



Resolution-dependent uncertainties in global potential dust emissions: A comparison of convection-resolving ICON (version 2.1.02) and parameterized ICON-ESM (version 1.0) configurations

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Abstract. Mineral dust is a key component in aerosol–climate modeling due to its strong effects on radiation, clouds, and biogeochemical cycles. Dust emissions are strongly driven by convective systems, requiring convection-resolving simulations. Recent studies have identified significant uncertainties in simulated dust emissions associated with the representation of moist convection, particularly when contrasting convection-resolving and parameterized approaches. This study extends such analyses from Northern Africa to the major global dust source regions, including the dust belt from North Africa to Central Asia, as well as East Asia and Australia. We compare dust uplift potential (DUP) derived from convection-resolving ICON simulations (DYAMOND, ~2.5 km) with coarse-resolution CMIP6 climate models (~200 km). DUP, based solely on threshold-exceeding near-surface winds, isolates the role of wind representation by excluding surface effects. Systematic discrepancies between the model classes emerge consistently across regions and seasons. Four key deficiencies in coarse-resolution results are identified: (1) underestimation of afternoon and nighttime convective dust events; (2) overestimation of daytime winds linked to low-level jet breakdown; (3) overlapping drivers causing compensating biases; and (4) under-representation of strong, persistent local wind systems. These biases arise primarily from the treatment of moist convection rather than grid spacing alone. Overall, the results demonstrate that explicitly resolving convection is essential for realistic dust emission estimates, with implications for aerosol–radiation interactions, satellite interpretation, and future high-resolution aerosol–climate modeling.

1 Introduction

Mineral dust emitted from arid and semi-arid regions with large fractions of bare soil constitutes one of the most important components of the global aerosol system. The largest source region is the Sahara Desert in northern Africa, followed by other major desert regions such as the Arabian Peninsula, Central and East Asia, Australia, and additional smaller sources worldwide (Tegen and Schepanski, 2009; Ginoux et al., 2012). With annual global emission estimates ranging from approximately 1000 to 4000 Tg year⁻¹, mineral dust accounts for about 70 % of the global aerosol mass burden and represents a major contributor to the atmospheric aerosol load (Kinne et al., 2006; Huneus et al., 2011). Despite decades of research, estimates of global dust emissions still span a wide range, reflecting substantial and persistent uncertainties (Huneus et al., 2011; Wu et al., 2020; Zhao et al., 2022).



Once emitted, mineral dust can be transported over thousands of kilometers and exerts far-reaching impacts on the Earth
25 system (Schepanski, 2018). Dust plays a crucial role in marine and terrestrial ecosystems by supplying essential nutrients such
as iron and phosphorus, thereby influencing bio-geochemical cycles and ecosystem productivity (Yu et al., 2015). In the climate
system, dust affects the Earth's radiation budget through aerosol–radiation interactions (ARI) and aerosol–cloud interactions
(ACI) (Bellouin et al., 2005; Choobari et al., 2014; Kok et al., 2023). Depending on its size, composition, and optical properties,
dust particles scatter and absorb shortwave solar radiation and scatter and re-emit longwave radiation, thereby contributing
30 significantly to radiative forcing (Haywood et al., 2005; Granados-Muñoz et al., 2019). Coarse dust particles alone contribute
roughly 25 % to the global aerosol optical depth (Haywood et al., 2005; Kinne et al., 2006). In addition, mineral dust acts as an
efficient cloud condensation nucleus and, in particular, as an effective ice-nucleating particle, influencing cloud microphysics,
precipitation formation, and cloud radiative properties (Niemand et al., 2012; Dang et al., 2015). When deposited on snow and
ice surfaces, dust can reduce surface albedo and enhance melting (Shi et al., 2021; Roussel et al., 2025). Beyond its role in
35 the Earth system, dust has substantial socio-economic impacts, affecting human health (Zhang et al., 2016; Hu et al., 2024),
economic activity (Tozer, 2012; Opp et al., 2021; Al-Hemoud et al., 2025), and transportation and aviation safety (Baddock
et al., 2013). Dust storms are therefore the subject of numerous scientific studies across disciplines (e.g. Middleton, 2017; Kok
et al., 2023).

Given its importance for weather and climate, mineral dust is a key component of aerosol–climate and Earth system models
40 (Kok et al., 2023). However, a comprehensive observational quantification of global dust emissions is still lacking, and current
estimates rely primarily on model simulations (She et al., 2018; Kok et al., 2021). These simulations are difficult to constrain
and are associated with large uncertainties, as demonstrated by various regional and global dust model inter-comparison studies
(Todd et al., 2008; Huneus et al., 2011; Wu et al., 2020; Zhao et al., 2022). Emission estimates vary by up to an order of
magnitude, a situation that has not improved substantially over recent decades. The sources of uncertainty are manifold and
45 include poorly constrained surface boundary conditions such as soil particle size distribution, aerodynamic roughness, land use
and land cover, soil moisture, surface crusting, salt content, and vegetation cover (Heinold et al., 2013).

In addition to surface properties, the representation of dust-mobilizing near-surface winds is a major source of uncertainty
in dust emission modeling (Pope et al., 2016). Dust emission is initiated through saltation, a threshold-dependent and highly
non-linear process with respect to wind speed (Tegen et al., 2002). Typically, dust uplift occurs at near-surface wind speeds
50 exceeding about 7 ms^{-1} (Marsham et al., 2013). Relevant wind systems capable of generating such conditions include dry
convection and dust devils, moist convective cold pools and haboobs, the breakdown of nocturnal low-level jets, frontal systems,
and large-scale persistent winds, such as the Harmattan in the Sahara, the Shamal over the Arabian Peninsula, the Levar winds
in Central Asia, and other regional wind systems (Sutton, 1925; Schwanghart and Schütt, 2008; Fiedler et al., 2013; Kaskaoutis
et al., 2015; Yu et al., 2016). These processes operate across a wide range of spatial and temporal scales and are often poorly
55 represented in coarse-resolution models.

Most contemporary Earth system and aerosol–climate models are still operated at horizontal grid spacings on the order of
50–100 km (e.g., Eyring et al., 2016). At these resolutions, key processes such as turbulence, gravity wave breaking, and moist
convection have to be parameterized, which necessarily introduces inaccuracies in the simulated wind fields relevant for dust



emission and transport, as well as in aerosol–cloud interactions (Arakawa, 2004; Kok et al., 2014). Recent advances in numerical modeling and the availability of high-performance computing resources have enabled simulations at convection-resolving scales of approximately 1–5 km over large domains and for climatologically meaningful periods (e.g., Stevens et al., 2019; Segura et al., 2025). Results from such convection-resolving models indicate that the parameterization of moist convection in coarse-resolution models leads to systematic misrepresentations of dust-mobilizing winds. Notably, these deficiencies are not confined to regions dominated by moist convection but also affect other regions through large-scale pressure adjustments and compensating circulations. Several studies have demonstrated these effects for North African deserts (Heinold et al., 2013; Marsham et al., 2013; Garcia-Carreras et al., 2021).

Since coarse-resolution, non-convection-resolving models will continue to be widely used in the near future, it is essential to identify and quantify the associated uncertainties in dust emission estimates, both for future projections and for the interpretation of past simulations. An assessment of the current state of global dust modeling is provided by recent evaluation studies based on simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6), an international initiative of the World Climate Research Programme (WCRP) that standardizes and compares global climate and Earth system models worldwide (Eyring et al., 2016). Using simulations from 16 CMIP6 models, Zhao et al. (2022) evaluated the representation of mineral dust against multiple observational and reanalysis datasets, focusing on dust emissions, burden, lifetime, deposition, and dust aerosol optical depth (DOD). While the multi-model ensemble mean captures the large-scale spatial distribution and broad seasonal cycles of dust reasonably well, substantial inter-model spread and systematic regional biases persist. Global dust emission estimates across CMIP6 models differ by approximately a factor of five, with the ensemble mean exceeding reanalysis-based estimates. This result highlights the large uncertainties in the model representation of dust-mobilizing surface winds (Zhao et al., 2022). Furthermore, most models overestimate DOD in key source regions such as North Africa, North China, South Africa, and Australia, while they underestimate DOD over South Asia. Large discrepancies are also found in simulated dust lifetime and deposition, indicating that biases in emission strength affect subsequent transport and removal processes. These findings demonstrate that, despite advances in model complexity, current-generation climate models do not converge on robust global or regional dust cycle estimates, and that deficiencies in the representation of near-surface winds remain a dominant source of uncertainty.

In this study, we therefore extend the work of Garcia-Carreras et al. (2021) by systematically examining the sensitivity of global dust source regions to model resolution and the representation of moist convection. While previous studies have primarily focused on North Africa, the dominant but not exclusive global dust source, additional regions contribute substantially to the global dust budget, including the deserts of Central and East Asia, the Arabian Peninsula, Australia, and other arid regions worldwide (Tegen and Schepanski, 2009; Ginoux et al., 2012). A global perspective is therefore required to assess whether resolution-dependent deficiencies in the representation of dust-mobilizing winds are a general feature of climate models or confined to specific regions and regimes. This is achieved through the use of two global datasets containing meteorological variables, with a particular focus on near-surface wind fields. The first dataset is derived from ICON-Earth System Model (ICON-ESM) simulations carried out as part of the CMIP6 model intercomparison initiative (Eyring et al., 2016), which are typically conducted at horizontal resolutions of around 100 km and rely on parameterized moist convection. The second dataset



originates from the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) initiative (Stevens et al., 2019), providing convection-resolving global simulations of the atmosphere at kilometer-scale resolution. In particular, we analyze simulations performed with the ICON model at a grid spacing of approximately 2.5 km, in which moist convection is explicitly resolved. Data are available for August 2016 and February 2020, allowing an assessment of dependencies for summer conditions in both hemispheres.

Following Marsham et al. (2013) and Garcia-Carreras et al. (2021), we do not directly analyze dust emissions or transport; instead, we focus on the Dust Uplift Potential (DUP). The DUP is a diagnostic quantity that depends solely on near-surface wind speed exceeding a threshold for dust emission. By construction, it deliberately neglects surface properties and their associated uncertainties, thereby isolating the effects of wind representation. In addition, we incorporate a dependence on vegetation cover following Tegen et al. (2002) and apply a cutoff for ground frost. The global datasets are used to analyze major dust source regions in detail, including the Sahara, the Sahel, Central and Eastern Asia, and Australia. The objectives of this study are to evaluate how different wind patterns relevant to dust emission manifest across source regions at varying model resolutions, assess seasonal and diurnal variability, and identify where and when parameterized moist convection leads to the largest uncertainties in dust emission modeling. At the same time, we aim to identify regions and conditions under which existing low-resolution models perform satisfactorily.

This manuscript is structured as follows. Section 2 describes the methods used in the study, including the model datasets and the formulation of the Dust Uplift Potential. Section 3 presents the results for selected representative regions. Section 4 synthesizes and discusses the patterns found across all regions and examines whether the uncertainties are associated with differences between parameterized and explicitly resolved representations of convection or instead arise primarily from the choice of grid resolution. Finally, Section 5 summarizes the key findings and provides recommendations for future research.

2 Methods

The objective of this study is to assess the sensitivity of dust-mobilizing near-surface winds to model resolution and the representation of moist convection on a global scale. Rather than directly simulating dust emissions or transport, we adopt a process-based diagnostic approach that isolates the role of atmospheric dynamics by focusing exclusively on wind-driven dust uplift. This strategy allows us to quantify differences arising from model resolution and convection treatment while deliberately avoiding additional uncertainties related to surface properties and emission parameterizations.

Central to the methodology is the Dust Uplift Potential (DUP), a wind-based diagnostic that characterizes the potential for dust emission as a function of near-surface wind speed exceeding a prescribed threshold. The formulation of the DUP, including its dependence on wind speed, vegetation cover, and temperature constraints, is described in detail in Sect. 2.1. The DUP is computed using near-surface wind fields from two complementary classes of global climate simulations: Coarse-resolution climate model output is obtained from the Coupled Model Intercomparison Project Phase 6 (CMIP6), which represents the current generation of global climate models operating at horizontal resolutions of order 100 km and relying on parameterized moist convection (Sect. 2.2). These simulations are contrasted with convection-resolving global simulations from the DYnamics



of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) initiative. Here, we make use of simulations performed with the ICON model at kilometer-scale resolution, in which moist convection is explicitly resolved (Sect. 2.3).

130 Finally, Sect. 2.4 outlines the data processing and statistical analysis applied to the computed DUP fields, including spatial aggregation over major dust source regions, the analysis of seasonal and diurnal variability, and the diagnostics used to quantify differences between model classes. These steps form the basis for the results presented in Sect. 3.

2.1 Dust Uplift Potential

Physically based dust emission schemes typically relate the vertical dust flux to near-surface wind speed exceeding a threshold
135 for particle mobilization while accounting for additional surface characteristics such as soil texture, surface roughness, vegetation cover, and soil moisture (e.g. Tegen et al., 2002; Ginoux et al., 2012). These formulations provide a comprehensive framework for simulating dust emissions but inherently combine uncertainties arising from both atmospheric dynamics and surface properties. In this study, the primary objective is to isolate and quantify the sensitivity of dust-mobilizing winds to model resolution and the representation of moist convection. For this purpose, we employ the Dust Uplift Potential (DUP),
140 a diagnostic quantity introduced by Marsham et al. (2013), which depends solely on near-surface wind speed exceeding a prescribed threshold for dust emission:

$$\text{DUP} = u^3 \left(1 + \frac{u_t}{u}\right) \left(1 - \frac{u_t^2}{u^2}\right), \quad (1)$$

where u is the near-surface wind speed and u_t is the wind speed threshold for dust uplift. The threshold velocity u_t primarily depends on soil grain size and is further modulated by surface characteristics such as sparse vegetation cover, which increases
145 the effective threshold for particle mobilization (Tegen et al., 2002; Shao, 2004). Here, $u_t = 7 \text{ ms}^{-1}$ is assumed globally, following the methodology proposed by Marsham et al. (2013) for North Africa. As expressed by Eq. 1, high wind speeds lead to a very high DUP, meaning that a high DUP is associated with extreme wind speeds. Since high wind speeds occur only over short periods, most of the DUP events take place on short time scales. The equation agrees well with observed dust uplift; however, as already explained, it does not take into account other important factors affecting dust emissions, such as soil
150 moisture, soil type and texture, and seasonal and regional variations in vegetation.

By construction, the DUP deliberately excludes such surface characteristics and therefore removes a major source of uncertainty unrelated to atmospheric dynamics. This makes it particularly well suited for diagnosing differences in wind fields between model configurations with parameterized and explicitly resolved convection. The DUP should therefore be interpreted as a measure of the atmospheric potential for dust uplift rather than as a direct estimate of dust emissions. While it does not
155 aim to replace physically based emission schemes, it provides a robust and transparent framework for process-based inter-comparison studies focused on the representation of near-surface winds. Following Marsham et al. (2013) and subsequent applications (e.g., Garcia-Carreras et al., 2021), the DUP is used here as a consistent metric to assess resolution-dependent differences in dust-relevant wind systems across global dust source regions.



Previous studies have shown that uncertainties in prescribed surface characteristics contribute substantially to uncertainties in dust emission estimates. In particular, Heinold et al. (2013) demonstrated that approximately 25–35 % of the uncertainty in modeled dust emissions over northern Africa can be attributed to uncertainties in vegetation type and coverage. While the present study aims to isolate the role of near-surface winds, accounting for the effective availability of dust source areas remains an important consideration when diagnosing dust uplift potential.

To incorporate the effect of vegetation on the availability of erodible surfaces, we follow the approach introduced by Tegen et al. (2002), who defined an effective dust source area, A_{eff} , which modulates the potential for dust uplift. Seasonal variations in vegetation cover are represented using the fraction of absorbed photosynthetically active radiation (FPAR), which is derived from the Normalized Difference Vegetation Index (NDVI). Here, NDVI is taken from the ICON model output and converted to FPAR following Tegen et al. (2002):

$$\text{FPAR} = 1.222 \cdot \left(\frac{\text{NDVI}}{0.559} - 0.1566 \right). \quad (2)$$

Vegetation type is prescribed using the equilibrium terrestrial biogeography model BIOME4 (Kaplan, 2001), which distinguishes 27 biome classes based on monthly mean temperature, precipitation, net radiation, and soil type. For grass-dominated biomes, dust uplift is assumed to be possible only when green vegetation cover is sparse. Accordingly, the effective dust source area is set to zero for $\text{FPAR} > 0.25$ and increases linearly to unity as FPAR approaches zero. Shrublands are considered more resistant to complete vegetation shielding and are therefore assumed to remain susceptible to wind erosion and dust uplift up to higher vegetation fractions, with dust uplift permitted for $\text{FPAR} > 0.5$ (Tegen et al., 2002).

The effective dust source area is then defined as:

$$A_{\text{eff}} = 1 - (\text{FPAR}_{\text{max,ann}} \cdot f_{\text{shrub}} + \text{FPAR}_{\text{month}} \cdot f_{\text{grass}}) \cdot \frac{1}{0.25}, \quad (3)$$

where f_{shrub} and f_{grass} denote the fractional coverage of shrub and grass biomes, respectively, and $\text{FPAR}_{\text{max,ann}}$ and $\text{FPAR}_{\text{month}}$ represent the annual maximum and monthly mean FPAR.

The inclusion of mid- and high-latitude dust source regions further necessitates consideration of snow cover, which effectively suppresses dust emissions. Due to the limited availability of snow-related variables in the archived DYAMOND-ICON dataset, near-surface air temperature is used as a proxy. Dust uplift potential is therefore masked when surface air temperatures fall below 0 °C, under which conditions dust emission is unlikely. This pragmatic constraint effectively suppresses unrealistically high dust uplift potential in mountainous regions and high-latitude areas, particularly during winter.

