

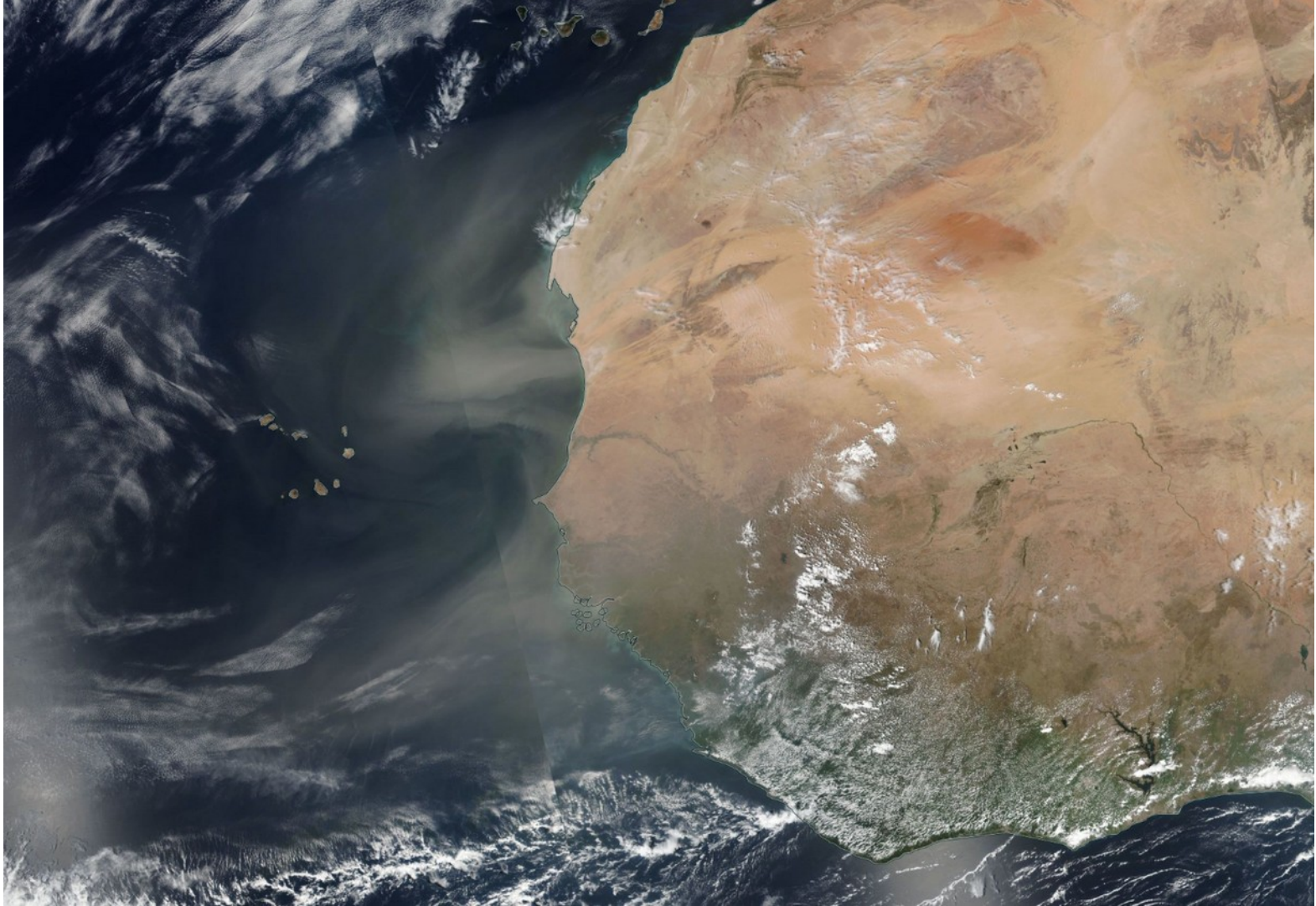
Fizyka Procesów Klimatycznych Chmury

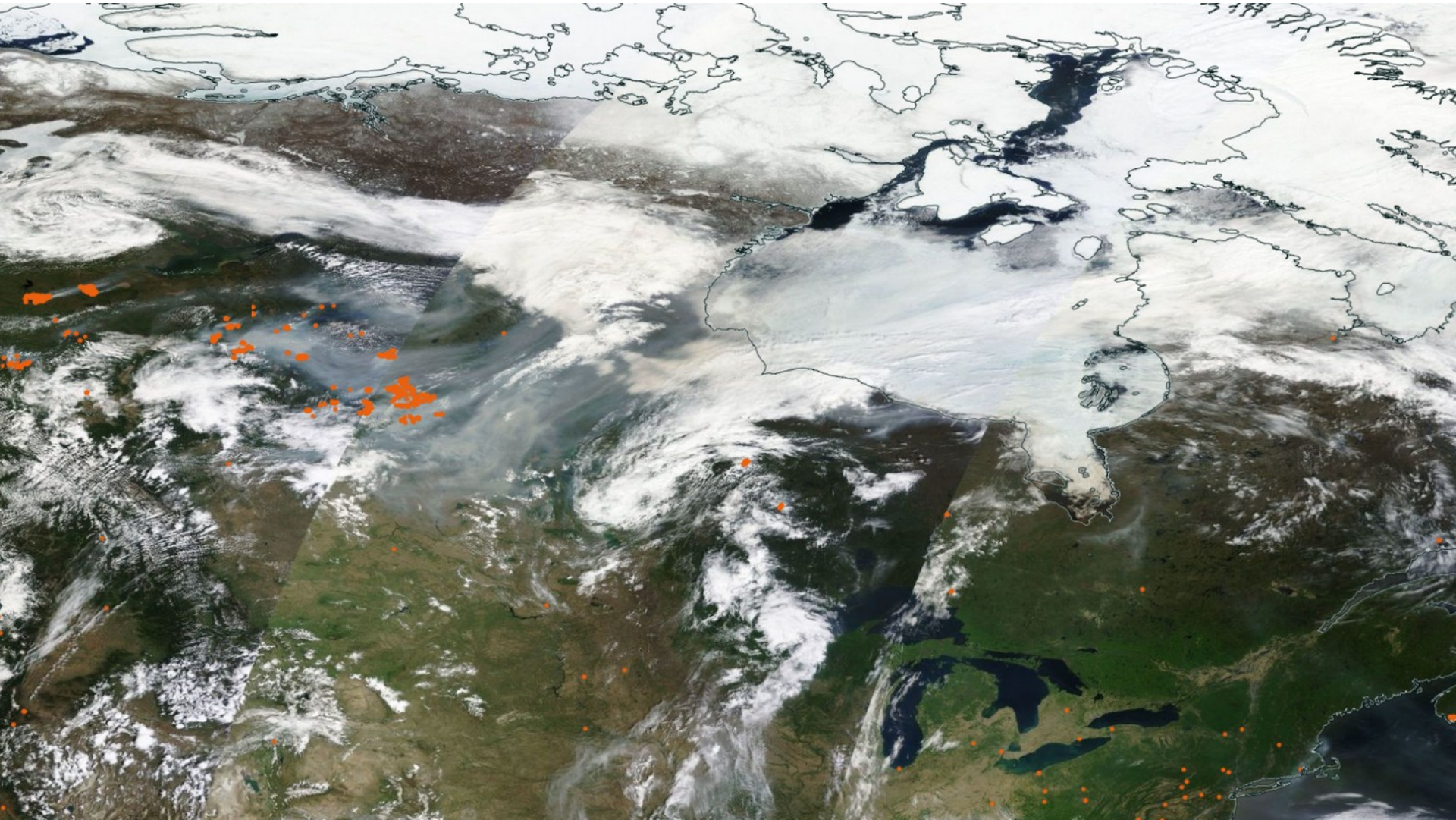
**prof. dr hab. Szymon Malinowski
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Uniwersytet Warszawski
kmark@igf.fuw.edu.pl**

Aerozole







Chmury

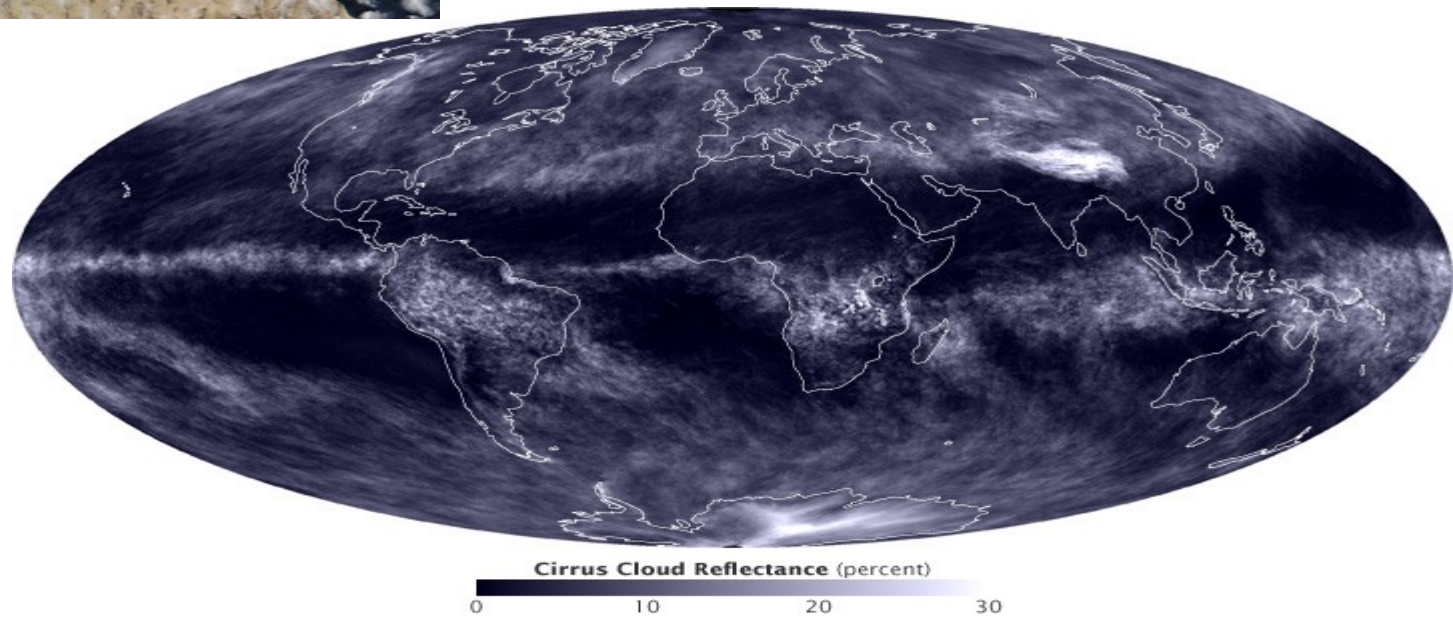


Chmury niskie:
dominuje efekt albedo





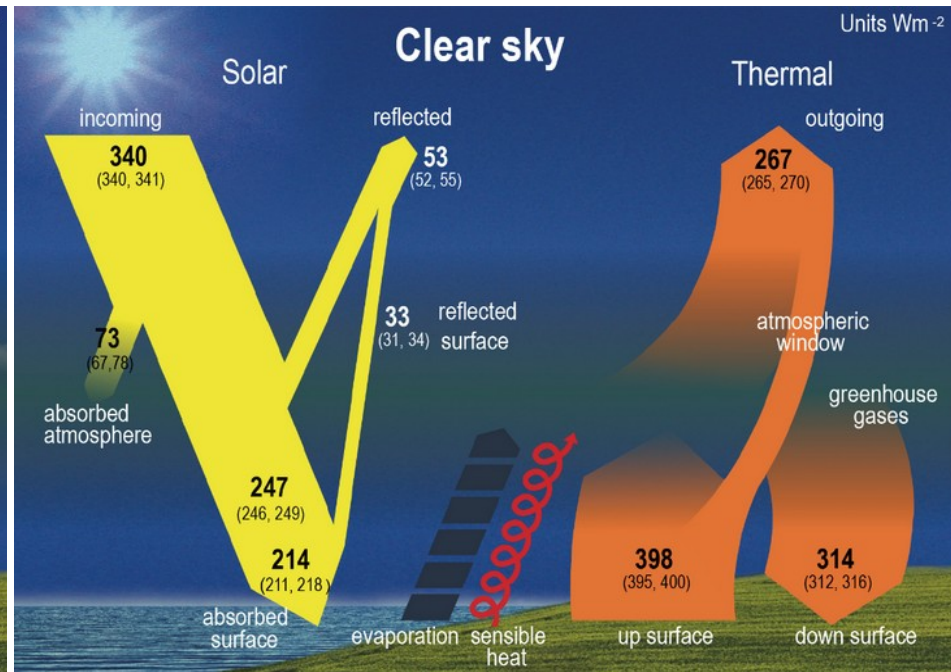
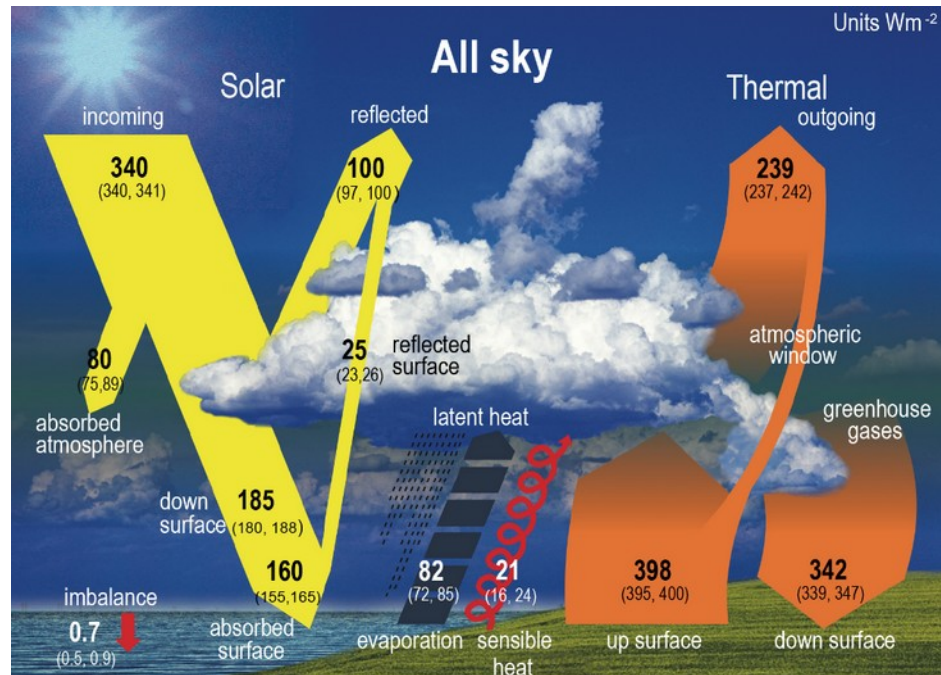
Chmury wysokie: ważny zarówno efekt cieplarniany jak i albedo



