PACIFIC CLIMATE IMPACTS CONSORTIUM

# PCIC SCIENCE BRIEF: ON CLOUD-CIRCULATION COUPLING AND CLIMATE SENSITIVITY

**One of the key uncertainties in climate model simulations has to do with the response of low-lying marine clouds to increasing temperatures. A recent paper in the journal *Nature* uses a mix of radar, lidar and data from atmospheric probes to test one of the mechanisms by which cloud cover is projected to be reduced under climate change. Their findings show that this mechanism is not evident in the trade wind regions, which suggests that might not occur in nature. This further suggests that the most extreme estimates of the climate's response to greenhouse gas emissions are less likely than earlier research suggests. Here we discuss what these results tell us about changes to the Earth's sensitivity to greenhouse gas emissions and what this may mean for our province.**

## Introduction

The climate of our province is governed, in large part, by trends in the larger global climate. If the global climate system is one with a higher climate sensitivity—that is, one that is more strongly affected by atmospheric greenhouse gas concentrations—then it will warm more from a given amount of greenhouse gas emissions, and our province will warm more and experience greater climate impacts as a result. Adding to this, being more northerly, British Columbia (BC) will warm more than the global average[1]. Several of the key uncertainties surrounding the Earth's climate sensitivity have to do with clouds[2].

Clouds have multiple effects on the Earth's climate and the effects that they have depend on the type of cloud in question. Low-lying clouds shade the planet. They are highly reflective, directing sunlight back out into space during the day, and, being quite warm, they emit almost as much infrared radiation to space as would the surface below. At night they absorb and reradiate heat back to the surface, acting as an insulating blanket. Their overall effect is one of cooling. High altitude clouds can be thick, effectively blocking incoming sunlight, or thin and wispy, blocking comparatively little incoming sunlight. They are also cold, and thus reradiate little heat back toward the Earth's surface. The overall effect of high altitude clouds is one of warming[3]. So, low altitude clouds act to cool the Earth, high altitude clouds act to warm the Earth and, when considered together, the cooling effect is larger. Overall, clouds reflect more radiation back out to space than they radiate back toward the ground, cooling the Earth by about 5 degrees Celsius (°C). Clouds also participate in the transfer of heat from the Earth's surface due to the phase changes of water, with evaporation cooling the surface and condensation warming the atmosphere.

Clouds are difficult to represent in global climate models (GCMs), because such models have resolutions on the order of a hundred kilometres, whereas many of the processes involved in cloud formation—such as droplet formation and growth on aerosols, evaporation, the effects of tiny turbulent eddies, freezing, melting, and small-scale radiative fluxes, etc.—occur on much smaller scales. While, in a simple sense, clouds form when water vapour condenses out of the air, generally on the surface of an aerosol, to form water droplets and ice crystals, the processes by which this happens can be incredibly complex and multiple different processes are often occurring beside each other and interacting. Aerosols, along with water in multiple phases, are can all be carried through clouds, with water condensing, freezing, melting and so on, and with tiny droplets and ice particles interacting in complex ways the entire time. The details of these microphysical processes control the phase (e.g. solid, liquid), size, number and shape of particles in the cloud and are critical for the transfer of radiation within clouds and, in turn, on cloud formation and climate. Also, the amount, type and size distribution of aerosols affects the number and size distribution of droplets.

Much information can be, and has been, gained through studies in laboratory conditions, and from observations such as radar and lidar measurements of the atmosphere. Nevertheless, gathering data from different types of natural clouds to verify the results of laboratory experiments

1. There are multiple mechanisms that contribute to the amplification of warming in the high latitude regions, including changes in energy transport throughout the Earth system. For more on these, see Hahn et al. (2021).
2. For an overview and assessment of the different processes that control Earth's climate sensitivity, see Sherwood et al. (2020).
3. For more on the net effects of high-altitude clouds, see Chapter 7: Clouds in Tziperman, E. (2022).

against, and to quantify the rates of microphysical processes within natural clouds, remains incredibly challenging. Correctly representing the effect of these microphysical processes, at least in terms of their bulk characteristics[4], is crucial to developing climate simulations that capture the response of the climate system to greenhouse gas emissions. GCMs use parameterizations, which are simplified versions of these small-scale processes that represent these bulk characteristics and estimate their overall effects on the climate system. Gathering observations of cloud processes and testing GCMs against them can help to constrain, confirm and rule out some of the projections of these models and be used to further refine their parameterizations, such that GCMs can be improved and better projections can be made.

