EXECUTIVE SUMMARY

Introduction. THORPEX (THe Observing system Research and Predictability Experiment) is a ten year (2005-2014) global international research programme which aims to accelerate improvements in the accuracy of 1-day to 2-week forecasts of high impact weather. These improvements will lead to substantial benefits for humanity, as the research community responds to the weather-related challenges of the 21st century. THORPEX is an integral element of the WMO World Weather Research Programme (WWRP) and is a major contributor to the WMO Natural Disaster Reduction and Mitigation Programme. Close links are maintained with the World Climate Research Programme (WCRP).

The main THORPEX research priorities are to address:-

- Global-to-regional influences on the evolution and predictability of weather systems
- Global observing-system design and demonstration
- Targeting and assimilation of observations
- Societal, economic, and environmental benefits of improved forecasts

The THORPEX International Science Plan (WMO/TD-No. 1246; WWRP/THORPEX No. 2) was published in November 2003 and was followed by a THORPEX International Research Implementation Plan (WMO/TD-No. 1258); WWRP/THORPEX No. 4) in December 2004 (both plans are available at www.wmo.int/thorpex/plans.html).

Governance and Structure. The Programme is overseen by an International Core Steering Committee (ICSC) and also receives scientific guidance and direction from the WWRP Joint Scientific Committee (JSC). It is supported by a Trust Fund to which nations are invited to contribute. The THORPEX International Programme Office acts as the focal point for the day to day implementation of the programme. Originally it was envisaged that the Trust Fund would attract contributions amounting to around 1M CHF per annum. As it turned out the contributions only reached about half that level. This meant that the available effort and resources from the IPO has been somewhat limited and as result some aspects of the plans were not implemented e.g. the Stakeholders Panel was not formed. In retrospect the programme was also perhaps rather too ambitious and somewhat administratively complex.

Three THORPEX Working Groups are currently active. They develop and coordinate specific activities aimed at addressing the THORPEX research priorities. These are,

- Predictability and Dynamical Processes Working Group (PDP WG) – global-to-regional influences on the evolution and predictability of weather systems
- Data Assimilation and Observing Systems Working Group (DAOS WG) – global observing system design; targeting and assimilation of observations
- Global Interactive Forecasting System (GIFS) – THORPEX Interactive Grand Global Ensemble Working Group (GIFS-TIGGE WG). The initial task given to the GIFS-TIGGE WG was to develop and test global multi-model ensemble prediction systems and to develop prototype multi-model ensemble products

The WWRP Societal and Economic Research Aspects Working Group has, as one its tasks, the responsibility for the co-ordination of the assessment of the societal, economic and environmental benefits of improved forecasts for the THORPEX Programme and thus addresses the fourth research priority.

Consortia of nations have also established THORPEX Regional Committees (RCs) that define regional priorities for participation in THORPEX activities within the framework of the THORPEX International Science and Implementation Plans. These THORPEX Regional Committees facilitate provision of funding, logistical and other support, planning, coordination and implementation of THORPEX activities conducted by the region and as part of global initiatives with respect to the THORPEX International Research Implementation Plan. THORPEX Regional Committees have been established for Asia (ARC), Africa (AfRC), Europe (ERC), North America (NARC) and the Southern Hemisphere (SHRC). The THORPEX Regional Committees have developed a series of regional plans which reflect key issues in their own areas of interest.

Major Achievements THORPEX has provided a very effective and important framework for close international collaboration and has brought together scientists from around the world to participate in field campaigns and research activities. It has also provided an essential catalyst for significant resource mobilisation. Since its inception rapid progress has been made and many notable successes have been achieved. Amongst these are the following,

- ***Major real-time international observational programmes and experiments have been completed: the Atlantic- THORPEX Regional Campaign (A-TReC) and the THORPEX - Pacific Asian Regional Campaign (T-PARC)****.*

The objective of the 2003 Atlantic THORPEX Regional Campaign (A-TReC) was to test the hypothesis that short term forecast errors over Europe and the Eastern seaboard of the USA can be reduced by targeting extra observations over sensitive areas determined each day by the forecast flow patterns using NWP techniques. The field campaign took place in the autumn of 2003 and was the *first attempt at real time adaptive control of a full set of operational observing systems (in an international context) in addition to the deployment of research aircraft.* The A-TReC field campaign was very successful technically and has provided valuable datasets to test targeting issues. Various data impact experiments have been performed, showing a small but very slightly positive impact of targeted observations.