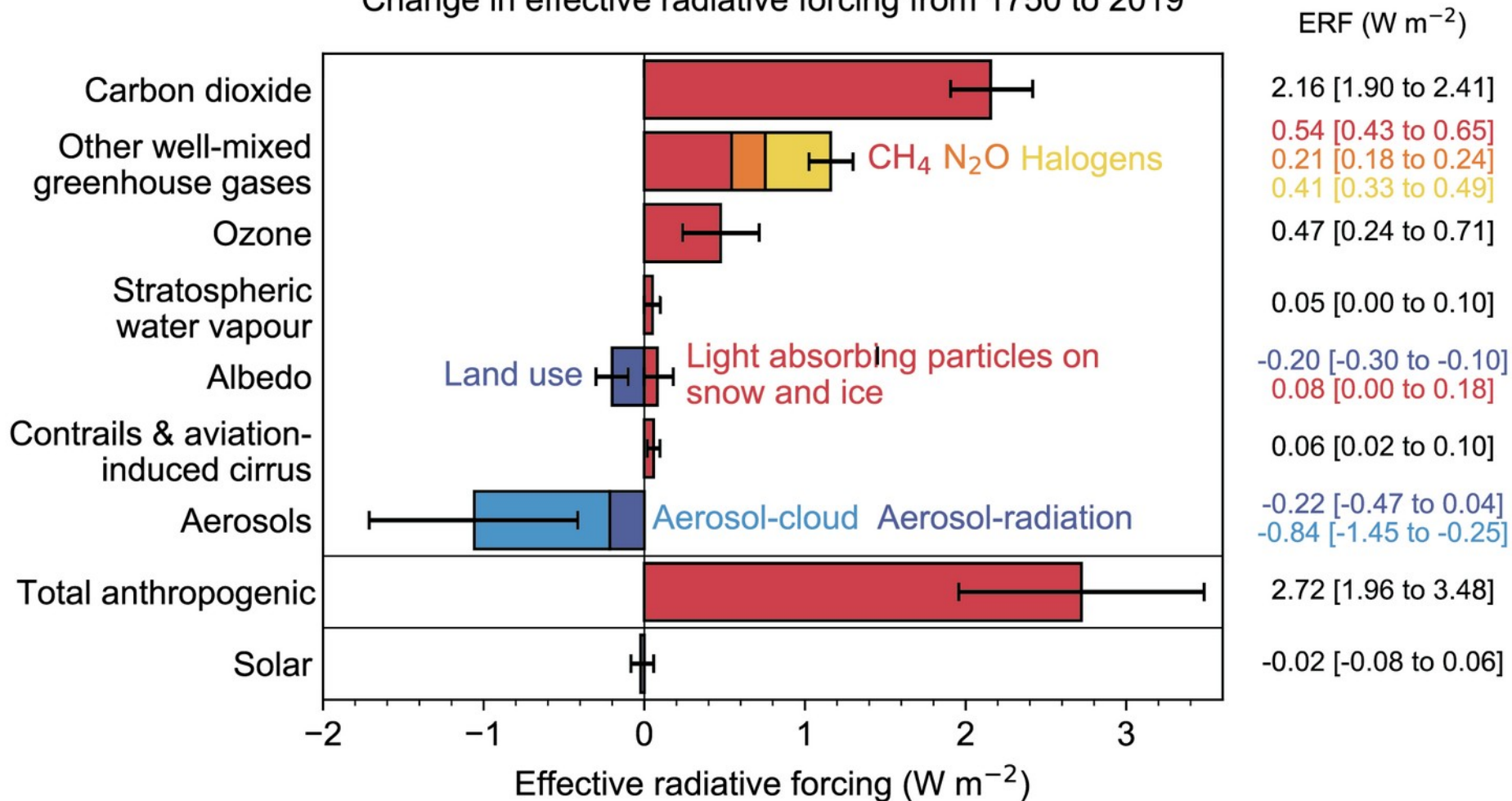
Chmury rozbudowane w pionie: ważne wszystkie efekty



Schematic representation of the global mean energy budget of the Earth (left panel), and its equivalent without considerations of cloud effects (right panel).



Change in effective radiative forcing from 1750 to 2019



Wróćmy do chmur...

Woda w atmosferze – domieszka do tzw. „powietrza suchego” występuje w trzech stanach skupienia - stałym, ciekłym i gazowym.

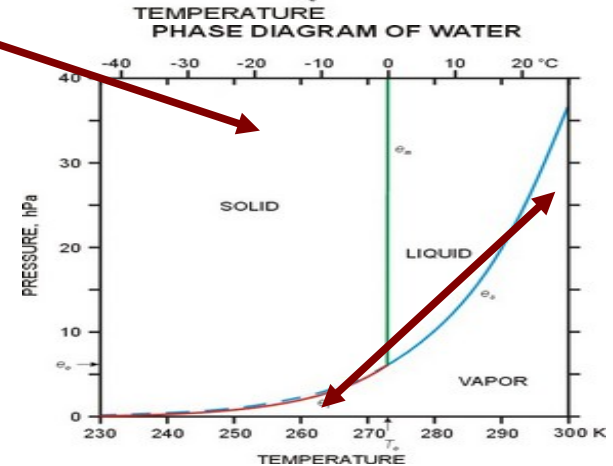
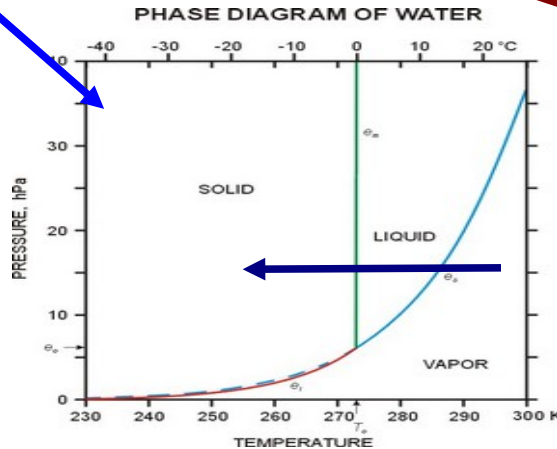
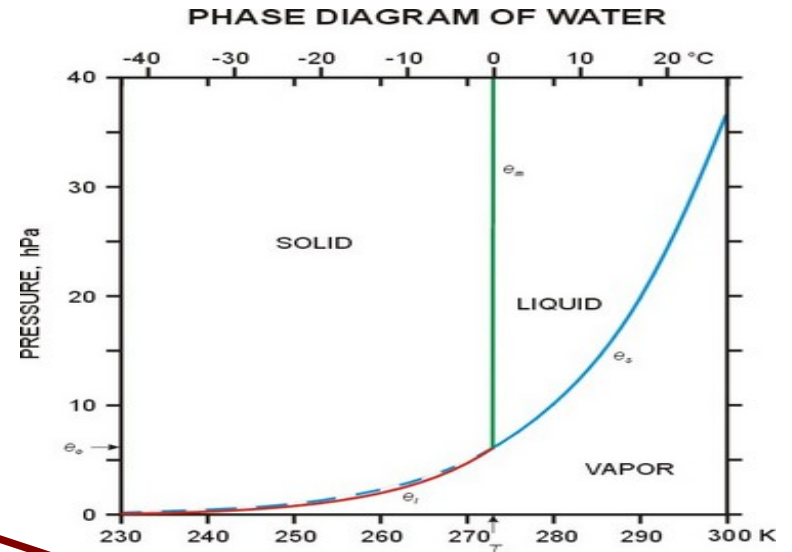
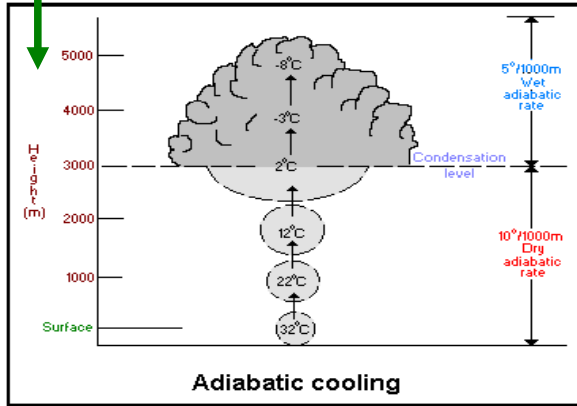
Przejścia pomiędzy tymi stanami mają swoje nazwy i tak - między stanem stałym i ciekłym topnienie i zamarzanie: między stanem ciekłym i gazowym - parowanie i kondensacja: między stanem ciekłym i gazowym - sublimacja i resublimacja.

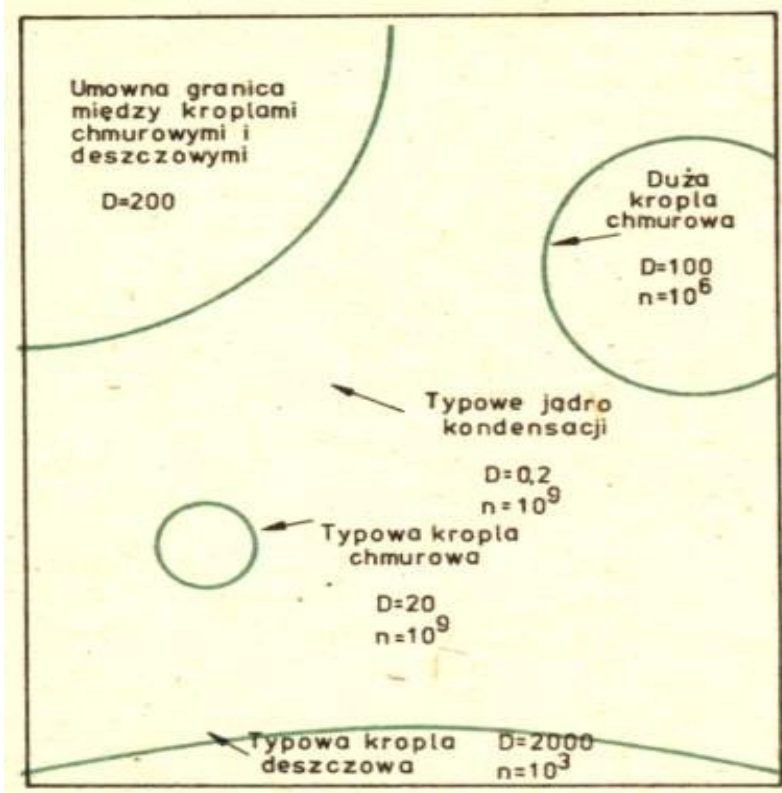


Procesy fizyczne prowadzące do kondensacji pary wodnej obecnej w powietrzu:
 rozprężanie adiabatyczne (np. w ruchach wstępujących);

ochładzanie izobaryczne (radiacyjne, przez przewodnictwo);

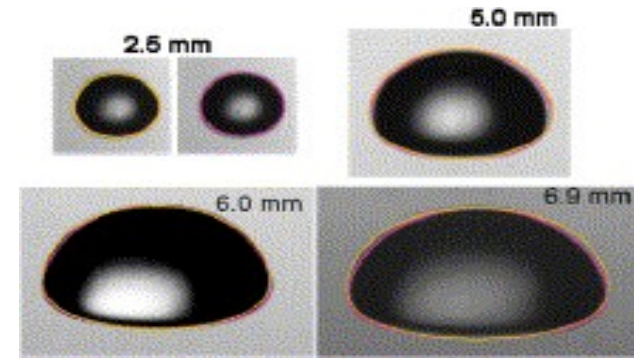
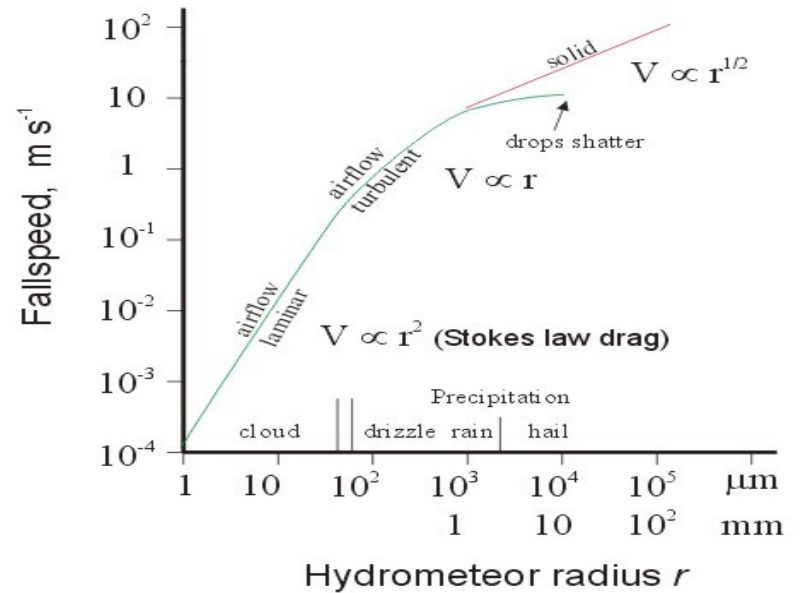
mieszanie izobaryczne.



