GPC Newsletter
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APS TOPICAL GROUP ON THE PHYSICS OF CLIMATE

IN THIS ISSUE

Message from the Editor

This is the twelfth GPC Newsletter, published twice per year. You, the GPC membership, can be of enormous value. We invite comments, event notices, letters, and especially specific suggestions for content. Any of the above, addressed to GPCnews@aps.org, will be gratefully acknowledged in a timely fashion.

Message from the GPC Chair

Chris Forest, Pennsylvania State University

Welcome to the Fall 2019 Newsletter of the APS Topical Group on the Physics of Climate (**@APS_GPC**)!

Based on the streak of hurricanes, a summer of climate extreme events, and a fall filled with highlights of Climate Action in the news, I decided to look back at how GPC has brought these issues to the APS community through past March Meeting sessions. In 2017, we had one on "Extreme Events in a Changing Climate," and in 2013, we participated in the Kavli Foundation

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2020 APS March Meeting

The GPC will be hosting one Invited Session and one Focus Session at the upcoming APS March Meeting 2020 in Denver, CO from March 2-6. The sessions are being organized by the GPC Program Committee, Chaired by William Collins (LBL, GPC Chair-elect).

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ARTICLE: Tutorial Papers on Greenhouse Effect

Stephen E. Schwartz, Environmental and Climate Sciences Department, Brookhaven National Laboratory

Members of the APS Topical Group on the Physics of Climate may be interested in a pair of Resource Letters published in the *American Journal of Physics* that are meant to provide an introduction to the greenhouse effect and the anthropogenically intensified greenhouse effect for students and for physicists who are not engaged in climate research.

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ARTICLE: The Economic Value of a More Accurate Climate Observing System

Bruce Wielicki, NASA Langley Research Center, Hampton, VA
Roger Cooke, Resources for the Future, Washington, DC
Alexander Golub, American University, Washington, DC

Climate change drives a wide range of current and future societal impacts that cross the spectrum of economic activities. Unfortunately, large uncertainty remains in key climate science questions that in turn drive uncertainty in cost/benefit analyses of societal mitigation and adaptation strategies. One of the largest of these factors is the uncertainty in climate sensitivity which remains a factor of 4 at 90% confidence level (IPCC, 2013). Climate sensitivity can be thought of as the volume dial on the climate system: it determines the amount of long term

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Message from the GPC Chair – *continued from p. 1*

Special Session "Forefront Physics for Real World Problems: Energy, Climate, and the Environment." While we keep pushing the edge on critical topics that require strong science, we are seeing evidence that these are more relevant every year to society and the next generations.

And speaking of predictability… Despite the snowstorm leading up to the 2019 March Meeting, we had a good turnout for the events in Boston and I thank all the speakers for their contributions to the sessions and thank the Program Committee for all their work.

For the 2020 March Meeting GPC will be sponsoring an invited session titled **"Predictability of the climate system"** and a focus session titled **"Hysteresis, tipping points, and abrupt changes in the climate system."** For the latter, we strongly encourage you to submit contributed talk abstracts (deadline October 25).

The GPC Election will be happening in October and please vote!

In other APS activities, the APS Division of Fluid Dynamics (DFD) annual meeting will be held in Seattle, Washington on November 23-26, 2019, with many sessions related to GPC themes (a.k.a. Geophysical Fluid Dynamics and Turbulence). For its Centennial year, the American Geophysical Union Fall Meeting will be back in San Francisco, CA on December 9-13, 2019. Also, the American Meteorological Society will host its 100th AMS Annual Meeting in historic Boston, Massachusetts, from 12 to 16 January 2020. Both will be great places to share your research on the Physics of Climate.

In closing, first, I would like to thank the GPC Executive Committee for all their work and guidance this past year and particularly the help of Raymond Shaw joining as the Treasurer/Secretary and learning the new APS systems. I would like to thank prior chair Michael Mann for his helpful leadership and also welcome Bill Collins as the next GPC Chair starting in January, with Mary Silber transitioning to Chair-Elect. Please follow us on twitter at **@APS_GPC** for key research findings, occasional announcements, and general items of interest. Finally, we look forward to seeing you in Denver at the 2020 March Meeting!

2019 APS March Meeting – *continued from p. 1*

The **Invited Session** will be **"Predictability of the climate system".** Our planet is a complex dynamical system involving numerous and diverse processes interacting across a wide range of spatiotemporal scales. Achieving the seamless prediction of its climate from sub-seasonal to decadal time scales is a primary goal of the global Earth sciences community. Yet there remain gaps in the fundamental understanding of the sources and impacts of decadal climate variability and predictability. This session is dedicated to facilitate presentations and discussion of the recent progress in addressing these gaps. It focuses on advances in methodological, theoretical and applied studies in system dynamics across the climate sciences directed towards the physical understanding and predictability of regimes, transitions and extremes. The session further encourages discussion on mathematical and physical approaches to climate system dynamics, ranging from traditional stochastic-dynamic and information-theoretic formulations to emerging methodologies aimed at far-from-equilibrium processes in non-ergodic systems. The talks will span a range mathematical and physical geosciences and feature diverse approaches ranging from dynamical modeling to data mining and analysis grounded on fundamental physical principles.

