4DAtlantic-DOMOS

DUST-OCEAN MODELLING & OBSERVING STUDY

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Table of Contents

1 Executive Summary

The ESA "4D-Atlantic Dust-Ocean Modelling & Observing Study" (DOMOS) kicked off in September 2021, with the overarching objective of advancing our fundamental understanding on the complex atmospheric dust-ocean interactions and processes governing the Atlantic Ocean, in the context of climate change, through an innovative approach of integrated use of modelling, EO-based products and in-situ datasets.

The project will develop and thoroughly validate against both the ESA-ASKOS campaign dataset and surface-based dust deposition measurements across the Atlantic Ocean, a novel product of dust transport and deposition from optical measurements from spaceborne satellite lidar systems (CALIOP and ALADIN) and radiometers (MODIS and IASI). Moreover, DOMOS envisages to validate the dust deposition field from the CAMS reanalysis and will also provide assimilation tests of IASI and Aeolus aerosol products with the goal of providing a better description of the dust aerosols, for applications in aerosol radiative impacts and ocean biogeochemistry.

The DOMOS products will contribute to an improved representation of the physical and chemical characteristics of dust deposition over the ocean which is crucial to interpret the observed climatic change responses and to better describe the future ones. This includes a better understanding and quantification of the deposition of soluble iron from natural and anthropogenic dust and of its contribution relative to biomass burning and anthropogenic aerosols that will be achieved through the use of a coupled climate model (EC-Earth3-Iron).

Finally, DOMOS foresees providing a scientific roadmap to highlight the findings of the project and identify possible gaps in the modelling and the observing approaches of atmospheric dust-ocean interaction.

In the document the outcomes of WP1000 (Consolidation of Open Scientific Issues and Definition of Pilot Cases) will be outlined. The objective of this Task was to identify the main technical and scientific challenges, to provide a comprehensive description of the science goals, methods and datasets to be used, and provide detail on the test areas and science cases of the activity, including the scientific and technical requirements, a consolidated risk analysis, and the proposed solutions.

Additionally, the review process performed under Task 1 aimed at identifying the candidate pilot test areas and describing the available in-situ and reference data that will be used to perform a solid validation of the DOMOS products, including specification of the content/description of the products, spatial/temporal resolutions, spatial coverage and timeframe of the datasets.

Furthermore, this Task identified the main European and international projects and initiatives relevant to the proposed activity, to maximize DOMOS scientific outcome and outreach. Early adopters have also been identified and involved either through email surveys as well as direct contact.

2 Background

2.1.1 Scientific motivation

The ocean plays a key role in climate by exchanging energy and climate-relevant gases with the atmosphere. According to the IPCC (AR5 2013[1]), 90% of the total energy in excess in the atmosphere was absorbed by the ocean between 1971 and 2010. At the same time, gaseous CO_2 is absorbed in the surface layer of the ocean and becomes available for the process of photosynthesis performed by microscopic phytoplankton cells. The resulting organic carbon compounds are transferred into the ocean's interior through gravitational sinking (particulate), mixing and subduction (both particulate and dissolved). This combination of processes, known as biological carbon pump, together with another set of physical processes known as solubility carbon pump (Volk and Hoffert, 1985[2]; Ito and Follows, 2003[3]), contribute to slowing down the increase of atmospheric CO_2 that results from anthropogenic activities. Although only a fraction of primary production (5-20%) is ultimately exported to the deep ocean (Henson et al., 2019[4]; Falkowski et al., 1998[5]), several studies have documented the importance of primary production in modulating surface oceanic CO_2 concentrations and, as a consequence, the exchange of CO_2 between ocean and atmosphere (Falkowski et al., 2000[6]; Hauck and Volker, 2015[7]). Moreover, primary production is at the base of the marine food-web sustaining all marine life, including commercially relevant species for fisheries. Finally, the abundance and variability of phytoplankton in the open ocean have a dominant role in determining ocean colour and, as a consequence, the penetration of light into the water column. This in turn affects sea surface temperature resulting in a feedback potentially significant in determining the trajectory of tropical storms (Gnanadesikan et al., 2010[8]).

Primary production is currently estimated by global ocean biogeochemical models and

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[1] https://www.ipcc.ch/report/ar5/syr

[2] Volk, T., & Hoffert, M. I. (1985). Ocean carbon pumps: analysis of relative strengths and efficiencies in ocean-driven atmospheric CO2 changes. In E. T. Sundquist, & W. S. Broecker (Eds.), The carbon cycle and atmospheric CO 2 : natural variations Archean to present. Chapman conference papers, 1984 (pp. 99-110). American Geophysical Union; Geophysical Monograph 32.

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[6] Falkowski, P. G., et al.: The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System, Science, 290(5490), 291–296, doi:10.1126/science.290.5490.291, 2000.

[7] Hauck, J., and C. Völker (2015), Rising atmospheric CO2 leads to large impact of biology on Southern Ocean CO2 uptake via changes of the Revelle factor, Geophys. Res. Lett., 42, 1459–1464, doi:10.1002/2015GL063070.

[8] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010GL044514

satellite-based methods to be in the order of 30 - 70 Pg-C yr^{-1} (Carr et al., 2006[9]; Anav et al., 2013[10]) with spatial distribution depending, among other factors, on the input of nutrients from atmospheric sources (Krishnamurthy et al., 2010[11]; Myriokefalitakis et al., 2020[12]) . Among other species deposited onto the open ocean surface, nitrogen (N), phosphorus (P), silica (SiO_2), and iron (Fe) are the nutrients that can limit phytoplankton growth, directly impacting marine productivity, ocean colour and the ocean's capacity to absorb CO_2. Among these, iron availability is the most important limiting factor for phytoplankton growth over large oceanic areas (Okin *et al.*, 2011[13]).

Iron concentrations in vast areas of the ocean are very low, due to the low solubility of iron in seawater (Boyd and Ellwood, 2010[14]). Aeolian dust is the principal source (~95%) of Fe to the surface open ocean, followed by Fe-containing aerosols from biomass burning and fossil-fuel combustion emissions (e.g., Mahowald et al., 2009[15]). In the Atlantic Ocean, Fe deposition from Saharan dust can drive significant variability in deep carbon export (Pabortsava et al., 2017[16]). However, Fe can only be utilized by phytoplankton in its bioavailable (dissolved) form (e.g., aqueous, colloidal, or nanoparticulate). Although the essential role of iron in oceanic productivity is well established (Tagliabue et al., 2017[17]), considerable uncertainty remains on the impact of atmospheric composition on phytoplankton Fe-limitations and consequently the oceanic carbon-cycle. Indeed, due to the role played by phytoplankton in the transfer of carbon dioxide into organic carbon and carbon sequestration, iron limitation likely plays a major role in the global carbon cycle. It has been also suggested that variations in oceanic primary productivity, spurred by changes in the deposition of iron in atmospheric dust, control atmospheric CO_2 concentrations through a delicate balance, and hence global climate, over

[9] Carr. M.E., et al.: A comparison of global estimates of marine primary production from ocean color, Deep-Sea Res. II, 53, 741-770, doi:10.1016/j.dsr2.2006.01.028, 2006.

[10] Anav, A., et al.: Evaluating the Land and Ocean Components of the Global Carbon Cycle in the CMIP5 Earth System Models, J. Clim., 26 (18), DOI: https://doi.org/10.1175/JCLI-D-12-00417.1, 2013.

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glacial-interglacial timescales (Street and Paytan, 2005[18]). Another important biogeochemical parameter to characterize ocean productivity is marine nitrogen fixation, i.e., the reduction of gaseous N_2 to ammonium performed by marine organisms. N_2-fixing species (e.g., diazotrophs) have elevated Fe requirements and their growth may also be limited over large areas of the Atlantic ocean (Pabortsava et al., 2017[19]; Schlosser et al, 2014[20]).