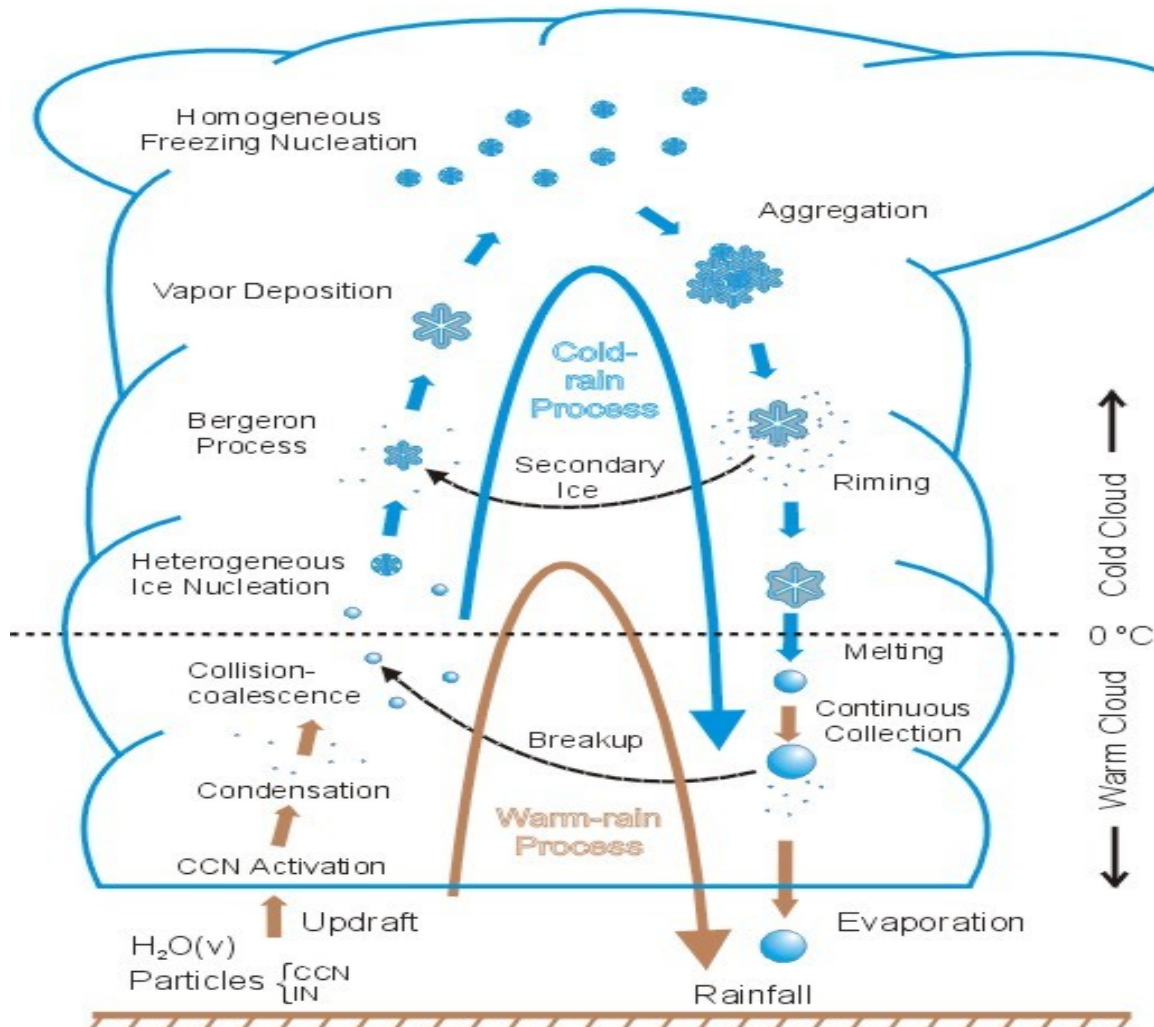


KROPLE CHMUROWE I OPADOWE

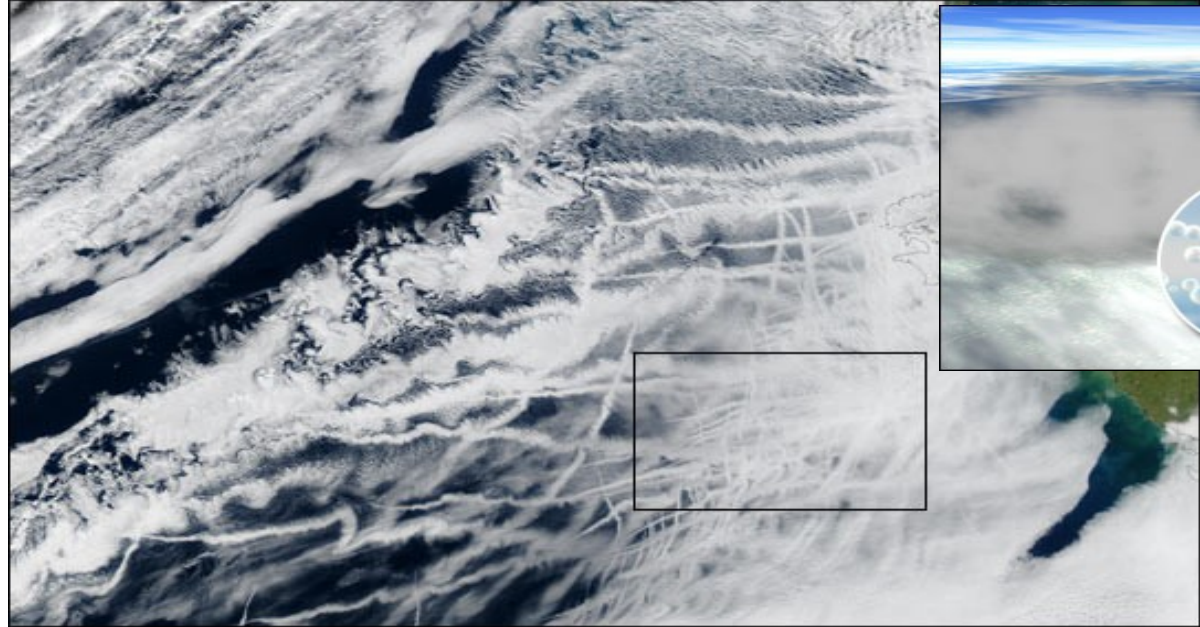
CLOUD-PARTICLE FALLSPEEDS



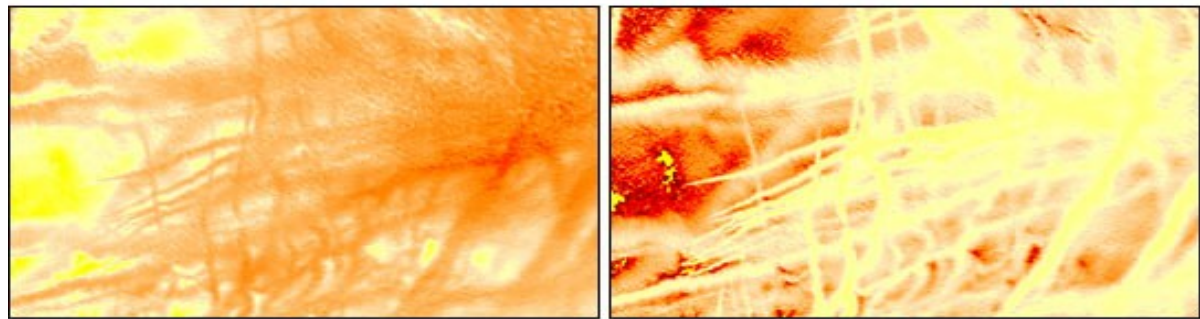
PRECIPITATION MECHANISMS



Mechanizmy opadowe



True Color



Optical Thickness

Effective Particle Radius (μm)

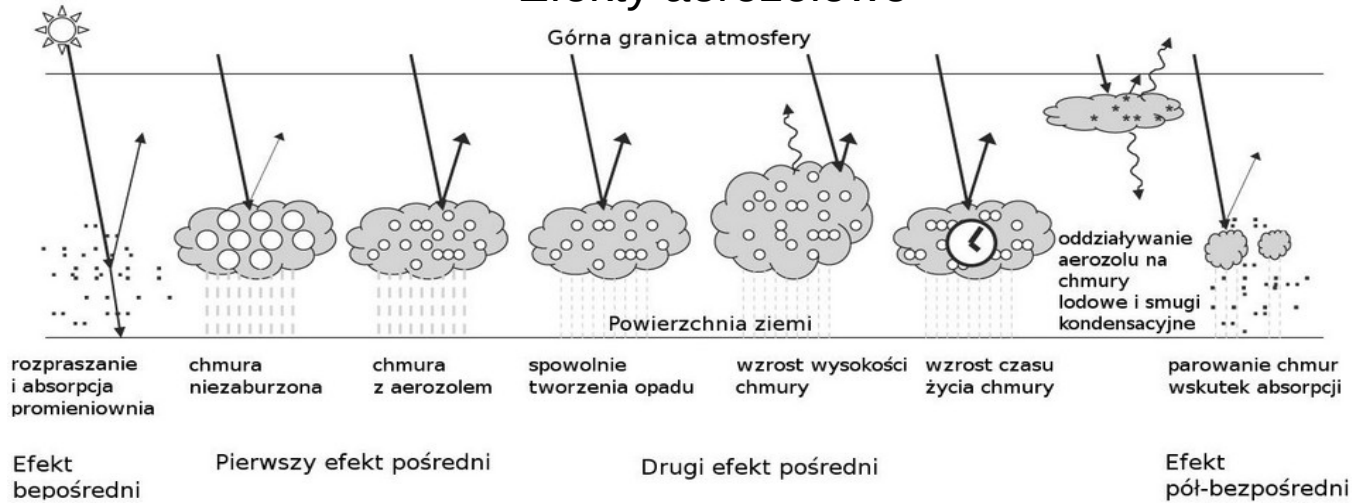


Wpływ aerozolu na budowę chmur (rozmiar kropelek) i w konsekwencji na ich własności radiacyjne:

tzw. pośrednie efekty aerozolowe:

- pierwszy (albedo chmur)
- drugi (czas życia chmur).

