Dynamical and microphysical controls of ice supersaturation and ice crystal formation in high tropospheric clouds

Bernd Kärcher

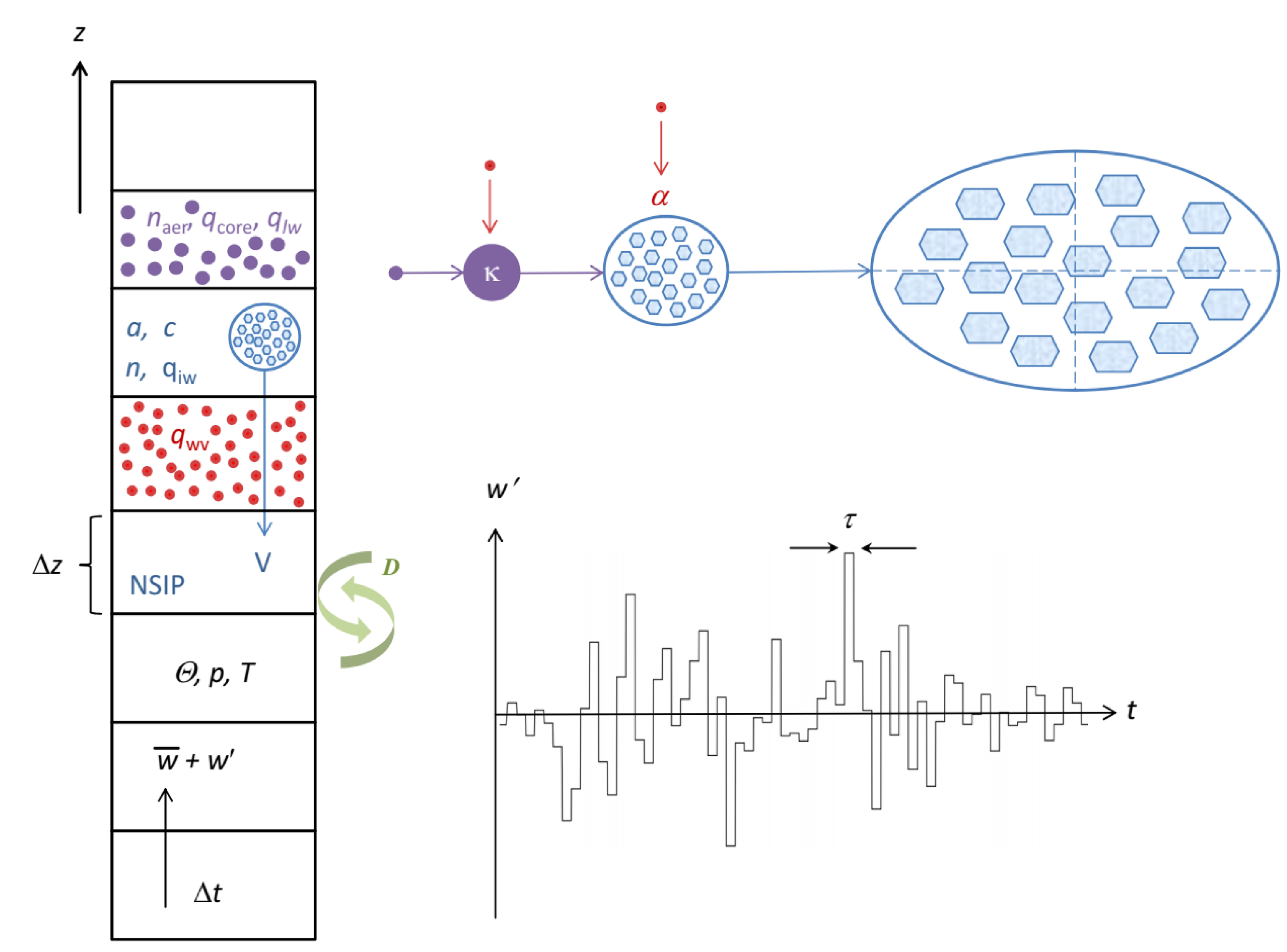
Cirrus (pure ice) clouds either form *in-situ* or develop as anvil clouds from detrained deep convection in the upper troposphere. Persistent contrails and the contrail cirrus clouds evolving from them — defined by the World Meteorological Organization as *Cirrus homogenitus* — are the only man-made type of ice clouds. These high altitude clouds warm and dry the atmosphere affecting circulation patterns and modify the hydrological cycle. A lack of proper representation of them in global models compromises the fidelity with which weather and climate can be simulated. Two intertwined research issues form a roadblock to scientific progress: the dynamical forcing driving cirrus ice crystal formation and the ice-forming properties of mixed-phase and solid aerosol particles (INP). To help overcome this roadblock, my research is based on laboratory and airborne measurements employing numerical process models and theoretical cloud physics methods to investigate: effects of mesoscale gravity waves and sub-km scale turbulence on cirrus ice crystal nucleation and aerosol indirect effects, and to develop or improve parametrizations of ice crystal formation for use in low resolution models.

