



Dust variability and trends



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Carlos Pérez García-Pando and Emily Elhacham

BSC and ICREA





Outline of the session

- ⑩ Lifecycle of dust storms
- ⑩ Types of dust events according to meteorological conditions (high frequency variability)
- ⑩ Seasonality
- ⑩ Long term trends
- ⑩ Drivers of trends



Life cycle of dust storms

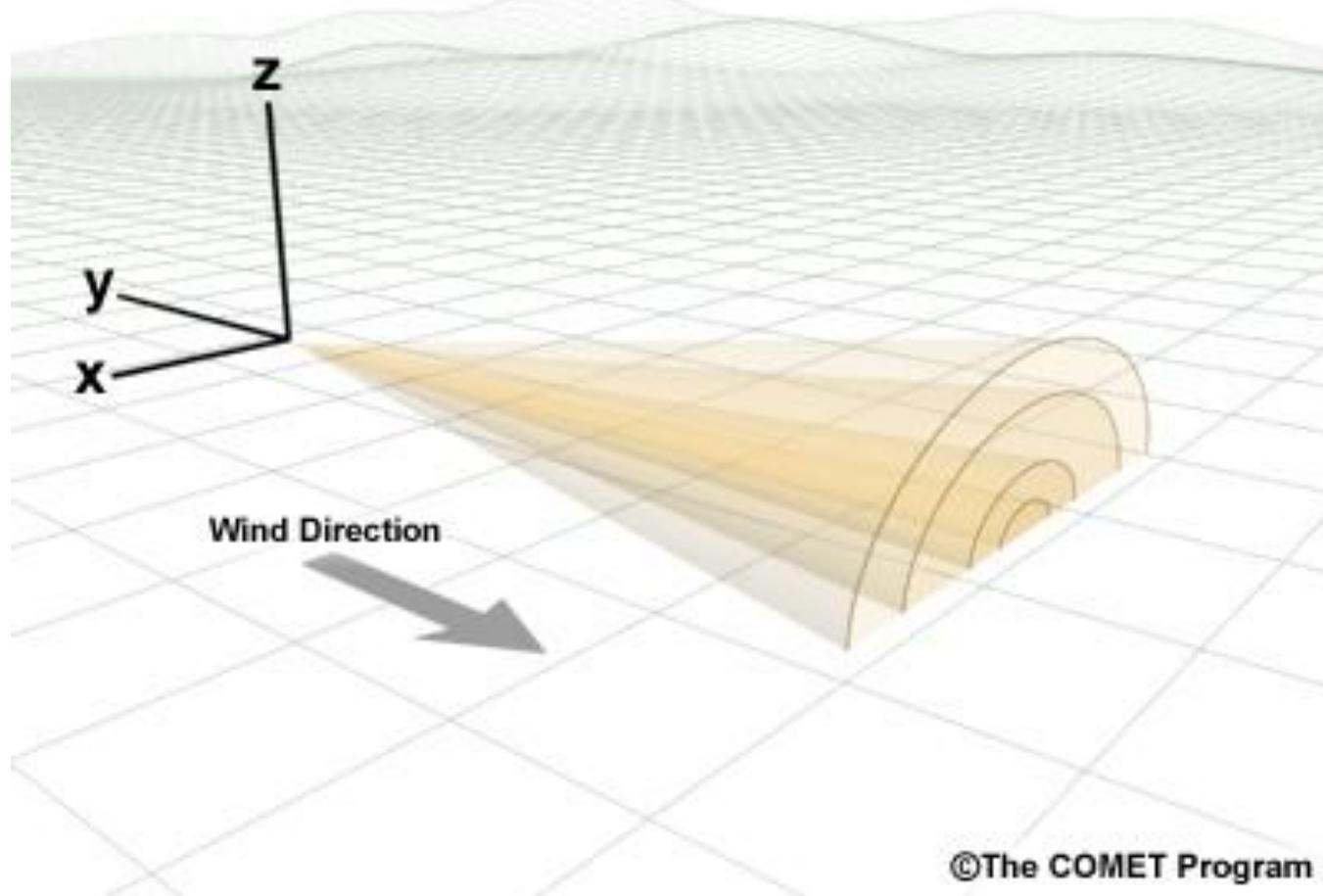


Lifecycle of a typical Shamal



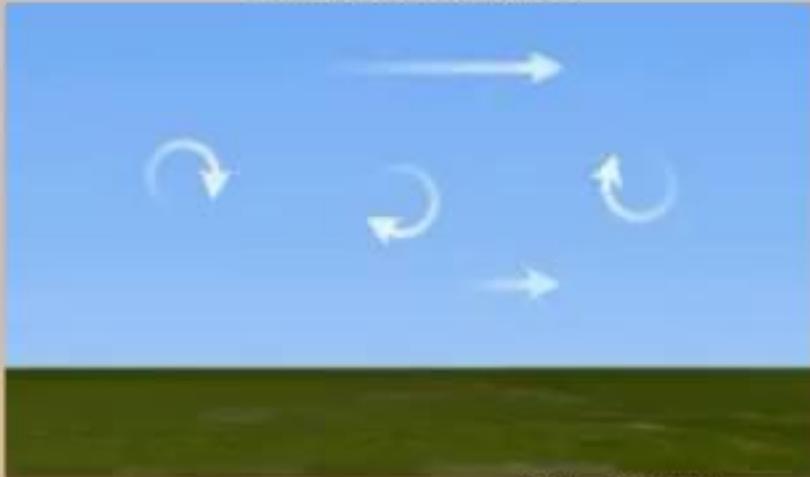
Dispersion

Dust Plume Geometry



Causes of dispersion

Shear Turbulence



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Mechanical Turbulence



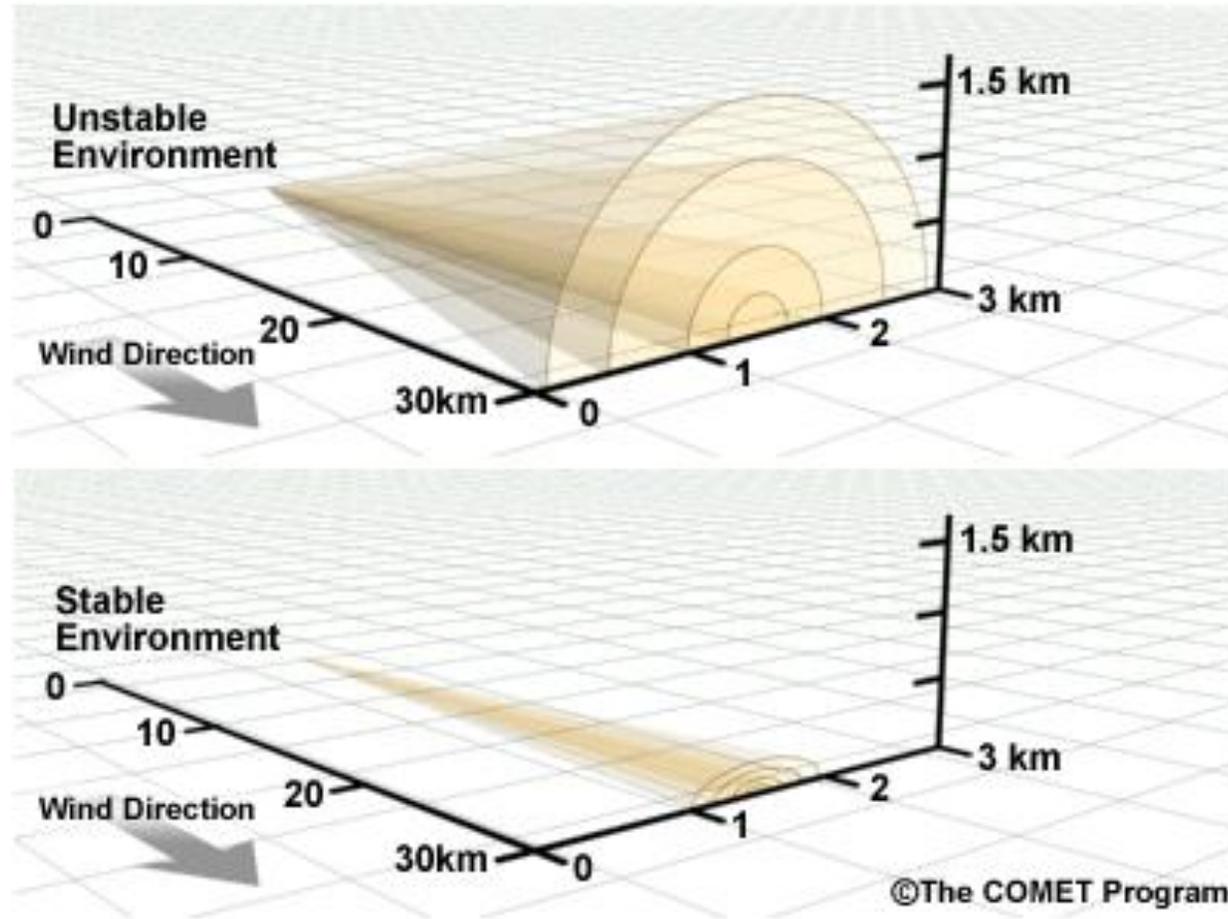
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Buoyancy Turbulence



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Dispersion and stability



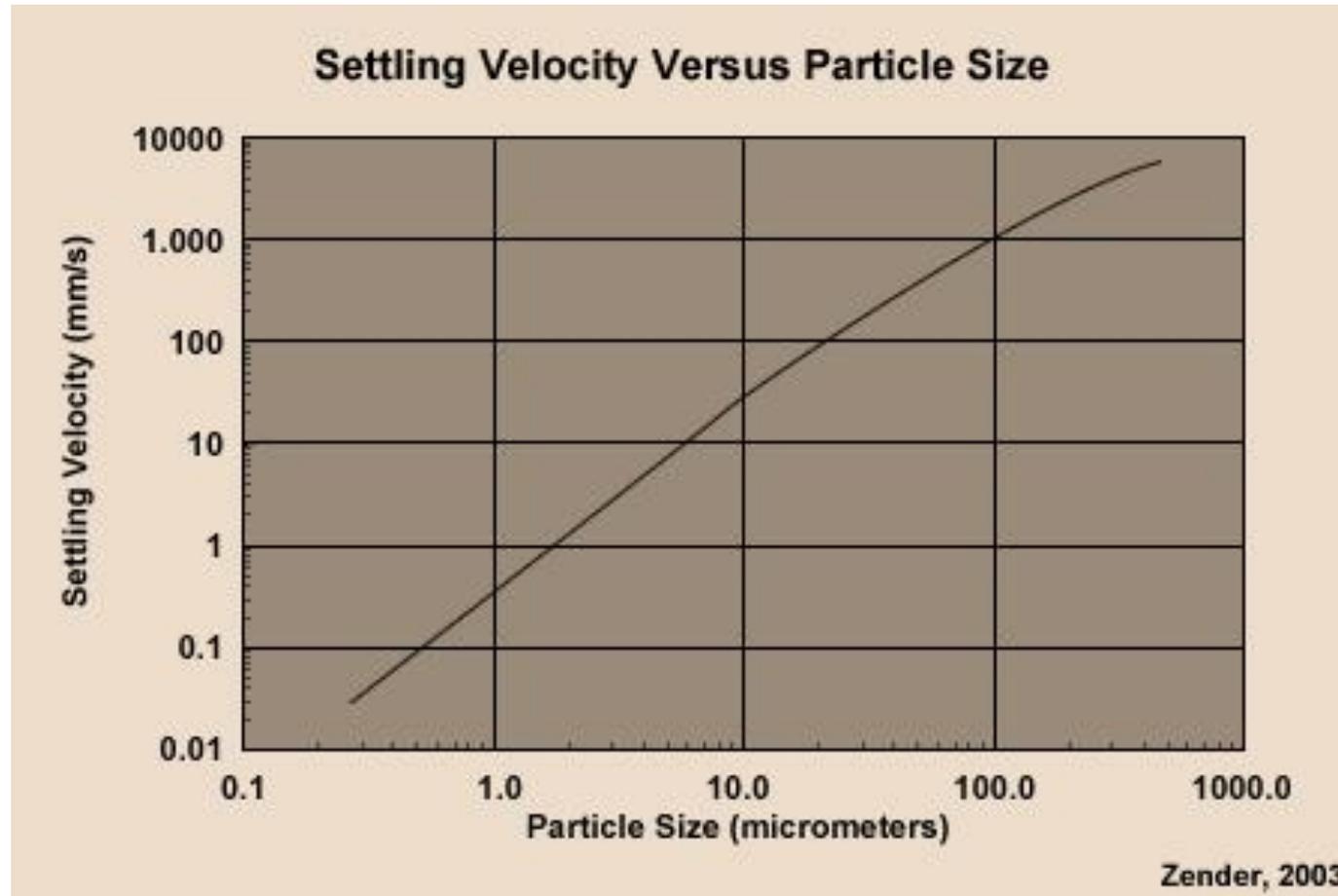
Advection



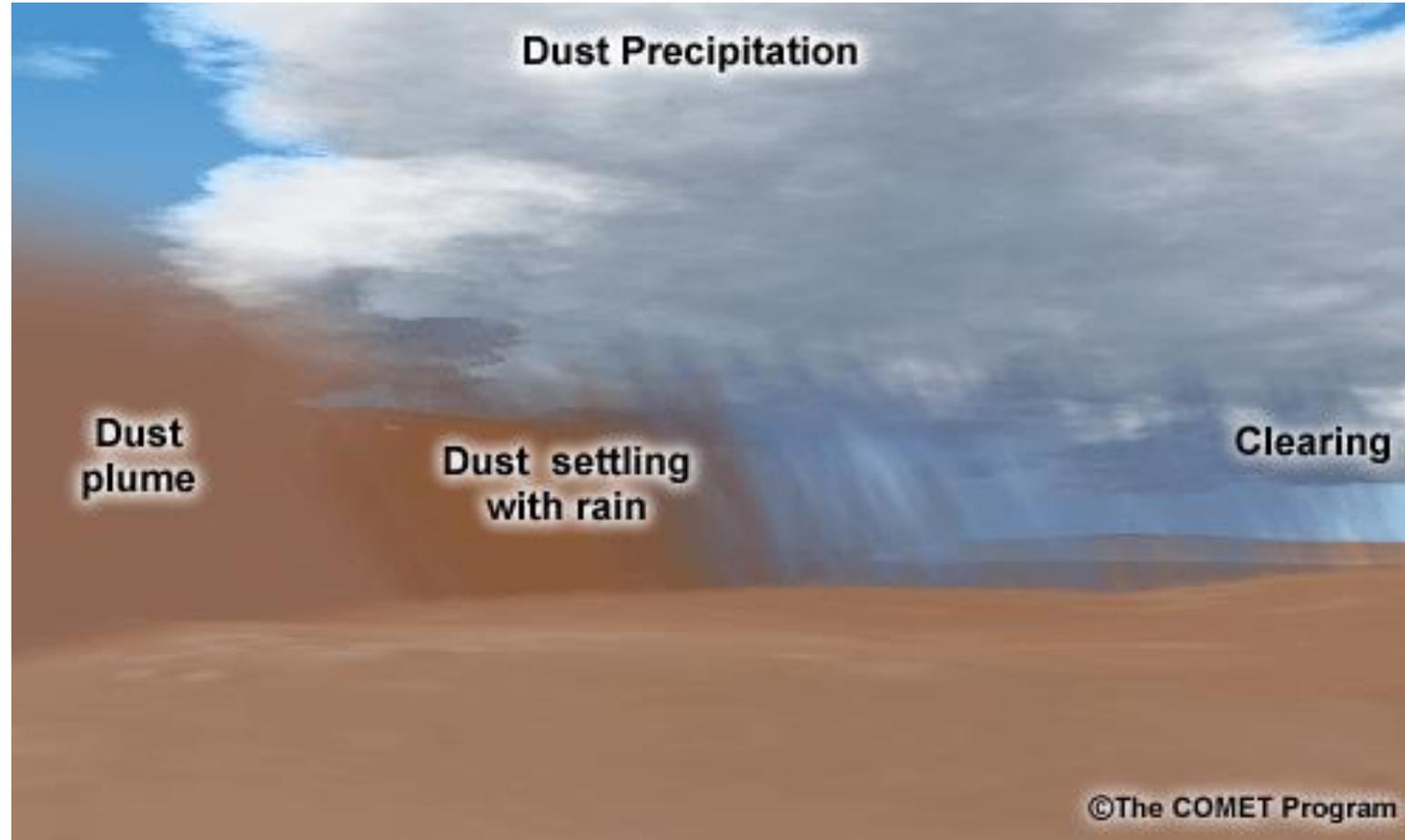
Dust settling (sedimentation)



Settling velocity



Dust scavenging



Types of dust events and storms (according to meteorological conditions)

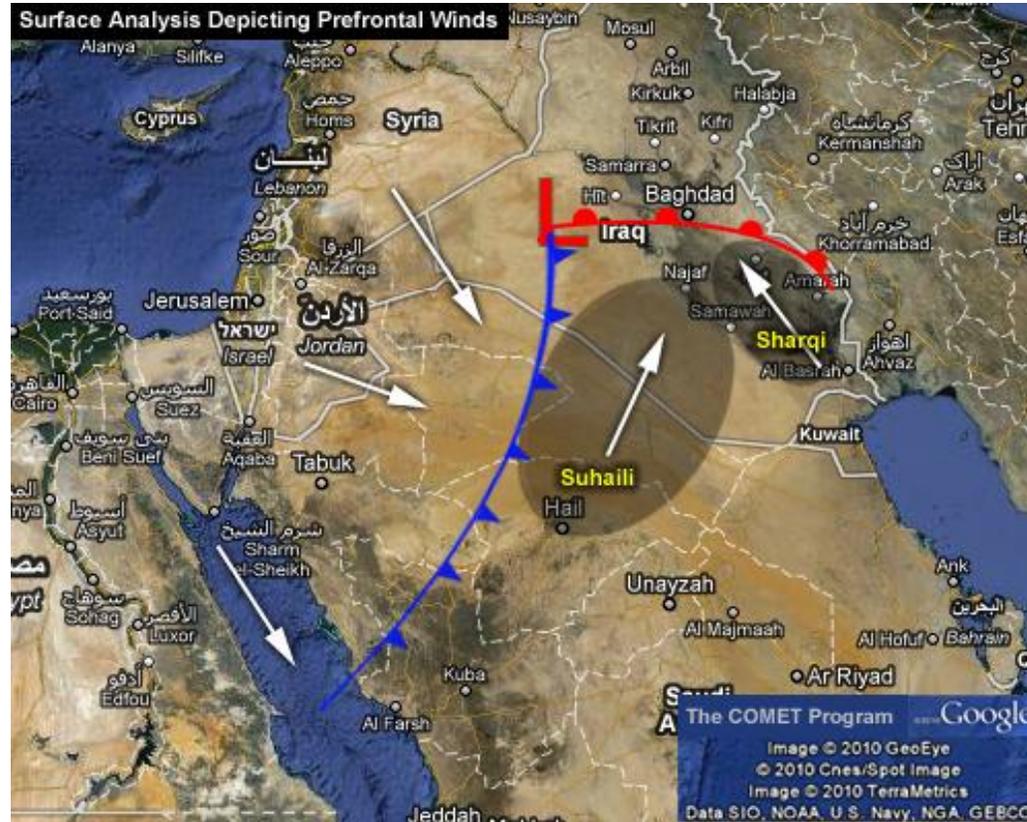


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Synoptically forced dust outbreaks

