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ICAO CAEP/12 Assessment Report: Understanding the potential environmental impacts from supersonic aircraft: an Update

Authors

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Abstract

There is renewed interest in the potential development of commercial and civil aircraft that fly at supersonic speeds. Noise and emissions impacts were extensively studied first in the 1970s, then again in the 1990s and early 2000s. As a result, there is a need to update our understanding of the potential impacts on noise and the environmental concerns relating to emissions, especially the resulting impacts on ozone and climate. Supersonic transport (SST) fleets of different size aircraft using conventional fuels are being considered, extending from business jets to larger aircraft that can transport hundreds of passengers. Scientists are now undertaking new studies using state-of-the-art models of global atmospheric chemistry and physics to understand the potential effects on stratospheric ozone and the radiative forcing of climate associated with SST fleets. These studies set the stage for the next generation of analyses of potential environmental effects from supersonic aircraft that gain consideration for development. Along with the emissions of long-lived carbon dioxide (CO_2), the radiative forcing of climate in turn depends on the spatial changes in concentrations of water vapor (H_2O), ozone (O_3), methane (CH_4) (primarily due to feedbacks from the emissions of nitrogen oxides (NO_x) and water vapor), and particles (both inorganic and organic aerosols). The emissions from the fleet of aircraft depend especially on the fleet size, flight characteristics, the Mach speed, the cruise altitude, the fleet fuel use at cruise, the NO_x emission index, and the assumptions about sulphur in the fuel and soot emissions. For projections of the number and type of aircraft currently under evaluation for SST fleets, there is likely to be less than a 1% change in globally-averaged total ozone over the next 2-3 decades, with whether the change is positive or negative depending on specific fleet parameters. The climate effects are also likely to be small, resulting in generally much less than a 0.03°C change in globally-averaged surface temperature (total effect will also depend on whether sustainable aviation fuels are used). Significant progress has been made to model and mitigate the effect of sonic booms from supersonic flight. Ongoing research to assess the impact on the public indicate that future low-boom supersonic aircraft designs will create quieter sonic 'thumps' that are much less annoying than conventional sonic booms. Nonetheless, further studies are necessary to fully evaluate the noise effects for specific aircraft.

Key Messages

- Increasing demand for air travel, the aspiration for more intercontinental travel, and the desire for shorter flight times, have all contributed to a renewed interest in the potential development of civil aircraft that fly at supersonic speeds. Several companies throughout the world, especially in the United States, Europe, Japan and Russia, are currently considering the development of new supersonic commercial aircraft that cover a range of potential platform sizes, from business jets (typically less than 20 passengers) to mid-size aircraft (50-80 passengers) to large aircraft (several hundred passengers). Research studies are needed to understand the potential noise and other environmental impacts from such aircraft.
- The potential impacts on the global environment, especial on stratospheric ozone and climate, from a commercial fleet of supersonic transport aircraft (SSTs) have led to several different assessments by governments around the world over the last 50 years, but the most recent international assessment was about 20 years ago.

- The impacts from a fleet of supersonic aircraft on stratospheric composition are primarily of concern because of resulting absolute changes in ozone and changes in the radiative forcing on climate. These aircraft would likely burn conventional aviation fuel and, as a result, emit nitrogen oxides (NO_x) and water vapor (H_2O) directly into the stratosphere, where chemical reactions can then affect the concentrations of the important layer of ozone found there. Along with the emissions of long-lived carbon dioxide, the radiative forcing on climate in turn depends on the spatial changes in concentrations of water vapor, ozone, methane (primarily due to feedbacks from the NO_x and H_2O emissions), and particles (both inorganic and organic aerosols).
- The emissions and resulting impacts on ozone and climate from an assumed fleet of SST aircraft will depend especially on the fleet size, flight characteristics, the Mach speed, the cruise altitude, the fleet fuel use at cruise, the NO_x emission index, and the assumptions about sulphur in the fuel and soot emissions. In general, it is expected that the RF from non-CO_2 emissions will be larger than that from CO_2, with the total RF from CO_2 depending on the lifespan and size of the fleet as well as the source of fuel. The use of sustainable aviation fuels would likely greatly reduce sulphur and soot emissions as well as reducing the RF from CO_2.
- The proposed SST fleets are likely, for projections of the number and type of aircraft currently under evaluation (as discussed in the report), to result in less than a 1% change in total ozone, with an increase or decrease in total ozone depending on the specific design and fleet size. The estimated climate effects are also likely to be small, generally much less than a 0.03°C change in globally-averaged surface temperature, which is much smaller than effects on climate projected from other human related activities. Further study of these impacts is needed for specific aircraft designs.
- Existing analyses for supersonic aircraft show that the fleet size, the physical location of the emissions, and the magnitude of emissions have significant effects on the ozone and climate impacts, and that there is a strong sensitivity of these impacts to Mach speed and the related changes in the cruise altitude.
- Along with the advances in observations and laboratory studies, there has been a substantial increase in the understanding of tropospheric and stratospheric physical and chemical processes over the last few decades; as a result, the current generation of atmospheric chemistry-climate and chemistry-transport models are far advanced over those used previously in studies of SST fleets. Nonetheless, the findings for ozone and climate changes are similar to those from the earlier modeling studies.
- Much progress has been made to model and mitigate the effect of sonic booms from supersonic flight. However, the scientific view of supersonic en route noise impacts (i.e., sonic boom noise impacts) has not changed in recent years. No supersonic civilian aircraft are flying, therefore there are no current data available to assess noise impacts. The landing and takeoff (LTO) noise impacts of supersonic aircraft could be different from the noise impacts of conventional subsonic aircraft due to the higher velocity takeoffs and landings, and the high-performance operational capabilities of supersonic aircraft.
- Ongoing research to assess the impact on the public indicate that future low-boom supersonic aircraft designs will create quieter sonic booms (thumps) that are much less annoying than conventional sonic booms.

Introduction

Increasing demand for air travel, the aspiration for more intercontinental travel, and the desire for shorter flight times, have all contributed to a renewed interest in the potential development of civil aircraft that fly at supersonic speeds. As a result, various governments and companies around the world have been reconsidering development of supersonic aircraft for the business jet and commercial airline markets. Fleets of hundreds to thousands of these supersonic business jets (SSBJs) and/or supersonic transport (SST) aircraft are likely necessary to make their development economically feasible (e.g., Liebhardt, and Lütjens, 2011; Carioscia et al., 2019; Hardeman and Maurice, 2021). This report is aimed at providing an update on the understanding of the noise and the environmental concerns relating to emissions, and resulting impacts on climate and ozone, associated with the significant use of such aircraft. We begin with a short summary of the history of these environmental concerns.

The first SSTs: A historical perspective

By the mid-1960s, the rapid growth in passenger air travel led to designing, and the consideration of potential fleets, of SST commercial aircraft. As a result, three major aircraft platforms were studied, the Boeing SST in the United States, the Concorde in Europe (led by the United Kingdom and France), and the Tupolev Tu-144 in the then Soviet Union.

Even as designs were underway and the first prototypes being built, environmental concerns began to arise, initially with noise, especially from takeoff at airports and from the sonic boom when these aircraft reached supersonic speeds (e.g., Lundberg, 1965). Then concerns about potential impacts on stratospheric ozone (O_3) from a fleet of SSTs arose, first with emissions of water vapor (Harrison, 1970) and then from emissions of nitrogen oxides (Johnston, 1971). By this point it had been discovered that certain gases, including hydrogen oxides (e.g., OH and HO_2) and nitrogen oxides (NO_x, e.g., NO and NO_2), can react catalytically with ozone (e.g., Hunt, 1966; Crutzen, 1970) such that aircraft emissions could have a potential impact on atmospheric ozone. It was quickly determined that emissions of water vapor and subsequent production of hydrogen oxides from SSTs would likely be too small to have a significant effect on stratospheric ozone, but the direct emissions of nitrogen oxides (NO_x) from SSTs and other aircraft remained a significant concern. Stratospheric ozone was an issue both because a reduction in ozone concentrations would allow for more biologically harmful levels of ultraviolet sunlight to reach the Earth's surface and because ozone, especially in the upper troposphere and stratosphere, is a greenhouse gas that can affect climate (along with direct effects on climate from carbon dioxide (CO_2), water vapor (H_2O), soot and other particles, and possible sulphur in the fuel).