Anthropogenic factors causing cirrus cloud changes and the likelihood and scale of their impact [1]. The potential of those factors to change natural cirrus in the future is also included. In judging these changes, it is assumed that the magnitude of each controlling factor increases independently.

Anthropogenic impacts on cirrus clouds

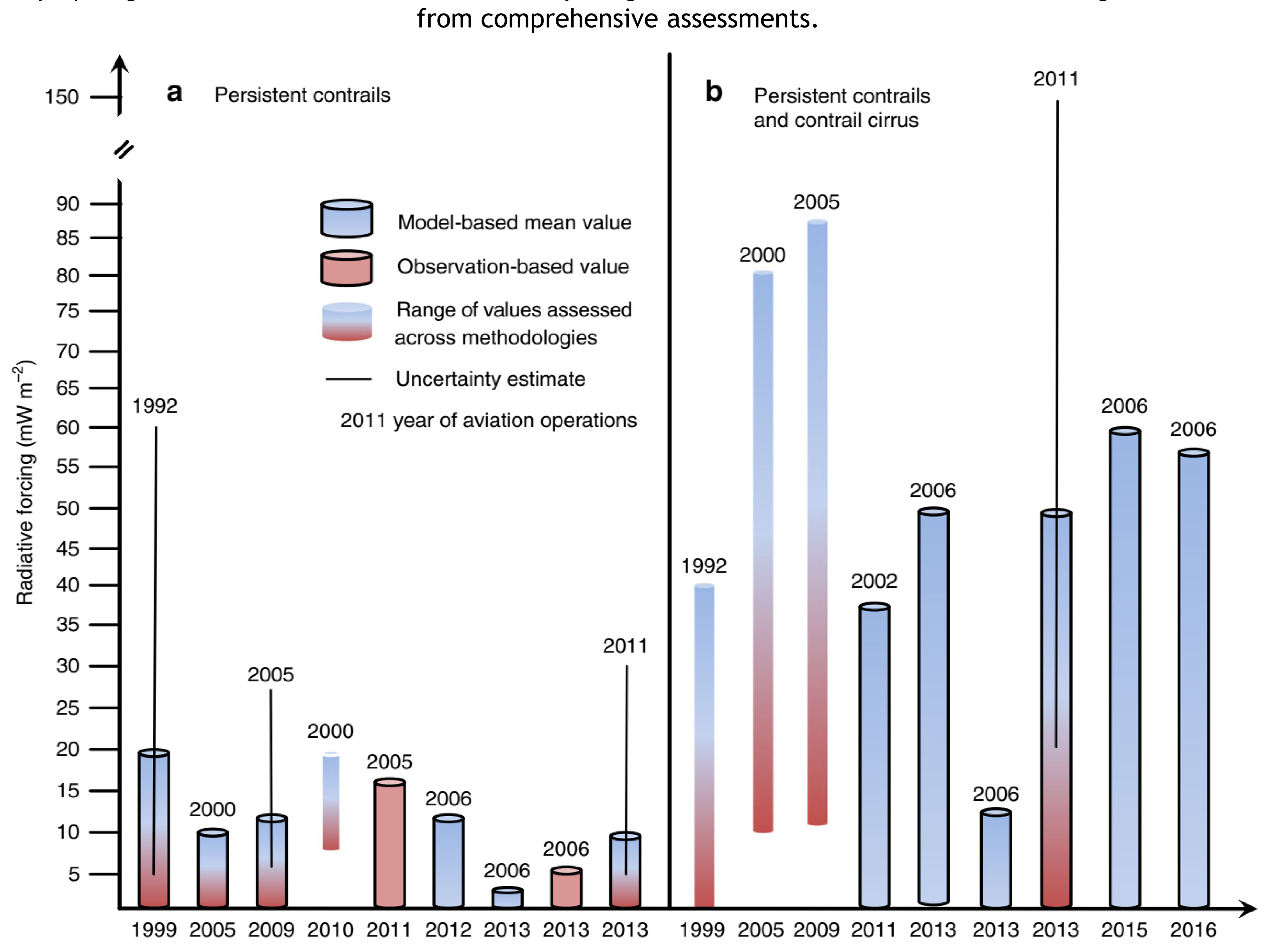
Cirrus-controlling factor	Assumed future changes	Natural cirrus changes	Likelihood of impact	Scale of impact
Meteorological changes				
Vertical wind (cooling rate) fluctuations[a]	Not known	More and smaller ice crystals[b]	High	Local
Relative humidity	Constant	Constant coverage	High	Regional
Tropopause altitude	Increase	Less ice water content[c]	High	Regional
Aerosol-induced changes				
Supercooled aerosols	Increase[d]	Moderate changes	Low	Local
Dust	Increase[d]	Depending on dynamical forcing[e]	High[f]	Local
Black carbon	Increase[d]	Depending on dynamical forcing[e]	Low	Local
Cloud-induced changes				
Contrail cirrus	Increase	Lower coverage[g]	Medium[h]	Regional
Deep convection	Not known	Higher coverage[b]	High[i]	Regional