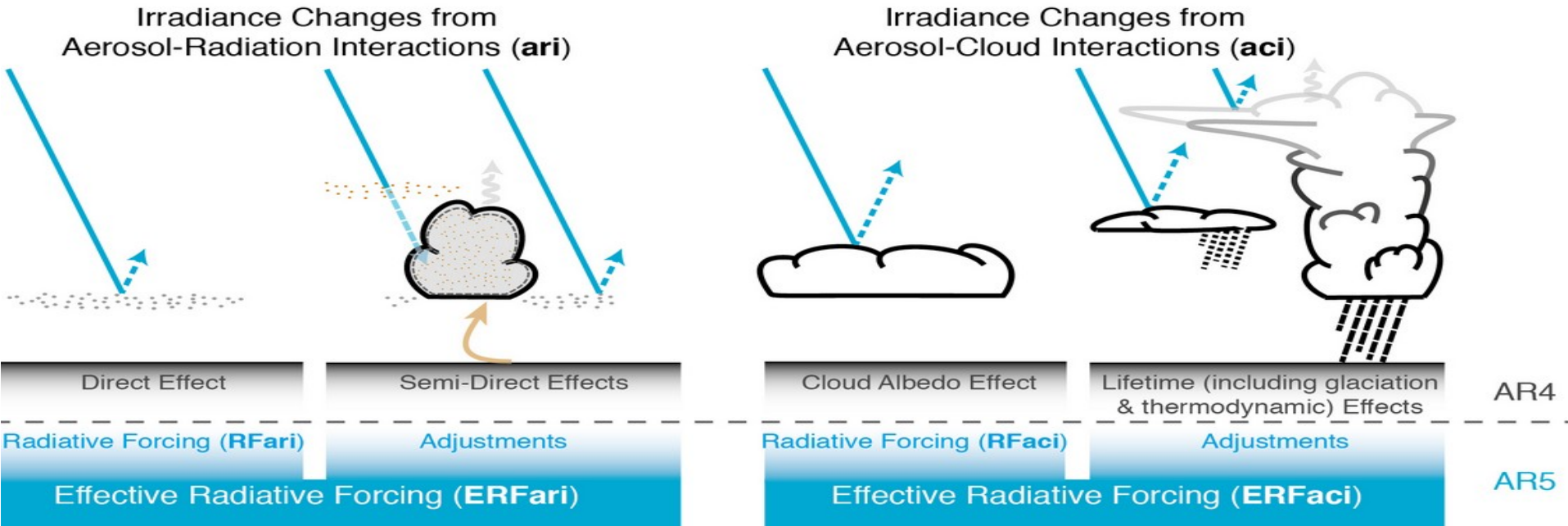
Efekty aerozolowe



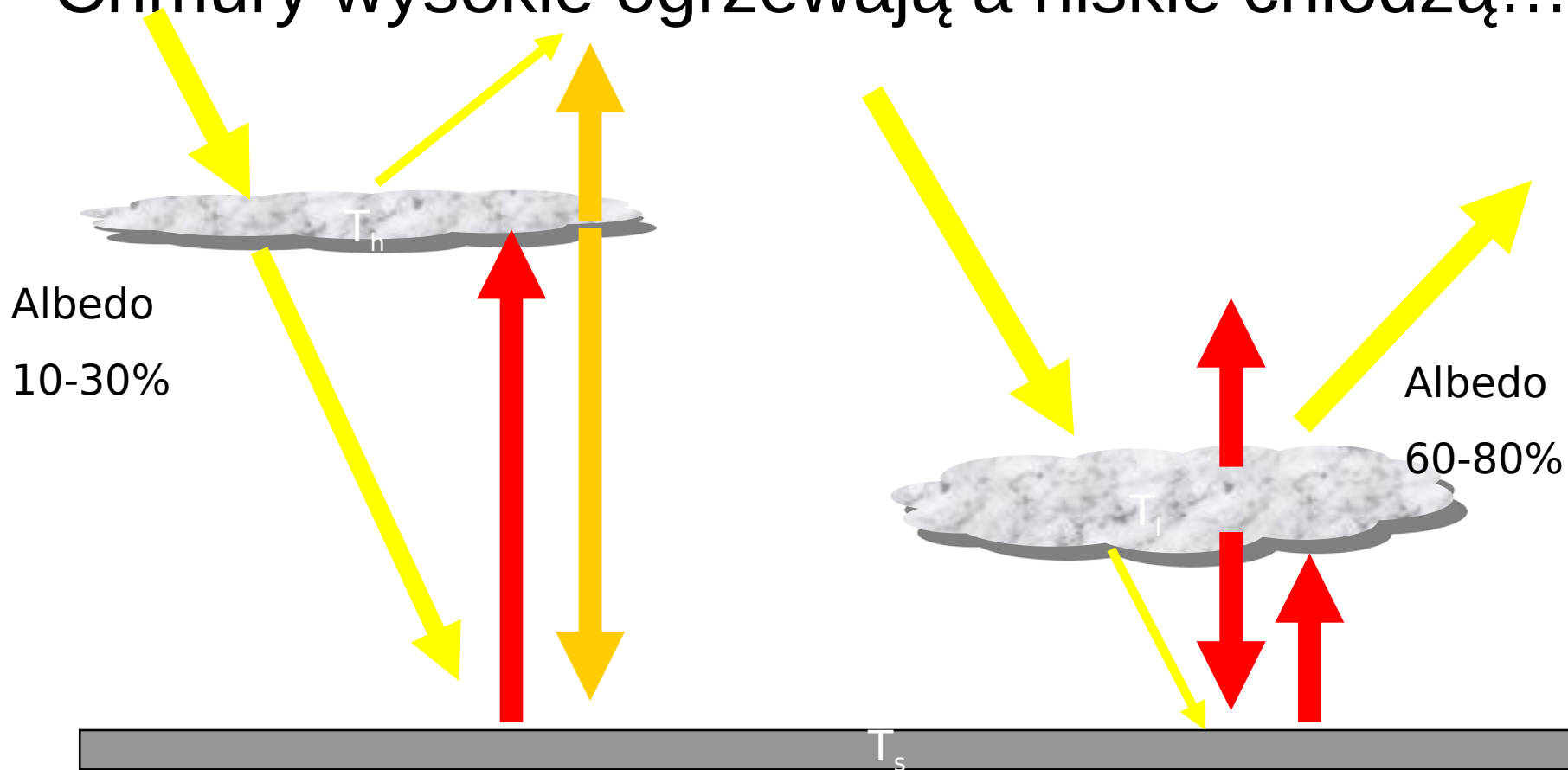
Efekt Twomeya

Efekt Albrechta

Efekty aerozolowo-chmurowe wg. V Raportu IPCC

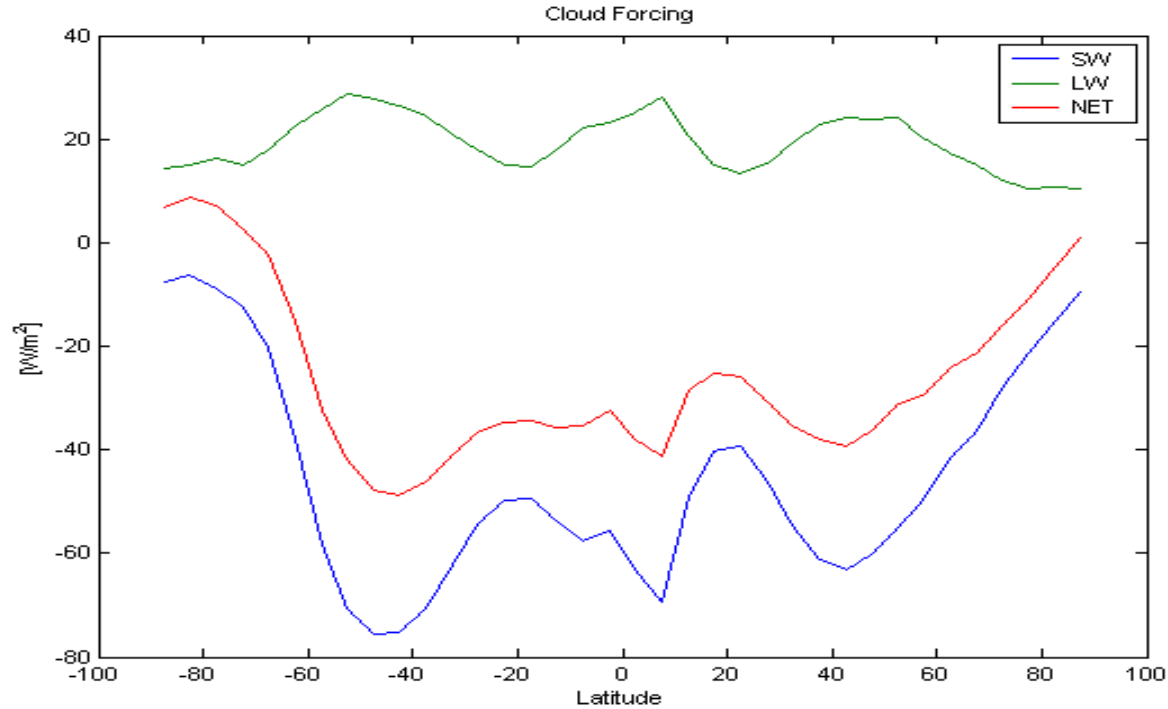


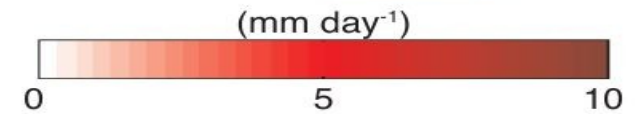
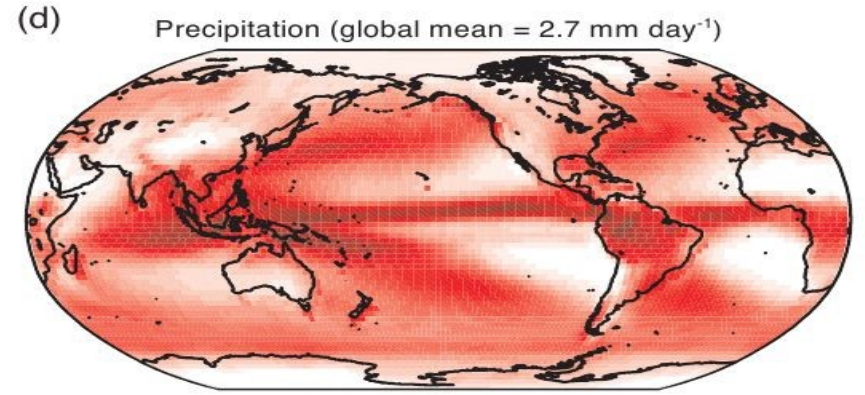
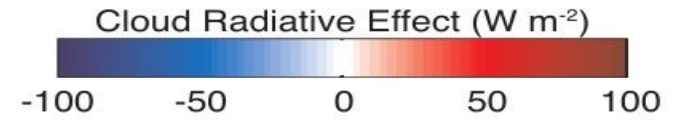
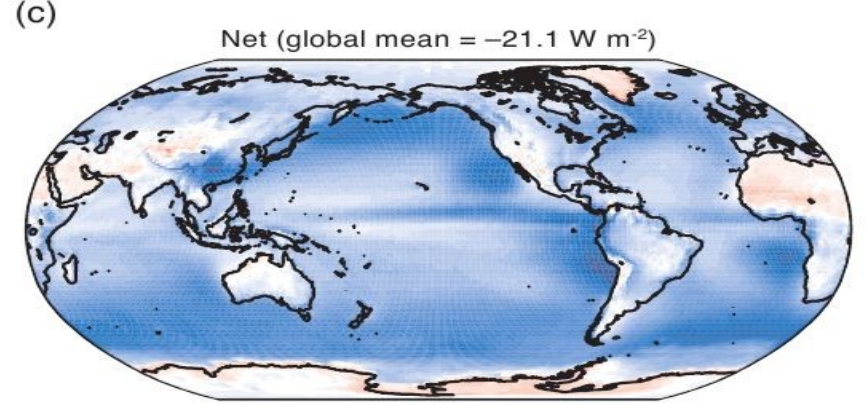
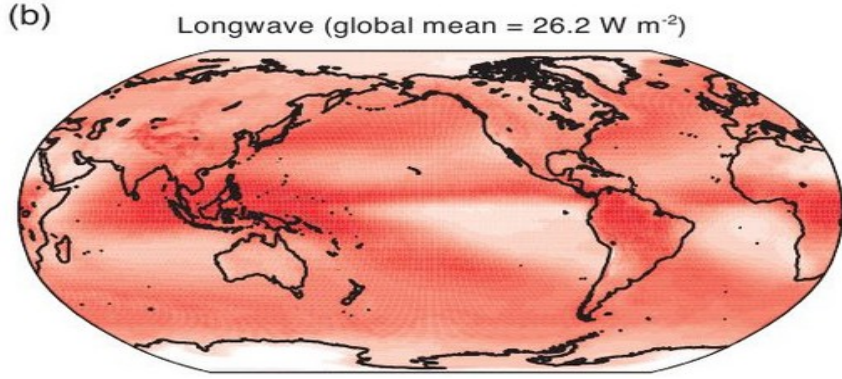
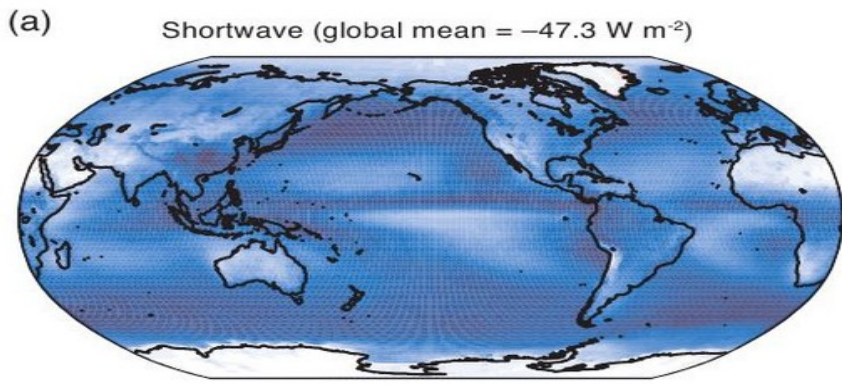
Chmury wysokie ogrzewają a niskie chłodzą...



$$T_s \approx T_l \quad T_s \gg T_h$$

Wymuszanie radiacyjne chmur

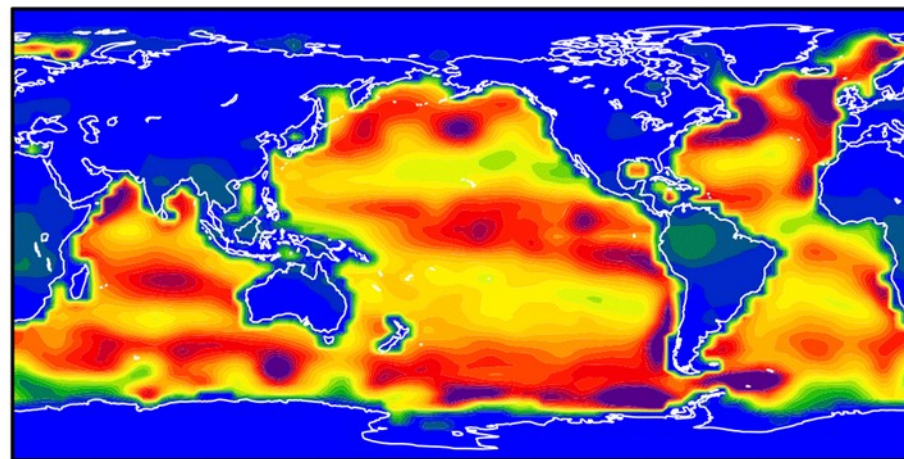
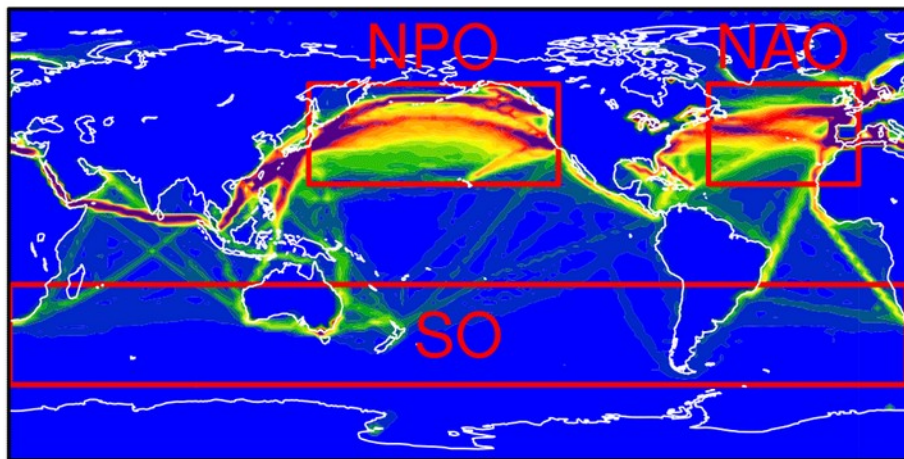




Chmury i ich rola w procesach radiacyjnych i klimatycznych

(a) Shipping SO₂

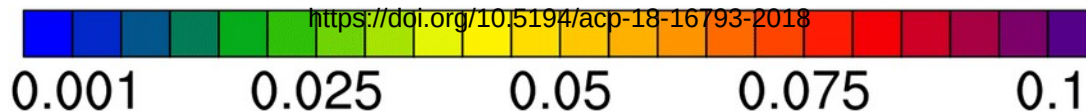
(b) DMS



5.4 Tg S yr⁻¹

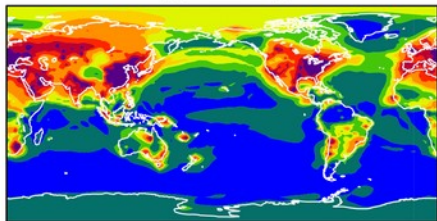
(g S m⁻² yr⁻¹)

18.2 Tg S yr⁻¹

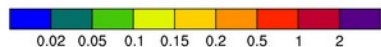


Spatial patterns of annual means of sulfur emissions (g S m⁻² yr⁻¹) from (a) international shipping and (b) natural DMS in the simulation at the reference emission level.

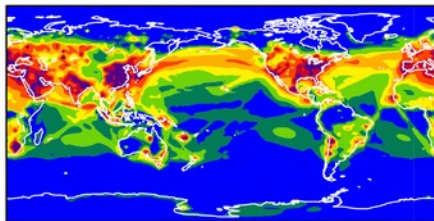
(a) Total SO₂



(p.p.b.v.)



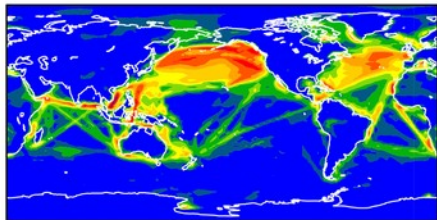
(d) Total sulfate



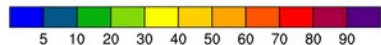
(p.p.t.v.)



