SCIENTIFIC PROGRAM OVERVIEW THORPEX PACIFIC-ASIAN REGIONAL CAMPAIGN (T-PARC)





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Executive Summary

Weather accounts for nearly 75% of the global incidence of disasters, nearly 66% of the property damage, ~90% of the number of people impacted and nearly 98% of the fatalities. The majority of weather disasters are due to flooding and wind storms (i.e., typhoons, hurricanes and other cyclonic storms). Weather disasters can also trigger other natural disasters, such as disease, famine, and even the destabilization of governments when developing nations try to cope with major meteorological disasters. Over the past several decades, there has been slow steady progress in mid-latitude forecasting skill with a rate of improvement of ~1 day per decade. The rate of advancement is even slower for many parameters of critical interest to society, such as the prediction of heavy precipitation. This slow, linear increase in forecast skill is being outstripped by an increased demand driven by i) an exponential growth of the world's population, ii) economies that are becoming increasingly global in nature, iii) an urbanization of society that often includes dramatic increases in population densities in areas at risk, iv) modern technological infrastructure that can be brought to a standstill with major weather disasters. Consistent with society's need for improved forecast skill, the 14th Congress of the World Meteorological Organization, representing approximately 180 nations, initiated THORPEX (The Observing System Research and Predictability Experiment) as a research program of the World Weather Research Program to accelerate the current rate of improvement in forecast skill for high-impact weather and to increase the utilization of weather products for the benefit of society, the economy and environmental stewardship.

One aspect of THORPEX is to develop research plans to meet the regional forecast needs for Asia, North America, the EU, and the Southern Hemisphere. The THORPEX Pacific Asian Regional Campaign (T-PARC) is a multi-national field campaign planned by the Asian and North American Regional Committees and their associated national science committees that address the shorter-range dynamics and forecast skill of one region (Eastern Asian and the western North Pacific) and its impact on the medium-range dynamics and forecast skill of downstream regions (eastern North Pacific, North America and perhaps stretching to Europe). The field phase of T-PARC is 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 is desirable as 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. T-PARC will take between May and December 2008 with a concentrated US measurement campaign during August and September. Asian facilities include both fixed measurements over land in the primary Asian wave-guides and research aircraft deployed near areas of interest. Studies into the T-PARC foci requires a comprehensive set of observations and effective data assimilation and modeling strategies to increase understanding and prediction of the mechanisms responsible for the generation and variation of downstream effects. These activities range from basic research by the academic community to the applied activities of the operational centers. THORPEX research tools, such as the THORPEX Interactive Grand Global Ensemble (TIGGE), will further the scientific goals of T-PARC by allowing increased access of the academic community to operational data sets and increased collaboration between these two communities. The research outcomes of T-PARC will benefit society, since both of these classes of phenomena have major societal impacts and forecasts have significant room for improvement. Research into society's response to weather disasters is also planned to be part of T-PARC. The experiment includes the participation of researchers from China, Japan, Korea, US, Canada and countries of the European Union. In addition to being a proposed THORPEX program, T-PARC has received the enthusiastic endorsement of both the International Polar Year (IPY) Joint (ICSU and WMO) Committee as part of a THORPEX research cluster for IPY, by the participants at the WMO International Workshop on Tropical-Extratropical Interactions, and by the WMO/CAS Working Group on Tropical Meteorology Research.

Table of Contents

1.0 Introduction

Meteorological disasters are of critical importance to society as weather dominates the long-term global statistics of natural disasters. Weather disasters account for nearly 75% of the global incidence of disasters, nearly 66% of the property damage, ~90% of the number of people impacted and nearly 98% of fatalities[1]. Deadly and economically devastating weather disasters impact both the developing and developed world. Society's ability to mitigate and respond to a weather disaster depends on many factors, but ultimately begins with the accuracy of the prediction and the forecast lead-time. Operational weather prediction is steadily improving for many parameters, although the progress is relatively slow. The average rate of improvement for operational measures of global predictive skill varies with the parameter predicted, but generally shows an improvement over the past several decades of order one day per decade. Thus, the four-day global forecasts of today have skill that approximately equals the skill of the three-day forecast a decade earlier. Unfortunately, the rate of improvement can be even slower for measures of forecast skill that are more closely related to societal need, such as the skill in forecasts of heavy precipitation. Societal responses to recent weather disasters in Asian and North American suggest that this slow, linear increase in forecast skill is being outstripped by an increased demand for accurate weather information given our planet's exponential population growth, economies that are becoming increasingly global in nature, an urbanization of society that often includes dramatic increases in population densities in areas at risk, and modern technological infrastructure that can be brought to a standstill with major weather disasters. Another issue is whether the frequency of meteorological disasters is increasing and the extent to which any increase is dependent on natural variability or global change. Regardless of the cause of any potential increase in weather disasters, an increased burden is being placed on weather prediction systems and society's ability to mitigate these events.

As recognition of this increasing value of improvements in weather prediction skill, the ~180 nations of the 14th World Meteorological Congress established the THORPEX (The Observing System Research and Predictability Experiment) research and development program. Specifically, THORPEX is a component program of World Weather Research Program within the World Meteorological Organization (WMO/WWRP). The THORPEX Science (Shapiro and Thorpe 2004) and Implementation Plans (EG-TIP 2005) outline an ambitious research agenda designed to accelerate improvements in the accuracy of 1-day to two-week forecasts of high-impact weather for the benefit of society, the economy, and the environment. THORPEX also seeks to improve the utilization of weather products, since, for example, the mitigation and response to a weather disaster also depend on decision-making, communication, allocation of existing resources, and the ability of governments and aid organizations to mobilize a response. The international component of THORPEX results from the realization that forecast improvements on the 1 to 14-day time-scale rest on global prediction models and the global observing system. The core objectives of the international THORPEX program (see Shapiro and Thorpe 2004 and http://www.wmo.int/thorpex) include advancing knowledge of the global-to-regional influences on the initiation, evolution and predictability of high-impact weather and contributing to the development of advanced data assimilation and ensemble prediction systems, and to the design of the future global observing system. The core objectives include international field campaigns focused on regional forecast problems facing Africa, Asia, Europe, North America and the Southern Hemisphere. For example, North America experiences, with some frequency, a variety of weather disasters with individual events that cause damage over a billion dollars and present a significant risk to public safety. Such weather events include floods, the dry gusty conditions of fire weather, severe convection outbreaks, tropical cyclones (TCs), and winter storms capable of freezing rain, high winds, snow, freezing rain, and heavy rainfall. For the Asian nations of the Pacific Rim, a key forecast problem is to better mitigate and respond to heavy rainfall and TCs, since these events are their most damaging natural disasters. The experimental design is illustrated with Fig. 1.

Recent research clearly points to the western North Pacific playing an important and unique role in defining many characteristics of the middle latitude circulation of the Northern Hemisphere. Over the western and central North Pacific, baroclinic energy conversion generates a large amount of kinetic energy

[1] See for example the OFDA/CRED international disaster statistics at http://www.cred.be

Collaborative Campaigns and Research Facilities for PARC

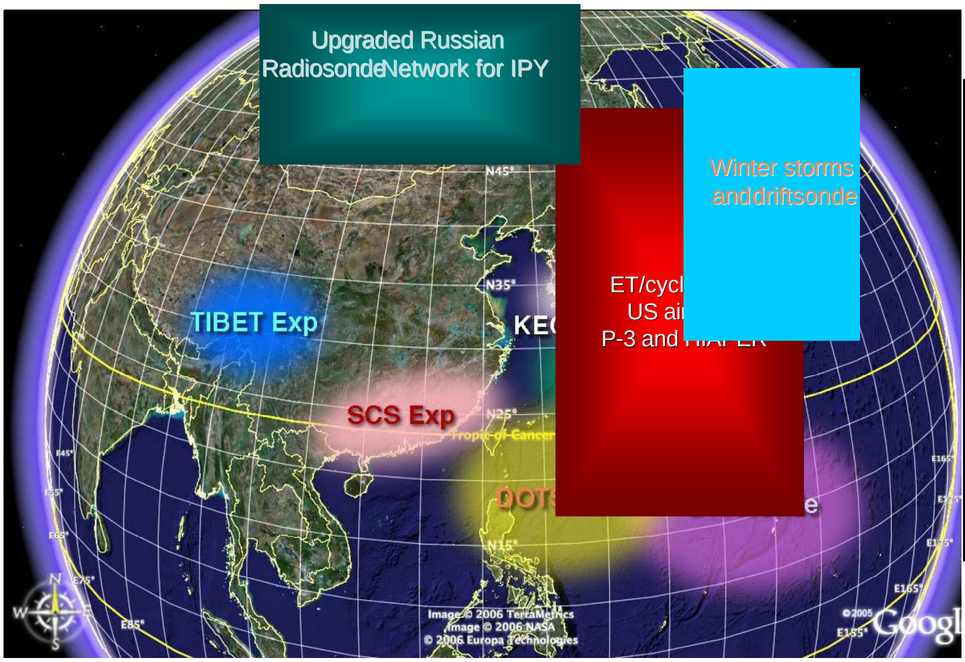

Figure 1: An overview of the experimental design. T-PARC includes facilities explicitly deployed for the experiment, but also includes collaborate with other measurement campaigns taking place in the 2008 time-frame.

