A Systems Perspective on the Environmental Prediction Enterprise

Duane E. Waliser

ABSTRACT: Our success with environmental prediction could be considered among humankind's most remarkable developments over the past 50 years. It protects lives and property, and helps us advance the well-being of society. Vast changes have occurred recently to the complexity and scope of our weather enterprise. Given its importance to society, there is reason to optimize our approaches for advancing its scope and capabilities. This essay highlights three points that may help facilitate this optimization, with an overarching suggestion to more overtly embrace a systems (engineering) approach. 1) Continued emphasis should be placed on advancing Earth system science as the foundational knowledge that advances weather prediction as well as the more holistic scope of environmental prediction (EP). 2) The complexity and coupling of the social, programmatic, observation, modeling, analytic, and interdisciplinary landscapes within the EP enterprise suggest adding a system engineering perspective/approach to further optimize outcomes and limit vulnerabilities. 3) The consideration of the enterprise as a data to information flow problem highlights opportunities and focal points to leverage that could help to advance the societal benefits derived from the EP enterprise. A generalized, highly simplified systems perspective on the advancement of Earth science and environmental prediction is offered by framing a simple equation involving the synthesis of observations, models, and programmatics that in turn yield science and applications benefits. Simplifications and derivatives of this equation are used to distill challenges and opportunities for further advancing enterprise benefits and to motivate considerations of scope and priorities related to our community's decadal survey(s).

<https://doi.org/10.1175/BAMS-D-19-0178.1>

Corresponding author: Duane E. Waliser, duane.waliser@jpl.nasa.gov

Supplemental material: <https://doi.org/10.1175/BAMS-D-19-0178.2>

In final form 20 June 2020

©2020 American Meteorological Society

For information regarding reuse of this content and general copyright information, consult the [AMS Copyright Policy](#).

AFFILIATION: Waliser—Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

In a previous BAMS essay, Thorpe and Rogers (2018, hereafter TR18) point to the many ways the global weather enterprise (GWE) has changed substantially in just the last decade or two. Drivers of this change include new and more integrated science, new technology, increasing societal needs for weather and hazard information, the added complexities of a changing climate, and the growth of the private sector. They suggested ways forward that included developing a shared vision for the public, private, and academic sectors; increased dialogue and cooperation internationally and among the different resource sectors; improving regulatory frameworks for data; and developing new business models for the GWE.

Taken together, the scope of the above considerations is on par with the motivation and challenges surrounding a proposed “weather enterprise” study being considered by the National Academy of Sciences’ (NAS) Board on Atmospheric Science and Climate (BASC). For the last two years, BASC has been exploring the need and virtues of a milestone study on the weather enterprise that has the expansiveness on the order of the recurring NAS Decadal Survey for Earth Science and Applications from Space (ESAS; National Research Council 2007; NASEM 2018). A number of community discussions involving relevant agency and community representation have been held, such as during the 2018 AMS Summer Community Meeting¹ and the annual meeting of the AMS in 2019,² to examine the scope and needs of such a study, which has also been recommended in Congressional testimony.³

The perspective and suggestions presented in this essay stem from the considerations and discussions mentioned above, as well from internal discussions at the Jet Propulsion Laboratory (JPL) regarding the applications of system engineering to complex Earth system science and Earth system application challenges. For reference, *system engineering* is an interdisciplinary element of the fields of engineering and engineering management that focuses on how to understand, design, and manage complex systems (e.g., Chestnut 1967; Sage 1992; Buede and Miller 2016). It utilizes systems thinking/theory (Von Bertalanffy 1969; Checkland 1999) to *understand* a system of interworking components and/or *construct* a system of components that synergistically work together to perform a useful function. It deals with requirements development, logistics, team coordination, testing and evaluation, costs, reliability, work processes, optimization, risk management, and often the overlaps between technical and human systems. Evidence for the beneficial impacts of formally embracing systems engineering approaches can be found across a number of disciplines, particularly those composed of so-called “systems of systems” (SoS), including communication and transportation systems, complex civil or defense constructs and their operation, modern health care systems, combined space-based and ground data support systems, etc. (e.g., Revelle et al. 2003; National Academy of Engineering and Institute of Medicine 2005; NASA 2007; DoD 2008; Boehm et al. 2008; Honor 2014; MITRE 2014; Proakis and Salehi 2001; Ingber et al. 2017). The following three sections, each relevant to the weather enterprise, highlight areas where the tangible application of the above sorts of expertise and perspectives could yield benefits in the further improvement of our weather enterprise.

