

Tropical anvil clouds and climate sensitivity

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The surface temperature of Earth is being increased by human activities, principally by the release of greenhouse gases (1). Future warming will depend upon the rate at which greenhouse gases are released and the sensitivity of Earth's surface temperature to those increased greenhouse gases. An often used metric of the sensitivity of Earth's climate is the equilibrium climate sensitivity, the amount of global average surface warming that is the steady, long-term response to a doubling of carbon dioxide. The equilibrium climate sensitivity remains uncertain by about a factor of two, despite decades of study using evidence from basic theory, instrumental observations, paleoclimatic data, and global climate models (2). Global climate models indicate that a large contributor to uncertainty in climate sensitivity is the strength of cloud feedbacks. Cloud feedback is a response of cloud structure or amount to warming, which then alters the energy balance of Earth, which causes an additional change of surface temperature. An advance was made in the most recent report of the Intergovernmental Panel on Climate Change, which concluded that cloud feedback is likely positive, meaning that the response of clouds to climate change acts to increase the magnitude of the surface temperature change (3). This consensus is based in part on the development of basic physical understanding of why high clouds get higher (4) and low clouds decrease their area coverage in a warmed climate (5, 6). In PNAS, Bony et al. (7) propose a basic thermodynamic mechanism that may cause the temperature profile to become more stable in the upper troposphere when the Earth warms. They expect this stabilization to cause anvil cloud area to decrease in a warmed climate, although they conclude that the effect of this anvil area reduction on cloud feedback is uncertain.

An understanding of the role of cloud feedback begins with the measurement of the effect of clouds on the energy balance of the present climate. Earth's surface and atmosphere are warmed by absorption of solar radiation and cooled by the emission of thermal infrared radiation to space. The fluxes of radiative energy to and from Earth can be measured

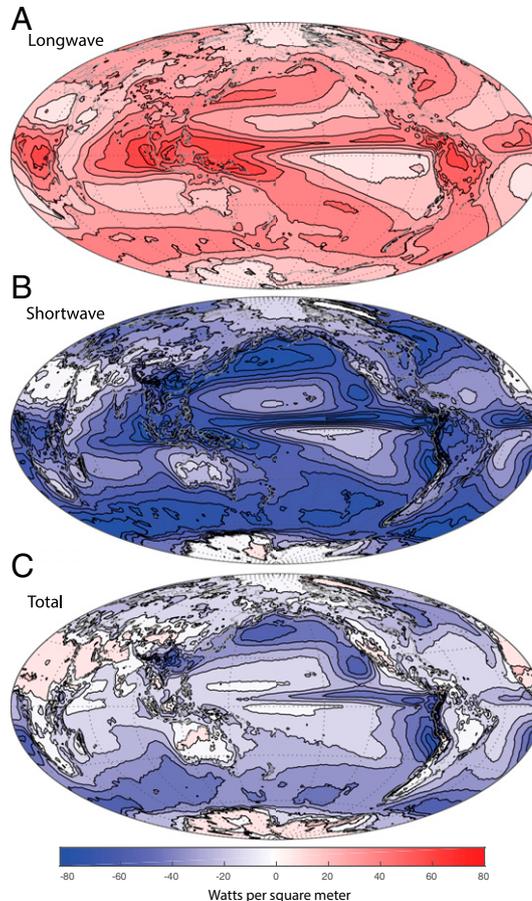


Fig. 1. Annual mean (A) longwave, (B) shortwave, and (C) total cloud radiative effects from the CERES EBAF data product (19) averaged over the years 2000–2013. Contour interval is 10 Wm^{-2} . The map projection is an equal-area Hammer projection with 180°E in the center of the plot.

accurately from Earth-orbiting satellites. If the geographical area of the footprint of the measurement is small enough, then the energy exchange in cloudless areas can be separately estimated; the difference between the average and the cloudless energy balances is called the "cloud radiative effect" (8). The cloud

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radiative effect has a solar or shortwave component, an infrared or longwave component, and a total effect, which is the sum of the longwave and shortwave contributions.

The geographic distributions of the longwave, shortwave, and total cloud radiative effects illustrate the potential power and complexity of cloud feedback (Fig. 1). A positive longwave cloud radiative effect results because clouds absorb and emit longwave radiation very efficiently. Because cloud tops are colder than the atmosphere below them, they emit less longwave radiation to space than clear skies, especially as the cloud tops get higher and colder. Therefore, the longwave cloud effect is large and positive in regions of deep tropical convection, as over the west Pacific and eastern Indian Ocean regions, and over equatorial South America and Africa (Fig. 1A). In these same regions, the shortwave cloud effect is negative, because clouds reflect solar radiation back to space much more effectively than the ocean or forest below them (Fig. 1B). The shortwave cloud effect is not very sensitive to the altitude of the clouds, but depends mostly on the optical thickness of the clouds, which is determined by the mass of cloud water or ice and the size of the cloud particles. Therefore, the low stratocumulus decks off the west coasts of North and South America have a large negative shortwave cloud effect, but a much smaller positive longwave effect.

