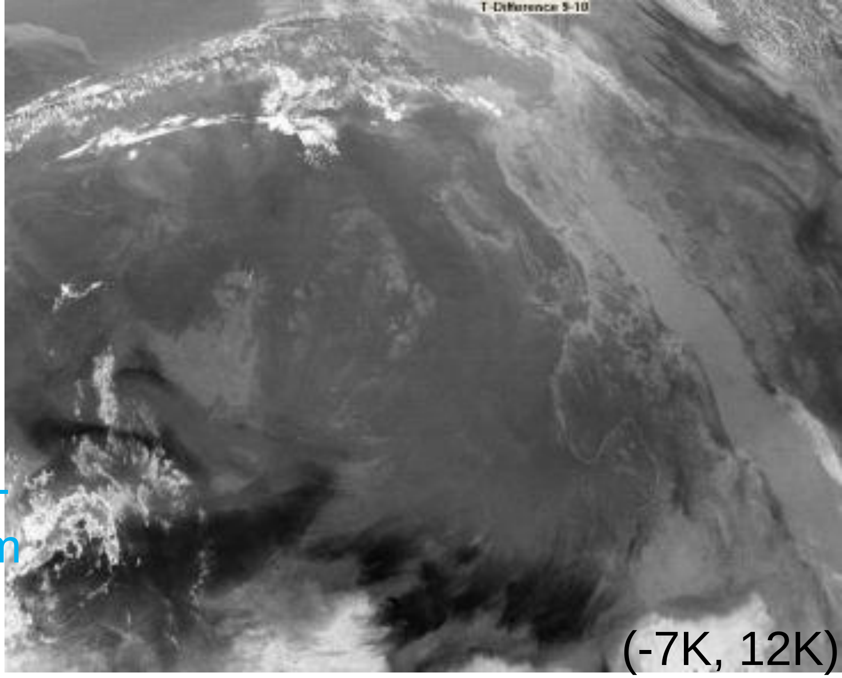
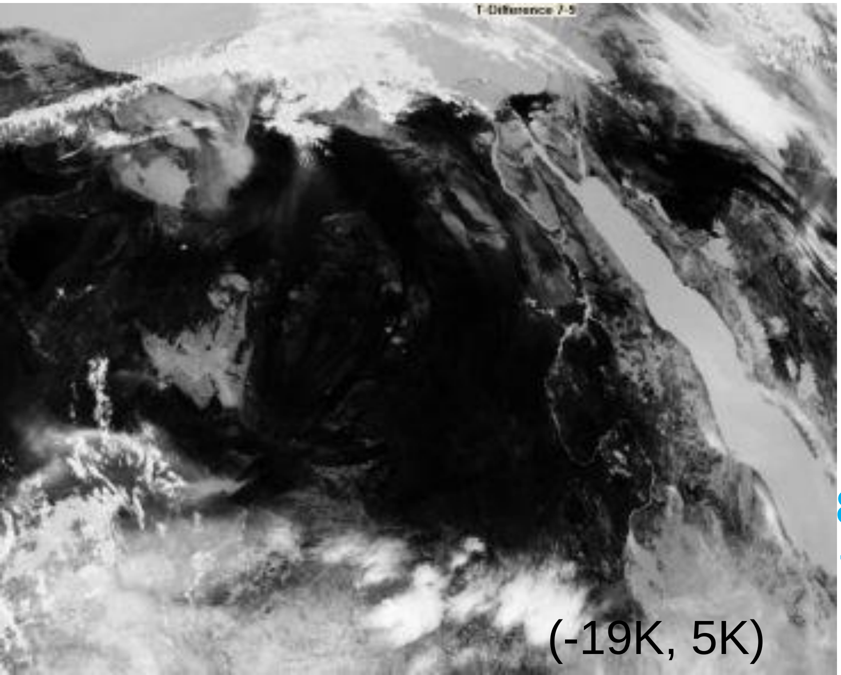



10.8µm

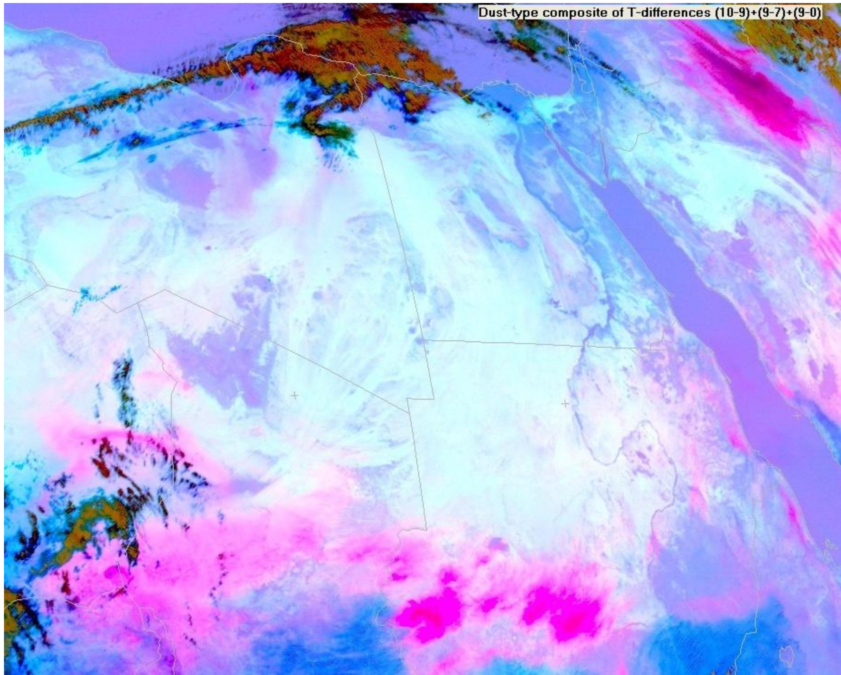



10.8-
12µm

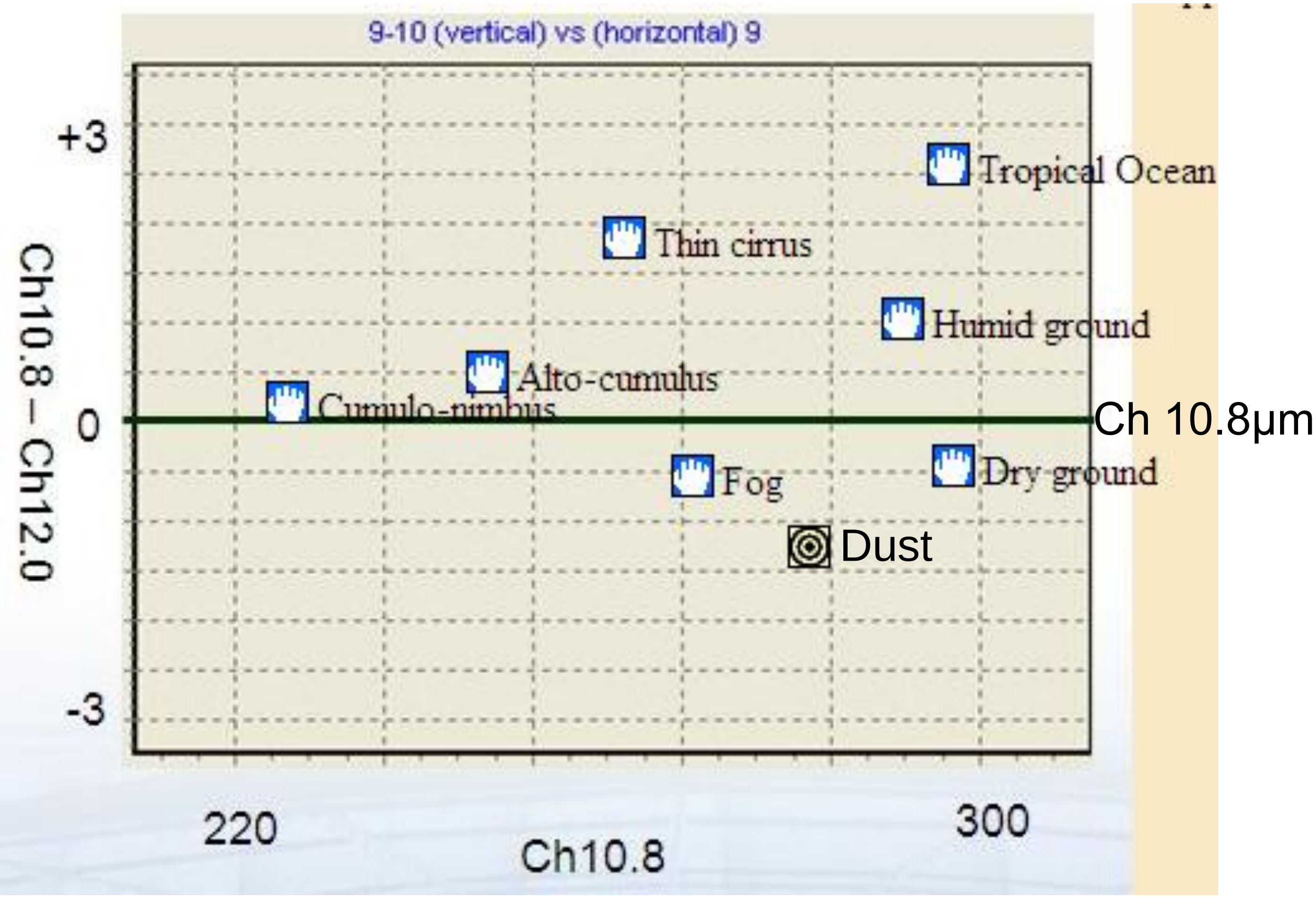
Ch9 (*upper left*), two independent differences, and all together as colour




8.7-
10.8µm



# The 10.8µm-12µm difference (vertical)

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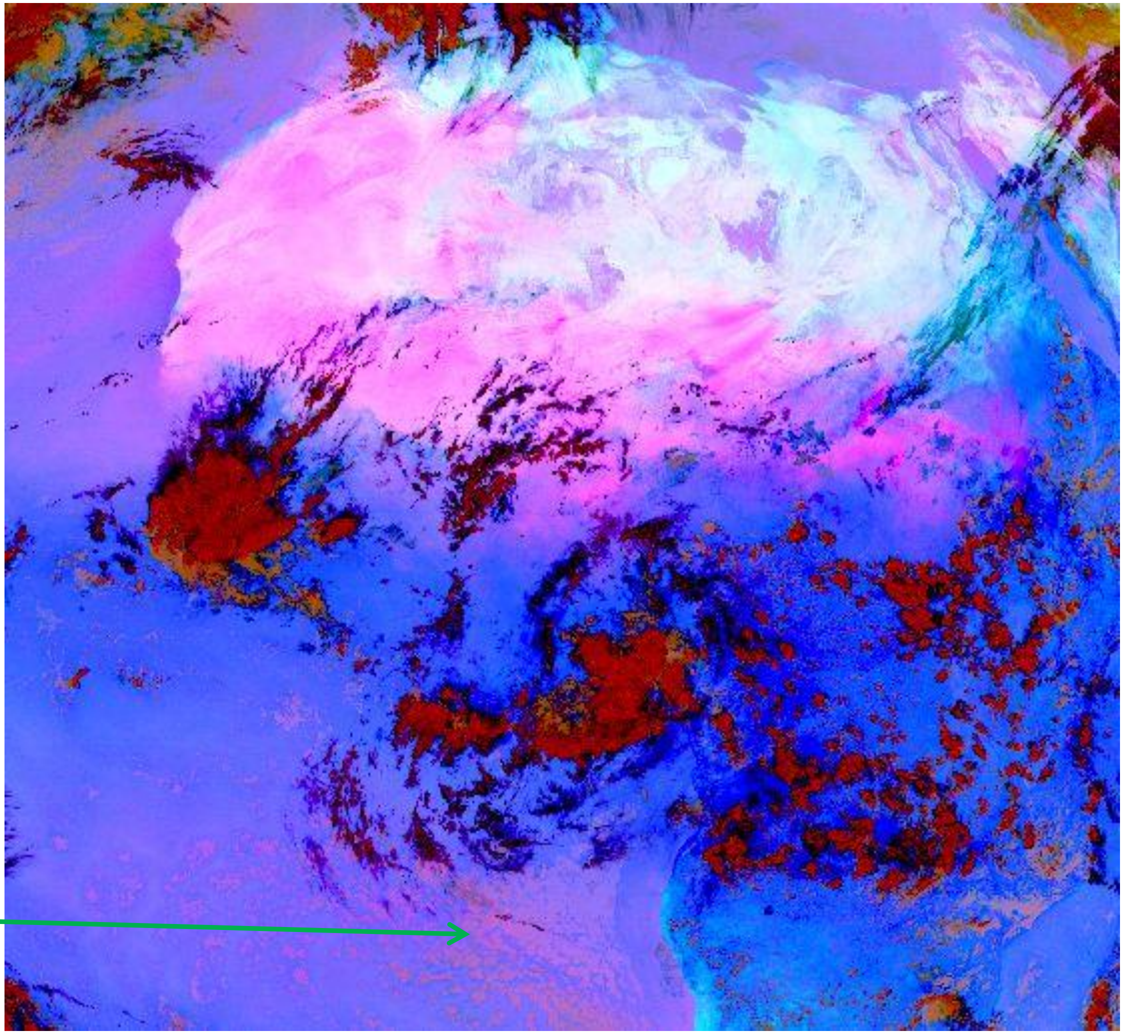
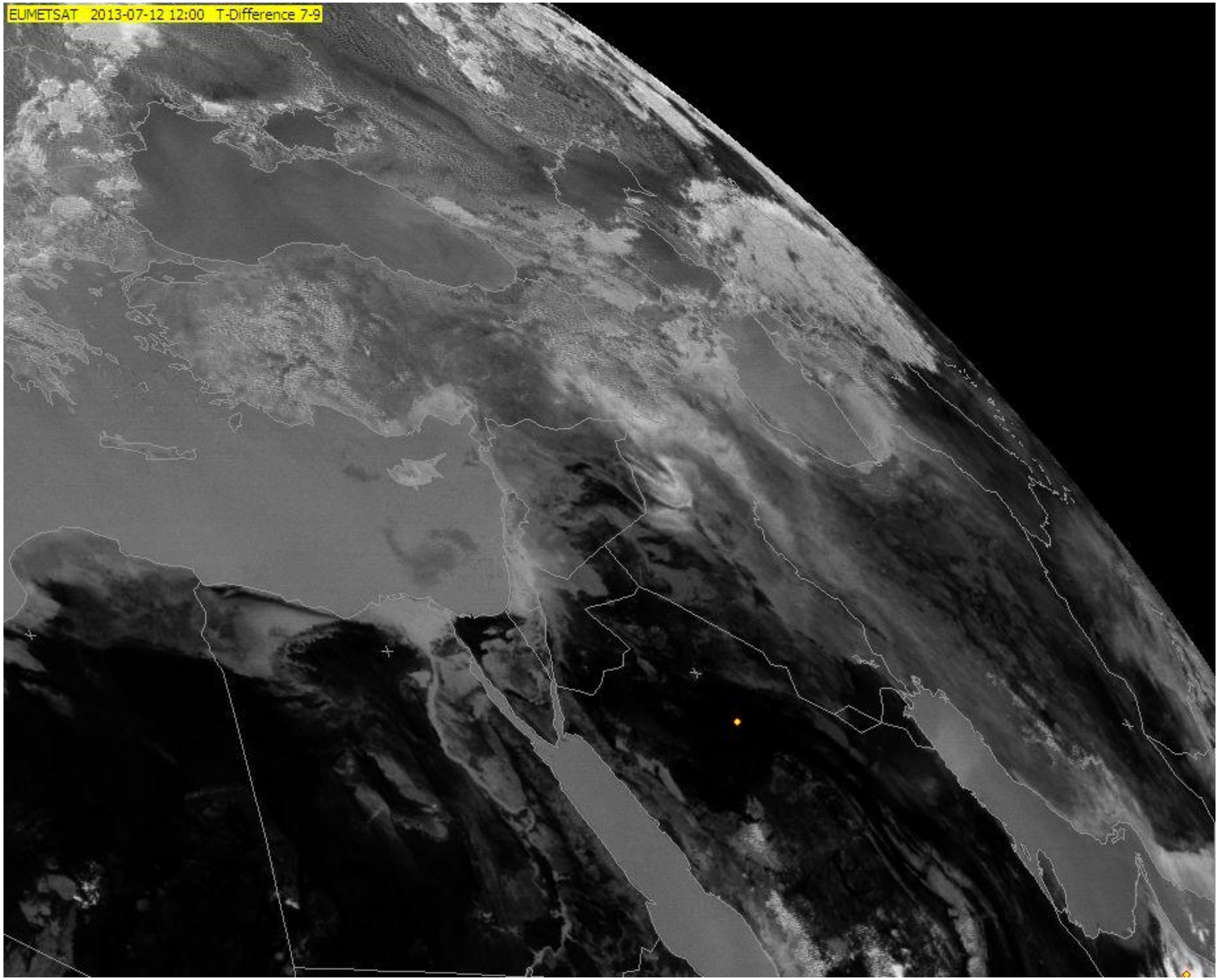
# Dust RGB 21 March 2010 12UTC

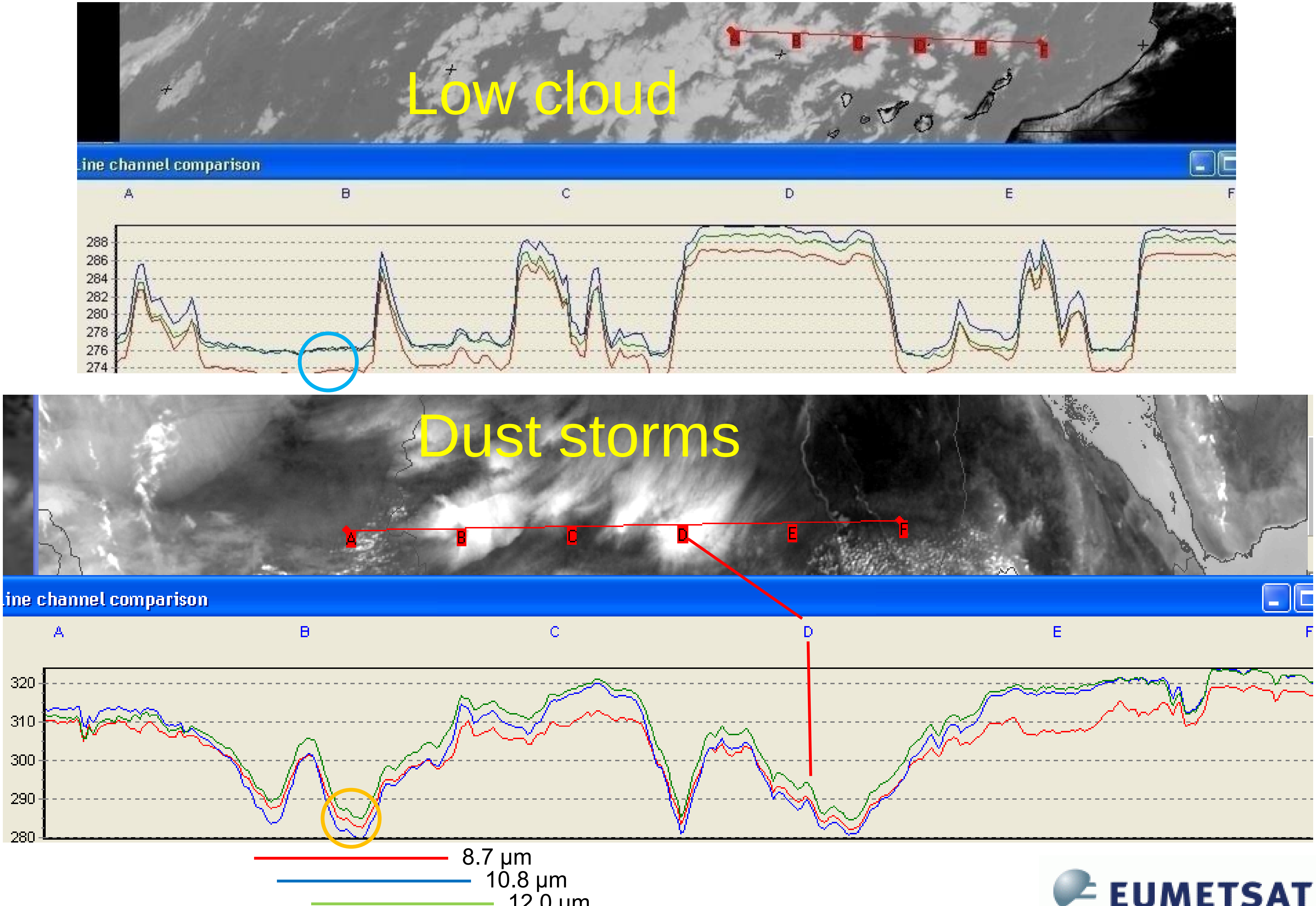


pink is not always dust




Met-8, 2013 July 12 12UTC, ch9-ch10, ch7-ch9 (-17K to 5K) differences and Dust RGB

