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GLOBAL WARMING AND THE NEXT ICE AGE

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Earth's climate is a complex dynamical system that is responding to an array of forcings, which include anthropogenic carbon dioxide and aerosols and solar variability. Aeorsol and solar forcings are imperfectly constrained and only monitored by observational systems with limited sensitivity and coverage. The Second International Conference on Global Warming and the Next Ice Age (GWNIA), like its predecessor in 2001 in Halifax, Nova Scotia, aimed to provide a venue for detailed discussions of how global climate responses to natural and anthropogenic forcings besides long-lived greenhouse gases (GHGs; Chylek et al. 2007a). Conference delegates discussed the shortcomings of current models, observations, and theory, and developed a path toward using observational data to refine these models. The second half of the conference focused on understanding and reducing climate prediction uncertainties caused by anthropogenic aerosol forcing.

U.S. House Representative Tom Udall of New Mexico met with participants informally, then welcomed conference attendees with a taped presentation and expressed appreciation for research contributing to understanding climate change. He also announced a congressional bill he introduced that would enable a cap and trade program for carbon dioxide to help mitigate the risks of potential climate change. Introductory remarks by senior Los Alamos National Laboratory (LANL) officials stressed the synergy among climate change research, energy security, and threat reduction programs to move toward a solution. These were the focus of a keynote session on progress toward clean and carbon neutral energy.

Observations of worldwide decadal to interdecadal climate variability, with a focus on North America, show that spatial patterns of sea surface temperature (SST) and night mean air temperature (NMAT) warming are very similar. Meteorologists and researchers with the Hadley Centre and the Met Office attribute much of the winter European warming in the decades 1965–95 to the change from a generally negative to a generally strong positive phase of the North Atlantic Oscillation (NAO). However, this

THE SECOND INTERNATIONAL CONFERENCE ON GLOBAL WARMING AND THE NEXT ICE AGE

WHAT: More than 120 scientists from 14 countries with expertise in the observation, theory, and modeling of climate change met to discuss how Earth's climate responds to non–greenhouse gas forcings, and how to improve predictions of these responses.
WHEN: 17–21 July 2006
WHERE: Santa Fe, New Mexico

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positive phase now seems to be ending. Hadley Centre scientists also believe that some of the current rapid warming of the North Atlantic is due to an accelerating thermohaline circulation related to the Atlantic multidecadal oscillation (AMO), although this is controversial. However, they predict a natural thermohaline circulation (THC) slowdown starting in about the next decade, which could be enhanced by increasing greenhouse gases (Parker et al. 2007).

Careful attribution of regional climate change between natural and anthropogenic causes was the subject of many lively discussions at the conference. Beginning with an overview of observed and modeled twentieth-century climate change, comparisons of the Geophysical Fluid Dynamics Laboratory (GFDL) model to satellite data show that relative humidity has remained nearly constant in the upper troposphere, which suggests that global warming triggers H_2O feedbacks similar in strength to those used in general circulation models (GCMs). An applied mathematician's view of the butterfly effect was used to carefully distinguish integration errors arising from initial conditions from those arising from the simplification of processes (Essex et al. 2007). Observations were used to derive an effective heat capacity and an adjustment time of the Earth's climate system (about 5 yr, shorter than many other estimates), whose ratio is the climate sensitivity parameter (Schwartz 2007; Chylek et al. 2007b). Removing the direct GHG forcing from the sensitivity estimate yields an estimate of the total non-GHG direct and indirect forcing. Many subsequent presentations demonstrated that climate models continue to improve representations of processes that were previously oversimplified or were completely neglected as intractable.

Satellite measurements yield convincing data for the spatiotemporal distribution of indirect aerosol effects. For example, the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol retrieval algorithms have helped to constrain aerosol direct radiative forcing. In addition, Multiangle Imaging Spectroradiometer (MISR) and MODIS-retrieved aerosol optical depths (AODs) are more accurate over land and ocean, respectively. MISR can also retrieve aerosol plume height using stereo observational methods. Optimal satellite viewing angles for retrieving AOD occur at medium-scattering angles where the phase function is less sensitive to assumed aerosol properties. An approach to inferring how aerosols increase cloud lifetime or cloud fraction over the Atlantic, developed by Yoram Kaufman[1] [Goddard Space Flight Center (GSFC)], is being applied globally by other groups. Alternately, data gaps within the Aerosol Robotic Network (AERONET) implicitly contain information about cloud fraction that can be used to understand local aerosol cloud interactions (Popp et al. 2007). Polarimetric remote sensing platforms are increasing the spatial coverage and accuracy of measured aerosol size distributions and refractive indices. The spaceborne Polarization and Anisotropy of Reflectance for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) mission uses polarimetric principles to characterize aerosols. Likewise, the National Aeronautics and Space Administration (NASA) Glory mission uses similar principles to measure the freezing transition in clouds, and a future Glory-like mission that would retrieve very accurate liquid cloud droplet size distributions was recommended.

