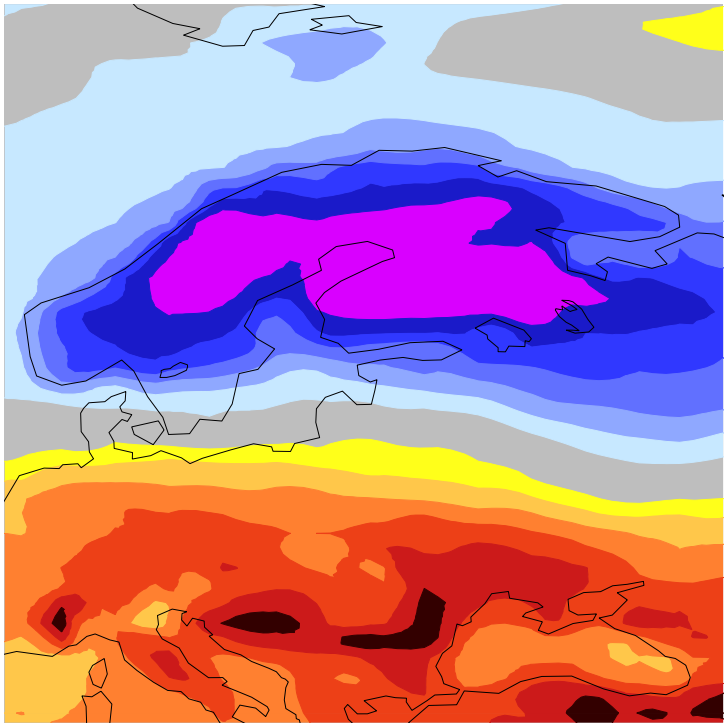
ECMWF Feature article

from Newsletter Number 179 – Spring 2024

EARTH SYSTEM SCIENCE

A new time-varying tropospheric aerosol climatology for the IFS



www.ecmwf.int/en/about/media-centre/media-resources

doi: 10.21957/ba371f56ts

This article appeared in the Earth system science section of ECMWF Newsletter No. 179 – Spring 2024, pp. 26–32.

A new time-varying tropospheric aerosol climatology for the IFS

Tim Stockdale, Retish Senan, Robin Hogan, Zak Kipling, Johannes Flemming

Tropospheric aerosol has an important radiative impact on the atmosphere and wider Earth system. In configurations of ECMWF's Integrated Forecasting System (IFS) for medium-range and seasonal forecasting, it is represented as a fixed climatology, which was last updated some years ago. The present fixed climatology has two main weaknesses: it is unable to represent the large changes in anthropogenic aerosol that have occurred over recent decades, which have driven changes in the radiative balance relevant for both reanalysis and the calibration of seasonal forecasts; and it is incompatible with the representation of aerosol in the latest configurations of the EU-funded Copernicus Atmosphere Monitoring Service (CAMS), implemented by ECMWF, hampering work to assess the possibility of including interactive aerosols in our configurations for numerical weather prediction (NWP). We have therefore developed a new, decadally-varying climatology of tropospheric aerosol, derived from and compatible with the aerosol modelling used in CAMS, to support and improve our work in core NWP activities and the EU-funded Copernicus Climate Change Service (C3S) implemented by ECMWF. It is driven by the latest versions of emission datasets used in the World Climate Research Programme's CMIP6 project, and proposed for CMIP7. This new time-varying climatology is planned for IFS Cycle 49r2, for use in both the forthcoming ERA6 reanalysis and the SEAS6 seasonal forecast upgrade, and subsequently in other NWP configurations.

The importance of tropospheric aerosols

Aerosols in the atmosphere are important in many ways. They can absorb solar radiation, heating the air but reducing the sunlight at the surface; they can reflect sunlight directly to space, cooling the planet; they modify absorption and emission of longwave radiation; and they can modify the formation and properties of clouds, although cloud-aerosol interactions are not well represented by the IFS. There are many types and sizes of aerosol particles, whose optical properties can vary greatly with composition, size and the wavelength of light they are interacting with. Aerosol concentrations vary over many orders of magnitude, and their radiative impact depends on both their intrinsic properties and their surrounding environment. The regional variation in importance of aerosols in the IFS can be demonstrated with an experiment in which all tropospheric aerosols are removed from the model: Figure 1 shows the impact of doing so on the net surface solar radiation, which increases by about 30% over parts of Africa, and on the 2-metre temperature, which increases by up to about 0.5 K in southern Europe.

