

Climate Change Science
Prof. J. Srinivasan
Department of Environmental Science
Indian Institute of Science, Bengaluru

Lecture 46
Climate Models

In the previous lecture, the role of aerosols in climate was discussed, emphasizing the challenges in estimating their impact. The most significant difficulty arises from the interaction between aerosols and clouds, which introduces substantial uncertainty into climate model projections. This was illustrated through a study by Seinfeld et al., published in the *Proceedings of the National Academy of Sciences*, using the GFDL model from Princeton - renowned for contributions by Nobel Laureate Syukuro Manabe.

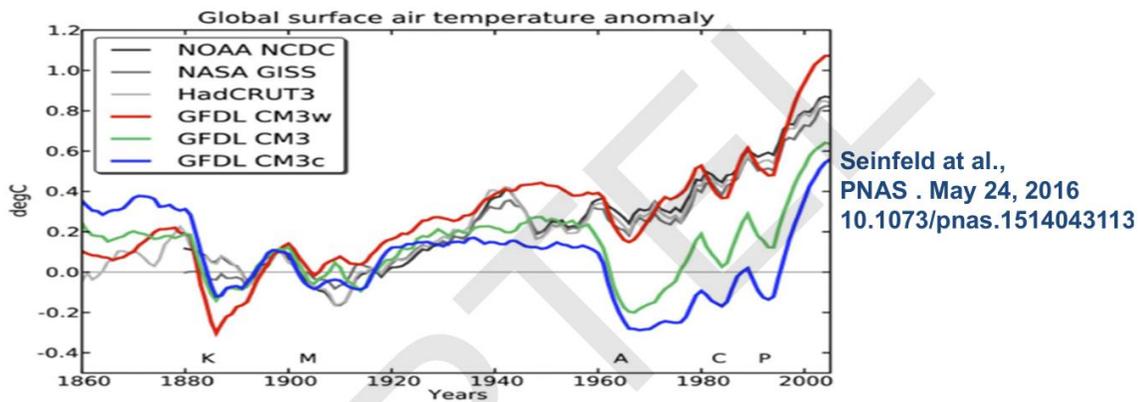
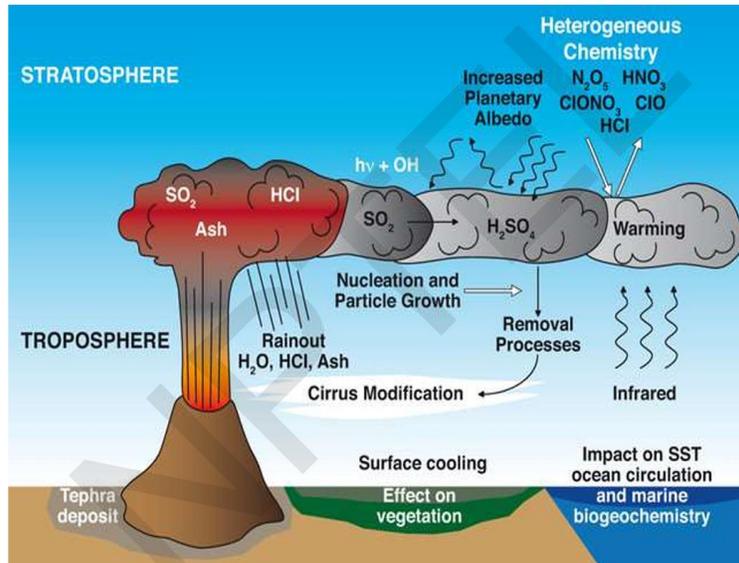