Invited speakers:

- Juan Restrepo, Oregon State University
- Michael Ghil, UCLA and Laboratoire de Météorologie Dynamique
- Katie Dagon, National Center for Atmospheric Research
- Tapio Schneider, Caltech
- Peter Jan van Leeuwen, Colorado State University

The **Focus Session** will be **"Hysteresis, tipping points, and abrupt changes in the climate system."** The Earth system has strong internal variability on many time scales. Large-scale transitions can occur due to tipping points in components of the climate system, and in many cases these depend on complex interaction between different sub-systems. However, the role of small-scale processes in inducing these transitions is not well understood for many important tipping points. These issues have been elevated in importance since the Earth's climate is currently experiencing an unprecedented transition under non-stationary anthropogenic radiative forcing and is far out of equilibrium with this forcing. This session aims at connecting fluctuations and responses for the climate system with a focus on issues involving abrupt climate change, climatic hysteresis, and tipping points. General approaches and novel measures to quantify the climate response to non-stationary forcing in the climate system are encouraged. We also seek talks on complex interactions between the different components and subcomponents of the Earth system that illuminate how these interactions can induce rapid, large-scale transitions in its major components. Submissions which are focused on the study of reasons and mechanisms of the emergent behavior are especially welcome.

Contributed abstract submission deadline for the Focus Session is October 25, 2019.

We look forward to your contributions and seeing you in Denver in March.

ARTICLE: Tutorial Papers on the Greenhouse Effect – *continued from p. 1*

The first paper **[1]**, dealing with Earth's natural greenhouse effect, presents an overview of Earth's radiation budget and of Earth's climate system, followed by an examination of the role of the greenhouse effect in Earth's climate. The second paper **[2]** introduces the concept of radiative forcing of climate change, examines increases in greenhouse (infrared absorbing) gases over the Anthropocene epoch and the resultant radiative forcings and describes climate system response to these forcings. The climate sensitivity concept that relates global temperature change to forcings is introduced, and implications for prospective future climate

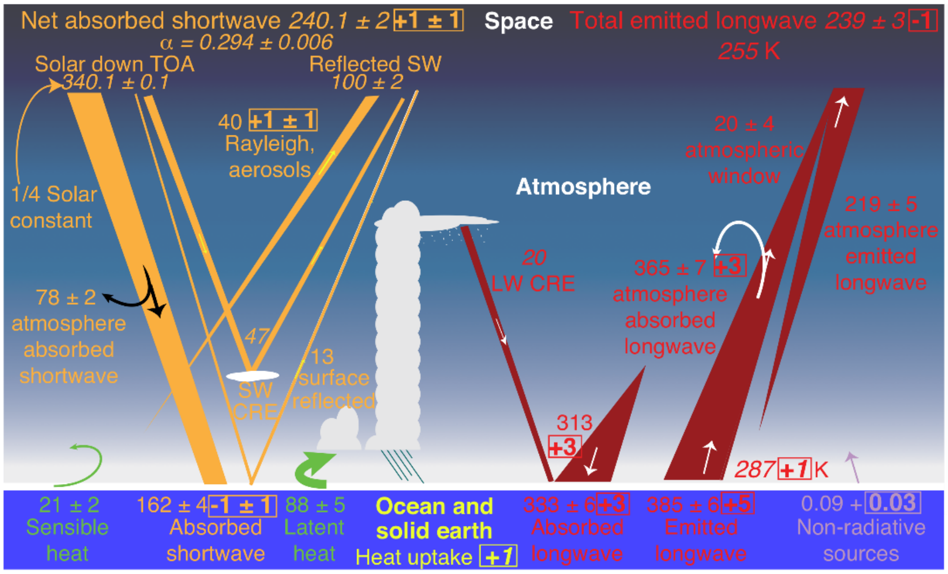

Figure 1: ***Earth's radiation budget. Energy flows (flux densities, W/m²) comprising the energy budget of the planet are shown in orange for the shortwave (SW, solar) region of the spectrum and red for the longwave (LW, thermal infrared). Also shown (green) are transfer of energy from the surface to the atmosphere by sensible heat and latent heat (transfer of water vapor from the surface to the atmosphere, followed by condensation in the atmosphere). The quantity α denotes the planetary albedo, the fraction of shortwave radiation incident on the planet that is reflected back to space (i.e., not absorbed). Cloud radiative effect (CRE) denotes difference, clouds minus cloud-free. Also shown are absolute temperatures (K) corresponding to thermal infrared fluxes by the Stefan-Boltzmann radiation law for emissivity taken as unity. Quantities in boxes denote anthropogenic perturbations. Quantities in italics are derived directly from measurements, from space, by satellite-borne instruments, or, for heat uptake rate, from the increase in ocean heat content with time. Uncertainties are given as 1 sigma estimates. Modified from Refs. [1,3].***

