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"AVIATION AND THE ENVIRONMENT: EMISSIONS"

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Introduction

Good afternoon, Mr. Chairman and members of the Committee. I am David Fahey, research physicist in the National Oceanic and Atmospheric Administration's (NOAA's) Office of Oceanic and Atmospheric Research. NOAA's mission is to understand and predict changes in the Earth's environment and conserve and manage coastal and marine resources to meet our nation's economic, social, and environmental needs. The Office of Oceanic and Atmospheric Research conducts and sponsors the scientific research, environmental studies, and technology development needed to improve NOAA's operations and applications, and broaden our understanding of the Earth's atmosphere and oceans.

I work at NOAA's Earth Systems Research Laboratory in Boulder, Colorado where I conduct research related to the chemical and particle composition of the atmosphere and work with policymakers to describe and evaluate the science of ozone depletion and climate change. As part of my research over the past 10 years, I have been investigating the role emissions from aviation operations play in climate change. I was a coordinating lead author of the chapter on aviation-produced particles and cloudiness in the Intergovernmental Panel on Climate Change's (IPCC) Special Report on *Aviation and the Global Atmosphere* published in 1999. More recently I was a lead author of a chapter of the IPCC 4th climate science assessment released in 2007 that included an evaluation of the influence of global aviation on climate.

Thank you for inviting me to discuss the impact of aviation emissions on climate. Today, I will provide an introduction to this hearing by presenting some aspects of our basic understanding of the role of global aviation in climate change, the key uncertainties in that understanding, and outstanding gaps in our knowledge.

Aviation is one component of human activities that contribute to climate change. Human activities contribute to climate change by altering the natural amounts of greenhouse gases, small particles, or cloudiness in Earth's atmosphere. Greenhouse gases, particles, and clouds affect climate by influencing the balance between incoming solar radiation from the sun and the outgoing infrared (thermal) radiation. This radiation balance is what controls Earth's temperatures and other climate features. When humans change the specific amounts or certain properties of greenhouse gases, particles, and clouds in the atmosphere, they change the radiative balance and create what scientists call a *radiative forcing* of the climate system. Radiative forcing, or RF as it is often designated, is the widely accepted measure of how hard the climate system is being *pushed* away from its natural state. This push is also known as climate forcing, and can be caused by natural mechanisms or through manmade pollution, such as the emissions of greenhouse gases. We know that if the climate is forced too hard, the climate state will change, altering basic climate parameters such as temperatures and precipitation. An important goal for climate scientists is to quantify climate forcing from all human activities and estimate how and when our climate system might respond to the total forcing. It is in this context that the contribution of aviation to climate change is most appropriately viewed and evaluated.

The radiative forcing contribution of aviation has been the focus of international scientific interest for some time. In 1999, the IPCC released its special report titled *Aviation and the Global Atmosphere*, which comprehensively addressed, for the first time, the processes by which aviation leads to radiative forcing. U.S. scientists, including myself, played leading roles in this effort. This report and subsequent refinements in the IPCC 4th scientific assessment of climate change released in 2007 are the preferred basis for any scientific discussion of aviation's contribution. The uncertainties and knowledge gaps identified in the 1999 report, while reduced in some respects in the intervening years, remain an important limitation in our understanding of the issue.

What are the aspects of aviation operations that lead to climate forcing (or change)?

There are three aspects of aviation that are of key importance in understanding and defining its role in climate change.

- *Aviation emits gases and particles into the atmosphere.* Global aviation burns fossil fuel, primarily in jet engines, to propel and operate a wide variety of aircraft. The combustion of aviation fuel (kerosene) produces a variety of gases and particles in the exhaust. Primary among them are the gases carbon dioxide (CO_2), nitrogen oxides (NO_x) and water vapor, and particles composed of soot and sulfate (*e.g.*, H_2SO_4). All of these components contribute to climate forcing.

- *Some gases and particles emitted by aviation at cruise altitudes have enhanced roles in climate change processes.* A large fraction of aviation fuel is burned at cruise altitudes (greater than 25,000 ft). At these altitudes, the removal of some gases and particles from the atmosphere is slower, thereby allowing these components to accumulate and stay in the atmosphere longer and have greater effect than they otherwise would if the emissions had occurred near Earth's surface.

- *Aviation operations often increase cloudiness along and near aircraft flight tracks.* Under certain atmospheric conditions, jet aircraft produce contrails (condensation trails), which are a form of cirrus cloud, in the engine exhaust plume. These contrails can sometimes persist and spread for hours to days, depending on conditions (see Figure 1). Since clouds are an important aspect of Earth's radiation balance, increasing cloudiness is a component of climate change.