# Comparison of water cloud and dust in the IR window

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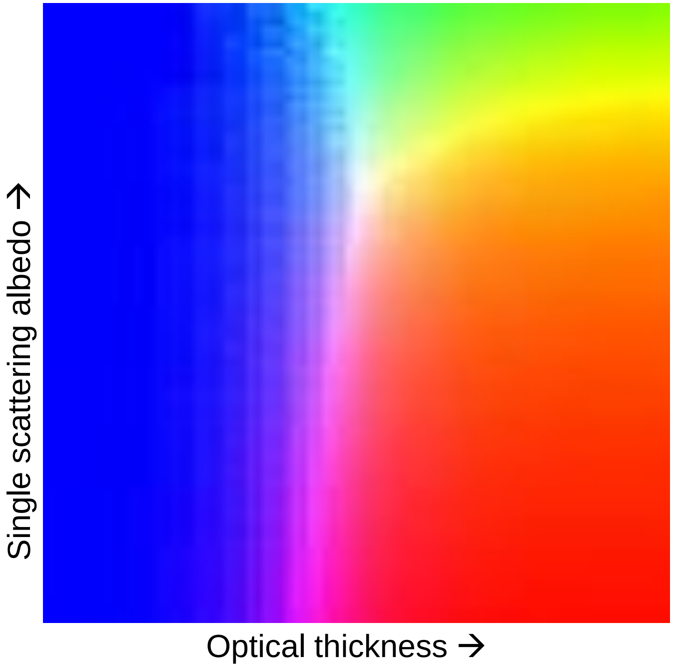
# Find the colour for each interaction regime

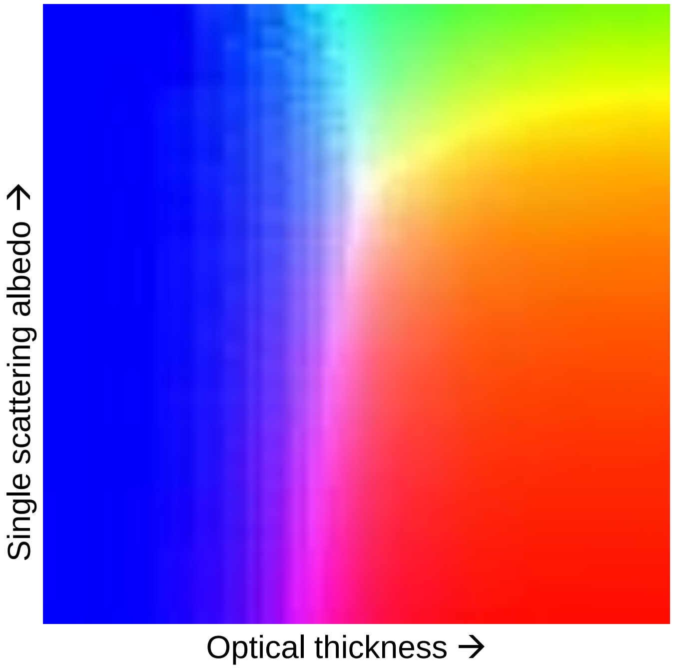



Absorbed

Back scattered

Forward scattered

# Find the colour for each interaction regime




Absorbed

Back scattered

Forward scattered

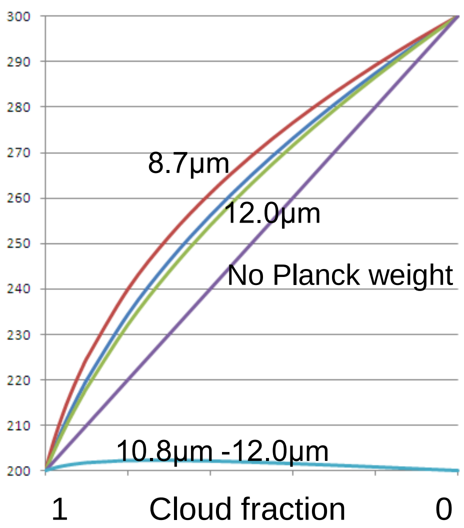
# Channel differences: How do they generate?

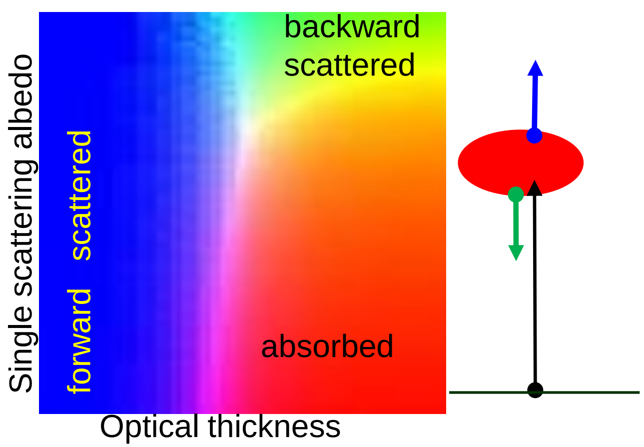
- Emissivity: reduced by *scattering*, increased by **absorption**

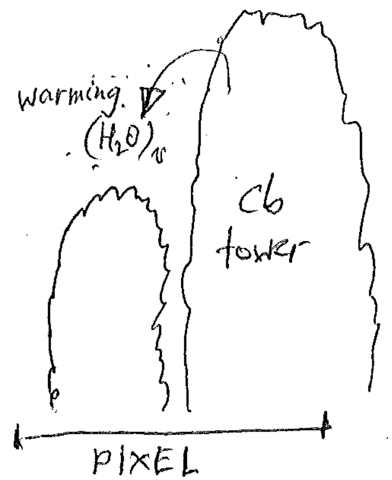
- Sub-pixel effect: scene mixture or semi-transparency

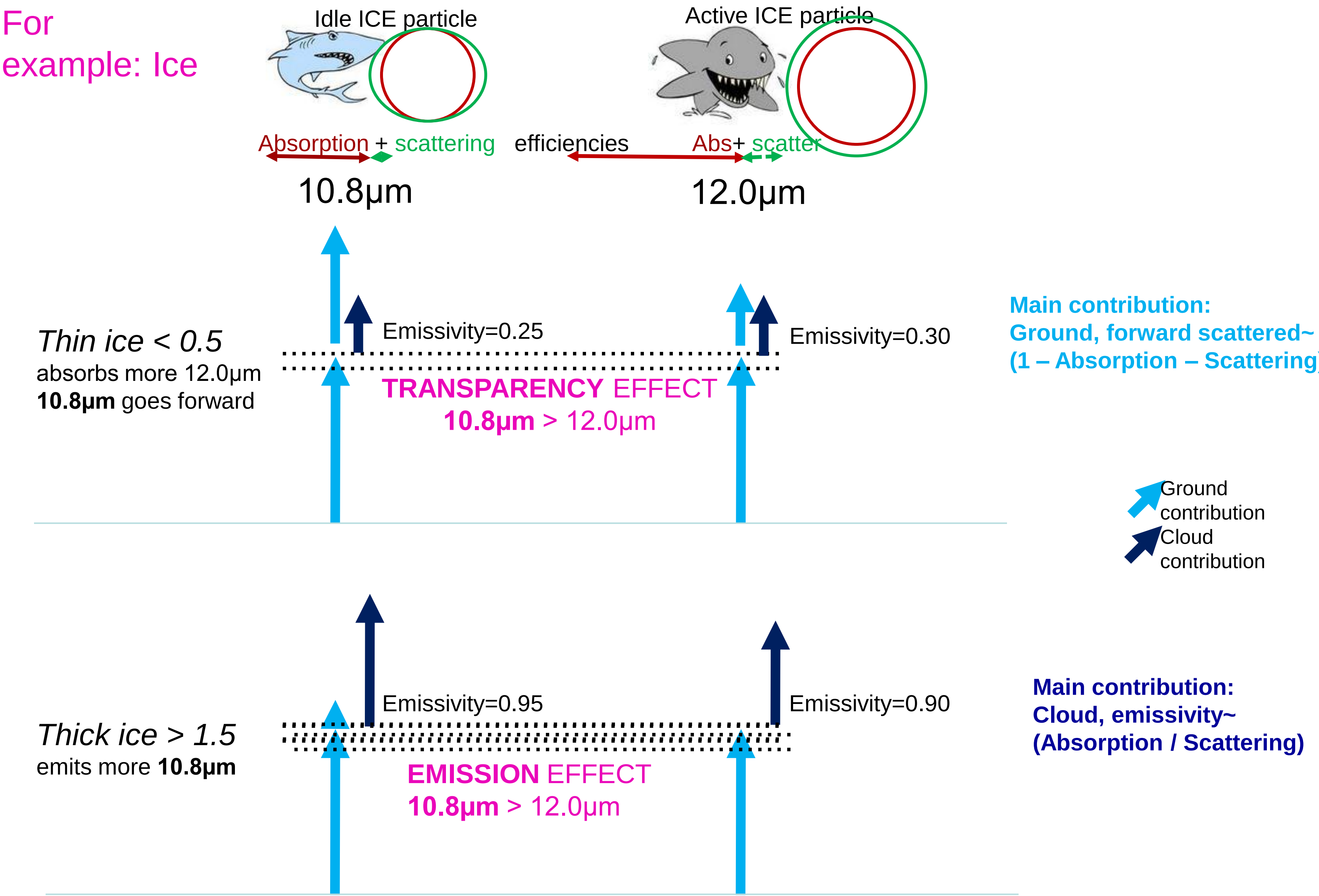
- Contribution layer: emission from different depths and temperatures

- Water vapour absorption (thermal inversion above shield cloud, adiabatic cooling inside the Cb tower)

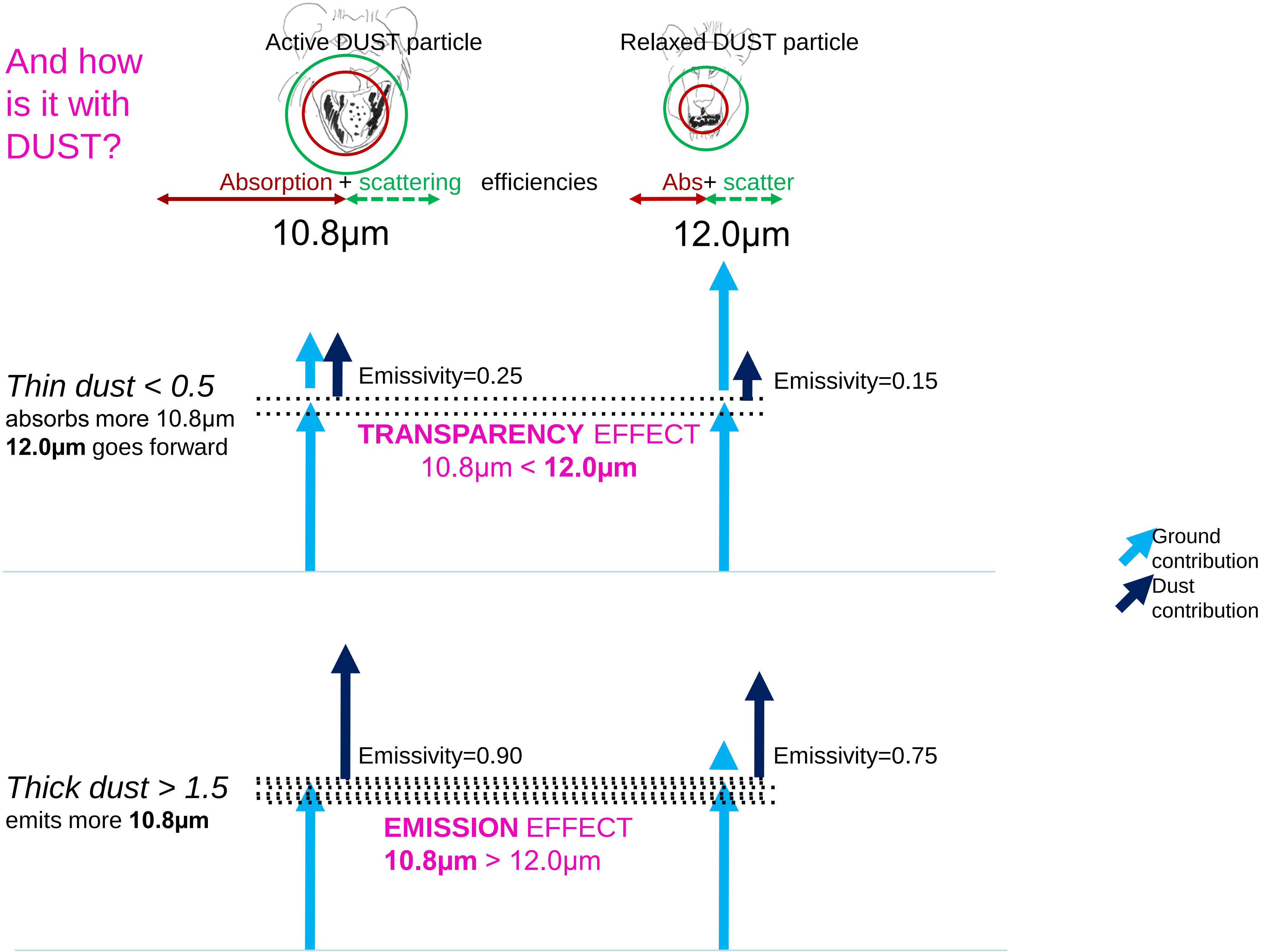


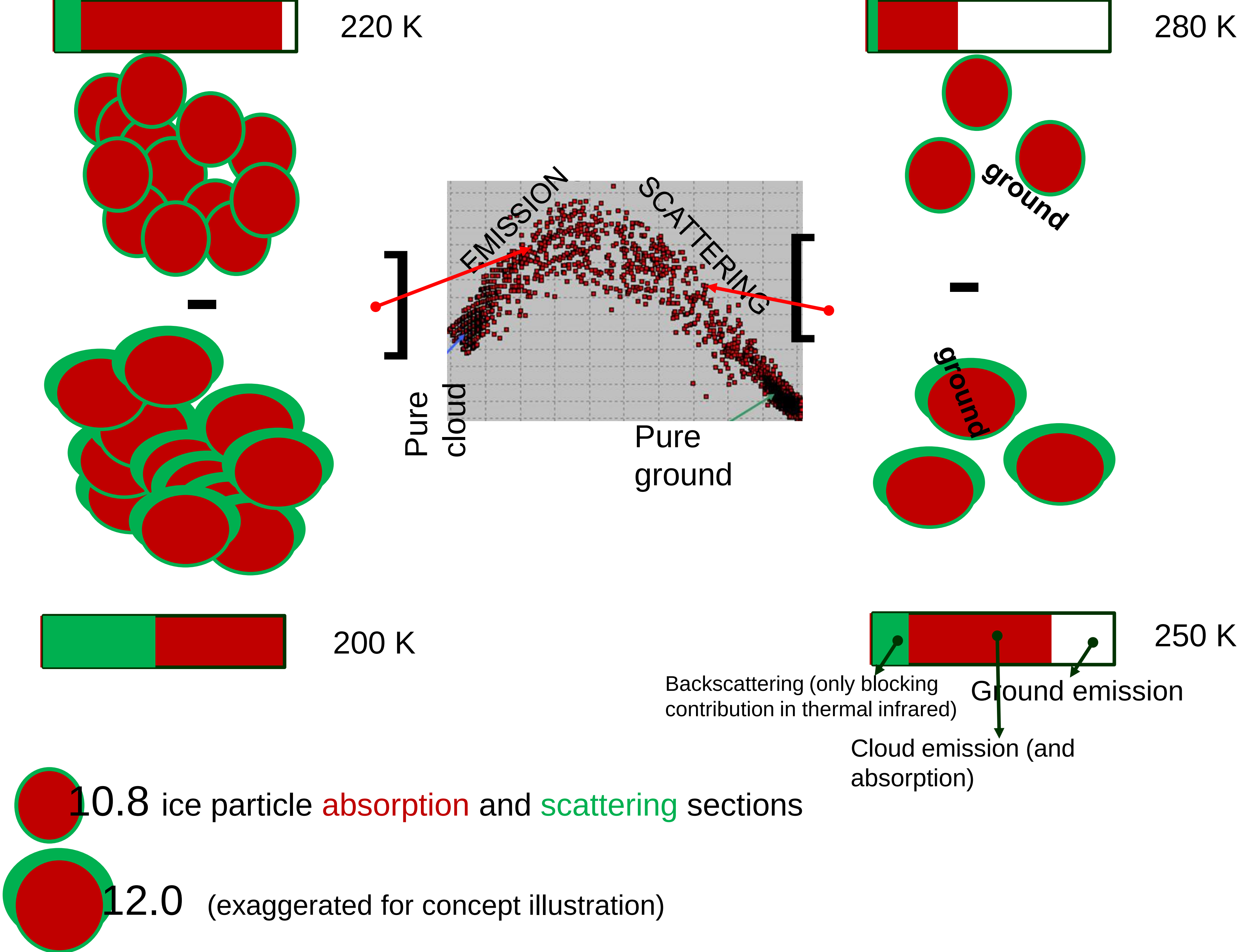




For example: Ice
Idle ICE particle
Active ICE particle
Absorption + scattering
efficiencies
Abs+ scatter
10.8µm
12.0µm
Thin ice < 0.5
absorbs more 12.0µm
10.8µm goes forward
Emissivity=0.25
Emissivity=0.30
TRANSPARENCY EFFECT
10.8µm > 12.0µm
Main contribution:
Ground, forward scattered~
(1 – Absorption – Scattering)
Ground contribution
Cloud contribution
Thick ice > 1.5
emits more 10.8µm
Emissivity=0.95
Emissivity=0.90
EMISSION EFFECT
10.8µm > 12.0µm
Main contribution:
Cloud, emissivity~
(Absorption / Scattering)

