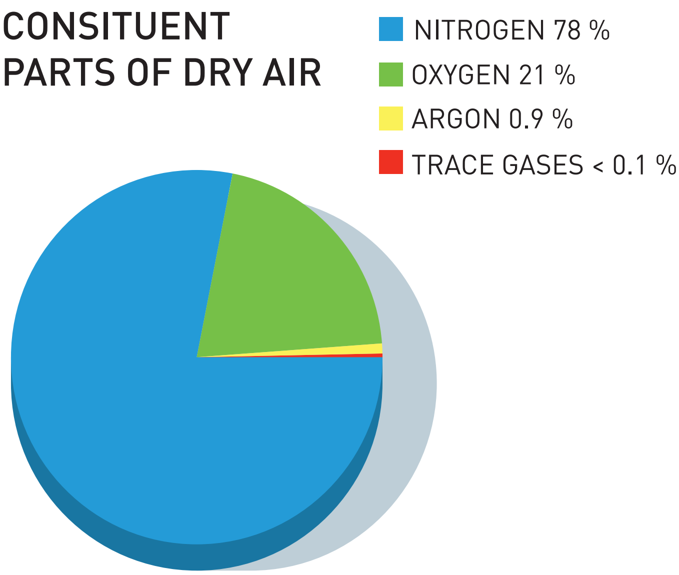
Computer models and Antarctic clouds – keys to climate riddles

The dynamics of the atmosphere and the Earth's climate have long been studied. Riddles that puzzled researchers have included the effect of manmade greenhouse gas emissions on the world's temperature and climate. Or why, at the end of every winter since the late 1970s, a hole has appeared in the ozone layer above the Antarctic. And how does this ozone hole affect the climate? ***Syukuro Manabe*** *and* ***Susan Solomon*** *have played leading roles in this field of research. They are awarded the Crafoord Prize in Geosciences 2018 for their fundamental contributions to the understanding of the role of atmospheric trace gases in the Earth's climate system.*

The Earth's atmosphere is a thin shroud of gases that is held in place thanks to gravity. Due to the heating effect of the sun and the Earth's rotation, the atmosphere is in constant motion. At ground level we perceive the movements of the lowest layer of the atmosphere as continually shifting weather, but how is atmospheric dynamics linked to its chemical composition and the climate trends of the Earth?

Investigations into atmospheric dynamics and the Earth's climate have been conducted for over a century but, until the end of the 1950s, this research was descriptive, which is to say it was basically founded on measurements and observations linked to solar radiation, air temperature, precipitation and the distribution of vegetation. It was not yet possible to realistically calculate atmospheric circulation and future climate trends. One insight that began emerging was how new approaches were necessary for solving the complex issues that arise when the Earth and its atmosphere are regarded as an integrated system.

Since the 1800s, researchers had been confounded by the question of the extent to which an increase in atmospheric carbon dioxide affects the Earth's temperature. When measurements from the new observatory on Hawaii, which was established in 1958, showed that the amount of carbon dioxide in the atmosphere is continually increasing – and that one possible explanation for this increase was manmade emissions of carbon dioxide and other greenhouse gases – the potential link between carbon dioxide and temperature became a hot topic.



Powerful tools in the service of research

In 1958, the Japanese atmospheric physicist Syukuro Manabe moved to the USA. He had received his Ph.D. from the University of Tokyo, and there was an attractive research environment at the National Oceanic and Atmospheric Administration's (NOAA's) Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey. Its director, Joseph Smagorinsky, created the right conditions for teams of researchers to work with large-scale numerical modelling, using the latest and most powerful computer technology. Here, in the 1960s, Syukuro Manabe and his colleagues conducted a series of ground-breaking studies. Initially, he investigated which physical calculations were necessary to create a realistic circulation model of the Earth's atmosphere.

