Clouds - their formation and importance for climate

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PSI, March 30, 2023
Variety of clouds

Sources: Fabian Mahrt own photos
Summer 2022: lack of and too many clouds

China, France: drought, Pakistan: flooding
Sources: Tagesschau; media news, Handelsblatt
Outline

How are clouds formed?

How are clouds and aerosols influencing our climate?

What do we expect in future? Can clouds and aerosols be used to (partly) offset global warming?
How are clouds formed?
Cloud formation:

- Sufficient moisture in the atmosphere
- Rising and cooling of air parcels/air masses
- Aerosol particles, on which water vapor can condense/deposit to form cloud droplets/ice crystals
Cloud formation:
Lifting of air at frontal surfaces or orography

Source: MeteoSchweiz
Cloud formation: heating from below

Source: MeteoSchweiz
Downpour over lake Millstätt, Austria

Courtesy: Christoph Schär
Variety of aerosol sources:
No particles – no clouds

ASCOS research cruise in summer 2008:
• Temperature: -8 °C,
• Aerosol concentration: < 10 cm$^3$ (typical concentration over continents: 1000 cm$^3$)

Tjernström et al., ACP, 2013. Movie: Zoran Ristovski, http://www.youtube.com/watch?v=EneDwuOHrVg
No particles - no clouds

Zoran Ristovski, http://www.youtube.com/watch?v=EneDwu0HrVg
How are clouds and aerosols influencing our climate?
Global energy budget

Updated from Lohmann et al., 2016
The transition between these regimes depends on both cloud height and optical depth but is decidedly skewed toward an albedo effect for most cloud types owing to the asymptotic behavior of the longwave radiative effect, which saturates at relatively low optical depth. Only high, thin cirrus clouds and, to a much lesser extent, altostratus, exert positive net radiative effects globally.

The SW and LW radiative effects of each cloud type are presented in Figs. 8 and 9, respectively. Single-layer cirrus are found to reduce SW absorption by only 0.8 W m\(^{-2}\) but decrease outgoing LW by 2.8 W m\(^{-2}\) resulting in a net warming effect of 2 W m\(^{-2}\). In contrast, stratocumulus clouds reduce SW absorption by 10.4 W m\(^{-2}\) on the global annual mean, an effect nearly five times stronger than their greenhouse effect noted above. While single-layer nimbostratus, altostratus, and deep convective clouds exert significant effects in both SW and LW radiation individually, these effects largely cancel over the midlatitudes and tropics resulting in comparatively weak global mean net radiative effects.

Cloud shortwave effects at the TOA are dominated by the grid box mean cloud optical depth, which peaks in areas of frequent stratocumulus a few hundred kilometers off the west coasts of North America, South America, Africa, and Australia. Stratus exert significant shortwave radiative effects but in smaller regions confined closer to the coasts while altostratus and nimbostratus exert strong shortwave effects in the higher-latitude storm tracks. Once again, infrequent single-layer deep convective clouds lead to a relatively small net SW radiative effect that is confined to the ITCZ and west Pacific.

Cloud longwave effects are generally dominated by the distribution of cloud-top height within each grid box peaking in regions where cirrus and altostratus are prevalent such as the intertropical and South Pacific convergence zones. At higher latitudes, frequent, relatively deep nimbostratus exert a significant longwave radiative effect that sums to a global impact comparable in magnitude to that of cirrus and altostratus. Perhaps less intuitively, clouds identified as stratocumulus in 2BCLD are also found to exert a substantial longwave radiative effect, owing to their large populations in storm tracks in North Atlantic and Pacific and over the southern oceans. While it may be debated whether it might be more appropriate to classify these clouds as cumulus, these results clearly indicate that, in sufficient numbers, purely liquid bearing clouds with high emissivities and tops warmer than 273 K exert a significant radiative effect.
Aerosol’s influence on clouds:

Source: www.meted.ucar.edu
Radiative forcing due to anthropogenic aerosols

The relative contribution of different parameters to the uncertainty in forcing referenced to 1850 (47% versus 46% of variance; see Methods). Interactions generally account for less than 10% of the total forcing variance, demonstrating that the ranked uncertainty results are robust to uncertainties in the model set-up.
Contributions to the observed warming since 1750

Figure 7.7: The contribution of forcing agents to 2019 temperature change relative to 1750 produced using the two-layer emulator (Supplementary Material 7.SM.2), constrained to assessed ranges for key climate metrics described in Cross-Chapter Box 7.1. The results are from a 2,237-member ensemble.

Temperature contributions are expressed for carbon dioxide, other well-mixed greenhouse gases (WMGHGs), ozone, stratospheric water vapour, surface albedo, contrails and aviation-induced cirrus, aerosols, solar, volcanic, and total. Solid bars represent best estimates, and very likely (5–95%) ranges are given by error bars. Dashed error bars show the contribution of forcing uncertainty alone, using best estimates of ECS (3.0°C), TCR (1.8°C) and two-layer model parameters representing the CMIP6 multi-model mean. Solid error bars show the combined effects of forcing and climate response uncertainty using the distribution of ECS and TCR from Tables 7.13 and 7.14, and the distribution of calibrated model parameters from 44 CMIP6 models. Non-CO₂ WMGHGs are further broken down into contributions from methane (CH₄), nitrous oxide (N₂O) and halogenated compounds. Surface albedo is broken down into land use changes and light absorbing particles on snow and ice. Aerosols are broken down into contributions from aerosol-cloud interactions (ERFaci) and aerosol-radiation interactions (ERFarı). Further details on data sources and processing are available in the chapter data table (Table 7.SM.14).
Impact of anthropogenic aerosol emissions on climate
Cloud response to the Holuhraun eruption for October 2014

Conclusion: Holuhraun caused a reduced cloud droplet size but had no discernible effect on other cloud properties.