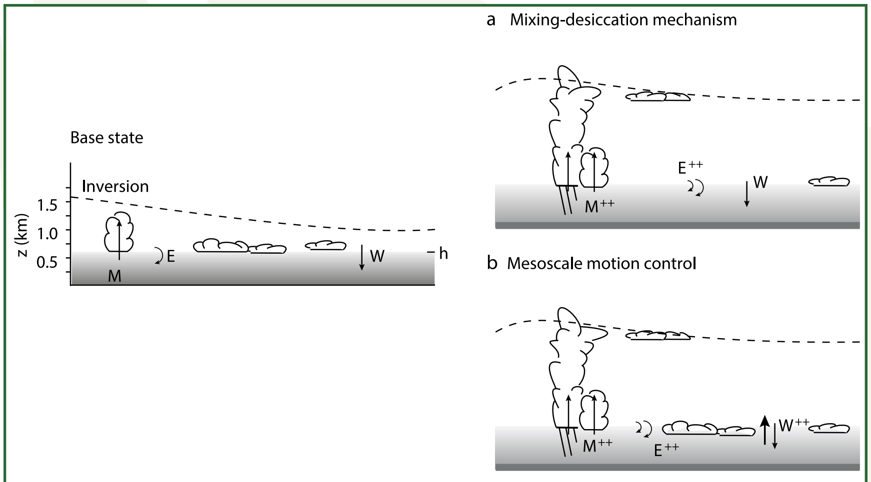


**Figure 1: Schematic Outline of Mechanisms of Convective Mixing and Cloudiness (from Vogel et al., 2022).**
This figure outlines the general processes tying together convective mixing (M), entrainment (E), mesoscale vertical air motions (W) and cloudiness. On the left is the base case, which shows a balance between M, E and W. Panel a) illustrates the desiccation hypothesis, with stronger vertical mixing ($M^{++}$) leading to stronger entrainment/"draw down" of dry air from aloft ($E^{++}$), leading to reduced cloud cover. Panel b) shows an alternative scenario, in which vertical mixing and entrainment increase, but mesoscale vertical air motions also increase ($W^{++}$) and the contribution of humid air from $W^{++}$ prevents the drying of the cloud layer and thus allows for cloud development.

## The Dessication Hypothesis

While clouds have always been one of the primary sources of uncertainty regarding Earth's climate sensitivity, they have been the subject of more discussion as of late following results from several climate modelling groups that suggested that low-lying marine clouds would become more sparse in a warming world.

Low-lying marine clouds currently cover about a fifth of the Earth's oceans. A reduction in these clouds with warming would cause an increase in the amount of sunlight reaching the Earth's surface and increase warming still further, potentially creating a feedback loop that would exacerbate global warming.

The proposed mechanism is as follows. The changing climate induces an increase in the height of low-lying marine cumulous clouds through an increase in mixing[5] (Figure 1, Panel a). As the clouds rise, this creates a region of low pressure that draws down dry air from above. This, in turn, dries the layer of the atmosphere where the clouds form and the reduction in available moisture reduces overall cloudiness. An alternative hypothesis, explored by Vogel et al. (2022) and shown in Panel b) of Figure 1, begins similarly, with an increase in mixing and dry air being drawn down from above. However, according to this alternative hypothesis, there will be a compensating increase in mesoscale vertical air motions that will bring in humid air and prevent the drying of the cloud layer.

If the cloud dessication apparent in the output from several GCMs is found to reflect actual features of the Earth's climate system, it would have significant implications for the Earth's climate sensitivity and thus future climate impacts. At the same time, this is an area of climate science in which significant uncertainty remains. It is therefore important to have a better understanding of how well the models are capturing the relevant processes for marine cloud formation, so that the scientific and policy communities can know what confidence to have in these aspects of future climate projections.