¹ AMS 2018 Summer Community Meeting: Expanding the Weather, Water, and Climate Enterprise’s Global Impact Through Enhanced Collaboration.

² AMS 2019 Meeting Spengler Session: The Future of the U.S. Weather Enterprise, <https://ams.confex.com/ams/2019Annual/meetingapp.cgi/Session/49516>.

³ <https://science.house.gov/hearings/the-future-of-forecasting-building-a-stronger-us-weather-enterprise>

The Earth system and the “weather” enterprise

While the BASC discussion has primarily focused on weather, this term is becoming less accurate over time for describing the scope of the enterprise as a whole, particularly when considering the complexities of the underlying physics of the prediction models and the breadth of the prediction products that are delivered from these systems. The term “weather” is typically defined as the state or condition of the atmosphere (American Meteorological Society 2020), and its prediction is typically associated with atmospheric conditions that impact human

activities (e.g., wind, temperature, precipitation). Part of this comes from the legacy of model and forecast development, which was initiated with the atmosphere. This initiation and its subsequent evolution is illustrated in Fig. 1. In this depiction, the atmosphere is only one part of the Earth system, albeit a foundational one,⁴ that needs to be represented to deliver weather predictions. Representation of the conditions of, and interactions with, the land surface, ocean, sea ice, etc., are all also crucial to improving accuracy and extending lead times (e.g., Randall et al. 2019; Benjamin et al. 2019; Shapiro et al. 2010; Nobre et al. 2010).

Along with the underlying models including more Earth science components to yield more process fidelity, the prediction suites available today have also grown dramatically in the last two decades both in terms of lead time and additional predictands of the Earth system beyond just weather (see Fig. ES1 in the online supplement). Today, operational predictions include lead times from hours (i.e., short term), days to week(s) (i.e., medium range), and weeks to months [subseasonal to seasonal (S2S)]. These longer lead capabilities stem from the greater Earth system coupling being represented by the models, allowing more sources of predictability to be leveraged (e.g., NASEM 2016). As mentioned above, the growing breadth of Earth system interactions being represented allows more aspects of the environment to be included in the forecast guidance and products (e.g., marine and sea ice conditions, water availability and its extremes, air and water quality). From this systems perspective, it is easy to see how weather, as traditionally interpreted, no longer encompasses the totality of the prediction enterprise, and why a number of operational prediction centers have already exchanged

⁴ The atmospheric component appears as the foundational, initial layer due to the pressing societal needs for “weather” information across sectors, because the atmospheric evolution is described by relatively tractable physical laws and equations, and atmospheric observations have been relatively more feasible to provide.

Fig. 1. A schematic representing the (co)development path for climate/Earth system projection and weather/environmental prediction models. Today’s “weather” prediction models are more aptly termed “environmental” prediction models as their scope involves significant more than what is traditionally termed weather. The maturing coupled model components of today’s Earth system models used for climate projections represent one of the development pathways toward more complex and capable environmental prediction models. Given this, EP models will continue to evolve toward more and more component and system complexity.

the word “weather” for “environment” [e.g., National Centers for Environmental Prediction (NCEP), Environment and Climate Change Canada (ECCC)]. Similarly, the WMO refers to what were previously referenced as weather forecast centers as Global Producing Centers (GPCs), recognizing their scope extends well beyond weather. In recognition of this, this essay uses “environmental prediction” (EP) and the “EP enterprise” in some of the forward-leaning considerations of the weather enterprise.

