July 15, 2022

The SCoPEX Advisory Committee invited a panel of experts to support a scientific review of the proposed SCoPEx experiment. The Panel (Jim Hurrell, Long Cao and Karen Rosenlof) was responsible for: (1) suggesting external reviewers to the advisory committee; (2) evaluating and summarizing the reviews, with a focus on the scientific merit of the experiment; and (3) communicating the findings to the Advisory Committee via a written summary.

The questions external reviewers were asked to address included:

1. Will the proposed study make an important scientific contribution? If so, what is that expected contribution?
2. Can the experiment, as designed, achieve its objectives by the methodology proposed in the experiment plan?
3. Is there anything else relevant to the scientific merit of this experiment plan that raises concern that has not been covered in the previous questions?

External reviews were obtained from five preeminent atmospheric scientists who specialize in aerosol and chemical processes. Some were instrumentalists and others were modelers. The five experts have also worked on issues related to stratospheric aerosol injection as a possible solar geoengineering technique.

The reviewers had overall agreement on many aspects of the proposed SCoPEx experiment. Overall, the reviewers noted that the proposal has some compelling and important goals that cannot be addressed in laboratory studies or from numerical modeling, and that the Harvard team has in-depth knowledge of key aspects and uncertainties of stratospheric aerosol injection approaches. However, all of the reviewers expressed some significant concerns about the proposed methodology and casted doubt on the successful achievement of the proposed goals. The reviewers also expressed concerns that the proposal falls short in delineating the benefits of SCoPEx. The reviewers made comments beyond the specific questions posed in the terms of reference, and some of those thoughts are captured in the summary below.

Overarching issues:

On common issue noted in the external reviews was that it was very difficult to assess from the proposal if SCoPEx can meet it scientific goals. Much more detailed information on methodology and implementation is needed. One reviewer, for example, desired information on the number of balloon flights that were being proposed, as well as the time period and how long will each flight be. This information is relevant to assessing the risk of complete failure. Reviewers asked whether multiple flights are planned to account for the possibility of failure on an initial attempt and whether adequate time is planned for the case when problems are encountered on the first attempt. Finding the plume is key to success, but there was skepticism whether that was possible, and not enough details were given to assess the likelihood of success. One comment was that to use a lidar to find the plume, the lidar can't be in the plume.

Specifically, to assess whether the experiment is viable, reviewers wanted to know: 1) What is the sequence of detection and sampling? 2) How does the communication work between balloon operations and gondola operations? And 3) Will there be adequate data collected and over a long enough period of time to measure turbulent dissipation and aerosol evolution? It was suggested

that a plume model be used to sample a simulated balloon flight in order to determine if useful results would be obtainable.

It was noted by one reviewer that an overriding issue in the proposal is the substantial risk of not achieving the objectives due to the complexity of developing and operating both a new platform and a new payload. Risk and risk mitigation are not discussed in the foundational document at all, and this was noted as a significant shortcoming.

Some reviewers raised important questions about the instrumentation. The optical particle counter was noted to not be well suited for the size of aerosol particles being studied. Two reviewers questioned whether the sun photometer would work to measure scattered light from the injected aerosol plume, and one questioned the detection limits cited for the sun photometer.

Another concern was that there needs to be attention paid to the issue of societal opposition, and the proposal needs to be clear, exact, and explicit about uncertainty. One of the scientific reviewers recommended an educational campaign be conducted in conjunction with SCoPEX.

Specific Goals:

The proposed work is structured as having three scientific goals: (1) Measurements of Turbulence for Small Scale Mixing; (2) Evaluation of Aerosol Microphysics of AM-Sulfate and Alternative SAI Materials; and (3) Evaluation of Process Level Chemical Models of Stratospheric Chemistry of Sulfate and Alternative SAI Materials.

Reviewers noted that the equipment and instruments are described in great detail in the SCoPEx proposal, but that the science questions are not. This is contrary to most proposals that begin with scientific questions, then follow with the proposed methodology to answer them.

The first goal, **measurements of turbulence**, was recognized as important. There is little experimental data related to this problem and some of the reviewers felt that this is where SCoPEX could make the most significant contribution. However, one reviewer stated that, because the balloon has propellers, that it would be unsuitable for making turbulence measurements, and that the injector would also make a gondola platform unsuitable. Another reviewer interpreted this portion of the experiment as useful mainly for understanding and testing coagulation theory for solid $CaCO_3$ particles in the wake of injection behind the balloon package. Although it is suggested that the "measurements which resolve the winds at the dissipation scale will allow numerical models to realistically close the atmospheric kinetic energy budget", details on how this analysis will be performed are missing. That is, this is not a standalone goal to inform SAI in general, but to understand coagulation for the injection specifically proposed in SCoPEx. If this aspect of the experiment could be modified to also address how turbulence would act to disperse gaseous SAI material that forms into particulates, it would be more useful. As currently designed, SCoPEx will likely only sample regions of low turbulence because the balloon will not be launched into regions of high winds. Also, the experiment will not be able to globally characterize turbulence, because of the limited number of measurements that can be obtained from a few balloon flights over a limited region. Understanding turbulent mixing in regards to SAI deployment is critical; however, as described in the SCoPEX document, it is not

clear that this portion of the experiment will be successful unless, perhaps, the objective is simply to understand the turbulence that is specific to SCoPEx. Even then, as already noted, other reviewer concerns regard the suitability of the proposed balloon gondola for measuring turbulence. Another reviewer noted that an actual SAI deployment is unlikely to use balloons; thus, the proposal should explain the relevance of the experiment to the more likely aircraft-based approach if SAI was ever implemented.

