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WHY ARE CLOUDS OVER THE SOUTHERN OCEAN SUPER-COOL?

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YOUNG REVIEWERS:

ARIA
AGE: 11

YUTONG
AGE: 12

When water drops below 0° Celsius, we assume it turns to ice. This is not always true though, especially inside of some clouds over the Southern Ocean. When water exists as a liquid below 0°C, it is known as super-cooled liquid water. Water only stays liquid below 0°C if it is extremely pure. Pollution and dust are two examples of impurities that can help water freeze. The water in Southern Ocean clouds has had very little contact with pollution or dust, so these clouds are often made up of super-cooled liquid water instead of ice. Super-cooled liquid water clouds reflect more sunlight back out into space than ice clouds do. Whether clouds are made of liquid or ice can control how warm the ocean is. This makes Southern Ocean clouds super cool as well as super important for the Earth's climate!

CLOUDS ARE COOL, BUT WHAT MAKES A CLOUD SUPER-COOL?

We have all spent time gazing up at clouds, looking for shapes, or hoping they will not rain on us. We think most people would agree that clouds are pretty cool! But what makes a cloud super-cool? It all starts with water. Clouds are made up of tiny droplets of water. Within these water droplets are tiny little particles that come from many sources, such as the ocean, the land, or pollution. These particles are often referred to as cloud "seeds". If the seeds are large enough, they are known as **cloud condensation nuclei**. For any cloud droplet to form, cloud condensation nuclei must be present. You can think of cloud condensation nuclei as the building blocks of clouds!

CLOUD CONDENSATION NUCLEI

Tiny particles in the air that water condenses on to form cloud droplets.

The other ingredient needed to form a cloud is water—of course! But not water in a liquid form. Clouds need water to be in the gas phase first, which is known as **water vapor**. Colder air can hold less water vapor than warmer air can.

WATER VAPOR

Water in the air that is in the gas phase.

When cool air touches a surface, the water vapor in it turns to liquid. In other words, it *condenses* on that surface. In wintertime, have you ever noticed water condensing on your windows? A similar process happens in clouds. In the atmosphere, as air rises, it cools. The water vapor in the cold air will condense on cloud condensation nuclei surfaces if they are present, forming liquid droplets. This is how the droplets in clouds, called cloud droplets, are formed. These cloud droplets then stick together and grow, until they get so heavy that they fall out of the sky as rain!

Some clouds are happy to remain liquid their whole lives, especially in warm places! But in places like the Southern Ocean, temperatures are well-below freezing. When water cools to below 0°C, it wants to freeze—and in most cases, it will. However, in some unique environments, water can stay as a liquid well-below 0°C! We call this **super-cooled liquid water**. A cloud that exists in temperatures below 0°C and remains liquid is known as a super-cooled liquid water cloud. Above the Southern Ocean, there are more super-cooled liquid water clouds than anywhere else in the world [1].

SUPER-COOLED LIQUID WATER

Water that exists as a liquid below 0°C.

Super-cooled liquid water can exist only if the water is extremely pure and does not contain a special type of cloud condensation nuclei known as an **ice nucleating particle**. If the water droplet contains an ice nucleating particle, or if it mixes with air that has ice nucleating particles in it, the water will freeze.

ICE NUCLEATING PARTICLES

Tiny particles in the air that help water turn from liquid to ice.

Only some types of cloud condensation nuclei can also act as ice nucleating particles—it depends on what the particle is made of. Pollution and dust are two examples of particles that can help water freeze into ice crystals. If a cloud droplet does not make contact with an ice nucleating particle, it will stay liquid until the temperature drops below −38°C! These processes are shown in Figure 1.