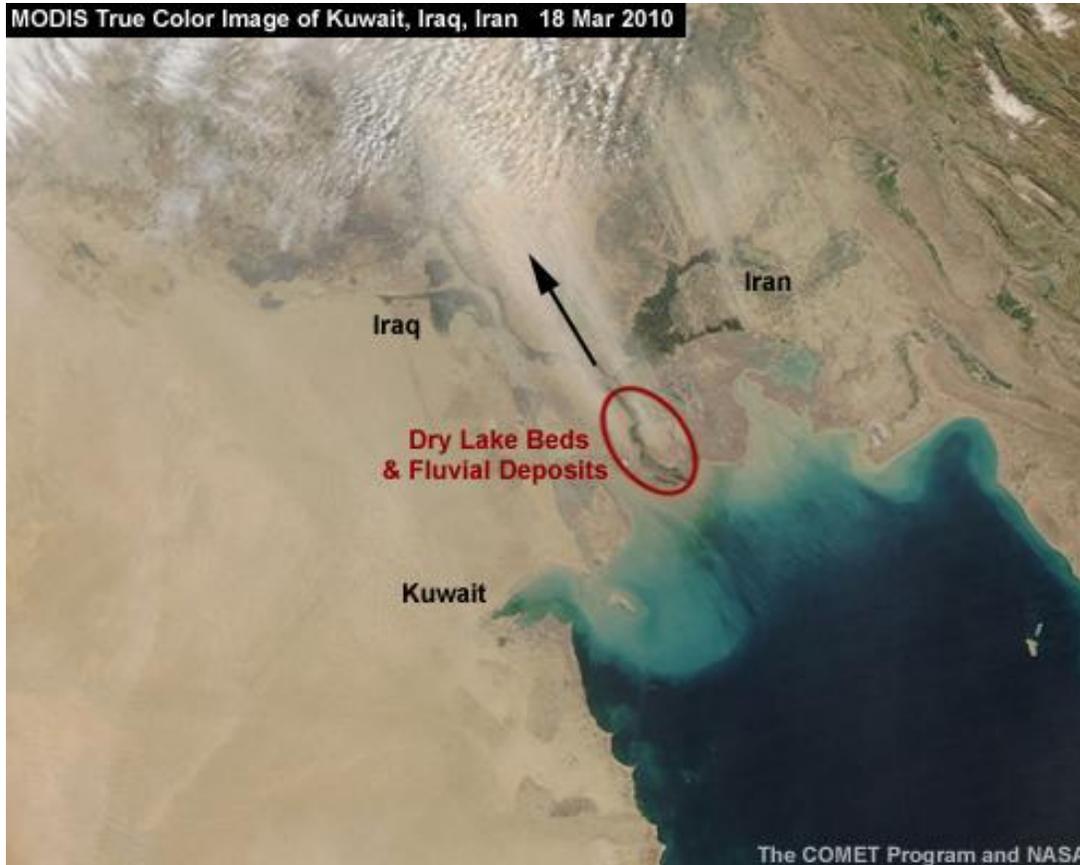
Caused by frontal winds that primarily occur in winter and spring



Prefrontal dust storms occur when a band of winds generated ahead of low-pressure areas moves across a dust source region such as the Sahara.

Synoptically forced dust outbreaks

Caused by frontal winds that primarily occur in winter and spring

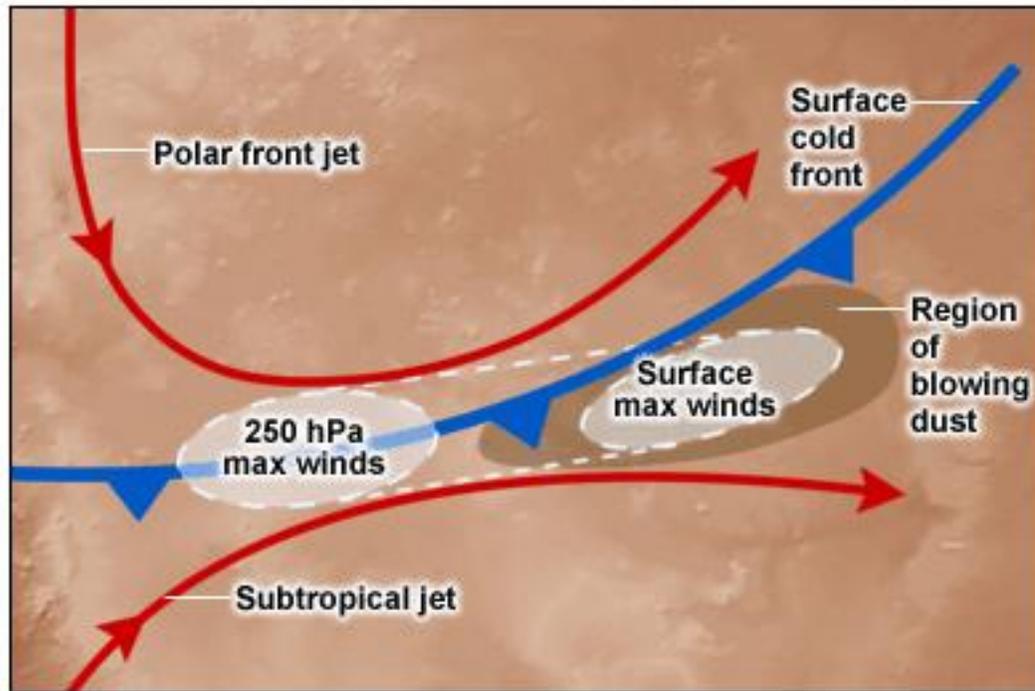


This MODIS true colour image shows Sharqi prefrontal dust plumes emanating from dry lake beds and fluvial deposits in southeastern Iraq. Fluvial deposits are associated with dry rivers and streams.

Synoptically forced dust outbreaks

Caused by frontal winds that primarily occur in winter and spring

Synoptic Conditions for a Prefrontal Dust Storm

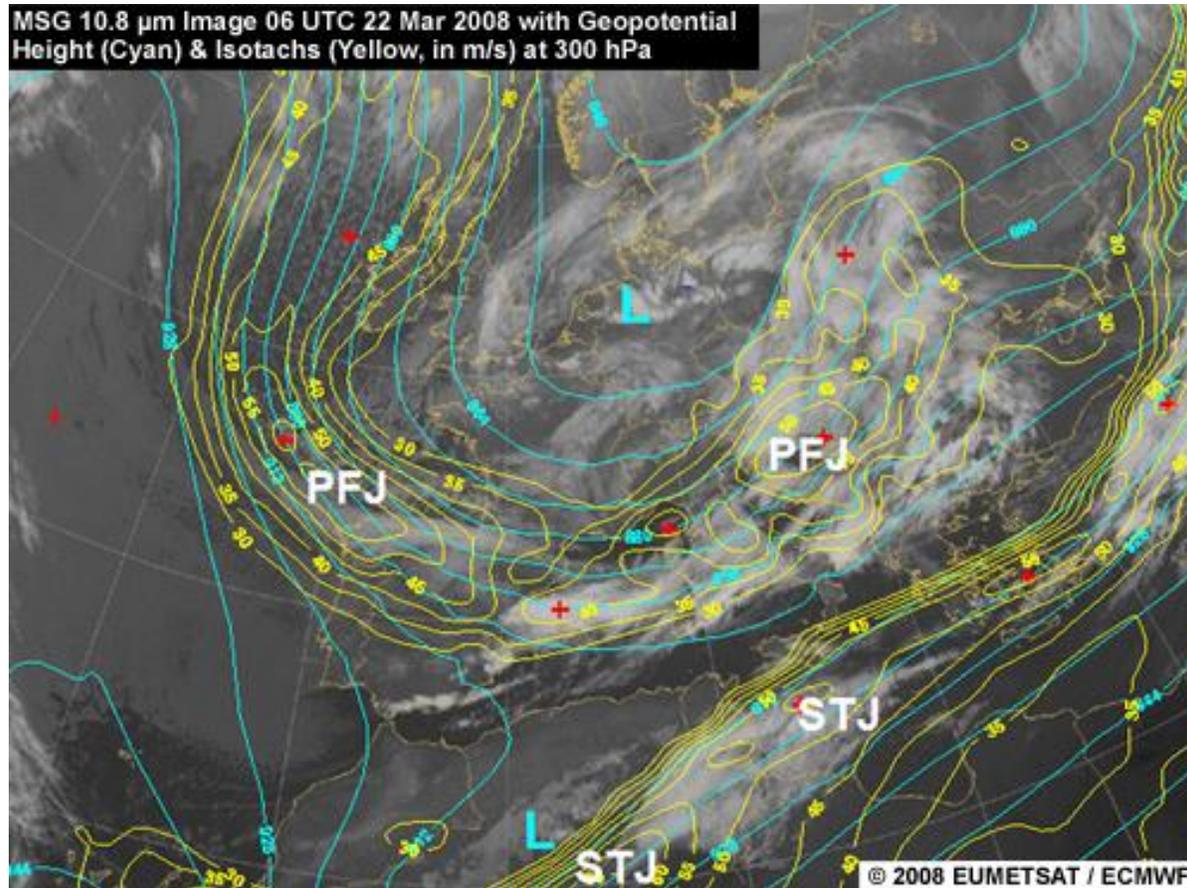


Wilkerson, 1991

The interaction of the polar and subtropical jet streams often strengthens the front, which induces stronger prefrontal winds ahead of the upper-level trough.

Synoptically forced dust outbreaks

Caused by frontal winds that primarily occur in winter and spring



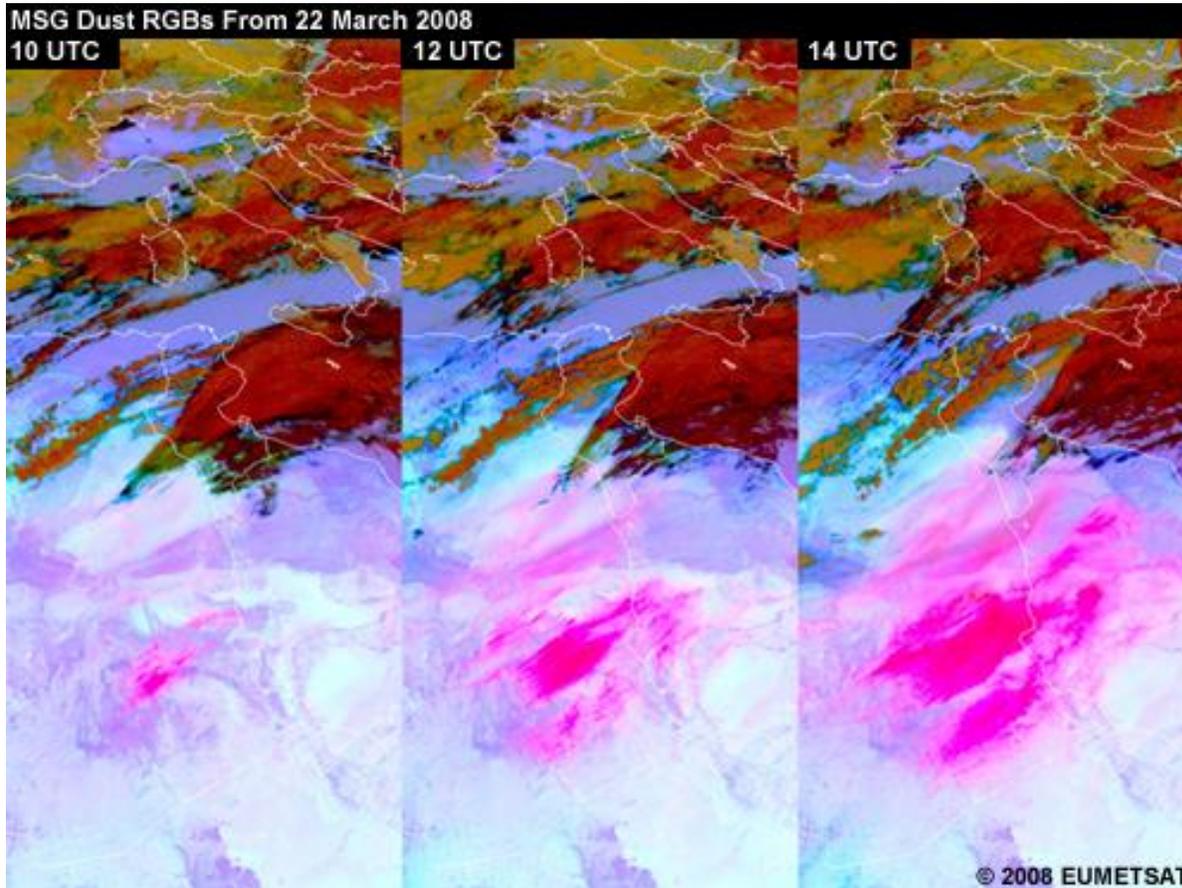
Prefrontal dust outbreak occurred on 22 March 2008 over Algeria, Tunisia, and Libya.

300-hPa polar frontal jet (PFJ)

Subtropical jet (STJ)

Synoptically forced dust outbreaks

Caused by frontal winds that primarily occur in winter and spring

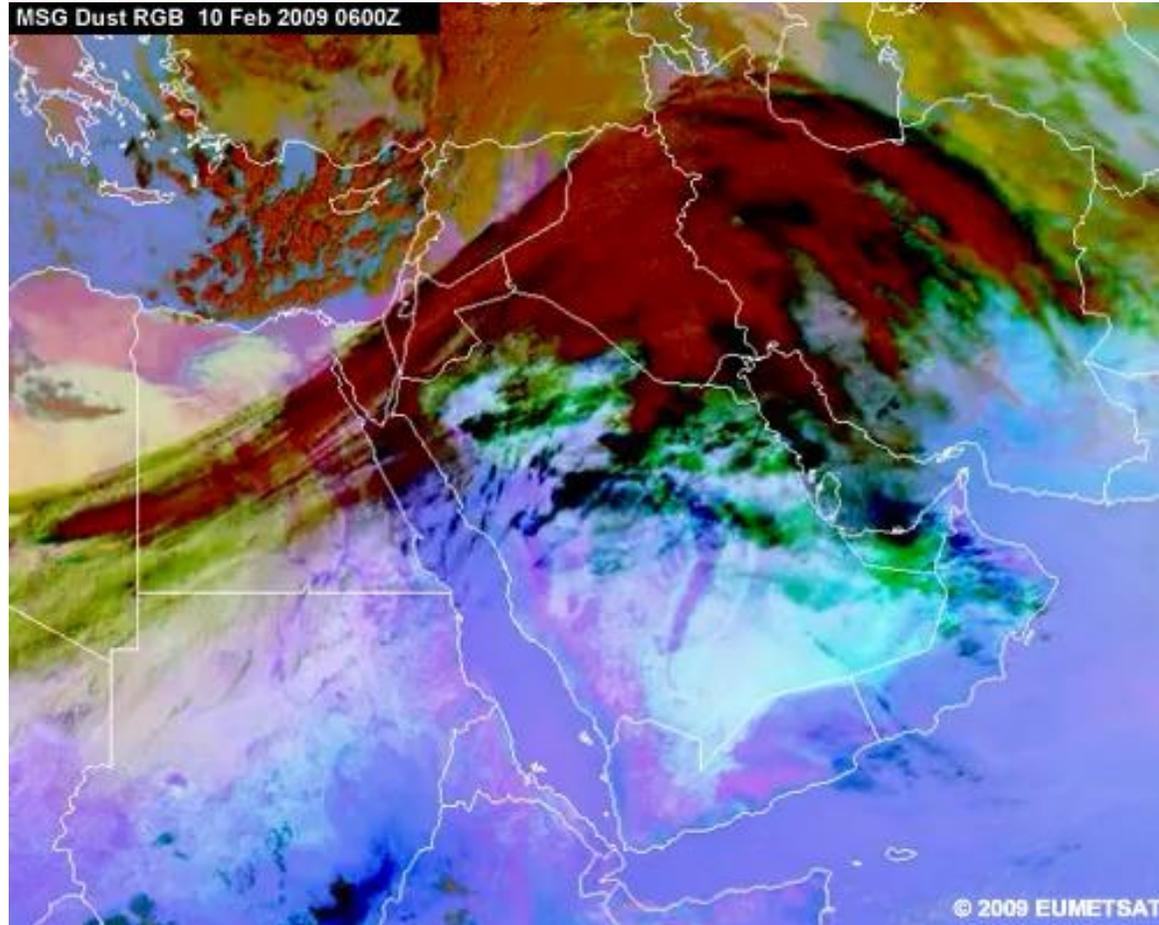


Prefrontal dust outbreak occurred on 22 March 2008 over Algeria, Tunisia, and Libya.

The prefrontal winds responsible for the blowing dust are referred to as the Scirocco in Tunisia, Ghibli in Libya, and Khamsin in Egypt. They can have speeds of up to 100 km/h and are most common during autumn and spring.