2.2 CMIP6

The Coupled Model Intercomparison Project (CMIP) coordinates experiments using global climate models that couple atmospheric processes with dynamic representations of the ocean, land surface, and sea ice (Meehl et al., 1997). CMIP has developed through six phases, with the newest phase 6 providing a new structure with three main components (Eyring et al., 2016). The



first component is the Diagnostic, Evaluation, and Characterization of Klima (DECK) and CMIP historical simulations. The
190 second important structure of CMIP6 is the standard documentation and infrastructure for the output, and the last part is an
adaptation of a new federated, more autonomous structure. The goal of the DECK and the historical simulations is to con-
tribute continuity between future CMIP phases. CMIP6 defines three central questions for the project: the response to forcings,
the origin and consequences of model bias, and the assessment of climate change. Various model inter-comparison projects
have been developed for different climate change scenarios and CMIP questions. The Scenario Model Intercomparison Project
195 (ScenarioMIP) uses century-timescales and socioeconomic pathways (SSPs) alongside representative concentration pathways
(RCPs). The goals of ScenarioMIP are to investigate the impacts of future scenarios, the effects of specific forcings, and to
quantify uncertainties.

The data used in this study are hosted by the German Climate Computing Center (Deutsches Klimarechenzentrum, DKRZ).
Surface wind data from CMIP6 ScenarioMIP simulations are used to calculate dust uplift potential (DUP; Eq. 1). We analyze
200 simulations from the low-resolution configuration of the Max Planck Institute Earth System Model (MPI-ESM1-2-LR), using
ICON-ESM version 1.0 as described in Jungclaus et al. (2022). The dataset consists of four experiments with 50 realizations
each (Mauritsen et al., 2019). From the full ensemble, 40 realizations with available data are selected, and an ensemble mean is
used. Wind fields are provided at a 3-hour resolution. The analysis focuses on August 2016 and February 2020, consistent with
the DYAMOND simulation period. Zhao et al. (2022) analyzed dust aerosol simulations from CMIP6 models that explicitly
205 incorporate the dust cycle. Since we use only surface wind fields from the CMIP6 model datasets here, we can draw on
those results to assess how well the simplified DUP calculations reproduce the full dust emission patterns simulated by the
low-resolution CMIP6 models.

2.3 DYAMOND

The DYnamics of the Atmospheric General Circulation Modeled On Non-hydrostatic Domains (DYAMOND) initiative brought
210 together global storm-resolving models for inter-comparison, facilitating a comprehensive 40-day global atmospheric simula-
tion. In contrast to the CMIP6 models, these simulations resolved atmospheric convection. The simulations cover periods
starting on 01 August 2016 at 00:00 UTC for the summer case and 01 February 2020 at 00:00 UTC for the winter case. The
40-day duration was deliberately chosen to cover one month of data in addition to a 10-day spin-up period (Stevens et al.,
2019). Regarding dust emissions, August marks the summer peak of dust storms in North Africa (Garcia-Carreras et al., 2021),
215 while February is particularly significant for dust activity in the Southern Hemisphere. A detailed description of the project is
provided by Stevens et al. (2019). This initiative employed a suite of different global models operating on a finely resolved grid
of less than 5 km spacing. The initial conditions for the simulations were derived from the European Center for Medium-Range
Weather Forecasts (ECMWF) global analysis with 9-km grid spacing, with the sea surface temperature and sea ice concen-
tration also supplied by ECMWF (Stevens et al., 2019). The data is hosted by the DKRZ and is made accessible through a
220 close partnership with the Center of Excellence in Simulations of Weather and Climate in Europe (ESiWACE), supported by
the European Commission (Stevens et al., 2019). Of the various models within the DYAMOND initiative, this paper uses the
results of the weather and climate model ICON version 2.1.02 as described in Hohenegger et al. (2020). The model output



comprises five variables defined on an icosahedral grid with a horizontal resolution of approximately 2.5 km. The simulations include explicit representation of shallow cumulus clouds and a turbulence kinetic energy (TKE) boundary layer scheme.

2.4 Statistical Analysis

For comparability, DUP-values computed from high-resolution model output are interpolated onto the grid size of the low-resolution models before assessing the differences between the model results at different resolutions. To facilitate the comparison of the regional distribution and exclude the biases between the model results at different resolutions, differences of normalized data are assessed, where the DUP data are normalized by dividing the values at each grid cell and timestep by the temporal and spatial mean of the region. This normalization allows for the evaluation of the significance of specific source regions within the models. To emphasize regions exhibiting the greatest differences between the two models, the Root Mean Square Error (RMSE) for every grid-cell is calculated as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n_{\text{time}}} \sum_{i=1}^{n_{\text{time}}} (\text{DUP}_{\text{CMIP}} - \text{DUP}_{\text{DYAMOND}})^2}, \quad (4)$$

To assess whether the identified discrepancies arise from differences in the representation of convection or from grid resolution effects in the DUP calculation, an additional experiment is performed in which high-resolution wind fields are re-gridded to the coarse grid before the DUP calculation. This "DYAMOND-re-gridded" case retains convection-resolving winds while applying the DUP calculation on the coarse grid. It is compared with both the native high-resolution and CMIP6 datasets. Agreement with the high-resolution case indicates a minor role of grid spacing, whereas similarity to the CMIP6 results points to deficiencies related to convection parameterization rather than resolution alone.

The three scenarios are compared by means of histograms depicting the relative frequency of surface wind speeds that are used for DUP calculations. Those histograms comprise all temporal output steps and grid cells within the considered dust source region. Furthermore, the data from the "DYAMOND-re-gridded" case are included, thereby enabling a more detailed investigation of the underlying drivers of the uncertainties.

In addition, to investigate the representation of wind systems in the individual dust source regions more closely, the diurnal cycle of DUP is analyzed. The study area is divided into major regional sub-sources, and regional mean DUP values are computed prior to deriving the diurnal cycle. Local time at the center of the domain is used as the temporal reference.

3 Results

This section examines uncertainties in four major dust source regions: North Africa, Central Asia, the Gobi and Taklamakan deserts in East Asia, and Australia. The focus is on the dominant wind regimes and their representation in the different model configurations. For each region, dust uplift potential and wind-speed distributions are analyzed to compare convection-resolving and coarse-resolution simulations.



3.1 North Africa

3.1.1 Key Wind Drivers of Dust Uplift

The North African desert regions, dominated by the Sahara, are by far the most productive dust source in the world, accounting for approximately 50 % of the total annual atmospheric mineral dust emissions (Kok et al., 2021). Dust emissions are mainly driven by two synoptic phenomena: the outflow of moist-convective cold pools, which predominantly occur in the Sahel and southern Sahara as well as south of the Atlas Mountains and the breakdown of the nocturnal low-level jet (LLJ), which is most important in the central Sahara (Heinold et al., 2013). Dust emissions in the Sahara and Sahel peak in the summer months of June and July and are at their minimum in autumn (Garcia-Carreras et al., 2021).

The breakdown of LLJs typically causes peak wind speeds in the morning, which are relevant for dust emissions in the region (Blackadar, 1957; Fiedler et al., 2013). The formation and breakdown of nocturnal LLJs are briefly described as follows. Nocturnal inversions lead to enhanced wind speeds above the decoupled boundary layer. After sunrise, turbulent mixing begins to erode the vertical wind maximum, and dust-emitting high winds occur at the surface (Blackadar, 1957). The nocturnal LLJs occur throughout the year but are most intense during the dry season (November to March) (Washington and Todd, 2005; Fiedler et al., 2013). Its effects are often amplified by regional topography, which can channel winds and boost dust emissions. These effects are particularly significant for dust emissions within the Bodélé Depression (Kraus et al., 1985; Washington and Todd, 2005).

In contrast, afternoon peaks in wind speed are primarily driven by moist convective processes. These phenomena originate from convective cells generated by vertical lifting, which may be induced by orographic forcing, radiative heating, frontal lifting, or other dynamical and thermodynamical processes (Sutton, 1925; Peters and Tetzlaff, 1988). Convective cells are therefore often linked to rainfall and cold-air outflows (Vizy and Cook, 2017). At their leading edge, cold-air outflows create gust fronts with strong winds and turbulence that lift dust particles into the atmosphere (Droegemeier and Wilhelmson, 1987). These events, often occurring along air mass boundaries and involving vertical mixing up to the level of free convection, produce large, visually striking dust fronts known as haboobs in arid and semi-arid desert regions (Sutton, 1925; Peters and Tetzlaff, 1988; Roberts and Knippertz, 2014). The highest frequency of haboobs in North Africa is observed in the western Sahel zone in Northern Hemisphere summer (Pantillon et al., 2016), where they are often connected to mid-tropospheric easterly wave disturbances and propagate westward (Garcia-Carreras et al., 2021). Haboobs vary in size, spanning horizontally from 10 to 100 km width and reaching altitudes of 2000 to 5000 m above sea level (Marsham et al., 2013).

Figure 1 highlights the principal dust source regions in North Africa, including the El Eglab region (I), located between the Hoggar and Aïr Mountains, as a well-known dust source. In the coastal regions (II), land–sea breeze circulations constitute an important controlling factor for dust emission. Another significant source region is the Sahel zone (III), where summertime dust emissions are predominantly associated with haboobs, and the Bodélé Depression (IV), where wintertime emissions are primarily driven by the persistent Bodélé LLJ (Washington and Todd, 2005; Garcia-Carreras et al., 2021).

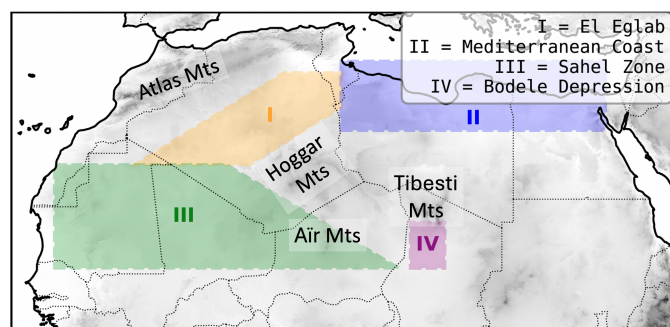


Figure 1. Topographic map of North Africa with four marked dust source regions: El Eglab (I), Mediterranean Coast (II), Sahel Zone (III) and Bodélé Depression (IV). Important mountain ranges are also marked.

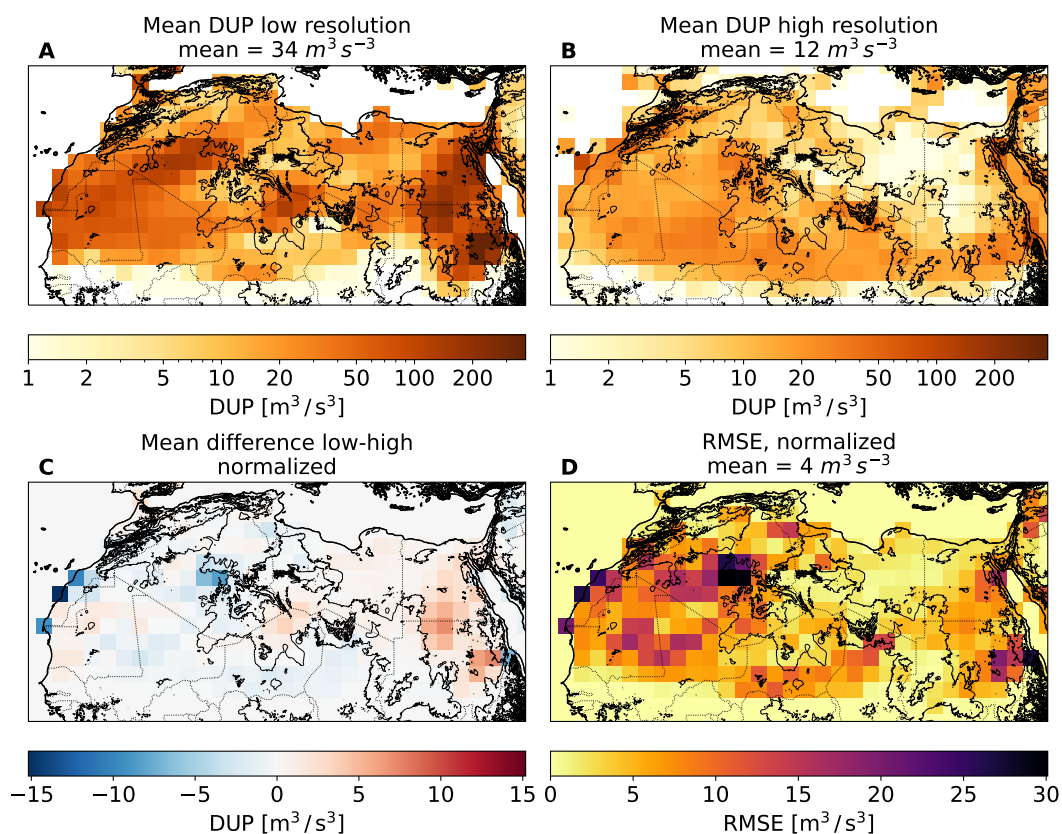


Figure 2. Map of dust uplift potential over North Africa for August 2016, calculated using (a) low-resolution CMIP data and (b) high-resolution DYAMOND data, as well as (c) the mean normalized difference between CMIP6 (a) and DYAMOND (b) and (d) the corresponding root-mean-square error (RMSE).

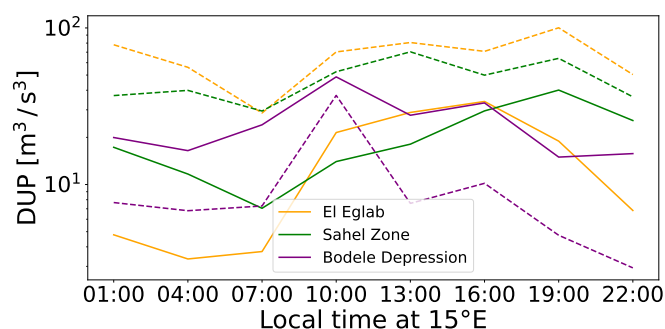


Figure 3. Diurnal cycle of dust uplift potential over North Africa for August 2016, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the three source regions El Eglab, Sahel, and Bodélé Depression. See Figure 1 for the location and spatial extend of the different source regions.

3.1.2 Dust Uplift Potential Across Model Resolutions

Figures 2a and 2b show the monthly mean dust uplift potential across North Africa for August 2016, as computed from the modeled surface wind data with parameterized and explicit moist convection, respectively. The DUP derived from the CMIP6 low resolution data indicates a pronounced maximum in the eastern parts of the domain, particularly in Northern Sudan near the Red Sea, as well as in the vicinity of the Nile region in Sudan and Egypt (Fig. 2a). An additional peak in potential dust emissions is observed between the Atlas and Aïr mountains, within the El Eglab region. Furthermore, elevated DUP values are calculated between the Hoggar and Aïr mountains in central and eastern regions of Northern Africa. Overall, this distribution agrees with the dust emission patterns in CMIP6 models reported by Zhao et al. (2022). Figure 2b shows the results based on the high-resolution ICON-DYAMOND simulations, which indicate a pronounced reduction in dust emission over nearly the entire study domain. In addition, regional maxima in DUP occur over the Southern Sahara and Sahel, which are regions known for pronounced haboob-activity in summer (Fig. 2b). Figure 2c shows the spatial differences between the normalized low-resolution and normalized high-resolution data for a more quantitative comparison. The panel reveals lower DUP in the high-resolution simulation compared to the coarse simulation, particularly over Sudan and in the El Eglab region. In contrast, the high-resolution DYAMOND simulations exhibit enhanced DUP values relative to the low-resolution CMIP6 data over the Sahel, indicating that current coarse-resolution climate models likely underestimate the contribution of haboobs to dust emissions. This finding is well in agreement with earlier studies by, e.g., Garcia-Carreras et al. (2021). To further quantify these differences, Fig. 2d presents the RMSE of the normalized differences between the high- and low-resolution models. The largest RMSE values are found in the El Eglab region, with substantial deviations also extending over Sudan, the Bodélé Depression, and the Sahel zone. The results obtained for the El Eglab region are of particular interest, as this area does not exhibit large values in the total differences yet shows elevated RMSE values. This pattern indicates that the region is subject to substantial temporal uncertainties between the two models.



305 The diurnal cycle of dust uplift in Northern Africa features two peaks: one in the morning linked to the breakdown of the nocturnal LLJ and an early night peak associated with moist convective events like haboobs. Haboobs, prevalent in summer, result in longer, more intense dust emissions than those associated with the LLJs, which dominate in winter. To further identify the drivers of dust emission by their characteristic time of occurrence for different model resolutions, Fig. 3 presents the diurnal cycle of DUP, averaged in August 2016 and for selected source regions in Northern Africa. The spatial extent of these regions is shown in Fig. 1. The DUP is displayed on a logarithmic scale and reveals distinct characteristics across the different sub-
310 regions. For the El Eglab region, both model configurations exhibit a DUP increasing in the morning hours after 07:00 LT and remaining persistently high until evening. The CMIP6 simulations generally yield higher DUP values throughout the entire day while maintaining a diurnal pattern that is broadly consistent with DYAMOND. However, the high-resolution DYAMOND model exhibits a more pronounced afternoon peak, which is consistent with the RMSE errors and underlines the uncertainty in
315 the temporal importance of the dust source in the El Eglab region. In the high-resolution DYAMOND simulation, dust emissions in the Sahel peak in the afternoon and at night, associated with the occurrence of haboobs. During these peak periods, the DUP values from DYAMOND are comparable to those from the coarser-resolution CMIP6 simulations. In contrast, CMIP6 produces systematically higher DUP values during the morning hours. Overall, the coarse-resolution simulations exhibit a less pronounced diurnal cycle in the Sahel region. These results suggest that current low-resolution climate models do not
320 adequately capture the effects of nocturnal haboobs, while they tend to overestimate potential dust emissions throughout the day compared to high-resolution models. This is again consistent with the findings reported in previous studies, for example by Heinold et al. (2013) and Garcia-Carreras et al. (2021). The Bodélé Depression displays a pronounced DUP peak around 10:00 LT, indicating the impact of the nocturnal LLJ as the dominant driver. This peak is more sharply defined in the CMIP6 dataset, suggesting that these processes are reasonably well represented in current climate models. During the peak period,
325 both simulations produce similarly high DUP values, whereas for the remainder of the day the DYAMOND simulations show higher DUP. This highlights the greater importance of convective processes, which are more effectively represented in the high-resolution simulations.