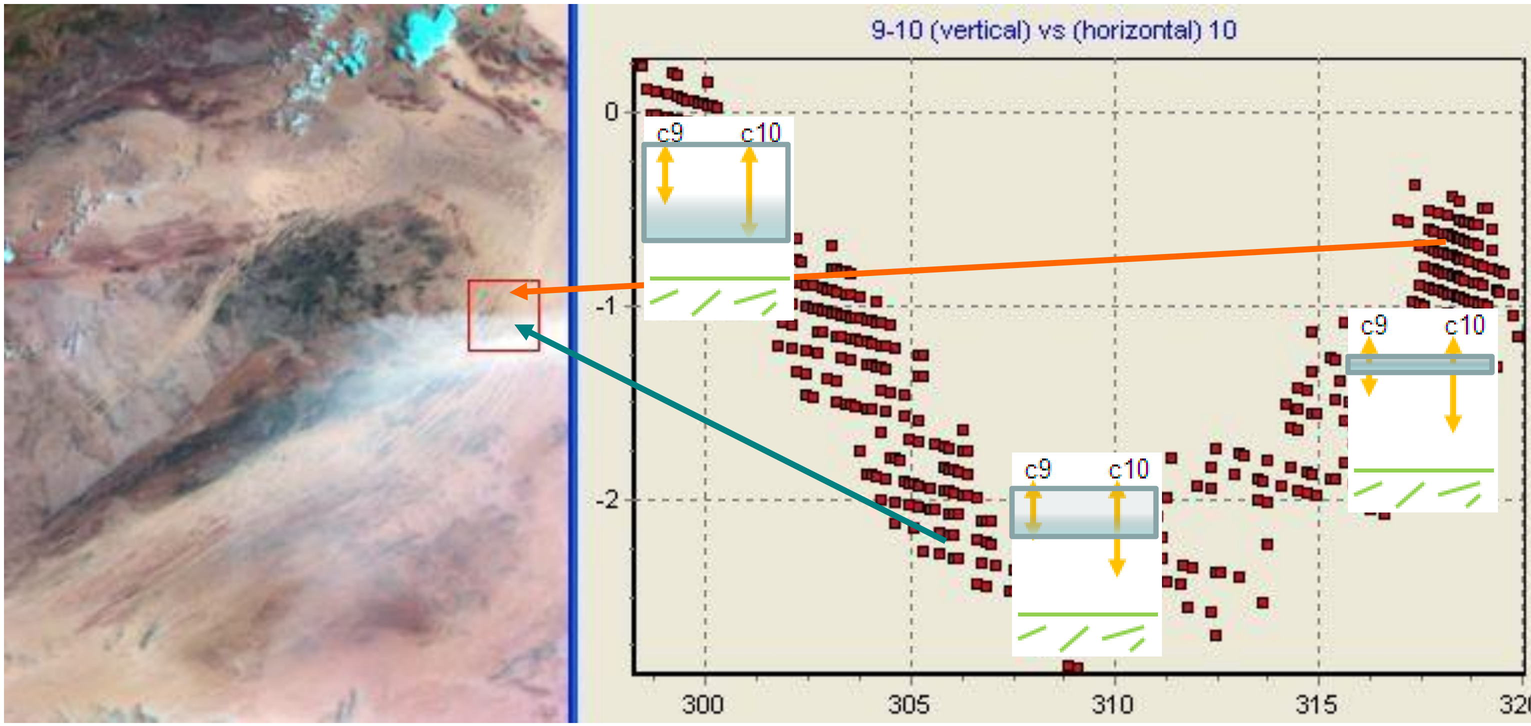
# And how is it with DUST?





220 K
280 K
EMISSION
SCATTERING
ground
ground
Pure cloud
Pure ground
200 K
250 K
Backscattering (only blocking contribution in thermal infrared)
Ground emission
Cloud emission (and absorption)
10.8 ice particle absorption and scattering sections
12.0 (exaggerated for concept illustration)

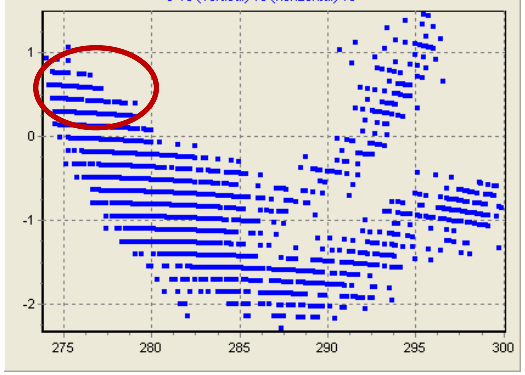
# Reversed transparency arc for dust: Ch9-Ch10 versus Ch10




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 (**CL**) at 10.8µm
- 10.8µm channel shows higher BT than 12µm for thick dust due to higher emissivity

# Exercise: plot 9-10 versus 10




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

T Ex ❑ Dust shows a higher emissivity at Ch9 than at Ch10

T NEx ❑ Dust has a scattering component, higher at Ch9 than at Ch10

T NEx ❑ Dust Ch10 signal comes from a thicker (on average warmer) top layer

Ex: explains NEx: does not explain

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# Contents

- Infrared dust properties
  - Where you learn how cool dust really is
- A  model of atmospheric dust
  - Where you learn to distinguish high but thin from low fat
- Validation via AERONET
  - Where you learn that models can help your eyes
- Mixed scenes: cloud and dust
  - Where you learn that life is impossible without water
- Conclusions
  - Where you learn that there is more dust on books than books on dust

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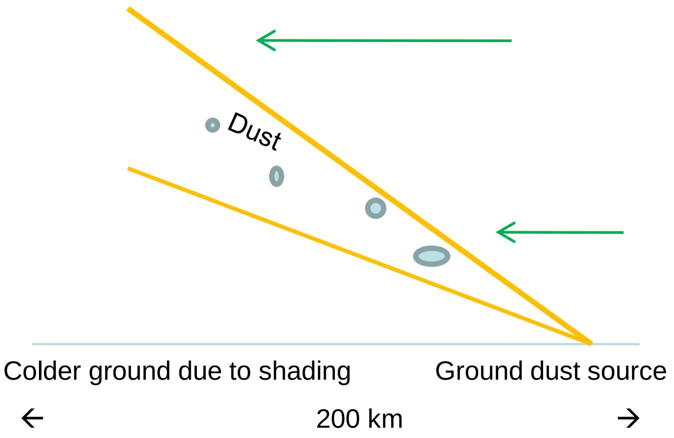
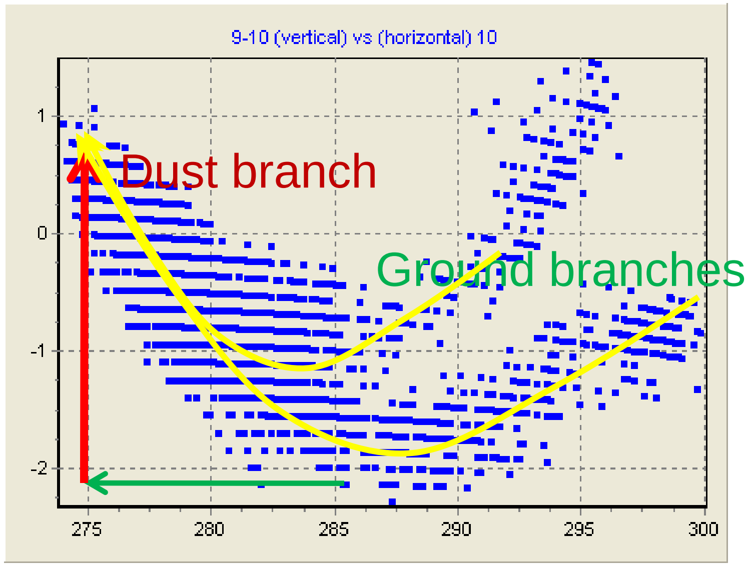
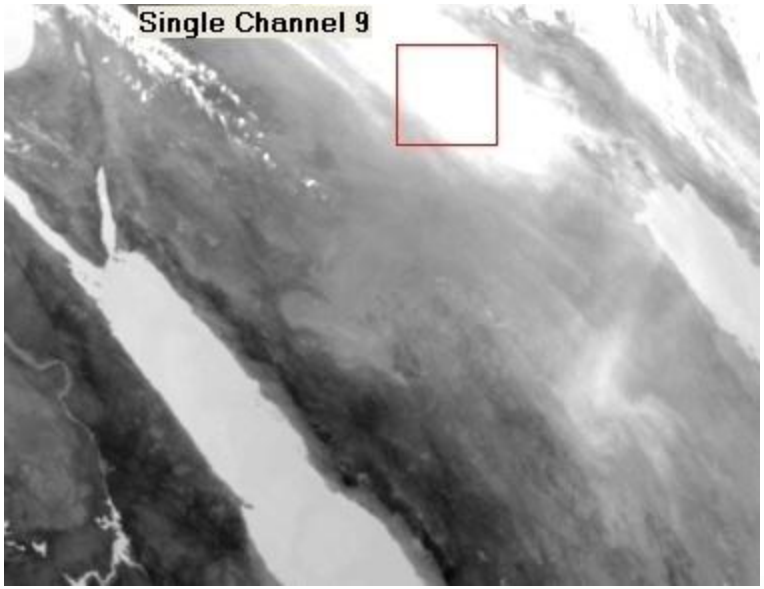
# Dust model




- Dust tends to higher levels far from the source, decreasing in **particle size**
- Decrease in 12.0µm BT due to height and dust thickness (and size and...)



# Model assumptions-limitations

- (32x32 surroundings): min T10.8-T12.0 < *-1.3K*
- Empirical AOT estimates for channel saturation:

  *AOT= 0.14 (detection)----1.3 (for 10.8µm)----3.5(for 12.0µm)----4.8(cloud contaminated)*
- Uniform dust type
- Dust in the pixel at a single height
- Size not dependent on height
- Ground temperature reduced by thick dust above
- Good results in areas 200 km across

- Four result categories:
  - Dust-free (or low-level only, or night-time, or dry ground)
  - Only dust traces
  - Measurable dust
  - Dust mixed with cloud

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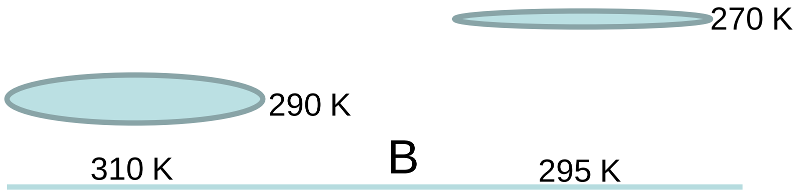
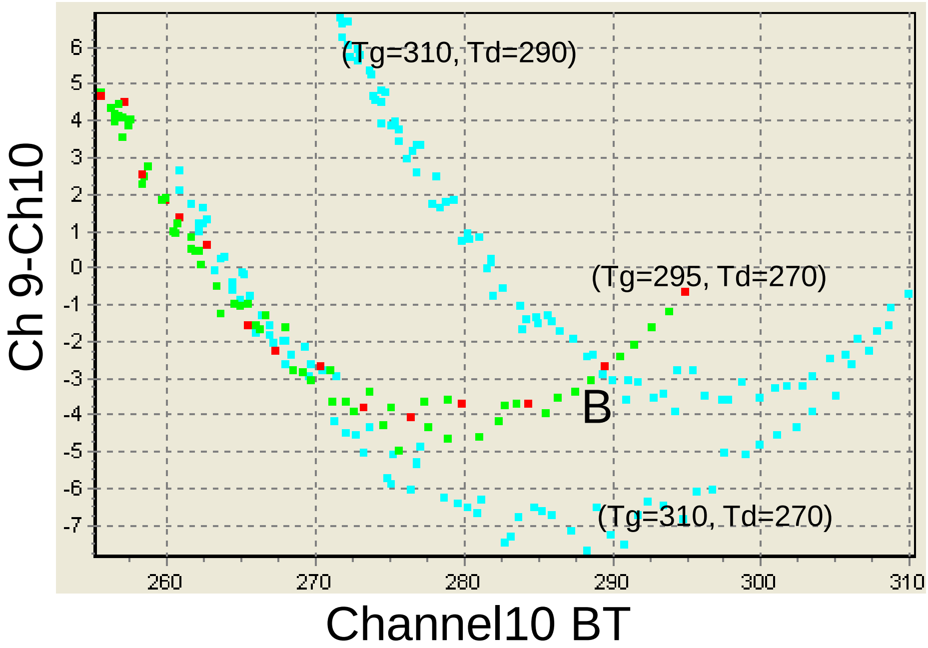
# Graphical analysis




- **Thick** dust cloud at **low** level can be confused with a **thin** layer **high** above
- Reduction of the ground temperature by dust screening the sun (‘thermal **deficit**’)
- Use channel difference **8.7µm – 10.8µm** (negative for thin, positive for thick)




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

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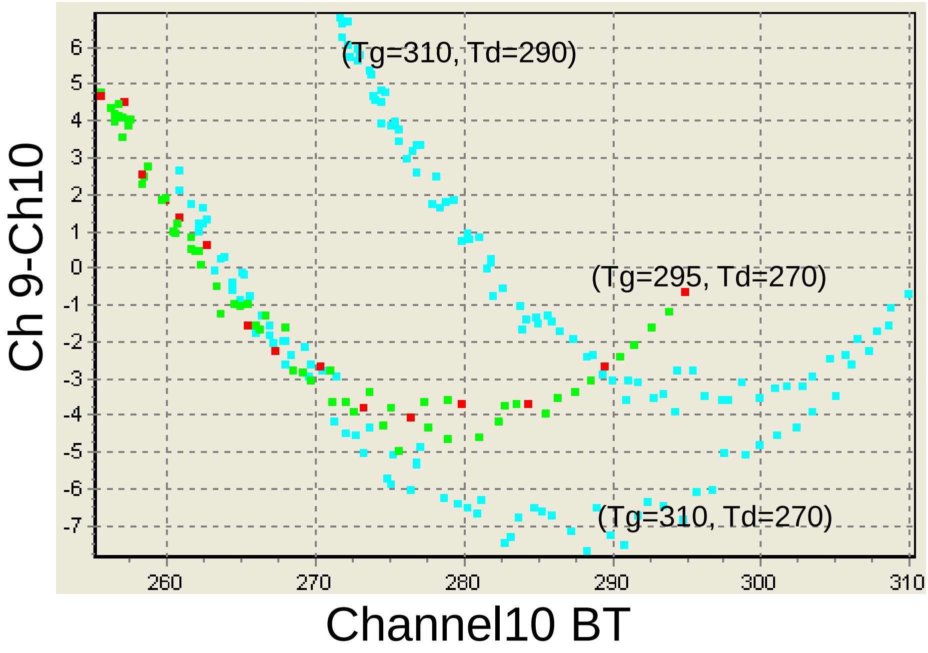
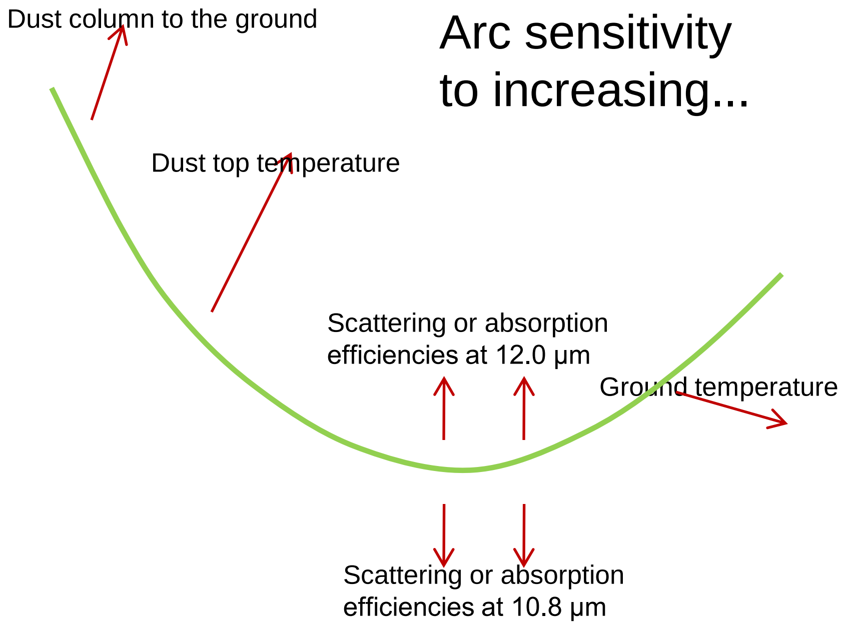
# Graphical analysis

The arc shape depends on temperatures (dust top, ground, dust vertical extension) and
The arc shape depends on efficiencies (dust composition, size, shape)
The dip in the curve depends on relative weights of efficiencies at 10.8 and 12.0 µm

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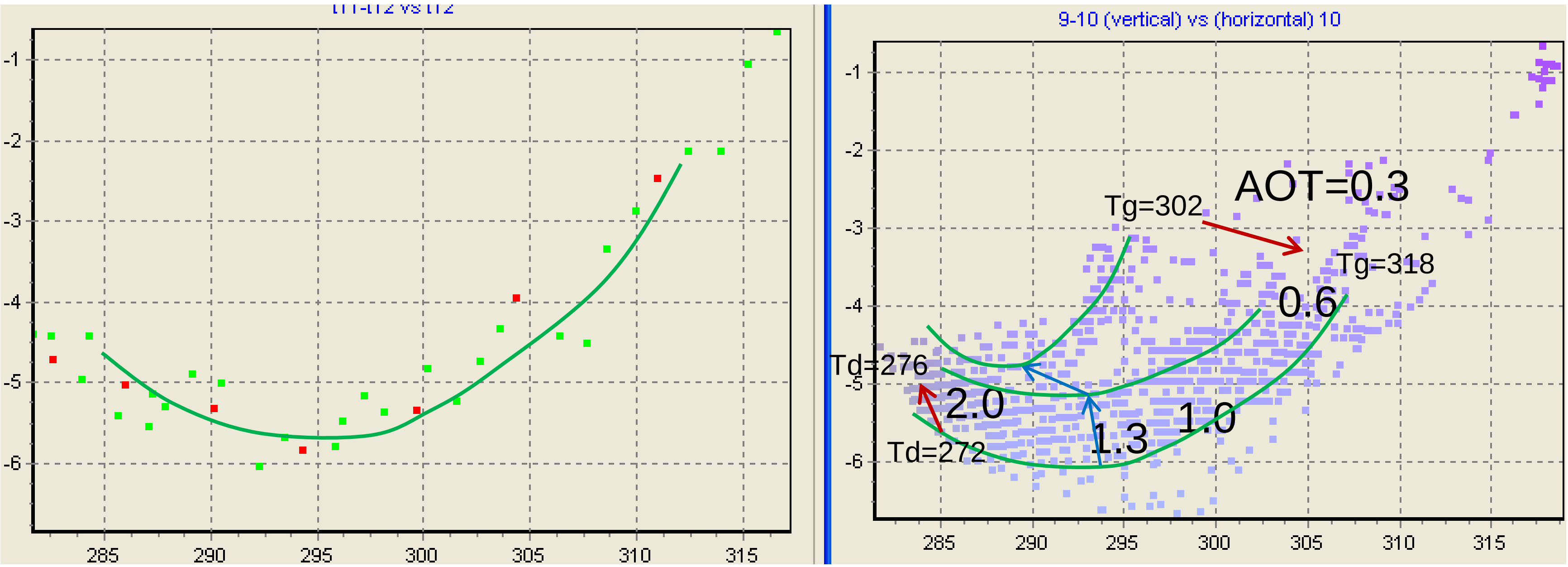
# Dust (Td) and ground (Tg) temperatures estimates