The "Next Ice Age" conference theme often manifested itself in animated discussions based on widely varying interpretations of observational data, its meaning, and future implications. One interpretation is that a natural pattern of low orbital obliquity exists where the dark tropical oceans warm at the expense of the polar regions, thereby increasing meridional vapor transport and glaciations. Based on an interglacial period ~400,000 yr ago, another interpretation estimated that the current interglacial period will persist for another 14,000 yr in the absence of anthropogenic forcing. Moreover, peat lands could modulate climate by storing carbon, while cosmic dust deposition alters climate through ocean fertilization and dimethyl sulfide emissions, and also explains some observed millennial-scale variability such as the Little Ice Age. Coccolithophores were used to infer significant North Atlantic slope water cooling during the Holocene, consistent with variations in Gulf Stream movements relative to the North American coast.

Progress in understanding the effects of solar variability on climate was also presented. In one recent study, results indicated less direct solar radiation variation on the century time scale than was previously thought. In another, the problems of homogenizing satellite solar radiance observations with dif-

[1] Yoram Kaufman (GSFC), one of the conference organizers, died in an accident a few weeks before the conference. In two sessions dedicated to him, and in many other talks, speakers noted Kaufman's many contributions to satellite remote sensing and climate studies. Kaufman's family felt that research carried out with Kaufman's positive attitude would help to keep his spirit alive.

ferent satellite offsets (a problem common to satellite data) raised concern about the continuity of future missions to monitor solar variability. Also, cosmic ray production was found to correlate with mid-plus high-level cloud amount over the International Satellite Cloud Climatology Project record, while radiocarbon (^{14}C) records were used to infer total solar irradiance (TSI) forcing of recent and paleoclimate temperature changes. These data suggest that up to 50% of the twentieth-century global warming could be explained by solar radiation variability (Scafetta and West 2007). Evidence of solar output variation effects on the water cycle were also presented; however, the mechanisms are not well understood and sensitivity studies using climate models are needed to help examine this (Ferguson and Veizer 2007). It was also theorized that the effect of waves on sea surface emissivity can cause important climate feedbacks, which models currently neglect.

Global temperature records were also critically examined (McKitrick and Michaels 2007; Pielke et al. 2007; Reiter 2007). In particular, three regions where surface temperature measurements disagree with recent trends from specific GHG-driven models were identified. Data quality concerns about surface temperature records used by the Intergovernmental Panel on Climate Change (IPCC) were raised with clear evidence of some bad sites and thus the likelihood of bad local/regional trends. It was recommended that ocean heat content would be a more robust method to quantify energy storage, for example, from increasing GHGs.

The effects of positive feedback processes in the stable nocturnal boundary layer, which amplify changes in the surface diurnal temperature range, such as the reduction induced by GHGs, were identified. It was argued that half of the tropospheric temperature trends over land in the twentieth century were attributable to sampling biases due to urban heat islands. It was also shown that Greenland had a previous warm period centered on 1930 and that the rate of warming was higher in 1920–30 than 1995–2005. These temperature variations correlated inversely with the NAO index at the time. A reconstruction of Greenland melting areas at high resolution (1 km^2) was also presented and linked to warming (Chylek et al. 2007c). High-resolution data are needed to understand what is really happening to the Greenland ice sheet.

The second half of the conference focused on the complex climate forcing by anthropogenic aerosols and how they confound the task of quantifying climate sensitivity.

Global dimming, a large reduction in total hemispheric irradiance at many stations worldwide, was explained by the increase in anthropogenic aerosols emanating from cities exceeding about 20,000 inhabitants. Dimming is not generally seen in truly rural areas. In a polar juxtaposition, evidence for natural (volcanic and biomass) and positive anthropogenic aerosol trends in the Arctic was discerned in data, but no anthropogenic trends were found in the Antarctic. Underscoring the importance of aerosol character, modelers emphasized the need to carefully represent aerosol shape and mixing state to calculate the direct forcing of climate and indirect effects on clouds: aerosols are regionally heterogeneous and can cool or warm the climate, depending on their optical properties, and aerosols also typically reduce surface winds by stabilizing the boundary layer.

