GPC Newsletter

Issue #13

February 2020

APS TOPICAL GROUP ON THE PHYSICS OF CLIMATE

IN THIS ISSUE

Message from the Editor

This is the thirteenth 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.

Welcome from the GPC Chair

William Collins, LBNL

Welcome to the Spring 2020 GPC Newsletter. We are excited to start a new year and continue providing a venue for Climate Science in the APS. This letter features articles on the relation between hurricanes and climate; on the surprising fidelity of old climate model projections for the present day; on the latest developments in detecting and attributing

(Continued on p. 2)

APS Fellows Nominations

APS GPC Members may nominate colleagues to become APS Fellows through GPC. You are invited to nominate those who have made exceptional contributions to promoting the advancement and diffusion of knowledge concerning the physics, measurement, and modeling of climate processes, within the domain of natural science and outside the

(Continued on p. 2)

ARTICLE: Hurricanes and Climate: State of the Science

Morgan E. O'Neill, Department of Earth System Science, Stanford University

The World Meteorological Organization recently commissioned a study into the past and future role of climate change in the world's tropical cyclone (TC) activity. The WMO Task Team on Tropical Cyclones and Climate Change has just published a two-part report in the Bulletin of the American Meteorological Society this December:

(Continued on p. 2)

ARTICLE: Old climate models got future warming right

Zeke Hausfather, Director of Climate and Energy, Breakthrough Institute

Climate models are a core part of our understanding of our future climate. They also have been frequently attacked by those dismissive of climate change, who argue that models have no predictive power, or suggest – often with little beyond anecdotes – that their past projections have failed to materialize.

(Continued on p. 4)

ARTICLE: Quantifying the effect of climate change on contemporary extreme weather events

Michael Wehner, Lawrence Berkeley Laboratory

The human influence on the climate system is clear. However, most people think that any danger to themselves or their loved ones is some rather nebulous threat in the distant future. We now know, through the science of extreme event attribution, that the risk and magnitude of severe weather has already increased enough to have caused real damages.

(Continued on p. 6)

Welcome from the GPC Chair

(Continued from p. 1)

anthropogenic influence on weather events; and on a recent workshop in support of creation of a large-scale aerosol-cloud-turbulence research facility. As a reminder, GPC has its own Twitter account, which may be followed for announcements about our meeting sessions, newsletter, etc. Please follow us at @APS_GPC.

We are very excited about the upcoming March APS Meeting in Denver this year. The meeting will feature a formal GPC sponsored scientific session beginning at 8:00 am on Thursday, March 5: Invited Session R37 on "Predictability of the Climate System" will be held in Room 605 of the Colorado Convention Center (CCC). Our speakers are Juan Restrepo, Michael Ghil, Katherine Dagon, Tapio Schneider, and Peter Jan van Leeuwen and they will discuss new directions in uncertainty quantification and Bayesian inference, data assimilation and data-informed climate models, and the implications of these developments for climate predictability. More details about the scientific session can be found inside this Newsletter. The GPC Business Meeting (Session V37) will be held at 5:45 pm on Thursday in the same Room CCC 605. All GPC members are invited to participate. For the considerable efforts of my colleagues whose terms on the Executive Committee finished in 2019, we thank you for your service. To Brad Marston, our Chair of the Nominations Committee and the keeper of institutional knowledge base of all things APS, thank you for keeping us on track this past year. To our past Chair, Chris Forest, thank you for guiding the ship and keeping me on track. We also owe a major thank you to our current Secretary/Treasurer Raymond Shaw for his exemplary service and to Peter Weichman for his substantial contribution as the Newsletter Editor. We welcome our new Executive Committee members starting in January 2020 including Vice Chair William Newman and Members-at-large Albion Lawrence and Justin Burton. We are very fortunate to have Mary Silber as the Chair Elect who will step into my role next year.

I look forward to working with all of you this year and beyond. For those at the March Meeting, you are invited to the GPC Climate Café to take place on Thursday evening following the GPC business session (with venue details to be announced both then and at the Invited Sesssion). This is an informal meeting where, over drinks and food, you can meet the March Meeting GPC speakers, as well as fellow GPC and other APS members. We'll discuss climate science, network, and chat with the Executive Committee members about GPC concerns. All APS members are welcome to attend. We look forward to seeing you in Denver!

APS Fellows Nominations

(Continued from p. 1)

domains of societal impact and policy, legislation, and broader societal issues.

Selection as an APS Fellow by one's professional peers is a great honor. The number of Fellows elected annually cannot exceed 0.5% of Society membership.

Any current APS member can initiate a nomination. The membership of APS is diverse and global, and the Fellows of APS should reflect that diversity. Fellowship nominations of women, members of underrepresented minority groups, and scientists from outside the United States are especially encouraged.

For information on how to nominate, and a list of current Fellows, please see the APS Fellows webpage.

The deadline for submitting fellowship nominations for review by the GPC Fellowship Committee is June 1, 2020. For further information regarding fellowship nominations, please email fellowship@aps.org

---

ARTICLE: Hurricanes and Climate: State of the Science

(Continued from p. 1)

Knutson et al. 2019a and 2019b, updating the previous WMO assessment (Knutson et al. 2010). Written by 11 authors from six countries, it carefully evaluates the latest science regarding detection and attribution of climate change on TC activity (Part I) and the projected change in TC activity due to future anthropogenic warming (Part II).

A characteristic of Part I is a systematic discussion of different types of errors for different applications. How do you quantify confidence in a result? What is the cost of a false positive or false negative detection of climate change, and to whom? Following Lloyd and Oreskes' (2018) work on detection and attribution of climate change, the authors systematically discriminate between Type I errors and Type II errors. From Knutson et al. 2019a:

> "Here, we interpret a type I attribution error as concluding that anthropogenic forcing had contributed nontrivially in a certain direction to an observed change when it had not done so, while a type II error means not concluding that anthropogenic forcing had contributed to some observed change or event in a certain direction when it had done so to a nontrivial extent. [...W]hether a type I or type II error is more important to avoid is context and audience dependent. If the goal is to advance scientific understanding, an emphasis on avoiding type I errors seems logical. However, for future planning and risk assessment, one may want to reduce type II errors in particular. For example, planners for infrastructure development in coastal regions may want to consider emerging

detection/attributions findings – even if not at the 0.05 significance level – in their planning and decision-making."

This is an essential difference in needs among communities that are served by such an assessment. If you hold any kind of optional insurance policy you probably agree that hedging your bets under uncertainty is prudent – and you are avoiding a type II error.

Avoiding a type I error, there is general author consensus that anthropogenic warming has likely not manifested in the observational TC record. From a type II error perspective, their perspective is very different, and most or all authors agree with the following statements: "Detectable increase in the global proportion of TCs reaching category 4 or 5 intensity in recent decades and anthropogenic forcing has contributed to this increase", and "Detectable increase in the global average intensity of strongest (hurricane intensity) TCs since the early 1980s; and anthropogenic forcing has contributed to this increase of global average intensity of strongest (hurricane intensity) TCs."

In a 2°C warmer world (Part II), authors mostly agree that the following are likely to increase: rainfall rates, storm surge heights due to sea level rise, TC peak wind speeds and fraction of total TCs that are Category 4-5. Though the balance of global TC modeling studies suggests that TC frequency may go down overall, authors have less confidence in the robustness of this result. Thus there is also lower confidence about whether the total number of Category 4-5 TCs will increase or decrease.