The potential impacts on the global environment from a commercial fleet of SSTs led to a number of different assessments by governments around the world. The U.S. Climatic Impacts Assessment Program (CIAP) was the largest and most extensive, resulting in six monographs plus four international conference proceedings (summarized in the Report of Findings, Grobecker et al., 1974). The U.S. National Academy of Sciences had a parallel program that reviewed CIAP as well as undertaking its own assessment (NAS, 1975). Other major efforts were from the Australian Academy of Sciences (1972), The UK's Committee on the Effects of Stratospheric Aircraft (COMESA, 1976), and France's Comité d'Études sur les Conséquences des Vols Stratosphèrique (COVOS, 1976). These programs were pioneering, including providing the first measurements of nitrogen oxides and other gases and particles in the stratosphere; greatly advancing the understanding of stratospheric composition through one-dimensional (vertical) models and the first two-dimensional zonally-averaged models; conducting comprehensive laboratory measurements of relevant reactions and their rates; and studying the economic impacts and biological damage caused by ultraviolet radiation. The new observations and scientific assessments resulting from these programs came to similar conclusions; namely, that the amount of the effects on stratospheric ozone from NO_x emissions could be significant depending on the size and cruise altitude of the SST fleet. The projected fleet of Concordes, with its flights being primarily in the very lower stratosphere, would have to become much larger than expected to have any significant impact on ozone. Largely because of economic concerns, and to a lesser degree, the potential environmental impacts, the Boeing SST development ended in 1971 and only a small number of Concorde and Tupolev SSTs were ever used commercially.

Revisiting SSTs (late 1980s to early 2000s)

The next major concerted effort towards considering the development of commercial supersonic aircraft began in the late 1980s. Johnston et al. (1989) were the first to revisit the question of SST potential impacts on stratospheric ozone. At about the same time, the U.S. government initiated NASA's High Speed Research Program (HSRP) that included both technology development and environmental analysis. The Atmospheric Effects of Stratospheric Aircraft (AESA) project was formally initiated under HSRP as a comprehensive effort to predict the atmospheric impacts of a future fleet of supersonic aircraft. A series of reports followed, and then in the late 1990s, several major assessment reports were published: (1) from NASA's combined supersonic and subsonic Atmospheric Effects of Aviation Project (AEAP; Kawa et al., 1999), and (2) a special international Intergovernmental Panel on Climate Change (IPCC) assessment of aviation impacts on climate that considered fleets of both subsonic and supersonic aircraft (IPCC, 1999).

The NASA and IPCC assessments assumed a specific SST design known as the High Speed Civil Transport aircraft (HSCT), which was assumed to be a large (300 passenger), long range (5000 nautical miles), Mach 2.4 supersonic transport aircraft with 84% of the emissions occurring in the Northern Hemisphere. This aircraft design was much larger, faster, and longer range than the Concorde. For the 1999 assessments, HSCTs were projected to have fleets of 500 and 1000 aircraft by the year 2015. Seven participating models in the assessments were zonally-averaged two-dimensional (2-D) models, the primary tools for studying stratospheric processes at that time (having replaced 1-D models), while three were early generation three-dimensional (3-D) models that had limited representations of stratospheric chemistry and physics. Computational limitations slowed the development of 3-D models. As seen in Figure 1, the model results from the 1999 NASA and IPCC assessments vary greatly in their dependence on NO_x emissions. The range and magnitude of the local ozone change vary between the different models used in the earlier assessments. These differences are likely related to differences in the representation of physical processes and the resulting odd-oxygen loss partitioning between NO_x, HO_x, and halogen chemical families between these older models. One of the major findings of the IPCC (1999) report was the potentially large impact on radiative forcing from water vapor emissions, which contrasted with the small equivalent forcing from subsonic emissions – in part, this is because the stratosphere is naturally very dry, so any additional water vapor can have a strong radiative impact.

The most recent prior studies on the environmental effects from potential supersonic aircraft emissions were from the European SCENIC (Scenario of aircraft emissions and impact studies on chemistry and climate) and HISAC (Environmentally friendly high speed aircraft) projects that assumed specific aircraft concepts to develop different emission scenarios relative to those used in the NASA and IPCC assessments (Grewe et al., 2007, 2008, 2010a, b). Both Grewe et al. (2007) and Grewe et al. (2010a) use the simplified linearized AirClim model to estimate radiative forcing due to CO_2, O_3, CH_4 and H_2O for the assumed fleets. Grewe et al. (2007) assumed a fleet of 500 to almost a thousand 250-passenger SSTs flying at Mach 2.0, or cruise at 16-19 km in 2050 (somewhat lower than the IPCC HSCTs). A number of different chemistry-climate models were used to determine the changes in H_2O and O_3. The results show a radiative forcing (RF) of about 20-30 mW m^{-2} from H_2O (compared to up to 100 mW m^{-2} for 1000 HSCTs in IPCC (1999)). A reduced supersonic cruise altitude or speed (from Mach 2 to Mach 1.6) reduces both the climate impact and ozone destruction by around 40%. Grewe et al. (2010a) assumed a fleet of up to 250 supersonic business jets (up to 19 passengers) with cruise at 15-16 km (Mach 1.6-1.8), resulting in a very small total change in RF of 0.1 mW m^{-2} in 2050. Within the HISAC project, the climate functions (as guidance in multi-disciplinary optimisation) have been developed, allowing minimisation of the climate impact from potential supersonic aircraft (Grewe et al., 2010b).

The importance of stratospheric aircraft aerosol emissions has been also highlighted (Søvde et al., 2007) and potential effects on the ozone column due to supersonic aerosol emissions have been shown. Dessens et al. (2007) also found this 'reduced' stratospheric O_3 destruction in the presence of aerosols; however, their total ozone column change is much more sensitive to varying the emission index of NO_x ($EINO_x$) compared with other studies (e.g., IPCC, 1999; Zhang et al., 2020a). Pitari et al. (2008) calculated the climate impact of supersonic aircraft due to sulphuric acid aerosol and black carbon of -11.4 and 4.6 mW m^{-2}, respectively, and observe that the particle-related RF is the second-largest component, after that of stratospheric water vapour, of RF from supersonic aircraft.

The concerns about noise

The noise impacts of future supersonic aircraft are difficult to predict, given that no supersonic civilian aircraft are currently flying. Since the best data we have for en route, sonic boom noise are from military jet operations and from the Concorde, existing regulations for supersonic aircraft are based on these datasets. Other than the Concorde legacy, there is little consensus science available either from the literature or from working groups to predict how people will react to repeated noise exposures to sonic booms (Sparrow, et al, 2019a,b). Landing and takeoff (LTO) noise could be quite similar to that from subsonic aircraft with lower bypass-ratio engines, since the sound source will likely be jet-noise dominated and thus broadband in nature. Supersonic aircraft are anticipated to have faster takeoff and landing speeds, leading to individual noise events with shorter durations and exposure times, than for subsonic aircraft. There are no published studies in recent years to obtain human subjective data that could lead to insights for the supersonic aircraft noise community to assess in advance the typical annoyance impacts or health impacts such as sleep disturbance, onset of cardiovascular disease, or detrimental effects on children's learning. For sonic boom noise, some sleep disturbance studies were planned by the EU's recent RUMBLE consortium project (https://rumble-project.eu), but for various reasons, no sleep studies were completed. It is hoped that some of the RUMBLE researchers will be able to move forward with those sleep disturbance studies in the future.