that is instrumental in maintaining the storm tracks downstream over the eastern North Pacific, North America, and North Atlantic (Chang and Yu 1999; Orlanski and Sheldon 1995; Nielsen-Gammon and Lefevre 1996; Danielson et al. 2004). This implies that many of the high-impact weather events that occur over North America have a dynamical origin upstream over the western North Pacific basin. Furthermore, forecasts of downstream developments in the storm track over the eastern North Pacific that impact western North America often contain large errors (McMurdie and Mass 2004). Therefore, it is hypothesized that improved treatment and increased understanding of the dynamical linkages between the development of high-impact weather events that occur over North America to specific weather systems upstream over the western North Pacific will lead to a significant increase in forecast skill of these downstream events. Indeed the calculation of average forecast sensitive areas for prediction of high-impact weather events over North America for the time-scales ranging from ~2 to 5 days show a strong sensitivity to conditions over the western and central portions of the North Pacific basin (e.g., see Figure 4a, b of Reynolds and Gelaro 2001). Forecasts of weather events over Alaskan and portions of the Canadian Arctic also show a strong sensitivity to conditions over the North Pacific (e.g., Szunyogh 2002).

One mechanism by which events over the western North Pacific may trigger downstream responses over the eastern North Pacific and North America is via upper-tropospheric wave packets (Fig. 2). Hakim (2003) and Chang (2005) have provided evidence that wave packets on the primary Asian waveguides increase the likelihood of the development of intense cyclones over the North Pacific. There are also indications that the wave packets are, in turn, invigorated by the cyclogenesis events, which makes their impacts farther downstream over North America potentially more significant. Hakim (2003 and 2005) demonstrated that upper-tropospheric, eastward-propagating wave packets are a dominant source of forecast errors over the North Pacific. The forecast error patterns move with an eastward group velocity of about 30^o-40^o per day, which means that the leading edge of increased forecast error can reach western North America in about 3 days and the Great Lakes region in 4-5 days. An example of Rossby wave trains apparently generated/amplified by high-impact events over the western Pacific associated with the lifecycle of TCs is shown in Fig. 2. These wave trains were associated with three major weather disasters on the western coast of the US that were relatively poorly predicted. Thus, accurate short-range (<3 days) predictions of aspects of the lifecycle of a TC near the east Asian coast will mean an increased likelihood of accurate medium range (2 to 7 day) predictions of floods, wide-spread severe weather outbreaks and damaging extratropical cyclones downstream over North America. This connection is the underlying focus of the THORPEX Pacific-Asian Regional Campaign (T-PARC). This document discusses the scientific motivation for T-PARC, while a separate Experimental Design Document discusses the experimental strategies designed to meet these scientific needs.

T-PARC is THORPEX's first scale-interaction experiment and perhaps the community's first field effort focused to a large degree on medium range weather phenomena and prediction. The experiment brings together research facilities from Asia, Europe and North America with participation ranging from the academic research community to scientists at the operational centers. We envision the T-PARC experiment to be embedded within a longer-term observational, theoretical and numerical THORPEX research focus on the scientific goals associated with Pacific Predictability. These scientific goals include:

1) Improved understanding of the dynamics and factors that limit the regional and downstream predictability of high-impact weather events (e.g, persistent deep convection, typhoons, extratropical transition events, and other intense cyclogenesis events) that occur over the North Pacific and adjacent land areas;

2) Understanding of forecast error growth and the role of scale interactions;

3) Developing, advancing, and evaluating data assimilation strategies in concert with superior utilization of satellite measurements with the goal of improving prediction of high-impact weather events both over the Pacific rim and downstream locations;

4) Testing the improvement in local and downstream forecast skill afforded by high-resolution, non-hydrostatic modeling of these high-impact weather events;

5) To quantitatively predict the reduction in forecast error variance due to supplemental/targeted observations and to test new strategies and observational systems for adaptive observing and modeling;

6) Improving the interpretation and utility of ensemble forecast systems; and

7) Understanding and improving society's response to weather disasters, including the appropriate use and evaluation of probabilistic information, and estimating the "value" to society that results from improvements in forecast skill.

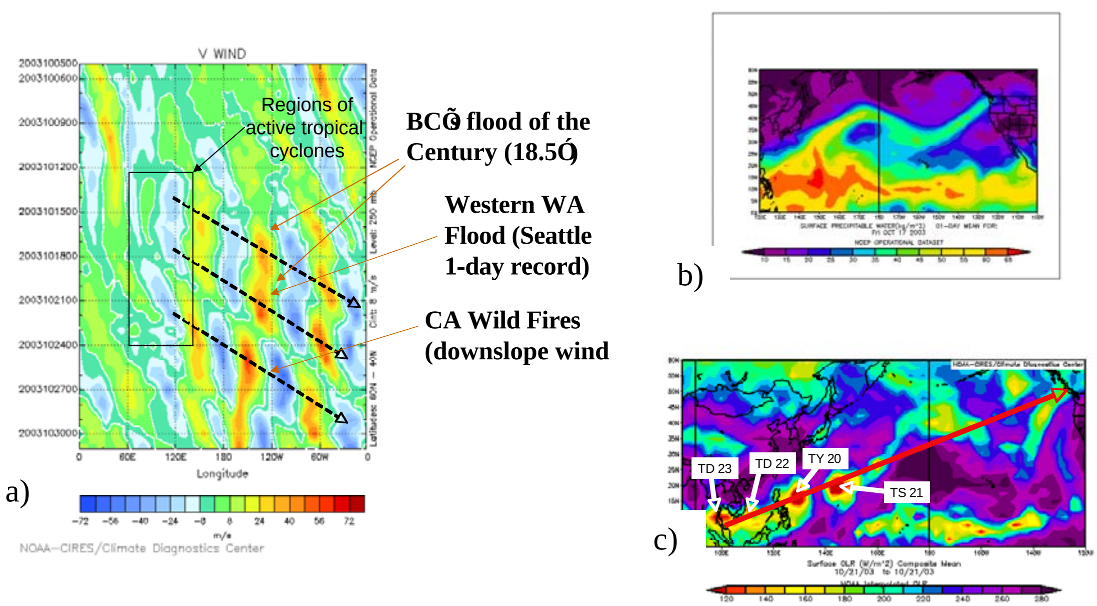

Fig. 2 a) Time-longitude diagram of 250 hPa meridional winds (m s^{-1}) from 0000 UTC 5 October 2003 – 1200 UTC 31 October 2003 (Figure made at http://www.cdc.noaa.gov). The diagonal dashed lines highlight eastward-moving, upper-tropospheric wave packets that originated over eastern Asia. Three relatively poorly predicted major west coast weather events are shown. b) Integrated water vapor on the 17th of October coinciding with the record flood in British Columbia showing the tropical moisture plume from the western Pacific being advected into the region with this first Rossby wave train. c) Outgoing longwave radiation for the 21 October 2003 showing four tropical convective events (at this time one typhoon, one tropical storm and two tropical depressions) in the region of the genesis/intensification of the Rossby wave trains. The red arrow shows the propagation wave train from the tropical convection as suggested in the OLR for the western

2.0 Advancing the Knowledge of Initiation, Evolution and Predictability of High-Impact Weather

This section describes the scientific issues associated with advancing knowledge of high-impact weather in the vicinity of the Asian Pacific rim and the generation of high-impact events over North America, the Arctic and other locations downstream. Improved forecasting accuracy for all these events would have significant societal benefits.

2.1 Advancing knowledge of extratropical transitions and their impact on forecast skill

One aspect of the Asian THORPEX interest in typhoons is the improved understanding and prediction of typhoon-recurvature, which is a critical forecast problem for the densely populated Pacific Rim from the Philippines to Japan and Korea. The poleward movement of a typhoon in the western North Pacific into the midlatitude baroclinic zone and jet stream presents another critical forecast challenge for Asian THORPEX interests as the initial development of an extratropical cyclone can also result in strong winds, high waves, and heavy precipitation. This extratropical transition (ET) is a key link between the North American and Asian THORPEX societal needs and research interests, as such storms also have dramatic meteorological effects downstream through triggering and amplifying upper-level wave trains. These wave trains subsequent propagate rapidly away from the ET storm itself generating high-impact events over North America (e.g., the U.S. wild fires in Fig. 2). In some cases, the wave-train path and high-impacts are over the continental United States, while at other times the wave-train path is more poleward toward Alaska and Northwest Canada. Thus, the ET storms have a link with the Arctic and the International Polar Year (IPY), because of the path of the wave-train, the sensitivity of the ET process to higher latitude conditions and the direct impact of ET storms on the Arctic as they move northward.