The point of emphasis here is that as the weather/EP enterprise continues to accept and/or demand additional Earth system components and complexity, their judicious incorporation—taking into account trades in requirements, costs, development, expertise, reliability, etc.—suggests that overt considerations from a more formal systems perspective (e.g., Schlager 1956; Sage 1992; SEBoK 2018) may be helpful. In some cases, this may result in a further recognition that the breadth and depth of expertise and resources needed for further advances in the Earth system aspects of our “weather” models may extend beyond the reach of a given operational weather prediction centers/agencies to make the needed enterprise-wide advancements, at least in a timely and efficient manner. It may be that a more judicious examination points to more overt and robust interagency, interdisciplinary, and other collaborative development efforts (e.g., UFS,⁵ UKMO UM⁶), along with effective public–private partnerships where viable (e.g., Shapiro et al. 2010; Earth System Prediction Capability activity⁷). Given the complexities that such considerations present (discussed further below), such pursuits could warrant a more explicit systems (engineering) perspective, for both the (Earth system) science and programmatic elements and their interplay. It is worth noting the significant number and breadth of organizational and research activities, a number of which implicitly drive at an Earth system view and a systematic programmatic approach (e.g., WMO and its recent reorganization, WCRP Grand Challenges, Future Earth, U.S. Global Change Research Program, Committee on Earth Observation Satellites), that has aided in the continued increase in benefits derived from the broader EP enterprise. While such efforts are valuable, it is possible that when augmented by an explicit and holistic systems of systems engineering consideration, additional benefit and alignment may be possible.

⁵ <https://ufscommunity.org>

⁶ <https://www.metoffice.gov.uk/research/approach/modelling-systems/unified-model>

⁷ <https://earthsystemprediction.gov>

Enterprise complexity and the “implementing centers” for prediction

The goal for a more thorough and strategic collaborative dialogue over the EP enterprise (highlighted in the introduction) stems from a combination of the rapid pace of change in the relevant observation and modeling realms (e.g., Fig. 1 and Figs. ES1 and ES2; TR18), the societal needs and demands for environmental predictions at all scales, and the growing complexities of the civil and commercial programmatic landscapes these operate. Table 1 is a simple attempt to capture some of this complexity, noting the key tasks (columns) and partners (rows) in the EP enterprise. This rudimentary system view of the EP enterprise facilitates a number of observations. The first is that EP is far from a simple enterprise, with a necessity for an array of core functions, involving requirements definitions and evolution, observation development and management, model and data assimilation development and improvement, forecast operations and analytics, product development and dissemination, reanalysis, as well as basic research. The second is the number of partners (i.e., rows), highlighting a complex, interwoven and collaborative landscape, involving 1) international and national elements, 2) a variety of public sector intersections, 3) a number of commercial interests, contributions and opportunities, and 4) even roles for local governments and citizens. *It is clear from this systems perspective that no one agency, institute, or company (e.g., NCEP, ECMWF, Weather.com) owns or operates the EP enterprise.* Evident from this table representation, the weather enterprise should be considered a complex system of interacting components, one that might be more

Table 1. A matrix view of the partners and tasks making up the Earth system/EP enterprise. Note that nearly all tasks have a number of players that contribute to the given task, except for “Operational Environmental Predictions,” which is mainly carried out by the GPCs (see Fig. E51). The X’s represent an indicator of the relative contribution of the given partners to the given task.

Partners	Tasks						
	Identifying and quantifying requirements	Observations—technology development, implementation, and acquisition	Model and data assimilation, development, and improvement	Operational environmental predictions	Product development, verification, and dissemination	Reanalysis development and production	Basic and applied science research: Physical and social science
Global EP Centers (NCEP, ECMWF, ECCO, JMA, UKMO, etc.)	X		XXX	XXX	XX	XXX	X
National Meteorological and Hydrological Services (NMHSs)	XXX	XXX	XXX	X	XXX	XX	XX
Earth observation agencies (e.g., NASA, ESA, NESDIS, ISRO, JAXA, EUMETSAT)	XX	XXX	XX		XX	X	XX
International—WMO, IOC, WHO, WFP, etc.	XXX				X		X
Other federal govt. agencies and labs (e.g., DoD, NSF, DOE in the U.S.)	XX	XX	XXX		XX		XXX
State and Local govt. and resource management agencies	XXX	X			XX		X
Universities		X	XX		X		XXX
Commercial sector—Technology and observations	X	XX					
Commercial sector—Value-added products, decision support	XX		X		XXX		
News/media—TV/radio, web outlets, phone apps	X				XX		
Citizens and communities	XX	X					

easily enhanced and optimized in terms of its function if we applied a systems engineering approach more formally and overtly.