Human activities have heavily perturbed[21] the atmospheric composition and, unavoidably, the atmospheric inputs to the global ocean. On the one side, dust aerosols are subject to atmospheric processing during their long-range transport, resulting in spatially variable solubility of nutrients and thus impacting the spatial distribution of marine productivity (e.g., Myriokefalitakis *et al*., 2020[22]). A major mechanism leading to an increase of Fe solubility is acidic (proton-promoted) dissolution, with low pH conditions in aerosol water favouring Fe dissolution through the weakening of Fe-O bonds of Fe oxides, Fe hydroxides and aluminosilicates in dust (Johnson and Meskhidze, 2013)[23]. Also oxalate, can act as an organic ligand, enhancing Fe dissolution in aqueous solutions under moderately acidic conditions. The oxalate-mediated mechanisms for Fe(II) formation depend upon the availability of oxalic acid or oxalate compounds and are largely dependent on sunlight. On the other side, combustion Fe (from biomass burning and anthropogenic emissions), while a much smaller source of iron, is considerably more soluble than dust Fe and is estimated to contribute up to 50% of the bioavailable Fe deposition (Luo et al., 2008[24]; Mahowald et al., 2009[25]; Ito, 2015[26]; Winton et al., 2015[27]).

The contribution of dust emitted from anthropogenically perturbed land remains still subject to debate, with values ranging from 10% to at least 50%. Ginoux *et al.* (2012a)[28] used high-

[18] Met Ions Biol Syst, 2005;43:153-93. doi: 10.1201/9780824751999.ch7

[19] See reference 13.

[20] Schlosser, C., Klar, J. K., Wake, B. D., Snow, J. T., Honey, D. J., Woodward, E. M. S., Lohan, M. C., Achterberg, E. P. and Moore, C. M.: Seasonal ITCZ migration dynamically controls the location of the (sub)tropical Atlantic biogeochemical divide, Proc. Natl. Acad. Sci., 111(4), 1438–1442, doi:10.1073/pnas.1318670111, 2014.

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[25] See reference 16.

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[28] Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C. & Zhao, M. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. Rev. Geophys. 50, RG3005 (2012b).

resolution MODIS radiances to identify sources where the atmospheric column is frequently dusty. Sources were attributed to cultivation according to a land use atlas (Goldewijk, 2001[29]). Maps of both natural and cultivated sources were introduced into a dust transport model and the anthropogenic fraction of present-day dust emission was estimated to be ~25 %. The anthropogenic dust fraction is potentially important for the Fe cycle; there is evidence that dust aerosols created by human activity have a distinct composition from dust arising from natural sources. Ginoux *et al.* (2012b)[30] show that anthropogenic dust sources are coincident with high levels of atmospheric ammonia. Ammonia is a precursor to heterogeneous chemical reactions associated with the uptake of nitrate aerosols and ammonium salts onto the surface of dust particles. Cultivated regions are enriched in ammonium precursors due to the use of fertilizers and large numbers of livestock (Beusen *et al.*, 2008[31]), both of which are expected to increase in the coming century as the demand for food security increases with population. Cultivated sources are also expected to be enriched in Fe-bearing minerals including hematite and clays. This is because agriculture is practiced in regions where soil moisture is present during at least part of the year, and this moisture chemically weathers silicate minerals, creating clays along with Fe oxides and hydroxides like hematite and goethite.

Modelling studies estimate a global atmospheric dissolved Fe deposition flux into the ocean in the range 0.2–0.4 Tg-Fe yr^{-1} for present-day conditions (Myriokefalitakis et al., 2018[32]; Ito et al., 2019[33]), a factor of ~2 higher than during the preindustrial era (e.g., Scanza et al., 2018[34]). Models of the atmospheric iron cycle with different levels of complexity have been employed to simulate atmospheric Fe dissolution: from simple schemes including first order rate processing constants applied to a globally uniform 3.5% of Fe in dust, to more complex ones allowing different types of acidic species to interact with dust that account for mineral-specific dissolution rates and oxalate processing (e.g., Myriokefalitakis et al., 2018[35]; Ito et al., 2019[36]). However, most IPCC-class Earth System Models use simplified climatological representations of dust deposition and of its nutrients content and solubility (e.g. Aumont et al., 2015[37]; Seland

[29] Goldewijk K.K. Estimating global land use change over the past 300 years: The HYDE Database, 2001, https://doi.org/10.1029/1999GB001232.

[30] Ginoux et al. (2012b) Atmos. Chem. Phys., 12, 7351–7363.

[31] Beusen et al. (2008) Atmos. Environ., 42, 6067–6077.

[32] Myriokefalitakis, S., et al.: Reviews and syntheses: the GESAMP atmospheric iron deposition model intercomparison study, Biogeosciences, 15(21), 6659–6684, doi:10.5194/bg-15-6659-2018, 2018.

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[34] Scanza et al., 2018 Atmos. Chem. Phys., 18, 14175–14196.

[35] Myriokefalitakis, S., et al.: Reviews and syntheses: the GESAMP atmospheric iron deposition model intercomparison study, Biogeosciences, 15(21), 6659–6684, doi:10.5194/bg-15-6659-2018, 2018.

[36] Ito, A., et al: Pyrogenic iron: The missing link to high iron solubility in aerosols, Sci. Adv., 5, eaau7671, https://doi.org/10.1126/sciadv.aau7671, 2019

[37] Aumont, O., Ethé, C., Tagliabue, A., Bopp, L. and Gehlen, M.: PISCES-v2: an ocean biogeochemical model for carbon and ecosystem studies, Geosci. Model Dev., 8(8), 2465–2513, doi:10.5194/gmd-8-2465-2015, 2015

et al., 2020[38]), although it is widely accepted that dust deposition is by nature highly episodic (Guieu et al., 2014[39]).

Therefore, a better representation of the mechanisms behind the spatial and temporal variability of atmosphere-ocean interactions is required. An improved representation of the physical and chemical characteristics of dust deposition over the ocean could be key to interpret the observed climatic change responses and to better describe the future ones. This includes a better understanding and quantification of the deposition of soluble iron from natural and anthropogenic dust and of its contribution relative to biomass burning and anthropogenic aerosols.

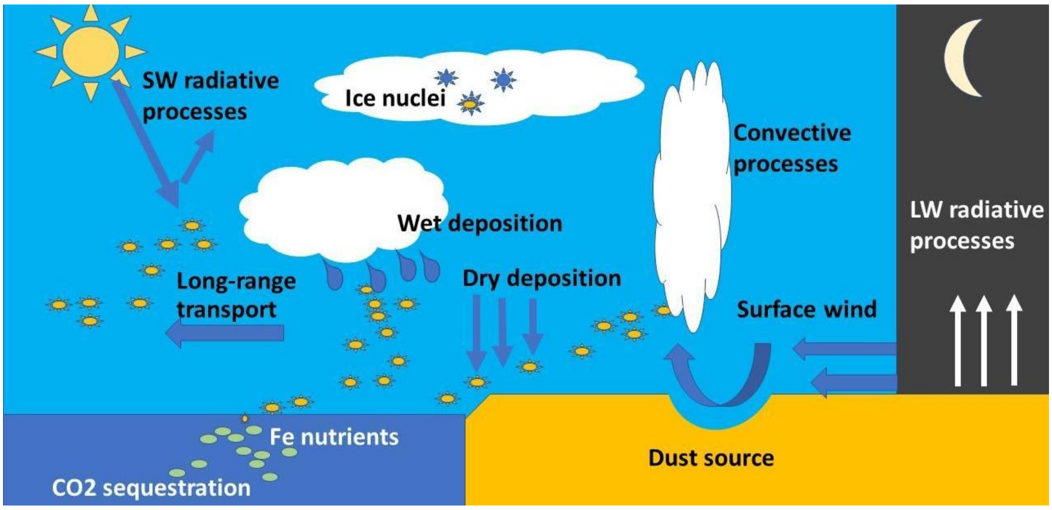

Figure 1. *Dust processes, adapted from Ginoux P., [Mineral Dust Cycle.]*

Mineral dust is mechanically produced by surface winds breaking soil cohesion over surfaces with no vegetation and dry soil such as deserts. North Africa, including the Sahara and the Sahel, is the biggest producer of dust contributing to a ~46 % of the global emissions and and a ~50% of the global dust loading and dust optical depth (Kok et al., 2021[40]). Dust is essentially composed of clay and silt soil particles, whose diameters vary between 0.1 to 20 micrometers. Larger particles are also found at large distances from the sources (van der Does et al., 2018[41]). The lifetime of dust particles in the atmosphere is of the order of one week, over which period they can be transported several thousand kilometers by winds. Dust is removed from the atmosphere by wet deposition (i.e. scavenging through precipitation in the water or ice phase), dry deposition/gravitational settling and turbulent mixing in the Planetary Boundary Layer

[38] Seland, Ø., et al.: Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations, Geosci. Model Dev., 13, 6165–6200, https://doi.org/10.5194/gmd-13-6165-2020, 2020.

