WWRP 2007 - 1

Sixth WMO International Workshop on Tropical Cyclones (IWTC-VI)

(San José, Costa Rica, 21-30 November 2006)

WORLD WEATHER RESEARCH PROGRAMME

World Meteorological Organization

Weather • Climate • Water

WMO/TD - No. 1383

WORLD METEOROLOGICAL ORGANIZATION

WORLD WEATHER RESEARCH PROGRAMME

WWRP 2007-1

SIXTH WMO INTERNATIONAL WORKSHOP ON TROPICAL CYCLONES (IWTC-VI)

(SAN JOSE, COSTA RICA, 21 - 30 NOVEMBER 2006)

WMO TD No. 1383

TABLE OF CONTENTS

WORKSHOP PROCEEDINGS

ANNEXES

FOREWORD

The World Meteorological Organization (WMO) attaches great importance to its World Weather Research Programme's (WWRP) research efforts relating to high-impact weather systems, such as tropical cyclones; in particular, to the application by Members of research results aimed at further improving tropical cyclone early warning systems as well as tropical cyclone disaster prevention and mitigation measures.

Recognizing these benefits, the Fourteenth World Meteorological Congress (2003) and the subsequent sessions of the Executive Council had endorsed the continuation of this quadrennial international workshop and so, at the kind invitation of the Government of Costa Rica, the Sixth WMO International Workshop on Tropical Cyclones (IWTC-VI) was organized in San Jose from 21 to 30 November 2006.

The primary objective of the workshop was to facilitate the exchange of information between tropical cyclone research scientists and operational weather forecasters, with the goal of reducing through improved prediction the associated risk and damages caused by tropical cyclones.

The programme of the workshop was developed by an International Committee co-chaired by Mr C.Y. Lam and Prof Johnny Chan, both from Hong Kong, China. It is worth noting that the recent increase in tropical cyclone associated disasters worldwide generated such an interest in the science community, that this particular workshop not only brought operational forecasters and researchers together but also attracted the participation of a significant number of hydrologists, as well as storm surge and disaster management experts.

Discussions during the ten-day workshop resulted in a number of useful recommendations that were addressed to the tropical cyclone research community, to operational tropical cyclone forecasters and to WMO. They were focused on an expanded approach for sustained efforts in further improving tropical cyclone predictions, to consequently reduce the damaging effects of these natural weather hazards.

Another noteworthy outcome of the workshop was the issuance of an updated statement on the possible effects of climate change on tropical cyclone activity/intensity. The full statement is available online at http://www.wmo.ch/pages/prog/arep/tmrp/documents/iwtc_statement.pdf

I wish to take this opportunity to thank all the members of the international and local organizing committees, the topic chairpersons, rapporteurs, participants and all those who assisted in the preparation of this publication, for their valuable contributions.

Finally, I would like to thank the host country, Costa Rica, and to express my appreciation to the Governments of Australia, Canada, China, France, Germany, Japan, Republic of Korea, Spain, the United Kingdom and the United States of America, for providing the additional support that enabled numerous participants to take part in the workshop.

(M. Jarraud)
Secretary-General

PREFACE

The Sixth International Workshop on Tropical Cyclones (IWTC-VI) opened on 21 November 2006, marking the 21 years since the first workshop in the series, was organized by the World Meteorological Organization (WMO) in Bangkok in 1985. In many countries, this would be the age marking full adulthood. Indeed, the IWTC has come of age in all aspects.

The IWTC was conceived in the early eighties by a core group of tropical cyclone meteorologists among whom Professor William Gray stood out prominently. The goal was to bring together forecasters and researchers from all over the world, to review latest developments, to identify needs and requirements and to plan for future work. The Bangkok workshop turned out to be a resounding success and further workshops have followed at roughly four-year intervals.

In the past two decades, the channelling of scientific advances and emerging technologies into operational tropical cyclone forecasting has brought about very significant gains in terms of track forecasting and short-term forecasting of wind, rain and storm surge associated with the close passage of tropical cyclones. The IWTC series now well supported by WMO's World Weather Research Programme (WWRP) and Tropical Cyclone Programme (TCP) have no doubt contributed to this considerable feat of improvement.

The IWTC-VI has followed the well-established model of previous IWTC's. Topic chairs and rapporteurs, assisted by working groups of volunteers, summarized the advances in forecasting and research in the previous four years. Their work was collated to form the volume Workshop Topic Reports IWTC-VI, published as WMO Tropical Meteorological Research Programme Report Series No. 72 (WMO/TD No. 1353) and distributed to workshop participants before the workshop. It is now available online at: http://severe.worldweather.org/iwtc/.

IWTC-VI placed special emphasis on two aspects viz (a) quantitative forecasts of tropical cyclone landfall in relation to an effective warning system and (b) climate change and tropical cyclones. The former was represented by a special theme session while the latter was the subject of much discussion which ended up as a consensus statement.

For five days, 125 participants from 35 countries met in Costa Rica to search for ways to save lives threatened by severe weather and flooding caused by tropical cyclones. This report presents the result of their hard work. It contains a summary of the proceedings of the workshop, the recommendations for the next four years formulated by the participants and the statement on climate change and tropical cyclones.

Finally, we would like to thank the participants, the topic chairs and rapporteurs, the discussion group leaders and scribes, the international committee, the local organizing committee and the staff of WMO's Atmospheric Research and Environment Programme and Tropical Cyclone Programme (TCP) for their collective effort which made this workshop a most fruitful event of learning and sharing.

(Chiu Ying LAM)
(Johnny C. L. CHAN)
Co-chairs, IWTC-VI

CHAPTER 1

INTRODUCTION

J. C. L. Chan (Hong Kong, China)

1. Background

The International Workshop on Tropical Cyclones (IWTC) series started in November 1985 following the directive of the Ninth Congress in 1983 as one of the main activities of the WMO Commission on Atmospheric Science (CAS) Tropical Meteorology Research Programme (TMRP). The objective of the Workshop was to review the current state of knowledge on tropical cyclones and to summarize the various tropical cyclone forecasting practices in different forecast offices around the world. The Workshop ended with a set of recommendations to WMO that included the publication of a "textbook", *A Global View of Tropical Cyclones*.

Since then, an IWTC has been organized about every four years, each of which had one or more important accomplishments. IWTC-II (Manila, Philippines 1989) initiated the preparation of the *Global Guide for Tropical Cyclone Forecasting*, which was published just before IWTC-III (Huatulco, Mexico 1993). A special session on global climate change and tropical cyclones was held during IWTC-III under the chairmanship of J. Lighthill of ICSU, a summary of which was subsequently published in the *Bulletin of the American Meteorological Society*. In addition, a revision of the textbook *A Global View of Tropical Cyclones* was proposed and later published under the title *Global Perspectives on Tropical Cyclones* (WMO/TD No. 693). In IWTC-IV (Haikou, China 1998), revisions to the *Global Guide for Tropical Cyclone Forecasting* were proposed to include the latest knowledge on tropical cyclones and forecasting methods. A keynote session on the Present, Imminent and Future Satellite Observations for Tropical Cyclones was organized in IWTC-V (Cairns, Australia 2002), which was very well received by tropical cyclone forecasters.

The Sixth IWTC (IWTC-VI) was held in San José, Costa Rica in November 2006, details of which are provided in this volume. In this Chapter, the organization and topics of the Workshop are described. A very important session during IWTC-VI was on the relationship between tropical cyclones and climate change. Extensive discussions were held, which resulted in the endorsement by the participants of a Statement on Tropical Cyclones and Climate Change, presented in Chapter 2. Recommendations made to WMO, forecasters and researchers are listed in Chapter 3. Summaries of each of the topics, especially the discussions made during the sessions, are presented by each of the topic chairs in Chapters 4 to 9. The Appendices include the daily schedules and the list of participants.

2. International Committee (IC)

The IC for IWTC-VI consisted of

- Professor J. C. L. CHAN, – Hong Kong, China, Co-Chairman
- Mr C. Y. Lam, – Hong Kong, China, Co-Chairman, PR, Hong Kong, China
- Dr Lixion Avila – USA
- Mr Philippe Caroff – France
- Professor L.-S. Chen – China, Chair, CAS/TMRP
- Mr J. Davidson – Australia

- Professor R. L. Elsberry – USA, CAS Rapporteur on Tropical Cyclones
- Mr R. Prasad – Fiji
- Mr S. K. Subramanian – India

3. Objectives of IWTC-VI

- To examine the current knowledge of, and forecasting and research trends on, tropical cyclones from an integrated international perspective;
- To report on these aspects and to offer recommendations for future research with special regard to the varying needs of the different regions; and
- To promote future collaboration between tropical cyclone specialists and especially between research, forecasting, and warning communities.

4. Workshop Topics and Organization

In view of the tremendous disasters brought about by tropical cyclones making landfall, the IC proposed to have a Special Theme for the Workshop – Quantitative Forecasts of Tropical Cyclone Landfall in relation to an Effective Warning system. This was held on the first day of the Workshop, during which various observational and forecast aspects of tropical cyclone landfall were discussed, including track, wind and rainfall distributions, storm surges and other hydrological aspects. Details of this theme session are presented by J. Davidson in Chapter 4.

Five other topics were then presented and discussed during the subsequent days, one per day. These are listed below:

Topic 1: Tropical cyclone structure and structure change
Topic 2: Tropical cyclone formation and extratropical transition
Topic 3: Tropical cyclone motion
Topic 4: Climate variability and seasonal prediction of tropical cyclone activity/intensity
Topic 5: Disaster mitigation, warning systems and societal impacts

Understanding and forecasting structure change of a tropical cyclone continue to be a challenging problem, and was the first topic after the Special Theme. Topic 2 reflects the increasing attention on the understanding and prediction of tropical cyclone formation, as well as extratropical transition. In the latter, a special focus was on the THORPEX project and how it relates to this issue. The topic of motion was largely discussed in the context of an improvement in forecast skill as significant advances have been made in the past two decades on our understanding of the physics of tropical cyclone motion so that very little research on this topic has been carried out. Topic 4 has received substantial attention in recent years, from both the seasonal forecasting and climate change perspectives. It was therefore discussed as a separate topic. As pointed out in the Introduction, an outcome from the discussion of this topic is a Statement on Tropical Cyclones and Climate Change (see Chapter 2). To echo the Special Theme further, the last topic specifically addresses the effectiveness of the tropical cyclone warning systems, the societal impacts of tropical cyclones and the mitigation strategies, which highlights the interest of the tropical cyclone community to work with other communities in disaster reduction and mitigation in tropical cyclone landfall situations.

