Controlling Cloud Albedo: Recent Advances in Understanding the Geo-engineering Technique Proposed by John Latham

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Abstract

This review discusses and analyzes the geo-engineering method proposed by John Latham to increase cloud albedo as a way to mitigate temperature increases caused by greenhouse gas emissions. Recent studies improve our understanding of the parameters for optimal cloud albedo manipulation, as proposed by Latham. These studies relate to local microphysical properties of cloud albedo, as well as global radiative fluxes from large-scale cloud albedo manipulation. Although these studies support the validity of Latham's idea, there remain significant uncertainties that need to be resolved before the geo-engineering technique should be implemented.

1 Introduction

Anthropogenic carbon dioxide (CO_2) emissions have caused an increase in the concentration of CO_2 in the atmosphere from 280 ppm (IPCC, 2001) to over 380 ppm (NOAA, 2008) since the Industrial Revolution. Most experts now accept that this increase in CO_2 is causing a global climate change that may lead to higher sea levels (Douglas and Peltier, 2002), ocean acidification (McNeil and Matear, 2007), ocean circulation modification (Guemas, and Salas-Melia, 2008), and extinctions (Keith et al. 2008). The rate of climate change is outpacing implementation of source mitigation to reduce CO_2 emissions. This puts the impetus on scientists to develop geo-engineering methods to counteract the effects of climate change. These methods are designed to provide a temporary solution to slow the effects of the current climate problem until anthropogenic CO_2 emissions are sufficiently reduced.

One method of geo-engineering involves increasing the albedo of low-level marine stratocumulus clouds, proposed by John Latham (Latham, 2002). He hypothesized that if seawater droplets were disseminated at or near the sea surface to create salt particles approximately 1 μm in diameter, the salt particles would act as cloud condensation nuclei (CCN) in the atmosphere. CCN are crucial in the formation of clouds because they act as a condensation surface for water vapor. One of the major sources of naturally occurring CCN are sea salt particles formed by winds, waves, and air bubbles bursting on the ocean surface (Curry, 1999). Thus, this method would increase the number of naturally occurring CCN, making it a relatively attractive option ecologically compared with other proposed geo-engineering methods. First, it does not release any polluting chemicals into the atmosphere. Second, if any unexpected consequences arise, the entire operation could be shut down immediately, and its effects would disappear within a couple weeks (Latham, 2002).

By artificially increasing the seawater droplet concentration (N) inside the clouds, the albedo, or the solar radiation reflected from Earth, and possibly cloud longevity could be increased. Increasing albedo reduces the total solar energy that is absorbed by the Earth, thus reducing the amount of energy available to warm the planet, resulting in a net cooling of the planet. An increase in longevity would result in an increase in albedo as well, since the clouds would reflect solar radiation for a longer period of time. This method could potentially be used to offset the increase in global temperature caused by anthropogenic CO_2 emissions.

In this review, we will present and analyze the assumptions and logic that were used by John Latham to develop his geo-engineering method to control cloud albedo. Recent advances in the understanding of optimal parameters for cloud albedo manipulation will be provided. First, the microphysics of local cloud albedo will be introduced, which forms the backbone for this proposed method. Second, the changes in planetary albedo and global radiative forcing due to wide-spread cloud albedo alterations will be discussed. There are several uncertainties that remain unresolved which will be discussed as well. It is out of this paper's scope to determine whether or not this idea is viable, and it is not our intention to support or disclaim it. Further research is necessary to assess the significance of the uncertainties before concluding whether Latham's geo-engineering technique is reliable for implementation.

2 Microphysics of Cloud Albedo

2.*1 Cloud Albedo Characteristics*
Radiation from the sun is a major driving force of the Earth's climate system. A fraction of the radiation that reaches the Earth will be reflected back to space, determining the planetary albedo. The type of surface (land, ocean, clouds, ice) greatly influences the extent of the albedo. Clouds are particularly influential to albedo because they have relatively high reflectivity and cover a significant portion of the Earth.