The primary scientific issues associated with ET cyclogenesis and downstream impacts of ET events may be placed in a framework of mechanisms, predictability, and strategies for increasing predictability. Periods of low predictability are expected from uncertainty theory because the ET involves complex physical interaction within three interrelated regions (Fig. 3). All three regions of the ET process likely play important roles in the mechanisms responsible for downstream impacts due to ET. A Rossby wave response (e.g., triggering and/or amplification) may be forced by several mechanisms in an ET environment. Deep convection in the remnant TC core may contribute to advection of vorticity due to the divergent wind (Sardeshmukh and Hoskins 1988) and the impingement of a balanced large-scale low potential vorticity anomaly on the midlatitude tropopause. The enhanced upward motion along sloping isentropic surfaces that exist at the TC-midlatitude interface (Harr and Elsberry 2000a,b) may contribute to generation of diabatic Rossby waves (Parker and Thorpe 1995) in an ET environment (Agusti-Panareda et al. 2005). Finally, the midlatitude impact region provides the avenue by which the wave energy impacts the midlatitude circulation into which the decaying TC is moving as the predictability is dependent on the phasing between the decaying TC and the midlatitude circulation (Klein et al. 2002). This uncertainty in predicting the initial Rossby wave response together with the potential amplification of the wave train by subsequent cyclogensis events downstream causes the impacts of an ET event to be fast-spreading, far-reaching, and associated with intense downstream weather events with reduced predictability. Thus it is not surprising, that ET events over the North Pacific have been observed to coincide with periods of reduced forecast model skill (Jones et al. 2003).

The complex physical and dynamical processes during ET are extremely sensitive to sources and impacts of initial condition errors and forecast model uncertainty. Therefore, factors that impact forecast model error growth downstream of an ET event must be identified. Research questions have also arisen from the operational centers experience with ET storms and the associated loss of predictability. For example, certain centers insert a synthetic vortex into the initial conditions in a process called bogusing. However, little is actually know about the 4-D nature of the vortex during the ET process and observational knowledge will assist those centers that rely on these bogusing techniques. Preliminary research[2]

[2] Presented by J. Evans at the International Workshop on Extratropical Tropical Interactions, Dec. 2005, Perth.

suggeststhat current techniques may delay forecasts of ET. Other centers forgo the insertion of a vortex and rely on data assimilation. However, the ECMWF (Martin Miller, ECMWF personal communication) notes that the assimilation process in the vicinity of ET storms can systematically reduce the intensity of the ET vortex, which suggests the need for improvement of the data assimilation process in the vicinity of ET storms. Other issues include how well centers predict the evolution of the TC and ET vortices and the extent to which resolution is a shortcoming. Tests of existing and new assimilation systems and high-resolution research models will prove valuable to address these questions.

To increase predictability associated with ET and its downstream impacts, the contributions of key *in-situ*, targeted, and adaptive satellite measurements to a forecast model must be established, which will require development and testing of advanced data assimilation and ensemble techniques applied to ET events. Because of the varied physical characteristics of the three primary ET regions (Fig. 3), a mix of data types and platforms is being explored to increase the predictability of ET-related weather. Since the TC core region and the TC-midlatitude interface region may be sources of Rossby wave-like disturbances, it is important to establish optimal data sampling strategies for these regions. T-PARC proposes a two aircraft strategy with the NRL P-3 carrying the ELDORA Doppler radar investigating the vicinity of the decaying tropical cyclone and the middle latitude interface with the middle latitude impact region and the interface sampled by the HIAPER aircraft carrying the DLR wind lidar. Both aircraft would have dropsonde capability. Such a strategy would allow the development and testing of targeting strategies applied to ET and source regions of downstream-propagating waves, while providing the data sets to support satellite data assimilation and dynamical studies. A comprehensive program of study is required such that increased understanding of the mechanisms responsible for the generation and variation of downstream effects is related to an increase in predictability via improved sampling strategies, data assimilation techniques, and ensemble systems such that downstream impacts due to initial condition errors and model uncertainties associated with an ET are reduced. The western Pacific region is ideal for studying ET storms as the average number of TCs over the Pacific is similar in magnitude to the record years over the Atlantic.

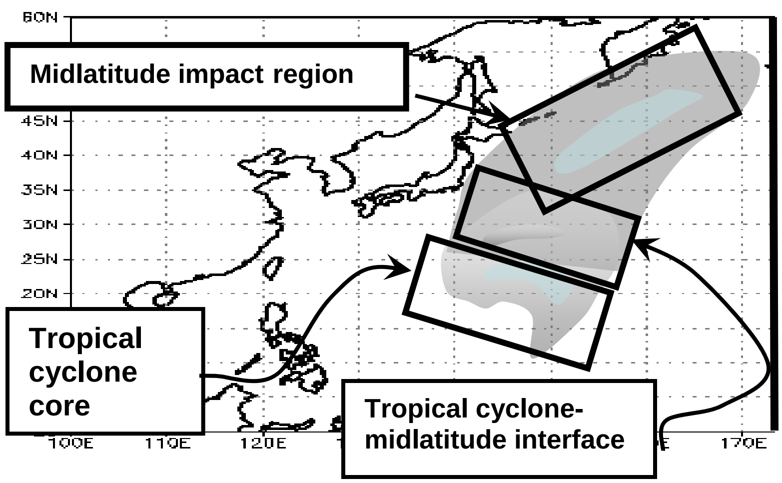

Fig. 3. Schematic of three regions associated with the ET of a decaying TC over the western North Pacific. The light gray shaded region represents overall cloud patterns. Darker shading within the light gray areas indicates regions of concentrated cloud amounts defined by convection in the TC core region, large-scale precipitation in the TC midlatitude-interface region, and cirrus in the midlatitude impact region.

2.2 Advancing knowledge of upper-tropospheric wave trains and their impact on forecast skill

T-PARC'a proposed contributions to the study of ET events and their downstream effects were discussed in detail in section 2.1. In this section, the focus is on the general subject of the effects of *upper-tropospheric wave packets propagating from Asia and the Northwest Pacific*. Recent research, based on modern statistical techniques applied to reanalysis data sets, diagnostic techniques applied to numerical weather forecasts, satellite imagery, idealized model experiments, and case studies with state-of-the-art numerical weather prediction models, suggests that these regions play a unique role in shaping the circulation of the Northern Hemisphere (NH) extratropics. The evidence for this relationship includes i) the role of the maintenance of the storm track by the generation of a vast amount of kinetic energy by baroclinic energy conversion in the western and central North Pacific, ii) studies of mid-latitude analysis and forecast errors suggest that errors in the western North Pacific spread downstream at a speed of about 30 m s^{-1}, with their effects reaching the U.S. and Canada within a few days, and iii) studies into the skill of North American and Arctic forecasts show a strong sensitivity to areas over the NW Pacific. While the ET storms discussed earlier are one source of these wave trains and ET storms are relatively common over this region, other events in the western Pacific and east Asia (e.g., intense cyclogenesis, persistent tropical convection) result in a Rossby wave response. It is not surprising then that many forecast failures in the prediction of Northern Hemisphere extratropical storms have their roots in the western and central North Pacific. The number of forecast failures is significant as average errors, for example, in the 48-h prediction of west coast winter cyclones can be several 100s of kilometers (McMurdie and Mass 2004). The proposed research aims to reduce the number of these forecast failures by improving the analysis and modeling of the processes that initiate and maintain the primary cyclogenesis in the western and central North Pacific and of those that propagate the effects of the primary cyclogenesis downstream.

Recent papers (Hakim 2003 and Chang 2005) have provided strong statistical evidence that the presence of wave packets on the two Asian waveguides increases the likelihood of the occurrence of deep cyclones over the western and central North Pacific. The northern waveguide crosses through Siberia, while the southern waveguide runs along the subtropical jet across southern Asia (Chang and Yu 1999; Hoskins and Hodges 2002, also Fig. 4). It has been hypothesized (Chang 2005) that wave packets originating from the northern waveguide trigger cyclogenesis, while wave packets originating from the southern wave guide only enhance, but do not trigger, cyclogenesis. There are also indications that these wave packets are in turn invigorated by the cyclogenesis events, which makes their impacts farther downstream potentially more significant. We note that strong statistical evidence exists for the close relationship between upper-tropospheric wave packets originating from the Pacific region and high precipitation events in Europe in the boreal autumn and winter (Scwierz et al. 2004).