[39] Guieu, C., Dulac, F., Ridame, C. and Pondaven, P.: Introduction to project DUNE, a DUst experiment in a low Nutrient, low chlorophyll Ecosystem, Biogeosciences, 11(2), 425–442, doi:10.5194/bg-11-425-2014, 2014.

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(PBL). Dust aerosols have a big impact on the incoming solar radiation through scattering and on the outgoing terrestrial radiation through absorption. They also play an important role by acting as ice nuclei, particularly the bigger particles, therefore affecting cloud lifetime and optical properties (Figure 1).

This last year has seen one of the biggest dust events of the decade, in June 2020, with a huge amount of dust being transported from the Sahara to the tropical Atlantic Ocean. The dust can be clearly seen in visible satellite imagery, such as from the Suomi NPP/VIIRS imagery on 17 June 2020 (Figure 2). Some studies have shown that the dust transport over the Atlantic has instead decreased in recent years (Ridley et al, 2014[42]), in connection to a weakening of surface winds possibly induced by changes in anthropogenic aerosol forcing in Western Africa. A potential increase (decrease) in dust transport over the ocean, could make iron and other nutrients, such as silica (SiO_2) and phosphorus (P), more (less) available for phytoplankton, hence triggering changes in marine primary production and the biological carbon pump. This mechanism is relatively well understood from a theoretical point of view but has not been systematically shown with an integrated approach of modelling and satellite and in-situ observations. For example, one of the biggest unknowns remains the amount of dust which is actually deposited to the ocean. Some estimates based on reanalysis and satellite data indicate that 218 ± 48 Tg of dust is annually deposited into the Atlantic (Ridley et al, 2012[43]). However the model timeseries used in the study only covered two years. Similarly, Yu et al. (2019)[44] on the basis of a ten-year (2007-2016) analysis of CALIOP, MODIS, MISR, and IASI observations, estimated the amount of dust deposited into the Tropical Atlantic Ocean at 136-222 Tg/year. Reanalysis datasets which provide long-term series (2003 to present) of dust deposition based on modelled emissions and transport and assimilated satellite observations such as the Copernicus Atmosphere Monitoring Service (CAMS) reanalysis (Inness et al 2019[45]) are available but have not yet been validated with independent observations of dust deposition over the ocean. Questions remain still open regarding closing the relationship between sources, long-range transport and deposition processes.

From the point of view of satellite-based Earth Observations to address the link between atmospheric composition, dynamics and ocean biogeochemistry, a significant amount of new information has become available through large programs such as the ESA's Earth Explorer missions and its wind lidar mission Aeolus, and EU-ESA Copernicus missions such as Sentinel 5P, which is now producing a wealth of observations related to atmospheric composition as well as ocean colour variables. Additionally the ESA Climate Change Initiative (CCI) has funded new retrievals and long timeseries reprocessing of climate relevant products such as aerosol optical depth, land cover, ocean colour from various sensors. It has also promoted their use and exploitation among the climate community by establishing the Climate Model User

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[42] Ridley, D. A., C. L. Heald, and J. M. Prospero. "What Controls the Recent Changes in African Mineral Dust Aerosol Across the Atlantic?" Atmospheric Chemistry and Physics 14, no. 11 (2014): 5735–5747.

[43] D. A. Ridley C. L. Heald B. Ford: North African dust export and deposition: A satellite and model perspective, Volume117, IssueD2, https://doi.org/10.1029/2011JD016794, 2012

[44] Yu, H., et al.: Estimates of African Dust Deposition Along the Trans-Atlantic Transit Using the Decadelong Record of Aerosol Measurements from CALIOP, MODIS, MISR, and IASI, Journal of Geophysical Research: Atmospheres, 124(14), 7975–7996, https://doi.org/10.1029/2019JD030574, 2019.

[45] Inness, A., et al.: The CAMS reanalysis of atmospheric composition, Atmos. Chem. Phys., 19, 3515–3556, https://doi.org/10.5194/acp-19-3515-2019, 2019.

Group (CMUG).

From 2012 to 2016, a Transatlantic Saharan dust-monitoring campaign was carried out using an array of both submarine sediment traps and ocean-surface dust-collecting buoys. The sediment traps collected material settling through the water column at 1200m water depth, which includes Saharan dust, marine organic matter, and fossil remains of phytoplankton living in the surface ocean. It was shown that there is a strong seasonality in Saharan dust deposition, and in the properties of the dust particles themselves; a clear downwind fining could be demonstrated and a strong difference in particle size with coarser-grained material deposited in summer as opposed to winter[46] [47]. In addition, for the first time it was shown that aeolian dust particles are frequently 'giant' (>75µm) and can include individual quartz grains as large as 450µm[48]. The mechanisms playing a role in the emission, transport, and deposition (*wet* as well as *dry*) of Saharan dust are still far from understood, as are the marine environmental consequences of the dust deposition, although Guerreiro et al., 2017[49], and 2019[50] managed to show a relationship between dust deposition and response of opportunistic coccolithophorid species. However, the role of dust as a nutrient supplier to the ocean and its consecutive role as ballast material, which is required for a significant export of organic matter from the surface ocean to the deep, is still far from understood.

During the last two decades the amount of available observations of the ocean's interior has tremendously increased thanks to the Argo program, which has fostered the deployment of autonomous floats across the global ocean. Some of these floats, known as BGC-Argo floats (Chai et al, 2020[51]), are equipped with a set of biogeochemical sensors that make them able to measure, amongst others, Chl concentration, nitrate, pH or oxygen; on top of depth, temperature and salinity. BGC-Argo floats are particularly useful to study open ocean waters at any time of the year regardless of the sea conditions and to evaluate the impact of extreme and episodic atmospheric events, such as tropical or dust storms, on marine primary production (Chai et al, 2021[52]).

The challenge is now to bring together all this wealth of observations with state-of-the-art models to provide a full 4D reconstruction of the ocean/atmosphere interactions, including aspects that are not directly observable. This is the main goal of the DOMOS project.

[46] Van der Does et al., 2016; www.atmos-chem-phys.net/16/13697/2016/

[47] Korte et al., 2017 www.atmos-chem-phys.net/17/6023/2017/

[48] van der Does et al., Sci. Adv. 2018;4 : eaau2768.

[49] https://doi.org/10.5194/bg-14-4577-2017.

[50] https://doi.org/10.1016/j.pocean.2019.102140.

[51] Chai, F., Johnson, K.S., Claustre, H., Xing, X., Wang, Y., Boss, E., Riser, S., Fennel, K., Schofield, O., Sutton, A., 2020. Monitoring ocean biogeochemistry with autonomous platforms. Nature Reviews Earth & Environment 1–12. https://doi.org/10.1038/s43017-020-0053-y

[52] Chai, F., Wang, Y., Xing, X., Yan, Y., Xue, H., Wells, M., and Boss, E.: A Limited Effect of Sub-Tropical Typhoons on Phytoplankton Dynamics, Biogeosciences Discuss, https://doi.org/10.5194/bg-2020-310, accepted, Jan 2021.

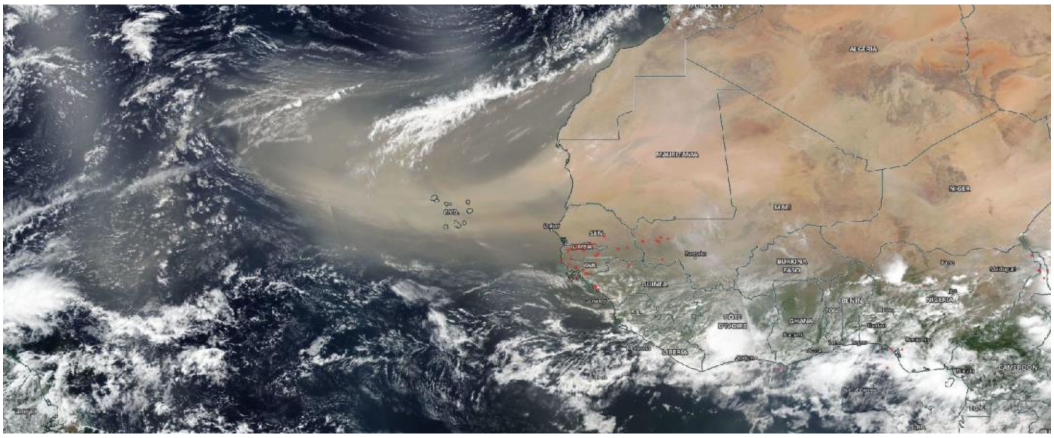

***Figure 2**. NASA Suomi NPP/VIIRS visible imagery showing Saharan dust over the tropical Atlantic on 17 June (right) 2020 (downloaded from NASA Worldview).*

2.1.2 Scientific questions

The DOMOS science is centred around three main scientific questions.