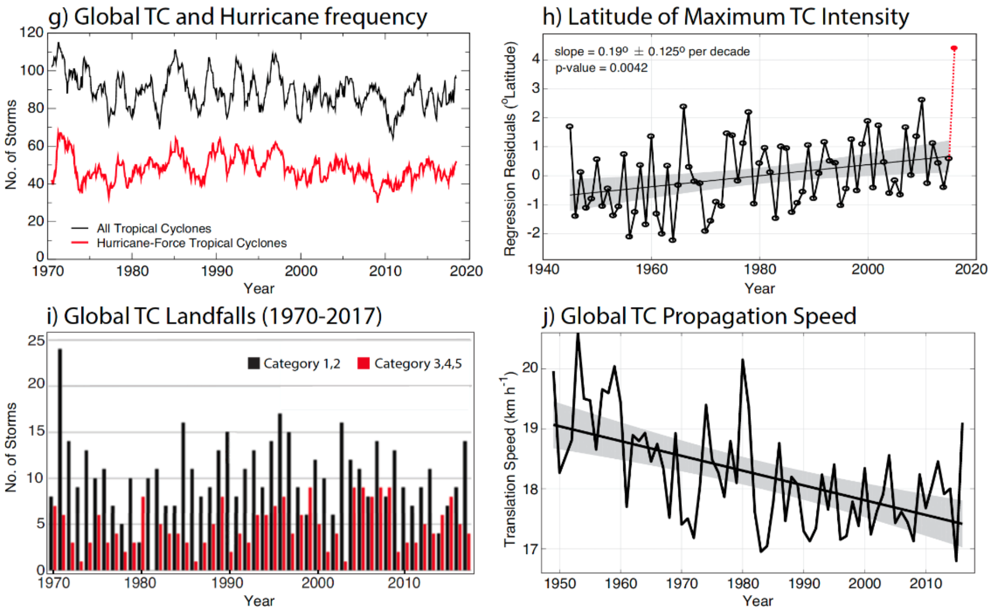


Figure 1 [Adapted from Fig. 1 of Knutson et al. 2019a]: (g) Global annual occurrence frequency of all TCs (top curve) and hurricane-intensity TCs (bottom curve) as 12-month running sums for 1970–May 2018. (h) Annual average latitude of maximum TC intensity in the western North Pacific, with El Niño and Pacific decadal oscillation influences removed by linear regression, straight line depicting the linear trend excluding the final year, and gray shading depicting the 95% confidence bounds (Kossin 2018). (i) Global frequency of landfalling TCs of hurricane strength (blue) or major-hurricane strength (red) for 1970–2016. (j) Global average propagation speed of tropical cyclones for 1949–2016 and its linear trend, with gray shading depicting the 95% confidence bounds on the trend (Kossin 2018). All plots use approximately the same data source: different revisions of version 3 of IBTrACS without adjustment.

The assessment that rainfall rates and peak TC wind speeds are likely to increase is not only supported by numerous sophisticated modeling studies but simple physical arguments. The Clausius-Clapeyron relation indicates that water vapor content in the air increases approximately 7% for every 1 degree Celsius increase in air temperature, so there is more capacity to rain in a warmer world. And Carnot cycle theory has been successfully applied to TCs, demonstrating that maximum realizable TC wind speed (or minimum central pressure) is proportional to the thermodynamic efficiency of the system: the difference between the sea surface temperature and the temperature of the upper troposphere (Emanuel 1986, 1988; Bister and Emanuel 1998).

In contrast, there yet exists no theoretical understanding of even the order of magnitude of TC frequency globally (some selected data is shown in Fig. 1). We observe 80-90 TCs per year around the world. Why? Given this dearth of understanding, we rely on modeling studies to help us understand how this frequency might change. Perhaps surprisingly, global models tend to get global frequency and even basin-scale seasonality storms roughly right – at least within an order of magnitude. What do they know that we don't? This is an interesting and active area of research, and also the reason that it is hard to have high confidence about how TC frequency will change in a warming world.

The eleven authors were very transparent about often divergent opinions concerning the likelihood of a particular climate attribution or forecast of hurricane activity changes. Published with Part II is a table that shows where, on a scale from "low confidence" to "high confidence: virtually certain", each author assesses the likelihood of a particular future scenario. These scenarios include global predictions as well as basin-specific predictions for change in 1) TC frequency, 2) TC intensity, 3) average latitude of peak intensity occurrence, and 4) TC precipitation rates.

There is some new research that was published too recently to be considered in the WMO assessment, including further work on TC translation speed – the speed at which the storm moves over ocean or land. It can matter a lot at landfall. Hurricanes Harvey (2017) and Dorian (2019) were exceptionally slow-moving TCs upon landfall, bringing unyielding rain in the same location that led to widespread freshwater flooding. Slower translation speeds can lead to more damage at a given location. (There is no single storm parameter that matters most to impact: Hurricane Ike (2008), which made landfall over Galveston Bay, moved rapidly and caused a 20 ft storm surge, indicating that translation speed may potentially have a non-monotonic impact function). Kossin (2018, 2019) showed in the historical record that storms have been slowing down [see Fig. 1(j)], potentially increasing the likelihood that we will see more Harveys and fewer Ikes. However that result has been hotly contested and/or contradicted (Moon et al. 2019, Lanzante 2019, Yamaguchi et al. 2020), and the debate begs for an improved understanding of how the general circulation itself will change under global warming. After all, TCs are (for the most part) passively advected by the large-scale flow.

The NOAA Geophysical Fluid Dynamics Laboratory (GFDL) maintains a web page that explains the latest science and literature regarding the hurricane-climate connection: https://www.gfdl.noaa.gov/global-warming-and-hurricanes/. The American Meteorological Society hosts a Conference on Hurricanes and Tropical Meteorology every second year; this year it is May 10-15 in New Orleans.

References:

Bister, M. & Emanuel, K.A. Dissipative heating and hurricane intensity. Meteorl. Atmos. Phys. (1998) 65: 233.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. J. Atmospheric Sci., 43 (6), 585–605.

Emanuel, K. A., 1988: The maximum intensity of hurricanes. J. Atmospheric Sci., 45 (7), 1143–1155.

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi, 2010: Tropical cyclones and climate change. Nat. Geosci., **3**, 157–163.

Knutson, T., S.J. Camargo, J.C. Chan, K. Emanuel, C. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2019: Tropical Cyclones and Climate Change Assessment: Part I: Detection and Attribution. Bull. Amer. Meteor. Soc., **100**, 1987–2007.

Knutson, T., S.J. Camargo, J.C. Chan, K. Emanuel, C. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2020: Tropical Cyclones and Climate Change Assessment: Part II. Projected Response to Anthropogenic Warming. Bull. Amer. Meteor. Soc.

Kossin, J.P. A global slowdown of tropical-cyclone translation speed. Nature **558,** 104–107 (2018).

Kossin, J.P. Reply to: Moon, I.-J. et al.; Lanzante, J. R.. Nature **570,** E16–E22 (2019).

Lanzante, J.R. Uncertainties in tropical-cyclone translation speed. Nature **570,** E6–E15 (2019).

Lloyd, E. A., and N. Oreskes, 2018: Climate change attribution: When is it appropriate to accept new methods? Earth's Future, **6**, 311–325.

Moon, I., Kim, S. & Chan, J.C.L. Climate change and tropical cyclone trend. Nature **570,** E3–E5 (2019).

Yamaguchi, M., Chan, J.C.L., Moon, I. *et al.* Global warming changes tropical cyclone translation speed. Nat. Commun. **11,** 47 (2020).

Zhang, G., Murakami, H., Gudgel, R., & Yang, X. (2019). Dynamical seasonal prediction of tropical cyclone activity: Robust assessment of prediction skill and predictability. Geophys. Res. Lett. **46**, 5506–5515.

