STATEMENT OF

Shuyi S. Chen, Ph.D.
Professor of Atmospheric Sciences
University of Washington

On

"The Future of Forecasting: Building a Stronger U.S. Weather Enterprise"

Before the
Subcommittee on Environment
U.S. House of Representatives Committee on Science, Space, and Technology

May 16, 2019

I wish to thank Chairwoman Fletcher, Ranking Member Marshall, and other Members of the Subcommittee for the opportunity to testify on the need to build a stronger weather enterprise and improve weather forecasts for the Nation. I am a Professor of the Atmospheric Sciences at the University of Washington. I serve as the Vice Chair of the National Academies' Board on Atmospheric Sciences and Climate (BASC). I am a Fellow of the American Meteorological Society (AMS).

My research and professional service have centered on understanding and improving prediction of weather systems, especially high-impact weather. I served as an Editor for *Weather and Forecasting* of the AMS. I currently serve on the Advisory Board for the Weather Research and Forecast (WRF) modeling community. I was on the National Academies' Committee on Progress and Priorities of U.S. Weather Research and Research-to-Operations Activities, which produced the 2010 report *When Weather Matters: Science and Services to Meet Critical Societal Needs.* I was appointed to oversee the review of the National Academies' report *Weather Services for the Nation: Becoming Second to None* (2012). I also chaired the Workshop Planning Committee for *The Future of Atmospheric Boundary Layer: Observing, Understanding, and Modeling* (2017). Most recently, I served on the steering committee that authored the National Academies' report *Thriving on our Changing Planet: A Decadal Strategy for Earth Observation from Space* (2018). While I have not been invited to testify on behalf of the National Academies, my testimony is deeply informed by their reports and my involvement in their activities to convene stakeholders from across the Weather Enterprise.

In the past 25 years, I have conducted research focusing on understanding extreme weather events (e.g., hurricanes) and intraseasonal variability that affect the global weather and climate system, and improving their prediction. I take interdisciplinary approaches to study coupled atmosphere-ocean systems in the tropics and coastal environment using satellite and airborne observations and atmosphere-ocean coupled numerical models. I have led national and international research programs in both field observations and coupled atmosphere-ocean modeling. My research group at the University of Washington has developed a first-generation high-resolution coupled atmosphere-wave-ocean model to better understand and predict high-impact weather such as hurricanes. I was a lead scientist of the National Oceanography Partnership Program model development team to build a new high-resolution, fully coupled atmosphere-wave-ocean model with a unified air-sea interface that is designed with inter-operability to facilitate the transition of research to operations.

Accurate and actionable weather forecasts and warnings can help prevent natural hazards from becoming disasters by saving lives and reducing economic loss. Continuation and acceleration of improving weather forecasts and warnings must be a national priority. Over the past two decades, weather research in the U.S. has enabled tremendous progress in better understanding weather processes and in advancing our ability to observe and predict weather. Atmospheric scientists of the United States are among the best in the world. Our weather research capability is admired by all other nations.

Despite leading the field of numerical weather prediction (NWP) since its inception in the 1950's and 1960's, the United States no longer leads the field. Our operational weather prediction skill has fallen behind those of some other nations, as found by three National Academies' reports (2010a[1]; 2010b[2]; 2012[3]). I believe we can fully realize our potential in weather forecasting and be the best in the world. This requires us to first identify the weaknesses and the challenges we are facing, so we can find solutions to them and make anticipated progress. I applaud the Committee for taking the leadership to address this important issue of building a stronger U.S. Weather Enterprise for the Nation's future of weather forecasting.

Following the suggestion in the Subcommittee's letter inviting me to testify, I organized my testimony around the following four topics:

1. Building a stronger U.S. Weather Enterprise and working towards a common goal
2. Enhancing national forecast capability
3. Meeting workforce needs to support national forecast capability
4. Charting a way forward for the U.S. Weather Enterprise

1. Building a stronger U.S. Weather Enterprise and working towards a common goal

Recognizing the importance of weather forecasting for the Nation, Congress passed the Weather Research and Forecasting Innovation Act of 2017 (H.R. 353) with bipartisan support. The law defines the Weather Enterprise as the "individuals and organizations from public, private, and academic sectors that contribute to the research, development, and production of weather forecast products, and primary consumers of these weather forecast products." The 2003 National Academies' report *Fair Weather: Effective Partnerships in Weather and Climate Services* recognized the important contributions of all sectors of the enterprise and defined the roles and responsibilities of each. This guidance has served the weather community well, but changes in the

[1] NRC, 2010a: *When Weather Matters – Science and Services to Meet Critical Societal Needs.* National Academy Press, Washington, DC.
[2] NRC, 2010b: *Assessment of Intraseasonal to Interannual Climate Prediction and Predictability.* National Academy Press, Washington, DC.
[3] NRC, 2012: *Weather Services for the Nation – Becoming Second to None.* National Academy Press, Washington, DC.

U.S. Weather Enterprise in the intervening years mean that the guidance no longer fully or accurately addresses how the sectors are interacting.

The U.S. Weather Enterprise has changed significantly over the past 15 years and is evolving rapidly. Advances in technology currently underway and anticipated in the coming decade will present a number of opportunities and challenges for the Weather Enterprise. Foremost among these opportunities are advances in high performance computing, cloud-based computing, and artificial intelligence; new observing technology and curation; and new communication technology and practice. The Weather Enterprise is also facing a number of challenges, such as

- a shifting balance between the traditional government responsibility and increasing roles of the private sector in collecting data, developing forecasting capabilities, making forecasts, and dissimilating forecast products;
- regulating and facilitating the fast-growing use of robotic devices in both air and water for data collection;
- extending traditional weather forecast models to Earth System forecast models to meet broad societal needs;
- international collaboration and coordination; and
- particularly transitioning from research by broad academic and private communities to operations by NOAA.

Building a stronger U.S. Weather Enterprise critically depends how we seize these opportunities and meet these challenges.