Synoptically forced dust outbreaks

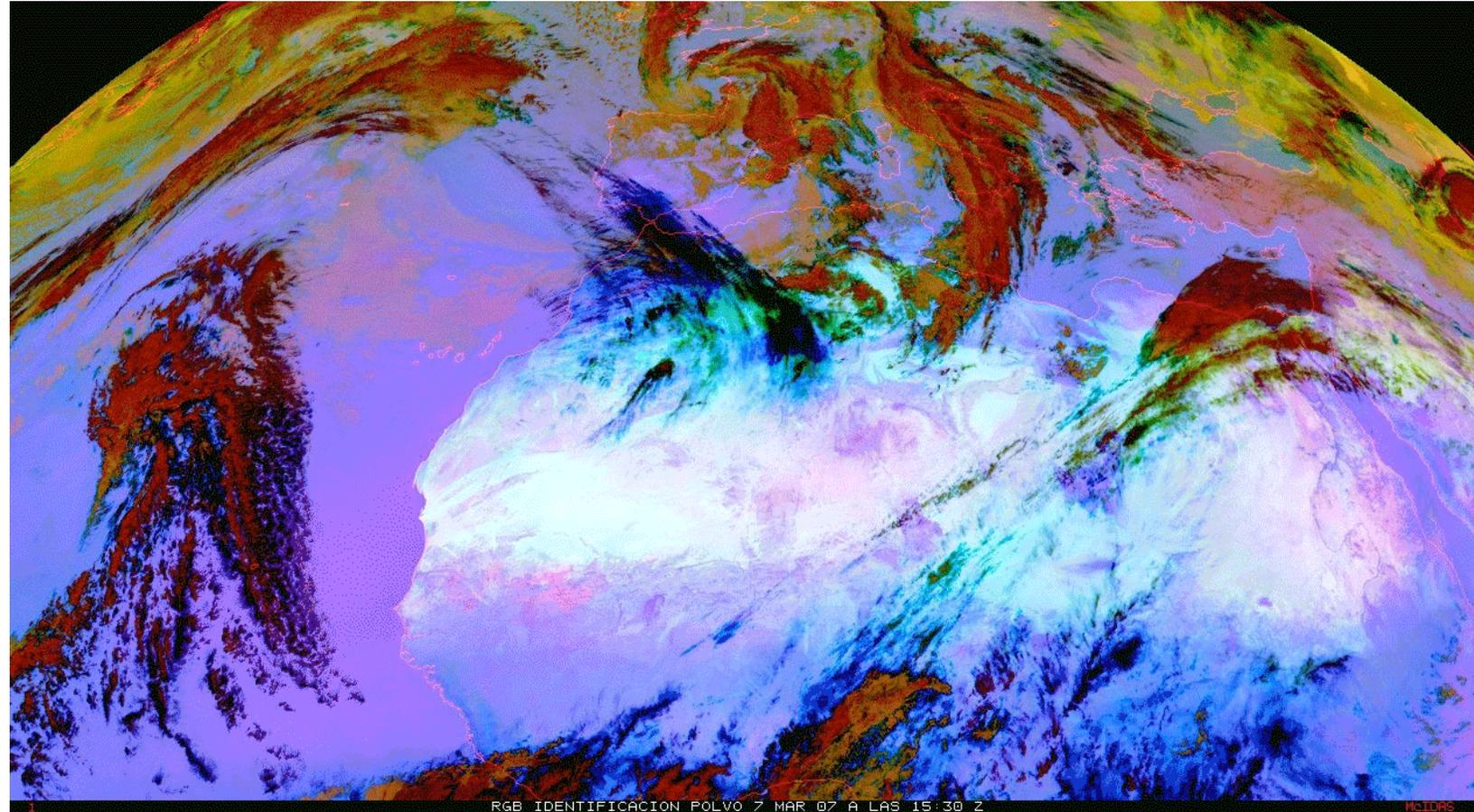
Caused by frontal winds that primarily occur in winter and spring



Post-frontal dust outbreak:
Widespread dust can also occur behind a cold front.
The resulting dust storm is referred to as a “Shamal” Shamals produce the most widespread hazardous weather in the Middle East.

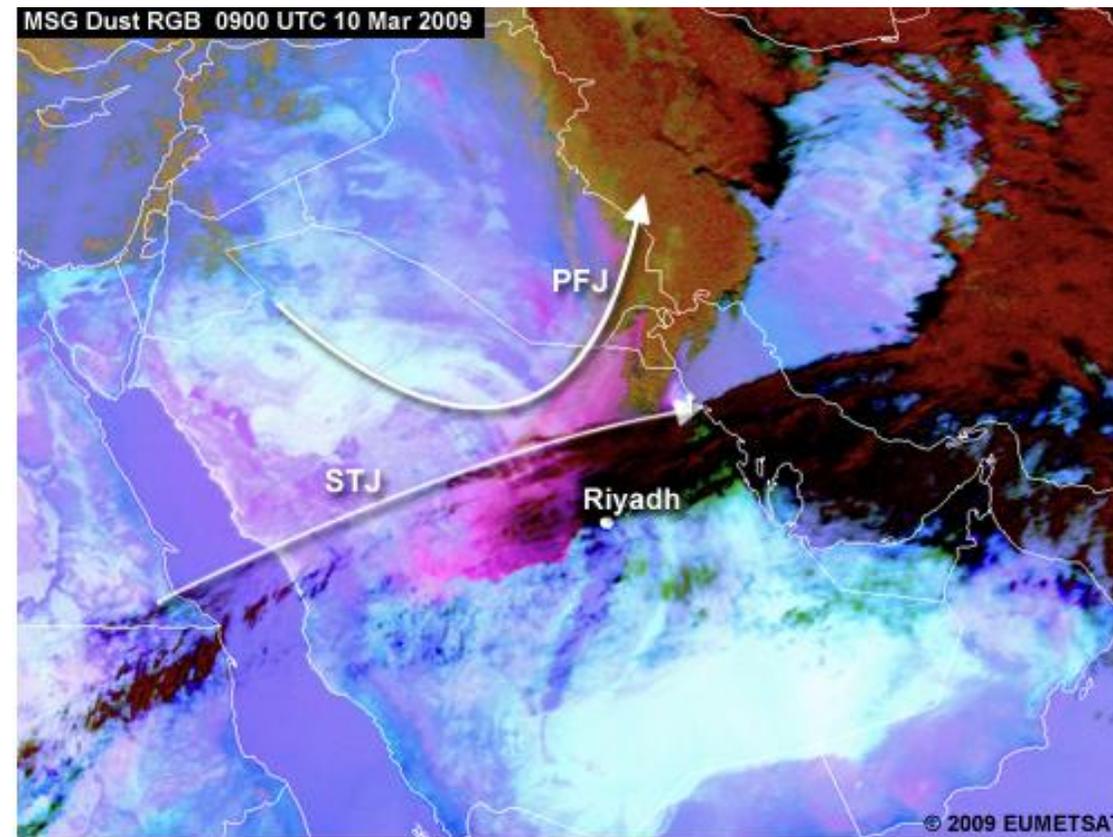
Synoptically forced dust outbreaks

Caused by frontal winds that primarily occur in winter and spring



Synoptically forced dust outbreaks

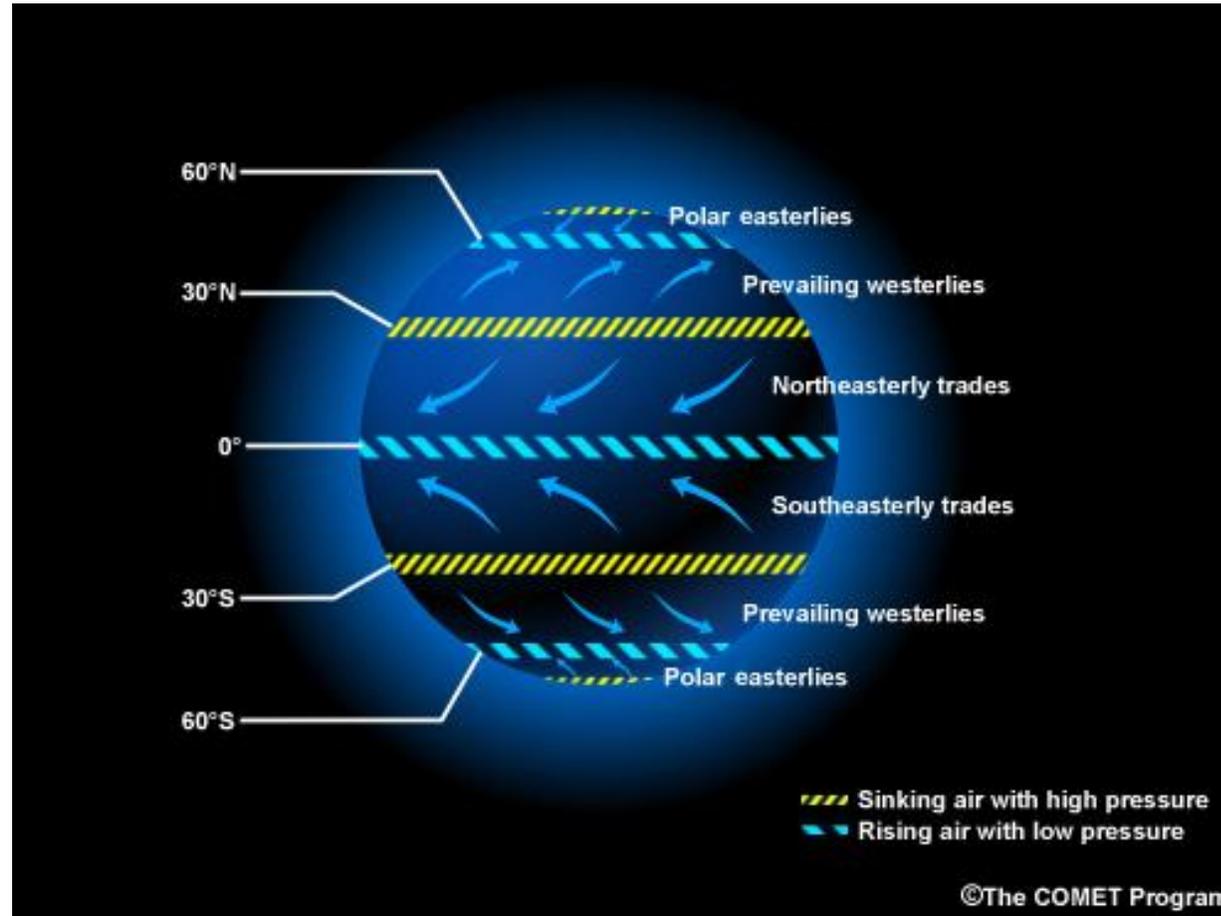
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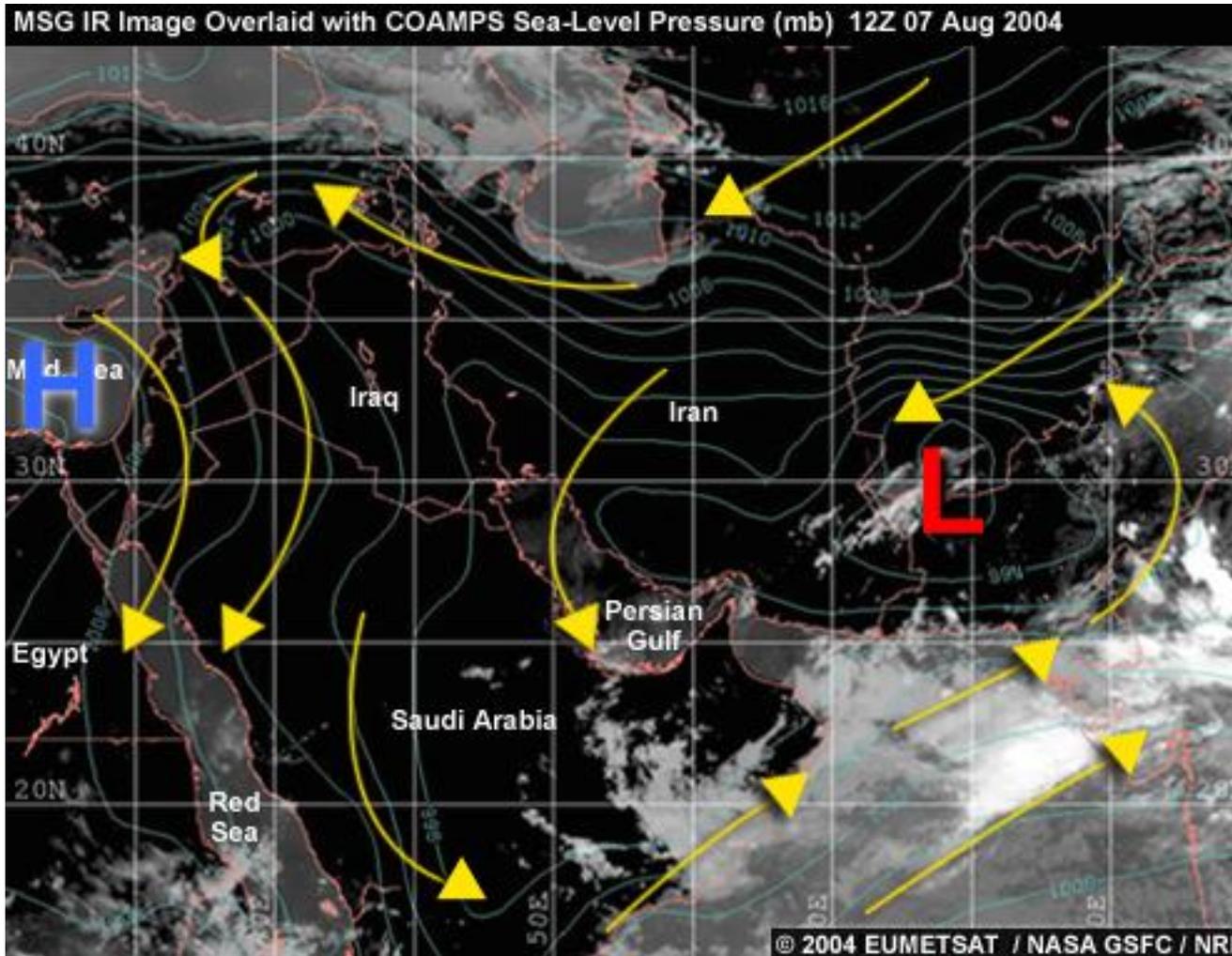


Dust events caused by large-scale trade winds

.... non-frontal persistent trade winds

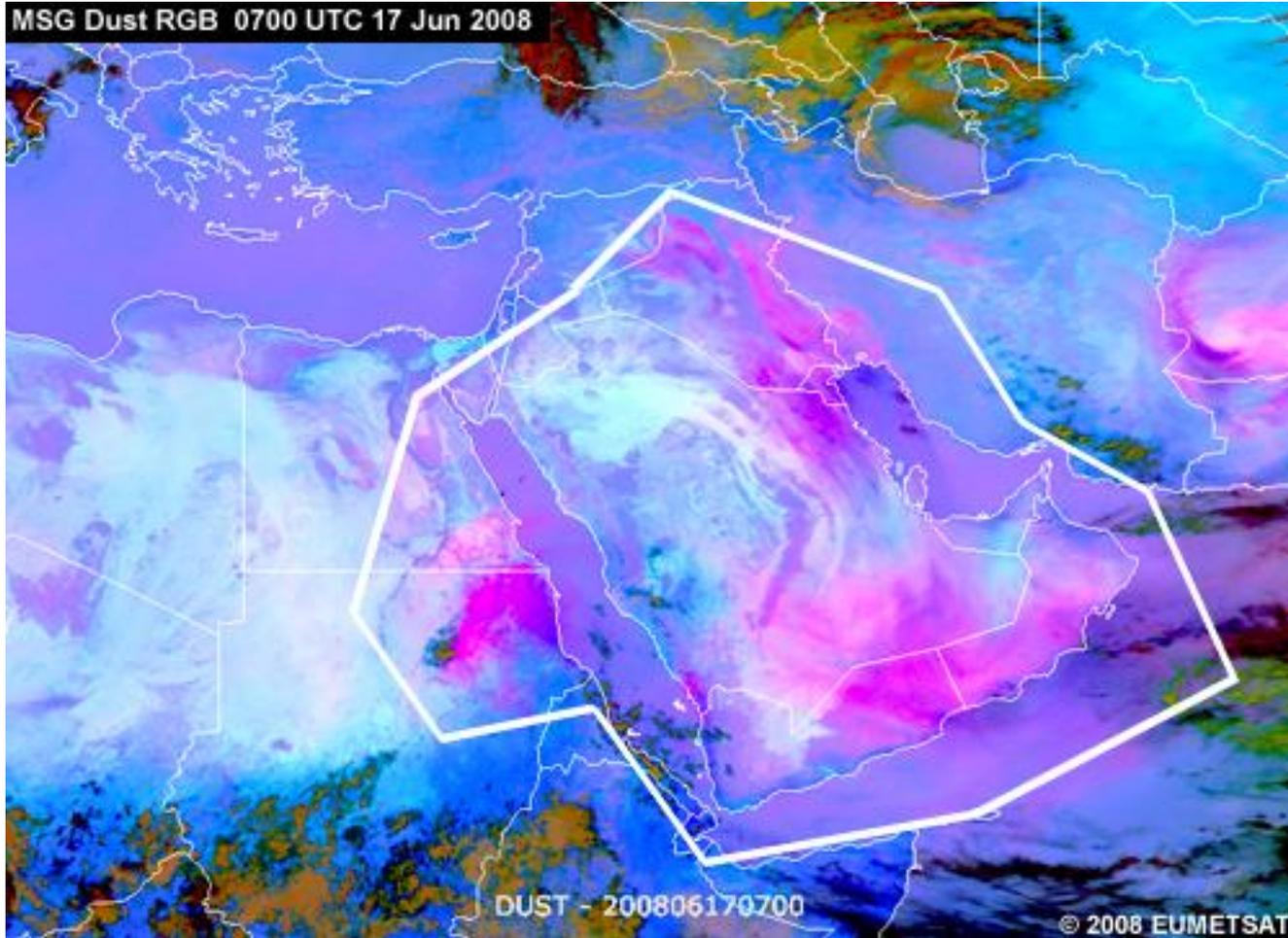


Summer Shamals



- A semi-permanent high-pressure cell extending from the eastern Mediterranean to northern Saudi Arabia (a subtropical high)
- A thermal low-pressure cell over Afghanistan/Pakistan (part of the northern branch of the ITCZ)
- Thermal low pressure associated with the monsoon trough extending into southern Saudi Arabia