ARTICLE: Old climate models got future warming right

(Continued from p. 1)

Evaluating the performance of past model projections can be challenging, as it requires a long enough period post-publication for the climate signal to emerge from the noise of natural variability. There has historically been relatively little work evaluating the performance of climate model projections over their future projection period, as much of the research tends to focus on "hindcasts" of the latest generation of modeling results.

In a recent paper in Geophysical Research Letters, we took a look at how well climate models have actually been able to accurately project warming in the years after they were published. We gathered *all* the climate models we could find published between 1970 and the mid-2000s that gave projections of both future warming and future concentrations of CO_2 and other climate forcings – from Manabe (1970) and Mitchell (1970) through to CMIP3 in IPCC 2007.

We evaluated these models both on how well modeled warming compared with observed warming after models were published, and how well the relationship between warming and CO_2 (and other climate forcings) in models compares to observations (the implied transient climate response). The second approach is important because even if an old model had gotten all the physics right, the future projected warming would be off if they assumed we would have 450 ppm CO_2 in 2020 (which some did!).

Future emissions depend on human societal behavior, not physical systems, which are fundamentally

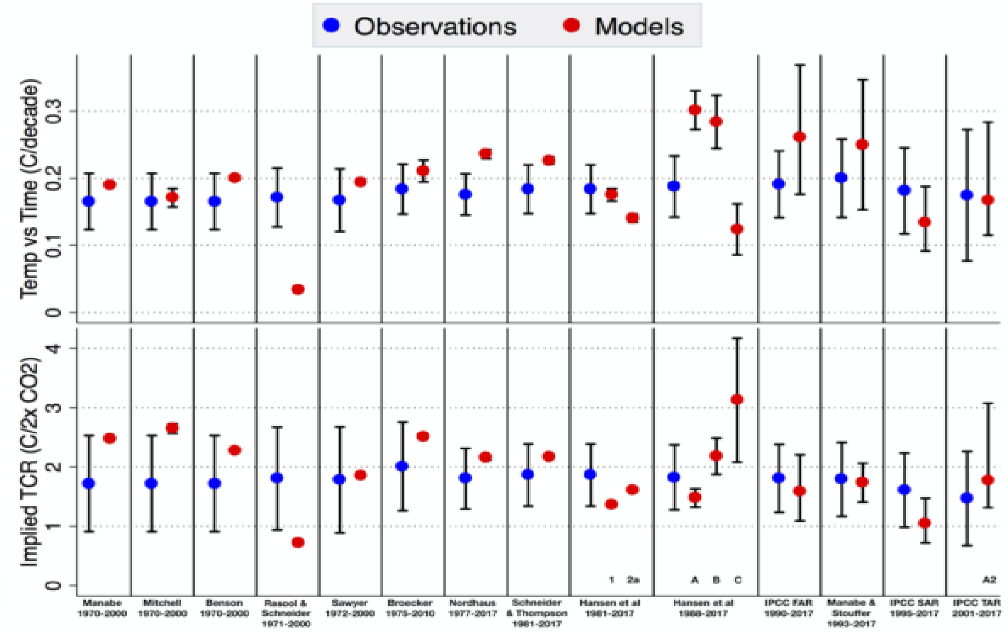


Figure 2 from Hausfather, et al (2019) showing the comparisons between model predictions and observations for a) the temperature trends (above) and b) the implied Transient Climate Response (TCR) which is the trend divided by the forcing and scaled to an equivalent 2xCO2 forcing.

unpredictable with the level of accuracy. Many early climate models made very simple assumptions around future emissions – for example, that they would increase by 1% per year – and the best physics-based model will still be inaccurate if it is driven by future changes in emissions that substantially differ from reality. By comparing the relationship between warming and CO_2 between models and observations we can separate the evaluation of climate models physics from paths of future concentrations.

We found that climate models – even those published back in the 1970s – did remarkably well. Using our first approach, in 10 out of 17 projections, the future warming projected by the models was statistically indistinguishable from what actually occurred (of the other seven, four were too warm and three too cold). When we used the second approach – which controls for potential mismatches between projected and actual CO_2 concentrations and other climate forcings – we found that 14 out of the 17 model projections agreed with subsequent observations.

However, it is not totally obvious how one should correct for the forcing assumptions because of subtle issues related to the different efficacy of different forcings and, of course, the remaining uncertainty in the real value of the actual forcings (driven predominantly by the aerosol component). For forcing projections that were close to linear, this didn't make that much difference, but for scenarios that weren't (notably scenario C in Hansen et al (1988)), the correction does not work well.

There are a few other results that stand out, notably the low sensitivity result in Rasool and Schneider (1971), which was mainly due to a lack of stratospheric adjustment and water vapor short wave absorption in their formulation. This was noted by Schneider (1975) and the calculation redone by Schneider and Thompson (1981) which turned out to be far more accurate. On the other hand, only Mitchell (1970) appears to have substantially overestimated the TCR – even while he predicted the temperature rise quite accurately (due to a compensation between a too large sensitivity driven by too-low low ocean heat uptake and an underestimate of future forcings due to only considering CO_2).

It is worth noting that this comparison includes two kinds of climate model – those published prior to 1988 which are energy balance models of varying complexity, and those published afterwards which are true GCMs and include atmospheric (and eventually, ocean) dynamics. Of the early models, the work of Sawyer (1972) stands out as being the most accurate in terms of both temperature trends and forcings, though this must be considered somewhat fortuitous.

The fact that both classes of climate model did so well in projecting future warming should increase our confidence that current climate models are getting things right for mostly the right reasons. The projection skill of the 1970s models is particularly impressive given the limited observational evidence of warming at the time, as the world was thought to have been cooling for the past few decades (e.g. Broecker 1975; Broecker 2017). While there are still real uncertainties in future warming associated with climate sensitivity, we can confidently state that the rate of surface warming we are experiencing today is pretty much what past climate models projected it would be.

Note: all the data and code for this study are available here.

References

Broecker, W. S. (1975). Climatic Change: Are We on the Brink of a Pronounced Global Warming? Science, 189(4201), 460 LP-463. https://doi.org/10.1126/science.189.4201.460

Broecker, W. (2017). When climate change predictions are right for the wrong reasons. Climatic Change, 142(1), 1–6. https://doi.org/10.1007/s10584-017-1927-y

Hausfather, Z., Drake, H.F., Abbott, T., and Schmidt, G.A. (2020). Evaluating the Performance of Past Climate

Model Projections, Geophysical Research Letters, vol. 47. http://dx.doi.org/10.1029/2019GL085378

IPCC (AR4) (2007). Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.B.; Tignor, M.; and Miller, H.L. (eds.), Cambridge University Press, ISBN 978-0-521-88009-1 (pb: 978-0-521-70596-7).

Manabe S. (1970) The Dependence of Atmospheric Temperature on the Concentration of Carbon Dioxide. In: Singer S.F. (eds) Global Effects of Environmental Pollution. Springer, Dordrecht.

Mitchell, J. M. (1970). A Preliminary Evaluation of Atmospheric Pollution as a Cause of the Global Temperature Fluctuation of the Past Century. In: Singer S.F. (eds) Global Effects of Environmental Pollution. Springer, Dordrecht, p. 139.