Our greatest asset is the integrated capability of the three sectors—government, academia, private industries—each bringing complementary capabilities. However, the three sectors often have complex disjointed goals, and the need for specialization can lead to undesirable stovepipes. The relative roles of the three sectors are evolving more rapidly than simple coordination can accommodate. The process for extending these roles to an ever-expanding community has been unclear and inconsistent. To overcome these barriers, we must establish a shared vision and work together towards a common goal of serving the growing need of society for accurate and actionable weather forecasts.

2. Enhancing national forecasting capability

Making U.S. operational weather forecasting capability the best in the world again will require both research investments to improve modeling capability and enhanced efforts to transition research to operations.

a. Model development

Weather knows no boundaries. Traditional weather forecast models represent regional atmospheric processes without interacting with the ocean, surface waves, and land processes. We need to develop Earth System models that can accurately represent the global atmosphere, ocean, land, and sea ice, processes that not only affect weather but also are an important part of holistic environment prediction. Within NOAA, the National Weather Service (NWS) and National Ocean Service (NOS) use separate models for operational weather and ocean forecasts. A unified coupled atmosphere-ocean model will benefit forecasting for the blue economy (fisheries, shipping) as well as forecasting weather with a longer lead time, as the ocean and land evolve slower than the atmosphere. The inclusion of these more slowly varying components of the Earth system is one reason for the improved performance of the UK Met Office weather model. They first developed their Unified Model with seamless prediction capability across scales in the atmosphere in the 1990's and continued to develop it into a coupled Earth System model that allows for both fine detailed, high-impact weather forecasts at short timescales and climate forecasts on long timescales.[4] This is perhaps the best example in the global Weather Enterprise of accomplishing an ambitious goal with a well-thought-out strategic plan.

Impacts of weather are local. The impacts are determined not only by the weather conditions, but also by the local landscape. A paradigm shift has already started from weather to explicit impact forecasting to inform decisions related to many sorts of systems, such as electric grids, transportation, and increased coastal flooding due to sea level rise. These are particularly active research topics by academics in geosciences and civil and environment engineering, and applications by private companies. Very high-resolution (down to the street level) impact modeling and forecasting systems are needed, which are driven by the global Earth System model. However, development of storm surge, land, and inland water models are uncoordinated at the national level.

Impacts of weather span many timescales. On the one hand, there are growing societal needs for accurate and actionable weather forecasts with increased lead times for severe weather events that occur over minutes to days (e.g., tornadoes, hurricanes) to support emergency management. On the other hand, decision makers desire seasonal probabilistic prediction of wildfires, heat waves, drought and flooding for long-term planning. To maximize the socio-economic benefits to society, we need predicative capability across a wide range of timescales.

Accurate weather forecasts beyond two weeks would be highly valuable. There is a growing need for extending weather forecasts beyond two weeks to subseasonal-to-seasonal (S2S) timescales (four weeks to two years) for long-term planning. This has been documented in the World Weather Research Program (WWRP) Implementation Plan[5] and two National Academies' reports (2010b, 2016). The Weather Research and Forecasting Innovation Act (H.R. 353) clearly identifies S2S prediction as part of the goal of improving the U.S. weather forecast capability.

NOAA's National Center for Environmental Prediction (NCEP) and other operational centers have demonstrated measurable but limited success with operational S2S forecasts. Yet, demands for these forecasts outpace its provision. S2S forecast products are still limited, their errors and uncertainties often large. With focused research-operation integration, substantial improvement of S2S forecasts and elevated societal benefit are within our grasp.

Now we have the will; what we need is a well-thought-out plan. However, as we speak, on the national level, we have only recommendations from the National Academies (2016) on a framework to develop a U.S. S2S prediction capability. There is no national strategy that enables the public, private, and academic sectors to work together to achieve this common goal.

[4] https://www.metoffice.gov.uk/binaries/content/assets/mohippo/pdf/research/met_office_science_strategy_2016-2021.compressed.pdf

[5] WWRP, 2013: *Subseasonal to Seasonal Prediction.* Research Implementation Plan. WMO.

NOAA's NCEP has pioneered atmosphere-ocean operational Coupled Forecast System (CFS) and led the field of seasonal forecasting for a decade or so. This coupled system could have served as a basis to develop a coupled forecast model for S2S prediction. However, this leading edge is being eroded as NOAA is focused on developing a new atmosphere model (FV3 based NGGPS) for short-range (within two weeks) forecasts while other operational centers (e.g., European Centre for Medium-Range Weather Forecasts [ECMWF] and UK Met Office [UKMO]) are quickly developing coupled models for S2S prediction. This happened partially because there is no national strategy for developing the U.S. S2S prediction capability.

The capability to observe the state of the atmosphere, land, ocean, and sea ice is absolutely essential to weather research and prediction. It is critical for us to understand how cutting-edge technologies should help improve the current observing systems and also build new observing systems for better weather forecasts. The private sector is playing an increased role in collecting environmental data for their own applications and to fill gaps in the current observation systems developed and maintained by governments. Data sharing between private and public sectors is an unmet challenge. At the national level, numerical models and observing systems must be advanced jointly.

Adaptability of current models to future exascale high-performance computing facilities is key to ensure continued progress in model development. We should invest in scientific software engineering so that we are ready for future computing capabilities. With increased computing capability comes increasing volumes of data. Extracting scientific value from those data will require improved data management, archiving, and sharing capabilities, especially with our science partners. Academic and public research institutes and private companies are using the latest data analytics, artificial intelligence, and machine learning for both model development and innovative application of complex forecast information.

b. Research-to-Operation Transition

U.S. weather research has been on the leading edge in terms of innovation and breadth in basic research that has led to improvement in weather forecasting, especially in the area of high-impact weather forecasting and warnings by NOAA. Much of the advancement today would have not been possible without basic research by the academic, government, and private research community funded by the National Science Foundation (NSF), the Office of Naval Research of DoD, DoE, NASA, NOAA, and others over the past several decades. However, the fruits of the weather research have not been fully harvested by the operations in NOAA. This issue has been the focus of several National Academies' studies and reports. Many have reached similar conclusions, namely a lack of national strategy and strong leadership are the main reasons for the lapse, as found in *From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death* (NRC 2000[6]). A similar view was expressed in a provocative article entitled "The Uncoordinated Giant: Why U.S. Weather Research and

---

[6] NRC, 2000: *From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death.* National Academy Press, Washington, DC.