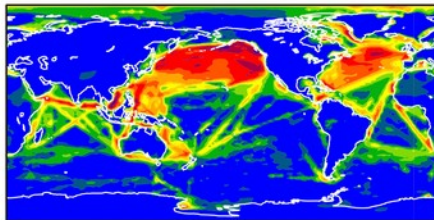
(b) Percentage of total SO₂ from shipping



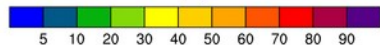
(%)



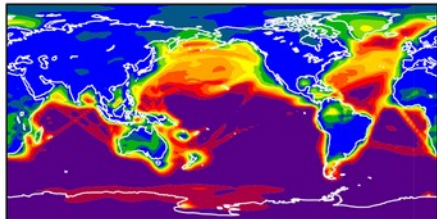
(e) Percentage of total sulfate from shipping



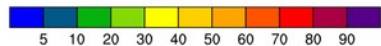
(%)



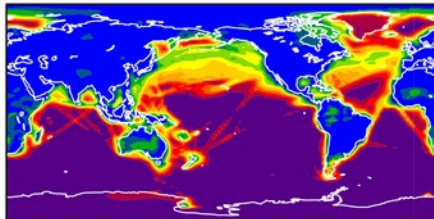
(c) Percentage of total SO₂ from DMS



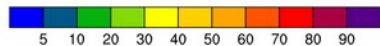
(%)



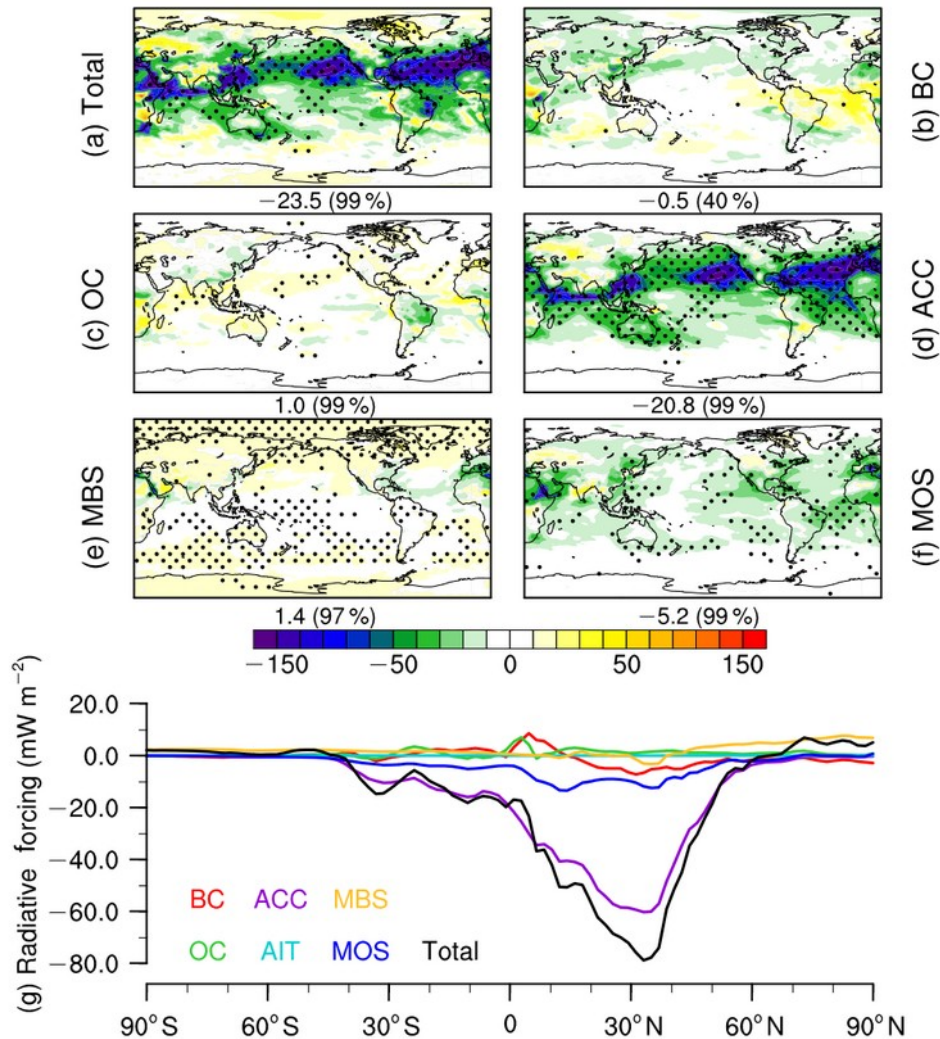
(f) Percentage of total sulfate from DMS



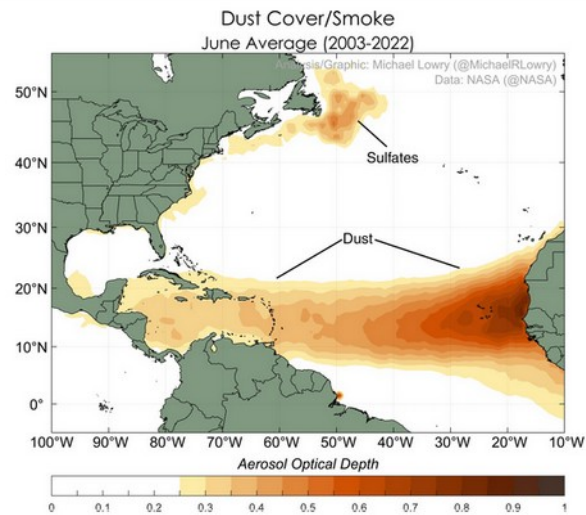
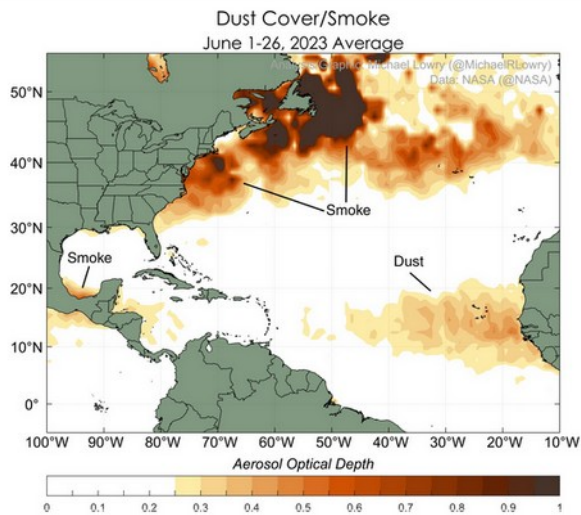
(%)



Spatial patterns of (a) annual mean concentrations of total SO₂ (parts per billion by volume; ppbv). Panels (b, c) show, respectively, the contributions of shipping emissions and natural DMS to total SO₂ in the lowest model layer. Panels (d)–(f) are the same as (a)–(c), but for sulfate aerosols.

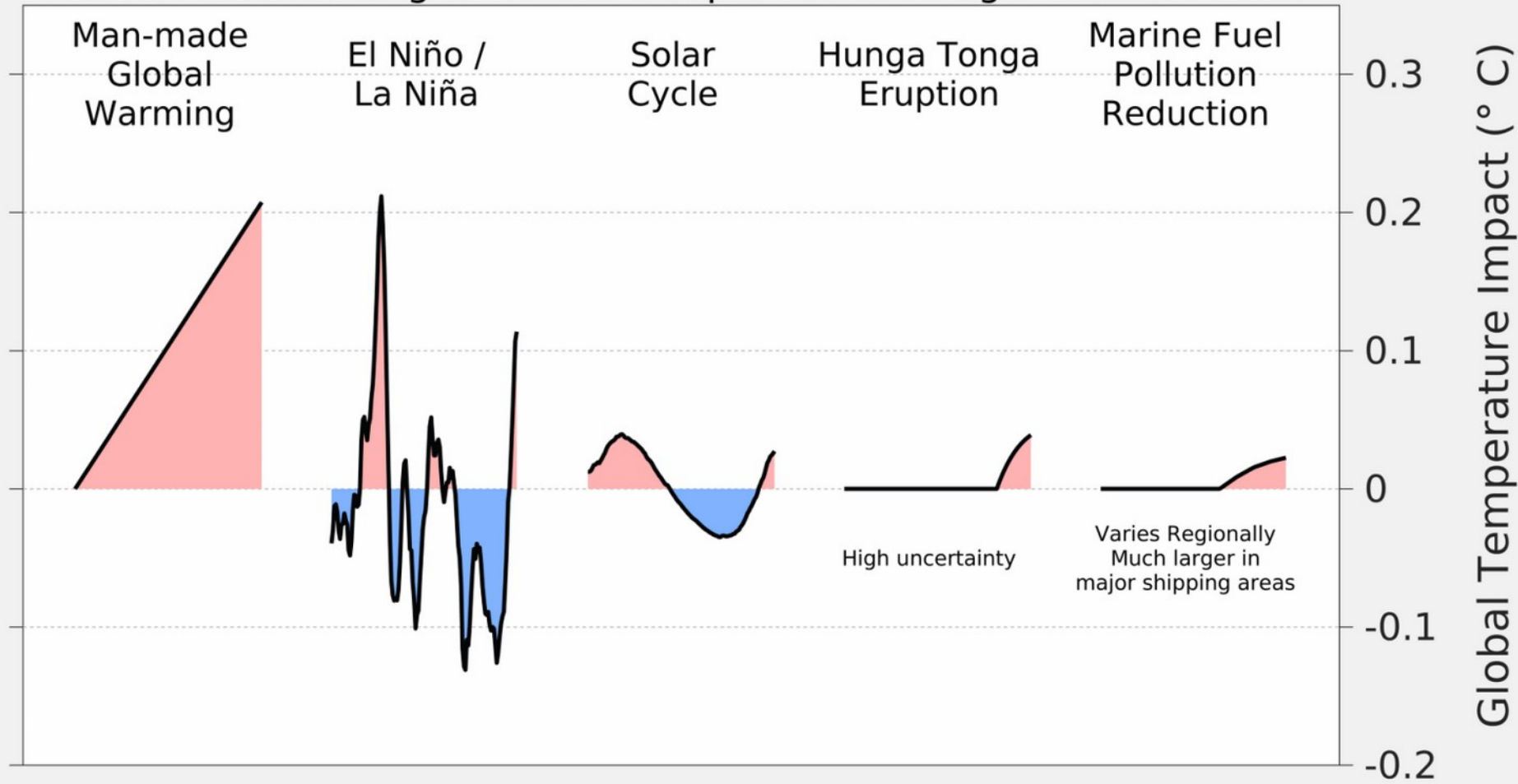


Simulated direct radiative effect (DRE; mW m^{-2}) of ISE at the TOA by MARC. The DRE is calculated as the difference between simulation results with and without ISE (i.e., ShipRef_DMSRef minus ShipZero_DMSRef) and averaged over the 30-year period of simulations at all-sky conditions. Panels (a)–(f) show the spatial patterns of DRE due to ISE with the global mean differences and the associated significant levels indicated by the numbers below each panel, and panel (g) shows the meridional variations in zonal mean DRE for various aerosol types from ISE and their total effects.



Comparison of June dust in 2023 (left) to the typical dust cover (2003-2022). NASA via Berkeley Earth

Factors Contributing to Global Temperature Change - Last 10 Years



Upper Atmosphere Water Vapor Content

Column total 20 to 80 km altitude, averaged 82 °S to 82 °N

Hunga Tonga-Hunga Ha'apai Eruption

January 15, 2022

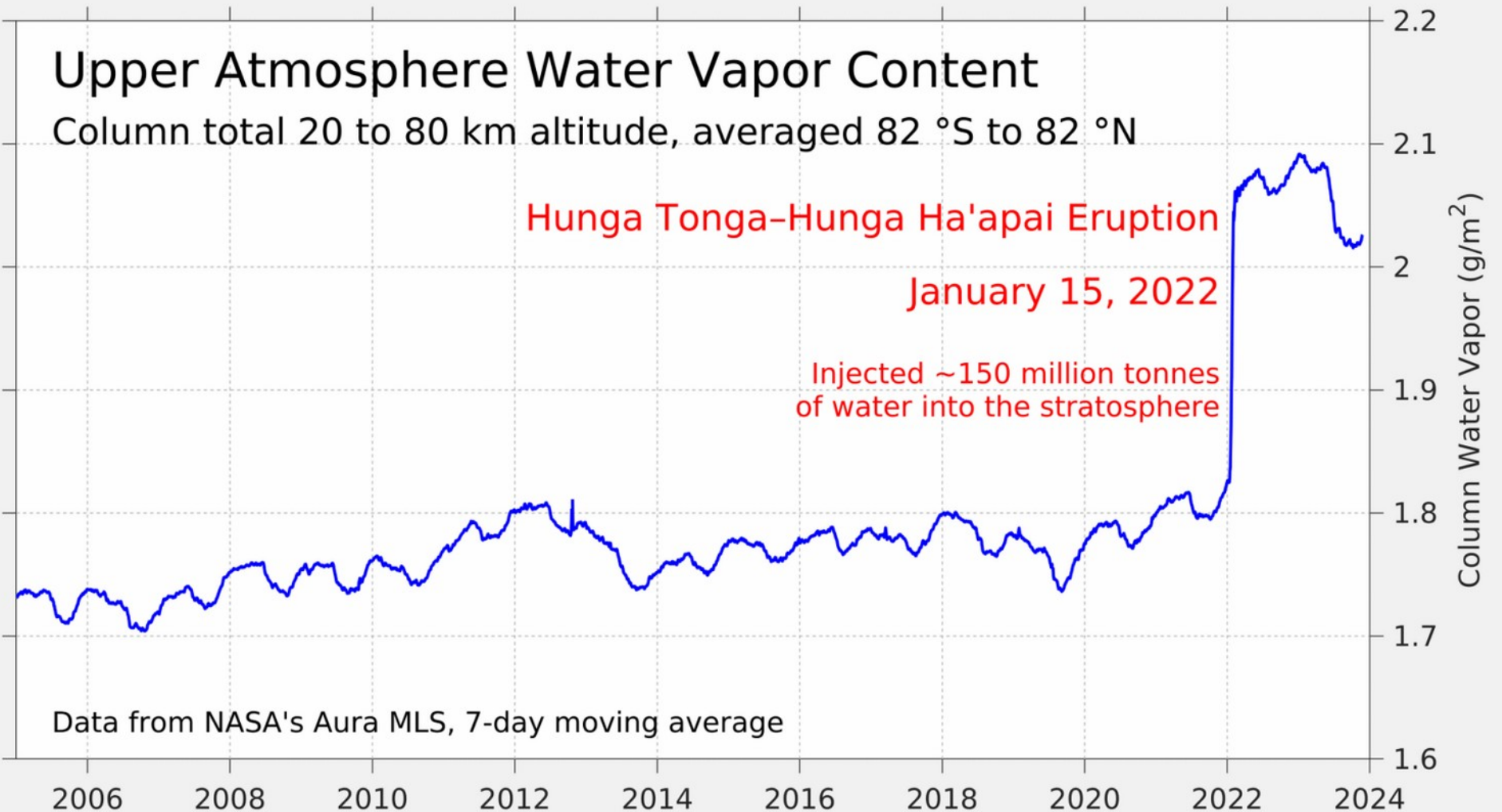
Injected ~150 million tonnes
of water into the stratosphere

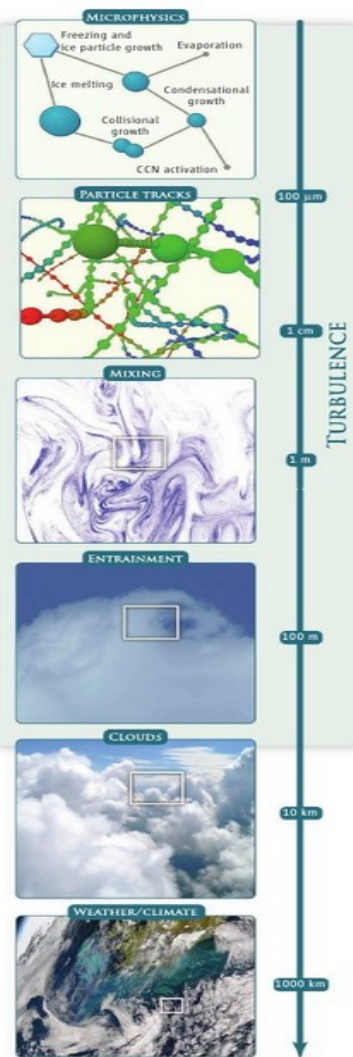
Data from NASA's Aura MLS, 7-day moving average