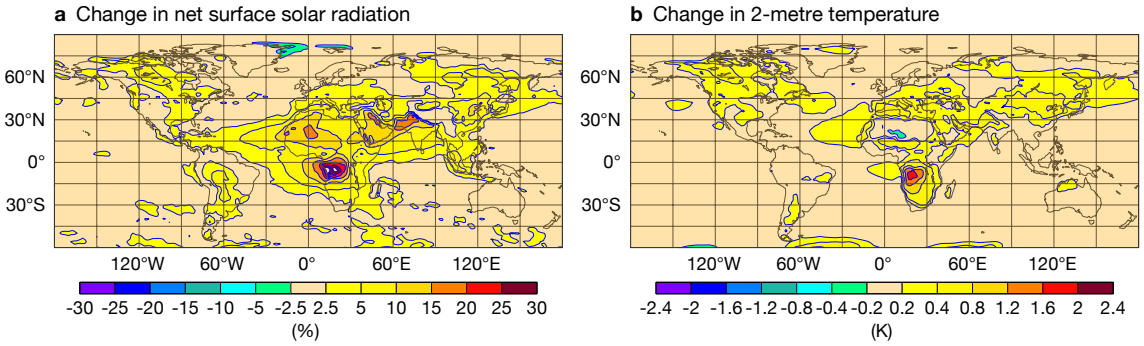


Figure 1 Climatological June–July–August (JJA) impact of removing all tropospheric aerosol from the IFS. We show (a) the percentage change in net surface solar radiation, and (b) the change in 2-metre temperature, calculated from 10 years of 10-member seasonal forecasts (2011 to 2020) starting on 1 May.

doi: 10.21957/ba371f56ts

A good model representation is hampered not only by the complexity of aerosols, but by the difficulty in accurately measuring their distribution and properties on a global scale. For many years, aerosols in the IFS were specified as a climatology based on external datasets, such as the Tegen et al. (1997) climatology used operationally until 2017. The most recent upgrade, used since IFS Cycle 43r3 and described by Bozzo et al. (2020), gave us for the first time a climatology based on aerosol modelling run at ECMWF. This climatology was created by first running the IFS and its CAMS aerosol model with realistic winds and specified emissions for the period 2003–2013 to create a model estimate of the climatology. The resulting 11 aerosol fields were then all scaled with a common factor at each horizontal grid point, such that the total aerosol optical depth summed over all aerosol species matched the values given by the CAMS interim reanalysis. This approach was taken because the reanalysis had enough satellite data to help constrain this vertical integral, but it was less successful in partitioning the optical depth between species, something which remains challenging today. Further adjustments, in particular an arbitrary reduction of aerosol over Africa in boreal summer, were found necessary to produce a climatology which could be used for NWP without damaging the scores.

Developing a new time-varying aerosol

Since this first CAMS climatology was produced, there have been major improvements in the chemistry and aerosol modelling used by CAMS. This motivates us to try to produce an improved version of the aerosol climatology. The approach we follow is similar, but with two key differences. Firstly, rather than use estimated aerosol values for a limited period of time to estimate a fixed climatology, we generate a dataset covering multiple decades, allowing us to calculate a decadally-averaged climatology that is time-varying. Secondly, we rely entirely on the specification of emissions and the CAMS chemistry model to generate the aerosols, because satellite-constrained reanalyses of aerosol optical depth are not available over longer historical periods. The aerosol fields are constrained by meteorological and emissions data, but are not directly analysed, so we refer to the result as a pseudo-reanalysis. We had expected to need some final calibrations of total aerosol amount from a recent period for which CAMS analyses are available, but in fact the quality of the latest model means that this was not necessary.

