Doktorska disertacija – Sažetak
D.Sc. Thesis – Extended abstract

OBILJEŽJA ATMOSFERE TIJEKOM TRANSPORTA SAHARSKOG PIJESKA NAD JADRANOM

Characteristics of the atmosphere during Saharan dust transport over the Adriatic

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Sažetak:

Mineralna prašina, kao jedan od najrasprostranjenijih tipova aerosola iznimno je važan čimbenik u procjenama klimatskih promjena. Ona utječe na atmosfersko zračenje, formiranje oblaka, a prilikom taloženja prenosi mikronutrijente kako kopnenim tako i oceanskim ekosustavima. Saharska pustinja jedan je od glavnih globalnih izvora prašine koja putem atmosferskog transporta ima utjecaj na Sredozemlje, uključujući i Jadran. Atmosfersko taloženje mineralne prašine igra važnu ulogu u opskrbi mora hranjivim tvarima. U ovom istraživanju po prvi put izrađena je klimatološka analiza taloženja prašine na području Jadranskog mora na temelju podataka reanalize MERRA-2 za razdoblje 1989. – 2019. Ustanovljeno je da godišnji hod ima bimodalnu strukturu s jačim maksimumom u proljeće i slabijim u jesen pri čemu se pokazalo da je mokro taloženje dominantan proces, a žarišta su duž crnogorske obale i u blizini Otranta. Korištenjem metode empirijskih ortogonalnih funkcija (EOF) izdvojeno je osam sinoptičkih situacija s obzirom na prva tri moda i pripadne faze. One su analizirane u odnosu na prostornu varijabilnost optičke debljine aerosola (AOD) i taloženje prašine u Jadranu. Pripadni vremenski nizovi koeficijenata za svaki mod daju kvalitativno objašnjenje bimodalnosti godišnjeg hoda taloženja s obzirom na sinoptičke situacije za koje se ustanovilo da imaju najznačajniji utjecaj na ovaj proces. U ovom interdisciplinarnom istraživanju opažena je i visoka razina zasićenosti kisikom u Rogozničkom jezeru što je indikacija biološke aktivnosti povezane s povećanjem prisutnosti fitoplanktona nakon izdvojenih epizoda pojačanog atmosferskog taloženja prašine u morski sustav Rogozničkog jezera (Zmajevo oko kod Rogoznice).

Klimatološka analiza taloženja prašine na području Jadranskog mora na temelju podataka reanalize the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) omogućila je izdvajanje ekstremnih događaja u bazu podataka. Iz baze podataka, uvažavajući iznadprosječne koncentracije PM_{10} izmjerene na urbanim i ruralnim prizemnim postajama za praćenje kvalitete zraka na području Jadrana, odabrane su dvije epizode koje su simulirane i detaljno istražene modelom Weather Research and Forecasting združenim s kemijskim modelom (WRF-Chem). U prvoj od ove dvije epizode dnevna vrijednost koncentracije PM_{10} izmjerena 27. 3. 2020. u Rijeci iznosila je 216 μgm^{-3}, a satne vrijednosti diljem Hrvatske dosezale su vrijednosti i do 400 μgm^{-3}. Analiza sinoptičke situacije, putanja unazad modela Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT), produkata AOD-a iz reanalize MERRA-2 i simulacije WRF-Chem ukazuje na advekciju prašine iz područja istočno od Kaspijskog jezera. Advekcija se odvijala do visine ~ 2 km nad tlom s izvorom na širem području isušenog Aralskog jezera. Međutim, kemijska i morfološka analiza lebdećih čestica ukazala je i na prisutnost prašine iz područja Sahare što se može pripisati utjecaju ciklone Sharav prisutne u Sredozemlju koja je prethodila advekciji prašine s istoka. Druga simulirana epizoda odnosi se na utjecaj visinske doline, što je karakteristična pojava za jesen pri čemu je donos prašine zahvatio sjeverno područje Jadrana.