Figure 4 compares the relative frequency distributions of near-surface wind speeds in the CMIP6 ensemble and the high-resolution DYAMOND simulations for the Sahel and El Eglab regions. To further isolate sources of uncertainty, the figure also
330 includes a DYAMOND simulation with explicitly resolved convection that has been remapped to the coarse CMIP6 grid. The vertical line marks the dust emission threshold of 7ms^{-1} , such that wind speeds exceeding this value are most relevant for dust emission.

For the Sahel (Fig. 4a), the DYAMOND simulations exhibit substantially higher frequencies of wind speeds above the emission threshold, whereas CMIP6 produces almost no occurrences in this range. This indicates that current climate models fail to
335 adequately capture convective events associated with high wind speeds in the Sahel. The regridded DYAMOND case closely matches the original high-resolution distribution, demonstrating that the discrepancies primarily arise from the representation of convection rather than from differences in grid resolution.

In the El Eglab region (Fig. 4b), DYAMOND likewise shows higher frequencies at large wind speeds, but the CMIP6 and DYAMOND distributions intersect near the emission threshold. Around this threshold, CMIP6 exhibits higher relative fre-

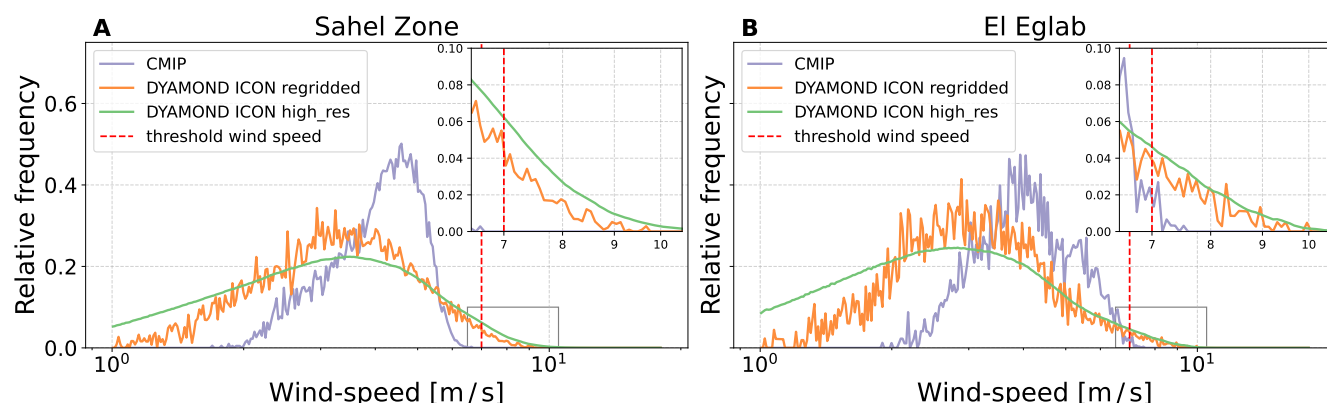


Figure 4. Histogram of 10-m wind speed over North Africa for August 2016, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) the Sahel Zone and (b) the El Eglab region. See Figure 1 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization. The scale range that is particularly relevant for dust emissions is shown enlarged.

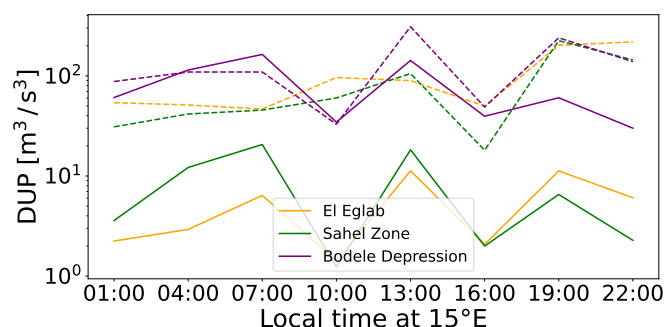


Figure 5. Diurnal cycle of dust uplift potential over North Africa for February 2020, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the three source regions El Eglab, Sahel, and Bodélé Depression. See Figure 1 for the location and spatial extend of the different source regions.

quencies, indicating an over-representation of moderate wind speeds just above the emission threshold. As in the Sahel, the lack of high wind-speed events in CMIP6 points to an underestimation of haboob-related convection. However, the enhanced frequency of near-threshold winds leads to a compensating bias, which is linked to the breakdown of the nocturnal low-level jet. Consistent with the diurnal cycle and spatial patterns (Figs. 2d and 3), this LLJ-related overestimation dominates the overall bias in CMIP6. As in the Sahel, the regridded DYAMOND case closely follows the high-resolution simulation, confirming that these differences are primarily attributable to convection parameterization rather than grid resolution.

Winter DUP patterns (February 2020) differ from the summer behavior, as illustrated by the mean diurnal cycles for selected source regions in Fig. 5. In the El Eglab and Sahel regions, the diurnal cycles are similar in shape, but CMIP6 generally produces



higher DUP values than DYAMOND. The differences between the two datasets exhibit pronounced temporal variability, with CMIP6 showing distinct peaks during the afternoon and nighttime and a minimum in the early afternoon. In contrast, the high-resolution DYAMOND simulations display three peaks over the course of the day. Despite these differences, the overall bias patterns are consistent with those identified for El Eglab in summer, although the morning peak is less pronounced. Together with previous studies, these results point to a continued influence of nocturnal LLJ breakdown. In the Bodélé Depression, however, the behavior differs: here, the high-resolution and CMIP6 simulations agree closely, particularly during daytime with only minor discrepancies at night. This indicates that the LLJ-related morning behavior is represented consistently across model configurations in this region.

3.2 Central Asia

3.2.1 Key Wind Drivers of Dust Uplift

Central Asian deserts are important sources of dust but have received much less attention compared to the North African or East Asian dust sources. Together with dust sources from the Arabian Peninsula they account for approximately 25 % of the total annual atmospheric mineral dust emissions (Rahimi et al., 2013; Kok et al., 2021). The region is characterized by pronounced variability in the prevailing climatic regimes. The Aralkum exhibits a mid-latitude climate, Iran is dominated by a continental, arid to semi-arid climate, and India experiences a subtropical climate that is strongly modulated by the monsoon system. The Shamal and Levar winds are key contributors to dust emissions. The Shamal, caused by a thermal low over Iran and Saudi Arabia and high pressure over the Mediterranean, results in strong winds and significant dust emissions in western Iran and the Dasht-e Kavir (Alizadeh-Choobari et al., 2016). The Levar wind, known as the '120 day wind' is a constant wind and drives dust emissions in the Sistan Basin due to pressure differences between the Hindu Kush and Caspian Sea (Rashki et al., 2021). Haboobs and the breakdown of the nocturnal LLJ (see description Sect. 3.1.1) also contribute to dust emissions. The primary dust season is summer, although some emissions occur in winter despite precipitation suppression (Raispour et al., 2016). Important landmarks and major dust sources in Central Asia are shown in Figure 6. The Sistan Basin is an especially notable source region due to the consistent Levar wind and drying lakes, primarily active between June and August (Miri et al., 2010). Along the Makran coast, there are known sources of dust that have not yet been adequately studied (Rashki et al., 2021). Additionally, other dust sources in Central Asia include Mesopotamia, anthropogenic dust sources in Iraq, and dust originating from the dried-up regions of the former Aral Sea (today known as the Aralkum). The Northern Hemisphere mid-latitude jet organizes the variability in cyclones, blocking, and cold-air outbreaks over the continental mid-latitudes of Eurasia and thus modulates the frequency and intensity of strong surface wind events over the Aralkum, thereby controlling the integrated dust emission from this source region (Xi, 2025). On the Indian subcontinent, agricultural activities are contributing to significant dust emissions in the Ganges region. Further dust emissions are evident from the Rajasthan Desert in Western India and the mountainous areas of the Hindu Kush (Ginoux et al., 2012). In the Indus Basin region and along the coastlines of Pakistan and Iran, wind speed is influenced by land–sea circulation dynamics.

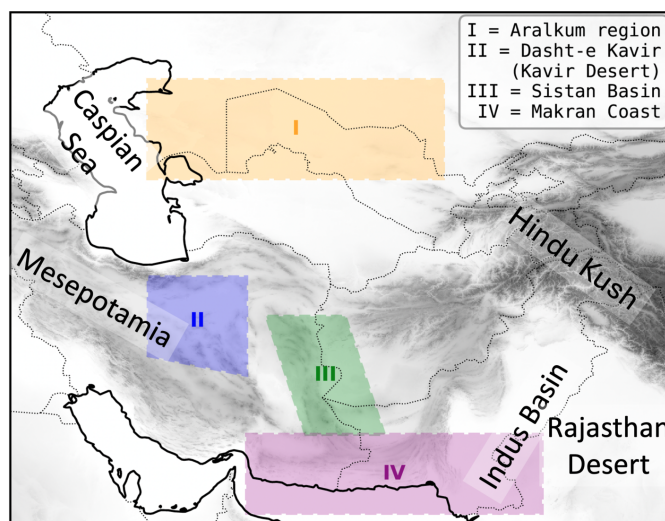


Figure 6. Topographic map of Central Asia with four marked dust source region: Aralkum (I), Dast-e Kavir Desert (II), Sistan Basin (III), and the Makran Coast (IV). Important landmarks are also shown.

3.2.2 Dust Uplift Potential Across Model Resolutions

Figure 7 presents the summer mean DUP for Central Asia. The CMIP6 results (Fig. 7a) show elevated values across Iran, particularly in the southern mountainous regions and the Kavir Desert, as well as in the Aralkum region along the eastern Caspian Sea and near the Pakistan–India coastal border. The high-resolution DYAMOND simulation (Fig. 7b) identifies the Sistan Basin, located at the Afghanistan–Iran border, as a major dust source, with additional elevated DUP values in central Iran. The normalized differences (Fig. 7c) reveal a pronounced underestimation of dust emissions in the Sistan Basin in CMIP6, with smaller underestimations in some southern coastal regions. This suggests that the persistent Levar wind is not adequately represented in coarse-resolution models.

In contrast, CMIP6 overestimates DUP in other regions, particularly in the mountains of southern Iran, indicating an over-representation of these sources relative to DYAMOND. The spatial distribution of these discrepancies is confirmed by the RMSE of the normalized differences (Fig. 7d), which highlights the same regions, with the Sistan Basin dominating the overall error. Despite regional variations, CMIP6 exhibits a systematic overestimation of dust emissions across the entire domain.

The diurnal cycle (Fig. 8) provides further insight into the underlying wind systems. The Sistan Basin shows the highest DUP values and exhibits minimal diurnal variability, with persistently strong emissions throughout the day. In this region, CMIP6 systematically underestimates DUP relative to DYAMOND, with only minor temporal variation in the bias. This behavior reflects the dominance of the persistent Levar wind, whose contribution to dust emission is underestimated in coarse-resolution models.

In the Kavir Desert, the simulations differ markedly. CMIP6 shows a pronounced diurnal cycle, with maxima in the afternoon and nighttime and a minimum in the morning. In contrast, DYAMOND exhibits weaker variability, with a nighttime

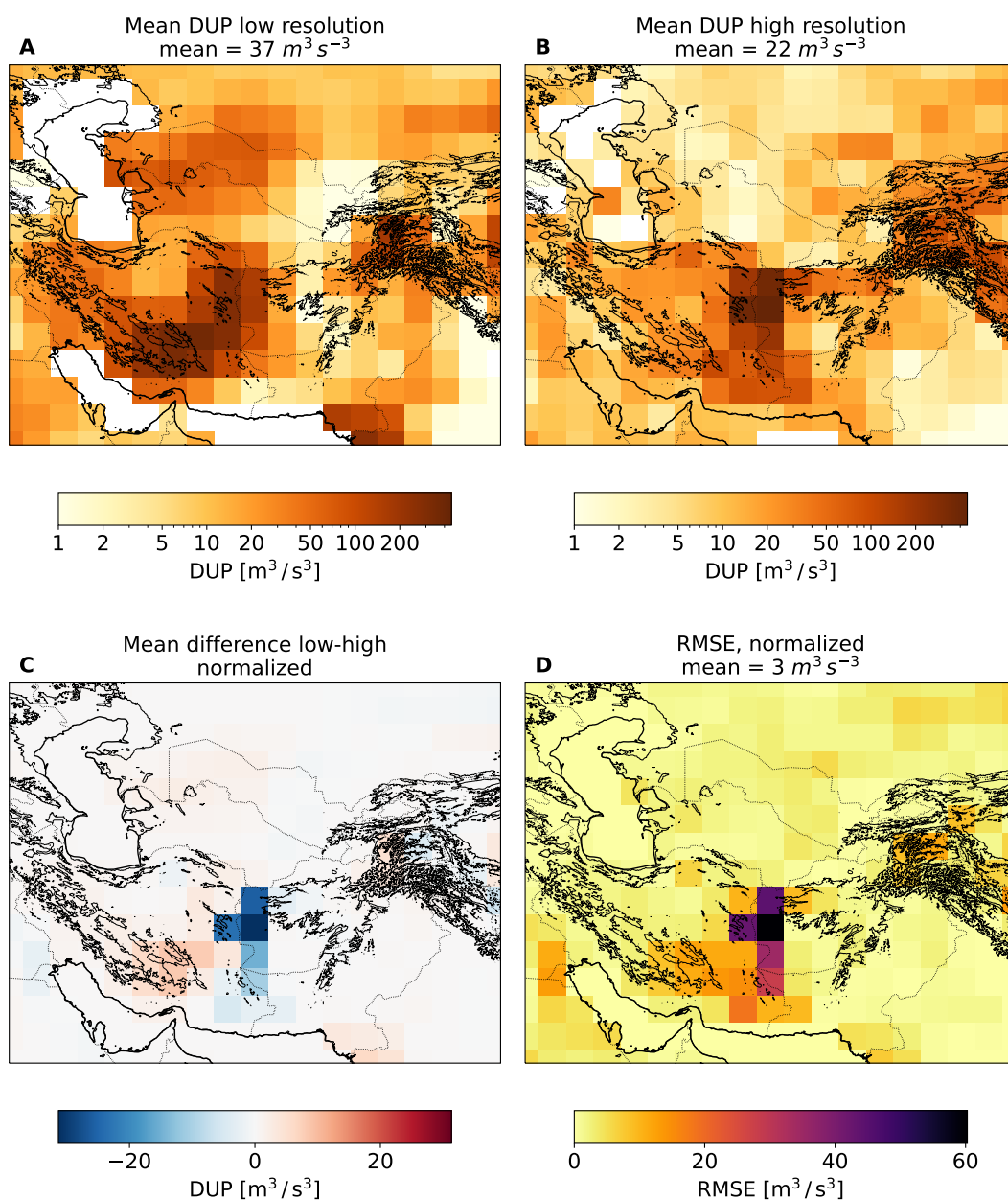


Figure 7. Map of dust uplift potential over Central Asia for August 2016, calculated using (a) low-resolution CMIP6 data and (b) high-resolution DYAMOND data, as well as (c) the mean normalized difference between CMIP6 (a) and DYAMOND (b) and (d) the corresponding root-mean-square error (RMSE).

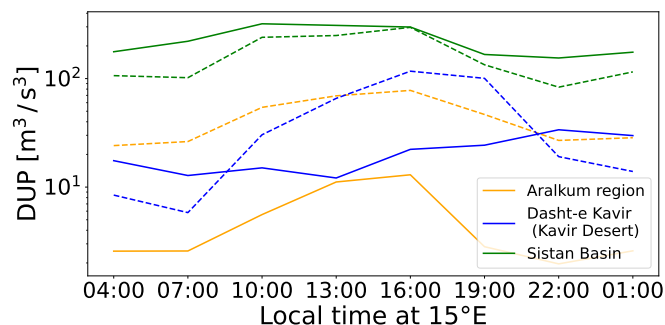


Figure 8. Diurnal cycle of dust uplift potential over central Asia for August 2016, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the three source regions Aralkum, Dacht-e Kavir, and Sistan Basin. See Figure 6 for the location and spatial extend of the different source regions.

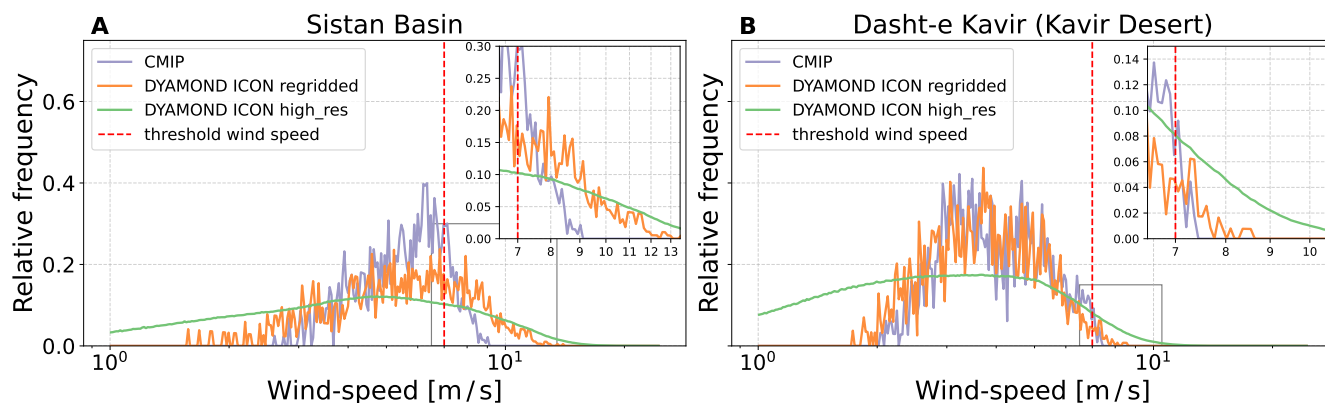


Figure 9. Histogram of 10-m wind speed over central Asia for August 2016, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) the Sistan Basin and (b) the Dasht-e Kavir. See Figure 6 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization. The scale range that is particularly relevant for dust emissions is shown enlarged.

maximum and a minimum around local noon. These differences lead to a phase-dependent bias: CMIP6 overestimates DUP during daytime, while DYAMOND produces higher values at night. This pattern reflects the influence of multiple drivers: LLJ breakdown leads to a daytime overestimation in CMIP6, whereas nocturnal haboobs increase DUP in DYAMOND and are underestimated in coarse-resolution models. These findings are consistent with the behavior identified in the El Eglab region (Sec. 3.1.2), although the daytime biases are larger in magnitude.