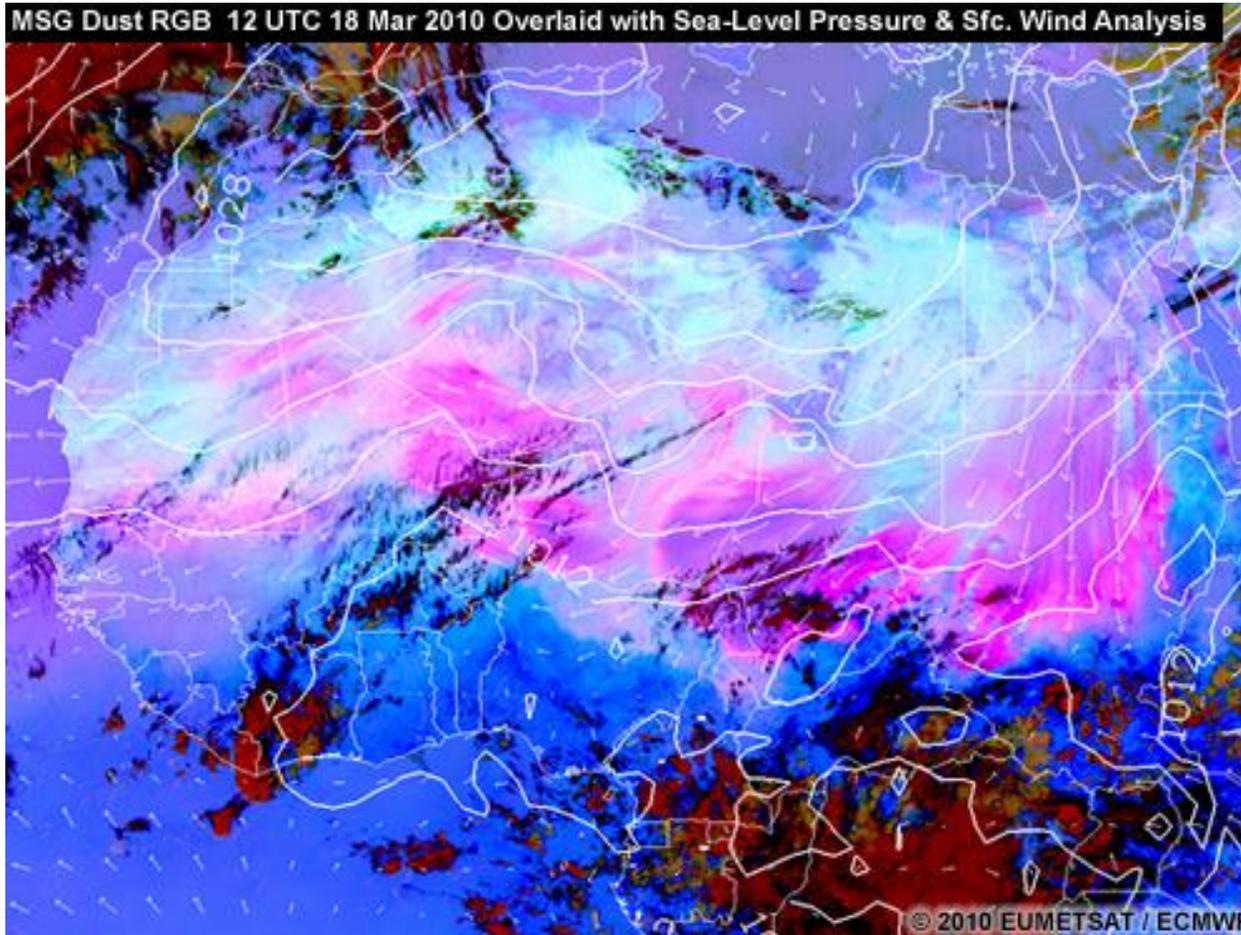
Summer Shamals



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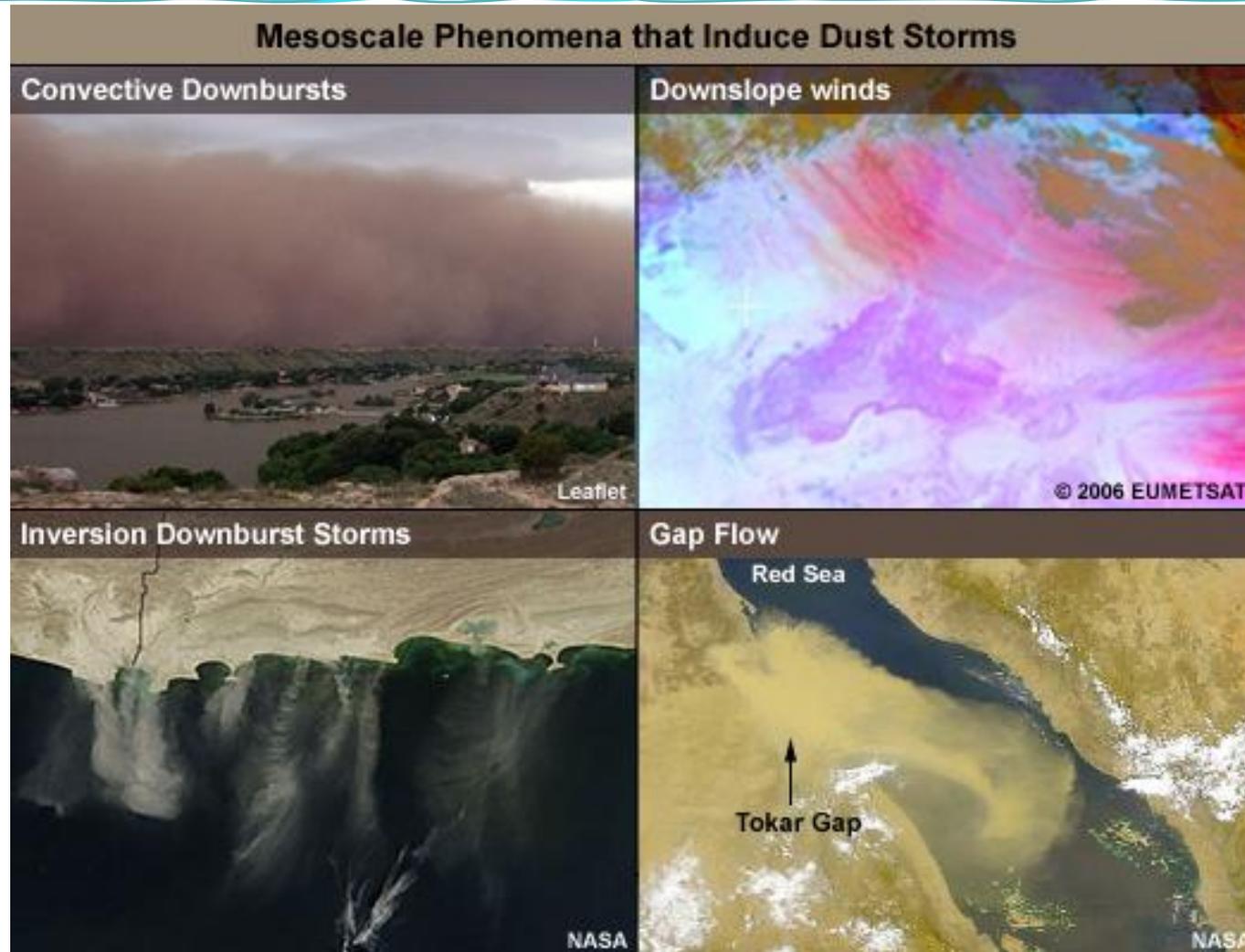
Note the absence of any frontal system

Harmattan winds

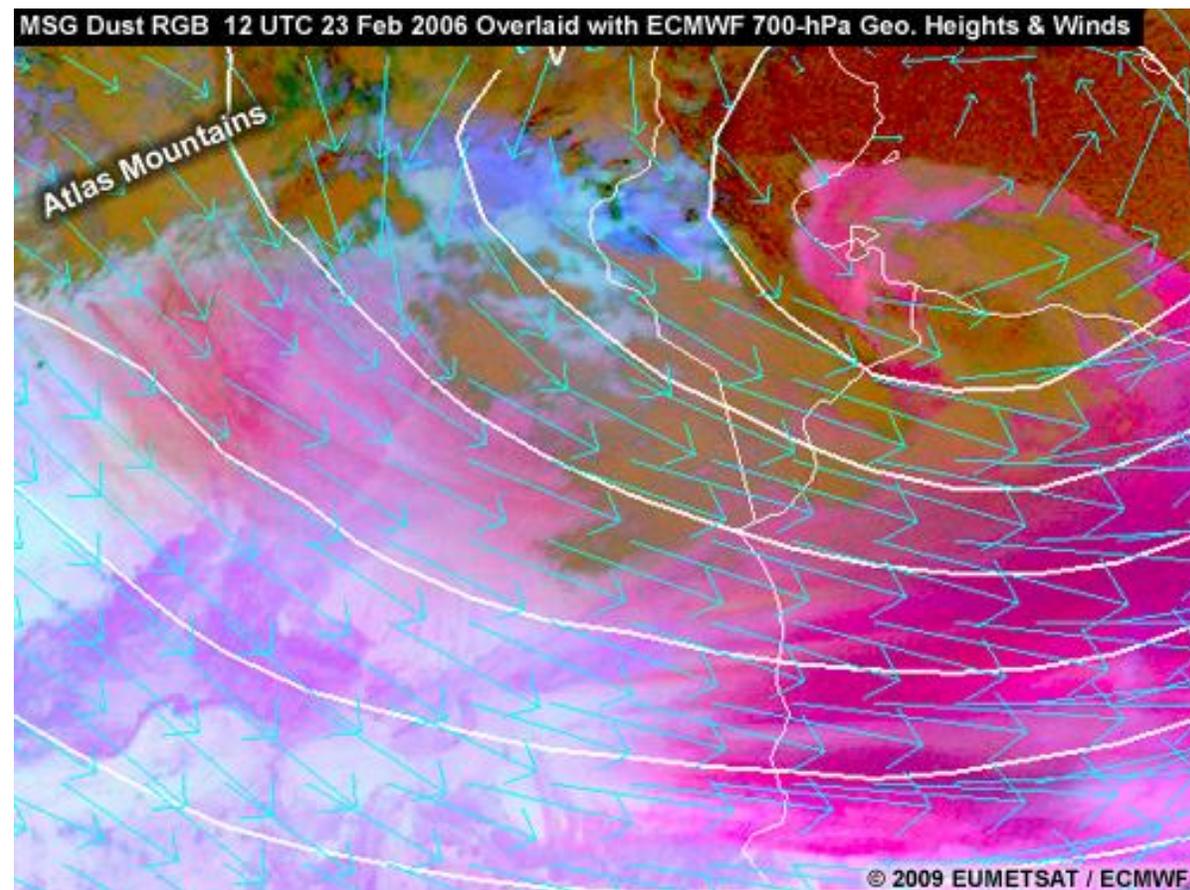
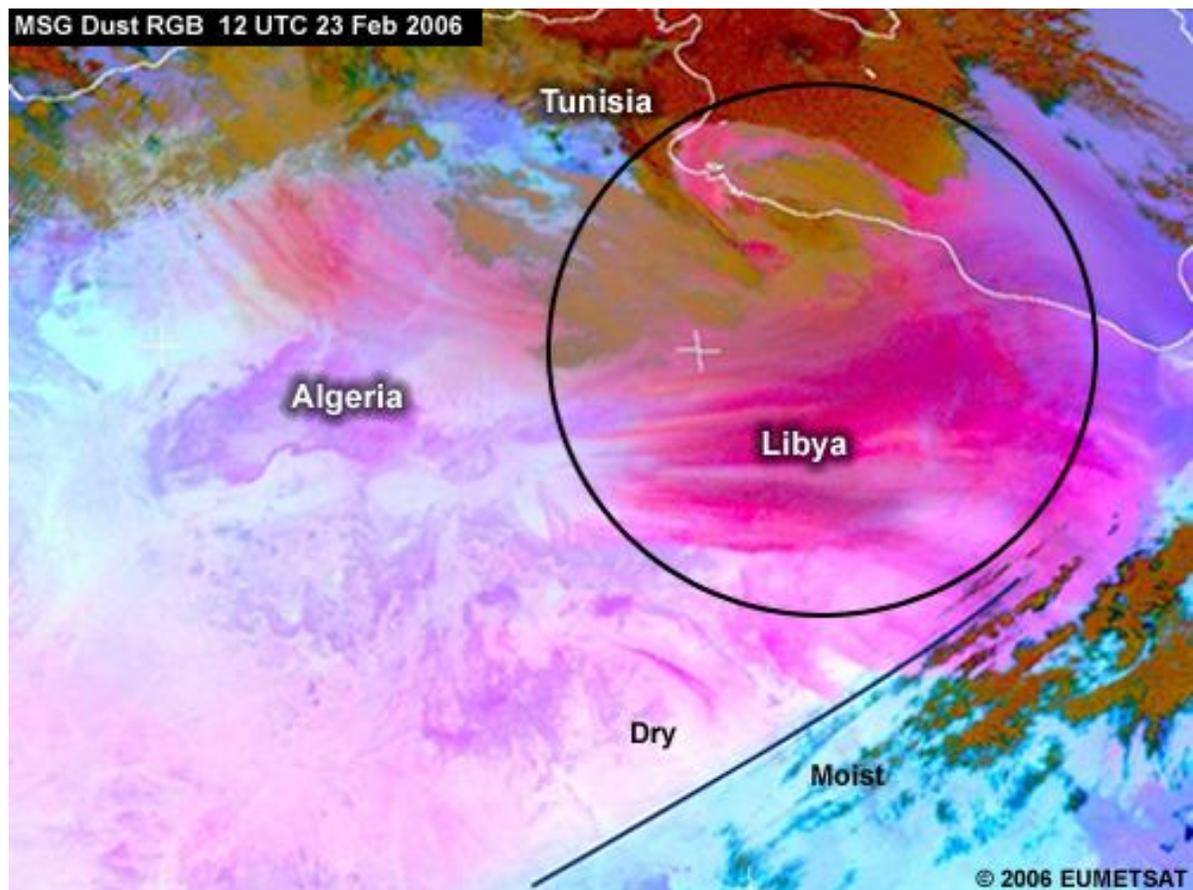


- There's a high-pressure area over northern Africa, which is strengthened by cold air outbreaks from Europe
- There's a low-pressure area over the southern Sahel, which is related to the northward movement of the ITCZ
- The high-pressure area presses against the low-pressure area, with strong Harmattan winds in between

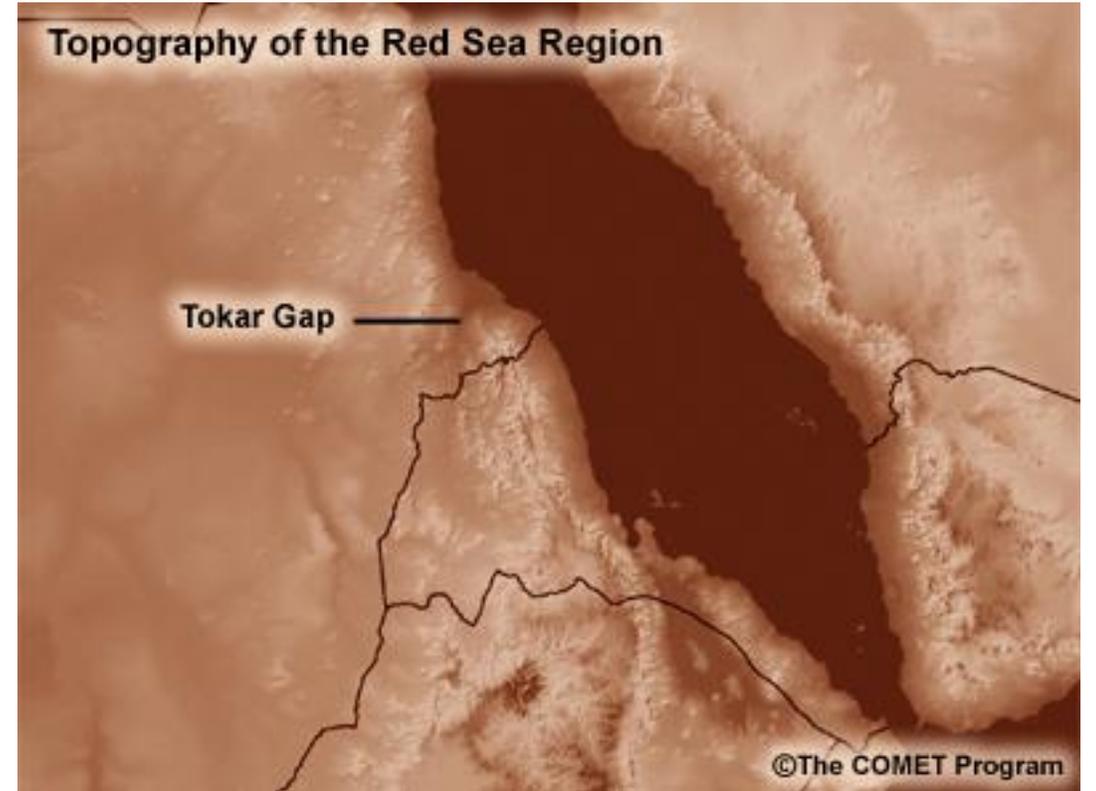
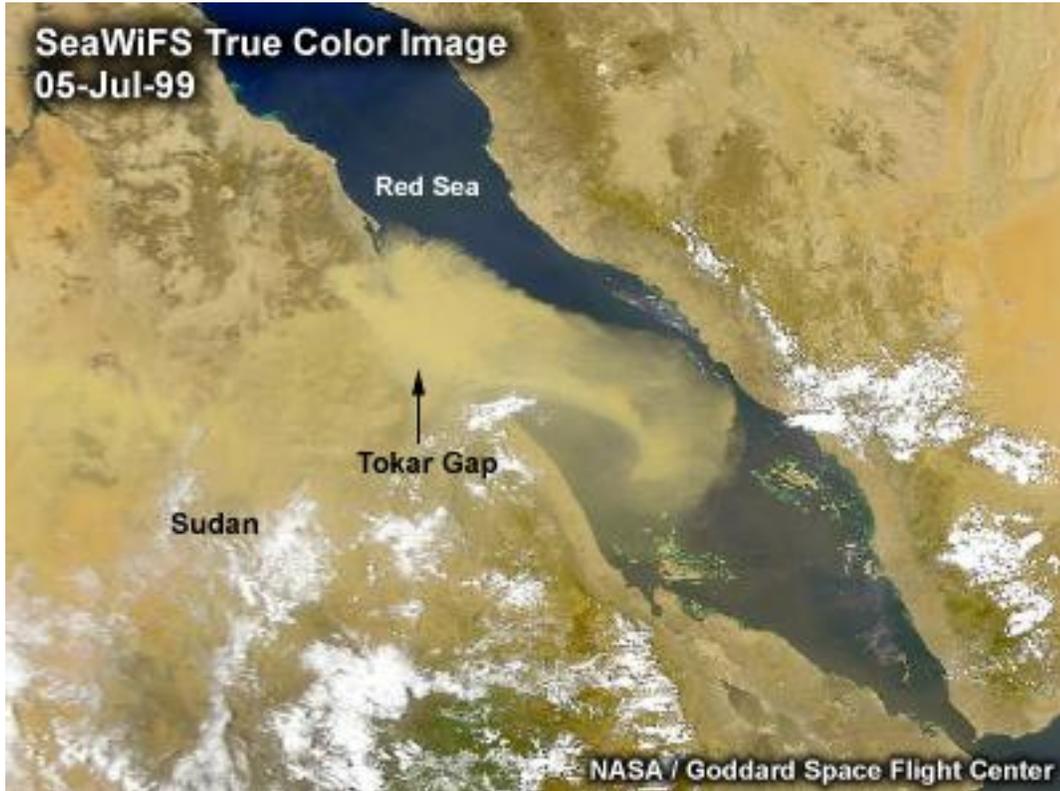
Dust Storms caused by mesoscale systems