Fig. 1. Sensitivity of predicted global temperature evolution to three versions of the aerosol–cloud submodel in the GFDL climate model: CM3w, CM3, and CM3c (8). In the simulations, emissions of sulfate precursors, organic and black carbon, and GHG concentrations were held constant at their 1990 values. For CM3w, increased cloudiness (the lifetime effect) owing to reduced autoconversion of cloud droplets to rain is partially offset by increased cloud erosion. For CM3c, the increased cloudiness that results from less efficient autoconversion of cloud droplets to precipitation is offset by reducing the lower bound on the vertical velocity variance for CCN activation. The net warming predicted by the three different submodels is: CM3w, 0.57 °C; CM3, 0.22 °C; and CM3c, –0.01 °C. By comparison, predictions of three other GCMs are: NOAA NCDC,

The study compared three simulations - CM3w, CM3, and CM3c - each with different assumptions about aerosol-cloud interactions. For instance, CM3w, which assumes reduced auto-conversion of cloud droplets to rain (leading to more cloudiness), predicted a 1°C global warming by the year 2000, whereas CM3c predicted a lower warming of around 0.6°C. These results highlight the sensitivity of climate model outcomes to the assumptions about aerosol effects on cloud microphysics, including changes in droplet number, radius, and cloud lifetime. The scientific community lacks consensus on these processes, and this persistent uncertainty significantly limits confidence in future climate projections.



In addition to anthropogenic aerosols from industrial activity, natural sources such as volcanic eruptions also contribute significantly to atmospheric aerosol loads. During major eruptions, large quantities of sulphur dioxide (SO₂) are injected into the stratosphere, typically around 20 km altitude, where it converts into sulphate aerosols. These aerosols are highly reflective and cause short-term global cooling by scattering incoming solar radiation. Thus, volcanic eruptions act as episodic natural experiments that demonstrate the cooling potential of sulphate aerosols in the stratosphere.

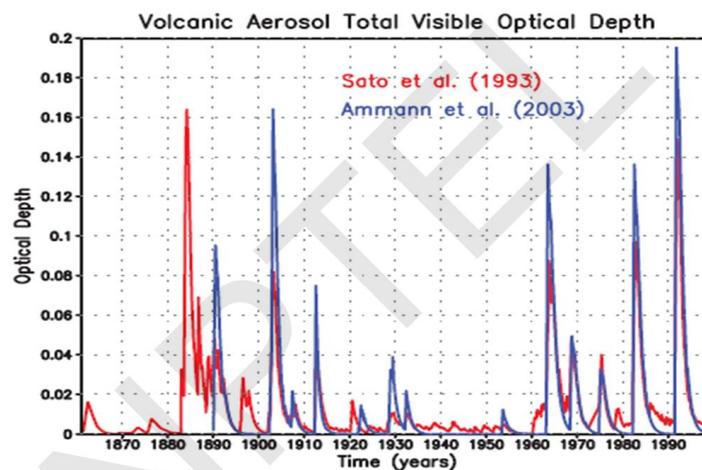
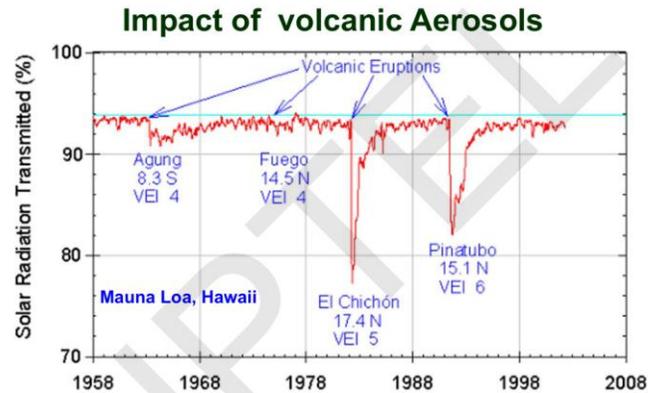


Figure 2.18. Visible (wavelength 0.55 μm) optical depth estimates of stratospheric sulphate aerosols formed in the aftermath of explosive volcanic eruptions that occurred between 1860 and 2000. Results are shown from two different data sets that have been used in recent climate model integrations. Note that the Ammann et al. (2003) data begins in 1890.

