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ARTICLE OPEN

Impact of vertical air motions on ice formation rate in mixed-phase cloud layers

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The relationship between vertical air velocity at cloud base and primary ice formation has been measured for shallow mixed-phase cloud layers (thickness <380 m) by means of ground-based cloud radar and Doppler lidar. For layers with a cloud-top temperature below −12 °C, an increase of vertical-velocity standard deviation from 0.1 to 1.0 m s^{-1} leads to an increase in the mass flux of ice water by two orders of magnitude. The cloud layers under study were selected in such a way that secondary ice-formation processes played a minor role, and primary ice formation was the dominant source of ice formation. Phenomenological parameterizations of the ice mass and the ice mass flux as functions of standard deviation of vertical air velocity are given.

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INTRODUCTION

Ice formation in clouds is a key component of the hydrological cycle on Earth. Given the complex interaction of aerosols, atmospheric dynamics, and cloud microphysical properties[1], it is a challenge in weather and climate research to isolate the single process leading to the formation of ice in tropospheric clouds[2–6] and to disentangle aerosol and dynamics-related effects on ice nucleation and growth. Nevertheless, detailed process understanding is a prerequisite for improving the representation of ice-formation mechanisms in numerical weather and climate models and to enable a thorough evaluation of the latter.

Characterizing the multitude of pathways of ice formation in clouds is difficult because the relevant processes take place in a turbulent environment on different scales.[3] In the recent decade, shallow supercooled cloud layers (altocumulus and stratocumulus) have been used repeatedly for studying ice-formation processes.[7–9] Recently, Bourgeois et al.[10] showed that these mid-level clouds can have a significant cooling effect on Earth's climate.

Shallow cloud layers have the advantage that they can be easily probed by lidar and radars without significant attenuation effects.[11–14] They also provide narrow constraints on temperature, pressure, and humidity and, as shown by Ansmann et al.,[8] Westbrook and Illingworth[9], and de Boer et al.,[15] immersion freezing may be the dominant ice-formation processes at temperatures above −27 °C. Down to this temperature, ice-formation occurs predominantly via the liquid phase. Hence, ice-forming shallow cloud layers provide an ideal natural laboratory for the study of aerosols, dynamics, ice formation, and their interactions.[13,14,16,17] Despite the simple conditions in and around shallow cloud layers, the measurement of vertical air velocity in cloud layers is still challenging. The velocity of the air cannot be measured directly and, therefore, tracers like aerosol particles or cloud droplets have to be present as proxies for wind velocity.

Kanitz et al.[13] found large differences in the ice-formation efficiency of mixed-phase cloud layers between the northern and southern hemisphere. It is an ongoing debate whether this effect is attributed to a larger natural and anthropogenic aerosol forcing on the northern hemisphere[18] or a result of differences in vertical-velocity conditions.[5,19] This complex question can only be answered if quantitative information can be derived about the impact of vertical velocities on ice formation.

Knowledge about the vertical wind conditions inside the mixed-phase top layer (MPTL, see Fig. 1) of such clouds is an inevitable prerequisite for a detailed understanding and precise numeric modeling of cloud layers. There are many possible pathways how increased turbulence may increase ice-formation efficiency in clouds. E.g., Korolev and Field[2] as well as Pinsky et al.[20] explored the effect of dynamics on mixed-phase cloud layers and found that their microphysical properties are mainly driven by vertical motions. Recent theoretical and modeling studies showed that updrafts can recreate liquid water even if ice water is present within the cloud layer and drawing water from the liquid droplets by the Wegener–Bergeron–Findeisen process.[21,22] This effect will increase the stability of the cloud layer and hence facilitate ice formation. Also, increased turbulence may lead both to a stronger entrainment of ice-nucleating particles (INP) into the cloud layers, as well as to stronger efficiency for droplet coalescence which results in larger droplets which again a higher probability for nucleation.[23] There are also indications that inside-out freezing of droplets plays a major role under downdraft conditions at cloud top.[24]

Despite the deep theoretical insights into aerosol–cloud–dynamics interaction obtained by these efforts, measurements of the direct impact of vertical motions on ice formation in tropospheric cloud layers are absent. Satellites can indeed deliver a global picture of cloud layers,[11] but they cannot provide detailed insight into the dynamics of air motions inside of these cloud layers. Aircraft can measure cloud air motions plus ice crystal concentration and ice water content (IWC), but their measurement time is expensive and usually restricted to short campaign-based observations.[7,25] Hence, long-term observations of air motions in clouds and the consequences on cloud ice conditions from which significant statistical results can be drawn can only be made with ground-based remote-sensing instrumentation.