Current Status: Ozone and Climate Impacts

A number of companies throughout the world, especially in the United States, Europe, Japan and Russia, are currently considering the development of new supersonic commercial aircraft. These aircraft cover a range of potential platform sizes, from business jets to mid-size aircraft (50-80 passengers) to large aircraft (several hundred passengers). The designs all use jet fuel, either conventional and/or biofuel-based versions, and the concerns about the environmental impacts of supersonic flights remain focused largely on the emissions of carbon dioxide, nitrogen oxides, and water vapor, as well as the aircraft takeoff and flight noise (including sonic boom). There are other emissions and feedbacks that need to also be considered; attention needs to be given to the direct and chemical production of particles (including both inorganic and organic aerosols) and feedback effects on the stratospheric concentrations of methane (that result primarily from the chemical interactions that follow the NO_x and H_2O emissions).

Since the earlier studies, computers have become much more powerful, and the observations of stratospheric processes and composition have greatly advanced. As a result, 3D climate-chemistry models have matured and are now the workhorses for atmospheric studies, including those involving tropospheric and stratospheric processes. Because of their scientific limitations, 1-D and 2-D models are seldom used any longer.

Along with the advances in observations and laboratory studies, there has been a substantial increase in the understanding of tropospheric and stratospheric physical and chemical processes over the last few decades; improved understanding of the processes affecting water vapor in this region; and improved microphysics parameterizations affecting the distributions of particles. Chemistry-climate models, like the Whole Atmosphere Community Climate Model with interactive chemistry (WACCM; Marsh et al. 2013; Zhang et al., 2021a,b) and chemistry-transport models like the GEOS-Chem model (Eastham et al. 2014, 2021) far better represent tropospheric and stratospheric processes than the earlier models. They now include complete representations of tropospheric and stratospheric chemical and physical processes, within the limits of any remaining uncertainties in the existing understanding of these processes, and often extend to much higher altitudes beyond the stratosphere. Some of these new models (e.g., the WACCM model) can also represent the complexity of the quasi-biennial oscillation (QBO), a transport feature of the stratosphere that is important to representing the year-to-year variability in the stratospheric ozone distribution. As a result, there has been a substantial improvement in the ability of these models to evaluate the potential effects of supersonic aircraft on ozone and climate, and they are also being used in studies to evaluate potential environmental effects from even higher-flying hypersonic aircraft (Kinnison et al., 2020).

Scientists are now undertaking new studies with state-of-the-art models to understand the potential effects on stratospheric ozone and climate associated with SST fleets. Although these impacts are potentially large enough to be of concern, these fleets are likely, for current projections of the type and number of aircraft, to result less than one percent change in total ozone at most and much smaller effects on climate than projected from other human related emissions. The results from the new studies have been presented in several peer-reviewed journal papers. The evaluations of new designs will require much more study. Below, the few existing peer reviewed studies available at this time are summarized.

Towards establishing a baseline relative to the prior studies, Zhang et al. (2021a) used the WACCM model to compare new analyses with results from the 1999 aviation assessments, using the same aviation emissions as used in the 1999 assessments. The model background chemistry and dynamics are also based on a 2015 atmosphere to correspond to those assessments. As seen in Figure 1, the resulting effects on stratospheric ozone from the assumed fleet of 500 HSCTs flying at 17-20 km (corresponding to a fleet of Mach 2.4 aircraft and fuel burn of 47.2 Tg/yr) are similar to those from many of the models in the prior assessment, although with a stronger ozone sensitivity to NO_x emissions. They show that the resulting ozone effects largely depend on the NO_x and H_2O emission levels and the net changes in stratospheric ozone are determined by the chemical interactions between different ozone production and depletion cycles. Figure 1 also shows that emissions in the lower stratosphere (cruise altitude at 17-20 km) from this fleet of HSCTs result in larger ozone decreases as the emission index for NO_x increases. The changes in total ozone are small, ranging from a decrease in total ozone of 0.1% (due to H_2O emissions only) to slightly more than 0.6% (for $EINO_X$ = 15 g/kg fuel). In the Zhang et al. (2021a) study, ozone increases in the lower stratosphere from the NO_x and H_2O emissions and decreases in the upper stratosphere, with zero being crossed at about 21 km.

The analyses of stratospheric-adjusted radiative forcing (Figure 2) in Zhang et al. (2021a) also confirm that stratospheric H_2O emissions are an important factor in potential climate impacts from the fleet of supersonic aircraft emissions, reaching about 41 mW m^{-2} at steady state. RF effects from changes in ozone depend strongly on the level of NOx emissions with an assumed $EINO_X$ of 15 g/kg fuel giving about 19 mW m^{-2}. The total of 60 mW m^{-2} for this fleet would result roughly in a steady-state temperature change of 0.01 - 0.02°C. This change is based on using the IPCC (2021) evaluation for the equilibrium climate sensitivity for a doubling of the CO_2 concentration, which results in a RF of 3.7 Wm^{-2} and a likely change in globally-averaged temperature of 2-4°C.

In contrast, the radiative forcing for CO_2 from the assumed 500 HSCT fleet would have a RF (based on 10-years of emissions) of 4.0 mW m^{-2} (Zhang et al. 2021a). This value is much smaller than the current changes in RF for CO_2 globally from all human related sources since 1979 of 1.05 W m^{-2} (NOAA ESRL website, February 2021). This relatively small RF for CO_2 from supersonic aircraft, despite the larger CO_2 emission per passenger km, is because of the short integration time. The CO_2 RF for a supersonic fleet would also be much smaller if biofuels are largely used.

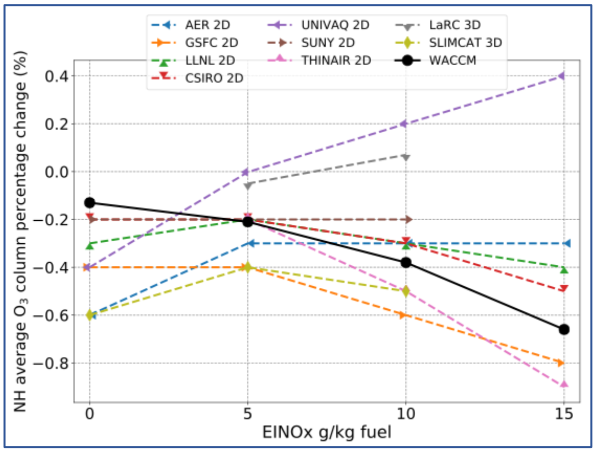

Figure 1. Northern Hemisphere total ozone column change (%) at steady state as a function of $EINO_x$ for a fleet size of 500 supersonic aircraft operating at cruise altitudes of 17-20 km (fuel burn of 47.2 Tg/yr). Results from IPCC (1999) models are shown with dashed lines while the WACCM results from Zhang et al. (2021a) are shown with the solid black line. Other 2-D and 3-D model results are from IPCC 1999). Note that both NO_x and H_2O emissions are included so the ozone column value for zero NO_x emissions represents the effects of H_2O emissions alone.

