US THORPEX Science Plan

Prepared by the US THORPEX Science Steering Committee[1]
for the
US THORPEX Executive Committee

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1) Introduction

US THORPEX will strive to identify and remove barriers to higher quality probabilistic forecasts and effective utilization of such forecasts for high-impact weather over North America. US THORPEX research will focus on the intersections between three research thrusts: (1) processes and phenomena research, (2) the science of prediction, and (3) socio-economic research and applications.[2] This approach allows for the identification of weather phenomena and forecasts that have the most important societal, economic and environmental consequences (leading to high-impact forecasts), thereby providing focus for efforts to improve our understanding of associated upstream atmospheric processes. By identifying the sources of forecast uncertainty and limited societal utilization of forecast information for these high impact events, targeted research and improvements (perhaps adaptive and interactive) can be made to the observing system, data assimilation techniques, numerical models, ensemble techniques, and socio-economic application practices. These advances are expected to lead to improvements in forecast quality, improvements in understanding of the atmospheric system, as well as improvements in society's utilization of weather forecasts and strategies to mitigate weather-related natural disasters.

A cornerstone of US THORPEX efforts is the collaboration of scientists across all of the communities engaged. It is envisaged that work across disciplinary boundaries (e.g. collaborations between economists and data assimilation scientists) and across scientists with different research drivers (e.g. collaborations between academia and operational forecasting centers) will be particularly facilitated by the THORPEX framework through a heightening of the profile of these collaborations and a concerted, coordinated effort by the relevant funding agencies. These collaborations will lead to accelerated advances in understanding and applications as well as new scientific directions.

Improved understanding of atmospheric phenomena is a central component of US THORPEX. However, given the complex web of interactions across atmospheric scales and between atmospheric processes, improved understanding of specific phenomena may be insufficient to improve forecasts. US THORPEX will therefore concentrate on those atmospheric phenomena for which forecasts are particularly poor or whose representation in the forecast model is especially important, as determined both through scientific verification and user-based (societal impact measures) verification.

While this plan focuses on the scientific issues, it is recognized that the full impact of THORPEX science research will not materialize unless the results of THORPEX research can be successfully transitioned to the operational arena. Thus it is essential that

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[2] This plan draws heavily from the science of prediction whitepaper entitled "THORPEX Predictability Research and the National Science Foundation Research Community <http://www.ucar.edu/na-thorpex/documents/THORPEX_community_white_paper_Jun30.doc> with 28 authors, the North American THORPEX Societal and Economic Research and Applications (NAT SERA) Workshop held August 14th – 16th, 2006 in Boulder, Colorado with 40 participants <http://www.sip.ucar.edu/thorpex/agenda.jsp >, and the Tropical Convection & The Weather Climate Interface Retreat held July 10th – 14th, 2006 in Boulder, Colorado with 41 participants < http://www.tiimes.ucar.edu/events/wc-retreat06.htm>.

the academic community should work closely with the operational community to foster quick transition of THORPEX science results to operations.

The plan is structured as follows. The importance of US THORPEX science goals is motivated in section 2 by highlighting some of the societal implications of high-impact weather. The three research thrusts central to US THORPEX are related to the four sub-programs of the international THORPEX efforts, and the interconnectedness of the three research thrusts is highlighted. Sections 3 through 5 provide US THORPEX science goals in the context of the individual research thrusts. The interconnectedness of these science goals are made clear in section 8 where examples of short-term, medium-term, and long-term efforts are discussed after attempts are made in section 6 to identify US THORPEX leveraging opportunities by presenting numerous international THORPEX efforts.

2) Motivation

Improving the skill and utility of forecasts of high-impact weather is one of the great scientific and societal challenges of the 21st century. US THORPEX efforts respond to this challenge. Despite notable increases in numerical forecast skill over the last 25 years, for greater societal benefits there is a need to shift to a more probabilistic, ensemble-based approach to forecasting. Such a change introduces new challenges while at the same time introducing new potential benefits, especially in the areas of high-impact weather forecasts, building understanding in both the physical processes that limit our ability to forecast high-impact weather, and in the use of weather forecast information.

High-impact weather events, and high-impact weather forecasts, are defined by their effect on society, the economy and the environment. Advances in our ability to forecast the likelihood of high-impact weather, and advances in our understanding of forecasts that have high-impact, will provide important, new support to decision makers and planners. While often associated with cyclones of extratropical and tropical origin that contain significant embedded mesoscale weather (leading to localized flooding by convective and orographic precipitation, blizzard snows, dust-storms, destructive surface winds, coastal erosion etc. – see Table 1), high-impact weather events also encompass less violent meteorological phenomena such as trace amounts of snow, heat waves, fog, or the location of the rain/snow line. A high-impact forecast can be distinct from the actual occurrence of an event. Meteorological conditions affecting air quality (smog), periods of anomalous high or low temperature (heat waves or cold spells), and drought are all of societal importance. Thus, a forecast of the end of a drought – or a missed forecast of heavy fog or snowfall during a weekday commute – can have very high societal impacts, even though the individual events may be otherwise unremarkable. For these reasons, both high impact weather and high impact forecasts are included in the US THORPEX strategy.

The THORPEX International Science Plan[3] (TISP) and the THORPEX International Research Implementation Plan (TIP)[4] highlight four research sub-programs: i)

[3] http://www.wmo.ch/thorpex/pdf/CD_ROM_international_science_plan_v3.pdf

Predictability and Dynamical Process Research, ii) Observing Systems Research, iii) Data Assimilation and Observing Strategies Research, and iv) Societal and Economic Applications Research. Each of the research questions outlined in the current document can be categorized under these sub-programs, but the current document utilizes a different form of organization. In the US, three distinct research communities have self-organized to respond to the THORPEX challenge and produce whitepapers that outline important research directions: i) improved understanding of atmospheric processes and phenomena[5], ii) advances in the science of prediction[6], and iii) socio-economic research and applications[7]. US THORPEX science is driven by the response of the US research community to the challenges of the societal needs for improved high-impact weather forecasting, and the research questions raised in the three community whitepapers – in conjunction with the NOAA THORPEX Science and Implementation Plan[8] – form the basis of the US science efforts and prioritizations described in this document. The large degree of intersection between the US THORPEX goals and the overarching themes of the TISP reflect the importance and timeliness of these research themes across nations.

Condition	Annual average*	Maximum events	Date
Tornadoes	82–100	739 322	Mar 1925 Apr 1974
Heavy rains and floods	100–160	2200 732	May 1899 Mar 1913
Hurricanes	38–63	6000 1836	Sep 1900 Sep 1928
Hail	1	22	May 1981
Windstorms	60–115	105	Dec 1972
Lightning	100–156	Unknown	—
Winter storms and cold	130–200	500 270	Dec 1983 Mar 1992
Heat waves	1000	>10 000 > 9500	1980 1901

*ranges reflect data from various sources

Table 1: Number of deaths directly attributed to weather in the United States (source: Changnon et al. 1996).

[4] http://www.wmo.ch/thorpex/pdf/CD_ROM_implementation_plan_v1.pdf
[5] Currently under development.
[6] http://www.ucar.edu/na-thorpex/documents/THORPEX_community_white_paper_Jun30.doc
[7] http://www.ucar.edu/na-thorpex/documents/2005_04_07_Cahir_Thorpex.doc
[8] http://wwwt.emc.ncep.noaa.gov/gmb/ens/THORPEX.html

The interconnectedness of the three research communities is emphasized under the proposed US THORPEX framework. Figure 1 is a schematic that represents the research goals of the three US THORPEX science thrusts. While some science questions can be tackled in isolation, US THORPEX is interested in the intersection of two or even all three; THORPEX research goals should be viewed in this collaborative context. The overlapping regions in Figure 1 are too large for a focused research effort, but prioritization within the US THORPEX Science Plan of specific overlapping components that are likely to be the most successful in the research time horizon of a decade demonstrates the richness of the research questions afforded by the THORPEX framework.

