Modeling of emission, transport, and deposition of mineral dust in different climate epochs

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(1) Introduction

- **Mineral dust** is an important component of the Earth's **climate system**. During atmospheric transport, dust particles directly and indirectly influence weather and climate.
- **Nutrients** contained in the dust particles constitute an important fertilizer **for oceans** (see Fig. 1) **and rain forests**. Part of the productivity of the Amazon rain forest depends on dust from North African source regions (*Swap et al. 1992*).
- Here we apply the global climate model **EMAC** (see (2)) for simulations of the mineral dust cycle under different climatic conditions.
- **Eulerian and Lagrangian** analyses of a 5-year time slice simulation are used to determine **transport time** and major **source regions** of dust, transported from North Africa across the Atlantic to the Americas in the recent climate.
- Comparison with a simulation representing the year AD 1600 – during the **Little Ice Age** – show the impact of the dynamics on the mineral dust cycle.

Fig. 1: Saharan dust plume over the Bay of Biscay and surroundings and algae growth west of Portugal, supported by the dust.

(2) Modelsystem EMAC

- **E**CHAM5: Global climate model used as base model
- **M**ESSy: Modular Earth Submodel System (see *http://www.messy-interface.org/*): Interface between base model and submodels, that calculate modularized processes, as
- **A**tmospheric **C**hemistry
- Determination of **most appropriate model setup** for simulations of the mineral dust cycle described in *Gläser et al. 2012.* It comprises:
  - **basic sulfur chemical mechanism** to simulate aging of dust particles in a realistic way
  - Horizontal resolution **T85** (~155 km)
  - Dust emission scheme from ***Tegen*** *et al. 2002*
- Results are based on **5-year time slice** simulations, boundary conditions represent
  - AD **2000** for the recent climate
  - AD **1600** for the Little Ice Age

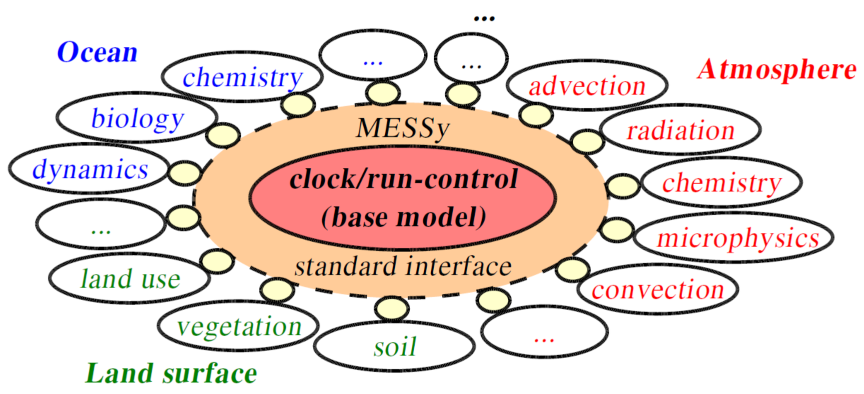

Fig. 2: Schematic illustration of the connection of different, modularized processes (outer ring) with each other and with a base model via the MESSy interface (*Jöckel et al. 2005*).

(3) Transatlantic dust transport

Trajectory calculations with LAGRANTO (*Wernli & Davies 1997*) based on EMAC model output

- At each grid point and each time where/when dust is emitted in North Africa, 15-day forward trajectories are initialized from each grid box within the planetary boundary layer.
- Only those are retained that cross 30ºW between 20ºS and 40ºN.
- This yields about 150 000 trajectories for all boreal winter months (DJF) and about 250 000 for the summer months (JJA).
- Due to the shift of the ITCZ the dust reaches the Caribbean (CAR) mainly in JJA and the Amazon Basin (AMA) in DJF.
- Fig. 4 shows a snapshot of such trajectories for one day in February.