The optical depth is an important parameter to describe a cloud's radiative property. Clouds with a larger optical depth will reflect more shortwave radiation (Twomey, 1974). Optical depth, τ, is determined by several cloud microphysical parameters:

$$\tau = \int_0^h k_E dz = \pi \int_0^h \int_0^\infty r^2 Q_E (r/\lambda) n(r,z) dr dz$$

[Equation 1]

where n=concentration of cloud droplets, Q_E is the extinction[1] efficiency factor, r is the effective radius of the drops, k_E is extinction coefficient λ is radiative wavelength, and z and h are measurements of thickness of the cloud. Using classical electromagnetic theory, complicated radioactive transfer equations can be derived which predicts the relation between albedo and optical depth [refer to Figure 1]. This theory has been supported by experiments (Ackerman, 1993).

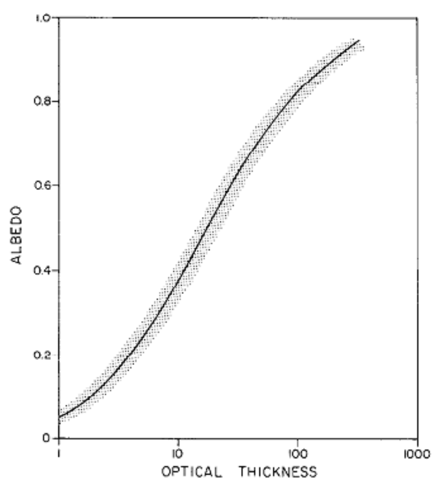

Figure 1: Optical Depth vs. Albedo (Twomey, 1974). A clear correlation between optical thickness and albedo can be observed.

According to equation 1, an increase in the concentrations of small radius cloud droplets in clouds would lead to an increase in optical depth and thus, cloud albedo. This idea was first developed by Sam Twomey (1961).

Before Twomey's research, scientists had only realized the direct effect of the aerosols on the reflectivity and absorptivity in the clear sky, and little attention was given to the effects aerosols had on cloud albedo (Budyko, 1969). Twomey showed that aerosols could act as CCN and significantly increase the number concentration of cloud droplets (N). This increases the total surface area of the condensed water in a cloud, thus increasing the reflectance of the cloud. This is referred to as the first indirect effect, or the Twomey effect.

A second indirect effect of aerosols is related to the longevity of the clouds. Reduction in cloud droplet size reduces the precipitation efficiency, which tends to increase the cloud's lifetime and the cloud thickness (Albrecht, 1989). Until recently, the second indirect effect has received much less attention than the first indirect effect. Both effects contain many uncertainties, such as the relationship between cloud droplet concentration to aerosol concentration, and its impact on cloud optical properties. Further research is necessary to resolve these uncertainties (Pincus and Baker, 1994).

The method proposed by John Latham involves the seeding of marine stratocumulus clouds using seawater aerosol. After spraying seawater into low clouds and lowering the environmental humidity, the salt droplets will crystallize and then produce nuclei, which provide an effective CCN source for water vapor to condense and form cloud droplets.

[1] Extinction refers to a decrease in radiation intensity caused by reflection or absorption when radiation interacts with matter.

Given the limited amount of water vapor available to condense, the increase of number concentration of cloud droplets will lead to smaller cloud droplets, which will increase cloud albedo and longevity, according to Twomey's effect and the second indirect effect, respectively.

2.2 Recent Advances in Understanding:
Recent cloud model studies have determined the sensitivity of cloud albedo enhancement to the cloud's microphysical parameters (Bower et al. (1999, 2006). The parameters effecting marine stratocumulus cloud albedo and droplet concentrations are:

- cloud characteristics (thickness and cloud-base temperature)
- environmental aerosol characteristics (clouds in pure air versus polluted air)
- seawater aerosol characteristics that are introduced to the cloud (salt mass and concentration).

The modeling study found that changes in cloud albedo are very sensitive to changes in seawater aerosol concentration. However, changes in cloud albedo are insensitive to changes in salt mass concentration, cloud thickness, and cloud-base temperature. Another finding was that albedo enhancement is more effective in clouds formed in pure air opposed to polluted air. This provides some insight for determining the proper location to implement the cloud seeding scheme proposed by Latham.

2.3 Uncertainty
There are several uncertainties that need to be resolved before the proposed geo-engineering technique should be implemented. The uncertainties described here are specific to cloud physics.

Further research is required to fully understand the role of precipitation development on cloud albedo enhancement (Latham, 2002). Seawater droplets could potentially grow very rapidly by collision and form drizzle, which would initiate precipitation and impact cloud longevity.