One of the first steps was taken by Manabe and Robert Strickler (1964). He studied why the temperature in the atmosphere is the way it is. Why is there a troposphere and a stratosphere? Why is the temperature different at different latitudes and at different times of the year? Using the circulation model, it was possible to prove that the atmosphere's content of water vapour and trace gases, such as carbon dioxide and ozone, determines its temperature and vertical temperature layers. However, to obtain realistic results, convection must also be taken into account, i.e. how the atmosphere moves due to temperature changes, which proved to be the key to deeper understanding.

Subsequently, Manabe and Richard Wetherald (1967) took the physical calculations another step further. He was able to show that relative humidity is an important factor, allowing realistic calculations of how the atmosphere's temperature is affected by changes in carbon dioxide levels, for example. Using the model, it was calculated that a doubling in the level of carbon dioxide in the atmosphere is equivalent to a temperature increase of around 2^{0}C.

The first real climate model sees the light of day

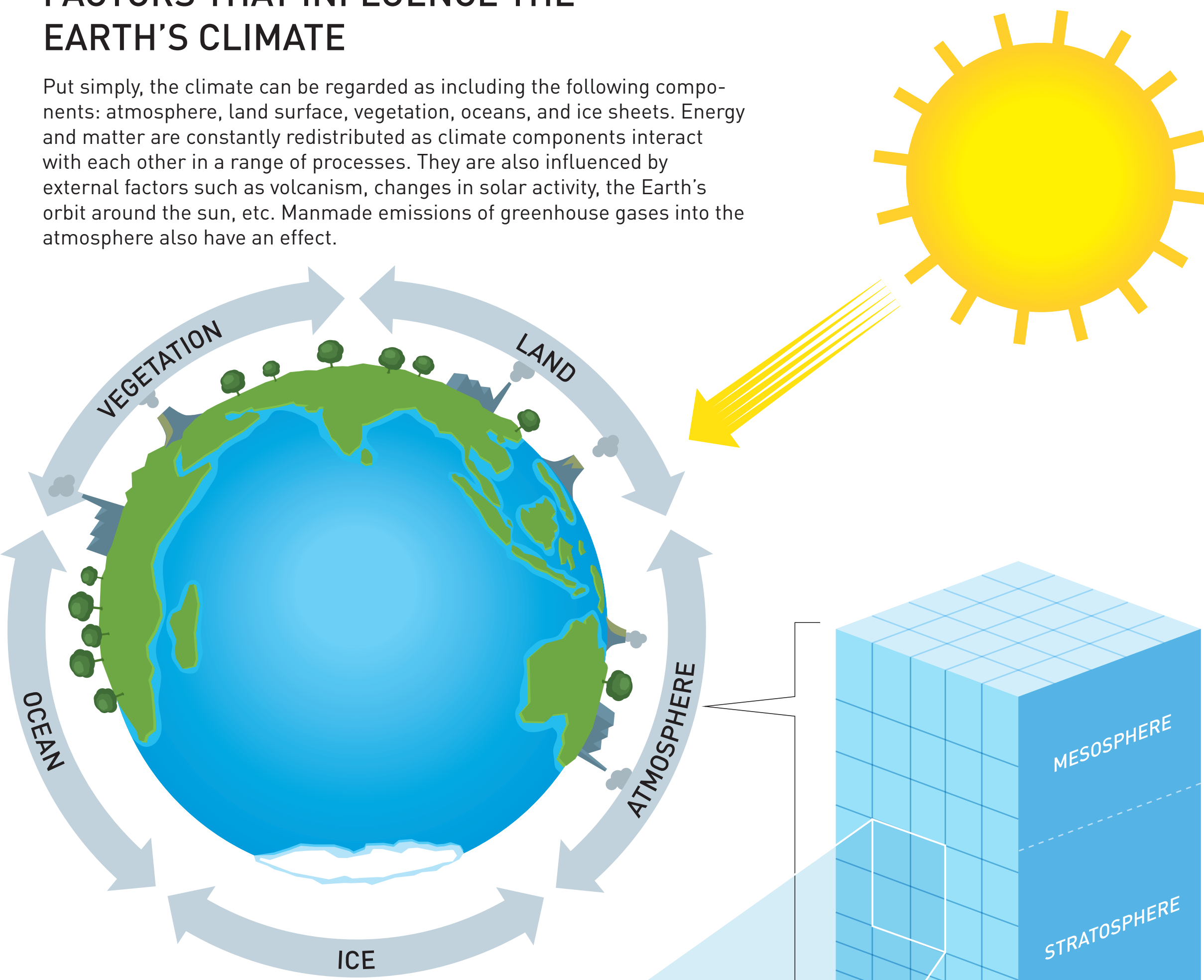
Syukuro Manabe and Kirk Bryan (1969) took another step forward when they linked processes that take place in the atmosphere and at ground level with the oceans' movements and thermal balance. Now there was a model to describe the feedback between the two main components of the climate system: the oceans and the atmosphere. The first complete climate model had been born.