Extended abstract:
1. Introduction

Airborne mineral dust is a significant factor in climate change estimates. Dust influences atmospheric radiation properties, cloud formation, and biogeochemical cycles, delivering micronutrients to both terrestrial (Yu et al., 2015) and oceanic ecosystems (Jickells and Moore, 2015). According to many studies, the Saharan Desert is one of the main global dust sources. It is estimated that 46% of global natural dust emissions originate in North Africa (Kok et al., 2021b) although there is also high variability in emission estimates Huneeus et al. (2011). The research of dust related processes are affected by both the limitations of the numerical model and uncertainties existing in satellite measurements, which are hampered by clouds or the high content of column water vapor (Schepanski et al., 2012). A significant amount of dust from the Sahara is advected to the Amazon forest (boreal winter, Bakker et al., 2019) and the Caribbean (boreal summer). But the dust transport to the Mediterranean is not negligible or rare (Barkan et al., 2005; Israelevich et al., 2012). Schepanski et al. (2016) estimated that 100 Tg yr^{-1} of Saharan dust is exported toward the western and central Mediterranean basins.

The large-scale transport routes depend mainly on synoptic-scale features (Moulin et al., 1998; Huneeus et al., 2011; Israelevich et al., 2012; Schepanski et al., 2016; Varga, 2020). In spring (mostly April), the most probable transport paths are toward the eastern Mediterranean due to Sharav cyclones (Alpert and Ziv, 1989). In August and September, Balearic cyclogenesis is the dominant process responsible for transport routes toward the western Mediterranean (Israelevich et al., 2012). In June and July, the highest probability of dust transport is over the central Mediterranean and central Europe with the support of the near-surface thermal low pressure system, that is, the Saharan heat low and the high pressure system over Libya (Israelevich et al., 2012). The most related studies are based on the coarse grid data (Huneeus et al., 2011; Israelevich et al., 2012; Mahowald et al., 2014) and/or relatively small data sets (Barkan et al., 2005; Israelevich et al., 2012) and they cannot fully explore the regional and local characteristics of certain parts of the Mediterranean on longer time scales. Therefore, one of the goals of this study is to evaluate the climatological aspects of dust transport and the annual cycle of dust deposition over the northernmost part of the Mediterranean, that is, the Adriatic Sea, which has not been examined in detail so far.

In addition to the impact of aerosols on the characteristics of the regional climate, Saharan dust also affects the biogeochemical cycle. Desert dust deposition in the otherwise oligotrophic, lownutrient, and low-chlorophyll Mediterranean Sea is the crucial source of nutrients, mainly nitrogen (N), phosphorus (P), and iron (Fe) (e.g. Richon et al., 2017). Chlorophyll production has strong seasonal and spatial variation and could be significantly affected by atmospheric deposition (Richon et al., 2017, 2018). The effects of N deposition span over large and deep basins such as the Ionian, Levantive, and Tyrrhenian whereas P deposition effects are mainly observed in shallow areas such as the Adriatic, Aegean, and coastal western basin (Richon et al., 2017). In general, organic matter concentration can be taken as a direct consequence of biological and biogeochemical activity.

For the first time, the climatological aspects of dust transport and the annual cycle of dust deposition over the Adriatic Sea are evaluated. This research is mainly focused on detecting the synoptic situations related to the most intense dust deposition events. For each characteristic synoptic situation, the goals were to examine and determine: (a) dust emission intensity and source locations, (b) the atmospheric transport routes and spatial distribution of dust deposition in the Adriatic, (c) the threshold for dust deposition events (DDEs) for the entire study area, and (d) their annual averages. Interannual variability in dust deposition is also analyzed using average values for the investigated area. Additionally, the central Adriatic marine system of Rogoznica Lake (43°32’N, 15°58’E), as a site with stable seasonal physicochemical stratification, atmospheric input as the only source of freshwater (Ciglenečki et al., 2015, 2017; Čanković et al., 2019), and relatively short residence time of trace metals (Fe, Mo) in the water column due to interaction with sulfide (Helz et al., 2011), is taken to prove the effect of dust deposition on primary production. Atmospheric mineral dust is one of the most abundant aerosols, but estimates of emissions and deposition are quite unreliable and variable. According to the study by Huneeus et al. (2011) estimated range of global dust emissions is 514 – 4313 Tg yr^{-1}, while depositions are in range 676 – 4359 Tg yr^{-1}. In general, a problem in estimating dust emissions is the lack of measurements over large desert areas, and so dust emissions are calculated from models that are highly variable in their estimates. This affects the simulated concentration of dust in the air, especially deposition, which is also rarely measured (Vincent et al., 2016). A more advanced approach to emission estimates is available in the form of gridded reanalysis data where modeled values are improved by assimilating optical properties observed by satellites and ground measurements (Buchard et al., 2017). A recent study by Kok et al. (2021a) using inverse modeling for the period 2004–2008 indicated even higher global dust emissions (up to ~ 5000 Tg yr^{-1}) compared to most models. The reason for this is the higher emission of dust particles up to 20 μm in diameter (PM_{20}), which is underestimated in the models (Kok et al., 2021a). In this dissertation, two dust episodes were simulated and analysed using WRF-Chem model.