In the Aralkum region, both simulations show a similar diurnal cycle, with maxima in the afternoon and minima at night. However, CMIP6 consistently produces higher DUP values throughout the day, indicating a systematic overestimation relative to DYAMOND, in agreement with the spatial patterns shown in Fig. 7.



To further assess regional differences, the wind-speed distributions are also examined for the Sistan Basin and the Kavir Desert (Fig. 9). In the Sistan Basin (Fig. 9a), the highest frequencies occur near the dust-emission threshold (red line), in contrast to the behavior observed in North Africa. Around this threshold, CMIP6 shows higher frequencies than DYAMOND, whereas at higher wind speeds—more relevant for effective dust emission—DYAMOND dominates. The distributions intersect at approximately 8 m s^{-1} . This pattern reflects the influence of the persistent Levar wind, which produces frequent elevated wind speeds in both simulations. Small differences in wind speed between the models translate into large DUP differences due to the cubic dependence on wind speed. The regridded simulation closely follows DYAMOND, indicating that discrepancies arise from a combination of convection representation and resolution effects in the threshold-based DUP calculation.

In the Kavir Desert (Fig. 9b), DYAMOND similarly shows higher frequencies at elevated wind speeds and fewer occurrences below the emission threshold. However, CMIP6 produces almost no wind speeds exceeding 7 m s^{-1} , effectively suppressing dust emission. Here, the regridded simulation closely matches CMIP6, indicating that grid resolution - rather than convection representation — is the dominant factor. Interpolation reduces the occurrence of high wind speeds while increasing frequencies near the threshold, shifting the distribution toward marginal dust-emitting conditions. Consistent with the spatial patterns (Fig. 7), the resulting bias arises from an over-representation of near-threshold winds in CMIP6, rather than from differences in convective processes.

3.3 Gobi and Taklamakan Desert

3.3.1 Key Wind Drivers of Dust Uplift

Within the East Asian region, the Taklimakan and Gobi Deserts constitute major dust source areas, together contributing approximately 10 % of the total annual atmospheric mineral dust emissions. (Kok et al., 2021; Gui et al., 2022). Over East Asia, the variability in the position and strength of the Northern Hemisphere mid-latitude jet shapes the occurrence and tracks of extra-tropical cyclones, including frequent Mongolian cyclones originating near the Gobi, along with cold fronts and cold-air outbreaks fueled by the Siberian High. These processes modulate strong surface winds across northern China and the Gobi Desert (Li and Chen, 2023; Hu et al., 2024). A topographic map in Fig. 10 shows relevant geographical features as well as the location of main dust source regions: Tian Shan, Taklamakan and western Gobi Desert, and the Tibetan Plateau. In the Tarim Basin, cold-air intrusions from the northwest through the Tianshan and Pamir gaps trigger frontal passages and nocturnal low-level jet breakdown, driving particularly intense dust emissions from the Taklimakan Desert and Lop Nur region (Yumimoto et al., 2019). The Gobi Desert shows a relatively low frequency of dust emission because its surface is dominated by coarse gravel and pebbles; nevertheless, episodic deflation events can generate large-scale dust storms (Gui et al., 2022). In addition, Northern China frequently experiences dust events comparable in intensity to other major dust sources. Additional summer dust sources are identified in the source regions near 40°N (Chen et al., 2025). February represents the period of minimum dust emissions across all regions. Precipitation acts to suppress dust mobilization, and internal atmospheric variability is the primary driver of dust emissions in East Asia (Laurent et al., 2006). Nevertheless, an active winter dust source is also present on the Tibetan Plateau (Chen et al., 2025).

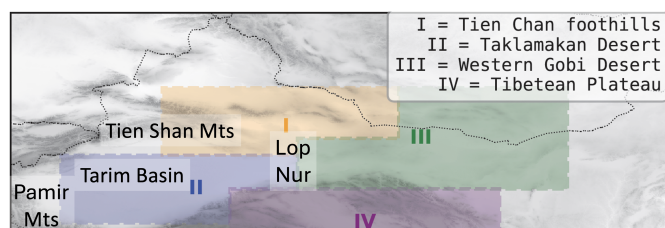


Figure 10. Topographic map of the Gobi and Taklamakan region with four marked dust source regions: the Tian Chan foothills (I), the Taklamakan Deserts (II), the western Gobi region (III) and the Tibetan Plateau (IV). Important landmarks are also shown.

3.3.2 Dust Uplift Potential Across Model Resolutions

The regional distribution of mean DUP for the Gobi–Taklamakan region is shown in Fig. 11. The CMIP6 results (Fig. 11a) indicate maxima along the China–Mongolia border in the western Gobi Desert, as well as elevated values in the southern and eastern Taklamakan. The high-resolution DYAMOND simulation (Fig. 11b) produces overall higher DUP values, with maxima in the Taklamakan Desert, particularly along its southern and eastern margins, as well as in the Gobi Desert and at the western foothills of the Tian Shan. The normalized differences (Fig. 11c) reveal a mixed pattern: CMIP6 overestimates DUP in the Gobi Desert, the southwestern Taklamakan, and parts of the Tian Shan, while underestimating it in the Taklamakan interior and surrounding mountainous regions, indicating a misrepresentation of moist convective processes. Localized maxima in the differences occur at the Tian Shan foothills west of the Gobi. These regions are also highlighted by elevated RMSE values (Fig. 11d), particularly in the southeastern Taklamakan, the western Gobi, and the Tian Shan foothills.

The diurnal cycle (Fig. 12) provides insight into the underlying drivers. In the Taklamakan Desert, both simulations show a pronounced cycle with afternoon maxima and nighttime minima. However, CMIP6 produces higher DUP values from noon to sunset, whereas DYAMOND dominates during nighttime and morning hours. This behavior is consistent with patterns found in the El Eglab region and the Kavir Desert. CMIP6 exhibits a daytime overestimation linked to nocturnal LLJ breakdown, while DYAMOND captures enhanced nocturnal moist convection (e.g., haboobs), leading to higher nighttime DUP.

In the Tian Shan foothills, both models show a similar daytime evolution but diverge in the afternoon. Here, DYAMOND exhibits a secondary increase, while CMIP6 declines toward a nighttime minimum. The resulting differences peak in the late afternoon and are associated with convective activity captured only in the high-resolution simulation. In the western Gobi Desert, both simulations reproduce a similar diurnal cycle, with an early afternoon maximum and nighttime minimum. However, CMIP6 consistently yields higher DUP values throughout the day, indicating a systematic bias likely linked to large-scale wind systems.

Wind-speed distributions (Fig. 13) further clarify these differences. In the Taklamakan Desert (Fig. 13a), the simulations show relatively similar behavior near the emission threshold compared to other regions. The re-gridded case lies between the high- and low-resolution results. Nevertheless, the spatial patterns indicate substantial discrepancies, which can be traced to a slightly higher frequency of strong wind events in DYAMOND, likely associated with convective phenomena such as haboobs.

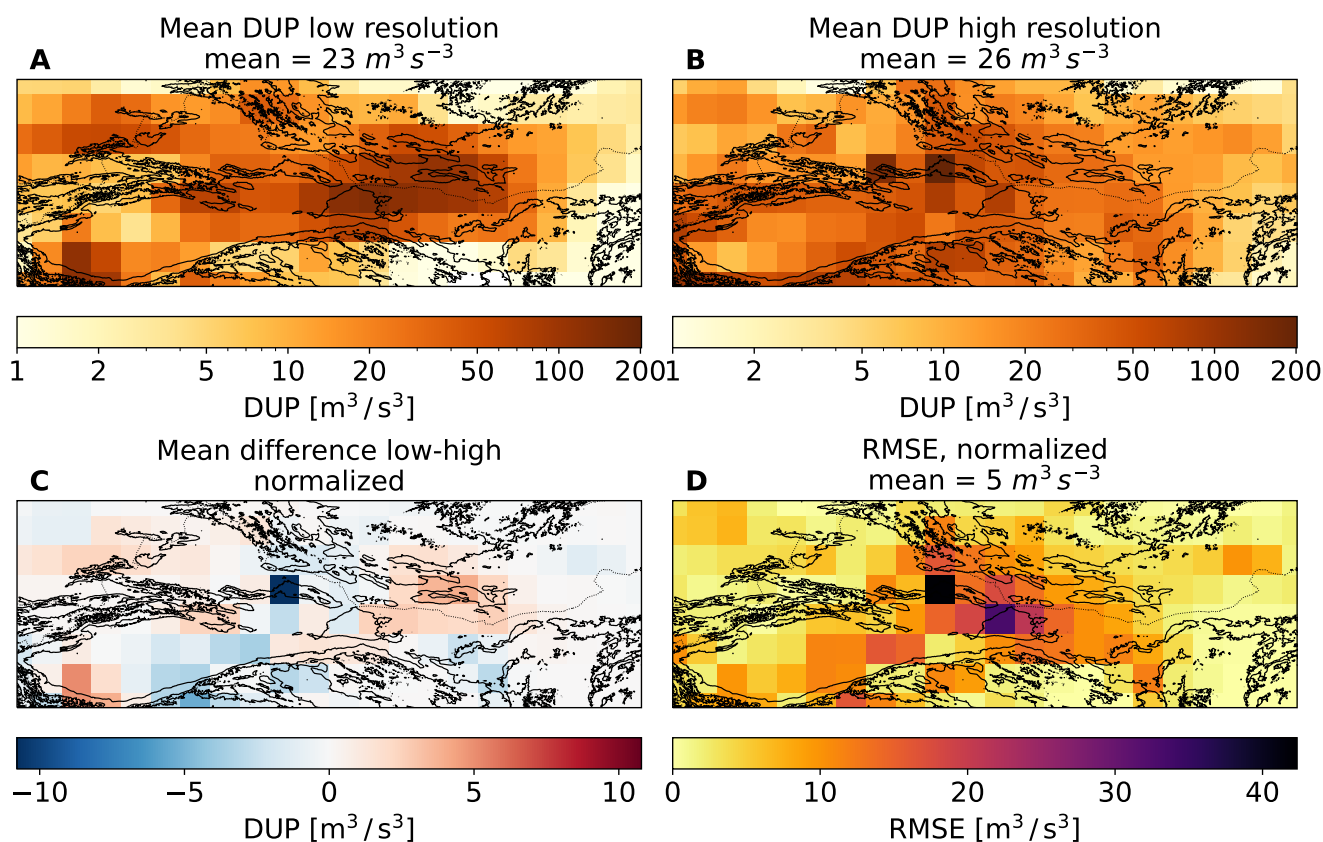


Figure 11. Map of dust uplift potential over the Gobi and Taklamakan region for August 2016, calculated using (a) low-resolution CMIP data and (b) high-resolution DYAMOND data, as well as (c) the mean normalized difference between CMIP6 (a) and DYAMOND (b) and (d) the corresponding root-mean-square error (RMSE).

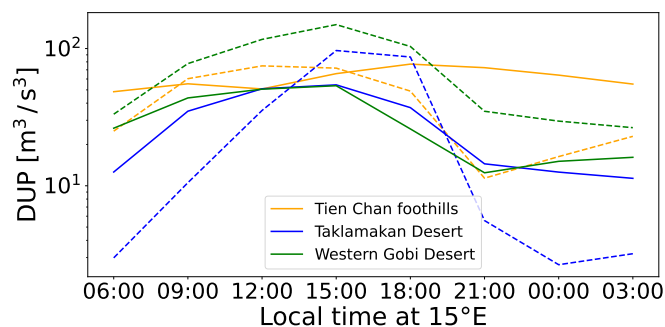


Figure 12. Diurnal cycle of dust uplift potential over central Asia for August 2016, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the three source regions Tian Chan foothills, Taklamakan Desert and Western Gobi Desert. See Figure 10 for the location and spatial extend of the different source regions.

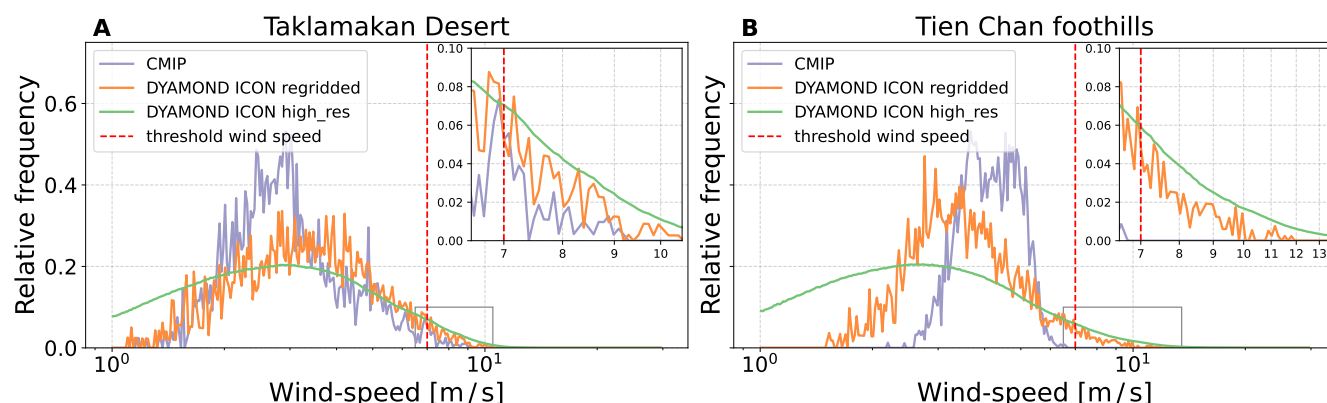


Figure 13. Histogram of 10-m wind speed over the Gobi and Taklamakan region for August 2016, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) the Taklamakan Desert and (b) the Tian Chan foothills. See Figure 10 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization. The scale range that is particularly relevant for dust emissions is shown enlarged.

465 In the Tian Shan foothills (Fig. 13b), CMIP6 produces almost no wind speeds near or above the emission threshold, while DYAMOND shows substantially higher frequencies in this range. The re-gridded simulation closely follows DYAMOND near the threshold but exhibits a faster decline at higher wind speeds. As in other regions, these discrepancies are primarily driven by convective processes that generate strong near-surface winds, which are not captured in coarse-resolution models. Although CMIP6 shows elevated frequencies at lower wind speeds of around 5 ms^{-1} , these remain below the emission threshold and
470 thus do not contribute to DUP.

The regional distribution of the “DYAMOND-re-gridded” simulation is shown in Fig. 14. While overall DUP values are lower than in the original simulations, the spatial pattern of maxima remains similar, with peaks in the southeastern Taklamakan and at the Tian Shan foothills. The reduced magnitude is primarily due to weaker-emission regions, where wind speeds close to the threshold are shifted below it during regridding, suppressing dust emission. This highlights the sensitivity of DUP
475 to threshold effects in marginal regions. In contrast, the main dust source areas retain similarly high DUP values across all simulations.

3.4 Australia

3.4.1 Key Wind Drivers of Dust Uplift

Australian dust emissions are predominantly driven by frontal systems associated with mid-latitude extra-tropical cyclones,
480 particularly cold fronts and southerly changes that bring strong gusty winds exceeding $10 - 15 \text{ ms}^{-1}$ over key source regions like the Lake Eyre Basin, Simpson Desert, and Channel Country (Radhi et al., 2010; Baddock et al., 2015; Che et al., 2024) (see Fig. 15 for their geographical location). These synoptic events often feature three sequential wind regimes: prefrontal

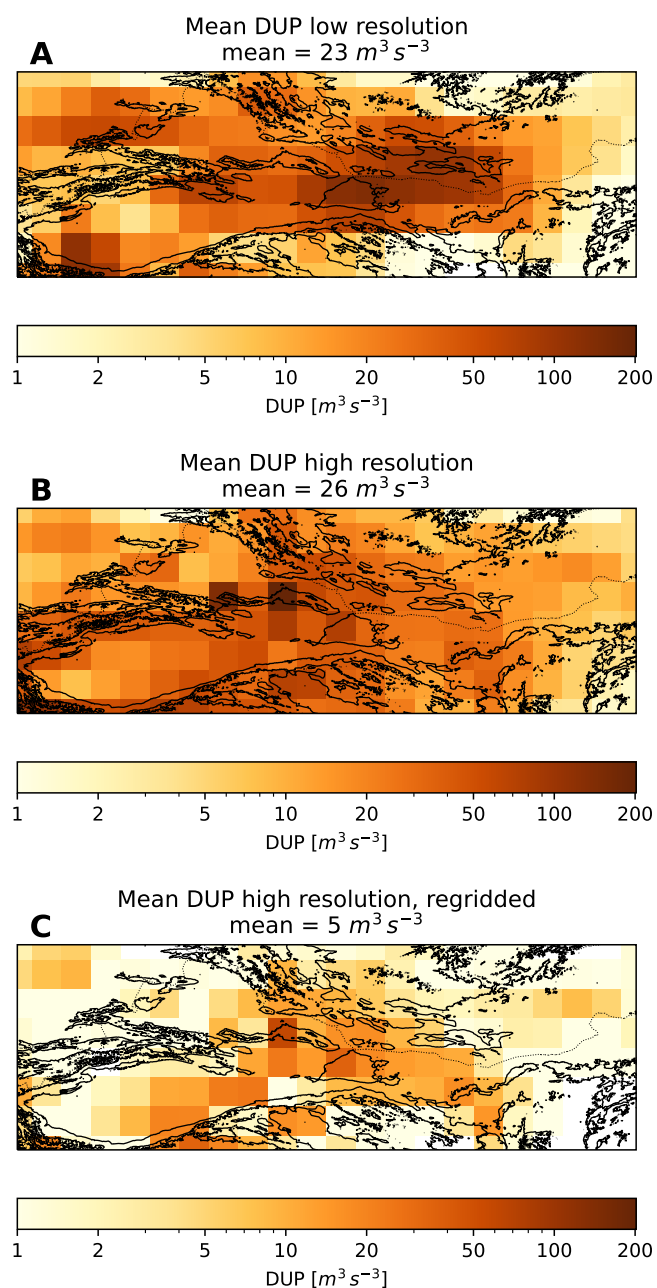


Figure 14. Map of dust uplift potential over over the Gobi and Taklamakan region for August 2016 including the "DYAMOND-regridded"-case. Panel (a) and (b) match with Panel (a) and (b) of Figure 11. Panel (c) shows the results of the "DYAMOND-regridded"-case.