We start by generating the multi-decadal pseudo-reanalysis. Since some aerosol species are strongly influenced by chemistry, we run the full Cycle 47r3 IFS-COMPO scheme with 123 chemical species and 16 aerosols. For affordability, we use a low-resolution TL255 system with a grid spacing of 80 km, which is appropriate as input for our final 3° x 3° product, unchanged from the resolution of the previous climatology. Climatologies are inherently rather smooth: the radiative impacts of aerosol are most important on larger scales, and a higher model resolution would not reduce the many uncertainties in emissions and modelling.

Emissions of some aerosol types (sea-salt, mineral dust) are calculated by the IFS as it runs, but for most aerosols and chemical species, emissions must be specified from external data. Most of the emissions data comes from the latest version of the Community Emissions Data System (CEDS version v_2021_04_21), an extensive database developed to support climate change modelling such as CMIP6 and CMIP7. It contains very detailed information, specified as daily data on high-resolution grids, and with sector-specific information such as aviation, shipping, land transport, power plants, industry, agriculture etc. Natural emissions sources, including biogenic sources and effusive (low-level) volcanic emissions, are also provided. Another important source of aerosol is fire emissions, either from human-directed burning or from forest fires. Here we use estimates from the historical global biomass burning emissions gridded dataset for CMIP6 (BB4CMIP6) for the period up to 2014 and from the Global Fire Assimilation System (GFAS) thereafter. A key chemical species for tropospheric chemistry is the hydroxyl radical (OH), and changes in this can drive changes in, for example, nitrate aerosols. Concentrations of OH in turn depend on methane (CH4), which has increased substantially over the last 70 years and had to be properly accounted for.

The pseudo-reanalysis is created by initialising IFS-COMPO, running a 24-hour forecast, using the resulting chemistry and aerosol values to create initial conditions for the next 24-hour forecast, and repeating this continually. The meteorological initial conditions come from ERA5 and are reset every 24 hours, so the winds and aerosol transports are constrained to be accurate, but the chemistry and aerosols evolve freely according to the emissions and chemical and physical model processes. It would take too long to run this sequentially for the whole period, so the pseudo-reanalysis is run as a series of overlapping chunks, with a 6-month spin-up period discarded in each case. The pseudo-reanalysis runs from 1951 to 2019. For some aerosol types (sea-salt, mineral dust), we form a fixed climatology using the last 27 years of data, because we do not expect to resolve any significant long-term trends. Most aerosol types, however, have emissions dominated by human activity, and we calculate a time-varying climatology from a 9-year running mean. This is then sampled at 3-year intervals, giving an effective smoothing of the data closer to 10 years.

Figure 2 shows a few examples of the aerosol climatology for July in two different epochs, 1975 and 2015. Industrial emissions of sulphate aerosol were high over Europe and the US in the 1970s, but have since reduced substantially, while emissions have increased in India, China and the Middle East over the same period. Some black carbon is from industrial emissions, whose growth in some regions can be seen, but it is dominated by biomass burning, some deliberate (as over Africa), but also increasingly by forest fires (Canada and Siberia). The increase in high latitude burning is related to a warming climate and is likely to continue to increase. Fine nitrate, an aerosol which originates from combustion processes and agriculture but further depends on chemical balances in the atmosphere, has increased in many areas. The figures here are only a snapshot: the full story of aerosol variation over time is complex.