For each topic, a rapporteur of a sub-topic first gave his/her summary of the state of knowledge of that topic and the roadblocks for further advancement. The floor was then open for discussion. After all the rapporteurs have made their presentations, the topic chair then made a summary of the topic followed by general discussion. The participants were then divided into eight groups, with a mix of researchers and forecasters in each group. A group leader was assigned to each group and charged to lead the members of the group to make recommendations on the topic based on the material presented as well as the discussions during the plenary sessions. These recommendations were then passed to the Recommendations Committee. To enhance dialogue among the participants, they were assigned to a different group each day.

A Recommendation Committee was formed at the beginning of the Workshop, the members of which are P. Caroff (France, Chair), J. Davidson (Australia), C. Guard (USA) and E. Ritchie (USA). The Committee synthesized the recommendations from all discussion groups and presented them at a plenary session on 29 November. The recommendations were discussed by all participants and subsequently modified. The final set of recommendations is listed in Chapter 3.

****

CHAPTER 2

STATEMENT ON TROPICAL CYCLONES AND CLIMATE CHANGE

Summary Statement on Tropical Cyclones and Climate Change

The surfaces of most tropical oceans have warmed by 0.25 – 0.5 degree Celsius during the past several decades. The Intergovernmental Panel on Climate Change (IPCC) considers that the likely primary cause of the rise in global mean surface temperature in the past 50 years is the increase in greenhouse gas concentrations.

The global community of tropical cyclone researchers and forecasters as represented at the 6th International Workshop on Tropical Cyclones of the World Meteorological Organization has released a statement on the links between anthropogenic (human-induced) climate change and tropical cyclones, including hurricanes and typhoons. This statement is in response to increased attention on tropical cyclones due to the following events:

a) There have been a number of recent high-impact tropical cyclone events around the globe. These include 10 landfalling tropical cyclones in Japan in 2004, five tropical cyclones affecting the Cook Islands in a five-week period in 2005, Cyclone Gafilo in Madagascar in 2004, Cyclone Larry in Australia in 2006, Typhoon Saomai in China in 2006, and the extremely active 2004 and 2005 Atlantic tropical cyclone seasons - including the catastrophic socio-economic impact of Hurricane Katrina.

b) Some recent scientific articles have reported a large increase in tropical cyclone energy, numbers, and wind-speeds in some regions during the last few decades in association with warmer sea surface temperatures. Other studies report that changes in observational techniques and instrumentation are responsible for these increases.

<u>Consensus Statements by International Workshop on Tropical Cyclones-VI (IWTC-VI) Participants</u>

1. Though there is evidence both for and against the existence of a detectable anthropogenic signal in the tropical cyclone climate record to date, no firm conclusion can be made on this point.
2. No individual tropical cyclone can be directly attributed to climate change.
3. The recent increase in societal impact from tropical cyclones has largely been caused by rising concentrations of population and infrastructure in coastal regions.
4. Tropical cyclone wind-speed monitoring has changed dramatically over the last few decades, leading to difficulties in determining accurate trends.
5. There is an observed multi-decadal variability of tropical cyclones in some regions whose causes, whether natural, anthropogenic or a combination, are currently being debated. This variability makes detecting any long-term trends in tropical cyclone activity difficult.
6. It is likely that some increase in tropical cyclone peak wind-speed and rainfall will occur if the climate continues to warm. Model studies and theory project a 3-5% increase in wind-speed per degree Celsius increase of tropical sea surface temperatures.
7. There is an inconsistency between the small changes in wind-speed projected by theory and modelling versus large changes reported by some observational studies.
8. Although recent climate model simulations project a decrease or no change in global tropical cyclone numbers in a warmer climate, there is low confidence in this projection. In addition, it is unknown how tropical cyclone tracks or areas of impact will change in the future.

9. Large regional variations exist in methods used to monitor tropical cyclones. Also, most regions have no measurements by instrumented aircraft. These significant limitations will continue to make detection of trends difficult.

10. If the projected rise in sea level due to global warming occurs, then the vulnerability to tropical cyclone storm surge flooding would increase.

The comprehensive scientific statement including recommendations follows:

Statement on Tropical Cyclones and Climate Change

This statement was authored by participants of the WMO International Workshop on Tropical Cyclones, IWTC-6, San Jose, Costa Rica, November 2006. This resulted from discussion and review through the two weeks of the workshop. The process was overseen by the WMO Tropical Meteorology Research Programme TMRP Committee TC2: Impact of Climate Change on Tropical Cyclones. Membership: John McBride (Australia, Committee Chair); Kerry Emanuel, Thomas Knutson, Chris Landsea, Greg Holland, Hugh Willoughby (USA); Johnny Chan, C-Y Lam (Hong Kong, China); Julian Heming (United Kingdom), Jeff Kepert (Australia).

1. This statement was developed, discussed and endorsed at the World Meteorological Organization (WMO) Sixth International Workshop on Tropical Cyclones, San Jose Costa Rica, November 2006. These invitation-only WMO International Tropical Cyclone Workshops are held every four years to bring together researchers and practitioners in the field of tropical cyclone forecasting. The Sixth Workshop was attended by 125 delegates from 34 different countries and regions. The Statement has been requested by WMO leadership and many heads of National Meteorological and Hydrological Services so they can respond to questions from the media, and also to assist in advising their governments on future activities and how to respond to climate change effects.

Purpose

2. To provide an updated assessment of the current state of knowledge of the impact of anthropogenically induced climate change on tropical cyclones.

Background Material

3. The International Workshop on Tropical Cyclones series are organised by the Tropical Meteorology Research Programme (TMRP) of the WMO Commission for the Atmospheric Sciences. Subcommittees of the TMRP have previously produced two statements on tropical cyclones and climate change. One of these has been published in the refereed literature: Henderson Sellers et al. (1998). The other (TMRP, 2006) was presented at the February 2006 fourteenth meeting of the Commission for the Atmospheric Sciences, in response to the high level of international publicity on the topic arising from the severe northern hemisphere hurricane season of 2005, which included the disaster associated with Hurricane Katrina. What was significant about the February 2006 statement is that the authors included prominent scientists from both sides of the recent debates that appear in the literature and at conferences.

4. This current statement draws on the contents of these previous statements. In addition, as preparation for the sixth IWTC in Costa Rica, international working groups were formed to review recent progress on all aspects of tropical cyclone research. These were distributed one month prior to the Workshop and are published as the WMO technical Report series (WMO, 2006). The current statement borrows freely from these Working Group Reports. In particular one of these

reports (Knutson et al, 2006a) is a review of research progress on “Possible relationships between Climate Change and Tropical Cyclone Activity”. Both the main statement and the summary were developed by the Workshop Participants during the course of the 2-week international workshop.

5. In this document, the term “tropical cyclone” is used as the generic name for a non-frontal synoptic scale low-pressure system over tropical or sub-tropical waters with organized convection (i.e. thunderstorm activity) and a definite cyclonic surface wind circulation (following Holland, 1993). The term includes systems referred to as tropical storms in some parts of the world as well as the systems called hurricanes and typhoons. These latter systems (hurricane, typhoon) are regionally specific names for a strong or intense tropical cyclone. Tropical cyclone intensity is primarily recorded in observational databases as the maximum sustained [either 1 min or 10 min] surface winds. The maximum wind observation is averaged over either 1 minute or 10 minutes, depending on the region of the globe.

Current Understanding of the Impact of Climate Change on Tropical Cyclone Activity

6. The climatological conditions under which tropical cyclones occur have been well established over decades of research. These include a requirement for warm sea surface temperatures, low vertical wind shear and high values of large scale relative vorticity in the lower layers of the troposphere (Gray, 1968, 1975; McBride, 1995).

7. It is also well established observationally that over the past several decades the sea surface temperatures over most tropical ocean basins have increased in magnitude by between 0.25 – 0.5 degrees C (e.g., Webster et al. 2005; Santer et al., 2006).

8. It is well accepted by most researchers within the field of climate science that the most likely primary cause of the observed increase of global mean surface temperature is a long term increase in greenhouse gas concentrations (IPCC, 2001; IADAG 2005). It is likely that most tropical ocean basins have warmed significantly due to this same cause (Santer et al., 2006; Knutson et al., 2006b; Karoly and Wu, 2005). If anthropogenic increases in greenhouse gases are the primary cause, then it would be expected that tropical sea surface temperatures will increase by an even greater amount in the 21st century than during the 20th century, as described in the climate projections of the IPCC (2001).

9. Globally the major factor affecting tropical cyclone frequency and tracks on an interannual (e.g., 2-7 year) time scale is the ENSO phenomenon. This has been shown to affect the genesis regions and the subsequent motion in all tropical cyclone basins (Nicholls, 1979, 1984; Chan, 1985, 2000; Gray and Sheaffer, 1991; Landsea et al., 1999; Irwin and Davis, 1999; Chia and Ropelewski, 2002; Wang and Chan 2002; Chu, 2005; Ho et al., 2006). On the interannual time-scale, there is no established in-situ positive relationship between sea surface temperature and tropical cyclone frequency (Nicholls, 1984; Raper, 1992; Chan and Liu, 2004) The exception to this is the North Atlantic, where it is well established that sea surface temperature is one of the factors impacting on the number and severity of cyclones (Shapiro, 1982, Raper 1992, Shapiro and Goldenberg, 1998, Landsea et al., 1998). No such in-situ relationship has been established for the other cyclone basins.