The US THORPEX efforts will span a forecast range of 1-14 days -- recognizing the multi-scale nature of the atmosphere system. In order to improve forecasts in week two it is necessary to improve analyses, 6hr forecasts, 1 day forecasts, etc., because short-lead forecast errors grow to impact long-lead forecast efforts. The time-scales are further intermingled from a process perspective; it is the short-timescale processes embedded in larger-scale flows that can cause or lead to a significant amount of high-impact weather. Also, there is no hard barrier at day 14. Challenges associated with the long-lead weather forecast problem are shared by the 15-90 day intra-seasonal forecast problem. Synergy should exist between THORPEX research and seasonal forecasting research efforts led internationally by the WCRP to improve intra-seasonal forecasting (15-90 days). The linking of space and time scales is implicit throughout this document.

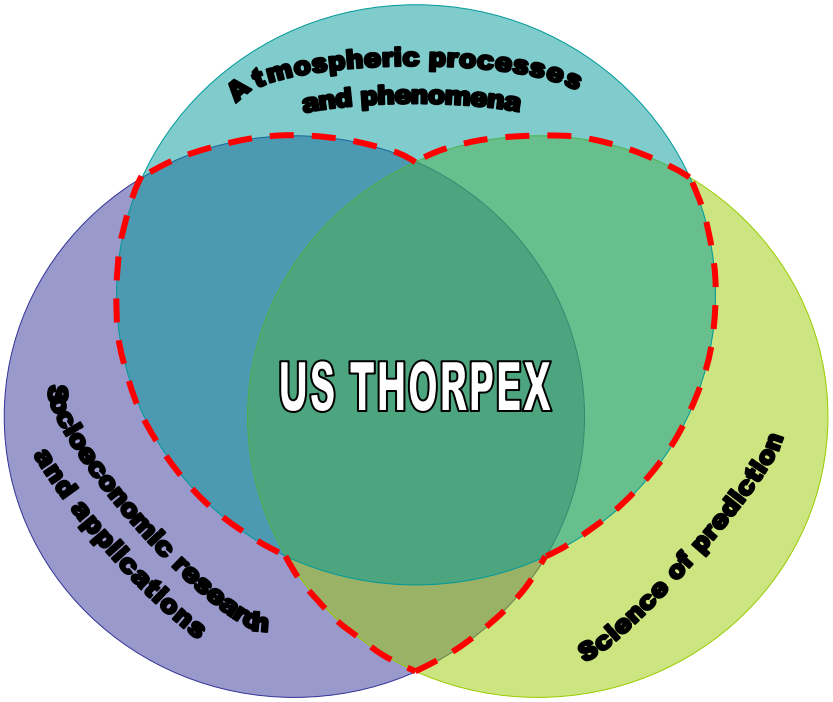

Figure 1: A schematic emphasizing the intrinsic inter-connectedness of US THORPEX. Accelerating the rate of forecast improvement requires the coordination of the prediction science, process and phenomena, and socio-economic research communities.

At extended ranges, forecasts over North America are impacted by processes over the entire globe. The suite of international field campaigns that took place in the Tropical Pacific during Fall 2008[9] (see section 6) motivated the Tropical Pacific and downstream effects being the initial focus for the US THORPEX research efforts. US research associated with the International Polar Year (IPY) has a strong climate emphasis, but the impact of the polar region on US weather motivates future THORPEX research in polar/midlatitude interactions. Ultimately, coupled tropical/midlatitude/polar interactions must be considered. The US THORPEX Science Plan is a living document, and we anticipate the science priorities evolving with time.

[9] T-PARC (THORPEX Pacific Asian Regional Campaign), CHERES—II (Chinese Heavy Rainfall Experiment and Study with measurements over Tibet and the South China Sea (SCS)), an expansion of the DOTSTAR (Dropsonde Observations for Typhoon Surveillance Near the Taiwan Area) to include both research aircraft and driftsonde, upgrades and expansions of the Russian radiosonde network including the possibility of additional measurements in sensitive regions for the International Polar Year, the Korea Extensive Observing Period (KEOP), Japan's Typhoon Heavy Rainfall 08 Experiment (TH08), and the US and EU contribution to provide instrumented aircraft to study typhoon genesis, ET events and intense winter storm cyclogenesis and their impact on downstream processes over North America

3) Improved understanding of atmospheric processes and phenomena

Much of the US THORPEX focus here is driven by improving understanding of processes at a variety of scales (both spatial and temporal) to make a meaningful improvement in both operational forecasts and to the numerical simulations that support these forecasts. Efforts under the science of prediction (section 4) are linked through the ultimate goal of improving forecasts out through week 2. The translation of these improvements into meaningful societal responses and the societal drivers for this component of the research are outlined in section 5. Examples of specific questions that are most relevant to US THORPEX efforts relating to processes and phenomena are presented here.

3.1) Tropical/Extratropical interactions

The tropics were once thought of essentially as a "boundary condition" to midlatitude forecasting. Getting the characteristics of the equatorward boundary to the limited area model correct was the goal. The work of Tyrell et al. (1996), for example, has highlighted the importance of tropical forcing on midlatitude development. The importance of the so-called pineapple express to flooding events in North America has recently become accepted (e.g. Higgins et al. 2000). Further, extratropical forcing of tropical cyclone development (e.g. Bosart and Bartlo 1991) has been shown to be a potentially important contributor to the North Atlantic tropical storm climatology (Guishard et al. 2006).

Examples of specific issues associated with tropical/extratropical interactions include:

- Extratropical transition of tropical cyclones (discussed in detail in section 3.2).
- The upper level jetstream off the coast of East Asia acts as a strong wave-guide for the propagation and excitation of Rossby waves. Research is needed to better understand the role of the upper level jetstream in regulating Rossby wave forcing and propagation between the tropics and mid-latitudes.
- Understand the ways in which the midlatitudes modulate the tropics and impact TC genesis.
- Improve understanding of troposphere/stratosphere interactions and the ways in which the tropics impact global-scale features such as the Arctic Oscillation (AO).
- What is the role of tropical/midlatitude interactions on subsequent meso-synoptic evolution and significant downstream weather development? This encompasses initiation of systems in both the midlatitudes and the tropics.
- To what extent does the MJO impact mid-latitude predictability relative to convection flare-ups associated with, for example, the ITCZ or the monsoon trough?

3.2) Extratropical transition (ET) of tropical cyclones (TC)

Extratropical transition of tropical cyclones (often referred to simply as "ET") has come to be recognized as both a direct source of intense weather at the poleward land boundaries of the tropical cyclone basins and as a driver of downstream developments that may result in extreme weather phenomena far from the original tropical cyclone.

Anecdotal records of these events extend back hundreds of years in both the Atlantic and the Pacific basins (Rossabi 1988), but their relative frequency of occurrence has only become apparent recently.

A recent climatology of these systems for the North Atlantic (Hart and Evans 2001) has documented the importance of these systems as sources of extreme rain and wind events in the US mid-Atlantic and New England regions, Canada and Western Europe. The seventh typhoon to strike Japan in 2004 (JTWC 2004), Supertyphoon Tokage, was also the deadliest storm to make landfall there in almost twenty years. Tokage subsequently underwent ET and made another landfall, this time in Alaska! The long term impacts of this storm in an already challenging Alaskan climate include extreme coastal erosion (e.g. .TISP). Studies of ET in the western North Pacific (e.g. Harr and Elsberry 2000) have confirmed its importance as a direct source of similar extreme events in Japan, Korea and China. Further, Riemer (2006) reports on the indirect genesis of an extreme flooding event in southern Germany and Austria as a result of the ET of Hurricane Irene (2004). The effects of these storms both locally and via teleconnections and their wide impacts make this a truly international problem – one that has become a major focus of the proposed T-PARC field campaign (see section 7). This motivates highlighting ET as a tropical/extratropical interaction research focus of particular relevance to the US.

Examples of specific questions associated with ET include:

- What controls the timescales associated with ET?
- How does the air column cool when a storm transitions from warm-core to cold-core?
- What is the role of TC-induced Rossby waves on the subsequent phasing of ET TCs with midlatitude troughs?
- How do the phasing of TC-induced Rossby waves, the phasing of the ET itself, and the phasing of waves on midlatitude jets impact the predictability of midlatitude primary and secondary cyclogenesis?
- How do we advance numerical simulations of ET to improve the predictability of these phenomena and the (near and far field) weather associated with them?