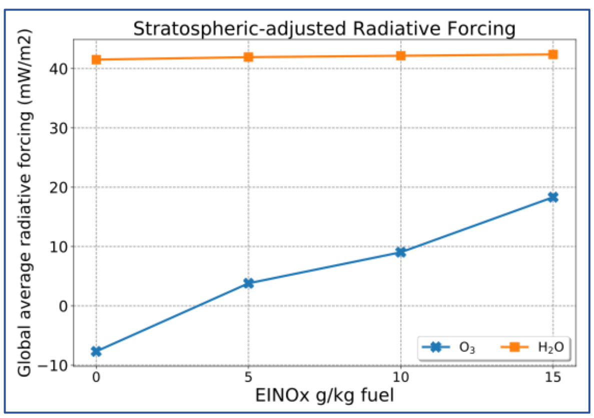

Figure 2. Annually-averaged change in stratospheric-adjusted radiative forcing (mW m^{-2}) from changes in H_2O and O_3 in steady state as a function of $EINO_x$ for a fleet size of 500 supersonic aircraft operating at cruise altitudes of 17-20 km. From Zhang et al. (2021a).

Zhang et al. (2021b) have conducted a series of sensitivity experiments of possible future cruise altitudes (that correspond to a range of speed or Mach number) to evaluate the potential atmospheric response for a fleet of supersonic aircraft that are assumed to be fully operational in 2050. For this sensitivity study, the emissions assumed are the same as in Zhang at al. (2021a) while systematically varying the cruise altitude, except that the study assumes an $EINO_x$ of 20 g/kg fuel. The sensitivity analyses are done for a range of different altitudes from 13 to 23 km for 8 different cases assuming that the fleet emissions are spread over 2 km. The background chemistry and dynamics in the model are based on those for a projected 2050 atmosphere, akin to when there could be a mature fleet of these aircraft. These studies show that the impact on stratospheric ozone from supersonic transport varies strongly with cruise altitude. The total column ozone change is shown to have a small increase for emissions from 13 to 17 km, with the ozone impact not very dependent on cruise altitude. At the emission altitude, NO_x not only destroys ozone directly, but also can interfere with reactions of other gases that destroy ozone; as a result, NO_x emissions can cause a net increase or decrease in ozone. For emission altitudes greater than 17 km, the total column ozone impact of NO_x transitions from production to depletion as the NO_x catalytic cycle becomes a dominant effect, and the resulting column ozone depletion strongly depends on the cruise altitude. Thus, these results (Figure 3) indicate that Mach number is an important criterion for determining the resulting changes in stratospheric ozone for a supersonic aircraft fleet.

In Zhang et al. (2021b), the impact of SST emissions on stratospheric ozone and water vapor also show a strong dependence on emission altitude (Figure 4), with stronger positive forcing for water vapor and stronger negative forcing for ozone associated with higher cruise altitudes. The ozone increase in the lower stratosphere dominates for SST emissions below 20 km, while ozone destruction dominates in producing a negative forcing for cruise altitudes above 20 km. The increase in stratospheric water vapor from a SST fleet becomes a larger fraction of background values as the cruise altitudes increases, which causes the radiative forcing from water vapor emissions to increase with altitude.

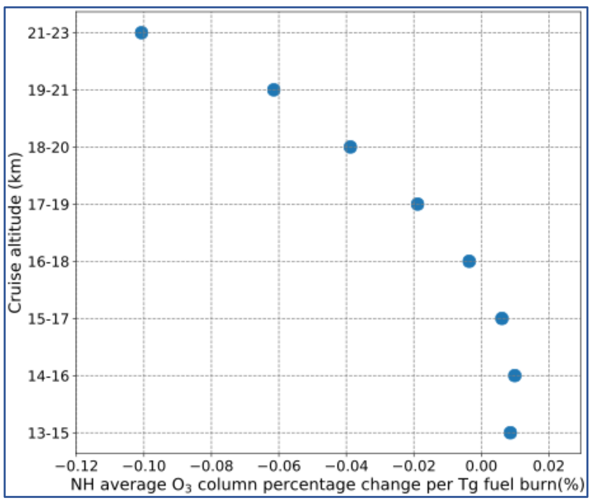

Figure 3. Northern Hemisphere total column ozone change (%) per Tg of fuel burn at steady state as a function of cruise altitudes for a fleet of 500 SSTs (fuel burn of 47.2 Tg/yr). From Zhang et al. (2021b).

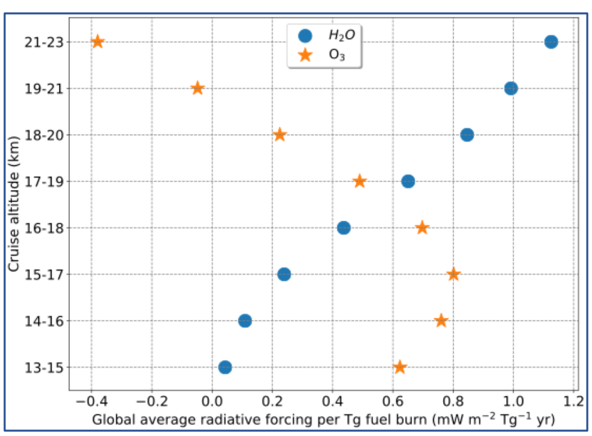

Figure 4. Annually and globally averaged change in stratospheric-adjusted radiative forcing per Tg of fuel burn (mW m^{-2} Tg^{-1} yr) at steady state as a function of cruise altitudes for the changes in H_2O and O_3 from the emissions of 500 aircraft. From Zhang et al. (2021b).

The Zhang et al. (2021a,b) studies do not consider emissions of sulphur or soot, and thus assume that these emissions are insufficient to be relevant to effects on ozone or climate. This assumption corresponds to the reductions in sulphur and soot expected from potential use of Sustainable Aviation Fuel (SAF) (see Lobo et al. 2021 and papers referenced therein). However, SAFs are not yet in general use and its emissions are not fully evaluated. So it also makes sense to consider conventional fuels that do contain sulphur and that can emit significant levels of soot.

Eastham et al. (2021)[1] assess the environmental impacts of a near-future supersonic aircraft fleet with conventional, sulphur-bearing jet fuel and current-generation engine technology to understand the environmental impacts of near-future supersonic fleets. Using vehicle performance modeling, market demand projection and global atmospheric chemistry-transport modeling, they examine potential impacts from fleets for two specific designs, one for Mach 1.6 (15-17 km cruise altitude) and one for Mach 2.2 (18-20 km cruise altitude). The market projections and experimental design used for Eastham et al., along with a detailed evaluation of impacts for a wider range of aircraft, are described in the Speth et al. (2021) report done for NASA. The Speth et al. report develops emissions inventories for commercial supersonic air services for 2035 using a scenario-based approach. The scenarios examine variability and uncertainty in outcomes regarding aircraft specification, regulatory scenarios, and market adoption of commercial supersonic services. For the aircraft specification scenarios, a set of notional aircraft are defined spanning the types of aircraft currently being developed with 3,500 to 6,000 nautical mile (nmi) range, 20 to 100 passengers, and cruise speeds of Mach 1.4 to 2.2. The SST45-1.6-60 fleet corresponds to an aircraft with a range of 4500 nmi, a cruise speed of Mach 1.6, and 60 passenger seats. The SST35-2.2-60 fleet correspond to an aircraft with a range of 3500 nmi, a cruise speed of Mach 2.2, and 60 seats. NO_x emissions are assumed to be 8.8 g/kg fuel for the Mach 1.6 aircraft and 19 g/kg fuel for the Mach 2.2 aircraft. Based on the projected market demand, the estimated fleet sizes in these analyses are 440-470 (SST45-1.6-60) and 160-170 (SST35-2.2-60) (see Speth et al., Table 9).

The extended version of the GEOS-Chem model (4°×5° (latitude × longitude) and with 72 non-uniform vertical layers) is used in their study along with the aerosol treatment based on the WACCM4 model. The dynamics in the model is based on reanalysis data for current conditions while the chemistry and background composition have been updated to 2035 based on the IPCC RCP4.5 scenario. Eastham et al. find that their missions from the SST 1.6 and SST 2.2 fleets result in the global mean ozone column changing by -0.045% and -0.77% respectively. As was found in the Zhang et al. studies, the SST 1.6 and SST 2.2 fleet emissions cause a combination of increased ozone at lower altitudes and decreased ozone at higher altitudes.