10. During 2005 two highly publicised scientific papers appeared documenting evidence from the observational record for an increase in tropical cyclone activity. Emanuel (2005) has produced evidence for a substantial increase in the power of tropical cyclones (denoted by the integral of the cube of the maximum winds over time) for the West Pacific and Atlantic basins during the last 50

years. This result is supported by the findings of Webster et al (2005) that there has been a substantial global increase (nearly 100%) in the proportion of the most severe tropical cyclones (category 4 and 5 on the Saffir-Simpson scale), from the period from 1975 to 2004, which has been accompanied by a similar decrease in weaker systems. Mann and Emanuel (2006) reported that tropical cyclone counts in the Atlantic closely track low-frequency variations in tropical Atlantic SSTs, including a long-term increase since the late 1800s and early 1900s.

11. A number of authors attribute the reported increases as being due primarily to data reliability issues, in that the strong tropical cyclones are more accurately monitored in the recent years. Numerous tropical cyclones may have been missed and not counted even in the Atlantic basin, especially prior to 1910 (Landsea et al. ,2004, 2006 and Landsea, 2005). The historical record of tropical cyclone tracks and intensities is a by-product of real-time operations. Thus its accuracy and completeness changes continuously through the record as a result of the continuous changes and improvements in data density and quality, changes in satellite remote sensing retrieval and dissemination, and changes in training. Current estimates of tropical cyclone intensity are highly dependent on a satellite imagery interpretation technique, known as the Dvorak technique (Velden et al, 2006). Consistent with this, a step-function change in methodologies for determination of satellite intensity around the globe occurred with the introduction of geosynchronous satellites in the mid to late 1970's. Further changes in methodologies occurred through the 1980's as satellite instrumentation changed and as the technique evolved. Klotzbach (2006) restricted his analysis to the last 20 years when there were consistent satellite imagery and found no significant change in global net tropical cyclone activity and a small trend (~+10%) in category 4 and 5 frequencies. Kamahori et al. (2006) – using the Japanese Meteorological Agency (JMA) typhoon database – found that there was a substantial drop in the amount of category 4 and 5 typhoon activity between the periods 1977-1990 and 1991-2004, which is in contrast to the Webster et al. (2005) study that utilized the Joint Typhoon Warning Center (JTWC) typhoon database. Undoubtedly, this discrepancy relates to JMA vs JTWC satellite treatment of tropical cyclone intensities once aircraft reconnaissance was discontinued there in 1987. Chan (2006) extended the analysis of Webster et al for the Northwest Pacific basin back to earlier years and argued that the trend in that basin is part of a large inter-decadal variation, similarly to what Goldenberg et al. (2001) argue for the Atlantic basin.

12. In the Atlantic basin, where the most reliable historical hurricane records are believed to exist, the causes of the pronounced multidecadal variability of major hurricane activity in recent decades is currently being debated. Goldenberg et al. (2001) argue that Atlantic major hurricane activity is oscillatory, being modulated (via vertical wind shear and other circulation changes) by a multidecadal mode of SST variability referred to as the Atlantic Multidecadal Oscillation. Mann and Emanuel (2006) dispute this claim, attributing decadal changes in tropical Atlantic sea surface temperature to variations in radiative forcing caused by varying solar activity, volcanic and manmade aerosols, and greenhouse gases. Expectations about future trends vs cyclical variations of Atlantic hurricane activity would be quite different depending upon the relative importance of these two proposed factors in explaining Atlantic tropical cyclone variations in recent decades.

13. The scientific debate concerning the Webster et al and Emanuel papers is not as to whether global warming can cause a trend in tropical cyclone intensities. The more relevant question is how large a change: a relatively small one several decades into the future or large changes occurring today? Currently published theory and numerical modelling results suggest the former, which is inconsistent with the observational studies of Emanuel (2005) and Webster et al. (2005) by a factor of 5 to 8 (for the Emanuel study). The debate is on this important quantification as to whether such a signal can be detected in the historical data base, and whether it is possible to isolate the forced

response of the climate system in the presence of substantial decadal and multi-decadal natural variability. This is still hotly debated area for which we can provide no definitive conclusion.

14. Through the work of many researchers (Emanuel 1999, Emanuel et al. 2004, Free et al. 2004, Holland 1987, Holland 1997, Tonkin et al. 2000, Persing and Montgomery 2003, Montgomery et al. 2006) there is a developing theory governing maximum tropical cyclone intensity. The key concept is that for a given ocean temperature and atmospheric thermodynamic environment there is an upper bound on the intensity a tropical cyclone may achieve. This upper bound is referred to as the Maximum Potential Intensity (or MPI). As discussed in the papers by Emanuel, Holland and collaborators, few tropical cyclones actually achieve their MPI, as before such a state can be achieved they make landfall, recurve, undergo an unfavourable atmospheric environment (such as vertical wind shear) or experience an unfavourable thermal structure of the upper ocean. Emanuel (1987) and Tonkin et al (1997) presented evidence that CO_2 induced climate change would bring about a substantial increase in the MPI of tropical cyclones around the globe. Knutson and Tuleya's (2004) idealized hurricane model experiments support the theoretical predictions of the MPI theory in the context of CO_2-induced climate warming. Given, however, that only a small percentage of tropical cyclones attain their MPI and that the sensitivity of hurricane intensity to CO_2-induced warming is 3-5% per degree Celsius in these simulations and theories, Knutson and Tuleya (2004) have speculated that CO_2 induced tropical cyclone intensity changes are unlikely to be detectable in historic observations and will probably not be detectable for decades to come.

15. Climate models (global and regional) remain an important tool for investigating tropical cyclone variability and change. These contain hypotheses for how the climate system works, in a framework which allows experiments to be performed to test various hypotheses or compare models' historical simulations against historical observations. The models can provide physically based scenarios of future climate change for large-scale fields (e.g., SST, MPI, large-scale wind fields) of relevance to tropical cyclone activity. However, the uncertainty associated with future projections from climate models is generally larger for the regional scale phenomena of importance to tropical cyclone activity (e.g., El Niño) than for such measures as global mean temperature. Even for global mean temperature, uncertainties in future projections are substantial (e.g., IPCC 2001) owing to uncertainties in such factors as future anthropogenic emissions of greenhouse gases, global and regional climate sensitivity (e.g., cloud feedback), indirect aerosol forcing, and ocean heat uptake. The notion of substantial 21st century climate warming appears to be robust to these uncertainties (IPCC 2001) although the magnitude of the warming still has large uncertainties.

16. Currently there is large overall uncertainty in future changes in tropical cyclone frequency as projected by climate models with future greenhouse gases. The most recent results obtained from medium and high resolution GCM indicate a consistent signal of fewer tropical cyclones globally in a warmer climate (Sugi et al., 2002; McDonald et al., 2005; Bengtsson et al., 2006; Oouchi et al., 2006) , with some regions showing increases in some simulations, though these findings are still not conclusive. Based on the model simulations, the broad geographic regions of cyclogenesis and therefore also the regions affected by tropical cyclones are not expected to change significantly. Most models used for such global warming experiments have not been examined extensively concerning their ability to reproduce known historical variations (interannual to interdecadal) in tropical cyclone activity in various basins. While these models generally produce weak tropical cyclone-like storms in roughly the correct locations and seasons, many in the hurricane research community are sceptical of the tropical cyclogenesis process in these low-resolution models, which calls into question the reliability of their future projections.

17. Concerning future changes in tropical cyclone intensity, there is substantial disagreement among recent global and regional climate modelling studies, although the highest resolution models available show evidence for some increase in intensity (Oouchi et al, 2006; Walsh et al., 2004), in support of both potential intensity theory and idealized hurricane model simulations. A limitation of the climate models used thus far is that the simulated tropical cyclones are substantially weaker than observed—and dramatically so for the lower resolution models—and the models have not demonstrated that they can reproduce the observed increase of attainable tropical cyclone intensities with increasing SST. In cases where this relationship has been examined (e.g., Yoshimura et al. 2006) the dependence is much weaker than observed.

18. Given the consistency between high resolution global models, regional hurricane models and MPI theories, it is likely that some increase in tropical cyclone intensity will occur if the climate continues to warm.

19. A robust result in model simulations of tropical cyclones in a warmer climate is that there will be an increase in precipitation associated with these systems (Knutson and Tuleya, 2004; Hasegawa and Emori, 2005; Chauvin et al., 2006; Yoshimura et al., 2006). The mechanism is simply that as the water vapour content of the tropical atmosphere increases, the moisture convergence for a given amount of dynamical convergence is enhanced. This should increase rainfall rates in systems (viz tropical cyclones) where moisture convergence is an important component of the water vapour budget. The only observational study addressing tropical cyclone -rainfall variations is that by Groisman et al. (2004) for the United States, which showed substantial multidecadal variability but no long-term trend in total tropical cyclone -related rainfall, a metric which they stated was primarily related to the frequency of tropical cycloness. Other measures such as per-cyclone precipitation intensity at landfall were not assessed. Groisman et al. did report a significant increase (26% per 100 yr) in the annual frequency of very heavy precipitation unrelated to tropical cyclones in the southeast coastal U.S. Until further observational studies are carried out on observed trends in tropical cyclone rainfall, quantitative estimates for the anticipated rainfall increase must thus rely primarily on model projections.

20. The tropical cyclone seasons of 2004 and 2005 were highly unusual globally. Ten fully developed tropical cyclones made landfall in Japan in 2004, causing widespread damage. Southern China experienced much below-normal tropical cyclone landfalls and subsequently suffered a severe drought. Four major hurricanes caused extensive damage and disruption to Florida communities in 2004. In March 2004 southern Brazil suffered severe damage from a system that had hurricane characteristics, the first recorded cyclone of its type in the region. Five fully developed cyclones passed through the Cook Islands in a five week period in February-March 2005. The 2005 North Atlantic Hurricane Season broke several records including number of tropical cyclones, number of major hurricanes making landfall and number of category 5 hurricanes. In particular, the landfall of Hurricane Katrina at New Orleans and Mississippi caused unprecedented damage and more than 1300 deaths.