Global climate models divide the atmosphere, land and oceans into a three-dimensional grid. The climate model is then run for a specific period of time in the past, present or future. Using the basic laws of physics, each part of the grid calculates the development of the meteorological, hydrological and oceanographic parameters. The computer that was used to develop and run the first global climate model had a memory capacity of 0.5 Mb, which was that time's leading edge technology. Despite the incredible progress in computer technology since then, the same principles are still used for current climate models. The physical associations described by Syukuro Manabe and his colleagues remain fundamental to our more advanced and high-resolution numerical models for forecasting the Earth's climate trends, for example those linked to manmade emissions of carbon dioxide and other greenhouse gases.

Syukuro Manabe has a unique ability to formulate the necessary questions, and then approach them through the optimal simplification of the questions' mathematical descriptions, drawing up strategies for explanatory simulations using the available computing resources. He has long been a world-leader in the development of physically-based numerical climate models.

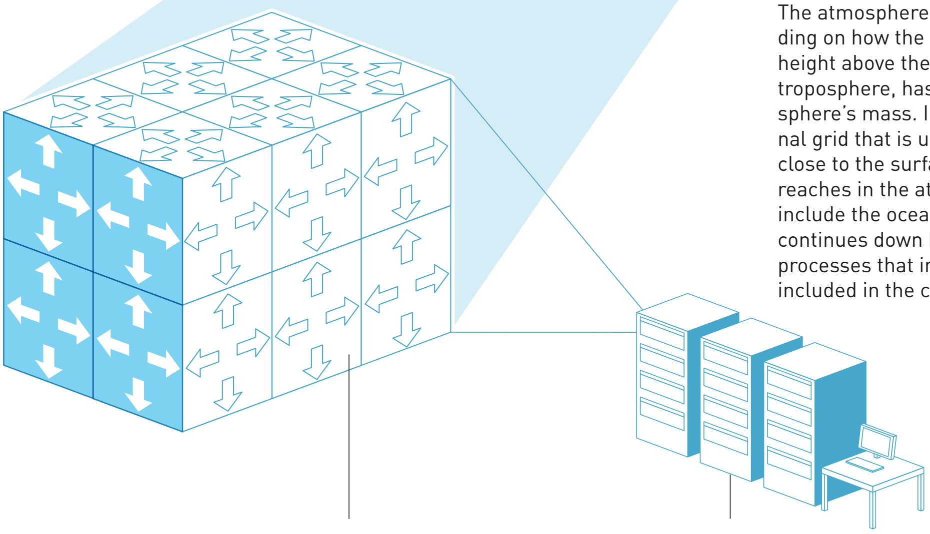
FACTORS THAT INFLUENCE THE EARTH'S CLIMATE