1. **To what extent dust deposition over the Atlantic has changed over the last 20 years? Can we identify robust trends in the reanalysis and model datasets and if yes, how can we verify them?** Although estimates have been attempted before, there is the need to look at longer time-series such as those provided by atmospheric composition reanalysis and climate models and develop taylor-made satellite retrievals from multiple sensors and platforms, aimed at quantifying dust deposition. This is a challenge as dust deposition is not directly observable from satellite. Observations must be complemented with model-based information. Also, independent observations of dust deposition are needed to quantify the quality of the model-based and reanalysis-based reconstructions as well as to evaluate the performance of the bespoken satellite retrievals.

2. **What is the contribution of anthropogenic and natural sources of dust compared to biomass burning and anthropogenic aerosols to soluble iron deposition over the Atlantic?** While dust is the largest contributor to total iron deposition by far, it is unclear what its contribution to soluble iron deposition is.

3. **What are the impacts of changes in dust deposition on marine biogeochemistry and their potential effects on ecosystems?** The connection between changes in dust deposition and the nutrients available for marine ecosystems needs further investigation with a concerted synergy of modelling and observations.

In order to answer these science questions, **DOMOS will use innovative and ground-breaking approaches involving both model simulations and observations.** An integrated approach is required when dealing with a complex problem such as the ocean-atmosphere interaction as outlined above. On the one hand, model simulations can provide an understanding of the interconnections between the different variables, such as dust emissions, transport, deposition and bioavailable nutrients at the ocean surface. On the other hand, observations are necessary to validate model simulations, and provide direct information on observable components of the atmospheric dust-ocean nutrients cycle. Satellite measurements such as those provided by the ESA CCI program offer an insight on the large-scale environment, providing long time series and global coverage. In situ measurements provide accurate albeit localized information and are necessary to anchor both model simulations and satellite observations. In recent years, **composite multi-platform retrievals and reanalyses have emerged as tools to combine model information and observations**. Physically-based retrievals may rely on model variables that are not observed but are needed as *a priori* to be able to extract the desired information from the observations. For example, most current aerosol optical depth retrievals from satellite visible radiances rely on assumptions regarding the type of aerosols that are present in a given pixel as well as regarding the reflectance properties of the underlying surface. In some retrievals, these assumptions are provided by models. In this sense, an assimilation system could be considered like a complex and sophisticated retrieval system in which the model provides all the necessary background information in order to simulate the observations. The difference between model background and observations is then minimized with respect to the parameters of interest, which for Numerical Weather Prediction are usually the initial values of temperature, humidity, winds and pressure. In the case of assimilation systems for composition variables, the variables optimized are usually the concentrations or the emissions of the aerosols or the chemical compounds.

In the DOMOS project we will have access to two of the most advanced systems for assimilation of aerosol observations in the world: the ECMWF/CAMS 4D-Var and the BSC Ensemble Kalman filter. Feeding these systems with cutting-edge dust observations from the upgraded and extended LIVAS database and the ESA CCI IASI dust product we will attempt to constrain the dust analyses in the best possible way and estimate indirectly the dust deposition field implied by the analyzed concentrations. Additionally**, the LIVAS product will be enhanced and improved to provide atmospheric dust and related dust deposition fields over the Atlantic Ocean**, estimated from lidar backscatter and depolarization observations. This will allow a four-dimensional reconstruction of the pure-dust atmospheric component, allowing separation of mineral dust from other aerosol types. This product will be one of the main DOMOS outputs. All prototype products will be validated using the best available observations from mooring instruments and from research vessels, as well as ground-based observations that will be collected during the Aeolus CAL/VAL ESA-campaign ASKOS. These datasets, in particular those from the mooring instruments will be instrumental to also validate the dust deposition field from the CAMS reanalysis as well as the model dust deposition climatologies from an improved version of the state-of-the-art Earth System Model (EC-Earth3). EC-Earth3 contains an advanced representation of the dust-iron cycle, which allows to quantify the contribution of different sources (dust, biomass burning and anthropogenic aerosols) and processes (acidic and oxalate processing) to the soluble iron deposition into the ocean. Both the CAMS reanalysis and EC-Earth3 will be used to link all the various components of DOMOS and to address the science questions above.

The next section outlines the pilot cases that have been selected to test the DOMOS dust deposition product which will be developed at NOA and the scout reanalyses of BSC (with focus on assimilation of LIVAS) and ECMWF (with focus on the assimilation of the IASI-dust ULB product).

3 Pilot cases

Two pilot cases have been selected:

1. "Godzilla" dust event in June 2020 (see figure 2)

In early June 2020 a high-pressure system off the west coast of Africa trapped enormous amounts of Saharan dust near its continental source regions. The break-down of this weather system in mid-June sent large pulses of dust traveling thousands of kilometers westward across the Atlantic Ocean. The dust plumes resulted in historically high dust AOD over the Caribbean basin and exceedance of air quality standards for particulate matter concentrations along the US Gulf Coast and anomalous dust transport across US (Yu et al 2021[53]). Colarco et al (in preparation) have looked at the performance of the models participating to the International Cooperative for Aerosol Prediction for this case and found that the models without any assimilated aerosol data underpredicted the event while models with data assimilation had a better representation of the dust plume in terms of intensity (see figure 3).

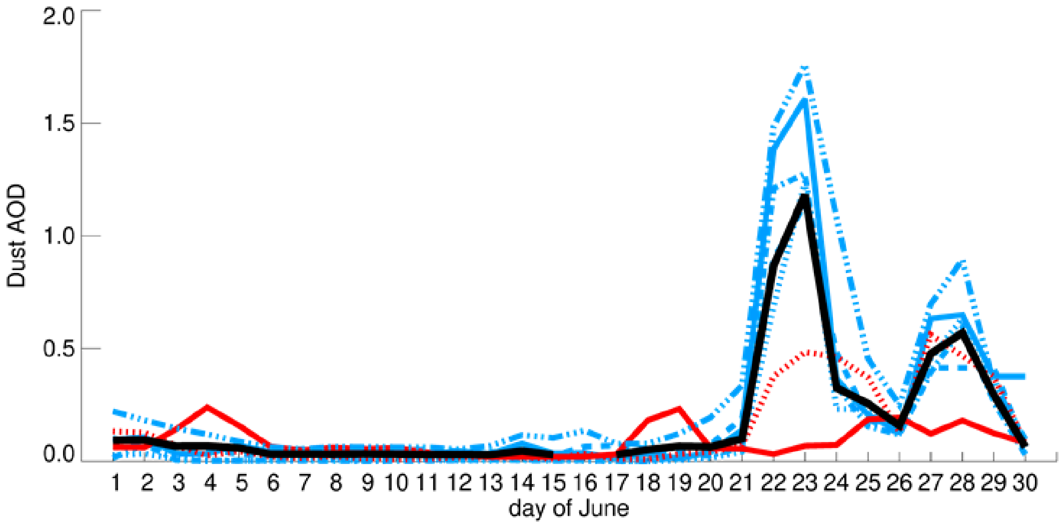

Figure 3. *Dust Aerosol Optical Depth for the ICAP models with assimilation of aerosol data (blue) and the ICAP models without assimilation of aerosol data (red). The black line represents the Multi-Model Ensemble (Xian et al,2019[54]).*

[53] Yu et al, Atmos. Chem. Phys., 21, 12359–12383, 2021. https://doi.org/10.5194/acp-21-12359-2021