The IPCC reports in 1999 and 2007 quantified many of the climate effects of aviation emissions and cloudiness. Chart 1 graphically illustrates the radiative forcing from each of the eight principal components associated with aviation as reported by IPCC. The quantitative values are radiative forcings given in units of *watts per meter squared* (Wm^{-2}), which is the accepted nomenclature within IPCC. *Positive* radiative forcing values shown in Chart 1 lead to a warming of Earth's climate while *negative* forcings lead to a cooling. Larger forcings are expected to cause larger climate responses. Each bar in the chart represents the *best estimate* of scientists using available data and atmospheric models. I will briefly summarize each component for the committee.

1. *Carbon dioxide (CO_2).* Carbon dioxide, a well-known greenhouse gas, is the largest emission (by mass) of aviation. It is a direct product of the combustion of aviation fuel, which primarily contains elemental carbon, hydrogen, and sulfur. The radiative forcing from carbon dioxide is positive (warming) and is associated with a small uncertainty. The climate role of carbon dioxide emissions from aviation is no greater or less than the same amount of surface emissions of carbon dioxide because of its long lifetime in the atmosphere.

2-3. *Nitrogen oxides (NO_x).* Nitrogen oxides are a byproduct of high-temperature combustion of aviation and other fuels. Most nitrogen oxides are not greenhouse gases but influence climate indirectly by causing changes in other greenhouse gases; namely ozone (O_3) and methane (CH_4). In chemical processes that occur in the sunlit atmosphere, nitrogen oxides lead to ozone formation and methane reductions. Methane is emitted in other human activities. These effects have opposite climate effects with ozone increases causing a positive forcing (warming) and methane decreases causing a negative forcing (cooling).

4. *Water vapor*. Water vapor (H_2O), a potent greenhouse gas, is a direct product of the combustion of aviation fuel. The highest altitude aircraft emissions occur in the lower stratosphere, where water vapor abundances are low. The accumulation of aviation water emissions in this region leads to a small positive radiative forcing (warming). The accumulation of water emitted at lower cruise altitudes (troposphere) has a negligible climate effect because the natural abundance of tropospheric water vapor is far larger.

5-6. *Sulfate and soot particles.* Sulfate and soot particles are emission products of aviation. Sulfate particles derive from the sulfur content of the fuel. Soot particles are a byproduct of incomplete combustion. The direct effects of the accumulation of these particles are opposite: sulfate particles reflect sunlight causing a small negative forcing (cooling) while soot particles absorb sunlight causing a small positive forcing (warming).

7. *Persistent contrails.* Persistent (linear) contrails form in the jet engine exhaust plume when atmospheric humidity conditions are favorable for ice cloud formation (*i.e.,* supersaturation). Contrails are ice clouds that are formed primarily from atmospheric water vapor but whose formation is triggered by emitted water vapor. Natural and contrail cirrus clouds can both cool

and warm the atmosphere depending on specific cloud properties. Contrails from the current aviation fleet are estimated to cause a net positive forcing (net warming).

8. *Induced cloudiness.* Induced cloudiness, also known as contrail cirrus, is defined as cirrus cloudiness that spreads or evolves from persistent contrails as they lose their characteristic linear shape. Induced cloudiness represents cloudiness that otherwise would not have occurred in the atmosphere. As with contrails, induced cloudiness has a net positive forcing (warming) of climate. The forcing for induced cloudiness is shown as a range in Chart 2 because no best estimate value is available.

<u>Total aviation radiative forcing</u>: The best estimate of the total aviation radiative forcing is positive, leading to a warming influence on climate. The total is a sum over the individual components except for induced cloudiness, which is excluded because it lacks a best estimate. Thus, the total shown is an underestimate of the actual total contribution from aviation. The contributions from carbon dioxide and ozone are the largest terms in the total. The total aviation radiative forcing in Chart 1 can be compared to the total forcing from other human activities and the natural forcing from changes in solar output as displayed in Chart 2. The comparison shows that aviation in 2005, excluding induced cloudiness, represents approximately 3 percent of that from all human activities since the start of the industrial era.