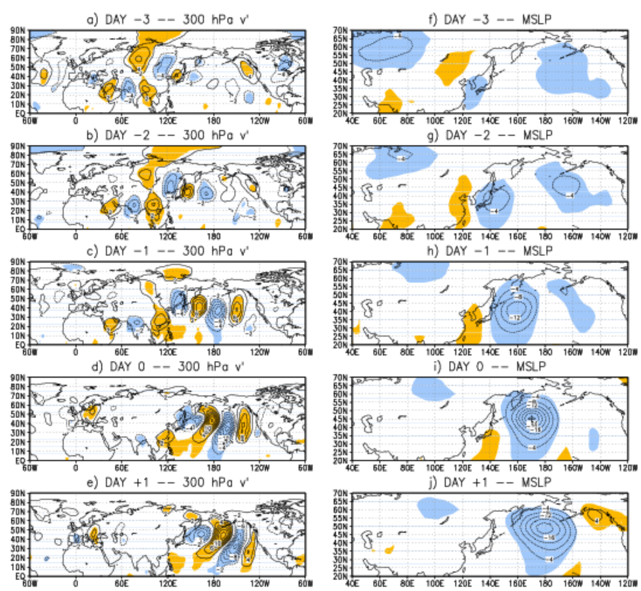

Fig. 4. Time lagged composites, based on mean sea-level pressure (MSLP) anomalies. The statistical inference is based on data from 24 winter seasons from 1979/1980 to 2002/2003. The anomalies are defined by deviations from the seasonal mean. At each grid point, the composite is done by averaging all instances when the MSLP anomaly at the grid point 45^{0}N, 170^{0}E falls within the lowest 5% on day 0. (left) The 300 hPa anomaly of the meridional wind component; contour interval 2ms^{-1}. (right) MSLP anomalies, contour interval 4 hPa. Color shaded regions correspond to 95% confidence level based on a two-tailed t test with 100 degrees of freedom (approximately equal to number of independent cyclones composited over the 24-year period). (Figure adapted from Chang 2005.)

The observational coverage in the region of the waveguides will also be improved through collaborative measurements programs such as: (1) The funded CHERES II effort will provide additional Chinese radiosonde observing stations over the Tibetan Plateau within the southern waveguide. (2) Upgrades to the existing, but currently underutilized, Russian radiosonde stations in Siberia perhaps in an enhanced, or even adaptively controlled, observations during the T-PARC field campaign. (3) The enhanced radiosonde network that will be deployed to support air quality forecasts during the Beijing

Olympics in the summer of 2008 could be further operated to support a field campaign that would run well into the cold season (e.g., until the end of December). Aside from the observations in the vicinity of the ET events, the additional US measurements planned by T-PARC during November and December will extend from the vicinity of the systems to downstream locations over the Pacific providing important dynamical and physical insight into the northern wave-guide and the triggering/enhancement of Rossby wave trains. Such measurements planned by T-PARC and collaborating programs will also result in an improved analysis in regions where forecast skill and the initial conditions are often lacking. These data sets would also be useful for satellite assimilation studies, understanding/reducing model errors, and investigation into observing strategies as will be discussed later in this document.

2.3 Advancing knowledge and the predictability of the genesis and evolution of tropical cyclones

One of the primary foci of the THORPEX Asian Regional Committee is a strong need for accurate predictions of TC track and landfall with the goal of improved prediction and extending the forecast lead-time. The life cycle of a TC may be divided into several phases, including cyclogenesis, development and motion of a mature cyclone, the subsequent extratropical transition and/or landfall. Each phase brings a new spectrum of issues related to physical and dynamical processes, and their predictability. In this subsection, we focus on the TC during its infancy through to its fully tropical phase. Only a small fraction of tropical disturbances eventually become TCs. The challenges of advancing understanding of the dominant mechanisms and factors that limit the predictability of tropical cyclogenesis in a broader context have recently received increasing attention in both research and operational prediction. For example, the leading scientists from the research community and operational centers that comprise the WMO/CAS Working Group on Numerical Experimentation (WGNE) recommended that the operational centers provide statistics on genesis. Accurate forecasts of genesis would open up the possibility of greatly increasing the time scales of when typhoon predictions have utility with a variety of benefits (e.g., ocean shipping, energy production, planning and carrying out evacuations, rescue and early recovery efforts especially for urban centers, organization of international aid) as well as improving downstream predictions. Initial studies have shown some level of skill at relatively long lead times, but this research also raise questions about false alarms and missed events. The ability of numerical models to accurately represent physical quantities relevant to genesis such as warm core magnitude, the vertical wind shear, convective instability and mid-level moisture requires assessment. Unfortunately, the lack of detailed data sets and hence quality of analysis compromises our ability to evaluate critical aspects of model performance and confirm or deny current hypotheses. The combination of high-resolution, cloud-resolving models in conjunction with in-situ observational data collected during T-PARC is necessary to address the aforementioned issues on the processes, scale interactions and predictability of tropical cyclogenesis. Summaries of the recent forecast skill in tropical cyclones includes (McAdie and Lawrence 2000; Aberson 2001; Powell and Aberson 2001; Franklin et al. 2003).

The theoretical basis behind the physical processes and interactions in the genesis process is yet to be fully elucidated. A variety of competing theories are being investigated including the ability of deep convection to concentrate low-level vorticity within regions where pre-existing vorticity exists (Montgomery and Enagonio 1998, Hendricks et al. 2004, Montgomery et al. 2006, Harr et al. 1996a), the role of pre-existing middle level vortices generated by mesoscale convection systems (Bister and Emanuel 1997, Harr et al. 1996b), and dynamical mechanisms such as applications of the wave accumulation as proposed by Webster, Holland and collaborations. The western Pacific region is a challenging region in which to understand the physical and dynamical processes that control the genesis process and where the genesis of multiple systems can occur with changes in the Asian monsoon trough. Genesis in this region is also enhanced by processes over the equatorial tropics (i.e., the Madden-Julian Oscillation and westerly wind bursts), and the remnants of middle latitude processes (Tropical Upper-Tropospheric Troughs). A variety of critical questions arise for this region, such as (i) Which synoptic processes create initial vorticity?; (ii) What is the relative importance of vorticity at the surface and middle levels?; and (iii) To what degree is genesis influenced by synoptic disturbances or mesoscale systems? (iv) How well is the genesis environment and the response of deep convection to this environment simulated? (v) How different are the factors governing genesis over the Atlantic and western Pacific?

As the TC develops from its infant stages, the key issues switch to predicting the storm motion (track) and changes in the structure, intensity and rainfall distribution. It is noteworthy that while numerical forecasts of cyclone track over the Pacific and Atlantic have improved steadily over the past decade, forecasts of their intensity and structure have not. The current consensus is that cyclones are generally steered by the deep-layer (850-200hPa) mean wind, and the existence of a relationship between the layer depth to intensity is open to question (Aberson 2003). A recent investigation of the dynamical sensitivity of global model cyclone track predictions to changes in the initial conditions revealed that track forecasts are sensitive to changes in the analysis both local to the cyclone and in approaching troughs far upstream (Peng and Reynolds 2006) with conditions near one cyclone impacting the another despite the fact that the two systems were well over 1000 km apart. For northwest Pacific typhoons, the trough is usually over eastern Asia. For Atlantic hurricanes, the incipient upstream mid-latitude trough may be linked to Rossby waves over the Pacific, especially on time-scales of >3 days, and hence T-PARC observations may help improve medium-range forecasts of Atlantic hurricanes. While one may speculate that the TC motion is most sensitive to changes in the initial conditions in the steering flow, the structure, and hence its intensity, is a function of many physical processes, including air-sea interaction, deep convection, and cloud microphysics. The extent to which each process controls the dynamic and thermodynamic structure of the cyclone is not well known. An improved knowledge of the dominant factors that limit the predictability of intensity and structure would assist efforts to improve the pertinent model parameterizations.

Observations relevant to genesis studies that are planned during T-PARC include driftsonde measurements in the monsoon trough before and during the genesis period, Asian dropsonde aircraft and some flights of the NRL P-3 with ELDORA and dropsondes. Using these observations and accompanying satellite data, global and mesoscale numerical simulations, the following questions on TC predictability may be addressed: (i) what are the key length-scales of interest in TC track and intensity prediction?; (ii) do errors in the initial conditions dominate errors due to model resolution and physics parameterizations, in track and intensity forecasts?; (iii) are new ensemble-based methods (using TIGGE) able to produce improved probabilistic forecasts and reveal new insights into TC dynamics?; (iv) what is the dynamical basis, and what are the key locations and variables for collecting targeted observations to improve forecasts of Pacific and Atlantic TCs?; and (v) is a bogus vortex necessary for accurate TC initialization?; (vi) what mechanisms cause the orographic impacts on typhoon tracks, such as the looping in the vicinity of Taiwan, and can the track variations be better predicted? The data from the THORPEX Grand Global Ensemble (TIGGE) will be extremely useful in this regard as it will allow researchers to have direct (and for the first time easy) access to the ensemble forecast outputs from 11 major operational centers that will contain all these different parameters as well as information as to whether genesis took place in these models.