Rasool, S.L. and Schneider, S.H. (1971) Atmospheric Carbon Dioxide and Aerosols: Effects of Large Increases on Global Climate. Science, 173, 138-141. http://dx.doi.org/10.1126/science.173.3992.138

Sawyer, J. S. (1972). Man-made Carbon Dioxide and the "Greenhouse" Effect. Nature, 239(5366), 23–26. https://doi.org/10.1038/239023a0 http://dx.doi.org/10.1038/239023a0

Schneider, S.H. (1975). On the Carbon Dioxide–Climate Confusion. J. Atmos. Sci., 32, 2060–2066, https://doi.org/10.1175/1520-0469(1975)032<2060:OTCDC>2.0.CO;2

Schneider, S. H., and Thompson, S. L. (1981), Atmospheric CO_2 and climate: Importance of the transient response, J. Geophys. Res., 86(C4), 3135– 3147, doi:10.1029/JC086iC04p03135.

GPC 2020 Executive

Chair
(through 12/2020):

William D. Collins
Division Director
Climate &
Ecosystems Sciences
Lawrence Berkeley
National Laboratory
wdcollins@lbl.gov

Chair-Elect
(through 12/2020)

Mary Silber
Department of
Statistics
University of Chicago
Chicago, IL 60637
msilber@uchicago.edu

Vice Chair
(through 12/2020)

William Newman
Department of Earth,
Planetary, and Space
Sciences
UCLA
Los Angeles, CA
90095
win@ucla.edu

Past Chair
(through 12/2020):

Chris E. Forest
Department of
Meteorology and
Atmospheric Science
The Pennsylvania
State University
University Park, PA
16802
(814) 865-0710
ceforest@psu.edu

Secretary/Treasurer
(through 12/2021):

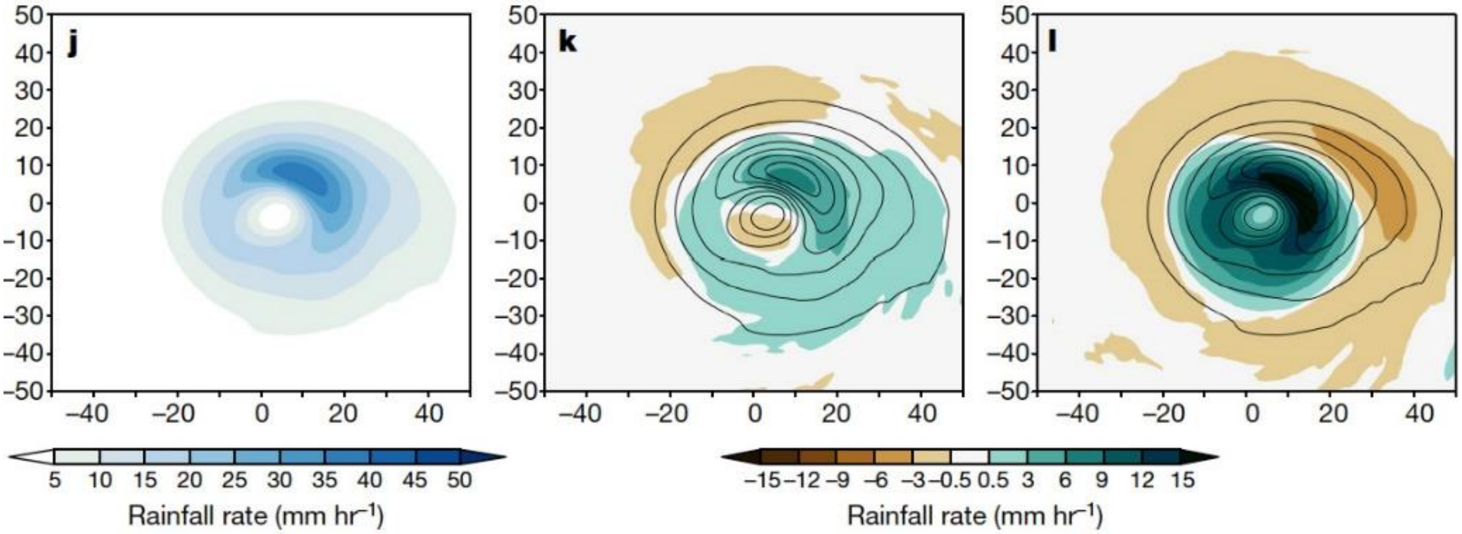
Raymond A. Shaw
Department of
Physics
Michigan Technical
University
1400 Townsend Dr
Houghton, MI 49931
(906) 487-1961
rashaw@mtu.edu

ARTICLE: Quantifying the effect of climate change on contemporary extreme weather events

(Continued from p. 1)

As of 2020, the global mean temperature has been increased since the mid-19th century by just over 1°C from our consumption of fossil fuels (Wuebbles et al., 2017). While a single degree warmer does not sound like much, the effect of this amount of warming on extreme weather events such as heat waves, droughts, floods and severe storms can be profound. Borrowing methods from epidemiology, extreme event attribution attempts to quantify the influence of this global warming, if any, on individual weather events in a probabilistic framework. Two related questions are posed by event attribution. First, has climate change altered the chances of the occurrence of a specific event at the observed magnitude? Second, if the rarity of an observed event can be estimated, has climate change altered the magnitude of events at that fixed rarity?

Both of these questions are exercises in causal inference, hence the connection to epidemiology. A familiar method of causal inference involves constructing two experiments isolating the postulated causal drivers. For example in medicine, dividing patients into two groups, one receiving a drug and the other a placebo, is often used to determine the efficacy of the drug. This form of causal inference, as



Changes in peak precipitation rates exceed Clausius-Clapeyron scaling during Hurricane Maria. Left: Composite ensemble simulation of average precipitation rate during Hurricane Maria. Middle: Hurricane Maria current anthropogenic precipitation change. Right: Anthropogenic precipitation change if Hurricane Maria occurred at the end of this century in a "no-policy" emissions scenario. Units: mm/hour

detailed by Pearl (2009), is often used in extreme event attribution by performing two sets of climate model simulations, one with human changes to the climate system, the other without. In the first such study, Stott, Stone, & Allen (2004) analyzed seasonal temperatures produced by multi-decadal simulations concluding that the chances of the 2003 European heat wave were doubled by anthropogenic climate change. Of course, global warming has continued unabated since 2003 and the current chances of such high European summer temperature are increased at least 10x over the pre-industrial era (Christidis, Jones, & Stott, 2015). Confidence in these attribution statements is high as the models are demonstrated to reproduce observed temperature trends (Bindoff et al., 2013). Since this pioneering work, Pearl causality methods have been applied to many other large scale seasonal extreme events. An annual series of the State of the Climate reports in the Bulletin of the American Meteorological Society highlights selected extreme weather events of the previous year (Herring, et al. 2019; Herring et al., 2016; Herring et al., 2014; Peterson et al., 2013; Peterson et al., 2012). In these reports and throughout the literature, hundreds of different large-scale weather and climate extremes have been analyzed for the influence of climate change on them. Analyses have been extended from hot or cold temperature extremes to moisture related extremes including floods and droughts. While a human influence on such moisture events has often been found, there are also instances where an expected signal has not yet arisen out of the noise.

Recently attention has focused on short term extreme weather events such as intense storms and tropical cyclones. Precipitation during Hurricane Harvey was found by several authors (Risser & Wehner, 2017; Van Oldenborgh et al., 2017; Wang et al. 2018) to have experienced a very large increase from global warming, exceeding that expected from thermodynamic considerations alone. Available moisture was increased by about 7% due to the 1°C attributable warming in the waters of the Gulf of Mexico and by constraints from the Clausius-Clapeyron relationship. However, best estimates of anthropogenic precipitation increases from these authors were substantially larger, ranging from 15% to 38%. The higher of these estimates (Risser & Wehner, 2017) was obtained from a causal inference method using observational data alone and without climate models (Granger, 1969). When different authors using different methods come to such similar conclusions, confidence in attribution statements is enhanced.