An important aspect of the contributions of aviation to climate forcing is the *lifetimes* of the individual contributions. The lifetime refers to how long a particular effect persists in the atmosphere. All of the aviation components except carbon dioxide have short lifetimes. Carbon dioxide emitted into the atmosphere has a lifetime of 100-1000 years. Thus, a large fraction of the carbon dioxide emitted into the atmosphere from aviation in the year 2000 will still be contributing to climate forcing in 2100. This is true for carbon dioxide emitted in all other human activities. In contrast, the effects of other emissions and clouds from aviation have short lifetimes (less than 1 year). Thus, the non-carbon-dioxide effects of aviation in 2000, for example, will represent a negligible contribution to climate forcing well before 2100. Another consequence is that in a future scenario in which aviation operations remain constant, the contribution of carbon dioxide forcing relative to all other aviation forcings would continually increase. The contrast in lifetimes for the different effects is an important aspect of the long-term influence of aviation on climate.

What are the uncertainties in evaluating the impact of aviation operations on climate forcing (or change)?

The climate effects of aviation are the result of complex interactions involving emissions and clouds in the atmosphere. As a consequence, the effects must be calculated with computer models of the global atmosphere. The processes contained in models are an attempt to represent comprehensively the chemical transformations among atmospheric trace gases, the formation and removal of particles, atmospheric air motions that transport gases and particles throughout the atmosphere, the regional and seasonal responses of the radiative forcings, and the response of the climate system to the applied forcings. The resulting model estimates are associated with varying uncertainties because our knowledge of the processes and our ability to represent them quantitatively in models is imperfect. In this presentation, I address only the uncertainties associated with the forcings.

The largest term in Chart 2, that of carbon dioxide, has one of the smallest relative uncertainties, in part, because carbon dioxide is gas with a long atmospheric lifetime and is well studied as a principal greenhouse gas associated with many non-aviation human activities.

The two radiative forcing components from nitrogen oxide emissions have large uncertainties because complex, chemical processes link nitrogen oxides to ozone and methane changes, and the natural abundances and variabilities of ozone and methane are generally larger than the calculated changes.

Contrail radiative forcing also has a large uncertainty. Contrails, despite being a visible component of climate change, are difficult to assess on the global scale required for aviation. Contrail formation on any flight is critically dependent on the atmospheric humidity conditions along the flight track. Global models have difficulty predicting atmospheric humidity along air traffic routes with the needed precision and accuracy.

The uncertainties associated with the remaining components; namely water vapor and sulfate and soot particles, are relatively small in comparison with other uncertainties. The radiative forcings associated with these components is also small relative to the carbon dioxide component.

What are the gaps in our knowledge on climate forcing from aviation?

Significant gaps exist in our knowledge of the effect of aviation on current and future climate. Two gaps are worth noting in this presentation:

Estimate of induced-cirrus cloudiness. Currently no best estimate is available for the climate forcing of induced cloudiness from aviation. Many observations have shown the existence of induced cirrus. Chart 1 shows a common example of spreading contrails forming induced cirrus. However, scientists lack the necessary observations and framework to detect and quantify induced cirrus for global aviation. Principal difficulties are distinguishing induced cirrus from background cirrus that forms in the same region and establishing the radiative forcing properties of induced cirrus. Without a best estimate for induced-cirrus, the aviation impact on climate will be incomplete and likely underestimated.

Estimate of the role of aviation particles in background cloud formation. Aviation particles containing sulfate, soot, and unburned hydrocarbons have the potential to alter the formation and properties of clouds in the atmosphere. Studies show that aviation likely increases the number of soot particles, for example, in the upper atmosphere, particularly near flight corridors. The presence of these particles in regions of cloud formation could potentially alter the formation rates of clouds or their radiative properties. Studies have confirmed these effects in the lower atmosphere for other sources of particles from natural and human activities, but estimates are uncertain. Studies have not been undertaken to demonstrate these effects for aviation particles.

Summary

Global aviation emits gases and particles into the atmosphere that affect Earth's climate. The gases include carbon dioxide, a principal greenhouse gas. The emissions occur primarily at cruise altitudes, which increases their potential to cause climate effects. In addition, aviation indirectly increases cloudiness through the formation and spreading of persistent contrails. The net result of aviation emissions and cirrus cloudiness is a positive radiative forcing which leads to a warming of climate. Global atmospheric models are required to evaluate and quantify the separate effects of aviation on climate. Model calculations for aviation are associated with notable uncertainties, particularly for contrails and the indirect effects of NO_X emissions. Identifiable gaps in our understanding of aviation effects are the lack of best estimates for the forcing of induced cirrus formed by spreading contrails and for the possible effect of aviation particles on background cirrus formation and properties. The lack of a best estimate for induced cirrus leads to an underestimate of aviation climate forcing. The lifetimes of the non-carbon-dioxide effects of aviation are dramatically shorter than the effect of carbon dioxide. The contrast in lifetimes for the different effects is an important aspect of the long-term influence of aviation on climate.

References

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