Most of the modelling studies for the Europe and Mediterranean are based on a Saharan dust origins. In the literature, there is not much evidence for dust advection from Asia towards this part of Europe, and this path was not found in the climatological study for the period 2005–2013 (Ge et al., 2016). In contrast to these studies, the unusual and intense dust outbreak involving transport from the deserts east to the Caspian Sea set stage at the end of March 2020. Among the first studies that analyzed this phenomenon was the one by Strelec Mahović et al. (2020) and Tositti et al. (2022). Both studies are based on analysis of (in situ and remote) measurements, reanalysis and backward HYSPLIT trajectories. Strelec Mahović et al. (2020) preliminary analyzed the observed PM_{10} concentrations at the stations within the Pannonian part of Croatia. The highest values up to ~ 400 μgm^3 (on 27 March 2020 at 14 UTC) were recorded in Zagreb (Croatia) during the mentioned case, presenting it as the most polluted city at that time in Europe. Backward trajectories and satellite images indicated the Aral region as the area from which dust transport occurred. The results in the study of Tositti et al. (2022) suggest that the transport from the east was preceded by the transport from the Saharan area. This raises the question of the complexity of this event and the potential combined effects of transport from several regions to the central Mediterranean, which is not revealed until now. Results shown in this dissertation for the wider Rijeka area at the Adriatic coast indicated that a Saharan contribution existed during this extreme case.

The second episode simulated with WRF-Chem model occurred in the period 14–19 September 2015. The dust sources affecting the outbreak were detected in simulations and HYSPLIT forward trajectories which were used to track the dust transport starting at the time of peak dust emissions. This case was used to test the different modeling options against the measurements at the ground based air quality stations in the Adriatic coast.

2. Data and methods

The area chosen for dust deposition climatology research is the Adriatic Sea which is a body of water separating the Balkans and the Apennine Peninsula, and extends northwest from 40°N to 45°47’N, representing the Mediterranean’s northernmost portion (Cushman-Roisin et al., 2001). The sea is geographically divided into the North Adriatic (NAd), Central Adriatic (CAd), and South Adriatic (SAd). To investigate the response of the biological system to dust deposition, the site of Rogoznica Lake is chosen (CAd; 43°32’N, 15°58’E). The lake is a typical example of a highly stratified (thermally, densely, and chemically) marine system characterized by permanent anoxia (below 8 m depth). Rogoznica Lake is a karstic depression filled with seawater, with an area of 10,276 m^2 and a maximum depth of 15 m, with no direct connection to the open sea. A weak connection with the sea exists through cavities in the karstic terrain, but the only supply of freshwater to the lake is atmospheric precipitation, which directly affects the salinity of the lake water column (Ciglenečki et al., 2015).