3.3) Tropical processes

Through various tropical-extratropical interactions such as those discussed above, organized tropical convection has a significant impact on mid-latitude weather. Therefore, as noted in the THORPEX/WCRP/ICTP Workshop on organization and maintenance of tropical convection and the Madden Julian Oscillation[10], both our limited understanding of multi-scale organized convection in the tropics, and our very limited capability to simulate it are fundamental barriers to advancing global weather and climate prediction on timescales from days to years. Given current interest in TC intensity studies and landfall forecasts, THORPEX is in a position to fill a niche by exploring the environment that supports the genesis of these storms, the genesis itself, and the multi-scale interactions needed to nurture them, in both the Atlantic and Pacific basins.

[10] http://www.usclivar.org/Organization/MJO%20WorkingGroup/TriesteReport.pdf

THORPEX, and in particular the tropical and subtropical observations collected during T-PARC, will provide an excellent opportunity to increase our fundamental understanding of tropical processes that impact midlatitude phenomena and predictability.

Examples of specific tropical process of interest include:

- Improve understanding of organized tropical convection with variation timescales of up to two weeks.
- Improve understanding of the processes leading to tropical moisture streamers into midlatitudes.
- Better understand the processes leading to tropical cyclogenesis, including subtropical to tropical transition.
- Understand the different ways in which wave accumulation and equatorial wave forcing impact TC genesis.

3.4) Polar/Midlatitude interactions

Accessibility due to extreme weather conditions, as well as special difficulties related to satellite observations make the Arctic and Antarctic regions arguably the least observed areas of the Earth surface. Understanding of the relevant physical processes, as well as forecast system tool development consequently also lags behind developments over other areas of the Earth. Yet polar regions are among the most vulnerable environments, often pushed to the edge of sustainability due to the aggravating effects of recent climate changes. In addition, interactions with midlatitude and possibly tropical processes are not well understood, hindering progress toward improved global forecasting.

Examples of specific questions associated with polar/midlatitude interactions include:

- To what degree polar circulation, and in particular, cross-polar flow impedes 1-14 day predictability in different areas of the globe? What processes govern cold air outbreaks?
- To what extent is predictability over the Northern and Southern Hemisphere extratropics influenced by the nature of the flow regimes in the polar regions (a more symmetric circumpolar vortex with little to no cross polar flow over the Antarctic, and a less symmetric vortex with major episodes of cross polar flow over the Arctic)?
- Do the circumpolar circulations act as “graveyards” for baroclinic disturbances originating from the midlatitude jets, and if so, what mechanisms are at work?
- What processes govern polar-extratropical interactions?
- In what ways do the tropics impact the predictability of polar conditions?

3.5) Aerosols

While the importance of the large scale circulation associated with tropical and extratropical processes in governing the accumulation, deposition and transport of aerosols are well recognized, the possible impacts of aerosol effects on large scale circulation are relatively unknown. At present, there is emerging evidence that aerosols,

particular airborne dust through absorption of solar radiation may alter the atmospheric and surface energy balance, and thus influence atmospheric phenomena with diverse spatial and temporal scales ranging from monsoons to tropical easterly waves to hurricanes. Aerosol studies and their impacts on clouds and precipitation and weather prediction are now being pursued by various WCRP and WMO, and US national programs. For the long-term goals of US THORPEX, it is important that aerosol studies with connections to the aforementioned science themes be included.

Examples of specific questions associated with aerosols include:

- How do aerosol-cloud radiation feedbacks, and aerosol impacts on severe weather, differ over the Atlantic and Pacific basins.
- What is the impact of Saharan dust on tropical cyclogenesis over the Atlantic, and what are the possible impacts on long lead-time forecasts over the East Coast of the US?

4) The science of prediction

Many fundamental predictability and dynamic processes research questions have direct operational relevance. The science of prediction community has identified the following research topics as having both high intellectual merit and large projection on international THORPEX goals. Progress on these topics is likely to have substantial impact through improvements in operational forecasts. The topics are not independent, and to maximize progress and impact collaborative interactions between groups working on each topic should be encouraged through, e.g., informal workshops, participation in various interest groups organized under the international Research Working Groups, etc..

4.1) Reducing and accounting for model inadequacy

Modern numerical models have state-dependent errors that affect predictability. These errors directly affect state estimation (see section 4.2) and forecasts at all lead times through systematic and state-dependent biases and contribute to the under-dispersive nature of many ensemble forecast systems. In part, the model biases are due to the complex parameterizations of unresolved processes and our lack of understanding of relevant processes.

Examples of specific questions associated with accounting for and reducing model inadequacy include:

- Is there a lack of basic understanding that limits our ability to simulate Rossby wave forcing between the tropics and mid-latitudes, or is it simply a question of model resolution?

- How do forecast errors arising from both mid-latitude and tropical (and ultimately polar) processes over the Pacific lead to forecast errors over North America? Which phenomena are the most poorly forecast/simulated and contribute the most to downstream errors?
- Do long-lead North America forecast errors arise primarily from analysis errors over the Pacific or from deficiencies in the forecast models, such as their treatment of tropical convection? What techniques can provide objective and robust answers to this question?
- Although parameterizations that are more faithful to the underlying physics may prove useful, a greater need exists for comprehensive model calibration of simpler, and computationally more efficient, schemes. How can parameter estimation be best utilized to improve probabilistic forecasts while extracting as much physically-based (process oriented) understanding of model deficiencies as possible.
- By what methods can we best elucidate the relative importance of model error and initial condition error on forecast error statistics?
- How is model inadequacy best characterized, and how can it be most usefully incorporated into data assimilation and ensemble forecasting systems (e.g. multi-model ensembles, stochastic modeling, explicit model error covariances)?
- A promising approach to accounting for model error for ensemble methods involves adding stochastic noise to uncertain model aspects. By what objective means should the properties of this noise be estimated, and how should it be applied?
- The TIGGE archive (see section 7) will facilitate an evaluation of the potential value of multi-model ensemble forecast systems. How can multi-model ensemble forecasts such as TIGGE be best exploited for post-processing (down-scaling) and ensemble-based data assimilation, and are there aspects of multi-model ensemble forecast systems that inform about the ways in which the models are wrong?

4.2) Data Assimilation

Historically, data assimilation research has been confined to large operational centers. Modular schemes, commodity computing, and high-speed networks have now enabled the academic research community to contribute to rapid progress in this area. Novel and efficient approaches and extensions to data assimilation and observation processing need to be explored and developed within both the operational and academic communities.

Examples of topics and specific questions associated with data assimilation include:

Improved assimilation of satellite observations
Improved assimilation is a high priority for improving forecasts, but is also important for providing better understanding of atmospheric processes and phenomena.

- What additional value can be extracted from existing satellite datasets, both in terms of the operational analysis and in terms of improved understanding of processes such as organized tropical convection and moisture streamers emanating from the tropics?
- What are the scientific and technological barriers that are prohibiting advances in the assimilation of satellite observations?
- How do we go about assimilating satellite parameters such as rainfall and cloudiness?

The importance of state-dependent uncertainty information

- What is the impact of state-dependent and covarying observation errors, including representativeness errors? How can these errors be best approximated?
- In what ways can ensemble forecasting systems be beneficially coupled with data assimilation systems? What approaches offer the easiest path for operational implementation?
- What are the best ways to exploit analysis and forecast distributions produced by ensemble-based data assimilation schemes for studies of dynamics and predictability?

Non-traditional observations

- Insofar as meteorological conditions impact potential user-relevant forecast variables (e.g. hospital asthma admissions, electricity load), observations of those variables have the potential to inform meteorological conditions. Can non-traditional, Socio-Economic Research and Applications (SERA)-related observations be usefully utilized by data assimilation systems?

4.3) Observing systems

A primary THORPEX goal is knowledge of how to systematically alter the current observing network, observing strategies, observing systems, and sampling locations to reduce forecast errors in the 1-14 day period. An interesting question concerns how to achieve this goal for both high impact systematic error reductions (day-to-day) and less frequent, extreme events. The role of adaptive observations also needs to be explored in light of reconfigurations to the existing fixed network, increasing number of satellite observations, and the possibility for adaptive data assimilation (see section 4.2).