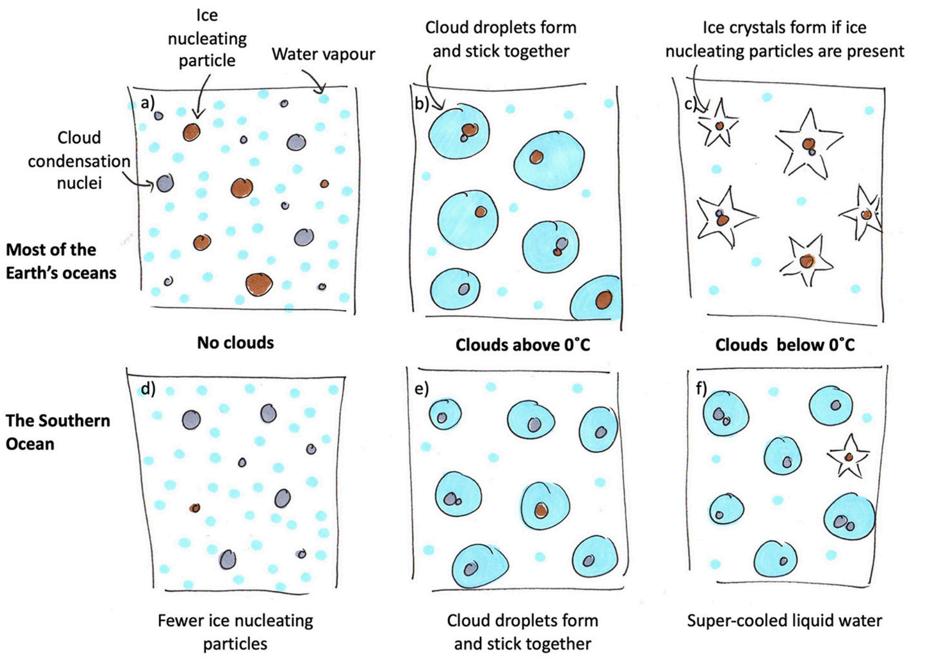

Figure 1

(a) In most of the world's oceans, both cloud condensation nuclei and ice nucleating particles are present. **(b)** When water vapor condenses onto these particles, cloud droplets form. **(c)** If the temperature drops below 0°C when ice nucleating particles are present, the cloud droplets turn to ice. **(d)** In the Southern Ocean, fewer ice nucleating particles are present than in other parts of the world. **(e)** Cloud droplets still form when water condenses on the particles that are present, but **(f)** when the temperature drops below 0°C, the droplets remain as super-cooled liquid water.

THE SOUTHERN OCEAN IS A UNIQUE ENVIRONMENT

The Southern Ocean is very far away from land and humans (Figure 2). This means the water in the clouds has had very little contact with pollution or dust. Because of how far away it is, few ice nucleating particles are present in the Southern Ocean. Clouds in the Southern Ocean are mostly formed with cloud condensation nuclei from the ocean, such as sea spray, or from the gases released by tiny plants that live in the ocean, such as phytoplankton [2]. Some particles in sea spray can act as ice nucleating particles. However, we are not sure how big a role those particles play yet.

Not many other parts of the world, including other oceans, are as pure as the Southern Ocean. The lack of ice nucleating particles causes more clouds in the Southern Ocean to be made up of super-cooled liquid water than anywhere else in the world. The Earth's other polar ocean, the Arctic Ocean, is very close to land and human influences, meaning that more ice nucleating particles exist there. Super-cooled liquid water clouds *can* form in the Arctic under the right conditions, but satellite data show they occur much less frequently.

The remoteness of the Southern Ocean makes it unique. But its remoteness also makes it one of the most difficult places in the world to study!