In this paper, we combine the data set of Bühl et al.[16] with the Doppler lidar measurements in order to investigate the mass flux of ice crystals falling from a mixed-phase cloud layer as a function of the vertical-velocity statistics in the ice-producing cloud-top

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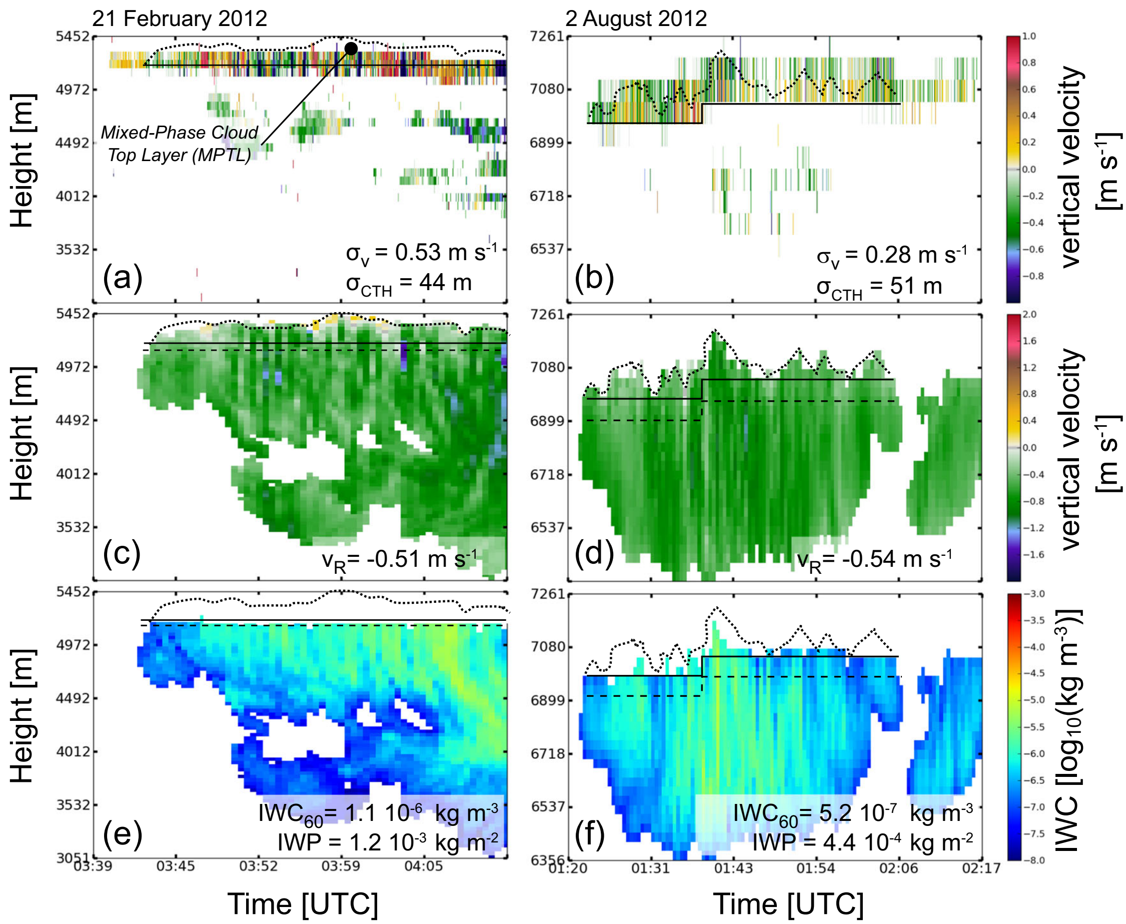