Examples of topics and specific questions associated with observing systems include:

Observation system design

- Observing system simulation experiments (OSSEs) should play a central role in testing the potential for new sensors and observing platforms. Results from these OSSEs are essential prior to planning any future observational campaigns.
- What are the best ways to utilize data assimilation for the science-based design of next generation satellite systems for global weather prediction?
- Data denial experiments play an important role in evaluating the impact on analyses and predictions of observations (and observing strategies and observing

- What are the most promising novel in-situ observing systems that capitalize on ongoing advances in miniaturization of sensors and transmitters, ground-based and airborne remote sensors, innovative uses of airborne and ship-based observing platforms, and complement next-generation satellite-borne remove sensors?

Observability

- How tightly does the state of the atmosphere need to be constrained in order to adequately forecast certain events (such as those highlighted in section 3)?
- For which atmospheric variables (or function of atmospheric variables) would improved observations yield the most forecast benefits? Similarly, what improvements to assimilation systems, forecast models, ensemble forecasting systems, and/or post-processing systems are most crucial to improving forecasts?
- What observations are necessary to best understand important physical processes?

Adaptive observing and predicting observation impact

- Adaptive observations using a small number of dropsondes have found their way into NOAA operations[11]. What is the role of satellites in the adaptive observation problem, and is there benefit in considering the coordinated control problem associated with a fleet of mobile observing platforms?
- What are the best methods for quantitatively predicting the impact of observations?
- For practical reasons, the satellite data stream is thinned before being incorporated into the operational data assimilation system. How can this thinning be made adaptive to, for example, sample differently for short and long lead-time forecasting?

4.4) Intrinsic midlatitude predictability

Midlatitude predictability varies on seasonal, monthly, weekly and daily time scales in response to intrinsic internal instabilities in the baroclinic westerly flow and external interactions across the poleward and equatorward boundaries associated with extrusions of polar and tropical air masses into midlatitudes. Internal instabilities that impact midlatitude predictability may be associated with thermally and orographically forced planetary-scale waves on monthly and seasonal time scales, and families of synoptic-scale transient features with embedded subsynoptic-scale disturbances and trough/jet interactions in split-flow regimes on weekly and daily time scales. External interactions associated with tropical air masses may occur in conjunction with the phase of ENSO (El Niño-Southern Oscillation), the great Asiatic monsoon or the Madden-Julian Oscillation (MJO) on seasonal and monthly time scales, and recurving tropical cyclones and upper-

[11] http://www.aoc.noaa.gov/article_winterstorm.htm

tropospheric plumes of water vapor (aka atmospheric rivers) on weekly and daily time scales. External interactions associated with polar air masses may occur in conjunction with the phase of teleconnection features such as the Northern Hemisphere Annular Mode, the North Atlantic Oscillation or the Pacific-North American pattern on seasonal and monthly time scales, and with subsynoptic-scale disturbances extracted from the arctic on weekly and daily time scales.

Specific examples of phenomena that appear to act to constrain midlatitude predictability on weekly (5-10 day) time scales include:

- The interaction (or non-interaction) of trough/jet systems in split flow regimes.
- The potential for elongated potential vorticity (PV) tails from higher latitudes that often extend well southwestward into subtropical latitudes to initiate cyclogenesis (sometimes tropical).
- The impact of recurving and transitioning tropical cyclones on downstream ridge building and associated downstream development.
- The ability of extracted arctic PV anomalies to trigger explosive midlatitude cyclogenesis through the mutual interaction with moisture-laden midlatitude disturbances.
- Are midlatitude cyclonic storms in the western and central Pacific Ocean on average more robust in late autumn and early winter because of a greater likelihood of interactions with decaying tropical cyclones (and the down-stream effects of tropical cyclones) at this time of the year as compared to later in the winter?
- To what extent are large-scale regime changes (e.g., the Pacific-North American pattern transforms from negative to positive) influence by the frequency and type of synoptic activity over the western and central Pacific Ocean and what role do tropical-midlatitude and arctic-midlatitude interactions play in these regime changes?

4.5) The error dynamics of ensemble prediction systems

While generic properties of error growth in complex flows are well established (Lyapunov stability, and singular vectors), there remain important fundamental questions about error growth and propagation and the degree to which they are adequately simulated in ensemble forecasting systems. Thus, in addition to basic questions about the best ways to use the output from ensemble forecasting systems (covered primarily in section 5) a particularly important area is basic research into ensemble error dynamics addressed from a phenomenological perspective, whereby the structure, evolution, and growth of model forecast error are conditioned on flow pattern.

Examples of specific questions associated with the perturbation dynamics of ensemble prediction systems include:

- In what ways can ensemble forecasts be exploited, and ensemble construction be improved to tackle science questions raised in sections 3 and 5? How many ensemble members are required for adequately addressing different science and

forecasting questions, and what are the trade-offs between ensemble size and resolution?

- Are ensemble-based measures of forecast confidence inherently over confident? Can ensemble-based forecast confidence and uncertainty measures be determined that can be fed into "downstream" socioeconomic modeling systems?
- What are the best ways to post-process and verify ensemble forecasts for the purpose of improved scientific understanding?
- Methods exist for assessing the long-term reliability and resolution of ensemble forecast systems, but compensating state-dependent errors can mislead such measures. Is it possible to assess the *state-dependent* reliability and resolution of ensemble forecast systems in the absence of true analogs?

5) Socio-economic research and applications (SERA)[12]

This US THORPEX research effort will lead the movement to better integrate social science into meteorology. The movement is in its infancy but there is wide recognition that SERA work can inform efforts to better connect with stakeholders ranging from scientists and forecasters, to less technical weather information users for the benefit of the entire research and applications enterprise. US THORPEX efforts aim to expand the community of meteorologists and social scientists dedicated to integrating the work of scientists, forecasters and stakeholders to make science and forecasts more useful.

SERA activities bring together users, researchers, and tools from many disciplines, including meteorology, economics, statistics, decision science, psychology, sociology, and geography. Societal aspects of weather information require interdisciplinary and social science research methods unfamiliar to many atmospheric scientists including surveys, focus groups, and other qualitative and quantitative tools. Employing such methods can bring new insights to our understanding of the complex weather / weather forecast / society system and, significantly increase the value of weather information to society. To make the necessary next leaps in our integrated work, societal and economic research and applications requires interdisciplinary efforts, involving physical scientists and social scientists and other stakeholders

The SERA community has identified the following research priorities to serve as the foundation for their THORPEX efforts.

5.1) Use of forecast information in decision making

Forecast information benefits society primarily through its use in decisions. Research is required to understand how users receive forecast information, interpret it, and to what degree they apply it in particular decisions — and when and why they do not.

Examples of questions associated with the use of forecast information in decision making include:

[12] This section draws heavily from Morss et al (2008).

- How do diverse decision-makers interpret weather forecast information and combine it with other inputs in their decision processes?
- How is information used in specific decision contexts, such as emergency management and water resource management? Results from different geographic and societal contexts will need to be compared to draw broader conclusions.

5.2) Communicating forecast uncertainty

Weather forecasts as predictions of the future state of the atmosphere are inherently uncertain. All weather forecasts are communicated, interpreted, and used with some elements of uncertainty. Ways to estimating weather forecast uncertainty are rapidly evolving. At the same time, meteorologists recognize how presenting forecasts without uncertainty can mislead users and limit forecasts' usefulness (NRC 2006). Research must continue to explore how to effectively communicate weather forecast uncertainty, for hazardous and everyday weather.

Examples of questions associated with communicating uncertainty include:

- How does uncertainty propagate through the forecast use and value process?
- In what ways do users interpret forecast uncertainty?
- How do users take forecast uncertainty into account in decision making?
- How do different user communities comprehend and respond to different forms of uncertainty?

5.3) User-relevant verification

Forecast verification procedures have been developed within the meteorology community with little emphasis on the impacts of the forecasts. Traditionally verification, without input from stakeholders, has determined how administrators allocate resources for forecasting, particularly model development; it was assumed that the variables and statistics being evaluated were the most relevant for a broad spectrum of users. Meteorologists' perceptions of elements of forecast quality are important components of forecast-related decision processes and systems, but to be most useful, we must learn what measures of quality are relevant to the users' decisions.