Figure 5 compares the Eastham et al. analyses for changes in global ozone with results from prior published results on a total NO_x emitted basis. Their results show the effects of interannual variability in the background atmosphere as a vertical line on the open symbol. There is no clear agreement regarding the effect of increasing NO_x emissions indices, indicated for individual studies in Figure 5 by dashed lines (however, many of those studies are from quite old modeling results that are likely not representative of current models). All studies find increasing impact with increased cruise altitudes.

Eastham et al. found a net non-CO_2, non-contrail radiative forcing (climate impact) of -3.3 mW/m2, varying between -2.8 and -3.8 mW/m2 year to year. The use of zero-sulphur fuel would halve net ozone depletion at the cost of increasing mean radiative forcing to +2.9 mW/m2 due to the loss of a cooling effect from sulfate aerosols. A smaller fleet of Mach 2.2 aircraft results in a radiative forcing of uncertain sign,

[1] Eastham, S. D., T. Fritz, I. Sanz-Morère, P. Prashanth, F. Allroggen, R. G. Prinn, R. L. Speth, and S. R.H. Barrett, 2021: Atmospheric impacts of a near-future supersonic aircraft fleet. *Environmental Science: Atmospheres*, submitted.

averaging +1.5 mW/m2 but varying between -2.2 and +4.2 mW/m2 year to year. Figure 6 shows the net non-CO_2, non-contrail radiative forcing resulting from each fleet's emissions, broken down by component. Each bar shows the 14-year average value, while error bars indicate the maximum and minimum annual mean RF over the same period. Results from simulations using a fixed methane boundary condition are shown in dark colors, while results from simulations in which methane is allowed to evolve freely (i.e., including methane feedbacks) are shown in paler colors. For SST 1.6, Eastham et al. also show results for the zero-sulphur case (ULS), which includes methane feedbacks. Unlike previous studies, they find that the largest positive RF component is due to changes in ozone rather than water vapor.

While finding impacts of supersonic aircraft NO_x that are generally consistent with prior work, the Eastham et al. results show that assessments of near-future supersonic aviation should also consider the potential effects of fuel sulphur and black carbon from the fuel used, and that the net environmental impacts will be a trade-off between competing environmental concerns.

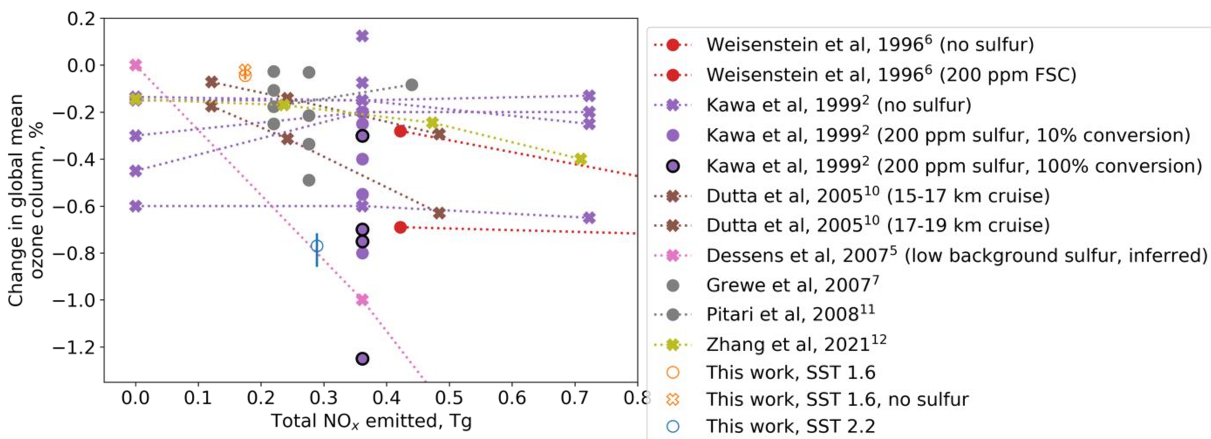

Figure 5. Change in global mean ozone column as a function of total supersonic fleet NOx emitted annually from Eastham et al. (2021) (this work) compared with prior published studies with emissions from 17-20 km (except for Dutta et al., 2005). Estimates in which sulfur emissions from supersonic aircraft were simulated are shown with circles, while those showing crosses include only NO_x and H_2O. If a study performed multiple simulations for identical fleets with different NO_x emissions indices, the estimates are connected by a dotted or dashed line. One color is used per study, apart from for this work where two are used to delineate the two aircraft. Results from this study include a vertical bar indicating the range of interannual variability. Numbers on the references are the numbering system for references from the Eastham et al. paper. Note that Zhang et al. (2021) in the figure is the Zhang et al. (2021a) paper. From Eastham et al. (2021).

In Speth et al. (2021), an adjoint modeling approach was also used to calculate the expected change in global column ozone at steady state that would result from an increase in aviation emissions at any location up to 25 km in the Northern Hemisphere. Their results suggest that cruise altitudes of around 14-15 km would result in a net zero change in global mean ozone column. While their crossover is lower than the Zhang et al. (2021b) results, the emissions scenarios assumed are also very different. In general, the sign and magnitude of the changes in ozone depend on not only the altitude of the emissions, but also the latitude and sulphur content of the fuel.

In the above studies, the focus has been on the non-CO_2 emissions. In general, it is expected that the RF from non-CO_2 emissions will be larger than that from CO_2, with the total RF from CO_2 depending on the lifespan and size of the fleet as well as the source of fuel. However, the proposed SSTs under consideration are likely to be much less fuel efficient than existing commercial aircraft, by factors of 3-9 on a per passenger-km basis, depending on the configurations being compared (Kharina et al. 2018; Weit et al. 2020; Wen et al. 2020). The use of sustainable aviation fuel based on full consideration of biofuel development would likely greatly reduce the net RF from CO_2.

Future analyses of proposed aircraft designs and associated fleets will need to compare the results from different atmospheric chemistry-climate models for the resulting effects on ozone and climate so that a consensus is arrived at about the environmental impacts. These also need to be done relative to the same background atmosphere for the likely time period when the fleet SST is fully in place. It may also be important to examine time dependence in the development of that fleet in such analyses because the background atmosphere will be changing from, for example, decreasing levels of chlorine and bromine, and potentially increasing levels of NO_x and HO_x from increasing background amounts of N_2O and CH_4.

More sensitivity studies of new proposed SST aircraft fleets are also needed. In general, the changes in atmospheric chemistry and climate from SST fleet emissions are nonlinear and depend heavily on the specific emissions assumptions. For example, emission effects from flights in the tropics will be significantly different than the effects on ozone and climate from flights at the same altitude in polar regions. As a result, effects on atmospheric composition from SST emissions, including effects on stratospheric ozone and on radiative forcing, depend on the specific assumptions about emissions characteristics and aircraft movements assumed for the supersonic aircraft fleet. To fully understand these effects and the resulting implications, it is important to provide these findings as the change in ozone and climate forcing for the global movements of a fleet a given SST design. Providing results in other units such as fleet fuel burn or total passenger kms can support intercomparison, but must be used with care alongside assessment of total impact. Sensitivity studies may ultimately show that other units are acceptable under some fleet assumptions.