The reasons for the super Clausius-Clapeyron scaling of Harvey's precipitation were not fully explored in these early studies. However, Patricola & Wehner (2018) studied 15 other tropical cyclones with a convection permitting weather forecast model at a horizontal resolution of ~4.5 km finding that the portion of these storms that rained the most also experienced the largest enhancement from climate change, often exceeding the Clausius-Clapeyron constraint. Although Harvey was an unusual storm due to its prolonged stall, Houston, Texas also had the unfortunate circumstance to be under its most intensely precipitating portion. Complex structural changes in storm dynamics due to global warming in Harvey and other intense tropical cyclones led to such large precipitation increases in the inner regions of the cyclone at the expense of the outer regions.

The figure above shows this typical structure change for Hurricane Maria. The middle panel shows peak precipitation increases of over 20% at present compared to a preindustrial when only about 4% would be expected from Clausius-Clapeyron scaling of the local ocean temperatures. In the much warmer future of the right panel, peak increases of 40% are projected but only 14% would be expected from thermodynamic effects alone. Integrated over the entire area of this and the other 14 simulated storms in Patricola & Wehner, total precipitation changes are indeed limited by Clausius-Clapeyron scaling but the patterns of change are far from uniform.

This insight into the effect of climate change on severe storms illustrates that extreme event attribution serves two purposes. The first is to inform the public about the present dangers of climate change and how it may directly affect them. But the second is to increase our understanding of how anthropogenic climate change affects extreme weather now and in future warmer climates. Such knowledge is critical for informed decision and policy making.

References

Bindoff, N. L., Stott, P. A., AchutaRao, K. M., Allen, M. R., Gillett, N., Gutzler, D., Zhang, X. (2013). Detection and Attribution of Climate Change: from Global to Regional. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 867–952). https://doi.org/10.1017/CBO9781107415324.022

Christidis, N., Jones, G. S., & Stott, P. A. (2015). Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *Nature Climate Change*, *5*(1), 46–50. https://doi.org/10.1038/nclimate2468

Granger, C. W. J. (1969). Investigating Causal Relations by Econometric Models and Cross-spectral Methods. *Econometrica*, *37*(3), 424–438. https://doi.org/10.2307/1912791

Herring, S. C., Christidis, N., Hoell, A., Hoerling, M. P., & Stott, P. A. (2019). Explaining Extreme Events of 2017 from a Climate Perspective. *Bulletin of the American Meteorological Society*, *100*(1), S1–S117. https://doi.org/10.1175/BAMS-ExplainingExtremeEvents2017.1

Herring, S. C., Hoell, A., Hoerling, M. P., Kossin, J. P., Schreck, C. J., & Stott, P. A. (2016). Explaining Extreme Events of 2015 from a Climate Perspective. *Bulletin of the American Meteorological Society*, *97*(12), S1–S145. https://doi.org/10.1175/BAMS-ExplainingExtremeEvents2015.1

Herring, S. C., Hoerling, M. P., Peterson, T. C., & Stott, P. a. (2014). Explaining Extreme Events of 2013 from a Climate Perspective. *Bull. Amer. Meteor. Soc.*, *95*(9), S1–S96.

Patricola, C. M., & Wehner, M. F. (2018). Anthropogenic influences on major tropical cyclone events. *Nature*. https://doi.org/10.1038/s41586-018-0673-2

Pearl, J. (2009). *Causality*. Cambridge, U. K., Cambridge University Press.

Peterson, T. C., Hoerling, M. P., Stott, P. A., & Herring, S. C. (2013). Explaining Extreme Events of 2012 from a Climate Perspective. *Bulletin of the American Meteorological Society*, *94*(9), S1–S74. https://doi.org/10.1175/BAMS-D-13-00085.1

Peterson, T. C., Stott, P. A., & Herring, S. (2012). Explaining Extreme Events of 2011 from a Climate Perspective. *Bulletin of the American Meteorological Society*, *93*(7), 1041–1067. https://doi.org/10.1175/BAMS-D-12-00021.1

Risser, M. D., & Wehner, M. F. (2017). Attributable Human-Induced Changes in the Likelihood and Magnitude of the Observed Extreme Precipitation during Hurricane Harvey. *Geophysical Research Letters*, *44*(24), 12,412-457,464. https://doi.org/10.1002/2017GL075888

Stott, P. A., Stone, D. A., & Allen, M. R. (2004). Human contribution to the European heatwave of 2003. *Nature*, *432*(7017), 610–614. https://doi.org/10.1038/nature03089

Van Oldenborgh, G. J., Van Der Wiel, K., Sebastian, A., Singh, R., Arrighi, J., Otto, F., Cullen, H. (2017). Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/aa9ef2

Wang, S. Y. S., Zhao, L., Yoon, J. H., Klotzbach, P., & Gillies, R. R. (2018). Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/aabb85

Wuebbles, D. J., Easterling, D. R., Hayhoe, K., Knutson, T., Kopp, R. E., Kossin, J. P., … Wehner, M. F. (2017). Our globally changing climate. In D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, & T. K. Maycock (Eds.), *Climate Science Special Report: Fourth National Climate Assessment, Volume I* (pp. 37–72). https://doi.org/10.7930/J08S4N35.

Summary: Workshop to Explore Science Opportunities and Concepts for a Large-Scale Aerosol-Cloud-Turbulence Research Facility

Raymond A. Shaw, Department of Physics, Michigan Technological University, Houghton, Michigan

APS GPC members may be particularly interested in the discussions and outcome of a NSF-sponsored workshop held 21-22 November 2019 at the National Center for Atmospheric Research in Boulder, Colorado. Over 60 scientists from a wide range of fields overlapping with the chemistry and physics of aerosols and clouds in turbulent flows gathered to discuss scientific questions, priorities, and concepts for future laboratory research facilities and associated instrumentation.

Clouds and aerosols, and the turbulent flows that both generate and respond to them, are central to the prediction of weather and the understanding of earth's climate. The purpose of the workshop was to explore scientific questions and set priorities for a large-scale aerosol-cloud-turbulence research facility. Specifically, at the workshop we attempted to gauge community interest and to obtain a sense of priorities for the range of scientific challenges likely to be amenable to laboratory investigation. The two overarching questions guiding the workshop presentations and discussion were:

- What can we learn with a large-scale aerosol-cloud research facility that would be difficult to learn otherwise?
- What would a large-scale aerosol-cloud research facility look like and what measurement capabilities should be associated with it?

The workshop format consisted of a series of overview talks to highlight scientific questions in various areas that could potentially be investigated in a large-scale aerosol-cloud-turbulence laboratory facility. Topics included warm and mixed-phase cloud microphysics, aerosol and cloud chemistry, atmospheric turbulence, radiative transfer, cloud/aerosol instrumentation, and remote sensing. Twelve presentations were given to provide an overview of key science questions in these areas, as well as to summarize what large research facilities already exist in Asia, Europe and North America. The agenda was organized to provide ample time for discussion following each overview presentation. In addition, due to the large number of participants, we broke into three groups for several hours to have more active interaction with all participants. The ideas and concepts from those breakout sessions was considered a key outcome of the workshop.