Malavelle et al., Nature, 2017
MODIS vs. ML (random forest) for 2001-2020 (w/o 2014) left

Oct 2014 right

Chen et al., NatGeo, 2022
Cloud responses to the Holuhraun eruption (Oct 2014)


Chen et al., NatGeo, 2022
Conclusions from the Holuhraun study:

- The Holuhraun eruption led to an increase in cloud cover by approximately 10% with no change in liquid water path.

- This effect is larger than the albedo increase from the reduced cloud droplet size.

Chen et al., NatGeo, 2022
Can clouds and aerosols be used to (partially) offset global warming?
We decide if and how we reach the 2 °C climate goal

1) No mitigation

2) Mitigation

3) Mitigation and CDR

4) Mitigation and CDR and SRM

CDR: carbon dioxide removal

SRM: solar radiation management

Jones et al., Earth Future, 2018
Global energy budget

<table>
<thead>
<tr>
<th>Solar reflected by clouds, aerosol and gases</th>
<th>Atmosphere</th>
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<tr>
<td>Solar down surface</td>
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<td>Solar absorbed</td>
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<td>Sensible heat</td>
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<td>Up surface</td>
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<td>Atmospheric window</td>
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<tr>
<td>Thermal outgoing</td>
<td>239</td>
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<td>Earth’s surface</td>
<td>25</td>
</tr>
</tbody>
</table>

Solar reflected by clouds, aerosol and gases: 75
Solar down surface: 185
Solar absorbed: 80
Absorbed solar: 160
Sensible heat: 21
Latent heat: 82
Up surface: 398
Down surface: 342

Imbalance: 1
Atmospheric window: 40
Thermal outgoing: 239
Global energy budget updated from Lohmann et al., 2016
Radiation management methods

Sources: meteo.sf.tv/sfmeteo, Univ. Washington, Lohmann and Gasparini, Science, 2017
Natural analogon: volcanic eruptions

Reflecting solar radiation

SO$_2$ => H$_2$SO$_4$

Gas aerosol (aq)

Stratosphere troposphere

10-15 km

Cooling

Courtesy Blaz Gasparini
Observed temperature response after Mt. Pinatubo

Courtesy Blaz Gasparini
Effect of stratospheric aerosol injections on temperature & precip

Temperature and precipitation cannot be simultaneously restored with solar radiation management

Boucher et al., IPCC, 2013, Fig. FAQ 7.3.2
Limits of stratospheric aerosol injections

2/3 of the year 2000 sulfur emissions of 145 Tg S are needed to counteract the radiative forcing of the RCP8.5 scenario in 2100. Higher aerosol injection rates result in faster coagulation and sedimentation.

Niemeier and Timmreck, ACP, 2015; Kleinschmitt et al., GRL, 2018
Ship traffic in the Southern Atlantic causes a radiative forcing of $\approx -2$ W m$^{-2}$.
Temperature evolution with vs. without marine cloud brightening

Ensemble mean temperature change: climate engineering - RCP4.5: -1°C

Stjern et al., 2018 and Univ. Washington
Can artificially altered clouds save the Great Barrier Reef?

Australian scientists are rushing to develop new technologies — such as ways to block sunlight — to help preserve corals in the face of climate change.

Jeff Tollefson

During a field trial, a turbine generates plumes of seawater droplets that rise into the sky. Credit: Brendan Kelaher/SCU
Importance of mixed-phase clouds

Mülmenstädt et al., GRL, 2015
Cloud radiative effect of high latitude MPCs

Villanueva et al., ERL, 2022
Cloud radiative effect of wintertime MPCs

Villanueva et al., ERL, 2022
Hole-punch cloud

source: wikipedia
Cloud radiative effect of seeded high-latitude oceanic MPCs

\[
\Delta \text{CRE (Wm}^{-2}\text{)}
\]

Seeding concentration $[\text{L}^{-1}]$

Villanueva et al., ERL, 2022
Climate implications of MPC seeding

Villanueva et al., ERL, 2022
Take-home messages: mixed-phase cloud seeding

Mixed-phase cloud seeding could offset about 25% of the expected increase in polar sea-surface temperature due to the doubling of CO$_2$.

This is accompanied by an annual increase in sea-ice surface area of 8% around the Arctic, and 14% around Antarctica.

Mixed-phase cloud seeding, however, cannot prevent sea-ice loss during summer and as every climate intervention method only cures the symptoms.
Thanks a lot for your attention!

Questions?
Formation of a hole-punch cloud

As/Ac
T < 0 °C

RH_{w} \approx 100\% \quad \text{p} \downarrow \rightarrow \text{T} \downarrow

RH_{w} < 100\%
RH_{i} > 100\%
WBF

RH_{i} \approx 100\%

Courtesy of Cyril Brunner