Downslope winds

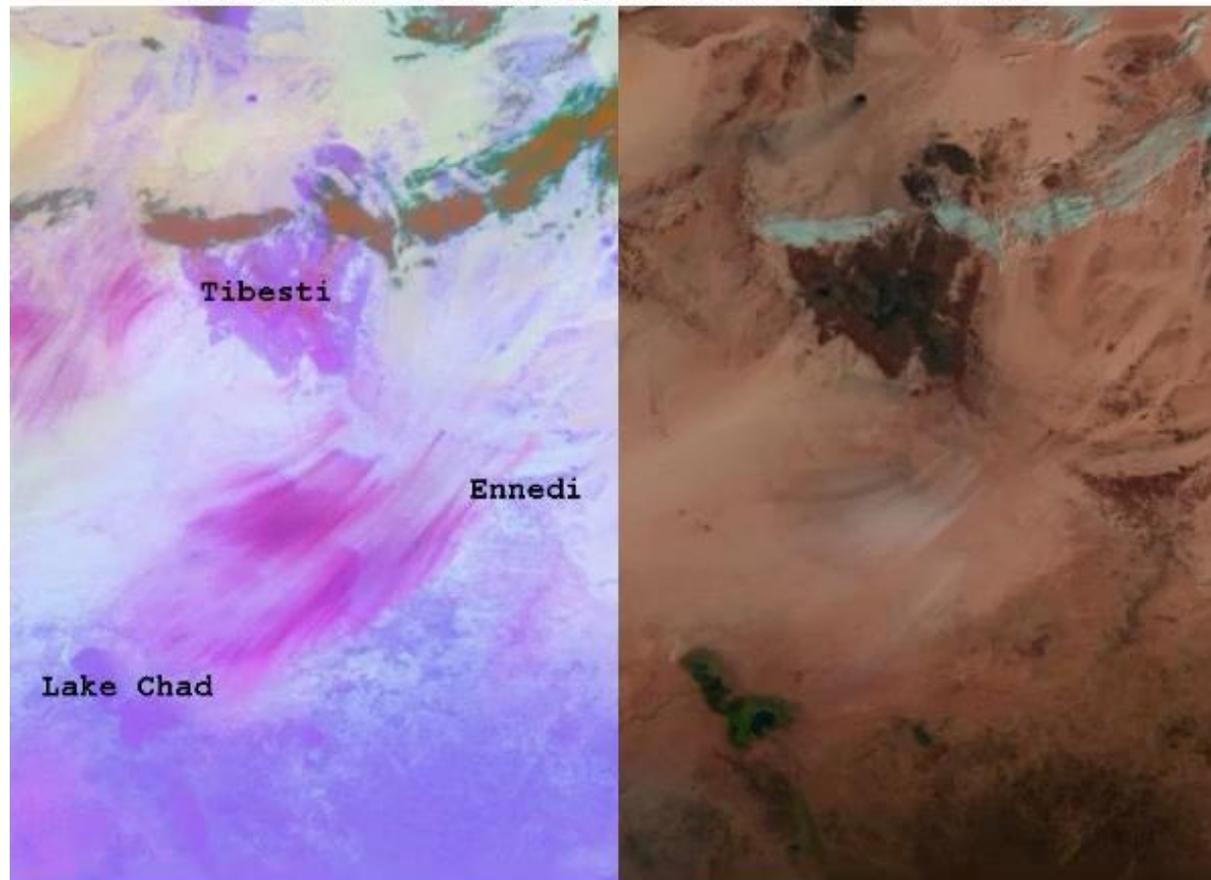


Gap flow



Gap flow

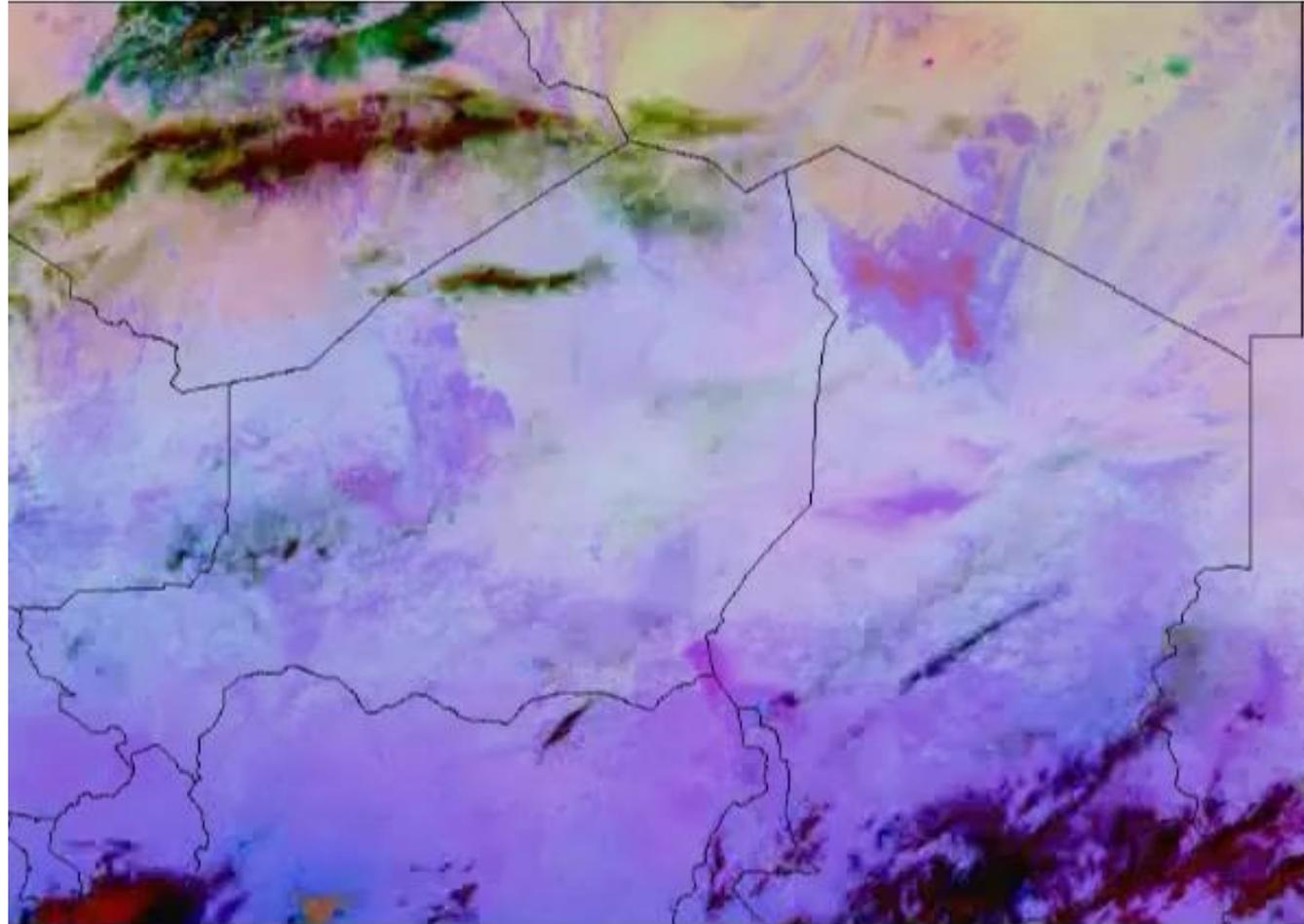
MSG Dust RGB (Left) & MODIS Natural Color RGB (Right) Showing a Dust Storm in the Bodele Depression 08 to 16 UTC 5 Jan 2005



© 2005 EUMETSAT / NASA

Diurnal cycle of winds: The low level Jet

MSG Dust RGB Images Over the Bodélé Depression 13 to 18 Nov 2009

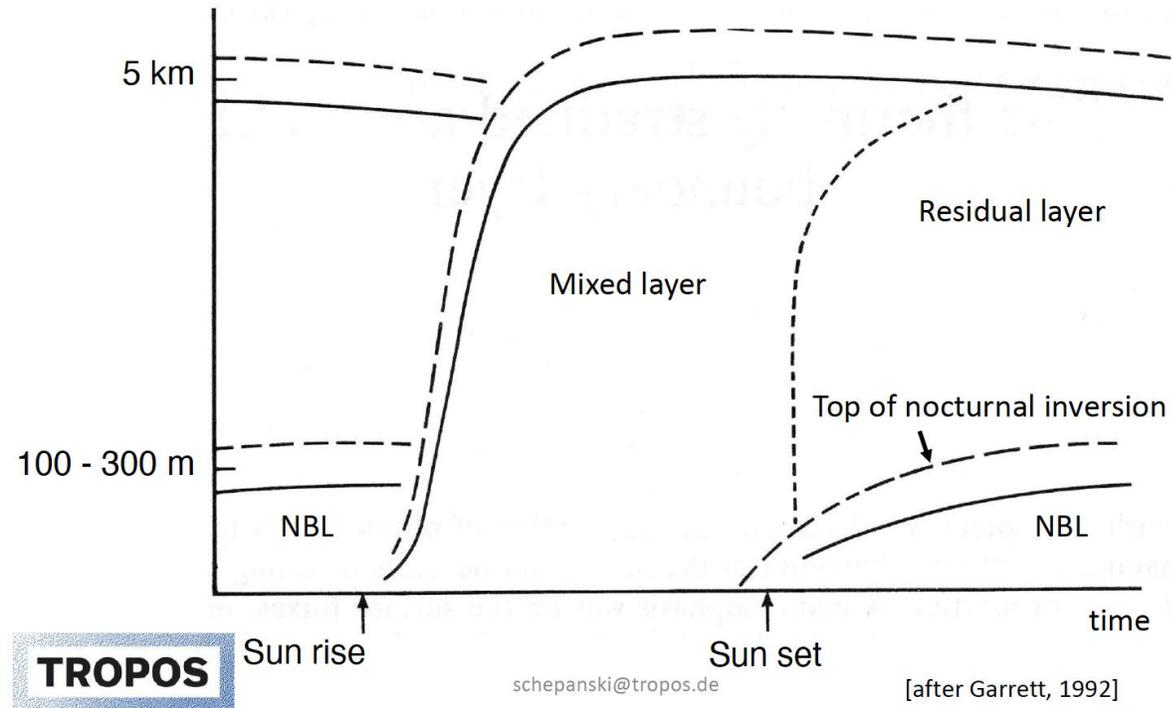


© 2009 EUMETSAT

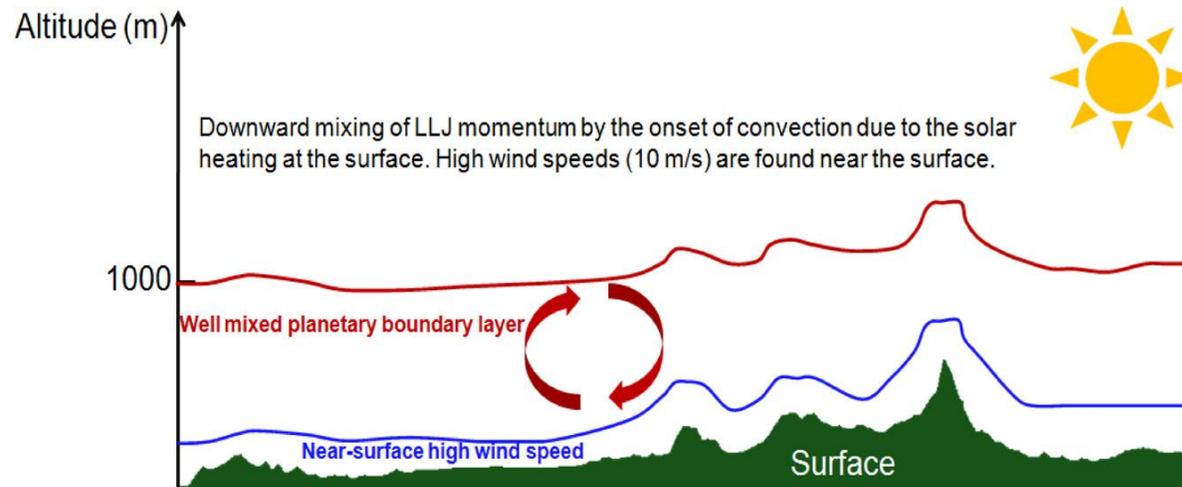
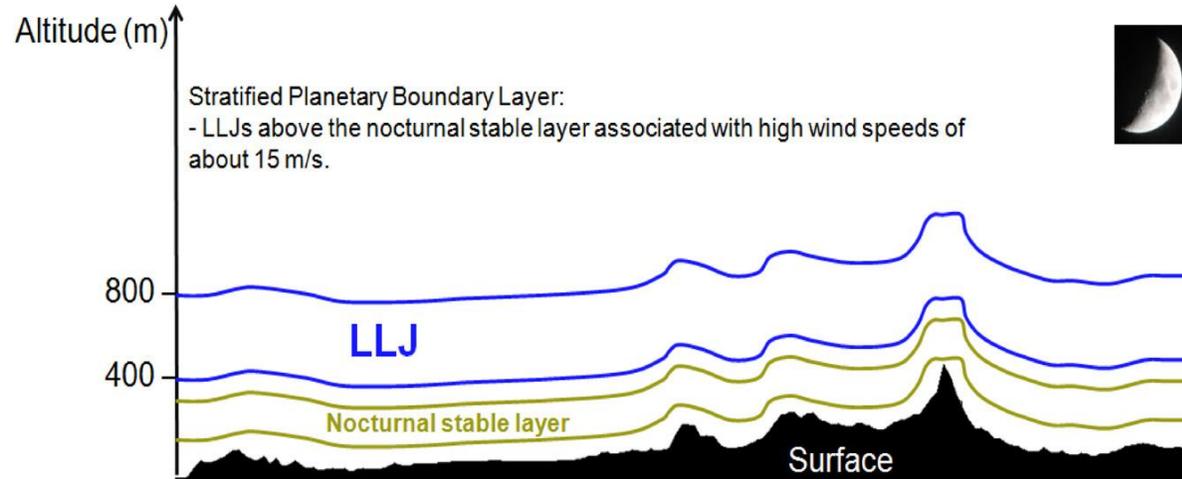
Diurnal cycle of winds: The low level Jet

The nocturnal low-level jet (LLJ)

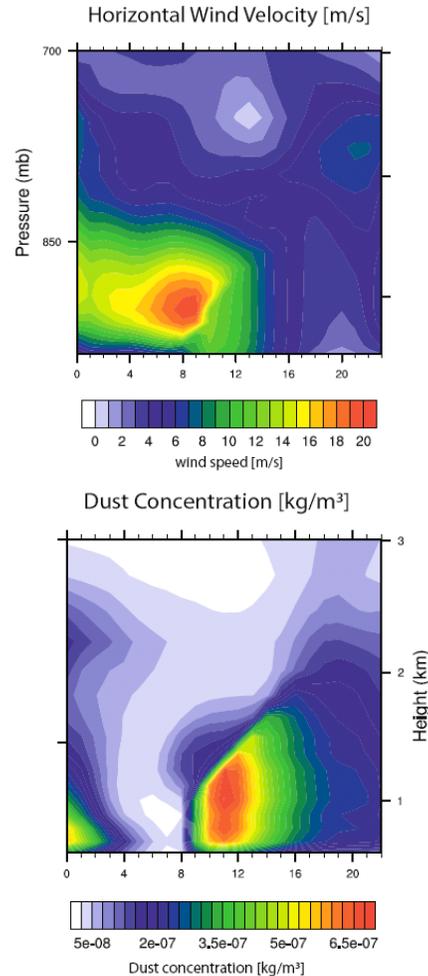
Temporal evolution of the boundary layer, technical terms



Diurnal cycle of winds: The low level Jet



Diurnal cycle of winds: The low level Jet



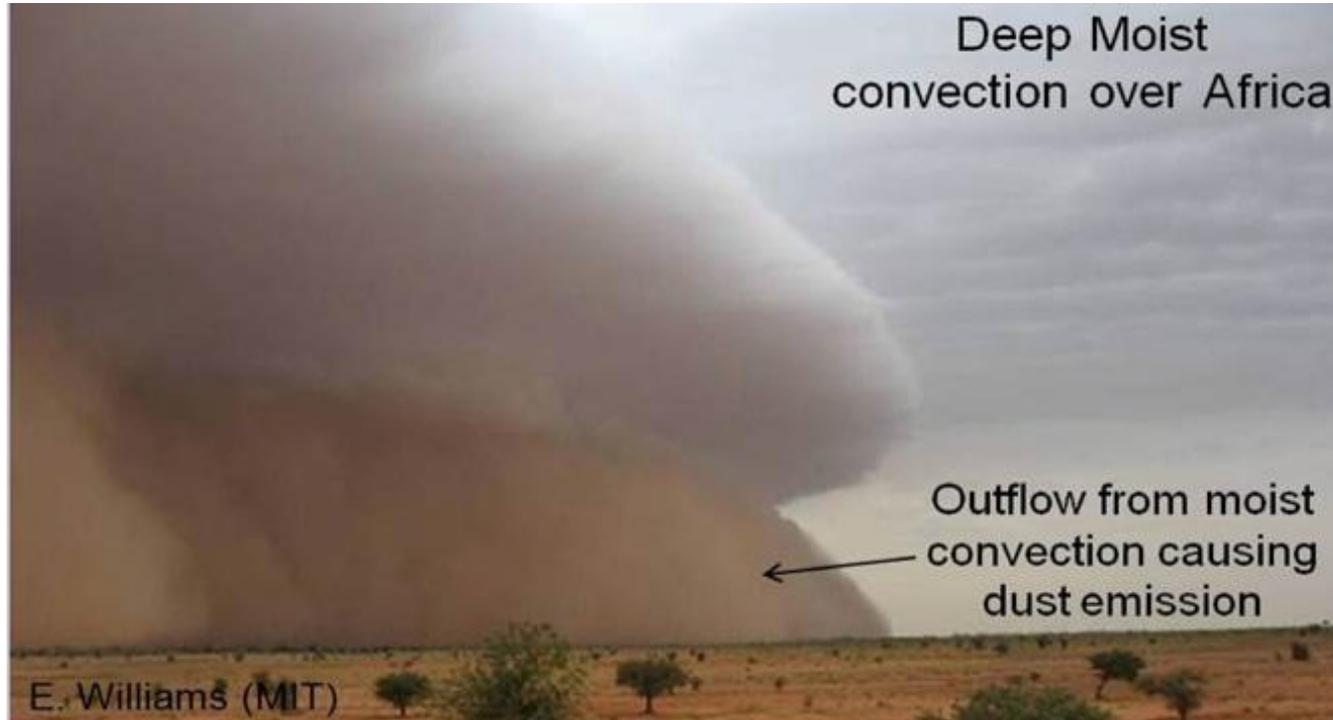
Decoupling of the residual layer from the surface due to the formation of the nocturnal boundary layer (NBL).

