Aerosols, the Ocean and Ice: Impacts on Future Climate and Sea Level

1. **Shortcomings in climate modeling: towards improved climate change projections.** With a new multidisciplinary Earth system approach, we will address major issues that affect the ability of climate models to project climate change – anthropogenic aerosols, ocean mixing and heat uptake, and ocean-ice interactions and their implications for sea level – via analysis of observational data, global modeling, and testing against emerging paleoclimate data, all involving innovative international cooperation.

   Global aerosols affect Earth's energy imbalance and can be described in unprecedented detail by high-precision polarimetry. Best prospect for initiation of a data record is in China, but international cooperation is crucial to fully exploit polarimetry's potential, including determination of aerosol-cloud climate forcing.

   Ocean heat gain is a basic diagnostic of Earth's energy imbalance and climate change. Argo float data capture the bulk of the signal and with suitable model studies can help resolve uncertainties in ocean mixing and dynamics, and important regional ocean response, especially in the Southern and North Atlantic Oceans.

   Ice sheet interactions drive key climate feedbacks and future sea level. Field campaigns are collecting data on ocean-ice interactions; utilization of these data is needed urgently. The end of the prior interglacial, the Eemian, offers a special opportunity, as evidence suggests rapid sea level rise as the Southern Ocean warmed. Successful modeling of end-Eemian climate may be the key to understanding the climate threat. Although not an explicit objective of our proposal, it is worth noting that international scientific cooperation may be a helpful prelude to future governmental cooperation in addressing climate change.

2. **Area of Focus: the Earth System.** Ameliorating the threat of uncontrolled large sea level rise requires understanding of the entire climate system and knowledge of human-made forcings. Aerosols are the largest uncertainty in global climate forcing. The fate of ice shelves and ice streams, gateways of land ice to the ocean, depends on warming of the abutting ocean and ice surface processes. Ocean mixing and the sensitivity of large-scale ocean dynamics to surface forcings in models are suspect and require testing against ongoing observations and paleoclimate data. End-Eemian climate change provides a particularly relevant test case.

   Aerosols are believed to cause a forcing of the global climate system second only to greenhouse gas (GHG) climate forcing. On global average aerosols likely offset a substantial fraction of GHG warming, at present, but aerosol climate forcing is complex, changing, and largely unmeasured. Absorbing aerosols, especially, alter precipitation amount and variability, affecting large regions. Understanding of atmosphere-land interactions and impacts on vegetation in the regions of the world that will be affected most by human-caused climate change depends upon knowledge of aerosol changes.

   Aerosol forcing is difficult to observe, requiring precise global monitoring of aerosol and cloud particle microphysics. The Chinese government is currently initiating high-precision polarimetric observations from polar orbiting spacecraft. These provide the best hope for establishing a continuous global record of aerosol microphysical properties of the fine and coarse size modes, analogous to Keeling's CO_2 record.

The ocean is a big source of uncertainty in climate projections. The ocean provides most of the thermal inertia of the climate system that limits the pace of global surface temperature change. However, the realism in models of the temporal response of ocean surface temperature caused by surface forcings is uncertain, because the response depends upon the realism of ocean mixing, dynamics and heat storage.

Increasing meltwater from Greenland and Antarctica raises the possibility of rapid regional and global climate change, but different ocean models produce highly variable responses to the resulting upper ocean salinity anomalies. Evidence exists that surface climate is responding already to freshwater injection in the North Atlantic and Southern Oceans, but most models seem to be less sensitive than what observations indicate. The importance of this issue for future climate and sea level requires focused study of likely sources of the difficulties in modeling the ocean response to freshwater anomalies.

Ocean-Ice interactions around Antarctica and Greenland have substantial control on the loss of ice sheet mass and thus global sea level rise. Ice shelves in Antarctica and tidewater glaciers in Greenland are affected strongly by the temperature and currents in the abutting ocean and ice surface processes that affect meltwater and mechanical stress. Ocean models as well as ice sheet models need to be tested and evaluated in cooperation with top experts in observations of the ice shelves, glaciers and surrounding oceans.

Paleoclimate. Global temperature today is already close to that in the Eemian period, about 120 thousand years ago, when sea level reached heights 6-9 meters (20-30 feet) higher than today. Dating of paleoclimate records has improved and allows the possibility of informative modeling analyses of the Eemian period, particularly the late Eemian when there is evidence of rapid sea level rise.