Due to a lack of any dust deposition measurements in the Adriatic Sea, the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2; Buchard et al., 2017) was used here as a source for dust optical properties and deposition over the investigated area. MERRA-2 contains atmospheric reanalysis data from 1980 onward using the NASA Goddard Earth Observing System, version 5 (GEOS-5), Earth System model (Molod et al., 2015), and the three-dimensional variational data assimilation (3Dvar) Gridpoint Statistical Interpolation analysis system (GSI) (Kleist et al., 2009). The MERRA-2 reanalysis data are at a resolution of 0.5° × 0.65°, which is still too coarse for the Adriatic. Therefore, over the Adriatic Sea surface, a mask was created using the General Bathymetric Chart of the Oceans (GEBCO) topography with a resolution of 15 arcsec. The MERRA-2 deposition fields were interpolated to every 10th point of GEBCO topography. Although the interpolation here does not yield better results, it is useful to precisely divide the Adriatic area depending on the existing knowledge about the climate characteristics of the atmosphere. To evaluate the MERRA-2 dust deposition data, the available data from the dustsampling network established for the measurement campaign within the CharMex project (Vincent et al., 2016; https://mistrals.sedoo.fr/ChArMEx/) were also employed. The base of the network is the special, standardized deposition sampler CARAGA (Collecteur Automatique de Retombées Atmosphériques insolubles à Grande Autonomie in French, Laurent et al., 2015). Due to the limited measurements (CARAGA) from the broader Mediterranean area, one of the goals was to compare them with the MERRA-2 reanalysis over the investigated area. The methodology of comparison (e.g. Pielke and Mahrer, 1978; Teixeira et al., 2014; Kehler-Poljak et al., 2017) is performed using the set of statistical parameters: standard deviations of observations (σ_o) and model (σ_m), Root Mean Square Error (RMSE), Root Mean Square Difference (RMSD) and by checking if the reanalysis demonstrates acceptable performance by applying the following criteria: (a) $\sigma_m \approx \sigma_o$, (b) RMSE $\lesssim \sigma_o$, and (c) RMSD $\lesssim \sigma_o$.

For the simulation of the dust episodes, the Weather Research and Forecasting (WRF) model version 3.7.1 (Skamarock et al., 2008, 2019) coupled with the Chemistry model (WRF-Chem; Grell et al., 2005) was used. The WRF-Chem coupled modeling system is often applied for general PM_{10} concentration evaluations (e.g. Gašparac et al., 2020) and/or more specifically on dust transport events, but the studies for the Europe and Mediterranean are in general focused on the Saharan dust advection (e.g. Teixeira et al., 2016; Rizza et al., 2017; Palacios-Peña et al., 2019). The WRF (Skamarock et al., 2008, 2019) model was used to study the influence of Aral lake desiccation on climate and the effect of the substantial air warming over the dried lake's surface during summer in Roy et al. (2014) and in Sharma et al. (2018) where reduction of rain during winter was detected. Several dust WRF-Chem simulations for Aral lake were made (e.g. Karami, 2021; Li and Sokolik, 2018), which indicates that the model system is well tested for simulations of this type and indicates reliable use in this study. Here, the model is used to simulate the dust episodes influenced both by Asian and Saharan sources.

The optical properties here were used to identify the dust plumes and verify the performance of the WRF-Chem simulations. To identify the development and position of dust plumes, satellite data can be used, but uncertainties in measurements arise from clouds or the high content of column water vapor (Schepanski et al., 2012), in this case particularly over the area of interest during the dust episode. Therefore, instead, the Aerosol Optical Depth (AOD) product from MERRA-2 (GMAO, 2015d) was used, particularly for the simulation of episode in 2020. To compare the WRF-Chem AOD with the observations, the data obtained at two AErosol RObotic NETwork (AERONET) stations were used for both episodes. AERONET is the worldwide network of sunphotometer stations measuring the spectral extinction of direct beam radiation using a BeerLambert-Bougner law (Holben et al., 1998). AOD from WRF is available at four wavelengths

(300, 400, 600, 999), while the measurements are available at multiple different wavelengths (Holben et al., 1998). To compare the modeling results the Ångström power law is applied (as in the paper of Kumar et al., 2014) to WRF-Chem AOD.

In order to test the capability of WRF-Chem to simulate hourly values of surface PM_{10} concentrations, data from the ground based stations were used. For the episode in 2020 the data were obtained from the air quality stations available from the Ministry of Economy and Sustainable Development (http://iszz.azo.hr/iskzl/index.html). For the episode in 2015 the data were taken from the stations of region Marche in Italy operated by Environmental Protection Agency of region Marche and stations located in region Primorsko-goranska županija, in vicinity of city Rijeka and operated by Teaching Institute of Public Health (TIPH). The chemical analysis was made on a filter containing PM_{10} which was sampled on 27 March 2020. at TIPH site. The concentration was determined by the gravimetric method after the conditioning and weighing. Then, the filter was cut into eight parts used for different analyses. The heavy metals concentrations (Pb, Cd, Cu, Zn, Fe, Mn) were obtained from the process of mineralization of the filter, and analysis was made afterward by using ICP-MS (Inductively Coupled Plasma-Mass Spectrometry). The other parts of the filter were used for Polycyclic Aromatic Hydrocarbons (PAHs) and scanning electron microscope (SEM) analysis. These analysis were not used to verify the model's performance but to determine the origin of the collected dust.