21. There is general agreement that no individual events in those years can be attributed directly to the recent warming of the global oceans. A more appropriate question is whether the probability of an event happening in a particular basin has been increased by the ocean warming, as for example the probability of cyclone development can change according to the phase of ENSO or of the Madden Julian Oscillation. It is well established that global atmospheric structure responds to the tropical sea surface temperature, and that such a response will affect the potential intensity (MPI) as well as other environmental factors such as vertical shear and relative vorticity. Thus it is possible that global warming may have affected the 2004-2005 group of events as a whole. The possibility that greenhouse gas induced global warming may have already caused a

substantial increase in some tropical cyclone indices has been raised (e.g. Mann and Emanuel, 2006), but no consensus has been reached on this issue.

22. Tropical cyclones are characterized by large horizontal gradients of wind and pressure and their structure is difficult to measure and estimate. Satellite-based tropical cyclone structure estimates (past, present and future) are limited by both their sampling and instrument characteristics, and errors inherent to the technique used (Velden et al 2006, Demuth et al 2006, Bessho et al. 2006). Nonetheless, these techniques are used exclusively, with great success, to monitor tropical cyclone structure in most parts of the world. Even when aircraft-based reconnaissance is used to assess cyclone structure, operational procedures that are based upon understanding at the time can provide different estimates of the surface wind speed (Franklin et al. 2003, Knaff and Zehr 2006). The evolution of satellite-based techniques, satellite data capabilities and operational procedures have resulted in a far from ideal historical record of tropical cyclone maximum wind speeds (Landsea et al. 2006).

23. This community of international researchers and tropical cyclone forecasters believes that the public perception and response to cyclone forecasts are somewhat hampered by a lack of uniform forecast, monitoring and recording practices. Issues include different averaging periods for surface wind estimates, non-uniform operational gust factors, and multiple tables used to estimate maximum wind from satellite (e.g., the tables in Dvorak, 1975;1984 versus Koba 1990). These differences can result in a confusing public message as well as non-uniform historical records that produce significantly different tropical cyclone climatologies (Kamahori et al. 2006).

24. Recent decades have seen a continuous increase in economic damage and disruption by tropical cyclones. This has been caused, to a large extent, by increasing coastal populations, by increasing insured values in coastal areas (e.g., Pielke 2005) and, perhaps, a rising sensitivity of modern societies to disruptions of infrastructure. For developing countries large loss of human life will continue as the increasing coastal populations are a result of population growth and social factors that are not easily countered (Zapata-Marti, 2006).

25. Projected rises in global sea level (IPCC 2001, Meehl et al., 2005) are a cause for concern in the context of society's vulnerability to tropical cyclone induced storm surges. In particular for the major cyclone disasters in history the primary cause of death has been salt-water flooding associated with storm surge.

26. A large body of research has been conducted on the potential impacts of climate change on tropical cyclones. This research has increased in volume over the past year in response to the recent research reports and in response to a number of recent high-impact tropical cyclone events around the globe. These include 10 landfalling tropical cyclones in Japan in 2004, five tropical cyclones affecting the Cook Islands in a five-week period in 2005, Cyclone Gafilo in Madagascar in 2004, Cyclone Larry in Australia in 2006, Typhoon Saomai in China in 2006, and the extremely active 2004 and 2005 Atlantic tropical cyclone seasons - including the catastrophic socio-economic impact of Hurricane Katrina. This recent international research is leading to major advances in understanding of the relationships between tropical cyclones and the large scale atmospheric state or "climate" as well as advances in the understanding of the observational record of tropical cyclones. Because of the rapid advances being made with this research, the findings in this statement may be soon superceded by new findings. It is recommended that a careful watch on the published literature be maintained.

27. Despite the diversity of research opinions on this issue it is agreed that if there has been a recent increase in tropical cyclone activity that is largely anthropogenic in origin, then humanity is faced with a substantial and unanticipated threat.

References

Bengtsson, L., K. Hodges, and E. Roeckner, 2006: Storm tracks and climate change. J. Climate, 19, 3518-3543.

Bessho, K., M. DeMaria, J.A. Knaff, 2006: Tropical Cyclone Wind Retrievals from the Advanced Microwave Sounder Unit (AMSU): Application to Surface Wind Analysis. J. of Applied Meteorology. 45:3, 399 - 415.

Chan, J.C.L., 1985: Tropical cyclone activity in the Northwest Pacific in relation to the El Nino/Southern Oscillation phenomenon. Mon. Wea. Rev., 113, 599-606.

Chan, J. C. L., 2000: Tropical cyclone activity over the western North Pacific associated with El Niño and La Niña events. J. Climate, 13, 2960-2972.

Chan, J.C.L., and K.S. Liu, 2004: Global Warming and Western North Pacific Typhoon Activity from an Observational Perspective. J. Clim., 17, 4590-4602.

Chan, J.C.L., 2006: Comment on "changes in tropical cyclone number, duration and intensity in a warming environment, Science, 311, p1713.

Chauvin, F., J.-F. Royer and M. Déqué, 2006: Response of hurricane-type vortices to global warming as simulated by ARPEGE-Climat at high resolution. Clim. Dyn., 27, 377-399.

Chia, H.-H., and C.F. Ropelewski, 2002: The interannual variability in the genesis location of tropical cyclones in the northwest Pacific. J. Climate, 15, 2934-2944.

Chu., P.-S, 2005: ENSO and tropical cyclone activity, in Hurricanes and Typhoons: Past, Present, and Potential, edited by R.J. Murnane and K.B. Liu, pp297-332, Columbia University press, New York.

Demuth, J., M. DeMaria, and J.A. Knaff, 2006: Improvement of Advanced Microwave Sounding Unit Tropical Cyclone Intensity and Size Estimation Algorithms, Journal of Applied Meteorology and Climatology, 45:11, 1573–1581.

Dvorak, V. F., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. Mon. Wea. Rev., 103, 420-430

Dvorak, V.F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Technical Report NESDIS 11, 45pp.

Emanuel, K.A., 1987: The dependence of hurricane intensity on climate. Nature, 326, 483-485.

Emanuel, K.A., 1999: Thermodynamic contro; of hurricane intensity. Nature, 401, 665-669.

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. Nature, 436, 686-688.

Emanuel, K., C. DesAutels, C. Holloway and R. Korty, 2004: Environmental control of tropical cyclone intensity. J. Atmos. Sci., 61, 843-858

Franklin, J. L., M.L. Black, and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational implications. Wea. Forecasting, 18, 32-44.

Free, M., M. Bister and K. Emanuel, 2004: Potential intensity of tropical cyclones: Comparison of results from radiosonde and reanalysis data. J. Climate, 17, 1722-1727

Goldenberg, S. B., C. W. Landsea, A.M. Mesta-Nuñez, and W. M. Gray, 2001: The recent increase in Atlantic hurricane activity: causes and implications. Science, 293, 474-479.

Gray, W.M., 1968: Global view of the origin of tropical disturbances and storms. Mon. Wea. Rev., 96, 669-700.

Gray, W.M., 1975: Tropical cyclone genesis. Dept. of Atmospheric Science Paper No. 234, Colorado State University, Fort Collins, CO, 121 pp.

Gray, W.M., and J.D. Sheaffer, 1991: El Nino and QBO influences on tropical cyclone activity. In Teleconnections linking worldwide climate anomalies, edited by M.H. Glantz, R.W. Katz, and N. Nicholls, 257-284, Cambridge University Press, New York.

Groisman, P. Y., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore, 2004: Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ. J. Hydrometeorology 5, 64–85.

Hasegawa, A. and S. Emori, 2005: Tropical cyclones and associated precipitation over the Western North Pacific: T106 atmospheric GCM simulation for present-day and doubled CO2 climates. SOLA, 1, 145-148, SOI:10.2151/sola.2005-038

Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S.-L., Webster, P., McGuffie, K. 1998: Tropical Cyclones and Global Climate Change: A Post-IPCC Assessment. Bull. Amer. Meteor. Soc., 79, 19–38.

Ho, C.-H., J. –H. Kim, J. –H. Jeong, H. S. Kim, and D. Chen, 2006: Variations of tropical cyclone activity in the south Indian Ocean: ENSO and MJO effects. J. Geophys. Res. In Press.

Holland, G.J, 1993: Global Guide to Tropical Cyclone Forecasting. WMO, Geneva. _

Holland, G.J., 1997: The maximum potential intensity of tropical cyclones. J. Atmos. Sci., 54, 2519-2541.

International Ad Hoc Detection and Attribution Group (IADAG), 2005: Detecting and attributing external influences on the climate system: a review of recent advances. J. Climate, 18, 1291-1314.

IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Irwin, R.P., and R.E. Davis, 1999: The relationship between the Southern Oscillation Index and tropical cyclone tracks in the eastern North Pacific. Geophys. Res. Lett., 20, 2251-2254.

Kamahori, H., N. Yamazaki, N. Mannoji, and K. Takahashi, 2006: Variability in intense tropical cyclone days in the western North Pacific. SOLA, 2, 104-107, doi:10.2151/sola.2006-027.

Karoly, D.J., and Q.Wu, 2005: Detection of regional surface temperature trends. J. Climate, 18, 4337-4343.

Klotzbach, P. J., 2006: Trends in global tropical cyclone activity over the past twenty years (1986-2005), Geophys. Res. Lett., 33, L10805, DOI:10.1029/2006GL025881

Knaff, J. A., and R. M. Zehr, 2006: Reexamination of Tropical Cyclone Wind-Pressure Relationships, Wea. Forecasting, in press

Knutson, T.R. and R.E. Tuleya, 2004: Impact of CO2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Parameterization. J. Climate ., 17, 3477–3495.

Knutson, T.R., K. Emanuel, S. Emori, J. Evans, G. Holland, C. Landsea, K-b Liu, R. E. McDonald, D. Nolan, M. Sugi, Y. Wang. 2006a. Possible Relationships Between Climate Change and Tropical Cyclone Activity. Working Group Report 4.2. in Workshop Topic Reports, Sixth WMO International Workshop on Tropical Cyclones. Tropical Meteorology Research Programme Report Series. TMRP No. 72. WMO, Geneva.