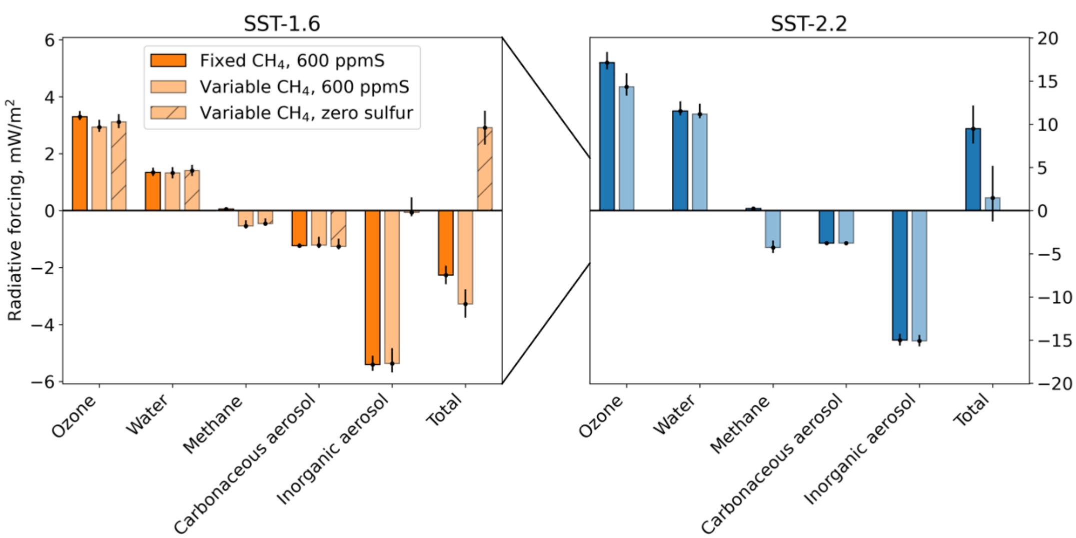

Figure 6. Radiative forcing (RF) due to the two supersonic fleets. Left: RF due to the SST 1.6 fleet emissions. Right: RF due to the SST 2.2 fleet emissions. Dark colors show data from simulations using a fixed methane boundary condition, while paler colors show results from simulations with variable surface methane. Error

bars shown the range of annual mean values over the 14 years used to determine the average value. Hatched bars show data from a simulation with zero fuel sulphur (SST 1.6 only). From Eastham et al. (2021).

Current Status: Noise Impacts

The noise impacts of SST aircraft are discussed in two distinct sections. The first addresses the unique en route noise known as sonic boom and, the second addresses the SST landing and takeoff (LTO) noise.

In 2021 the knowledge base related to sonic boom noise is essentially unchanged since the release of the 2019 CAEP Environmental Report. Hence the section on sonic boom noise from that white paper will be repeated here, without change. The permission of the authors (A. Loubeau of NASA and V. Sparrow of Penn State) to reproduce these next paragraphs has been secured. Almost all ongoing noise research regarding supersonic aircraft is focused on certification of those aircraft, not on the impacts on the public. Once an SST aircraft fleet is operational, new acceptability data will come quickly.

Introduction to Sonic booms

Sonic booms are the unique sounds produced by supersonic aircraft. This section summarizes many of the properties and impacts of sonic booms, as we know them today.

Conventional sonic booms are widely considered to be loud, and this forms the basis of current regulations in many countries that prohibit supersonic overland flight. However, new research has enabled aeronautical engineers the tools to develop quiet “low-boom” aircraft designs that may be available in 5 to 10 years. Hence, sonic boom research needs to clearly distinguish whether the sonic booms are the conventional N-wave sounds, so called because of their letter N pressure versus time shape, or the new low-booms which are considerably smoothed. The low-booms, or “sonic thumps”, can be as much as 35 dB quieter than conventional booms.

Human response studies

Studies have shown that sonic booms can be reproduced quite accurately in the laboratory, and this makes it possible to perform subjective experiments under controlled conditions. Although no supersonic aircraft has produced a low-boom signature yet, a similar surrogate sound can be created using a special aircraft dive manoeuver. This makes it possible to conduct tests with real aircraft outdoors for either N-waves or low-booms, complementing the laboratory tests.

A number of subjective tests have been conducted. One trend seen in studies from both the U.S. and Japan is that annoyance to sonic boom noise is greater indoors compared to outdoors. The findings show that indoor annoyance can be estimated based on the outdoor sonic boom exposure. There has been recent work to establish that both rattle and vibration contribute to indoor annoyance of sonic booms. One interesting point is that although conventional N-waves can be accompanied by a startle response, it turns out that low-booms are of low enough amplitude that they don’t induce a consistent physiological startle response.

There has been substantial work in recent years to establish metrics to assess sonic boom noise. Out of a list of 70 possible metrics, a group of 6 metrics has been identified for the purposes of use in certification standards and in developing dose-response curves for future community response studies. Clearly the low-booms are much quieter than the conventional N-wave booms, but additional community studies with a low-boom aircraft need to be conducted to assess public response.

Non-technical aspects of public acceptability for sonic boom

An additional aspect that should be considered for sonic booms includes the non-technical aspects of acceptability. The CAEP Steering Group specifically requested that ISG look into this topic. A preliminary discussion has revealed a strong resemblance to the non-acoustical factors of subsonic aircraft noise, previously mentioned in Section 2 “Community Noise Annoyance” of the 2019 CAEP Environmental Report. There are currently no peer-reviewed studies on the topic of non-acoustical factors for sonic boom noise, but it seems plausible that the knowledge of subsonic aircraft non-acoustical factors could be extended for application to sonic boom noise non-technical aspects.

Impacts of noise on animals

Recently there has been renewed interest regarding the impacts of sonic boom noise on animals. Fortunately, there is an extensive literature extending from before the days of Concorde to recent years, mostly for conventional N-wave aircraft.

There have been substantial studies for both livestock and other domesticated animals, and detailed studies of some wildlife species. For conventional sonic booms the animals usually show no reactions or minimal reactions, although occasionally they may startle just as humans do. There are no reported problems of developing fish eggs or of avian eggs due to sonic boom exposures. NASA conducted a number of studies in the late 1990s and early 2000s to assess the impact of overwater sonic booms on marine mammals. There is a good bit of knowledge as to how much sonic boom noise transitions from air into water, and fortunately, very little of the sound gets into the water. For the California sea lion, elephant seals, and harbor seals, careful lab experiments showed no temporary hearing shifts in those species.

In 1997 and 1998 a study of a colony of seals exposed to Concorde booms on a regular basis showed that the booms didn’t substantially affect the breeding behavior of gray or harbor seals. It instead seems that these animals substantially habituated to hearing these N-wave sonic booms on a routine basis.

Most of what is known about noise impacts on animals comes from the literature of the effects of subsonic aircraft and other anthropogenic noise sources, not sonic booms, on animals. It is well known that human activities can interfere with animal communication, for example.

There have not been many specific studies on the effects of sonic boom noise on animals in recent years. Some species with good low-frequency hearing, such as elephants, have never been evaluated regarding sonic boom noise. But it makes sense that if the already tested animals were not negatively affected by sonic boom noise from conventional N-waves, that they will likely not be affected by the proposed low-booms of the future. Long-term effects of sonic boom exposure on animals seem unlikely.

Landing and Takeoff noise

As has already been stated, with the absence of supersonic aircraft since the retirement of Concorde, there is no scientific literature on human reactions to landing and takeoff noise (LTO) from supersonic aircraft. In order to operate at supersonic speeds, aircraft will need to be designed to have sufficient cruise thrust and jet exhaust velocity. This pushes the aircraft designer towards the use of lower bypass-ratio engines. The evolution of subsonic aircraft to use higher bypass ratio engines has significantly reduced jet noise and overall LTO noise.