The workshop began by outlining the benefits of a laboratory facility for aerosol-cloud-turbulence interactions:

- Well characterized boundary and initial conditions
- Known inputs, such as aerosol (controlled composition and size)
- Removal of large-scale feedbacks, e.g., constant forcing (aerosol-cloud interactions with no "meteorology")
- Detailed measurement of aerosol and cloud microphysical properties (size distributions and particle phase, interstitial and residual aerosols, etc.)
- Repeatability, or ability to sample under steady-state conditions (dynamic equilibrium)
- Isolation of processes or mechanisms
- All of these factors enable detailed comparison to theory and computational (simulations and models)

In spite of these compelling advantages, it was noted that there has been a decline of laboratory studies and in the availability of laboratory facilities in North America (only one cloud chamber facility, the Pi Chamber at Michigan Technological University, was reported as currently functioning). It was noted that there has been a significant bias towards observational and numerical simulation studies. Furthermore, it was argued that *in situ* observations have limited capability to enhance existing knowledge on cloud microphysics due to their limited sample volume, the poorly-known or unknown boundary and initial conditions, and challenges with multiple sampling of the same cloud. Laboratory studies provide the only practical means to quantify individual microphysical processes rates under controlled conditions.

Workshop participants were asked ahead of time to read the report of a similar workshop held in the mid-1980s and to consider how the science had progressed since that time, what facilities had been developed, and even what hindered the achievement of some recommendations. The following points were discussed at the workshop, regarding what has changed since the mid-1980s, and why a large-scale facility should be considered again:

- Many of the same science problems exist: collision-coalescence efficiency, primary and secondary ice formation in mixed-phase clouds, etc.
- The problems are broader: beyond cloud and precipitation physics, they now include aerosol-cloud indirect effects, radiative transfer, aerosol and cloud chemistry, and turbulence interactions.
- Availability of new experimental approaches and improved instrumentation for aerosol, cloud, turbulence, radiation measurements.
- Emergence of high-fidelity computational models that need to be validated and improved, but also that can be used to enhance the interpretation of measurements.

Science questions and priorities were discussed in several key areas: Boundary-layer turbulence and cloud-turbulence interactions, aerosol-cloud interactions and warm cloud microphysics, aerosol and cloud chemistry within a large-scale cloud chamber, and mixed phase cloud microphysics, including aerosol, turbulence, and secondary-ice interactions. Participants were struck with the wide-ranging and rich diversity of science problems that would benefit from laboratory investigation. For brevity, only a couple of representative examples are given here.

A longstanding challenge in cloud physics has been to understand the onset of precipitation in a reasonable amount of time: including cloud droplet activation on aerosol particles, cloud droplet growth by condensation, and finally growth by collision-coalescence of cloud droplets. Related questions are, how does formation of a cloud and its related growth processes modify the aerosol that led to cloud formation in the first place? Do we understand the effects of turbulent entrainment of environmental air and subsequent mixing on droplet growth and cloud structure? Collision-coalescence is an example of a problem that can be studied in the laboratory using 'bottom-up' or 'top-down' approaches: the former is to construct collision rate coefficients from individual droplet pairs, whereas the latter involves looking at input and output (initial, final) droplet size distributions and inverting to obtain the collision rates.

Basic problems in the microphysics of mixed-phase (liquid and ice) clouds include, how to define a mixed phase cloud as opposed to adjacent regions of warm and cold clouds, the spatial scales of interaction between ice particles and liquid droplets, the conversion rate of liquid to ice, the time for glaciation, and the role of vertical velocity and turbulence on the maintenance of mixed phase clouds. Laboratory investigation is still needed for understanding aspects of single ice particle growth, such as the metamorphosis and growth rate of ice particles under varying temperatures and relative humidities. Problems involving collective ice growth and secondary ice production, such as ice splintering or breakup, are even more numerous and are ripe for laboratory investigation.

A primary motivation for considering the development of a large-scale facility for aerosol-cloud-turbulence interactions is the phenomenal advancement of measurement and computational capabilities. Three aspects were reviewed during the workshop. First, significant science opportunities now exist for remote sensing methods that could be applied within a large-scale cloud chamber. These include high-resolution radar and high-resolution photon time-tagging lidar. Besides the benefit these tools could provide to scientific capabilities of a facility, a large-scale cloud chamber could also help reduce uncertainties in hydrometeor remote sensing. For example, a topic of great current relevance to remote sensing retrievals is the fall velocity of various hydrometeor classes, especially how that is impacted by the presence of turbulence. In short, rapid developments in instrumentation and signal processing could provide a leap forward in cloud chamber observational capabilities from 3-D imaging of individual hydrometeors for spatial distribution and motion of hydrometeors, to water vapor and temperature measurement.

Second, challenges in cloud/aerosol instrumentation will need to be met in order to support science in a large-scale facility. There is a need for Lagrangian measurements of 3-D fluid velocity and fluid thermodynamic properties within 10 to 100 cm-scale samples. Measurement of water vapor supersaturation has persisted as a significant challenge, and should be a top priority. Advances in the fluid mechanics community in measurement of 2-D and 3-D velocity fields (e.g., particle tracking and laser induced fluorescence) are prime for adaptation. Volumetric rather than single-particle measurement methods are ideal for a laboratory setting.

Third, turbulence and aerosol/cloud microphysics computational capabilities have advanced to the point where intercomparison of detailed simulations can be made with laboratory measurements. Computational models can be verified and improved by using laboratory measurements, with the ultimate goal being to improve the representation of aerosol-cloud dynamics and their representation in large-scale atmospheric models. For experimentalists, access to detailed models allows investigation of processes or quantities difficult to observe with existing instruments (e.g., supersaturation), as well as an economical way to design and test new experiments. Problems that are ideal for investigation with synergistic modeling and laboratory approaches include turbulence effect on droplet condensation growth, aerosol processing, ice formation in mixed-phase stratocumulus, and even radiative transfer.

As participants explored facility concepts, ranges of spatial and temporal scales needed to address the identified scientific questions were emphasized. As facility concepts were discussed, two points were emphasized. First, experiments and facility designs need not reproduce, and indeed usually cannot, reproduce exact conditions of the atmosphere. Therefore, their development should be guided by dimensionless variables such as Reynolds, Rayleigh, and Stokes numbers. The photon or droplet-collision mean free path relative to a chamber length scale was discussed as a key parameter (this could be considered as an optical depth or a Knudsen number). Second is the critical role of simulation in guiding the design of future facilities, as well as using computational modeling to explore how laboratory results can be scaled to atmospherically relevant scenarios. It will be crucial that any large-scale facility should be fully explored using high-fidelity modeling. One aspect of that should be the development and verification of model boundary conditions, such as particle loss rates to chamber walls.

Discussion at the workshop was free-flowing and explored a wide range of ideas for research facilities. As expected from a group of over 60 scientists representing a variety of disciplines, there was not convergence on one chamber type. It was recognized that no single facility is suitable for investigation of all scientific questions, and in fact one takeaway message from the workshop was the exciting opportunity that would arise from having a site with multiple interacting facilities, where instrumentation and expertise could be shared. There were even some brainstorms suggesting that one facility for cloud formation would "feed" another facility. As the discussion progressed, four concepts emerged with significant levels of support. Very briefly, in no order of priority, they were: 1) A large chamber in which turbulent Rayleigh-Bénard convection leads to cloud formation via isobaric mixing. This is the mode of operation of the Pi Chamber, which has been used for studies of activation, aerosol processing, and cloud droplet and ice condensation growth in a turbulent environment. Scaled up sufficiently, such a cloudy convection chamber could be used for investigations of turbulence effects on droplet growth by collision-coalescence, secondary-ice generation, and radiative transfer through clouds. 2) A piston-type expansion chamber with a fixed volume of air, rather than through exhaust of the pumped air. This would allow multiple-cycling of cloud formation and evaporation, and the associated aerosol processing. 3) A mineshaft cloud chamber with a long, vertical path could address many problems in cloud physics and radiative transfer, such as interaction of falling hydrometeors and propagation of photons. If the facility has sufficiently large vertical extent, cloud formation could be induced through the reduction in pressure with height. 4) A stratified mixing layer in which cloud-clear air mixing could be studied in a stratified environment. One possible conceptual design would be a horizontal wind tunnel with lower and upper sections where cloud and above-cloud thermodynamic conditions would be set. The cloud could be artificially generated using sprays, or, in one brainstorm configuration, it could be fed by the outflow from a mineshaft cloud generator.