[54] Xian et al, 2019, https://doi.org/10.1002/qj.3497

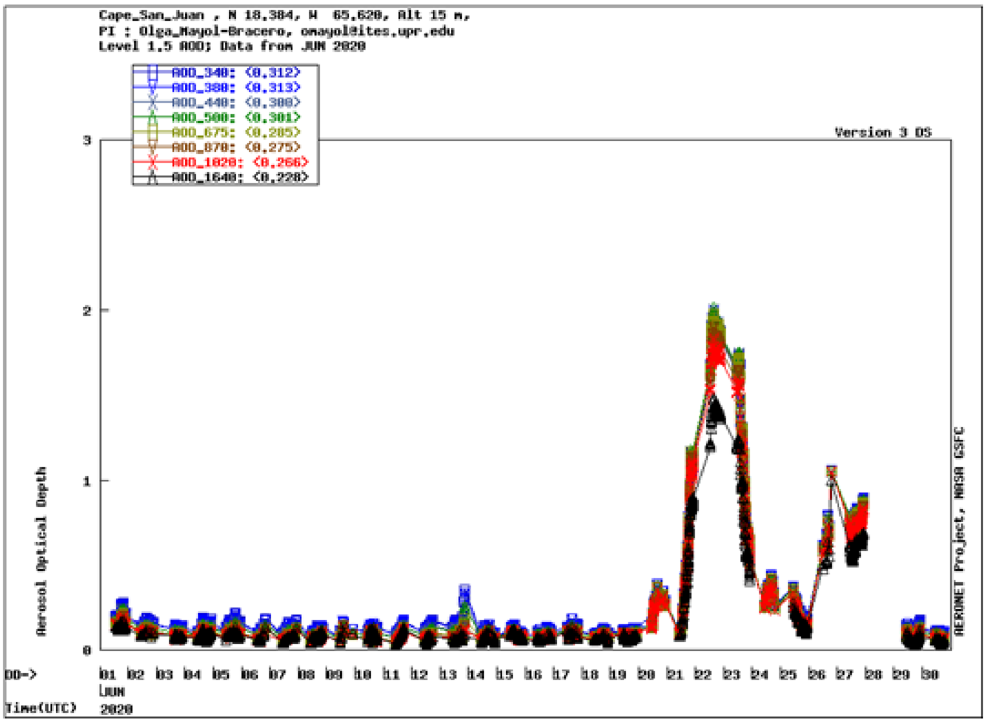

Figure 4. *Dust Aerosol Optical Depth at Cape St Juan for the month of June 2020.*

At ECMWF, the impact of MODIS and PMAP AOD observations in the assimilation was evaluated by comparing forecasts, initialized from analysis, against its control run with no data assimilation for June 10th at 12UTC (Figure 5). The assimilation tends to reduce the dust AOD over the Sahara and Eastern Atlantic but increases the dust AOD over the Western Atlantic.

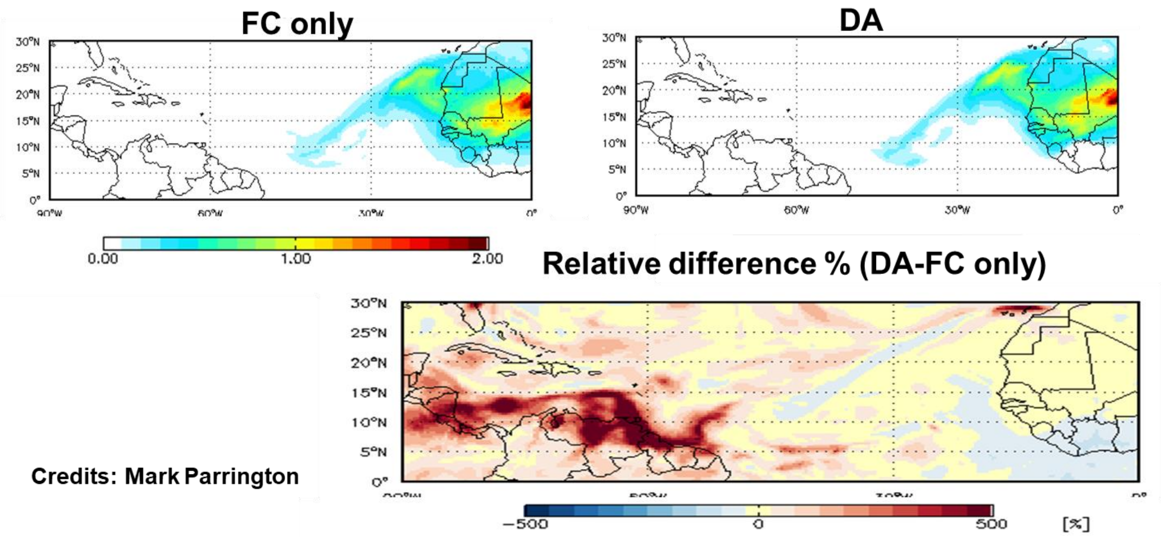

Figure 5. *Forecast of dust AOD for Jun 10th from a run without assimilated aerosol observations (top left) and a run with assimilated AODs from MODIS and PMAP (top right). The top right panel shows the relative differences between the two runs.*

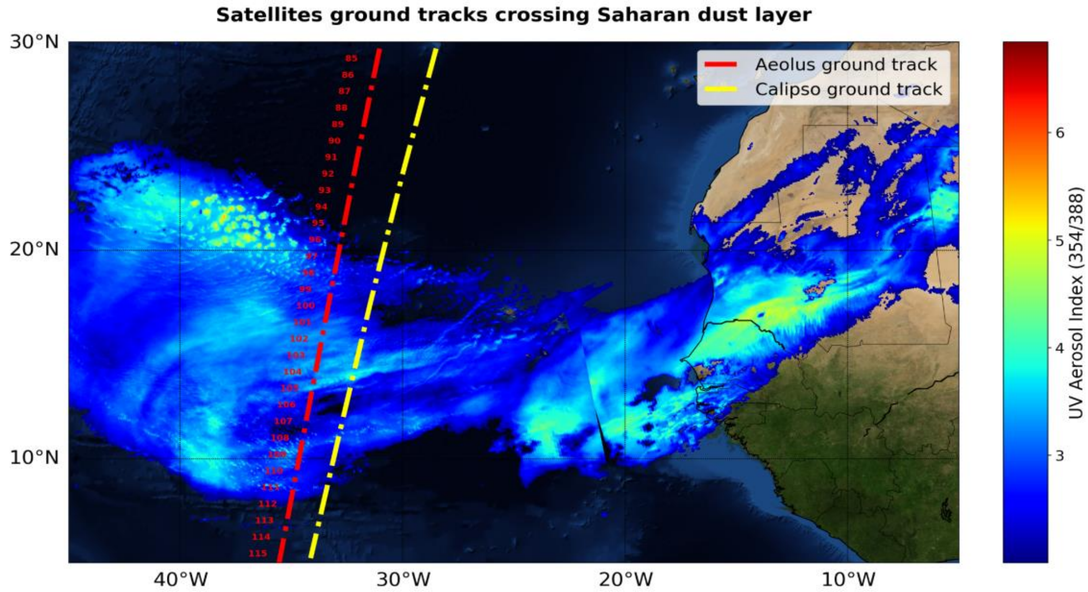

Figure 6. *Aeolus and CALIPSO tracks across the dust layer (19 June 2020). From Flament et al, 2021*[55]*.*

On June 19 2020 Aeolus crossed the Saharan dust plume above Cape Verde (Figure 6). The event was observed also by CALIPSO and Aeolus, an example is shown for June 18 and June 19 2020 in Figure 7 and Figure 8, respectively.