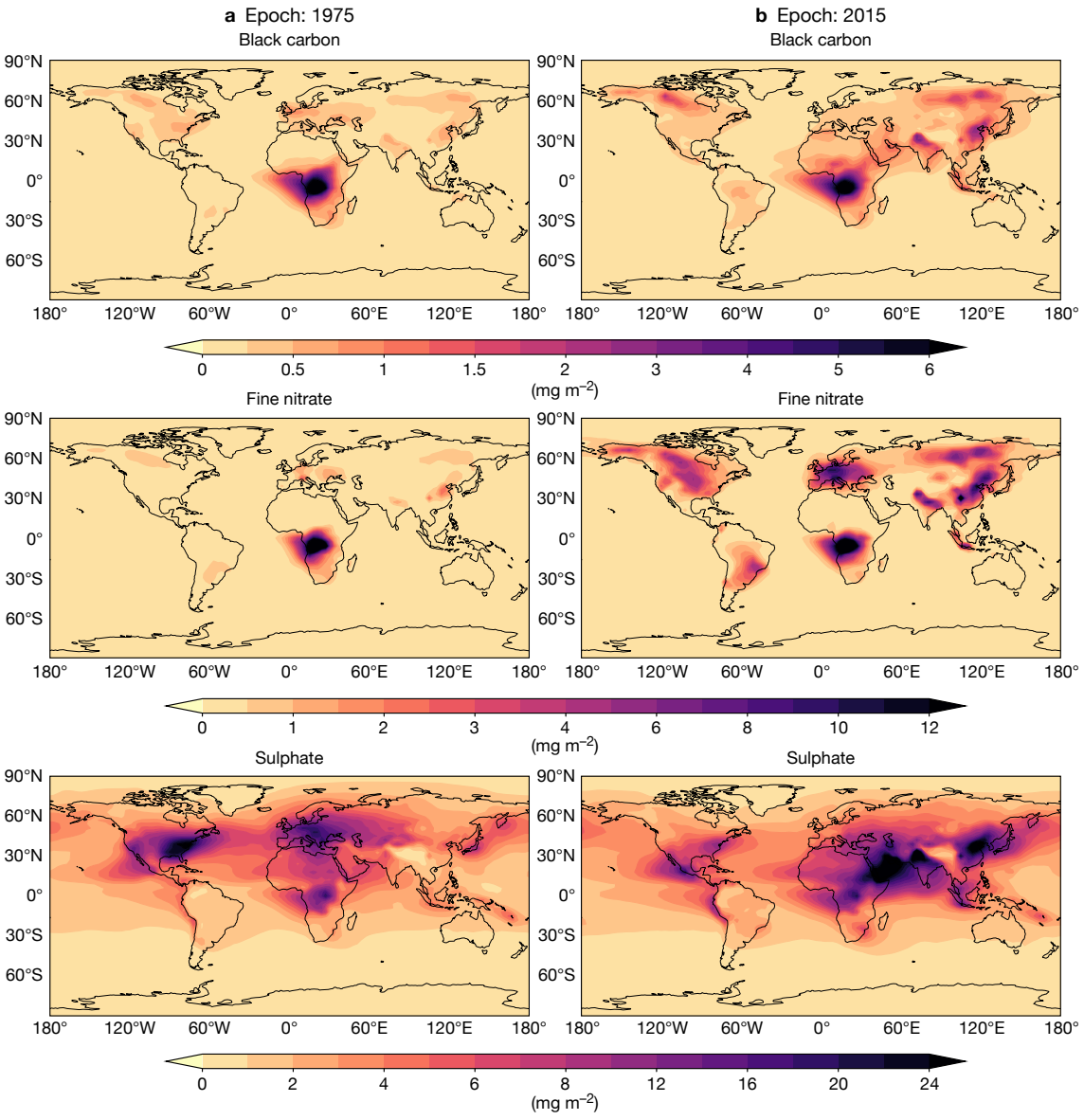


Figure 2 The time-varying vertically integrated July mass climatology shown for (a) 1975 and (b) 2015 for three epoch-varying species.

The aerosol climatology represents aerosols which are formed or emitted in the troposphere, including those transported into the stratosphere. The stratospheric part of the solution requires longer spin-up times, achieved in a climatological sense with a multi-year 'pre-spin-up' run, although low frequency variation of tropospheric-origin aerosols in the stratosphere will not be properly represented. A bigger source of stratospheric aerosol is that formed after the injection of sulphur by large volcanic eruptions – this is represented separately in the IFS, either as a constant background (for NWP) or varying according to the history of volcanic eruptions (for reanalysis and seasonal forecasting).