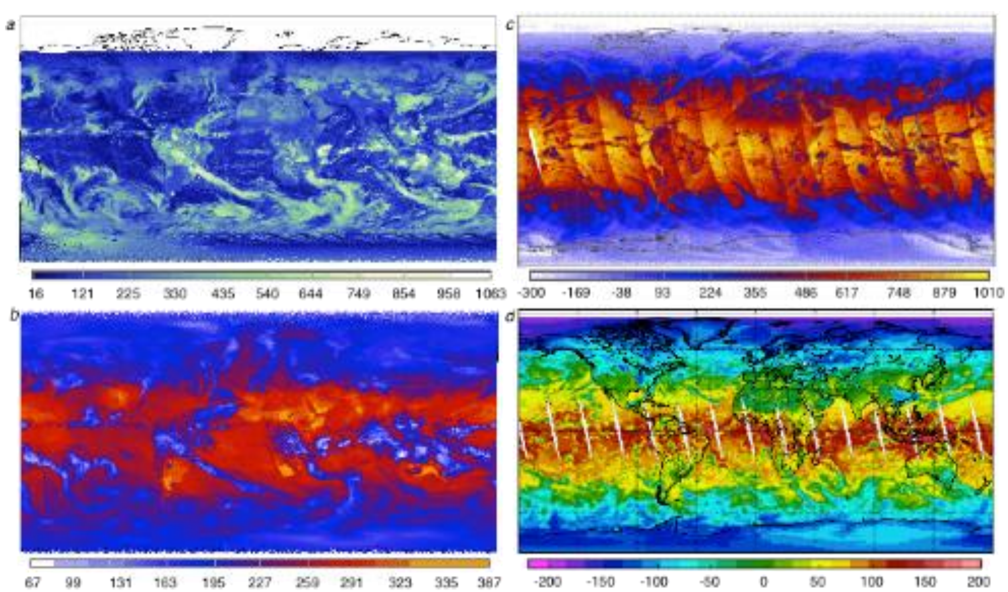

Figure 2: ***Local top-of-atmosphere radiative fluxes (W/m²) as determined from satellite measurements, March 10, 2012. (a) Instantaneous shortwave reflected flux; (b) instantaneous longwave flux (positive upward); (c) instantaneous net daytime flux (positive downward), evaluated as $J_S cos(\theta_0)$ minus the sum of upwelling SW and LW fluxes, where J_S is the solar constant and θ_0 is the solar zenith angle; (d) daily mean net flux (positive downward) after temporal integration. The depicted discontinuities are artifacts resulting mainly from changes, especially in cloudiness, between successive satellite overpasses. Data from the NASA CERES (Clouds and the Earth's Radiant Energy System) program; courtesy, Norman Loeb, NASA. From Ref. [1].***

change are examined, with emphasis on current uncertainties.

Several supplementary notes provide detail or lend perspective, dealing with the consequences of a global energy imbalance; the reasons that water vapor and carbon dioxide are strongly infrared-active whereas nitrogen and oxygen are not; correlations between climate properties and greenhouse gases over the glacial ice ages; calculation of radiative forcing by an incremental greenhouse gas, measurability of forcing, the budget and adjustment time of incremental atmospheric CO_2; and the linearity of change in global temperature to the magnitude the radiative perturbation in Earth's radiation budget.

Earth's climate system derives virtually all its energy from the sun. Solar energy (visible to near infrared) is absorbed, and longwave (thermal infrared) is emitted, maintaining a near steady state of global heat content. However increases in atmospheric CO_2 and other infrared active ("greenhouse") gases have exerted a net imbalance of the system that is confidently considered responsible for increases in global temperature and for other changes in climate over the past several decades.

Although this situation and the more general situation of climate response to this net energy imbalance are qualitatively well understood, many first order issues remain very poorly quantified. Even the so-called equilibrium climate sensitivity, the increase in global mean surface temperature that would result from a sustained doubling of atmospheric CO_2, is uncertain to a factor of 3 between the one-sigma estimates of this quantity.

A representation of Earth's radiation budget, **Figure 1**, drawn from Ref. **[1]**, shows global and annual mean values of the fluxes that constitute transfer of energy into and out of the climate system from space and between the major compartments that comprise the climate system. These fluxes are averages of quantities that vary greatly as a function of space and time (**Figure 2**). Some of these fluxes are determined directly by measurement; the others are inferred based on measurement together with modeling and the constraint that the preindustrial budget be balanced, *i.e.*, total flux into and out of each compartment is zero. The energy budget at the top of the atmosphere is balanced within the uncertainty of satellite measurements, the imbalance, consisting mainly of the rate of increase of ocean heat content, being less than the measurement uncertainty. Earth's climate system is driven almost entirely by uptake of solar radiation, the increment from non-radiative sources (natural radioactivity, geological collapse; anthropogenic energy production) being negligible. The difference between the emitted longwave flux at the Earth's surface, 385 W/m^2, corresponding to global means surface temperature 287 K (14 ˚C) and that at the top of the atmosphere, 239 W/m^2, is a consequence of, and a measure of, Earth's natural greenhouse effect.