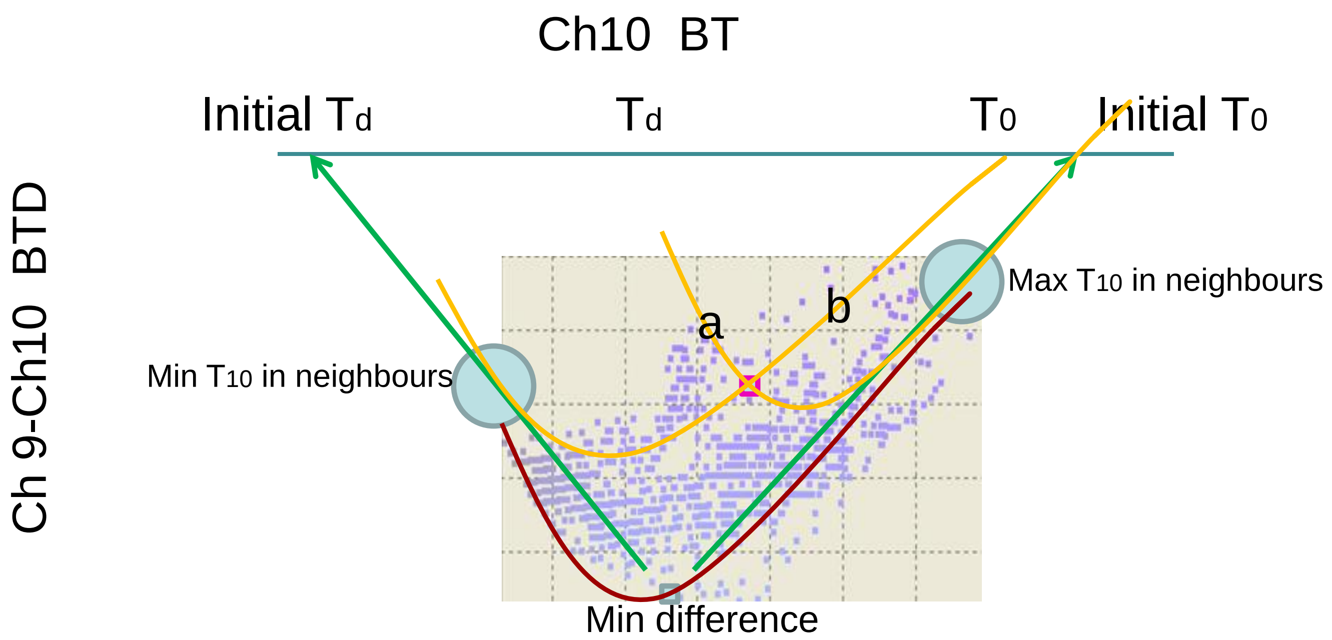



Real (blue dots, right h.s.) compared with simulated (green-red dots left h.s. and lines) scatterograms based on Tg=318 Td=272 Σ11=0.6, 0.3 Σ12=0.2, 0.25

Dust column down to 50% of that temperature difference

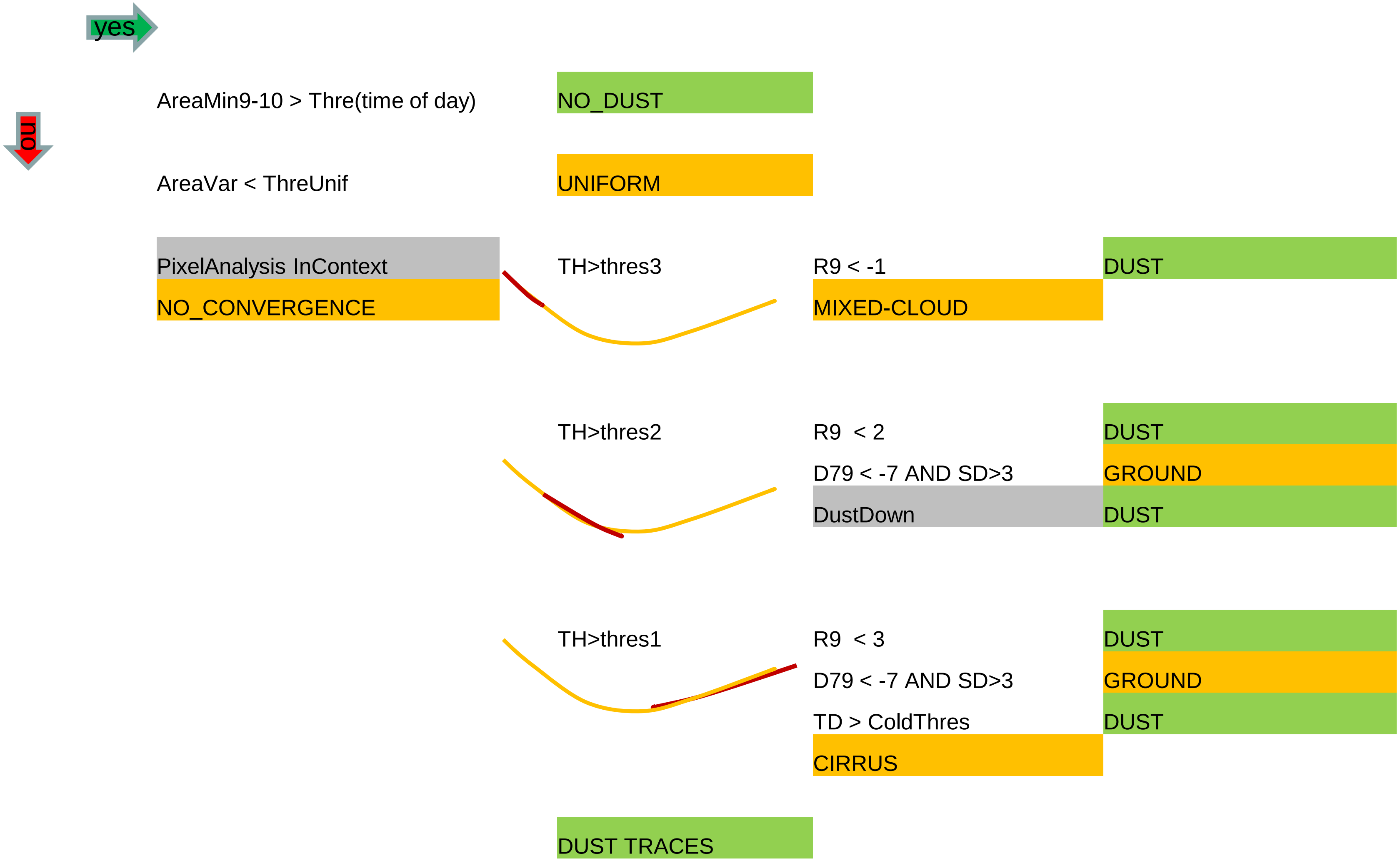
Smaller arcs, higher in the scatterogram, indicate less temperature contrast (Tg – Td)

# IR model operation



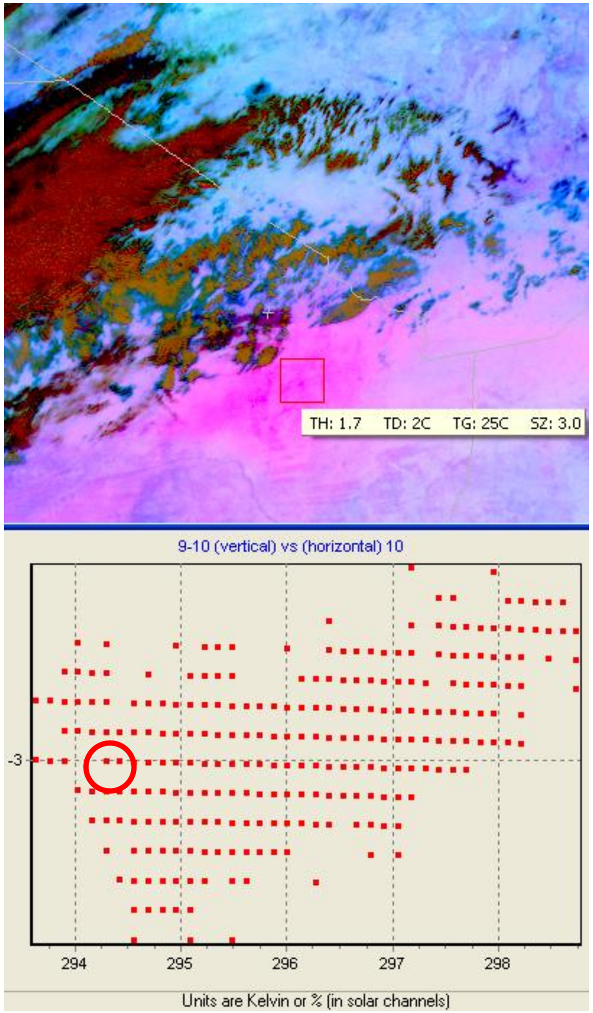

If slope=b, refresh $T_0$
If slope=a, refresh $T_d$

# Decision tree

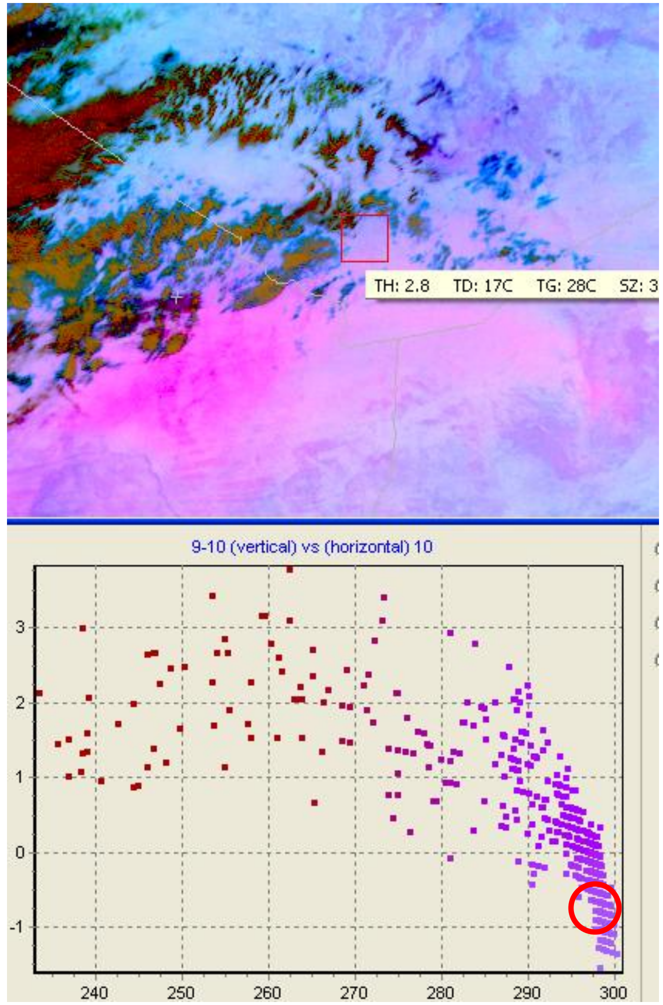



1. Subjective **verification** against masks, images and news media: Done
2. **Verification** from other sources (AERONET, LIDAR): In progress
3. **Inter-comparison** with other methods (Solar): Starting

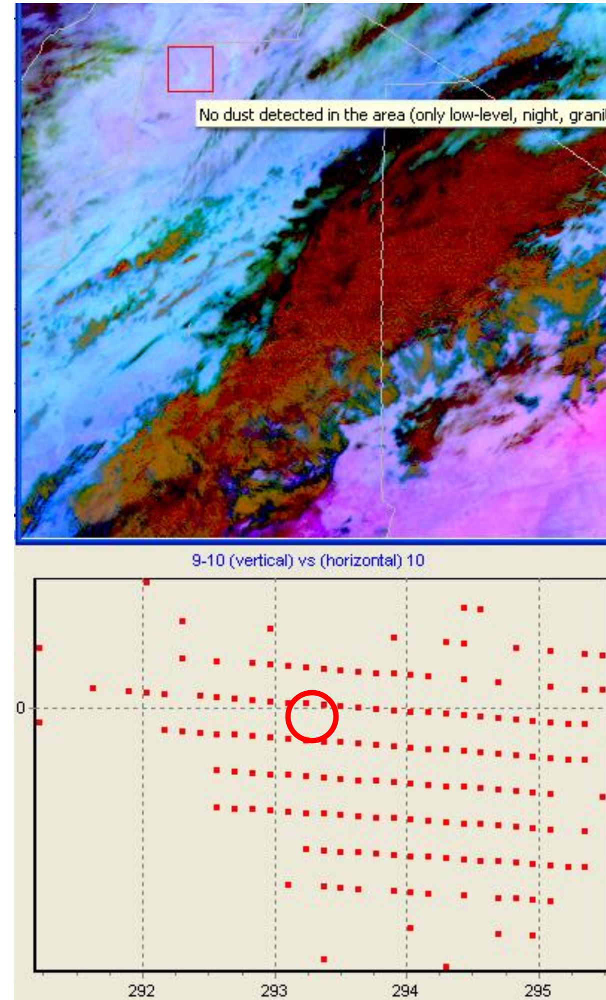
# Graphical validation




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




threshold ch9-ch10 < -1.3K
AOT =2.8, too strong depth
Due to location of minimum

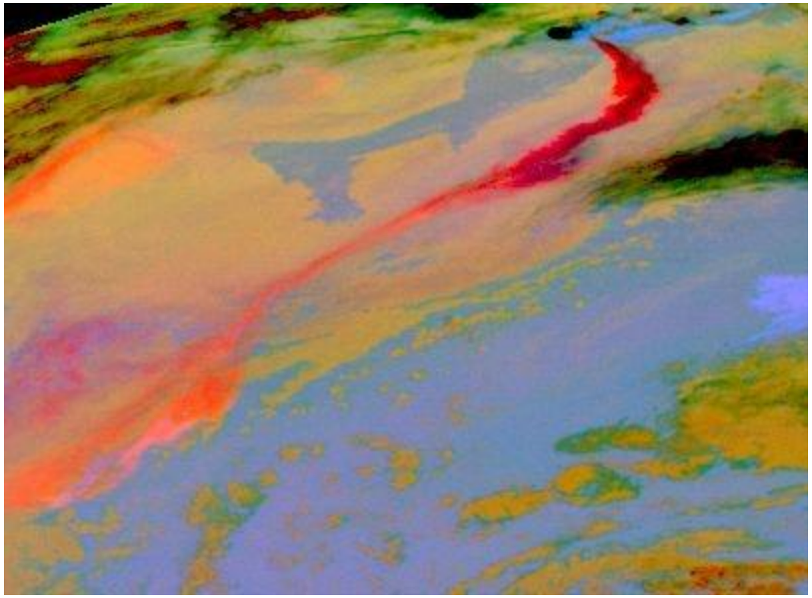



threshold NOT < -1.3K
AOT not calculated

# Applicable to volcano ash

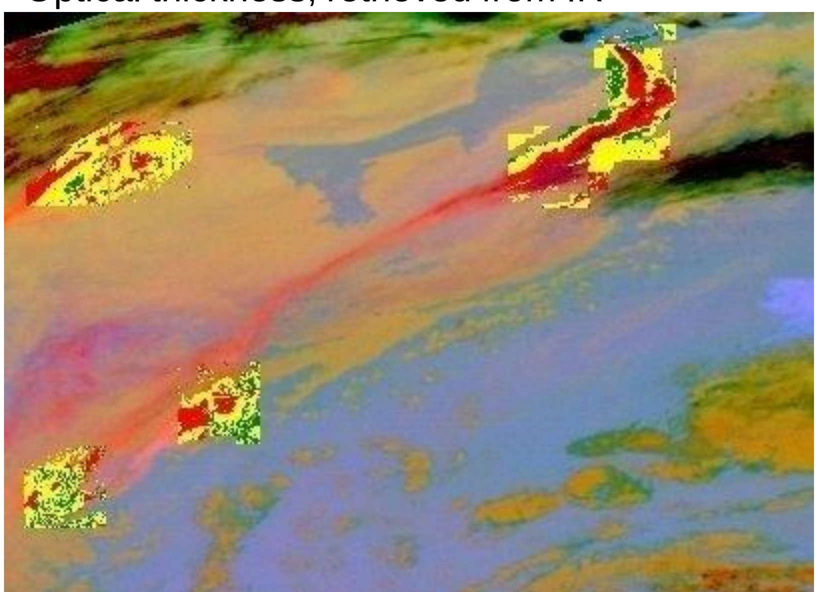
•Model results are quite different from the RGB visual impressions, and add information in RGB non-pink areas with small dust depth

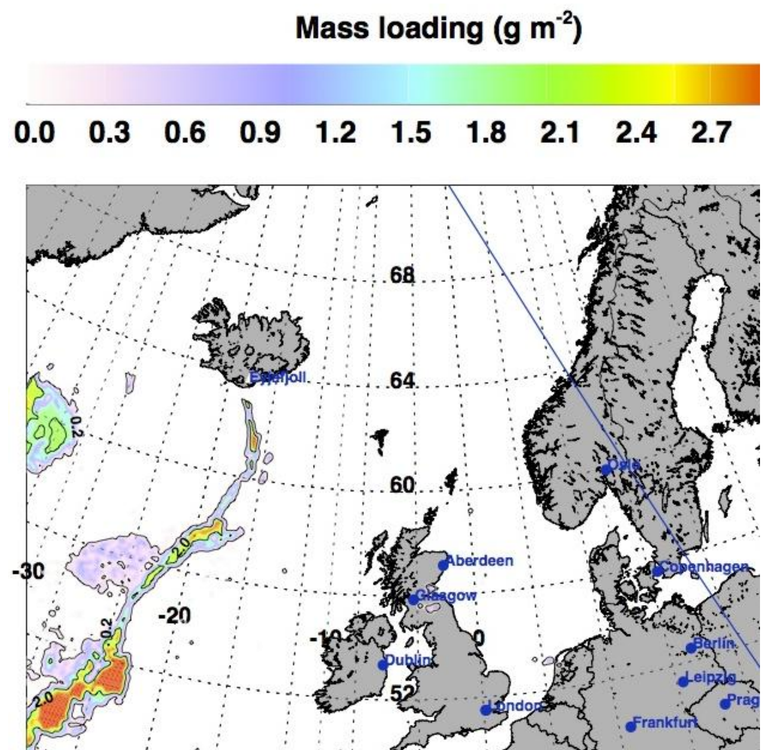
•No direct comparison with mass loading (uncertain ash density estimate)



