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Guidelines on
Sand and Dust Storm Mitigation

Review of monitoring, forecasting and impact assessment to improve warning services and support interdisciplinary approaches

WORLD METEOROLOGICAL ORGANIZATION

Guidelines on Sand and Dust Storm Mitigation

Review of Monitoring, Forecasting and Impact Assessment to Improve Warning Services and Support Interdisciplinary Approaches

(GAW Report No. 305)

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EXECUTIVE SUMMARY

Mineral dust emitted from drylands is one of the most abundant aerosols in the atmosphere. Tiny dust particles can be transported thousands of kilometres away from sources by the atmosphere, and deposited on land and in the ocean. Sand and dust storms (SDS) have major impacts on weather, climate, the Earth's ecosystems, air quality and human health, as well as on various socioeconomic sectors, including ground transportation, aviation, agriculture and solar energy. SDS inflict severe harm to property and infrastructure, thus leading to significant economic losses. Negative SDS effects include decreased safety of ground, marine and aviation transportation; reduced effectiveness of solar power plants; transport of agricultural and human pathogens; and diminished air quality. Despite the documented risks associated with SDS, they are often underestimated by the public. There are, however, certain beneficial effects of dust on the environment. Minerals carried by airborne dust and deposited in the ocean and on land provide important nutrients for the biosphere – iron, phosphorus and silicon oxides in mineral dust are major micronutrients for remote ecosystems.

In 2007, in response to high societal interest in SDS, WMO endorsed launching the WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS). Its mission is to deliver timely information on SDS and advise WMO Members and other United Nations organizations on the potential impacts of SDS on society and the environment. Over the past decade, the SDS community has intensified efforts to fill gaps in forecasts and assessments on the one hand, and to help mitigate negative SDS impacts on the other. WMO and relevant United Nations organizations responsible for implementing optimal measures to mitigate potentially disastrous SDS impacts have started collaborating through the United Nations Coalition on Combating SDS. The Coalition was launched in September 2019 and is a partnership of more than 15 United Nations agencies and non-United Nations organizations. It seeks to catalyse global and regional actions to reduce SDS impacts on people's health, agriculture, the environment and other economic activities. The predictability of SDS needs to be improved to support mitigation and adaptation strategies, including early warning systems.

Scientific advances in SDS forecasting enable reliable information with sufficient accuracy and lead time to be issued to users in the form of warnings about incoming SDS events. The main objective of the present publication is to advise National Meteorological and Hydrological Services (NMHSs) and other governmental agencies (such as Environmental Protection Agencies (EPAs)) on how to effectively "translate" SDS monitoring, predictions and assessments into impact-based forecasts and warning services. The impact-based section reviews approaches proposed for long-term assessments and producing short-term impact-forecast for sectors/activities affected by SDS (for example, health, the environment, energy, transport, agriculture and climate). It also details good practices in developing impact-based forecast and warning services for the public as well as end users in specific socioeconomic sectors.

Close collaboration between NMHSs and other relevant international, regional and national organizations with additional expertise, resources and knowledge (for example, demographic data, geographical distribution of environmental and economic resources/conditions) is required for successful impact-based forecasting and/or assessment. Such collaboration should enable the delivery of impact-based services that NMHSs cannot provide on their own. This concept is consistent with *The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129) and with the *WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services* (WMO-No. 1150).

الملخص التنفيذي

الغبار المعدني، المُنبعث من الأراضي الجافة، هو أحد أكثر الأهباء الجوية وفرة في الغلاف الجوي. ويمكن لجسيمات الغبار الصغيرة أن تنتقل آلاف الكيلومترات بعيداً عن مصادرها عن طريق الغلاف الجوي، وأن تترسب على اليابسة وفي المحيطات. وتؤثر العواصف الرملية والترابية تأثيراً كبيراً على الطقس، والمناخ، والنظم الإيكولوجية لكوكب الأرض، وجودة الهواء، وصحة الإنسان، وكذلك على مختلف القطاعات الاجتماعية والاقتصادية التي تشمل النقل البري والطيران والزراعة والطاقة الشمسية. وتُلحق العواصف الرملية والترابية أضراراً جسيمة بالممتلكات والبنية التحتية، ومن ثم تؤدي إلى خسائر اقتصادية فادحة. ومن الآثار السلبية لهذه العواصف قلة سلامة النقل البري والبحري والجوي، وتراجع فعالية محطات الطاقة الشمسية، وانتقال مُسبّبات الأمراض التي تصيب النبات والإنسان، وانخفاض جودة الهواء. وعلى الرغم من المخاطر المُوثَّقة المرتبطة بالعواصف الرملية والترابية، فإنها لا تحظى بالاهتمام الكافي من جانب عموم الناس في كثير من الأحيان. بيْد أن للتراب بعض الآثار المفيدة على البيئة. والمعادن التي يحملها التراب جواً وتترسب في المحيطات وعلى اليابسة هي مُغذِّيات مهمة للغلاف الحيوي – فأكاسيد الحديد والفسفور والسيليكون التي يحملها الغبار المعدني هي مُغذِّيات دقيقة رئيسية للنظم الإيكولوجية النائية.

وفي عام 2007، واستجابة لتزايد الاهتمام المجتمعي بالعواصف الرملية والترابية، وافقت المنظمة العالمية للأرصاد الجوية على إطلاق نظامها للإنذار بالعواصف الرملية والترابية وتقييمها (SDA-WAS). وتتمثل مهمة هذا النظام في توفير معلومات في الوقت المناسب عن هذه العواصف، وتقديم المشورة لأعضاء المنظمة وسائر منظمات الأمم المتحدة بشأن الآثار المحتملة لهذه العواصف على المجتمع والبيئة. وطيلة العقد الماضي، كثَّفت الأوساط المعنية بالعواصف الرملية والترابية جهودها لسد الفجوات في مجال التنبؤ بهذه العواصف وتقييمها من جهة، وللمساعدة في التخفيف من الآثار السلبية لهذه العواصف من جهة أخرى. وقد بدأت المنظمة العالمية للأرصاد الجوية ومنظمات الأمم المتحدة المعنية والمسؤولة عن تنفيذ التدابير المثلى للتخفيف من الآثار الكارثية المحتملة للعواصف الرملية والترابية في التعاون فيما بينها تحت مظلة تحالف الأمم المتحدة المعني بمكافحة العواصف الرملية والترابية، الذي انطلق في أيلول/ سبتمبر 2019، وهذا التحالف هو شراكة تضم أكثر من 15 من وكالات الأمم المتحدة والمنظمات غير التابعة للأمم المتحدة. ويسعى التحالف إلى تحفيز العمل العالمي والإقليمي الرامي إلى الحد من آثار العواصف الرملية والترابية على صحة الناس، والزراعة، والبيئة، والأنشطة الاقتصادية الأخرى. ولا بد من تحسين القدرة على التنبؤ بهذه العواصف من أجل دعم استراتيجيات التخفيف والتكيف، ومنها نظم الإنذار المبكر.

ويساعد التقدم العلمي في مجال التنبؤ بالعواصف الرملية والترابية على تزويد المستخدمين بمعلومات موثوقة تتسم بالدقة الكافية وتتاح في الوقت المناسب، وتأخذ هذه المعلومات شكل إنذارات بشأن ظواهر العواصف الرملية والترابية التي ستحدث في المستقبل. ويتمثل الهدف الرئيسي من هذا المطبوع في إسداء النصح والمشورة إلى المرافق الوطنية للأرصاد الجوية والهيدرولوجيا (NMHSs) وسائر الهيئات الحكومية (مثل الهيئات المعنية بحماية البيئة) بشأن كيفية "ترجمة" مراقبة العواصف الرملية والترابية وتنبؤاتها وتقييماتها بفعالية إلى تنبؤات وخدمات إنذار قائمة على الآثار. ويرد في هذا المطبوع قسم خاص بالآثار يستعرض النُّهُجَ المقترَحة للتقييمات على المدى الطويل، وإعداد تنبؤات بالآثار على المدى القصير تستفيد منها القطاعات/ الأنشطة التي تتأثر بالعواصف الرملية والترابية (ومنها على سبيل المثال قطاع الصحة والبيئة والطاقة والنقل والزراعة والمناخ). كذلك، يبين هذا القسم بالتفصيل الممارسات الجيدة في تطوير خدمات التنبؤ والإنذار القائمة على الآثار الموجَّهة للجمهور والمستخدمين في قطاعات اجتماعية واقتصادية معينة.

ولا غنى عن التعاون الوثيق بين المرافق الوطنية للأرصاد الجوية والهيدرولوجيا وسائر المنظمات المعنية على الأصعدة الدولية والإقليمية والوطنية التي تتمتع بالمزيد من الخبرات والموارد والمعارف (ومنها على سبيل المثال البيانات الديمغرافية، والتوزيع الجغرافي للموارد/ الأوضاع البيئية والاقتصادية) حتى يُكتَب النجاح للتنبؤ و/أو التقييم القائمين على الآثار. وينبغي أن يساعد هذا التعاون على تقديم الخدمات القائمة على الآثار التي يتعذر على المرافق الوطنية للأرصاد الجوية والهيدرولوجيا أن تقدمها بمفردها. وينسجم هذا المفهوم مع *استراتيجية المنظمة العالمية للأرصاد الجوية لتقديم الخدمات وخطتها التنفيذية* (مطبوع المنظمة رقم 1129) *"The WMO Strategy for Service Delivery and Its Implementation Plan"*، و*المبادئ التوجيهية للمنظمة العالمية للأرصاد الجوية بشأن خدمات التنبؤ والإنذار بالأخطار المتعددة على أساس الآثار* (مطبوع المنظمة رقم 1150).

执行摘要

旱地排放的矿物粉尘是大气中最富集的气溶胶之一。微小粉尘颗粒可被大气带到数千公里以外，并沉积在陆地和海洋中。沙尘暴（SDS）对天气、气候、地球生态系统、空气质量和人类健康以及包括地面交通、航空、农业和太阳能在内的各个社会经济部门产生了重大影响。SDS会严重损害财产和基础设施，导致重大经济损失。SDS的负面影响包括削弱地面、海上和航空运输安全；减少太阳能发电厂的有效性；传播农业和人类病原体；降低空气质量。尽管与SDS相关的风险多有胜记，但公众往往低估这些风险。不过，粉尘对环境也有一定的有益影响。由浮尘携带并沉积在海洋和陆地的矿物为生物圈提供了重要营养物质 - 矿物粉尘中的铁、磷和硅氧化物是偏远地区生态系统的主要微量营养物。

2007年，为响应社会对SDS的高度关注，WMO核准并启动了WMO沙尘暴警报咨询与评估系统（SDS-WAS）。其使命是及时提供SDS相关信息，并就SDS对社会和环境的潜在影响向WMO会员和其他联合国组织提供咨询意见。在过去的十年中，SDS界一方面大力填补预报与评估方面的空白，一方面协助减轻SDS的负面影响。WMO与负责实施最佳措施以减轻SDS潜在灾难性影响的相关联合国组织已开始通过“联合国抗击SDS联盟”展开合作。该联盟于2019年9月启动，是15个以上联合国机构和非联合国组织组成的伙伴关系。它旨在促进全球和区域行动、减少SDS对人类健康、农业、环境和其他经济活动的影响。SDS的可预测性还有待提高，以支持包括预警系统在内的减缓和适应战略。

SDS预测科学已有很大进展，能够以警报形式向用户提供即将发生的SDS事件的可靠信息，且具有足够的准确性和提前时间。本出版物的主要目标是就如何有效地将SDS监测、预测和评估“转化”为基于影响的预报和警报服务，向国家气象水文部门（NMHS）及其他政府机构（如环境保护机构（EPA））提供咨询意见。基于影响的一节审查了为长期评估和为受SDS影响的部门/活动（如卫生、环境、能源、运输、农业和气候）编制短期影响预报拟议的办法。它还详细介绍了为公众及特定社会经济部门的最终用户开发基于影响的预报和警报服务的良好做法。

NMHS与拥有其他长才、资源和知识（如人口数据、环境和经济资源/条件的地理分布）的其他相关国际、区域和国家级组织之间需要密切合作，以便成功开展基于影响的预测和/或评估。此类合作应能提供NMHS无法单独提供的基于影响的服务。这一概念符合《WMO服务提供战略及其实施计划》（WMO-No.1129）以及《WMO基于影响的多灾种预报和预警服务指导原则》（WMO-No.1150）。

RESUME ANALYTIQUE

La poussière minérale émise par les terres arides est l’un des aérosols les plus abondants dans l’atmosphère. De minuscules particules de poussière peuvent être transportées par l’atmosphère à des milliers de kilomètres de leurs sources pour se déposer sur les terres émergées et dans les océans. Les tempêtes de sable et de poussière ont un impact majeur sur les conditions météorologiques et climatiques, les écosystèmes terrestres, la qualité de l’air et la santé humaine, ainsi que sur divers secteurs socio-économiques, notamment les transports terrestres, l’aviation, l’agriculture et la production d’énergie solaire. Elles causent de graves dommages aux biens et aux infrastructures et occasionnent par conséquent des pertes économiques considérables. Leurs effets négatifs incluent une diminution de la sécurité des transports terrestres, maritimes et aériens; une réduction de l’efficacité des centrales solaires; le transport d’agents pathogènes agricoles et humains; et un abaissement de la qualité de l’air. Malgré les risques bien établis qui leur sont associés, elles sont souvent sous-estimées par le public. Il existe cependant certains effets bénéfiques de la poussière sur l’environnement. Les minéraux transportés par les poussières atmosphériques et déposés dans les océans et sur les terres émergées fournissent des nutriments importants pour la biosphère. Ainsi, les oxydes de fer, de phosphore et de silicium présents dans les poussières minérales sont des micronutriments essentiels pour les écosystèmes distants.

En 2007, pour répondre au vif intérêt du public pour ce phénomène, l’Organisation météorologique mondiale (OMM) a approuvé le lancement du Système d’annonce et d’évaluation des tempêtes de sable et de poussière (SDS-WAS). Ce système a pour mission de fournir des informations actualisées et d’émettre des avis, à l’intention des Membres de l’OMM et d’autres organismes des Nations Unies, sur l’impact potentiel de ces tempêtes sur les populations et sur l’environnement. Ces dix dernières années, les spécialistes du domaine ont redoublé d’efforts tant pour combler les lacunes en matière de prévision et d’évaluation que pour contribuer à atténuer les retombées négatives de ces tempêtes. Dans le cadre de la Coalition des Nations Unies pour la lutte contre les tempêtes de sable et de poussière, l’OMM a commencé à collaborer avec des organismes des Nations Unies chargés d’appliquer des mesures optimales d’atténuation des répercussions potentiellement désastreuses de ces tempêtes. La Coalition a été lancée en septembre 2019 et rassemble plus de 15 organismes, appartenant ou non au système des Nations Unies. Elle vise à stimuler les activités mondiales et régionales destinées à atténuer les effets de ces tempêtes sur la santé des populations, l’environnement, l’agriculture, et d’autres activités économiques. Il est nécessaire d’améliorer la prévisibilité des tempêtes de sable et de poussière pour soutenir les stratégies d’atténuation et d’adaptation, y compris les systèmes d’alerte précoce.

Les progrès scientifiques réalisés dans le domaine de la prévision de ces tempêtes permettent de fournir aux utilisateurs des informations fiables, suffisamment précises et rapides sous la forme d’alertes relatives aux tempêtes à venir. L’objectif principal de la présente publication est de donner des conseils aux Services météorologiques et hydrologiques nationaux (SMHN) et aux entités gouvernementales (comme les organismes de protection de l’environnement) sur la façon de transposer efficacement les résultats de la surveillance, de la prévision et de l’évaluation de ces tempêtes en prévisions axées sur les impacts et en services d’alerte. La section de la publication consacrée aux impacts permet de passer en revue les approches proposées s’agissant des évaluations à long terme et de la production de prévisions d’impact à courte échéance pour les secteurs/activités touchés par les tempêtes de sable et de poussière (par exemple, la santé, l’environnement, l’énergie, les transports, l’agriculture et le climat). Y sont également détaillées les bonnes pratiques en matière de développement de services de prévision et d’alerte axées sur les impacts à destination du public et des utilisateurs finals de secteurs socio-économiques spécifiques.

Il convient que les SMHN collaborent étroitement avec des organisations internationales, régionales et nationales disposant de compétences, de ressources et de connaissances supplémentaires (par exemple, données démographiques, répartition géographique des ressources/conditions environnementales et économiques) pour que les prévisions et/ou évaluations axées sur les impacts portent leurs fruits. Une telle collaboration devrait permettre d'offrir des services axés sur les impacts que les SMHN ne peuvent fournir seuls. Ce concept de collaboration concorde avec la *Stratégie de l'OMM en matière de prestation de services et plan de mise en œuvre* (OMM-N° 1129) et les *Directives de l'OMM sur les services de prévision et d'alerte multidanger axées sur les impacts* (OMM-N° 1150).

РЕЗЮМЕ

Минеральная пыль, выбрасываемая из засушливых районов — один из самых распространенных аэрозолей в атмосфере. Крошечные частицы пыли могут переноситься атмосферой на тысячи километров от источников и оседать на суше и в океане. Песчаные и пыльные бури (ППБ) оказывают серьезное воздействие на погоду, климат, экосистемы Земли, качество воздуха и здоровье людей, а также на различные социально-экономические секторы, включая наземный транспорт, авиацию, сельское хозяйство и солнечную энергетику. ППБ наносят серьезный ущерб имуществу и инфраструктуре, что приводит к значительным экономическим потерям. К негативным последствиям ППБ относятся снижение безопасности наземного, морского и авиационного транспорта, снижение эффективности солнечных электростанций, перенос сельскохозяйственных и человеческих патогенов, а также ухудшение качества воздуха. Несмотря на документально подтвержденные риски, связанные с ППБ, общественность часто недооценивает их. Однако существует и определенное благотворное воздействие пыли на окружающую среду. Минералы, переносимые пылью по воздуху и оседающие в океане и на суше, обеспечивают биосферу важными питательными веществами — оксиды железа, фосфора и кремния, содержащиеся в минеральной пыли, являются основными микроэлементами для удаленных экосистем.

В 2007 году, в ответ на высокий интерес общества к ППБ, ВМО одобрила запуск Системы предупреждений ВМО о песчаных и пыльных бурях и их оценки (СДС-ВАС). Ее задача — предоставлять своевременную информацию о ППБ и консультировать Членов ВМО и другие организации системы Организации Объединенных Наций по вопросам потенциального воздействия ППБ на общество и окружающую среду. За последнее десятилетие сообщество специалистов по ППБ активизировало усилия по заполнению пробелов в прогнозах и оценках, с одной стороны, и по смягчению негативных последствий ППБ, с другой. ВМО и соответствующие организации системы Организации Объединенных Наций, ответственные за осуществление оптимальных мер по смягчению потенциально катастрофических последствий ППБ, начали сотрудничать в рамках Коалиции Организации Объединенных Наций по борьбе с ППБ. Коалиция была создана в сентябре 2019 года и представляет собой партнерство более чем 15 учреждений Организации Объединенных Наций и организаций, не входящих в систему Организации Объединенных Наций. Она призвана стимулировать глобальные и региональные действия по снижению воздействия ППБ на здоровье людей, сельское хозяйство, окружающую среду и другие виды экономической деятельности.

Научные достижения в области прогнозирования ППБ позволяют предоставлять пользователям надежную информацию с достаточной точностью и заблаговременностью в виде предупреждений о приближающихся событиях ППБ. Основная цель настоящей публикации — дать рекомендации национальным метеорологическим и гидрологическим службам (НМГС) и другим правительственным учреждениям (таким как агентства по охране окружающей среды (EPA)) о том, как эффективно преобразовать мониторинг, прогнозы и оценки ППБ в обслуживание основанными на воздействии прогнозами и предупреждениями. В разделе, посвященном воздействию, рассматриваются подходы, предлагаемые для проведения долгосрочных оценок и составления краткосрочных прогнозов с учетом воздействия для секторов/деятельности, на которые влияют ППБ (например, здравоохранение, окружающая среда, энергетика, транспорт, сельское хозяйство и климат). В нем также подробно описывается передовой опыт разработки основанных на воздействии прогнозов и предупреждений для населения, а также конечных пользователей в конкретных социально-экономических секторах.

Тесное сотрудничество между НМГС и другими соответствующими международными, региональными и национальными организациями, обладающими дополнительным

опытом, ресурсами и знаниями (например, демографическими данными, географическим распределением экологических и экономических ресурсов/условий), необходимо для успешного прогнозирования и/или оценки воздействия. Такое сотрудничество должно способствовать предоставлению обслуживания, основанного на воздействии, которое НМГС не могут предоставлять самостоятельно. Эта концепция согласуется со *Стратегией ВМО в области предоставления обслуживания и Планом ее осуществления* (ВМО-№ 1129) *Руководящими указаниями ВМО по обслуживанию прогнозами и предупреждениями о многих опасных явлениях с учетом их возможных последствий* (ВМО-№ 1150).

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RESUMEN EJECUTIVO

El polvo mineral proveniente de zonas áridas es uno de los aerosoles más abundantes en la atmósfera. Esas diminutas partículas de polvo pueden ser transportadas por la atmósfera a miles de kilómetros de distancia de su fuente y depositarse en tierra y en los océanos. Las tormentas de arena y polvo tienen consecuencias de gran calado para el tiempo, el clima, los ecosistemas de la Tierra, la calidad del aire y la salud de las personas, así como para varios sectores socioeconómicos, en especial los del transporte terrestre, la aviación, la agricultura y la energía solar. Además, provocan daños graves a bienes e infraestructuras, lo que acarrea elevadas pérdidas económicas. Entre sus efectos negativos se cuentan la disminución de la seguridad del transporte por tierra, mar y aire; la reducción de la eficiencia de las centrales eléctricas solares; el transporte de agentes patógenos que afectan a personas y plantas, y el deterioro de la calidad del aire. Si bien los riesgos que acarrean están documentados, la sociedad suele subestimarlos. A pesar de lo anterior, el polvo también tiene algunos efectos positivos para el medioambiente. Los minerales que transporta el polvo en suspensión en el aire y que se depositan en tierra y en los océanos aportan importantes nutrientes a la biosfera: el óxido de hierro, fósforo y silicio presentes en el polvo mineral constituyen micronutrientes capitales para ciertos ecosistemas remotos.

En 2007, como respuesta al elevado interés de la sociedad en las tormentas de arena y polvo, se puso en marcha, bajo los auspicios de la Organización Meteorológica Mundial (OMM), el Sistema de Evaluación y Asesoramiento para Avisos de Tormentas de Arena y Polvo de la OMM (SDS-WAS). Su objetivo es proporcionar información oportuna sobre las tormentas de arena y polvo e informar a los Miembros de la OMM y otras organizaciones de las Naciones Unidas acerca de las consecuencias potenciales de estos fenómenos para la sociedad y el medioambiente. Durante el último decenio, los colectivos que se ocupan de las tormentas de arena y polvo han redoblado esfuerzos a fin de subsanar las carencias en materia de pronóstico y evaluación y ayudar a mitigar las consecuencias negativas de las tormentas. La OMM y las organizaciones pertinentes de las Naciones Unidas encargadas de aplicar medidas óptimas para mitigar las potenciales consecuencias desastrosas de las tormentas de arena y polvo empezaron a colaborar en el marco de la Coalición de las Naciones Unidas para Luchar contra las Tormentas de Arena y Polvo. La Coalición vio la luz en septiembre de 2019 y ha establecido asociaciones con más de 15 organismos de las Naciones Unidas y organizaciones ajenas al sistema de las Naciones Unidas. Tiene por objeto dinamizar las medidas a escala mundial y regional para reducir los efectos de las tormentas de arena y polvo sobre la salud de las personas, la agricultura, el medioambiente y otras actividades económicas. Mejorar el pronóstico de las tormentas de arena y polvo ayudará a aplicar las estrategias de mitigación y adaptación, en especial respecto a los sistemas de alerta temprana.

El progreso científico en materia de pronóstico de las tormentas de arena y polvo permite generar avisos que dotan a los usuarios de información sobre estos fenómenos con una exactitud y antelación suficientes. El principal objetivo de la presente publicación es informar a los Servicios Meteorológicos e Hidrológicos Nacionales (SMHN) y a otros organismos gubernamentales (como las Agencias de Protección Ambiental) sobre cómo aprovechar el monitoreo, los pronósticos y las evaluaciones de las tormentas de arena y polvo para elaborar previsiones y servicios de aviso que tengan en cuenta los impactos. En el apartado sobre la toma en consideración de los impactos se examinan varias estrategias para elaborar evaluaciones a largo plazo y previsiones a corto plazo que tengan en cuenta los impactos para sectores y actividades que se ven afectados por las tormentas de arena y polvo, entre otros, la salud, el medioambiente, la energía, el transporte, la agricultura y el clima. Asimismo, se detalla una serie de buenas prácticas para la elaboración de previsiones y servicios de aviso que tengan en cuenta los impactos destinados a la sociedad, así como a los usuarios finales de sectores socioeconómicos concretos.

Para disponer de buenas evaluaciones y previsiones que tengan en cuenta los impactos, es esencial la colaboración estrecha entre los SMHN y otras organizaciones pertinentes a escala internacional, regional y nacional que puedan aportar más información, recursos y conocimientos especializados, como datos demográficos o información sobre la distribución espacial de las condiciones y los recursos medioambientales y económicos. Dicha colaboración posibilitaría la prestación de servicios que tengan en cuenta los impactos que los SMHN no pueden ofrecer por sí solos, lo que es coherente con La Estrategia de prestación de servicios de la OMM y su Plan de aplicación (OMM-Nº 1129) y las Directrices de la OMM sobre servicios de predicción y aviso de peligros múltiples que tienen en cuenta los impactos (OMM-Nº 1150).

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1. SAND AND DUST STORM IMPACTS

Sand and dust storms (SDS) are natural atmospheric events generated in arid and semi-arid regions, usually caused by strong near-surface winds associated with thunderstorms and frontal synoptic conditions. During these weather-driven extreme events, large amounts of particles of a broad range of sizes are uplifted from the soil. Sand and dust distinguish the size of the particles involved in SDS – "sand" refers to coarse particles (with diameters of > 60 micrometres (mm)) and "dust" refers to finer particles (with diameters of < 60 mm, including silt and clay).

SDS sources can be defined either as a bare topsoil surface susceptible to wind erosion or any surface capable of emitting soil particles in favourable wind conditions (Vukovic, 2019; Klose et al., 2022). Favourable conditions for the emission of soil particles from such surfaces include low topsoil moisture, unfrozen soil and surface wind velocity above a certain threshold, closely related to particle size distribution. Surface soil is susceptible to wind erosion when it contains smaller dust particles, especially if it is disturbed in such a way that particles are easily dislodged and uplifted. Depending on changes in activity, SDS sources may be permanent or dynamic. Human activities can affect the formation of SDS, and anthropogenic sources come from different sectors of the economy: agriculture, water, forestry, energy, transportation and so forth. Knowledge of SDS sources is a necessary input for risk and impact assessments, mitigation planning, forecasting and the establishment of early warning systems (EWSs).

Megatons of dust are lifted each year into the atmosphere by strong near-surface winds. Dust particles can be transported from hundreds to thousands of kilometres away from sources (Figure 1). By interacting with radiation and clouds, dust modifies weather and climate. Furthermore, airborne dust particles deteriorate air quality, and those that are deposited on snow and ice reduce reflected solar radiation. Dust particles are a conglomerate of different components, including large proportions of minerals (also known as crustal) such as quartz, clay, carbonate, feldspar and iron oxide, and variable proportions of salts such as gypsum. Minerals in dust particles represent important nutrients that fertilize both terrestrial and marine ecosystems. The proportion of different minerals depends on the origin of the dust.

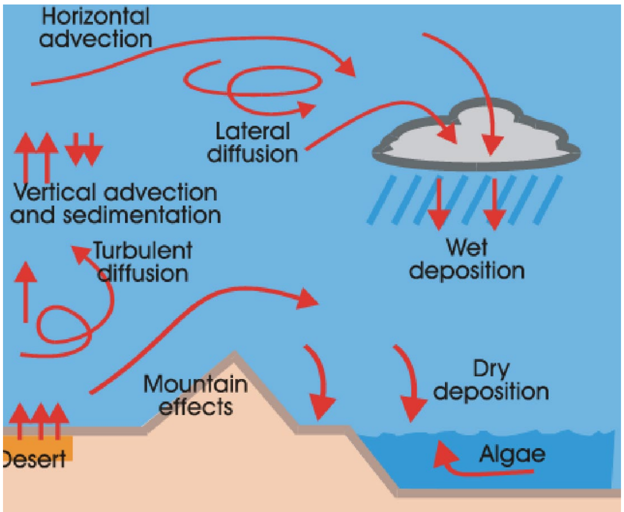


Figure 1. Atmospheric dust cycle

Source: Shao et al., 2011

Airborne dust is a serious risk for human health. The effect of dust on health depends on where dust is present and where people live. In places close to deserts, SDS can have an immediate negative impact on human health. Furthermore, long-term exposure to high concentrations of dust can cause premature death from cardiovascular disorders and lung cancer, especially in dusty areas like North Africa. Meningitis is another disease associated with the dusty season in Sub-Saharan Africa (Pérez, 2014). At least 1.2 million cases of bacterial meningitis are estimated to occur every year, with high mortality rates. It is thought that one of the causes of meningitis is the physical damage to lung tissue caused by dust particles, which allows bacteria to enter the bloodstream more easily. Moreover, iron oxides embedded in dust particles may enhance the risk of infection. SDS are also believed to trigger Valley fever – a potentially deadly disease – with dust acting transporting soil-dwelling fungi spores from the south-west United States of America, northern Mexico, and Central and South America (Tong et al., 2023a).

At a longer timescale, SDS are recognized as a climatic impact-driver, meaning that they can be considered as a climate hazard in risk assessments. The most recent Intergovernmental Panel on Climate Change (IPCC) reports (see https://www.ipcc.ch/reports/) conclude that SDS are still ranked as a climate factor with low confidence, and there is no agreement about the direction of future changes in dust emissions. It is recognized, with high confidence, that airborne dust concentrations are sensitive to changes in climate and land use. At the same time, climate change can alter dust sources and winds that generate the emission of airborne dust. Changes in land surface properties, like land cover, soil texture and composition, can be occasioned either by humans or by climate change. Consequently, although the most important connections between climate change and airborne dust are known, low confidence remains in respect of quantitative estimates of atmospheric dust transport due to climate change.

During the fourteenth session of the Conference of the Parties (COP 14) to the United Nations Convention to Combat Desertification (UNCCD) in 2019, the United Nations Coalition on Combating SDS was launched as a proactive approach to combat SDS, and to enhance cooperation and coordination in respect of SDS mitigation and adaptation strategies (FAO, 2022; see Annex 1). The Coalition is a partnership of more than 15 United Nations agencies and non-United Nations organizations aligned to take part in mitigating the impacts associated with SDS. The main goals of this Coalition are to address SDS-related problems in an organized and coherent way, on all scales (local, regional, global); to share and increase knowledge on, and actions to combat, SDS; and so forth. The Coalition recognizes that SDS impacts are felt all over the world, in all regions, in developing and developed countries alike, and that such impacts represent a challenge to achieving the Sustainable Development Goals (SDGs). There are several working groups within the Coalition, which address different sets of actions related to combating SDS, and WMO leads Working Group II: Forecasting and early warning.

SDS are among the most significant extreme meteorological phenomena. Owing to the significant amounts of airborne mineral dust particles generated during these events, SDS affect the climate, the environment, human health and many socioeconomic sectors (for example, aviation, road and air transport, solar energy production and solar energy management) (Nemuc et al., 2020).