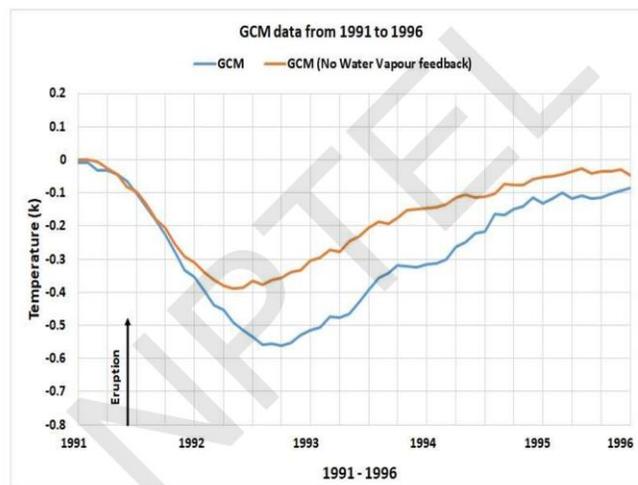
Volcanic eruptions are a significant natural source of stratospheric aerosols, but estimating their climatic impact involves considerable uncertainty. Different research groups provide varying estimates of aerosol optical depth (AOD) following major eruptions, particularly for events over the last 100 years. While there is better agreement among estimates for eruptions in the last 60 years, the discrepancies become more

pronounced for older eruptions due to uncertainties in the sulfur content, aerosol composition, and total emission.



It is currently thought that the effect of global dimming is probably due to the increased presence of **aerosols** in the atmosphere

The impact of these eruptions on solar radiation transmission is also variable. For example, under clear-sky conditions, around 94% of visible solar radiation (at $\sim 0.5 \mu\text{m}$ wavelength) is typically transmitted at sites like Hawaii. However, during volcanic aerosol events, this transmission can drop sharply, as observed during eruptions of El Chichón, Pinatubo, and Agung. Transmission fell to as low as 74% for a few months after El Chichón. The magnitude of this reduction depends heavily on the amount of SO_2 emitted, with Agung being relatively weak, El Chichón stronger, and Pinatubo somewhere in between. These variations underscore the complexity in quantifying the climatic influence of individual volcanic eruptions.



A simulation of the Mount Pinatubo eruption demonstrates the Earth's immediate cooling response following a major volcanic aerosol injection. When general circulation models (GCMs) include water vapour feedback, the simulated global cooling reaches around 0.6°C , closely matching observations. This occurs because aerosols cause surface cooling, which reduces atmospheric water vapour, a greenhouse gas, thus amplifying the

initial cooling - an example of negative water vapour feedback. This is in contrast to greenhouse gas-induced warming, where water vapour increases and enhances warming. The consistency between model simulations and observed temperature changes indicates that climate models are reasonably effective at capturing the climatic impact of volcanic aerosols.

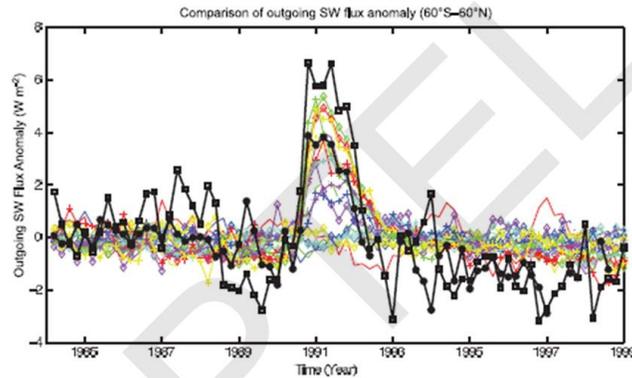
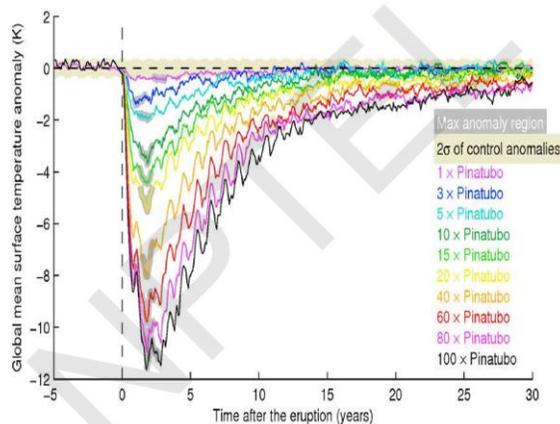