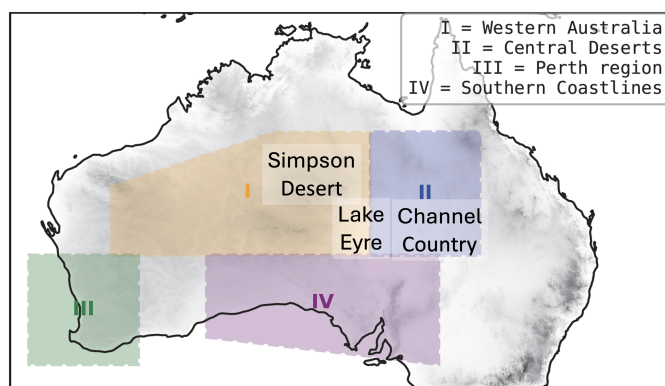


Figure 15. Topographic map of Australia with four marked dust source regions: Western Australia (I), the central Deserts (II), the Perth region (III) and the southern coastlines (IV). Important landmarks are also shown.

easterlies, frontal gust fronts, and postfrontal southerlies. They progressively entrain dust from dry lake beds and ephemeral river floodplains (Ekström et al., 2004; Baddock et al., 2015). At smaller scales, dust lifting is enhanced by dust devils (especially common in Australia due to intense surface heating and low humidity) convective downdrafts, dry microbursts from thunderstorms, and katabatic flows over arid surfaces (Oke et al., 2007). Australian dust activity tends to increase during El Niño events, which promote drier pre-conditions, reduced vegetation cover, and stronger frontal wind events due to anomalous circulation patterns. In contrast, La Niña phases suppress emissions through heavier rainfall and higher soil moisture (Risbey et al., 2009; Ginoux et al., 2012; Evans et al., 2016). In February 2020, the Oceanic Niño Index (ONI) recorded a value of 0.6, suggesting a very weak El-Niño phase. In August 2016, an ONI of 0 was observed, indicating neither an El-Niño nor a La-Niña phase. Nevertheless, August 2016 was immediately followed by a very strong El Niño phase.

3.4.2 Dust Uplift Potential Across Model Resolutions

Figure 16 shows the February 2020 (austral summer) mean DUP over Australia. The CMIP6 results (Fig. 16a) exhibit elevated values along the southern coast, particularly near Perth and Adelaide, as well as north of Perth in regions with ephemeral lakes. The high-resolution DYAMOND simulation (Fig. 16b) instead has maxima in the central and western parts of the continent, including the Simpson Desert. The normalized differences (Fig. 16c) reveal a clear contrast: CMIP6 overestimates DUP along the southern coasts, whereas DYAMOND shows higher values in central and northwestern Australia, pointing to the influence of convective processes in these regions. The RMSE of the normalized differences (Fig. 16d) confirms this pattern, with maxima primarily in the central-western regions, underscoring the role of convection in driving model discrepancies, while smaller maxima also occur in eastern and coastal areas.

The diurnal cycle of DUP for selected regions is shown in Fig. 17. In the Central Desert, both simulations exhibit a similar overall cycle, with elevated DUP throughout the day, a decrease in the late afternoon, and a maximum in the early night. The afternoon enhancement in DYAMOND indicates convective activity, which is underestimated in CMIP6, consistent with

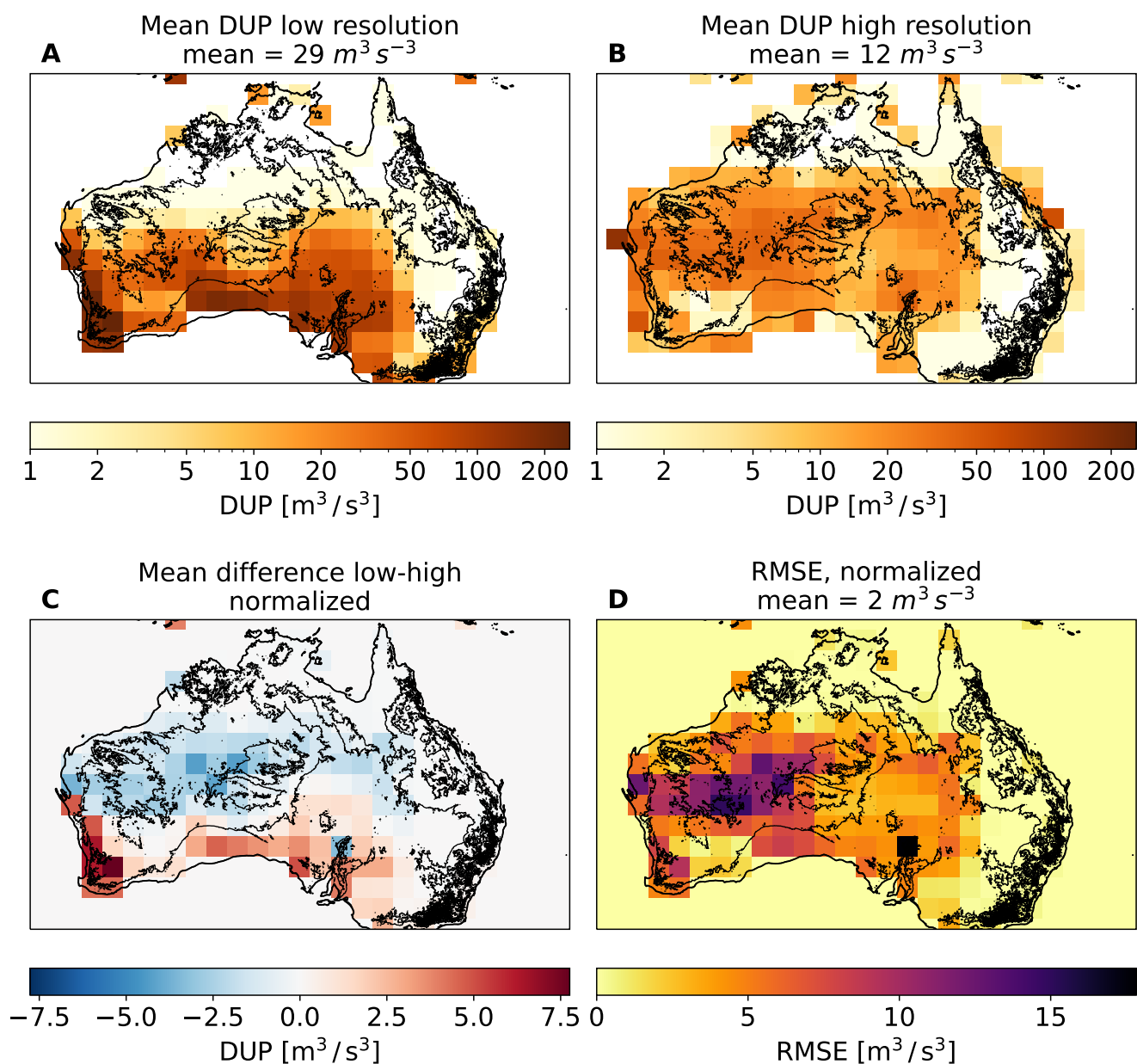


Figure 16. Map of dust uplift potential over Australia for February 2020, calculated using (a) low-resolution CMIP data and (b) high-resolution DYAMOND data, as well as (c) the mean normalized difference between CMIP6 (a) and DYAMOND (b) and (d) the corresponding root-mean-square error (RMSE).

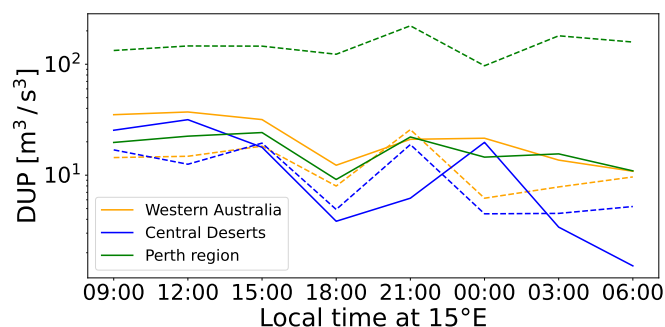


Figure 17. Diurnal cycle of dust uplift potential over central Asia for August 2016, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the three source regions Western Australia, Central Deserts and the Perth region. See Figure 15 for the location and spatial extend of the different source regions.

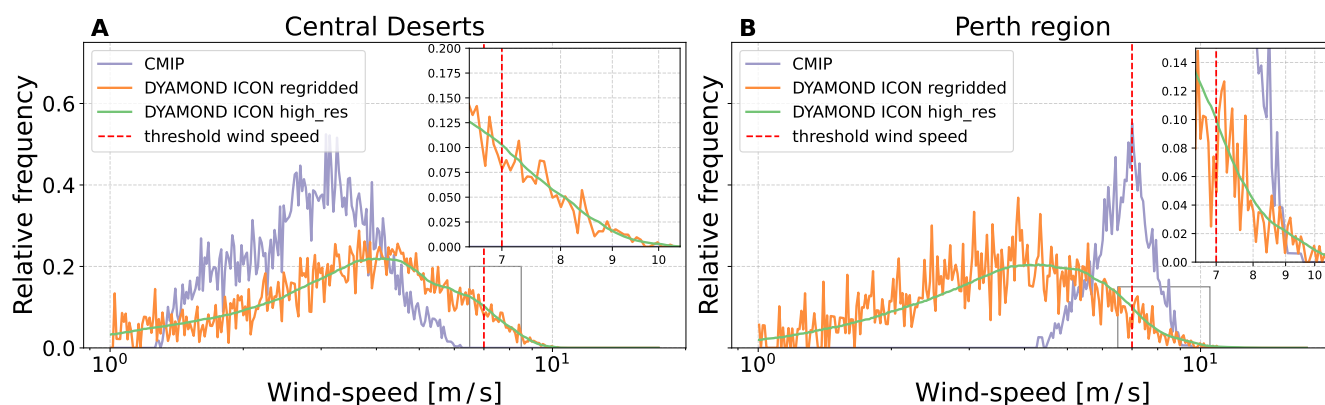


Figure 18. Histogram of 10-m wind speed over Australia for February 2020, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) the Central Deserts and (b) the Perth region. See Figure 15 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization. The scale range that is particularly relevant for dust emissions is shown enlarged.

findings for haboobs in North Africa. In the Western region, both models show a comparable structure, but the DYAMOND nocturnal maximum is broader and more sustained. As a result, CMIP6 begins to decline earlier in the night, leading to pronounced differences during this period. This again points to an under-representation of convective processes in the coarse-resolution simulations. In the Perth region, both models reproduce a similar diurnal pattern, but CMIP6 yields substantially higher DUP values, resulting in a systematic positive bias. The relatively weak diurnal variability suggests a persistent wind regime, which appears to be overestimated in the climate model compared to the high-resolution simulation.

The wind-speed distributions in Fig. 18 again provide key insight into the origin of these biases. In central Australia (Fig. 18a), CMIP6 produces almost no wind speeds near or above the emission threshold, effectively suppressing dust emission.



In contrast, DYAMOND exhibits a substantial frequency of threshold-exceeding winds. The regridded DYAMOND simulation closely follows the native high-resolution distribution, demonstrating that these differences primarily arise from the explicit representation of convection rather than grid resolution. This behavior is consistent with other regions with predominant moist convection, where coarse-resolution models fail to capture strong, short-lived wind events (e.g., haboobs) that are critical for dust mobilization. While CMIP6 shows some increase in lower wind speeds, these remain below the emission threshold and therefore do not contribute to DUP.

In the Perth region (Fig. 18b), the distributions differ fundamentally. CMIP6 exhibits a pronounced and narrow peak near the emission threshold, indicating frequent moderate winds that are just sufficient to trigger dust emission. However, the frequency drops rapidly at higher wind speeds, where DYAMOND dominates. The DYAMOND and regridded distributions are similar in both shape and magnitude, confirming that the high-resolution structure is preserved under re-gridding. This contrast highlights two distinct mechanisms: in central Australia, dust emission is controlled by convective high-wind events that are missing in CMIP6, whereas in the Perth region, the bias arises from an over-representation of persistent near-threshold winds. The latter leads to an overestimation of dust emissions in CMIP6, despite an under-representation of extreme wind speeds. The agreement between DYAMOND and its re-gridded counterpart further indicates that this bias is primarily linked to convection parameterization rather than grid resolution.

4 Discussion

4.1 Consistent Patterns and Discrepancies Across Dust Sources

Despite regional variability, the four key dust source regions presented in this study exhibit similar patterns in dust uplift potential (DUP) that reflect the dominant meteorological drivers for summer conditions. These include convective cold-pool outflows (haboobs), synoptic-scale forcing from mid-latitude pressure systems and trade winds, nocturnal low-level jet breakdowns, persistent wind regimes, as well as combinations of multiple drivers. Furthermore, regions with similar results at both resolutions were found. Examining these mechanisms across both convection-permitting and parameterized simulations allows us to identify systematic differences and regionally consistent features, providing a framework to discuss implications for dust mobilization, transport, and modeling accuracy. These features are not only present in the four regions described previously but also occur in other dust source areas that could not be presented in the main text but are shown in the appendix. They include, for example, the Arabian Peninsula, South Africa and Namibia, as well as South and North America. This section characterizes these features in detail and identifies all regions in which these patterns are observed. The associated plots can be found in the appendix.

4.1.1 Convective Events

As discussed previously, convective events constitute a key mechanism for the emission of mineral dust particles. Several regions with high convective activity show similar patterns. Moist convection-driven dust emissions are mostly evident by



evening and nocturnal peaks in DUP. Results in all considered dust source regions indicate that these peaks are systematically underestimated by current climate models represented by the CMIP6 ensemble when compared with high-resolution ICON simulations from DYAMOND. The analysis of wind-speed frequency distributions shows that models with parameterized convection fail to capture the high surface wind-speeds associated with convective outflows, which generate the substantial dust emissions that can be reproduced in high-resolution convection-resolving model simulations. Further evaluation shows that these discrepancies primarily arise from the capability to explicitly represent convection rather than from differences in horizontal grid resolution.

This is particularly evident in the Sahel region, which is characterized in summer by exceptionally frequent convective activity, especially haboobs, as described in Section 3.1.2. However, comparable patterns are also found in summer in the Tian Shan foothills in East Asia, as well as in the Central Deserts of Australia. The summer results also apply to other global dust sources, which cannot be discussed in detail here and are therefore listed in the appendix. These include additional regions within the dust belt, such as the Bodélé Depression (see Fig. A1 and A2), the Asir Mountains, and the Tibetan Plateau (Fig. A11 and A12), as well as other Northern Hemisphere regions, which are not shown here, including the High Plains of North America. Several Southern Hemisphere source regions are also affected, including the Central Australian deserts, the Namib Desert, and the agricultural areas surrounding Cape Town, South Africa. For these Southern Hemisphere regions, the results for summer and winter are similar, indicating that convection-driven uncertainties persist throughout the year. In addition, several Northern Hemisphere regions exhibit comparable patterns in winter, including the Taklamakan Desert, the Tian Shan foothills in northern China (Fig. A13 - A15), and the Nafud Desert at the northern margin of the Arabian Peninsula, underscoring the importance of wintertime convective events there.

4.1.2 Nocturnal Low-Level Jet Breakdown

An important driver of dust emission in Northern Africa is also the breakdown of the nocturnal LLJ, as described earlier. Emissions associated with these events are characterized by a pronounced peak during the morning hours or daytime, consistent with findings from several regions. The results reveal that current climate models systematically overestimate DUP values due to the breakdown of the LLJ relative to high-resolution simulations. The relative frequency distributions of near-surface winds indicate that elevated DUP values in the CMIP6 simulations, in regions where LLJs dominate dust emissions, are mainly driven by wind speeds only slightly above the emission threshold. These moderate wind events occur frequently and thus contribute substantially to the cumulative DUP, which serves as a proxy for total dust emissions.

An example of regions where DUP values are affected by the nocturnal LLJ breakdown is the El Eglab region in Northern Africa (see Sec. 3.1.2) or the Perth region in Australia (Sec. 3.4.2). Similar patterns are found in several other regions around the world where CMIP6 simulations consistently overestimate DUP relative to the high-resolution DYAMOND data. These include southern Australia and adjacent coastlines (see Fig. A16 - A20 in the appendix), as well as the Namibian coast, in both seasons of the Southern Hemisphere. Comparable behavior is also observed in Northern Hemisphere regions, including the Mediterranean coasts of North Africa (Fig. A1 - A5) and the western Gobi Desert in northern China (Fig. A11 - A15). The Aralkum shows a similar pattern in summer (Fig. A6 and A7), while the Kavir Desert (Fig. A15 - A10) and the Sahel (Fig.



A3 - A5) exhibit analogous behavior in winter. Despite these similarities, the regions differ in the timing of the diurnal peak, indicating the influence of distinct regional wind systems on DUP as additional drivers of dust uplift.