A third notable observation that can be made from the table is in the distinction between the operational prediction task (column 5) and the others. For most tasks (i.e., columns), there are important contributions from many of the partners (rows). For example, whether it is the development and management of observations upstream of the actual prediction analytics (column 3), or the development and dissemination of products after the

predictions are produced (column 6), a whole cast of players is involved in these tasks. This speaks to the need for optimizing the coordination among these players to produce the most impactful results from these enterprise functions, a core desire expressed in TR18 and in the motivation for the BASC-proposed “weather enterprise” study. In contrast, the column representing the operational predictions task (column 5) has very few contributors, namely, just the major environmental prediction centers, or the GPCs (see Fig. ES1), and, to a lesser extent, the National Meteorological and Hydrological Services (NMHSs) offices. The GPCs represent a fundamental backbone to the whole enterprise, the means by which the observations (see Fig. ES2) are combined with global, and in some cases regional, models (e.g., data assimilation) to produce physically based, quantitative forecast guidance. This core prediction information then undergoes value-added processing, including various statistical postprocessing steps and consumer-friendly product generation, and it is used to drive other component models of the environment (e.g., hydrology, air quality). Thus, in contrast to much of the EP enterprise, for which many partners combine to accomplish a given task (i.e., column), one of, if not the most, fundamental EP tasks is performed by only one segment of the EP enterprise. *From this systems perspective, a number of agencies and institutes, namely, the GPCs (NCEP, ECMWF, UKMO, ECCO, etc.), stand apart in terms of their importance to the success of the EP enterprise.*

System engineering, data flow, and analytic pipelines

To undertake and yield value from a systems perspective, one has to stand fully apart from the system under consideration and view it in its totality. Even a limited attempt at taking such a perspective as done above illustrates the unique and core role of the GPCs (i.e., the “Implementing Centers” for EP) within an otherwise highly complex enterprise with many multipartner tasks. To emphasize this system perspective even further, and highlight it as a highly impactful data/information flow, Fig. 2 shows a (very) high-level data science perspective of EP. The left side emphasizes the enormous amounts of data and hints at the data science challenges associated with the Earth observations used to support the EP enterprise (see Fig. ES2). The European Space Agency’s Copernicus program⁸ is an illustrative example and activity that cultivates and leverages this left observation side, particularly by way of satellite information, for decision support across a number of dimensions. The right side emphasizes the enormous societal benefits associated with EP. Note the left and right sides are measured in terms of *billions* (e.g., data points per day, people impacted, dollars). The center column emphasizes that all that data, for all those benefits, goes through just a

⁸ https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus

Fig. 2. A schematic of the EP enterprise, with a data science and data flow perspective in mind. A key message is the funneling and utilization on the order of billions [O(Billions)] or more observations per day (see Fig. ES2) into an O(10) handful of data assimilation–model prediction–analytic pipelines (i.e., EP centers; aka GPCs; see Fig. ES1), whose predictions/products are used to support O(Billions) of decisions that influence O(Billions) of dollars and aid O(Billions) of people.

handful of model and analytic (e.g., data assimilation) pipelines—namely, the EP centers (i.e., NCEP, ECMWF, UKMO, ECCC, etc.), aka the GPCs. Again, the prediction products from these few centers makes up a vast majority of core EP guidance at time scales from 0 days to 1 year (and soon to a decade or more as our quasi-operational decadal prediction systems become operational at the GPCs⁹) to fully yield the benefits on the right side (albeit leveraging considerable multipartner value-added processing; see Table 1, column 6).

With this data flow configuration in mind, in concert with the value of EPs to society, the following questions should be considered:

- 1) Given the tremendous impacts, is our current framework (e.g., Table 1) efficient and optimized? Does it have vulnerabilities? Where are the most sensitive leverage points for increasing EP guidance?
- 2) Can we see and treat this data flow narrowing or focal point (Fig. 2) as an opportunity for identifying priorities for effort/resources, optimizing advances, and limiting vulnerabilities?