Examples of questions to address associated with user-relevant verification include:

- Which users would most benefit from advanced, user-relevant verification information?
- What are the most user-relevant forms of forecast verification and how do they vary within and between user communities?
- To what extent can ensemble post-processing techniques utilized for scientific forecasting and verification be usefully employed for user-relevant forecasting and verification?
- To what extent should forecast system development be driven by socioeconomic, as opposed to atmospheric science-based, verification measures?
- How can users best be incorporated in the development of new verification measures?

5.4) Quantifying the value of forecasts

Weather forecasts are information, providing value primarily by being used in people's decisions in ways that improve outcomes. In economic terms, if improved weather forecasts make people better off, then the value of the improved forecasts is measured by people's increase in well-being (or satisfaction, or utility), broadly defined. Such increases in well-being are often, but not always, monetized (expressed in dollar terms). Economic valuation studies can not only estimate or monetize changes in well-being associated with changes in forecast information, but also contribute to fundamental understanding by identifying trade-offs among forecast modifications and shedding light on preferences for modifications.

Examples of topics and specific questions associated with quantifying the value of forecasts include:

- What are relevant examples of high-impact weather and high-impact weather *forecasts*?
- How do various stakeholder groups value weather predictions and how can we evaluate the potential benefits of improved probabilistic forecasts and the potential added value of existing and new products?
- How can the benefits of weather prediction be increased for developed and developing nations?
- What are the real costs of hurricane warnings? Do they depend on geography and the length of warning time (relating to the forecast accuracy)?
- What is the value of different forecast modifications (different changes in forecast attributes)?
- How are people's preferences for different forecast modifications evaluated?
- What are equitable ways of adaptively configuring resources, with particular emphasis on needs in less developed nations?

5.5) Developing decision support tools and systems

Decision support connects particular users with weather information providers. Decision support systems, as defined in the information technology, management, and organizational behavior communities, typically consist of computer-based platforms that integrate problem-relevant data to help decision-makers structure problems and objectively identify and evaluate decision alternatives (Eierman et al., 1995; Reich and Kapeliuk, 2005). Decision support systems and tools can help users incorporate new forecast information into their decisions and gain further value from already-used forecast information. They can also help forecast providers understand users' needs and provide more useful forecast information.

Examples of questions associated with developing decision support tools and systems include

- What are the best practices for assessing forecast user needs and building decision support tools?
- How can TIGGE be best leveraged by existing and/or new decision support tools?

6) Linking US THORPEX research with international THORPEX and other efforts

In this section we identify past, present, and proposed international THORPEX activities and research thrusts that may inform or compliment US THORPEX priorities. We also include US research initiatives still in their formative stages whose goals are synergistic with some elements of the US THORPEX plan.

The THORPEX Interactive Grand Global Ensemble (TIGGE) and the Global Interactive Forecast System (GIFS)

Following the recommendations of the TIP, global ensemble forecast information generated by various NWP centers are being archived and made accessible with a 2-day delay to the research communities at three centers (CMA, ECMWF, and NCAR). Limited Area Model (LAM) ensemble forecasts are also planned to be generated and saved for various regions (TIGGE-LAM). The THORPEX Interactive Grand Global Ensemble (TIGGE, Bougeault et al 2010) dataset may also be expanded by corresponding observational data, and by numerical simulations of nature for Observing System Simulation Experiments (OSSEs). The TIGGE archive is expected to support a multitude of research efforts, including those concerned with adaptive observations, error dynamics, process studies, forecast applications, uncertainty analysis and forecast verification.

Research based on the TIGGE data sets will be used to develop new forecast methods leading to NWP activities organized on the international level. The first phase of the Global Interactive Forecast System (GIFS) will combine ensemble forecasts from a number of centers to improve the skill and utility of advanced probabilistic warnings for high impact events, especially for developing regions. In later stages of GIFS, observing and data assimilation tools may also be used in a coordinated fashion to best address the needs of forecasts in an adaptive fashion, targeted toward the highest priority large impact weather events.

The Global Earth Observation System of Systems (GEOSS)

"The Group on Earth Observations (GEO) is coordinating international efforts to build a Global Earth Observation System of Systems (GEOSS). This emerging public infrastructure is interconnecting a diverse and growing array of instruments and systems for monitoring and forecasting changes in the global environment. This "system of systems" supports policymakers, resource managers, science researchers and many other experts and decision-makers" (quoted from: http://www.earthobservations.org/index.html). THORPEX is uniquely positioned to contribute to the objectives of GEOSS by articulating observational needs and designing optimum observing networks for high impact 1-14 day weather forecasts, as well as

advancing probabilistic weather forecasting methods and real world applications such as hydrologic, health and food safety related and other applications especially in developing regions of the globe. THORPEX projects that are registered under GEOSS include TIGGE/GIFS and environmental predictions related to health and food security over Africa.

North American Ensemble Forecast System (NAEFS)

NAEFS is a prototype multi-center ensemble forecast system developed and operationally implemented by the weather services of Canada, Mexico, and the US. NAEFS combines, bias corrects, and weights ensemble forecasts generated by the Canadian and US weather services and generates a suite of products based on this combined ensemble. NAEFS offers real time forecast guidance for THORPEX demonstration projects and can be considered as the operational application outlet for most US and north American THORPEX research, offering critical feedback to the academic community regarding the needs of the operational community.

The National Unified Operational Prediction Capability (NUOPC)

NUOPC is an agreement between the US weather services to collaborate on coordinated research and development and ensemble operations. Operationally, NUOPC will expand on the NAEFS ensemble to provide a managed ensemble system including common post processing. NUOPC will provide a vehicle for the US weather services to develop and champion a common NWP research agenda and align transition processes to accelerate the transition of research into operations.

Earth System Prediction Capability (ESPC)

The Earth System Prediction Capability is meant to meet the national imperative of tactical through climatic prediction to mitigate impacts of near-term significant events as well as long term climate change for multiple level agencies. By definition it is a fully coupled air, ocean, land, ice and space numerical prediction capability operating at appropriate (cloud and eddy resolving) spatial and temporal resolution to produce a zero-hour to decadal seamless prediction. Of course a capability with this scope will necessitate an advance observing architecture and data assimilation techniques, as well as product development and distribution, therefore ESPC is a "system" not just a model.

The THORPEX Pacific Asian Research Campaign (T-PARC) and Tropical Cyclone Structure-2008 (TCS-08)

The THORPEX Pacific Asian Regional Campaign (T-PARC) is a multi-national field campaign that addresses the shorter-range dynamics and forecast skill of one region (Eastern Asian and the western North Pacific) and its downstream impact on the medium-range dynamics and forecast skill of another region (in particular, the eastern North Pacific and North America). The field phase of summer T-PARC (1 August – 3 October 2008) was designed to leverage multi-national efforts to address these two overarching

foci. While T-PARC encompasses varying time and space scales, the primary objectives of each region are the same *(i.e., to increase understanding of the mechanisms that will lead to improved predictive skill of high impact weather events)*. This multi-scale approach of T-PARC is desirable as high impact weather events over these two regions have strong dynamical links. For example, high-impact weather events over the western North Pacific and East Asia, such as persistent deep tropical convection and intense cyclogenesis, can trigger downstream responses over the eastern North Pacific and North America via upper-tropospheric wave packets on the primary Asian wave guides. These wave packets can, in turn, be invigorated by subsequent cyclogenesis events, which make the impacts farther downstream fast-spreading, far-reaching, and associated with reduced predictability. The high-impact weather events over North American driven by these processes include intense extratropical cyclones, orographic precipitation, flooding, severe weather and the hot, dry winds that increase the risk of wild fires and the severity of droughts.

Although many significant weather events occur over eastern Asia and the western North Pacific, the focus of summer T-PARC is on various aspects of typhoon activity, which include formation, intensification, structure change, motion, and extratropical transition. The tropical component of T-PARC was comprised primarily by U.S. lead TCS-08 program. The Office of Naval Research and National Science Foundation cooperatively provided funding for TCS-08 and T-PARC.

Overall, the field phase of the T-PARC/TCS-08 and affiliated programs were conducted with great success. The results of the data collection strategies during the field programs were such that sufficient resources were applied to each objective, which will lead to significant advances in understanding and increase in predictability of high-impact weather over eastern Asia, the western North Pacific, and regions downstream.

T-PARC and TCS-08 offer an excellent opportunity for the entire U.S. and North American research community to converge on a set of well-defined problems and promote advancement in high-impact weather forecasting.