There is strong societal interest in understanding, managing and mitigating the risks of SDS to, and their effects on, life, health, property, the environment and the economy (Figure 2). In the light of this, international initiatives (for example, the European Union-funded International Network to Encourage the Use of Monitoring and Forecasting Dust Products (inDust) (see https://www.cost.eu/actions/CA16202/)), are promoting the creation of networks involving researchers, providers and potential end users in order to develop tailored services.

Figure 2. Overview of SDS impacts

Source: inDust (see https://cost-indust.eu/)

1.1. The Earth system: interactions with weather, climate and ecosystems

The dust cycle includes emissions of mineral dust particles from the surface, their transport and transformation and deposition (Shao et al., 2011). Each of these components of the dust cycle comprehends complex processes of dust–environment interactions. In general, the dust cycle interacts with the Earth’s governing climate system cycles: energy, water and carbon. Processes that contribute to the dust cycle and its implications for the climate system (Box 1) are of a large range of spatial and timescales (from local to global, and from seconds to millions of years). Mineral aerosol, emitted into the atmosphere by near-surface turbulence and convective mixing, is injected in the higher layers of the atmosphere with dominant horizontal currents, where it can be transported far from source regions by synoptic and global-scale circulations. It is deposited on the surface – land and ocean – by dry or wet deposition and can be stabilized by wetting the surface and encouraging the formation of vegetation cover.

Box 1. Implications for the climate system of the dust cycle

The uniqueness of the impact of airborne dust transport on the climate system is that atmospheric dust originates from relatively small-scale extreme weather events. The emission of dust is highly dependent on surface conditions, interacts with the environment in a way closely related to the characteristics of the particles, and can have regional, and even global-scale, impacts, while being highly variable in space and time. Therefore, it is difficult to: (a) measure and model the implications of dust for the climate system; (b) understand the historical trends and spatial distribution of trends; and (c) predict the future behaviour of airborne dust transport and its role in

After sea salt, mineral dust is one of the most abundant aerosols by mass in the Earth’s atmosphere. The largest proportion of global dust emissions happen in desert areas when weather conditions produce high near-surface winds. While estimates of global dust emission amounts differ in literature (Luo et al., 2003; Zender et al., 2003;

Miller et al., 2004; Tanaka and Chiba, 2006; Andreae and Rosenfeld, 2008; Huneeus et al., 2011), recent calculations reach 5 000 Tg of particles finer than 20 μm (PM_{20})/year (3 400 Tg–8 900 Tg/year) (Ginoux et al., 2012; Kok et al., 2017; Kok et al., 2021a,: Kok et al., 2021b). All agree that the most productive sources are in Africa and Asia. Recent estimations by Kok et al. (2021a) conclude that North Africa contributes 50% of the global dust load (15% from south Sahara and Sahel) and Asia is the source of 40% (with three quarters from the Middle East and Central Asia and one quarter from East Asia). Minor source regions contribute 10% (with one quarter from North America and three quarters from Australia, South America and Southern Africa).

In respect of the ocean, the largest amount of dust is deposited over the North Pacific Ocean (close to 500 Mt) according to Duce and Tindale (1991). Later studies (Prospero, 1999; Ginoux at al., 2001; Luo et al., 2003; Zender et al., 2003; Tegen et al., 2004; Jickells et al., 2005) show that the largest deposition is over the North Atlantic (about 200 Mt), over the Indian Ocean (100 Mt) and over the North Pacific (30 Mt–100 Mt). Studies also show that dry deposition is responsible for up to two times more deposited dust than wet deposition, while in Ginoux et al. (2001), the ratio of dry to wet deposition is over 6 to 1. Most dust is deposited on land surfaces (77%–91%), and 9%–23% over the ocean. More details about the mineral dust cycle, intercontinental and global transports, interactions with the Earth system energy and carbon cycles, and consequently with the water cycle, can be found in Shao (2008) and Shao et al. (2011).

Rapid advances in Earth system numerical modelling and satellite observations, especially motivated by increasing climate change, have enabled further advances in assessing the dust cycle and related uncertainties. By using Coupled Model Intercomparison Project Phase 5 (CMIP5) data with aerosol reanalysis and observations, Wu et al. (2020) show that global dust emission in models differs by a factor of 4 to 5 for the same size range, with large differences in the spatial distribution of average annual emission rates. The model gave global emission estimates in the range 2 218 Tg–8 186 Tg yr^{-1} (or megatons (Mt) per year) for dust particles the size of clay or silt (up to 63 mm in diameter), and 735 Tg–3 598 Tg yr^{-1} for PM_{20}. Emissions from North Africa account for 36%–79% of global dust emissions; from the Middle East, 7%–20%; from East Asia, 4%–20%; from Central Asia, 1%–14%; and from South Asia, 0.9%–10%. Estimates of contributions from other major source areas (North America, Southern Africa, Australia, South America) are even less consistent among the models. Wu et al. (2020) highlight the importance of coupling dust emission with dynamic vegetation to better reproduce source areas and assume that it will reduce the uncertainties in global emission assessments and emission distribution. In these assessments, it is highlighted that Earth system models are not capturing the relevant contributions of smaller-scale processes.

Depending on the mineral composition of airborne dust, it interacts in different ways with governing climate system cycles. While transported in the atmosphere, iron oxides in dust directly affect the radiation balance by absorbing and reflecting short- and long-wave radiation (Sokolik and Toon, 1999). Airborne dust particles are weak short-wave absorbers ; however, dust absorbs long-wave radiation, causing heating, which consequently affects thermal conditions in the lower troposphere, cloud cover and so forth (Nickovic et al., 2004; Amiri-Farahani et al., 2017; Doherty and Evan, 2014). In this way, dust can alter atmospheric vertical heat distribution and affect atmospheric stability, and consequently vertical mixing and other related processes. Perturbation of the radiation energy balance can further affect atmospheric large-scale circulation. More about dust–radiation interaction can be found in Claquin et al. (1999), Balkanski et al. (2007), Schepanski (2018), Feng et al. (2022) and Gonçalves et al. (2023). Increasing the resolution of global models in respect of assessing the impact of dust on net radiation improves outputs, as presented in Feng et al. (2022).

Airborne mineral dust can trigger ice nucleation and the formation of higher clouds (Klein et al., 2010), and thereby significantly affect weather and climate. Dust mineral composition plays an important part in the ice nucleation process (for example, feldspar; DeMott et al., 2003). Field and numerical studies have shown that clay minerals (particles that are less than 2 mm) are dominant in this process (Pruppacher and Klett, 1997; Chen et al., 1998; Zimmermann et al., 2008). Parameterizations suitable for the inclusion of dust involvement in ice nucleation, depending on mineralogy (that is, mineral dust components), and the formation of cold clouds in atmospheric dust transport numerical modelling can be found in Lohmann and Diehl (2006) and Hoose et al. (2008). Conversely, mineral dust in the atmosphere may suppress precipitation and thereby intensify aridification, causing a possible desertification feedback loop, as explained in Rosenfield et al. (2001).

When dust is deposited over ice and snow, it reduces albedo and thereby increases the ability of the surface to absorb solar radiation, which can contribute to snow and ice melting (Warren, 1984). Consequently, dust can accelerate the thinning and disappearance of glaciers, which contributes to increasing the surface temperature and consequently the heating of the atmosphere. Sarangi et al. (2020) show that dust deposited over high-mountain Asia causes snow darkening and snow melt, and at altitudes of over 4,000 m the effects of are greater than those of deposited black carbon. With rising snowlines on account of climate change, the authors highlight the increasing contributions of dust to snowmelt.

Climate change can cause decreases in snow cover duration, retreat of glaciers and permafrost thaw, and increase the intensity and frequency of droughts and heatwaves. This leads to topsoil conditions that are more favourable for dust emission, thereby increasing the probability of SDS. However, in the global models used in IPCC assessments to estimate the impact of dust on the global climate, the effects of dust are still poorly represented.

Cryosphere – the frozen water part of the Earth system that includes, among others, snow cover, glaciers, ice caps and ice sheets – is an important part of the global climate system. Ice and snow in Greenland and Antarctica are the largest part of the cryosphere and play an important role in the Earth’s climate. Snow and ice reflect solar radiation, thus regulating the global thermal balance. Deposition of airborne dust on glaciers causes positive radiative forcing and enhances melting by reducing surface albedo. Small changes in the amount of radiation reflected and/or absorbed by snow or ice surfaces can have considerable impacts on the state of the cryosphere, and therefore on the Earth’s climate (Meinander et al., 2022). As polar regions are some of the most sensitive to climate shifts, the cryosphere includes places where global changes in the climate have been identified. Accelerated warming in the Arctic and Antarctica is of particular public and scientific concern. The IPCC has identified mineral dust aerosol as an important short-lived climate forcer (SLCF) and linked it with cryosphere changes (IPCC, 2019).

In the *Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC, 2021), SDS are recognized as a climatic impact-driver. They are driven by wind, and by changes in temperature and precipitation as emissions depend on land surface conditions. Overall, with medium confidence, the Report shows that SDS are increasing in some regions. However, large uncertainty in assessing these events, which supply the climate system with dust, remains. The conclusion is that there is low confidence in the direction of change in Africa, Asia, South America and Europe, and that there is an increasing trend, with medium confidence, in Australia and parts of North America. In some regions, SDS are not recognized as broadly relevant. Meinander et al. (2022) provided new data and improved knowledge for polar regions (see Box 2).

Box 2. Icelandic Aerosol and Dust Association

The Icelandic Aerosol and Dust Association (IceDust) is a scientific society committed to supporting research in the field of aerosol science, with a focus on dust at high latitudes. The main goals of IceDust are to:

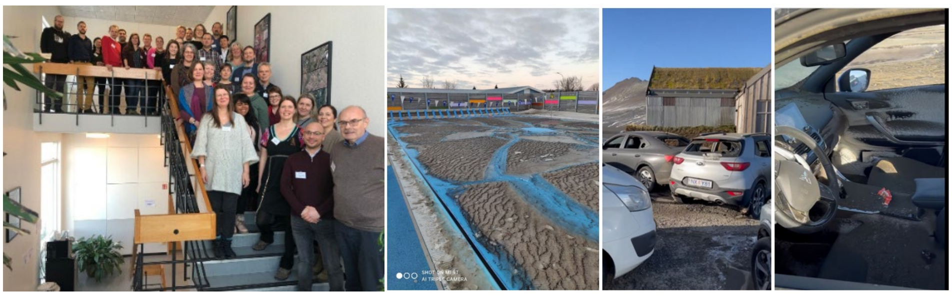
Promote collaboration and communication in the field of aerosol research in Iceland, with an emphasis on local volcanic dust;

Serve as a platform for communication between Icelandic and non-Icelandic aerosol researchers, as well as to provide missing information to other academic bodies from Iceland and abroad;

Increase awareness by producing easy-to-understand sources of knowledge on aerosol for the general public and media.

IceDust is keen on promoting knowledge of basic aerosol processes and expanding the broader discipline of aerosol science. It is a multinational organization with 109 members, including student members, from 55 research institutions in 21 countries. IceDust has held at least one general meeting a year since 2016, when it was established. The European Aerosol Assembly (EAA) accepted IceDust as a new member aerosol association in 2022. IceDust members are active in promoting high-latitude aerosol research at international level. They have produced over 50 scientific publications on high-latitude aerosol, with a focus on dust at high latitudes (see the full list here: https://icedustblog.wordpress.com/publications/) and maintaining high-latitude dust-related sessions at large international conferences such as the general assemblies of the European Geosciences Union (EGU) and the International Union of Geodesy and Geophysics (IUGG). Members also contribute to Arctic, Nordic, Antarctic and southern hemisphere networks. IceDust provides advisory services related to high-latitude dust, and operational dust forecasts for Iceland and through the Agricultural University of Iceland dust forecast service.

The largest high-latitude dust field campaign took place in the desert of Dyngjunsandur, north-east Iceland, in 2021, where more than 25 dust scientists from 11 research institutions in six countries conducted seven-week measurements to investigate high-latitude dust in a changing climate. Over fifty aerosol and meteorological instruments were employed on one main tower and multiple subsites to measure the atmospheric composition, soil properties and processes leading to dust emission and long-range transport towards the high Arctic and Europe, along with impacts on cloud formation and cryosphere.



(right) The International Arctic Science Committee (IASC) Workshop on Effects and Extremes of High Latitude Dust organized by IceDust at the Agricultural University of Iceland, Reykjavik, on 13 and 14 February 2019. (left) Damage caused by extreme dust storms in Iceland in 2022 (left: swimming pool in Hella, south Iceland; middle and right: damaged cars in Möðrudalur, north-east Iceland).

Source: Pavla Dagsson-Waldhauserova

In a recent publication, Kok et al. (2023) address the complex role of mineral dust in the climate system and give a summary of mechanisms through which dust interacts with the atmosphere, and thereby affects weather and climate (Figure 3).

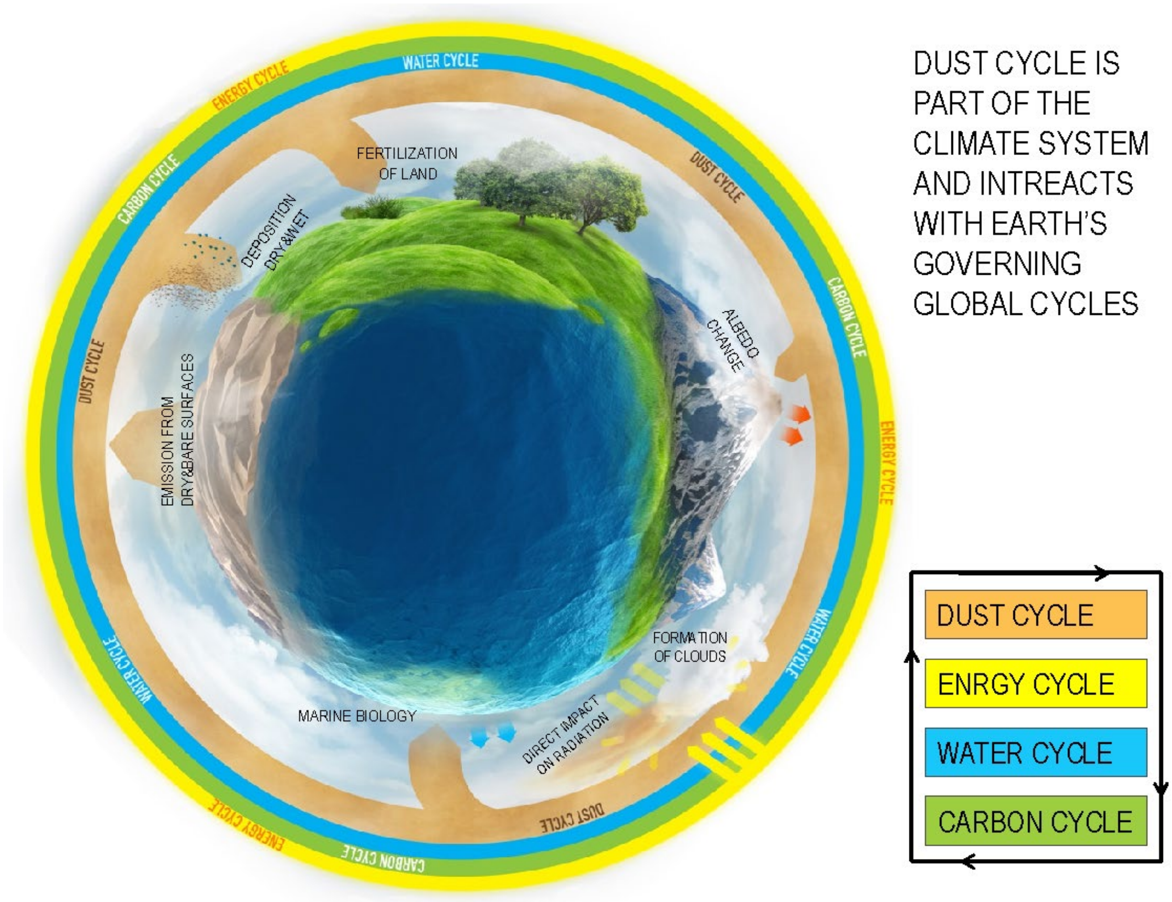


Figure 3. Simplified overview of the global dust cycle, which highlights the synergy of the governing cycles of the climate system and implications of the dust cycle. Note that not all impacts and interactions are included.

Source: Ana Vuković Vimić

Kok et al. (2023) assess the total effect of dust by choosing an indicator related to the impact of airborne dust on the Earth's energy budget– namely the dust effective radiative effect (Figure 4a). There is a 90% confidence interval that the dust effective radiative effect has a value of -0.2 ± 0.5 W m^{-2}. Consequently, on climate scales, it is highly probable that airborne dust reduces energy and may have a cooling effect. The intensity of direct and indirect radiative effects was assessed (Figure 4) and a range of confidence for each assessment was given. A comparison between the period 1981–2000 and pre-industrial times suggests that there has, more probably, been an increase in global atmospheric loading of 55% ± 30%. In addition, at the global level, records showed that airborne dust loading has increased in Asia, North Africa and the southern hemisphere. The authors find that climate models do not reproduce this historical increase in airborne dust loading and highlight the importance of improving the representation of dust in climate models. Another uncertainty of climate models in predicting/projecting dust cycles concerns their inability to reproduce intensive convective events, which cause high emissions of dust, on account of coarse resolution (Garcia-Carreras et al., 2021).

Changing land cover is a direct anthropogenic impact on airborne dust transport, causing more or less erodible surfaces, which may act as dust sources. Emissions of greenhouse gases are an indirect anthropogenic impact on the dust cycle – they affect atmospheric circulations, temperature and precipitation, and, consequently, can make surfaces more susceptible to wind erosion. Although assessments of anthropogenic dust fraction as a proportion of total atmospheric dust loading show a wide range of values, from 10% to 60% (IPCC, 2021), all highlight the importance of considering anthropogenic contributions to the global dust cycle.

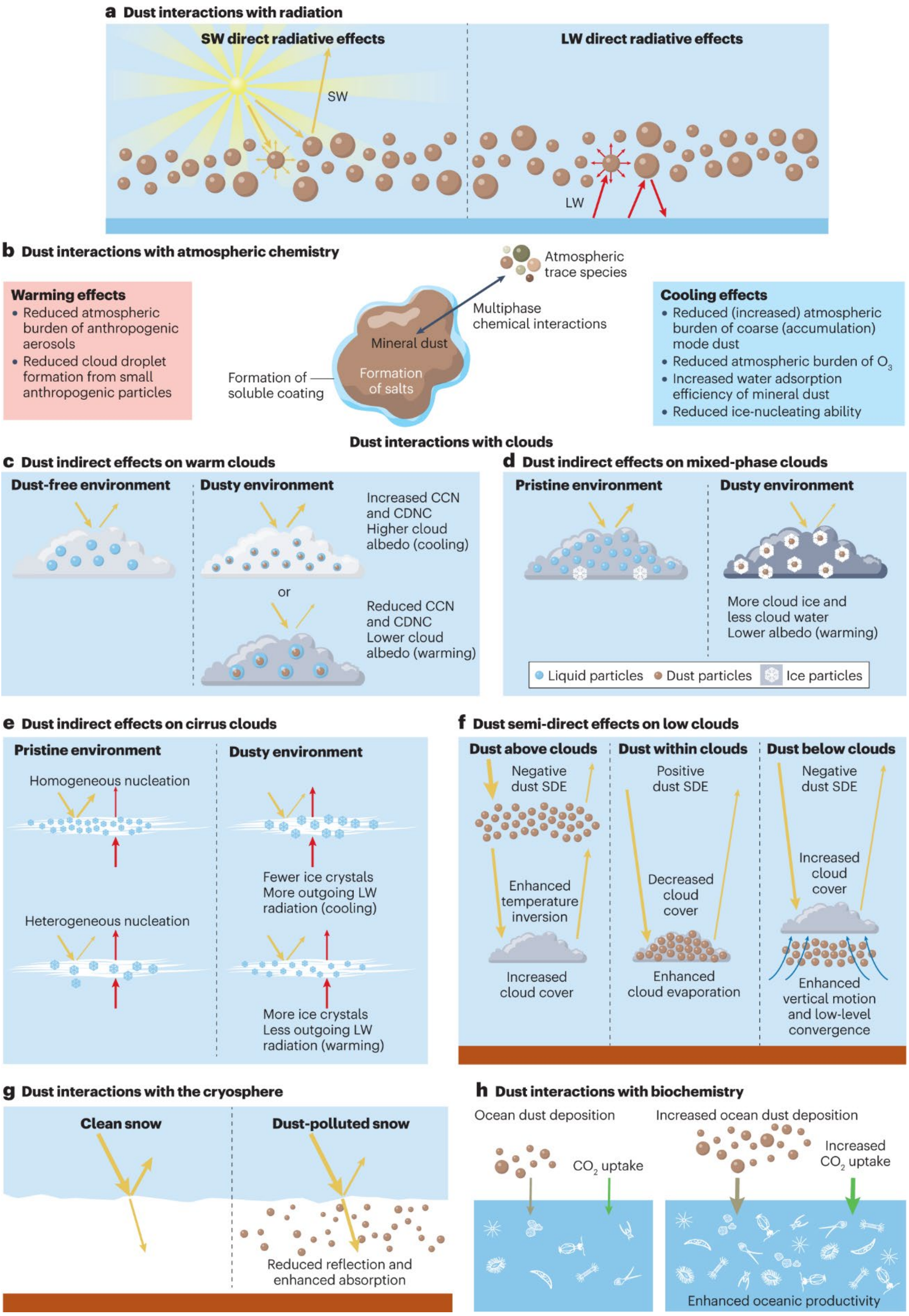


Figure 4. Mechanisms through which dust affects short-wave (SW) radiation (yellow arrows) and long-wave (LW) radiation (red arrows). Arrow thickness depends on intensity (thicker arrows represent higher energy radiation).

Key:

CCN = cloud condensation nuclei

CDNC = cloud droplet number concentration

CO_2 = carbon dioxide

O_3 = ozone
SDE = semi-direct effect

Source: Kok et al., 2023

Minerals carried by airborne dust and deposited on the ocean surface after long-range atmospheric transport can provide important nutrients for living organisms — Singh et al. (2008), for example, observed sea blooming several days after significant deposition of mineral dust, which temporarily decreased sea-surface temperature (SST). There are ocean regions (such as the Southern Ocean) that are rich in nutrients necessary for marine productivity yet have low chlorophyll, which is an indicator of effective marine primary production. In these zones, called "high-nutrient, low-chlorophyll" (HNLC) areas, it has been hypothesized that there is limited availability of iron as an ocean micronutrient (Box 3) (Martin, 1992). In comparison, the Tropical Atlantic and the Pacific are frequently exposed to Saharan and Asian dust containing iron, which enhances marine primary productivity (Figure 5). Iron is one of the key nutrients needed by phytoplankton during photosynthesis, and when phytoplankton grow, they absorb carbon dioxide (CO_2) dissolved in the water, which in turn draws the gas out of the air. Mahowald et al. (2010) showed that iron input into the ocean thereby contributes to carbon sequestration, which is important for decreasing net emissions (in other words, for mitigating climate change). In biogeochemical terms, therefore, the key flux into the ocean is not dust itself, but soluble (bioavailable) iron (Jickells et al., 2005).

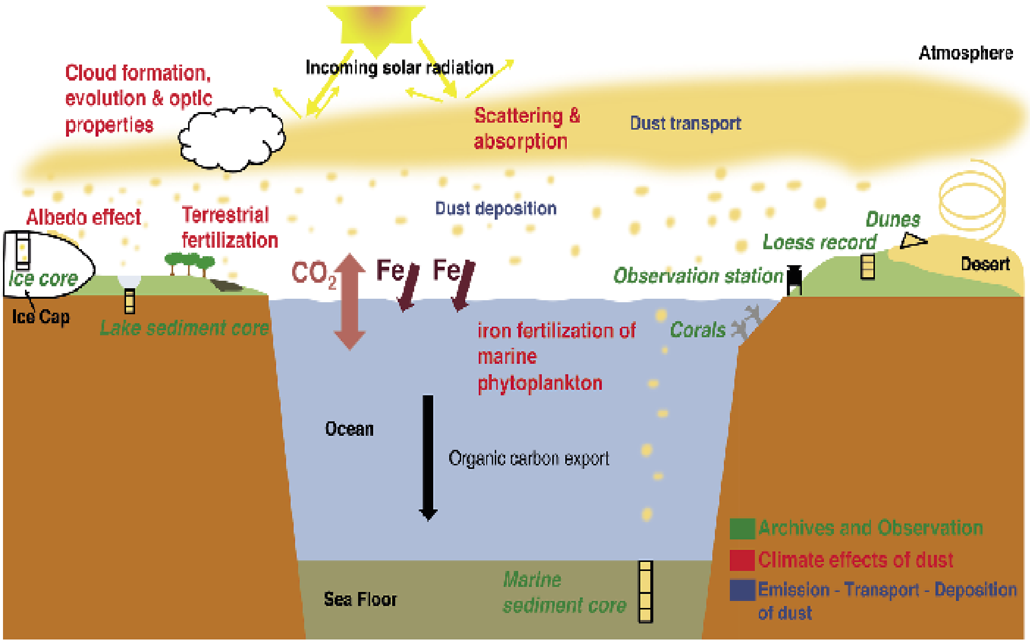


Figure 5. Schematic image showing mineral dust–ocean interaction

Key:
Fe = iron

Source: Winckler and Mahowald, 2014

Box 3. Iron as an ocean micronutrient

In July 1988, during a lecture at the Woods Hole Oceanographic Institution (WHOI), oceanographer John Martin stood up and said, “Give me a half tanker of iron, and I will give you an ice age”, so paraphrasing the words of Archimedes, “Give me a lever long enough and a fulcrum on which to place it, and I shall move the world”. Martin’s words were illustrating his theory, known as “the iron hypothesis”. Martin theorized that, by sprinkling a small amount of iron into HNLC areas of the ocean, one could create large blooms of unicellular marine plants commonly known as algae. If enough of these HNLC zones were fertilized with iron, Martin believed the growth in algae would take in so much carbon from the atmosphere that it would reverse the greenhouse effect and cool the Earth.

Several months after his death in 1993, the theory was proved to be correct by his colleagues at the Moss Landing Marine Laboratories (MLML). They spread an iron solution into a HNLC zone near the Galapagos Islands, and algae bloomed (Weier, 2001).

The photosynthetic activity of marine microorganisms depends on the solubility of the deposited iron. When emitted from soil sources, dust carries iron of a rather low solubility (typically less than 2%). However, iron solubility can increase by up to 80% during dust atmospheric transport (Baker and Jickells, 2006; Journet et al., 2008) owing to the following chemical processing mechanisms (Figure 6):

Clouds, which provide a relatively high acidic environment;

Solar radiation, causing photochemical processing;

Air pollution from biomass burning and industrial/urban emissions;

Dust particle size separation, whereby smaller particles remain longer in the atmosphere and are thus more exposed to chemical processing.

Furthermore, some dust-productive soils are potentially more soluble if, through their geological history, they have been more exposed to weathering through wetting and drying (Shi et al., 2011).

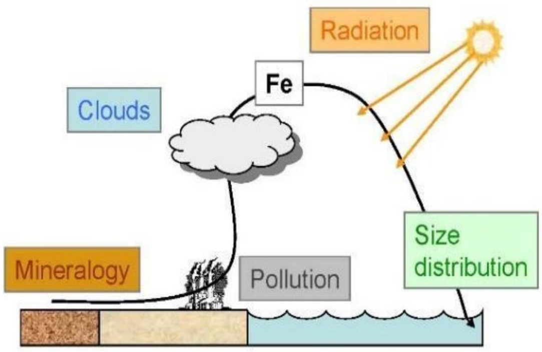


Figure 6. Iron atmospheric processing

Key:
Fe = iron

Source: Slobodan Nickovic

Examples of numerical modelling of iron transport from the Sahara to the Atlantic Ocean, including its transformation from insoluble to soluble form in dust, are given in Nickovic et al. (2013), which uses the global map of dust mineral composition in source areas presented in Nickovic et al. (2012). Phosphorus and silicon are also important nutrients for marine life. Although, like iron, they are mainly injected into the ocean by river inflow, their deposition in the form of dust further contributes to nutrition in remote ocean areas (Mahowald et al., 2005; Tegen and Kohfeld, 2006).

Deposits of mineral dust over land are also an important contributor to the fertilization of areas rich in vegetation. Mineral dust transported from West Africa, for example, is thought to fertilize the phosphorus-limited soils of the Amazon rainforest and thereby to increase primary productivity (Prospero et al., 1981; Yu et al., 2015b). In addition to their role in global atmospheric circulation, desert areas therefore prove their importance to the climate system as the supplier of nutrients for living organisms in distant parts. This, in turn, contributes to an understanding of the complex interconnections between components and processes in the climate system. Prospero and Lamb (2003) discuss the process of dust transport from North Africa to the Caribbean, with measurement-based evidence and references to trade winds, precipitation regimes and dust concentrations. They conclude that dust emission in arid regions and its subsequent transport are sensitive to climate change.

In summary, as the interactions of aerosols (including dust) with the climate are a major source of uncertainty in climate predictions (for example, Myhre et al., 2013), an improved understanding of the role of aerosols represents an important contribution to projections of future climate change.

1.2. Health and safety impacts

Dust transport has an adverse, indirect impact on human health. When exposed to higher concentrations of airborne dust through mechanisms of dust–environment interactions, humans suffer from different diseases, many of which are still not well recorded or understood. The WHO *Air Quality Guidelines Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide* (WHO, 2021) are a set of evidence-based recommendations of limit values for specific air pollutants (including particulate matter (PM)) developed to help countries achieve air quality that protects public health. During SDS, levels of both fine particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}) (that is, PM with an aerodynamical diameter of less than 2.5 μm and 10 μm, respectively) can rise significantly, posing health risks to people exposed to the polluted air and leading to increasing rates of hospitalization (Middleton et al., 2008).

A variety of microorganisms, or microbes, are found in dust, including algae, archaeans, bacteria, viruses and fungi. The populations of viruses and bacteria range from $\sim 10^3$ to 10^7 per gram of topsoil in various desert environments (Gonzalez-Martin et al., 2013). Fungal populations are typically the same at approximately 10^6 per gram of topsoil (Tate, 2021). Cyanobacteria is ubiquitous in the surface crusts of desert soils and playa sediments (Metcalf et al., 2012). Microbes attached to dust particles can travel long distances, even across oceans and continents (Griffin, 2007; Prospero et al., 2021). Insects as large as locusts have been transported across the Atlantic to the Caribbean and South America in Saharan dust plumes (Rosenberg and Burt, 1999). Many bacterial pathogens have been identified in air samples during dust storms (Griffin, 2007). Rodriguez-Gomez et al. (2020) also found that viable bacterial and fungal propagules in the Yucatán peninsula (Mexico) were more abundant during African dust intrusions, with up to five-fold higher concentrations of $PM_{2.5}$ and PM_{10} than during the non-dusty period (Ramirez-Romero et al., 2021). Similarly, Adachi et al. (2020) and Souza et al. (2019) detected various microorganisms over Manaus, Brazil, in particles consistent with dust sources in Africa.

Microorganisms, once airborne, are important environmental pathogens in urban areas. Dust, either locally generated or transported over long distances, increases the abundance and diversity of microorganisms. Consequently, cities built in drylands or along transport pathways are susceptible to the settling of microorganisms.