Fig. 1 Mixed-phase layered clouds measured with Doppler lidar and cloud radar on 21 February 2012 (left) and 2 August 2012 (right). Vertical velocity v_L from Doppler lidar (**a**, **b**) is depicted together with vertical velocity v_R from cloud radar (**c**, **d**) and IWC derived with the method of Hogan et al.[30] (**e**, **f**). Lines indicate cloud top derived from cloud radar (dotted lines), base of the mixed-phase top layer (MPTL, solid lines), and the height 60 m below MPTL in which microphysical parameters of the falling ice crystals are derived (dashed lines). The units of the colorscale of (**e**, **f**) represent mass density in a logarithmic representation

layer, confirming the hypothesis of a close relationship between in-cloud vertical motions and ice formation. In Bühl et al.,[16] the mass flux $F = \mathrm{IWC} \times v_p$ of ice crystals falling from mixed-phase cloud layers has been characterized (v_p being the particle fall velocity as derived from cloud radar). In this work, we show that the relation between the standard deviation of vertical velocity σ_v and ice-formation rate can be measured directly with ground-based remote sensing. F is a very useful parameter for the study of ice formation in mixed-phase clouds, describing the vertical flow of ice mass through a unit area. Assuming steady conditions, F measured at cloud base is equal to the rate of ice mass generation in the cloud column above.

In the following, the two microphysical quantities will be used: IWC_{60} and $\mathrm{F}_{60} = \mathrm{IWC}_{60} \times \mathrm{v}_{60}$ (with v_{60} being the mean Doppler velocity of the precipitating ice particles measured with cloud radar at 60 m below the MPTL base). In the context of this work, both quantities are always averages over the occurrence time of a cloud case.

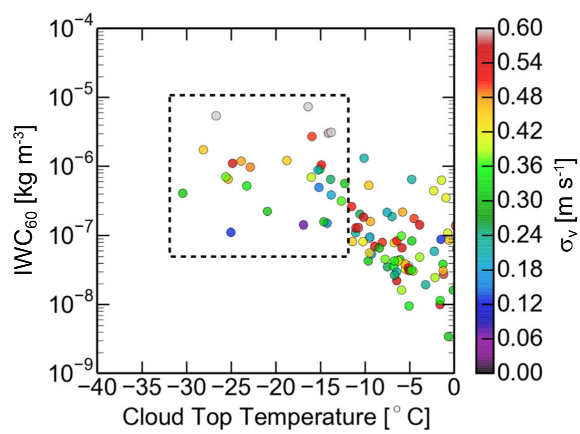

Fig. 2 IWC_{60} and σ_v from Doppler lidar are shown as a function of CTT

RESULTS

In this section, the measurements are presented with the aim of deriving empirical relationships between ice formation and turbulence in mixed-phase cloud layers. In Fig. 2, values of cloud-top temperature (CTT) and σ_v are shown for all selected cloud cases together with IWC_{60}. Below a temperature of −12 °C, a plateau of IWC_{60} is visible, while at warmer temperatures no clear relationship between IWC_{60} and σ_v can be found. In the following, we analyze this dependence in order to come up with empirical parameterizations of the observed relationships of ice properties with σ_v. In Fig. 3, IWC_{60} is shown as a function of σ_v for cloud cases with CTT < −12 °C. In Fig. 4, F_{60} is shown also as a function of σ_v. Both IWC_{60} and F_{60} can be described as an exponential function of σ_v. Hence, nonlinear fitting of the data is applied in order to come

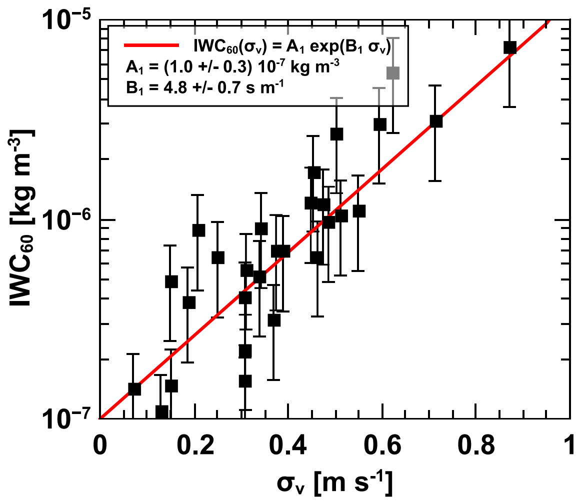

Fig. 3 IWC_{60} (ice water content 60 m below the MPTL) as a function of the standard deviation of vertical velocity for all clouds with CTT < −12 °C. Maximum uncertainty of σ_v is 0.045 m s^{-1} and not shown in the plot