4. A similar point is true for nearly the entire scientific project outside of those areas studying the fundamental building blocks of the universe. If we have a sufficient understanding of the bulk characteristics of a system and its large-scale processes, we often do not need to resort to simulating its smallest elements and smallest-scale processes. Thus, we can calculate how long a pot of water will take to boil under a given set of conditions without resorting to quantum physics simulations. One of the issues with clouds is that we are still developing an understanding of how to represent their bulk characteristics at the scale at which GCMs perform their calculations. (Of course, how exactly we are to fit our knowledge of small-scale processes together with our knowledge of larger-scale processes is a broad issue that also remains an active area of research and discussion in multiple areas.)
5. Mixing is used here to refer to the vertical convection of air in the atmosphere. The atmosphere is disturbed by vertical convection due to the rising of warm air near the Earth's surface, and as this air rises, it mixes with the air above it.

Writing in the journal *Nature*, Vogel and colleagues attempt to address this question for trade wind regions through measurements taken over a one-month field study[6] by airplane-based radar and lidar (a remote sensing method using pulsed lasers), and from atmospheric probes dropped from an airplane[7].

## Aerial Observations of Mixing, Cloudiness and Relative Humidity

The authors began by taking measurements of cloud cover using radar and lidar sensors on one aircraft while a second aircraft released 800 probes into the atmosphere while flying in 200 km circles, in order to measure the slow circulation of the air over the region. This allowed them to get measurements of cloud cover, relative humidity[8], vertical convective mixing[9] (rising warm air for the surface), entrainment[10] (the air being drawn down as a result of the vertical mixing) and mesoscale vertical velocity[11] (the air being moved vertically as a result of circulation patterns on the order of kilometres to hundreds of kilometres).

Vogel and colleagues found that larger vertical mixing did not lead to decreased cloudiness or decreased relative humidity (Figure 2). Instead, increased vertical mixing increased cloud cover. The authors also found that, while mesoscale vertical velocity was near zero on average, it had substantial variability. Both entrainment and mesoscale vertical velocity contributed to the variability in relative humidity, with entrainment drying reducing relative humidity and mesoscale vertical velocity increasing relative humidity through supplying moisture. The latter effect prevents the drying of the cloud layer. This is consistent with the schematic outline in Figure 1, Panel C.

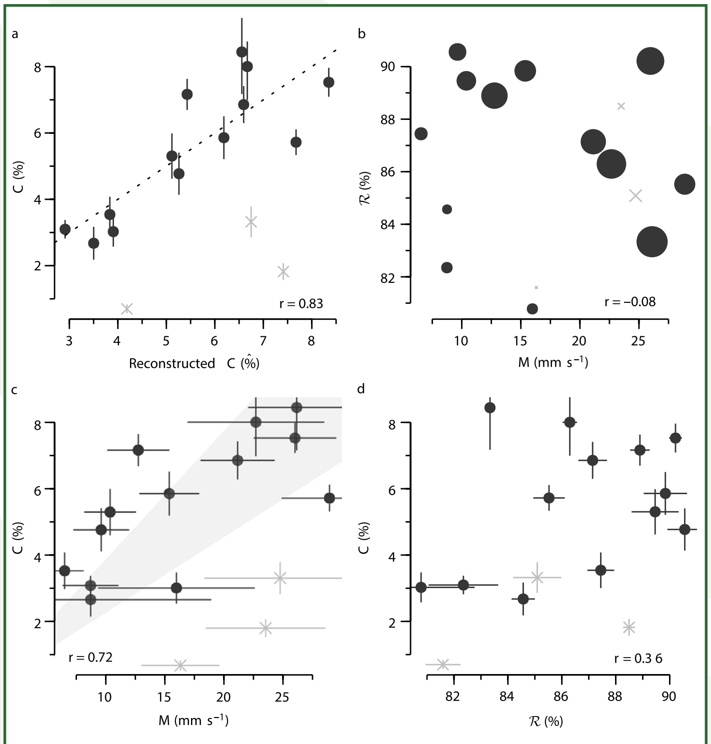


**Figure 2: Relationships Between Vertical Mixing, Relative Humidity and Cloud Cover (from Vogel et al., 2022).** This figure shows the relationships between vertical mixing (M), relative humidity (R), observed cloud cover (C) and cloud cover as calculated from R and M (Reconstructed C). Panel a) shows the relationship between C and Reconstructed C. Their close agreement suggests that R and M dominate the variability in cloud cover. Panel b) shows the relationship between R and M, Panel c) shows the relationship between C and M. Panel d) shows the relationship between C versus R. A key point is that, by the dessication hypothesis, increasing M should lead to decrease in R and a decrease in C, but this is not evident in the observations. Grey data points were excluded due to inconsistent sampling between the two aircraft that were gathering data.