Long-range, intercontinental dust transport is associated with premature respiratory and cardiovascular disease morbidityThe smallest particles can penetrate the lungs and enter the bloodstream (Liu et al., 2009), occasioning cardiovascular diseases, asthma, bronchitis and heart attacks. Furthermore, inhalation of dust can cause pneumonia (Prospero, 1999) and cancer (Fubini and Areán, 1999) depending on its composition, and there is a hypothesis that it can affect reproductive functions (Yoshida et al., 2008). Specific illnesses related to the inhalation of dust have also been identified, like Valley fever (Sprigg et al., 2014; Tong et al., 2017). Meningitis in the Sahel region (Thomson et al., 2013; Pérez García-Pando et al., 2014) is correlated with increasing dust concentrations. Thomson et al. (2013) recognized some mechanisms related to desert dust as possible triggers of this illness, but how the epidemic broke out is not fully understood. A comprehensive summary of the relationship between dust and health (including short- and long-term, direct and indirect impacts) is given in Tong et al. (2022).

Assessments (Giannadaki et al., 2014) show that, globally, 380 000 deaths per year are caused by exposure to inhalable mineral dust particles, and the health effects of dust particles are observed worldwide. Figure 7 provides a graphical summary of documented or anecdotally reported health and safety effects of airborne dust across the Americas. Among these risks, most are reported around the world, while some are confined to specific regions, such as Valley fever, which is believed to be endemic to the Americas. However, similar infectious diseases caused by dust-borne microorganisms, such as bacterial meningitis and Rift Valley fever, have been reported in Africa, Asia, Western Europe and the Middle East (Tong et al., 2023a, and references therein). Most of the mortality and morbidity impacts of dust particles are found in the global dust belt (in the northern hemisphere) and Australia.

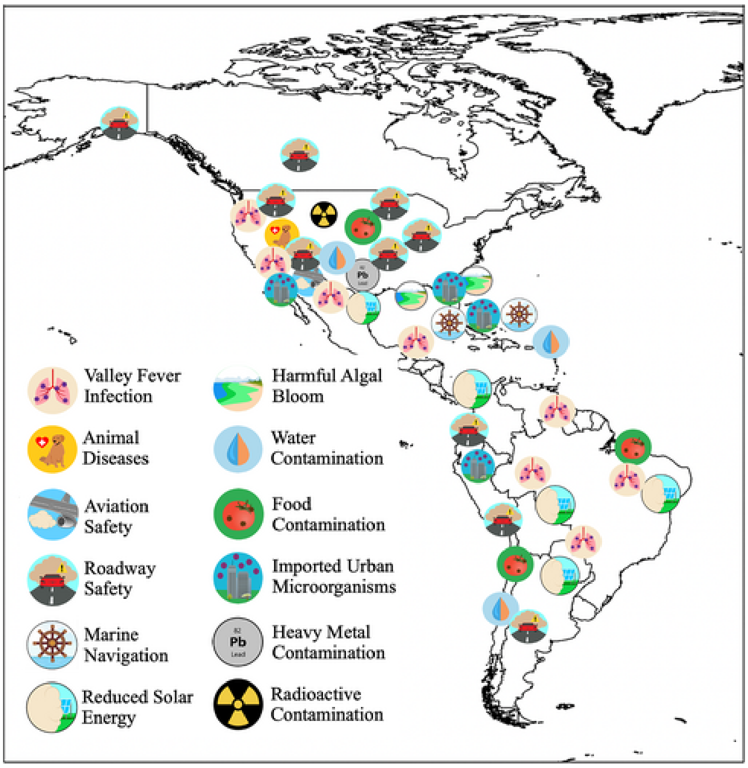


Figure 7. Health and safety impacts of airborne dust across the Americas

Source: Tong et al., 2023a

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

1.3. Agriculture impacts

Agricultural production has a two-way relationship with SDS (Box 4). Agricultural practices, if implemented in a way that exposes soil surfaces to wind erosion, tend to contribute to the generation of SDS by producing/increasing potential dust source surfaces. Such practices are not within the scope of sustainable land management (FAO, 2023). Tillage, intensive grazing and the absence of cover crops are some of the factors that produce favourable surface conditions for the generation of SDS (that is, they are anthropogenic sources). Conversely, SDS may affect agricultural production by, for example, reducing crop yields and damaging the health of livestock.

Croplands are recognized as significant SDS sources that have contributed to many severe events at relatively local scales. SDS generated from croplands are considered hazards that cause health and traffic safety problems (see, for example, Sundram et al., 2004; Vukovic et al., 2014; Sprigg et al., 2014; Hyde et al., 2018; Vukovic Vimic et al., 2021; Joshi, 2021; Tong et al., 2022). In semi-arid areas where natural sources are mixed with agricultural surfaces, like the Islamic Republic of Iran (Vukovic Vimic et al., 2021) and Arizona, United States (Joshi, 2021), dust emissions from croplands contribute about 50% or more of the total concentration of dust carried during SDS events. Furthermore, during such events, PM_{10} values can be of an order of magnitude of 10 000 μg/m^3 in the vicinity of sources (ADEQ, 2012). Hyde et al. (2018) show that, during short-lived intensive SDS in Arizona, one-hour PM_{10} values are in some cases 80-times higher than guideline values. High-resolution coupled dust–atmospheric modelling needs to be employed to estimate source areas of severe, local and short-lived SDS (commonly referred to as haboobs), as observations of dust are scarce, usually not near source areas, and storms are often not captured by remote sensing instruments. SDS generated from agricultural fields degrade the fertility of the soil and may trigger/accelerate the process of land degradation and desertification (Stefanski and Sivakumar, 2009). The 1930s Dust Bowl in the United States is the most famous example of human-induced, large-scale land degradation. It was triggered by unsustainable agricultural production and amplified by frequent and severe SDS over agricultural bare lands, which most likely also exacerbated drought conditions (Cook et al., 2009).

Although dust deposition over farmland may have positive consequences in terms of fertilization, the major impacts are negative (Stefanski and Sivakumar, 2009). Severe SDS over agricultural lands bury seedlings, destroy plant tissue and reduce photosynthetic activity, which may prolong plant development and increase drought risk. Unsheltered livestock suffer in ways comparable to humans, with injuries, health problems, lack of food and fresh water, and, consequently, reduced productivity. Large amounts of deposited dust may impede irrigation by filling up channels, affecting water quality and so forth. A study in Iraq showed that crop yields are reduced in the range 0.9%–3% per day of SDS (Ahmadzai, 2023). In a report related to risk assessment in Asia and the Pacific (APDIM, 2021), it was found that a large proportion of farmlands are affected by dust deposition (Turkmenistan, 71%; Pakistan, 49%; Uzbekistan, 44%). In areas with high salt content, soil is contaminated by deposition from saline SDS (Abuduwaili et al., 2010), which damages crops and reduces yields. Furthermore, the higher frequency of abundant dust in the atmosphere decreases solar radiation, which reduces the photosynthetic activity of plants. Zia-Khan et al. (2015) showed that dust deposition is associated with significant reductions in yields of cotton (see also Abdullaev and Sokolik (2020)). The problems that SDS cause along transportation routes and the damage they inflict on equipment can also be considered an indirect agricultural impact.

The effects of severe events on agriculture are not necessarily restricted to areas where SDS are recognized as a hazard. They may also appear in Europe, when wind gusts affect exposed, dry croplands, as happened in Poland (Hojan et al., 2019). In 2007, dust from farmlands in Ukraine was transported all the way to Germany (Birmili et al., 2008).

Owing to the close relationship between agricultural production and SDS in terms of both causes and consequences, applications of risk management strategies can be found in the agricultural sector (FAO, 2023). According to Stefanski and Sivakumar (2009), there are several potential agricultural applications of SDS warning systems that can be grouped in three categories: tactical, strategic and research related. Tactical applications include decision-making when crops have already been planted, such as on-time harvests or physically protecting crops and sheltering livestock. Strategic applications focus on long-term planning and investments in cases where long-term predictions provide SDS forecasts – for example, installing windbreaks. Research-related applications may include improving models and developing predictions of pathogen movement. More details about the uses and upgrades of knowledge in respect of weather and SDS forecasting in agriculture, and related model developments, are given in Stefanski and Sivakumar (2009).

On account of the growing frequency and intensity of droughts caused by increasing climate change, agricultural lands are expected to be more conducive to dust emissions, and production is likely to reduce if no adaptation measures are implemented (IPCC, 2021, 2023). Implementing adaptation measures, including sustainable land management practices; reaching land degradation neutrality; and preserving biodiversity above and below ground represent a synergetic approach to achieving the targets of United Nations conventions (for example, the United Nations Framework Convention on Climate Change (UNFCCC), UNCCD and the Convention on Biological Diversity (CBD)). They also contribute to most of the SDGs. Combating SDS, including mitigating sources and reducing impacts, would greatly benefit from, and contribute to, sustainable agriculture (FAO, 2023). The development of warning and advisory services related to SDS, including short-term and seasonal predictions, could contribute to short-term adaptation to potential hazards. It would also provide climate-scale predictions and projections for long-term planning, and supplement warning systems for other hazards, like heatwaves, droughts and floods.

Box 4. SDS as agricultural hazards

Although agricultural production may contribute to the generation of SDS by exposing soil to wind erosion and disturbing the soil surface, it also suffers much from SDS, directly and indirectly. SDS damage crops, reduce soil quality and sunlight, hurt animals, and damage equipment and agricultural infrastructure.

Combating SDS is closely related to achieving the targets of United Nations conventions (UNFCCC, UNCCD, CBD) the SDGs and, because of overlapping actions related to the mitigation of sources and their impacts, to achieving land degradation neutrality (LDN); adapting to climate change; and preserving/improving biodiversity to achieve regenerative, sustainable agriculture. The development of tailored services for agriculture and their expansion to encompass different timescales, from short-term adjustments to long-term planning, would benefit decision-making.

Examples of dust storms and their impacts in relation to agriculture: (upper left) U.S. Route 59, south of Lamar, Colorado, United States, May 1936 (Trimarchi, 2023); (upper right) August 2014, haboob at a farm near Ritzville, Washington, United States (photo courtesy of Susan DeWald); (lower left) Corn damaged by a dust storm on 15 May 2018, Nebraska, United States (Elmore et al., 2018); (lower right) April 2011, after a dust storm in Poland (Hojan et al., 2019).

1.4. Terrestrial and marine effects

In addition to agriculture, SDS are known to affect terrestrial and marine life. Dust and aerosols carry significant amounts of key nutrients, such as iron (Fe), phosphorus (P), that stimulate growth of primary productivity and sink atmospheric carbon dioxide (Mahowald, et al., 2011). African dust transported to South America in winter and spring is thought to fertilize the P-limited soils of the Amazon rainforest and to increase primary productivity (Prospero et al., 1981; Yu et al., 2015).

Trace metals in dust, such as copper, can be toxic for phytoplankton, resulting in changes in marine community composition and/or reduced primary productivity (Paytan et al., 2009). Excess inputs of nutrients from dust deposition may help create suitable conditions for harmful algal blooms, which in turn disrupt marine ecosystems and emit toxic air pollutants. Occurrences of SDS have been found to correlate with increased phytoplankton biomass and harmful algal blooms in freshwater lakes and coastal and oceanic regions worldwide (Cropp et al., 2013; Tan and Wang, 2014; Winton et al., 2016; Farahat and Abuelgasim, 2019). Red tide toxins can cause significant direct mortality to marine organisms and indirect morbidity to terrestrial organisms through bloom-associated aerosol exposures. Furthermore, cyanobacteria-derived toxins known to be carried in desert dust storms may have a direct impact on human health through aerosol exposure (Cox et al., 2009). Deposition of dust from the Sahara in the Atlantic Ocean and the Gulf of Mexico produces short-lived blooms of *Vibrio* species, many of which are known human and marine organism pathogens (Westrich et al., 2016, 2018).

Deposition of dust, in particular lead-based dust, on foods may pose risks. The bacteria and pathogens carried by dust may be hard to remove from leafy vegetables such as lettuce and spinach, and those attached to the skin of fruits such as melons may contaminate the edible flesh when the fruit is sliced (Annous et al., 2005). For instance, in March 2022, supermarkets in the United Kingdom of Great Britain and Northern Ireland issued warnings about washing fruit and vegetables from their stores, on account of the contamination occasioned by a Saharan desert dust cloud (Blackburne, 2022). If windblown soil dust containing *Salmonella* settles on the blossom of tomato plants, the bacteria can be incorporated into and diffused within the flesh of the fruit (Kumar et al., 2018). Similarly, *Salmonella* internalized in cucumbers through blossom inoculation (Burris et al., 2020) and *Escherichia coli* (*E. coli*) incorporated into apples through their blossom (Burnett et al., 2000) have been observed. The authors of these publications suggest that the blossom inoculation pathway may explain some otherwise incomprehensible recent outbreaks of foodborne illnesses.

1.5. Transportation impacts

In addition to endangering human and environmental health, SDS and related weather conditions, such as high winds, low visibility and slippery surfaces, are a major safety hazard for transportation, including roadway transportation, marine navigation and aviation.

During blowing dust events, driver distraction and disorientation, loss of awareness of the road and other vehicles, sudden changes in vehicle speed, and changes in traction owing to sand and dust deposited on the road surface increase the risk of crashes (Day, 1993; Ashley et al., 2015). Small-scale and localized blowing dust events favour the occurrence of "chain-reaction", or multiple-vehicle, crashes (Figure 8). Dust and sand hazardous to motorists may come from many sources, including wind erosion of permanent drylands and temporarily fallow croplands, as well as land disturbance by human and animal activities, such as vehicles driving on unpaved road, agricultural operations, construction, mining and quarrying, and feed-lots.

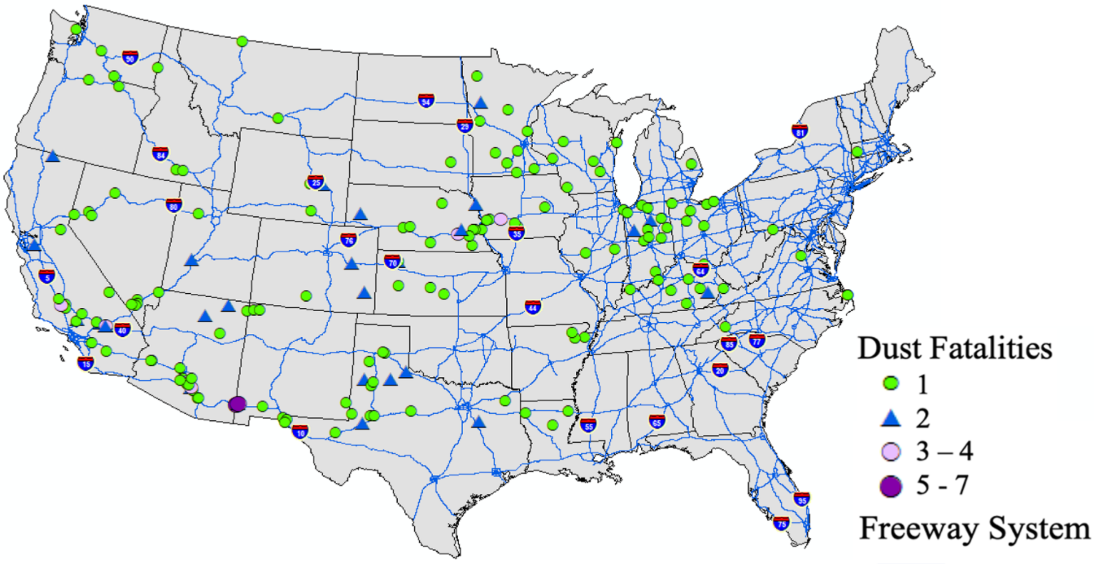


Figure 8. Fatal roadway crashes caused by windblown dust from 2007 to 2017 in the United States (the size of the circles is proportional to the number of deaths)

Source: Tong et al., 2023b

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

Low visibility during SDS is also a concern for marine navigation. When the extreme Saharan dust event "Godzilla" spread over the Greater Caribbean, the Gulf of Mexico and the southern United States between 21 and 24 June 2020, visibility dropped in many locations from 10 km–30 km to below 10 km, posing various risks to boat and ship captains and helicopter pilots. Strong winds and blinding dust were blamed for the grounding of the container ship *Ever Given* on 23 March 2021 in the Suez Canal. The grounded ship blocked international trade until it was freed on 29 March 2021, with the economic consequences estimated at billions of United States dollars (US$). Help in the form of dust and wind forecasts and observed environmental conditions for the safe navigation of the Canal had been available before, and were available during and after, the incident.

SDS can affect different phases of aviation: cruising, landing, take-off and ground operations. Mineral dust can mechanically damage the aircraft parts through the abrasion process, by affecting the engine interiors and sensors through long-term exposure to dust. Furthermore, dust can be melted in turbines under their high operating temperatures. During intense SDS, airport visibility – which depends, inter alia, on humidity and the concentration and composition of dust – can be drastically reduced, leading to flight diversions and cancellations (see Box 5, Weinzierl et al., 2012). Even short interruptions can cause economic damage amounting to many millions of euros (€) (WMO, 2021; Monteiro et al., 2022).

As a very efficient atmospheric ice nucleation agent, dust generates heterogeneous cloud glaciation, even in regions distant from desert sources. Ice particles in the cold clouds of the upper troposphere are dangerous for cruising aircraft (Nickovic et al., 2021). Evidence from aviation practice indicates that cloud icing has caused numerous fatal accidents, and the accretion of small ice crystals in jet engines appears to have been responsible for more than 150 engine power-loss and damage events over the past

20 years (Haggerty et al., 2019). Cockpit radars generally cannot detect such small ice crystals. High numbers of ice particles that are potentially dangerous for aviation typically exist in the outflow of the broad anvils associated with convective storm complexes. Heterogeneous ice nucleation can be enhanced by the presence of dust, and it can obstruct the normal functioning of important instruments (for example, pitot tubes and air pressure sensors), confuse the crew, and therefore both disrupt and decrease the security of aircraft operations.

Dust is also present at aircraft cruising altitudes, albeit in smaller concentrations. Long-term exposure to mineral aerosol leads to the gradual erosion and corrosion of engines' components. Substantial increases in air traffic in dusty regions (for example, over the Middle East and Northern Africa), and a new generation of aero turbines that are less tolerant of atmospheric aerosols, require more frequent costly engine maintenance. Engines that regularly fly in and out of sandy and dusty airports – like Dubai, United Arab Emirates; Riyadh; and Cairo – gradually accumulate damage. The accumulative, long-term effects of dust on aircraft include detectable declines in engine performance or reduction in the service life of components. However, such a level of damage does not require immediate action to be taken – engines can be left in the aircraft for many more flights, and the timing of repairs managed to minimize cost and/or disruption (Clarkson, 2017).

Volcanic ash melts at temperatures that are several hundred degrees lower than those at which mineral dust melts. Unlike dust, ash has been a serious concern for aviation for decades because of the high risks associated with melted deposits of ash in jet engines. Dust can reach extreme concentrations during major storms, especially in the lower atmosphere during landing and take-off. Current aero turbines have significantly increased operating temperatures of 1 300 °C or more, meaning that mineral dust can melt in engines and thus degrade aircraft performances. The amount of melted dust deposited in engines mainly depends on (a) its concentration, (b) its physical and mineralogical properties, and (c) the length of exposure. Particles that melt inside the combustor and solidify in the cooler part of the engine (Figure 9) can block cooling holes and lead to engine shutdown. The resultant engine damage requires prompt attention and the possible removal of engines from aircraft, occasioning unscheduled and prolonged reductions in aircraft availability, and extensive engine repairs.

Figure 9. Example of an aircraft engine damaged by mineral aerosol

Source: Prata and Rose, 2015

Box 5. The "Minoan-Red" event, March 2018 – flight delays, cancellations and assessed economic loss

In late March 2018, a large part of the Eastern Mediterranean experienced an extraordinary episode of African dust – one of the most intense in recent years – referred to as the "Minoan-Red" event. It mainly affected the Greek island of Crete, where the highest aerosol concentrations in 15 years were recorded.

During the event, there were 11 cancellations and 7 delays at Heraklion International Airport, Greece. Based on aircraft type, seat capacity and length of delay (between 30 minutes and 10 hours), and following the recommendations of the European Organisation for the Safety of Air Navigation (EUROCONTROL) for cost–benefit analyses, it has been estimated that the total cost of the documented disruptions were ~€ 360 000 (Monteiro et al., 2022).

Enormous amounts of Saharan dust across the central and eastern Mediterranean during the Minoan-Red event, as seen (left) from space and (right) in Timbakion, Crete, Greece

Source: Severe Weather Europe (see https://www.severe-weather.eu/wp-content/gallery/satelite-images/dust_Crete_Mediterranean_March22_2018.jpg and https://www.severe-weather.eu/wp-content/gallery/weather-photos/28947798_10216486393131202_9180526840839128045_o.jpg)

1.6. Energy impacts

Many deserts are located in tropical or subtropical regions, making them suitable for both solar photovoltaic (PV) and concentrated solar power plants owing to strong solar irradiation and the low cost of land. The performance of these power stations is hindered when dust, also abundant in these regions, settles on insolation-receiving surfaces (Al-Addous et al., 2019) and attenuates solar radiation (Polo and Estalayo, 2015; del Hoyo et al., 2020).

The coating of insolation-receiving surfaces with dust (soiling) reduces their ability to generate power and shortens their lifespan, in part owing to the consequent increase in heat stress (Sarver et al., 2013; Shi et al., 2020). Dust deposition rates depend on factors such as wind speed, cell orientation, angle of incidence and relative humidity (hygroscopic aerosol growth) (Goossens et al., 1993; Hammond et al., 1997; Chen et al., 2019). This soiling, combined with water scarcity in arid regions, represents a challenge for current as well as future projects (Xu et al., 2016). Cleaning and mitigation are fundamental to the solar industry due to soiling's dramatic degradation of energy production (Gupta et al., 2019) – large dust particles have greater consequences than small particles (Shi et al., 2020). SDS can reduce PV panel efficiency by up to 80% per hour (Ghazi et al., 2014). Cleaning techniques involve either manual labour or self-cleaning mechanisms (Jamil et al., 2017; Gupta et al., 2019), such as hydrophobic and hydrophilic surfaces, mechanical and robotic devices, and electrostatic shields (Jamil et al., 2017). Application of these techniques depends on the region and associated costs – for instance, washing methods are difficult to implement in areas of water scarcity, like deserts. Other mitigation measures require interventions in the surroundings of PV panels (Ghazi et al., 2014), such as concreting the surface or planting grass—a challenge in dry regions and insufficient when dust sources are off site. Furthermore, unique challenges require sui generis solutions – for example, bird droppings, which cause dust particles to adhere to exposed solar panels (Gupta et al., 2019), cannot be removed with a mechanical brushing system (Ghazi et al., 2014). Cleaning costs in respect of soiling are affected by many factors, including the nature of dust accumulation, dust composition and the governing meteorological conditions. It is worth noting that large-scale solar energy facilities, such as utility-scale solar energy, affect dust sources and the environment, including biodiversity, land use, land cover change, soil, water resources and human health (Hernandez et al., 2014).

2. AVAILABLE SAND AND DUST INFORMATION

Dust-related observations and the prediction/modelling of the atmospheric dust process play an essential role in near real-time SDS monitoring, early warnings and long-term assessments of the effects of atmospheric dust. Observational products (including ground-based networks and satellite retrievals) are used to: identify sources; help parameterize different components of dust models (for example, emission, transport and deposition); verify/validate model predictions; integrate observed information into dust models to specify initial conditions; and perform observation-based dust climatology.

2.1. Monitoring

Over the past decade, significant improvement in dust observational capabilities has been achieved with respect to enlarging the number and quality of dust-related parameters, their geographical coverage and timely delivery. Products tailored to the needs of both the scientific community and end users (Mona et al., 2023) have also been developed. The fact that dust is often a component of mixtures of other types of aerosols frequently complicates dust detection measurements. At present, there are no instruments for in situ (PM10) or atmospheric column observations (that is, aerosol optical depth (AOD) or aerosol extinction profiles) that provide direct measurements of dust; instead, they provide total aerosol content. To estimate the sand and dust fraction of observed aerosol mixtures, additional auxiliary parameters and techniques are used. Techniques and methodologies focused on identifying and quantifying the contribution of dust to total aerosol content need to be developed in order to improve dust observations, data assimilation and model validation.

2.1.1. Ground-based measurements

PM_{10} and/or $PM_{2.5}$ measurements are widely employed on a routine basis to estimate dust concentrations at ground level, using automatic instruments such as beta attenuation gauges, tapered element oscillating microbalances (TEOM) and optical particle sizers (Mona et al., 2023). Although these measurements include aerosol components like sea salt and sulfate, the impact of dust is frequently identified by sharp increases in PM (especially in PM_{10} fractions). In situ dust observations can also incorporate data from surface meteorological stations in respect of visibility and current weather conditions. Near-surface dust concentration can be estimated indirectly by using empirical equations with horizontal visibility data (inversely proportional to surface aerosol extinction) (see, for example, Camino et al., 2015) obtained from meteorological surface synoptic observations (that is, SYNOP) and aerodrome meteorological reports (that is, METARs).

Photometers are powerful pieces of atmospheric remote sensing technology that retrieve the column-integrated microphysical and optical properties of aerosols, including dust. As passive sensors, photometers measure the attenuation of direct solar spectral irradiance by aerosols, at different wavelengths from the top of the atmosphere to their location. Two basic parameters can be retrieved from photometer measurements: (a) columnar multiwavelength AOD, which is a unitless measure of suspended aerosol load; and, (b) the Ångström exponent, which provides information about aerosol size. Recently, innovative instruments and related algorithms have enabled the use of photometers at night (Barreto et al., 2017, 2019). Specifically, dust optical depth (DOD) is usually estimated by combining AOD and Ångström exponent values (Dubovik et al., 2002; O'Neill et al., 2003; Todd et al., 2007; Basart et al., 2009). However, this approach entails some uncertainties, especially if dust is mixed with other types of aerosols. The Aerosol Robotic Network (AERONET) (see http://aeronet.gsfc.nasa.gov) (Holben et al., 1998; Dubovik and King, 2000; Giles et al., 2019) is the largest network of photometers (with more than 400 stations worldwide) for monitoring atmospheric aerosols, including atmospheric mineral dust. AERONET is one of the "golden" networks that supports nowcasting, forecasting and modelling activities. It was established by the National Aeronautics and Space Administration (NASA) and Photométrie pour le Traitement Opérationnel de Normalisation Satellitaire (PHOTONS) (managed by the Laboratoire d'Optique Atmosphérique at the University of Lille, France; see https://www-loa.univ-lille1.fr/photons) and is greatly expanded by regional networks such as the Iberian network for aerosol measurements (Red ibérica de medida fotométrica de aerosols (RIMA), see http://www.rima.uva.es/). There is a high density of AERONET stations over Europe, the Americas and East Asia, but the two most important dust sources in the world (Northern Africa/Sahara and West Asia) have very few photometers (Figure 10).

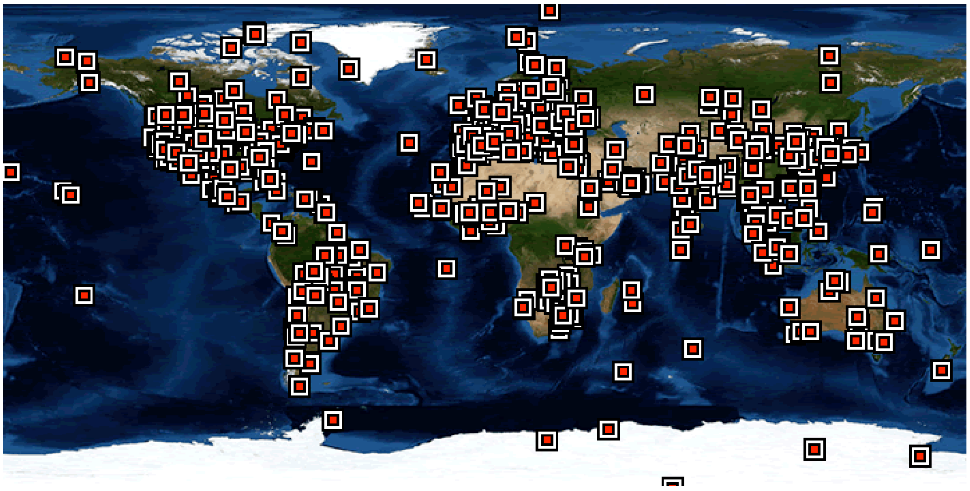


Figure 10. Map of AERONET station distribution

Source: Screenshot taken on 15 November 2024 at 1700 UTC from AERONET (see https://aeronet.gsfc.nasa.gov)

Aerosol profiles can be retrieved from lidars (Mona et al., 2012) and ceilometers (Illingworth et al., 2019). There are different techniques for investigating aerosol properties using lidars, including widely distributed simple, automatic elastic backscatter lidars, and more complex and advanced multiwavelength Raman lidars and high-spectral-resolution lidars (HSRLs). Observed lidar particle depolarization ratio profiles are used to determine the presence of mineral dust. These profiles provide information on particle shape and make it possible to distinguish mineral dust from other particles (see, for example, Ansmann et al., 2012). Microphysical properties, such as refractive index and size distribution, can be retrieved by advanced multiwavelength lidars using sophisticated algorithms to provide aerosol profile products. The combination of advanced lidar and photometer observations is highly valuable and meets the need for vertically resolved information on the mass concentration of suspended aerosol particles and their fine and coarse components. Furthermore, the Generalized Aerosol Retrieval from Radiometer and Lidar Combined data (GARRLiC) (Lopatin et al., 2013) and Lidar–Radiometer Inversion Code (LIRIC) (Chaikovsky et al., 2016) algorithms enable estimates of fine- and coarse-mode volume concentrations, which are very useful for detecting mineral dust layers in the atmospheric column (Tsekeri et al., 2017). There are several aerosol lidar networks that provide coordinated standardized observations at the regional level: the Aerosol, Clouds, and Trace Gases Research Infrastructure/European Aerosol Research Lidar Network (ACTRIS/EARLINET) (see www.earlinet.org) (Pappalardo et al., 2014); the Asian Dust Network (AD-Net) (see https://www-lidar.nies.go.jp/AD-Net/) (Shimizu et al., 2016; Murayama et al., 2001); the Latin America Lidar Network (LALINET) (see http://lalinet.org/index.php) (Antuña-Marrero et al., 2017); and the global NASA Micropulse Lidar Network (MPLNET) (see https://mplnet.gsfc.nasa.gov/) (Welton et al., 2001). These networks constitute the WMO Global Atmosphere Watch (GAW) Aerosol Lidar Observation Network (GALION) (see https://galion.world/) (WMO, 2007) (Figure 11). At present, there are two large lidar observation gaps in desert dust sources in Northern Africa and the Middle East. There are many ceilometers distributed worldwide (in most cases at airports to measure the height of cloud base) and they could provide valuable information about aerosol vertical layering in the non-cloud atmosphere, albeit less accurately than lidars. Aerosol profile information is being provided in near real time by an increasing number of ceilometers of the E-PROFILE operational network of the European Meteorological Services Network (EUMETNET) (Illingworth et al., 2019).