Prediction Are Not Achieving Their Potential" by Mass (2006)[7]. Despite an awareness of the problem and recommendations from many entities, there has been little progress in improving the transition of research to operations, especially in terms of NWP models.

For decades, NCEP/NWS has been developing its NWP models for operations in isolation, while the Office of Oceanic and Atmospheric Research (OAR) laboratories have developed separate NWP models. Under the Weather Research and Forecasting Innovation Act 2017, there have been efforts to consolidate modeling activities within NOAA. Engagement with the broader academic community has been limited, which leads to intellectual segregation.

To develop a national strategy and a systematic approach to transition state-of-the-art weather research into operations, NOAA cannot do it alone. It needs to "***Engage the entire (weather) enterprise to develop and implement a national strategy for a systematic approach to research to operations and operations to research"***, a key recommendation by the National Academies (2012). Without a well-defined national strategy, a systematic approach, and sufficient infrastructure to support and facilitate continual adaptations of new research results to operations, the goodwill from research community outside NOAA cannot meet the ultimate challenge of research-to-operation transition at the national level.

To restore the U.S. leadership in weather forecasting, I believe that we need a new, transformative, integrated system to connect state-of-the-art weather research to operations. This system should be overseen by a consortium of experts from research, operations, and user communities of the Weather Enterprise. The consortium should design the pathway to ensure success in reaching the capability of:

- Developing a community-based modeling and data assimilation system that is flexible, using a community-standard code to incorporate innovations in weather research and technology (i.e., unified global fully coupled atmosphere-wave-ocean-land-ice model and coupled data assimilation system);
- Rapidly transferring research products and new technologies to NOAA and other operations (including the private sector);
- Providing accurate weather forecasts and emerging needs for impact forecasts (e.g., tornado outbreaks, hurricane-related storm surges, flash floods and power outages) and warnings on the short lead time of days to hours, and potential risk for drought, floods, wildfires, hurricane genesis and track on extended lead time of weeks and beyond.

The next-generation community-based system(s) should also have the capability of providing user-driven impact forecasts, which was one of the key recommendations in the National Academies' report *When Weather Matters* (NRC, 2010a). It will be more transparent and efficient for:

- Communicating with federal and local governments to optimize the utility of the forecasts and assessment products in public response;
- Training the next-generation of scientists and forecasters with innovative tools for prediction and impact mitigation;

---

[7] Mass, C., 2006: *The Uncoordinated Giant: Why U.S. Weather Research and Prediction Are Not Achieving Their Potential.* ***Bull. Amer. Meteor. Soc.***, **87**, 573–584.

- Educating vulnerable residents on the application value of the new information coming out of the integrated forecast system on short and long lead times.

The rapid advancement of science and technology presents us with an unprecedented capabilities and opportunities to develop an integrated weather forecast and response system that will support risk assessments and emergency management by reducing warning areas and providing forecasts with longer lead time. There is a critical need for the involvement of NSF to support the ambitious and risky interdisciplinary basic research agenda, in ways that go beyond what is feasible in individual mission-oriented government agencies. The development and operation of such an integrated weather forecast and response system requires collaboration and coordination among many research disciplines and among research, operations, and management. Further, successful implementation of such a system requires education of a new generation of scientists, engineers, forecasters, managers, and will guarantee a smooth transition from research to NOAA operations.

3. Meeting workforce needs to support national forecast capability

Workforce development and training is essential for future weather forecasting. A significant challenge will be the increasingly diverse knowledge and skills that are needed to advance modeling and forecasting. Many new and emerging job markets require interdisciplinary and multidisciplinary education. The desired skill sets range from emerging science (meteorology and its coupling to other Earth systems on multiple timescales) and technologies (e.g., computing, data analytics, machine learning), to a host of disciplines and skills related to decision support (e.g., impacts, communication, social and behavioral science).

A new generation of scientists and forecasters are needed to communicate high-impact weather in a changing climate to support effective decision making. Indeed, a recent National Academies' report (2018[6]) emphasized an urgent need for better integration of physical science and social and behavioral sciences within the Weather Enterprise.

Another area of growing concern is the difficulty in attracting and retaining talented computer scientists to apply their skills to building the next generation of weather models, data analytics, and forecasting systems. This problem will become even more acute as efforts proceed to move current models to future exascale high-performance computing facilities.

The atmospheric science education in universities has not changed significantly over the last a few decades. It still mostly follows the traditional disciplinary curricula, which cannot meet the needs for more broadly trained professionals in the Weather Enterprise. Universities need to modernize their curricula to meet the growing needs for an interdisciplinary and multidisciplinary workforce. There are opportunities for working partnerships and collaborations across public, private, and academic sectors in workforce development and training.

4. Charting a way forward for the U.S. Weather Enterprise

The challenges facing the U.S. Weather Enterprise can be addressed with bold action to harness and coordinate the capabilities that span the public, private, and academic sectors. Here I provide three ambitious recommendations that I believe are particularly promising. The views I share are my own, shaped by my 25 years of research in the field, by the authoritative work of the National Academies, and by extensive engagement with multiple stakeholders across the public, private, and academic sectors.