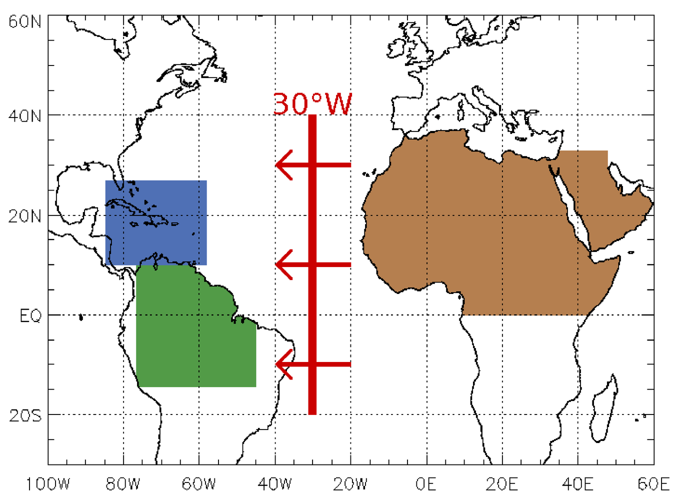

Fig. 3: North Africa and the Arabian Peninsula (brown) are the potential dust emission regions, where trajectories are initialized. The Caribbean (blue) and the Amazon Basin (green) are the target regions. Trajectories not crossing the red line are not considered.

Lagrangian transport time

i.e. the time the trajectories need to reach the eastern border of CAR and AMA, respectively.

JJA	30ºW	→	CAR	3.7 days
	Emission	→	CAR	10.3 days
DJF	30ºW	→	AMA	4.7 days
	Emission	→	AMA	9.3 days

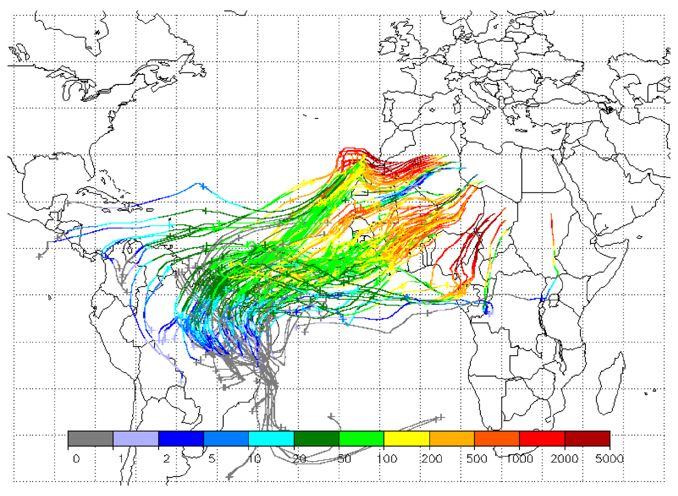

Fig. 4: Example for trajectories initialized over North Africa, crossing the Atlantic, and reaching the Amazon Basin. Colors show the dust concentration in µg m^{-3}.

It is necessary to check if the chosen trajectories represent the Eulerian transatlantic dust transport. Therefore, in the following results for Lagrangian transport time and vertical distribution of the transport are compared with the respective Eulerian values.

Eulerian time series

1) of transport across 30ºW between 20ºS and 40ºN
2) of mean dust concentration in AMA and CAR

- Calculate time-lagged correlations of these time series. The time lag with the maximum correlation represents the transport time (Fig. 5).
- Averaging over 4 winters and 5 summers, respectively, yields:
  - JJA : 30ºW → CAR: 5.3 days
  - DJF: 30ºW → AMA: 5.7 days
- The dust needs 1-1.5 days to spread from the eastern border over the entire domains.