To determine the area of dust sources, the HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) backward trajectories (Stein et al., 2015) using the web-based Real-time Environmental Applications and Display sYstem (READY) (Stein et al., 2015). This method was applied in analyses of dust events of 2015 and 2020 and also in analysis of dust deposition event in Rogoznica Lake in 2019. For this event the deposition of Fe and P in Rogoznica Lake was estimated using mineralogical database (Nickovic et al., 2012).

3. Results and concluding remarks

The verification of MERRA-2 dust deposition with the CARAGA measurements shows a good correlation, although the deposition in reanalysis is overestimated. This bias can be due to the assimilation of both AOD and meteorology. AOD is a 2-D field and it does not account for neither the different types of aerosols nor the aerosol size distribution. Therefore, uncertainties in dust vertical profile, size distribution, and types of aerosols can lead to misrepresentation of dust deposition fluxes. Since AOD is the only aerosol-related assimilated parameter and if the model has a bias in one aerosol component, this may lead to discrepancies in dust deposition flux (Wu et al., 2020). Also, the model generated precipitation in MERRA-2 which is corrected with observations before being used for the wet deposition of aerosols over land and ocean (Gelaro et al., 2017; Reichle et al., 2017) can be a source of uncertainties. The additional possible cause of the uncertainties can be related to the dust deposition measurements at the CARAGA stations, in particular due to the loss of material during the filter handling, weighing and ignition process. Despite the mentioned disadvantages, the MERRA-2 is among the best databases for dust related fields (Wu et al., 2020; Kok et al., 2021a) and can be used for the purpose of assessing the impact of dust deposition in the Adriatic.

Although dust deposition events are of sporadic nature, the annual cycle in Adriatic Sea shows a certain level of regularity revealing the bimodal shape. This pattern depends both on the seasonality of dust transport occurrence due to synoptic patterns and the local precipitation cycle. Globally, the annual position of the Intertropical Convergence Zone (ITCZ) is the crucial factor. From the winter to the summer season, ITCZ moves northward and passes through desert areas. As a consequence, in the Mediterranean area during spring Saharan dust is mostly transported toward the eastern and central Mediterranean (Moulin et al., 1998; Israelevich et al., 2012). Later, the dust plumes are shifted toward the central and western Mediterranean during summer and autumn, respectively. The results within this dissertation are in agreement with this dynamics, both in regard to the annual cycle and spatial distribution of dust deposition. Dust deposition in the Adriatic was found the be mostly in the form of wet deposition, ranging from 62 to 89% of total mass deposition, which is in agreement with measurements from CARAGA stations. Therefore, overall dust deposition strongly depends on precipitation, which at most stations along the eastern Adriatic coast has two maxima in the annual cycle: stronger maxima in autumn and weaker maxima in spring due to intense cyclonic activity (Penzar et al., 2001). Summer is characterized by scarce precipitation associated with anticyclonic weather conditions (Belušić Vozila et al., 2021), except on the northwestern coast of the Istrian Peninsula (Mikuš et al., 2012).

However, dust deposition in the Adriatic Sea is the most intense in April, representing the primary maximum, while the secondary maximum occurs in November. The EOF analysis revealed the characteristic synoptic patterns related to the dust transport in relation to the sources, spatial distribution of deposition intensity in Adriatic Sea and it's annual cycle. The most important synoptic situation for dust deposition in the Adriatic Sea is driven by an upper-level trough aligned in a SW-NE direction with a deep Mediterranean cyclone centered over Corsica. This cyclone is known as Sharav cyclone (Alpert and Ziv, 1989). Driven by baroclinic temperature gradient between the sea and land in spring, it travels eastward along the northern African coast, lifting the dust from Atlas Mountains to the Gulf of Sirte in Libya. Dust transport occurs at the foreside of cyclone towards eastern Mediterranean affecting the deposition in Adriatic Sea with a gradient from the NAd to SAd, particularly along the Dalmatian and Montenegrin coast in the CAd. The synoptic situation characteristic for the autum is defined by an upper-level trough with a cyclone in Biscay Bay extending down to southern Algeria. The dust emissions are in the Atlas Mountains, while the increase in AOD is extended to the western Mediterranean, including the entire Adriatic. The deposition is the strongest along the eastern Adriatic coast, but it has a relatively strong impact in the NAd. This finding is also coincident with studies by Varga et al. (2014); Varga (2020), and it is related to the most important situation for dust episode occurrence in the central Mediterranean area and is responsible for 67.4% of dust episodes in the Carpathian Basin.