Launch a National Academies study on the Future of the U.S. Weather Enterprise. Over the last several years, I have participated in numerous conversations with a wide range of public, private, and academic stakeholders on how best to foster U.S. leadership in weather forecasting, modeling, and communication. One common theme that has emerged is the need for a comprehensive study to engage the broad weather community to develop a shared vision for the next generation U.S. weather enterprise. to the National Academies' Board on Atmospheric Sciences and Climate (BASC) has developed a proposal for such a study. The proposed study would gather experts in the physical, natural, social and behavioral sciences, technology, and weather operations, from academia, public agencies (including NOAA, NSF, NASA, DoD, DOE, DoT), and the private sector, to assess the current state of the U.S. Weather Enterprise and recommend priority investments and coordination mechanisms needed to achieve this vision. I personally believe that this proposed National Academies' study would be a highly effective way to bring the community together in a structured process that can provide guidance for all the sectors.

Establish a unified modeling and forecasting system for the United States. I believe that the multiple national investments and capabilities in weather forecasting could yield much improved performance if planning and implementation of these multiple components was approached as an integrated system. A first step will be to develop a vision and strategic plan for a unified modeling and forecasting system (including coupled atmosphere-ocean-land-ice modeling, data assimilation, and ensemble predictions) and a supporting observing system that facilitates innovation, research-to-operation, operation products that in turn support and demand further research. This strategic plan should be developed by experts from all three sectors of the Weather Enterprise. In my view, implementation of this holistic approach will require a consolidated national center—similar to that of ECMWF and the UK Met Office—with the participation from all relevant government agencies, academia, and private industries that can effectively use the best possible new technologies for computing, data analytics, and continued scientific innovations in modeling, observations, and data assimilation.

Create mechanisms for sustained resources and ongoing accountability. Restoring and maintaining U.S. leadership in weather forecasting will require a sustained commitment and coordination among multiple federal agencies and other partners, which are each balancing other competing priorities. The efforts described above to develop a community vision and unified modeling and forecasting system will put the nation on the right track. I believe that Congress should also act to ensure the outcome of these community efforts will be implemented and supported through sustained resources commensurate with the scale of the challenge and with the expected value to the nation. It also will be important to establish clear mechanisms for ongoing accountability, develop and track metrics of success, and provide incentives for collaborations among government agencies and their partnerships with academia and the private sector. Many in the community have suggested that a "decadal survey" model of Congressionally mandated National Academies studies that provide community-driven priorities every 10 years, combined with interim reports to assess progress, could address these needs for ongoing accountability. As this Committee knows well, this approach has worked well for other science areas that require significant resources to achieve long-term community-driven goals (such as astronomy, earth science and applications from space). It is my personal opinion, based on my experience with other decadal surveys, that this Committee should establish a similar ongoing mechanism for the Weather Enterprise.

There is no doubt that improving the weather forecasts and response to save lives and reduce economic loss should be a national priority. Restoring U.S. leadership in weather forecasting for the benefit of society should be a national priority. No single federal government agency can do it alone. It will take the entire Weather Enterprise.

Curriculum Vitae: Shuyi S. Chen

Professor, Department of Atmospheric Sciences, University of Washington
Box 351640, Seattle, WA 98195, shuyic@uw.edu, http://orca.atmos.washington.edu/, (305) 479-6551

EDUCATION

1990 Ph.D. Meteorology, The Pennsylvania State University
1985 M.S. Meteorology, University of Oklahoma
1982 B.S. Geophysics/Meteorology, Peking University

PROFESSIONAL APPOINTMENTS

2017 – Present	Professor, Department of Atmospheric Sciences, University of Washington
2006 – Present	Affiliate Scientist, National Center for Atmospheric Research
2007 – 2017	Professor, Ocean Sciences/Met and Phys Oceanography, University of Miami
1998 – 2017	Affiliate Professor, Atmospheric Sciences, University of Washington
2000 – 2007	Associate Professor, Meteorology and Physical Oceanography, Univ. of Miami
1997 – 2000	Associate Research Professor, Met and Phys Oceanography, University of Miami
1996 – 1997	Assistant Research Professor, University of Washington
1991 – 1995	Postdoc Research Associate, University of Washington

HONORS & AWARDS

2012 Fellow of the American Meteorological Society
2007 A.P. Sloan Foundation Leadership Award for Advancing Underrepresented Minority Students in Mathematics, Science and Engineering
2006 NASA Group Achievement Award for Tropical Cloud System Processes

FIELD PROGRAMS

2017 – PI/Team Leader, NASA Convective Process Experiment (CPEX), Fort Lauderdale, FL
2012 – Lead Scientist for mini-Met/Ocean surface drifters, Grand Lagrangian Deployment (GLAD) Experiment, Miami, FL
2011 – PI/Lead Scientist Aircraft Observations, Dynamics of MJO (DYNAMO), Diego Garcia
2010 – PI, Impact of Typhoons on Ocean over Pacific (ITOP), Guam
2005 – PI/Chief Scientist, Hurricane Rainbands and Intensity Change Experiment (RAINEX)
2003–04 PI, Coupled Boundary Layers Air-Sea Transfers (CBLAST)-Hurricane, Miami, Florida
1992–93 Satellite & Aircraft Mission Scientist, Tropical Ocean and Global Atmosphere Coupled Ocean and Atmosphere Response Experiment (TOGA COARE), Honiara, Solomon Islands

EDITORSHIP

2012 – Editorial Review Appointee for National Research Council Reports
2004 – 2006 Editor, *Weather and Forecasting*, AMS
2000 – 2003 Associate Editor, *Weather and Forecasting*, AMS

SYNERGISTIC ACTIVITIES AND SERVICE

a) Congressional Testimonies and Briefings:

- Testimony at the Hearing on: *Restoring U.S. Leadership on Weather Forecasting*, before the Subcommittee on Environment, Committee on Science, Space, and Technology of United States House of Representatives, 26 June 2013.
- Testimony at the Joint Hearing on: *The State of Hurricane Research and the National Hurricane Research Initiative Act of 2007*, before the Subcommittee on Energy and Environment and the Subcommittee on Research and Science Education, Committee on Science and Technology of United States House of Representatives, 26 June 2008.
- Congressional Briefings on Capital Hill in July 2007 and June 2015

b) Recent/Current Science Committees:

- **Vice Chair**, the National Academies Board on Atmospheric Sciences and Climate (BASC) (2011–present)

- The National Academies Steering Committee for the 2017–2027 Decadal Survey for Earth Science and Applications from Space (ESAS2017) (2015–2018)
- UCAR Board of Trustees (2017–2018)
- UCAR Community Advisory Committee for NCEP (UCACN) (2014–present)
- **Chair**, NASEM/BASC Committee for Future Boundary Layer Observing Workshop (2017)
- American Geophysical Union – Executive Committee of the Atmospheric Sciences
  Chair, AS FM Committee, Secretary for Physics, Dynamics and Climate (2014–2018)
- Science Advisory Board for the Weather Research and Forecasting (WRF) Model (2008–present)

RESEARCH

My research focus on understanding extreme weather events (e.g., hurricanes) and intraseasonal variability such as the MJO that affect the global weather and climate system, and improving their prediction. I take interdisciplinary approaches to study coupled atmosphere-ocean systems in the tropics and coastal environment using satellite and airborne observations and coupled models. I have led national and international research programs in both field campaigns and coupled atmosphere-ocean modeling. My research accomplishment includes:

- advancing our understanding of the dynamics, air-sea interaction, and predictability of tropical convective systems and their intraseasonal variability,
- understanding wind-wave-current interaction on upper ocean circulation and its applications (e.g., storm surge, oil spill and transport, and loads on offshore wind turbines),
- developing new generation coupled atmosphere-wave-ocean models for understanding and prediction of tropical cyclones and impacts at landfall (extreme wind, rain, waves, storm surge, and floods).

My focus on air-sea coupling through surface waves using stress vectors and explicit wave physics (e.g., breaking and dissipation, etc.) is fundamental to momentum, heat, and mass exchange between the atmosphere and ocean. My work on the diurnal/bi-diurnal cycle of tropical convective systems using satellite, airborne, and buoy observations during TOGA COARE led to the discovery of the interplay between convection and the sea surface temperature, namely "*diurnal dancing*." My work using coupled atmosphere-upper ocean observations in DYNAMO has shown that air-sea interaction plays an important role in the MJO through variabilities of convective cold pools, air-sea fluxes, and boundary layer recovery. Observations from RAINEX, CBLAST and ITOP and coupled air-sea modeling have led to several scientific breakthroughs, including formation of concentric eyewalls on hurricane intensity change, effects of TC-induced ocean cooling and stable boundary layer on storm structure and intensity. My recent work on using ocean drifter data in hurricanes/typhoons to evaluate and verify coupled atmosphere-wave-ocean models, wind-wave-current coupling on upper ocean transport and its application in prediction of both natural and manmade hazards (such as oil spill) are both interesting and rewarding.

TEACHING

Undergraduate Courses: Introduction to Atmospheric Science, Survey of Modern Meteorology, Hurricane and Society, Current Weather and Climate Topics, Introduction to Meteorology, Dynamic Meteorology I, Hurricanes and Societal Impact, Advanced Weather Analysis and Forecasting, Tropical Meteorology I

Graduate Courses: Tropical Large-scale Dynamics, Numerical Weather Prediction, Synoptic Meteorology, Tropical Meteorology, Dynamics and Modeling of Weather and Climate Systems

GRADUATE STUDENTS ADVISED

Joel Cline (MS), Robert Wolfe (MS), Manuel Lonfat (PhD), Wei Zhao (PhD), David Mechem (PhD), John Cangialosi (MS), Peter Kozich (MS), Derek Ortt (MS), Melicie Desflots (PhD), Chia-Ying Lee (PhD), Ronald Gordon (MS), Patricia Sanchez (MS), Falko Judt (PhD), Milan Curcic (PhD), Ajda Savarin (MS), Kuan-Jen Lin (PhD), and Andrew Smith (MS).

POSTDOCTORAL ASSOCIATES ADVISED

Wei Zhao, Olivier Nuissiur, Brandon Kerns, Chia-Ying Lee, Falko Judt, and Milan Curcic.

Selected Publications

Doviak, R. J., **S. S. Chen**, and D. R. Christie, 1991: A thunderstorm generated solitary wave observation compared with nonlinear wave theory for a compressible fluid. *J. Atmos. Sci.*, **48**, 87-111.

Chen, S. S., and W. M. Frank, 1993: A numerical study of the genesis of extratropical convective mesovortices. Part I: Evolution and Dynamics. *J. Atmos. Sci.*, **50**, 2401 - 2426.

Chen, S. S., R. A. Houze, Jr., B. E. Mapes, S. Brodzik, and S. Yuter, 1995: TOGA COARE satellite data summaries available via World Wide Web. *Bull. American Meteor. Soc.*, **76**, 329-333.

Chen, S. S., R. A. Houze, Jr. and B. E. Mapes, 1996: Multiscale variability of deep convection in relation to large-scale circulation in TOGA COARE. *J. Atmos. Sci.*, **53**, 1380-1409.

Chen, S. S., and R. A. Houze, Jr., 1997a: Diurnal variation and lifecycle of deep convective systems over the tropical Pacific warm pool. *Quat. J. Roy. Meteor. Soc*., **123**, 357-388.

Chen, S. S., and R. A. Houze, Jr., 1997b: Interannual variability of deep convection over the tropical warm pool. *J. Geophys. Res.*, **102**, 25,783-25,795.

Su, H., **S. S. Chen**, and C. S. Bretherton, 1999: Three-dimension week-long simulations of TOGA COARE convective systems using the MM5 Mesoscale Model. *J. Atmos. Sci*., **56**, 2326-2344.

Houze, R. A. Jr., **S. S. Chen**, D. Kingsmill, Y. Serra, S. E. Yuter, 2000: Convection over the Pacific warm pool in relation to the atmospheric Kelvin-Rossby wave. *J. Atmos. Sci.*, **57**, 3058-3089.