Column Water Vapor (g/m²)

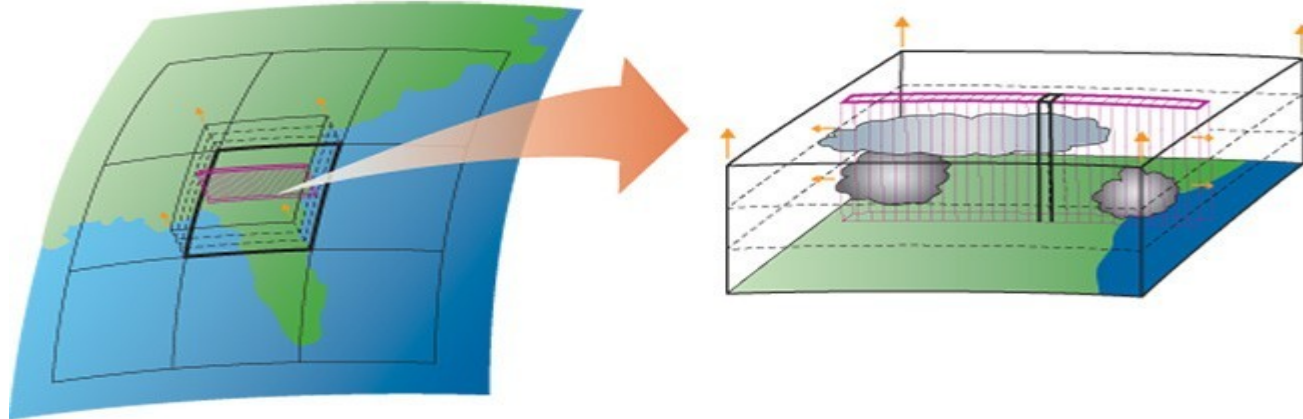
2006 2008 2010 2012 2014 2016 2018 2020 2022 2024

2.2
2.1
2
1.9
1.8
1.7
1.6





Jak sobie radzimy z problemami?
 „Multiscale modeling” - modelowanie wieloskalowe,
 superparametryzacje, GIGA-LES, ILES,
 explicit cloud resolving

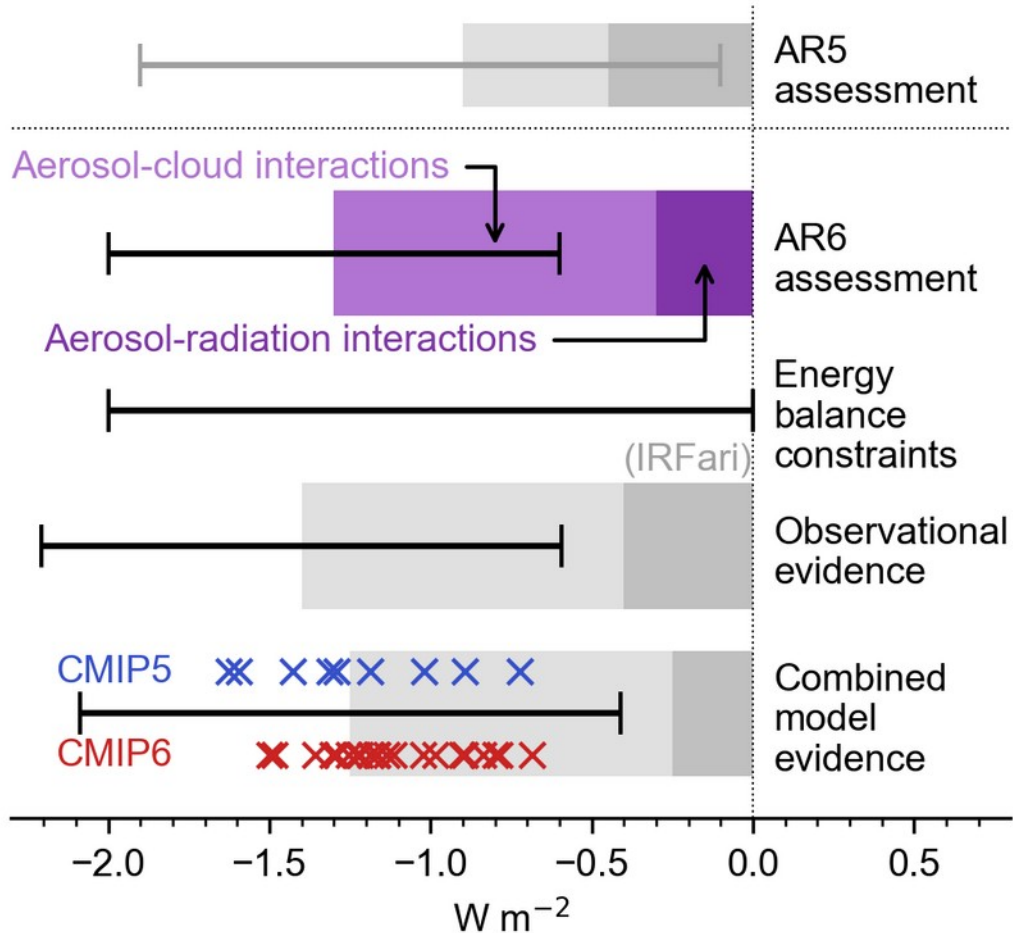


Bodenschatz, E., S.P. Malinowski, R.A. Shaw, F. Stratmann, 2010: Can We Understand Clouds without Turbulence? *Science*, **327**, 970 – 971.

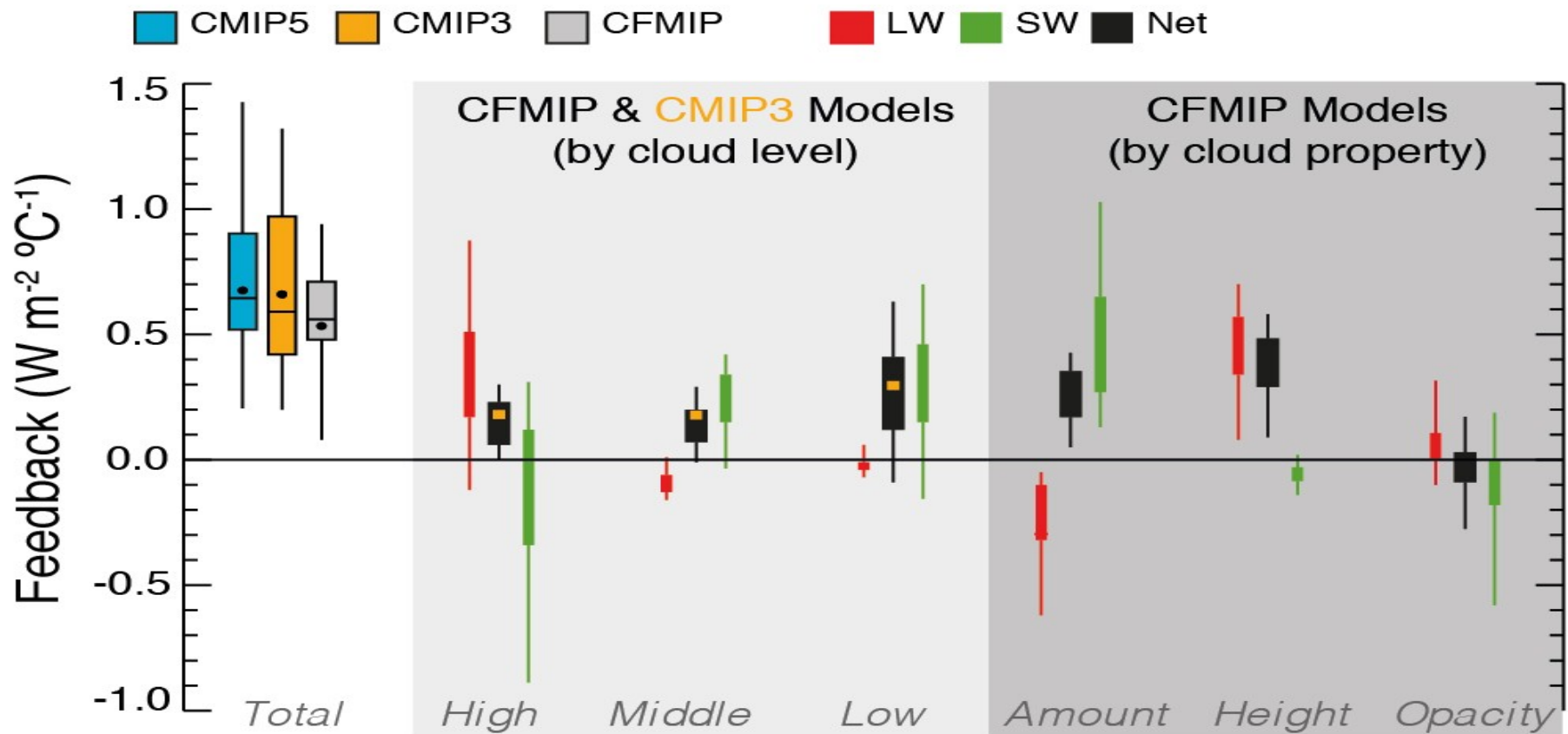
Randall D.A, Khairoutdinov M, Arakawa A, Grabowski W.W., 2003: Breaking the cloud parameterization deadlock . *Bull. Amer. Meteorol. Soc.*, **84**, 1547-1564.

I wiele wiele innych.....

Aerosol effective radiative forcing



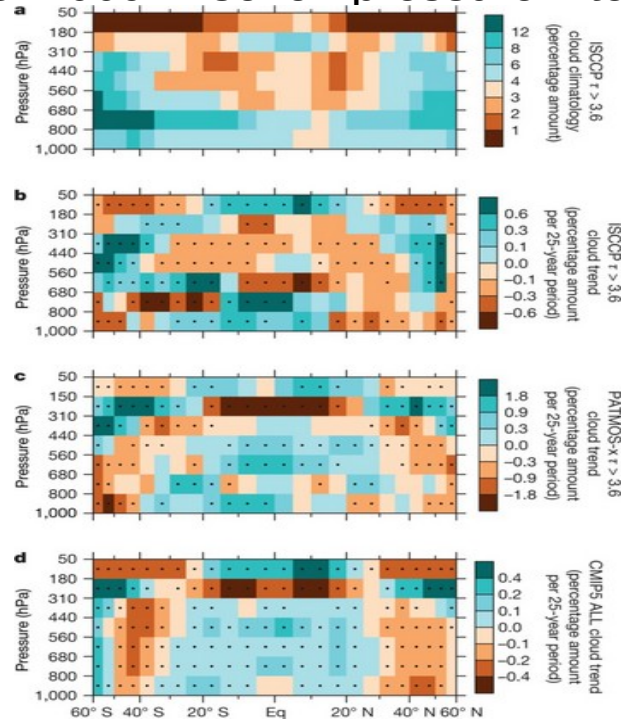
Net aerosol effective radiative forcing (ERF) from different lines of evidence. The headline AR6 assessment of $-1.3 [-2.0 \text{ to } -0.6] W m^{-2}$ is highlighted in purple for 1750–2014 and compared to the AR5 assessment of $-0.9 [-1.9 \text{ to } -0.1] W m^{-2}$ for 1750–2011. The evidence comprising the AR6 assessment is shown below this: energy balance constraints $[-2 \text{ to } 0 W m^{-2}$ with no best estimate]; observational evidence from satellite retrievals of $-1.4 [-2.2 \text{ to } -0.6] W m^{-2}$; and climate model-based evidence of $-1.25 [-2.1 \text{ to } -0.4] W m^{-2}$.



Efekty sprzężeń związanych z chmurami wskutek z zmian koncentracji CO₂ w atmosferze.