doi: 10.21957/ba371f56ts

Assessing the impact of the new aerosol climatology

The old aerosol climatology was adjusted to work well with the IFS, and subsequent IFS developments have been implemented so that they work well with these aerosols. The risk of degrading performance with a new aerosol climatology is thus real, even if it has a well-founded basis. Indeed, if we simply substitute the new climatology for the old with no further changes, the large changes in aerosol masses (see Box A) cause noticeable deterioration in both the model climate and NWP scores. However, alongside recent changes in aerosol modelling, CAMS has made improvements to the aerosol optical properties. When we use these new properties with the new aerosol climatology, the model behaviour becomes much closer to the model behaviour with the old climatology and with the old aerosol properties. NWP testing shows a slight overall cooling of the troposphere, with improved patterns of atmospheric heating in the tropical and sub-tropical lower troposphere, leading to a modest reduction in root-mean-square errors of medium-range temperature and wind. Longer runs show a variety of modest impacts on climate, either positive or negative depending on whether the change reduces or reinforces biases from other sources. One small but helpful improvement in the model climate is a reduction in the excessive easterly winds in the eastern equatorial Indian Ocean (see Figure 3). These erroneous winds drive excess upwelling, giving a cold sea-surface temperature (SST) bias. Since this is an error in a very non-linear part of the tropics, it has been a high priority to try to reduce it. The improvement from the new aerosols is only moderate, but still welcome.

Aerosol species and global mean mass loadings in the new and old climatologies **A**

Aerosol type	Old climatology	New climatology
Sea salt 1	1.1	4.4
Sea salt 2	63.0	47.0
Sea salt 3	76.4	15.4
Mineral dust 1	8.9	0.7
Mineral dust 2	27.7	6.5
Mineral dust 3	30.7	76.8
Organic matter (hydrophilic)	3.9	1.7
Organic matter (hydrophobic)	0.7	0.024
Black carbon (hydrophilic)	0.36	0.21
Black carbon (hydrophobic)	0.10	0.005
Sulphates	3.8	3.5
Nitrates (fine)		0.6
Nitrates (coarse)		3.0
Ammonium		1.1
Secondary organic (biogenic)		0.89
Secondary organic (anthropogenic)		0.61

This table compares the global-mean vertically integrated aerosol mass (in mg per m^2) by species for the old and new climatologies for 2015. Salt and dust have three different size bins, and the last five species (formed from gases) are present only in the new climatology, although secondary organic aerosols were previously accounted for together with organic matter. The optical properties of the aerosols have also changed, so changes in radiative impact cannot be deduced solely from changes in the mass of aerosol.

doi: 10.21957/ba371f56ts

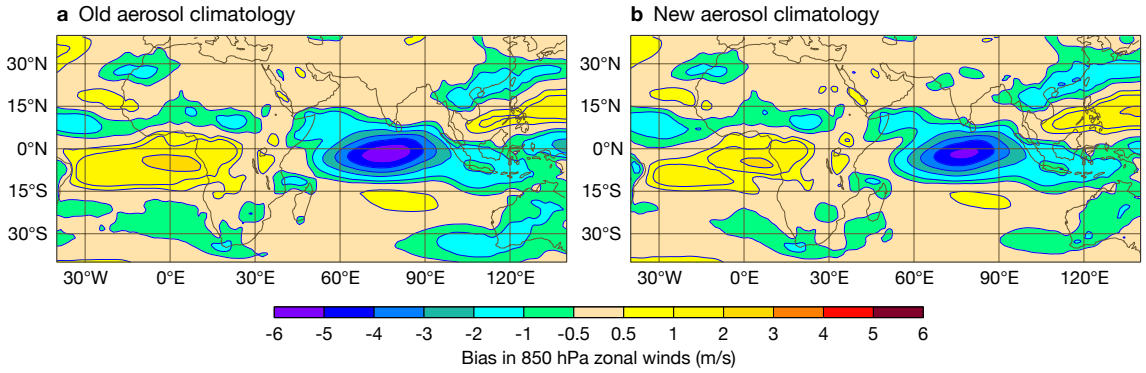


Figure 3 The bias in 850 hPa zonal (east–west) winds in September–October–November, in seasonal forecasts from 1 May, with (a) the old and (b) the new aerosol climatology, in the period 2001–2020.