- Acceleration of winds above the top of the NBL within the residual layer: low-level jet.

- Shortly after sun rise, the convective mixed layer grows, and the residual layer including the LLJ erodes.

- Momentum from the LLJ is distributed over the growing mixed layer resulting in an increase of wind speed.

Moist convection and haboobs



This dust squall is a Haboob, that is, a dust storm caused by convective downbursts. Haboobs are the true walls of dust and sand that most people think of as strong dust storms. The term is used in Argentina as well as Africa, Asia, and the desert southwest of the United States.

Mosit Convection and Haboobs

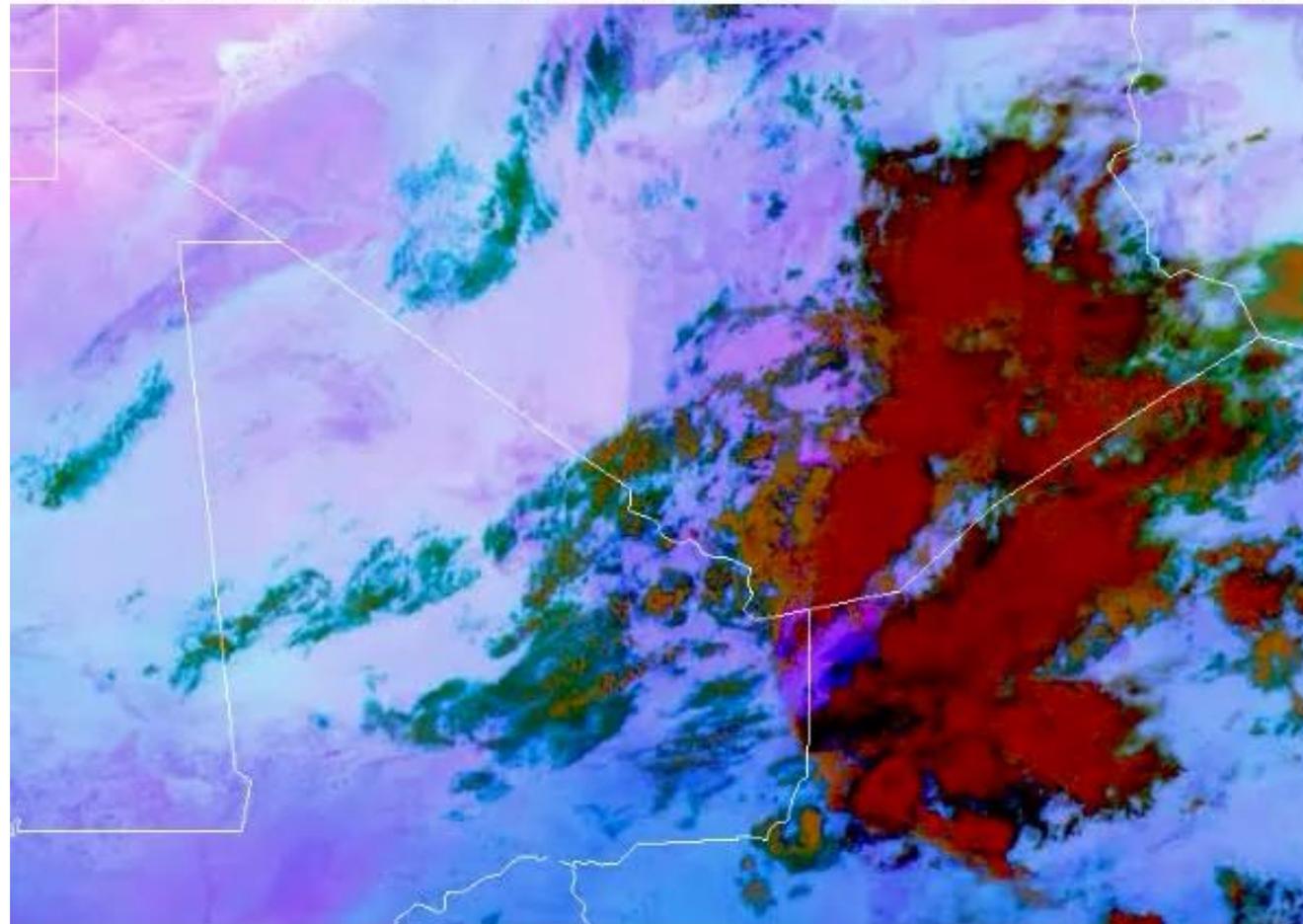


Winds associated with the gust front of a dry downburst from a convective storm can easily excite a dust storm when they encounter an appropriate source area.

Haboobs tend to be rather small, on the order of 100 to 150 kilometers, except in the Sahel area where they can extend up to 1000 kilometers horizontally.

Moist Convection and Haboobs

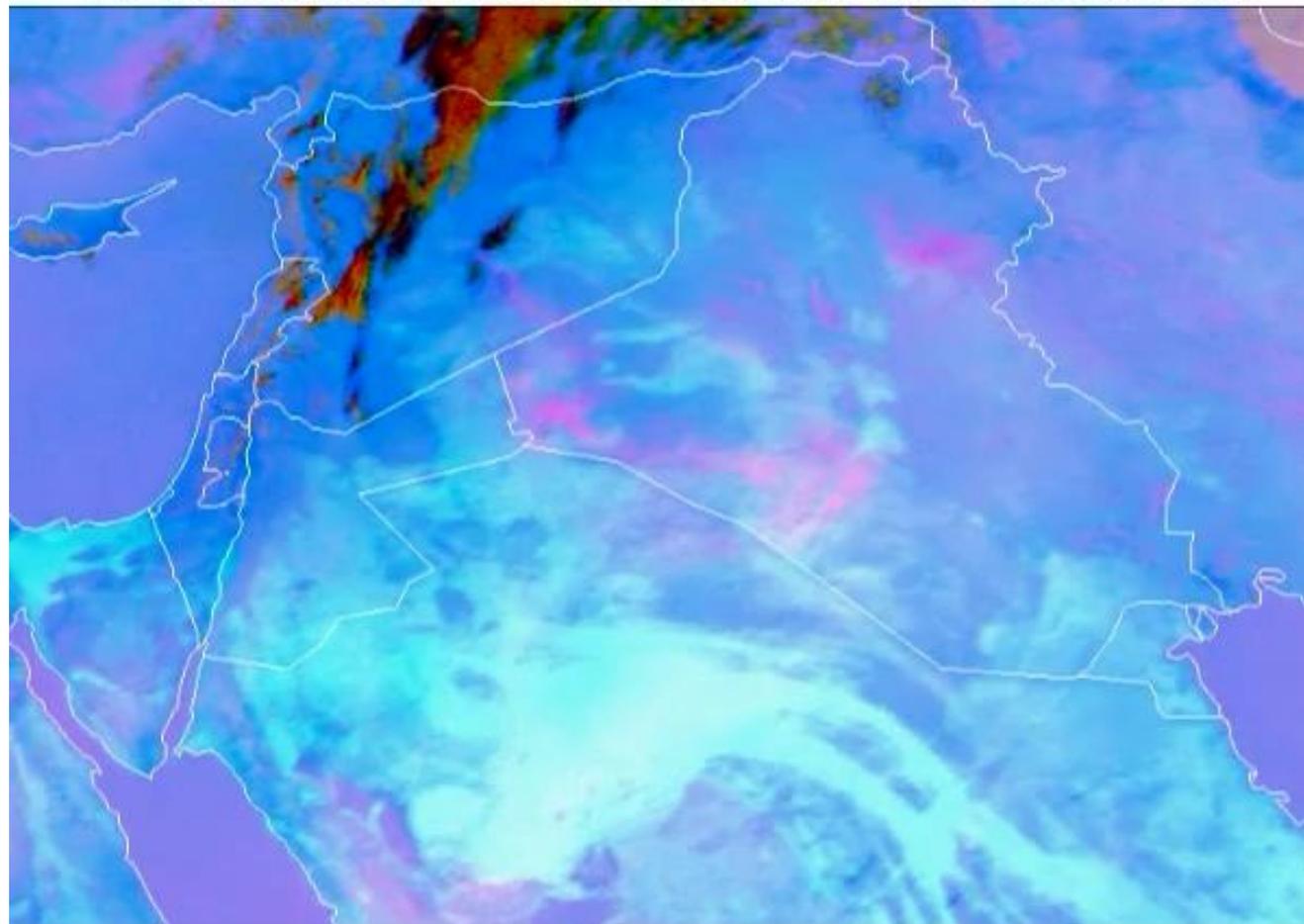
MSG Dust RGB Hourly Images Over West Africa 00 UTC 9 Jun to 10 UTC 10 Jun 2010



© 2010 EUMETSAT

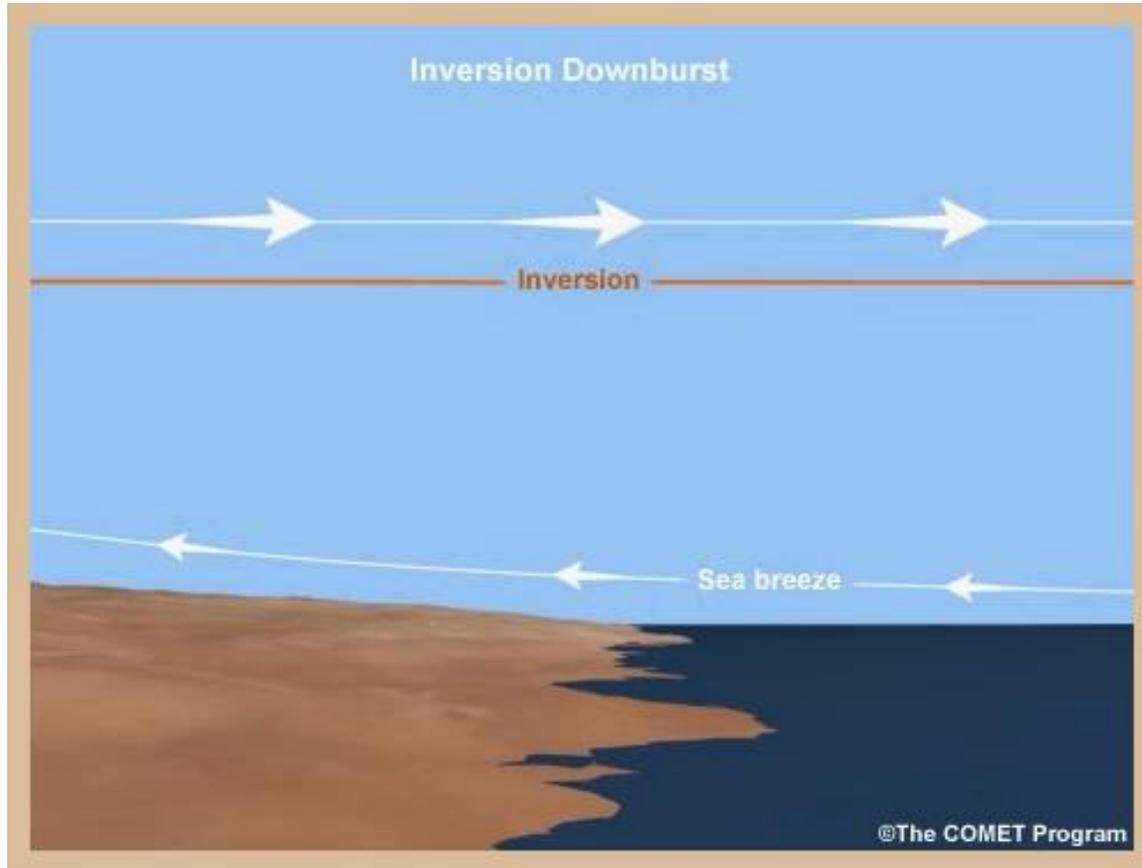
Moist Convection and Haboobs

MSG Dust RGB Products Over Lebanon and Syria 0900 to 2345 UTC 5 June 2005



© 2005 EUMETSAT

Inversion downbursts



As the sea breeze intensifies, convergence along the sea breeze front can generate sufficient lift to break a capping inversion.

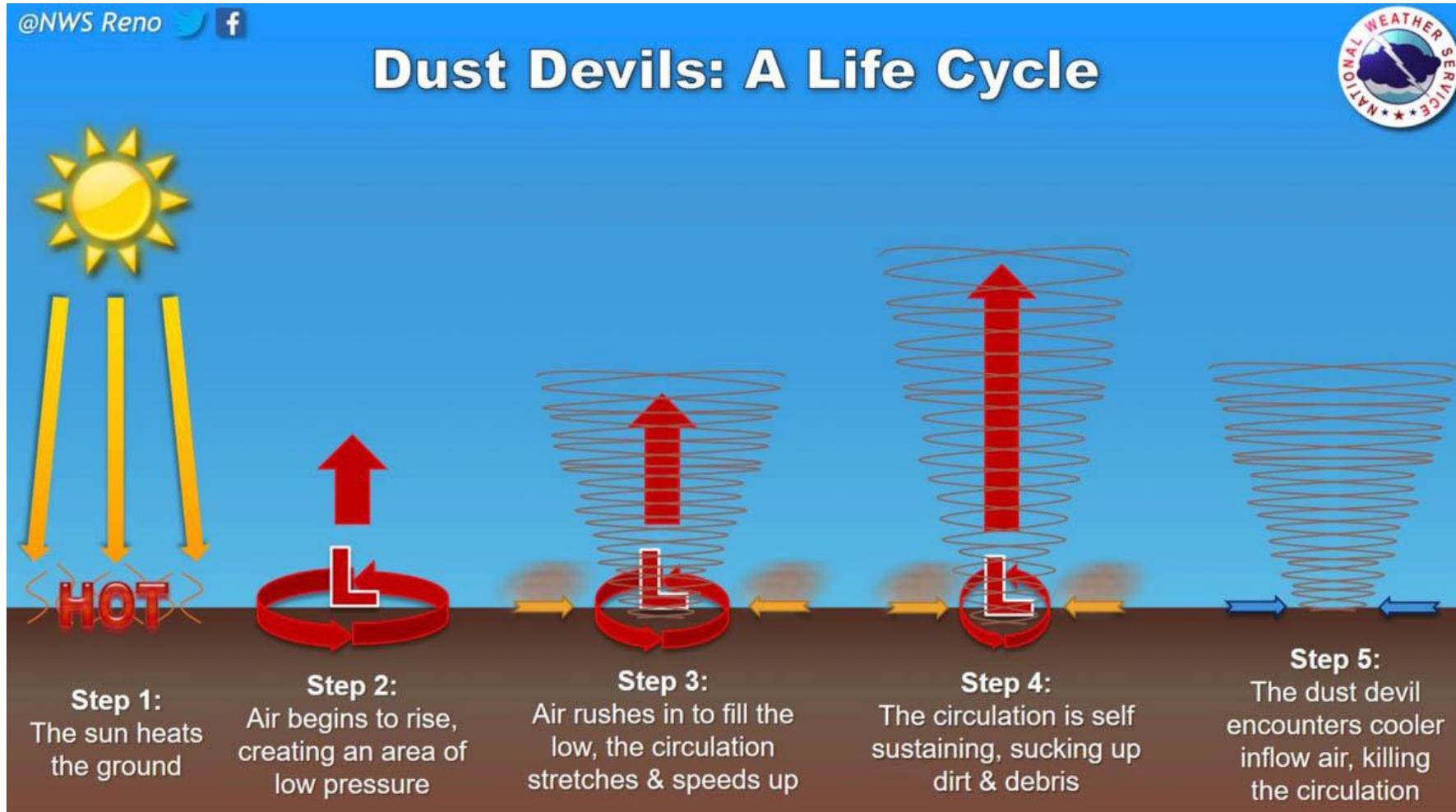
This potential instability results in the downward mixing of cool air aloft, which flows downslope and out over the water.



Dust devils

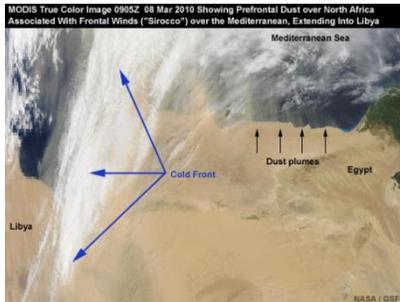


Dust devils

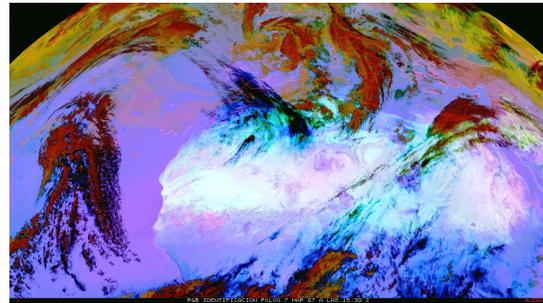


How models captures these events

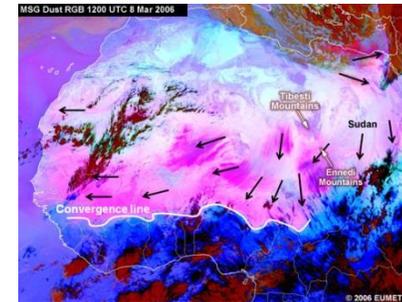
Synoptic dust storms (large scale weather systems)



Pre-frontal winds



Post-frontal winds

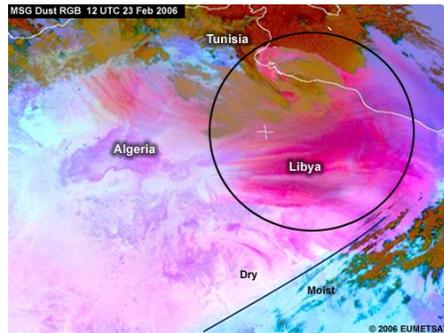


Large-scale trade winds

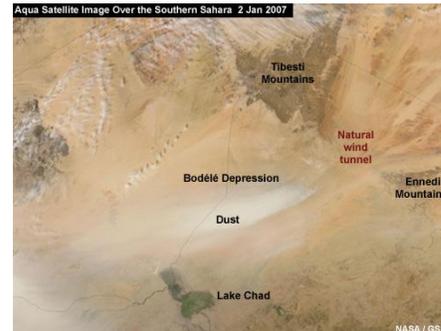
Well captured by models.