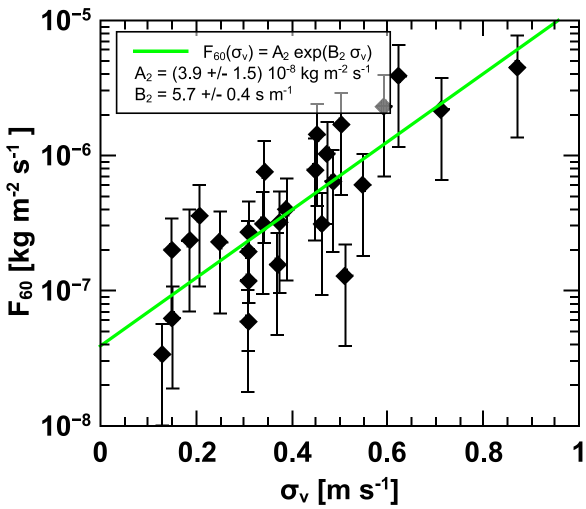

Fig. 4 The ice crystal mass flux $F_{60} = IWC_{60} \times v_R$ (60 m below mixed-phase MPTL) is plotted against σ_v, again for all clouds of Fig. 2 for CTT < −12 °C

up with two empirical parameterizations for the relationships of σ_v with IWC_{60} and F_{60}, respectively:

$$IWC_{60}(\sigma_v) = (1.0 \pm 0.3)10^{-7} \exp[(4.8 \pm 0.7)\sigma_v] \text{ kg m}^{-3} \quad (1)$$

$$F_{60}(\sigma_v) = (3.9 \pm 1.5)10^{-8} \exp[(5.7 \pm 0.4)\sigma_v] \text{ kg m}^{-2} \text{ s}^{-1}. \quad (2)$$

For both fitted curves the squared residual coefficient $R^2 = 0.7$. The parameterizations are valid for mixed-phase cloud layers with CTT < −12 °C, a geometrical thickness of the MPTL < 380 m and a duration of more than 900 s. Possible co-variations with CTT or cloud-top height (CTH) are investigated in Figs 5 and 6. On basis of these results, any relationship of σ_v on CTH and CTT can be ruled out.

DISCUSSION

Observations of the vertical velocity in ice-precipitating shallow supercooled mixed-phase cloud layers were used to derive a correlation between the efficiency of ice formation and the vertical-velocity variance σ_v. For both, the ice water content IWC_{60} and the ice mass flux F_{60} at 60 m below the mixed-phase cloud

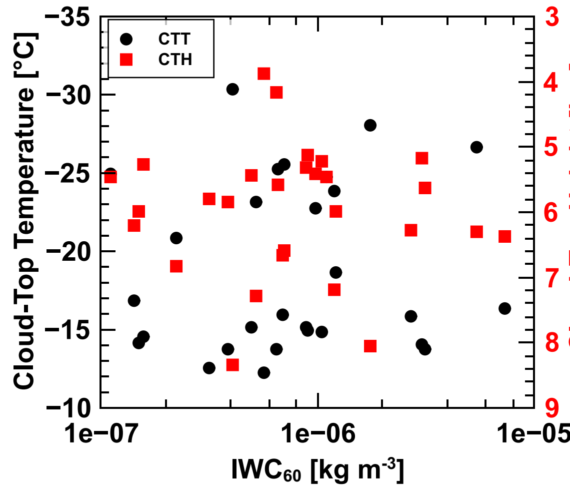

Fig. 5 Correlation between IWC_{60}, CTT, and CTH, indicating that there is no systematic height or temperature dependence of IWC_{60}