Additionally, the spraying of sea-salt aerosols would actually result in a range of N values (Latham et al., 2008). The sensitivity of cloud albedo and longevity to a range of N values needs further study.

3 Radiative Forcing due to Cloud Albedo Changes

3.1 Background
Radiative forcing is known as the change in irradiance at the tropopause and is measured in units of Watts per square meter. Irradiance can generally be thought of as the difference between incoming and outgoing radiation, which should be equal to zero to maintain static average temperatures. A positive forcing means that incoming radiation is greater than outgoing radiation, which increases temperature of the Earth's climate. Conversely, a negative forcing is associated with more outgoing radiation than incoming radiation, and decreases temperature.

The change in irradiance (or radiative forcing) is measured relative to the year 1750, which is considered the start of the industrial era.

Different types of clouds vary in terms of their effectiveness in reflecting incoming radiation and trapping outgoing radiation. Refer to the Earth's energy budget diagram in Figure 2 for an illustration of incoming and outgoing radiation. Shortwave radiation is on the left, while longwave radiation is on the right. Thin, high-altitude cirrus clouds are nearly transparent to incoming shortwave radiation but are very effective at trapping outgoing longwave radiation; an increase in this type of cloud would result in a net warming effect. Dense low-altitude cumulus and stratocumulus clouds are also effective at trapping outgoing longwave radiation, but they have a very high reflectance of incoming shortwave radiation, which results in a net cooling effect.

Low level marine stratocumulus clouds cover approximately a quarter of the oceanic surface (Charlson et al. 1987) and typically are characterized by their albedos, A, in the range of 0.3-0.7 (Schwartz &Slingo 1996) and droplet concentrations N of 50-200 cm^{-3}. Previous calculations show that doubling the droplet concentration N in all marine stratocumulus clouds globally (covering approximately 25% of the oceanic surface) could increase albedo to sufficiently offset warming caused by doubling CO_2 concentration

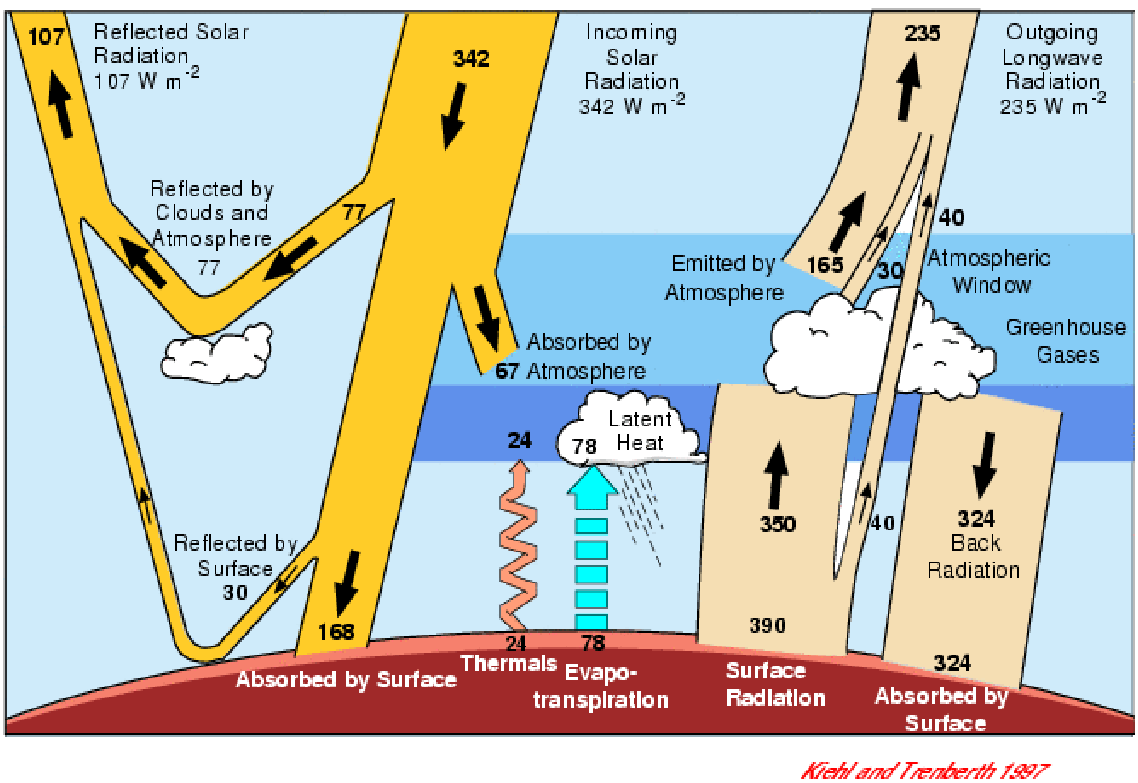

Figure 2: Global Heat Budget. The left side represents the shortwave radation, and the right side represents the longwave radiation.