*Dust* RGB 2010-05-08 12UTC Icelandic ash

Optical thickness, retrieved from IR






courtesy of F Prata

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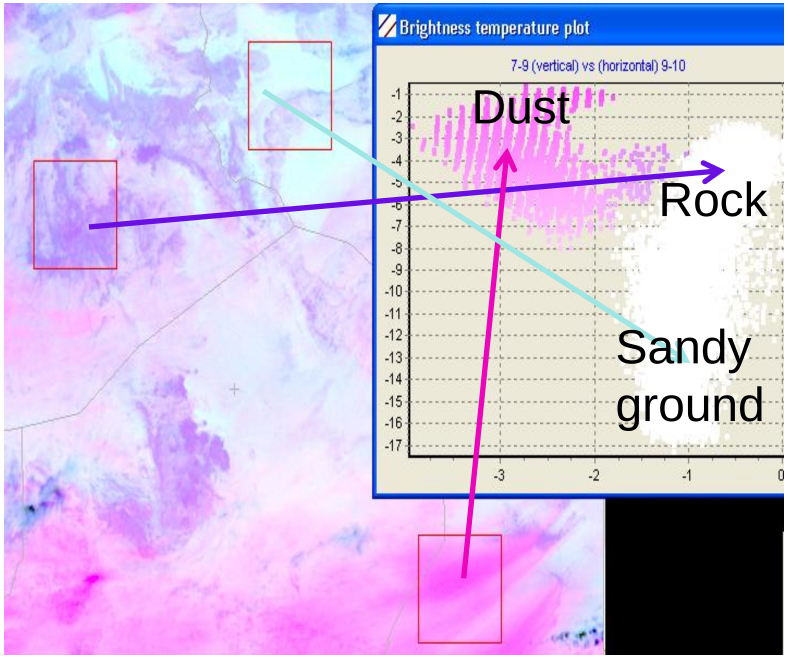
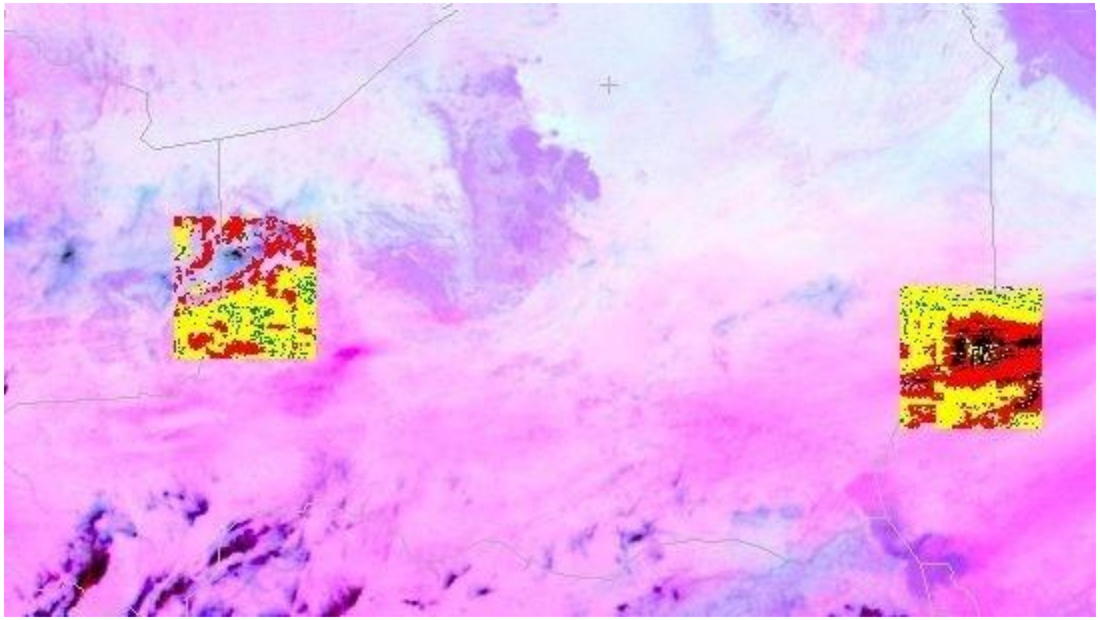
# Ground versus dust skill




IR model does not usually pick on rock or sand areas

21Mar2010 12UTC Meteosat-9



The IR model separates the **dust** areas from the **ground** dry areas

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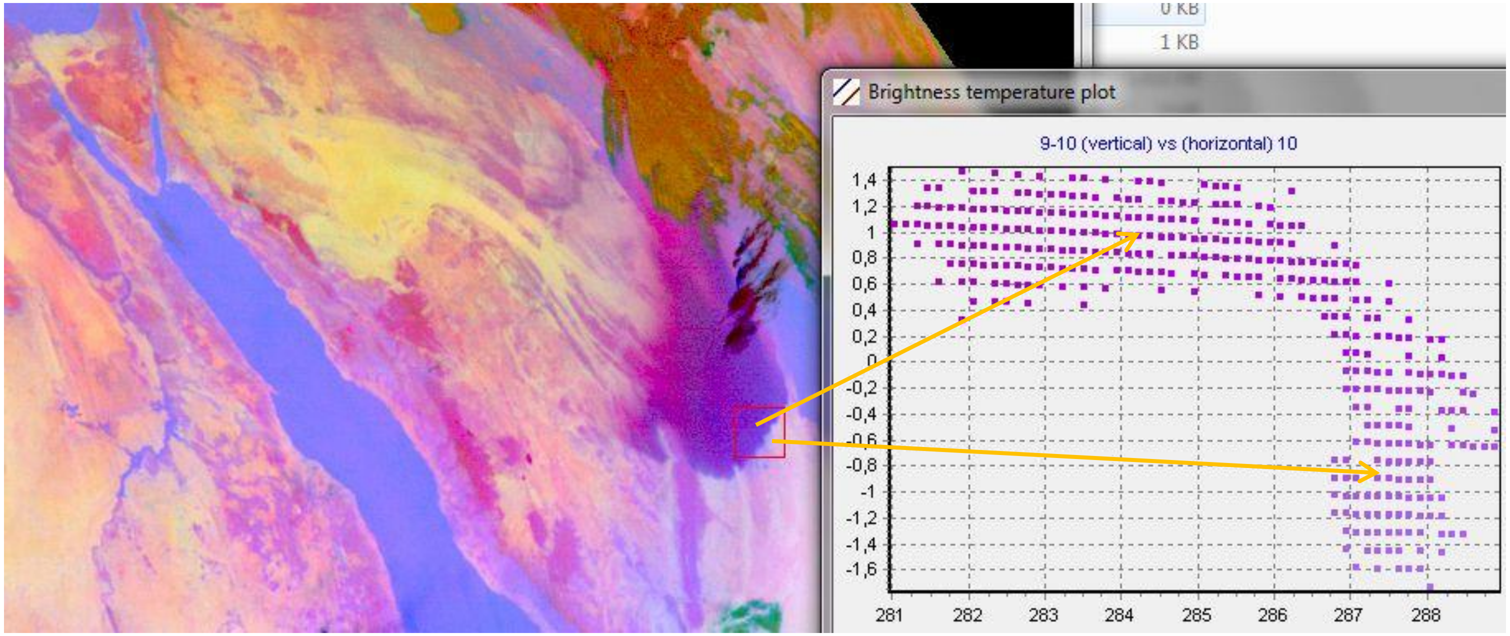
# Model fails for atmospheric inversions

- Occasionally, during night, thermal inversions duct dust at high speed
- Due to the thickness, no negative 10.8µm – 12 µm difference appears above the dust
- However, negative differences appear over clear ground

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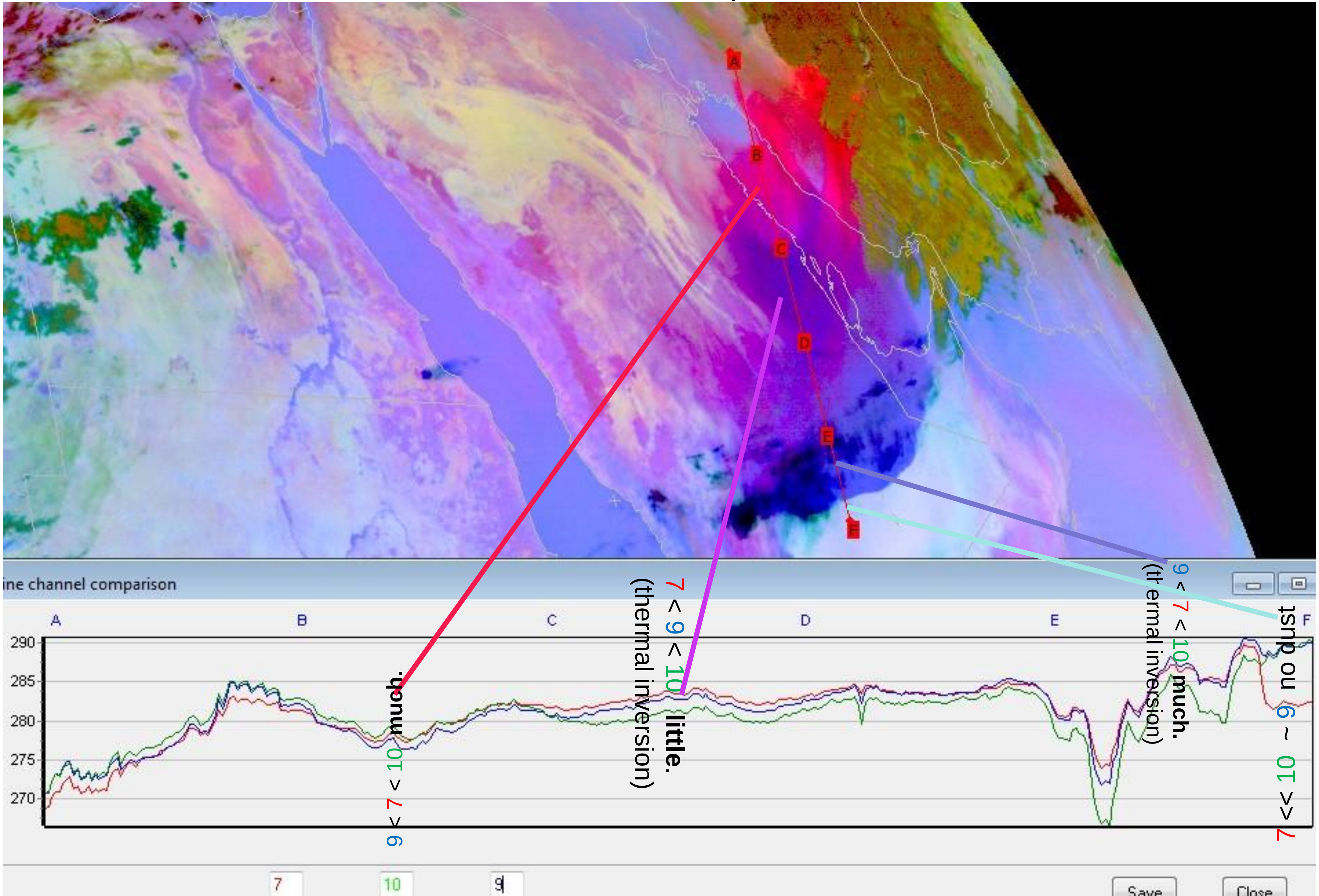
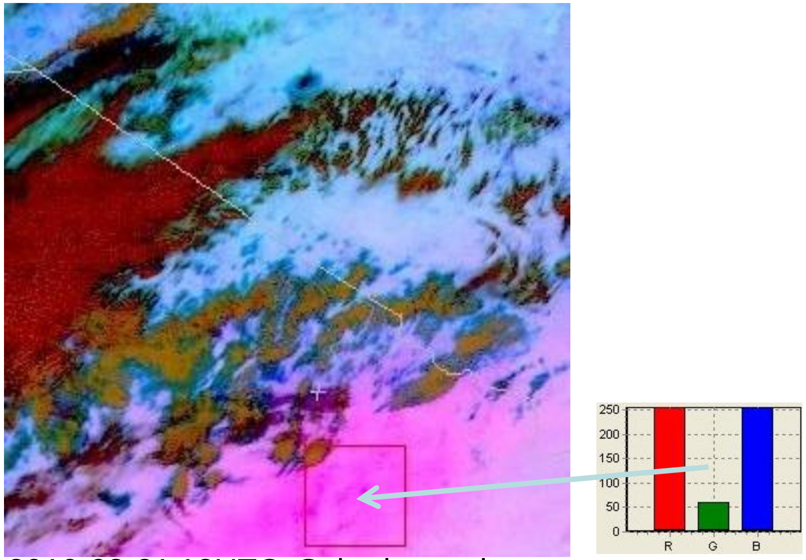
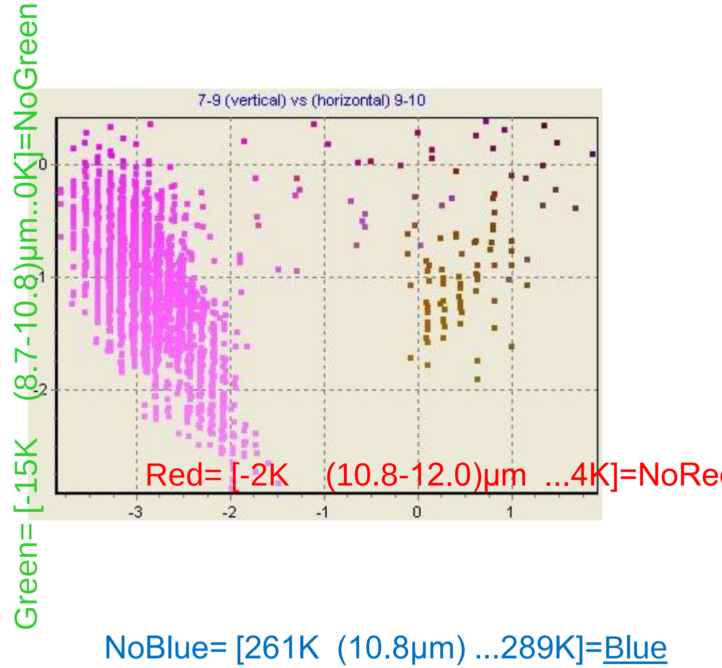
# Met-10 2015-04-01 23UTC, Dust composite



# Dust RGB

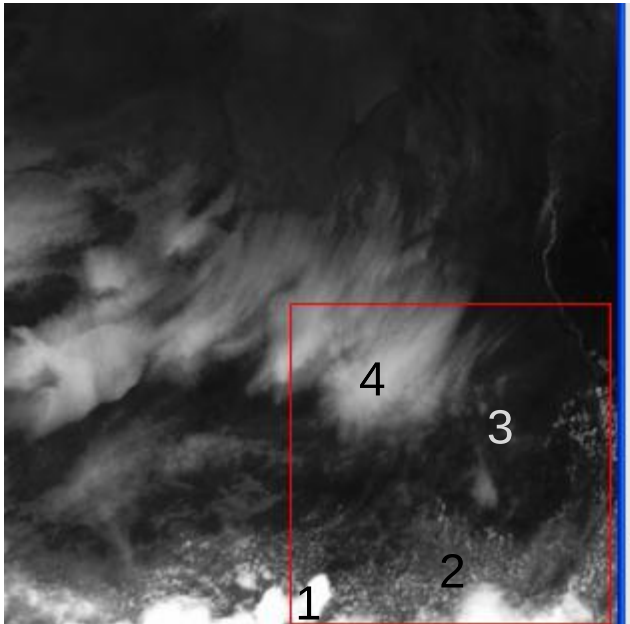


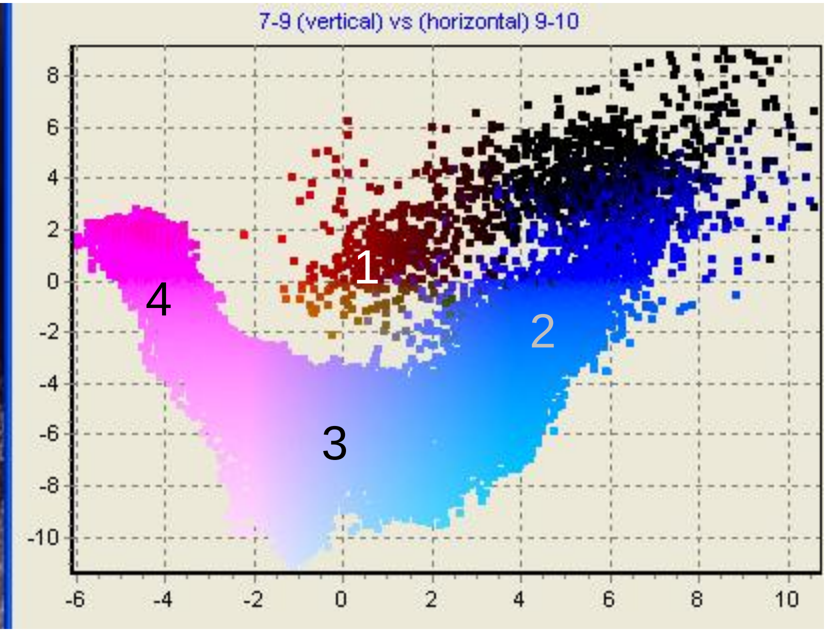

2010-03-21 12UTC, Saharian region



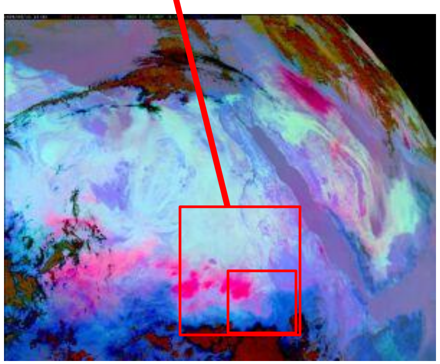

•Magenta areas are typically dusty: neither necessary nor sufficient condition
•Inside **magenta** areas, **darker** (less green) pixels show a smaller difference c7-c9 which means **higher AOD**
•The threshold in the red component (-2K) is exceeded in most pixels of the dust storms.
•Blue component is most of the time saturated (>16°C) over desert areas during day. During night it generates a yellow hue for desert.

# The cloud-to-dust spiral in the differences diagram




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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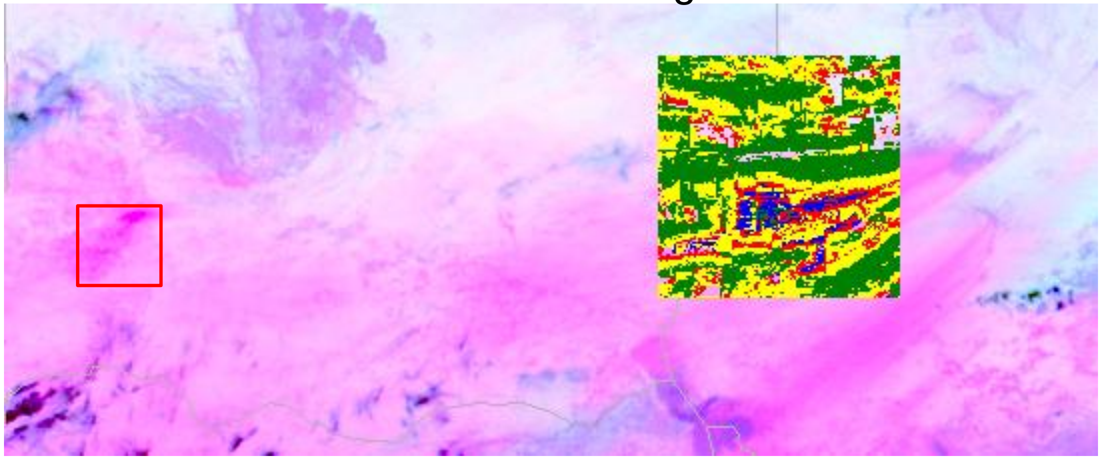
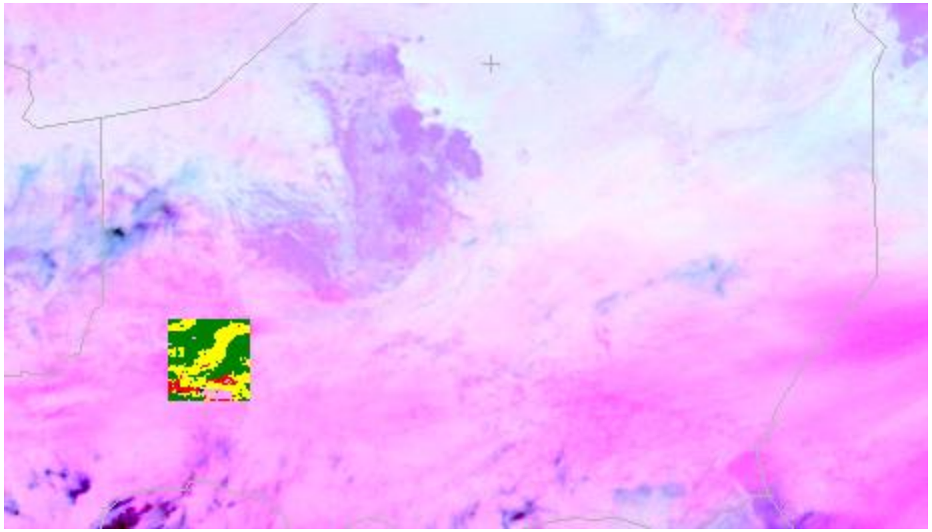
# RGB worse than IR-MODEL ?