4.1.3 Multiple Drivers

580 Other regions indicate that both key drivers—nocturnal LLJ breakdown and moist convective activity—substantially contribute to dust emissions. During the morning and daytime, the influence of LLJ breakdown is evident in an overestimation of dust emissions in the coarse CMIP6 climate models relative to high-resolution simulations. In contrast, during nighttime, when moist convective activity dominates, models with convection parameterization tend to underestimate dust emissions due to their limited ability to represent moist convective processes. This combined behavior is evident, for example, in the Taklamakan
585 summer case (Sec. 3.3.2) and similarly in the Kavir Desert in central Iran (Sec. 3.2.2).

4.1.4 Persistent Wind Regimes

In persistent wind regimes, dust emission is governed by sustained, strong near-surface winds, resulting in a highly consistent diurnal cycle. In such environments, coarse climate models tend to systematically underestimate dust emissions relative to high-resolution simulations, particularly during periods of elevated wind speeds, as indicated by the frequency analysis. The
590 Sistan Basin, dominated by the strong and persistent Shamal wind, represents a clear example of this behavior. The evaluation of the DYAMOND re-gridded simulations further shows that horizontal resolution is important for capturing weaker dust-mobilizing winds. However, for the strong wind events that dominate total dust emissions, owing to the cubic dependence of DUP on wind speed, the results exhibit pronounced sensitivity to the representation of convection, with explicit schemes outperforming parameterized ones.

595 4.2 Grid-Spacing Induced Biases

Since dust uplift is as a threshold process, spatial resolution directly affects its calculation. Averaging over coarse grid cells can reduce wind speeds below the emission threshold, thereby suppressing dust emission. To isolate this effect, wind fields from the convection-resolving DYAMOND simulation were re-gridded onto the CMIP6 grid, and all configurations were compared using relative wind-speed frequency histograms (see Sec. 3).

600 In most dust source regions, the “DYAMOND-re-gridded” results closely resemble the original high-resolution simulation, indicating that the main source of discrepancies with CMIP6 lies in the representation of moist convection rather than grid spacing alone. In some regions, all simulations show similar wind-speed distributions, either reflecting weak dust activity during the analyzed season or genuinely good agreement between model configurations.

However, in a limited number of regions, like the Arabian Peninsula near Dubai, the Kavir Desert, and the Tibetan Plateau
605 in summer, the “DYAMOND-re-gridded” simulation converges toward the CMIP6 results. This behavior demonstrates that, in these cases, the grid spacing at which DUP is computed is a dominant source of uncertainty. The Kavir Desert represents a particularly clear example. Here, the agreement between the “DYAMOND-re-gridded” and CMIP6 simulations indicates that



differences are primarily driven by grid resolution effects, with a comparatively minor role of convection parameterization. In contrast, regions such as the Gobi–Taklamakan system show pronounced discrepancies among all simulations, especially
610 outside the main dust source areas, pointing to additional complexities in the controlling processes.

5 Summary and Outlook

This study compares estimates of dust uplift potential (DUP), which is used as a wind-based proxy for dust emissions, from high-resolution, convection-resolving models from the DYAMOND project with those from coarse-resolution climate models in CMIP6 employing parameterized convection, with the aim of systematically assessing the sensitivity of global dust source
615 regions to model resolution and the representation of moist convection.

Previous work by Zhao et al. (2022) has already highlighted substantial inter-model variability and uncertainties in CMIP6 dust simulations, particularly for regions such as northern China and Australia, while North Africa and the Middle East show more consistent contributions among the CMIP6 model ensemble. The simulations analyzed here align closely with the CMIP6 multi-model mean in terms of regional source contributions, although a slight overestimation of dust activity over northern
620 China is evident.

The comparison in this study reveals systematic and spatially coherent discrepancies between the convection-resolving ICON simulations (2.5 km) and their coarse-resolution counterparts (~ 200 km), with variations depending on region and season. The coarse CMIP6 models, which rely on parameterized convection, systematically underestimate convectively driven dust events and fail to capture their temporal and spatial characteristics. This deficit is partly compensated by an over-representation of
625 synoptic-scale wind systems, leading to biases such as enhanced dust emissions associated with low-level jet breakdowns and persistent strong winds. Extending previous studies, these effects are shown here to occur consistently across major global dust source regions, rather than being confined to North Africa. These findings underscore the critical role of explicitly resolving convection for accurately simulating dust mobilization. The resulting biases have important implications for the interpretation of satellite observations, as well as for modeling dust–radiation interactions and predicting dust transport and deposition on
630 regional to global scales.

Recent work, for example by Ying et al. (2026), suggests that discrepancies in high-resolution dust simulations, particularly in the eastern Sahel, are primarily driven by differences in friction velocity, with secondary contributions from soil moisture variability. A logical next step is therefore to extend the present analysis to fully coupled dust emission and transport simulations, enabling direct evaluation against observational data. Emerging developments in global convection-resolving aerosol
635 modeling (e.g., Weiss et al., 2025) provide a promising pathway for such efforts, allowing a more comprehensive and scale-consistent assessment of dust processes, from emission to transport and deposition.

Code and data availability. The data and scripts used to process the data and generate the figures are available on Zenodo (<https://doi.org/10.5281/zenodo.21337882>; Kunze et al. (2026)).



The simulations analysed in this study were originally performed with two versions of the ICON modeling framework. The DYAMOND simulations were performed with ICON version 2.1.02 (Hohenegger et al., 2020). The exact source code for this historical model version was not archived in a publicly accessible repository. The closest archived and documented successor of this model configuration is the ICON-AES branch nextgems_cycle1_dpp0066 (commit 62dbfc), which evolved directly from the DYAMOND model configuration. The corresponding source code and experiment configuration are archived at <https://doi.org/10.17617/3.1XTSR6> (Hohenegger et al., 2020) (last accessed: 27 July 2026). The archive contains the complete model source code together with the experiment definition (exp.dpp0066) used to configure the simulations. Details of the specific DYAMOND winter and summer configuration can be found on the DYAMOND project website (<https://easy.gems.dkz.de/DYAMOND>) (last accessed: 27 July 2026).

The CMIP6 comparison simulations were performed with ICON-ESM-V1.0. The source code of ICON-ESM-V1.0, the primary model output, and the scripts used for the analyses and to produce the figures are archived in the WDCC Long Term Archive (DOI: https://doi.org/10.35089/WDCC/RUBY-0_ICON-ESM_V1.0_Model) (last accessed: 27 July 2026). The current ICON modeling framework is distributed as open-source software under the BSD 3-Clause License. The current source code, licence information, and authorship information are available from the official ICON project website (<https://www.icon-model.org>). (last accessed: 27 July 2026)

Appendix A

A1 North Africa

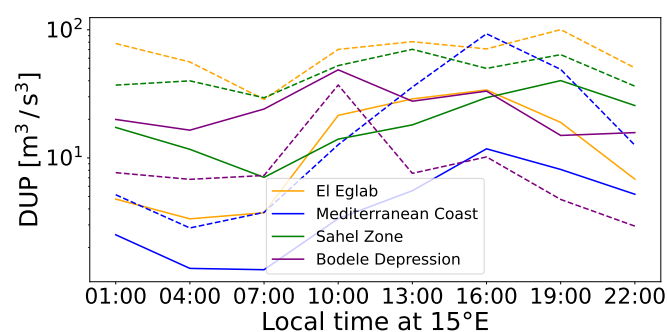


Figure A1. Diurnal cycle of dust uplift potential over central Asia for August 2016, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the four source regions El Eglab, Mediterranean Coastlines, Sahel and Bodélé Depression. See Figure 1 for the location and spatial extend of the different source regions.

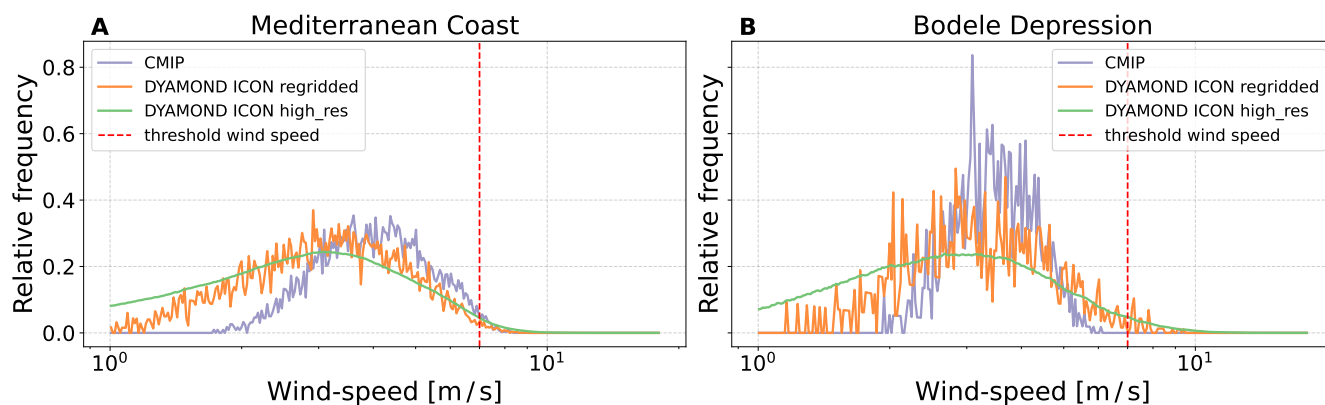


Figure A2. Histogram of 10-m wind speed over Northern Africa for August 2016, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) Mediterranean Coastlines and (b) the Bodélé Depression. See Figure 1 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization.

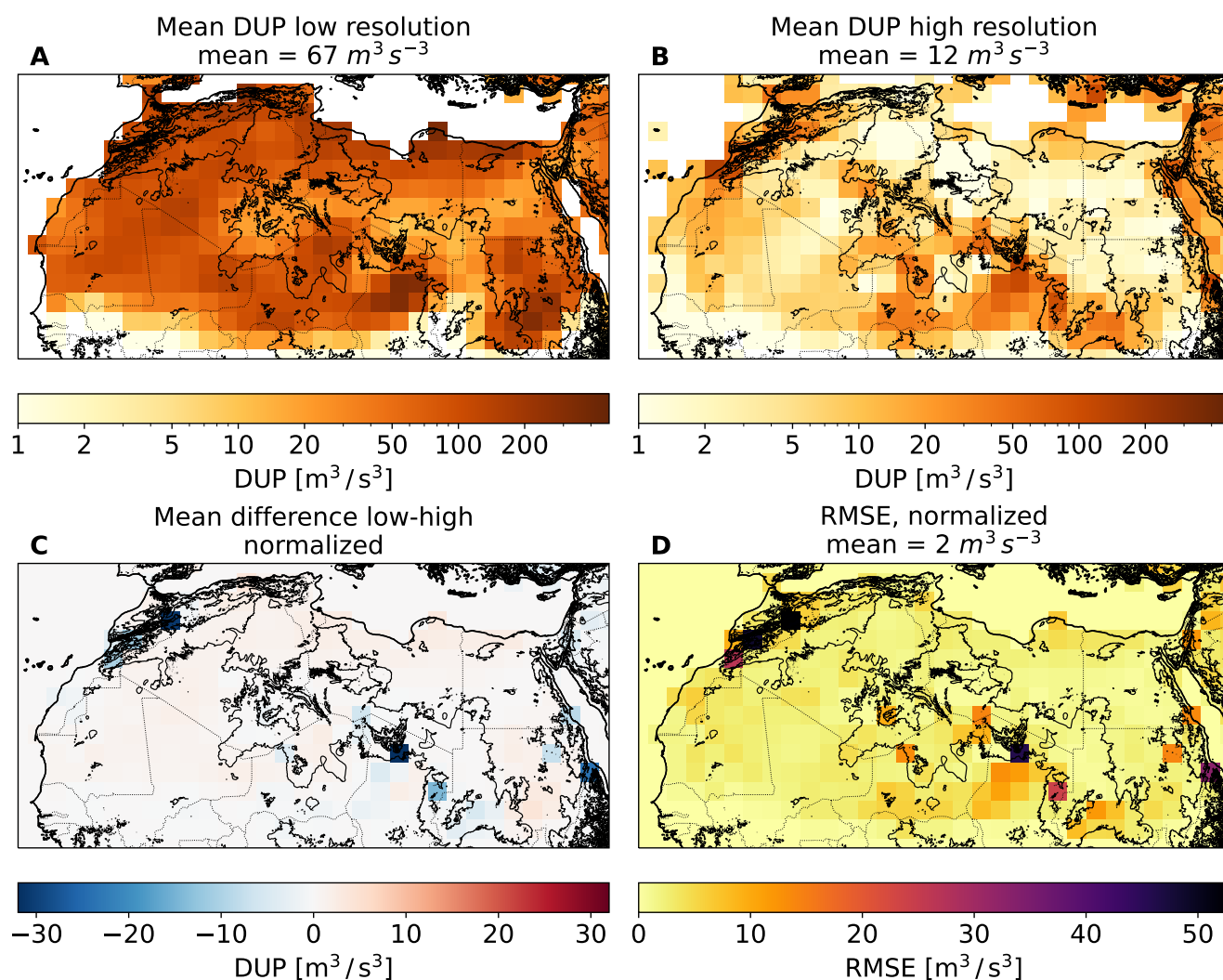


Figure A3. Map of dust uplift potential over northern Africa for February 2020, calculated using (a) low-resolution CMIP data and (b) high-resolution DYAMOND data, as well as (c) the mean normalized difference between CMIP6 (a) and DYAMOND (b) and (d) the corresponding root-mean-square error (RMSE).

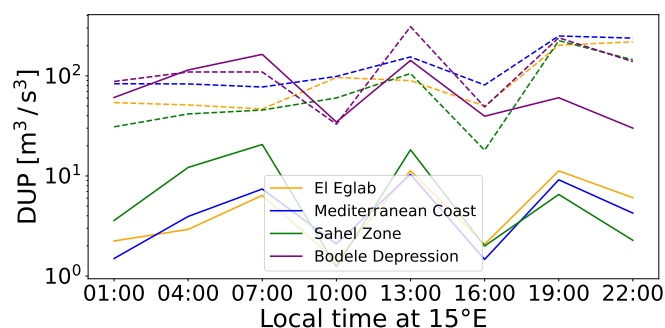


Figure A4. Diurnal cycle of dust uplift potential over central Asia for August 2016, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the four source regions El Eglab, Mediterranean Coastlines, Sahel and Bodélé Depression. See Figure 1 for the location and spatial extend of the different source regions.

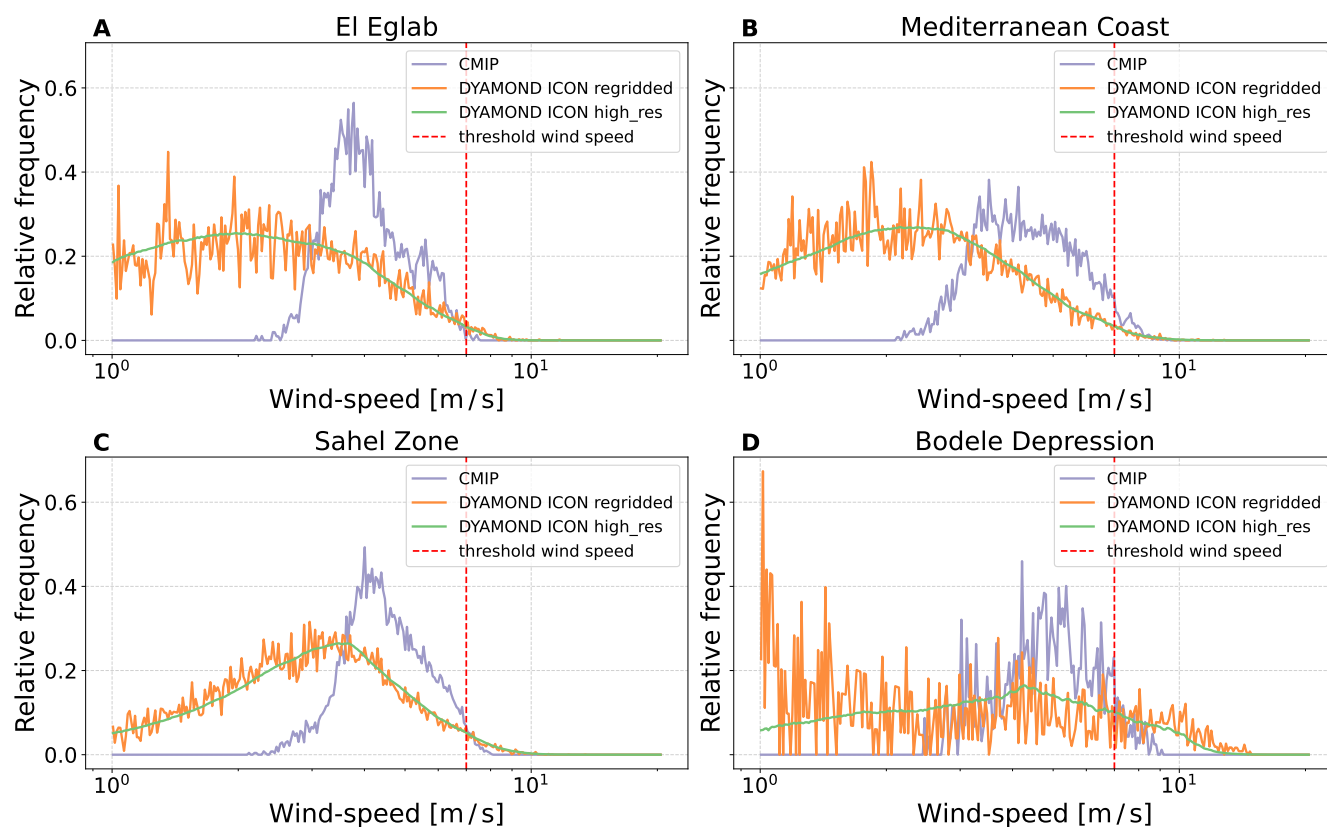


Figure A5. Histogram of 10-m wind speed over Northern Africa for February 2020, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) the El Eglab region, (b) the Mediterranean Coastlines, (c) the Sahel Zone and (d) the Bodélé Depression. See Figure 1 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization.