The T-PARC was a major multi-national field campaign and research initiative which addressed the shorter-range dynamics and forecast skill of tropical cyclones/typhoons over eastern Asian and the western North Pacific and the downstream impact on the medium-range dynamics and forecast skill of the eastern North Pacific and North America. During T-PARC/TCS-08, the *first systematic data targeting operation applied to tropical cyclones over the western North Pacific was conducted*. This included comparison of several methods from a variety of operational and research organizations. Another first-time accomplishment was the four-plane operation within Typhoon (TY) Sinlaku. The combination of aircraft types and special observing capabilities allowed data to be gathered in the storm inner core, the near-storm environment and remotely-located targeted regions. Many instruments were deployed for the first time into the environment of a west Pacific tropical cyclone. These included the ELectra DOppler RAdar (ELDORA) and the Twin Otter Doppler Wind Lidar (TOWDL) on the NRL P-3, the Stepped Frequency Microwave Radiometer on the USAF 53rd Weather Squadron WC-130J, and the DLR Doppler wind lidar and Differential Absorption Lidar (DIAL) water vapour lidar.

Overall, the field phase of the T-PARC/TCS-08 and affiliated programmes were conducted with great success. The results of the data collection strategies during the field programmes 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 was unique in monitoring the full cycle of tropical cyclones from genesis to recurvature and ET.

- ***International data bases (TIGGE) of near-real time global ensemble predictions from ten prediction centres have been established and the results provided for research by three archive centres. Prototype multi-model ensemble products have been developed including tropical cyclone tracks and heavy precipitation.***

The first data were stored in the TIGGE archives on 1st October 2006, starting with forecasts from ECMWF, UK Met Office and JMA. Data from the other centres were added in the following 2 years. Currently, the TIGGE archive is hosted by three archive centres (ECMWF, NCAR and CMA) and contains global ensemble forecast data from 10 NWP centres: BoM, CMA, MSC, CPTEC, ECMWF, JMA, KMA, Météo France, NCEP and the Met Office. The establishment of the TIGGE database of operational global ensemble forecasts has been a major achievement of the GIFS-TIGGE Working Group.

The TIGGE archives provide a key research facility to enhance cooperation between universities and the operational weather prediction centres, with a focus on improving the forecasting of high-impact impact weather. As well as promoting the concept of probabilistic forecasts and development of new methods of combination and verification of forecasts, the TIGGE archive is a tremendous resource for other aspects of the THORPEX research programme. The data bases are accessed routinely by research scientists and have resulted in numerous publications in the literature.

Prototype probabilistic forecast products are being specifically designed for and tested in a few selected regions, where the transfer of new approaches can have the greatest benefit, in association with the CBS Severe Weather Forecast Demonstration Projects. Initially these include tropical cyclone tracks and heavy precipitation. Regions of strong winds are also being considered.

- ***The THORPEX IPY cluster of projects have made a major contribution to observing and NWP in Polar Regions***

The IPY-THORPEX project cluster includes 10 individual IPY projects from nine countries with the following main objectives: exploring the use of satellite data and optimized observations to improve high-impact weather forecasts (for Polar THORPEX Regional Campaigns (TReCs) and/or provide additional observations in real-time over the WMO Global Telecommunication System), better understand physical/ dynamical processes in Polar Regions, achieve a better understanding of small -scale weather phenomena, utilize improved forecasts to the benefit of society, the economy and the environment and utilize the THORPEX Interactive Grand Global Ensemble (TIGGE) of weather forecasts for polar prediction.