The overriding sentiment of the workshop was that there is a strong need for a significant investment in laboratory cloud and aerosol research facilities in order to improve weather prediction models and climate simulations. The ultimate goal of a cloud-aerosol-turbulence facility will be the development of next-generation, physically-based parameterizations for microphysical processes in cloud and climate models. Laboratory research therefore plays a crucial role in catalyzing numerical simulation and in-situ observations for further progress in our understanding of cloud processes. Access to a large-scale cloud-aerosol-turbulence facility is envisioned as especially important to the North American scientific community.

The workshop was supported by the US National Science Foundation (NSF) and by the NCAR Geophysical Turbulence Program. Details of the workshop and a list of speakers and participants can be found at https://sites.google.com/mtu.edu/aerosol-cloud-facility-workshp.

GPC Executive Committee Members-at-Large, Assigned Council Representative, and Newsletter Editor:

Left to right: Barbara Levi (12/2020), Isabel McCoy (12/2020), Katie Dagon (12/2021), Daniel Rothman (12/2021), Juston Burton (12/2022), Albion Lawrence (12/2022), Student Member Adria Schwarber (12/2021), Assigned Council Representative (DFD) Howard A. Stone, Peter Weichman (Newsletter Editor, 12/2020).

GPC Program Committee:

Left to right: Chris Forest (Chair), William Collins, Norman Loeb, Maria Rugenstein, Mark Zelinka

The role of the Program Committee is to work with the Executive Officers in scheduling contributed papers within areas of interest to the GPC and in arranging symposia and sessions of invited papers sponsored by the GPC at Society meetings. From time to time the Program Committee may also organize special GPC meetings and workshops, some with and some without the participation of other organizations.

GPC Communications Committee

Left to right: Peter Weichman (Chair), Barbara Levi

The role of the Communications Committee is to have oversight of the Newsletter and any other publications that may be established by the GPC. The Communications Committee shall also be responsible for keeping the physics community and other interested communities informed about climate physics issues, activities, and accomplishments through the Newsletter, GPC website and email messages.

GPC Climate Café

(7:30-10:00 pm, Thursday, March 5)

You are cordially invited to the GPC Climate Café!

The Climate Cafe will take place 7:30-10:00 pm Thursday evening, where, over drinks and food, you can meet the March Meeting GPC speakers, as well as fellow GPC and other APS members. We'll discuss climate science, network, and chat with the Executive Committee members about GPC concerns. In keeping with its informal nature, we will announce the venue for the event at the Thursday Invited Session. You are also invited to the GPC business meeting **(5:45-6:45 pm, Thursday March 5, Room 605).**

All APS members are welcome to attend both!

GPC Invited Session: Predictability of the Climate System

(Session R37, 8:00 – 11:00 am, Thursday, March 5, Rm. 605

JUAN RESTREPO
Oregon State University

Title: Data Assimilation and Uncertainty Quantification in the Geosciences

Synopsis: Data assimilation is the name commonly given to the estimation process that generates moments of probability density functions of time dependent processes modeled by physics, and observations. The inherent uncertainties of model and data are taken into account using a Bayesian framework. Data assimilation is presently used in applications as diverse as weather forecasting and spacecraft navigation. I will appeal to familiar statistical physics to present the general methodology. I will briefly describe a couple of computational implementations of the method summarize some of the key research challenges that arise in their application. I will also describe some novel applications of the methodology, potentially useful in tracking targets, hurricanes, and ongoing research in the application of stochastic parametrization and machine learning for the purpose of dimension reduction.

The complexity of accurately predicting the track of hurricanes in time to respond to their potential socio-economic impact. A long-term goal is to reduce the risk/uncertainty of these tracks to allow for responders to station their resources within a short driving distance of the most affected population areas. *Image from NOAA*.

MICHAEL GHIL
Ecole Normal Supérieure and UCLA

Title: Climate Change and Climate Variability: A Unified Framework

Synopsis: The "death of stationarity" poses a substantial challenge to climate predictability and to the climate sciences in general. This challenge is addressed herein by formulating the problems of change in the climate's intrinsic variability within the framework of the theory of nonautonomous and random dynamical systems (NDS and RDS) with time-dependent forcing. A key role in this theory is played by the pullback attractors (PBAs) that replace the strange attractors of the more familiar theory of autonomous dynamical systems, in which there is no explicit time dependence of either forcing or coefficients.

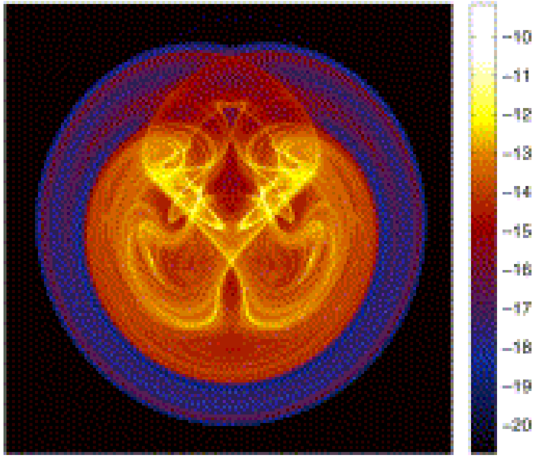
The concepts and methods of the NDS and RDS approach will be introduced and will be illustrated using a stochastically perturbed version of the Lorenz (1963) convection model. This illustration will be followed by applications to models of the wind-driven ocean circulation and the El Niño–Southern Oscillation (ENSO). One finds that two local PBAs, a quiescent and a chaotic one, coexist within the wind-driven ocean model's decadally modulated global PBA, whereas a critical transition between two types of chaotic behavior occurs in the seasonally forced ENSO model.

Implications for the climate sciences in the era of anthropogenic change will be discussed.

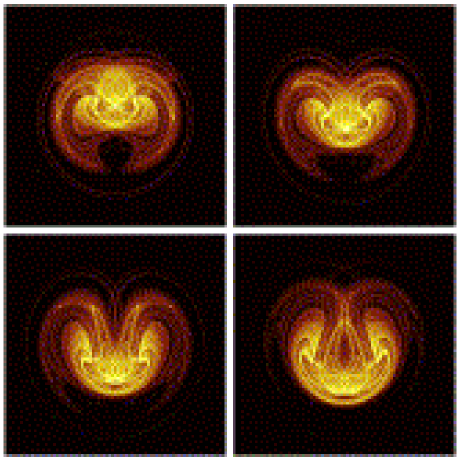
References:

[1] Ghil, M. and V. Lucarini: The physics of climate variability and climate change, *Rev. Mod. Phys.*, submitted, arXiv:1910.00583.

[2] M. D. Chekroun and E. Simonnet, Video of one day in the life of the Lorenz model's random attractor (2011): https://vimeo.com/user73335205.



Snapshot of the Lorenz (1963) convection model's random attractor and of the corresponding sample measure, for a given, fixed realization of the noise. The parameter values for the Rayleigh, Prandtl and wave number are the classical ones, i.e., 28, 10 and 8/3. Notice the interlaced filamentary structures between highly (yellow) and moderately (red) populated regions of the attractor.