Satellite and in situ data were analyzed to show that estimates of shortwave (SW) clear-sky top-of-atmosphere (TOA) aerosol direct radiative forcing (ADRF) are very robust, whereas all-sky estimates are much less robust due to absorption uncertainties. New evidence showed that absorbing aerosols amplify natural snowpack–albedo feedbacks and that soot and dust in the snowpack have caused significant warming in past and present climates. In addition, modeled snow albedo feedback (SAF) was found to be an excellent predictor of a model's sensitivity to GHG forcing, although the range of model-predicted snow albedo was determined to be unrealistic, which currently explains much of the intermodel spread in SAF and climate response.

New experimental methods (Magi and Redemann 2007; Pan et al. 2007) and model techniques indicated progress is being made to improve our ability to quantify aerosol interaction with solar radiation and treatments of clouds. For example, new measurements of the 3D fractal geometry of complex soot particles can lead to significantly more efficient and accurate extinction estimates than properties based on 2D soot imagery (Adachi et al. 2007). Fortuitously, the widely used Optical Properties of Aerosols and Clouds (OPAC) soot properties, which are based on incorrect properties, yield approximately correct results. We now have more confidence in our ability to estimate atmospheric warming by soot. Ground-based aerosol optical depth and remote sensing measurements in polar regions were reviewed to decipher trends. This is important since Arctic ice is melting faster than models predict and pollution could be a potential culprit. The treatment of clouds and aerosol effects on them are highly idealized in climate models and a source of significant uncertainty. It was shown that clear-sky ice super-saturated regions (ISSRs) occur more frequently in nature than in models due to shortcomings in ice cloud and cirrus cloud parameterizations (Fusina et al. 2007). Detailed models of inorganic and organic aerosols and the effect of cirrus clouds on radiation were developed (Amundson et al. 2007). Novel process-level models to capture activation of black carbon (Henson 2007) and a probability distribution function method to improve the description of subgrid details and to improve cloud treatment in climate models and treat aerosol indirect effects were developed (Jeffery 2007). Cloud-resolving models, which treat aerosol-cloud processes in detail, are used to incorporate laboratory and field observations to develop parameterizations for coarse global climate models (Tao et al. 2007). A new comprehensive cloud-resolving model that explicitly treats aerosol activation processes in detail was used to successfully reproduce field observations, which previous models had failed to do (Andrejczuk et al. 2008). These new methods will stimulate improvements in treatment of cloud processes in next-generation climate models.

A conference session highlighted the important connections between climate and energy to move forward toward solutions. For example, it was shown that widespread carbon dioxide sequestration is required to stabilize atmospheric levels below 1,000 ppmv. One method would be to pump carbon dioxide underground. In fact, Department of Energy (DOE) pilot programs have demonstrated the feasibility of geologic storage for GHGs, but scaling remains a challenge. Hydrogen-based fuels could facilitate carbon capture and storage and curtail the growth of GHGs while also improving air quality. Before the widespread adoption of hydrogen fuels, however, natural hydrogen variability should be characterized to provide an important baseline for the assessment of future anthropogenic changes.

Plenary discussions highlighted a number of issues requiring attention before the third GWNIA conference planned for 2011. The following were identified as priorities of global climate research: 1) improve the global quality and coverage of in situ and satellite climate observations; 2) determine the sign and size of cloud feedbacks through a targeted observation of cloud properties and dynamics; 3) decrease the uncertainty in a number of forcing factors of climate change, particularly the forcing due to anthropogenic and natural aerosols; 4) quantify the potential impact of solar cosmic ray and cloud nucleation-induced forcings in GCMs with aerosol-cloud parameterizations; and 5) involve expert statisticians in key climate change studies.

It was determined during this conference that the optimal path to reduce uncertainties and increase precision of climate change forecasts is by bringing in observations to inform, test, and refine climate models. This is particularly important for aerosols and clouds, which are complex and influence the planetary albedo and radiation budget significantly. Progress is being made and the outlook it good since many aerosol-cloud perturbations and processes operate on shorter time scales rendering them measurable. However, this is a daunting task for other longer-term feedbacks such as ocean–ice–atmosphere changes where our community will have to use paleoclimate data or gather longer records to validate climate models, an interaction that our meeting also catalyzed. Observationalists and modelers (Xiao and Li 2007) must play a synergistic role in climate change research to increase the precision of climate forecasts for future energy options.

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