A1 Central Asia

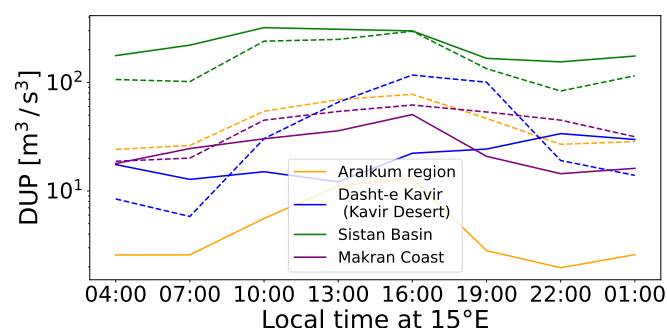


Figure A6. Diurnal cycle of dust uplift potential over central Asia for August 2016, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the four source regions Aralkum region, the Dasht-e Kavir, the Sistan Basin and the Makran Coastlines. See Figure 6 for the location and spatial extend of the different source regions.

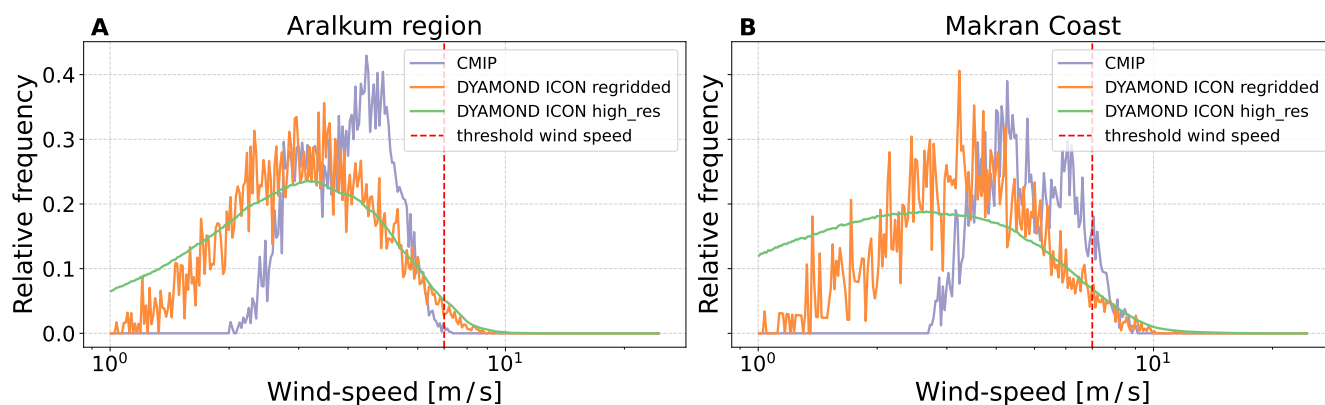


Figure A7. Histogram of 10-m wind speed over Central Asia for August 2016, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) the Aralkum and (b) the Makran Coastlines. See Figure 6 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization.

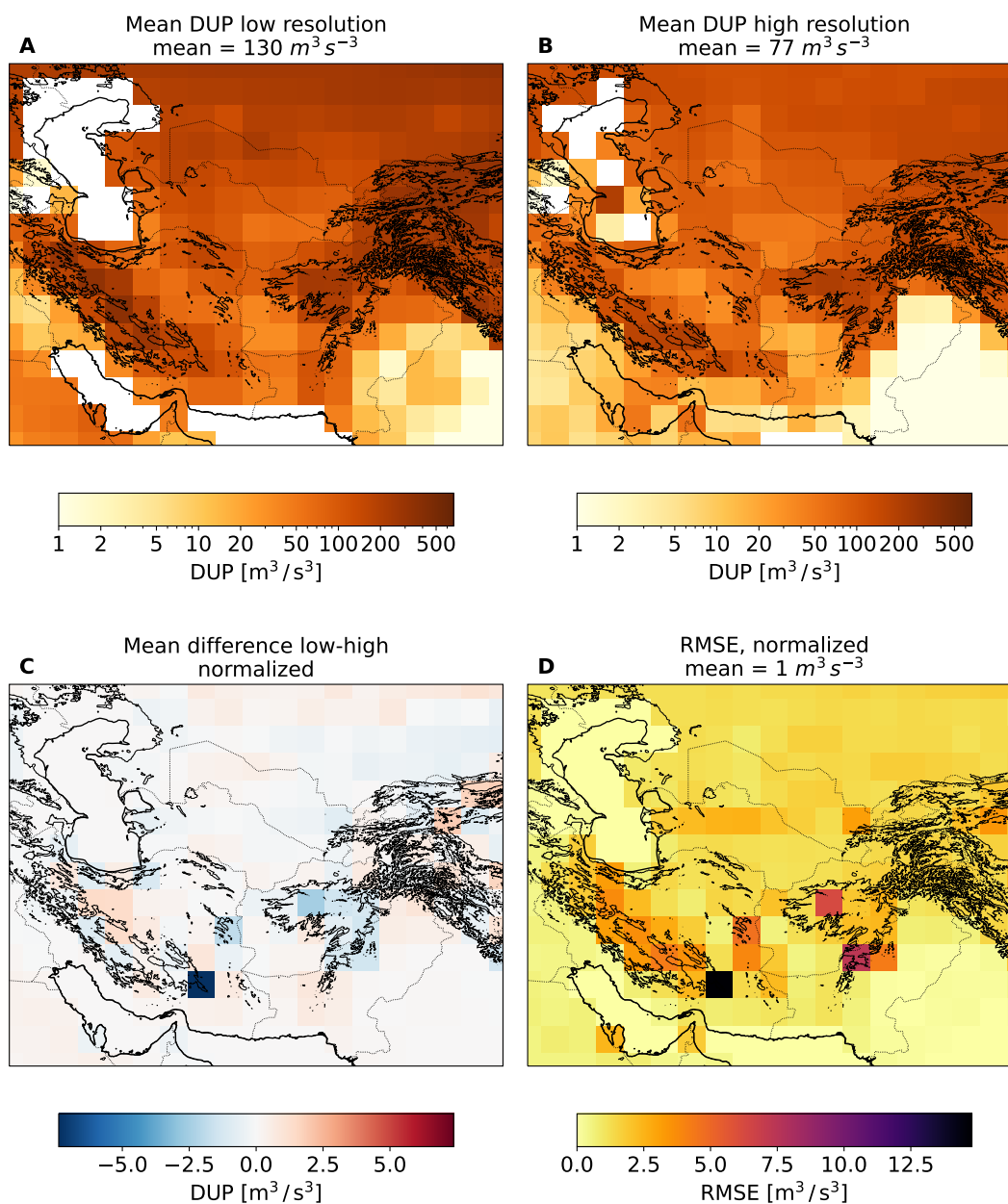


Figure A8. Map of dust uplift potential over Central Asia for February 2020, calculated using (a) low-resolution CMIP data and (b) high-resolution DYAMOND data, as well as (c) the mean normalized difference between CMIP6 (a) and DYAMOND (b) and (d) the corresponding root-mean-square error (RMSE).

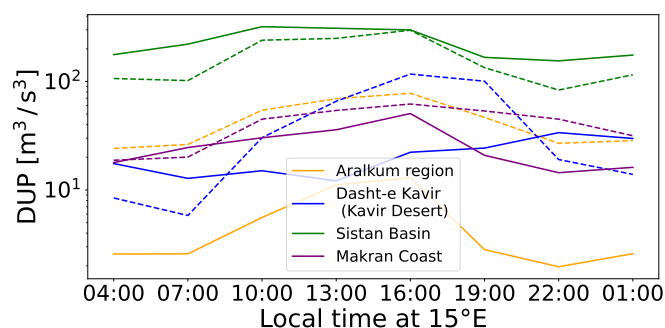


Figure A9. Diurnal cycle of dust uplift potential over central Asia for August 2016, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the four source regions Aralkum region, the Dasht-e Kavir, the Sistan Basin and the Makran Coastlines. See Figure 6 for the location and spatial extend of the different source regions.

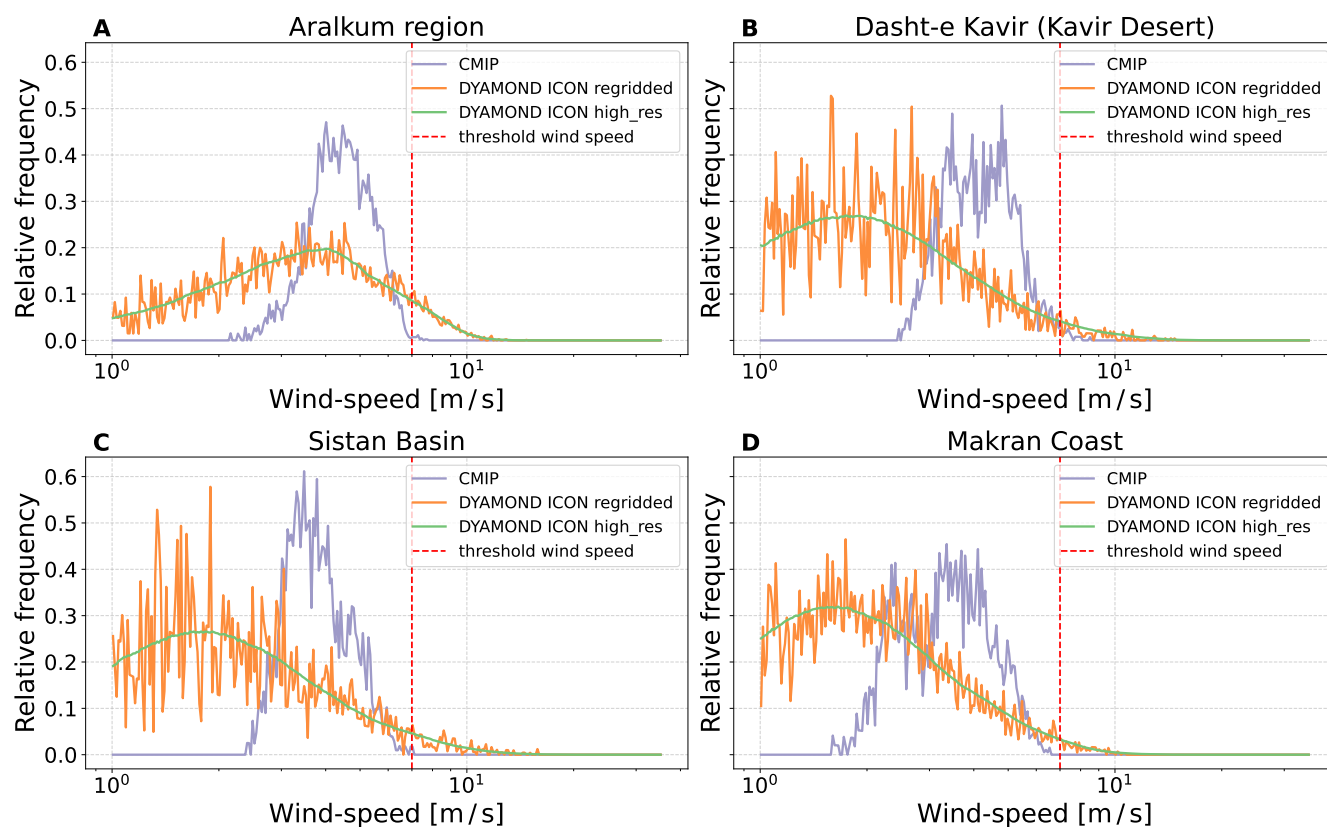


Figure A10. Histogram of 10-m wind speed over Central Asia for February 2020, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) the Aralkum, (b) the Dasht-e Kavir, (c) the Sistan Basin and (d) the Makran Coastlines. See Figure 6 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization.



655 A2 Gobi and Taklamakan Desert

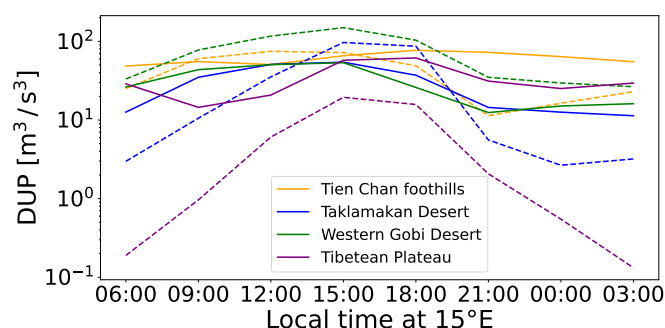


Figure A11. Diurnal cycle of dust uplift potential over central Asia for August 2026, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the four source regions Tian Shan foothills, the Taklamakan Desert, the Western Gobi Desert and the Tibetan Plateau. See Figure 10 for the location and spatial extend of the different source regions.

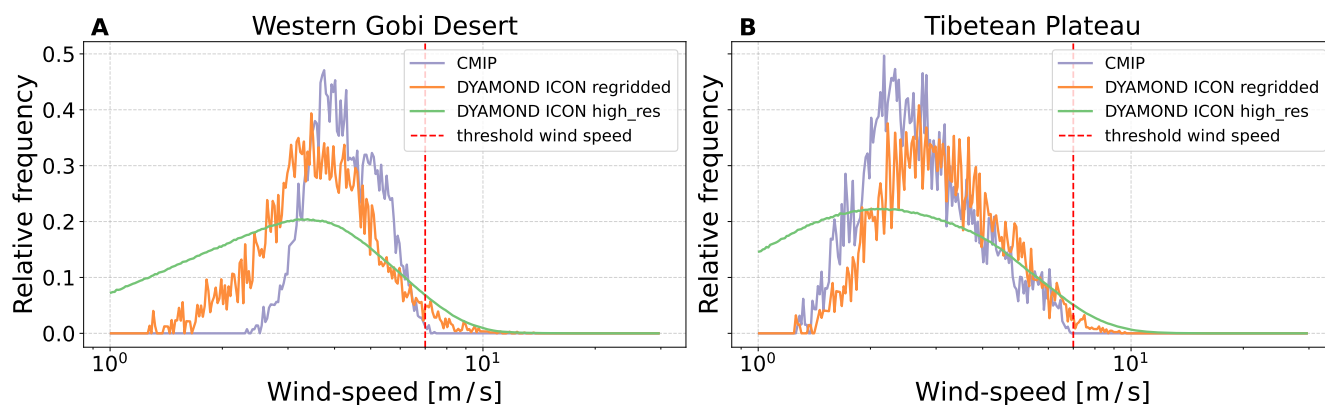


Figure A12. Histogram of 10-m wind speed over the Gobi and Taklamakan Desert for August 2026, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) the Western Gobi Desert and (b) the Tibetan Plateau. See Figure 10 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization.

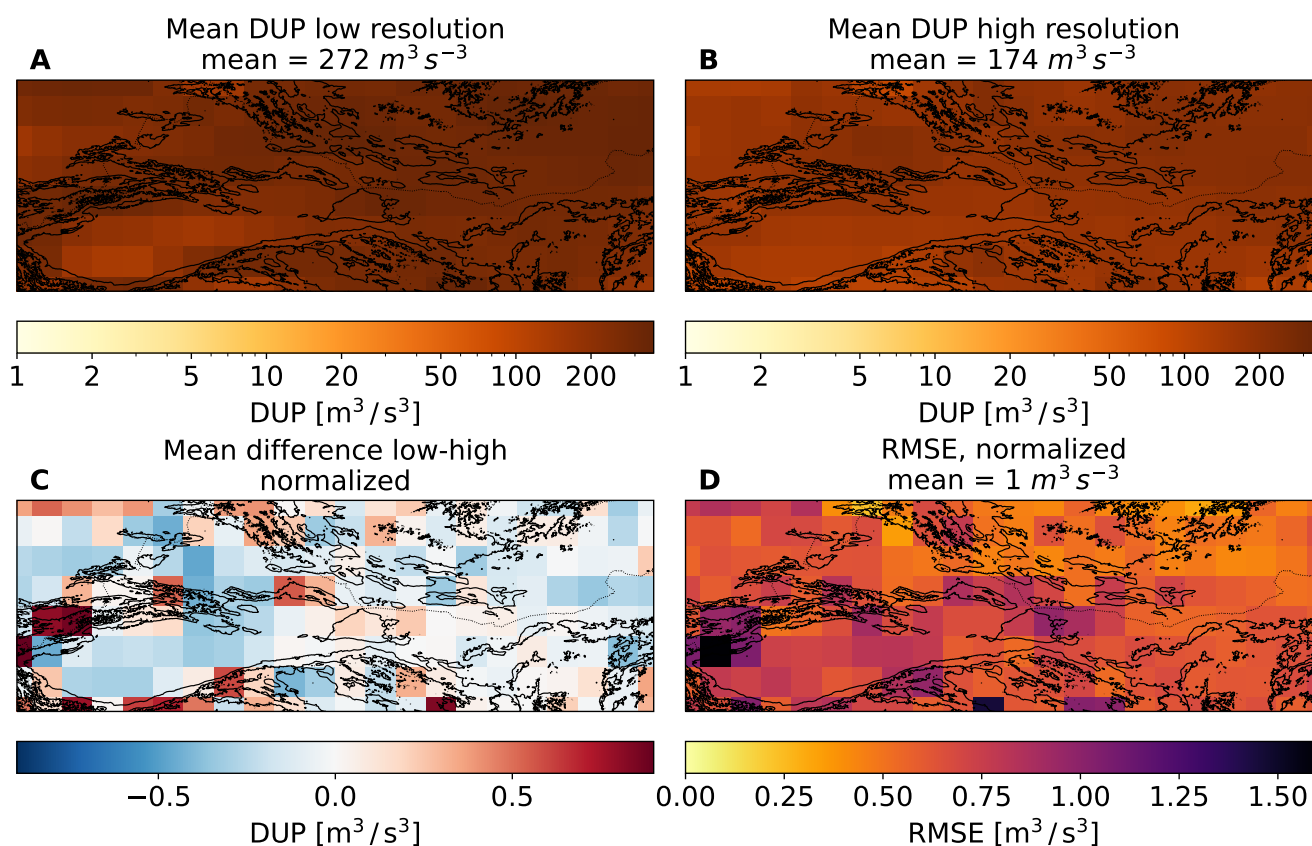


Figure A13. Map of dust uplift potential over the Gobi and Taklamakan Desert for February 2020, calculated using (a) low-resolution CMIP data and (b) high-resolution DYAMOND data, as well as (c) the mean normalized difference between CMIP6 (a) and DYAMOND (b) and (d) the corresponding root-mean-square error (RMSE).