Trends in aerosols and interaction with clouds

One of the aims of including time-varying aerosols in the IFS is to improve the representation of temperature trends in seasonal forecasts. Operational seasonal forecasts of temperature, presented as the expected temperature for a coming season relative to past decades, have become largely dominated by the effects of global warming, and our model must reproduce these well if the real-time forecasts are to be accurate.

Aerosols interact with radiation in many and complex ways, but on seasonal timescales changes in surface temperature are typically dominated by changes in top-of-the-atmosphere (TOA) net solar radiation. We illustrate the impacts of time-varying aerosols by looking at the difference between the recent 20-year period 2001–2020 and the preceding 20 years, 1981–2000, which we will refer to for brevity as ‘the trend’. From the earlier to the later period, there are many changes in aerosols, including a substantial reduction in reflective sulphate aerosol over Europe and eastern North America, together with an increase over South and East Asia.

Figure 4a shows the impact of the aerosol change on the trend of northern summer clear-sky TOA (top-of-the-atmosphere) net solar radiation (that is, the net solar radiation calculated at each grid point assuming no clouds are present). Changes of up to 5 W/m^2 can be seen in the regions of largest sulphate aerosol change. However, we also need to account for how aerosol changes affect the clouds. The shortwave cloud radiative effect is the difference between the net TOA solar radiation with the actual cloud cover, and that calculated assuming no clouds. It is thus the effect of the clouds on the net top solar radiation. The difference in the trend of the cloud radiative effect, Figure 4b, shows that in the IFS the reduction in aerosol over Europe has led to an increase in the reflection of sunlight to space by clouds; this surprising result is explained below. In much of northern Europe, this cloud change entirely offsets the reduction in reflection by aerosol itself, and in places it results in the aerosol change causing a slight cooling in surface temperature (Figure 4c). In the Eastern Mediterranean, the absence of clouds means that aerosol-induced temperature changes are mostly driven by direct radiative aerosol forcing changes, which drive additional warming of several tenths of a degree. The result is that here the overall temperature trends due to all causes, including greenhouse gases and aerosols (Figure 5a), are closer to those from ERA5 (Figure 5b). Note that the impact of aerosols on IFS cloud trends over Europe is on top of a reduction in cloud over time due to other causes, most likely a positive feedback from global warming.