Knutson, T.R., T.L. Delworth, K. W., Dixon, I. M. Held, J. Lu, V. Ramaswamy, D. Schwarzkopf, G. Stenchikov, and R.J. Stouffer, 2006. Assessment of twentieth-century regional surface temperature trends using the GFDL CM2 coupled models. J. Climate, 19(9), 1624-1651.

Koba, H., T. Hagiwara, S. Asano, and S. Akashi, 1990: Relationships between CI number from Dvorak's technique and minimum sea level pressure or maximum wind speed of tropical cyclone. J. of Met. Research, 42, 59-67. (in Japanese)

Landsea, C.W., G.D. Bell, W.M. Gray, S.B. Goldenberg, 1998: The extremely active 1995 Atlantic hurricane season: environmental conditions and verification of seasonal forecasts. Mon. Wea. Rev., 126, 1174-1193.

Landsea, C.W., R.A. Pielke, Jr., A.M. Mestas-Nuñez, and J. A. Knaff, 1999: Atlantic basin hurricanes: Indices of climatic changes. Climatic Change, 42, 82-129.

Landsea, C. W., C. Anderson, N. Charles, G. Clark, J. Dunion, J. Fernandez-Partagas, P. Hungerford, C. Neumann, and M. Zimmer, 2004: The Atlantic hurricane database re-analysis project: Documentation for the 1851-1910 alterations and additions to the HURDAT database. In: Hurricanes and Typhoons: Past, Present and Future, R. J. Murname and K.-B. Liu, Eds., Columbia University Press, p. 177-221.

Landsea, C. W., 2005: Hurricanes and global warming. Nature, 438, doi:10.1038/nature04477.

Landsea,C.W., B.A.Harper, K.Hoarau, and J.A.Knaff, 2006: Can we detect trends in extreme tropical cyclones? Science. 313, 452-454.

Mann, M. and K. Emanuel, 2006: Atlantic hurricane trends linked to climate change. EOS, 87, 233-241.

McBride, J.L., 1995: Tropical Cyclone Formation. Global perspectives on tropical cyclones, WMO/TD-No. 693, 289 pp.

McDonald, R.E., D.G. Bleaken, D.R. Creswell, V.D. Pope, and C.A. Senior, 2005: Tropical storms: representation and diagnosis in climate models and the impact of climate change. Clim. Dyn., 25, 19-36.

Meehl G.A., W.M. Washington, W.D. Collins, J.M. Arblaster, A. Hu, L.E. Buja, W.G. Strand and H. Teng, 2005: How much more global warming and sea level rise? Science, 307, 1769-1772.

Montgomery, M. T., M. M. Bell, S. D. Aberson, and M. L. Black, 2006: Hurricane Isabel (2003): New insights into the physics of intense storms. Part I: Mean vortex structure and maximum intensity estimates. Bull. Amer. Met. Soc., 87, 1335-1347.

Nicholls, N., 1979: Possible method for predicting seasonal tropical cyclone activity in the Australian region. Mon. Wea. Rev., 107, 1221-1224.

Nicholls, N., 1984: Southern Oscillation, sea surface temperature, and interannual fluctuations in Australian tropical cyclone activity J. Climatol., 4, 661-670.

Oouchi, K., J.Yoshimura, H. Yoshimura, R. Mizuta, S. Kusunoki, and A. Noda, 2006: Tropical cyclone climatology in a global-warming climate as simulated in a 20km-mesh global atmospheric model: frequency and wind intensity analysis. J. Meteorol. Soc. Japan, , 84, 259-276.

Persing, J., and M. T. Montgomery, 2003: Hurricane superintensity. J. Atmos. Sci., 60, 2349-2371.

Pielke, R. A., Jr., 2005: Are there trends in hurricane destruction? Nature, 438, E11.

Raper, S., 1992: Observational data on the relationships between climatic change and the frequency and magnitude of severe tropical storms. In Climate and Sea Level Change: Observations, projections and implications, R.A. Warwick, E.M. Barrow, and T.M. L. Wigley (Eds) Cambridge University Press, 192-212.

Santer, B.D., T. M. L. Wigley, P. J. Gleckler, C. Bonfils, M. F. Wehner, K. AchutaRao, T. P. Barnett, J. S. Boyle, W. Brüggemann, M. Fiorino, N. Gillett, J. E. Hansen, P. D. Jones, S. A. Klein, G. A. Meehl, S. C. B. Raper, R. W. Reynolds, K. E. Taylor, and W. M. Washington, 2006: Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions. Proc. National Academ. Science, 103, 13905-13910.

Shapiro, L.J., and S.B. Goldenberg, 1998: Atlantic sea surface temperatures and tropical cyclone formation. J. Atmos., Sci., 11, 578-590.

Shapiro, L., 1982: Hurricane climatic fluctuations. Part II: Relation to the large scale circulation. Mon. Wea. Rev., 110, 1014-1040.

Sugi, M., A. Noda, and N.Sato, 2002: Influence of global warming on tropical cyclone climatology: an experiment with the JMA global model. J. Meteorol. Soc. Japan, 80, 249-272.

Tonkin, H., G. Holland, C. Landsea, and S.Li, 1997: Tropical cyclones and climate change: A preliminary assessment. In Assessing Climate Change: Results from the Model Evaluation and Consortium for Climate Assessments, W. Howe and A. Henderson Sellers, eds., Taylor and Francis Group, plc., London, 327-360.

Tonkin, H., G.J. Holland, N. Holbrook, A.Henderson-Sellers, 2000: An evaluation of thermodynamic estimates of climatological maximum potential tropical cyclone intensity. Mon. Wea. Rev., 128, 746-762

Tropical Meteorology Research Programme (TMRP), 2006: Statement on Tropical Cyclones and Climate Change. Available at http://www.bom.gov.au/bmrc/clfor/cfstaff/jmb/CAS-statement.pdf

Velden, C., B. Harper, F. Wells, J. L. Beven II, R. Zehr, T. Olander, M. Mayfield, C. Guard, M. Lander, R. Edson, L. Avila, A. Burton, M. Turk, A. Kikuchi, A. Christian, P. Caroff, and P. McCrone, 2006: The Dvorak Tropical Cyclone Intensity Estimation Technique: A Satellite-Based Method that Has Endured for over 30 Years. Bull. Amer. Meteor. Soc., 87, 1195-1210.

Walsh, K. J. E., K.-C. Nguyen, and J. L. McGregor, 2004: Fine-resolution regional climate model simulations of the impact of climate change on tropical cyclones near Australia. Clim. Dyn., 22, 47-56, DOI: 10.1007/s00382-003-0362-0

Wang, B. and J. C. L. Chan, 2002: How ENSO regulates tropical storm activity over the western North Pacific. J. Climate, 15, 1643-1658.

Webster, P.J., G.J. Holland, J.A. Curry, and H-R. Chang, 2005: Changes in tropical cyclone number, duration and intensity in a warming environment. Science, 309, 1844-1846.

WMO., 2006. Workshop Topic Reports, Sixth WMO International Workshop on Tropical Cyclones. Tropical Meteorology Research Programme Report Series. TMRP No. 72. WMO, Geneva.

Yoshimura, J., M. Sugi and A. Noda, 2006: Influence of greenhouse warming on tropical cyclone frequency. J. Meteor. Soc. Japan, 84, 405-428.

Zapata-Marti, R., 2006. Disaster's impact: Understanding and attributing trends and projections of damage and losses. The ECLAC perspective, White paper prepared for Workshop on Climate Change and Disaster Losses: Understanding and Attributing Trends and Projections, UNITED NATIONS - Economic Commission for Latin America and the Caribbean (ECLAC).

****

CHAPTER 3

RECOMMENDATIONS

*Philippe Caroff (France), Elizabeth Ritchie (USA), Jim Davidson (Australia)
and Chip Guard (USA)*

Summary of Major Recommendations from IWTC-VI

These high-priority recommendations are in no particular order of importance and are stratified in the same way as the entire set of recommendations: *WMO-directed in italics,* **Research-directed in bold** and ***Operational-directed in italics and bold.***

- *IWTC-VI urges the WMO Space Programme to convey to all consortiums and entities involved in the development of satellite programmes the importance of maintaining and even increasing the level of remote sensing coverage, with specific attention given to instruments that provide data for monitoring and prediction of tropical cyclones (microwave data, scatterometer data, altimeter data, total precipitable water data, etc.).*

- *In particular, the issue of decreased scatterometer and altimeter data availability in the near-future is a matter of major concern to the tropical cyclone community.*

- *WMO should take action to ensure the operational, timely availability and dissemination of all satellite data of major interest to the tropical cyclone community. Please refer to actions proposed on page 20 of the recommendations for achieving this goal.*

- *The WMO should take all necessary action to:*

a) *Improve the communication between operational centres and facilitate the dissemination of all tropical cyclone-related NWP products, such as the deterministic and ensemble forecasts (including the full set of ensemble runs), and*

b) *Make them available to all RSMCs, TCWCs and researchers in real-time.*

- ***NWP centres should verify their forecasts (including probabilistic forecasts) and document their performance in a common standard format.*** *WMO/CAS could ask, in cooperation with WWRP, the Working Group on Forecast Verification to put in place a formal mechanism for this purpose, defining a common methodology and set of parameters appropriate to tropical cyclones to be verified.*

- The re-analysis of past data using current understanding and new techniques was recognised by the IWTC-VI as a major necessity***. IWTC-VI strongly encourages all forecast centres to continue revising their historical best-track data base*** at the highest possible temporal resolution.