3.0 Development and Testing of Strategies to Improve Predictability

This section describes the research associated with strategies to advance forecast skill for the type of weather events investigated by the T-PARC campaign as the influence of tropical convection and associated scale interactions on extratropical circulations remains an unsolved problem. A central tool to address relevant predictability issues such as reducing analysis and forecast errors, observational network design, model design and calibration, is data assimilation (DA). Related adaptive sampling methods combine DA of new observations (e.g., new satellite instrument channels) with multi-scale dynamics. The T-PARC offers a focus for innovative basic and applied research in areas related to data assimilation and adaptive measurement techniques. In addition, T-PARC will be a focal point for testing whether higher resolution modeling will improve the prediction of Asian weather systems and downstream weather events. For example, if a high-resolution simulation improves the prediction of a typhoon track and its movement into the middle latitude westerlies, one would expect an improvement in the simulations of any developing ET event and its downstream effects because one key aspect of the uncertainty in the forecast has been removed. T-PARC will also be an excellent opportunity to examine the impact of improved representation of the large-scale flows on regional simulations. Work beginning in these areas prior to the field phase would prove extremely valuable.

3.1 Improved use of satellite data

Improved assimilation of satellite observation data is essential to T-PARC (and overall THORPEX) goals for deterministic and ensemble weather prediction, and also for establishment of high-quality atmospheric analyses required for climate monitoring. The Pacific basin is a region of particular importance for satellite data assimilation because it is a vast area in which in-situ observations are sparse or non-existent, and it produces a wide variety of high-impact weather events that affect adjacent heavily populated areas of Asia and North America. Recent and ongoing increases in the amount, quality, and variety of satellite atmospheric observations represent a tremendous opportunity for progress in numerical weather prediction, including improved local and downstream forecasts of devastating TCs, subsequent ET events and intense winter cylogenesis. Currently, space-based observations represent more than 80 percent of all data assimilated for operational numerical weather prediction. The ultimate goal is assimilation of satellite data at the scale of the observations. Progress towards this goal depends on improved techniques for satellite data assimilation and on increases in computational capability. Whereas developing new satellite technology represents an investment of billions of dollars by many nations, only a very small percentage of this large technology investment has been spent on research to make better *use* of the satellite data that are provided. THORPEX can accelerate progress in satellite data assimilation that is needed to improve weather prediction and climate monitoring.

Studies of weather predictability show that key analysis errors often occur in cloud-covered areas where satellite data are currently not well utilized. A recent working group sponsored by the U.S. Joint Center for Satellite Data Assimilation concluded that the assimilation of cloud and rain-affected observations carries a large potential for forecast improvement, but will not be realized without a strong combined effort by the observation, modeling and data assimilation communities. T-PARC can focus these communities on an international level toward the goal of improved use of satellite data for numerical weather prediction. Fig. 5 illustrates several key issues associated with the use of satellite data within clouds and precipitation. T-PARC research will seek to improve the calibration and validation of space-based observations, using in-situ observations from radiosondes, dropsondes, aircraft, and other platforms to validate instrument bias and observation error in satellite temperature, wind, and moisture observations. The T-PARC effort will focus in particular on cloud-covered regions, where the most severe limitations on satellite data currently exist. The observations obtained in the field campaign will also be used to refine estimates of background error that are required for accurate assimilation of satellite observations, and to validate model moist physical parameterizations.

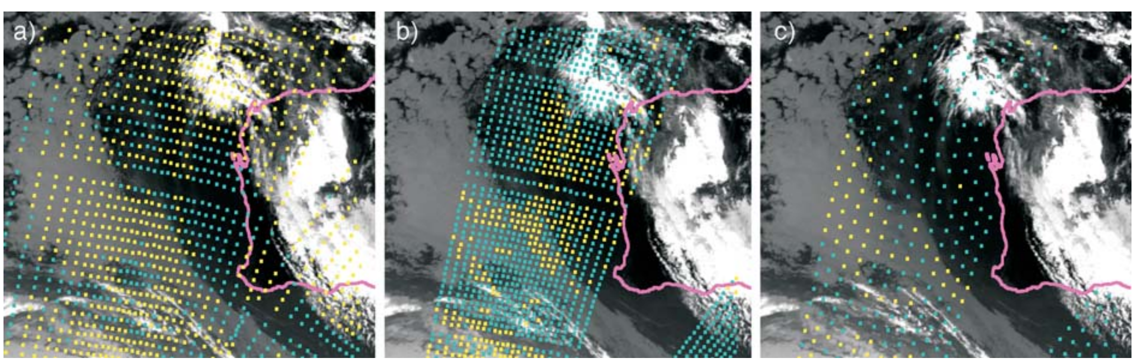

Fig. 5: The use of satellite radiance data in current data assimilation systems is restricted by clouds and precipitation with the identification of "clear-sky" depending on the measurement sensitivity to cloud liquid water. This figure shows data coverage for the used (cyan) and discarded (yellow) data in ECMWF's operational 4DVAR system for 20030126, plotted on a 2330 UTC GMS cloud image. (a) Infrared tropospheric measurements (HIRS channel-7) used only in cloud-free areas, leaving large data voids. (b) Microwave temperature-sounding measurements (AMSU-A channel-6) used in most non-precipitating areas (provided accurate modeling of surface emissivity effects). (c) Moisture-sounding microwave data (SSM/I channel-7) are discarded in areas with thick clouds or precipitation. T-PARC will further research aims at extending the direct radiance assimilation methods in clouds and precipitation. From Andersson et al. (2005), copyright held by American Meteorological Society, included here by permission of E. Andersson.

The impact of the observation data on deterministic and ensemble weather forecasts will be evaluated using state-of-the-art assimilation and forecast systems, and will include tests of new data-thinning and satellite channel selection procedures. The general measurement strategy with in-situ observations over a season covering the typhoon genesis region, the areas surrounding mature TCs, and ET storms and in winter cyclogenesis events will provide unprecedented data sets for the use of in-situ measurements during a period when research (i.e. COSMIC, EOS/Aqua, Aura, Calipso, Cloudsat) and operational (e.g., POES, DMSP, METOP, China's FY3 series, the Russian Meteor series, EUMETSAT, GOES and MTSAT) networks are increasing. Measurements from GPS (COSMIC, GRAS) occultation also provide a non-biased source for observation calibration, at least in the stratosphere and parts of the upper troposphere. The in-situ measurements, in turn, will provide increased knowledge of the accuracy of these GPS measurements in the lower troposphere in cloudy regions, areas of active deep convection and in the moist tropical boundary layers. Finally, observations from the Japanese MTSAT geostationary satellites and GOES-West will be collected in rapid-scan mode to derive rapid-refresh imagery, high-resolution wind fields from state-of-the-art automated feature-tracking methods during T-PARC intensive observing periods.

3.2 Advancing Assimilation Techniques and Forecast Impacts

Recently developed four-dimensional assimilation methods, such as the Ensemble Kalman Filter and 4D-Var, have new capabilities for the description of developing dynamical features. An understanding of the inherent qualities and limitations of each method may be gained via a combination of Observation System Simulation Experiments (OSSEs), Observing System Experiments (OSEs), and operational frameworks. T-PARC will provide a focal point for the community to conduct experiments to advance data assimilation techniques through testing these advances on a challenging set of problems with significant societal and economic benefits for a large portion of the world's population. The DA issues that require attention include:

(a) Cycling of flow-dependent error covariance matrices. An assessment of the benefits of using background error covariance matrices based on the weather regime versus current quasi-static formulations requires further exploration. In tandem, adaptive data quality control methods based on the uncertainty in the background estimate may be designed. Flow-dependent error covariance matrices may also be used as a new tool to investigate the primary dynamical mechanisms that play a role in the development of features such as extratropical cyclones and could be important in the assimilation of flows with unusual geometries – such as the cylindrical structure of a mature TC.

(b) Model uncertainty. The presence of model error limits the quality of atmospheric analyses. New studies to explore different ways of representing model-related uncertainty in different DA methods are necessary. For example, stochastic parameterization schemes in 4d-Var and ensemble DA, and the use of a weak constraint in 4d-Var can be explored. The removal of model bias from the background error covariance matrix is another problem that requires addressing.

(c) Multi-scale observations and increments. Although operational global weather forecasts are approaching mesoscale resolution, the DA systems that supply initial conditions for these forecasts are still calibrated for the synoptic scale. An important near-term challenge involves the scale-consistent assimilation of observations from the mesoscale through the synoptic and planetary scales. One essential aspect of this problem is the accurate specification of a fully flow-dependent background error covariance matrix that accounts for the greater spatial and temporal variability, and observation density, on the mesoscale. The necessary adjustments in DA such as covariance localization should also be scale-dependent; e.g., different localization length scales for the scales contained in the background error covariance. Future research is needed to extract the useful information from state-dependent covariances in flows containing a wide range of spatial scales.