In the absence of supersonic aircraft and associated scientific literature on reaction to supersonic aircraft LTO noise, we can broadly surmise that supersonic aircraft LTO noise could sound quite similar to that from subsonic aircraft with lower bypass-ratio engines, since the sound source will likely be jet-noise dominated and thus broadband in nature. Thus, the sound character will not be distinctly different. Supersonic aircraft would be anticipated to have faster takeoff and landing speeds, leading to individual noise events with shorter durations and exposure times, than for subsonic aircraft. Thus, apart from noise level differences, there would not be anticipated changes to human reaction, i.e., annoyance and sleep disturbance, due to the sound character and/or duration of the noise events.

Research Needs

The impacts from a fleet of supersonic aircraft on stratospheric composition are primarily of concern because of resulting absolute changes in ozone and changes in the radiative forcing on climate. Along with the emissions of long-lived carbon dioxide, the radiative forcing on climate in turn depends on the spatial changes in concentrations of water vapor, ozone, particles (both inorganic and organic aerosols) and indirect effects on methane (primarily due to feedbacks from the NO_x and H_2O emissions, and their effects on ozone).

The emissions from the fleet of aircraft depends especially on the fleet size, fleet flight characteristics, the speed, the cruise altitude, the fleet fuel use at cruise, the NO_x emission index, assumptions about sulphur in the fuel, and assumptions about soot emissions. The distribution of emissions may depend to a lesser extent on the geographical distribution because many city pairs assumed will be similar for SST commercial aircraft, although, as mentioned earlier, the ratio of flights in the tropics to the extratropics is important. The fleet fuel use primarily depends directly on the fleet size, the flight hours at cruise per day, and fuel burn rate at cruise.

The aircraft design (speed, size, technology level, range, etc.) all factor into the fuel efficiency. The geographical distribution depends on the perceived market (business jet, small business class commercial aircraft, or mixed class commercial) of the aircraft. The market for supersonic aircraft values long range but this is balanced by the increased fuel use rates at higher speeds and the limited volume for fuel tanks. Supersonic market analyses typically reveal a demand for aircraft with greater range than engineers may be able to achieve. While the published studies provide valuable insights on the important factors, specific supersonic concepts will have their own combination of these factors and hence we should be careful not to extrapolate model results too generally; we will need to put more focus into examining the actual aircraft designs and aircraft utilizations once they become available.

The vision here is that the incorporation of sustainability in aircraft design might help in the resumption of supersonic transportation (Russel et al., 2020). At this point, there are very few studies of the potential environmental impacts from a proposed fleet of newly designed supersonic aircraft. As more designs and resulting noise characterizations and emission inventories for a fleet of these aircraft are developed and become available, analyses will be needed for their potential noise and other environmental impacts, including impacts on stratospheric ozone and on climate radiative forcing. There are a number of criteria that will need to be considered in these analyses. These criteria include:

- Aircraft design (Mach speed, intended use, etc.) and corresponding cruise altitude.
- Aircraft range capability and possibility of supersonic flights over land in addition to oceans.
- Cruise fuel burn rate, noise and emissions for the aircraft and its specific engines.
- Projected number of aircraft in daily and annual use for an economically viable fleet and date of operational use.
- Specific choices of city pairs and variations with latitude where emissions occur, and the number of flights for each city pair as a function of time and possibly time of day (these are factors requiring further study through sensitivity studies).
- Sulphur content of the fuel and the associated effects from sulphur emissions and the dependence of those effects on the background atmosphere.

- Resulting derived global inventory of fuel burn and emissions of CO_2, NO_x, H_2O, sulphur, and particles.
- Potential effects from changes in composition occurring in the aircraft exhaust plume.
- Specifications of the background atmosphere used in the modeling studies.

Regarding noise concerns, much progress has been made to model and mitigate the effect of sonic booms from supersonic flight. Ongoing research to assess the impact on the public indicate that future low-boom supersonic aircraft designs will create quieter sonic 'thumps' that are much less annoying than conventional sonic booms. Upcoming NASA community tests with a low-boom demonstrator aircraft will collect important data relating to noise exposure and resulting public reactions.

There are several recent and ongoing projects sponsored by governments around the world where analyses are being done related to potential environmental impacts from supersonic aircraft. Examples of these programs are summarized below:

- U.S. FAA ASCENT Program Research
- NASA Aeronautics (https://www.nasa.gov/subject/7566/supersonic-flight/)
- RUMBLE (RegUlation and norM for low sonic Boom Levels), EU H2020, 2017-2020: A collaboration of European and Russian organizations committed to the production of scientific evidence for supporting the new international regulations regarding the low-level sonic booms.
- SENECA, ([LTO] noiSe and EmissioNs of the supErsoniC Aircraft), EU H2020, 2021-2024: A collaboration of academic and industrial aerospace entities from Europe aiming to focus on noise and emissions in the vicinity of airports and the global climate impact of supersonic aircraft.
- MORE&LESS, MDO and REgulations for Low-boom and Environmentally Sustainable Supersonic aviation, EU H2020, 2021-2024: A collaboration of European and US partners determined to improve the understanding of sonic boom, jet noise and pollutant emissions that will lead to a holistic assessment of the environmental impact of supersonic aircraft at local, regional and global levels.

Various companies are also considering the design and development of supersonic aircraft that will need to be evaluated as they get closer to fruition. As the aircraft industry gets closer to considering the full development of real aircraft, coordinated efforts are needed across the world to examine and better understand the potential environmental impacts from fleets of these aircraft, including potential noise pollution and effects on air quality, on stratospheric ozone and on climate.

References

Australian Academy of Sciences, 1972: *Atmospheric Effects of Supersonic Aircraft*. Report Number 15, Canberra.

Carioscia, S. A., J. W. Locke, I. D. Boyd, M. J. Lewis, and R. P. Hallion, 2019: *Commercial Development of Civilian Supersonic Aircraft*. IDA Document D-10845, IDA Science & Technology Policy Institute. https://www.ida.org/-/media/feature/publications/c/co/commercial-development-of-civilian-supersonic-aircraft/d-10845.ashx.

Committee on the Meteorological Effects of Stratospheric Aircraft (COMESA), 1976: *The Report of the Committee on Meteorological Effects of Stratospheric Aircraft. Vol. 1 and 2*. United Kingdom Meteorological Office, Bracknell.

Comité d'Études sur les Conséquences des Vols Stratosphèrique (COVOS), 1976: *Rapport finale, COVOS, Activités 1972-1976*. Boulogne: Société Météorologique de France.

Crutzen, P. J., 1970: The influence of nitrogen oxides on the atmospheric ozone content. *Quarterly J. Royal Met. Soc*., 96, 320-325.

Dessens, O., H. L. Rogers, and J. A. Pyle, 2007: A change in the calculated impact of supersonic aircraft NO_x emissions on the atmosphere. *The Aeronautical Journal*, 111(1119), 311–314.

Dutta, M., K. O. Patten and D. J. Wuebbles, 2005: *Parametric Analyses of Potential Effects on Upper Tropospheric/Lower Stratospheric Ozone Chemistry by a Future Fleet of High Speed Civil Transport (HSCT) Type Aircraft*. National Aeronautics and Space Administration report NASA/CR—2005-213646.

Eastham, S. D., D. K. Weisenstein, and S. R. H. Barrett, 2014: Development and evaluation of the unified tropospheric–stratospheric chemistry extension (UCX) for the global chemistry-transport model GEOS-Chem. *Atmospheric Environment*, 89, 52-63.

Fritz, T. M., S. D. Eastham, R. L. Speth, and S. R. H. Barrett, 2020: The role of plume-scale processes in long-term impacts of aircraft emissions. *Atmos. Chem. Phys*., 20, 5697–5727, https://doi.org/10.5194/acp-20-5697-2020.