How the second goal, **evaluation of aerosol microphysics**, will be addressed was not viewed favorably by most of the reviewers. One reviewer noted that this is the highest risk objective of the proposal due, in part, to the lack of details of the approach. Another comment was that we already have a decent understanding of the size, chemistry, and radiative impact of stratospheric aerosol, both in background and volcanically enriched conditions, and that SCoPEx is unlikely to add new information to that understanding. Evaluating how aerosols in a plume evolve is important for SAI, but it wasn't clear from the proposal whether an evolving plume could actually be followed, especially for the time period relevant for SAI injections. This reviewer further noted that even if the gondola could be maneuvered into the plume, it would be difficult (if not impossible) to know where it was within the plume, noting that the lidar cannot measure close to itself. Another reviewer noted that it is very likely that the team can add a known mass of an alternative SAI material; however, exactly how AM-Sulfate will be added was not clear, nor was how an appropriate size distribution would be generated. The results of this portion of the experiment should allow improved understanding of how the size distribution will evolve immediately after injection. However, whether this is useful to inform any realistic future injection effort was questioned.

One reviewer noted that the proposed aerosol particle counter is not well suited for the size of the aerosol particles being studied. Another stated that the primary issue for SAI is the relationship between the injected material and the subsequent evolution of the aerosol size distribution. In situ measurements are the way to measure the evolution, and at present it is not well understood. A much better description of the methodology for this part of the experiment is needed. Another comment was that SCoPEx will not be able to look at the conversion of SO_2 to H_2SO_4, because the time scale for the flights is too short.

The third goal, **evaluation of process level chemical models**, was not viewed favorably. One reviewer noted that the study of alternate materials would be of little interest to the broader atmospheric community. Another had a different opinion, stating that understanding how the addition of SAI materials might alter the distribution of photochemically active constituents that impact ozone chemistry is important, as it will inform whether alternative SAI agents would provide benefits compared to SO_2 or sulfate addition. However, that reviewer noted that it was not clear what new environmental information SCoPEx might reveal that would not be available from appropriate laboratory studies. The availability in the laboratory of much broader analytical capabilities to study both the gas and condensed phase chemistry, moreover, would likely provide a much more robust and less expensive evaluation of these chemical interactions. Another reviewer expressed the opinion that this was a very high-risk aspect of the proposed experiment, largely because it was not clear that the instruments could sample over the length of time needed to sample heterogeneous chemical processes. Another reviewer felt that this was a

topic for the future, and sufficient details were not provided to assess how SCoPEX will address this topic.

To summarize comments regarding the primary two questions noted:
Will the proposed study make an important scientific contribution? If so, what is that expected contribution?
Overall the reviewers were not convinced that SCoPEx, as described, will make an important scientific contribution. Exploring turbulent mixing was deemed to be important, although adjustments to the experimental design are likely needed in order to reduce risk and achieve success.

Can the experiment as designed, achieve its objectives by the methodology proposed in the experiment plan?
There were many comments from the reviewers noting that the methodology was not adequately presented to be able to actually answer this question.

Whether the experiment will achieve its goals is questionable. Overall, the reviewers noted that there is compelling science to be addressed by SCoPEx. Specific goals include improving understanding of near-field properties and the surface chemistry of injected aerosols, and turbulent mixing in ambient stratospheric conditions. These are important goals that, if achieved, would represent a contribution to SAI research in the form of improved process understanding, useful SAI modelling studies and could provide information for decisions related to SAI implementation. The foundational document provides justification for in situ measurements to better understand the relevant microphysical and chemical processes.

One reviewer noted that the most likely result will be a well-documented model for the near-field coagulation physics for solid and liquid particles in the wake of the balloon under a subset of well characterized small scale turbulence conditions. Another reviewer had difficulty stating that the experiment is likely to achieve its goals because the methodology was not adequately described. Even considering that, however, that reviewer noted that the experiment has merit: society needs information to make informed decisions about SAI, and this cannot be done in the absence of observed data.

One reviewer noted that the best outcome is that the experiment will yield useful, but flawed, information that will require subsequent experiments to obtain better data. There should also be more attention paid to the societal challenges, in that this experiment may be objected to by some people and organizations. It would make sense to preemptively point out why these injections are not an environmental risk.

In summary, the experiment itself has negligible potential to alter the background stratosphere or harm the atmosphere or the Earth's climate. There may be valuable information gained from this experiment, but the reviewers did not indicate that this will make an important scientific contribution. Also, the reviewers noted that much more information is needed on the details of implementation. However, SCoPEx could be a first step that may provide guidance as to how future related experiments should be conducted.