Robustly answering these questions for such a vital and complex system of systems may warrant the application of system engineering considerations. Given the close legacy-association of weather forecasting with the GPCs (i.e., EP centers), it is tempting to presume that the corresponding sponsoring weather agencies/institutions have singular responsibility and capability to identify the shortcomings and gaps in the overall enterprise, and then identify and implement the needed developments and optimizations. To say the least, the breadth of the enterprise and its rapid pace of change make this a very challenging task. Figure 2, along with the categorization of the EP enterprise into partners and tasks in Table 1, suggests that this enterprise is substantially larger in scope and complexity than the EP centers may have expertise and resources to manage, let alone stand back and judiciously design, improve, and optimize the overall system—even with the significant support and guidance from WMO and other such bodies alluded to above. It is from this perspective, combined with the incalculable value of the enterprise, that BASC is proposing to carry out a significant study on at least a weather subset of the EP enterprise. The recommendation from the points raised thus far suggest that adding a formal systems perspective or element to that proposed study may have some as yet untapped value.

A simplified systems framework and Earth system applications

A generalized, yet highly simplified (for illustrative and discussion purposes), systems framework for the above sorts of considerations can be constructed as follows. Let

$$f(\sum O, \sum M, P) = B = S + A, \quad (1)$$

where O is the satellite or other observing system; M is the model that provides for interpolation, extrapolation, and/or prediction; P is programmatics, interagency collaborations, and partnership elements; S is making science advances (e.g., better understanding of Earth system processes); A is applications for societal benefits; B is science and application benefits = advancing knowledge + safeguarding lives/property; and f is the process for translating O , M , and P into B , which involves data assimilation, analytics and data science, uncertainty quantification, high-performance computing (HPC) resources, product development, and dissemination.

⁹ See WCRP activities: 1) Decadal Climate Prediction Project (www.wcrp-climate.org/dcp-overview), 2) Near-Term Climate Prediction Grand Challenge (www.wcrp-climate.org/gc-near-term-climate-prediction), plans for the Global Framework for Climate Services (fcs.wmo.int), and the information posted by the WMO's Lead Centre for Annual-to-Decadal Climate Prediction (hadleyserver.metoffice.gov.uk/wmolc/).

Note that a number of items encapsulated in f could be broken out as specific arguments in the equation to make their importance or role more explicit (e.g., data assimilation; HPC resources); however, the intent and scope of the equation's use in this essay warrants keeping it simple for illustrative purposes. In addition, while the science and applications on the right-hand side are the yield from the system represented on the left-hand side, science and application outcomes eventually get incorporated into the left-hand side. For example, present science knowledge can be said to be embedded into the left-hand side via its incorporation into state-of-the-art models that appear on the left-hand side. Thus, such an equation could be argued to be nonlinear and/or time dependent, but that level of preciseness is not warranted for this essay's purposes. Note that this highly simplified systems view could be viewed as a "value chain" (Porter 1985) in equation form.

A general application of Eq. (1) could be toward the Earth science and application enterprise as a whole, i.e., an even broader consideration than the weather enterprise, or it could be considered relative to a given agency's contribution/role within a larger Earth science landscape, or to a satellite mission (e.g., GRACE gravity, GPM precipitation, and Aeolus wind measurements), or other more programmatic research activity [e.g., a given agency's research portfolio/objectives, Coupled Model Intercomparison Project (CMIP)].

Our community's collective efforts at trying to yield more Earth science and applications benefits amount to augmenting our current system of systems (e.g., Figs. 1, 2 and Figs. ES1, ES2) or modifying one of its/their components (e.g., adding a new satellite mission, delivering an improved model, advancing our data assimilation capabilities, developing a new research program or funding approach). In this simple framework, such changes would be represented via a simplified differential form of Eq. (1):

$$\Delta f(\Sigma O, \Sigma M, P, \Delta O, \Delta M, \Delta P) = \Delta B = \Delta \text{Science} + \Delta \text{Applications}. \quad (2)$$

The left-hand side represents new research, development and/or program directions, and activities. The right-hand side represents the new benefits of advancing science knowledge and application capabilities that result from the left side enhancements. The equation could be applied retrospectively in a diagnostic sense or applied prospectively in a strategic sense.