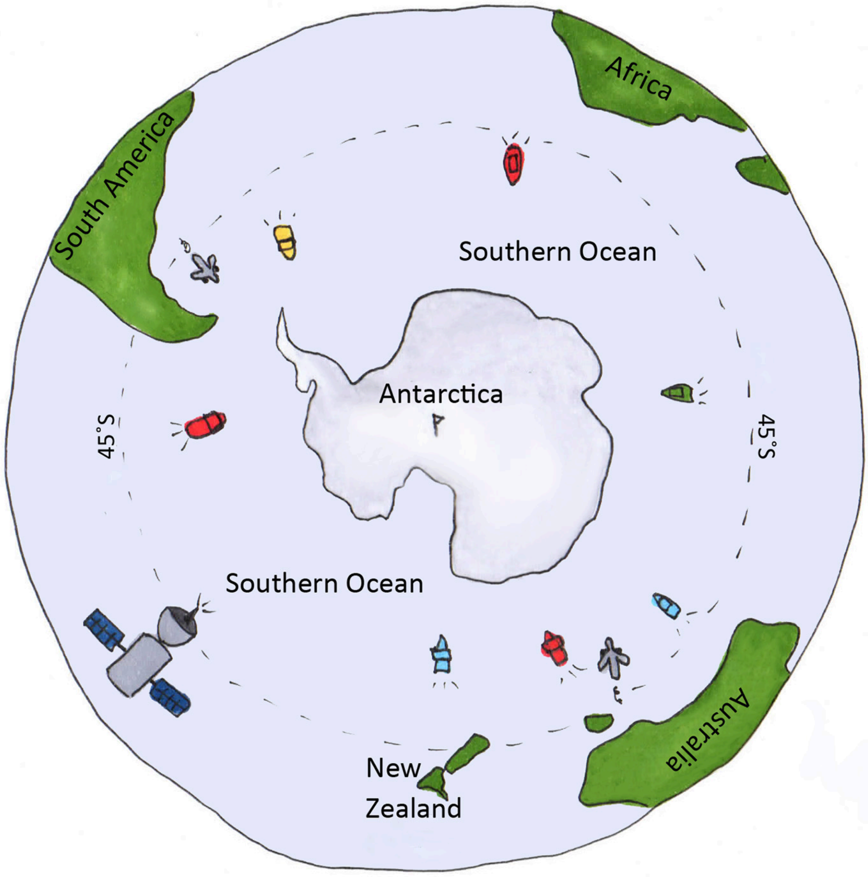

Figure 2

Figure 2

The Southern Ocean, which circles Antarctica, is a remote place, far from human populations or large, ice-free land masses. This means that there are fewer ice nucleating particles in the Southern Ocean to help cloud droplets freeze, which is why the clouds in the Southern Ocean are made up of super-cooled liquid water!

SUPER-COOL AND SUPER-IMPORTANT FOR THE PLANET!

In addition to sounding cool, super-cooled liquid water clouds are also important for Earth's weather and climate.

WEATHER

The state of the atmosphere at a particular place and time.

CLIMATE

The long-term, average conditions of the atmosphere.

Weather and climate are different. The **weather** is the current state of the atmosphere, which can often change quickly. For example, if it is sunny one day and raining the next—that is the weather. The **climate** consists of the average conditions over a long time. For example, you may know that summertime is usually warm and dry, or warm and raining at your place, depending on where you live. Both weather and climate need to be understood because they impact the choices we make every day. Should I take an umbrella today? Check the weather! I want to spend my holidays swimming at the beach—where would I go? Somewhere with a warm and dry climate!

Super-cooled liquid water clouds are important for both weather and climate because they behave differently compared to ice clouds. They last longer than ice clouds and they also reflect more sunlight back out into space (Figure 3). Both of these behaviors can help to cool the surface of the ocean when the sun is shining. This means that whether clouds are made of liquid or ice can influence how warm the surface of the ocean is.

This is important for the long-term climate in balancing the amount of energy in the Earth's atmosphere, as well as for all the marine animals that live near the surface and are influenced by the weather.