The wintertime component of the T-PARC (WTPARC) was an international field campaign designed to study and to improve forecasts of high-impact weather events over North America. The major research objective is to understand how atmospheric perturbations from the tropics, Eurasia and polar fronts evolve through the Pacific waveguide and influence the development and predictability of high-impact weather events. In WTPARC a large number of adaptive ("targeted") observations were deployed in dynamically-sensitive regions to improve numerical forecasts of high-impact weather over the northeast Pacific and North America. The targeted observations in WTPARC included dropsondes deployed over the Pacific from manned reconnaissance aircraft (NOAA G-IV and US Air Force C-130s), and additional profiles from many stations in the Russian radiosonde network. Non-targeted observations in WTPARC included data provided by commercial aircraft over East Asia in the E-AMDAR program. WTPARC was led by NOAA and joined by researchers from agencies and universities in the US, Canada, Russia, Europe, Japan, and Mexico. During WTPARC the special targeted and non-targeted observational data were assimilated by operational centers to improve real-

time analyses and forecasts. Research using WTPARC observations will focus on data impact and predictability experiments, storm process studies, and the societal value of improved numerical weather forecasts. The data for winter T-PARC will be archived at NASA, and will provide scientists with a valuable data source to study medium range predictability and impact of targeted observations.

African Monsoon Multidisciplinary Analysis (AMMA)

African Monsoon Multidisciplinary Analysis (**AMMA**) is an **international project** to improve our **knowledge and understanding** of the West African monsoon (WAM) and its variability with an emphasis on daily-to-interannual timescales. AMMA is motivated by an interest in fundamental scientific issues and by the societal need for **improved prediction** of the WAM and its **impacts** on West African nations. Recognizing the societal need to develop strategies that reduce the socioeconomic impacts of the variability of the WAM, AMMA will facilitate the **multidisciplinary research** required to provide improved predictions of the WAM and its impacts.

We are currently hindered in providing skillful predictions of WAM variability and its impacts. There are still fundamental gaps in our knowledge of the coupled atmosphere-land-ocean system at least partly arising from lack of appropriate observational datasets but also because of the complex scale interactions between the atmosphere, biosphere and hydrosphere that ultimately determine the nature of the WAM. The monitoring system for the WAM and its variability is inadequate with many gaps in the standard routine network and lack of routine monitoring of some key variables. While the next generation of satellites will undoubtedly help with routine monitoring and prediction efforts, more research is required to validate and exploit these data streams. Dynamical models used for prediction suffer from large systematic errors in the West African and tropical Atlantic regions; current models have problems simulating fundamental characteristics of rainfall such as the diurnal, seasonal and annual cycles. Finally, there is a lack of integrative science linking the work on WAM variability with work on food, water and health impacts. More effort needs to be made to integrate scientists working in these different areas.

There was an AMMA special observing period that took place during the summer of 2006 in which NASA played a large role. The NASA African Monsoon Multidisciplinary Analyses (NAMMA) campaign was based in the Cape Verde Islands, 350 miles off the coast of Senegal in west Africa. Commencing in August 2006, NASA scientists employed surface observation networks and aircraft to characterize the evolution and structure of African Easterly Waves (AEWs) and Mesoscale Convective Systems over continental western Africa, and their associated impacts on regional water and energy budgets. NASA made extensive use of its orbiting satellites (including Aqua, TRMM, and the recently-launched Cloudsat/CALIPSO) and modeling capabilities to improve its forecasts and flight plans. The major research topics of this mission were tp examine the formation and evolution of tropical hurricanes in the eastern and central Atlantic and their impact on the U.S. east coast, and the composition and structure of the Saharan Air Layer, and whether aerosols affect cloud precipitation and influence cyclone

development. Extensive observation data sets have been archived and can be utilized by the international THORPEX community.

The NOAA Hurricane Forecast Improvement Project (HFIP)

The NOAA Hurricane Forecast Improvement Project is a 10-year program to "1) provide the basis for NOAA and other agencies to work towards a national effort to coordinate national hurricane research needed to significantly improve guidance for hurricane track, intensity, and storm surge forecasts, and 2) engage and align the inter-agency and larger scientific community efforts toward addressing the challenges posed to improve hurricane forecasts"[13]. Specific goals include the reduction of track and intensity errors by 50% for days 1 through 5, increase the probability of detection for rapid intensity change and decrease the false alarm ratio for rapid intensity change out to day 5, and extend the lead time for hurricane forecasts out to day 7. The program encompasses enhanced observing strategies, improved data assimilation and forecasting system, and expanded applications from both high resolution and ensemble-based guidance.

HFIP and US THORPEX are complementary in their approach to hurricane research. HFIP focuses on hurricanes specifically threatening the US out to 7 days. In contrast, US THORPEX focuses on tropical cyclones throughout the globe and their down-stream impacts out to 2 week lead times. THORPEX research will build on achievements on the smaller scales, while providing improved information on the background flow for detailed hurricane dynamics research.

The NOAA Intensity Forecasting Experiment (IFEX)

The NOAA Intensity Forecasting Experiment is a multi-year experiment intended to improve the understanding and prediction of hurricane intensity change by collecting observations that will aid in the improvement of current operational models and the development of the next-generation operational hurricane model. The data gathered by the program will be very useful to THORPEX missions.

International Polar Year (IPY)

IPY is a multidisciplinary program, covering many research areas and scales, with a global view but a focus on the polar regions. The THORPEX program focuses on global weather prediction research. The two programs naturally intersect: THORPEX is considered the weather prediction component of IPY. THORPEX and IPY established institutional linkages, resulting in the submission of THORPEX related pre-proposals under the IPY program. These proposals have been clustered under the name "Weather and climate (including improved forecasts), THORPEX-IPY". The timing of the field phase of IPY, running from March 2007 through February 2009, was ideal for closely coordinated activities with summer T-PARC (August-September 2008) and winter T-

[13] From "Proposed Framework for Addressing the National Hurricane Research and Forecast Improvement Initiatives. NOAA's Hurricane Forecast Improvement Project, July 18, 2008" at www.nrc.noaa.gov/plans_docs/HFIP_Plan_073108.pdf

PARC (January-February 2009). Such a collaboration, including forecast application activities in Alaska and other polar regions, offered great opportunity for mutual leveraging of observational and other resources.

Using data collected during T-PARC and IPY, there is a unique opportunity to study the main sources of forecast uncertainty in global NWP forecasting, to quantitatively assess the major impediments to extending weather forecasts to day 14 and short term climate forecasts beyond week two over the Northern Hemisphere, namely to quantify the effects of (1) Tropical excitation of waves from the Pacific ocean, especially from the area of the Maritime Continent; (2) The mid-latitude flow regime over the Pacific Ocean; and (3) The polar circulation with episodes of cross polar flow. A major effort must be undertaken to assess the relative importance of each of these three sources of forecast uncertainty and the interaction among them, as well as the optimal mix of observations required to reduce them. The US THORPEX program will promote collaborative research aimed at the exploitation of the IPY and T-PARC datasets for the mutual benefits of both the IPY and THORPEX programs.

Year of Tropical Convection (YOTC)

The WCRP and WWRP-THORPEX are jointly coordinating an observing, forecasting and research project, Year of Tropical Convection (YOTC). The emphasis is organized tropical convection and its interaction with the global circulation on time scales up to seasonal; namely, seamless prediction. Progress to date is published by Moncrieff et al. (2007), and Waliser and Moncrieff (2008), with more extensive information at http://www.ucar.edu/yotc.

The draft YOTC Implementation Plan describes: i) ECMWF, NCEP and NASA/GMAO high-resolution global analysis and forecast data sets; ii) satellite data resources (e.g., NASA A-Train, TRMM, geostationary) and the proposed NASA Giovanni data-dissemination framework; iii) overlapping field programs, e.g., T-PARC, VOCALS, Asian Monsoon Years (AMY); iv) various events of interest during the Year for research purposes, such as MJOs, easterly waves, tropical cyclones, monsoon variability and tropical-extratropical interactions; v) advanced multi-scale modeling frameworks, e.g., global cloud-system resolving models, super-parameterization, and tropical channel models.