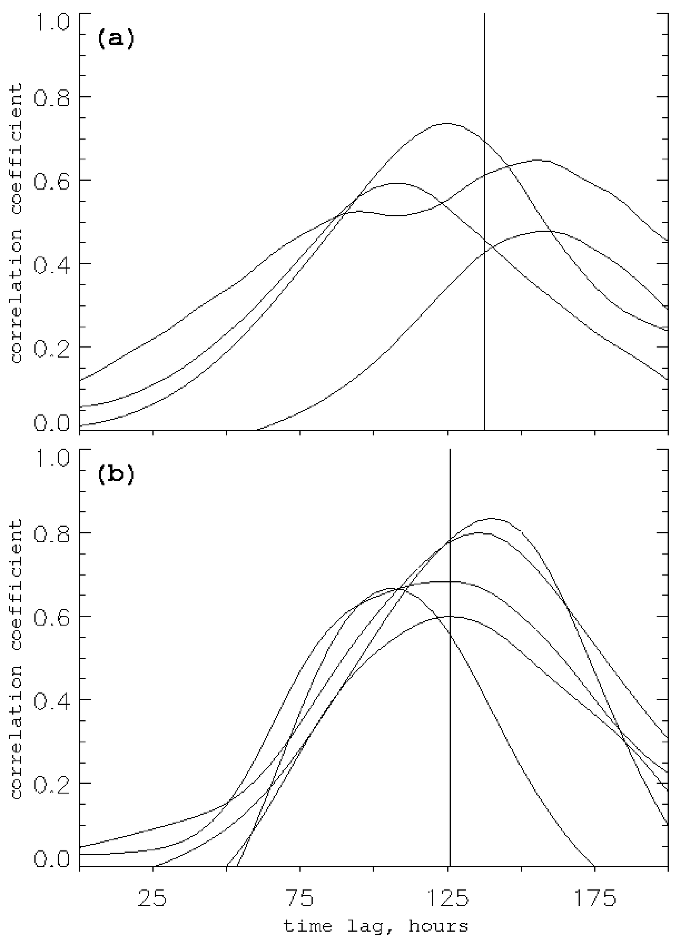

Fig. 5: Time lagged correlations of the time series of dust transport across 30ºW and the mean dust concentration in (a) the Amazon Basin during DJF and (b) the Caribbean during JJA.

Vertical distribution

- Consistent results from Eulerian and Lagrangian calculations (Fig. 6).
- Chosen trajectories do represent the Eulerian model output.