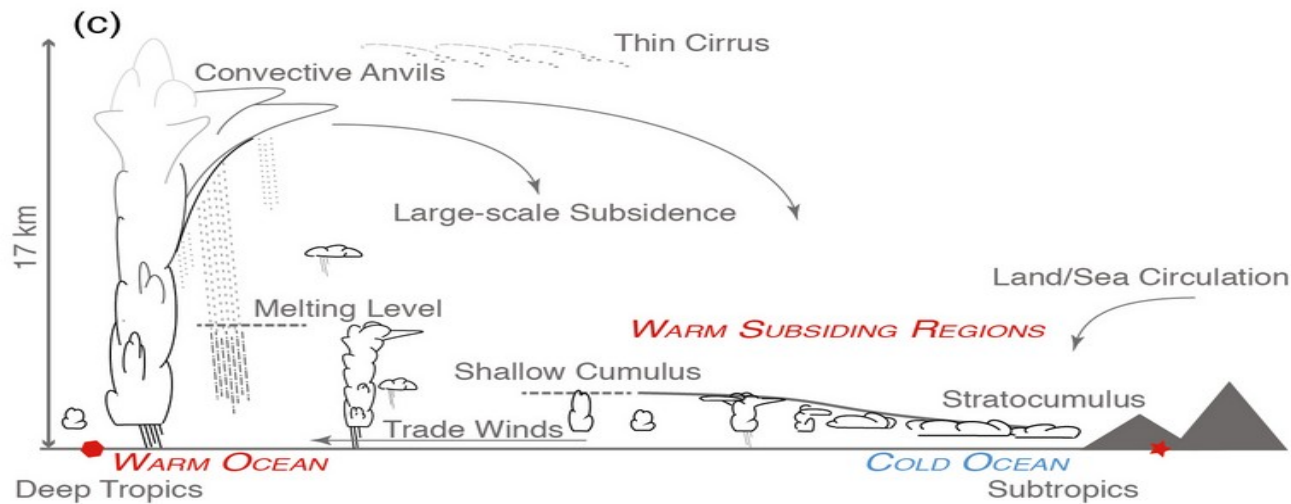
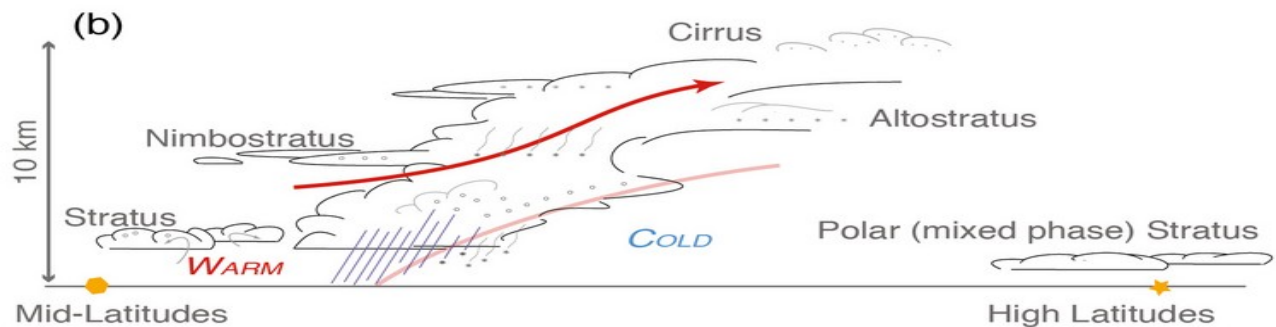
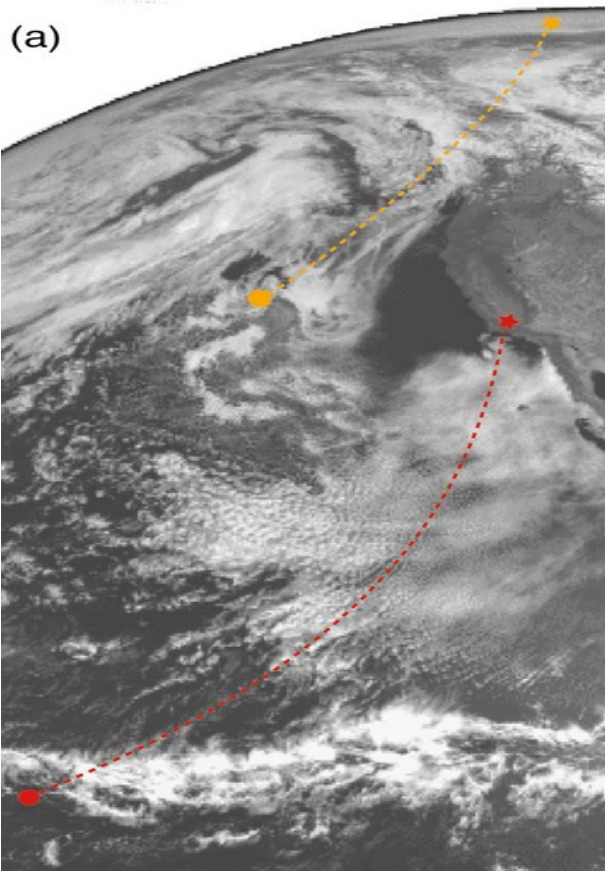
Zonal mean change in observed and simulated cloud amount during the period 1983–2009 in seven pressure intervals

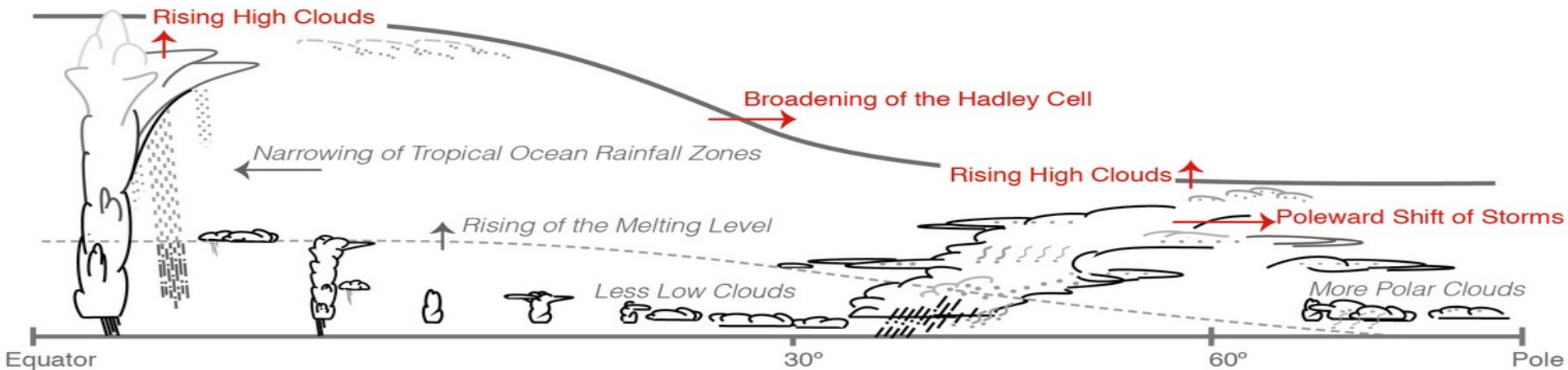
Układy chmur przesuwają się w kierunku biegunów i w górę, co wzmacnia ocieplenie klimatu.



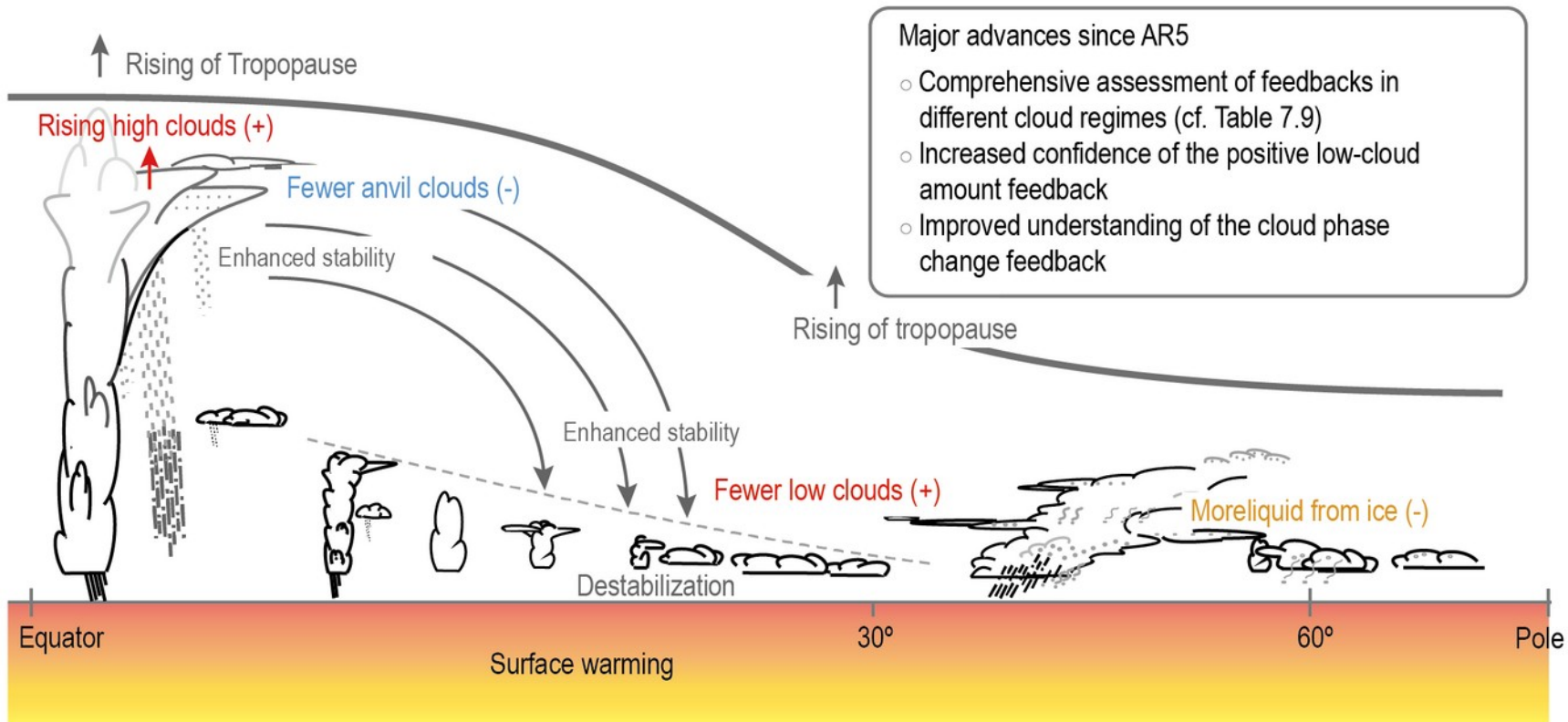
J R Norris et al. *Nature* 1–4 (2016) doi:10.1038/nature18273

Chmury i aerozole, a ściślej cykl hydrologiczny wpływają nie tylko na strumienie radiacyjne, ale i na dynamikę atmosfery i oceanu.

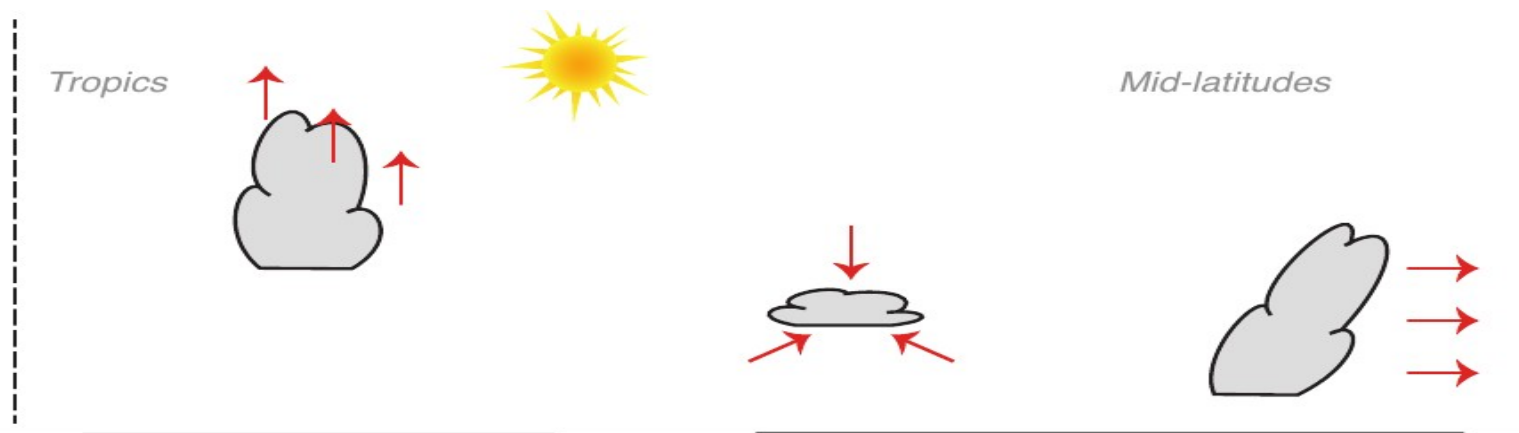




Zmiany w strukturze i dynamice atmosfery związane ze zmianami zachmurzenia na ocieplającej się Ziemi.



Greenhouse Warming



Cloud Response

High clouds rise as troposphere deepens, increasing difference between cloud top and surface temperature.

Reduction in mid- and low-level cloudiness (left). Shift of cloudy storm tracks poleward into regions with less sunlight (right).

Feedback Mechanism

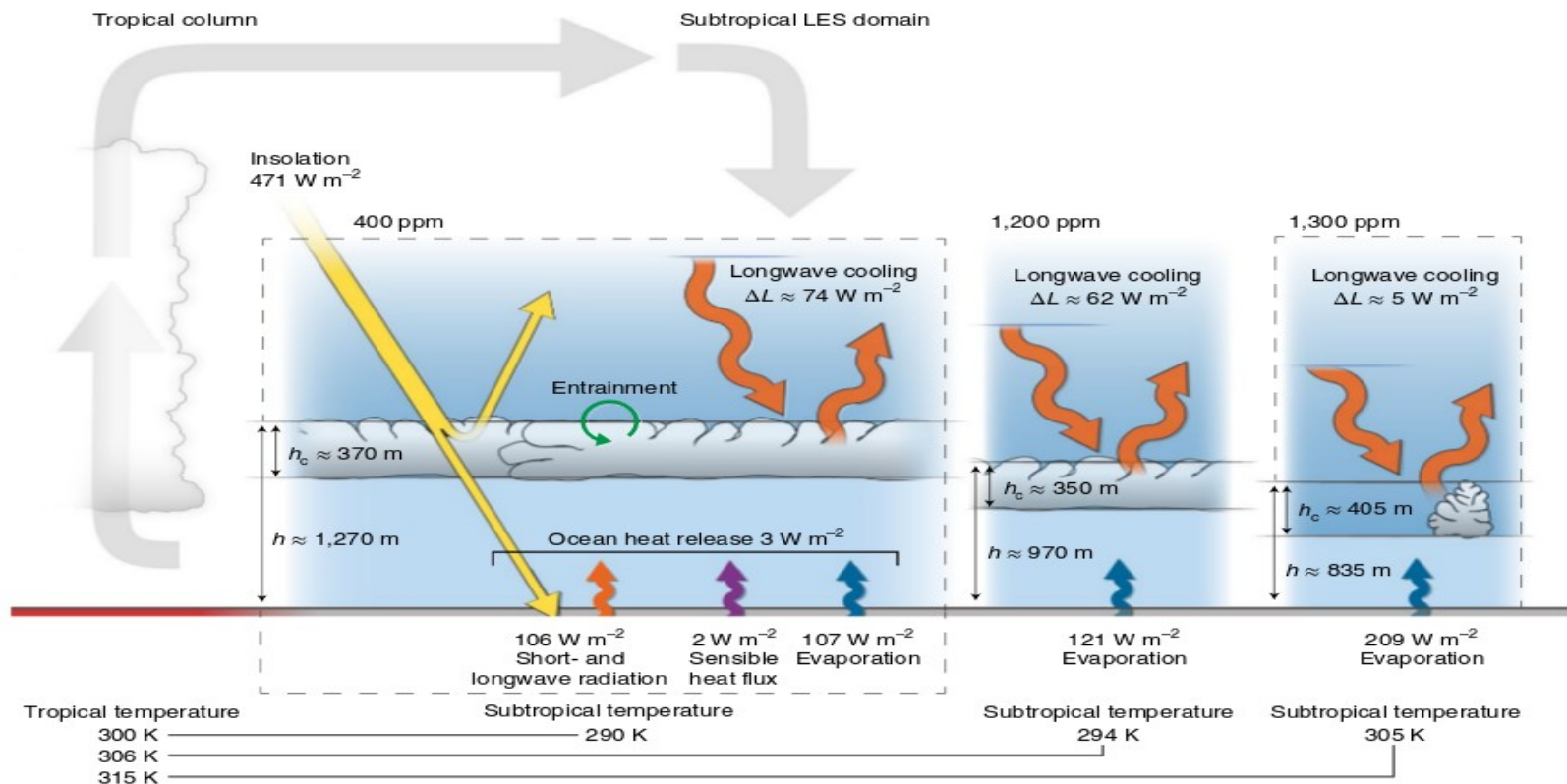
High clouds more effectively trap infrared radiation, increasing surface warming.