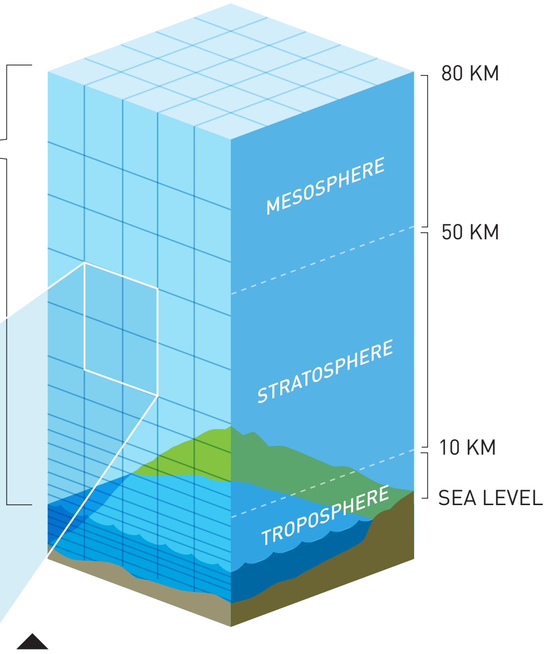
Put simply, the climate can be regarded as including the following components: atmosphere, land surface, vegetation, oceans, and ice sheets. Energy and matter are constantly redistributed as climate components interact with each other in a range of processes. They are also influenced by external factors such as volcanism, changes in solar activity, the Earth's orbit around the sun, etc. Manmade emissions of greenhouse gases into the atmosphere also have an effect.



CLIMATE MODELLING

In a climate model, the atmosphere is divided into a three-dimensional grid along the Earth's surface and up into the atmosphere. The atmosphere's movement and conservation of energy, water and mass follow physical laws that are described using mathematical formulas. Climate modelling then involves the stepwise calculation of the development of parameters such as temperature, precipitation and wind for each cell in the grid.





UP THROUGH THE ATMOSPHERE

The atmosphere is divided into different layers depending on how the average temperature changes with height above the Earth's surface. The lowest layer, the troposphere, has around 70-80 per cent of the atmosphere's mass. In a climate model, the three-dimensional grid that is used in the calculations is also densest close to the surface, becoming less so the higher it reaches in the atmosphere. A climate model can also include the oceans. The three-dimensional grid then continues down below the water's surface so that processes that influence the climate can also be included in the calculations.

Entirely new theory focused on the Antarctic's stratospheric clouds

The discovery of the ozone hole above the Antarctic was another decisive event for the atmospheric sciences. In the mid-1980s, researchers in the UK and the USA were able to show thinning in the ozone layer above the Antarctic every year since the end of the 1970s. But what was causing this phenomenon? Researchers had previously shown that CFCs (chlorofluorocarbons) break down ozone, but the decomposition now being measured was far more extensive than what was expected. Nor was it possible to explain why the hole was only above the Antarctic, and only at a certain time of year. Significant resources were put to work in the search for the explanation. This is where atmospheric chemist Susan Solomon has played a vital role.