Mooers, C. N. K., H. S. Kang, and **S. S. Chen**, 2000: Several aspects of the simulated response of the Japan (East) Sea to synoptic atmospheric forcing due to Siberian cold air outbreaks, *La Mer*, **38**, 233-243.

Su, H., C. S. Bretherton, and **S. S. Chen**, 2000: Self-aggregation and large-scale control of tropical deep convection: A modeling study. *J. Atmos. Sci*. **57**, 1797-1816.

Chen, S. S., W. Zhao, J. E. Tenerelli, R. H. Evans, V. Halliwell, 2001: Impact of the Pathfinder sea surface temperature on atmospheric forcing in the Japan/East Sea, *Geophys. Res. Lett.*, **28**, No. 24, 4539-4542.

Mechem, D. B., R. A. Houze, and **S. S. Chen**, 2002: Layer inflow into precipitating convection over the western tropical Pacific, *Quat. J. Roy. Meteor. Soc*., **128**, 1997-2030.

Rogers, R., **S. S. Chen**, J. E. Tenerelli, and H. E. Willoughby, 2003: A numerical study of the impact of vertical shear on the distribution of rainfall in Hurricane Bonnie (1998), *Mon. Wea. Rev.,* **131**, 1577-1599.

Lonfat, M., F. D. Marks, **S. S. Chen**, 2004: Precipitation distribution in tropical cyclones using the Tropical Rainfall Measuring Mission (TRMM) microwave imager: A global perspective. *Mon. Wea. Rev.,* **132**, 1645-1660.

Stensrud, D. J., H. E. Brooks, **S. S. Chen**, and P. J. Rebber, 2004: Editorial. *Weather and Forecasting,* **19**, 3-4.

Mechem, D. B., **S. S. Chen**, and R. A. Houze, Jr., 2005: Momentum transport processes in the stratiform regions of mesoscale convective systems over the western Pacific warm pool, *Quat. J. Roy. Meteor. Soc*., **132A**, 709-736.

Chen, S. S., J. Knaff, F. D. Marks, 2006: Effect of vertical wind shear and storm motion on tropical cyclone rainfall asymmetry deduced from TRMM. *Mon. Wea. Rev.*, **134**, 3190-3208.

Houze, R. A., **S. S. Chen**, and co-authors, 2006: The Hurricane Rainband and Intensity Change Experiment (RAINEX): Observations and modeling of Hurricanes Katrina, Ophelia, and Rita (2005). *Bull. Amer. Meteor. Soc*, **87**, 1503-1521.

Dorman, C. E., C. A. Friehe, D. Khelif, A. Scotti, J. Edson, R. C. Bearsley, **S. S. Chen**, 2006: Winter atmospheric conditions over the Japan/East Sea: Structure and impact of severe cold-air outbreaks. *Oceanography*, **19,** 3.

Chen, S. S., J. F. Price, W. Zhao, M. A. Donelan, and E. J. Walsh, 2007: The CBLAST-Hurricane Program and the next-generation fully coupled atmosphere-wave-ocean models for hurricane research and prediction. *Bull. Amer. Meteor. Soc*, **88**, 311-317.

Houze, R. A., **S. S Chen**, B. Smull, W.-C. Lee, M. Bell, 2007: Hurricane intensity and eyewall replacement. ***Science,*** **315**, 1235-1239.

Rogers, R., M. Black, **S. S. Chen**, and R. Black, 2007: Evaluating microphysical parameterization schemes for use in hurricane environments. Part I: Comparisons with observations. *J. Atmos. Sci.*, **64**, 1811-1834.

Davis, C., W. Wang, **S. S. Chen**, Y. Chen, K. Corbosiero, M. DeMaria, J. Dudhia, G. Holland, J. Klemp, J. Michalakes, H. Reeves, R. Rotunno[1], and Q. Xiao, 2008: Prediction of landfalling hurricanes with the Advanced Hurricane WRF Model, *Mon. Wea. Rev.*, **136**, 1990-2005.

Langousis, A., D. Veneziano, **S. S. Chen**, 2008: A boundary layer model for moving tropical cyclones, *Hurricanes and Climate Change*, Springer, 71-85.

Chen, S. S., 2009: The next-generation coupled atmosphere-wave-ocean-ice-land models for ocean research and prediction, *Oceanography in 2025, The National Academies Press*, 26-27, pp 198.

Ray, P., C. Zhang, J. Dudhia, and **S. S. Chen**, 2009: A Numerical Case Study on the Initiation of the Madden-Julian Oscillation, *J. Atmos. Sci.*, **66**, 310-331.

Judt, F., and **S. S. Chen**, 2010: Convectively Generated Potential Vorticity in Rainbands and Formation of Secondary Eyewall in Hurricane Rita of 2005, *J. Atmos. Sci.*, **67**, 3581–3599.

Tao, W.-K., J. J. Shi, **S. S. Chen**, and co-authors, 2011: The impacts of microphysical schemes on hurricane intensity and Track, *Asia-Pacific J. Atmos. Sci.,* **47**, 1-16.

Donelan, M. A., M. Curcic, **S. S. Chen**, and A. K. Magnusson, 2012: Modeling waves and wind stress, *J. Geophys. Res.* **117**, DOI: 10.1029/2011JC007787.

Lee, C.-Y., and **S. S. Chen**, 2012: Symmetric and asymmetric structures of hurricane boundary layer in coupled atmosphere-wave-ocean models and observations, *J. Atmos. Sci.*, **69**, 3576-3594.

Chen, S. S., W. Zhao, M. A. Donelan, and H. L. Tolman, 2013: Directional wind-wave coupling in fully coupled atmosphere-wave-ocean models: Results from CBLAST-Hurricane, *J. Atmos. Sci.*, **70**, 3198-3215. https://doi.org/10.1175/JAS-D-12-0157.1

Lin, I.-I., P. Black, J. F. Price, C.-Y. Yang, **S. S. Chen**, C.-C. Lien, P. A. Harr, N.-H. Chi, C.-C. Wu, and E. A. D'Asaro, 2013: An ocean cooling potential intensity index for tropical cyclones, *Geophys. Res. Lett.*, **40**, 1878-1882, doi: 10.1002/grl.50091.