The main projects carried out were the Greenland Flow Distortion Experiment, Storm Studies of the Arctic, Concordiasi, the Norwegian IPY-THORPEX, TAWEPI – the THORPEX Arctic Weather and Environmental Prediction Initiative, Greenland Jets Experiment, Arctic Regional Climate Model Intercomparison Project, Impacts of surface fluxes on severe Arctic storms, climate change and Arctic coastal orographic processes and T-PARC.

The IPY-THORPEX cluster of projects were very successful and have demonstrated that improvements in NWP for Polar Regions are possible and significantly increased our understanding on how to improve models and the use of data in the Arctic, as well as providing a much deeper understanding of the physical processes involved.

- ***A major contribution has been made to AMMA in the area of prediction of severe weather***

The need to improve weather forecasting for implementation of early warning systems motivated the scientific community to define three major objectives for AMMA: To improve our understanding of the West African Monsoon (WAM) and its influence on the physical, chemical and biological environment regionally and globally, to provide the underpinning science that relates variability of the WAM to issues of health, water resources, food security and demography for West African nations and defining and implementing relevant monitoring and prediction strategies and to ensure that the multidisciplinary research carried out in AMMA is effectively integrated with prediction and decision making activity.

Early in its implementation, THORPEX established collaborative links with AMMA through joint membership of the AMMA-THORPEX Working Group and THORPEX Working Groups. The two most fruitful examples of the collaboration were THORPEX support for additional radiosondes for AMMA and the evaluation of AMMA observational data through Observing System Experiments and co-operative efforts between AMMA and the THORPEX African Regional Committee, in particular for the development of the Forecasters Handbook for High Impact Weather

- ***The Year of Tropical Convection (YOTC) programme has been initiated in conjunction with the WCRP and a Project Office established***

Coordinated jointly by the World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP)-THORPEX and involving numerous institutions, research groups and individuals world-wide, the YOTC project addresses key strategic problems at the intersection of weather and climate (seamless prediction). The emphasis is tropical convection, its multi-scale organization and their interaction with the global circulation and role in the global water cycle. Highlights research includes the Madden-Julian Oscillation (MJO), convectively-coupled equatorial waves, the monsoons, easterly waves and tropical cyclones, tropical-extratropical interaction, and the diurnal cycle. All these meteorological phenomena severely challenge global models, both weather and climate.

The most essential satellite data sets and associated archiving and dissemination systems have been identified. High resolution analyses and deterministic forecasts, with diabatic and other process-oriented fields, are being archived: ECMWF at T799 (about 25km), NASA/GMAO GEOS5 (¼ degree), and NCEP at about 35km. NASA supports the development of a unique satellite data analysis facility and dissemination framework (YOTC-Giovanni). The "year" includes El Nino, La Nina, and Arctic Oscillation conditions, giving unique information on short-term climate variability.

The YOTC Science Plan has been completed, and the YOTC Implementation Plan is a living web document (www.ucar.edu/yotc). It includes links to data, science items, documents, meeting reports, and general information. In addition a YOTC Task Force to focus on understanding and modelling the MJO has been set up.

- ***Comprehensive Reports on the effectiveness of data-targeting (adaptive observations) in NWP have been completed***

The Data Assimilation and Observing Systems Working Group have completed an important and comprehensive review of the impact of adaptive observations in NWP systems. The work carried out by the group has led to better understanding of the impact of observations in NWP using adjoint sensitivity tools. The impact on short range forecasts is found to be very similar across major NWP centres. The largest impacts are now from AMSU-A, satellite winds etc., although the global radiosonde network and data from aircraft remain very important. These general results are very helpful to space agencies and others involved with developing and maintaining in-situ data networks.

The generally positive impact of additional dropsondes on the forecast track of tropical cyclones has been demonstrated. However, there is no improvement in the forecast intensity of the storm probably due to the models not accurately capturing entrainment of dry air into the system. It has also been shown that impacts vary from model to model, for example, typically the impacts of targeted observations in the KMA system for the summer T-PARC period are larger than those found by JMA.