Water vapor, temperature, and vertical wind speed influence the large-scale distribution and level of ice supersaturation supporting cirrus formation and persistence. Vertical air motion (cooling rate) variability on the lower mesoscale affects the local supersaturation around ice-nucleating aerosol particles and therefore ice nucleation. Aqueous particles are mainly composed of sulfates, nitrates, ammonium, and organic compounds, many of which arise from air pollution. They constitute the vast majority of ubiquitous background particles capable of homogeneous freezing. Solid particles include black carbon particles deriving from a number of combustion-related anthropogenic activities as well as mineral dust originating from desert regions and soil dust particles originating mainly from and water use. Solid particles, a small subset of the atmospheric aerosol, may be internally mixed with other species either due to co-emission or atmospheric chemical processing, which affects their propensity to form ice by heterogeneous nucleation. Contrail cirrus generated by jet aircraft enhance cloudiness and change natural cirrus by altering the moisture and heat budget on regional scales. Deep convective clouds affect cirrus by upper tropospheric moistening and by injection of frozen condensate.

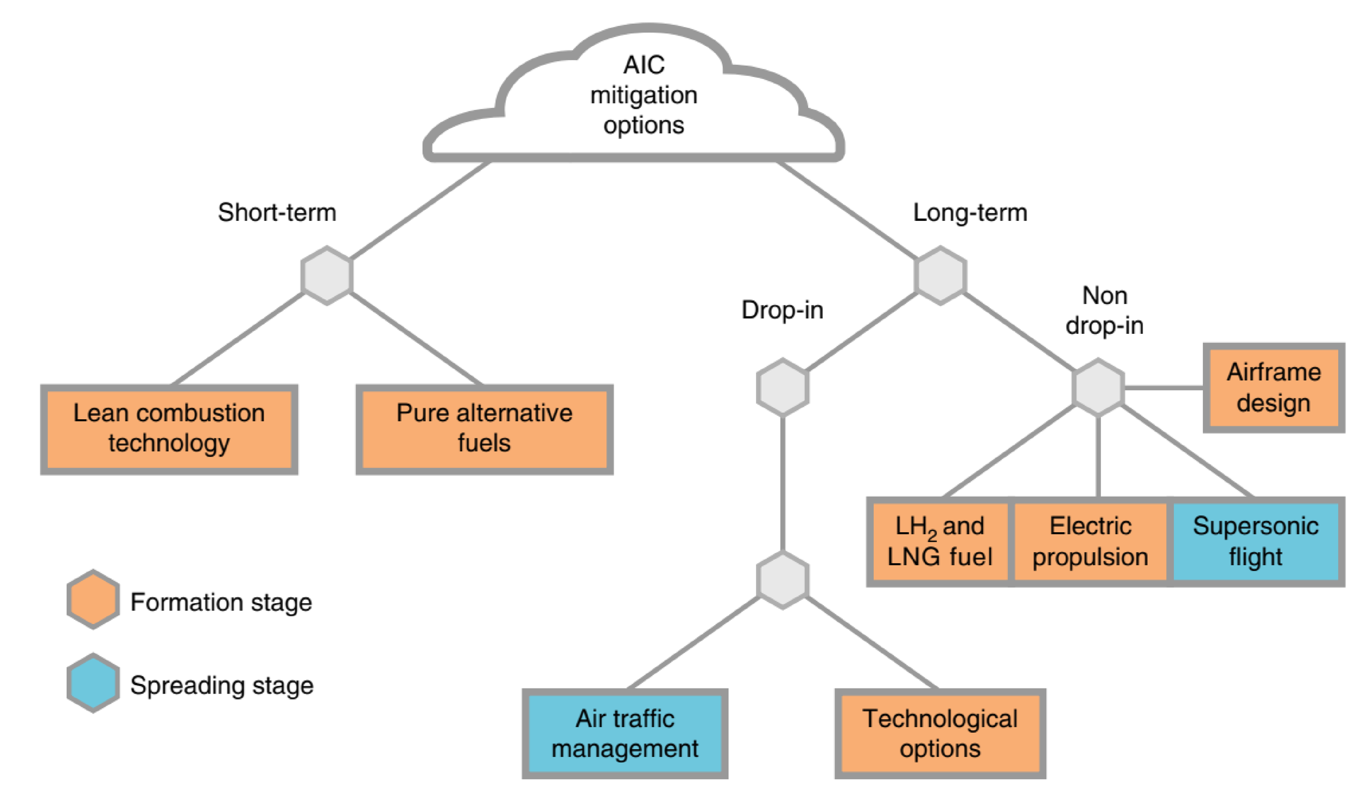


Physical processes represented within a high-resolution, one-dimensional cirrus model [2], developed to simulate the formation of primary (pristine) ice crystals from liquid aerosol particles and/or INP. In a vertical air column, potential temperature and water vapor mixing ratio are driven by a prescribed wind field and turbulent diffusion. Besides a slowly varying mean component, the vertical wind may include stochastic, gravity wave-driven perturbations. Growth and evaporation of aqueous aerosol particles is calculated in a Lagrangian manner. They may freeze homogeneously depending on their non-equilibrium water activity. The ice phase is simulated by tracking the history of a large number of simulation ice particles. The latter are represented by spheroids as a surrogate for real crystal shapes. Growth by uptake of water vapor allows for axis-dependent water vapor fluxes and supersaturation-dependent deposition coefficients.