3. Transformational methodological advances being pursued.

Aerosols. Polarization of reflected sunlight, if measured to a precision approaching 0.1%, at wavelengths between the near-UV and near-IR, and at a wide range of scattering angles, has the potential to reveal as many as 10 parameters defining atmospheric aerosol properties, or cloud properties in the case of a cloudy sky, as we have demonstrated for Venus clouds and the Earth's atmosphere observed from aircraft. China is just initiating polarimetric observations from space that largely satisfy the measurement requirements and plans to continue observations indefinitely. We will cooperate to help assure initiation of a Keeling-like long-term aerosol record, as an input to climate modeling analyses.

Ocean. Evidence exists that the parameterization of small-scale mixing in the ocean affects the response time of surface climate to a climate forcing and likely affects the nature of the ocean response. Mixing parameterizations as well as model resolution, grid scheme, finite differencing method and other model characteristics affect the outcome. We will test the effect of alternative treatments, organize a workshop, and invite participation in well-defined sensitivity studies to illuminate the issues.

Ice Sheets. We will compare several approaches for quantifying the response of ice shelves and tidewater glaciers to current ocean warming and precipitation anomalies using data from a wide variety of ongoing and past field programs such as NASA's Oceans Melting Greenland (OMG), Operation Ice Bridge (OIB) and other in situ campaigns in Antarctica and Greenland, as well as remote sensing assets. We will involve global experts in a workshop to discuss and compare alternative analyses.

Climate Simulations. In addition to simulating historical climate change including projection into the future, we will make climate model studies relevant to understanding what happened in the late Eemian period. A major advance of understanding is feasible, as it seems now possible to put events in the North Atlantic and Southern Oceans on a common time scale. A workshop with global experts will be organized.

4. **Role or needs envisioned for additional engineering support from the Core Team.** We expect that most of our computing will be covered by co-investigator facilities, but it is possible that we will require computing support, especially if our workshops lead to the need for substantial simulations using alternative models.

5. **A data source code management plan.** We will have a focus on clear presentation and availability of our data. We agree with the requirement of data and source code availability.

6. **Potential Principal Investigators and partner institutions.**
Lead organization: Climate Science, Awareness and Solutions (CSAS), Earth Institute, Columbia University, Principal Investigator: J. Hansen, Co-I Investigator: M. Sato, P. Kharecha, C. Rye, E. Jeong
Boston College: Jeremy Shakun, Hilary Palevsky
China: Junji Cao (Key Lab of Aerosol Chemistry and Physics, Institute of Earth Environment, Xi'an, CAS), Zhengqiang Li (Institute of Remote Sensing and Digital Earth, CAS), Jing Li (Peking University)
Denmark: Emilie Capron (Niels Bohr Institute, University of Copenhagen)
France: Karina von Schuckmann (Mercator Océan); Yves Balkanski (Université Paris-Saclay)
Switzerland: Thomas Stocker (University of Bern)
Lamont-Doherty Earth Observatory: Pierre Dutrieux, Marco Tedesco
Columbia University: Larissa Nazarenko, George Tselioudis, Kostas Tsigaridis
Massachusetts Institute of Technology: John Marshall
University of California, Irvine: Eric Rignot, Isabella Velicogna
University of Iowa: Jun Wang

7. **Required Budget and justification.** Major pieces of this investigation are funded independently, specifically: China investigators and satellite observations (Junji Cao, Zhengqiang Li and Jing Li), Ocean Melting Greenland (OMG) project (Josh Willis) and Hesing-Simon foundation study of Helheim ice stream in Greenland (Marco Tedesco). Proposed budget will be in the range $1-1.5 M/year, allowing typical co-investigator support of order $50K/year to assure adequate dedication. Funding includes international workshops, computing support, travel and publications.

   Funding would be dispersed by the non-profit organization CSAS.inc, where there is no overhead or indirect cost. Funds dispersed to university co-investigators would be made consistent with the requirement that indirect costs not exceed 10 percent. CSAS.inc is a non-profit separate from Columbia University Earth Institute CSAS. CSAS.inc allows us to avoid indirect costs on non-salary expenditures.