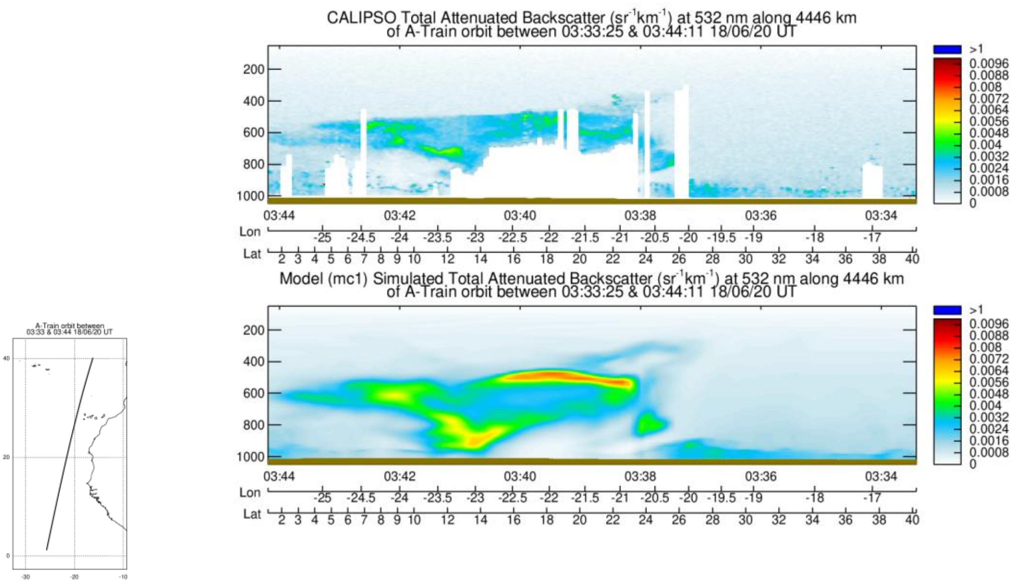

Figure 7*. CALIPSO Total Attenuated Backscatter at 532nm over the Atlantic along the orbit shown on the left as compared to the CAMS model output on June 18th.*

[55] Flament et al, AMT Discuss., https://doi.org/10.5194/amt-2021-181, in review, 2021.

Figure 7 shows that the location of the plume is well captured by the ECMWF/CAMS model, although the intensity of the backscatter signal seems much larger than the CALIPSO observations.

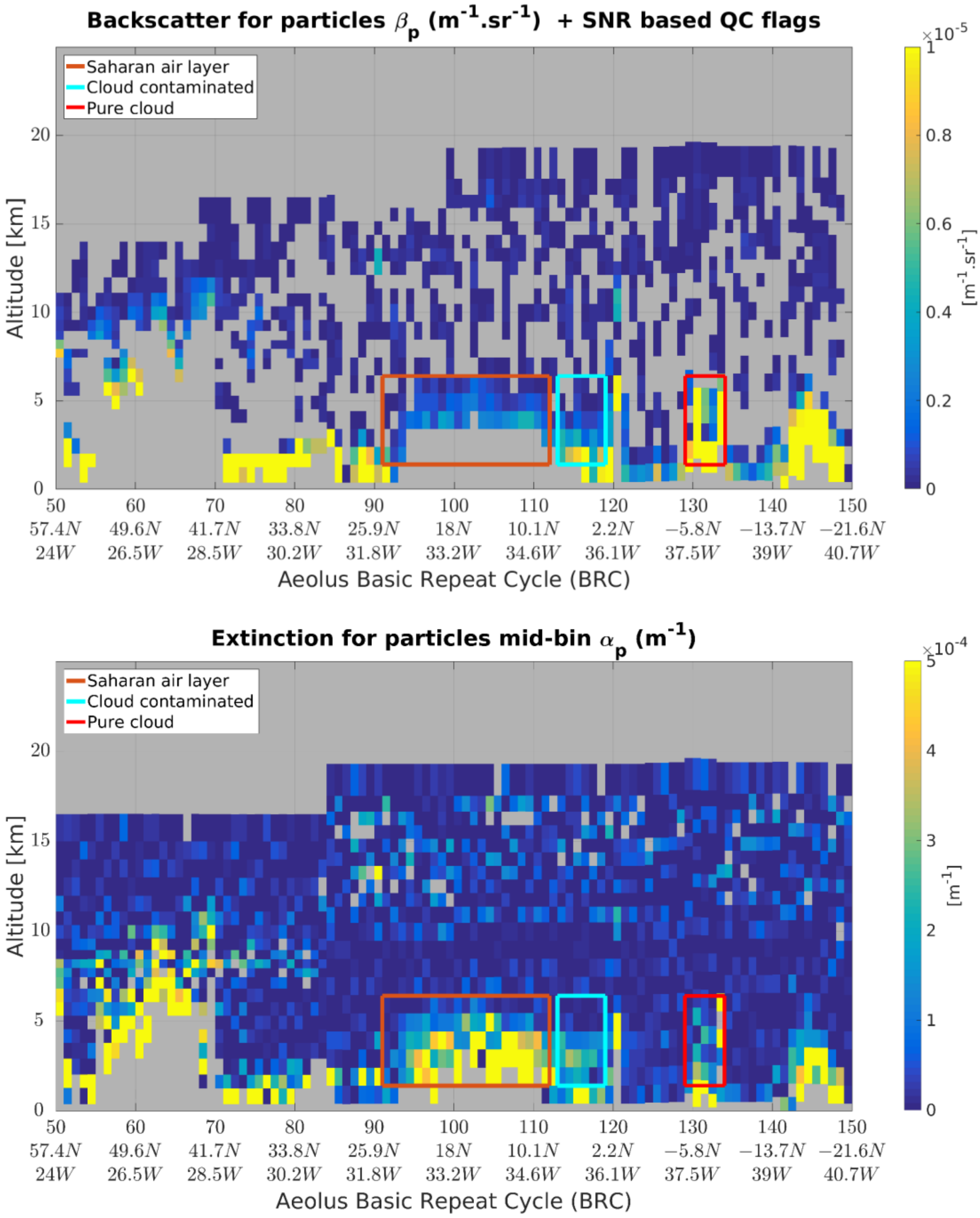

***Figure 8**. Aeolus particle backscatter (top) and extinction (bottom) on June 19th with identified features. From Flament et al, 2021.*

2. The ESA ASKOS/JATAC campaign

The first stage of the ASKOS campaign, with intense ground-based remote sensing (RS) measurements, was performed in summer/autumn 2021 at the Mindelo city of São Vicente island in Cabo Verde (CV). At the Ocean Science Center in Mindelo (OSCM), a full ACTRIS aerosol and cloud RS super site was set up in June 2021 and accordingly operated in September 2021. The instrumentation includes **(1)** a multiwavelength-Raman-polarization lidar PollyXT, **(2)** an AERONET sun photometer, **(3)** a Scanning Doppler wind lidar, **(4)** a microwave radiometer, **(5)** a cloud radar belonging to ESA fiducial reference network (FRM4Radar), **(6)** ESA's novel reference lidar system EVE, a combined linear/circular polarization lidar system with Raman capabilities capable to mimic the observations of the space-borne lidar ALADIN onboard AEOLUS.

The ASKOS campaign was classtered with the joint Aeolus – Tropical Atlantic Campaign (JATAC) where, in addition to the ASKOS observations, an impressive airborne fleet collecting RS and in-situ measurements, in the broader Capo Verde region in September 2021. The in-situ aerosol flights (from a light-weight airplane of the University of Nova Gorica) were based in the same island as ASKOS, and collected in-situ measurements above ASKOS site, from altitudes up to 3 km, for 2 weeks in September. Additional airborne remote sensing flights (from DLR and LATMOS) were based in Sal island and collected airborne aerosol, cloud, wind RS and cloud is-situ measurements in the broader CV region for 3 weeks in September, overpassing above ASKOS site during 7 days in September.

During this intensive period in September 2021, very different aerosol conditions were observed in the JATAC-ASKOS region (Fig. 9). ASKOS observations between 08/09/2021 and 26/09/2021, shows that the marine boundary layer was up to an altitude of about 1 km and was topped with Saharan dust layers reaching up to 6 km altitude. The amount and height of the Saharan dust aerosol varied during the 3-weeks campaign, providing a wide variety of aerosol conditions. Moreover, volcanic aerosol from the la Palma volcano was observed on the island in the local boundary layer and partly above. The first 2 weeks of the campaign revealed that, in the first dust event of the campaign, the Saharan dust layer was very homogeneous in space (horizontally and vertically) and time, while the second dust event had strong horizontal and vertical gradients in aerosol composition and concentration could be found. The airborne in-situ measurements show that the first event was dust dominated, while the second had a significant anthropogenic component.