Also indicated as boxed quantities in **Figure 1** are changes in fluxes over the Anthropocene due mainly to changes in atmospheric composition: increased absorption and emission of longwave radiation by increased amounts of greenhouse gases and increased reflection of solar radiation due to increases in atmospheric aerosols. As these changes in the radiation budget and the associated increase in global mean surface temperature are small perturbations on the natural budget. For example the incremental absorption of longwave irradiance due to increases in greenhouse gases over the Anthropocene is less than 1% of the absorption taking place in the unperturbed atmosphere. Quantification of these changes and their consequences is an enormous challenge to the climate research community.

At high time- and space-resolution, upwelling radiative fluxes at the TOA are much more variable than in global and longer-term means, **Figure 2**. The figure illustrates the richness of the processes that govern absorption and emission of radiant energy from and to space. The local spatial structure is due largely to clouds, which are cold in the thermal infrared (because of the decrease in temperature with altitude) and bright in the shortwave. Notable is the intertropical convergence zone near the equator that is characterized by strong rising motion of the atmosphere and is readily apparent in the Pacific. Contrast of bright land areas with adjacent ocean areas may be discerned. Likewise, the contrast between hotter land surfaces and adjacent oceans is readily discerned in the thermal infrared flux at the Persian Gulf. The figure illustrates the high dynamic range of the individual upwelling radiation terms, more than 1000 W/m^2 in the shortwave and more than 300 W/m^2 in the longwave. The instantaneous net daytime flux exhibits even greater dynamic range, ~1300 W/m^2. As this net flux is confidently thought to be less than 1 W/m^2 on global, annual average, the large dynamic ranges of the several fluxes place stringent requirements on measurement accuracy. Although the instruments aboard the Sun-synchronous satellites that are the principal sources for Earth radiation budget data are quite accurately calibrated, current satellites sample only a limited portion of the diurnal cycle. Consequently, accounting for the full diurnal cycle requires that the rest of the diurnal cycle be filled in by measurements made with less-well calibrated instruments aboard geostationary satellites. Similar accuracy is thus required from those measurements and from models used to calculate diurnal averages. The results of such calculations are illustrated in panel *d*, which shows the smoothing that results from the summation of the several terms that is manifested in the reduced dynamic range of the data. This panel also illustrates the consequence of latitudinal transport of heat from equatorial regions (net absorption) to high latitudes (net emission).

A key strength of spatially resolved measurements is the ability to identify cloud-free regions and thus determine separately the irradiance from planet as a whole and from the cloud-free regions. The contribution of clouds to the short- and longwave irradiance components of the total upwelling flux, denoted cloud radiative effect, CRE, **Figure 1**, is determined by difference.

In sum the two Research Letters **[1,2]** both provide an introduction to the physics of Earth's climate system for non-specialists and amply demonstrate the many areas of physics and allied sciences that are essential to improve understanding Earth's climate and representation of the climate system in models of varying degrees of complexity.

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ARTICLE: The Economic Value of a More Accurate Climate Observing System – *continued from p. 1*

warming that will occur for a given level of radiative forcing from greenhouse gas increase. The amount of warming in turn drives a host of global and regional climate system changes including sea level rise, temperature and precipitation extremes, water resources, and ecosystems. Those climate system changes then drive economic impacts. While economic impacts of climate change including costs of mitigation and adaptation strategies have been studied extensively (e.g. IPCC Working Group II and III reports), little attention has been placed on the economic value of improved climate science. For science, business as usual means doing the best science for the usual societal investment in scientific research. In the U.S., federal government investment in climate science is ~$2 Billion dollars/year, and has remained constant for the last 25 years when adjusted for inflation (see USGCRP annual reports). Yet the proper economic question to ask is "How much should society invest in climate research?" Such a question falls under the umbrella of research called "Value of Information" or VOI. We will summarize in this article the need for an improved climate observing system, as well as recently documented estimates of such an observing system's economic value and return on investment.

There are many observations that are used by climate scientists to determine climate change over decades and even centuries. Unfortunately, very few of them were designed with climate change observations in mind. A good example is our weather observing system: with typical temperature absolute accuracy of 0.3 K, compared to the desired 0.03 K for decadal climate change (NRC, 2015). For many if not most observations, climate change observations would typically require a factor of 5 to 10 more accuracy than weather or process observations including high accuracy traceability to international standards (e.g., SI standards maintained by the international metrology laboratories). A second challenge is that there are roughly 50 essential variables in the climate system (WMO GCOS, 2016) compared to 5 for weather prediction. This large difference is driven by the many complex systems that interact in determining the Earth's climate system and its impact on society. These include measures of the global atmosphere, ocean, cryosphere, biosphere (land and ocean), land use, land hydrology, chemistry, solar variability and geology including volcanism. Third, weather can be thought of as one small part of the climate system at a subset of climate time scales: those out to a few days as opposed to those including seasonal, annual, decadal, and even century time scales. As a result, climate system observations must deal with much greater complexity, at much higher accuracy, over much longer time scales than weather. The observations must maintain their accuracy and traceability to international standards over decades: times longer than the life of in-situ or even satellite based instrumentation, indeed longer than the length of a scientist's or engineer's career.