How models captures these events

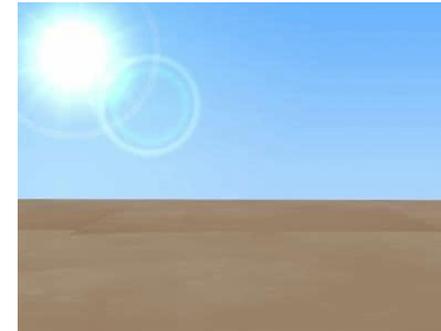
Mesoscale dust storms



Downslope winds



Gap flow



Dust devils



Haboobs

Poorly captured or totally missed by models.

Some types improve in high resolution models.

Seasonality and trends

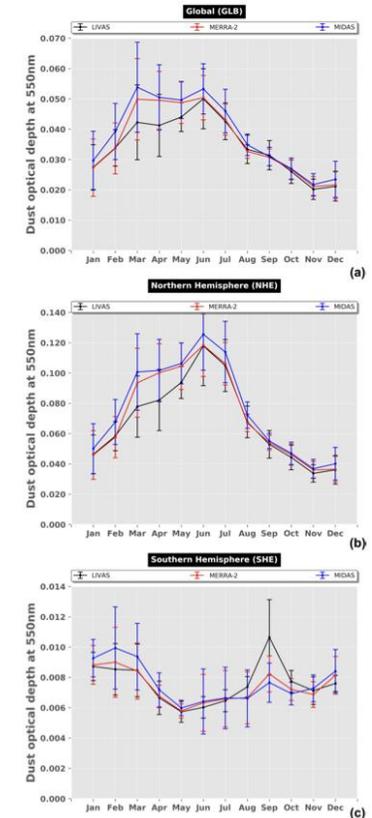
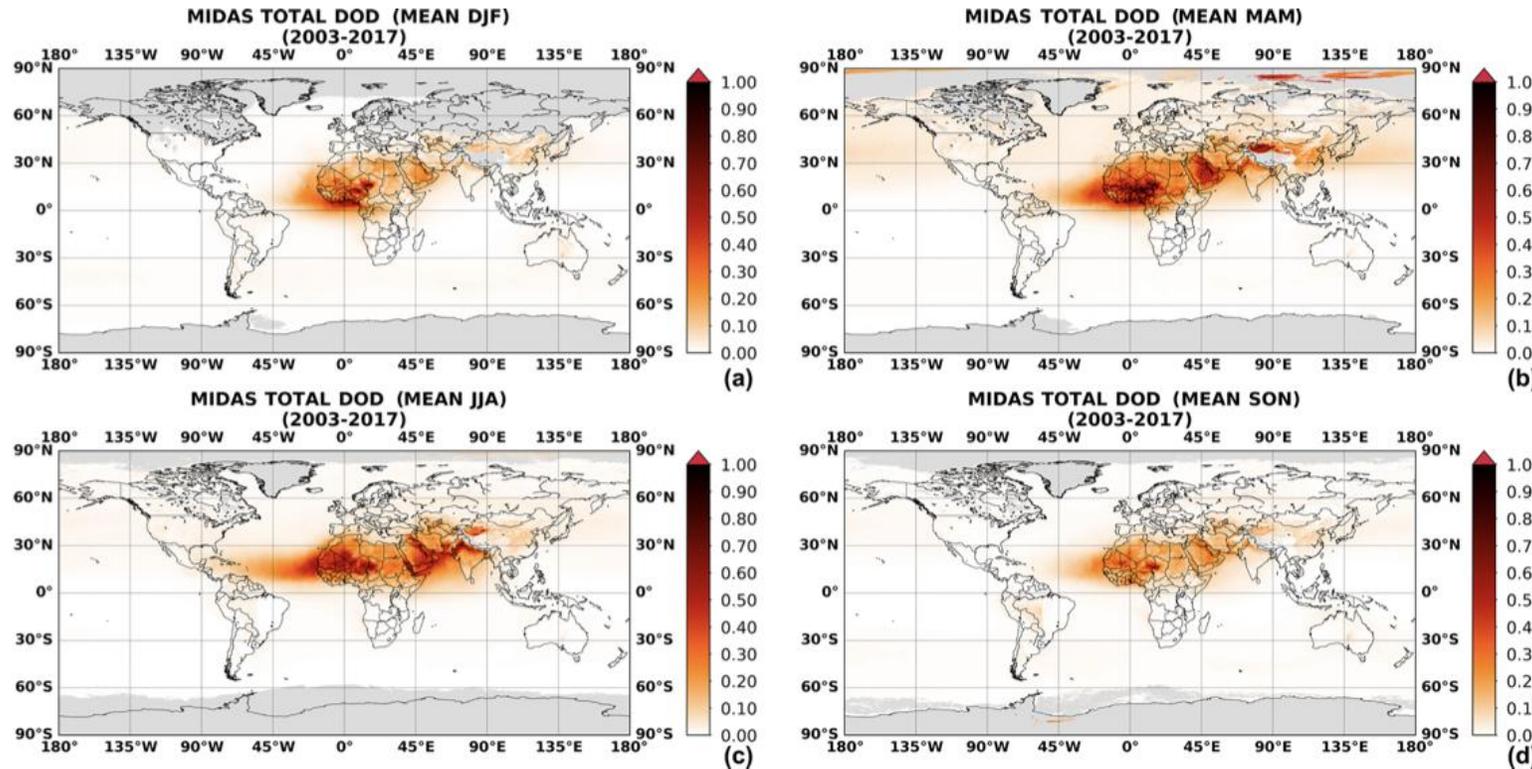


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Seasonal variations

Seasonal dust distributions follow seasonal changing weather regimes (mainly) and vegetation changes (in semi-arid areas)

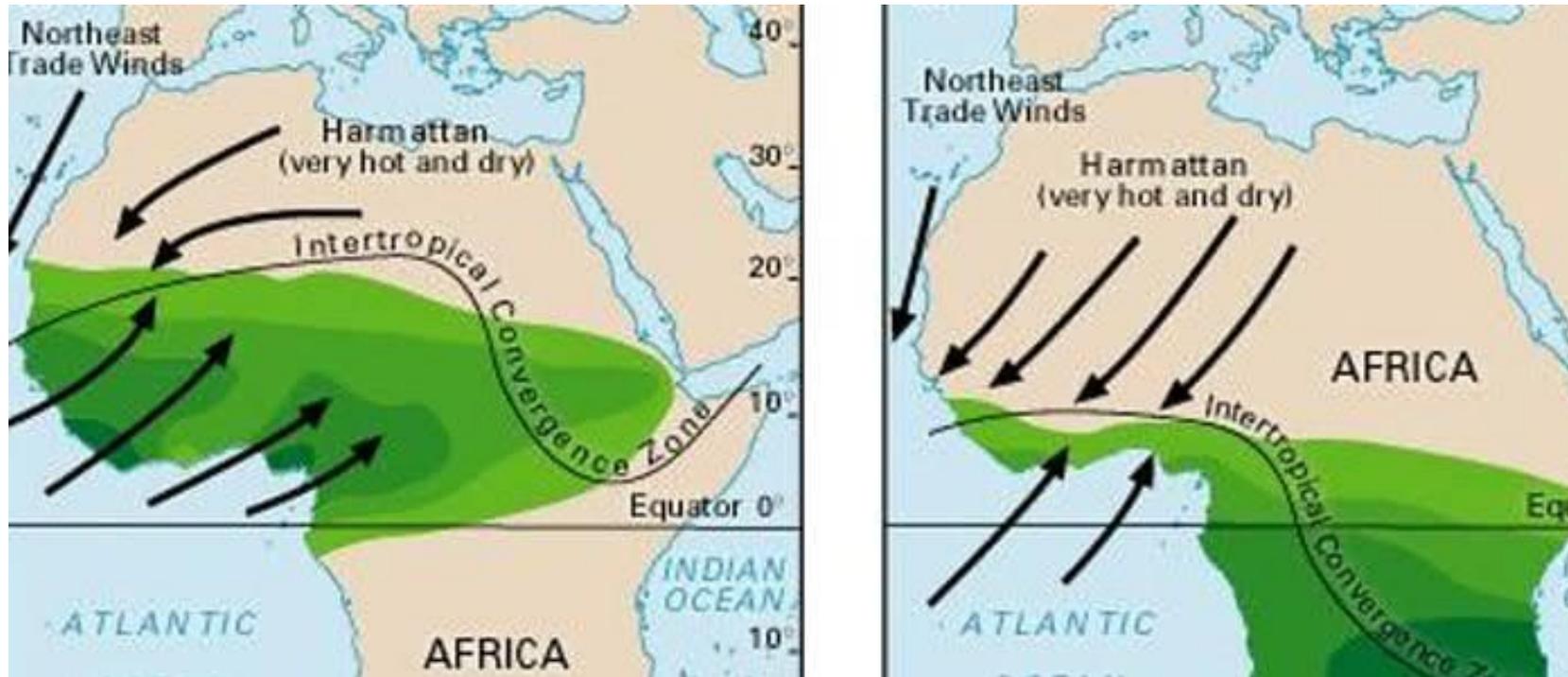


MIDAS, Gkikas et al. 2020

Seasonal variations

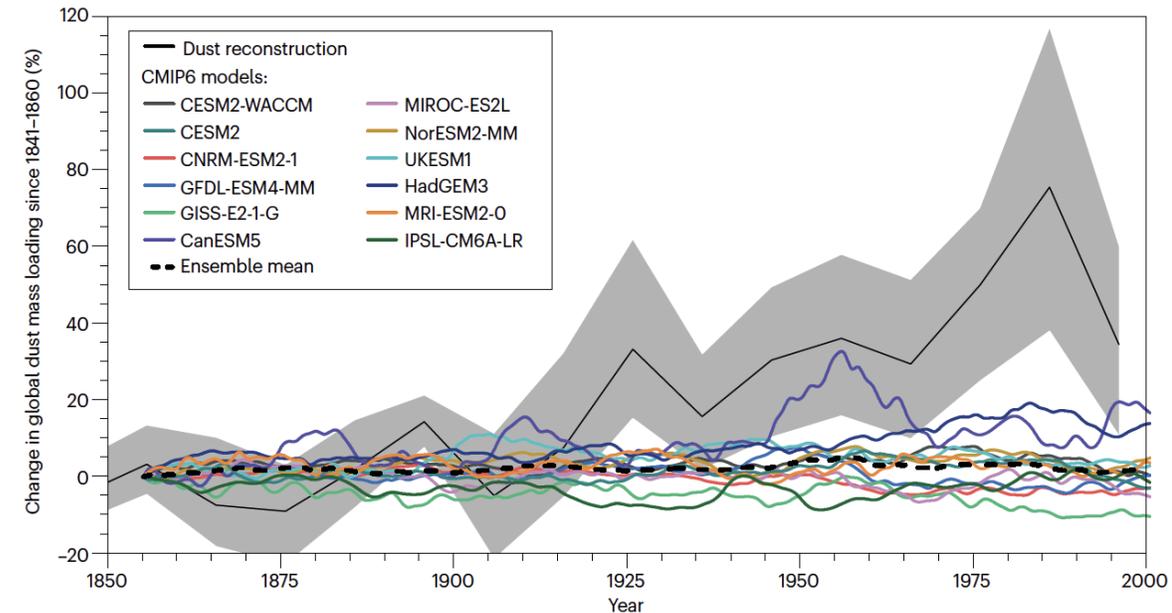
Seasonal dust distributions follow seasonal changing weather regimes (mainly) and vegetation changes (in semi-arid areas)

Hartmattan and West African Monsoon



Decadal variations and long term trends

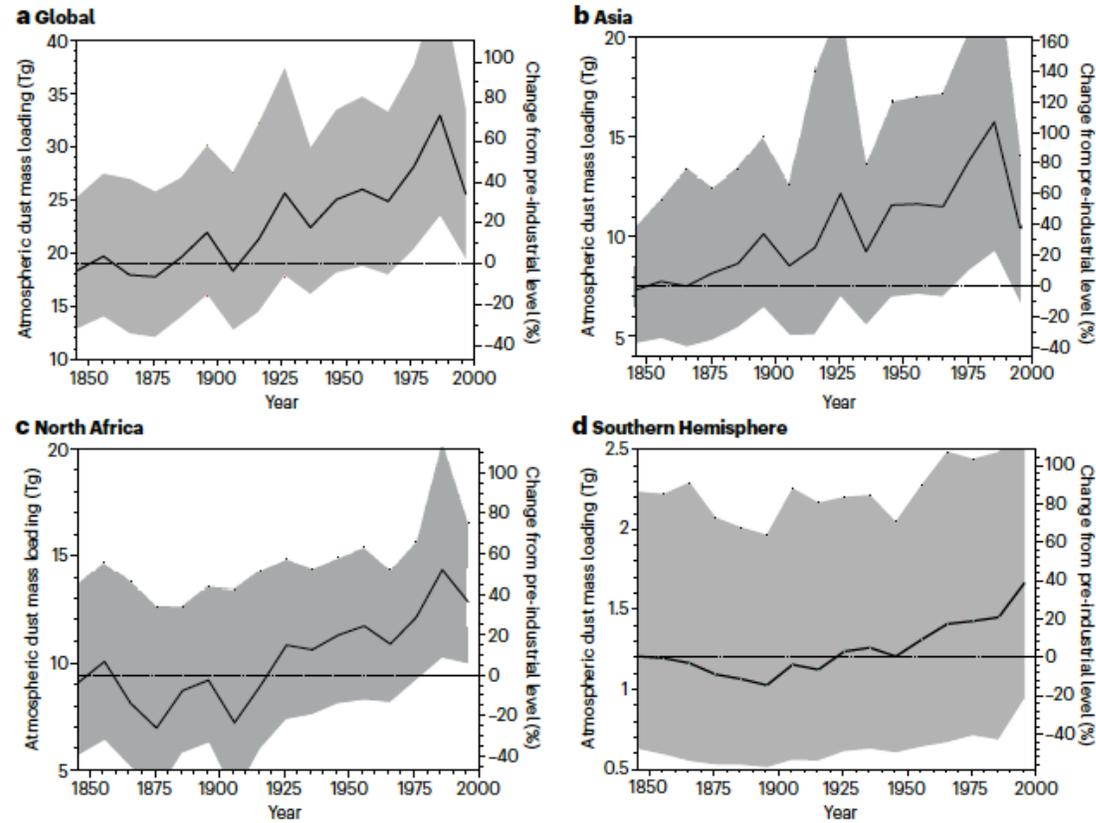
- Past trends and potential future changes in dust INP are uncertain
- Dust has likely increased by ~55 % since the pre-industrial (based on observationally constrained modeling)
- Climate models are unable to dynamically represent pre-industrial to present days trends
- A wide variety of possible causes that remain elusive (e.g. land use vs climate)



Kok et al. (2023)

Decadal variations and long term trends

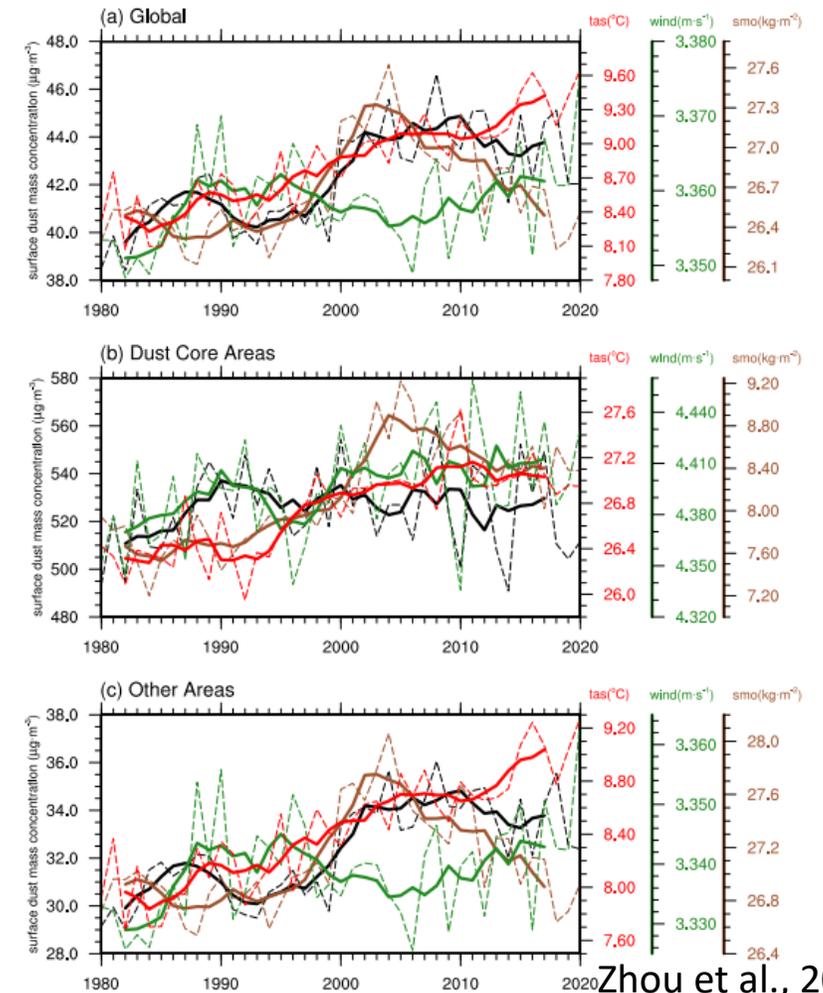
The global rise in dust is mostly affected by the increases over North Africa and Asia



Kok et al. (2023)