(d) Correlated observation error statistics. The majority of operational NWP centers presently do not account for correlated observation errors. However, cross-channel measurements in satellite-based radiometers and sounders are likely correlated, and hence only a limited amount of information is presently being extracted from these sources. If a DA scheme can be generalized to account for cross-channel and also horizontal observational error correlations, a potentially very large number of observations can subsequently be assimilated. In fact, available computing facilities will likely pose a limit to the number of hyper-spectral observations that can be assimilated. Thus, among the wealth of available observations, adaptive data-thinning methods are required to target the most useful observations for assimilation.

(e) Linearity. Conventional DA methods assume Gaussian error statistics and linear dynamics. The extent to which these assumptions are compromised in regime transitions and features of high gradient such as jet streaks, convective regimes, and frontal cyclones requires further evaluation.

3.3 Adaptive sampling

It is important to build on previous targeting results, including the operational programs in the US for winter storms and hurricanes, DOTSTAR, and the previous A-TREC program over the Atlantic, when deploying resources to investigate adaptive sampling strategies during T-PARC. Three general topics arise concerning adaptive targeting during T-PARC.

(1) Adaptive targeting of tropical cyclones for improved prediction: A focus of the THORPEX Asian Regional Committee for T-PARC on adaptive measurements for typhoon prediction is prompted by successful dropwindsonde observations in the synoptic environment of typhoons (Wu et al. 2004; 2005) and hurricanes (Aberson 2003) to improve operational forecasts. Studies such as Aberson (2003) have shown that incorporation of dropwindsonde data around TCs approaching landfall has significantly increased the rate of increase in forecast skill. Although these aircraft-borne observations have been shown statistically to improve the accuracy of global model track forecasts (i.e., the average improvement typically ranges between 20 and 30%), the scientific premise of how observations influence forecasts of TC motion and structure remains unexplored. Another basic research topic to be explored is increase the scientific understanding of the significant differences in the prediction of targeting locations by different targeting techniques (Majumdar et al. 2006). The techniques include sensitivity to conditions near the cyclone, but sometimes also include features within the middle latitudes. For the first time in a targeting experiment, we have the opportunity to oversample to better understand the impact of following different targeting experiments. Moreover, the benefits of assimilating additional observations from different platforms, including airborne and satellite remote sensing, on multiple spatial and temporal scales using novel data assimilation methods have not been studied. For example, studies will be provided to determine the relative contributions from in-situ adaptive measurements versus new satellite systems such as COSMIC or whether complementary approaches (in-situ winds only) should be developed.

(2) Impact of adaptive measurements for tropical cyclones on the predictability of downstream events: Section 2.1 presents evidence that ET events are a major source of downstream uncertainty as well a trigger for the downstream generation of high-impact weather. Since research to date suggests that track forecasts of tropical system will improve through adaptive measurements, the question arises as to whether adaptive measurements taken to improve typhoon track prediction will improve the prediction of ET and downstream effects? Such an improvement is expected, since one would expect improvement in the prediction of where and when a TC enters the middle latitude westerlies. For this reason adaptive measurements will be taken during the recurvature of the TC. Alternate hypotheses are that the uncertainty lies with the middle latitude westerlies, a lack of resolution of the vortex moving into the westerlies or in the cyclogenesis process itself. The ensemble sensitivity for the ET of Super Typhoon Tokage is shown in Fig. 6.

(3) Adaptive techniques for middle latitude events: The case for in-situ targeting in winter storms is the subject of active debate, since the results are generally positive, but with the exception of a few events, relatively weak. Many of the issues associated with targeting of middle latitude systems are discussed in Langland (2006), Shapiro and Thorpe (2004) and in the report from the THORPEX Data Assimilation and Observing System Working Group (Rabier 2006).

(a) Techniques. In tandem with multi-scale DA, adaptive sampling techniques that identify the optimal spatial and temporal configuration of available space-borne and *in-situ* observations, subject to user-driven constraints, require further development. Current techniques are based on the hypotheses that they can: (i) predict the error reducing effect of any combination of targeted observations; and/or (ii) identify optimally growing errors between the observing time and targeted forecast time. Implicit within these hypotheses is the goal that targeted observations will improve analyses and/or forecasts more than non-targeted observations. However, the potential extent of the forecast benefit, which depends on the model, observational coverage, and DA scheme, remains unexplored to date.

(b) Open research issues. To improve upon current adaptive sampling techniques in a seamless adaptive DA framework, several issues require research related both to DA and the evolution of the forecast impact downstream. The pertinent DA issues listed above also apply to adaptive sampling techniques. Research issues related to downstream impacts include: (i) quantifying the potential forecast gain based on the importance of the weather event; (ii) the ability of adaptive sampling techniques to predict the evolution and growth of errors (e.g. using observation gradient operators, singular vectors, ensemble-based "signal variance"); (iii) the verification region selection method; (iv) the effect of linearity assumptions and spurious correlations on error variance evolution; (v) the dynamical basis for the propagation of the effect of targeted observations; (vi) the contamination of this propagation by locally growing errors downstream; and (vii) the adaptive use of satellite data such as selected use of channels and thinning (Fourier and Rabier 2004) as discussed earlier. Assessing the impacts of adaptive measurements in societal and user relevant terms is also relatively untapped and is really at the root of whether such strategies should be adapted.

(c) OSSEs. The OSSE provides a controlled environment in which several problems may be investigated prior to real-world implementation, for example: (i) the potential influence of new hypothetical fixed or adaptive observational platforms; (ii) the optimal mix of observations; (iii) comparing the strengths and limitations of DA and adaptive sampling methods and associated error dynamics; (iv) accounting for model errors; and (v) downstream effects due to assimilation of new observations. To increase progress, NWP centers and research organizations could share the same data used as "nature" and carry out coordinated experiments.

(d) Real-data experiments: THORPEX lays out a strategy to advance knowledge with OSSEs and OSEs. Based on results from prior field programs (WSR, A-TREC) and ongoing research, the above research issues (and others) can be addressed with T-PARC observations. The special observations range over a 6-month period, answering a criticism of previous field efforts being too short to draw meaningful conclusions. In addition, T-PARC is also focusing on more effective use of satellite measurements as has been proposed in Langland (2006).

Fig. 6: The ensemble sensitivity analysis for the ET of Super Typhoon Tokage showing the linear relationship between the 48-hour forecast pressure averaged over the region contained within the box (bold lines), and the 500 hPa field at the analysis time. The solid lines indicate the ensemble-mean 500 hPa field (m) and the sensitivity field in colors (m, for standardized averaged forecast surface pressure). The ET cyclone intensity is directly related to the intensity of Tokage while the troughs are either correlated or anti-correlated depending on the phasing with the cyclone. (Figure courtesy of Ryan Torn, University of Washington, see also Hakim and Torn 2005 .

3.4 High resolution modeling

A strong modeling component of T-PARC is necessary to reaching the overall THORPEX goal of accelerating improvements in forecast skill. One unique aspect of THORPEX is the THORPEX Grand Global Ensemble (TIGGE) that makes the full (e.g., all ensemble members) operational ensemble data sets available to researchers. The value of the operational data sets is increased by the inclusion of diagnostic fields (e.g., PV, CAPE, CIN, etc) along with the model variables. While, TIGGE contains a reduced number of levels and times in order to make a tractable data set that contains all the operational models, the North American Ensemble Forecast System (NAEFS) will make the entire data set available in real-time. T-PARC will be the first major field effort that makes use of TIGGE and NAEFS and it is hopeful that this data set will increase the interaction between the operational and research communities.

High resolution simulations, both covering regional domains and embedded within global models will prove useful to the goals of T-PARC for: i) understanding the physical processes associated with typhoons, ETs, intense cyclogenesis and the downstream weather generated from such disturbances; ii) assessing whether the use of local high-resolution grids improve prediction of Asian weather including TC genesis, track, intensity, and decay or ET; and iii) examination of whether any improvements in the simulation of Pacific and Asian weather have a corresponding improvement in the prediction of the Rossby wave response and other downstream effects over North America, the Arctic and Europe. An example of the recent usage of high-resolution simulations is improvements in the predictions of TC track and intensity. An obvious question is whether such improvements can also improve the prediction of the ET process and downstream wave generation as the process is dependent to some extent on the timing and location of when the tropical storms move into the westerlies.

High-resolution strategies for the North American goals of T-PARC will require either very large domain regional models or nested grids within global general circulation models (GCMs) to address the downstream effects. Another advantage of global model strategies is to capture other related sources of Rossby wave excitation such as the deep organized convection associated with Madden Julian Oscillation (MJO)/ El Niño–Southern Oscillation (ENSO) events (see Ferranti et al. 1990). The ENSO/MJO effect the frequency of TCs in both hemispheres (e.g., Keen 1982; Lander 1990) with some recent suggestions that TCs can also impact the ENSO events (Sobel and Camargo, 2005). The MJO is generally poorly simulated in weather and climate models. To capture the MJO, the modulation of deep convection and the global dispersion of Rossby waves, as well as the downstream high-impact events, the ideal situation would be to have a global model with cloud-resolving capabilities. The Canadian GEM model is already funded to simulate cases of MJO and radiation of Rossby wave responses in an unprecedented convective-scale to continental-scale simulation on the Earth Simulator Center (ESC). This simulation and others with lower resolution will be used to examine the expected implication of MJO for numerical weather forecasting through diagnostics studies, such as Charron and Brunet 1999) and sensitivity experiments to determine the important parameters that affect MJO and Rossby wave radiation that affect the North American and European regions. The global convective-scale modeling on the Earth Simulator will be one benchmark for other T-PARC simulations.