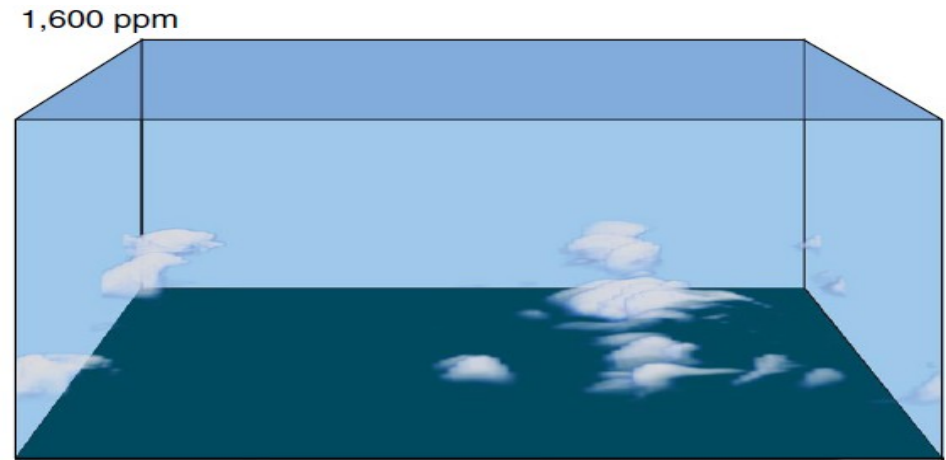
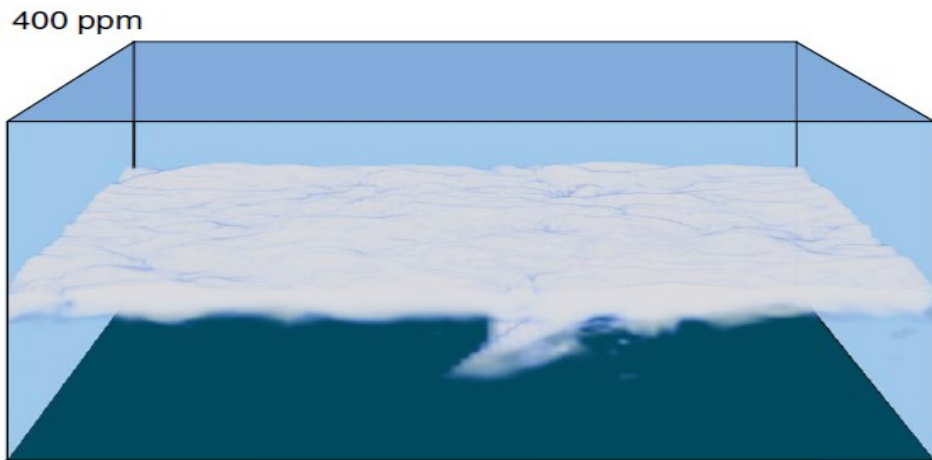
Less sunlight reflected by clouds back to space, increasing surface warming.

Zmiany w zachmurzeniu ocieplającej się planety – schematycznie.

Morskie chmury: nowo odkryte sprzężenie zwrotne destabilizujące klimat cieplarnianej Ziemi.

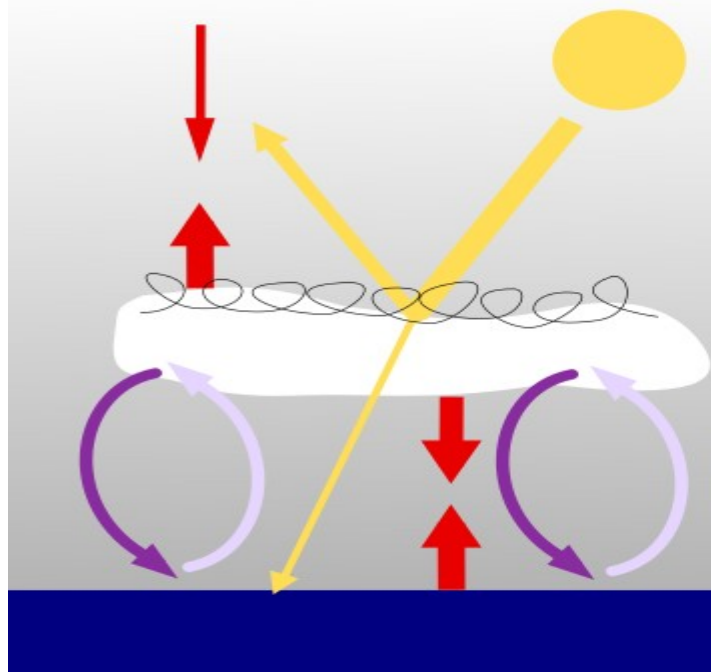




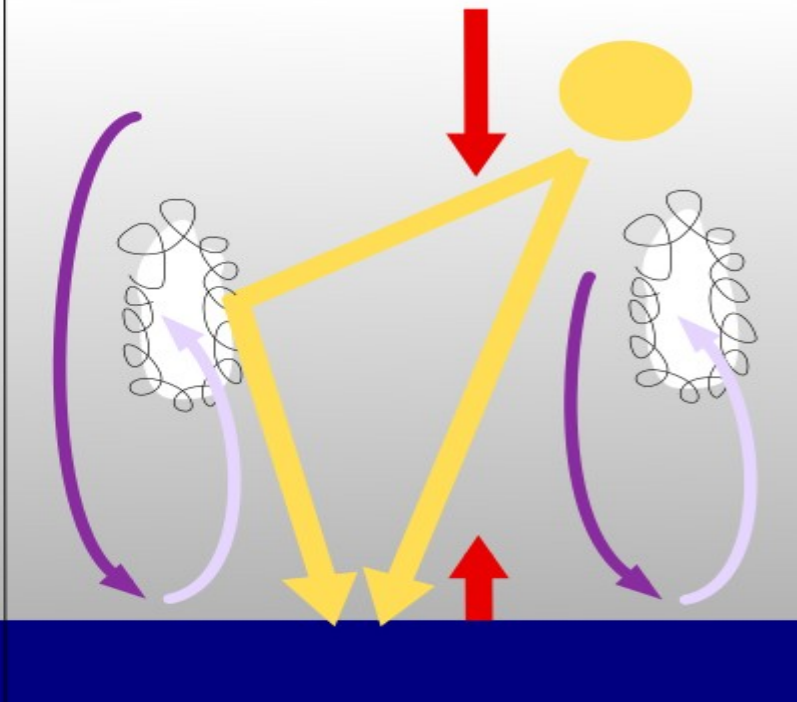


Wyniki symulacji zachmurzenia w rejonie podzwrotnikowym przy różnych średnich koncentracjach dwutlenku węgla. Po lewej – 400 ppm (stan obecny, ze średnią temperaturą powierzchni morza w tym rejonie ok. 17°C), po prawej – 1600 ppm (możliwy stan przyszły, ze średnią temperaturą morza w

400 ppm CO₂

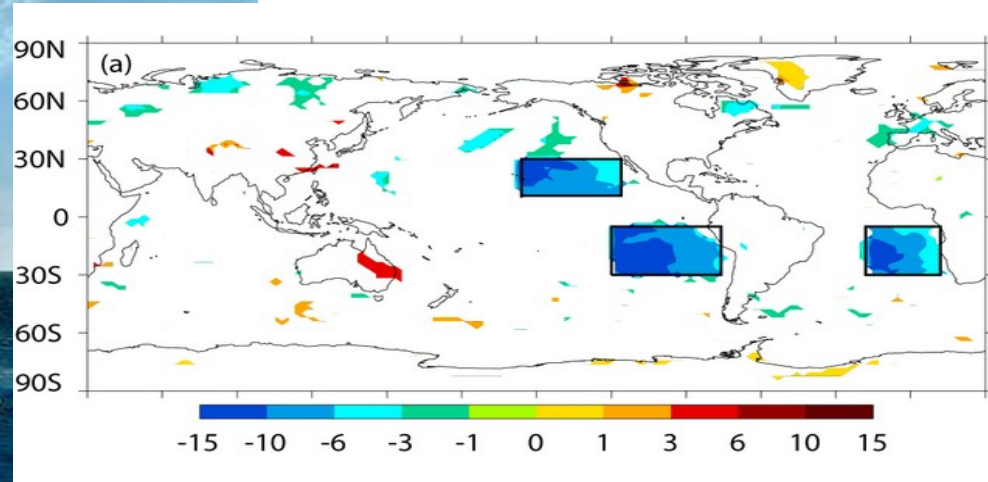
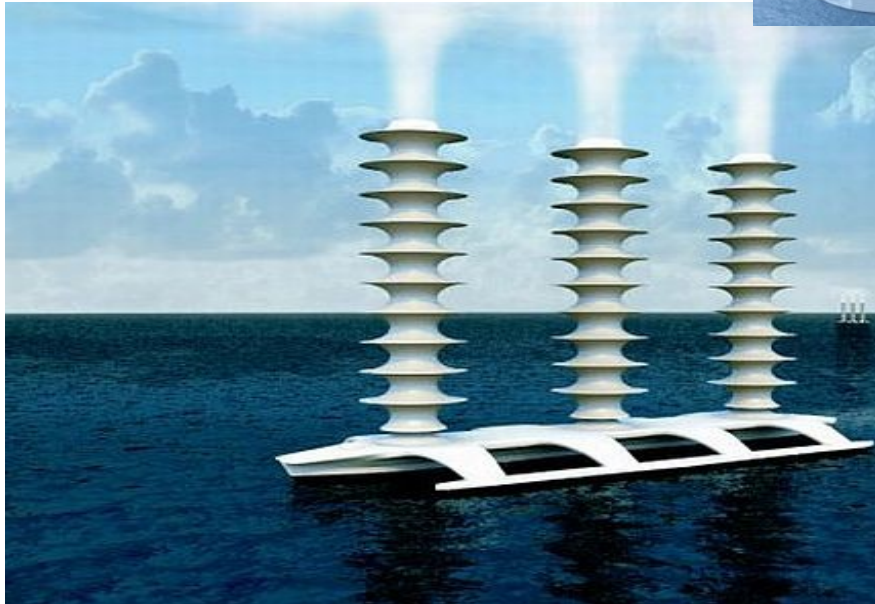
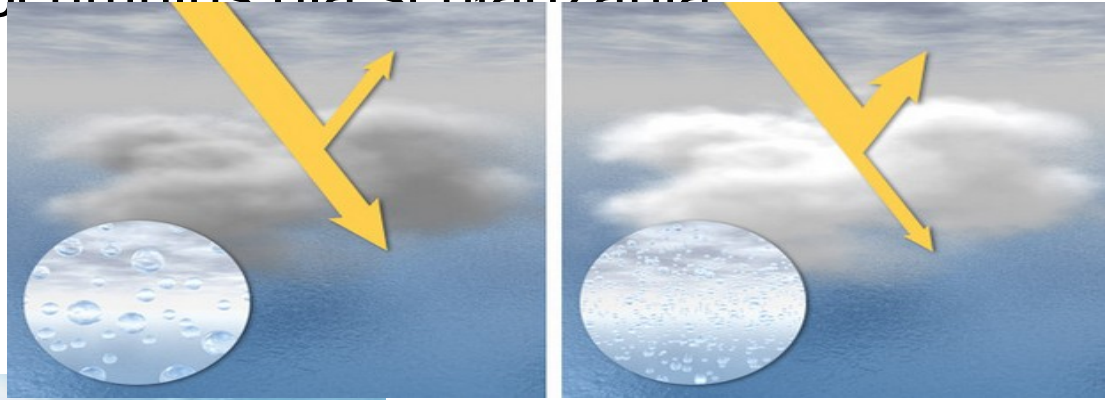


1600 ppm CO₂



Schemat zmian w bilansie energii i własnościach morskiej warstwy granicznej atmosfery nakrytej chmurą stratocumulus w sytuacji, gdy koncentracja CO₂ w atmosferze wzrośnie z wartości obecnych (ok. 400 ppm) do ok. 1600 ppm. (przyszłe stulecie w scenariuszu Biznes-jak-zwykle) Proste żółte linie ze strzałkami schematycznie pokazują bilans promieniowania słonecznego, czerwone – promieniowania podczerwonego (cieplnego). Fioletowe strzałki ilustrują transport konwekcyjny (mieszanie wskutek konwekcji) w dolnych warstwach atmosfery: pokazują, że przy konwekcji stratocumulusowej wymiana pary wodnej i wody ograniczona jest do płytkiej warstwy pokrytej chmurami, w przeciwieństwie do sytuacji z konwekcją cumulusową, gdzie mieszanie i transport pary wodnej z powierzchni oceanu obejmuje znacznie głębszy obszar.

„Wybielanie” chmur stratocumulus dla schładzania
planety?





Robert Wood

Professor, Atmospheric Sciences, Univ. of Washington

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MARINE CLOUD BRIGHTENING PROGRAM: PUBLICATIONS

Publications in process, not yet submitted:

The impact of the interaction of cloud microphysics and macro-physics with large-scale circulation on stratocumulus-to-cumulus transition. Je-Yun Chun, Robert Wood, Peter N. Blossey, and Sarah J. Doherty, 2024: To be submitted to Atmospheric Chemistry and Physics

Evaluation of E3SM version 2 marine boundary layer clouds over the northeast Pacific during the CSET Campaign. Kyoung Ock Choi, Philip J. Rasch, Robert Wood, Sarah J. Doherty, 2024: To be submitted to Journal of Geophysical Research – Atmospheres

Submitted, in review:

A protocol for model intercomparison of impacts of Marine Cloud Brightening Climate Intervention. Philip J. Rasch, Haruki Hirasawa, Mingxuan Wu, Sarah Doherty, Robert Wood, Hailong Wang, Andy Jones, James Haywood, Hansi Singh, 2024, submitted to Geoscientific Model Development (GMD).

[Aggressive aerosol mitigation policies reduce chances of keeping global warming to below 2C.](#) Robert Wood, Mika. A. Vogt, and Isabel. L. McCoy. Manuscript submitted to Earth's Future, October 2023.

[Exploring ship track spreading rates with a physics-informed Langevin particle parameterization.](#) Lucas A. McMichael, Michael J.

Short biography

[Clouds: structure, microphysics, variability](#)

[CloudScapes Blog](#)

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