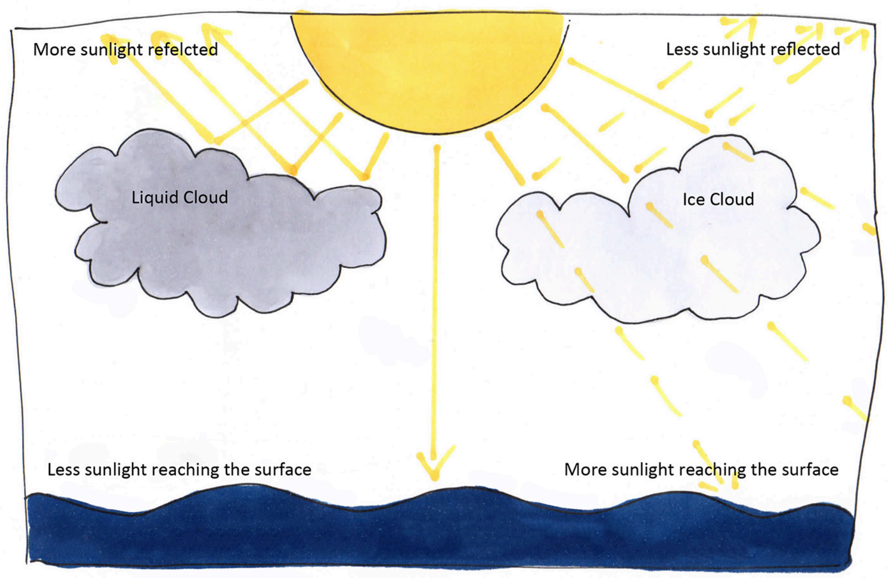

Figure 3

Figure 3

Liquid clouds can reflect more sunlight out into space than ice clouds do, which means less sunlight reaches the surface of the ocean. Ice clouds let more light through to the ocean surface. This means that whether a cloud is liquid or ice can impact how warm it is at the surface of the ocean.

HOW DO WE STUDY SOUTHERN OCEAN CLOUDS?

As scientists, we want to understand super-cooled liquid water clouds so that we can understand and predict the weather and climate of the Southern Ocean and the Earth. One way to do this is by using computers to make models. **Climate models** (and weather forecast models) use our knowledge of physics and chemistry to create a "virtual" version of our atmosphere on a computer. Right now, our climate models have some issues. They think that the Southern Ocean has the same amount of ice nucleating particles as the rest of the world's oceans [3]. We know this is not true. Because of this, the models predict fewer super-cooled liquid water clouds than what we observe, which means they also predict too much sunlight reaching the ocean [4]. All of this means that our climate models are less accurate about many other parts of the Southern Ocean climate, like the ocean surface temperatures!

CLIMATE MODELS

Mathematical models of the Earth's atmosphere over long time scales. We use these models for predicting the Earth's future climate.

Scientists are working hard to fix these problems by using observations to test and improve the models, but the data are hard to get—the Southern Ocean is a remote and harsh place, so very few measurements of the clouds over the Southern Ocean exist compared to other parts of the world. Most of the observations we have for the region were made during only the summer, and the expeditions often only last a month or so [5]. This lack of data over the Southern Ocean is one of the reasons the climate models think that there are many more ice nucleating particles in the region than there really are.

MORE MEASUREMENTS A MUST

Thankfully, scientists around the world are planning lots of research expeditions into the Southern Ocean over the next few years. These expeditions include ships, planes, drones, satellites, and land-based stations on islands and on the Antarctic continent. Scientists will be studying many areas of the vast Southern Ocean, and they will also try to take measurements in seasons besides summer, to try to fill in the gaps in our knowledge.

Many of these expeditions will be trying to understand these particles and how they change the clouds. Measurements will include how many particles are in the air, how big they are, what they are made of, and if they can act as ice nucleating particles. We also want to know where the particles came from, so we will measure what is in the ocean and look at what the wind might be carrying from far away.

We will also look at the types of clouds that are present and how much sunlight is passing through them. Super-cooled liquid water clouds look like any other clouds, so it is difficult for us to tell them apart just by looking at them. This is another reason why new measurements are so important. For example, we can use a technique called **Light Detection and Ranging (LiDAR)**, which shines a laser into the clouds and measures what is reflected back, giving us information that helps to identify what the clouds are made up of. LiDAR instruments can be carried by ships, to look up at the clouds, or can be located on satellites and planes, to look down at them.

LIGHT DETECTION AND RANGING (LIDAR)

A technique that sends out a laser beam and measures how long it takes to bounce off an object, telling you about the distance, shape and size of the object.

Measurements like these will then be fed into our computer models, to improve both weather forecasts and climate predictions!

SUPERCOOL SUPER-COOLED SOUTHERN OCEAN CLOUDS

We hope by now that you will agree with us in thinking that Southern Ocean clouds are supercool! Their importance for the Southern Ocean, as well as for the entire Earth, has been recognized by scientists for a long time. However, we still have a lot of work to do to make sure we understand these clouds and model them properly. The new research expeditions will go a long way in helping with this effort. Maybe one day *you* can help too!