doi: 10.21957/ba371f56ts

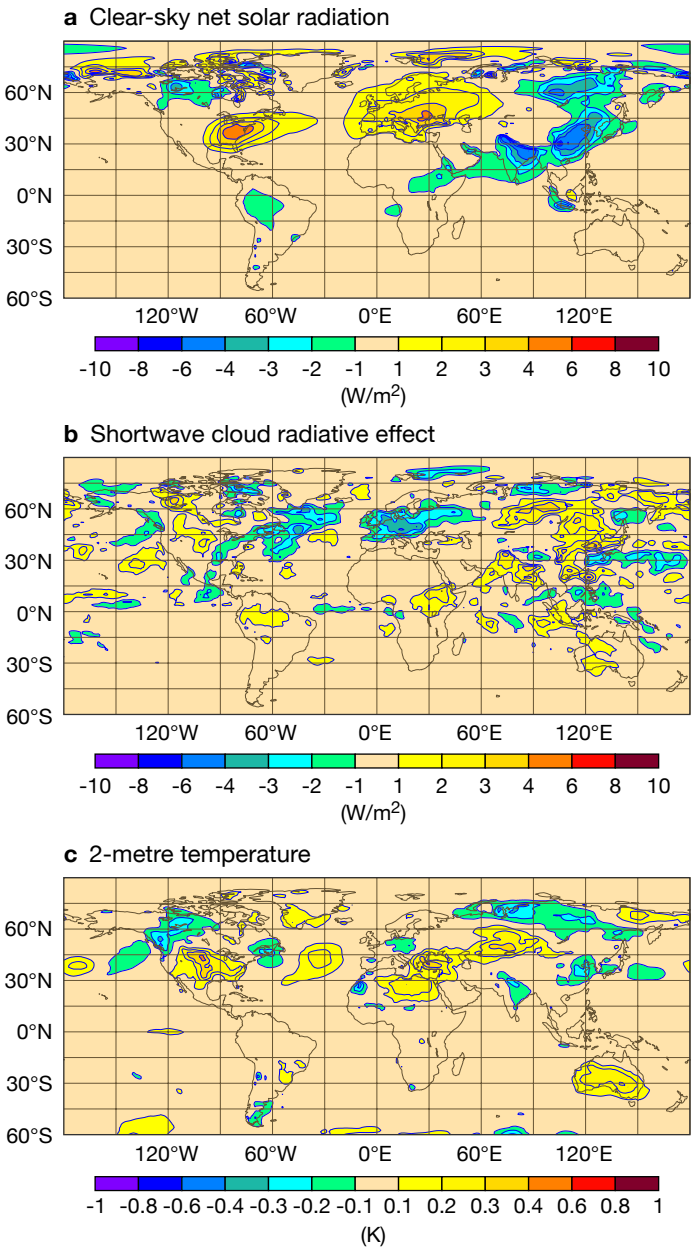


Figure 4 The difference in June–July–August (JJA) ensemble-mean 20-year trends between IFS experiments with the new time-varying and the old fixed aerosol climatology, for (a) top-of-the-atmosphere clear-sky net solar radiation, (b) the shortwave cloud radiative effect, and (c) 2-metre temperature.

Comparison of the trends in 2-metre temperature between seasonal forecasts and reanalysis in Figure 5 suggests we have a problem over Europe, though. The forecast trend is based on averaging 10-member ensembles, each of which has a slightly different trend pattern. The ERA5 values, on the other hand, are based on the single observed outcome of what happened, so we expect ERA5 to be noisier, and not to exactly match the forecast ensemble mean. Nonetheless, it is striking that the real warming trends in ERA5 have been very strong across the whole of Europe in this period, in which aerosol pollution has decreased. There are well understood mechanisms whereby a reduction in sulphate aerosol should give a reduction in cloud brightness and hence stronger solar input, which is consistent with the strong warming seen in ERA5. So why does the IFS cloud response go the wrong way? The problem is that the IFS cloud microphysics takes no account of the aerosol climatology we specify for the radiation – we are missing the positive feedback between sulphate aerosol and cloud brightness that is known to exist. On the other hand, the reduction in sulphate aerosol and other absorbing aerosols means that more solar radiation hits the surface, and less is absorbed in the troposphere. This means the troposphere is slightly cooler, and more conducive to creating clouds and extending their lifetime. This is the semi-direct radiative effect of aerosols, which the IFS faithfully represents. Since the IFS has this negative impact of aerosol on clouds but is missing the larger positive one, the net impact of aerosol-induced changes over the cloudier parts of Europe has the wrong sign. When added to the clear-sky effect, the impact of reducing aerosol on TOA solar radiation is very close to neutral, instead of being a large positive effect.

doi: 10.21957/ba371f56ts

This is disappointing, but the IFS cloud physics are being further developed to include aerosol indirect effects on clouds, and we expect better results in the future. In cloud-free areas such as the Eastern Mediterranean, we are seeing clear improvements in forecast temperature trends. NWP experiments suggest that the semi-direct effect is most relevant on longer forecast timescales, where tropospheric temperatures have time to respond to weak radiative forcing, and the semi-direct effect should thus be less relevant for reanalyses.

