Satellite observation of dust

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

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“Peach” for big particle dust

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

2017_05310600-06011100_m08
Can a satellite see dust particles?

- 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)
Better dust detection in the infrared?

<table>
<thead>
<tr>
<th>Best contrast ?</th>
<th>DAY</th>
<th>NIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VIS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Ocean</th>
<th>DAY</th>
<th>NIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td>strong</td>
<td>strong</td>
</tr>
<tr>
<td>VIS</td>
<td>very strong</td>
<td>A/N/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Desert</th>
<th>DAY</th>
<th>NIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td>very strong</td>
<td>weak</td>
</tr>
<tr>
<td>VIS</td>
<td>weak</td>
<td>A/N/A</td>
</tr>
</tbody>
</table>

- 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
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
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
Aerosol is more than dust

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

Forward fraction = \exp(-\text{AOD})
Contents

- Infrared dust properties
  - Where you learn how cool dust really is

- A model of atmospheric dust
  - Where you learn to distinguish high 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 dust associates with water

- Conclusions
  - Where you learn that there is more dust on books than books on dust
Dust characteristics

- Dust storms occasionally reach 5 km height, frequently thicker than 1 km.
- 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/m$^3$ (optical depth 0.1).
- Dusty air $\sim$ AOD=1 $\sim$ 1 mg/m$^3$ $\sim$ 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)
Ch9 (upper left), two independent differences, and all together as colour
The 10.8µm-12µm difference (vertical)
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

<table>
<thead>
<tr>
<th>Channel Comparison</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.7 µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.8 µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.0 µm</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Low cloud

Dust storms

EUMETSAT
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)
And how is it with DUST?

Thin dust < 0.5 absorbs more 10.8µm, 12.0µm goes forward.

Thick dust > 1.5 emits more 10.8µm.

Emissivity=0.25
Emissivity=0.15
Emissivity=0.90
Emissivity=0.75

Absorption + scattering efficiencies

TRANSPARENCY EFFECT
10.8µm < 12.0µm

EMISSION EFFECT
10.8µm > 12.0µm
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.
- 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...)
• **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)
Graphical analysis

The arc shape depends on temperatures (dust top, ground, dust vertical extension) and efficiencies (dust composition, size, shape). The dip in the curve depends on relative weights of efficiencies at 10.8 and 12.0 µm.
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 \( \Sigma 11=0.6, 0.3 \)  \( \Sigma 12=0.2, 0.25 \)

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 T₀
If slope=a, refresh T₀
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
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

AOT not calculated
Ground versus dust skill

IR model does not usually pick on rock or sand areas

The IR model separates the dust areas from the ground dry areas
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
7 < 9 < 10
little.
(thermal inversion)

9 > 7 > 10
much.
(thermal inversion)

no dust

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

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

2004-05-13 13:00 UTC, 10.8 µm
12.02E 13.22N, model on image at 12UTC: theta=0.6 31C-39C size=29

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

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

2.66E 13.53 N, model on image: theta=0.8 33C-42C size=14
Validation based on ground measurements
(AOD units)

<table>
<thead>
<tr>
<th>AERONET</th>
<th>IR-MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ 0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>✓ 0.35</td>
<td>0.2</td>
</tr>
<tr>
<td>✓ 2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>❖ 1.6</td>
<td>0.8</td>
</tr>
<tr>
<td>❖ 0.4</td>
<td></td>
</tr>
<tr>
<td>✓ 0.1</td>
<td></td>
</tr>
<tr>
<td>✓ 1.7</td>
<td></td>
</tr>
<tr>
<td>✓ 0.03</td>
<td></td>
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</tbody>
</table>

**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
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
Dust-cloud interaction

Cloud-dust index: $2 \times ch9 - ch7 - ch10$
Infrared dust properties
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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
Conclusions

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

• $T_{dust}$, $T_{ground}$ 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
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
Dust all over the world? (or not so much?)