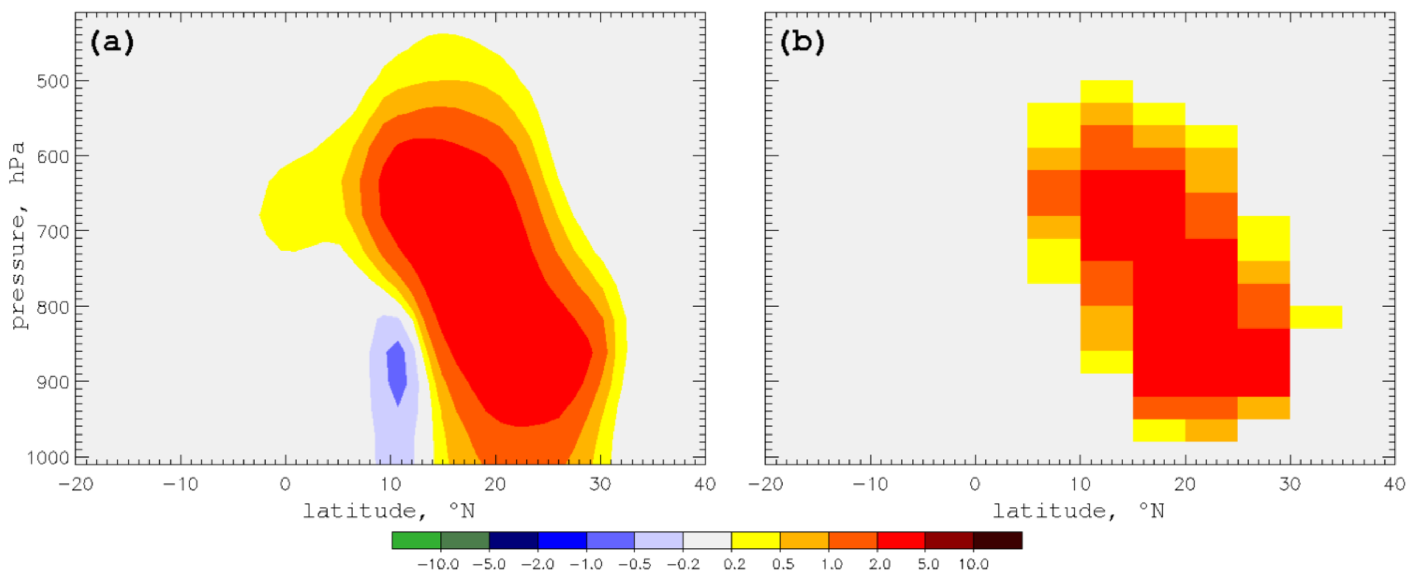

Fig. 6: Meridional cross sections of westward dust transport across 30ºW in kg m^{-2} per month during JJA from (a) Eulerian and (b) Lagrangian data.

Source regions of the dust reaching the Amazon Basin

1) Calculate the difference of the dust mixing ratio along trajectories from entering until leaving AMA.
2) Multiply with trajectory mass.
3) Add this amount of dust to the grid point where the trajectory was initialized.
4) Summing up over all trajectories yields Fig. 7.

- Major source regions are located in Central Algeria, Mali, and Mauritania.
- One of the World's most active dust source regions, the Bodélé Depression in Chad, does not contribute.

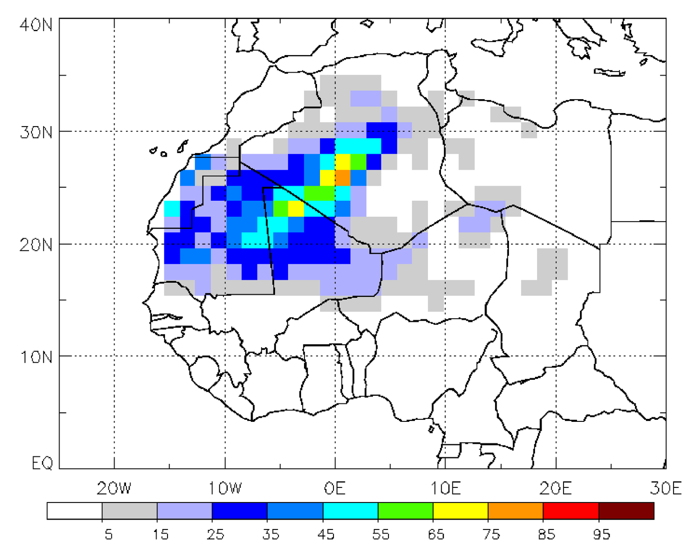

Fig. 7: Lagrangian-based calculation of source regions important for the transatlantic dust transport. The shading shows the contribution of these regions to the dust deposition in the Amazon Basin in kg ha^{-1} yr^{-1}.

(4) Little Ice Age

- The Little Ice Age (LIA) was a cold period between the 13th and 19th century.
- Adapt the model's forcing factors (SST, GHG-concentration, …) to conditions during the LIA.
- Only the influence of the dynamics is considered; surface parameters (e.g., roughness length) stay unchanged.
- Compare the 5-year time slice with these forcings for AD 1600 with the simulation in the recent climate.
- The model reproduces a cooling on the order of 0.5-1.0 K (Fig. 8), which is in the range of other reconstructions for that time (*Frank et al. 2010*).
- The annual global dust budget is similar to the recent climate. Differences occur on the regional and seasonal scale.
- Intensification of the West African Monsoon circulation in the LIA simulation causes higher dust emissions in JJA from the southern Sahara and the Sahel during the LIA (Fig. 9).
- There are no significant differences in the transatlantic dust transport between both climate epochs.
- Complex changes in the circulation of the Indian Monsoon cause lower emissions from the Arabian Peninsula in the recent climate while emission from the Thar Desert in NW-India are today higher.