Driving factors

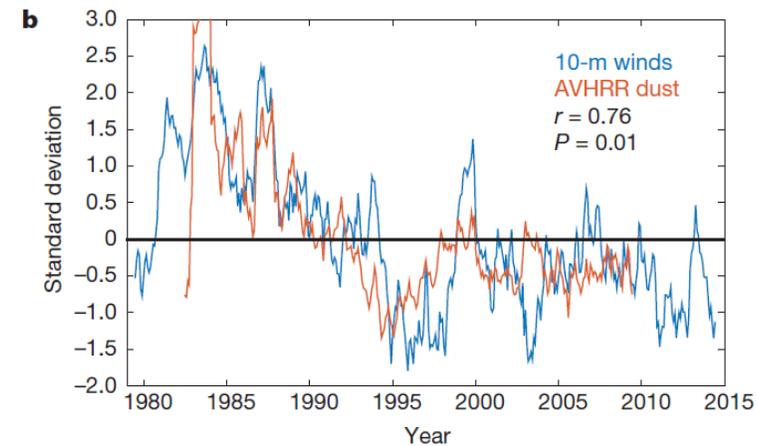
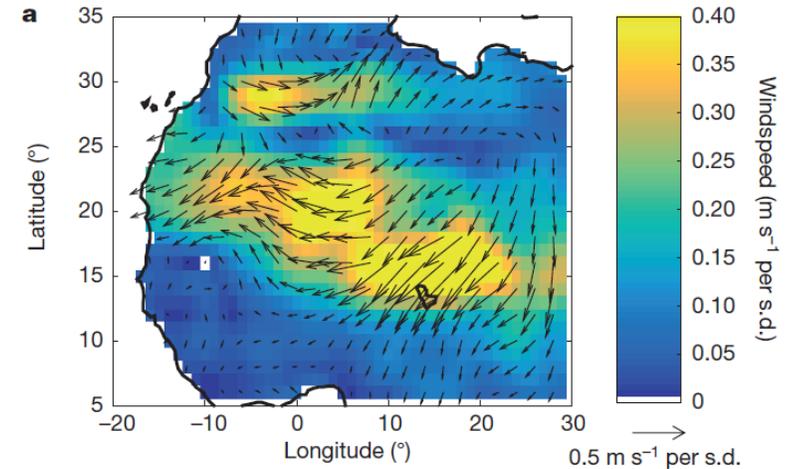
- Different variables can explain dust variability
- Over the key dust source regions, especially North Africa, surface wind is a primary factor
- Over other regions, other factors, including soil moisture, play a larger role



Zhou et al., 2023

Surface Wind

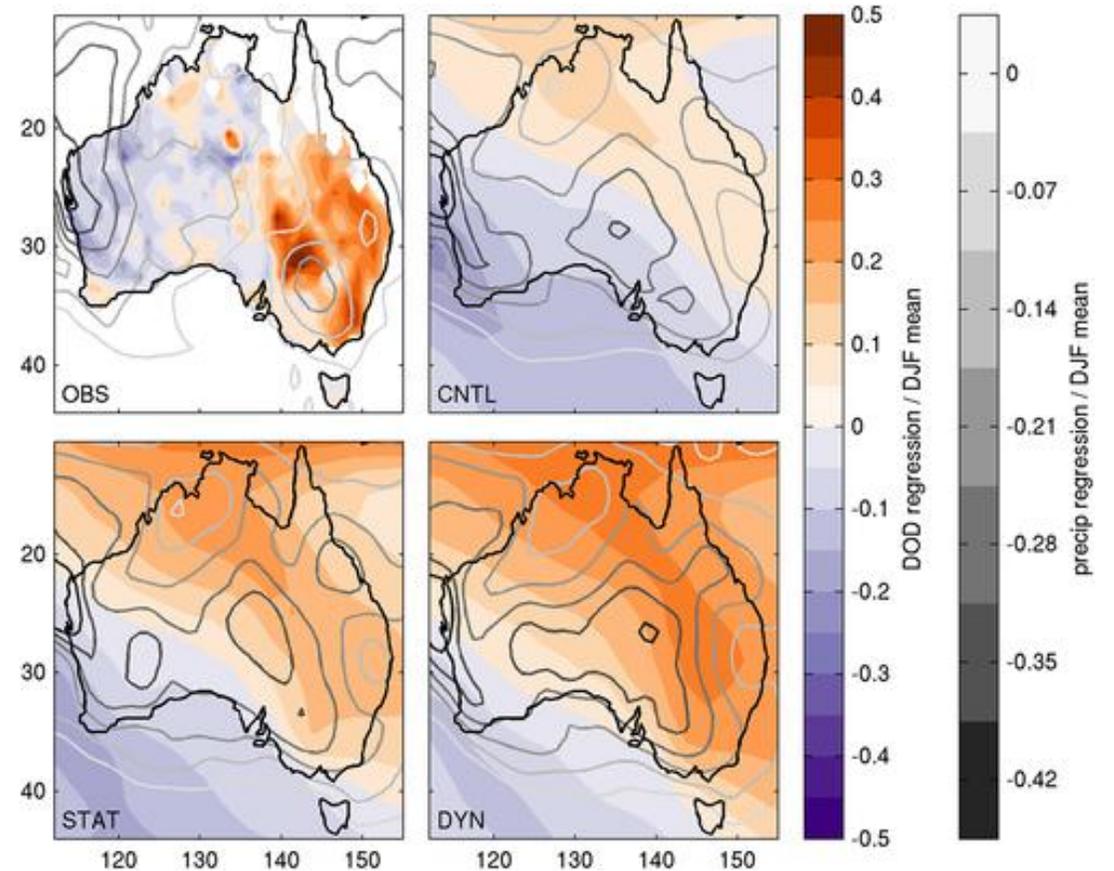
- Surface wind is considered a dominant factor affecting dust emission variability and trends, especially over North Africa



Evan et al., 2016

Vegetation

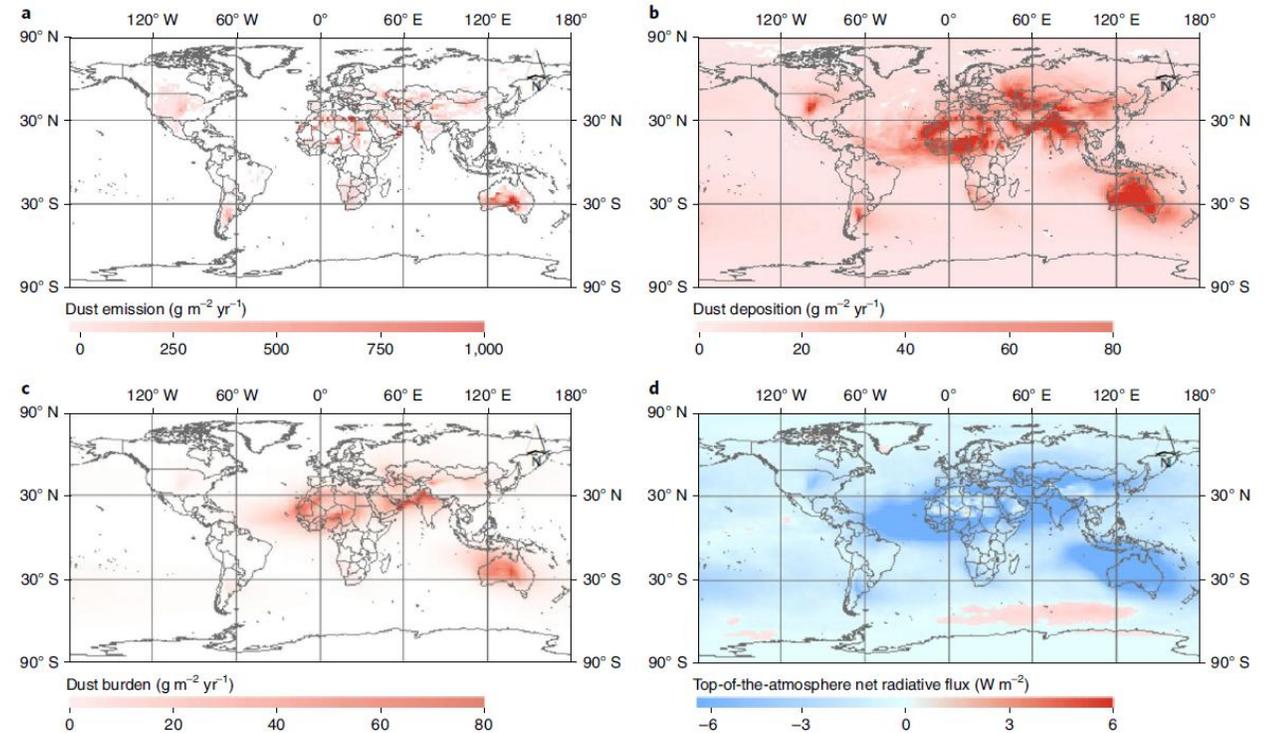
- Over Australia, vegetation changes were found to play a key role in explaining long term dust variability



Evans et al., 2016

Biocrust

- Currently covers about 12% of global land surface
- It is estimated that biocrusts reduce the global atmospheric dust emissions by 60%
- Climate change and land-use changes are projected to reduce the global biocrust, resulting in enhanced dust emission



Impact of biocrusts on current global dust cycling and aerosol radiative effect

Rodríguez-Caballero et al. 2022

Trends in the Middle East

- Yu et al. (2015)* describe some key drivers:
- Winter-to-spring La Niña enhances subsequent spring dust activity by decreasing rainfall across the country's primary dust source region, the Rub' al Khali Desert.
- A relatively cool tropical Indian Ocean favors frequent summer dust storms by producing an anomalously anticyclonic circulation over the central Arabian Peninsula, which enhances the Shamal wind.
- African dust variability affects the region as well.

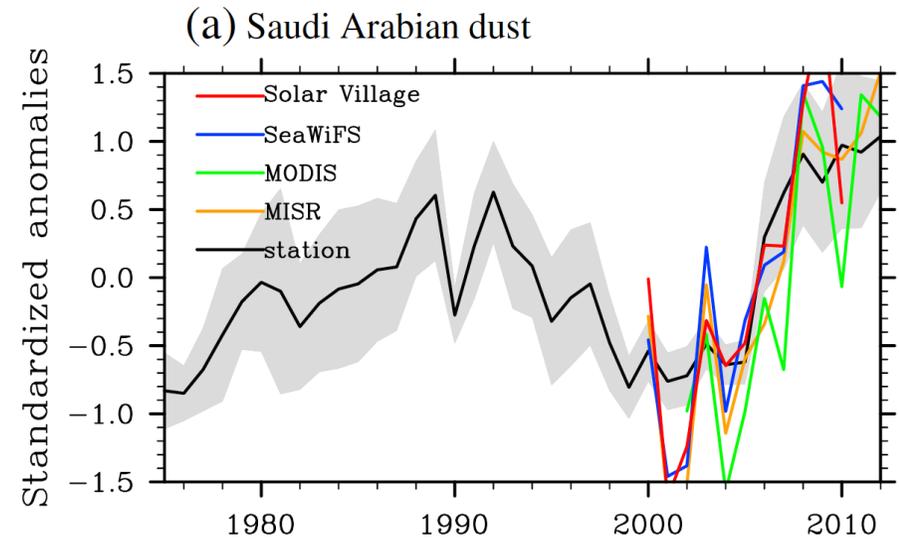
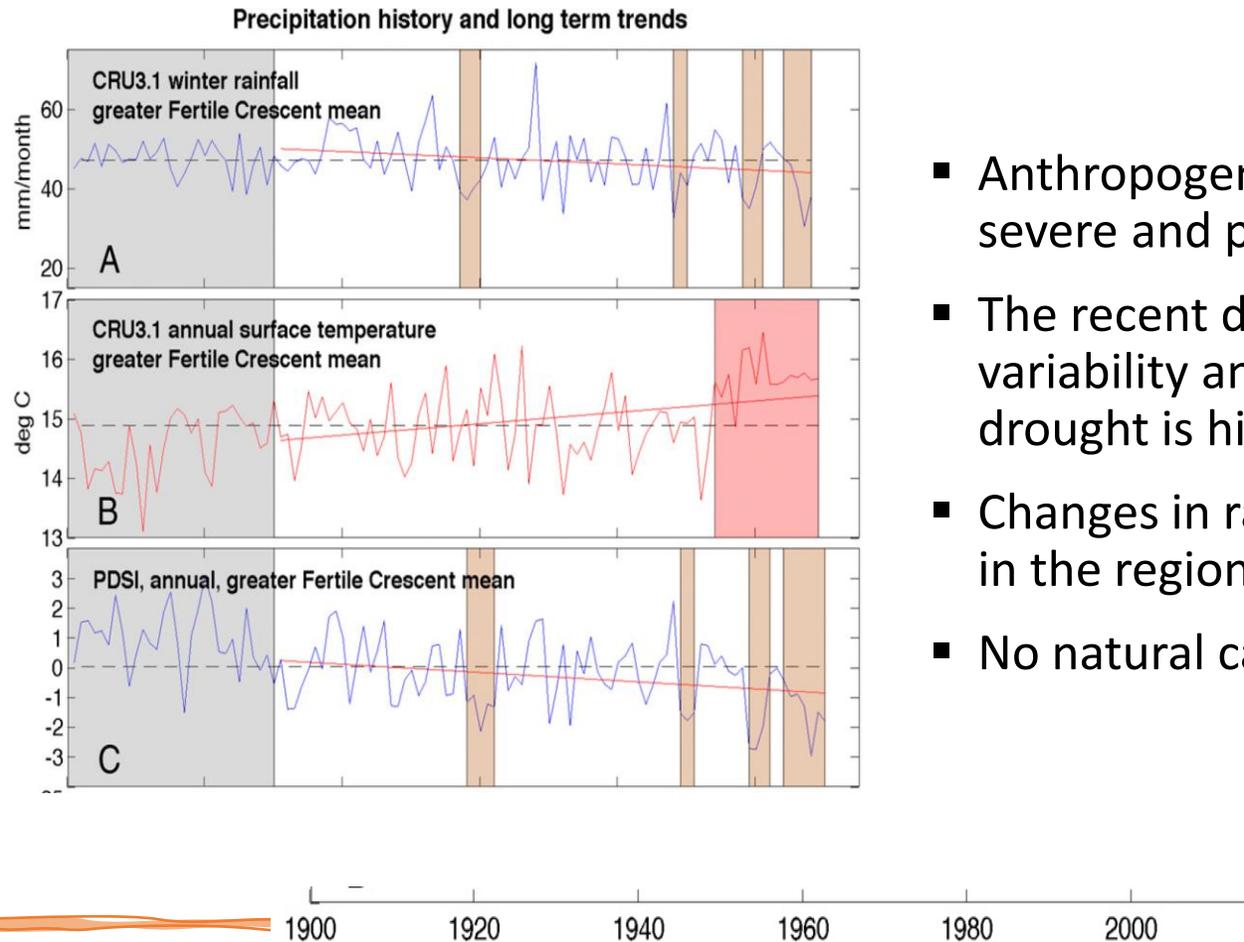


Figure: Cross-station average of annual mean standardized anomalies in monthly dust frequency (1975–2012) observed at 26 stations across Saudi Arabia (black), with the spread (± 1 SD) among stations denoted by the gray shading. Additional data shown include satellite-measured monthly AOD in and around Saudi Arabia (12°N – 30°N , 34°E – 56°E) from SeaWiFS (2000–2010, blue), MISR (2000–2012, orange) and MODIS (2002–2012, green), and AERONET-measured AOD (red) measured at Solar Village (24.907°N , 46.397°E) in Saudi Arabia

*Yu, Y., Notaro, M., Liu, Z., Wang, F., Alkolibi, F., Fadda, E. and Bakhrjy, F. (2015), Climatic controls on the interannual to decadal variability in Saudi Arabian dust activity: Toward the development of a seasonal dust prediction model. *J. Geophys. Res. Atmos.*, 120: 1739–1758. doi: [10.1002/2014JD022611](https://doi.org/10.1002/2014JD022611).

Trends in the Middle East

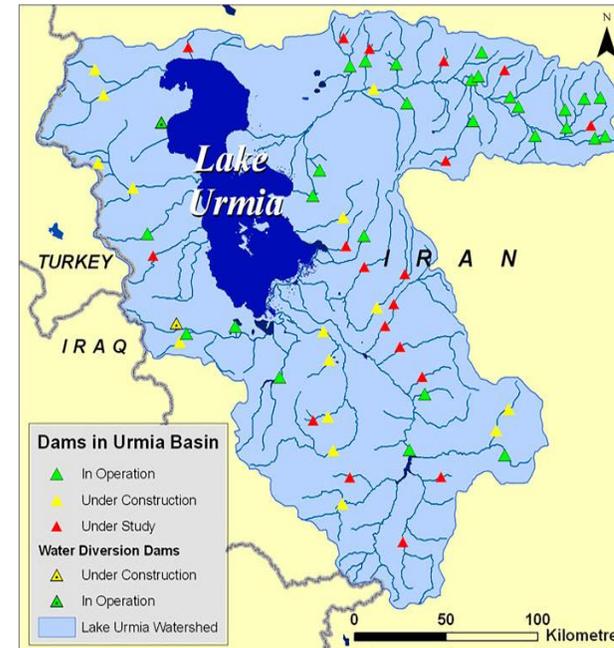
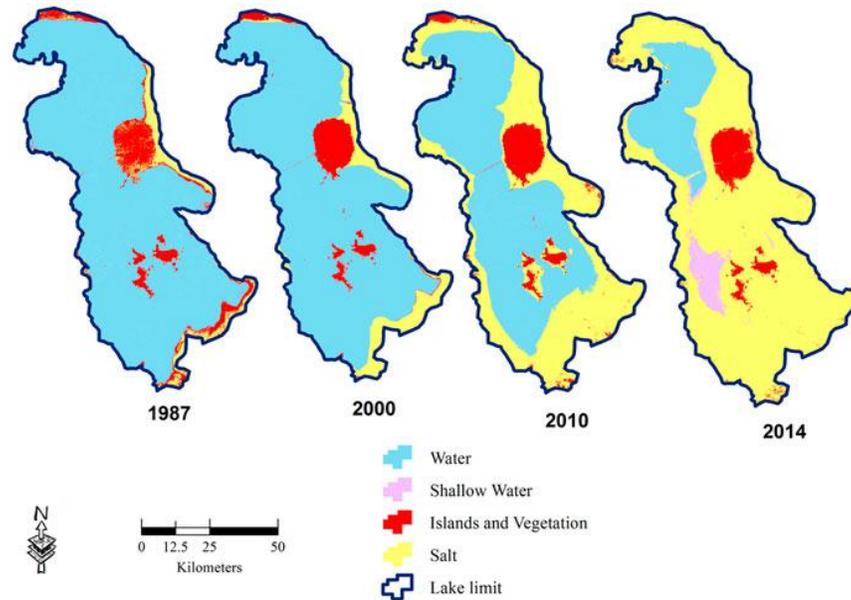
Colin P. Kelley, Shahrzad Mohtadi, Mark A. Cane, Richard Seager, and Yochanan Kushnir : Climate change in the Fertile Crescent and implications of the recent Syrian drought PNAS 2015 112 (11) 3241-3246; published ahead of print March 2, 2015, doi:10.1073/pnas.1421533112)



- Anthropogenic forcing has likely increased the likelihood of severe and persistent droughts in the region
- The recent drop in rainfall is the outcome of natural variability and long term drying trend, the magnitude of the drought is highly unlikely without this trend
- Changes in rainfall are tied to rising mean sea-level pressure in the region, exhibiting a long term trend
- No natural cause is apparent for these trends

Lake Urmia

- Lake Urmia has been significantly drying over the past few years
- Human activities are a major contributor to the drying



Rahimi and Breuste, 2021



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