IR-MODEL discriminates significantly several (>4) levels of AOD
RGB discriminates <4 levels
Pinkness is not a direct measurement of AOD at high AOD values



Reduced **ground temperature** under the thicker layer of dust (-5K to -10K for yellow pixels)

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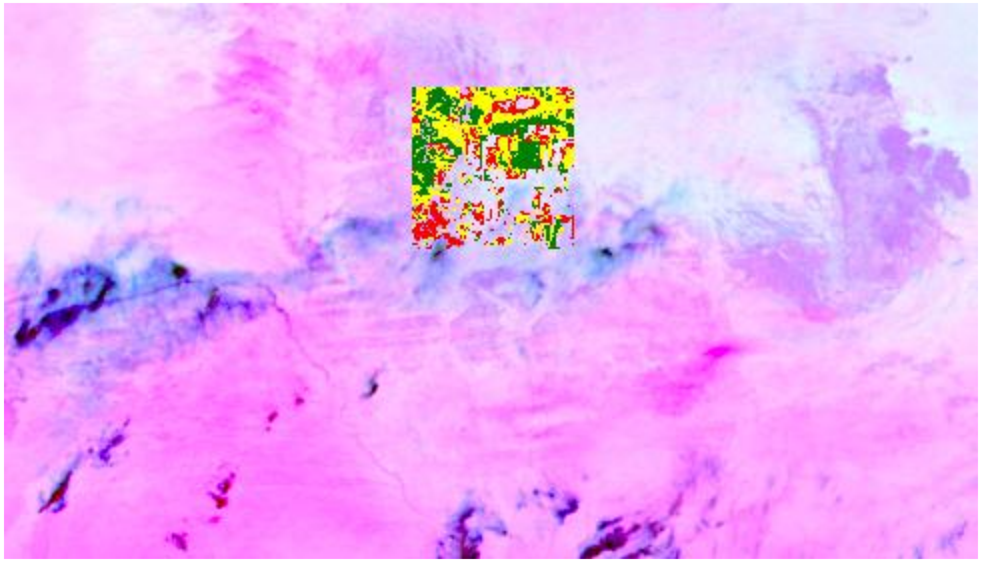
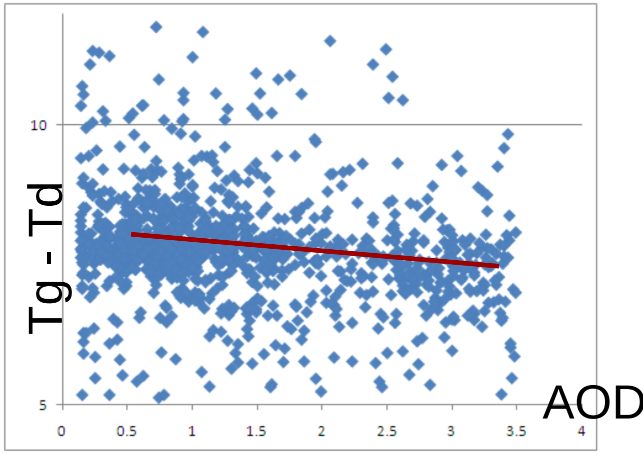
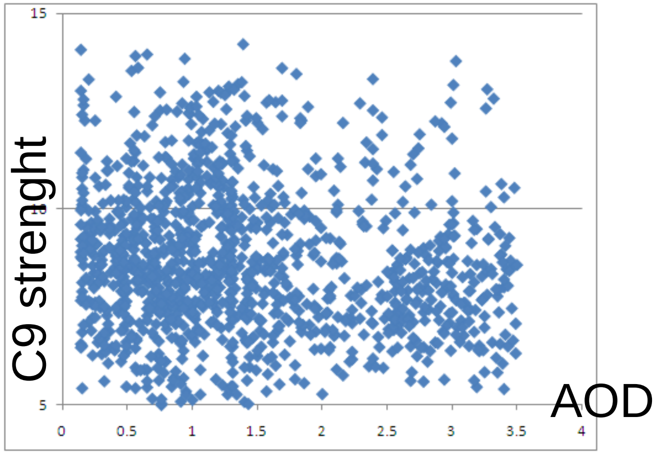
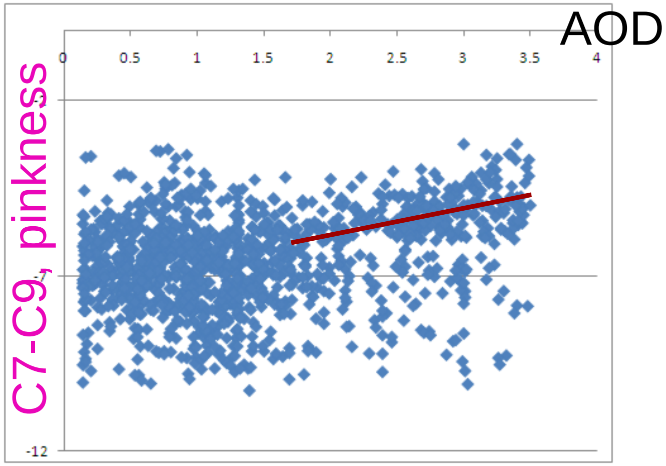
# Channel versus model parameter: correlations






Correlations are stronger for AOD > 2
Ch9  strength (compared with the other channels) is not a good indication of AOD
Ch7 – Ch9 is a better indication of AOD, still poor
The thermal deficit retrieved by the **model** is reverse-correlated to AOD

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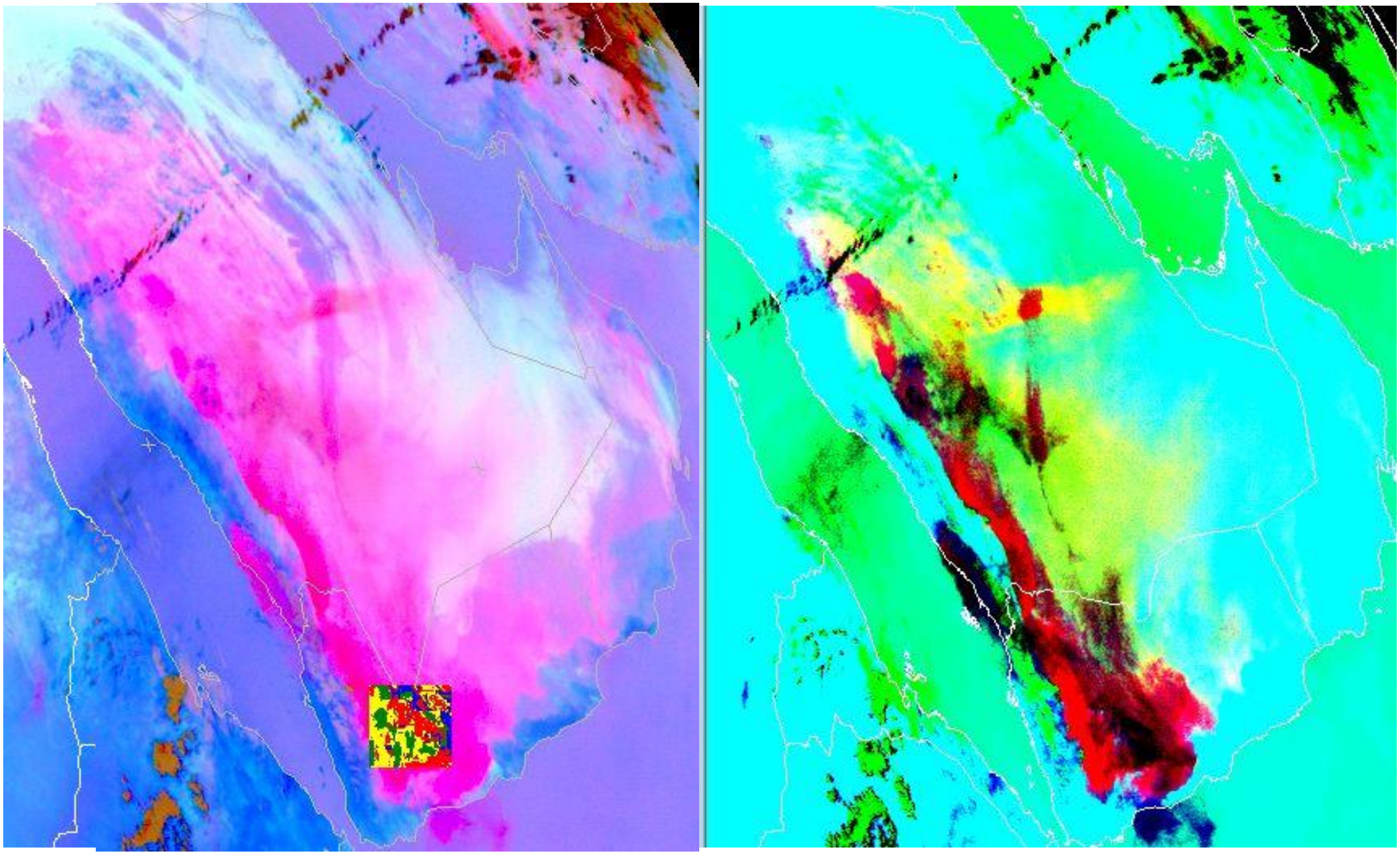

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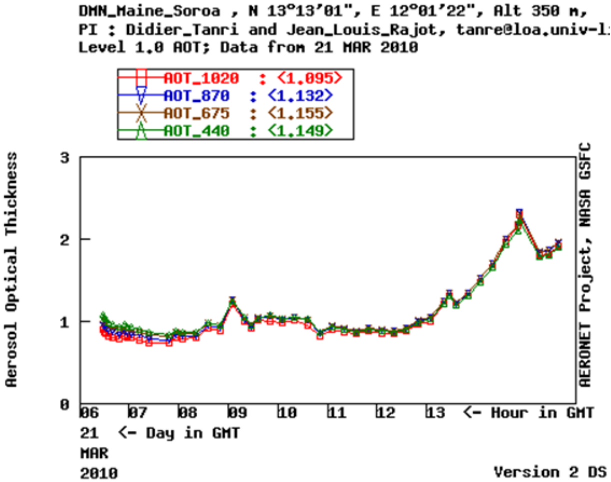
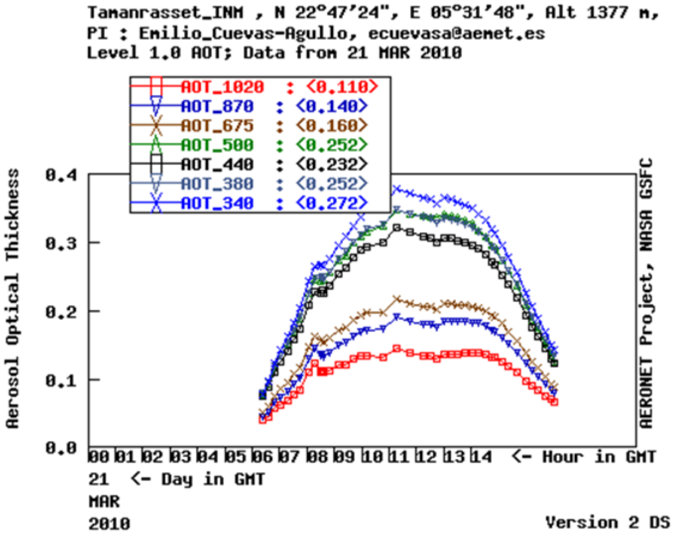
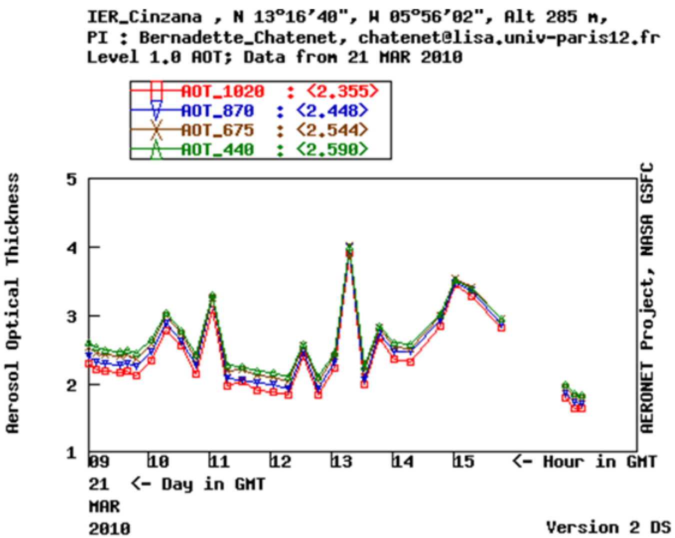


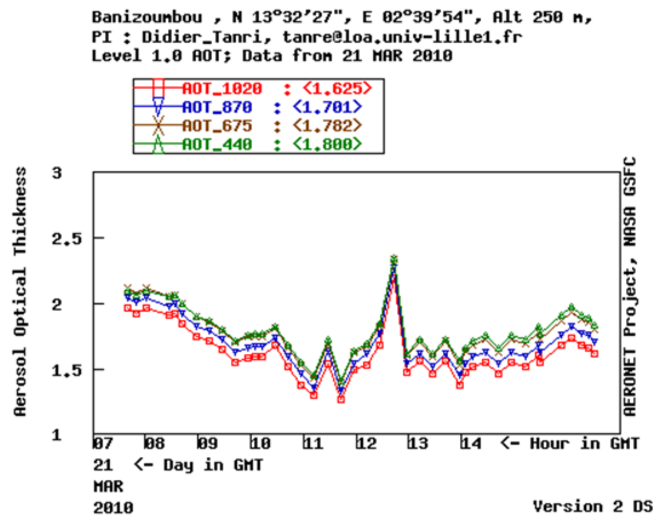

12.02E 13.22N, model on image **at 12UTC**: theta=0.6 31C-39C size=29




5.52E 22.77N, model on image: theta=0.16 40C-47C size=31




-5.94E 13.28N, model on image: theta=1.9, 31C-42C




2.66E 13.53 N, model on image: theta=0.8 33C-42C size=14

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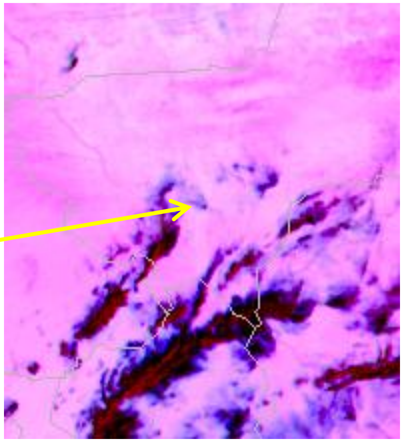
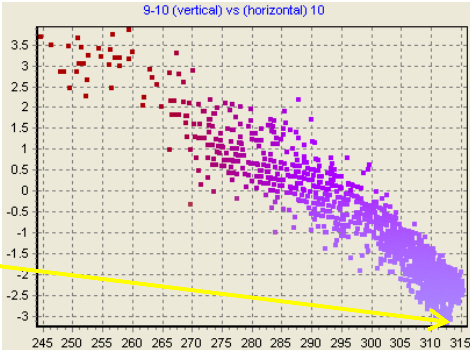
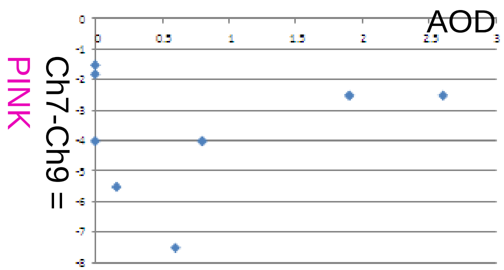
# Validation based on ground measurements (AOD units)

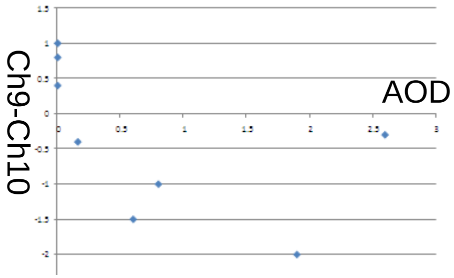
| AERONET | IR-MODEL | | |
|---|---|---|---|
| ✓ 0.9 | 0.6 | 31-39 C | 29 µm |
| ✓ 0.35 | 0.2 | 40-47 C | 31 µm |
| ✓ 2.1 | 1.9 | 31-42 C | |
| ❖ 1.6 | 0.8 | 33-42 C | 14 µm |
| ❖ 0.4 | NO DUST (too uniform) | | |
| ✓ 0.1 | NO DUST | | |
| ✓ 1.7 | 2.6 | 30-38 C | |
| ✓ 0.03 | NO DUST | | |






IR-MODEL is too sensitive to temperature at the arc minimum



# SAMPLE VALIDATION

based on AERONET ground measurements

- Good agreement (+/- 30%) over **desert** grounds

- Over the ocean or islands, lack of model sensitivity due to insufficient temperature contrast, dust thinness or **uniform** background for neighbour calculation

- Better match for **coarse** than for fine aerosol

- No sample validation done so far for dust temperatures (heights), using ground temperature. This is essential for evaluation of the thermal deficit