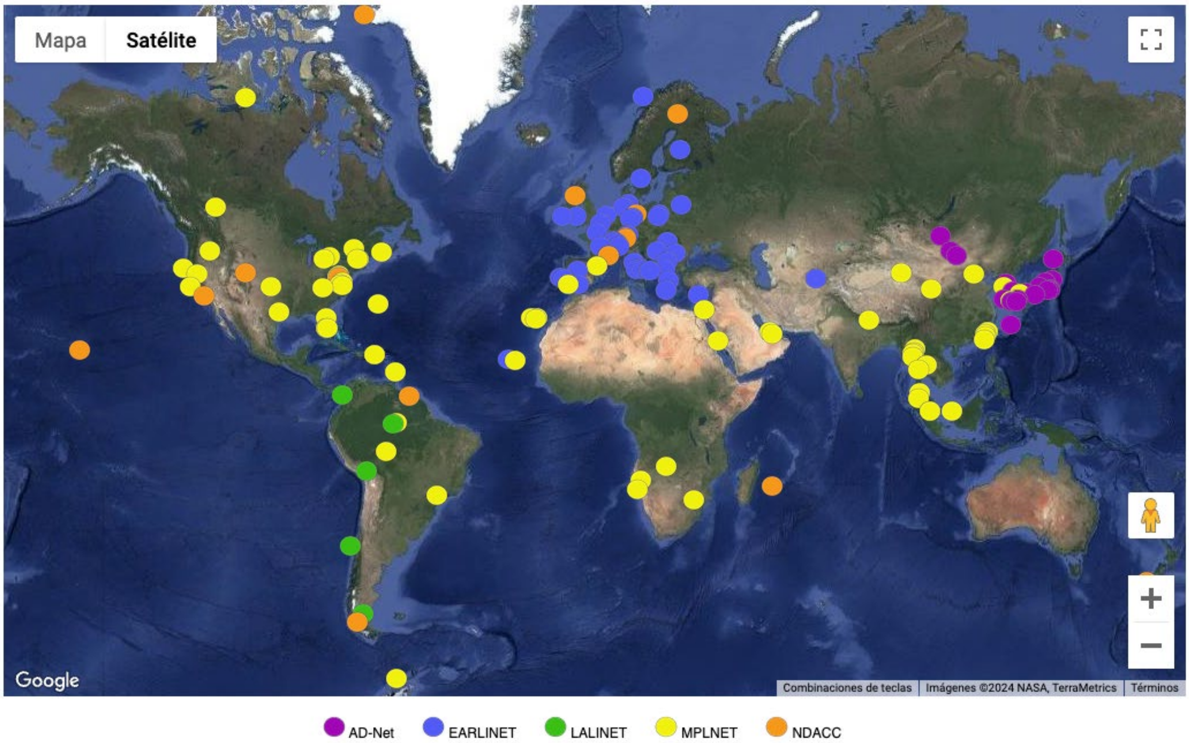


Figure 11. Global distribution of the lidar sites of different lidar networks (indicated by the colour of the dots)

Key:

NDACC = Network for the Detection of Atmospheric Composition Change

Source: Screenshot taken on 15 November 2024 at 1700 UTC from GALION website (https://galion.world/)

2.1.2. Satellite retrievals

Satellite-retrieved aerosol products have a key role in describing the horizontal and vertical distribution of dust. A detailed overview of the satellite aerosol products currently available to assess dust contributions can be found in Mona et al. (2023) and in Table 1. Spaceborne aerosol products are provided at resolutions varying from metres to degrees in terms of space, and from minutes to seasons in respect of time. Therefore, users are able either to derive data tailored to their needs or to process them according to the purposes of a given study. Passive sensors provide aerosol observations that are representative of the whole atmospheric column, whereas active sensors depict the structure of aerosol layers at different altitudes within the troposphere and the lower stratosphere, at fine vertical resolution (that is, metres). Furthermore, significant improvements in and evaluations of the different algorithms used for aerosol investigation through satellite measurements have been carried out; for instance, within the framework of the European Space Agency (ESA) Aerosol Climate Change Initiative (CCI) project (see, for example, Popp et al., 2020).

Spaceborne instruments provide aerosol optical properties, either vertically resolved or representative of the whole atmospheric column depending on the remote sensing technique applied. AOD retrievals span from ultraviolet (UV) to near-infrared wavelengths, mostly along the visible (VIS) spectrum. Satellite measurements also include particle properties such as size, shape and absorption. Other key optical properties are the single scattering albedo (ω) and asymmetry parameter (g) provided by satellite instruments, mainly at near-UV and VIS wavelengths. Finally, aerosol index retrievals, which are sensitive to the presence of absorbing particles, have been used to monitor dust plume evolution.

Some studies have developed sensor-specific methods of partitioning total aerosol into dust and non-dust components, with varying assumptions. In general, the separation methods are based on dust's physical and optical properties, such as its large particle size, irregular or non-spherical shape, and unique absorption characteristics. Such information has been acquired, for long-term periods and at a global scale, either by passive or active sensors providing columnar and vertically resolved aerosol retrievals, respectively. For instance, NASA Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol observations, available since 2000, have been fundamental for aerosol studies and mineral dust investigations at the global level (see, for example, Boucher et al., 2013). The wide spectral coverage of MODIS measurements enables the retrieval of aerosol particle size information, such as effective radius, fine-mode fraction (FMF) and aerosol extinction, as well as the spectral gradient of absorption (decreasing in absorption from UV to red) (Remer and Kaufman, 2005). This information provides the foundation for estimates of dust contribution based on the AOD retrieved from MODIS (Kaufman et al., 2005; Yu et al., 2009, 2020; Pu and Ginoux, 2018).

The vertical structure of aerosol layers can be depicted by satellite-based lidars, which sample the atmosphere from top to bottom. Using depolarization measurements, non-spherical particles (for example, dust aerosols) can be identified very accurately and separated from aerosol mixtures (Shimizu et al., 2004; Hayasaka et al., 2007; Tesche et al., 2009; Mamouri and Ansmann, 2015). This allows dust vertical profiles to be reproduced using the backscatter coefficient and the corresponding profiles of the extinction coefficient (Yu et al., 2012; Amiridis et al., 2013; Yu et al., 2015a). The NASA Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), available since 2006, provides the vertical structure of dust using accurate backscatter and depolarization retrievals worldwide (Winker et al., 2009, 2013).

There are still constraints that prevent more adequate observational characterization of mineral dust. For example, the scarcity of in situ and remote sensing observations (such as sun photometers, lidars, ceilometers) in desert dust source regions such as Northern Africa, the Middle East, East and Central Asia, or South America. Similarly, the lack of sufficient observations in high latitudes imposes significant limitations on the characterization and monitoring of mineral dust.

Table 1. Overview of the instruments deployed on satellite platforms

Sensor	Satellite	Active/Passive	Vertical resolution
MODIS	Aqua/Terra	Passive	Columnar
OMI	Aura	Passive	Columnar
CALIOP	CALIPSO	Active	Profiling
IASI	Metop-A/-B	Passive	Columnar
SEVIRI	MSG	Passive	Columnar
ATSR-2	ERS-2	Passive	Columnar
SeaWIFS	OrbView-2	Passive	Columnar
AATSR	ENVISAT	Passive	Columnar
GOME-1	ERS-2	Passive	Columnar
GOME-2	Metop-A/-B	Passive	Columnar
SCIAMACHY	ENVISAT	Passive	Columnar
POLDER	PARASOL, ADEOS I/II	Passive	Columnar
AIRS	Aqua	Passive	Columnar
IIR	CALIPSO	Active	Profiling
VIIRS	Suomi NPP	Passive	Columnar
MISR	Terra	Passive	Columnar
AVHRR	NOAA	Passive	Columnar
TROPOMI	Sentinel-5P	Passive	Columnar
TOMS	Nimbus-7/Earth Probe	Passive	Columnar
CATS	ISS	Passive	Columnar
ALADIN	Aeolus	Active	Profiling
EMIT	ISS	Passive	Columnar

Key:
AATSR = Advanced Along-track Scanning Radiometer
ADEOS I/II = Advanced Earth Observation Satellite I/II
AIRS = Atmospheric Infrared Sounder
ALADIN = Atmospheric Laser Doppler Instrument
ATSR-2 = Along-track Scanning Radiometer 2

AVHRR = Advanced Very-High-Resolution Radiometer
CALIPSO = Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations
CATS = Cloud–Aerosol Transport System
EMIT = Earth Surface Mineral Dust Source Investigation
ENVISAT = Environmental Satellite
ERS-2 = Earth Remote Sensing Satellite 2
GOME-1 = Global Ozone Monitoring Experiment 1
GOME-2 = Global Ozone Monitoring Experiment 2
IASI = Infrared Atmospheric Sounding Interferometer
IIR = Imaging Infrared Radiometer
ISS = International Space Station
Metop-A/-B = Meteorological Operational Satellite-A/-B
MISR = Multiangle Imaging Spectroradiometer
MSG = Meteosat Second Generation
NOAA = National Oceanic and Atmospheric Administration
OMI = Ozone Monitoring Instrument
PARASOL = Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar
POLDER = Polarization and Directionality of the Earth’s Reflectances
SCIAMACHY = Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SeaWIFS = Sea-viewing, Wide Field-of-view Sensor
Sentinel-5P = Sentinel-5 Precursor
SEVIRI = Spinning Enhanced Visible Infrared Imager
Suomi NPP = Suomi National Polar-orbiting Partnership
TOMS = Total Ozone Mapping Spectrometer
TROPOMI = Tropospheric Monitoring Instrument
VIIRS = Visible Infrared Imaging Radiometer Suite

Source: Mona et al., 2023

2.1.3. Other relevant information: deposition and minerology

Measurements of dust deposition are usually performed either by weighing the deposited mass on filters (see, for example, Guieu et al., 2002, 2019; Laurent et al., 2015; Stuut et al., 2022) or by measuring atmospheric aerosol concentrations and assuming the dust dry deposition velocity to scavenging ratio. Such observations, although sparsely distributed (see, for example, Pey et al., 2020), provide information on marine and terrestrial dust sinks. In the case of dust deposition over the ocean, it is particularly important to assess the amount and solubility of iron and phosphorus oxides in dust, because of their role as nutrients in terrestrial habitats and the climate system (see sections 1.1 and 1.4). The limited number of dust deposition observations represents a serious limitation in respect of adequately representing the global dust cycle in models to produce future climate scenarios.

There are several global gridded databases of key soil minerals present in emitted dust (see, for example, Claquin et al., 1999; Nickovic et al., 2012; Journet et al., 2014) and they are used as an input for studying and modelling the impacts of dust mineralogy on weather, climate, health and the environment. These databases employ the soil classification of the Food and Agriculture Organization of the United Nations (FAO) to assess the mineralogical structure of dust-productive soils (Nachtergaele et al., 2009). Based on recent developments, the Earth Surface Mineral Dust Source Investigation (EMIT), the NASA space sensor mapping instrument (see https://earth.jpl.nasa.gov/emit/), is being used to determine the mineralogical composition of most of the world’s dust sources. The European Frontiers in Dust

Mineralogical Composition and its Effects upon Climate (FRAGMENT) research project is deploying instruments to dust-forming regions in order to better understand the particle size distribution of emitted dust and its relationship with the parent soil. Researchers will use this information to refine models of mineralogy's role in mineral dust and its climate impacts.

Citizen science is the involvement of the public in the search for knowledge and new information. The options for public involvement in science have expanded rapidly in recent years. New digital technologies enable citizens to take an active part in large-scale research projects, wherever they are. Data can be collected via smartphone apps, for instance, or submitted through online portals. For example, the Global Learning and Observations to Benefit the Environment (GLOBE) Observer citizen science app allows volunteers to collect several different kinds of data using their phones, and join the GLOBE community. The data are used in multiple projects to track changes in the environment in support of Earth system science research. The resulting open data set is available to scientists at http://observer.globe.gov/get-data and is used by students of all ages doing a variety of research projects through the GLOBE Program. Some research projects would be impossible without this kind of support because scientific evidence often requires large volumes of data, which professional scientists are not able to collect on their own. Another recent example is included in Box 6 and details the citizen science project set up to address a Saharan dust event in February 2021 in Finland.

Box 6. Citizen science initiative for observations of Saharan dust in Finland on 23 February 2021

Saharan dust was transported and deposited in the southern part of Finland, north of 60°N, on 23 February 2021, reaching a long way inland. The event had been forecasted by the WMO Barcelona Dust Regional Center (see https://dust.aemet.es) five days in advance. At the time, the ground was covered with snow, and therefore dust deposition was more easily detectable. The Saharan dust event caused the public to contact the Finnish Meteorological Institute (FMI) and ask what was happening.

FMI responded quickly to these concerns from the public with the help of social media. Citizens were asked to collect Saharan dust samples in accordance with instructions given by FMI, and to mail these samples to the Institute for further investigation. People were also invited to report their observations on Saharan dust: what, where and when. The information and instructions soon spread via social media, the internet and the media, including newspapers, magazines, television and radio. Overall, the event attracted notable national attention and resulted in samples from 525 locations. With the help of these samples, FMI was able to investigate particle properties and verify various modelling results, satellite observations and regular aerosol measurements.

Modelling of SDS events needs to be verified using in situ measurements and satellite data. On 23 February 2021, satellite images over the middle of Finland were obscured by clouds, and the northern line of the dust deposition could not be identified. A further complication was that, although the dust deposition occurred mostly with snowfall, in areas close to the south coast of Finland it mixed with freezing rain. Therefore, citizen observations were the only way to verify where and how much dust had been deposited on the snow. As far as is known, this was the first citizen science project in Finland related to either dust storms or coloured snow.

Citizen science can fill gaps in data collection, and complete and help assess the status and impacts of dust events. Citizen engagement also raises awareness of changes in the environment and interest in environmental research. As a general notion, when citizens are asked to collect snow samples, it would be useful to have a set of instructions that ensured the highest, uniform sample quality possible.

Citizen science samples (photos courtesy of Outi Meinander)

2.2. Modelling

Atmospheric models for sand and dust forecasting are sophisticated computational tools designed to predict the movement and concentration of airborne particles. These models integrate meteorological data, including wind speed, temperature and humidity, with geographical information about dust sources and land surface characteristics. Advanced models also consider chemical interactions and provide critical information for environmental monitoring, disaster preparedness and mitigating the adverse effects of dust events.

2.2.1. Mapping dust sources

Dust sources can be understood as areas that are susceptible to wind erosion. The high spatial and temporal variability of sand and dust sources is a consequence of the high spatial variability of topsoil texture and structure, and of climate and weather conditions, as well as land use and socioeconomic impacts. Soil surface conditions and land cover can be affected by climate change, and human activities can directly alter soil characteristics (soil structure), thereby changing the susceptibility of the exposed soil to wind erosion. When it comes to mapping sources at a higher resolution, it is usually recognized that source areas are a mosaic of less and more SDS productive surfaces. To better understand the methodologies for source mapping and the expected outcomes, see the detailed explanation of the difference between source area and source in Annex 2.

In the present publication, source intensity and source activity are considered source parameters. "Source intensity" refers to the capacity of soil surfaces to produce airborne mineral soil particles, which, in turn, depends on topsoil conditions (moisture and temperature) and land cover (portion of bare surface). In comparison, "source activity" concerns source productivity. It depends on source intensity, and the frequency and intensity of surface winds. Frequently active sources do not necessarily have high source intensity, while sources that have high capacity to produce airborne particles could be less affected by high winds and therefore less active in producing SDS.

Sand and dust sources can be detected when they emit mineral soil particles, and by considering topsoil and land cover characteristics. The choice of methodology for mapping sources depends on the desired outcome. If the goal is to detect areas that most frequently produce SDS (or less intensive blowing dust events), source activity can be mapped using SDS observations or related variables (AOD, DOD, ground lidar measurements, visibility, PM observations and so forth (see section 2.1)). The outcome of this approach is the spatial distribution of the activity of source areas. However, the finer distribution of sources is barely perceptible when source areas are not homogeneous. In comparison, if the goal is to detect areas that have high capacity to produce SDS when high surface winds occur, source intensity needs to be mapped. In short: while source activity is gauged using observations on SDS occurrence, source intensity can be detected by employing soil and land surface parameters. More on SDS source mapping approaches can be found in Vukovic (2022). Table 2 gives several examples of what can be expected from the data on sources derived using different approaches.

Surfaces that have the highest capacity to produce SDS are known as source hotspots. These areas can be detected using satellite data (SDS occurrence), if available, over the region of interest (Lee et al., 2012; Engelstaedter and Washington, 2007). However, their true pattern and precise location can be determined from surface characteristics or field observations (see, for example, Vukovic et al., 2014; Arnalds et al., 2016; Vukovic Vimic, 2021; Cvetkovic et al., 2022).

On account of its importance to long-range dust transport and an understanding of the global dust cycle, the distribution of sources within the global dust belt is well addressed in different literature (see, for example, Ginoux et al., 2001; Shao et al., 2011; Ginoux, 2012). The main SDS productive source areas are situated in the desert belt in the northern hemisphere (North Africa, Middle East, Central Asia), the south-west United States, the southern part of South America, South Africa and Australia. This part of the Earth’s surface is well covered by satellite observations and is not frequently “contaminated” with clouds. Discussions on different global and regional SDS productive source areas are available in reports by WMO and the United Nations Environment Programme (UNEP) (2013) and UNEP, WMO and UNCCD (2016). Nevertheless, in such large-scale source areas, knowledge of the spatial distribution of dust emissive surfaces can be further refined using high-resolution data, and different methodologies to process and combine the input data (Lary et al., 2016; Feuerstein and Schepanski, 2019).

Table 2. Examples of SDS source parameters, depending on the question asked, and potential uses of the derived data

Question asked	Target	SDS source parameter	Potential uses of the derived data	Limitations
Where do SDS come from most frequently? Which are the most productive source areas?	Distinguish more and less productive SDS source areas. Recognize the most productive source areas.	Source activity	Learn about the distribution of the most productive SDS areas at global and regional levels, and seasonal variation. Use in dust transport modelling at global and regional levels (long-range transport).	Not all SDS can be observed, and infrequently active source areas can be missed.
Which areas can produce SDS, and how is this potential contribution spatially distributed in larger source areas?	Distinguish areas with different capacities to produce SDS (emit particles) at a higher resolution. Recognize sources within source areas.	Source intensity	Learn about the distribution of potentially emissive areas, from global to local levels, including seasonal variation and during extreme weather events. Can contribute to recognizing source hotspots. Use in dust transport forecasts from global to local levels; possible to update regularly using the latest soil and land cover data.	Highly dependent on the quality of soil and land cover data; does not include information on SDS occurrence.
Which areas are a priority for source mitigation?	Distinguish areas, at a high resolution, with higher capacities to produce SDS and that do so more frequently.	Source intensity and source activity	Learn about hotspots in SDS productive areas; identify areas where the implementation of source mitigation (actions to reduce dust emissions) would be most effective.	Requires many input data (related to SDS observations and to soil and land cover data), which increases the possibility of greater uncertainties in the results. Recommended for mapping limited (smaller-scale) areas.

There is no unique methodology for specifying SDS sources, nor is there a predefined measure of values. Combined parameters can provide information on the location of the most productive surfaces. For example, source areas can be mapped by setting threshold values for observed data and the frequency of SDS events. They can also be mapped by combining different input information and scaling derived values from 0 to 1 (see, for example, Shao et al., 2011; Ginoux et al., 2012; Vukovic, 2019). In areas with limited observations and highly variable SDS source intensity, sources can be mapped by collecting information on specific events that provide evidence of dust emissions, and by using data on surface characteristics. This integral methodology has been used to define high-latitude dust belts in the northern and southern hemispheres (Meinander et al., 2022). The contribution of specific sources to the generation of SDS can be assessed using a combined approach incorporating source intensity mapping and SDS modelling, rather than just sand and dust observations (Joshi, 2021; Vukovic Vimic, 2021). Considerable diversity in the methodologies used to map dust sources shows that this topic is highly dependent on the purpose it serves, as well as on the availability and quality of the data for a given region (see the example of the Islamic Republic of Iran in Box 7).

Box. 7. SDS sources in West Asia

Several studies have been published that address the impacts of dust in West Asia (see, for example, Karami et al., 2021; Namdari et al., 2022). The risk of the accelerated drying up of Lake Urmia is among the most serious problems that may cause huge dust and aerosol pollution in the Middle East and West Asia (especially in the west of the Islamic Republic of Iran) (Mardi et al., 2018).

A collaborative project between the Atmospheric Science and Meteorological Research Center (ASMERC); the Iranian Department of Environment; the University of Yazd, Islamic Republic of Iran; and the Geological Survey and Mineral Exploitation of Iran (GSI) used a combined method to identify dust sources in the Middle East for the period 2009–2018. This method included the Australian Land Erodibility Model (AUSLEM), dust storm detection using the Hybrid Single-particle Lagrangian Integrated Trajectory (HYSPLIT) model, MODIS observations (that is, AOD and vegetation index), visibility observations and Goddard Chemistry Aerosol Radiation Transport (GOCART) model simulations for the estimations of dust emissions (which depend on different variables as the percentage of vegetation, soil texture, soil moisture, roughness and wind speed at a height of 10 m).

According to the climate of each region and the type of soil and vegetation, the threshold values of the effective wind speed on the activation of dust centres are different. Since drought is one of the most important factors in the occurrence of dust events, several related indicators were investigated during the 10-year period. Easy and free access to satellite images with wide, long-term coverage made it possible to reveal and monitor vegetation stress caused by drought. Agricultural drought indices were calculated to quantify the lack of rainfall in the entire region, by extracting vegetation indices at monthly, seasonal and annual timescales from MODIS satellite images.

The analysis of all the observational and modelling data considered in this study revealed that in some areas, the occurrence of severe storms causes the emission of dust, and in some other areas, a gentle breeze can transfer a large number of particles from the surface to the air.

In the study region (Bahrain, the Islamic Republic of Iran, Iraq, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, the Syrian Arab Republic, Türkiye and the United Arab Emirates), five main hotspots were identified – two in Saudi Arabia, and one in Iraq, the Syrian Arab Republic and the United Arab Emirates.

Maps that are widely used to detect major global source areas of dust, and to model dust transport, combine soil characteristics (erodibility) with moisture conditions (Ginoux et al., 2001, Figure 12a). Derived results align with satellite observations of airborne dust. Improvements in the quality and diversity of satellite data, and the increasing availability of data in general, have made the more refined mapping of source area distribution possible. Data derived from observations of SDS occurrence provide information about global source activity (Figure 12b). A high-resolution Global SDS source Base Map (G-SDS-SBM) ((Figure 11c) has been developed by UNCCD in collaboration with UNEP and WMO (see https://maps.unccd.int/sds/). Besides this, many other approaches have been used to detect source areas from global to local scales (Vukovic, 2019).

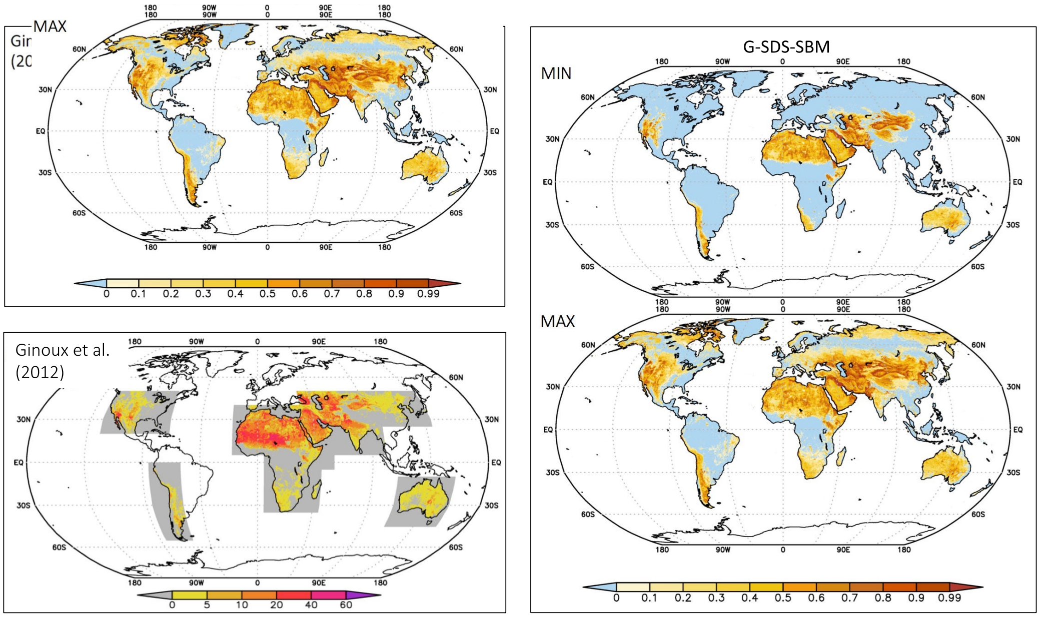


Figure 12. Global distribution of source areas: (top left) based on erodibility and satellite observations combined with precipitation maximum values to distinguish arid areas (Ginoux et al., 2001); (bottom left) based on the frequency of days when satellite-derived DOD was above a certain threshold (Ginoux et al., 2012); and (right) G-SDS-SBM developed from soil and land cover data, annual maximum and minimum values (UNCCD, see https://maps.unccd.int/sds/).

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

2.2.2. Modelling the dust cycle

Successful initial attempts to numerically represent the atmospheric dust process in the late 1980s encouraged later work on developing operational numerical dust prediction systems. Westphal et al. (1988) implemented a four-dimensional numerical dust transport model for the first time. The model included all the major physical processes of airborne dust, which confirmed that SDS could be numerically simulated. Another early effort to simulate the dust process (Joussaume, 1990) was based on a global-scale model used to study the impacts of dust on the climate. At the time, dust was considered a passive tracer with a single particle size.

In the period 1991–1993, the predecessor of the current Dust Regional Atmospheric Model (DREAM) (Nickovic, 1996) was developed as the first operational regional dust model in which dust concentration was one of the prognostic variables in the atmospheric model driver (the “on-line approach”). Dust concentration was updated for every model time step together with other conventional meteorological variables. Although the model used rather simplified parameterizations (for example, a single particle size, a simplified specification of Saharan dust sources), it was able to successfully predict basic features of most major SDS over the Mediterranean (Nickovic and Dobricic, 1996). Interestingly, the same theoretical on-line approach was proposed a hundred years ago by Lewis Fry Richardson, when he advocated for dust to be considered one of eight atmospheric variables in his theoretical numerical weather prediction (NWP) concept. Furthermore, in the mid-1990s, the United States Navy developed a global dust model driven by prescribed meteorology (that is, an "off-line approach"), used to perform the first global operational dust forecasts, providing six-day forecasts twice daily. During the first two decades of the 2000s, the number of dust models, both global and regional, substantially increased (Benedetti et al., 2014). This new generation of models providing daily dust forecasts has significantly increased accuracy by substantially improving dust emission specification, including multiple particle size distribution; implementing much higher horizontal resolutions (down to 10 km for global and 5 km for regional systems); and implementing various dust-related data assimilation techniques in many prognostic systems.

Aerosol data assimilation is a relatively new field of research and implementation. In general, it seeks to incorporate observations into atmospheric models to specify the initial meteorological and atmospheric composition conditions. Faced with a substantial lack of data on atmospheric dust, early models in the 1990s used 24-hour concentration predictions from the previous day as the initial model state, although the importance of dust data assimilation was pointed out (Nickovic, 1996). When, in the 2000s, dust prediction became a more extensive practice at many prognostic centres, various operational centres started to assimilate retrieved dust-related observation products (for example, AOD) rather than using raw observations. There are various techniques to operationally assimilate satellite AOD, such as three-dimensional (3D) variational assimilation (3DVar) (Benedetti et al., 2009; Niu et al., 2008), ensemble Kalman filter (EnKF) (Sekiyama et al., 2010; Di Tomaso et al., 2022) and the dynamic relaxation approach (Pejanovic et al., 2010).

Most aerosol assimilation schemes are based on AOD data from satellites. AOD observations from sensors with visible channels are generally more accurate over the ocean and less reliable over soil surfaces, for which reason important information about dust patterns is missing over desert areas in particular. This is, for example, the case with real-time AOD data from the MODIS or Visible Infrared Imaging Radiometer Suite (VIIRS) sensor satellites. Furthermore, since AOD data do not describe the vertical structure of dust patterns, they limit the performance of assimilation schemes. Aerosol profiles made by lidars on-board satellites (such as CALIOP) or ground-based networks (for example, GALION) (see section 2.1.1) can be used to partially complement AOD data, although the time frequency of these data is insufficient. A promising future alternative could be the use of airport ceilometers to profile aerosols in cloudless conditions, with preliminary studies confirming a reasonable correlation between data from collocated ceilometer and lidar equipment (Cazorla et al., 2017). Currently, the most limiting aspect of dust model data assimilation is the impossibility of using lidar (and potentially ceilometer) observations, as well as satellite aerosol vertical profiles, to further improve dust forecasts. In a recent study (Hsu et al., 2019), pixels with dust retrievals from the VIIRS Deep Blue AOD product were assimilated, along with Lidar Climatology of Vertical Aerosol Structure for Space-based Lidar Simulation Studies (LIVAS) pure-dust extinction coefficient profiles from CALIOP (Amiridis et al., 2013). Most recently, although not yet operationally implemented, a Local Ensemble Transform Kalman Filter (LETKF) (Escribano et al., 2022), combined with CALIOP-based LIVAS dust-related data, has been used for assimilation purposes. In most cases, assimilation of these products (and their combination) has shown to be beneficial, leading to improved model simulation skills.

Thanks to the above-mentioned improvements, many operational forecasts from several NWP and research centres around the world have become available to the community. An overview of the current operational systems delivering dust forecast products can be found in the inDust catalogue (see https://dust.aemet.es/products/dust-products-catalogue). Model intercomparisons are one of the main research activities promoted by WMO (Terradellas et al., 2022) (see Figure 13 and Box 8). They help improve the accuracy and reliability of forecasts and predictions by enabling researchers to identify and correct biases or errors across different models. These comparisons also foster collaboration among scientists, facilitating the sharing of data, methodologies and best practices. By highlighting discrepancies and uncertainties, model intercomparisons drive innovation in model development, ultimately leading to more robust and comprehensive understandings of atmospheric processes and their impacts on the global climate.

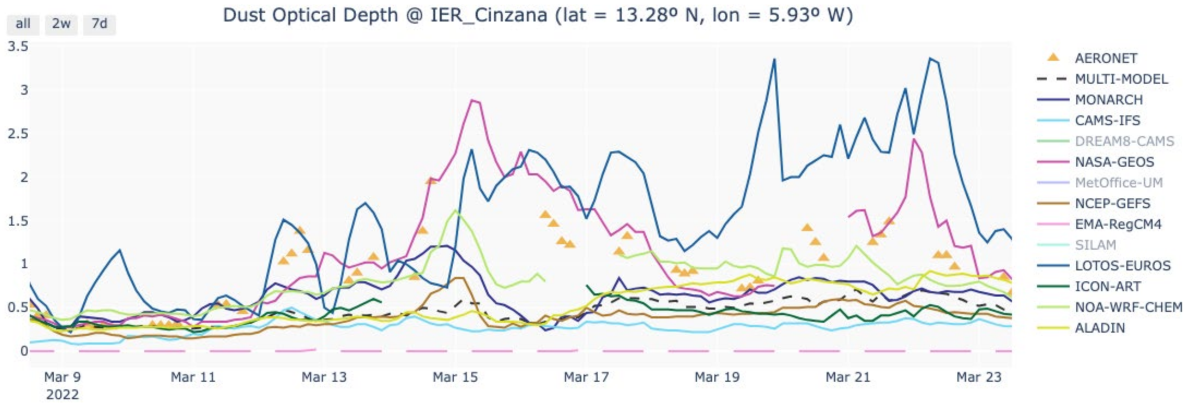


Figure 13. SDS-WAS model intercomparison over the IER Cinzana (Mali) station for March 2022. The comparison is for DOD and the coloured lines correspond to model forecasts; the yellow triangles are dust-filtered observations from AERONET. For the names of the models, see: https://dust.aemet.es/about-us/list-of-models.