## Comparing Observed Vertical Mixing, Relative Humidity and Cloudiness with Climate Model Output

The authors then compared their observations with the output from several of the GCMs used in the Cloud Feedback Model Intercomparison Project[12] (CFMIP). They find that the models disagree with each other in the magnitude and variability of both vertical mixing and cloud cover. The authors also find that the models all overestimate

6. Elucidating the role of clouds-circulation coupling in climate (EUREC$^{4}$A) is a field study that was undertaken in support of the World Climate Research Programme's Grand Science Challenge on Clouds, Circulation and Climate Sensitivity. It involved surface and air-based measurements of atmospheric properties to answer key questions about low-lying clouds and radiant energy transfer. For more on this field study, see Bony et al. (2017).
7. The probes used are called dropsondes. They are a device with a set of instruments that detect temperature, humidity and pressure, in a casing with a processor, battery and transmission device. They are designed to be released from airplanes, with their rate of descent controlled by a parachute. They take measurements and transmit their data as they fall.
8. Relative humidity is a measure of the amount of water vapour in the air, expressed as a percentage of the maximum amount of water vapour that the air could possibly "hold" at a given temperature. (Note that this is a simplification. The amount of moisture in a volume of air is given by Dalton's Law and a full treatment is outside the scope of this Science Brief.)
9. Rising warm air from near the Earth's surface.
10. The air being drawn down from aloft as a result of the vertical mixing.
11. The air being moved vertically as a result of atmospheric circulation patterns on the order of kilometres to hundreds of kilometres in size.
12. For more information on the Cloud Feedback Model Intercomparison Project, see Webb et al. (2017).

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the variability in cloud cover. The models show varying correlations between cloud cover and vertical mixing, with only one model showing the positive correlation between vertical mixing and cloud cover seen in the authors' observations. In addition, Vogel et al. find that all of the models strongly underestimate the variability in mesoscale vertical velocity. The authors attribute this to the fact that the processes leading to this variability, such as small-scale differences in sea surface temperature gradients and small, shallow circulation driven by varying radiative cooling on scales that are smaller than the size of climate model grid cells[13]. This is important, given that the authors' results suggest that mesoscale vertical velocity is key in preventing the cloud layer from drying and may at least partially explain the discrepancy between the models and observations.

## Summary

The sensitivity of the Earth's climate to greenhouse gas emissions will determine the magnitude of anthropogenic climate change and thus the magnitude of the resulting impacts. A substantial portion of the uncertainty regarding climate sensitivity is tied to how clouds will react to the warming climate. Prior research using output from some GCMs suggests that Earth's climate will react more strongly to greenhouse gas emissions than previously thought, because, as vertical mixing increases, dry air will be increasingly drawn down, reducing the moisture in the lower cloud layer. This would then reduce low-lying marine cloud cover, allowing for more solar radiation to be absorbed at the Earth's surface, causing the planet to warm further.

The work of Vogel and colleagues seeks to address this, by using radar, lidar and atmospheric probe data to measure key quantities for low-lying marine clouds in trade wind regions and examining the relationships between these quantities. Their work finds that the relationships between vertical mixing, relative humidity and cloud cover predicted by the desiccation hypothesis do not hold in their observations, because mesoscale vertical air motion supplies moisture to the cloud layer and thus, that the desiccation process discussed above does not occur in the trade winds region that the authors examined. Vogel et al. also find that the GCMs disagree with each other regarding vertical mixing and cloud cover, overestimate the variability in cloud cover, do not capture the relevant mesoscale vertical air motions and that only one model shows the relationship between vertical mixing and cloud cover present in the observations.

While the projected desiccation and reduction in marine clouds is strongest in midlatitude regions, and the authors' results are from the tropics, the fact that the models do not match with the authors' observations suggests that they may not be capturing key features of the atmosphere that are relevant to marine cloud cover. If this is the case, it reduces confidence in the more extreme estimates of the climate system's response to greenhouse gases. This is potentially good news, both globally and for BC. These results may also be useful for further refining how GCMs represent the processes relevant for cloud formation and, as a result, improving climate projections that will be made in the future.

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13. These grid cells are the areas into which the simulated Earth system is divided, with values for variables like temperature, pressure, the velocity of air or water and so on calculated for each cell. They are currently generally on the order of a hundred kilometres.

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