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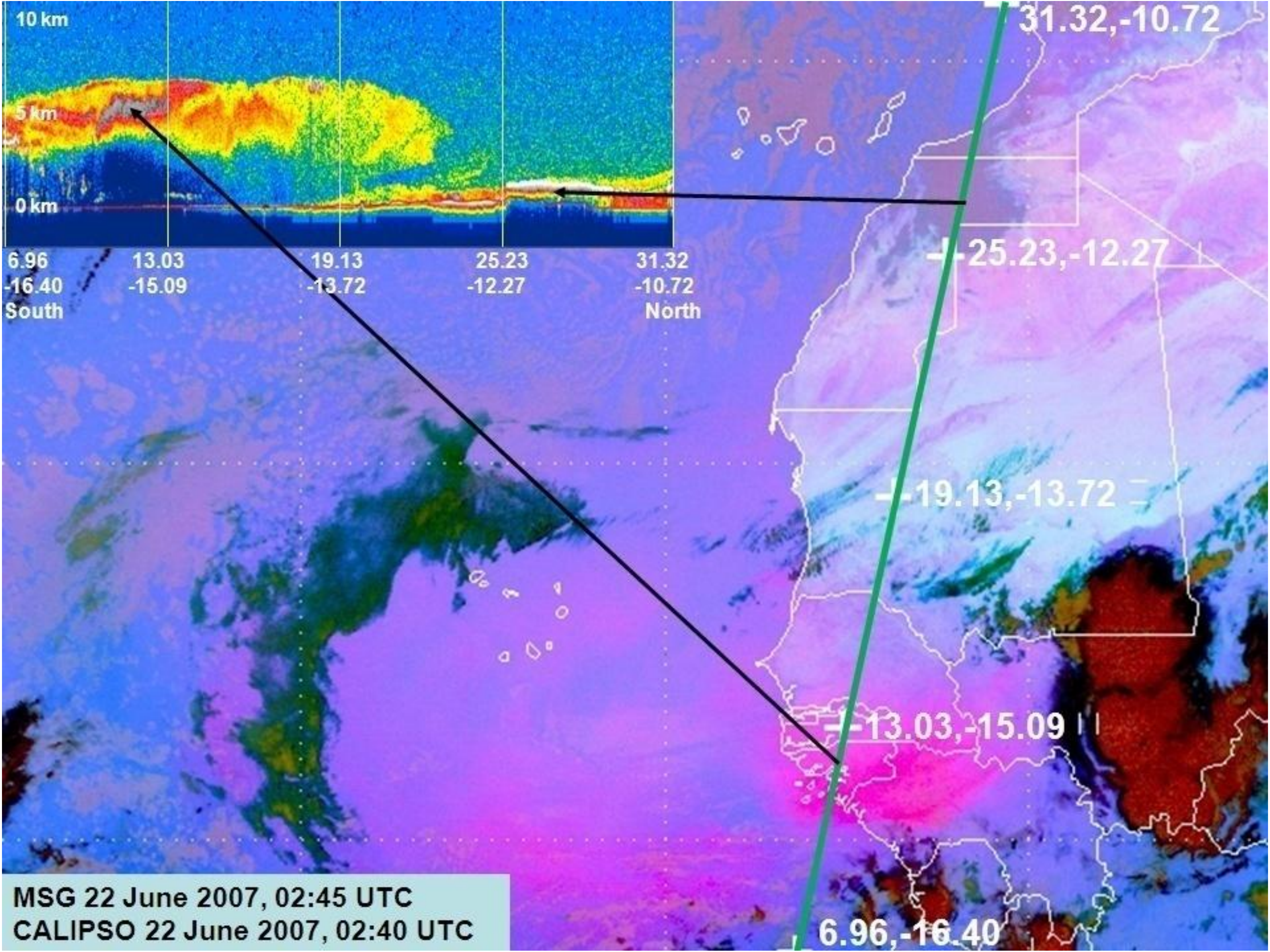
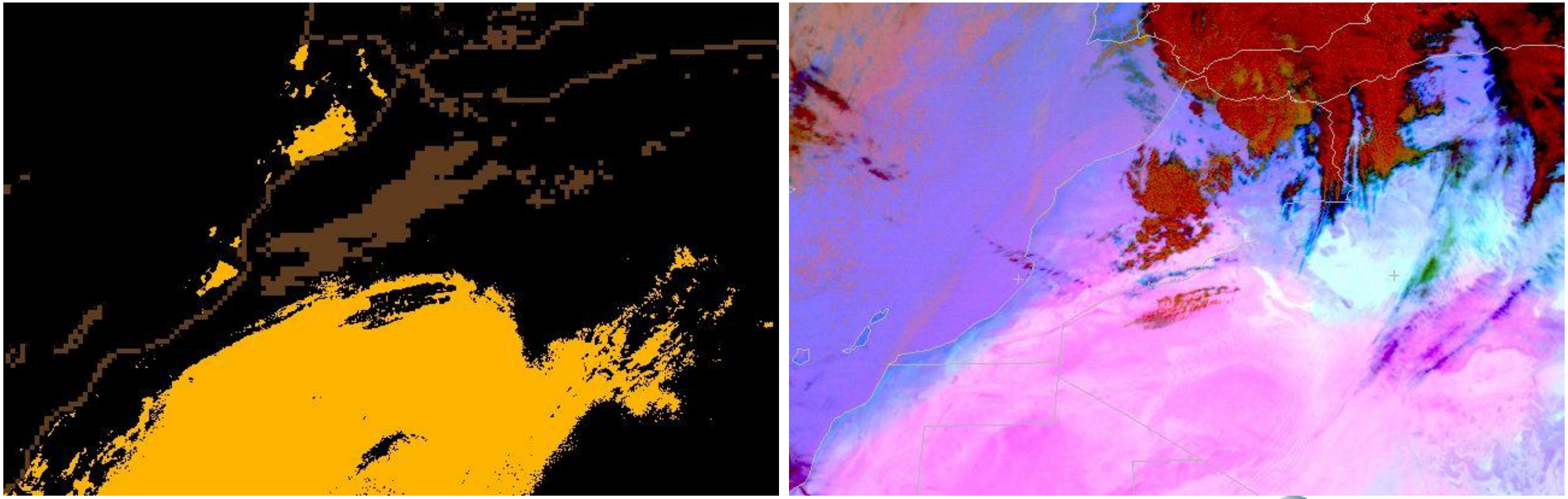

10 km
5 km
0 km
6.96
-16.40
South
13.03
-15.09
19.13
-13.72
25.23
-12.27
31.32
-10.72
North
31.32,-10.72
25.23,-12.27
19.13,-13.72
13.03,-15.09
6.96,-16.40
MSG 22 June 2007, 02:45 UTC
CALIPSO 22 June 2007, 02:40 UTC

# Other validation source: 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



Nowcasting SAF dust flag and Dust RGB 21-Mar-2010 12 UTC

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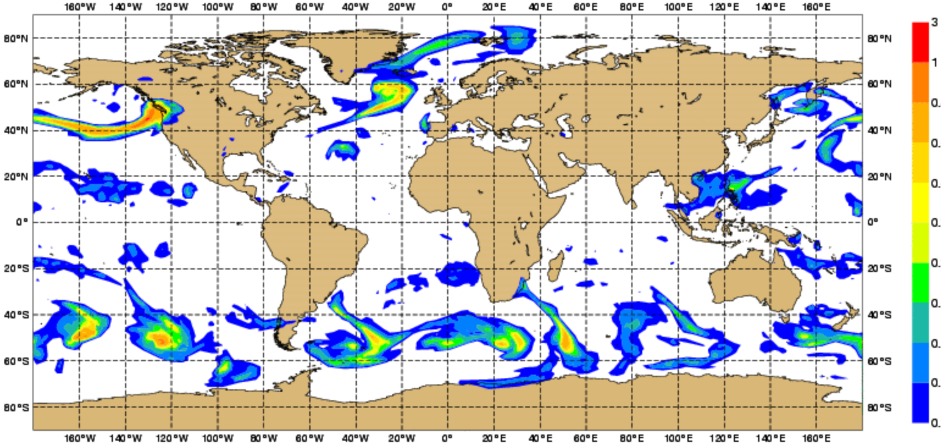
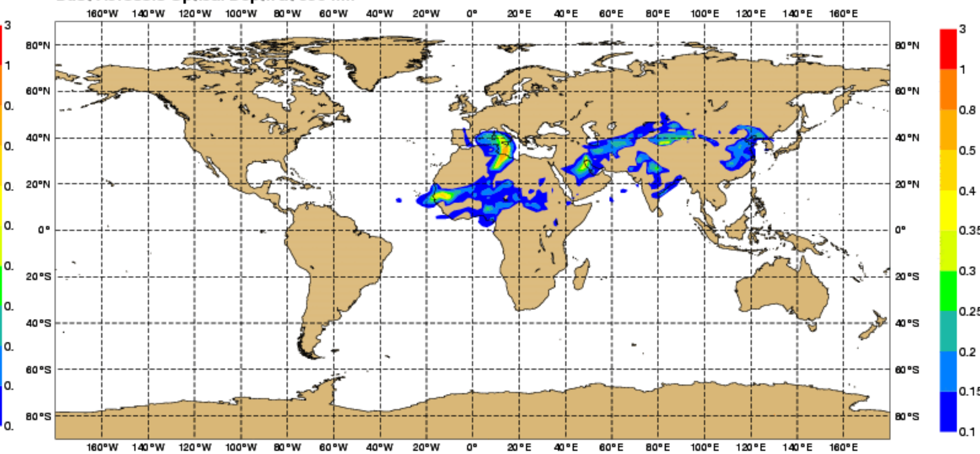
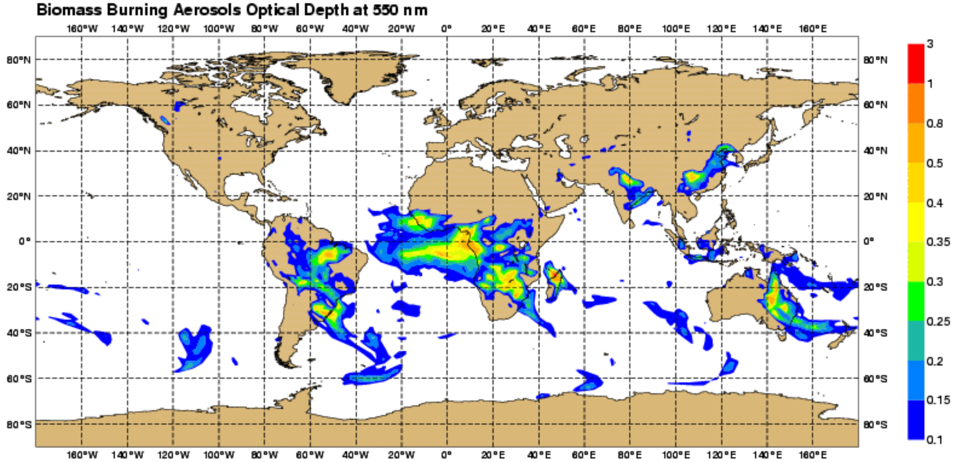
Sea-salt Aerosols Optical Depth at 550 nm



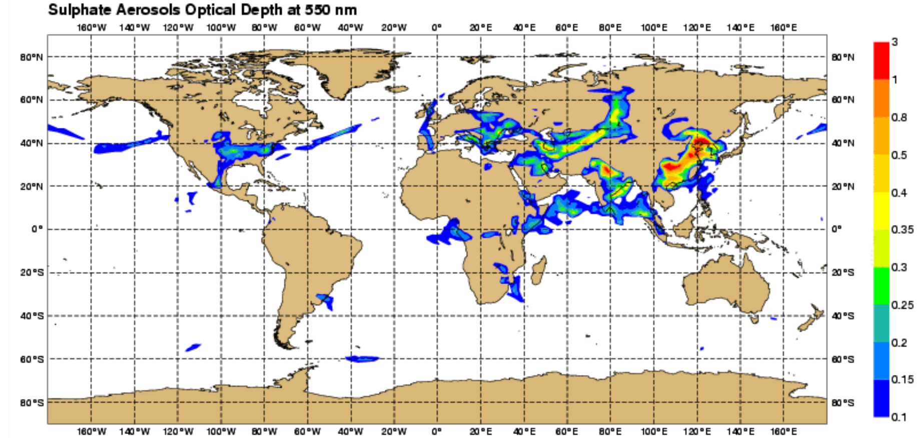

Dust Aerosols Optical Depth at 550 nm




Biomass Burning Aerosols Optical Depth at 550 nm




Sulphate Aerosols Optical Depth at 550 nm



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

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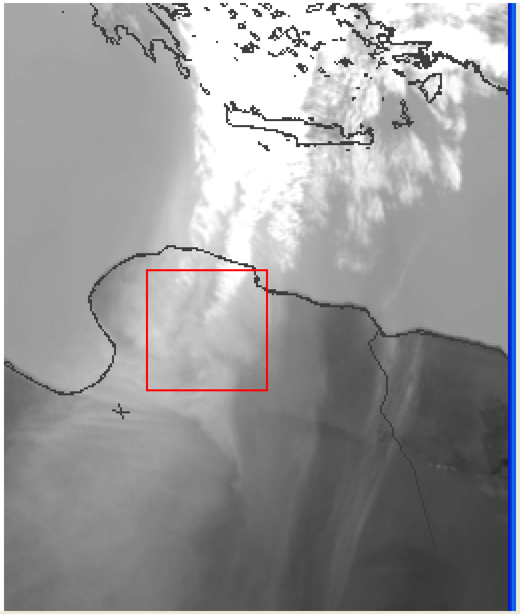
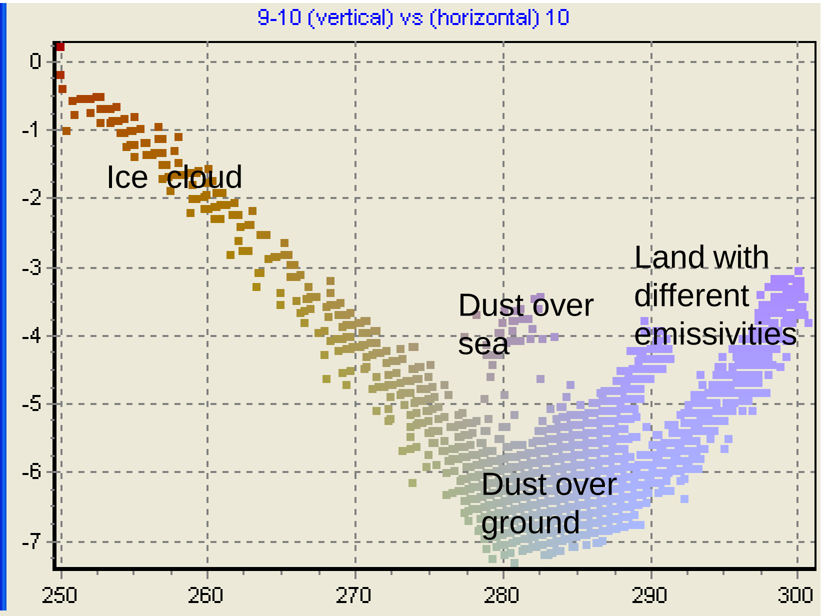
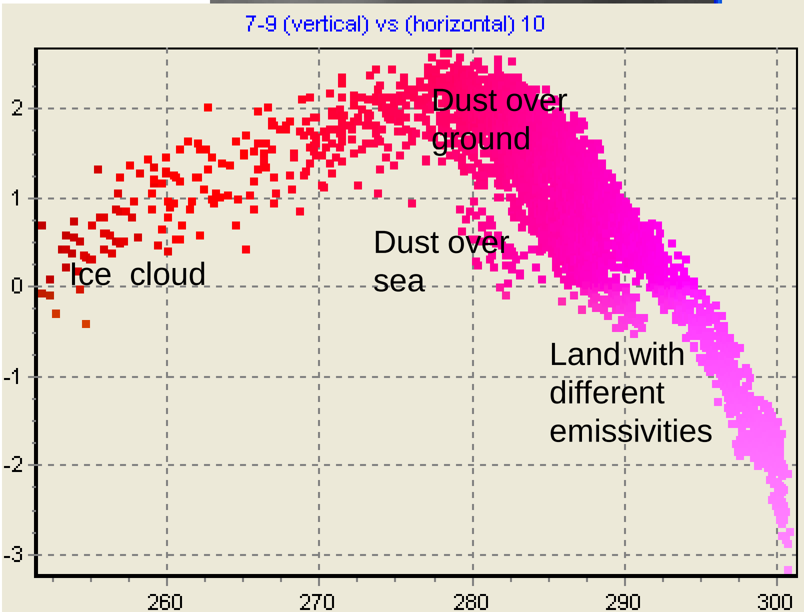
# Dust-cloud interaction

2008-03-23 11:30 UTC Meteosat Ch9






What is the ice temperature at the cloud boundaries?

265 K
275 K
285 K

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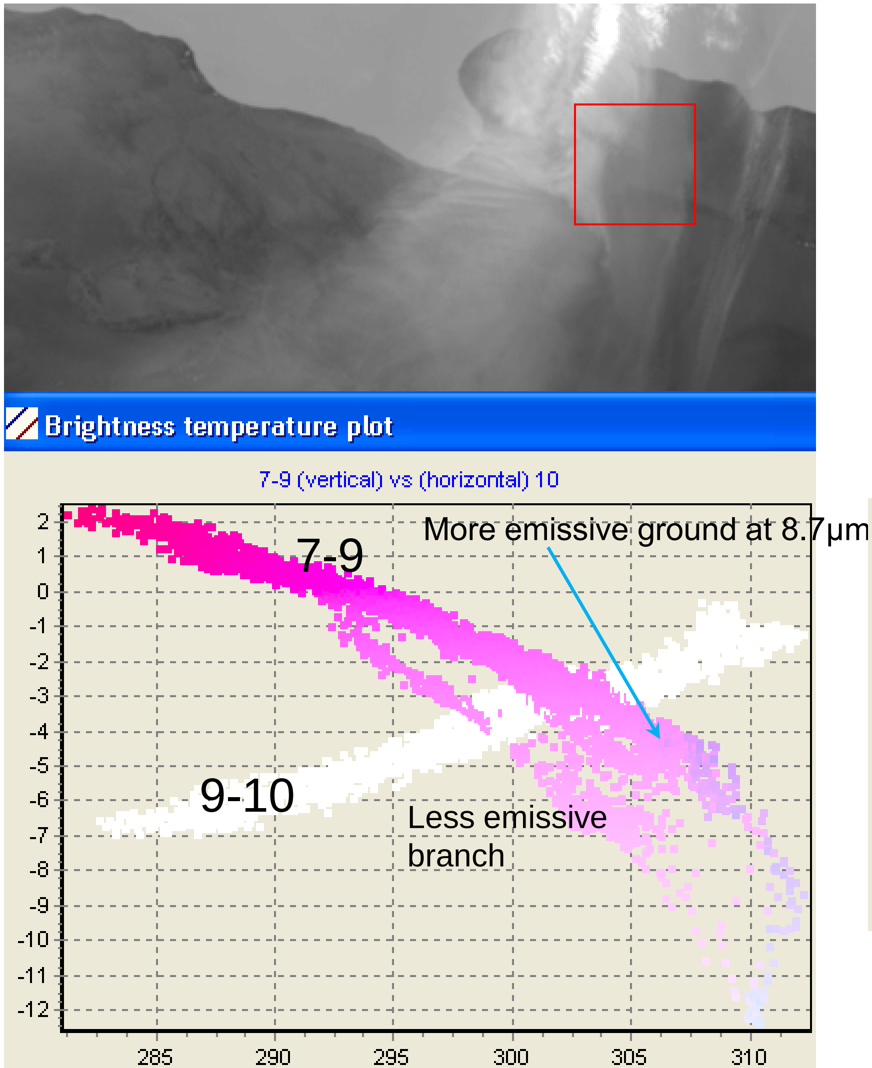
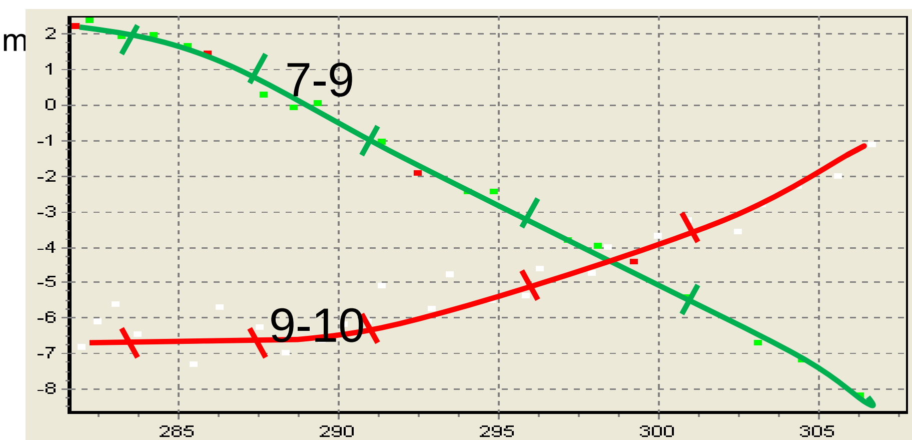
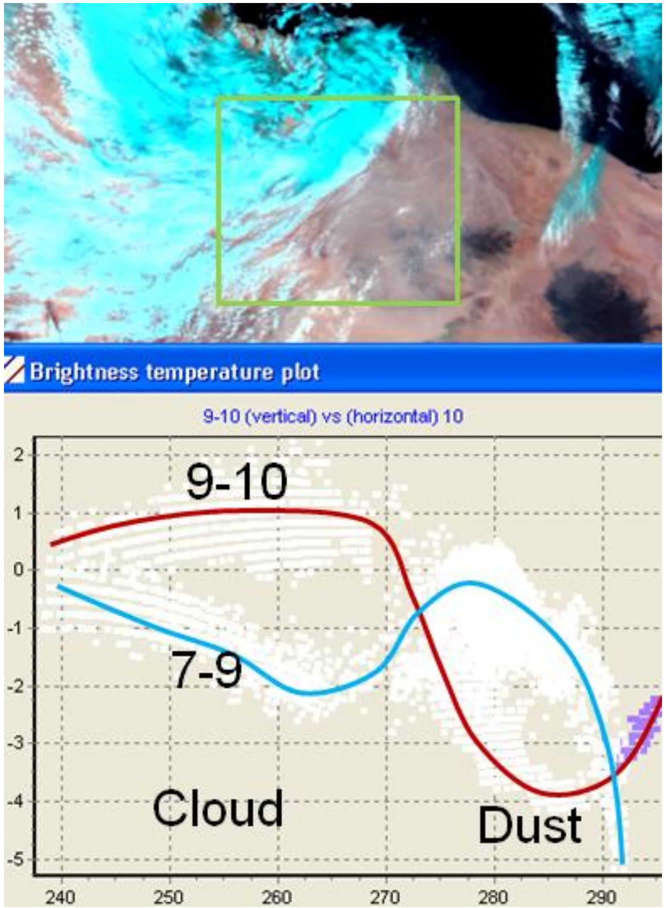
# Value added by channel 8.7µm