Another strategy for forecast improvement for these downstream events is to utilize high-resolution mesoscale or convective-scale modeling approaches downstream to whether these high-resolution models over North America will directly benefit from improvements in the lateral boundary conditions afforded by the previously described up-stream modeling, assimilation and observing strategies. The downscaling approach is also coupled with a modest downstream measurement strategy to test the ability of the global and regional model to capture the intense surface fluxes during high winds in these storms. Since wind speeds in these west coast storms can approach values similar to a category 1, 2, or even 3 hurricane, the problem of accurately representing these fluxes and the accompanying energetics of the boundary layer is similar to hurricanes and thought to be a source of model error for these events.

4.0 Societal and Economic Applications

THORPEX programs include a strong societal and economic impacts (SEA) subprogram. Specific SEA research opportunities in T-PARC include:

<u>Forecasting west coast severe weather:</u> T-PARC investigators will work with several forecast offices on the west coast of the US and Canada to quantify the impacts of T-PARC research and additional measurements on their forecasts. The work will include gaining insight into the forecast improvements made from T-PARC measurement strategies, development and testing of conceptual models, and improved understanding of the user needs and forecasters view of model short-comings.

Heavy rainfall, tropical cyclones, comparative human responses, and hazard mitigation/response: In terms of damage and human misery, typhoons are the overwhelming disaster of developing countries of temperate and tropical eastern Asia. T-PARC research activities will include: i) Undertake studies to identify populations specifically vulnerable to weather hazards and assess methods for improving forecast, warning, and response systems specific to the needs and capabilities of this/these populations; ii) Estimation of the health impacts of weather of heavy rainfall/typhoons and the degree to which negative outcomes can be mitigated; iii) Decision making in emergency management, how weather information is utilized in the face of major risk, and whether probabilistic information can be used to improve decisions and communication; iv) The different responses of the developing and developed world to significant weather disasters.

User-specific forecast use and benefits: Research will investigate the use of weather forecast information and its value in decision-making for specific groups of forecast users in Asia, Western North America and/or other regions affected by T-PARC forecasts. This will include research on users' perceptions of and preferences for different types of weather forecast information, the role of different types of forecast information in users' decisions, and the value of different types of forecast information services. The effort will focus on current and improved short- to mid-term (up to 14 days) weather forecast information related to T-PARC, including (TIGGE and NAEFS) probabilistic forecasts and other information about forecast uncertainty. Possible user groups to study include households (the public), water managers, energy sector decision makers, and/or emergency managers in developed countries. The intent is to use state-of-the-art survey, and comprehensive multivariate analysis of the results.

User-driven verification and evaluation of forecast quality: Traditional forecast verification approaches often do not link forecasts and the decision making process of users, due to their reliance and focus on single-measure scores to summarize forecast performance. Examples of possible user-driven verification goals include attempting to capture the location, intensity and structure of typhoons over Asia, high winds and heavy rainfall events over North America, improved aviation flight-level winds, hydrological applications of ensembles, medium-range forecasts of cold waves for energy consumption and a host of parameters associated with typhoons and inland flooding. The TIGGE data sets will allow for easy access of SEA researchers to probabilistic data. Existing decision models could be utilized to better incorporate weather information, specific verification measures, assess/quantify changes in decision-making and assess potential for quantifying benefits and costs based on verification metrics. Basic research and development are required to develop approaches that meet the decision-making needs of specific forecast users and to accurately represent the overall economic benefit.

Hydrological Ensemble Prediction Experiment (HEPEX): The hydrological community is making a large effort to utilize ensemble modeling for hydrological applications. T-PARC focuses on precipitation events over Asia, the Arctic, and North America with an effort to make use of the TIGGE ensemble data sets. The T-PARC campaign will request access in real-time to the TIGGE data sets from the THORPEX TIGGE working group. An opportunity exists for significant collaboration between T-PARC, and HEPEX to further the utilization of weather information in ensemble prediction systems for a season.

5.0 Observing Systems and Research Facilities

The observational strategy to accomplish these scientific and operational goals is discussed in the accompanying Experimental Design Overview and facility requests. Facilities from Asia, North America, and Europe will be used to accomplish these goals. The general research strategy will be to have T-PARC measurements and improved use of satellite observations utilized to advance knowledge and improve predictability of tropical cyclones from genesis through recurvature to extratropical transition or decay. In addition to these measurements additional measurements will be taken in other extratropical cyclogenesis events likely to trigger downstream high-impact weather or downstream forecast failures, particularly in the cyclogeneis regions near Japan and downstream over the North Pacific. The program represents a comprehensive effort to investigate Pacific predictability through international collaboration and begins in May for convection within the monsoon trough tropical cyclones and ends in late December for winter storms.

6.0 Why 2008?

The concept of a program in 2008 is driven by several external factors that will result in additional observations useful to T-PARC. Such additional measurements will cover broad regions of Asian and the Arctic so that there will be an unprecedented opportunity to investigate predictability problems over a broad range of the northern hemisphere. These observations include: (i) During 2008, an extensive set of measurements (e.g., additional radiosonde sites, profilers, surface stations and GPS) will be taken over a broad area of the Tibetan Plateau for the CHERES II program. These measurements will be useful for several T-PARC goals including studies of Rossby wave triggering/propagation in the southern waveguide and adaptive measurements over land for tropical cyclone prediction. (ii) Additional measurements and modeling efforts associated with the 2008 summer Olympics in Beijing will be useful to better characterize the westerlies flow and any forecast sensitivities for ET and typhoons. (iii) The Asian component of T-PARC is timed coincide with the 2008 Olympics. (iv) T-PARC will occur in association with the International Polar Year (IPY) and has been endorsed by IPY due to the tropical-extratropical aspects of T-PARC, such as the direct effects of ET storms on the Arctic and the importance of Pacific measurements to Arctic predictability. The Arctic is also a data void region both in terms of in-situ observations and the utilization of satellite-based measurements so that additional hypotheses to be investigated utilizing IPY measurements include the impact of Arctic measurements on predictability of events of interest to T-PARC relative to additional Pacific and Asian observations.

7.0 Project Management and Budget

To date, David Burridge (WMO), chair of the THORPEX International Executive Board (EB) has tasked the chairs/co-chairs of various THORPEX International bodies (Pierre Gauthier, Env Canada and co-chair of the Data Assimilation Working Group; Istvan Szunyogh, U Maryland and co-chair of the Predictability Working Group; Dr. Tetsuo Nakazawa, Japan Meteorological Agency and chair of the Asian Regional Committee; and David Parsons, NCAR and co-chair of the North American Regional Committee) to lead the preparation of a T-PARC science plan. This group and the co-PIs of this proposal have relied on broad community input as evidenced by the names in Appendix J and the well-attended workshop on Pacific Predictability. National/regional committees will be formed as needed. Two possibilities are being explored for the hosting of the operations center; the Japan Meteorological Agency and Monterey, California, USA where the Fleet Numerical Meteorology and Oceanography Center, Navy Research Laboratory, and the Naval Postgraduate School are located. US Interagency budget considerations fall under the US THORPEX Executive Community and with the planning logistics currently residing in the US THORPEX Project Office.

8.0 Data Management

The operational data sets will be part of the vast TIGGE archive. Plans already exist for regional archives and access points of TIGGE data at NCAR and the Chinese Meteorological Administration (CMA). T-PARC will request real-time access to TIGGE. The new NAEFS products will be available from NCAR, NCEP and/or a Canadian access point. It is proposed that the vast amount of satellite data be coordinated at the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin. The archival of special field data sets and saving of real-time products/images will be done at NCAR/JOSS and an Asian site. We anticipate the use of the JOSS real-time and post-experiment data catalogs.

9.0 Previous field campaigns

This field experiment is a unique scale-interaction campaign building on previous studies of adaptive measurements (e.g., A-TREC, NORPAC, FASTEX). T-PARC also uniquely seeks to address medium range weather prediction issues. THORPEX T-PARC moves beyond on in-situ targeting impact, but to testing advanced data assimilation techniques (ETKF, 4-D var and improved satellite assimilation), and increased dynamical understanding of Rossby wave triggering, typhoon genesis and the ET process. A strong international team is interested in participation in the program with extensive measurement campaign experience.