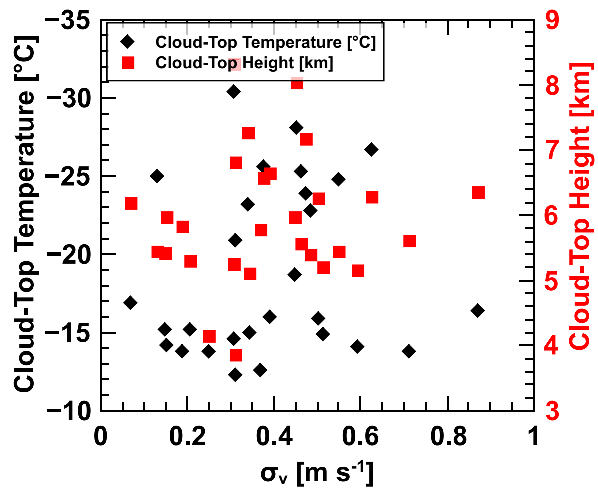

Fig. 6 Correlation between σ_v, CTT and CTH, indicating that there is no systematic height or temperature dependence of σ_v

base phenomenological power-law parameterizations have been established as functions of σ_v. The parameterizations are valid for cloud-top temperatures CTT < −12 °C.

It was shown by Morrison et al.[1] on the basis of simulations that increased turbulence does not directly increase ice formation, but enhances the entrainment of cloud condensation nuclei (CCN) and INP into the cloud layer. In such a case, the presence of more INP could increase the rate of ice nucleation. Different possible explanations can be found in order to explain the relationship between turbulence and ice particles, because there is a variety of indirect links between in-cloud ice production and vertical motions. E.g., layer stability, ice particle lifetime and ice particle growth are enhanced in upward moving air.[2]

In summary, increased turbulence in a mixed-phase cloud layer may lead to

- enhanced entrainment and activation of CCN and INP
- enhanced entrainment of dry air
- could increase the efficiency of inside-out ice nucleation[26]
- enhanced efficiency of droplet coalescence leading to larger droplets with a higher probability for ice nucleation
- a thicker liquid top layer in which ice particles can grow longer due to the Wegener–Bergeron–Findeisen process at the expense of liquid water

- enhanced cooling rates at cloud top and more efficient nucleation
- possibly a higher rate of contact freezing.

Unfortunately, a detailed definite conclusion about the nature of the effects observed cannot yet be drawn from the measurements. However, this study yields a phenomenological parameterization for the dependence of ice formation and vertical air motions in mixed-phase cloud layers. It targets the process of ice formation in a laboratory-like environment, revealing the nature of the effect intentionally without any disturbing secondary effect like ice multiplication, riming, or similar. The parameterizations are valuable for the evaluation and the further development of weather and climate models. Knowledge about the relationship between F_{60} and IWC_{60} with σ_v is also vital for disentangling the influence of air motions and aerosols on ice formation in present and future global contrast studies. The setup presented in this study is currently the only way to reach this goal by probing real clouds in the atmosphere.

An influence of vertical air motions has been proposed before, but experimental evidence was absent. The relationship between both IWC_{60} and F_{60} with σ_v is quantified for shallow mixed-phase clouds. Only the restriction to free-tropospheric mixed-phase cloud layers with a geometrical thickness <380 m and with a CTT < -12 °C makes the effect visible. All of these clouds under study have a CTH > 3500 m, putting their level of ice formation well into the free troposphere. For clouds with CTT > -12 °C no correlation is found with the evaluation method presented here. At higher CTT, cloud microphysical processes must be active which outweigh or overlay the inter-dependence of σ_v, IWC_{60}, and F_{60}. To date, it can only be speculated which processes might be responsible, but cloud dynamics are constrained by the aid of this study. Hence, the strong activity of ice-multiplication processes might be one reason. Nevertheless, possible reasons should also be looked for in the increasing influence of the Earth surface with its strongly spatiotemporally varying mix of potential INP whose activity can possibly dominate the vertical-velocity dependence of ice-formation efficiency at increasing temperatures.

METHODS

In order to enable a study of the relationship between cloud dynamics and ice-formation efficiency, observation techniques are required that provide information about the properties of liquid droplets, ice crystals, and the dynamic environment for an ensured absence of secondary and multiplied ice since these processes prohibit the drawing of any conclusions on the primary ice-formation processes taking place.