Planned YOTC modeling and analysis activities include:

- Multi-model experiments addressing critical issues in seamless prediction involving 5-day initialized forecasts for the Year using a range of models: CMIP5, CAPT/DOE-NCAR, GEWEX/EUCLIPSE, and CMMAP and NASA Goddard super-parameterization research.
- Global and/or regional cloud-system resolving experiments focused on YOTC events involving Japan NICAM, UK Cascade, GMAO GEOS-5, and NCAR models.

- Multi-model tropical intraseasonal 20-year hindcast experiments in association with CLIVAR Asian-Australian Monsoon Panel (AAMP) and AMY.
- Extension of the GEWEX Cloud System Study (GCSS) Pacific Cross-section Intercomparison (GPCI) to include the June-August 2008 period.
- Forecast and analysis studies in the Atlantic sector of easterly waves, tropical cyclones and their modulation by intraseasonal variability.
- Tropical-extratropical interaction studies focused on summer and winter T-PARC and impacts of tropical convection on the prediction and predictability of mid-latitude weather variability.
- Note that the extension of the ECMWF database to the 2-year period (May 2008 – April 2010) captures a full ENSO cycle: La Nina conditions during the first year evolved into the El Nino conditions of the second.

The Hydrologic Ensemble Prediction Experiment (HEPEX)

HEPEX is an international research and development program aimed at the development of advanced hydrologic forecast systems capable of quantifying state dependent uncertainty. Since weather forecasts are such a strong driver in hydrologic forecasting, and because of the great societal implications of hydrologic predictions, HEPEX is an ideal partner for the THORPEX program in a very important area of weather forecast applications. A hydrologic component, the THORPEX/HEPEX Hydrologic Ensemble Prediction System (THEPS) is proposed as a joint THORPEX/HEPEX collaborative activity within the THORPEX project. This project would have 3 goals:

1. Assess how the TIGGE datasets and THORPEX science plan can meet the requirements of the HEPEX community.

2. Provide feedback to the THORPEX community on the information content of TIGGE and THORPEX scientific questions , and hence contribute to the design and development of GIFS.

3. Help the HEPEX community in using the TIGGE datasets and THORPEX research outputs within Hydrological EPSs.

Hydrological applications range across scales from catchments of less than a few km^2 to continental scale. It can integrate responses over a range of variables (for example precipitation, evaporation, temperature, radiation etc) as well as across spatial and temporal scale. Hydrological systems act often as a low pass non-linear filter of atmospheric drivers. As such it can for example allow to assess *predictive skill at all forecast ranges, including potential predictability* of many near surface variables on a large range of scales. These scales are meaningful integrators of point observations and thus allow a suitable comparison to model predictions. Additionally, hydrology can act as a diagnostic *to quantify the contributions of initial condition* and *model uncertainty to forecast errors or investigate the relative effects of small and large-scale initial-condition uncertainty* and as such *develop improved global ensemble-prediction systems*. For example, many hydrological regimes can be sensitive to initial conditions and evaluate

the signal of changing configurations. Additionally, hydrological models are already part of many meteorological models in the form of land surface schemes. HEPEX can act as a communication platform between the traditional small scale hydrological community and the large scale hydrologists.

Scientific issues associated with THORPEX-HEPEX collaboration include:

1) What are the requirements for meteorological ensemble forecasts to support hydrological ensemble prediction and the scientific issues or questions that need to be addressed to meet these requirements?
2) How important is the feedback of hydrologic processes for the atmospheric circulation?
3) What downscaling methods (dynamical or statistical) can be used to interpret lower resolution atmospheric forecasts for hydrologic applications?
4) What is the best way for the user community to take advantage of ensemble forecasts?

Linkage between weather and climate forecasting (THORPEX and WCRP)

The focus of the THORPEX program is improving the skill and utility of forecasts over the 1-14 day lead-time range. With improved initialization and modeling techniques, the time range of useful NWP forecasts has been consistently extending. The goal of THORPEX, in fact, is to accelerate this extension by the introduction of a new forecast paradigm, from the current 7-10 days limit out to 14 days. No hard barrier, however, exists at day 14. Users require a forecast product suite that is seamless across different time ranges; and scientifically, predicting weather at shorter, or various statistics of weather at longer time ranges is based on the same laws of physics.

The 10-60 day Intra-Seasonal time range is a natural meeting ground for scientists who have been primarily working on the shorter (weather), or longer (climate) time horizons. The US THORPEX community will work together with the international climate community to realize the full predictability in the intraseasonal (IS) lead-time range (e.g. Brunet et al 2010). Beyond improving IS forecasting, the collaboration may, at least in some situations, also have a positive effect on shorter, 1-7 days (e.g., improved hurricane intensity forecasting due to more realistic ocean temperature forecasts), and longer than 60-day forecasting (e.g., capturing the initiation or modulation of an ENSO cycle by an MJO or tropical storm). In addition, a unified approach may also contribute to the establishment of a seamless suite of probabilistic weather, water, and climate products, ranging from hours to seasons ahead.

Culminating THORPEX international field campaign

It is our view that a global prediction experiment culminating in a field campaign forms the THORPEX capstone. Each of the science questions above ultimately projects onto the successful design, execution, and analysis of a successful experiment. Prior to obtaining observations in the field, students and academic researchers - in collaboration with THORPEX partners from the private sector and operational centers - would

formulate testable hypotheses using available datasets, operational products, SERA research, and a hierarchy of models. OSSE's would be used to evaluate new observational systems, observing strategies, and different data assimilation approaches prior to the field component of the experiment with the aim of contributing to a significant improvement of the forecast skill of "high-impact" events over the Pacific and downstream. Through a progressive approach of coordinated diagnostic, theoretical, and idealized experiments, the hypotheses and technologies would be refined, retested and refined further, *prior to field work*, to ensure that proven experimental designs (from somewhat idealized settings) are employed and achievable goals are put forth.

7) Agency Roles

NSF

In the context of THORPEX, NSF's goals are to: (i) advance knowledge about the processes that force and regulate the atmosphere's synoptic and planetary circulation and weather, and (ii) sustain the pool of human resources required for excellence in synoptic and global atmospheric dynamics and weather research.

Research topics include theoretical, observational and modeling studies of the general circulation of the stratosphere and troposphere; synoptic scale weather phenomena; predictability of the atmosphere; methods to predict extended weather; development and testing of parameterization of physical processes; numerical methods for use in large-scale weather models; the assembly and analysis of instrumental and/or modeled weather and climate data; and data assimilation studies.

NSF recently distributed a Dear Colleague Letter concerning connections between the environment, society and the economy (ESE), http://www.nsf.gov/pubs/2009/nsf09031/nsf09031.jsp. The goal is to increase collaboration between the geosciences and the social, behavioral and economic sciences (SBE) by augmenting funding for interdisciplinary research. In the context of THORPEX, this may provide an opportunity for projects that involve researchers who plan integrative projects involving the geosciences and SBE sciences.
Projects may also include other disciplines outside of the geoscience and the SBE sciences, but the primary contributions of the research must include both the geosciences and the SBE sciences.

US Navy

The Navy has broad research interests aligned with THORPEX goals, and will primarily invest and participate in S&T, and R&D activities, as well as operational support toward goals. Examples of Navy interests include:

- Understanding what physical mechanisms control the predictability of DoD high-impact weather, such as tropical cyclogenesis, intensification, structure change,

track and extratropical transition (e.g., is predictability controlled by small scale features, the environmental flow, or both? What is the role of scale interaction?)

- Understanding the limitations of our forecasting systems in predicting high-impact weather (e.g., model error, limited model resolution, uncertainties in the initial conditions).
- Developing methods to effectively quantify uncertainty in DoD forecasts, and to provide useful probabilistic forecasts of DoD high-impact weather. This will include research on appropriate methods for representing initial uncertainty and model uncertainty in ensemble design, and the post-processing of forecasts such that products are designed for operational support.
- Developing improved data assimilation methods, including 4-dimensional variational methods, ensemble-based methods, and hybrid methods.
- Optimization of both fixed and adaptive components of the observing system using adjoint and ensemble-based methods.
- Developing observation sensitivity techniques for the design of next-generation observing systems (including hyperspectral satellite data, etc.).
- Understanding the relevant physical processes that influence predictability in the polar region, and improving the representation of these processes in forecast models.