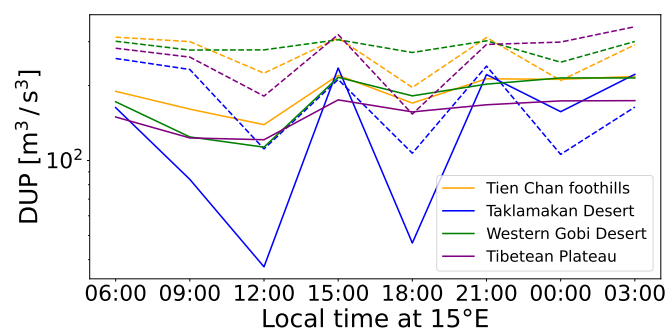


Figure A14. Diurnal cycle of dust uplift potential over central Asia for August 2016, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the four source regions Tian Shan foothills, the Taklamakan Desert, the Western Gobi Desert and the Tibetan Plateau. See Figure 10 for the location and spatial extend of the different source regions.

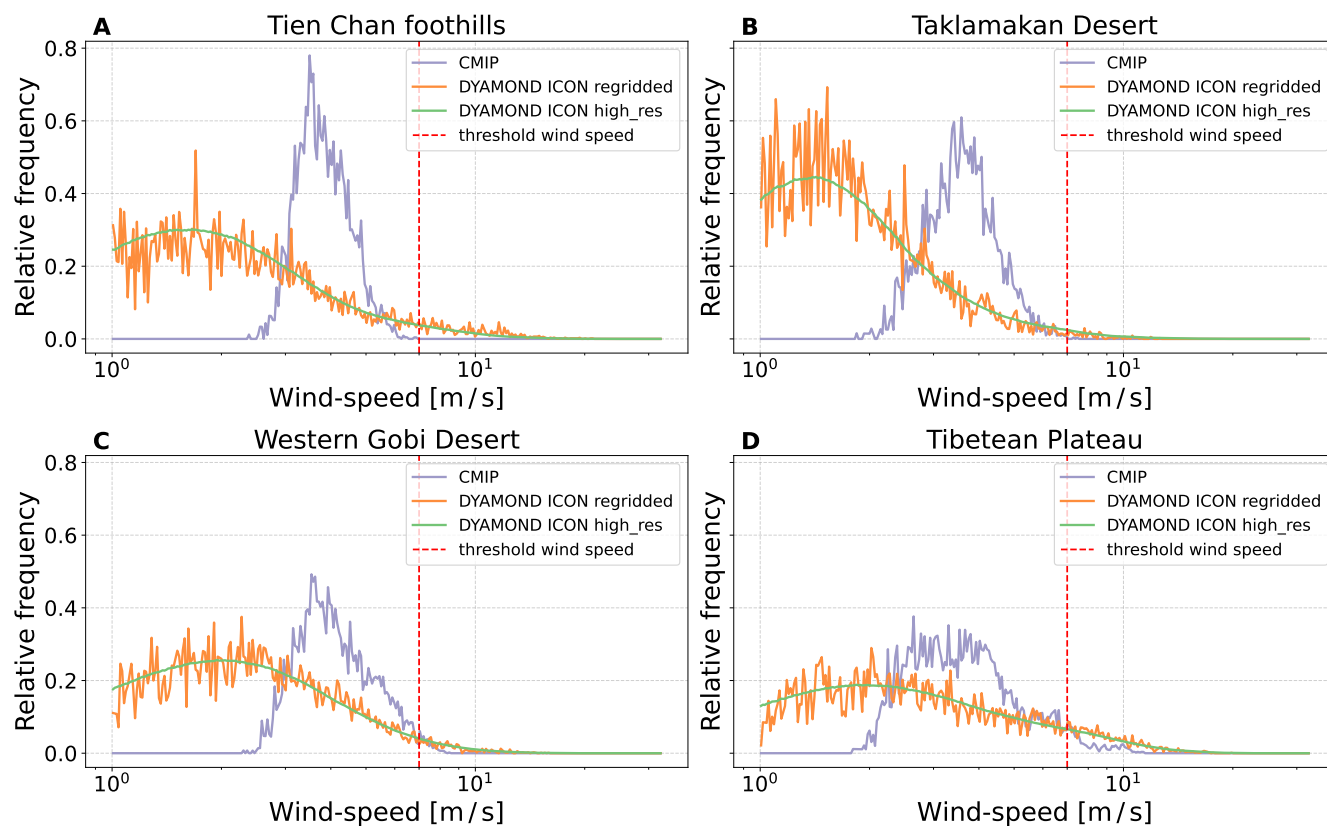


Figure A15. Histogram of 10-m wind speed over the Gobi and Taklamakan Desert for February 2020, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) the Tien Chan foothills, (b) the Taklamakan Desert, (c) the Western Gobi Desert and (d) the Tibetan Plateau. See Figure 10 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization.



A3 Australia

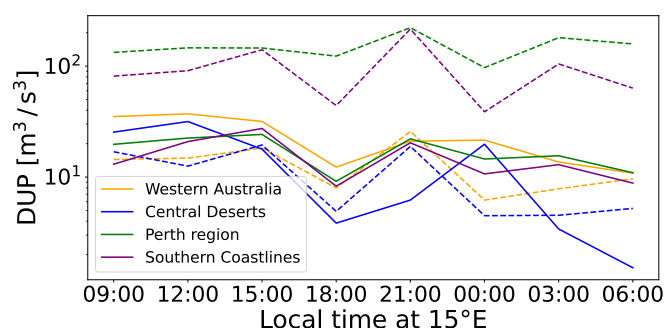


Figure A16. Diurnal cycle of dust uplift potential over Australia for February 2020, as computed from low-resolution CMIP data (dashed lines) and high-resolution DYAMOND data (solid lines) for the four source regions Western Australia, the Central Deserts, the Perth region and the southern Coastlines. See Figure 15 for the location and spatial extend of the different source regions.

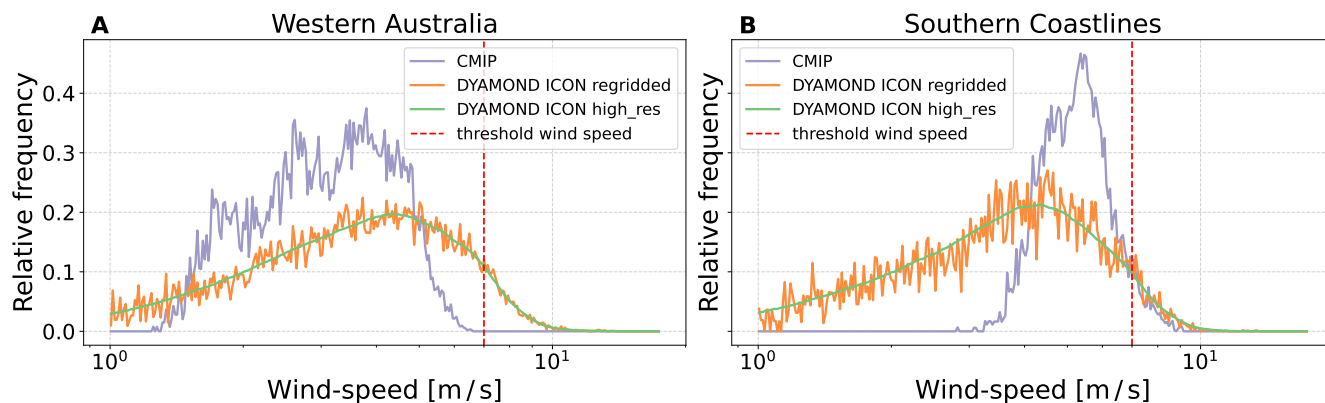


Figure A17. Histogram of 10-m wind speed over Australia for February 2020, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) Western Australia and (b) the Central Deserts. See Figure 15 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization.

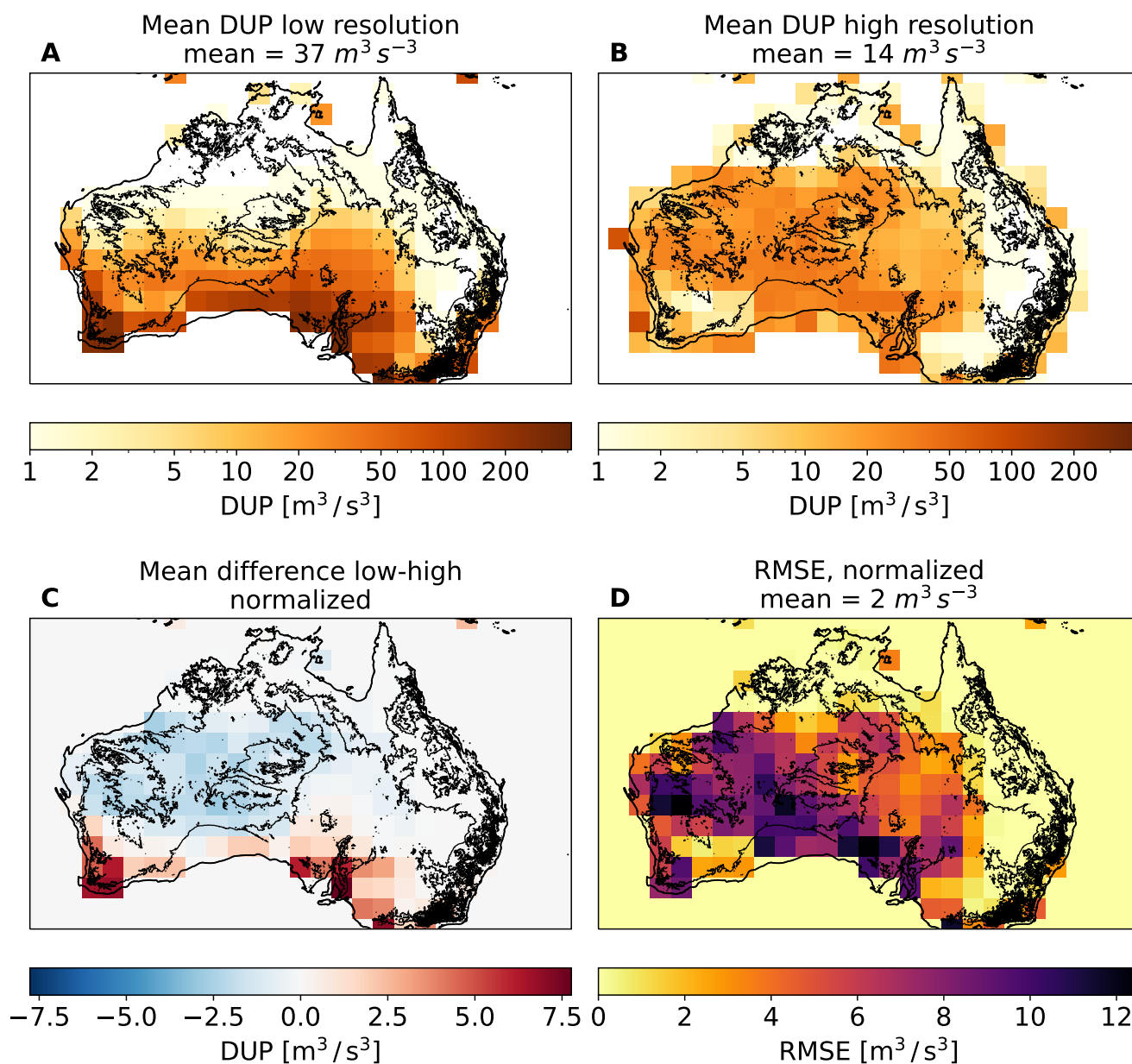


Figure A18. Map of dust uplift potential over Australia for August 2016, calculated using (a) low-resolution CMIP data and (b) high-resolution DYAMOND data, as well as (c) the mean normalized difference between CMIP6 (a) and DYAMOND (b) and (d) the corresponding root-mean-square error (RMSE).

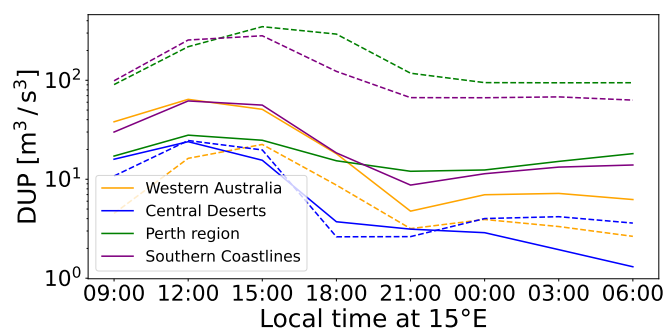


Figure A19. Diurnal cycle of dust uplift potential over central Asia for August 2026, calculated using low-resolution CMIP6 data (dashed lines) and high-resolution DYAMOND data (solid lines) for the four source regions Western Australia, the Central Deserts, the Perth region and the southern Coastlines. See Figure 15 for the location and spatial extend of the different source regions.

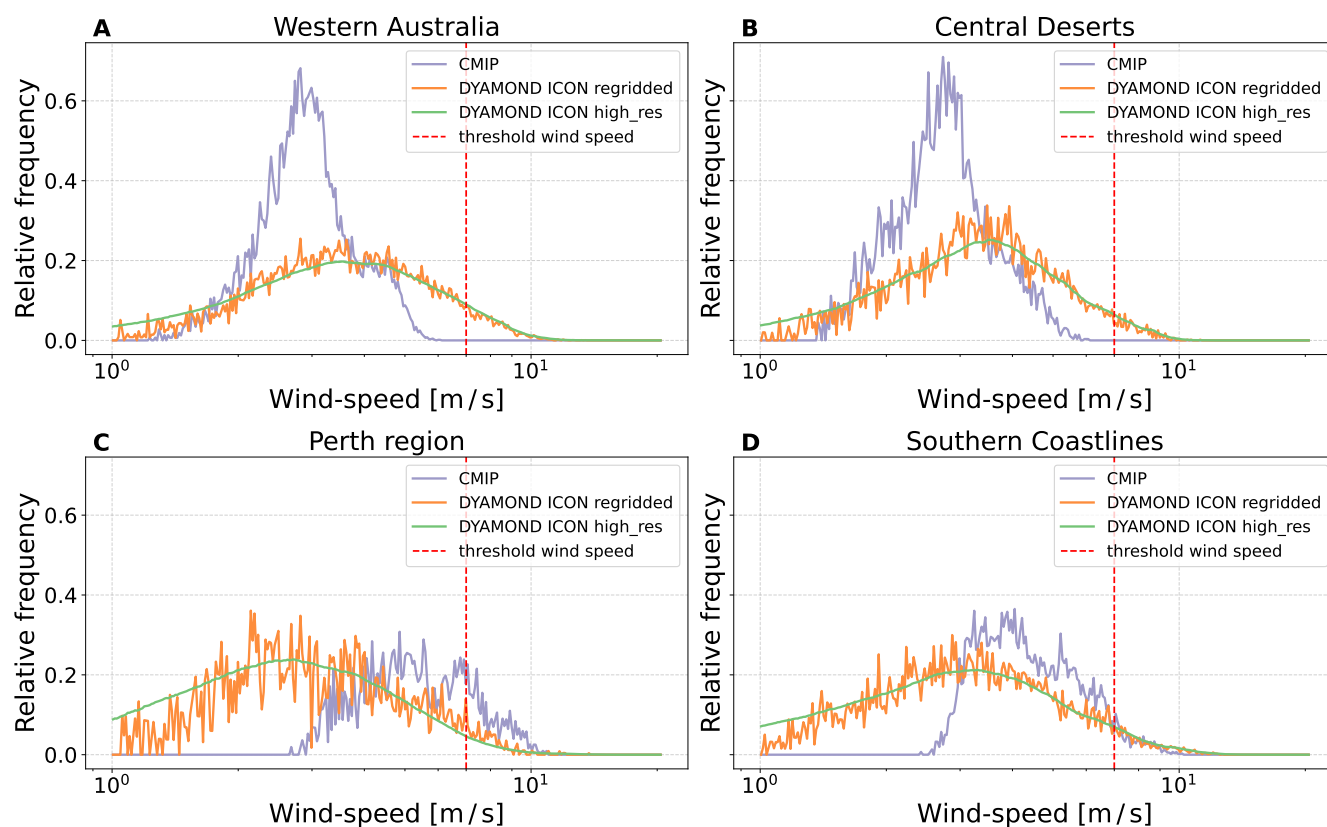


Figure A20. Histogram of 10-m wind speed over Australia for August 2026, from low-resolution CMIP6 data, high-resolution DYAMOND data, and DYAMOND data resampled to the CMIP6 grid for (a) Western Australia, (b) the Central Deserts, (c) the Perth region and (d) the southern Coastlines. See Figure 15 for the location and spatial extend of the different source regions. The dashed red line indicates the threshold wind speed assumed for dust mobilization.



Author contributions. Pascal Kunze, Bernd Heinold and Ina Tegen developed the concept of this study. Pascal Kunze performed data analysis, prepared figures and wrote the initial draft. Bernd Heinold supervised the work and reviewed the article. Ina Tegen contributed to the conceptual development of this work, edited the manuscript, and provided suggestions on visualization and data analysis.

660 *Competing interests.* The authors declare that they have no conflict of interest

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665 and innovation programme under grant agreements No. 675191 and No. 823988. Both datasets were provided by the German Climate Computing Center (DKRZ). This work used computing resources at DKRZ under project IDs bb1004 and bb1153. We also acknowledge the use of DeepL, Writefull, and ChatGPT for improving the language quality of the manuscript and for assistance with coding and debugging the scripts used to generate the figures.



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