Using a retrospective consideration of Eq. (1), one could illustrate various aspects of the evolution of Earth science and applications. For example, consider the evolution of our Earth observing satellites. During the so-called Earth-observing satellite (EOS) era, that include for example the launches of the *Aura*, *Terra*, and *Aqua* platforms, Eq. (2) would reduce to

$$\Delta f(P, \Delta O) \cong \Delta \text{Science},$$

with ΔO representing the new satellite observations, P being programatics associated with one or more space agency's science teams, and $\Delta \text{Science}$ representing the new science knowledge. In this early EOS period, when the observations tended to be first of a kind, complex and comprehensive models were less of the overall construct to obtaining science outcomes than they are now, and thus why M and ΔM are not highlighted as substantive pieces this example.

Moving to missions that arose from the 2007 ESAS Decadal Survey (National Research Council 2007), for example, where additional emphasis was placed on applications, such as SMAP and its development and use of the so-called "early adopter" program, would mean including two additional terms, namely, ΔP and $\Delta \text{Applications}$:

$$\Delta f(P, \Delta O, \Delta P) \cong \Delta \text{Science} + \Delta \text{Applications},$$

where ΔO represents the SMAP satellite and ΔP represents the development of a new approach to engaging stakeholders early to better realize application benefits, $\Delta Applications$, in addition to anticipated science returns.

For other research and modeling activities such as CMIP for example, where there is less focus on observations, or at least new observations, Eq. (2) would reduce to

$$\Delta f\left(\sum M, P, \Delta P\right) = \Delta Science + \Delta Applications,$$

with ΔP representing the needed development for collaborative programmatic and technical structures for the community (e.g., via WCRP and others), and with early versions of CMIP having $\Delta Science \gg \Delta Applications$, and more recent versions also having considerable benefit to applications ($\Delta Science \approx \Delta Applications$) through the impacts portion of the IPCC (e.g., Working Groups II and III).

Considering the equation from a prospective, strategic, and systems point of view provides a means to help frame and guide new developments (e.g., for the weather enterprise). For example, in one form or another, our broader community is often asking, what are the smallest Δ values on the left-hand side of Eq. (2) (in terms of effort and funding) that result in the largest impacts on the right, with ultimate interest typically in enhancing Applications. The discussion above regarding the weather enterprise and the major role of the GPCs, as illustrated in Table 1 and Fig. 2, suggests that a large $\Delta Applications$ would occur in conjunction with improvements to the models and analytic pipelines specifically associated with the GPCs; put more quantitatively, $\Delta Applications/\Delta M$ is largest when M represents one of the forecast models at the GPCs (e.g., ECMWF, NCEP, UKMO, JMA). This result might similarly be arrived at when considering Eq. (2), and asking for what M and associated ΔM would $\Delta Applications$ be largest? For the United States, for example, that M is quite likely the NCEP forecast model, with any finite ΔM having tangible and large impacts.¹⁰ Note that in this simplified example the ΔM could represent improvements in process representation, ensemble generation, computational efficiency, etc., or data assimilation improvements, depending on whether one chose to bookkeep data assimilation under O , M , $f(\cdot)$, or explicitly as a separate term within the left-hand side of Eq. (1).

¹⁰ This consideration dovetails well with the recent move by NCEP to provide a community version of their forecast model/system to increase the community's opportunity and means to help improve the model; a coordinated interagency support (i.e., a ΔP) could help realize the greatest ΔM and thus $\Delta Applications$.