Figure 9.3. Comparison of outgoing shortwave radiation flux anomalies (in $W m^{-2}$, calculated relative to the entire time period) from several models in the MMD archive at PCMDI (coloured curves) with ERBS satellite data (black with stars; Wong et al., 2006) and with the ISCCP flux data set (black with squares; Zhang et al., 2004). Models shown are CCSM3, CGCM3.1(T47), CGCM3.1(T63), CNRM-CM3, CSIRO-Mk3.0, FGOALS-g1.0, GFDL-CM2.0, GFDL-CM2.1, GISS-AOM, GISS-EH, GISS-ER, INM-CM3.0, IPSL-CM4, and MRI-CGCM2.3.2 (see Table 8.1 for model details). The comparison is restricted to 60°S to 60°N because the ERBS data are considered more accurate in this region. Note that not all models included the volcanic forcing from Mt. Pinatubo (1991–1993) and so do not predict the observed increase in outgoing solar radiation. See Supplementary Material, Appendix 9.C for additional information.

Further, model simulations of the increased solar radiation reflected to space after the Pinatubo eruption are compared with satellite observations. While some models accurately replicate satellite-measured increases in reflected solar radiation, others fall short, particularly those that exclude volcanic aerosol inputs. Overall, models that incorporate volcanic emissions perform better in simulating the shortwave radiative forcing and highlight the importance of accounting for natural aerosols in climate modeling.



A simulation study explored the potential climatic effects of varying the magnitude of aerosol emissions from the Mount Pinatubo eruption. The actual Pinatubo event resulted in a modest global cooling of approximately $0.5^{\circ}C$ due to its relatively small emission volume. However, the simulation demonstrated that if the emission had been 100 times

greater, the cooling could have reached up to 12°C. This highlights the possibility that some of the larger volcanic eruptions over the past 1,000 years, or more notably those that occurred millions of years ago, could have triggered significant global cooling events—potentially even pushing the Earth into an ice age. While most known ice ages from the past million years are attributed to orbital changes (Milankovitch cycles), earlier events—such as those around 65 million years ago—may have been caused by massive volcanic eruptions. Although the exact quantity of aerosols released during those ancient events remains uncertain, and direct evidence is limited, the simulation provides theoretical support for the hypothesis that extreme volcanic activity could induce substantial climatic cooling.

We conclude the discussion on aerosols by emphasizing a key distinction: while the climatic impacts of aerosols remain complex and difficult to predict due to various feedbacks and interactions, the health effects of aerosols are well established and unambiguous.

Regardless of aerosol type - black carbon, sulphates, or combustion-related particulates - all inhaled forms have been shown to adversely affect human health. This is supported by robust epidemiological data, particularly from studies on cigarette smoking. Health impacts include chronic respiratory disease, increased blood viscosity, elevated heart rate, and blood pressure fluctuations, even from short-term exposure in polluted urban environments. Studies have documented how physical activity like cycling in polluted air leads to immediate cardiovascular stress and promotes plaque deposition in blood vessels.

In India, the health burden is especially severe, with around 94 deaths per 100,000 people attributed to air pollution which is significantly higher than in many other countries. Overall, over a million deaths per year in India are linked to air pollution.

The conclusion is clear: air pollution must be reduced urgently for public health, even though such reductions may slightly reduce aerosol-induced cooling and thereby contribute to increased global warming. This unavoidable climate-health trade-off needs to be managed with informed policy.