Grewe, V., A. Stenke, M. Ponater, R. Sausen, G. Pitari, D. Iachetti, H. Rogers, O. Dessens, J. Pyle, I. S. A. Isaksen, L. Gulstad, O. A.Søvde, C. Marizy, and E. Pascuillo, 2007: Climate impact of supersonic air traffic: an approach to optimize a potential future supersonic fleet – results from the EU-project SCENIC. *Atmos. Chem. Phys.*, 7, 5129–5145.

Grewe, V., and A. Stenke, 2008: AirClim: an efficient tool for climate evaluation of aircraft technology. *Atmospheric Chemistry and Physics*, *8*(16), 4621-4639.

Grewe, V., M. Plohr, G. Cerino, M. Di Muzio, Y. Deremaux, M. Galerneau, ... and V. D. Korovkin, 2010a: Estimates of the climate impact of future small-scale supersonic transport aircraft–results from the HISAC EU-project. *The Aeronautical Journal*, 114, 199-206.

Grewe, V., A. Stenke, M. Plohr, and V. D. Korovkin, 2010b: Climate functions for the use in multi-disciplinary optimisation in the pre-design of supersonic business jet. *The Aeronautical Journal*, *114*(1154), 259-269.

Grobecker, A. J., S. C. Coroniti and R. H. Cannon, Jr., 1974: *Report of Findings: The Effects of Stratospheric Pollution by Aircraft*. Climatic Impact Assessment Program Report DOT-TSC-75-50, U.S. Department of Transportation, Washington, D.C., December 1974.

Hardeman, A. B., and L. Q. Maurice, 2021: Sustainability: Key to enable next generation supersonic passenger flight. *IOP Conf. Ser.: Mater. Sci. Eng., 1024,* 012053. https://iopscience.iop.org/article/10.1088/1757-899X/1024/1/012053/pdf.

Harrison, H., 1970: Stratospheric ozone with added water vapor: influence of high-altitude aircraft. *Science*, 170, 734-736.

Hunt, B. G., 1966: Photochemistry of ozone in a moist atmosphere. *J. Geophys. Res*., 71, pp. 1385-1398.

IPCC, 1999: *Aviation and the global atmosphere*. Penner, J. E., Lister, D. H., Griggs, D. J., Dokken, D. J., & McFarland, M. (Eds). Cambridge University Press, Cambridge, UK, 373 pp.

IPCC,2021: *Climate Change 2021: The Physical Science Basis.* Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland, 3949pp

Johnston, H., 1971: Reduction of stratospheric ozone by nitrogen oxide catalysts from SST exhaust. *Science*, 173, 517-522.

Johnston, H. S., D. E. Kinnison, and D. J. Wuebbles, 1989: Nitrogen oxides from high-altitude aircraft: An update of potential effects on ozone. *Journal of Geophysical Research: Atmospheres*, 94(D13), 16351-16363.

Kawa, S. R., J. G. Anderson, S. L. Baughcum, C. A. Brock, W. H. Brune, R. C. Cohen, D. E. Kinnison, P. A. Newman, J. M. Rodriguez, R. S. Stolarski, D. Waugh and S. C. Wofsy, 1999: *Assessment of the effects*

of high-speed aircraft in the stratosphere: 1998. National Aeronautics and Space Administration report. NASA/TMM1999-209237.
Kharina, A., T. MacDonald, and D. Rutherford, 2018: *Environmental performance of emerging supersonic transport aircraft*. International Council on Clean Transportation, Washington, DC.
Kinnison, D., G. P. Brasseur, S. L. Baughcum, J. Zhang, and D. Wuebbles, 2020: The impact on the ozone layer of a potential fleet of civil hypersonic aircraft. *Earth's Future*, 8, e2020EF001626.
Liebhardt, B., and K. Lütjens, 2011: *An Analysis of the Market Environment for Supersonic Business Jets*. https://core.ac.uk/download/pdf/11150642.pdf.
Lobo, P., D. Delhaye, D.Lee, E. Fleuti, P.Madden, J. Zelina, A. Oldani, and N. Brown, 2021: CAEP/12-ISG Task I.04: Fuel Composition Effects on nvPM emissions. International Civil Aviation Organization (ICAO), Montreal.
Lundberg, B. K. O., 1965: The supersonic adventure. *Bulletin of the Atomic Scientists*, pp. 29-33, February 1965.
Marsh, D. R., M. J. Mills, D. E. Kinnison, J. F. Lamarque, N. Calvo, and L. M. Polvani, 2013: Climate change from 1850 to 2005 simulated in CESM1 (WACCM). *Journal of climate*, 26(19), 7372-7391.
National Research Council, 1975: *Environmental Impact of Stratospheric Flight: Biological and Climatic Effects of Aircraft Emissions in the Stratosphere*. Washington, DC: The National Academies Press, 376 pp; DOI 10.17226/20101.
Pitari, G., D. Iachetti, E. Mancini, V. Montanaro, N. D. Luca, C. Marizy, O. Dessens, H. Rogers, J. Pyle, V. Grewe, A. Stenke and O. A. Søvde, 2008: Radiative forcing from particle emissions by future supersonic aircraft. *Atmospheric Chemistry and Physics*, *8*(14), 4069-4084.
Søvde, O. A., M. Gauss, I. S. A. Isaksen, G. Pitari, C. Marizy, 2007: Aircraft pollution – a futuristic view. *Atmos. Chem. Phys.*, 7, 3621–3632.
Sparrow, V. W., Gjestland, T., Guski, R., … and Cointin, R. 2019a: State of the Science 2019: Aviation Noise Impacts, Appendix C to WP/52 to CAEP/11, February 2019.
Sparrow, V. W., Gjestland, T., Guski, R., … and Cointin, R. 2019b: State of the Science 2019: Aviation Noise Impacts, Chapter 2 of 2019 ICAO Environmental Report.
Speth, R. L., S. D. Eastham, T. M. Fritz, I. Sanz-Mor`ere, A. Agarwal, P. Prashanth, F. Allroggen, and S. R. H. Barrett, 2021: *Global Environmental Impact of Supersonic Cruise Aircraft in the Stratosphere*. NASA/CR-20205009400, NASA Glenn Research Center, Cleveland, Ohio, February 2021, https://ntrs.nasa.gov/api/citations/20205009400/downloads/CR-20205009400.pdf.
Russel, R., L. Maurice, and R. Devine, 2020: Supersonic flight and sustainability: a new horizon. *The Bridge*, 50, 28–33. https://www.nae.edu/234398/Summer-Bridge-Issue-on-Aeronautics.
Weisenstein, D. K. , M. K. W. Ko, N.-D. Sze and J. M. Rodriguez, 1996: Potential impact of SO2 emissions from stratospheric aircraft on ozone, *Geophys. Res. Lett*., 23, 161–164.
Weit, C., J. Wen, A. Anand, M. Mayakonda, T. Zaidi, and D. Mavris, 2020: A Methodology for Supersonic Commercial Market Estimation and Environmental Impact Evaluation (Part I). Proceedings of the Aerospace Europe Conference, Feb. 25-28, 2020.
Wen, J., C. Weit, A. Anand, M. Mayakonda, T. Zaidi, and D. Mavris, 2020: A Methodology for Supersonic Commercial Market Estimation and Environmental Impact Evaluation (Part II). AIAA 2020-3261, DOI: 10.2514/6.2020-3261.
Zhang, J., D. Wuebbles, D. Kinnison, and S.L. Baughcum, 2021a: Potential impacts of supersonic aircraft emissions on ozone and resulting forcing on climate. An update on historical analysis. *J. Geophys. Res*., 126(6), e2020JD034130.
Zhang, J., D. Wuebbles, D. Kinnison, and S. L. Baughcum, 2021b: Stratospheric ozone and climate forcing sensitivity to cruise altitudes for fleets of potential supersonic transport aircraft. *J. Geophys. Res*., 126, e2021JD034971, https://doi.org/10.1029/2021JD034971.