Source: Screenshot taken on 15 November 2024 at 1700 UTC from WMO Barcelona Dust Regional Center (see https://dust.aemet.es)

However, operational dust models still cannot predict smaller-scale storms such as haboobs. The current horizontal and vertical model resolutions of available computer resources cannot successfully resolve atmospheric thermodynamics (for example, surface turbulence, convection downbursts, wind gusts) or emission sources, which are essential processes driving small-scale storms (WMO, 2023; Zhang et al., 2023). Recent haboob case studies (Vukovic et al., 2014; Vukovic et al., 2021) show that misrepresentation of local dust sources and the lack of non-hydrostatic effects in atmospheric model components are major causes of prediction failures.

To accurately assess and predict dust impacts, it is crucial to reconstruct previous dust storm conditions. Although observational data have the advantage of being ground-based measurements, there are limitations to the area and time that can be observed owing to budget and human resource constraints. Experience from NWP shows that numerical modelling has the advantage of being able to produce spatially and temporally uniform data, but it also contains errors. A reanalysis product using a data assimilation method that organically integrates observational data and models is undoubtedly the best tool for understanding past SDS. While reanalyses are not error-free, they include observational constraints that can support the reconstruction of past SDS in non-observed areas. There are several available global aerosol reanalyses that include dust, such as Modern-era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) (see https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/) (Gelaro et al., 2017; Randles et al., 2017; Buchard et al., 2017), Copernicus Atmosphere Monitoring Service (CAMS) reanalysis (see https://www.ecmwf.int/en/research/climate-reanalysis/cams-reanalysis) (Inness et al., 2019), Japanese Reanalysis for Aerosol (JRAero) (see https://www.riam.kyushu-u.ac.jp/taikai/JRAero/) (Yumimoto et al., 2017) and the Navy Aerosol Analysis and Prediction System (NAAPS) (Lynch et al., 2016). These global data sets have been produced at relatively coarse spatial resolution and by assimilating AOD.

Reanalysis is used for various social and climatological purposes, such as hazard maps, source distributions, trend analysis, NWP, dust–atmosphere direct and indirect interactions, and so forth. Conversely, the exact distribution of aerosols in the atmosphere by aerosol composition has not yet been clarified. Yamagami et al. (2022) investigated the relationship between aerosol distribution and the errors in the forecasts of lower air temperatures made by several numerical weather forecast centres (based on global aerosol reanalysis, including JRAero and CAMS). Figure 14 shows the correlation coefficients between the prediction errors made by each centre. The positive correlation may correspond to a decrease in temperature due to aerosols. The results show that the use of aerosol monthly values for numerical forecasting affects the results and indicates the effectiveness of aerosol reanalysis.

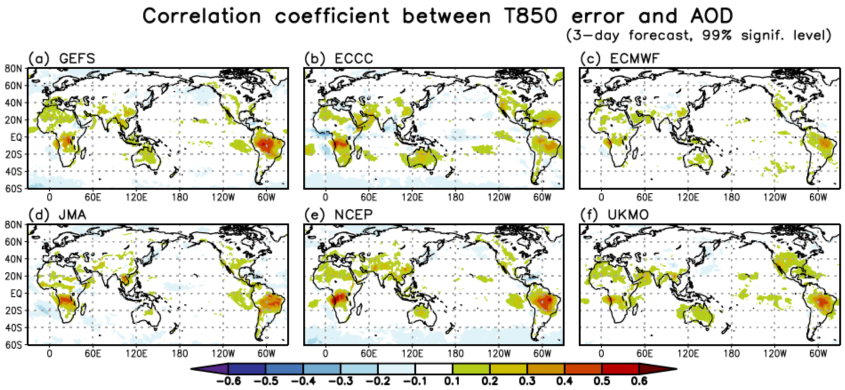


Figure 14. Correlation coefficient between temperature prediction errors and AOD in the three-day forecasts of (a) the Global Ensemble Forecast System (GEFS), (b) Environment and Climate Change Canada (ECCC); (c) the European Centre for Medium-range Weather Forecasts (ECMWF), (d) the Japan Meteorological Agency (JMA), (e) the National Center for Environmental Prediction (NCEP), and (f) the Meteorological Office (Met Office, United Kingdom).

Source: Yamagami et al., 2022

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

Possibilities for dust sub-seasonal-to-seasonal (S2S) prediction have been explored by several international institutions. Benedetti and Vitart (2018) investigated whether aerosol variability could afford some predictability to S2S forecasts using the ECMWF Ensemble Prediction System (EPS), including interactive prognostic aerosols. The authors showed that predictability is afforded by the aerosol variability associated with Madden–Julian Oscillation (MJO), particularly the variability of dust and carbonaceous aerosols.

The degree of improvement crucially depends on aerosol initialization, which underlines the importance of accurate aerosol analysis that is well constrained by observations. By way of an additional benefit, the research demonstrated the possibility of skilful dust forecasts at the monthly scale. The fact that the calculation of dust emissions is based on model parameters (that is, surface winds) allows for the provision of emissions throughout the forecast range. More research and effort will be needed in the coming years to move from these initial attempts to a service-like provision of dust forecasts at the S2S scale.

Using the prognostic products of dust atmospheric models, it is possible to derive other products that are more appropriate for different users. If the models were also developed to capture information about the composition of dust particles, they would be more useful still, but such improvements are in the scientific development stage.

3. RESEARCH EFFORTS

Societal and scientific interest in the SDS process and its various impacts has intensified significantly during the past several decades. In the 1970s, satellite technology could estimate dust loads from space (Knippertz and Stuut, 2014) for the first time. In 1979, the monograph *Saharan Dust: Mobilization, Transport, Deposition* gave the first comprehensive account of what was, at the time, state-of-the-art dust research (Morales, 1979). Also for the first time, atmospheric dust was recognized as a key source of iron as a nutrient for remote oceans (Duce, 1986). From the late 1980s, this accumulated observational evidence (see section 2.1) was followed by the vibrant development of numerical dust models. The initial focus was on simulating individual dust events (Westphal et al., 1988) and global-scale transport (Joussaume, 1990; Tegen and Fung, 1994) by including dust as a tracer in atmospheric models (see section 2.2).

Decision makers have long desired the ability to forecast severe dust events to mitigate their impacts on transportation, military operations, energy and human health, which demonstrates the practicality of monitoring and numerically simulating the atmospheric dust process. Community interest in atmospheric dust has led to rapid growth in the number of dust-related publications released per year, increasing exponentially from the mid-1980s to the present day (Knippertz and Stuut, 2014; Benedetti et al., 2018).

In 2004, in response to community interest in atmospheric dust, WMO and its Members started monitoring, forecasting and implementing EWSs for airborne dust through the SDS Project. In 2007, recognizing the need for international coordination of the diverse community that deals with the societal impacts of SDS, WMO took the lead by developing and implementing SDS-WAS (see https://community.wmo.int/en/activity-areas/gaw/science-for-services/sds-was).

Through international science coordination and successful partnerships, SDS-WAS leads understanding of the SDS process and its interactions with human activities, weather and climate change, and provides warnings/advisories for and assessments of SDS. Overall, SDS-WAS seeks to:

- Facilitate international coordinated research efforts and seamlessly integrate their findings into advancements in air quality management and chemical weather forecasting.

Assist operational implementation of SDS research.

- Promote the use of dust products through training activities.

Build capacity to further improve SDS monitoring and modelling capabilities.

SDS-WAS operates as an international hub of researchers, operational centres and end users. In collaboration with other WMO technical bodies, SDS-WAS supports the transfer of research observational and forecasting facilities to operational technology and to applications relevant for users, identifies research gaps and recommends solutions. SDS-WAS activities are coordinated by the SDS-WAS Steering Committee, which also defines SDS-WAS research policy and priorities. The SDS-WAS organizational structure is shown in Figure 15. SDS-WAS is structured as a federation of regional partners. Research collaboration takes place through Regional Nodes, which are self-organized structures with a high level of autonomy. SDS-WAS involves universities, research organizations, meteorological services, and end-user organizations in health, agriculture, transport and so forth. The main research areas and activities of SDS-WAS, as well as its governance, are described in the *Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS). Science and Implementation Plan: 2021–2025* (GAW Report No. 279).

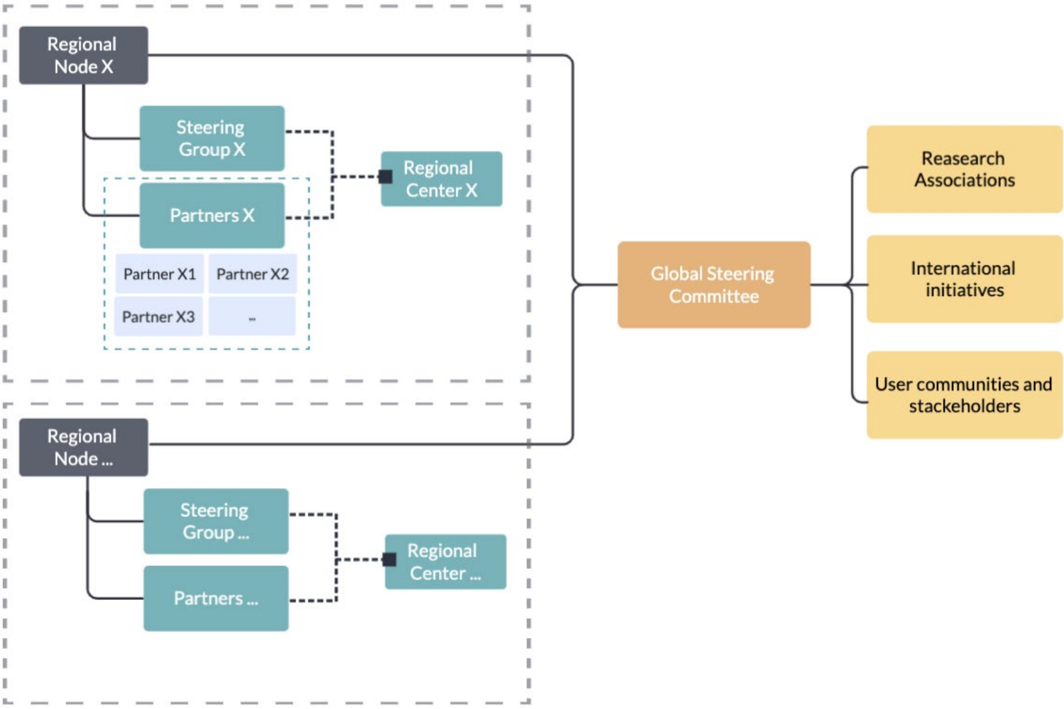


Figure 15. The SDS-WAS organizational structure

Source: SDS-WAS. Science and Implementation Plan: 2021–2025 (GAW Report No. 279)

Regional Node activities include (a) presenting daily experimental dust forecasts, (b) intercomparing forecasts and validating them against observations, and (c) providing training on uses of SDS-WAS research outcomes. The network of Regional Nodes allows flexibility, growth and evolution, while preserving the autonomy of individual institutions. Nodes involve a variety of partners: NMHSs, universities and research organizations, regional associations, data providers and so forth.

SDS-WAS Regional Nodes and associated Regional Centers collaborate with the corresponding WMO Regional Associations and Regional Offices to arrange relevant regional events, workshops and trainings, as well as to mobilize resources. SDS-WAS encourages all Regional Node partners to contribute to regional cooperation and innovation by delivering experimental forecasting and early warning advisory services, and by providing reanalysis data and scientific research. Working with WMO Regional Associations, the feasibility of extending the system will be established for different regions and interested countries. At present, there are four established SDS-WAS Regional Nodes with associated Regional Centers:

Northern Africa–Middle East–Europe, with the associated Regional Center in Barcelona, Spain;

Asia, with the associated Regional Center in Beijing;

The Americas, with the associated Regional Center in Bridgetown;

- The Gulf Cooperation Council (GCC) countries, with the associated Regional Center in Jeddah, Saudi Arabia.

Over the past few years, numerical prediction, and observational products from ground-based and satellite platforms, have become prominent at several research and operational weather centres owing to growing interest from diverse stakeholders. Current attempts to transfer tailored products to end users are not coordinated, which means that the same technological and social obstacles are tackled individually by all the different groups involved, hence the use of data is slow and expensive. To satisfy this demand, cooperation between producers of dust-related products and services on the one hand, and stakeholders on the other, has been built through the development of communication channels connecting scientists with user communities. On the user side, various stakeholders (air quality managers, health professionals, solar energy plant operators, aviation stakeholders, policymakers and so forth) have been involved to specify which new dust products, tailored to their respective needs, are appropriate. The main conclusions on impact assessments and the recommendations of these discussions are considered in United Nations technical reports (see, for example, WHO, 2021; ESCAP and APDIM, 2021) and scientific journals (see, for example, Monteiro et al., 2022; Mona et al., 2023).

One of the main research objectives of SDS-WAS is to coordinate and harmonize the process of transferring dust observations and predictions to users (in aviation, solar energy, health, air quality and climate service communities). SDS-WAS is the reference research group at WMO designated to support the implementation of operational SDS forecasts.

SDS-WAS has demonstrated that its successful research can be a basis to transfer its research outcomes to operations within its Regional Nodes and associated Regional Centers. In 2014, following the request of National Meteorological and Hydrological Services (NMHS), WMO included the Regional Specialized Meteorological Centre (RSMC) for Atmospheric SDS Forecasts (ASDF) (RSMC-ASDF) in the WMO Integrated Processing and Prediction System (WIPPS) (formerly the Global Data-processing and Forecasting System (GDPFS)). The mandatory functions of RSMC-ASDF are described in the *Manual on the WMO Integrated Processing and Prediction System. Annex IV to the WMO Technical Regulations* (WMO-No. 485).

The *WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services* (WMO-No. 1150) is, to a large extent, applicable to SDS as well, since dust is a component of weather and climate. The Guidelines advocates establishing an effective impact-based forecast and warning service (IBFWS), which, in many WMO Members, has become the standard approach for developing forecasting and warning procedures. The Guidelines is a response to the fact that adverse hydrometeorological events increase casualties and damage to property and infrastructure. All this happens even though many severe events are well forecast, with accurate and timely warning information disseminated by the responsible NMHS.

Most of the Guidelines' recommendations are also applicable to SDS, as they are meteorological events. Several institutions deliver timely dust-related observations, predictions and assessments. However, there is still a disconnect between forecasting SDS events and understanding which of their potential impacts should be forwarded both to the national authorities responsible for civil protection/emergency management and to the general population (that is, issued as warnings).

Following the WMO IBFWS concept, the present publication elaborates on how to transform experiences and information into effective SDS impact-based forecasts, assessments and warning services. However, there are some aspects of SDS warnings that require more specific consideration when compared with conventional hydrometeorological events. For example, SDS-WAS already provides daily updates on SDS observations and multiple model dust predictions in its Regional Nodes.

Furthermore, some research projects, such as inDust, seek to support the SDS-WAS strategic goal of transferring/tailoring dust information to end users.

Impact-based forecasts and impact-based assessments are both crucial tools in disaster risk management, but they serve distinct, if complementary, purposes. While forecasts seek to predict and mitigate weather and/or environmental events by providing timely information to authorities and the public, assessments evaluate the impacts of such events after they occur in order to analyse the effectiveness of responses and improve future preparedness strategies. In short, while impact-based forecasts help anticipate and reduce potential harm, impact-based assessments provide insights and lessons learned to enhance resilience and readiness. Together, they form a comprehensive approach to managing and reducing disaster risks. In the following sections, methodologies and products for, and examples of, impact-based assessments (section 4) and impact-based forecasts (section 5) are introduced.

4. IMPACT-BASED ASSESSMENTS

Impact-based assessments are essential tools in disaster risk management, focusing on evaluating the actual impacts of weather events after they have occurred. These assessments provide a detailed analysis of the damage and disruption caused, including economic losses, human casualties, environmental damage and affected infrastructure. By examining the effectiveness of pre-event planning and post-event responses, impact-based assessments offer critical insights that help improve future preparedness and mitigation strategies. This reactive, past-oriented approach ensures that lessons learned from previous events are incorporated into future risk reduction efforts, enhancing overall resilience and readiness for subsequent disasters. Ongoing research seeks to support impact-based assessments at regional and global scales. For example, a report by several United Nations entities includes a global assessment of SDS (UNEP, WMO, UNCCD, 2016), a regional assessment analyses the impact of SDS on health, solar energy, transport, glaciers, cities and agriculture (ESCAP, APDIM, 2021), and a UNEP report looks at the impacts of SDS on oceans (UNEP, 2020). Specific methodologies for impact-based assessments in the health, aviation and solar energy sectors are detailed in the present section.

4.1. Health

4.1.1. Exposure to particulate matter: premature mortality associated with fine particulate matter

Long-term exposure to desert dust is estimated to account for 400 000–600 000 deaths each year worldwide (Lelieveld et al., 2015; WHO, 2021). Most of these premature mortalities are attributed to cardiopulmonary and lung cancers (Giannadaki et al., 2014). The population at the highest risk are children, the elderly and people with pre-existing health conditions. Children raised in high air pollution regions are particularly sensitive because their lungs and immune system are still developing. There is a strong probability that these children will develop asthma and have several years taken off their life expectancy, and they are up to four times more likely to suffer from significantly reduced lung capacity in adulthood (WHO, 2021).

In remote regions, such as the Mediterranean, African dust intrusions contribute between 9% and 43% of measured annual ambient PM_{10} levels, which corresponds to 17%–37% of the days within a year (Querol et al., 2009; Pey et al., 2013). There is growing evidence that mineral dust in PM may contribute to certain deleterious health conditions (Giannadaki et al., 2014; WMO, 2024). The most health-damaging particles are $PM_{2.5}$, which can penetrate the lung barrier and enter the blood system (WHO, 2024). These particles affect more people than other pollutants and have health impacts even at very low concentrations. By reducing air pollution levels, countries can reduce the burden of disease.

PM is a mixture of natural (that is, dust and smoke pollution from wildfires) and anthropogenic local (pollution) components. In the case of dust, its mineralogy and particle size determine how harmful it can be to human health. The possible amount of dust present in the air and the length of time for which the population is exposed to it are important factors for assessing its effects. A proper understanding of dust exposure in epidemiological studies would help authorities take appropriate measures to adequately warn the population about expected local pollution during dust events. Long-term and quality-assured measurements of PM provided by reference air quality monitoring instruments (see Figure 16 and section 2.1.1) and dust model predictions (see section 5.2 and Hohsfield et al., 2023) are the major sources of relevant information for the systematic monitoring of the long- and short-term adverse effects of dust on health.

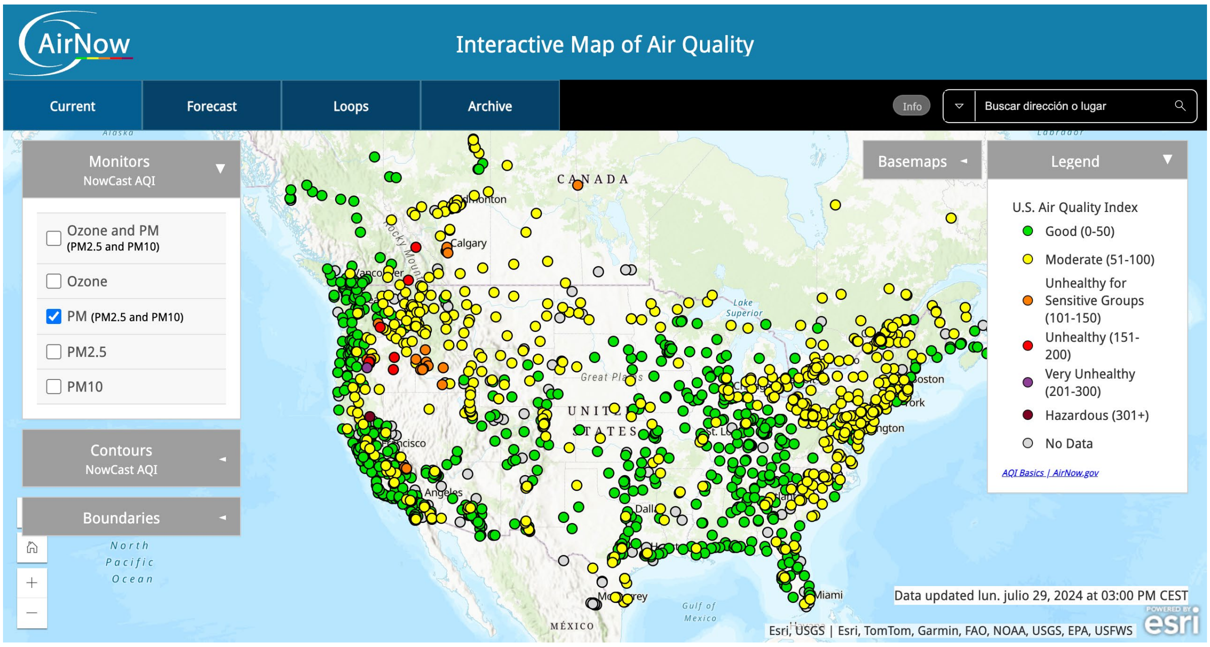


Figure 16. An example of a PM air quality observation network in North America

Key:
AQI = air quality index

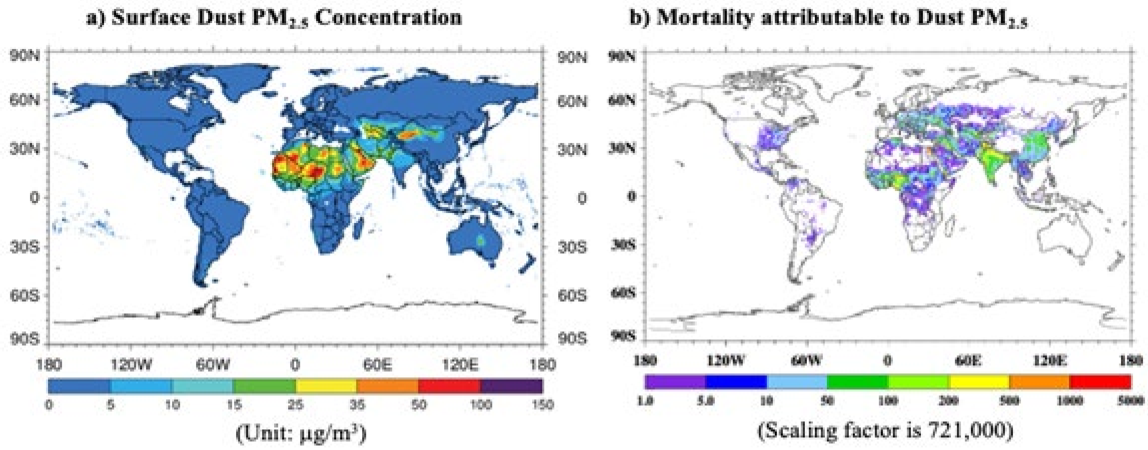
Source: Screenshot taken on 15 November 2024 at 1700 UTC from AirNow (see https://www.airnow.gov/aqaw/around-the-world/)

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

The mortality effect of desert dust, like other air pollutants, can be estimated from four factors: population, baseline mortality rate, dust pollutant concentration (that is, dust concentration) and a concentration–response coefficient (see Anenberg et al., 2010).

The baseline mortality rate is calculated for a given population group, such as adults (aged 30 years or over). Although dust concentration can be provided by measurements from ground monitors, these are sparse or non-existent in desert regions, hence computer models (Lelieveld et al., 2015), or a combination of model predictions and observations (Yang et al., 2022), are often used. These models simulate the life cycle of airborne dust particles, including emission from soil surface, dispersion by wind, and removal by gravitational settling and precipitation. To estimate the mortalities attributable to dust exposure, a cut-off value is usually introduced, with the assumption that dust exposure below this value causes little or no harm. The concentration–response coefficient is provided by epidemiological studies that examine the relative risk of a health endpoint (premature mortality in this case) in response to a unit increase in dust concentration. There is a limited number of epidemiological studies that specifically examine the concentration–response relationship between dust concentration and mortality. Therefore, it is common practice to utilize the concentration–response coefficient for total $PM_{2.5}$, which has been more extensively studied.

High levels of airborne dust particles are found along the dust belt, which extends from North Africa to the Middle East and East Asia (Ginoux et al., 2012; Yang et al., 2022). The mortality effect, however, is more widespread than dust concentration owing to the collocation of dust concentration and population (Figure 17). Dust mortality is higher in regions adjacent to deserts, such as the Sahel, West Africa and the Middle East, and in heavily populated Asian countries such as China and India. Dust also causes considerable mortality in regions far removed from large dust sources, including Western Europe and the eastern United States, on account of exposure to the intercontinental transport of mineral dust (Yu et al., 2012, 2013). In contrast, there is only a small number of dust-associated deaths in regions with the highest dust concentrations, such as the Sahara, owing to how sparsely populated they are.



17. (a) Global distribution of annual average $PM_{2.5}$ concentrations, based on MERRA-2 aerosol reanalysis, and (b) mortality effects attributable to long-term exposure to dust in 2019.

Source: Adapted from Yang et al., 2022

Notes: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

The background map has been modified to align with UN guidance on maps.

4.2.2. Diseases: meningitis

Meningitis is an infection of the meninges, the membranes that surround the brain and spinal cord. Although meningitis can be caused by fungi, viruses or bacteria, the highest global burden is attributable to bacterial infection, owing to its rapid onset and higher risk of death, mental retardation, deafness and other severe health consequences. Bacterial meningitis remains a public health threat worldwide, with the largest burden in the African meningitis belt, which extends from Ethiopia to Senegal (WHO, 2023).

The African meningitis belt is located next to the world's largest dust sources and is characterized by a long dry season and high loading of dust in the air (Figure 18). During the meningitis season (January–May), the incidence rates due to *Neisseria meningitidis* and *Streptococcus pneumoniae*, two major meningitis-causing bacterium, increase between 10- and 100-fold throughout the region (Molesworth et al., 2002). While there is no widely accepted theory about meningitis epidemiology, several hypotheses have been proposed. The most common is that, in dry and dusty conditions, physical damage to the upper respiratory system allows bacteria to pass easily into the bloodstream, causing infection (Pérez García-Pando et al., 2014). Exposure to indoor air pollution, such as cooking smoke, has also been associated with an increased risk of bacterial meningitis (Mueller et al., 2011), probably through similar mechanisms to pneumonia and other respiratory diseases. Other hypotheses include: (a) the potential role of dust particles in the fluid dynamics of airborne bacteria transmission; (b) increased susceptibility due to climate-related stress (high dust levels, low humidity and low evening temperatures); (c) the activation of meningococci by dust-borne iron; and (d) the effects of high dust levels on human behaviour (Pérez García-Pando et al., 2014). Factors other than weather and climate conditions, such as natural immunity levels among a population, vaccination, serotype, new strains, clonal virulence and coincident respiratory infections, are also thought to influence the temporal and spatial variations in meningitis incidence (Mueller and Gessner, 2010).

Models have been developed to use environmental factors to predict outbreaks. A statistical analysis of meningococcal meningitis and climatic variables found that disease resurgence in Burkina Faso and Niger is partially controlled by the boreal winter climate through enhanced harmattan (Yaka et al., 2008). Although these statistical models could explain 25% of the annual disease variance in Niger using only climate indices, they failed to represent the disease dynamics in Burkina Faso. The work of Yata et al. (2008) was extended by Pérez García-Pando et al. (2014), who explicitly added soil dust and wind as predictors of seasonal meningitis incidence in Niger. Based on an operational framework that accounts for changes in climate, dust, population and the incidence of early cases before the onset of the meningitis season, several models were constructed and tested using a time series of meningitis incidence from 1986 to 2006 for 38 districts in Niger. At the national level, the best-performing model used early incidence in December and averaged November–December zonal wind. Another model with surface dust concentration as a predictive variable performed equally well. At the district level, a combined model that included zonal wind, dust concentration, early incidence in December and population density predicted the spatial and temporal variations in localized outbreaks. Beyond Niger, Martiny and Chiapello (2013) found that the onset of the meningitis season in West Africa was closely related to surface mineral dust loading at the beginning of the year, and that each meningitis peak was preceded by a dust peak, with a 0–2-week lead time. Collectively, these studies show that dust, wind and other conditions are potentially conducive to meningitis epidemics.

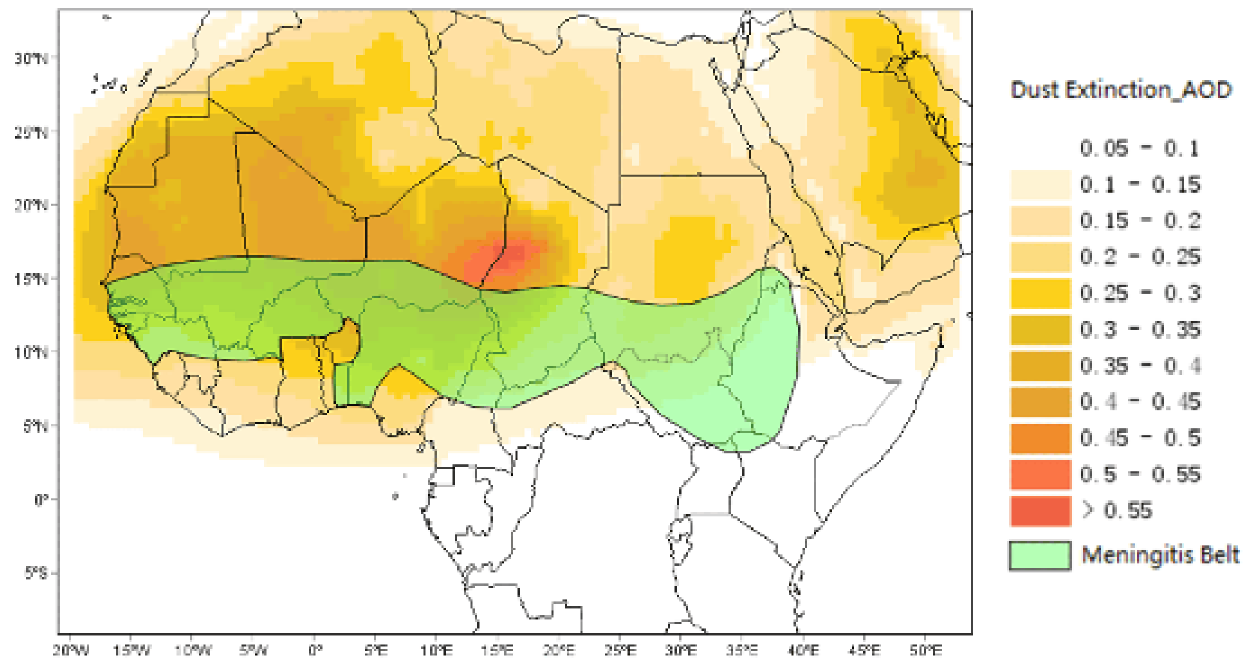


Figure 18. The African meningitis belt and the geographical distribution of dust loading from 1980 to 2015 over North Africa

Source: Revised from Zhang et al. (2016), where dust loading is represented by DOD extracted from MERRA-2

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

4.2. Aviation

Reduced visibility is the major and most common problem for ground traffic in dusty conditions, typically requiring reactive measures. During extreme SDS, visibility can be reduced to zero, significantly affecting airports by making any movement difficult, dangerous and even impossible (Ryder et al., 2024). Visibility depends on humidity (see, for example, Zieger et al., 2013) and the concentration of aerosols suspended in the air, as well as particle size (see, for example, Waggoner and Charlson, 1977). Economic and practical effects of disturbances to airport operations are caused by delayed departures and arrivals, flight rerouting, flight cancellations and even airport closures (see, for example, Monteiro et al., 2022). Moreover, Dust can have significant mechanical impacts on aircraft (see Section 1.5).