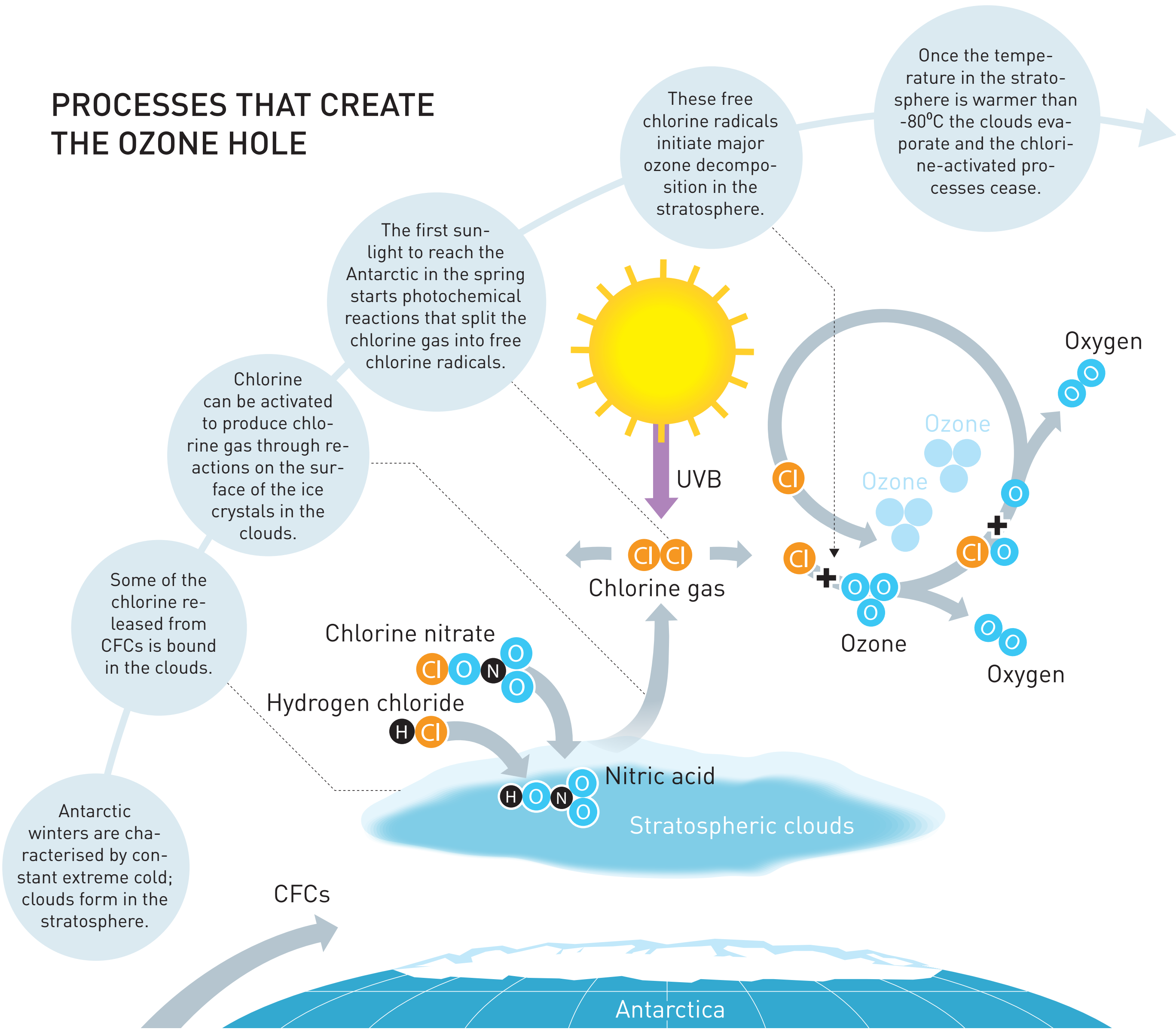
Susan Solomon obtained a Bachelor's degree in Chemistry from the Illinois Institute of Technology and, in 1981, she received her Ph.D. from the University of California, Berkeley. She then began working at NOAA's Aeronomy Laboratory in Boulder, Colorado. Susan Solomon's deep understanding of chemical and physical processes, and her ability to combine theoretical studies with experimental fieldwork were absolutely vital to work on solving the riddle of the ozone hole above Antarctica.