The challenge of such an observing system far exceeds typical scientific observing systems including those of weather, large particle physics experiments, or astronomy which are some of the largest current scientific endeavors. It is perhaps not surprising that we currently lack such a rigorous detailed and designed climate observing system. Instead we have a collage of weather, resources, and research observing systems that are cobbled together in a heroic effort to study climate change. In some cases like surface air temperature there are 7 different weather observing systems (surface sites, weather balloons, ocean buoys, ocean ships, aircraft, infrared satellite sounders, and microwave satellite sounders) allowing sufficient independence to verify, improve, and eliminate most artifacts that might confound climate change. But for most of the 50 essential climate variables there are at most 1 or 2 or none, leading to major challenges in detecting calibration drifts, changes in instrument design or sampling, or accurately crossing gaps in observations that may last several years.

There are many national and international documents that discuss the shortcomings in our current climate observations (Dowell *et al.* 2013; WMO GCOS, 2016; Weatherhead *et al.* 2017, NASEM, 2018, NRC 2015, Trenberth *et al.*, 2013). But the bottom line remains that we lack a rigorous designed and maintained climate observing system. In the most recent U.S. National Academy Earth Science Decadal Survey (NASEM, 2018), an examination of over 30 quantified and prioritized climate science objectives shows that critical observations are mission for 80% of the "Most Important" climate science objectives, 71% of "Very Important" objectives, and 47% of "Important" objectives. Critical observations are missing for roughly 2/3 of all climate science objectives. See Chapter 9 and Appendix B and C of the report for details (NASEM, 2018).

How would one design a rigorous international climate observing system? Discussion of this topic can be found in recent Academy of Science reports: the "Continuity Report" (NRC, 2015), and the Earth Science Decadal Survey (NASEM, 2018). An overview of the topic is also discussed in a recent journal article in AGU Earth's Future (Weatherhead *et al.* 2017). We give a summary of key points in the list below.

- Use of quantified climate science objectives based on major national and international reviews and reports such as the IPCC and USGCRP reports. Examples would be to narrow the uncertainty in long term climate sensitivity or aerosol radiative forcing by a factor of 2. Or to reach a specific level of accuracy in the rate of global and regional sea level rise. See a wide range of examples in the 2018 Decadal Survey (chapter 9 and Appendix B of NASEM, 2018).
- Rigorous quantitative requirements for instrument accuracy, sampling accuracy, and remote sensing retrieval accuracy sufficient to eliminate large delays in quantifying climate change trends. Observing system lack of accuracy increases trend uncertainty beyond the minimum caused by climate system internal natural variability. This increase typically extends the time to detect climate change trends by decades. (NAS, 2015, Leroy *et al.* 2008, Wielicki *et al.* 2013, Trenberth *et al.* 2013).
- Improved use of Observation System Simulation Experiments (OSSEs) to quantify the utility of a given observation to reduce scientific uncertainty in past and future climate change (NRC 2012, NASEM 2018, Weatherhead *et al.* 2017).
- Traceability of instrument observations to international (SI) standards to enable removal of calibration drifts and the ability to rigorously deal with data gaps. This is especially critical for space based observations which provide many of the global climate change data sets. (NRC 2007, NASEM, 2018)
- Provision of a much more complete set of climate system observations based on quantified climate science objectives, which currently suggest that critical observations are missing for 2/3 of all climate science objectives in the recent 2018 Decadal Survey report. GCOS implementation plans provide definition of the 50 essential climate variables (WMO GCOS, 2016).
- Follow existing GCOS observing principles (WMO GCOS, 2016)
- Provide independent observations of all essential climate variables (instruments, techniques, systems) to allow verification of climate system surprises after they occur.
- Provide independent analysis (methods, research groups) of all essential climate variables. Almost all computer code has errors, but independent development of analysis systems will have different errors, thereby allowing comparisons to discover and correct issues.

The above list indicates that major improvements are needed in climate system observations: both long term climate change and climate process observations. Some of the advances would simply require more rigorous processes than currently employed (independent analysis) while others would require improved global sampling, or design of instrumentation with more accurate traceability to international standards. In many cases more complete observations would require application of new technologies such as space based advanced lidar (wind profiles, aerosols, clouds, ocean phytoplankton), radar (rain, snowfall, convective vertical velocities) and radio occultation temperature profiles. New technologies for in-situ observations would also be key: such as adding chemistry measurements to deep ocean floats, and increasing the depths the floats reach.

How much would such an observing system cost? Adding independent observations, independent analysis, higher accuracy, and more complete observations might triple the cost of current global investments in climate research (observations, analysis, modeling, data storage/archive/distribution). Building a global climate observing system will also require increased investment in the data analysis, climate modeling, and data stewardship needed to benefit from such a system. The total of global climate research investments are currently estimated at $4 billion/yr, so that an additional $8 billion/yr might be required. The investment would be required for many decades (at least 30 years) because of the intrinsic long term nature of climate change itself. Once built, however, efficiencies of reproduction and scale might decrease costs over time for the basic instrumentation which is one of the largest costs.