Concluding remarks

The “weather enterprise” is growing in complexity and its importance to society, making advances to it more challenging as well as more critical for further safeguarding life and property (Bauer et al. 2015). The perspectives offered in this essay are to illustrate in relatively simple terms that complexity, whether scientific (e.g., Earth system science; Fig. 1), technical, logistical, and/or programmatic (e.g., Table 1), can be broken down and treated with some level of formality, yielding insights on approaches, risks, opportunities, trades, optimizations, etc. The working expertise of how to objectively treat, diagnose, develop, and/or operate such complex systems is, at least in part, the purview of systems engineering. The complexity and maturity of the “system of systems” (SoS) that make up our weather enterprise, and that we leverage for massive societal benefits, likely warrant a more explicit embracing of system engineering considerations and expertise. While this could take many forms over time and include application to a number of model, observation, and data subsystems relevant to the weather enterprise, at least one near-term consideration for an overarching application would be to engage systems expertise [e.g., National Academy of Engineers (NAE)] if and when an NAS study on the weather enterprise is undertaken.

Another perspective comes to mind when considering an NAS study to address the weather enterprise put in the context of Eq. (2). For this, it is instructive to first do so for the NAS Decadal Survey for Earth Science and Applications from Space (National Research Council 2007; NASEM 2018)—a study of comparable scope and impact. These milestone ESAS studies put emphasis on ΔO , particularly from space, and with $\Delta \text{Science} > \Delta \text{Applications}$, meaning the former is the driver for the overall study and its recommendations but with attention to the applications enabled from new observations. Some attention is given to ΔP [e.g., establishment of the Earth Ventures program from National Research Council (2007)], but (as expected) with little attention placed on model improvements ΔM . To reiterate, to first order, the ESAS studies are mostly about ΔO yielding $\Delta \text{Science}$, with the hope/expectation of yielding $\Delta \text{Applications}$, but with the overall scope of challenges to arrive at those application benefits not addressed. Interest in a milestone study for the weather enterprise is driving at a study primarily focused on $\Delta \text{Applications}$, originating from the recognition that “weather” represents a foundational component of these application benefits. But as discussed above, weather is just one element, albeit a critical one, of a rich interdisciplinary landscape of EP. How and where will this broader scope of applications be treated? Adding the applications scope, including and beyond weather, to the current ESAS study is likely out of scope for more than one reason. A consideration offered here is to view the weather enterprise study—especially if posed in a more generalized form—as a study somewhat analogous to ESAS but with the dominant focus being on improving Applications benefits from Earth science and technology. In particular, the goal of such a milestone study would be to identify and prioritize the ΔP , ΔM , and ΔO , and associated framework enhancements (Δf) on the left-hand side of Eq. (1) to provide the largest $\Delta \text{Applications}$. Given the increasing complexities of the EP landscape along with its innumerable societal impacts, as highlighted in this essay and as discussed more thoroughly in TR18, emphasizes the ever-growing need for such a concerted and focused milestone study, likely to reoccur at a pace similar to the ESAS decadal surveys.

Acknowledgments. The author graciously acknowledges the reviews, guidance, and suggestions from Xubin Zeng, Alan Thorpe and Tony Busalacchi, Riley Duren and Daniel Limonadi, and three anonymous reviewers. The author’s contribution towards this essay was carried out on behalf of the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