in the atmosphere (Charlson et al. 1987; Slingo 1990; Twomey 1977). The associated change in planetary and top of cloud albedo is approximately 0.005 and 0.02, respectively. This change in albedo could have a significant impact on global climate. It has been estimated that an increase of 0.01 planetary albedo results in a decrease of 1° Celsius in global temperature (Ramanthanan, 1989).

3.2 Recent Advances in Understanding

The discussion in this section focuses on the recent work done by Latham et al. (2008) to quantify the global radiative fluxes resulting from increased droplet concentrations in marine stratocumulus clouds, as proposed by the geo-engineering method of spraying sea-salt into the atmosphere.

3.2.1 Analytical Relationships

In order to understand the basis of predicted changes in radiative forcing, simple analytical relationships are provided by Latham et al. (2008) between an increase in droplet concentrations ΔN, the associated increase in cloud albedo ΔA, and the resultant globally average negative forcing ΔF. The average solar irradiance F (W m^{-2}) received at the Earth's surface is

$$F=0.25F_o(1-A_p) \qquad \text{[Equation 2]}$$

where F_o(equal to 1370 Wm^{-2}) is the solar flux at the top of the atmosphere and A_p is the planetary albedo. For a value of $A_p = 0$, the solar irradiance F is equal to 342 Wm-2 (illustrated in Figure 2). An increase of ΔA_p produces an approximate forcing ΔF of

$$\Delta F = -340\Delta A_p \qquad \text{[Equation 3]}$$

The average change in cloud albedo ΔA associated with a change in planetary albedo is

$$\Delta A = \Delta A_p/(f_1 f_2 f_3) \qquad \text{[Equation 4]}$$

where f_1 is the fraction of the Earth's surface covered by ocean, f_2 is the fraction of the oceanic surface covered by marine stratocumulus clouds, and f_3 is the fraction of the marine stratocumulus clouds that are seeded with sea-salt aerosol. Values of f_1 and f_2 are typically 0.7 and 0.25, respectively (Latham et al. 2008). The relationship between changes in cloud albedo and the seeded droplet concentration N from the natural concentration N_o is given (Schwartz & Slingo 1996) as

$$\Delta A = 0.075 \ln (N/N_o) \qquad \text{[Equation 5]}$$

Combining equations 4 and 5, and rearranging gives

$$(N/N_o) = \exp(-\Delta F/4.5f_3) \qquad \text{[Equation 6]}$$

Assuming that doubling of CO_2 concentrations in the atmosphere (from 275 ppm to 550 ppm) results in a positive radiative forcing of approximately 3.7 W m^{-2} (Ramaswamy et al. 2001), and assuming all marine stratocumulus clouds are modified (f_3=1), the ratio of N/N_o to produce a negative forcing of 3.7 W m^{-2} is 2.3, which is in agreement with previous estimates by Charlson et al. (1987) and Slingo (1990). The required increase in planetary and cloud albedo are 0.011 (3.7%) and 0.062 (12%), respectively, which are higher than previous calculations of 0.005 and 0.02 by Charlson et al. (1987), Slingo (1990), and Twomey (1977). The discrepancy could be a result of differing assumptions for the amount of positive radiative forcing caused by doubling CO_2 concentrations. If the assumed positive radiative forcing was less than the value assumed by Ramaswamy, the required increase in albedo to offset the positive forcing would not be as high.

3.2.2 General Circulation Models

Modern computer technology has significantly advanced scientific capabilities to estimate global radiative fluxes through the use of sophisticated general circulation models (GCM). Although these models require future research to develop more accurate and precise algorithms, they can provide general guidance to evaluate climate parameters. GCMs are useful tools that have been used to research the global effects of the proposed geo-engineering method, as well as the most ideal conditions (such as location and timing) to implement the method.