Sraj, I, M. Iskandarani**,** A.Srinivasan**,** W.C. Thacker**,** J. Winokur**,** A. Alexanderian**,** C.-Y. Lee**, S. S. Chen,** and O. M. Knio, 2013: Bayesian inference of drag parameters using Fanapi AXBT data, *Mon. Wea. Rev.*, **141**, 2347-2367.

Curcic, M., E. Kim, L. Emanuel, **S. S. Chen**, M. A. Donelan, and J. Michalakes, 2013: Coupled atmosphere-wave-ocean modeling to characterize hurricane load cases for offshore wind turbines, *51st AIAA Aerospace Sciences Meeting proceedings*, AIAA 2013-0198, http://dx.doi.org/10.2514/6.2013-198

Judt, F., and **S. S. Chen**, 2013: Reply to "Comments on 'Convectively Generated Potential Vorticity in Rainbands and Formation of the Secondary Eyewall in Hurricane Rita of 2005'". *J. Atmos. Sci.*, **70**, 989–992.

Kerns, B. W., and **S. S. Chen**, 2013: Cloud clusters and tropical cyclogenesis: Morphology and large-scale environment of developing and non-developing systems, *Mon. Wea. Rev.*, **141**, 190-210.

Judt, F., and **S. S. Chen**, 2014: A convective explosion and its environmental conditions in MJO initiation observed during DYNAMO, *J. Geophys. Res.,***119**, 2781–2795.

Kerns, B. W., and **S. S. Chen**, 2014a: Equatorial dry air intrusion and related synoptic variability in MJO initiation during DYNAMO, *Mon. Wea. Rev.*, **142**, 1326-1343.

Kerns, B. W., and **S. S. Chen**, 2014b: ECMWF and GFS Model Forecast Verification During DYNAMO: Multi-scale Variability in MJO Initiation over the Equatorial Indian Ocean, *J. Geophys. Res.,***119**, 3736–3755.

Lee, C.-Y., and **S. S. Chen**, 2014a: Stable boundary layer and its impact on tropical cyclone structure in a coupled atmosphere-ocean model, *Mon. Wea. Rev.*, **142**, 1927-1944.

Lee, C.-Y., and **S. S. Chen**, 2014b: Reply to comments on symmetric and asymmetric structures of hurricane boundary layer in coupled atmosphere-wave-ocean models and observations, *J. Atmos. Sci.*, **71**, 2786-2787.

D'Asaro, E., P. G. Black, L. Centurioni, Y-T. Chang, **S. S. Chen**, R. Foster, H.C. Graber, P.Harr, V. Hormann, R.-C. Lien, I.-I. Lin, T.B. Sanford, T.-Y. Tang, and C.-C. Wu, 2014: Impact of Typhoons on the Ocean in the Pacific: ITOP, *Bull. Amer. Meteor. Soc.*, **95**, 1405-1418.

Poje, A.C., T.M. Özgökmen., B. Lipphart, Jr., B. Haus, E.H. Ryan, A.C. Haza, G. Jacobs, A. Reniers, J. Olascoaga, G. Novelli, A. Griffa, F.J. Beron-Vera, **S. S. Chen**, et al., 2014: Submesoscale dispersion in the vicinity of the Deepwater Horizon spill. *Proceedings of the National Academy of Sciences*, 111(35), 12693-12698.

Jacobs, G. A., B. Bartels, D. Bogucki, F. J. Beron-Vera, **S. S. Chen**, E. F. Coelho et al., 2014: Data assimilation aonsiderations for improved ocean predictability during the Gulf of Mexico Grand Lagrangian Deployment (GLAD), *Ocean Modeling*, **83,** 98-117.

Judt, F., and **S. S. Chen**, 2015: A new aircraft hurricane wind climatology and application in assessing predictive skill of tropical cyclone intensity using high-resolution ensemble forecasts, *Geophys. Res. Lett.*, **42**, 6043-6050.

Kerns, B. W., and **S. S. Chen**, 2015: Subsidence warming as an underappreciated ingredient in tropical cyclogenesis. Part I: Aircraft observations, *J. Atmos. Sci.*, **72**, 4237-4260.

Coelho E., P. Hogan, G. Jacobs, P. Thoppil, H. Huntley, B. Haus, B. Lipphardt, Jr., A. D. Kirwan, Jr., E. H. Ryan, J. Olascoaga, G. Novelli, F. Beron-Vera, A. C. Haza, A. C. Poje, A. Griffa, T.M. Özgökmen, D. Bogucki, **S. S. Chen**, et al., 2015: Ocean current estimation using a multi-model ensemble Kalman filter during the Grand Lagrangian Deployment (GLAD) experiment. *Ocean Modelling*, **87**, 86–106.

Chen, S. S., and M. Curcic, 2016: Coupled Modeling and Observations of Ocean Surface Waves in Hurricane Ike (2008) and Superstorm Sandy (2012), *Ocean Modeling,* **103**, 161-176. doi:10.1016/j.ocemod.2015.08.005

Curcic, M., **S. S. Chen**, and T. M. Özgökmen, 2016: Hurricane-Induced Ocean Waves and Stokes Drift and their Impacts on Surface Transport and Dispersion in the Gulf of Mexico, *Geophys. Res. Lett*., **43**(6), 2773-2781, doi:10.1002/2015GL067619.