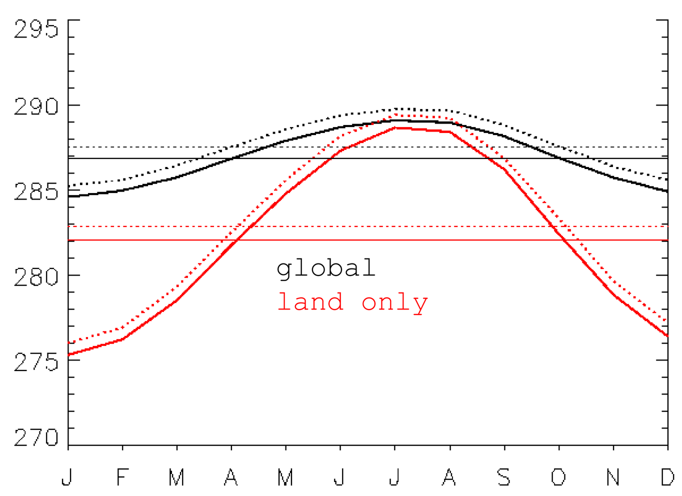

Fig. 8: Annual cycle of the temperature in K on the lowest model layer during the LIA (solid lines) and the recent climate (dotted lines) for the entire globe (black) and land grid points only (red).

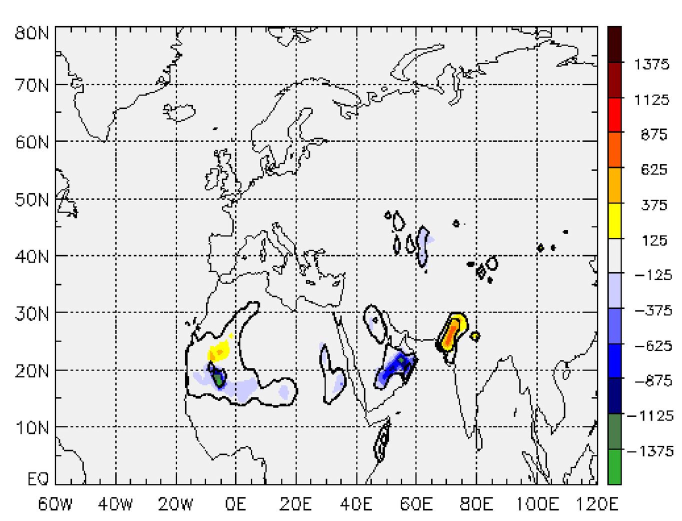

Fig. 9: Difference of the dust emission flux during JJA in kg ha^{-1} per season of the simulation in the recent climate minus the one during the Little Ice Age. Bold black isolines (200, 2 000 kg ha^{-1} per season) mark the regions where about 80% (20%) of the dust is emitted in the recent climate.

(5) Conclusions

- The mineral dust cycle influences weather and climate and provides essential nutrients to various ecosystems.
- Continuous 5-year time slice simulations with EMAC allow for detailed investigations of the dust cycle in different climate epochs.
- The transatlantic transport of dust from North African source regions underlies the seasonal shift of the ITCZ. The transport to the Caribbean in JJA takes about 10 days and to the Amazon Basin in DJF about 9 days.
- Major source regions of the dust that crosses the Atlantic are located in Central Algeria, Mali, and Mauritania.
- The Bodélé Depression in Chad – although one of the World's most active dust source regions – does not contribute the transatlantic dust transport.
- With adapted forcing factors, EMAC reproduces a stable simulation during the LIA with a realistic cooling of 0.5-1.0 K.
- Changes in the monsoon circulations in West Africa and India cause regional and seasonal differences in the dust cycle during the LIA.

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