The Navy participation in the above focus areas will be enhanced through in-kind investments, broad agency announcements, coordinated research, and active participations in joint programs related to THORPEX objects.

NOAA

The overarching goal of NOAA's THORPEX Program is to accelerate improvements in the quality and utility of 3-14 day high-impact weather forecasts, with linkages to shorter and longer ranges to provide a seamless suite of probabilistic weather, water, and climate predictions. Of the three topic areas identified in the U.S. THORPEX Science Plan, the main focus of NOAA's efforts is the "science of prediction", with input from the other two topic areas ("socio-economic applications" and "atmospheric processes and phenomena") relevant to improving the end-to-end forecast process. As an agency responsible for operational weather prediction with the aim of protecting life and property, NOAA strives to transition all relevant THORPEX research results into operations.

NOAA's THORPEX research and development efforts span all four major areas of research (observing system, data assimilation, predictability, and socio-economic applications) established in the THORPEX International Science and Implementation Plans, with an emphasis on the interactions among the four areas. In particular, to enhance the utility of high-impact weather forecasts, NOAA is working strategically toward the development of a new forecast paradigm, in which the NWP forecast process will be

1) Integrated: Improvements to the four sub-components will be designed, implemented, and evaluated in a coordinated fashion, based on the concept of end-to-end forecasting.
2) Adaptive: Observation, assimilation, ensemble forecasting, and application procedures will vary depending on the case and forecast situation.
3) User controllable: All four components of the forecast process, if desired, will be driven by the case specific collective needs and requirements of users. .

NASA

NASA is the US civilian space agency and in this role has key responsibilities in meeting the nation's needs for Earth observations from space. NASA provides the bulk of the global observations employed by the U.S. Global Change Research Program, and much of the observations and research that forms the basis of international scientific assessments of climate and other environmental change. NASA and NOAA are long-time collaborators in satellite systems for use in weather observation and forecasting. Today's civilian weather satellite system was built and launched by NASA under reimbursable arrangements with NOAA, and NOAA operates this system and manages the data for use in its operational forecasting role. In addition, NASA provides global ocean observations and research in partnership with NOAA, NSF, the U.S. Navy, and other agencies. NASA is a key participant in the interagency Climate Change Adaptation Task Force.

NASA, together with NOAA, USGS, NSF, and OSTP, provides leadership for the interagency effort to develop the U.S. Integrated Earth Observation System, America's contribution to the Global Earth Observation System of Systems. NASA maintains an expansive web of partnerships with foreign space agencies and international research organizations with common goals, which substantially leverages NASA's investment, ranging from data sharing agreements to joint development of satellite missions. Many of NASA's current and planned satellite missions include international partnerships and most of NASA's field campaigns are conducted internationally, involving close interactions with our partners.

NASA's program is an end-to-end one that encompasses the development of observational techniques and the instrument technologies needed to implement them; laboratory testing and demonstrations from an appropriate set of surface-, balloon-, aircraft-, and space-based platforms; development and operation of satellite missions and production and dissemination of resulting data products; research to increase basic process knowledge; incorporation of results into complex computational models that can be used to more fully characterize the present state and predict the future evolution of the Earth system; and development of partnerships with other national and international organizations that can use the generated information in environmental forecasting and in policy, business, and management decisions. These activities are grouped into the Flight Program, Research Program, Applied Sciences Program, and Technology Program.

8) Approach and Priorities

The most innovative activities in US THORPEX lie within the overlap between the three component areas (sections 3-5). Below is an *example research time-line* that demonstrates the value in an interconnected and coordinated US THORPEX science effort. The international THORPEX activities and thrusts outlined in section 6 are used as guidance for prioritizing the timing and emphasis on elements of the US THORPEX plan..

Short-term

In general, US THORPEX research should involve the intersection of at least two of the three research thrusts identified in Figure 1. There were two international THORPEX efforts that provided significant opportunities and a short-term focus for the US research community beginning in 2008. The international aspects of, and the large US interest in T-PARC (see section 7) motivated an immediate focus on issues that are well-suited to T-PARC observations. This implied a focus on tropical/extratropical interactions (section 3.1) and the extratropical transition of tropical cyclones (section 3.2)[14]. Ideally, process and phenomena scientists will partner with science of prediction researchers to bring to bear new tools to help address the science questions raised in sections 3.1 and 3.2 (see section 4.5). Increased understanding of the relevant processes will then find their way into operational models where their impact could be assessed both in terms of traditional forecasting measures, but also using SERA-relevant measures (section 5.3). It is recognized that it is likely to take many years to build the types of relationships and understanding necessary for such coordinated research efforts, but relevant US scientists and funding agencies are encouraged to move in this direction to leverage the observations and model runs produced during T-PARC and TCS08.

The second international THORPEX project that is immediately of value to the entire US THORPEX community is the TIGGE dataset. The TIGGE dataset represents an unprecedented resource for the atmospheric science and related communities and should be immediately leveraged for advances in all three overarching science foci. TIGGE projects onto nearly all science of prediction topics (section 4), but is especially relevant for the error dynamics of ensemble prediction systems (section 4.4) and research into model inadequacy (section 4.1). Further, TIGGE provides the first real window of reliable access for the academic community to a range of operational ensemble forecasts. Process and phenomena researchers can use the dataset to identify processes that are missing or misrepresented, and the SERA community can exploit the archive to explore issues associated with communicating forecast uncertainty (section 5.2), identify high-impact weather and forecasts (section 5.4), and, in partnership with the user community begin to develop decision support tools and systems (section 5.5). TIGGE isn't simply a common resource that facilitates research in the areas of the three US THORPEX science thrusts, it also permits collaboration. As is the case in T-PARC, science of prediction tools can be brought to bear to aid process and phenomena scientists in their efforts to better understand the atmosphere system and to improve forecast systems, ideally motivated by improving those forecast errors deemed particularly relevant to users, as

[14] Our emphasis is on science goals that can best leverage T-PARC observations.

determined by SERA research. Note that both the T-PARC and TIGGE-related research initiatives can leverage off the International Polar Year (March 2007 – February 2009), offering great opportunities for global observing system design and socio-economic application oriented research.

Medium-term

Medium-term efforts have a longer time horizon and do not hinge so directly on the existing T-PARC and TIGGE THORPEX efforts.

T-PARC observations and scientific findings can be leveraged to focus more closely on tropical processes (sections 3.1-3.3), especially those likely to have midlatitude impacts (section 5.4). This will also afford the opportunity to consider midlatitude predictability issues other than ET (section 4.4). The aftermath of the International Polar Year (IPY, see section 7) can also be leveraged to focus research on the role of the polar region on high-impact forecast (sections 3.5 and 5.4).

Lessons learned from T-PARC and TIGGE will motivate focused, continued efforts to take state-dependent uncertainty into account in data assimilation and verification (sections 4.2 and 5.3). This research, along with focused observing system research on new observations, targeted observations, and observability studies (section 4.3) represent efforts that will be taking place through the medium term. In a related thrust, advances in satellite data assimilation are a pressing need (section 4.2), especially the development of frameworks and/or testbeds in which the academic community can learn about and make operationally useful contributions.

As the US THORPEX community works towards quantifying forecast value and uses that information to improve probabilistic forecasts through targeted improvements to models and forecast system components, the SERA community will be well positioned to focus on the use of forecast information in decision making (section 5.1).

Long-term

Long-term US THORPEX research thrusts build upon results and collaborations obtained through the short- and medium-term research efforts.

US THORPEX efforts should ultimately extend the polar/midlatitude and tropical/midlatitude research efforts and strive to understand the coupled interactions between the tropics, poles, and midlatitudes. By this time the aerosol community should be in a position to understand and quantify the impact of aerosols on aspects of the tropical Pacific, and on high-impact weather forecasts over the US (section 3.6).

An ultimate aim of the THORPEX program is to more tightly integrate SERA activities with combined atmospheric process and phenomena and science of prediction efforts. It is envisioned that in the longer term US THORPEX efforts, SERA observations and verification will be effectively utilized in more traditional atmospheric science pursuits

(section 4.2), and ensemble forecasting systems will have developed to the point where SERA researchers can demonstrate significant utility in the development of ensemble-based decision support tools and systems (section 5.5).

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