Given that $8 billion/yr is a significant global investment, how could we estimate what the return on that investment might be? Four recent research papers (Cooke *et al.* 2014, 2016, 2019; Hope 2015) have estimated that economic value and concluded that through 2100 it ranges from $5 to $20 Trillion U.S. dollars. The cost of tripling the global investment in climate research (including development of the more rigorous climate observing system above) was estimated to provide a return on investment of roughly $50 per dollar invested (Cooke *et al.* 2014). All economic values are given in net present value using a discount rate of 3% (The nominal value from the U.S. Social Cost of Carbon Memo, 2010, hereafter SCCM2010).

As scientists, how do we understand such large economic value and return on investment estimates? We first need to consider some basic economic concepts. We begin by scaling the magnitude of global gross domestic product or "global economy" as roughly $85 Trillion U.S. dollars. Second, "business as usual" carbon dioxide emissions are predicted to cause climate damages in 2050 to 2100 that range from 0.5% to 5% of GDP annually (SCCM2010). Such damages would range from 400 billion to $4 Trillion per year. The large range is to first order because the uncertainty in climate sensitivity remains a factor of 4 at 90% confidence level (IPCC,

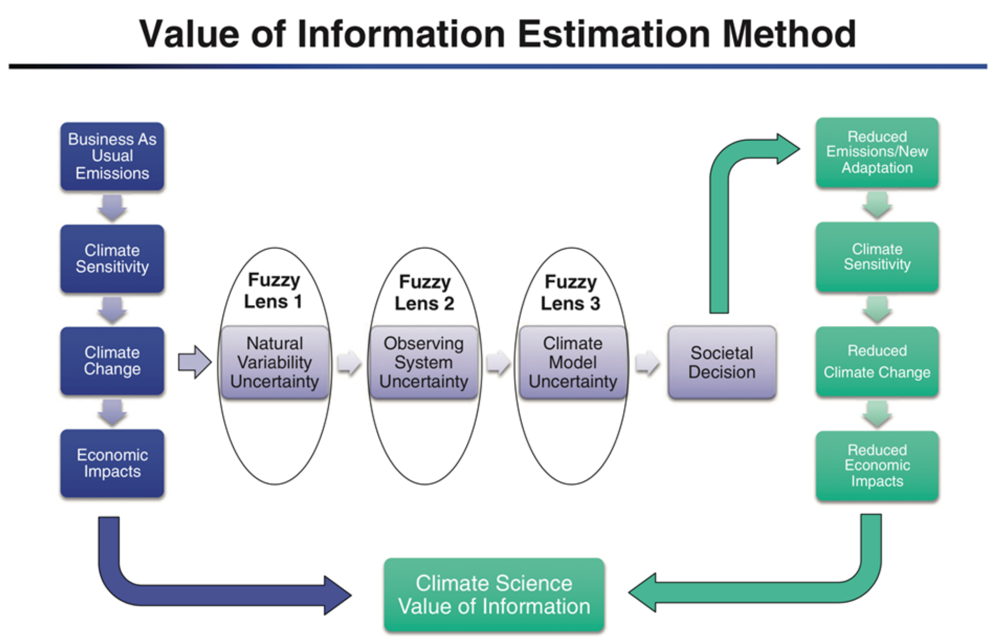

Figure 1: ***Schematic for estimating the economic value of improved climate change information (from Weatherhead et al. 2017).***

2013, SCCM2010). Climate sensitivity measures the amount of global temperature change per unit change in atmospheric carbon dioxide. A range of economic impact studies conclude that impacts rise roughly as the square of the amount of global temperature change (SCCM2010). The economic value of narrowing the uncertainty in critical issues like climate sensitivity as a result are very large (Cooke *et al.* 2014, 2016, 2019; Hope 2015).

Relating the economic value of benefits that return in the future to alternative investments that could be made requires the use of a concept called Discount Rate. All future benefits are discounted X% per year to account for the fact that most people would prefer to have money now vs the future, and to allow comparison of how the same funds could be invested in alternative investments, including those with short term goals. The nominal discount rate used for long term climate change is 3% (SCCM2010) but arguments have been made for both lower values at 1.5% (Stern, 2008), or higher values at 5%. Using the nominal 3% discount rate, an investment that pays back in 10 years is discounted by 1.03^{10} or a factor of 1.3, 25 years by a factor of 2.1, 50 years by a factor of 4.4, and 100 years by a factor of 21. This makes it obvious that discount rate is very important to such calculations, and that paybacks 100 years in the future are negligible. For climate change returns on investment, discount rate is then used to derive the Net Present value by discounting any return by the number of years into the future that it will be realized. There is another way to think about discount rate and why 3% might be a reasonable value for global issues such as climate change. The growth rate of global GDP averages about 3% and has so for a long period of time. Therefore discounting at 3% per year also provides a reference to returns that are above those expected for global average GDP increase.