The biological response to the dust deposition was proven by a high level of oxygen saturation (up to 250%) due to increased phytoplankton (mainly diatoms) abundance (>106 cells L^{-1}) and activities (Figure SE1 in Supporting Information S1) in the stratified middle layer (5–8 m depth) of Rogoznica Lake following intense deposition episodes. Additionally, in this dust coming from Libya, the deposited Fe and P were estimated by using HYSPLIT trajectories and mineralogical maps following the work of Nickovic et al. (2012), and fairly good agreement between estimated and measured Fe in the surface of Rogoznica Lake was obtained. Our results prove the positive significant trend for the 30-Y dust deposition time sets in the Adriatic Sea with the higher frequency of strong wet deposition events recorded after 2000.

In the second part of the dissertation, the two dust episodes over Adriatic region were simulated using the WRF-Chem model. The first was the extreme episode that occurred over Southeast Europe from 27 to 30 March 2020. In this case, the daily PM_{10} value observed at the TIPH station on 27 March 2020 was ~ 7.7 times higher than the average value in 2020. The remote sensing and the modeling results showed the influence of two different origins; the mid-troposphere plume from North Africa driven by deep Sharav cyclone was recorded the day before the occurrence of the plume from Asia and the max. PM_{10} values observed at multiple ground based stations in Croatia. The modeling results showed that the advection up to ~ 2 km a.g.l. can be attributed to the sources east to the Caspian Sea. This poses a question of the relative contribution from the African and Asian sources. The arguments supporting that the Asian sources are the most significant; increased AOD identifies the plumes from the both Saharan and Asian direction, but the advection from the east was in the lower troposphere and atmospheric boundary layer, while the African plume was in the mid-troposphere above the mixing layer. However, the chemical and SEM analysis of

PM_{10} collected during the most intensive March 2020 dust event over the northern Adriatic sampling site lead to the conclusion that PM_{10} filter reflects mainly the influence of Saharan dust. It is important to stress that Mediterranean cyclones can facilitate the long-transport of the giant mineral dust particles (> 75 µm, Flaounas et al., 2022). Therefore, if the coarser particles can be uplifted and advected to distant regions, the deposition by gravitational settling can be the main mechanism to explain the presence of Saharan dust in the filter. Modeling results showed a good agreement with PM_{10} hourly values observed at multiple air quality stations in Croatia in terms of correlation, but they underestimate the observations by 26–57% on average. According to the AERONET measurements at Lampedusa and Galata stations, the plume from the Asian sources was underestimated more. The HYSPLIT back trajectories point to the source located at the dried Aral lake. The erodibility map, based on the simple source function in WRF is proven to be inadequate for the smaller desert areas. In this case, the erodibility values over Aral lake are zero, and this is the most probable reason to explain most of the existing bias in PM_{10} and AOD. The second episode simulated in this dissertation occurred on September 2015. The dust transport from the sources in Algeria and Tunisia was on the foreside of the upper level through which extended from the Atlantic ocean to the south of the Pirineian peninsula. The dust emission time series over the two sources show the diurnal cycle with peak emission in the morning which can be attributed to the nocturnal low level jet break down process. For this episode, the sensitivity tests were performed using two different aerosol modules within the WRF-Chem model: MOZART-GOCART and MOZART-MOSAIC, and each was tested with and without the usage of the dust boundary conditions from global model MOZART-4. It was shown that there is a high correlation between the simulation and the measurements, both for AOD and for PM_{10}. Considering the sensitivity tests, the best agreement is in the case when the MOZART-GOCART module is used without applying the boundary conditions from the global chemical transport model MOZART-4. This results are mostly affected by the usage of different dust emission schemes within the specific modules.