- *As a major initiative an international database should be developed to track the loss of human life and socio-economic impacts of tropical cyclones as well as the costs associated with tropical cyclone forecasting and disaster mitigation initiatives. A small multi-disciplinary task force should be formed to monitor the development of the database and to liaise with other groups with a similar goal.*

- **IWTC-VI strongly recommends that greater efforts be put into intensity and structure prediction of tropical cyclones. The development of dynamical models, including coupled ocean-atmosphere models, statistical-dynamical models and all methodologies aimed at improving the skill in intensity and size prediction (and resulting wind and rainfall fields) should be strongly encouraged.**

- **IWTC-VI considers that the tropical cyclone community should engage and cooperate with the THORPEX activities of relevance to the tropics, especially the THORPEX Pacific Asian Regional Campaign (T-PARC) and the Interactive Grand Global Ensemble/Global Interactive Forecast System, which aims in particular to develop generic probabilistic forecast products from a global archive of ensemble forecasts originating from a number of NWP centres.**

Recommendations

The recommendations are categorised as *WMO-directed (in italics)*, **Research-directed (in bold)** and ***Operational-directed (in italics and bold).*** High-priority items are labelled as (HP) at the beginning of the recommendation.

1. DATA AVAILABILITY and RELATED ISSUES

1.1 Observations

Atmospheric and oceanic observations are the fundamental basis for all research and operational activities in meteorology and this is particularly true for tropical cyclones, which develop, evolve, and interact with, the data-sparse oceans. Maintaining or increasing the amount and quality of observations of both the atmosphere and ocean is critical to improving the quality of services provided to users and populations by the National Meteorological and Hydrological Services (NMHS) in order to reduce community impacts (including the loss of life) during tropical cyclone events.

The minimum requirement from the tropical cyclone community is a two-dimensional surface wind based on observational data and accumulated precipitation data at adequately high temporal and spatial resolution.

1.1.1 Satellite data are the greatest source of observations of tropical cyclones and we strongly recommend the continued support of satellite-based remote sensing technologies (both existing and future) for the purpose of tropical cyclone detection and structure characterisation, nowcasting, forecasting, and post-analysis.

The IWTC-VI has been advised of a likely reduction in meteorological satellite data, including microwave data that are critical for forecasting and research on tropical cyclones.

- (HP) *IWTC-VI urges the WMO Space Programme to convey to all consortiums and entities involved in the development of satellite programmes the importance of maintaining and even increasing the level of remote sensing coverage, with specific attention given to instruments that provide data for monitoring and prediction of tropical cyclones (microwave data, scatterometer data, altimeter data, total precipitable water data, etc…).*

• (HP) *In particular the issue of decreased scatterometer data availability in the near-future is a matter of major concern to the tropical cyclone community.*

• *Given the escalating importance of global ocean heat content on hurricane intensity and ENSO activity, the WMO should strongly emphasize the importance of satellite radar altimeter measurements from multiple platforms.*

• *IWTC-VI recommends that the WMO Space Programme strongly endorse the specific recommendations of the US National Oceanic and Atmospheric Administration Operational Satellite Ocean Surface Wind Vector Winds Requirements Workshop Report (workshop convened at the US Tropical Prediction Center/National Hurricane Center on June 5-7, 2006).*

• *The WMO Space Programme should also encourage NASA (National Aeronautics and Space Administration, USA) to continue with its plans to launch the Global Precipitation Mission platform.*

• *The WMO Space Programme should actively promote a better global cooperation between all agencies in the fields of oceanographic and meteorological remote sensing to guarantee the most cost-effective satellite coverage that will ensure short-, mid- and long-term availability of data.*

• *New satellite observing systems for tropical cyclones should be encouraged. In particular, WMO should promote the design and launch of geostationary active/passive sensors. There is a specific need for developing active microwave (Doppler radar) observing platforms enabling a permanent space-based global coverage.*

This would help monitor the 3-dimensional structure of tropical cyclones and contribute to improved assimilation of related mesoscale data into cloud-resolving tropical cyclone prediction models.

For this purpose, it is of extreme importance that these new technologies (both atmospheric and oceanic) be calibrated against in situ surface data.

The other major concern about remote sensing data deals with their dissemination. Many of the satellite data most useful for tropical cyclone monitoring and prediction, especially track forecasting, are available on web servers that are not continuously maintained (e.g., NRL, CIMSS, CIRA).

• *(HP) WMO should therefore take action to ensure the operational, timely availability and dissemination of all satellite data of major interest to the tropical cyclone community.*

• ***Whenever possible, dissemination in a digital manner through the GTS and through an operational website should be sought.***

• *The solution of establishing a WMO-sponsored operational "Satellite Observing Data Centre" should be explored.*

This central repository centre would serve (through real-time and archive access) all relevant tropical cyclone-related satellite data and products (including microwave data, scatterometer data – with wind ambiguities –, driftwinds-derived products, etc…).

• *The IWTC-VI recommends that improved scatterometer wind ambiguity selection techniques that account for the tight flow curvature in tropical cyclones and initialised by analysed cyclone centre positions, be developed and implemented by the scatterometer data centres.* ***These analyses should be placed in a gridded format and made available to all weather forecast centres.***

1.1.2 Rawinsonde Data

The IWTC-VI expressed concern about a diminution of rawinsonde observations.

• *WMO should explore all possible means to maintain, restore, and even expand, the existing upper-air network, especially in developing countries. Targeted observation strategies could be used to optimize the implementation of rawinsonde stations.*

1.1.3 Radar data and conventional data are of major interest for the tropical cyclone community so that:

• ***The timely dissemination of radar data, ship observations, rawinsondes and other conventional data, and fixes of all relevant specific observations not already routinely disseminated on the GTS by the NMHSs should be converted to operational routine procedures.***

1.1.4 Targeted observations – Experiments conducted in the environment of tropical cyclones in recent years have demonstrated value in significantly reducing track forecast errors when ingested in the data assimilation systems of Numerical Weather Prediction (NWP) models.

IWTC-VI recognizes that adaptive observations are a very promising way to improve tropical cyclone track prediction and therefore recommends that:

• *WMO encourage expansion of aircraft targeting capabilities in various tropical cyclone basins.*

• **Research on targeted data should be extended to other observing systems and data (e.g. satellite-derived soundings, ocean data, and rawinsondes). Application of new concepts in predictability and data assimilation should be tested.**

• **Further research should be undertaken to define the best way to optimise targeted observations.**

Furthermore, the following topics should be addressed: sampling strategies, sensitivity analysis of the different techniques and of the data assimilation schemes, definition of the most sensitive regions to be targeted for optimal and cost-effective efficiency and what subsets of data are the most effective in data assimilation for tropical cyclone prediction.

• **More work is encouraged to develop methods adequate to assess the impact of any changes on the current observing network and in making optimal use of the related data. In particular, targeted observation methodologies should be utilized to identify cost-effective strategies for maintaining and expanding the current rawinsonde upper-air observing network.**

- **Observing Systems Experiments should be conducted to assess the observing system impacts.**

The IWTC-VI further recommends that:

- ***Both field and community surveys regarding impact, response and preparedness should be conducted in the aftermath of landfalling tropical cyclones.***

- ***A comprehensive post-event report of all the wind, pressure and rain data collected during the tropical cyclone event, as well as its societal impact, should be documented, published,*** *and made available via an appropriate (password-protected) WMO web site.*

1.2 Numerical Weather Prediction Products

In light of the benefits yielded by the multi-model consensus approach, the *sharing* of all *ensemble and deterministic forecasts* issued by the different Numerical Weather Prediction (NWP) centres has been recognised by the IWTC-VI as a top priority.

- (HP) *The WMO should take all necessary action to: 1) improve the communication between operational centres and facilitate the dissemination of all tropical cyclone-related NWP products, such as the deterministic and ensemble forecasts (including the full set of ensemble runs); and 2) make them available to all RSMCs, TCWCs and researchers in real-time.*

WMO should investigate the most appropriate ways to achieve this goal:

- *Coordinate with the NWP and major operational centres (RSMCs and TCWCs) in order to define a set of resolvable tropical cyclone characteristics to be provided and timely disseminated by the NWP centres through the GTS (e.g. centre location, minimum sea level pressure, max wind, wind radii by quadrants, etc…) and define the appropriate standardised format.*

- *And/or find a WMO-sponsored dedicated reference centre* (similarly to what has been done with the Severe Weather Information Centre for the dissemination of the analysis and forecast products issued by the main operational centres) *able to host and maintain a single global data base of the tropical cyclone forecasts originating from the different NWP centres.*

The data should be made available through a timely and convenient access (password-protected platform or website – like the one hosted by the Japan Meteorological Agency – recommended). Posting of a significant subset of fields, including a suitable number of upper-level fields, from the NWP centres would provide great added value. *Interaction with the TIGGE initiative could be considered (see TIGGE item thereafter).*

- ***NWP centres and major operational centres should also coordinate to develop a common standardised vortex tracker to apply to their global and regional models.***

- ***It is further recommended that NWP centres flag model outputs when a synthetic tropical cyclone procedure has been used during initialisation of the model forecast with some agreed upon common flag. It is important that information regarding the bogussing procedure be made readily available to forecasters and researchers.***

- (HP) ***NWP centres should verify their forecasts (including probabilistic forecasts) using tropical-cyclone related metrics and document their performance in a common standard format (information on biases and variance of errors should be included).***

- *WMO/CAS could ask, in cooperation with WWRP, the Working Group on Forecast Verification to put in place a formal mechanism for this purpose, defining a common methodology and set of parameters appropriate to tropical cyclones to be verified (e.g. genesis, tropical cyclone tracks – including provision of along track and cross track error statistics –, intensities or intensity changes, size – wind radii –, rainfall prediction, etc…).*

- **IWTC-VI considers that the tropical cyclone community should engage and cooperate on a long-term basis with the THORPEX Interactive Grand Global Ensemble/Global Interactive Forecast System (TIGGE)/(GIFS), which aims in particular to develop generic probabilistic forecast products from a global archive of ensemble forecasts originating from a number of NWP centres. This would enable integration of single- and multi-model consensus approaches.**

- ***IWTC-VI requests that the TIGGE archived data include a set of tropical cyclone-related parameters (e.g. centre location, minimum sea level pressure, max wind, wind radii by quadrants, etc…). Tropical cyclone-related probabilistic product-generation tools should be included in the TIGGE phase-2 and also made available to operational centres in real time.***

- As one of the most important users, **the tropical cyclone community should also be involved in the design of the future operational GIFS system.**

- *WMO is asked to report these IWTC-VI recommendations to the upcoming meeting of the International Core Steering Committee (ICSC) for THORPEX in April 2007.*

1.3 Databases

All major operational centres (Regional Specialised Meteorological Centres (RSMC) and Tropical Cyclone Warning Centres (TCWC)) should maintain a comprehensive historical tropical cyclone database of best-track (post-storm analyses) in their respective basins.