Now that we have a few basic concepts in mind, **Figure 1** provides a schematic for the economic value of information (VOI) estimates in the Cooke *et al.* papers (2014, 2016, 2019). This figure shows the methodology for converting improved climate science knowledge into economic value. The blue boxes at left gives the baseline condition with Business as Usual greenhouse gas emissions (e.g., SCCM2010), which through climate sensitivity lead to the baseline amount of climate change, which in turn leads to the baseline amount of economic impacts. This is the state with no or modest societal action on climate change. Meanwhile society (and scientists) are looking through 3 fuzzy lenses at climate change: the first fuzzy lens is that of natural variability of the climate system such as swings between warm and cold phases of the ENSO cycle or the Arctic Oscillation or the Pacific Decadal Oscillation. All these are examples of internal variability of the climate system itself and represent noise that we must detect human climate signals against. Even a perfect observing system cannot eliminate this fuzzy lens. The second fuzzy lens is the fact that our climate observations are themselves inaccurate whether through calibration, sampling, or through weak relationships to the climate variable desired (e.g. indirect proxy observations). When added to the fuzzy lens of natural variability, these observing system uncertainties can delay the time to detect climate trends by 5 to 50 years (Leroy *et al.* 2008, NRC, 2015, Wielicki *et al.* 2013). This large information time delay is the factor in societal decisions that improved accuracy in our climate observations can directly impact. The third fuzzy lens is that of climate model uncertainty. Climate models are used to predict the change that will occur under a range of proposed emissions scenarios (e.g. weak, moderate, or strong greenhouse gas emissions policies). But those models are imperfect and currently show a range of a factor of 4 uncertainty in climate sensitivity (IPCC, 2013). Improving the models requires both improved climate process observations for driving model uncertainties (e.g. aerosol forcings, cloud feedbacks, glacier melt) as well as improved long term decadal observations of climate change to verify model performance and uncertainties. As a result, this fuzzy lens can also be improved through a more rigorous climate observing system.

The key concept used in **Figure 1** is that better observations, analysis, and modeling can shorten the time to reduce critical climate science uncertainties like climate sensitivity that are holding back improved societal decisions on balancing emissions reduction vs later climate change adaptation. The shortened time to reach a given level of confidence can be related to the amount of improvement in accuracy and quality of the observations of climate change for key elements such as cloud feedback (NRC, 2015; NASEM 2018; Wielicki *et al.* 2013). This shortened time to narrow uncertainty can in turn be used to relate changes in society decision points to change in emissions strategies. Once emission strategies are changed, then economic estimates of reduced economic impacts and costs of emissions reductions can be used to determine the Net Present Value of improved observations (Cooke *et al.* 2014, 2016, 2019).

While such studies cannot predict when society will make such decisions, they can compare the sensitivity of change in economic value if society requires more or less confidence in scientific predictions (e.g. 80% vs. 90% vs. 95%), requires lower or higher climate change signals to occur, changes which emissions reduction strategy is used (moderate or strong), which discount rate is used (2.5%, 3%, 5%), or even how soon such improved climate observations become available (5, 10, or 20 years). Sensitivity to how society makes the decision (moderate or high confidence, amount of signal, emissions reduction strategies) only varies the economic value by about 30% (Cooke *et al.* 2014). Discount rate variations can vary the economic value from $3 Trillion to $18 Trillion (Cooke *et al.* 2014). Changing when the more rigorous climate observations become available suggest that every year of delay costs society ~$500 billion in lost investment opportunity, a figure 50 times the estimated cost of such observation improvements.

What are additional caveats on such an economic analysis in addition to those mentioned? There are uncertainties in the cost of climate change impacts from factors that were not included in the SCCM2010 analysis and would therefore increase the economic value: ocean acidification, international conflicts over resources and refugees, species loss, unexpected climate change accelerations such as arctic or sea bottom methane release, larger than IPCC estimated range of sea level rise. Uncertainties that could reduce the economic value would include unexpected rapid shift to greenhouse gas emissions well beyond the current Paris agreement (factor of 2 to 4 faster) or unexpected early technological breakthroughs in cost reduction of renewable energy and battery technologies (e.g. a sudden factor of 4 reduction in 2020). Such technology breakthroughs would be in excess of the existing rapid reductions underway in solar, wind, and battery technologies with learning rates of 15 to 25% cost reduction for every doubling of cumulative production.

How do such economic value estimates compare to weather prediction economic value? An estimate for the U.S. alone was given as $33 billion/year and ROI of 6:1 (Lazo, 2011). The global climate change observing system value discussed above provides an ROI that is roughly 10 times as large as the U.S. current weather prediction ROI.

In summary, we lack a designed, rigorous and complete global climate observing system. The cost of providing such a system might be an additional $8 Billion U.S. dollars per year in global climate research investment (tripling current levels). A new improved climate observing system could reduce uncertainties 15 to 30 years sooner than current observations. The total value to the world of such a system is estimated at between $5 and $20 Trillion dollars. Return on investment is estimated as 25 to 100:1. The return on investment is expected to exceed that for weather observations. Inflation adjusted U.S. investments in climate research have stagnated over the last 25 years, despite the large remaining uncertainties and their large potential economic impacts. Even very large uncertainty of a factor of 5 in economic value would not change the conclusion: ROI would in that case range from 10:1 to 250:1. The cost of delaying such a system is estimated at roughly $500 Billion/yr. A new global international climate observing system would be one of the most cost effective investments that society could make.