The research community is promoting regional assessments as part of the Dust storms assessment for the development of user-oriented climate services in Northern Africa, the Middle East and Europe (DustClim) project (see https://dust.aemet.es/research/dustclim) of the European Research Area for Climate Services (ERA4CS). The project seeks to assess the impacts of SDS on health, solar energy and transport in Northern Africa, the Middle East and Europe. Using a high-resolution dust regional reanalysis (Di Tomaso et al., 2022; Mytilinaios et al., 2023), Votsis et al. (2020) did a first assessment of the effects of dust on the aviation sector in Northern Africa, the Middle East and Europe. This study focused on the effects of dust on aviation operations based on 14 flight levels and various temporal aggregations. It addressed the closing of airport operation because low-visibility conditions (and the implications of airport closures depending on instrument approach capacity) as well as the mechanical effects of dust by providing estimations of the accumulated exposure of aircraft and engines to particle concentrations (that is, engine abrasion) for about 70 000 flight routes and 14 flight levels (Figure 19).

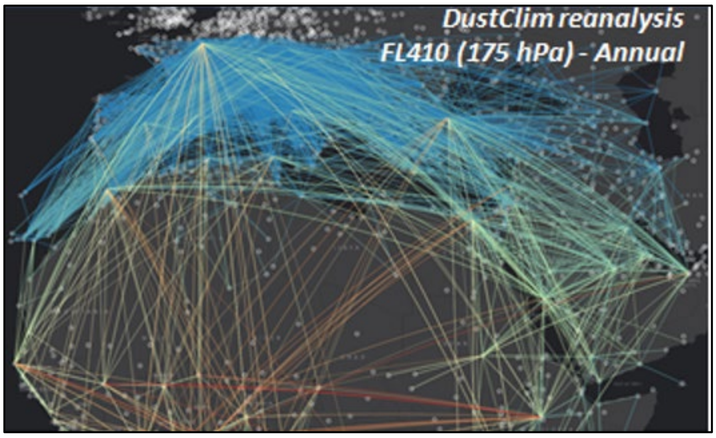


Figure 19. Example of aircraft exposure to dust based on 10-year reanalysis, applied to aviation routes in the Mediterranean region

Key:
FL410 = flight level 410

Source: Votsis et al., 2020

4.3. Solar energy

SDS effects in the solar energy sector are linked with reductions in the capacity of solar panels to produce energy. Dust deposited on transparent materials or glass decreases transmissivity capacity, and dust deposited on mirror materials decreases reflectance, thereby blocking incoming radiation.

By way of an example, the transport of electric energy in Israel can be seriously affected by the deposition of airborne aerosols over the electric insulators of the power supply network. The country is exposed to two dominant types of airborne particle – dust transported from the Sahara and deserts in the Middle East, and sea salt from the Mediterranean Sea – and experience shows that insulation pollution is one of the dominant factors controlling the reliability of electric transmission in Israel (Volpov and Kishcha, 2017).

Kishcha et al. (2020) performed a study based on dust and sea-salt model predictions over a 14-year period (Figure 20) to assess the regions where the Israeli National Electric Company (IEC) is most vulnerable to the adverse effects of aerosols, as well as when this tends to happen. This study introduced innovative technology to provide cost–benefit analysis for dimensioning and maintaining outdoor insulators, PV plants and other pollution-sensitive electric installations. The Tel-Aviv University dust and sea-salt prediction system used in the study provides estimates of the spatial–temporal distribution of aerosol dry deposition. Model climatology for five selected locations in Israel shows that dust deposition reaches its maximum concentrations in March.

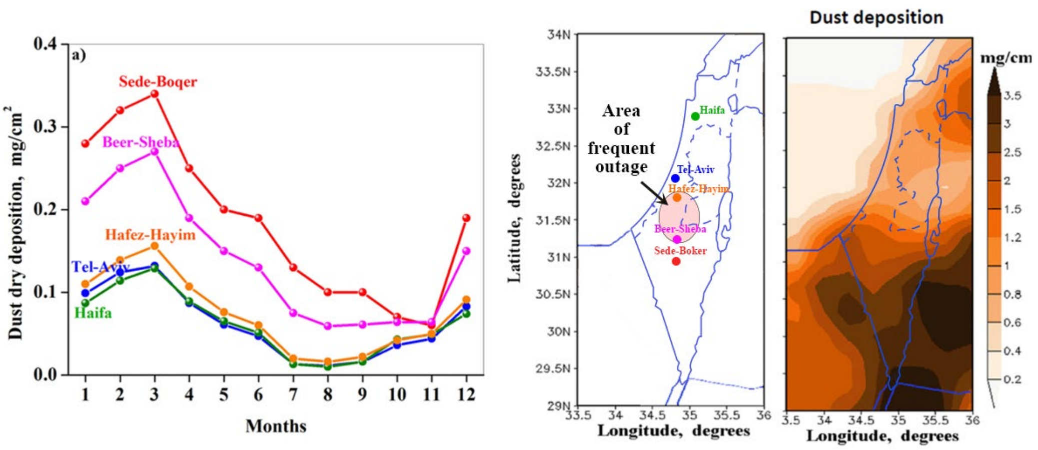


Figure 20. Fourteen-year mean seasonal variations in DREAM dust dry deposition: (left) time series at five selected sites in Israel; (centre) location of the selected sites (the shaded area experiences the most frequent electric network failures); and (right) mean seasonal distribution of dust dry deposition, in milligrams per cubic centimetre (mg/cm³).

Source: Adapted from Kishcha et al., 2020

Notes: The designations employed and the presentation of material on this map do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

The background map has been modified to align with UN guidance on maps.

The averages of dust and sea salt accumulated through dry deposition in March clearly indicate that the central region of Israel, where the most frequent electric power failures occur, coincides with the intersection of two aerosol sets. The results of this study provide important guidance for the industry to optimize the handling of electric power transfer and supply when increased aerosol depositions occur.

5. IMPACT-BASED FORECASTS/WARNING METHODOLOGIES

Impact-based, population-centred forecasts and early warning processes for SDS have been thoroughly described in joint publications by United Nations agencies (including WMO) as well as in the *SDS Compendium: Information and Guidance on Assessing and Addressing the Risks* (Kelly and Kang, 2022). As discussed therein, SDS should be addressed through an impact-based, people-centred forecast and warning process (Figure 21). While the National Disaster Management Agency (NDMA) usually leads the development and updating of SDS risk assessments, the NMHS integrates risk assessment outputs into the forecasting and warning process (Kelly and Kang, 2022). After an SDS event, the NMHS, NDMA and other stakeholders assess the effectiveness of forecast and warning messages by determining whether at-risk individuals took action to avoid or mitigate SDS impacts. These assessments feed back into the system to improve the forecasting and warning process and associated products.

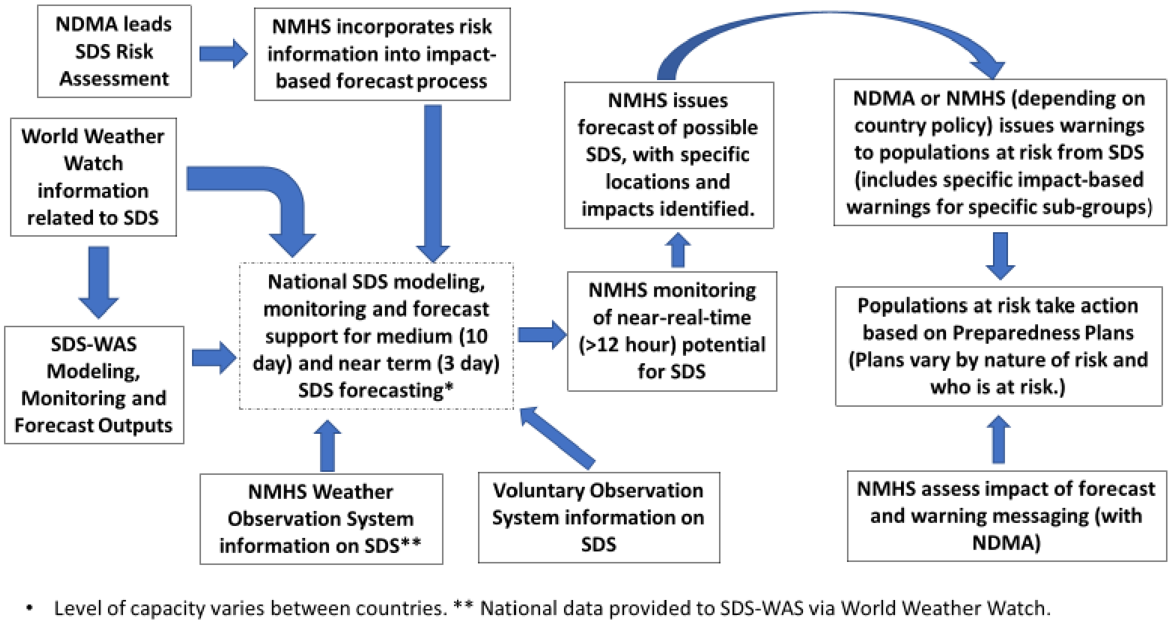


Figure 21. Impact-based, people-centred forecast and warning systems for SDS

Source: Kelly and Kang, 2022

At present, there are different operational systems that deliver daily SDS forecasts (see section 3). Forecasting systems not only predict future pollution levels (including PM) but also play a critical role in issuing warnings when pollutant concentrations are expected to reach harmful levels. These warnings are essential for safeguarding public health, as they advise people, especially vulnerable groups such as children, the elderly and those with respiratory conditions, to take necessary precautions. Transitioning from forecasts to warnings typically involves predefined thresholds for pollutants, with exceedances triggering public alerts. Governments can then issue advisories, restrict outdoor activities, or implement emergency measures to mitigate risks depending on the socioeconomic sector (including health). While Annex 3 presents worldwide examples of SDS operational systems with regional and national domains, the present section includes examples of impact-based forecasts and warning methodologies in respect of health and aviation.

5.1. Health

5.1.1. Exposure to particulate matter: premature mortality associated with fine particulate matter

During SDS, both $PM_{2.5}$ and PM_{10} levels can rise significantly, posing health risks to people exposed to the polluted air (see section 1.2). It is estimated that 1.4% of all deaths worldwide result from exposure to PM (WHO, 2021). Reducing air pollution levels can help decrease the incidence of strokes, heart disease, lung cancer, and both chronic and acute respiratory diseases.

The *WHO Global Air Quality Guidelines* provides an assessment of the health effects of air pollution and specifies thresholds for pollution levels that are harmful to health (Table 3). The thresholds are widely used as a reference tool by policymakers around the world to set standards and goals for air quality management.

Table 3. Annual and 24-hour means for $PM_{2.5}$ and PM_{10} recommended guideline levels

Mean	*$PM_{2.5}$ (micrograms (µg)/cubic metre (m^3)*	*PM_{10} (micrograms (µg)/cubic metre (m^3))*
Annual	5	15
24 hour	15	45

Source: World Health Organization (WHO), 2021

Model predictions of surface dust concentration should complement observations in respect of issuing warnings and/or performing health studies. Current models are capable of predicting major regional-scale SDS with reasonable accuracy. However, there are still large differences in predicted surface dust concentrations between models (see section 2.2.2 and Box 7).

Box 8. Surface dust concentration – different variables for different models

In numerical dust forecasting, surface dust concentration refers to total dust concentration in the lowest model layer. As models differ in terms of the range of sizes of dust/sand particles they include, the prognostic variable (that is, (total) surface concentration), is not uniform, which could result in considerable uncertainties when models are compared.

Figure 22 shows the outputs of several models contributing to the WMO Barcelona Dust Regional Center ensemble that include different particle size ranges in surface dust concentration, as well as the multimodel ensemble median value of the 16 participating models. The model that includes the smallest particle size range (0 µg–10 µg) (the Multiscale Online Non-hydrostatic Atmosphere Chemistry model (MONARCH)) gives lower surface dust concentration values. The model that includes medium-sized particles (0 µg–30 µg) (the System for Integrated Modelling of Atmospheric Composition (SILAM)) gives somewhat higher surface dust concentration values. The model that includes the largest-sized particles (0 µg–300 µg) (the Meteorological Office Unified Model (MetOffice-UM)) gives far greater surface dust concentration values. The differences between model results are also affected by dust source, emission, transport and deposition parameterization, as well as by differences in atmospheric and soil surface conditions, although this has more to do with a model's numerical representation of dust. The issue here is that the models do not produce a uniformly defined variable and therefore cannot be expected to coincide in terms of values. Furthermore, the height of the lowest model layer varies, hence the generated surface dust concentrations do not represent values at the same altitude. More intervention and greater efforts by modellers, aided by officially adopted guidelines, are needed to standardize the variables that the models produce.

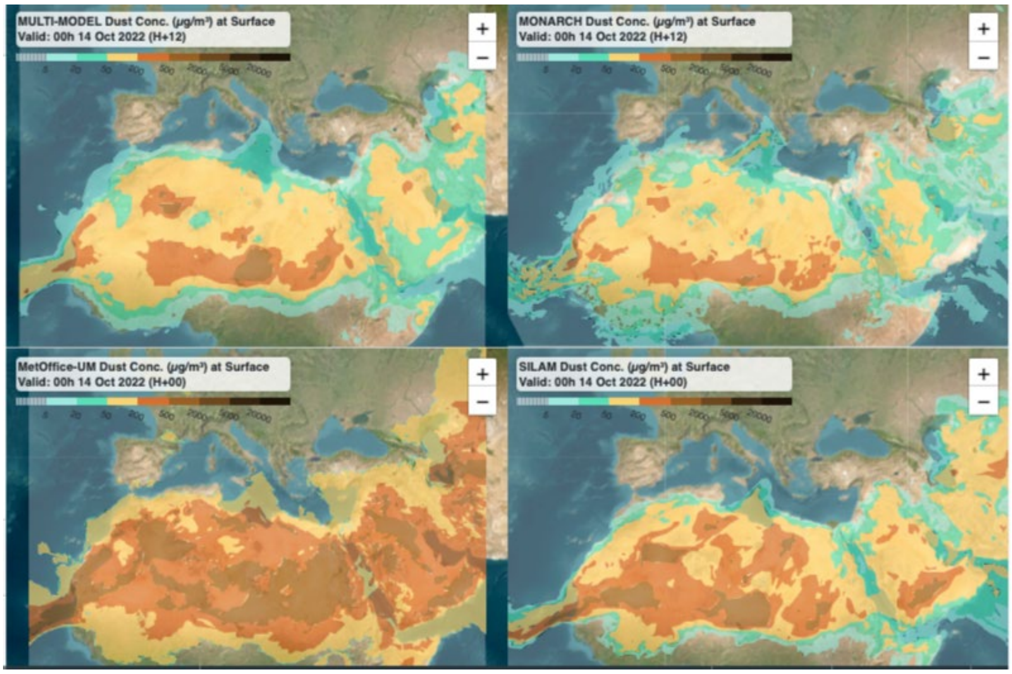


Figure 22. Surface dust concentration forecasts (in micrograms (µg)/cubic metre (m^3)) for 14 October 2022, at 0000 UTC, from the multimodel ensemble, MONARCH, MetOffice-UM and SILAM and the multimodel ensemble value (median value of the forecasts produced by the 16 participating models).

Source: Screenshot taken on 15 November 2024 at 1700 UTC from the WMO Barcelona Dust Regional Center

An intercomparison study (Uno et al., 2006) involving eight dust emission/transport models over Asia demonstrated that surface dust concentrations were predicted between the 25% and 75% percentiles, generally coinciding with PM observations. However, the maximum concentration predicted by each model differed by a factor of 2–4, which limits the usefulness of surface dust concentration forecasts in terms of assessing health effects. Nonetheless, models can still provide helpful, shorter-term information on expected dust episodes over a particular region, which is used to alert the most vulnerable populations and/or allow preparations for more detailed measurements during the episode (Querol et al., 2019). For example, it is known from empirical practice that, while the usual ratio of $PM_{2.5}$ to PM_{10} is about 1 to 10, it can increase up to 7 to 10 during SDS.

The WMO Barcelona Dust Regional Center (see section 3), which coordinates the activities of SDS-WAS for Northern Africa, the Middle East and Europe, provides access to SDS information in near real time. It collects operational dust forecasts from 16 (regional and global) models, which provides a unique framework for developing probabilistic products. The probability map depicted in Figure 23 shows the percentage of models predicting an exceedance of a given threshold of dust concentration (specifically, a daily mean of 50 micrograms (μg)/cubic metre (m^3), as per the *WHO Air Quality Guidelines*)) on 16 March 2022 (see also Annex 3.ii). This clear, concise information is expected to help plan activities that are vulnerable to airborne dust, or activate services and procedures that seek to mitigate the damage caused to health or any other vulnerable sector.

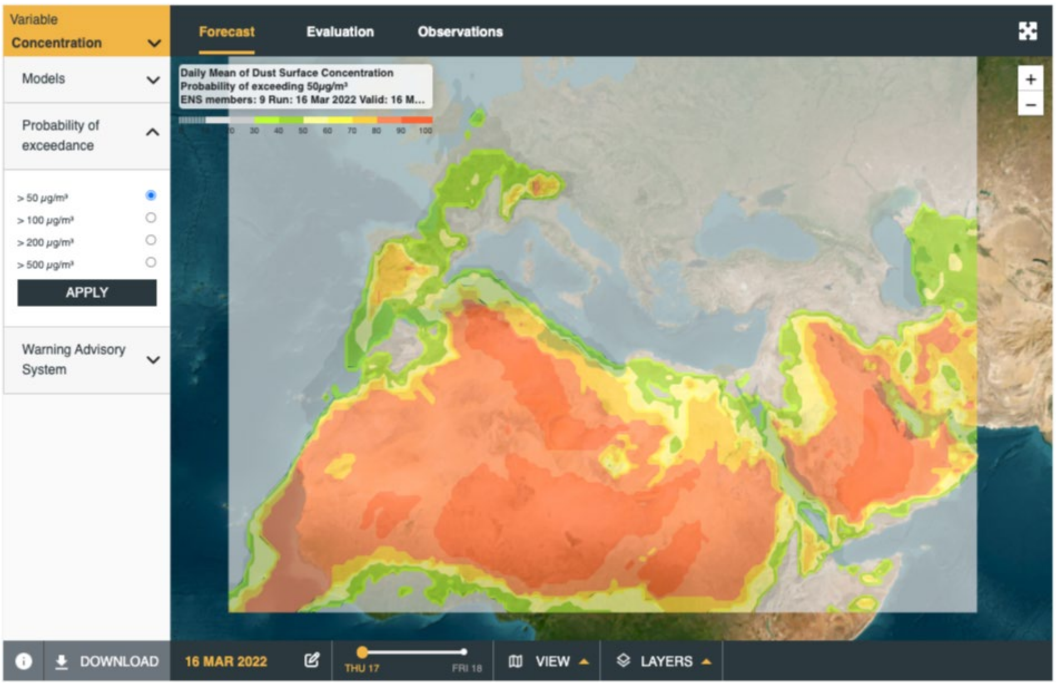


Figure 23. Probability of dust concentration exceeding a daily mean of 50 micrograms (μg)/cubic metre (m^3) for 17 March 2022

Source: Screenshot taken on 15 November 2024 at 1700 UTC from the WMO Barcelona Dust Regional Center

Another example is the North American Ensemble Forecast System (NAEFS) (see Annex 3.iii), which combines state-of-the-art weather forecast tools (ensemble forecasts) developed by the Meteorological Service of Canada (MSC) and the United States National Weather Service (NWS). It is based on several air quality operational and research prediction systems that also consider dust emissions.

5.1.2. Infectious diseases: Valley fever

Coccidioidomycosis, commonly known as Valley fever, is an infectious disease caused by inhaling the spores of soil-dwelling fungi such as *Coccidioides immitis* and *Coccidioides posadasii*. The Centers for Disease Control and Prevention (CDC) reported that infection rates of Valley fever increased by 700% between 2000 and 2019. CDC estimated that Valley fever has killed at least 4 000 people and infected 150 000 people in the United States (Gorris et al., 2021). While routine public health surveillance of this disease is limited to the United States, Coccidioidomycosis infection has been reported in many areas of North, Central and South America (Tong et al., 2023a). Treatments are expensive, with annual medical costs, lost income and economic welfare adding up to US$ 400 000 per case. Using the hospitalization rate, the total cost of Valley fever infection amounted to US$ 40 billion between 2011 and 2021 in the United States alone (Gorris et al., 2021). Valley fever outbreaks are known to occur after large dust storms and exposure to extreme dust events (Pappagianis and Einstein, 1978; Tong et al., 2017). The majority of Valley fever infections are reported in the same areas affected by dust storms (Figure 24). It has been suggested that climate warming and drought, which lead to more frequent windblown dust storms, and anthropogenic fugitive dust from unpaved roads are the cause (Tong et al., 2017). These conditions appear to favour saprobic growth, conidia formation and air dispersal of *Coccidioides* (Kolivras et al., 2001; Comrie, 2005).

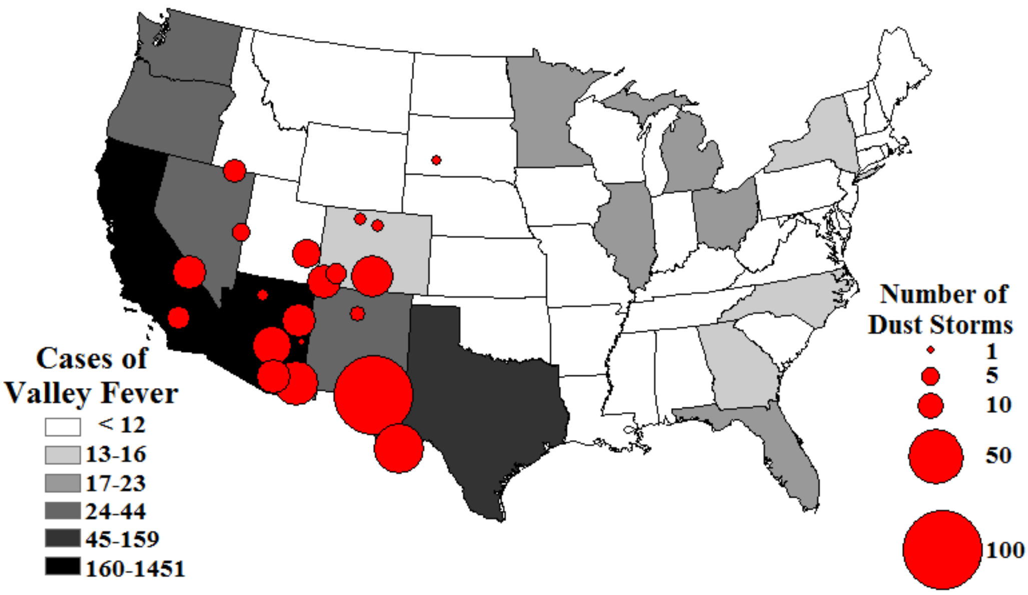


Figure 24. Dust storms (red circles) and Valley fever incidence (shading) in the United States

Source: Tong et al., 2017

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

Two types of method have been used to predict potential outbreaks of Valley fever. The first method uses statistical models that are constructed by fitting Valley fever incidence with selected environmental variables (controlling factors) in endemic regions. The variables considered include weather, climate, dust or aerosols, and socioeconomic metrics. Table 4 summarizes the environmental variables used in prior studies to predict Valley fever outbreaks. These models generally take the environmental variable(s) and time (month, season and year) as inputs; represent dust either directly or indirectly (via PM_{10} or precipitation/soil moisture, for example); and predict Valley fever incidence at monthly intervals.

Table 4. Environmental variables used to predict Valley fever incidence in the United States

Study	Environmental variables	Region
Smith et al. (1946)	Precipitation	San Joaquin Valley, California
Maddy (1965)	Wind, dust, precipitation	California
Kolivras and Comrie (2003)	Temperature, precipitation	Pima County, Arizona
Comrie (2005)	Precipitation, PM_{10}	Pima County, Arizona
Park et al. (2005)	Building permits, Palmer Z Index, Palmer Drought Severity Index (PDSI), wind, temperature, dust, precipitation	Maricopa County, Arizona
Zender and Talamantes (2006)	Precipitation, wind speed, temperature, surface pressure	Kern, California
Talamantes et al. (2007)	Precipitation, wind speed, temperature	Kern, California
Tamerius and Comrie (2011)	Precipitation	Maricopa County and Pima County, Arizona
Stacy et al. (2012)	Normalized difference vegetation index (NDVI)	Maricopa County, Pinal County and Pima County, Arizona
Coopersmith et al. (2017)	Soil moisture	Arizona and California
Weaver and Kolivras (2018)	Temperature, precipitation	Kern, California
Gorris et al. (2019)	Temperature, precipitation	Contiguous United States
Kollath et al. (2022)	PM_{10}, temperature, precipitation	Maricopa County, Pinal County and Pima County, Arizona

The most-used environmental variable was precipitation; even the two studies that did not include it in their Valley fever prediction models (Stacy et al. (2012); Coopersmith et al. (2017)) were designed to incorporate precipitation-related processes, such as evaporation and run-off, using soil moisture or the normalized difference vegetation index (NDVI) retrieved from satellites. Other environmental variables investigated include surface temperature, wind speed and surface pressure (see, for example, Kolivras and Comrie, 2003; Park et al., 2005; Zender and Talamantes, 2006). One study also considered socioeconomic variables that are related to soil disturbance, such as building permits and climate indices, including the Palmer Z Index and the Palmer Drought Severity Index (PDSI) (Park et al., 2005).

Since the early studies, the occurrence of SDS has been shown to affect Valley fever (Maddy, 1965; Kolivras et al., 2001; Tong et al., 2017). Arthrospores measure between 3 μm and 5 μm, meaning that they are easily lifted and dispersed during blowing dust events (Kolivras et al., 2001). The commonly accepted “grow and blow” hypothesis postulates that the occurrence of this disease is controlled by two phases: a wet season, which allows for the development of *Coccidioides* spores, followed by a dry season, which allows for spore dispersion and inhalation by humans and animals (Tamerius and Comrie, 2011). Several issues remain in respect of dust data and their application to geohealth studies, including on Valley fever (Tong et al., 2022; Ardon-Dryer et al., 2023).

The second method to predict Valley fever outbreaks is by simulating the processes of emission, dispersion and population exposure utilizing a coupled weather and air quality modelling system (Sprigg et al., 2014). This method adds *Coccidioides* as a tracer in atmospheric modelling experiments. In Sprigg et al. (2014), *Coccidioides* was incorporated into the Non-hydrostatic Mesoscale Model on E-grid (NMME)–DREAM model Nickovic et al. (2001) and used to conduct a hindcast of the haboob that took place on 5 July 2011 in the south-west United States. The model simulates weather conditions and the emission, transport and removal of dust particles. In areas that are known sources of *Coccidioides* arthroconidia, dust emission, calculated with the NMME–DREAM model, is further parameterized to estimate *Coccidioide*s abundance based on a digitized source map of the fungus. The model also considers the effect of soil texture, represented by silicon fraction. Using satellite surveys, the *cocci*-laden source map was updated every two weeks. It was assumed that the fungi are only emitted from presumed endemic areas with silicon-rich soils. Figure 25 shows the six-month mean concentrations of surface dust and airborne *Coccidioides* spores, from May to October 2011, in the south-west United States. While peaks in concentrations of both dust and *Coccidioides* spores occurred during the aforementioned haboob on 5 July 2011, these peaks were not very pronounced. The model was unable to reproduce the dust clouds and haboob features with a low (20 km) spatial resolution. In contrast, model simulations with a high (3.5 km) spatial resolution performed much better (Sprigg et al., 2014).

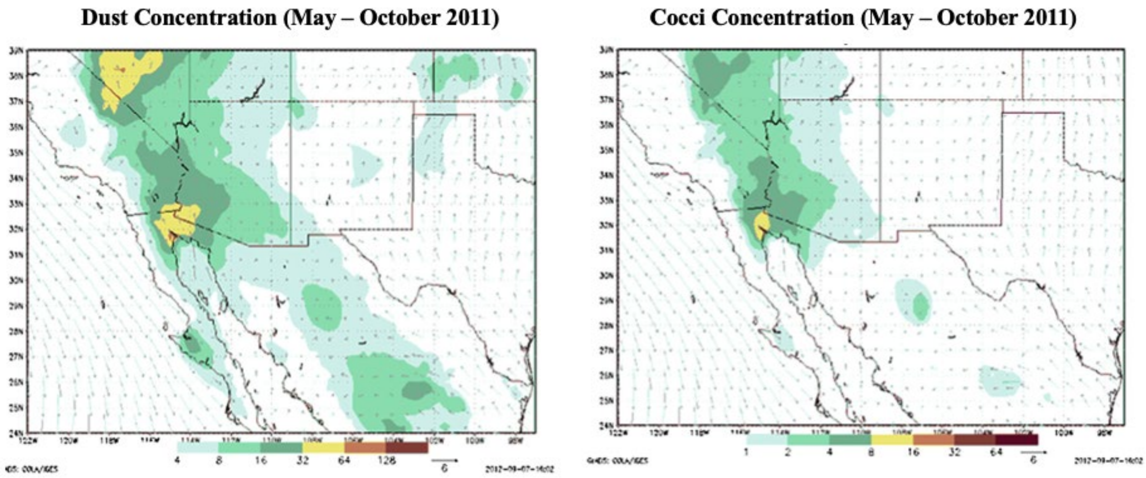


Figure 25. (left) Surface concentration of dust (μg/m^3) and (right) *cocci*-spore-laden dust (arbitrary units) (averaged over the period May–October 2011) in the south-west United States

Source: Sprigg et al., 2014

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

5.2. Aviation

Airlines require EWSs for fleet planners and dispatchers to make decisions. Warnings are even more important to assist crews when urgent decisions are required in respect of high-risk flights. Some operational systems produce visibility reduction forecasts that can support airport operations, but these products are yet to be fully deployed. Below are examples of warning systems that could be helpful for air traffic safety management affected by mineral dust.

5.2.1. Icing

The new generation of ice nucleation parameterization, which includes dust as an ice nucleation agent, opens possibilities in respect of the more accurate treatment of cold cloud formation in atmospheric models. Recent developments enable the use of ice nuclei as an input into the cloud microphysics schemes of atmospheric models. Such approaches could improve the accuracy of predictions of the formation of cold and mixed clouds in current NWP models (Weger et al., 2018).

The potential role of mineral dust in icing at aircraft cruising levels had not been studied until recently. Calculating different icing indices from numerical models is the standard approach to estimate icing conditions for the air traffic sector, and calculations usually include predicted temperature, cloud liquid water, relative humidity and vertical velocity. However, none of the icing indices currently used by the meteorological community consider icing caused by mineral dust (see, for example, Olofsson et al., 2003; de Laat et al., 2017; Morcrette et al., 2019). A newly proposed icing index combines both thermodynamic and dust parameters for the first time (Nickovic et al., 2021). It is applied for temperatures lower than −15 °C and is a function of predicted temperature, moisture, vertical velocity and dust concentration. This dust icing index was tested for two catastrophic aircraft accidents caused by ice formation along their routes. The modelling study showed that the predicted dust icing index sharply increased at the approximate locations and times of both accidents, where desert dust was brought to the upper troposphere by convective circulation. Consequently, it is apparent that predicted dust concentration, available from numerous coupled dust–atmospheric models, can be used to routinely support the aviation industry with more accurate predictions of cold cloud formation enhanced by dust (Figure 26). Figure 27 gives an example of a global modelling prototype adjusted to support aviation needs.