In the course of this study, measurements were performed with the Leipzig Aerosol and Cloud Remote Observation System (LACROS) at Leipzig, Germany between 2011 and 2012. LACROS is a suite of remote-sensing instruments. The LACROS 35-GHz cloud radar is pointing vertically and measures with a temporal resolution of 10 s and a range gate length of 30 m. The collocated Doppler lidar "WiLi"[27] was always pointed vertically and operated with a temporal resolution of 2 s and a vertical resolution of 75 m. Besides these two instruments, a microwave radiometer and a ceilometer are used to derive liquid–water path (LWP) and cloud-base heights with a time resolution of 30 s. LACROS has been part of the Cloudnet consortium since 2011, and the Cloudnet algorithms[28] are used to compute cloud microphysical products like the cloud-layer adiabatic and scaled adiabatic,[29] LWP, and IWC[30] on a continuous basis.

Mixed-phase cloud layers measured over Leipzig are analyzed with the data processing method presented in Bühl et al.[16] The method is used in order to select clouds that present clearly defined environmental conditions and a statistically significant number of Doppler lidar observations for a proper characterization of the vertical-velocity field within the cloud layers.

Selection criteria for the cloud layers investigated in this study comprise a geometrical thickness <380 m, standard deviation of measured cloud-top heights $\sigma_{CTH} < 150$ m throughout the cloud case and a minimum occurrence period of 15 min with a MPTL detected at least 85% of the time. Potential cloud seeding from above is identified via the cloud radar and avoided in the statistical analysis.

Vertical velocities are derived and quality controlled with the combination of the Doppler lidar instrument and the Cloudnet data set. The Cloudnet target classification scheme is used to automatically classify liquid and mixed-phase cloud layers.[16] When a cloud profile is classified to have a liquid-containing top, the vertical-velocity values are selected at the height where the Doppler lidar shows the strongest backscatter signal (solid lines in Fig. 1). In this way, vertical velocity is measured at the base of the predominantly liquid MPTL. Shallow cloud layers are selected (with an MPTL of <380 m geometrical thickness) in order to keep ice particle growth time below ~20 min[31] and, hence, to avoid effects of secondary ice formation.[16] Standard deviation of vertical air velocity σ_v is calculated from all vertical-velocity values observed at the base of the MPTL. σ_v is considered a measure of the mean turbulence strength inside of the complete MPTL. Temporal resolution of the Doppler lidar measurements of 2 s and restriction to cases with an observation time longer than 900 s with an MPTL occurrence time of at least 85% yields a minimum of 382 vertical-velocity values per cloud case. This number of measurements results in a factor of 0.05 as a maximum statistical error. Uncertainty of Doppler lidar measurement value is 0.05 m s^{-1},[27] which is negligible for the computation of σ_v.

The parameterization of Hogan et al.[30] is used to derive the IWC at a distance of 60 m below the MPTL (dashed lines in Fig. 1). At this height, cloud-top liquid water is absent and turbulence of the air are not influencing the radar measurements. It is important to make sure that liquid water is absent where IWC_{60} is derived, because the method of Hogan et al.[30] is developed explicitly for radar measurements of ice crystals only. At 60 m below cloud base, the properties of the ice crystals are still largely the same as inside of the cloud-top layer and have not yet strongly undergone transformation processes like evaporation, aggregation, or splintering.

DATA AVAILABILITY

The Cloudnet data used in this work is available via the database of the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) at https://actris.nilu.no. The corresponding Doppler lidar data set is available at https://doi.org/10.5281/zenodo.3385388.

CODE AVAILABILITY

For data processing mainly the Cloudnet framework has been used (latest release available at https://github.com/tukiains/cloudnetpy).

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AUTHOR CONTRIBUTIONS

Johannes Bühl performed the Doppler lidar measurements, data evaluation, data synthesis, and paper preparation. Patric Seifert was in charge of the additional synergistic measurements with cloud radar and for the Cloudnet data processing. He also helped in interpretation and presentation of results. Ronny Engelmann supervised the Doppler lidar measurements and contributed software for basic data processing. Albert Ansmann was initiator and supervisor of the UDINE project from which this research was financed primarily. He was also leading the corresponding measurement campaign at Leipzig and supervised the paper preparation and presentation of the results.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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