Susan Solomon (1986) and her colleagues formulated a new theory. They started looking at the ice crystals in the clouds created due to extreme cold in the stratosphere above the Antarctic; these form every winter at temperatures below -80^{0}C. They assumed that the ice crystals in these clouds can initiate chemical processes different to those that had previously been presumed to occur. Instead of assuming that only chemical reactions in the gas phase are important, the researchers proposed that heterogenous reactions are also significant, i.e. reactions that involve different phases (solid, liquid, gas). It was now possible to make new calculations about what happens above the Antarctic when molecules from ground-level CFC emissions eventually reach the stratosphere and the chlorine in the CFCs is released. Most of this chlorine is stable, in the form of chlorine nitrate and hydrogen chloride, which are unable to break down ozone. Supported by this new theory, Susan Solomon was able to prove: A) How, in the winter, some of these stable chlorine compounds are bound in the Antarctic's stratospheric clouds. B) How chlorine activation occurs due to chemical reactions on the surface of ice crystals in the clouds, resulting in chlorine gas. C) How, in the spring, sunlight starts photochemical reactions that split the chlorine gas into free chlorine radicals. D) That the presence of free chlorine radicals causes the extensive decomposition of ozone in stratospheric clouds. One free chlorine radical can break down 100,000 ozone molecules before it leaves the stratosphere. E) That chlorine activation continues until the spring is advanced enough for the temperature to be above -80^{0}C and the stratospheric clouds evaporate.

Susan Solomon led two expeditions to the Antarctic, in 1986 and 1987, where the researchers tested their theory by conducting extensive physical and chemical measurements in the stratosphere with aeroplanes and balloons. Their findings included how the lower levels of ozone measured in the stratosphere from August to October coincided with lower levels of chlorine nitrate. When ozone levels began to rise again in October, an equivalent increase was noted in the levels of chlorine nitrate. The correlation between the levels of ozone and chlorine nitrate confirmed Susan Solomon's calculations – and how there is a link between manmade emissions of CFCs and the depletion of the Antarctic ozone layer.

The chemical reactions proposed by Susan Solomon are now one of the cornerstones for all modelling of the stratosphere's chemical composition. In one important application of this theory, Susan Solomon and David Hofmann (1989) were able to explain how major volcanic eruptions can affect the ozone layer due to the release of sulphur compounds in the stratosphere.

PROCESSES THAT CREATE THE OZONE HOLE



The ozone layer also affects the climate

Following these expeditions to the Antarctic, Susan Solomon has continued her world-leading research on the stratospheric ozone layer. Not only the reasons for its depletion, but also how changes to the depth of the ozone layer are an important component in the Earth's climate system. In a number of articles in the 2000s, she and her colleagues have shown how changes to the thickness of the ozone layer above the Antarctic influence atmospheric circulation in the southern hemisphere. In turn, changes to air currents affect temperatures at ground level, for example changes to the summer temperatures above Antarctica and the Southern Ocean, New Zealand, Patagonia and the southern parts of Australia.

For more than thirty years, atmospheric chemist Susan Solomon has been at the absolute frontline of research into the ozone layer and climate change. Her contributions to knowledge building are unique in this field.

LINKS AND FURTHER READING

More information about the prize can be found on www.kva.se and www.crafoordprize.se.

NOAA's description of Syukuro Manabe's global climate model, the first global climate model.
https://celebrating200years.noaa.gov/breakthroughs/climate_model/welcome.html#vision

More information about global climate models.
https://www.gfdl.noaa.gov/climate-modeling/

The Keeling Curve for atmospheric carbon dioxide, with daily measurements on Hawaii since 1958.
https://scripps.ucsd.edu/programs/keelingcurve/

Film from NASA about modern global climate models (from 2010).
https://www.youtube.com/watch?v=jj0WsQYtT7M

Ozone decomposition in the stratosphere. Scientific article in Reviews of Geophysics, 1999.
http://onlinelibrary.wiley.com/doi/10.1029/1999RG900008/abstract

NOAA's description of the importance of Susan Solomon and her research.
https://celebrating200years.noaa.gov/historymakers/solomon/welcome.html

Facts about research on the ozone hole and work to prohibit CFCs.
http://www.theozonehole.com/twentyyear.htm

Article in Science, 2016, on indications that the ozone hole above the Antarctic is beginning to recover.
http://science.sciencemag.org/content/early/2016/06/30/science.aae0061

News item from NASA about ozone measurements in the Antarctic's stratosphere in 2017.
https://www.nasa.gov/feature/goddard/2017/warm-air-helped-make-2017-ozone-hole-smallest-since-1988

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