Judt, F., **S. S. Chen**, and J. Berner, 2016: Predictability of tropical cyclone intensity: Scale-dependent forecast error growth in high-resolution stochastic kinetic-energy backscatter ensembles, *Quat. J. Roy. Meteor. Soc*., **142**, 43-57. DOI:10.1002/qj.2626

Judt, F., and **S. S. Chen**, 2016: Predictability and Dynamics of Rapid Intensification of Tropical Cyclones Deduced from High-Resolution Stochastic Ensembles, *Mon. Wea. Rev*., **144,** 4395–4420. doi: 10.1175/MWR-D-15-0413.1

Judt, F., **S. S. Chen**, and M. Curcic, 2016: Atmospheric forcing of ocean transport in the Gulf of Mexico from seasonal to diurnal scales, *J. Geophy. Res.-Oceans*, **121**, 4416-4433. DOI: 10.1002/2015JC011555.

Kerns, B. W., and **S. S. Chen**, 2016: Large-scale precipitation tracking of the MJO over the Maritime Continent and Indo-Pacific warm pool. *J. Geophys. Res.-Atmospheres*, **121**, 8755–8776. DOI:10.1002/2015JD02466.

Chen, S. S., B. W. Kerns, N. Guy, D. P. Jorgensen, J. Delanoë, N. Viltard, C. Zappa, F. Judt, C.-Y. Lee, and A. Savarin, 2016: Aircraft observations of dry air, ITCZ, convective cloud systems and cold pools in MJO during DYNAMO: *Bull. Amer. Meteor. Soc.,* **97**, 405-423. https://doi.org/10.1175/BAMS-D-13-00196.1

Romero, I. C., T. Özgökmen, S. Snyder, P. Schwing, B. J. O'Malley, F. J. Beron-Vera, M. J. Olascoaga, P. Zhu, E. Ryan, **S. S. Chen**, D. L. Wetzel, D. Hollander and S. A. Murawski, 2016: Tracking the Hercules 265 marine gas well blowout in the Gulf of Mexico, *J. Geophys. Res. – Oceans*, **121**, 706–724, DOI: 10.1002/2015JC011037

Zhu, P., Y. Wang, **S. S. Chen**, M. Curcic, and G. Gao, 2016: Impact of storm-induced cooling of sea surface temperature on large turbulent eddies and vertical turbulent transport in the atmospheric boundary layer of Hurricane Isaac, *J. Geophys. Res. – Oceans*, **121**, 861–876. DOI: 10.1002/2015JC011320

Pullen, J., R Allard, H Seo, A.J. Miller, **S. S. Chen**, L.P. Pezzi, T Smith, P Chu, 2017: Coupled ocean-atmosphere forecasting at short and medium time scales, *The Sea: The science of ocean prediction. J. of Marine Res.* **75** (6), 877-921, doi: https://doi.org/10.1357/002224017823523991

Carlson, D. F., Özgökmen, T., Novelli, G., Guigand, C., Chang, H., Fox-Kemper, J. Mensa, S. Mehta, E. Fredj, H. Huntley, AD Kirwan Jr, M. Berta, Mike Rebozo, M. Curcic, E. Ryan, B. Lund, B. Haus, C. Hunt, **S. S. Chen**, L. Bracken, J. Horstmann, 2018: Surface ocean dispersion observations from the ship-tethered aerostat remote sensing system. *Front. Mar. Sci.* **5**, 479. doi: 10.3389/fmars.2018.00479

D'Asaro, E., A. Y. Shcherbina, J. M. Klymak, J. Molemaker, G. Novelli, C. M. Guigand, A.C. Haza, B. K. Haus, E. H. Ryan, G. A. Jacobs, H.S. Huntley, N.J. M. Laxague, **S. S. Chen**, F. Judt, J. C. McWilliams, R. Barkan, A. D. Kirwan, A. C. Poje and T. M. Özgökmen, 2018: Ocean convergence and the dispersion of flotsam, PNAS. 201718453. https://doi.org/10.1073/pnas.1718453115.

Dietrich, J.C., A. Muhammad, M. Curcic, A. Fathi, C. N. Dawson, **S. S. Chen**, and R. A. Luettich, 2018: Sensitivity of Storm Surge Predictions to Atmospheric Forcing during Hurricane Isaac, *J. of Waterway, Port, Coastal, and Ocean Engineering,* **144**, https://doi.org/10.1061/(ASCE)WW.1943-5460.0000419

Haza, A.C., E D'Asaro, H Chang, **S. S. Chen**, M Curcic, et al., 2018: Drogue-loss Detection for Surface Drifters During the Lagrangian Submesoscale Experiment (LASER), *J. of Atmospheric and Oceanic Tech*, **35**, 705-725, https://doi.org/10.1175/JTECH-D-17-0143.1

Kerns, B. W., and **S. S. Chen**, 2018a: Diurnal Cycle of Precipitation and Cloud Clusters Over the Equatorial MJO and ITCZ Regions of the Indian Ocean, *J. Geophy. Res.-Atmospheres*, **123**, 10,140–10,161. https://doi.org/10.1029/2018JD028589

Kerns, B.W., and **S. S. Chen,** 2018b: Evaluation of Satellite Surface Winds in Relation to Weather Regimes Over the Indian Ocean Using DYNAMO Observations. *J. Geophy. Res-Atmospheres*, **123**, 8561-8580, https://doi.org/10.1029/2018JD028292

Lin, K.-L, S.-C. Yang, and **S. S. Chen**, 2018: Reducing TC position uncertainty in ensemble data assimilation and prediction system: A Case Study of Typhoon Fanapi (2010), *Wea. Forecasting*, **33**, 561-582, https://doi.org/10.1175/WAF-D-17-0152.1

Li, G., M. Curcic, M. Iskandarani, **S. S. Chen**, O.M. Knio, 2019: Uncertainty Propagation in Coupled Atmosphere–Wave–Ocean Prediction System: A Study of Hurricane Earl (2010), *Mon. Wea. Rev.,* **147**, 221-245, https://doi.org/10.1175/MWR-D-17-0371.1

Chen, S. S., M. Curcic, 2019: A Unified Wave Interface for Fully Coupled Atmosphere-Wave-Ocean Models and Application in Tropical Cyclone Prediction, *Journal of Advances in Modeling Earth Systems,* in revision.