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GPC Elections

The upcoming GPC election features openings for Vice Chair, Secretary-Treasurer, two regular Members-at-Large, and one graduate student Member-at-Large. The election is to be held in October and elected candidates would begin their terms in January 1, 2020. We strongly encourage you to help shape your GPC by voting.

The nominating committee consists of members Azriel Genack (Queens College, CUNY), Donald Lucas (Lawrence Livermore), Daniel Rothman (MIT), Adria Schwarber (U. Maryland), and Michael Mann (Penn State) as Chair

Prospective candidates will be considered for their scientific standing and activity, their history of involvement with GPC and the APS, their perspective on the activities of the Group, and their likelihood of service to GPC if elected. Diversity in the GPC leads to vitality and innovation.

The position of the Vice Chair of GPC (currently held by Mary Silber) is a four-year commitment: after a year as vice chair the officer becomes in successive years the chair-elect (currently William D. Collins), chair (currently Chris E. Forest), and then past chair (currently Michael Mann) – each with distinct duties. The chair officers play a crucial role in providing leadership in organizing the scientific content of the March Meeting and other meetings and in representing climate physics within the American Physical Society. The position of Secretary-Treasurer (currently held by Raymond A. Shaw) is a three year position, plus an additional year to aid in the transition of duties. The duties are to maintain the records of the GPC, and have responsibility for all GPC funds.

The members-at-large (two regular positions, replacing Douglas Kurtz and Sharon Sessions, and the new graduate student position, replacing Adria Schwarber) serve a three-year term; they constitute the fellowship committee, help select the invited symposia and invited talks for the March Meeting and provide advice on issues important to the GPC.

Identifying excellent candidates who can provide a broad view of the diverse field that is climate physics is key to maintaining the vitality of GPC

Honors and Prizes

2019 Tyler Prize – On May 3, 2019, past GPC Chair Michael E. Mann, together with Warren M. Washington, were presented the 2019 Tyler Prize for Environmental Achievement: *"The Tyler Prize is honored to recognize two outstanding climate scientists, who have pioneered innovative scientific investigations and analysis of global change. Michael E. Mann and Warren M. Washington, have the courage and commitment to inform and advance public discourse and policy on climate change, as well as inspire civic engagement to take action to protect the planet and people."*

2019 APS Fellowships – The most recent election of new Fellows of the American Physical Society at the September meeting of the APS Council of Representatives includes two GPC Members. Past GPC Chair **Juan M. Restrepo**, Oregon State University, was nominated through GPC, and was *cited for advancing the understanding of wave dynamics and uncertainty quantification in the climate system.* GPC Communications Chair **Peter B. Weichman**, BAE Systems, was nominated through DCMP, and was *cited for definitive work on the dirty boson problem and on two-dimensional hydrodynamics.* The number of APS Fellows elected each year is limited to no more than one half of one percent of the non-student membership. It is a prestigious recognition by their peers for outstanding contributions to physics.

GPC Students and Early Career Investigators Prizes

Last year, GPC created a scholarship for young GPC members to attend the APS March Meetings and participate in the GPC sessions.

This year we will make two awards of $500 to a graduate student and an early career investigator. In future years, the GPC may expand the award if the Physics of Climate community grows and continues its success.

The first award will be "The GPC Students Prize" and will be given to a graduate student member of the APS that is pursuing work related to the GPC mission. The second award will be "The GPC Early Career Investigators Award" and will be given to an early career investigator (less than 5 years out of Ph.D.) and be a member of the APS GPC. Both awards will help cover the costs to attend and participate at the March Meeting in a GPC related session.

To apply for the scholarship, applicants should submit a CV, an abstract for a contributed (10 minute) talk, and a short summary (200-300 words) of how their work fits with the GPC mission.

Please send these items to msilber@uchicago.edu with the heading: "APS GPC Scholarship Application 2019"

Deadline for applications: December 15, 2019

The scholarship committee consists of the GPC Vice Chair (currently, Mary Silber) as the committee chair and three additional members.

For additional information, please contact Dr. Silber if needed.

Other News Links of Interest and Upcoming Events Calendar

1. 72nd Annual Meeting of the APS Division of Fluid Dynamics, Seattle, WA, November 23-26, 2019.
2. 100th American Meteorological Society Annual Meeting: 'The AMS Past, Present and Future: Linking Information to Knowledge to Society (LINKS)', Boston, MA, January 12-16, 2020.
3. 34th Conference on Hurricanes and Tropical Meteorology, New Orleans, LA, May 10-15, 2020
4. AMOS 2020, February 10-14, 2020, Esplanade Hotel, Fremantle, Australia.
5. AGU Fall meeting, Dec. 9-13, 2019, San Francisco, CA.
6. 2020 Ocean Sciences Meeting, February 16-21, San Diego, CA.
7. European Geosciences Union General Assembly 2020, May 3-8, 2020, Vienna, Austria.