Whilst it is clear that the impact on TC tracks was positive the impact of targeted data on the mid-latitudes although generally small and positive is much more variable. It has also been shown that the impact of targeted data in sensitive areas is higher than from randomly selected areas.

However, it is clear that earlier optimism concerning the potential benefits of a "global interactive forecasting and observing system" was not realised.

- ***Data Assimilation research has made major contributions to the development of the observing system through the use of operational data and THORPEX filed experiments***

The DAOS is comparing and contrasting current and new data assimilation systems including 4D-VAR with different options of inferring the background errors and the new EnKF systems. It has also requested a review of the nomenclature for the various data assimilation systems in current use and being developed as it can be confusing for non-scientists.

- ***Predictability and Dynamical Processes research***

THORPEX Predictability and Dynamical Process research has provided the framework for the academic dynamical meteorology community and the operational numerical weather prediction centres to carry out joint projects. The THORPEX Predictability and Dynamical Processes Working Group (PDP WG) has encouraged these communities to carry out dynamical process studies with the specific aim of improving the understanding of the relationship between particular processes and weather forecast accuracy.

During the first phase of THORPEX, these studies have contributed to the preparation and evaluation of international field experiments, raised the awareness in the PDP community of the research objectives of THORPEX and the availability of THORPEX data sets (notably TIGGE, T-PARC, YOTC), supported the development of research projects dedicated to THORPEX PDP research, established a linkage to WGNE on the issue of model uncertainties, promoted THORPEX through the organisation of summer schools, sessions at international conferences and dedicated workshops and identified key topics for future PDP research.

In addition the PDP WG, in conjunction with WGNE, organised two workshops on Model Errors (ETH Zurich, 2010) and on Stochastic Processes (ECMWF 2011). The Group also organised a first PDP summer school at the Banff International Research Station (BIRS) for Mathematical Innovation and Discovery, Canada, in July 2011 on *Advanced Mathematical Methods to Study Atmospheric Dynamical Processes and Predictability* as well as the organization of numerous PDP sessions at conferences and workshops.

- ***Three major International Symposia on THORPEX science, workshops and summer schools have been organised***

Three major International Science Symposia have been held at which numerous papers related to THORPEX topics were presented along with comprehensive poster sessions. In addition, workshops and summer schools on subjects of particular relevance and interest have been held.

- ***The THORPEX community and partners are leading three GEO tasks (for climate, ensemble-prediction and high impact weather in Africa) and these projects are now the main elements of the GEO weather prediction activity.***

There are several Tasks within the new Work Plan to which WWRP-THORPEX contributes including:

WE-01 C1 "Global Multi-Model Prediction System for High-Impact Weather"
WE-01 C2 "Easy Access to, and Use of, High-impact Weather Information"
CL-01 C3 "Weather, Climate and Earth-System Prediction Systems"

The contributions from the THORPEX area of responsibility form very important elements of the new GEO Work Plan and GEOSS. This is a two way supportive relationship in which the GEO

framework helps WWRP-THORPEX deliver its objectives in these areas by linking activities, providing visibility at ministerial level and identifying resource mobilisation opportunities.

The GEOWOW (GEOSS Interoperability for Weather Ocean and Water) proposal, which includes a TIGGE weather element, is led by the European Space Agency (ESA). The weather element of the proposal involves further development and integration of the THORPEX Interactive Grand Global Ensemble (TIGGE) global weather forecasts data products into the GCI which will be undertaken by the European Centre for Medium-Range Weather Forecasts, the UK Met Office and Météo-France – the requested funding for the TIGGE weather element is 1.2 M€.

- ***Initiated a polar prediction project***

The International Polar Year (IPY) THORPEX cluster of projects was a great leap forward which contributed to the enhancement of the observational network, a better understanding of physical processes, and improvements in the use of observations, modelling, and prediction in Polar Regions. Consequently, at its 15th session (November 2009), the WMO Commission of Atmospheric Sciences (CAS) recommended, as a legacy of the International Polar Year (IPY), the establishment of a THORPEX Polar Research project to improve understanding of the impact of polar processes on polar weather, the assimilation of data in Polar Regions, and the prediction of high impact weather over Polar Regions.