When the longwave and shortwave effects of clouds are combined to form their total effect on Earth's energy balance, an interesting cancellation occurs between the longwave and shortwave effects of tropical convective clouds, resulting in a small negative total effect (Fig. 1C). In particular, over the Indian and Pacific Ocean sector, the longwave and shortwave cloud effects cancel nearly exactly. This cancellation has long been noted (9, 10) and it is unclear whether it results from happenstance or from some not yet understood feedback process. Individual cloud elements can have strongly negative effects, such as an optically thick convective core, or strongly positive effects, such as an optically thin cirrus cloud. Therefore, the smallness and near neutrality of the total effect of tropical convective cloud is the aggregate effect of a population of clouds that can individually have very strongly positive or negative effects (11). If this population remains the same and its area coverage is changed, one would expect relatively little impact on Earth's climate from the cloud radiative effects. On the other hand, if the average cloud area stays the same, but the population shifts from cloud types with negative to cloud types with positive effects (or vice versa), then a substantial impact on Earth's climate could be produced without any change in high cloud area.

Convection in the tropics is driven by the need to move energy from the surface, where solar radiation heats the ocean, to the upper troposphere, where emission to space from water vapor in the atmosphere can cool the planet (12). Direct emission of infrared energy to space from the surface is extremely inefficient because of the strong absorption of infrared energy by water vapor in the first few kilometers of the tropical atmosphere. Energy is moved upward by tropical convective cores, strong local updrafts of warm, humid air. These upward plumes spread out to form anvil clouds below the tropopause at the level where the infrared optical depth of water vapor is declining rapidly with altitude, and where emission of radiation to space is most efficient. The area covered by these anvil clouds is much larger than the area occupied by the convective cores, and the anvils are thus the primary type of high cloud for modulating the Earth's radiative energy balance. They are called "anvil clouds" because the combined shape of the convective core

and the spreading clouds at upper levels resembles the shape of a blacksmith's anvil, with a narrow base and a larger working surface that extends laterally above the base. Anvil cloud refers specifically to the upper overhanging clouds.

The clear air below the anvil cloud is important for the maintenance and spreading of the anvil cloud. The bases of anvil clouds are strongly heated by infrared radiation because the upward flux of infrared from the warm atmosphere below is much larger than the downward emission from the colder anvil cloud bases. The anvil clouds are cooled at the top by infrared emission to space and heated at the bottom by net infrared absorption, so that their lifetime in the atmosphere and their area coverage are increased both by net heating and the generation of convection within the anvil cloud (13). Anvil clouds spread and become

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thinner until their water falls out as rain or evaporates. The area of the anvil cloud is thus determined not only by the supply of moisture from the convective towers, but also by radiative effects and convection within the anvil cloud layer (14).

Processes that determine the extent and radiative properties of tropical convective clouds occur at relatively small spatial scales. The effects of tropical convection on the mean climate must be expressed approximately in terms of variables resolved at the much larger spatial and temporal scales of the global climate model. Confidence in the behavior of clouds and convection in climate models is based upon process models that use much higher spatial and temporal resolution in smaller domains, or upon basic physical constraints that govern the net outcomes from all of the detailed processes going on in convective cloud systems. Basic constraints include energy, water, and mass balances. One of the most important additional constraints on the climate system is the dependence of saturation vapor pressure on temperature.

At terrestrial temperatures, for every degree centigrade (°C) of warming, the saturation vapor pressure increases by about 7%, and the rate of blackbody radiative emission increases about 1.5% (12). Therefore, the percentage increase of latent energy of water vapor near the Earth's surface will be nearly five times larger than the increase of longwave emission to space. The upward flux of air in convective cores will thus increase the latent heating of the atmosphere much faster than emission to space can dispose of the additional energy. These basic physical facts predict that we might expect the mass flux of air in convective systems to decrease in a warmer climate (15). If the anvil cloud area is proportional to the upward flux of air in the convective cores, then we would expect the anvil cloud area to decrease in a warmed climate. Other mechanisms that may reduce high tropical cloud area, as clouds move higher in the atmosphere after warming, are the static stability increases in the upper troposphere associated with ozone heating (16) and the pressure dependence of static stability (7). The ratio of anvil cloud area to convective core area may also change in a warmed climate, but this depends more strongly on small-scale cloud dynamics and microphysics, and is less constrained by basic conservation laws. One important result from high-resolution process models is the tendency of tropical convection to self-aggregate, to collect in one region of the

domain (17). This mechanism may also play a role in how convective cloud area responds to warming.

Global climate models explicitly include the pressure dependence of static stability (7), the saturation vapor pressure dependence on temperature, realistic radiative transfer, and the large-scale conservation of energy and mass. Global climate models do predict a significant reduction in high-altitude tropical clouds as the climate

warms, and this has a significant impact on the total cloud feedback (18). The small-scale dynamic, radiative, and microphysical processes that control the extent of tropical anvil clouds are not well represented in global climate models, and assessment of the effects of these processes on climate sensitivity is an ongoing area of research. A key goal is to understand what processes control the relative abundance of optically thick and thin anvil clouds.

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