10. References

Aberson, S.D., 2001: The Ensemble of Tropical Cyclone Track Forecasting Models in the North Atlantic Basin (1976-2000). *Bull. Amer. Meteor. Soc.,* **82**, 1895-1904.

Aberson, S. D., 2003: Targeted observations to improve operational tropical cyclone track forecast guidance. *Mon. Wea. Rev.*, **131**, 1613-1628.

Agusti-Panareda, A., C. D. Thorncroft, G. C. Craig, and S. L. Gray, 2004: The extratropical transition of hurricane Irene (1999): A potential vorticity perspective. *Q. J. R. Meteorol. Soc.*, **130**, 1047-1074.

Bister, M., and K. A. Emanuel, 1997: The genesis of Hurricane Guillermo: TEXMEX analyses and a modeling study. *Mon. Wea. Rev.*, **125**, 2662–2682.

Chang, E. K. M., 2005: The impact of wave packets propagating across Asia on Pacific cyclone development. *Mon. Wea. Rev.*, **133**, 1998-2015.

Chang, E. K. M., and D. B. Yu, 1999: Characteristics of wave packets in the upper troposphere. Part I: Northern Hemisphere winter. *J. Atmos. Sci*., **56**, 1708-1728.

Charron, M. and G. Brunet, 1999: Gravity Wave Diagnosis Using Empirical Normal Modes. *J. Atmos. Sci.*, **56**, 2706-2727.

Danielson, R. E., J. R. Gyakum, and D. N. Straub, 2004: Downstream baroclinic development among forty one cold-season eastern North Pacific cyclones. *Atmosphere-Ocean*, **42**, 235-250.

Ferranti, L., T.N. Palmer, F. Molteni and E. Klinker, 1990: Tropical-Extratropical Interaction Associated with the 30-60 Day Oscillation and Its Impact on Medium Range and Extended Range Prediction, J. Atmos. Sci., 47, 2177-2199.

Franklin, J.L., C. J. McAdie and M. B. Lawrence. 2003: Trends in Track Forecasting for Tropical Cyclones Threatening the United States, 1970-2001. *Bull. Amer. Met. Soc*., **84**, 1197-1203.

Hakim, G. J., 2003: Developing wave packets in the North Pacific storm track. *Mon. Wea. Rev*., **131**, 2824-2837.

Hakim, G. J., 2005: Vertical structure of midlatitude analysis and forecast errors. *Mon. Wea. Rev*., **133**, 567-575.

Hakim, G. J., and R. D. Torn, 2005: Ensemble Synoptic Analysis. Fred Sanders Monograph, American Meteorological Society, accepted.

Harr, P. A., M. S. Kalafsky, and R. L. Elsberry, 1996a: Environmental conditions prior to formation of a midget tropical cyclone during TCM-93. *Mon. Wea. Rev.*, **124**, 1693-1710.

Harr, P. A., R. L. Elsberry, and J. C. L. Chan, 1996b: Transformation of a large monsoon depression to a tropical storm during TCM-93. *Mon. Wea. Rev.*, **124**, 2625-2643.

Harr, P. A., and R. Elsberry, 2000: Extratropical transition of tropical cyclones over the western North Pacific. Part I: Evolution of structural characteristics during the transition process. *Mon. Wea. Rev.*, **128**, 2613-2633.

Harr, P. A., and R. Elsberry, 2000: Extratropical transition of tropical cyclones over the western North

Pacific. Part II: The impact of midlatitude circulation characteristics. *Mon. Wea. Rev.*, **128**, 2613-2633.

Hendricks, E. A., M. T. Montgomery, and C. A. Davis, 2004: On the role of "vortical" hot towers in tropical cyclone formation. *J. Atmos. Sci.,* **61**, 1209–1232.

Hoskins, B.J., and Kevin I. Hodges. 2002: New Perspectives on the Northern Hemisphere Winter Storm Tracks. *J. Atmos. Sci*. **59**, 1041–1061.

Jones, S. C., et al., 2003: The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. *Wea. Forecasting*, **18**, 1052-1092.

Keen, R. A., 1982: The role of cross-equatorial tropical cyclone pairs in the Southern Oscillation. *Mon. Wea. Rev.,* **110**, 1405–1416.

Klein, P. M., P. A. Harr, and R. Elsberry, 2000: Extratropical transition of western North Pacific tropical cyclones: An overview and conceptual model of the transformation stage. *Wea. Forecasting*, **15**, 373-395.

Klein, P. M., P. A. Harr, and R. Elsberry, 2002: Extratropical transition of western North Pacific tropical cyclones: Midlatitude and tropical cyclone contributions to reintensification. *Mon. Wea. Rev.*, **130**, 2240-2259.

Lander, M. A., 1990: Evolution of the cloud pattern during the formation of tropical cyclone twins symmetrical with respect to the equator. *Mon. Wea. Rev.,* **118**, 1194–1202.

Langland, R. 2006: Issues in Targeted Observing. (Invited Paper for Special Symposium Issue). In press, *Quart. J. Roy. Meteor. Soc.*

Majumdar, S. J., C. H. Bishop, B. J. Etherton, and Z. Toth, 2002: Adaptive sampling with the ensemble transform Kalman filter. Part II: Field program implementation. *Mon. Wea. Rev*., **130**, 1144-1165.

Majumdar, S. J., S. D. Aberson, C. H. Bishop, R. Buizza, M. S. Peng and C. A. Reynolds, 2006: A comparison of adaptive observing techniques for Atlantic tropical cyclones. *Mon. Wea. Rev.*, in press.

McAdie, C.J. and Miles B. Lawrence. 2000: Improvements in Tropical Cyclone Track Forecasting in the Atlantic Basin, 1970-98. *Bull. Amer. Meteor. Soc*., **81**, 989-997.

McMurdie, L., and C. Mass, 2004: Major numerical forecast failures over the Northeast Pacific. *Wea. Forecasting*, **19**, 338-356.

Montgomery, M.T., and Janice Enagonio. 1998: Tropical Cyclogenesis via Convectively Forced Vortex Rossby Waves in a Three-Dimensional Quasigeostrophic Model. *J. Atmos. Sci.* **55**, 3176 –3207.

Montgomery, M. T., M. E. Nicholls, T. A. Cram, and A. B. Saunders, 2006: A vertical hot tower route to tropical cyclogenesis. *J. Atmos. Sci*., in press.

Nielsen-Gammon, J. W., and R. J. Lefevre, 1996: Piecewise tendency diagnosis of dynamical processes governing the development of an upper-tropospheric mobile trough. *J. Atmos. Sci.,* **53**, 3120-3142.

Orlanski, I., and J. P. Sheldon, 1995: Stages in the energetics of baroclinic systems. *Tellus,* **47A**, 605-628.

Parker, D.J. and A. J. Thorpe. 1995: Conditional convective heating in a baroclinic atmosphere: A model of convective frontogenesis. *J. Atmos. Sci.*, **52**, 1699–1711.

Peng, M. S., and Reynolds, C. A., 2006: Sensitivity of tropical cyclone forecasts.

Powell, M.D. and S. D. Aberson. 2001: Accuracy of United States Tropical Cyclone Landfall Forecasts in the Atlantic Basin (1976-2000). *Bull. Amer. Meteor. Soc*., **82**, 2749-2767.

Reynolds, C.A. and R. Gelaro, 2001: Remarks on Northern Hemisphere Forecast Error Sensitivity from 1996 to 2000. *Mon. Wea. Rev*., **129**, 8, 2145-2153.

Sardeshmukh, P. D., and B. J. Hoskins, 1988: The generation of global rotational flow by steady idealized tropical divergence. *J. Atmos. Sci*., **45**, 1228-1251.

Shapiro, M.A., and A.J. Thorpe, 2004: THORPEX International Science Plan, Version 3, 2 November 2004 WMO/TD No. 1246 WWRP/THORPEX No. 2

Sobel, A. H. and S.J. Camargo 2005: Influence of Western North Pacific Tropical Cyclones on Their Large-Scale Environment. *J. Atmos. Sci.*, **62**, 3396-3407.

Szunyogh, I., Z. Toth, A. V. Zimin, S. Majumdar, and A. Persson, 2002: Propagation of the effect of targeted observations: The 2000 Winter Storm Reconnaissance Program. *Mon. Wea. Rev.*, **130**, 1144-1165.

Wu, C.-C., P.-H. Lin, S. D. Aberson, T.-C. Yeh, W.-P. Huang, J. -S. Hong, G.-C. Kiu, K.-C. Hsu, I.-I. Lin, K.-H. Chou, P.-L. Lin, and C.-H. Liu, 2004: Dropsonde observations for typhoon surveillance near the Taiwan region (DOTSTAR): An overview. *Bull. Amer. Meteor. Soc.*, **86**, 878-790.

Wu, C.-C., P.-H. Lin, J.-H. Chen, and K.-H. Chou, 2005: Targeted observations of tropical cyclones based on an adjoint sensitivity steering vector. *Geophys. Res. Letters*, submitted.