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REFERENCES

1. Huang, Y., Protat, A., Siems, S. T., and Manton, M. J. 2015. A-train observations of maritime midlatitude storm-track cloud systems: comparing the southern ocean against the north Atlantic. *J. Clim.* 28:1920–39. doi: 10.1175/JCLI-D-14-00169.1
2. Hamilton, D. S., Lee, L. A., Pringle, K. J., Reddington, C. L., Spracklen, D. V., and Carslaw, K. S. 2014. Occurrence of pristine aerosol environments on a polluted planet. *Proc. Natl. Acad. Sci. U. S. A.* 111, 18466–18471. doi: 10.1073/pnas.1415440111
3. Vergara-Temprado, J., Miltenberger, A. K., Furtado, K., Grosvenor, D. P., Shipway, B. J., Hill, A. A., et al. 2018. Strong control of southern ocean cloud reflectivity by ice-nucleating particles. *Proc. Natl. Acad. Sci. U. S. A.* 115, 2687–2692. doi: 10.1073/pnas.1721627115
4. Bodas-Salcedo, A., Hill, P. G., Furtado, K., Williams, K. D., Field, P. R., Manners, J. C., et al. 2016. Large contribution of supercooled liquid clouds to the solar radiation budget of the southern ocean. *J. Clim.* 29, 4213–4228. doi: 10.1175/JCLI-D-15-0564.1
5. Mallet, M. D., Humphries, R. S., Fiddes, S. L., Alexander, S. P., Altieri, K., Angot, H., et al. 2023. Untangling the influence of Antarctic and Southern Ocean life on clouds. *Elementa* 11, 1–18. doi: 10.1525/elementa.2022.0013

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YOUNG REVIEWERS

ARIA, AGE: 11

Aria loves playing with her two guinea pigs and feeding birds and squirrels in her backyard. She gave each squirrel a unique name and lots of peanuts. Aria is always curious about science and she has a lot of questions about nature, animals and the universe. She also likes singing and drawing in her spare time.

YUTONG, AGE: 12

Hello, I am Yutong. I enjoy swimming, skating, and hiking. I love music and singing, I also play the piano. I hope that by reviewing these articles I could learn about new and interesting stuff!

AUTHORS

SONYA L. FIDDES

Sonya Fiddes is an atmospheric scientist in the Australian Antarctic Program Partnership, at the Institute for Marine and Antarctic Studies, University of Tasmania in Hobart, Australia. Sonya is working on improving how computers can represent clouds over the Southern Ocean. She does this by working with lots of other scientists who observe clouds over the Southern Ocean and then using those observations to compare to a computer model. Sonya has been to Antarctica once, and she loved seeing all the whales, penguins, and seals! *sonya.fiddes@utas.edu.au

MARC D. MALLET

Marc Mallet is an atmospheric scientist at the University of Tasmania, Hobart, Australia, who works with the Australian Antarctic Program Partnership. He studies how sunlight and clouds interact with tiny particles in the air. Right now, he's trying to figure out how clouds and these particles form in the Southern Ocean. He does this by going by ship to the edge of Antarctica and making lots of measurements. Marc has been all over the world to measure what is in the air, from Africa to the Arctic!

SIMON P. ALEXANDER

Simon is an atmospheric physicist at the Australian Antarctic Division, in Hobart, Australia. He explores the unique clouds of the Southern Ocean and the rain and snow that they make. He does this by taking lots and lots of special equipment into the Southern Ocean, which can measure clouds, rain, snow, sunlight, and much more! Simon has been swimming in the Antarctic ocean during winter and would do it again!

ALAIN PROTAT

Alain Protat is an atmospheric scientist working at the Australian Bureau of Meteorology, Melbourne, Australia, where he leads the Radar Science Team. Radars send radio waves into the sky to detect objects. Alain uses radars from the ground, on ships, airplanes, and satellites to study clouds and severe storms. Understanding these weather patterns helps improve our knowledge on how clouds and storms form, and how they can be predicted by computer models. Alain is a champion at playing table tennis on a ship that is rocking in the sea.