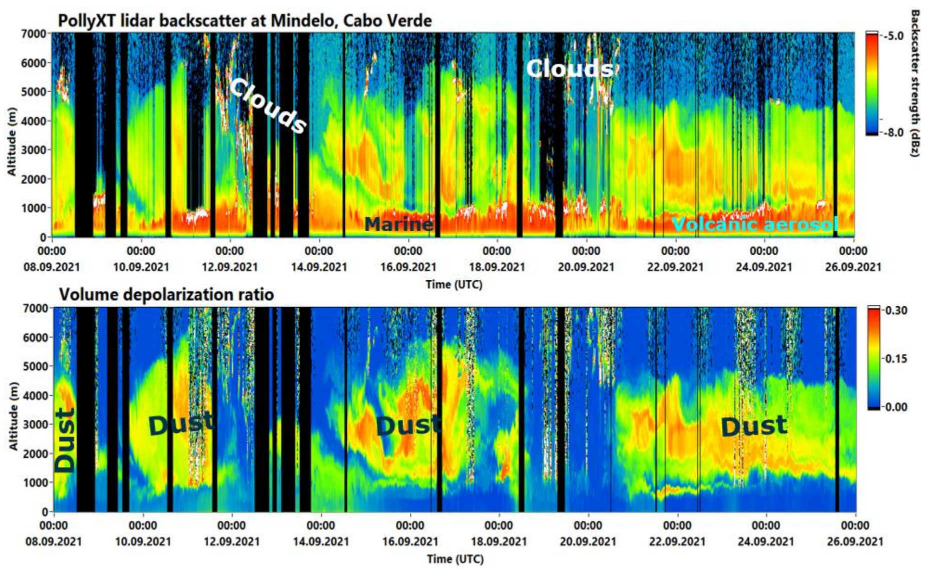

Figure 9. *ESA JATAC-ASKOS campaign PollyXT lidar backscatter coefficient at 532 nm (upper panel) and Volume depolarization ratio (lower panel) at 532 nm at Mindelo, Cabo Verde in September 2021.*

The ASKOS observational dataset will help us to understand the representativeness of the ground-based supersite in the context of the regional aerosol distribution. In this context, another intensive ASKOS campaign is planned for Summer 2022 (19 May - 19 June) on Sao Vicente Island, comprising a bigger instrument suite and covering the prime Saharan dust outbreak season.

4 Risk Analysis and Mitigation Strategy

Possible risks with low to medium probability have been identified and alternative solutions and contingency actions have been identified. Anticipated risks are listed below along with their remedial actions.

Table D1.1.1: Risk identification and contingency plan.

Risk no	Risk description	Probability	Impact	Contingency Plan
1.	Upgrade/Update delays of the ESA-LIVAS Pure-Dust database due to computational resources required (WPs 2100/3100), to the full DOMOS domain and temporal period.	Medium	Low	Establishment of the algorithms in the framework of WP3100/3200 over specific domain (i.e., ASKOS campaign domain / 09-2021) and according implementation of the broader spatiotemporal coverage.
2.	CALIPSO low-to-none provision of the atmospheric aerosol vertical structure due to extended cloud-coverage/contamination or CALIOP non-operation.	High over specific DOMOS grids/months.	Medium over specific DOMOS grids/months.	Alternative ESA-LIVAS pure-dust domain/grid spatiotemporal configuration scenarios will be applied, towards bridging non-observational information of the vertical atmospheric aerosol structure through grids/months where the corresponding information is available.
3.	Non-provision of all datasets to be used in the same spatiotemporal resolution	Medium	Low	LIVAS and MIDAS L2-to-L3 conversion will be performed, according to the accepted DOMOS proposal by the Agency. In the vertical LIVAS pure-dust ERA5 vertical resolution will be followed. Different EO datasets will be converted to 1x1 grid

				resolution, and monthly-mean temporal resolution.
4.	Non-provision of uncertainties in all datasets and products to be implemented under DOMOS.	Medium	Medium	In L2-to-L3 cases the sqrt of variances will be implemented. Uncertainties will be established based on validation/evaluation activities against ground-based and in-situ state-of-the-art reference observational datasets (WPs 2200/2300/2400).
5.	Delays in the simulation of LIVAS assimilation (WP 3200) due to unavaila bility of the computational resources required	Medium	Medium	Prioritized computing resources on the BSC supercomputer will be used through the PRACE (https://prace-ri.eu/) and RES (https://www.res.es/en) supercomputing access calls.
6.	Delays in BSC's contribution for WP4000/5000 due to the deployment of the new MareNostrum supercomputer at the BSC, expected in 2023.	Low	Medium	BSC will closely monitor the computing resources and any potential disruption associated with the deployment of the new supercomputer MN5. Should this impact the availability of MN4, the current supercomputer (which will remain active but might have some interrupted service) on which DOMOS simulations will be run, schedule adjustments will be proposed if necessary. The use of external computing resources through the PRACE (https://prace-ri.eu/) or RES (https://www.res.es/en) infrastructures will be considered.
7.	Delays in WP3300 experiments with ULB IASI dust AOD in relation to the move of the ECMWF's supercomputer to Bologna	Medium	Medium	ECMWF is making an effort to start the experiment *before* the switch off of the Cray computer in Reading which will happen in June 2022. Should that fail, there might be a delay of a couple of months in the delivery of the experiments.
8.				

5 DOMOS Data needs and availability

According to the SoW and the DOMOS accepted proposal, a synergy of available satellite, airborne, in-situ, campaign data, relevant existing climatologies, and model results, will be utilised to develop, derive, and accordingly validate/evaluate the DOMOS prototype pure-dust deposition algorithms and products across the Atlantic Ocean, and to address scientifics questions related to the biogeochemical effects of the deposited pure-dust atmospheric component.

The work foreseen will be established over a multi-mission range of EO products (i.e. CALIPSO-CALIOP, Metop IASI, Sentinel-3 SLSTR, Aqua-MODIS) and approaches (i.e. LIVAS database by NOA and EnKF/4D-Var). The methods and algorithms will provide a detailed description of the different use of EO to create dust-deposition and atmospheric dust products, supported by a sound inter-comparison and validation/evaluation over the different selected and identified test areas (i.e. ASKOS campaign - NOA, in-situ dust deposition measurements in buoys and incidental ship observations – NIOZ/UoC). The detailed cross-comparison of the resulting pure-dust deposition data products with existing equivalent datasets will be performed to gain a thorough understanding of the range of validity, limitations and benefits of the different existing products. This section provides an overview of to-be-used datasets.

European satellite-based EO data needs and requirements.

With respect to the WP3300 requirements of satellite EO datasets and products, DOMOS envisages to implement the following datasets, available to the DOMOS consortium and the broader scientific community:
Metop-IASI EO - DOD at 550nm and AOD product at 10-microns data access at the moment is provided via Copernicus Climate Data Store (CDS; https://cds.climate.copernicus.eu/cdsapp#!/home; last access 10/03/2022).
Aeolus data access at the moment is provided by ESA (https://aeolus-ds.eo.esa.int/oads/access/; last access 10/03/2022).
DOMOS foresees implementation of Sentinel-3 AOD and DOD at 550 nm and Sentinel-5P in pilot-cases. With respect to Sentinel datasets, Copernicus programme foresees the free, full and open data policy available to all users for the Sentinel data products, via a simple self-registration. In addition to the download services, the Sentinel Data Products are available in the Copernicus Data and Information Access Service (DIAS) cloud environments.

Non-European satellite-based EO data needs and availability.

In addition to to ESA's and Eumetsat's satellite-based EO datasets and products ESA-DOMOS will build on top of non-European databases, including in a multimission approach of synergistical implementation of both satellite-based EO active (i.e. CALIPSO-CALIOP, ISS-CATS) and passive (i.e. MODIS-Aqua/Terra) datasets and products.

With respect to DOMOS developments,

CALIPSO data can be obtained from the ICARE Data Center (http://www.icare.univ-lille1.fr/; last access: 10/03/2022), and available for access via https://search.earthdata.nasa.gov/search; last access 10/03/2022).

Detailed information related to CATS datasets and a CATS lidar quick-look browser can be found in the CATS Data Release Notes, Quality Statements and Theoretical Basis, available at https://cats.gsfc.nasa.gov/ (last access: 10/03/2022).

All NASA Terra and Aqua MODIS data use in the framework of DOMOS will comply with NASA's Data and Information policy, which promotes the full and open sharing of all data with the research and applications communities, private industry, academia, and the general public (the term data includes observation data, images, metadata, products, and documentation). Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC), located in the Goddard Space Flight Center in Greenbelt, Maryland (https://ladsweb.nascom.nasa.gov/), and via https://search.earthdata.nasa.gov/search; last access 10/03/2022).