Real (left h.s.) compared with simulated (right h.s.) scatterograms based on Tg=308 Td=266
$\Sigma_{8.7}$=.35, .2 $\Sigma_{11}$=.6, .3 $\Sigma_{12}$=.2, .25
and ground emissivity 85% at 8.7µm
Marks at optical-thickness third-units from the right ends



# Dust-cloud interaction




Cloud-dust index: 2*ch9 – ch7 – ch10

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# Conclusions

- A model based on three **infrared** window channels provides a set of parameters for dust storm severity

- *Tdust, Tground* and *Depth* values are essentially derived from **10.8µm** and **12µm**

- Channel at **8.7µm** provides **refinement** at the dust end of the curves. Not at the ground branch, due to uncertain ground emissivity

- The model validation against AERONET is satisfactory, but other validation measurements (NWCSAF, LIDAR) are recommended

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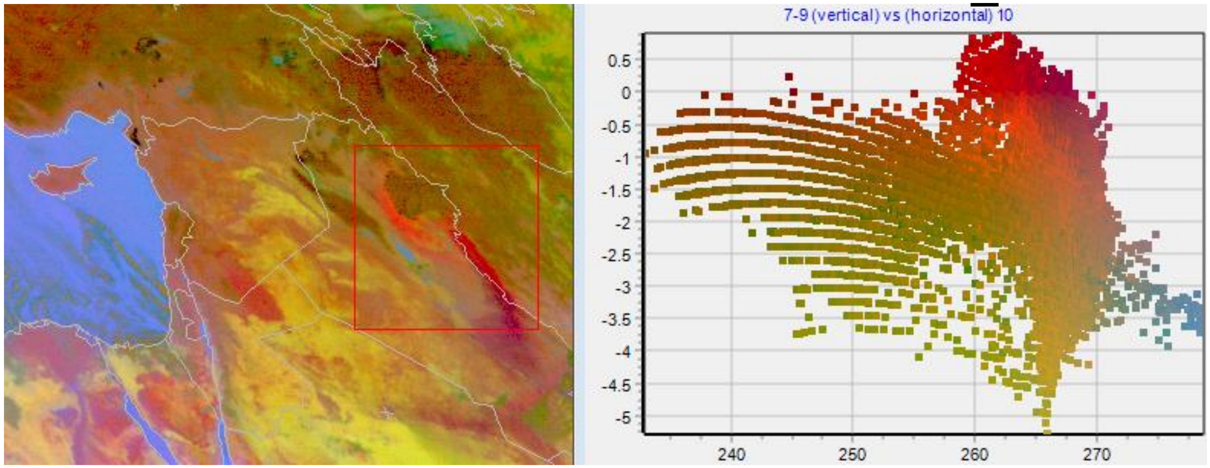
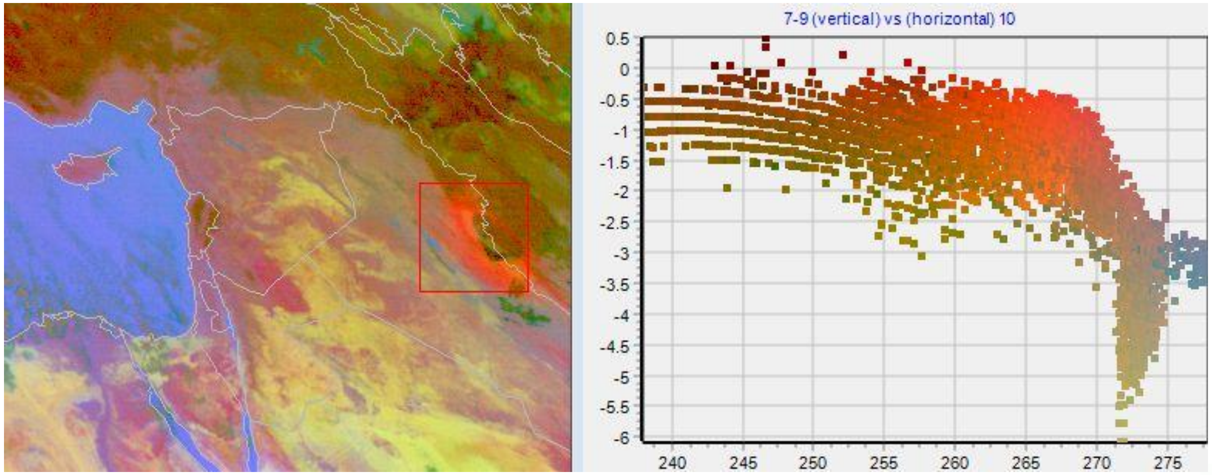
# Colour changes due to dust size or ground temperature?

2017-02-02_00UTC




2017-02-02_06UTC Meteosat-10

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# Size evolution on a homogeneous and isothermic surface

The Meteosat-8 Dust composite with the ECMWF 10m-wind and mean sea level pressure overlaid, Figure 1 (top right, click to expand) and ▸ **infrared composite animation**, 01 February 2017 00:00 UTC–02 February 12:00 UTC (MP4, 10 MB) indicate the presence of a weak circulation in the Middle East area, close to northern Iraq.

The wind associated with the cyclonic circulation on eastern Syria raises dust south of it, as shown in the infrared animation around 10:00 UTC on 1 February.

Over the northwestern part of Iraq, the dust joins the circulation along the south flank (red and pink on the left hand side of Figure 2), but it comes out mostly from the cyclone's west flank with a peach hue near Iraq's eastern border. An influence of the ground in the coloration is not evident. The time of the day plays no role, since the same hues show day and night.

**Image comparison**

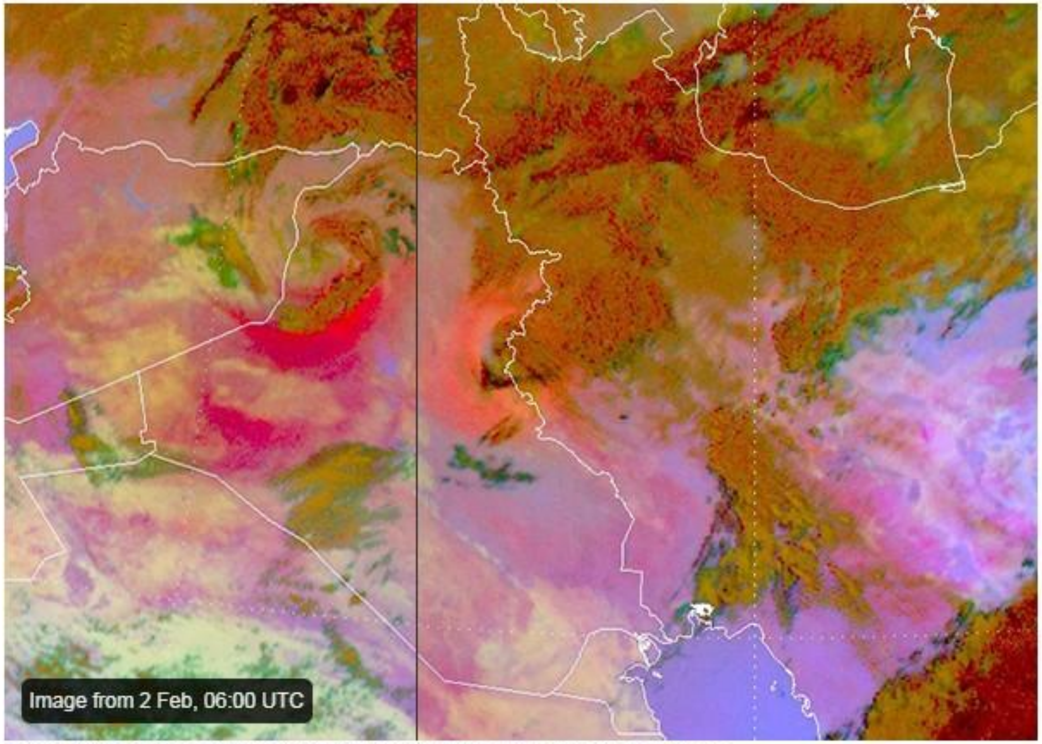


Figure 2: Comparison of two different moments in the evolution of the dust area.

Both Meteosat-8 and 10 see the same colours, so the viewing angle through a thicker humidity layer is not a sufficient explanation. Differences are only around 1 K between the measurements by the two satellites, so slant effects are not impacting colour hue either.

Orange (or peach) colour results from higher green, which is a larger positive Brightness Temperature Difference (BTD) between channels at 10.8μm and 8.7μm. In cloud free areas bigger BTD comes from higher water vapour, whereas in cloudy areas this BTD is affected by 1) dust height, 2) dust concentration and 3) dust properties, mainly particle size.

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# Outlook

- A pattern for **surface cooling by dust** and **particle size profiles** will improve the simulation of the observed radiances

- **Particle size** affects channel **emissivity** in a way to be learnt, usable to reduce the gap between expected and real radiances (residuals)

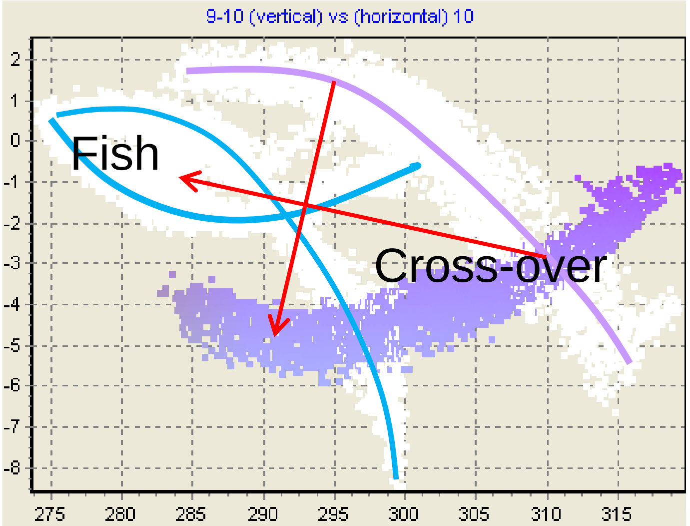
- Looking into the BT’s for **dust mixed with water or ice** will clarify the role of aerosols in cooling the atmosphere and inhibiting rain (or hurricanes!).

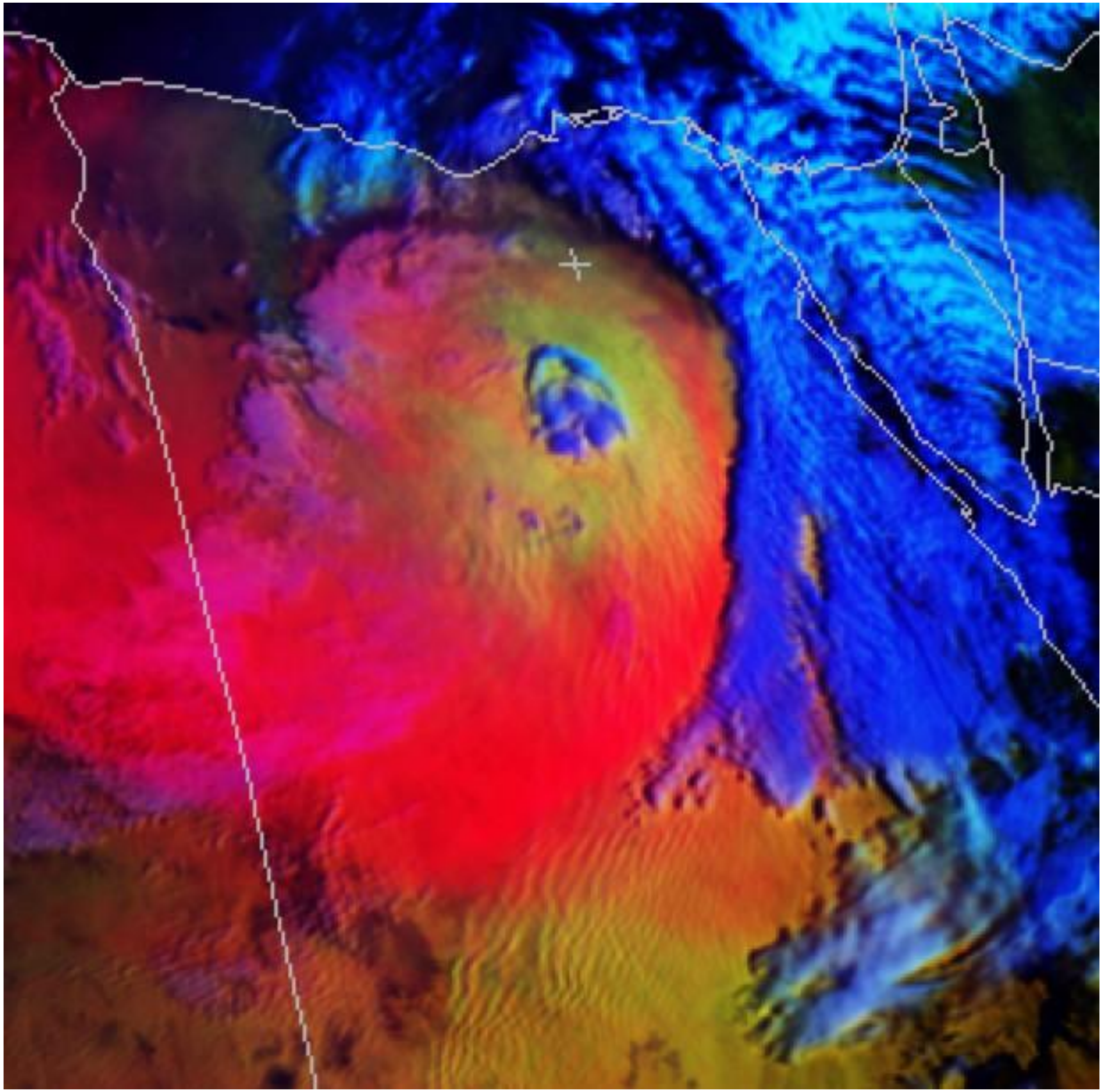
- Coupling IR technique with existing methods for **solar** channels will allow the simultaneous retrieval of surface **albedo** and **aerosol optical depth**

- A **calibration** against the **solar** technique will provide skill for the IR estimate, even during the night

# THANKS FOR YOUR ATTENTION !

- List of used 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

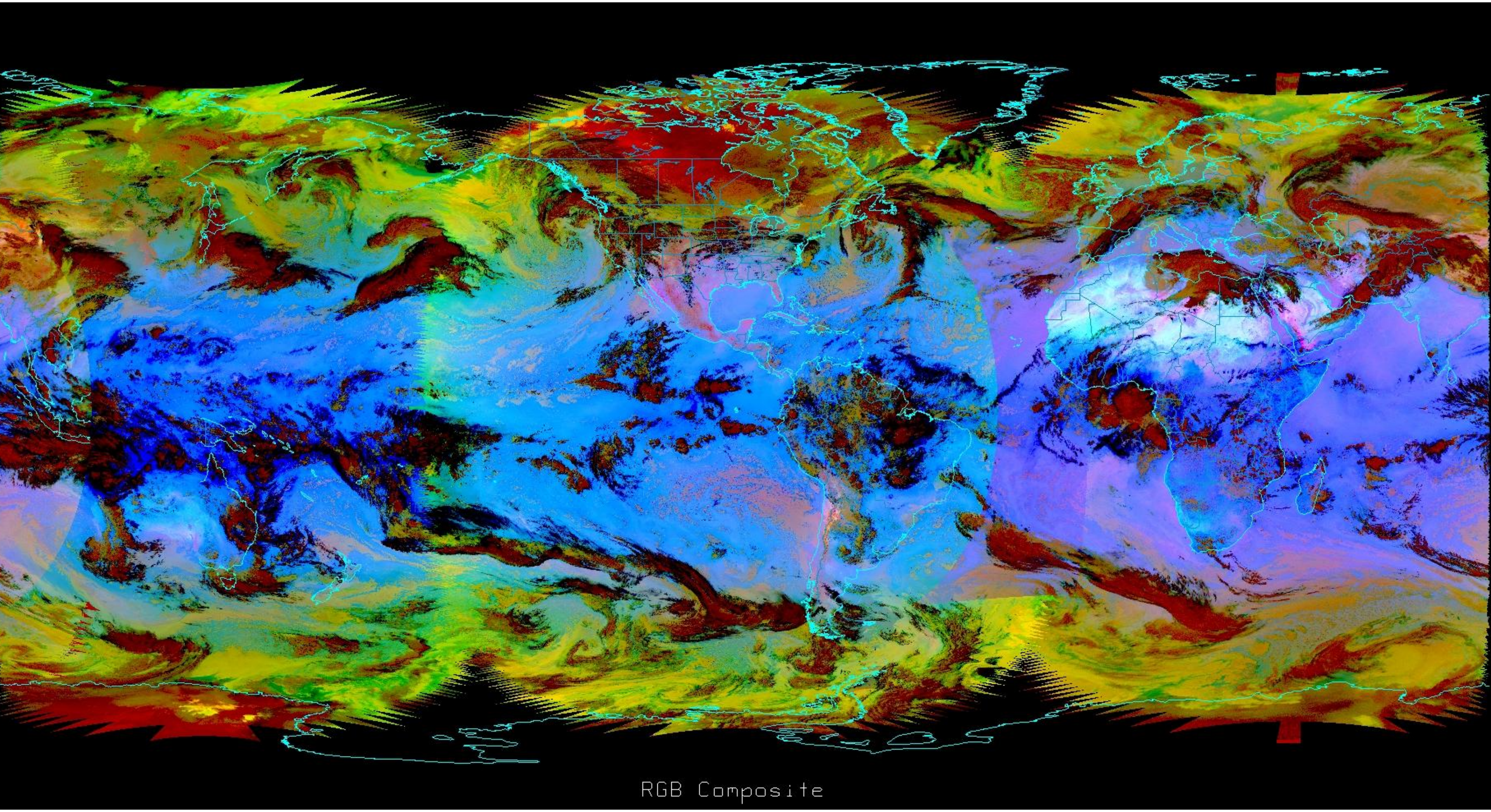




Variance PCA analysis  2017-03-18 07Z, Egypt Meteosat-10

EUMETSAT

# Dust all over the world? (or not so much?)



# Can you not think of a question?

No problem. Just choose one from the following:

1. Why do we see “pink” areas in southern Africa frequently? Is there a diurnal temperature cycle?

2. What can we do in case of thermal inversions? Do channel diagrams help identify those situations?

3. How can we produce the scatterograms by ourselves?