A Workshop was held the outcome of which was the establishment of the basis for an IPY legacy project which is intended to provide a framework for cooperative international research and development efforts to improve high impact weather, climate, and environmental prediction capabilities for the Polar Regions. Three forecast prediction ranges are of interest: short-term regional forecasts (one hour to 48 hours), medium-range forecasts (one day to two weeks) and sub-seasonal to one season forecasts. Plans are now proceeding to make this project a reality.

- ***Initiated a sub-seasonal to seasonal prediction project***

At its 15th session (November 2009), the WMO Commission of Atmospheric Sciences (CAS) requested the Joint Scientific Committees of the World Weather Research Programme (WWRP) and the World Climate Research Programme (WCRP) and also the THORPEX international Core Steering Committee (ICSC) to set up an appropriate collaborative structure to carry out an international research initiative on sub-seasonal to seasonal forecasting The initial response to this request was to convene a joint WWRP/THORPEX/WCRP Workshop which was held at the UK Met Office (1 to 3 December 2010).

As recommended by Workshop, an Implementation Plan is being developed which will give high priority to: sponsorship of a few international research activities, the establishment of collaboration and co-ordination between operational centres undertaking sub-seasonal prediction (to ensure, where possible, consistency between operational approaches to enable the production of data bases of operational sub-seasonal predictions to support the application of standard verification procedures and a wide-ranging programme of research), facilitating the wide-spread research use of the data collected for the CHFP (and its associate projects), TIGGE and YOTC for research and the establishment of a series of regular Workshops on sub-seasonal prediction.

Work is advancing well to set up this important new initiative.

- ***Planning for a new Regional Campaign (T-NAWDEX – Atmospheric dynamics and diabatic processes in the extratropics)***

The study of the role of diabatic processes for the genesis and evolution of extratropical weather systems has become an important theme of PDP-related research. Progress in this field requires a

combination of improved theoretical understanding, detailed process studies based upon numerical model simulations, and the application of novel observational facilities in field experiments dedicated to the analysis of dynamical and physical processes in developing high-impact weather systems. To this end, the THORPEX - North Atlantic Waveguide and Downstream Impact Experiment (T-NAWDEX) has been proposed by the PDP working group as a key element of the European THORPEX Science Plan.

Its overarching scientific goal is to investigate in detail the link between skill in forecasts on the 1-7 days range, systematic model errors and the representation of physical processes that contribute most to model error. The focus will be on the diabatic modification of air masses, the influence this has on the development of Rossby waves as they propagate across the North Atlantic and the subsequent effects on high impact weather forecasts for Europe. Although regional in experimental focus, the results and conclusions will be pertinent to the extra-tropics world-wide.

Several T-NAWDEX pilot flights have been carried and planning continues for the main experimental phase.

Beyond THORPEX. As the programme moves into the final three years of the planned 10 years it is clear that much important research remains to be done. Attention also naturally turns to the longer term future, the THORPEX legacy and post possible THORPEX arrangements. The worldwide research and development effort across a wide range of THORPEX topics continues to be very active e.g. prototype global ensemble forecast products for high impact weather are just reaching the stage for testing within a quasi-operational environment. Many new results from the major field campaigns are still emerging and the comprehensive data bases established for YOTC and TIGGE are attracting increasing interest in the scientific community. New lines for research are opening up. The sub-seasonal to seasonal and polar prediction projects are still at a very early stage of development.
Against this background early ideas are being formulated for a possible follow on programme. This might contain a series of projects that build on the THORPEX legacy and address key aspects of the prediction of high impact weather on longer time scales i.e. from a day to a season and within the context of a changing climate.

The THORPEX framework has been key to providing the stimulus and international collaboration without which the many successes and achievements outlined above would not have been possible. Scientists from all the major operational centres and many academic organisations worldwide have been provided with new opportunities for effective collaboration in areas and ways not previously possible. It is hoped that this legacy will provide an effective platform to launch a major new initiative to carry forward and build upon the successes of the THORPEX programme.