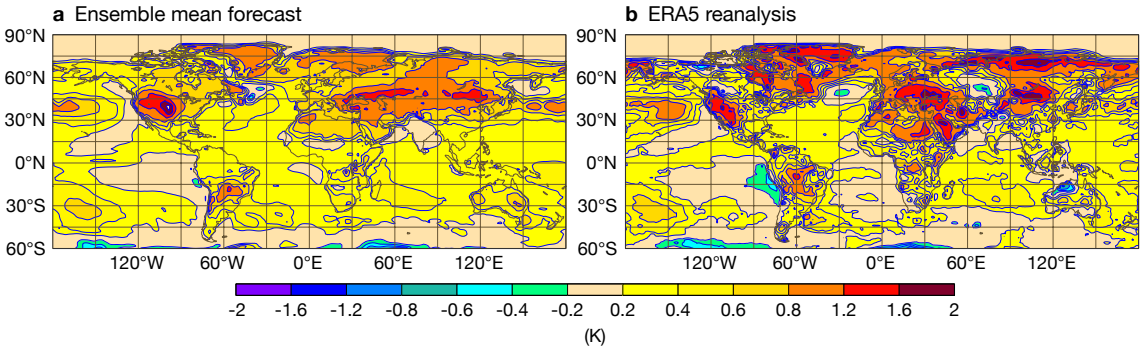


Figure 5 20-year trends in June–July–August (JJA) 2-metre temperature from (a) the 1 May ensemble mean seasonal forecasts with time-varying greenhouse gases and aerosol and (b) the ERA5 reanalysis.

Conclusion and outlook

A new time-varying climatology of tropospheric aerosols has been created for the IFS. It is cleanly derived from the CAMS chemistry and aerosol model and can be used in the IFS with the same aerosol optical properties as are used by CAMS. This is a big step forward in the coherence of our aerosol representation across different IFS configurations and is a step towards our longer-term strategy of representing highly variable species of aerosol, such as dust or fire-related emissions, interactively in NWP configurations.

The new aerosol climatology is an improved representation of aerosol, but there is still scope for development. The Cycle 47r3 aerosol and chemistry scheme was assessed by CAMS using in-situ data from the AERONET validation network. The assessment shows that the aerosol in a free-running version of the model is biased low in terms of total aerosol optical depth. This is most noticeably the case in areas with relatively low aerosol loading. This suggests that more widely dispersed and longer-lived aerosol is underestimated. Coincidentally, the IFS has long had an additional spatially constant tropospheric background aerosol term, on top of the explicit representation of various types of aerosol. There had been some hope that the new aerosol climatology might allow this term to be removed or reduced, but it turns out that we need to retain it to preserve both NWP scores and the fidelity of the model climate. We will need further improvements in IFS aerosol modelling before we can eventually remove this additional term.

The second aim of the new aerosol climatology was to represent anthropogenically driven time-variation, and hence improve our ability to model temperature changes over time. We have succeeded in creating a plausible time-evolving aerosol climatology, and the direct and semi-direct radiative impacts of changing aerosol are likely to be reasonably represented. However, the lack of indirect cloud aerosol feedbacks within the IFS means that the resulting changes in net radiative forcing are deficient in some regions, and thus the impact on surface temperature trends is incomplete. Work to allow cloud properties to explicitly depend on aerosol has started. This will both be helped by the improved climatology and, in time, contribute to a more realistic time evolution of clouds in response to changing aerosols. Correctly representing the impact of time-varying aerosols on clouds (and hence temperature) is a key challenge for the wider climate community.

The new aerosol climatology is useful in its own terms and will contribute to both ERA6 and SEAS6 as well as future NWP cycles. It also sets a foundation for further improvements in our treatment of aerosol and cloud-aerosol interactions.

Acknowledgement

The development of the time-varying aerosol climatology was partially supported by the CONFESS project, which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101004156.

Further reading

Bozzo, **A.**, **A. Benedetti**, **J. Flemming**, **Z. Kipling** & **S. Rémy**, 2020: An aerosol climatology for global models based on the tropospheric aerosol scheme in the Integrated Forecasting System of ECMWF. *Geosci. Model Dev.*, **13**, 1007–1034.

Tegen, **I.**, **P. Hoorig**, **M. Chin**, **I. Fung**, **D. Jacob** & **J. Penner**, 1997: Contribution of different aerosol species to the global aerosol extinction optical thickness: Estimates from model results, *J. Geophys. Res.*, **102**, 23895–23915.

doi: 10.21957/ba371f56ts