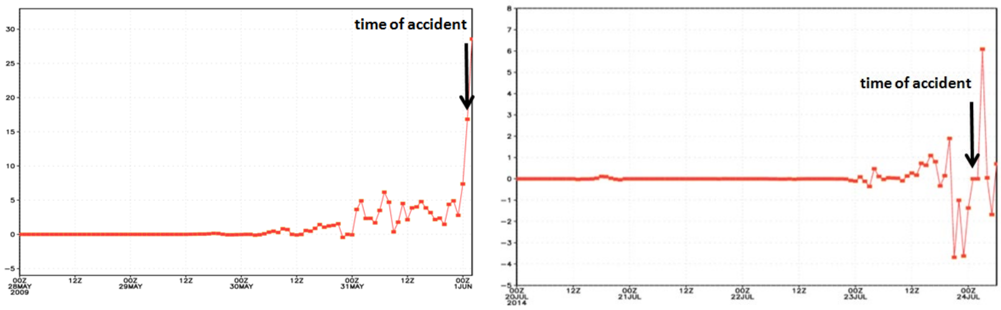


Figure 26. Temporal evolution of the dust icing index at the flight levels of two aircraft accidents

Source: Nickovic et al., 2021

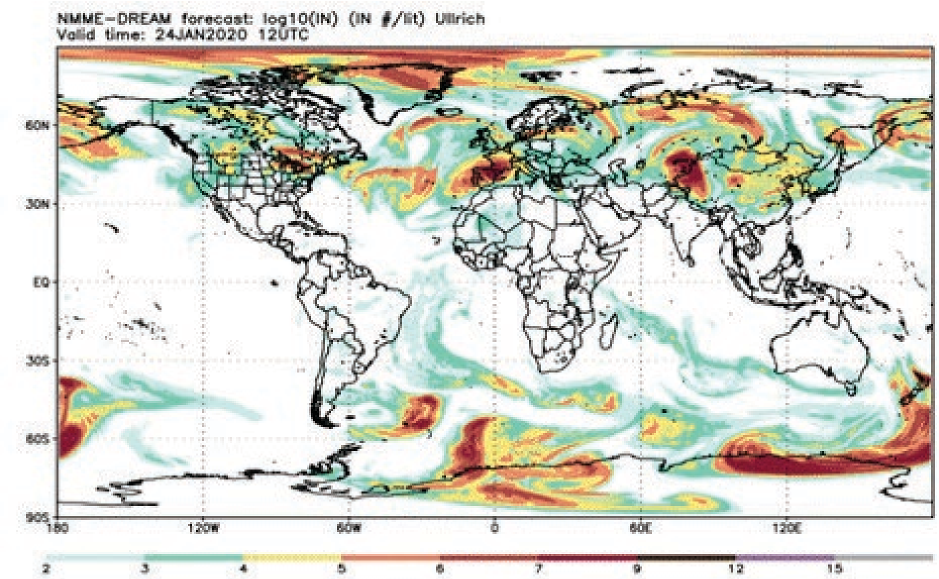


Figure 27. Example of a possible early warning product for aviation: 24-hour global model prediction of icing caused by mineral dust

Source: Republic Hydrometeorological Service of Serbia

Notes: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

The background map has been modified to align with UN guidance on maps.

5.2.2. Predicting dust melting in air engines

Dust mineralogical composition, length of exposure and particle size distribution are key factors in assessing how harmful the presence of mineral aerosol is to aircraft engines. The probability of dust melting in engines is a function of exposure time, dust concentration and mineralogical composition, which is determined by mineral types at source (see, for example, Journet et al., 2014; Gonçalves et al., 2023). The combination of different molten minerals determines the likelihood of adhesion to a surface in the hot section of an engine. Aerosol exposure laboratory tests are standard procedures for examining the harmful effects of dust particles on engine behaviour, with various samples injected into jet engines in manufacturing testbeds. These studies have investigated the behaviour of jet turbines in tests whereby controlled engines are exposed to synthesized mixtures of dusts and/or sampled volcanic ash (Clarkson, 2017). Although such approaches seek to mimic the effects of mineral dust on turbines, they cannot completely simulate real-time flight conditions. For example, the mineralogical composition of dust transported to airport zones during take-off/landing varies considerably. Even though controlled engine tests and susceptibility estimates provide useful general information for aviation operators, they cannot yet predict expected dust effects along flight trajectories in real time. As an alternative, predictions of dust concentration and mineralogy for airports where dust melting is expected could adequately warn aviation services and potentially decrease the risk of accidents.

Following such a concept, a numerical modelling system has been proposed to predict aerosol melting in engines when aircraft pass through dust clouds (Nickovic et al., 2018). It simulates not only transported dust concentration but also the mass fractions of eight typical dust minerals (illite, kaolinite, quartz, feldspar, calcite, gypsum, smectite and hematite). Emission of minerals from dust-productive soils is specified using the global minerals database (Nickovic et al., 2012). The probability of dust melting at a particular airport location is predicted by combining modelled mineral fractions with typical melting temperatures. The methodology was tested for an extreme dust storm that occurred on 1 and 2 April 2015 (Figure 28a) when dust melted in the turbines of aircraft landing at Doha International Airport (Clarkson, 2017). The event has been classified as a "long-term damage" case (Clarkson, 2017), with engines exposed to dust concentrations of several μg/m^3 for ~10–15 minutes during landing/take-off. The dust storm, which was generated in a desert area of Iraq the day before, passed swiftly along the eastern Arabian Peninsula before arriving in Qatar. According to the Qatari environmental and meteorological authorities, this was the strongest dust storm ever recorded.

The model accurately indicated the location and intensity of melted dust (Figure 28b). If routinely implemented, the proposed method could help the aviation industry avoid the considerable costs of repairing damaged turbines.

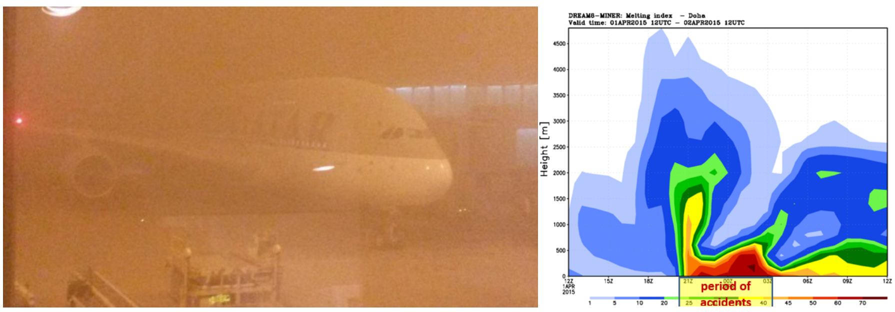


Figure 28. (a) An Airbus A380 at Doha International Airport on 1 April 2015, and (b) a time–height graph with the predicted dust melting index for Doha International Airport in April 2015.

Source: Walker et al., 2015; Nickovic and Cvetkovic, 2018

6. CONCLUSIONS AND RECOMMENDATIONS

Science and practice related to SDS include studies that concern the role of the dust cycle in the climate system and its interactions with the energy, water and carbons cycles, as well as ways to combat the damaging effects of SDS. The complexity and interdisciplinarity of SDS-related impacts and preventive actions is reflected in the interest expressed by United Nations bodies to form the United Nations Coalition on Combating SDS (see Annex 1) to discuss associated issues. Another synergy has arisen from SDS-related actions – they are the joint targets of three United Nations conventions (UNFCCC, UNCCD and CBD). Mitigating SDS sources is also related to implementing nature-based solutions, an umbrella concept proven to contribute to combating climate change through adaptation, with benefits for mitigation.

The capacities of SDS-related observations and modelling, as well as an understanding of mineral dust interactions with the environment, have shown great potential for further development to reduce uncertainties regarding SDS assessments, the climate system and the response of the climate system to climate change. The uniqueness of atmospheric dust transport is that it originates from intensive near-surface processes that are easily missed by observations and/or models because of their relatively small scales and short durations compared with other systems that also have wide-ranging effects. In short, SDS are the source of long-range dust transport, occur in frequently impacted areas and are recognized as hazards. On account of climate change and intensive land exploitation, favourable conditions for their development are spreading over much larger areas than those commonly recognized as the global dust belt, showing the international nature of SDS-related issues. Understanding, forecasting and projecting SDS and dust–environment interactions, including assessments of the role of the dust cycle in the climate system, require broad interdisciplinary collaborations between scientists and other experts in numerical weather forecasting, Earth system modelling, remote sensing, soil science and minerology, marine sciences, land management and so forth.

Developments in SDS-related knowledge, including modelling, can be summarized as (a) developments in SDS hazard prediction, and (b) developments in the understanding of the large-scale effects of the dust cycle. While the former targets the development of EWSs to provide information for user communities and short-term warnings to help decision makers, the latter looks at the role of the dust cycle in the climate system and the climate-changing world. These two development pathways have somewhat different priorities in terms of observations and model set-up. On account of the intricacies of dust behaviour and its large variability in time and space, decisions must be made to either enhance complexity or simplify parameterizations depending on expected outcomes. While SDS-WAS forecasts predict regional-scale events, local SDS events require warning systems that incorporate local source characteristics and higher-resolution modelling. In areas affected by large-scale dust transport and by dust emitted from local sources, SDS warning systems require nesting of transported dust from distant areas into local forecasts. Although high-resolution predictions can resolve intensive convective activity that generates severe SDS, resource restraints mean that, at present, they cannot be implemented over large model domains covering all the relevant sources for some affected areas.

While long-range (seasonal) weather forecasts are used by decision makers, especially in the light of more frequent extreme seasonal events, they are still not of the necessary quality or operational availability. Users would benefit from long-term SDS forecasts in respect of planning adjustments in agricultural production, mitigating SDS-related health impacts and so forth.

There is great uncertainty in climate projections in respect of assessing the total impact of dust on the energy balance of the climate system. Scientific analyses highlight that uncertainties may be caused by different model assessments of airborne dust abundance in the climate system, seasonal changes in activity, and a poor understanding of the relationship between dust and cloud formation. Complexity arises from the fact that the environmental response to dust, and vice versa, depends on the mineral composition of the dust, which is determined by the characteristics of source areas and the transformation dust undergoes when transported. As projections of dust emissions depend on land surface characteristics and atmospheric processes, changes in these variables are central to future climate changes.

Owing to the considerable advances in understanding and predicting SDS and dust cycle processes in recent decades, topics for greater knowledge improvement have been identified, as have user communities and the benefits of SDS prediction-related products. As summarized above, further advancements should be made in science and in building warning systems for specific implementation areas. While currently operational SDS forecasting systems cover short-term predictions of regional-scale processes, improvements are required for the development of warning advisories and assessments. Intense and short-live SDS, temporal dust sources or seasonal predictions are required to meet user needs.

Global-scale SDS observations that can help scientists and forecasters develop improved monitoring and forecasting systems, and verify their performance, are not easily collected, nor are they as simple to access as the well-systematized databases for other atmospheric variables. Furthermore, there is a lack of understanding that, for example, PM_{10} observations are essential for monitoring (weather-related) SDS hazards. Such data are not included in international exchange protocols and are considered pollution monitoring, rather than a weather-related variable. A similar problem exists for forecast output data. While for other atmospheric variables there are internationally accepted agreements on necessary output variables and related standards (including codes, formats and exact meanings), no such guidance/protocols are provided for SDS. Therefore, the understanding, use and formation of ensembles, and the verification of forecasts, could be affected by the use of different output variables.

Great advances have been made in developing scientific knowledge related to SDS processes (necessity, severity, globality). To understand needs and urgencies in respect of further improvements of SDS services, the dissemination of such information to different funding mechanisms (for science and operations) and organizations able to enhance data accessibility should be accelerated.

Considering this overview of SDS-related knowledge and gaps, the recommendations can be summarized as follows.

(a) Improve understanding of SDS and enhance capacities for further early warning developments:
   - (i) Redefine SDS in terms of different scales, causes and consequences, and origin areas – provide a unique definition of SDS through advances in knowledge of their appearance and impacts.
   - (ii) Use connections with focal points (at other United Nations entities) to (efficiently) report on SDS – improve understanding of the globality of SDS.
   - (iii) Advise on the creation of protocols for SDS-related data exchange to synchronize and promote the use of global and regional dust forecasts.

(b) Enhance capacities to promote SDS-related knowledge (scales of impacts, global coverage, environmental implications and so forth) to boost recognition and secure funds for relevant interdisciplinary scientific developments.

(c) Set priority targets for early warning development. Based on the presented analysis, possible priorities are:

   (i) Enabling implementation of local (national) EWSs by facilitating access to initial and boundary fields, and providing guidance to build local (national) capacity.

   (ii) Assessing capacities to develop seasonal SDS products based on the current operational S2S climate predictions

These recommendations could be most efficiently implemented by the United Nations Coalition on Combating SDS, guided by WMO (through the SDS-WAS), because of their experience and knowledge of policies and protocols, as well as their capacities to collect and disseminate relevant information and essential data.

In the climate-changing world, faster implementation of science into practice is required to prevent considerable losses. Although SDS are identified as a climatic impact-driver by IPCC, great uncertainties surround this hazard and the role of the dust cycle in the changing climate system. In other words, SDS are one of the weak points in climate system sciences and operational warning systems. For this reason, enhancing the collaboration within the partners of the United Nations Coalition on Combating SDS (including WMO) to implement the aforementioned recommendations is strongly advised.

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ANNEXES

Annex 1. A complex interdisciplinary problem and international cooperation framework

The challenge of sand and dust storms is one where multidisciplinary science has a clear and essential role in supporting policies for sustainable development. It is very important to enhance national, regional and international cooperation and partnerships to observe, predict, mitigate and cope with the adverse effects of sand and dust storms, and seek support from UN agencies to meet the relevant Sustainable Development Goals (SDGs).

Over the last decades, the social interest in and the eagerness of the research community to enhance the understanding of the physical processes associated with the dust cycle, to predict future events and to prevent their undesired impacts has increased rapidly. The World Meteorological Organization (WMO) was one of the first United Nations (UN) Agencies, that started addressing the problem of Sand and Dust Storms (SDS), their observations, assessments and forecasting since 2004 in response to the intention of 40 WMO member countries.

The WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) is operating to provide dust forecasts, which could contribute to risk reduction in many societal areas. In specific, a Global Dust-Health Early Warning System (D-HEWS) has been initiated as part of SDS-WAS to advise vulnerable populations of approaching dust plumes. However, these activities should be strengthened and implemented widely in affected countries and regions.

Several resolutions from the United Nations General Assembly (A/RES/70/195, A/RES/71/219, A/RES/72/225, A/RES/73/237, and UN SG report 73/306) have recognized the importance of the SDS problem and called on United Nations entities to promote a coordinated approach to combatting sand and dust storms globally for assistance from the United Nations system.

In response to A/RES/71/219, the United Nations Environment (UNEP), the World Meteorological Organization and the United Nations Convention to Combat Desertification (UNCCD) conducted together a “Global Assessment of Sand and Dust Storms” (UNEP, WMO, UNCCD, 2016). The assessment report, which was recognized in UN General Assembly resolution A/RES/70/195, sets out proposals for consolidated and coordinated technical and policy options for responding to sand and dust storms. These recommendations include an integrated policy framework to guide further action to mitigate sand and dust storms (**Table A1.**). It provides an integrated policy framework to guide further action to mitigate sand and dust storms. WMO is directly contributing to the Policy framework for mitigation of SDS (**Table A1**), leading the activities on monitoring, prediction and warning systems (i.e. Task 3). Derived SDS information can be used by WHO for health impact studies, by UN Environment (UNEP) for socio-economic impact assessments, and by UNCCD for combating SDS policy and mitigation measures and strategy. Otherwise, effectiveness of such mitigation scenarios can be also analysed by the use of modelling tools.

Table A1. Policy framework for mitigation of sand and dust storms (UNEP, WMO, UNCCD, 2016)

1. Measures to reduce anthropogenic emissions
    a. Sustainable land and landscape management
    b. Climate change mitigation and adaptation
2. Physical protection of valuable assets, such as towns, infrastructure, and irrigation schemes
    a. Reducing wind speed through tree planting around urban areas and infrastructure to deposit sand and trap dust outside these areas
    b. Aerodynamic methods to prevent sand and dust accumulation, such as alignment of roads, removal of obstacles to wind and land shaping
3. Monitoring, prediction and warning systems for sand and dust storms
    a. Monitoring of sand and dust storms through ground networks of meteorological and air quality monitoring stations, and combined use of satellite data
    b. Sand and dust storm forecasting and early warning systems, including mapping of trends and future scenarios of anthropogenic dust sources
4. Preparedness and emergency response procedures
    a. Preparedness and emergency procedures for coping with sand and dust storm events (e.g., for airport, rail and road closures; hospital emergency services; advisory communications to public services)
    b. Public awareness of sand and dust storm risks (via education, media and social networks and telecommunication) and emergency procedures
    c. Mainstreaming sand and dust storms into disaster risk reduction and emergency response measures
5. Policies, legal frameworks and action plans to support the above actions
    a. International environmental law (e.g., Rio Conventions; Sustainable Development Goal Target 15.3 on Land Degradation Neutrality) and initiatives (e.g., WMO Sand and Dust Storm Warning Advisory and Assessment System)
    b. Regional frameworks, agreements and action plans
    c. National action plans
6. Research to reduce critical uncertainties
    a. Improved knowledge on the interaction of dust with biogeochemical global systems and climate systems
    b. Improved methods for monitoring, prediction and early warning systems
    c. Assessing the impacts and costs of sand and dust storms at local to global scales

The priority in the **short to medium-term** is to reinforce protective strategies to reduce negative impacts of sand and dust storms on human health, infrastructure and operations. Monitoring, prediction, and early warning are critical for mobilizing emergency responses. In the **longer term**, emphasis should be on preventing new dust sources through integrated strategies that promote sustainable land and water management, including cropland, rangelands, deserts, and urban areas.

The important step forward the building a joint strategy for combating and mitigation of SDS was jointly organised and launched in 2019 the UN Coalition to Combat Sand and Dust Storms (UN SDS Coalition). In 2018 UN Environment suggested for the Environment Management group (EMG) to consider their proposal to build a UN Coalition on Combating Sand and Dust Storms. The EMG Senior Officials (including WMO) approved this in 2019 and it is included in the UN SG report on SDS 73/306. The MoU of the UN SDS Coalition was discussed and approved at the Coalition meetings in October 2020. The following working groups and leads/co-leads have been identified and approved by the Coalition:

- WG1 Adaptation and Mitigation: UNDP and FAO
- WG2 Forecasting and Early Warning: WMO
- WG3 Health and Safety: WHO
- WG4 Policy and Governance: UNCCD
- WG5 Mediation and Regional Collaboration: ESCAP and ESCWA.

The Working Groups are responsible for agreeing on when and how they meet, but the overall Coalition meetings can be coordinated and facilitated by the coordinator of the Coalition (2 yearly rotated UN Agencies: moved from UNEP to FAO, etc.).

One of the first joint activities within the UN SDS Coalition was co-organised in 2019 by the UN Environment (UNEP) and the World Meteorological Organization (WMO) a sand and dust storm (SDS) technical scoping meeting at the WMO headquarters in Geneva with key partners and experts to discuss and agree on the way forward for a technical project on sand and dust storm (SDS). The aims of this meeting were to learn about current work happening across the UN and partners on the topic of SDS, to identify problems and objectives and develop a Theory of Change. This led to determination of potential SDS project themes, outcomes and outputs and to outline the relative roles of UN agencies and partners, as well as to identify potential funding, donors and other stakeholders. One of the outcomes of that meeting was the jointly elaborated the scheme of the Theory of Change (ToC) to Combat SDS (**Figure A1.**).

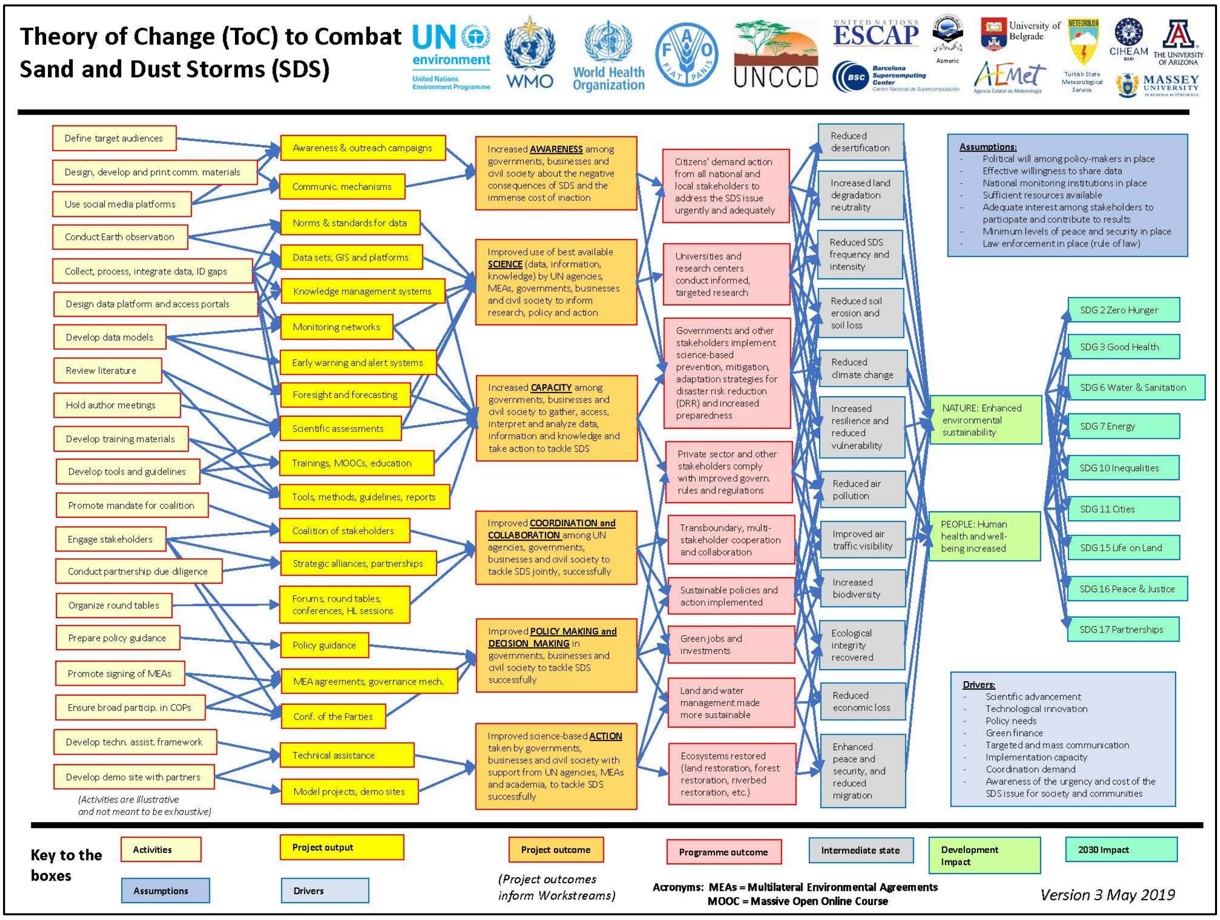

Figure A1. Elaborated scheme of the Theory of Change (ToC) to Combat SDS (UNEP-WMO, 2019).

Following the 18th World Meteorological Congress Resolution 19 (Cg-18, 2019): "Enhancing cooperation for monitoring and forecasting sand and dust storms", WMO has continued further development, extension and implementation of the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) and together with the UN SDS Coalition members promoted international cooperation to combat sand and dust storms through the exchange of knowledge, experiences, best practices and by launching training courses, and to enhance capacity building and technical assistance for monitoring and forecasting sand and dust storms and to support the implementation of national, regional, and global action plans of affected countries (WMO, 2020).

WMO is leading the WG2: Forecasting & Early Warning of the UN Coalition on Combating Sand & Dust Storms, organized regular meetings of WG2, reported previous achievements and build working plans for the next years. The next steps in realizations of this integrated approach for the combating SDS were done within the UN Coalition and under the UNCCD, which coordinated joint work of several UN Agencies (including WMO), to build joint recommendations for national stakeholders and other interested users.

One of the most important results of the UN Agencies collaboration and the UN SDS Coalition was the jointly written and UNCCD coordinated and published in 2022 a comprehensive "Sand and dust storms compendium: Information and guidance on assessing and addressing the risks". WMO SDS-WAS and its partners were actively involved in writing of this UN multi-Agency effort, and WMO was responsible for 3 chapters of this Compendium. The aim of the Compendium (UNCCD, 2022) is to provide information and guidance on how to assess and address the risks posed by sand and dust storms and plan actions to combat sand and dust storms (**Figure A2.**). The Compendium brings together information and guidance from a wide range of sources. It includes approaches and methodology frameworks on data collection, assessment, monitoring and early warning, impact mitigation and preparedness, and source mapping and anthropogenic source mitigation that are required in the development and implementation of policies related to sand and dust storms at sub-national, national, regional and global levels, taking into account the principles set out in the Policy Advocacy Framework for Sand and Dust Storms, and the cross-sectoral and multidisciplinary nature of the impact that sand and dust storms can cause to societies, economies, and the environment.

The WMO SDS-WAS is also closely working with the WHO expert team for joint report on SDS health impacts (to be published in 2023), and the with ESCAP Asian and Pacific Centre for the Development of Disaster Information Management (APDIM) on SDS Risk Assessment (ESCAP/APDIM, 2021) & Reduction and Developing Elements for a Regional Plan of Action on Sand and Dust Storms.

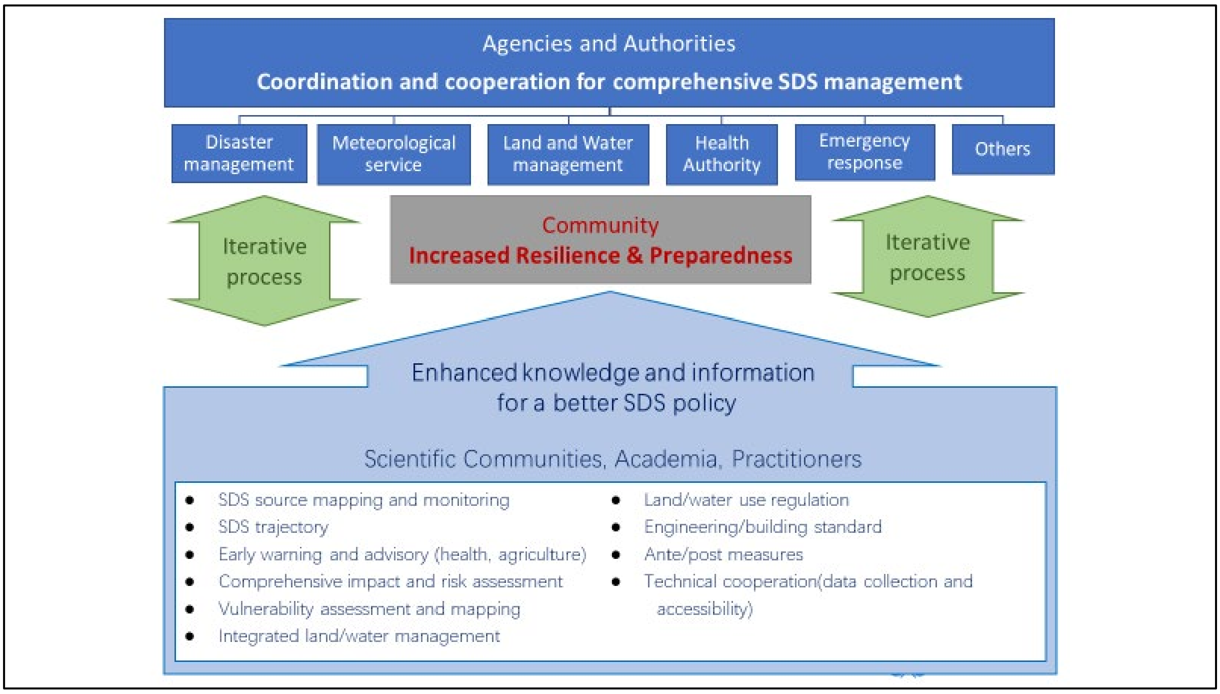

Figure A2. Framework for SDS risk management coordination and cooperation (UNCCD, 2022).

Annex 2. Source vs Source area

Source *is a bare topsoil surface susceptible to wind erosion in favourable wind conditions, where its susceptibility to wind erosion is determined by the topsoil condition and characteristics.* Sources can be: (**a**) **permanent** - they can be susceptible to wind erosion during the whole year and their productivity of soil particles under the same wind conditions do not change, and (**b**) **dynamical** – their productivity changes depending on the land cover change, change of topsoil conditions, and can be under the impact of human activities.

Source area can be (**a**) an area where spatial variability of surface characteristics is low and emission of soil particles is possible in the whole area under the higher surface winds, or (**b**) can be heterogenous are in sense of surface characteristics and the emission is possible in some surface fractions of the source area (i.e. it is a mosaic of productive and non-productive surface fractions). Thereby, source areas have larger or lesser portion of surface with the potential to act as ***sources*** under the windy conditions. *Source area* is a land surface area with the following characteristics (Vukovic et al., 2019; Vukovic, 2022):

- *soil surface exposed to wind*: fully bare (soil surface exposed to wind erosion) area or area which includes fractions of bare surfaces (fractions of exposed soil) among other land covers (vegetation, water, snow/ice, artificial); bare surfaces can be permanently without any land cover; can be seasonally exposed to wind erosion or can be exposed only during the extreme weather conditions which cause absence of land cover.

- *finer soil texture*: area where the topsoil includes soil particles of “relatively” smaller size so that they are possible to be emitted from the surface by the surface wind.

loose topsoil particles: area with topsoil which has low organic content (indicated as soil organic carbon), therefore low structure and loose particles.

- *drier topsoil*: area with the “relatively” dry topsoil (lower soil moisture content in the layer near the surface) so that the near surface wind can impact soil particles to leave the soil surface; threshold level of soil moisture under which the soil can produce airborne soil particles depends on the soil properties and on surface wind velocity; soil moisture can be permanently low or seasonally or during the extreme weather events which cause drying of the soil.

unfrozen soil: are where the soil surface is not frozen, which can be during the whole year or seasonally or during the extreme weather events which cause the warmer conditions in the topsoil; threshold for freezing of soil depends on the soil moisture.

Annex 3. Examples SDS operational systems

i. Asia

Users from Asian countries and non-profit organizations can access SDS information through the WMO Beijing Dust Regional Center (http://www.asdf-bj.net, see Section 3). The Beijing Dust Regional Center is managing by CMA and is hosting the research activities and products associated to the SDS-WAS Regional Center for Asia; as well as; the operational SDS forecasting products of the RSMC-ASDF of Beijing. All activities and products are accessible through the web portal at http://www.asdf-bj.net/.The reference model of the RSMC-ASDF is the chemical-aerosol-weather CUACE/DUST which is developed and maintained by the Chinese Meteorological Agency (CMA). The overview of the activities of this Dust Regional Center can be found its web portal as well its annual activity reports.

This Regional Center provides ensemble forecast and verification services of more than 5 regional and global forecasting systems including the CUACE/Dust model. Also, the Regional Center is offering some SDS-related observation products, such as PM_{10}, Infrared Difference Dust Index (FY4A-IDDI), visibility and SDS weather phenomena (**Figure A3.**) for monitoring SDS in real-time. The dust information is used by National authorities to inform about the occurrence of extreme events.