All CALIOP, MODIS and CATS data archives are additionally publicly available at EarthData database (https://search.earthdata.nasa.gov/search; last access: 10/03/2022).

Climatologies.

The MIDAS data set is available at https://doi.org/10.5281/zenodo.4244106 (Gkikas et al., 2020).

The LIVAS data set is available from the NOA IAASARS DOMOS group, upon personal communication with V. Amiridis (vamoir@noa.gr), E. Marinou (elmarinou@noa.gr), or E. Proestakis (proestakis@noa.gr).
Both the MIDAS and LIVAS datasets, will be established in 1x1 grid spatial resolution, and monthly-means temporal resolution, towards implementation in DOMOS.

OC-CCI https://www.oceancolour.org/ site (last access: 10/03/2022) provides satellite observations of ocean colour, focusing on the Ocean Colour Climate Change Initiative project.

Campaign datasets.

The ESA-ASKOS campaign deployed advanced instrumentation in the tropics - Cape Verde in September 2021, in order to provide unprecedented observations of high quality and accuracy for the Cal/Val of ESA's Aeolus mission, including aerosol lidars (e.g. NOA-EVE, NOA-WALL-E, TROPOS PollyXT lidar systems), ceilometers (CIMEL), photometers, microwave radiometers, cloud radars, and electrometers. ASKOS was complemented by UAV in-situ observations and dedicated radiosonde observations. The ASKOS dataset will be used as input to DOMOS activities.

Additional available in-situ or ancillary data.

DOMOS will implement marine in-situ datasets of Dust Deposition retrieved based on the activities of the Royal Netherlands Institute for Sea Research (NIOZ; Dr. Jan-Berend W. Stuut). In addition, DOMOS will implement marine in-situ observations from various publicly available data-archives (Indicative examples are provided in the following table).

Table D.1.1.2: Indicative available sources/databases.

Fluorescence Database	Access via
PANGAEA	https://www.pangaea.de/
WOD09	http://www.nodc.noaa.gov/
OGS database	https://nodc.ogs.it/?3
Cape Verde Ocean Observatory	Home - CVOO

DOMOS uses ship-based datasets of 1) aerosol optical depth and water vapour from the AErosol RObotic NETwork's (AERONET) Maritime Aerosol Network (MAN) (Smirnov et al., 2009) and 2) meteorological and oceanic routine measurements from German research vessels (RVs) reported via the DSHIP database. The MAN database provides aerosol optical depth (AOD) measurements at different wavelengths, namely 340, 440, 500, 675, 870, and 936 nm with the combination depending on the type of Microtops II sun photometer used. The data from DSHIP include for instance the geographical positions of the vessels and the underway measurements like air temperatures and water salinity.

The screening of the MAN database has identified 103 cruises in the North Atlantic and the Mediterranean Sea between 2004 and September 2021, covering all the seasons, that can be potentially used for DOMOS, although there is no MAN data for the selected DOMOS case studies. The MAN database is freely accessible via: https://aeronet.gsfc.nasa.gov/new_web/maritime_aerosol_network.html

The RVs used in the DOMOS study are from RV Sonne, RV Maria S Merian, and RV Meteor. The data from the measurements aboard the RVs are standardised and archived in the DSHIP database hosted by the Federal Maritime and Hydrographic Agency of Germany (Bundesamt für Seeschifffahrt und Hydrographie - BSH). After registration with the authorities, one can obtain access to DSHIP via: http://dship.bsh.de/. DSHIP data for the two months of the DOMOS case study was screened and acquired for use in DOMOS (June 2020 and September 2021). Fluorescence data is included in DSHIP. Additional sources for fluorescence data from RVs will be explored e.g., the Cape Verde Ocean Observatory.

6 Technical specs of DOMOS datasets

The prototype products will be established according to the Agency's requirements, as provided in the Statement of Work documentation, to provide dust-deposition fields to the full coverage of the Atlantic Ocean (including dust emission sources of Africa and S. America, the broader Atlantic Ocean, Caribbean Sea and Gulf of Mexico, confined between latitudes 40°N to 60°S), in 1x1 deg. grids, and of temporal coverage at least between 2010 and 2020.

The BSC LIVAS-based analyses will be provided over the Atlantic Ocean, Caribbean Sea and dust emission sources of Africa for June 2020. The analysis ensemble standard deviation will be provided as a proxy for the product uncertainty.

The BSC iron deposition fields will be generated with the EC-Earth3-Iron model for the period 1990-2020 with a monthly frequency and a horizontal resolution of 3°x2°.

The BSC ocean biogeochemistry reconstruction will cover the period 1990-2020 and will be driven with the newly generated iron deposition fields and will include several members to sample the product uncertainty.

The ECMWF model datasets from the DOMOS experiments for June 2020 and September 2021 will be made available via the Meteorological Archive (MARS). Access will be given to ESA directly for redistribution.

The CAMS reanalysis deposition dataset is publicly available via the Atmospheric Data Store (https://atmosphere.copernicus.eu/data).

7 Plan of DOMOS publications

This section provides a first overview of all the scientific contributions related to foreseen publications in peer-reviewed journals, established as outputs of the activities considered in the course of the project, according to DOMOS work-packages.

Based on “WP3100: Development of prototype DOMOS-4DAtlantic products”, “WP3200: LIVAS-based dust analysis” and “WP4100: DOMOS 4D atmospheric dust and dust deposition product generation”:

- Fine-mode and coarse-mode pure-dust atmospheric components over the Atlantic Ocean.
- Atmospheric pure-dust deposition over the Atlantic Ocean: Generation, Validation and Timeseries.
- Assimilation of LIVAS in MONARCH for the June 2020 episode.

Please note that these are not official project deliverables.

WP3300: Prototype dust analysis using IASI dust and Aeolus L2B/L2A products.

Journal article submission on DOMOS runs. This is not an official deliverable.

WP5000: Scientific Analysis and Impact Assessment

WP5100: Quantification of dust deposition variability and trends along with the contributions from different sources and processes to the deposition of soluble iron.

Journal article submission on soluble iron deposition. This is not an official deliverable.

WP5200: Dust deposition influence on the ocean biogeochemical properties.

Journal article submission on analysis of ocean biogeochemical reconstruction. This is not an official deliverable.

8 Identification of Early Adopters

The DOMOS project (objectives and scope) was presented during the 7th World Meteorological Organisation (WMO) Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Global Steering Committee meeting that was held virtually on 20th October 2021. One of the main objectives of the WMO SDS-WAS is the identification and improvement of sand and dust products. This goal is aligned with DOMOS' objectives which seek to contribute to an improved representation of the physical and chemical characteristics of dust deposition over the ocean, assessing the airborne dust transport.

Here it is worth mentioning that WMO (and in particular SDS-WAS) is one of the partners in the United Nations (UN) Coalition for combating Sand and Dust Storms. The Coalition, launched in 2019, seeks to strengthen coordinated action on sand and dust storms, which have damaging impacts on human health, the environment and key economic sectors in many countries around the world. Apart of WMO, the Coalition also includes the UN Convention to Combat Desertification (UNCCD), UN Development Programme (UNDP), UN Environment (UNEP), UN Food and Agriculture Organization (FAO), the World Health Organization (WHO) and World Bank - among other institutions.

Apart from UN agencies, it is planned to launch a survey in early 2022 to the WMO SDS-WAS and inDust networks for identifying potential users of the DOMOS outcomes. inDust (https://cost-indust.eu/) is an international network that involves researchers, data providers and user communities of information on airborne dust that can assist the diverse socio-economic sectors affected by the presence of high concentrations of airborne mineral dust.

Finally, researchers involved in key projects and initiatives also expressed their interest on the DOMOS' products and outcomes, such as:

- Samuel Remy (HyGEOS), CAMS aerosol model developer
- Jeff Reid (NRL), Pete Colarco (NASA), and Taichu Takaka (JMA), co-chairs of the International Cooperative for Aerosol Prediction
- Andrea Sealy (Caribbean Institute for Meteorology and Hydrology, CIMH) is involved in different projects related to air quality and health services in the Caribbean.

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