Global annual mean radiative forcing due to aircraft-induced clouds [3]. Radiative forcing (RF) due to **a** persistent contrails alone and **b** together with contrail cirrus from selected studies and assessments, sorted by publication date since the IPCC Special Report on Aviation (published in 1999). Purely observational global estimates derive from extrapolating local aircraft and regional satellite data. Pure model estimates are based on or rely upon global model simulations. Uncertainty ranges evaluated across several methodologies are taken from comprehensive assessments.



Options to mitigate the climate effect of aircraft-induced clouds (AIC) [3], broadly categorized into short-term and long-term solutions. The latter are further separated into drop-in (easily replaceable) and non drop-in solutions that require major changes in aircraft design, fuel production, or supply infrastructure.



Mitigation options may also be categorized according to their influence in the two principal stages of AIC evolution. Most options, including technological solutions addressing alterations of aircraft engine architecture and airframe/engine integration, affect the aircraft-dominated formation stage (red) by reducing or modifying particle emissions or affecting nucleation and sublimation of contrail ice crystals in aircraft exhaust plumes and wakes. Two options affect the atmospheric spreading stage (blue), requiring sound predictive capability of ice supersaturated areas or producing short-lived contrails in the dry lower stratosphere (supersonic flight) with negligible radiative impact.

[1] Cirrus Clouds and Their Response to Anthropogenic Activities. *Curr. Clim. Change Rep.* **3**, doi:10.1007/s40641-017-0060-3, 2017.

[2] Process-based Simulation of Aerosol-cloud Interactions in a One-dimensional Cirrus Model. *J. Geophys. Res.* **125**, doi:10.1029/2019JD031847, 2020.

[3] Formation and Radiative Forcing of Contrail Cirrus. *Nature Commun.* **9**, 1824, doi:10.1038/s41467-018-04068-0, 2018.

Deutsches Zentrum für Luft- und Raumfahrt e.V.

Institut für Physik der Atmosphäre

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