- (HP) The re-analysis of past data using current understanding and new techniques was recognised by the IWTC-VI as a major necessity.

- (HP) ***IWTC-VI strongly encourages all forecast centres to continue revising their historical best-track database*** at the highest possible temporal resolution (e.g., fixes are made more frequently than the archived 6 hours).

- Where multiple “best tracks” exist for a specific basin, these need to be incorporated into a unified, re-analysed tropical cyclone database.

Such re-analysis efforts will by nature generally create a heterogeneous time series because of differing available observations; however, it is also crucial that homogeneous tropical cyclone climate databases be developed.

- *For this purpose the WMO format for best track databases should be modified in order to include metadata relating to basic observational quantities and intensity estimate procedures.* ***All derived quantities such as pressure-wind relationships should be appropriately flagged.***

- ***Furthermore, uncertainty in the historical tropical cyclone databases should be determined and recorded***.

- **In addition, there is a need to identify a set of useful ocean metrics to be either maintained in the tropical cyclone best track database or kept in a separate oceanic tropical cyclone database. A careful re-analysis of past oceanic data should be undertaken as a part of the database development.**

- WMO/CAS/TMRP, should provide support for these activities where needed and encourage all efforts to assemble long-term, written, historical records (like the China 500-y record of landfalling typhoons, the Japanese records, and the Cuba records) and other relevant data coming other historical studies (e.g. paleotempestology work).

- *WMO should facilitate a working group of experts (operational and research) who maintain or work with these databases to produce a common set of standards on archiving these data and establish a standard procedure for the re-analysis of these best track data. A goal of this group should be to create a single, uniform global best track data base.*

1.4 Field Experiments

Sustained efforts to conduct field programmes and experiments should be encouraged.

- **They should not only focus on synoptic surveillance missions but inner core missions should also be planned, especially in cyclone basins that have not been yet investigated.**

- **Researchers from all countries and applicable forecast centres are encouraged to support and participate in the tropical and extratropical components of the THORPEX-Pacific Asian Regional Campaign (T-PARC) field experiment in the western North Pacific during 2008.**

- **Existing datasets from previous field experiments should be made available to all interested groups within the operational and research community, preferably in one central location.**

2. TRACK FORECASTS

The IWTC-VI affirms that although substantial improvements have been achieved in the past decade, *track forecasting* still remains a high priority. It is recommended that efforts should continue to further reduce track forecast errors. All potential sources of track errors (model physics, initial conditions, etc.) should be examined, but special emphasis should be given to the following issues:

- I**nvestigate the causes of large forecast errors and try to remedy them** through comprehensive examination of all relevant potentially linked elements: observations, data assimilation and vortex specification techniques for initial conditions, model resolution and physical processes representations, etc. ***Systematic review of major failures in track prediction should***

be undertaken with case studies and inter-comparison exercises. Synoptic patterns likely to be associated with large forecast errors should be documented including identification of model biases and weaknesses.

- ***While the dissemination of extended long-range forecasts by all operational centres should be encouraged,*** **consideration should also be given to improve short-range forecasts (6 to 24h), which is of critical impact for landfalling tropical cyclones.**

- **Development of high-resolution models should be encouraged**. Because they in particular resolve orography, they may be of great help to improve track and structure prediction of tropical cyclones near landfall (including wind and rainfall distribution). ***Serious consideration should therefore be given by operational centres benefiting from such high-resolution models to test the skill of these models and eventually put them into operations.***

3. INTENSITY and STRUCTURE PREDICTION

The IWTC-VI acknowledges that intensity changes and structure prediction of tropical cyclones remain a challenge and that past improvements on these aspects have been inadequate.

(HP) **IWTC-VI strongly recommends that greater efforts being put into these aspects and encourages the development of dynamical models, including coupled ocean-atmosphere models, statistical-dynamical models and all methodologies aiming to improve the skill in intensity and size prediction (and resulting wind and rainfall fields).**

- **More research is encouraged to improve our understanding of intensification, size changes, and weakening processes. Special interest should be put on addressing Potential Intensity theories.**

- *WMO should encourage and facilitate the transfer of research and technique developments, for example intensity guidance such as SHIPS, from the Atlantic and western North Pacific to other basins.*

- *WMO should organise a model inter-comparison study for evaluating the existing model capabilities on predicting tropical cyclone structure change including identification of metrics for structure and structure change validation (as in Macau Workshop).*

- **Research on multi-model consensus and single-model ensemble approaches, which show promise for intensity prediction, should be encouraged.**

- **More research (numerical and statistical) is also needed to improve tropical cyclone initialisation (e.g. bogussing), via data assimilation, parameterisation, and inclusive of the inner core and outer core regions.**

- ***Main operational NWP centres should explore ways of making suitable shear products available to users such as RSMCs and TCWCs. There is also a recommendation for the development of an interpretative measure of vertical wind shear in layers of varying depth.*** **The effects of various types of shear need to be better understood.**

• **The IWTC-VI recognised that more research and case studies should be conducted to understand the influences and interactions of the upper-level environment on the intensity and size changes of tropical cyclones.**

Key aspects of this “good trough” vs. “bad trough” issue may include finding objective ways to quantify upper-level forcing in NWP fields and its influence on tropical cyclone outflow.

• **Research is needed to assess coupled model performance with respect to air-sea interaction parameterisations, ocean model initialisations, and vertical mixing schemes used in the coupled models.**

A key aspect here is to understand how uncertainties in the parameterisations propagate through the coupled models.

• ***Centres performing ocean data assimilation should be encouraged to provide ocean heat content products for all tropical cyclone basins. These products should be evaluated and validated using common metrics.*** *The inclusion of a global ocean heat content product to the WMO tropical cyclone website should be considered.*

4. ENSEMBLE and CONSENSUS

IWTC-VI was presented evidence of the tremendous positive impact the recently developed *consensus techniques* have had for tropical cyclone track prediction since being implemented in the major operational centres.

• ***The development and utilisation of ensemble-based probabilistic guidance should be generalised and extended to prediction of all other tropical cyclone parameters (e.g., genesis, intensity, storm tide, waves, rain and flood forecasting).*** **However, more studies are needed in order to develop a more systematic and optimised approach for the best use of ensemble-based products in operations.**

• ***Forecast uncertainty information should be provided by operational NWP centres to operational forecasters. NWP centres should perform verification of tropical-cyclone related probabilities produced by ensemble prediction systems.*** **The possibility of improving the representation of uncertainty by exploiting the information contained in the spread of the models and of their ensemble should be explored in order to generate a true envelope of uncertainty in tropical cyclone forecasts.** ***Tools to best display ensemble products and also high-resolution models should be developed.***

• **Further research is also needed to refine the single-model ensemble techniques.** The impact of ensemble data assimilation techniques should be in particular explored and tested against variational assimilation techniques.

Multi-model (consensus) forecasts should be closely evaluated in collaboration with WGNE to identify:

(a) ***The minimum number and optimal combination of forecast members that adds value to the forecast process;***
(b) ***Scenarios that yield small errors; and***

(c) ***Strategies to deal with situations when the uncertainty associated with the consensus forecast is large (e.g. bifurcation scenario when members are in two different track types).***

5. EXTRATROPICAL TRANSITION and GENESIS

- NMHSs are requested to add a flag in their ***best-track data that indicates the period of extratropical transition (from onset to end). Furthermore, it is recommended that a common definition for the labelling of "ET" in the best tracks of all operational centres should be used for consistency.***

- **A systematic study is encouraged of NWP model predictability for tropical cyclone genesis and extratropical transition, including identification of conditions of model forecast failure.**

- **It is recommended that conceptual models of the physics of extratropical transition be developed** that will assist forecasters in forecasting ET, particularly when landfall is expected. ***It is further recommended that improved quantitative precipitation estimates (QPF), particularly at landfall, be a high priority for ET verification programmes.***

- **An ET ensemble forecast methodology to characterise the uncertainties in the forecast should be developed.**

We encourage the continued development of cyclone phase space and the evolution towards inclusion of satellite soundings in that development.

- *For the next IWTC it is recommended to have a section on ET forecasting. The inclusion of a section on subtropical and hybrid systems and on tropical transition should also be considered.*

- **The far-field effects of tropical cyclones should be investigated** via probabilistic forecasts with a view to determining and conveying how future predictability changes in response to the presence of a tropical cyclone in the model fields.

- **More research is required to improve our understanding of the structural changes in tropical cyclones, including genesis, size changes, intensity, and extratropical transition processes.** In particular, there is little understanding of the role of the upper ocean in all these processes (beyond the climatological factors). **It is recommended that research be undertaken to understand the role of the upper ocean thermal structure on all tropical cyclone processes in the various basins. It is further recommended that the spatial resolution of ocean data that is required to detect effects on cyclogenesis be determined and efforts made to attain that level of detail.** It is believed that this can be achieved through more observations of the atmosphere and ocean as well as through atmospheric and coupled models that include upper-ocean and air-sea interface effects.

- To better understand and forecast how genesis does occur in the different basins**, further research into the different modes of genesis is needed. Such studies should address the role of the upper ocean in genesis (beyond the climatological factors). Furthermore, stochastic processes should also be investigated. It is further recommended that the spatial resolution of ocean data that is required to detect effects on cyclogenesis be determined and efforts made to attain that level of detail.**

- **The utility of statistical-based techniques for forecasting genesis should be investigated.**

- We encourage research to improve understanding of the relationships between tropical cyclone genesis and the scales of circulation that can be forecast by climate models. Furthermore, we encourage research into establishing what those predictable scales of circulation are.