Latham et al (2008) used two general circulation models (GCM) to analyze the global aspects of using sea-salt aerosol to enhance cloud albedo. The first model was the UK Hadley Centre HadGAM numerical model (described in Johns et al. (2004)) and includes the *New Dynamics Core* (Davies et al. 2005). The model was used to calculate mean values for top of cloud droplet effective radius, liquid water path, and outgoing shortwave radiation flux at the top of the atmosphere (TOA) for two scenarios: one control simulation with N approximately equal to 100 cm^{-3} (no seeding) and one simulation with N equal to 375 cm^{-3}. The results showed that the increased N scenario resulted in smaller droplet radius, an increased liquid water path, and decreased precipitation development (causing increased cloud longevity), which supports the proposed geo-engineering theory.

The largest changes in effective radius are off the west coasts of Africa, North America, and South America. These areas are typically characterized with extensive marine stratocumulus clouds. An interesting finding was that the scenario of seeding concentrations of 375 cm^{-3} resulted in a negative forcing of 8.0+/- 0.1 Wm^{-2}, which is more than twice that required to compensate for the positive 3.7 Wm^{-2} forcing from doubling CO_2 concentration. This supports an argument that there would be sufficient global offset if only a fraction of marine stratocumulus clouds were seeded ($f_3<1$). The seeding could be implemented only in regions that clearly are more effective for cloud manipulation.

A similar calculation was performed using the NCAR community atmosphere model (CAM). The NCAR results also indicated that some geographic locations are more effective for cloud seeding than others. This model also showed strong seasonal variations in optimal seeding locations. The most effective seeding to increase albedo and produce a net cooling effect occurs when there is the greatest incoming radiation. During the calendar months of December, January, and February, the sun is most intense in Southern Hemisphere. Conversely, the seeding in the Northern Hemisphere is most effective in June, July, and August. The NCAR model shows that optimal seeding over 25% of the ocean surface (or all marine stratocumulus clouds) may produce a net cooling close to 3.5 Wm^{-2} in December January and February if N is equal to 375 cm^{-3}.

3.3 Uncertainty

There are many uncertainties to be resolved before concluding that the geo-engineering technique proposed by Latham et al. should be implemented. The following items are uncertainties related to radiative fluxes and global climate affects.

The intentions of the geo-engineering method are to introduce seawater aerosols to low level marine stratocumulus clouds. However, there is uncertainty related to inadvertent introduction of seawater aerosols to the clear atmosphere (no clouds) and to higher-level clouds. Further research is necessary to determine associated radiative impacts on higher level clouds, since they likely contain ice particles and have different microphysical properties than low level clouds. It is possible that introducing seawater aerosols to high level clouds could have a warming effect and negate the intentions of the geo-engineering method. The effect of potential precipitation development resulting from introducing seawater aerosols to high-level clouds is also unknown (Latham, 2002).

An important issue that needs to be thoughtfully considered is that the proposed geo-engineering method will not stop climate change and the meteorological effects remain unknown. Recent studies indicate specific geographic regions and seasons for which the cloud seeding scheme would be most effective to sufficiently offset global radiative forcing caused by increased CO_2 emissions. However, if cloud seeding occurred only in those specific areas of the world (opposed to uniform lateral distribution across the Earth's surface), it would alter climate regimes associated with ocean currents, temperature, rainfall, and wind patterns. Also, the temperature structure of the atmosphere would change and there would be an increase in the difference between land and ocean temperatures (Latham et al.,2008). All of these factors could result in unforeseen feedback processes. Further research is required to understand the impacts of these uncertainties.

4 Conclusion

This review discussed the geo-engineering method proposed by John Latham in detail, providing the assumptions and logic that were incorporated in his idea. Recent studies are also presented, which add further understanding of the parameters (in both local cloud microphysics and in global radiative fluxes) involved in implementing the proposed cloud manipulation technique.

When considering geo-engineering options, one must always keep in mind that these methods are not meant to solve the problem of climate change. They only address part of the problem. For example, mitigating the temperature rise caused by climate change does not address other problems such as ocean acidification. They are designed to act as a temporary bandage, providing time for the world to permanently solve the problem by reducing green house gas emissions.

It is clear that changing the albedo of marine stratocumulus clouds by spraying sea-salt aerosols could significantly influence the radiative flux on a global scale. However, there are several areas that need to be studied further before concluding that the science behind this geo-engineering method is robust.

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