We will now shift our discussion to the crucial topic of predicting climate change, emphasizing the limitations of relying on past climate statistics for future projections. While past climate changes such as the transition from the last ice age have been instrumental in helping us understand long-term climate variability, they occurred over millennia and at much slower rates compared to the rapid changes observed today. As a result, they can be used only to tune and validate climate models, but not as a reliable basis for forecasting future conditions.

Given this, the only viable tool for predicting future climate is the use of climate models. These models are built upon the fundamental laws of physics and attempt to simulate the

Earth system's behaviour under varying conditions. However, it is equally important to evaluate how good or bad these models are, since no model is perfect. The next part of the discussion will therefore focus on exploring the strengths and limitations of climate models, which is essential for assessing their reliability and interpreting their projections in the context of future climate policy and planning.

Climate models are indispensable tools for predicting future climate change - there is simply no alternative. These models simulate the Earth system using physical laws, but given the system's immense complexity, particularly in processes like cloud formation, they necessarily rely on several approximations. Although cloud modeling has significantly improved over the past four decades, it remains an unresolved challenge due to its sub-grid scale nature. Most models operate at resolutions of about 50×50 km, which means that small-scale processes occurring within each grid cell must be represented through parameterizations, introducing uncertainty.

Because of this, no single model can be considered fully reliable on its own. To address both the inherent chaos of the climate system and the structural differences among models, scientists employ ensemble modeling, running many simulations from a single model with slightly varied initial conditions, and also combining outputs from multiple different models. This ensemble approach helps average out errors and provides a more robust estimate of future climate behaviour.

The importance of understanding model performance stems from decades of engagement with climate change skeptics, especially in the context of the Intergovernmental Panel on Climate Change (IPCC). Critics often argue that model inaccuracies cast doubt on the anthropogenic nature of observed warming. However, extensive evidence strongly supports that the 1.5°C rise in global mean temperature over the last 150 years is primarily driven by human activities. Notably, global mean temperature is one of the more predictable metrics in climate science due to its integrative and large-scale nature, lending confidence to model projections at this aggregate level.

In the initial lectures, we dealt in detail on a simple energy balance model that used just four parameters - incoming solar radiation, Earth's albedo, the greenhouse effect, and the atmospheric absorption of solar radiation to explain why Earth's average surface temperature is around 15°C . Despite the complexities and limitations of advanced climate models, this foundational understanding still holds: global mean temperature can be simulated reasonably well across 30 to 40 models. However, when predicting the impacts of future climate change, especially in the context of rising greenhouse gases, regional climate change becomes far more critical than global averages.

Global mean temperature has primarily been used as a policy metric to guide international negotiations on emission reductions. It does not provide meaningful insight

into what the climate of a specific location, such as Bengaluru, will be like 10 years from now. For real-world applications and impact assessment, regional projections are essential. Unfortunately, models are far less accurate at this scale. The ability of climate models to simulate regional climate is limited by many factors, including coarse spatial resolution and incomplete information about future changes in aerosols, land use, urban development, and pollution control at the local level.

Therefore, while global models can reasonably estimate large-scale trends, claims that they can accurately predict district-level climate several decades into the future are misleading. Predicting regional climate change accurately requires far more refined models and detailed projections of socioeconomic, land use, and emission scenarios which are inherently uncertain. This nuance is often lost in public discourse and needs to be clearly understood, especially by those engaged in policy and climate action at local and regional levels.

Climate models offer high confidence in predicting global mean temperature, but their skill decreases significantly when it comes to regional temperature and especially rainfall patterns. From a societal perspective, rainfall is often more critical than temperature, as extreme rainfall events lead to floods, while rainfall deficits cause droughts, both of which have serious consequences for food security, infrastructure, and livelihoods.