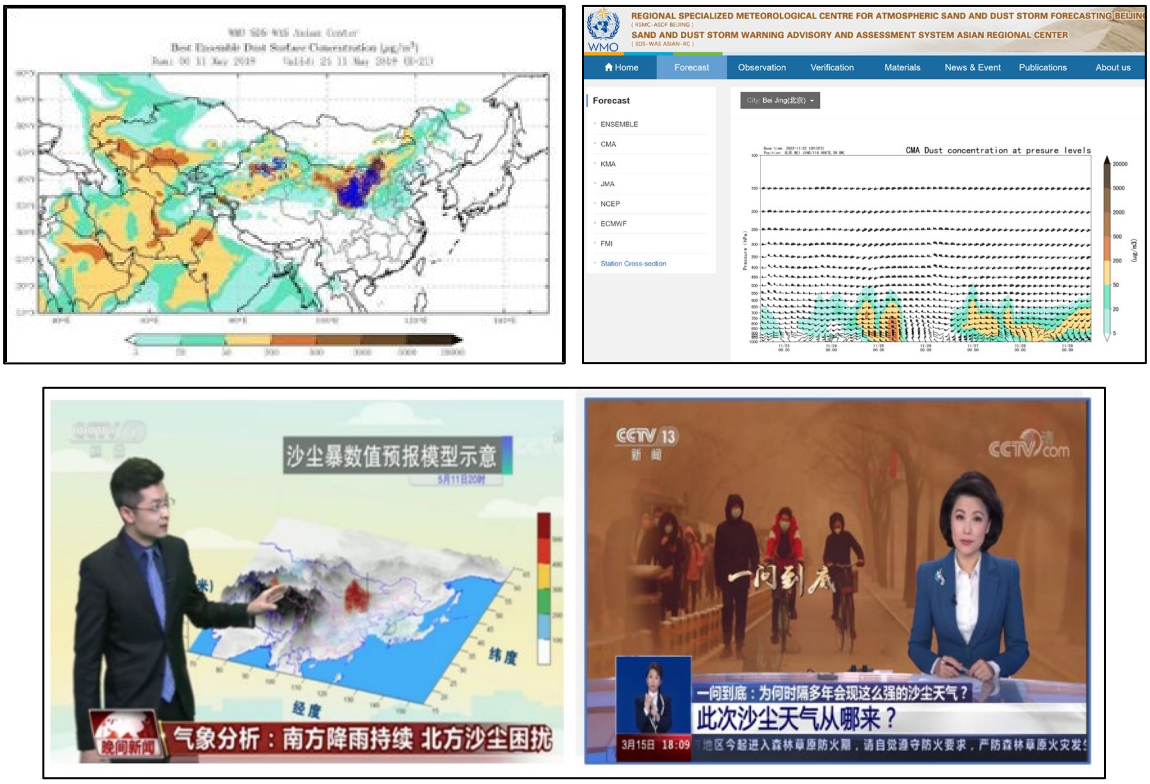

Figure A3. Extreme SDS in China on 11th May 2019. Sand and Dust ensemble forecast (top left); Vertical profile of dust concentration (top right). Sand and Dust Waring released by media in China (bottom).

Source: Screenshot taken on 15 November 2024 at 1700 UTC from the WMO Beijing Airborne Sand and Dust Forecasting Center (http://www.asdf-bj.net/)

Notes: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

The background map has been modified to align with UN guidance on maps.

ii. Northern Africa, the Middle East and Europe

Users from Northern Africa, the Middle East and Europe and non-profit organizations can access SDS information through the WMO Barcelona Dust Regional Center (https://dust.aemet.es, see Section 3). This Regional Center is jointly managed by the Spanish State Agency (AEMET) and the Barcelona Supercomputer Center (BSC). This Regional Center is hosting the research activities and products associated to the SDS-WAS Regional Center for Northern Africa, the Middle East and Europe; as well as; the operational SDS forecasting products of the RSMC-ASDF of Barcelona. All activities and products are accessible through the web portal at https://dust.aemet.es/.The reference model of the RSMC-ASDF is the chemical-aerosol weather MONARCH model, which is developed and maintained by the BSC. The overview of the activities of this Dust Regional Center can be found its web portal as well its annual activity reports.

Among the products accessible through the WMO Barcelona Dust Regional Center, there are daily probabilistic maps for the region. These probability maps are based on the multi-model median forecast based on the models participating in its model intercomparison (see here https://dust.aemet.es/about-us/list-of-models). The main objective of multi-model and probabilistic products is to summarize the information available from all the models available in a user-friendly way and offer an objective probability of an event happening, in this case, of exceeding a given threshold. Every day, the Regional is producing dust probability maps for the next three days. The probability maps show the percentage of models that are predicting an exceedance for a given threshold in a day. This clear, concise information is expected to help planning any activity vulnerable to airborne dust or activate services and procedures aimed at the mitigation of damages caused in agriculture, public health or any other vulnerable sector. The probability maps show the percentage of models that are predicting an exceedance for a given threshold considering daily means of dust AOD (see **Figure A4**) and surface concentrations. These probability maps are produced using the available models each day that are participating in the model intercomparison of this Regional Center.

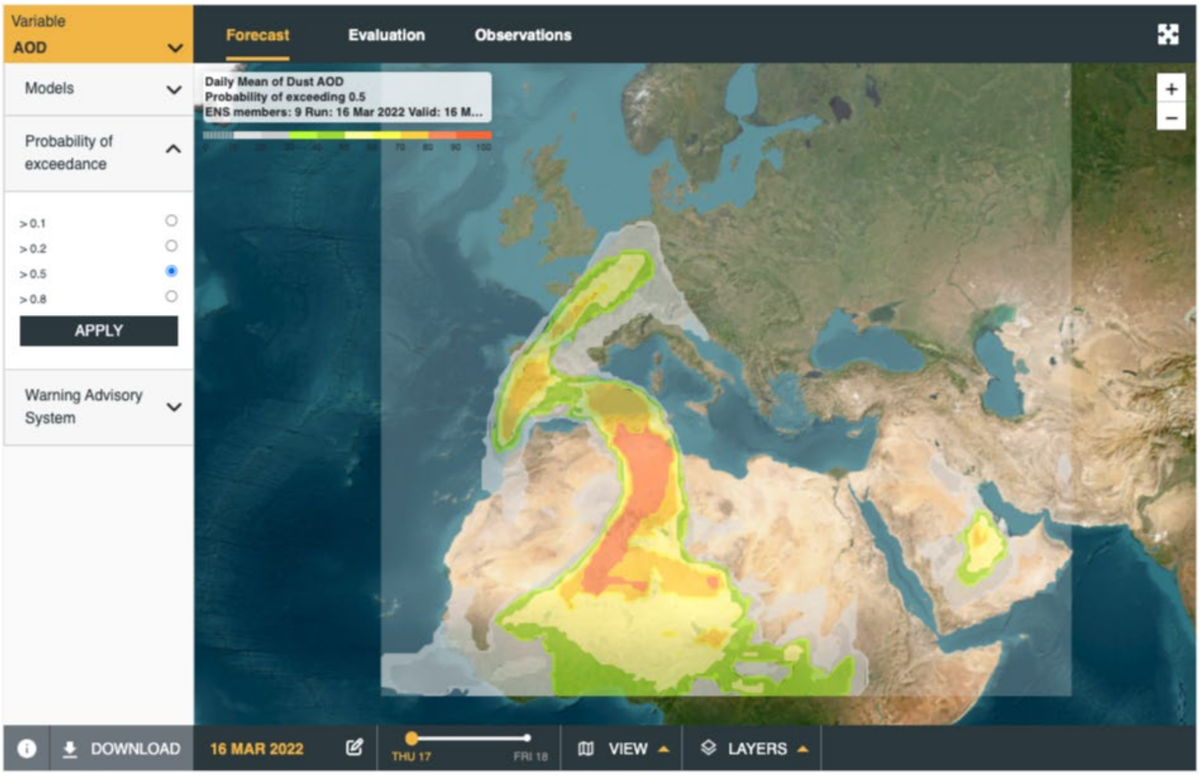

Figure A4. Probability map for AOD > 0.5 for 17 March 2022.

Source: Screenshot taken on 15 November 2024 at 1700 UTC from the WMO Barcelona Dust Regional Center (https://dust.aemet.es)

The Regional Center is also advancing on the provision of early warnings, with the creation of "Warning Advisory System" for specific countries in Africa including (Burkina Faso, Mali, Niger and Chad for CREWS - Cabo Verde, Mauritania and Senegal). The "Warning Advisory System" are designed to reduce adverse effects of dust for several African countries. This prototype has been developed thanks to the co-funding support of *MAC-CLIMA (Weather and ocean observing system as a tool for building resilience and adaptation to Climate Change in Cooperative Space)* and *CREWS (Climate Risk and Early Warning Systems)*. As a result, daily semaphore-type prognostic maps of surface dust concentration are produced for selected African countries (see Senegal in **Figure A5.**). These maps show about the magnitude of a predicted event based on a climatology. For more details about the methodology check Werner et al. (2020).

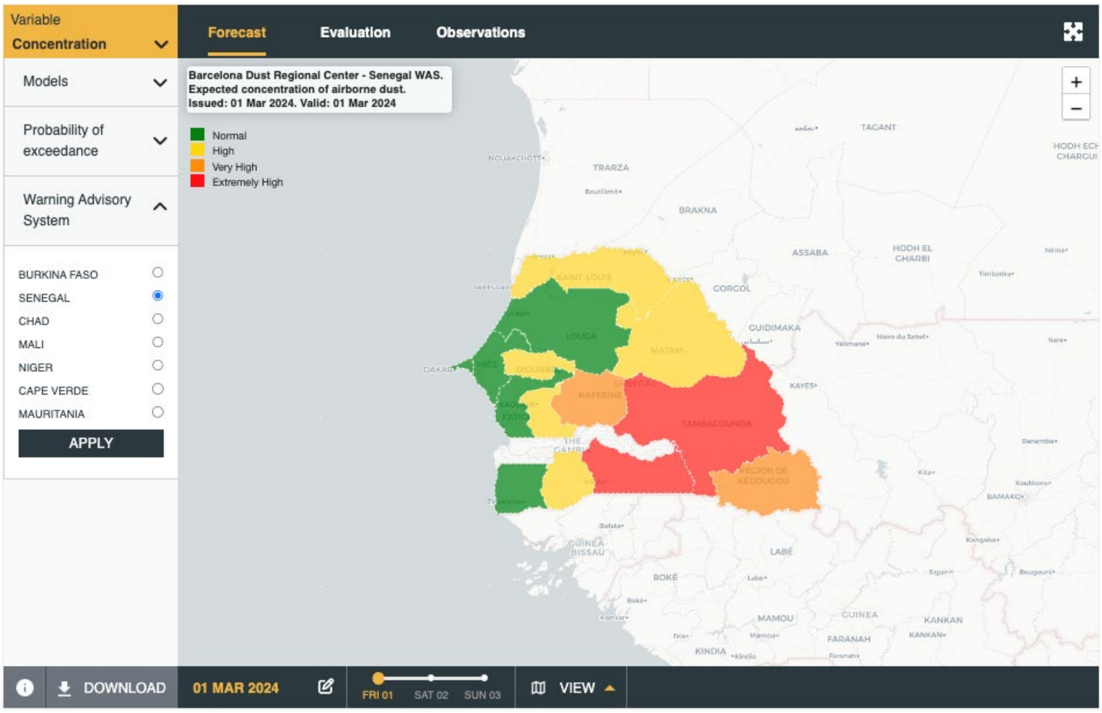

Figure A5. Warning Advisory System product for Senegal for 1 March 2024

Source: Screenshot taken on 15 November 2024 at 1700 UTC from the WMO Barcelona Dust Regional Center (https://dust.aemet.es/resources/ensemble-dust-products-probability-maps)

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iii. North America

The North American Ensemble Forecast System (NAEFS) combines state of the art weather forecast tools, called ensemble forecasts, developed at the Meteorological Service of Canada (MSC), and at the US National Weather Service (NWS). The North America Regional Ensemble Forecasting has been developed based on several operational and research prediction systems, including the National Air Quality Forecast Capability (NAQFC), and global aerosol forecasts systems participating also in the International Cooperative for Aerosol Prediction (ICAP). NAQFC is the operational air quality forecasting system operated by the United States National Weather Service. ICAP currently includes nine global forecasting models. Currently only three ICAP members the National Aeronautic and Space Agency (NASA) GEOS-5 model, the National Oceanic and Atmospheric Administration (NOAA) GEFS-Aerosol, and Naval Research Laboratory NAAPS, are incorporated in the ensemble forecasting, although other models are also being considered and tested. Different from ICAP, the North America Regional Ensemble Forecasting focuses on the region while takes advantage of high-resolution regional forecasts and unique observations from satellites and ground networks. An example of the ensemble forecasting is provided during a regional dust storm occurring over northern Chihuahua Desert (**Figure A6.**).

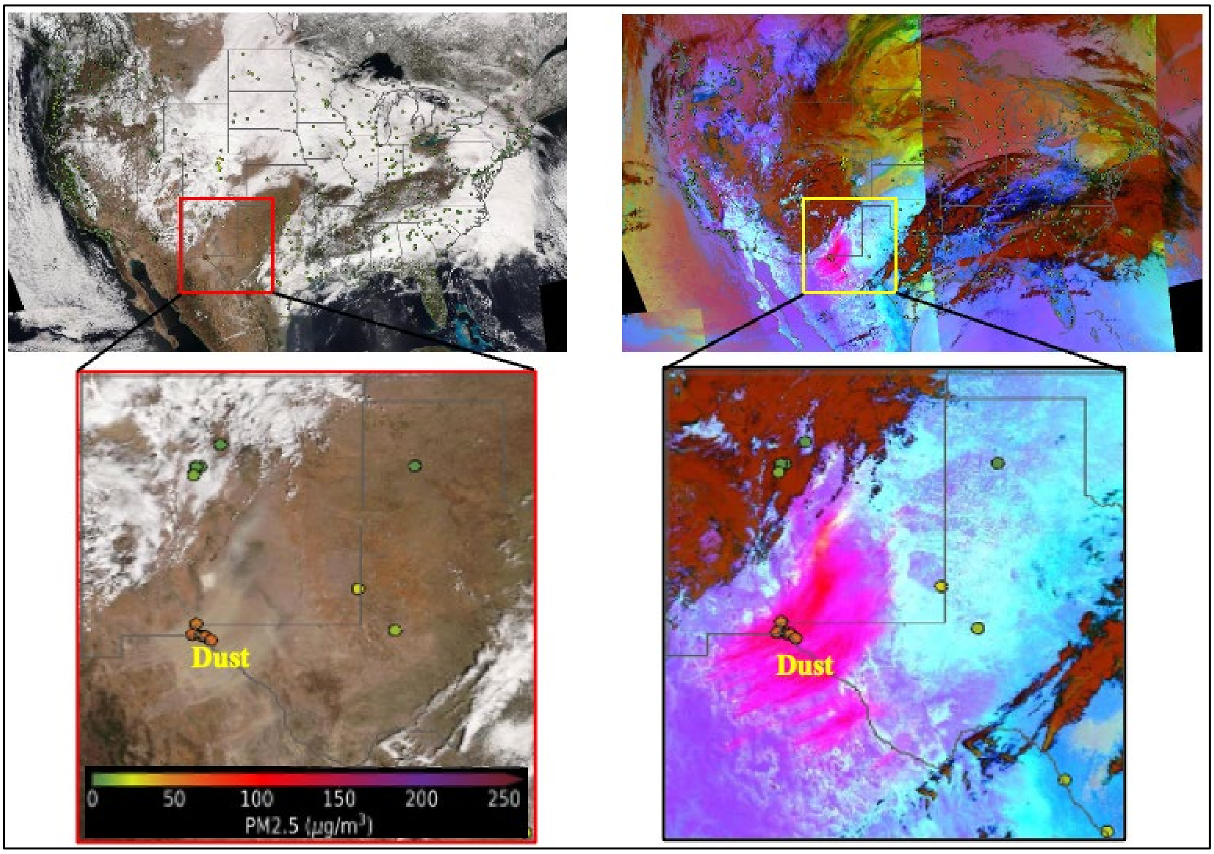

Figure A6. A regional dust storm on March 16, 2022 over the northern Chihuahua Desert, observed by the VIIRS sensor aboard the NOAA-20 satellite. Left panels: True Colour image overlaid by surface PM.25 concentration (circle) from the US Environmental Protection ground monitors. Right panels: dust RGB from the same sensor, with pinkish color representing dust plumes. The graphics are produced from NOAA AerosolWatch.

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the World Meteorological Organization or the United Nations.

Products of the ensemble forecasting include both surface concentrations of dust $PM_{2.5}$ and PM_{10}, which represents the nose levels of air pollution caused by dust storms, and dust AOD, which represents the total particle loading in the atmosphere. These products are calculated from averaging the individual forecasts from participating models, called ensemble means. In addition, a new product, the probability of air quality standard exceedance, is also calculated. A primary function of air quality forecasts, including dust forecasts, is to provide air pollution early warnings to the public. Early warnings are usually triggered when the model predicts levels of air pollutants exceeding health based thresholds, or air quality standards. It is crucial for the models to produce a reliable forecast of $PM_{2.5}$ exceedances. The North America Regional Ensemble Forecasting uses the US National Ambient Air Quality Standards (NAAQS). The probability forecast of $PM_{2.5}$ exceedance is calculated from dividing the number of predicted exceedances by the total number of predictions. For instance, if three of the five models predict exceedances, the exceedance probability is 50%. The performance of the ensemble in forecasting wildfire air pollution is assessed with satellite AOD observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard Terra and Aqua and Visible Infrared Imaging Radiometer Suite onboard the Suomi National Polar-orbiting Partnership (SNPP) (VIIRS-SNPP) satellite, and with ground $PM_{2.5}$ ground observations from the EPA AirNow network (**Figure A7.**).

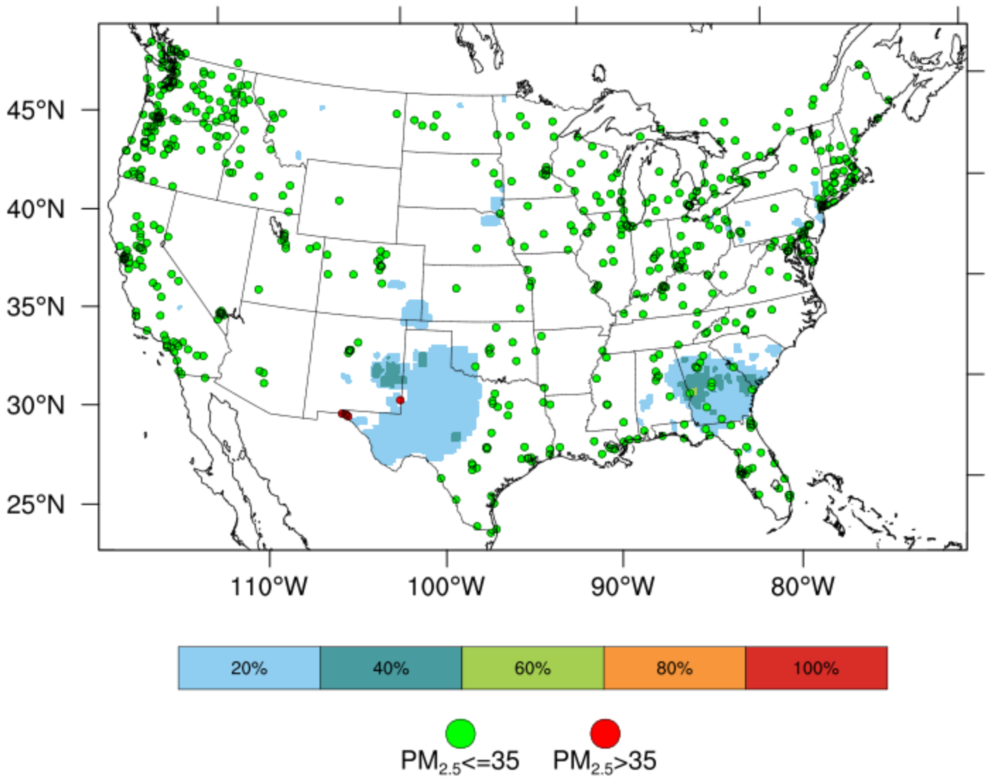

Figure A7. Ensemble probability forecast of $PM_{2.5}$ exceedances during the 16 March 2021 Chihuahua Dust Storm. Foreground colors indicate the probability values ranging from 20% (one out of five models forecasts the PM2.5 exceedance) (light blue) to 100% (all five models forecast the PM2.5 exceedances) (red). The $PM_{2.5}$ exceedances observed by the US EPA AirNow sites are displayed in the red/green circles (red means an exceedance recorded by the monitor, and green means no exceedance recorded).

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iv. Iceland and the Artic region

Mineral dust from Icelandic soils which is the largest European source of this aerosol, attract particular interest of the public and scientific communities because of numerous anticipated impacts to environment, health, and climate. Icelandic dust sources generated by long-term volcanic ash depositing has a rather dark color having therefore a potential to absorb solar energy much more efficiently than mineral dust from most other regions (Dagsson-Waldhauserova et al., 2015). Icelandic dust emission often occurs due to prevailing strong surface wind typical for the island. Under favourable synoptic conditions, it can be transported downwind up to a thousand km (Arnalds et al., 2016).

Following the public and scientific interest for HLD and related melting of glaciers and snow surfaces accelerated by dust deposition from high latitude dust sources, the SDS-WAS has included in its research program modelling and monitoring of HLD. There are also several other international initiatives/projects dealing with similar issues, including ICEDUST - the high latitude and cold climate network (The Icelandic Aerosol and Dust Association https://icedustblog.wordpress.com/).

Locally, there are Icelandic dusty days occurring more than a quarter of a year, during which air quality is often substantially reduced thus potentially affecting human health.

Road traffic is also affected by dust due to reduced visibility (**Figure A7.)**. Several car accidents are reported due to dust storms each year.

Figure A7. Dust storms in Iceland.

Source: https://www.iamreykjavik.com/sandstorms-iceland

Iceland is an active desert source where frequent dust storms occur all year-long. Dust storms reduce visibility, and they affect human health, local transport. Several car accidents are annually reported due to sandstorms. A high-resolution DREAM aerosol model (see **Figure A8**) has been developed through collaborative work between the Republic Hydrometeorological Service of Serbia, Agricultural University of Iceland, and Czech University of Life Sciences, and supported by the WMO SDS-WAS, EU COST inDust Action and the IceDust Association. The model is the first in the community providing operational daily predictions for Icelandic dust. In the model, detailed dust source specification is used, based on geographic distribution of soil data of the Agricultural University of Icelandic dust so-called dust "hot–spots" (geographically small but highly erodible areas whose emission is larger than from all other sources combined). Specification of fine-scale Icelandic dust sources with a resolution of about 3.5 km in a corresponding model (Cvetkovic et al., 2022) has been shown to be essential for appropriate prediction of Icelandic dust storms. Predicted snow cover and soil wetness are used to regulate the dust emissivity. This modelling system can be used as an operational forecasting system but also as a reliable tool for assessing climate and environmental Icelandic dust impacts.

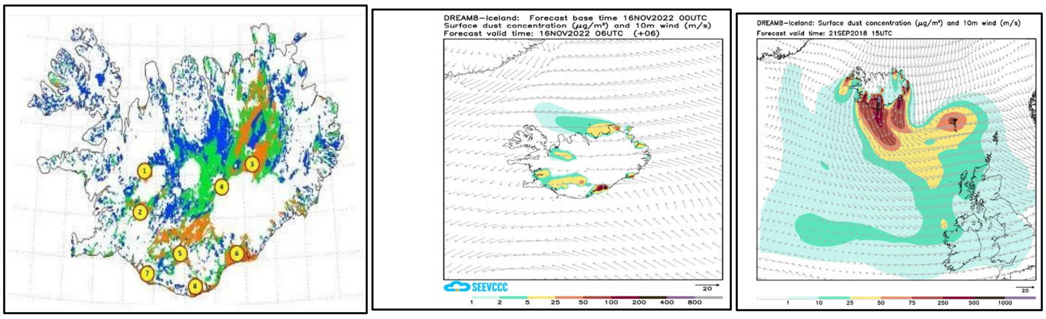

Figure A8. Left panel: areas vulnerable to erosion and hot–spots of dust emission (yellow circles); Central and right panels: examples of operational Icelandic dust predictions (http://www.seevccc.rs/?p=8; http://dustforecast.lbhi.is/desktop.html; https://sds-was.aemet.es/news/new-icelandic-dust-forecast)

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There are numerous observed examples of dust emissions in high-latitude regions generated from small-scale sources. Two dust-atmospheric models with a North Pole domain have been recently developed: DREAM and SILAM atmosphere-dust circumpolar models. DREAM model specifies dust sources using the UNCCD Global Sand and Dust Storms Source Base Map (see Figure A9) with resolution of 30 arcsec https://maps.unccd.int/sds/ (Vukovic, 2019, 2021a and 2021b; Meinander et al., 2022). Similarly, Dust SILAM model (https://ews.tropmet.res.in/ncmrwf.php) has also been implemented over the North Pole circumpolar region.

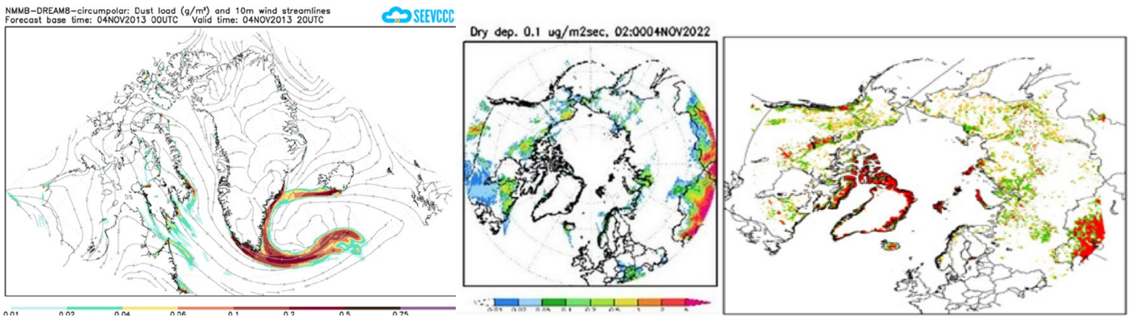

Figure A9. Dust predictions in the North Pole region. Left panel: DREAM dust load prediction for 4 November 2013. central panel: SILAM dust deposition prediction for 4 November 2022 Right panel: Dust sources used in the DREAM circumpolar model

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v. Japan

In Japan, dust particles are mainly seen in early spring, blown up by strong winds from arid regions such as the Gobi Desert. This phenomenon has been around for a long time and is even used as a seasonal term in haiku poetry. In Japan, this phenomenon can be seen in the form of visibility problems and health effects, and in the past, airports have been temporarily closed to passengers.

The Japan Meteorological Agency (JMA) provides SDS information from 2004, using a global aerosol model MASINGAR - Model of Aerosol Species IN the Global AtmospheRe (Tanaka and Chiba, 2005, Yukimoto et al., 2019) with 110 km horizontal resolution. The results of model calculations are provided along with SDS concentrations near the ground surface and the SDS air column volume concentrations. These model values are also provided to private weather companies. Subsequently, model improvements were made re. vegetation data in 2007, and the horizontal resolution was increased to 40 km. In 2020, a system that assimilates aerosol optical thickness from the geostationary meteorological satellite Himawari-8 (Yumimoto et al., 2016) was put into operation, resulting to improved forecast accuracy. The model uses JMA operational global analysis and forecasts weather fields for nudging.

In 2019, information such as dust RGB obtained from the geostationary meteorological satellite Himawari-8 was added to the JMA's SDS information website. This made it possible to capture the onset and arrival of SDS with finer time resolution. It monitors SDS during the daytime and night-time. The National Institute for Environmental Studies (NIES) in cooperation with Kyushu University, runs another aerosol model CFORS - Chemical Weather FORecasting System (Uno et al., 2003) of regional domain with horizontal resolution of 40 km (https://www-cfors.nies.go.jp/~cfors/) developed by Kyushu University, which provides dust forecasts up to 4 days ahead. NIES also provides a lidar data from the AD-Net network (Shimizu et al., 2106), and provides information on its website in near-real time (https://www-lidar.nies.go.jp/AD-Net/). The Ministry of the Environment and local governments operates a ground observation network

(Atmospheric Environmental Regional Observation System – AEROS which provides observations of PM2.5, SPM, SO2, NO NO2, Ox, NMHC, wind speed, temperature, which complements SDS monitoring (https://soramame.env.go.jp/).

Kyushu University has published the results of SDS and PM2.5 concentrations predicted by the global aerosol model SPRINATRS (Spectral Radiation-Transport Model for Aerosol Species; Takemura et al., 2000) for the next 7 days on its HP (https://sprintars.riam.kyushu-u.ac.jp/indexe.html). The horizontal resolution of SPRINTARS is about 40 km and the number of vertical layers is 56.

Private weather companies such as the Japan Weather Association, Weathernews, and Japan Meteorological Corporation provide information on SDS observations and forecasts for the public on their websites. The Ministry of the Environment and the JMA provide SDS observation and forecast information on their portal SDS information homepage (https://www.data.jma.go.jp/gmd/env/kosateikyou/kosa.html) from which various observation and prediction information can be accessed. The Japan Meteorological Agency, the Ministry of the Environment, Kyushu University, and other organizations are collaborating to provide monitoring and forecasting information on sand and dust storms (Figure A10.).

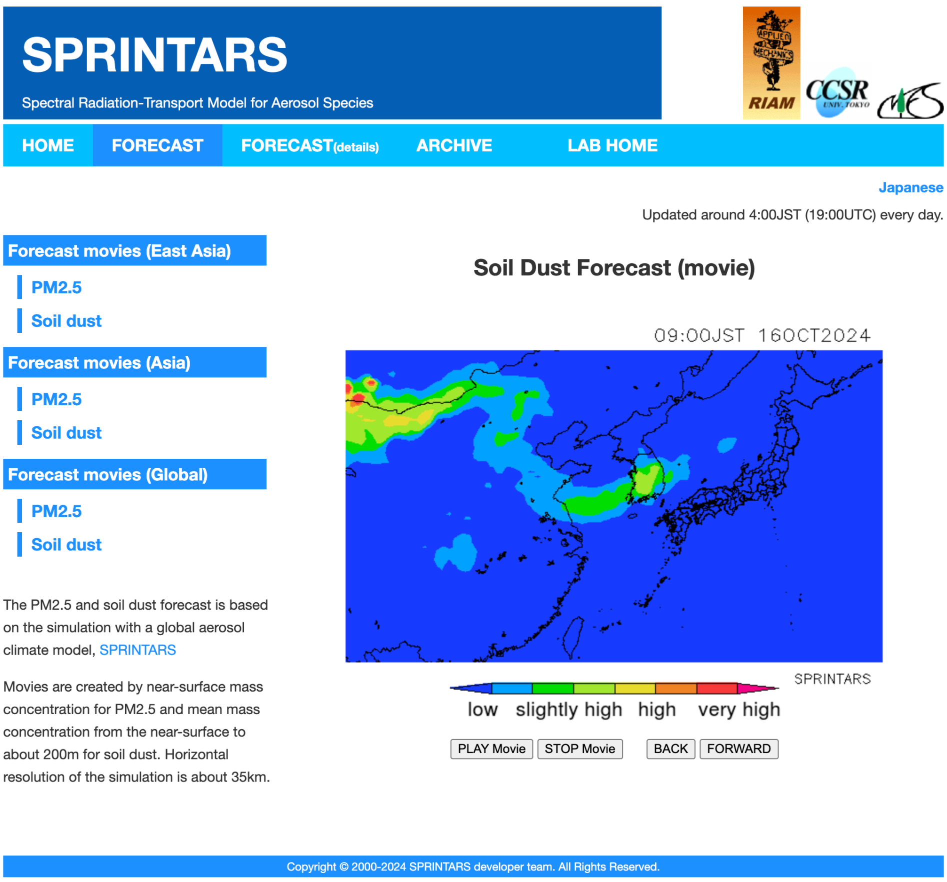

Figure A10. Daily dust forecast for 16th October 2024.

Source: Screenshot taken on 15 November 2024 at 1700 UTC from Sprintars website (http://sprintars.riam.kyushu-u.ac.jp/indexe.html)

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