- American Meteorological Society, 2020: Weather. Glossary of Meteorology, <http://glossary.ametsoc.org/wiki/Weather>.
- Bauer, P., A. Thorpe, and G. Brunet, 2015: The quiet revolution of numerical weather prediction. *Nature*, **525**, 47–55, <https://doi.org/10.1038/nature14956>.
- Benjamin, S. G., J. M. Brown, G. Brunet, P. Lynch, K. Saito, and T. W. Schlatter, 2019: 100 years of progress in forecasting and NWP applications. *A Century of Progress in Atmospheric and Related Sciences: Celebrating the American Meteorological Society Centennial*, Meteor. Monogr., No. 59, Amer. Meteor. Soc., <https://doi.org/10.1175/AMSMONOGRAPHS-D-18-0020.1>.
- Boehm, B., R. Valerdi, and E. C. Honour, 2008: The ROI of systems engineering: Some quantitative results for software-intensive systems. *Syst. Eng.*, **11**, 221–234, <https://doi.org/10.1002/sys.20096>.
- Buede, D. M., and W. D. Miller, 2016: *The Engineering Design of Systems: Models and Methods*. 3rd ed. John Wiley and Sons, 592 pp.
- Checkland, P., 1999: *Systems Thinking, Systems Practice: Includes a 30-Year Retrospective*. Wiley, 330 pp.
- Chestnut, H., 1967: *Systems Engineering Methods*. Wiley, 404 pp.
- DoD, 2008: Systems Engineering Guide for Systems of Systems, version 1.0. Office of the Deputy Under Secretary of Defense for Acquisition and Technology, Systems and Software Engineering, 135 pp.
- Honor, E. C., 2014: Understanding the value of systems engineering. *INCOSE Int. Symp.*, **14**, 1207–1222, <https://doi.org/10.1002/j.2334-5837.2004.tb00567.x>.
- Ingber, G. L., W. E. Bunting, D. M. Laredo, and M. K. Tun, 2017: Guide for creating useful architectures, version 1.1. Homeland Security Systems Engineering and Development Institute, 45 pp., www.mitre.org/sites/default/files/publications/pr-17-4589-guide-for-creating-useful-solution-architectures.pdf.
- MITRE, 2014: *The MITRE Systems Engineering Guide*. MITRE Corporation, 710 pp., www.mitre.org/sites/default/files/publications/se-guide-book-interactive.pdf.
- NASA, 2007: NASA Systems Engineering Handbook. NASA/SP-2016-6105 Rev 2, 343 pp., <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170001761.pdf>.
- NASEM, 2016: *Next Generation Earth System Prediction: Strategies for Subseasonal to Seasonal Forecasts*. National Academies Press, 350 pp., <https://doi.org/10.17226/21873>.
- , 2018: *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. National Academies Press, 716 pp., <https://doi.org/10.17226/24938>.
- National Academy of Engineering and Institute of Medicine, 2005: *Building a Better Delivery System: A New Engineering/Health Care Partnership*. P. Reid et al., Eds., National Academies Press, 276 pp., <https://doi.org/10.17226/11378>.
- National Research Council, 2007: *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. National Academies Press, 454 pp., <https://doi.org/10.17226/11820>.
- Nobre, C., and Coauthors, 2010: Addressing the complexity of the Earth system. *Bull. Amer. Meteor. Soc.*, **91**, 1389–1396, <https://doi.org/10.1175/2010BAMS3012.1>.
- Porter, M. E., 1985: *Competitive Advantage: Creating and Sustaining Superior Performance*. Simon and Schuster, 557 pp.
- Proakis, J. G., and M. Salehi, 2001: *Communications Systems Engineering*. 2nd ed. Pearson, 816 pp.
- Randall, D. A., and Coauthors, 2019: 100 years of Earth system model development. *A Century of Progress in Atmospheric and Related Sciences: Celebrating the American Meteorological Society Centennial*, Meteor. Monogr., No. 59, Amer. Meteor. Soc., <https://doi.org/10.1175/AMSMONOGRAPHS-D-18-0018.1>.
- Revelle, C. S., E. Whitlatch, and J. Wright, 2003: *Civil and Environmental System Engineering*. 2nd ed. Pearson, 552 pp.
- Sage, A. P., 1992: *Systems Engineering*. Wiley Series in Systems Engineering and Management, Vol. 6, Wiley-Interscience, 624 pp.
- Schlager, J., 1956: Systems engineering: Key to modern development. *IRI Trans. Eng. Manage.*, **EM-3**, 64–66, <https://doi.org/10.1109/IRET-EM.1956.5007383>.
- SEBoK, 2018: Guide to the Systems Engineering Body of Knowledge. www.sebokwiki.org.
- Shapiro, M., and Coauthors, 2010: An Earth-system prediction initiative for the twenty-first century. *Bull. Amer. Meteor. Soc.*, **91**, 1377–1388, <https://doi.org/10.1175/2010BAMS2944.1>.
- Thorpe, A., and D. Rogers, 2018: The future of the global weather enterprise: Opportunities and risks. *Bull. Amer. Meteor. Soc.*, **99**, 2003–2008, <https://doi.org/10.1175/BAMS-D-17-0194.1>.
- Von Bertalanffy, L., 1969: *General System Theory: Foundations, Development, Applications*. Rev. Ed. George Braziller, Inc., 296 pp.