Rainfall predictions pose a major challenge in climate science. While short-term weather forecasts have improved significantly enabling accurate cyclone tracking and precipitation forecasting over days, long-term rainfall projections at the regional or local level remain highly uncertain. Advances in numerical weather prediction have allowed modern models to predict cyclone landfall locations and intensities with great accuracy, saving countless lives. In contrast, decadal-scale forecasts (e.g., how many cyclones will occur or where they will hit 30 years from now) remain unreliable due to the chaotic nature of the atmosphere and the complex interactions between ocean, land, and atmospheric processes.

Thus, while short-term forecasts are dependable for precautionary action, long-term projections, especially for rainfall and extreme events, require caution and careful interpretation. Reliable impact planning at regional scales depends on improved models, higher-resolution simulations, and better understanding of local drivers like land use change and aerosol emissions.

While global mean temperature predictions from climate models are robust and reliable, local climate projections, especially for temperature and rainfall, remain highly uncertain.

The quote from William James “*The search for reality is a series of successive approximations*” is apt for describing how climate modeling has evolved. Over the past five decades, models have progressively improved, incorporating more physical processes and finer resolution. Yet, they still rely on approximations, especially at smaller (regional to city-level) scales. For instance, sub-grid processes like convection, cloud formation, and aerosol-cloud interactions still require parameterizations, which introduce uncertainty.

Climate models are indispensable for three core purposes:

1. Testing our understanding of the climate system – by simulating historical events and processes.
2. Attributing past climate changes – identifying how much of the observed change is due to human influence versus natural variability.
3. Predicting future climate change – using scenarios of greenhouse gas emissions, land use, and aerosols.

A timely example is 2023, one of the warmest years on record. To dissect the causes of that warming, scientists use climate models to simulate conditions with and without certain forcings:

- By removing aerosols, they examine the role of reduced pollution in amplifying warming
- By isolating El Niño effects, they assess the contribution of natural variability
- By changing greenhouse gas concentrations, they evaluate the contributions of greenhouse gases induced warming

Such detection and attribution studies are only possible because of advanced climate models, despite their imperfections. So, while models are not yet ready to forecast city-level rainfall 30 years from now, they are already powerful tools for understanding why climate is changing, and how confident we can be in the role of human actions.

Climate models have undergone remarkable advancement over the last 60 years, and much of the foundational work traces back to Professor Syukuro Manabe, widely regarded as the pioneer of climate modeling. His early efforts in coupling the atmosphere and radiation laid the groundwork for simulating the Earth’s climate system. Alongside him, Klaus Hasselmann made significant strides in ocean modeling and linking climate variability to stochastic processes, while Giorgio Parisi contributed with his work on complex systems and stochastic modeling. In recognition of their pathbreaking contributions to understanding the climate system, all three were awarded the Nobel Prize in Physics.



Klaus Hasselmann

Giorgio Parisi

Syukuro Manabe

The Nobel Prize in Physics 2021 was awarded "for ground breaking contributions to our understanding of complex systems" with one half jointly to Syukuro Manabe and Klaus Hasselmann "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"

Despite these advances, it is essential to understand that all models are approximations of the real world. Given the complexity of the Earth system, climate models inevitably include simplifications and parameterizations. These approximations are necessary because not all processes, especially those at small spatial and temporal scales, such as turbulence, convection, and cloud microphysics, can be resolved explicitly. As a result, while climate models are valuable tools, they are not infallible. Errors in approximations can lead to inaccuracies in projecting specific events, such as extreme rainfall or droughts.

Nevertheless, models remain indispensable because they are grounded in fundamental physical laws like thermodynamics, fluid dynamics, radiation, and conservation of mass and energy. As emphasized by Professor Michael Mann, climate models are not crystal balls offering precise predictions, but rather fuzzy tools that give the best available guidance based on scientific principles. They are far superior to speculation or gut feeling, especially when it comes to identifying long-term trends such as global warming, where observations over the past decades have aligned closely with model projections.

In summary, while climate models may not offer exact predictions at regional or local scales, they are scientifically rigorous, continually improving, and remain our most reliable instruments for understanding and responding to climate change.