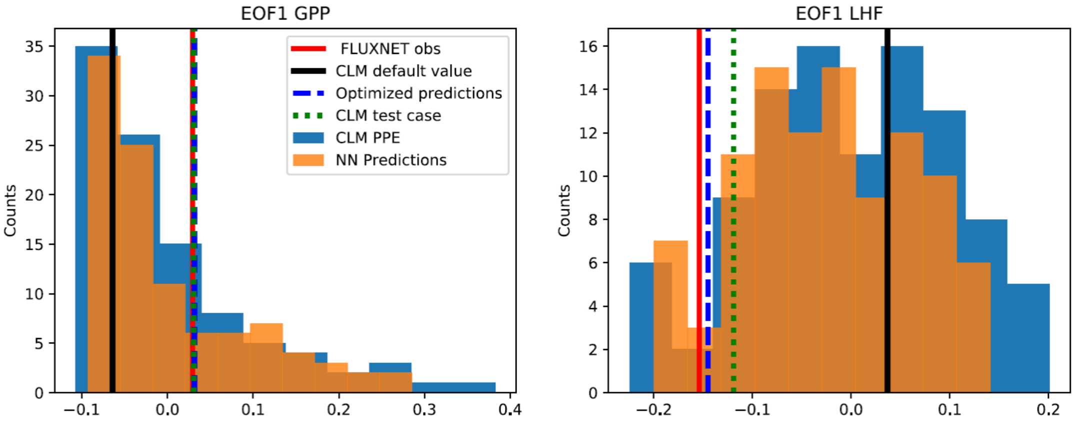


Four snapshots of the Lorenz model's random attractor. The time interval Δt between two successive snapshots — moving from left to right and from top to bottom — is Δt =0.0875. The interaction between the multiplicative noise and the nonlinearly deterministic flow in phase space produces surprising and rapidly changing patterns.

KATHERINE DAGON

NCAR

Title: Quantifying uncertainty in climate predictability using perturbed physics ensembles and climate model emulation



Distributions and point estimates of the first empirical orthogonal function (EOF1) for gross primary productivity (GPP) on the left, and latent heat flux (LHF) on the right. The distributions in blue are calculated across perturbed parameter ensemble (PPE) simulations with the Community Land Model (CLM), and distributions in orange are the associated neural network (NN) predictions of these values. Observational estimates from FLUXNET are shown as red vertical lines, and the CLM default values are shown as black vertical lines. Additional vertical lines denote optimization results (blue) and a CLM test case with optimal parameters (green).

Synopsis: Climate models are essential tools for understanding and predicting Earth system processes and feedbacks, but uncertainties in their future projections remain challenging to characterize. Improvements in physical process realism and the representation of human influence arguably make models more comparable to reality, but also increase the degrees of freedom in model configuration leading to parametric and structural uncertainties in projections. Perturbed physics ensembles sample the uncertainty space through different choices of parameter settings. Climate model emulators can be a computationally efficient method of producing large ensembles of climate model output, in order to study different sources of uncertainty. In this work we use a machine learning algorithm to build an emulator for the land surface component of a climate model. Using a perturbed physics ensemble of model simulations, we train the emulator to predict model output given a set of parameter values as input. We optimize parameter values by comparing emulated model output with observations across multiple relevant metrics, including global carbon and water flux benchmarks. We also account for structural and observational uncertainty through a novel Bayesian calibration approach. By sampling the resulting posterior distributions and running future climate simulations, we can then estimate the contribution of land model parameter uncertainty in future projections of climate change.

TAPIO SCHNEIDER

Caltech

Title: Earth System Modeling 2.0: Toward data-informed climate models with quantified uncertainties

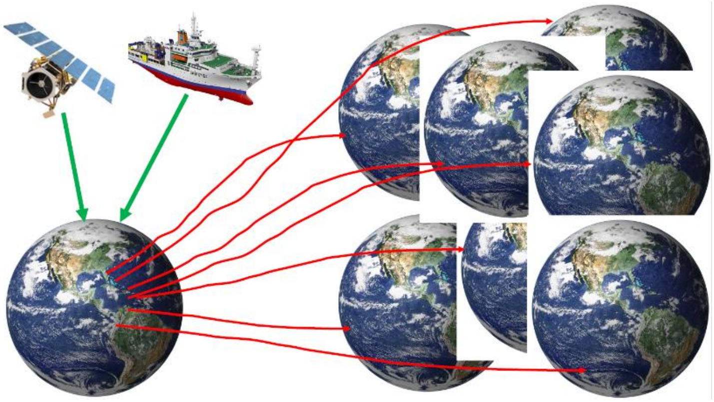
Synopsis: While climate change is certain, precisely how climate will change is less clear. But breakthroughs in the accuracy of climate projections and in the quantification of their uncertainties are now within reach, thanks to advances in the computational and data sciences and in the availability of Earth observations from space and from the ground. To achieve a leap in accuracy of climate projections, we are developing a new Earth system modeling platform. It will fuse an Earth system model (ESM) with global observations and targeted local high-resolution simulations of clouds and other elements of the Earth system. The ESM is being developed by the Climate Modeling Alliance (CliMA), which encompasses Caltech, MIT, and the Naval Postgraduate School. CliMA will capitalize on advances in data assimilation and machine learning to develop an ESM that automatically learns from diverse data sources, be they observations from space or data generated computationally in high-resolution simulations. It will also engineer the ESM from the outset to be performant on emerging computing architectures, including heterogeneous architectures that combine traditional CPUs with hardware accelerators such as graphical processing units (GPUs). This talk will cover key new concepts in the ESM, including turbulence, convection, and cloud parameterizations and fast and efficient algorithms for assimilating data and quantifying uncertainties.

PETER JAN VAN LEEUWEN

Colorado State University

Title: Bayesian Inference for Climate prediction

Synopsis: Bayesian Inference in the geosciences is called data assimilation. It studies how to best combine information from complex numerical models with information from observations of the system at hand, given limited computational resources. This requires knowledge of the physics, numerical modeling including computer architecture, quantification of deficiencies in the numerical models, characteristics of observations and their errors, and Bayesian inference and optimization techniques for very high dimensional highly nonlinear systems. We will discuss issues and potential solutions to the Bayesian Inference problem for climate prediction.



Climate prediction: Green arrows denote the assimilation of observations from satellites, ships etc., into the computer model of the Earth, and the red arrows denote an ensemble of predictions of possible future climates.

An important characteristic of the climate system is that the different Earth system components (e.g. atmosphere, ocean, land surface and icecaps) have vastly different internal time scales. The main work horse for weather prediction, a (variational) smoother in which observations over a time window of 6-12 hours are used to find the best starting point for predictions, is problematic because the optimal time window length is substantially different for the different components.

Even after 20 years of intensive research no satisfying smoother solution has been found.

This suggests to use a filter solution without an assimilation window, but the main workhorse there, the Ensemble Kalman Filter, suffers from too small ensemble sizes to accommodate the large number of observations (even when so-called localization is applied).

Another issue is that with its many feedbacks the climate system is highly nonlinear, while the standard methods for weather predictions are only optimal for linear, and perhaps weakly nonlinear systems. Furthermore, system updates are typically too abrupt and need to be added incrementally during the prediction.

We will discuss potential solutions based on existing techniques, and alternative ideas based on so-called particle flows. The latter are fully nonlinear while combining the strong points of smoothers and filters mentioned above, and have the potential to make substantial strides forwards towards better climate prediction.

Other News Links of Interest and Upcoming Events Calendar

1. 25th International Congress of Theoretical and Applied Mechanics (ICTAM 2020, Milano August 23-28, 2020) will include a mini-symposium on "Local Mechanics of Climate Processes" chaired by Eberhard Bodenschatz and John Wettlaufer.
2. 2020 International Conference on Clouds and Precipitation, Pune, India, August 3-7, 2020.