6. SEASONAL FORECASTS

Seasonal forecasts of tropical cyclone activity, some of them including prognosis on landfall probabilities, are issued by different agencies or operational centres in some cyclone basins. There is a need to better communicate and verify these forecasts.

- ***All seasonal predictions of tropical cyclone activity should be validated in a manner appropriate to their form of output*** *and reported on a central website hosted by WMO.*

- *Furthermore, we suggest that WMO form a working group of experts to develop a common set of metrics for evaluating the skill of seasonal forecasts of tropical cyclone activity.*

- *In addition, we encourage that group of experts, under the auspices of WMO, document the purpose and goals of seasonal forecasting and the uncertainties in these forecasts.*

- *Finally, once a common metric is developed, WMO should coordinate the post-season verification of these forecasts and report them on the website.*

6.1 Intra-seasonal and Inter-annual

Many research issues need to be addressed in order to improve the skill in seasonal forecasting. In particular, more work is needed on intra-seasonal and inter-annual variations and controls of tropical cyclone locations, including genesis and track.

- **Research to determine the accuracy and limitations of numerical forecasts of tropical cyclone genesis and activity on seasonal and climate time scales should be undertaken.**

- **The capability for forecasting intra-seasonal variability of MJO- and other tropical wave-forecasting-based techniques should be verified.**

We also encourage:

- **Research into the large-scale steering mechanisms in individual basins that control tropical cyclone track and genesis locations on inter-annual time scales (e.g., ENSO);**

- **Research in collaboration with the oceanographic community into the role of intra-seasonal, inter-annual, and multi-decadal ocean heat content variability in tropical cyclone activity on similar scales;**

- **Research and observations into the El Nino Southern Oscillation (ENSO), to better understand its role in modulating tropical cyclone activity, and research into the forecasting and predictability of ENSO as this is a major roadblock limiting seasonal forecast skill.**

It is recognized that there are significant interactions among ENSO, the MJO, and other global-scale circulations such as the Quasi-Biennial Oscillation (QBO) that are not well understood or forecast.

- **We encourage research into a more unified theory of how various modes of variability and various scales of tropical waves interact to affect tropical cyclone activity and seasonal predictability.**

- We suggest that WMO should facilitate a meeting between the interested operational and research experts to encourage interaction and collaborative research in this field.

6.2 Decadal Variability and Climate Change

Given the importance of this topic to humankind, including developing nations and island nations, it is recommended that WMO through the Tropical Meteorology Research Programme take steps to facilitate and encourage further research on climate effects (natural and human-induced) on tropical cyclones.

- **Research on multi-decadal variability and anthropogenic forcing effects on tropical cyclone activity in all basins, to more fully delineate the roles of natural variability and anthropogenic forcing.** Physical relationships should be established, not just correlation statistics.

- **More generally, we encourage development and research into greater understanding of the role of tropical cyclones in the general circulations of the atmosphere and ocean.**

- **There is a very large inconsistency between global warming modelling/theory (which suggests small changes in intensity several decades from now) versus some observational studies (which suggest that large changes have already occurred). Further global warming modelling/theory studies are needed to better understand the sensitivity to greenhouse forcing.**

- *To improve databases for the assessment of climate change and the development of improved tropical cyclone monitoring techniques, the IWTC-VI recommends that consortiums of nations develop the capability for continuous aircraft reconnaissance or as a minimum the validation of satellite-based intensity techniques in all tropical cyclone basins. We recommend that WMO take a lead role in facilitating such a programme.*

7. WINDS

- **The IWTC-VI strongly endorsed the need to develop a unified enhanced Dvorak-like technique that will incorporate storm structure changes (including wind-pressure profile variations). Development of systems such as the Advanced Dvorak Technique that can incorporate multiple sources of information such as microwave should be encouraged.**

- **The IWTC-VI recommends that a public domain parametric wind field model that includes asymmetries be developed and fully tested, documented and verified by peer review.** This model could then be used in conjunction with scatterometer data and the Dvorak technique to determine a cyclone's wind and intensity profile.

- ***The RSMCs and TCWCs are encouraged to work with a multi-disciplinary research community to develop graphic and text products that portray the tropical cyclone size and structure and the combined forecasted uncertainties in the track, intensity and size (e.g., wind probability tool) for public use.***

- **The IWTC-VI supports the requirement to improve understanding of the effects of variability of surface land roughness and topography on forecast wind speed. The IWTC-VI encourages research on land-surface variability impacts on the surface wind field.**

- *IWTC-VI reconfirms the requirement for a standard chart that enables users to convert between different wind-averaging periods and gust factors. The WMO should also help facilitate the standardisation of the wind reference amongst global tropical cyclone warning centres.*

It is recommended that the various tropical cyclone wind scales in use globally be identified and a summary of their features published for reference by WMO/RSMCs/TCWCs.

- ***IWTC VI endorses the need to review tropical cyclone Category Scales,*** with the particular objective of better defining the impacts hazard to improve public understanding of the level of threat. ***Designing new tropical cyclone Hazard/Risk/Threat Scales that would integrate other hazards like storm tide and rain fall should be considered as it is recognized that, in particular, storm tide is a site-specific sensitivity.***

- **It was recognised that there is a significant need for further studies into the asymmetry in tropical cyclone structure, upon landfall primarily, including developing a greater understanding of fine-scale and transient features such as mesovortices, boundary layer wind streaks and roll vortices.**

8. STORM TIDE and HYDROLOGIC FORECASTS

Flooding is one of the main impacts due to tropical cyclones. The forecasting of floods is tied to meteorological (mainly rainfall forecast) inputs and in many cases to the tidal forecast as well. However, in order to effectively initialise hydrologic and hydraulic models, some improvements are needed.

The IWTC-VI emphasises the need for improved *rainfall forecasts*. The IWTC-VI recommends that rainfall forecasting techniques for Quantitative Precipitation Forecast (QPF), at a greater spatial and temporal resolution, should be investigated.

- **A parametric precipitation model associated with landfalling tropical cyclones should be developed and evaluated. This model would combine a short-range track and intensity forecast with the rainfall rates derived from satellite and radar imagery calibrated from a rain gauge network.**

- ***The availability of short-range rainfall forecasting techniques would greatly assist in forecasting floods and flash flooding.*** In addition, it would help in forecasting other rainfall induced hazardous situations with short lead times, such as landslips, mudslides and debris flows. **Increased research efforts on developing forecasting models dealing with these phenomena are also recommended.**

• ***The IWTC-VI recommends that in areas where operational hydrological and hydraulic models need to be coupled to tidal models, these should be implemented in an operational environment.*** **The integration of meteorological, hydrologic, hydraulic, and tidal models should be evaluated and skill and uncertainties assessed.**

• The IWTC-VI recognises that storm tide is a major tropical cyclone-related hazard, which requires specific attention. Operational storm tide forecasting techniques therefore need to be provided to tropical cyclone warning centres that currently do not have this capability. The IWTC-VI recommends that WMO conducts a review of available storm-tide prediction methodologies with the purpose of advising warning centres on the most appropriate options according to their regional characteristics. In particular, the review should consider the individual storm tide components (tide, surge, breaking wave setup, and wave runup). The review should include model validation, ease of use, computational requirements, and training needs.

• The IWTC-VI recommends that more focus be placed at the next IWTC on water-related issues including oceanic, coastal, and inland-flooding processes.

9. HAZARD ASSESMENT and MITIGATION

• The IWTC recommends that the WMO assists least-developed and developing countries so as to engage in hazard assessment, risk mapping, and tropical cyclone simulation exercises, to be conducted especially in highly vulnerable coastal and inland areas. Information derived could then be used by NMHSs disaster managers, local governments and communities to better manage and strengthen national disaster and mitigation plans.

• *More prominence should be given at the next IWTC to the fields of disaster mitigation and societal impacts.* This might be achieved by interweaving those topics into the main programme or promoting those sessions to the start of proceedings. *Consideration should also be given to inviting representatives of a wider range of related disciplines to the Workshop.*

• *Regional workshops should be conducted for practitioners every 4 years (2 years out of phase with IWTCs) for the purpose of advancing the Total Warning System concept and the sharing of tropical cyclone societal impact and disaster mitigation experiences.*

(HP) *As a major initiative an international database should be developed to track the loss of human life and socio-economic impacts of tropical cyclones as well as the costs associated with tropical cyclone forecasting and disaster mitigation initiatives. A small multi-disciplinary task force should be formed to monitor the development of the database and to liaise with other groups with a similar goal.*

10. TRAINING/EDUCATION/OUTREACH/COMMUNICATION

There is a strong need to provide training to the forecasters to make best use of the new observing techniques (like those dealing with microwave and scatterometer data) and of new products from advanced NWP and operational centres.

IWTC-VI asks WMO to continue to support all initiatives aimed at that purpose: sponsoring of small focus thematic workshops, training courses, attachment of forecasters at the main operational centres (RSMCs and TCWCs), development of Computer Assisted Learning, etc.

Specific training focussed on the following topics should be promoted:

- *Ensemble and consensus approaches and related forecasting and probability forecast interpretation.*

- *Training on tropical cyclone rainfall and storm tide forecasting.*

- *Identify effective methods and tools to better communicate the forecasts, warnings and the realistic threats to emergency managers, media and the public.*

- *The IWTC-VI also recommends that WMO hosts a dedicated tropical cyclone web page including tutorials, training modules, frequently-asked-questions and links to useful related sites.*

- **Regarding the preceding recommendation, the IWTC-VI recommends that a group of experts including forecasters, and communications experts identify effective communication tools**.

- ***The IWTC-VI also recommends the use of education and outreach to aid in the process of communicating forecasts and warnings.***

The IWTC-VI reiterates the urgent need to issue a revised and updated version of the Global Guide to Tropical Cyclone Forecasting and endorses the content of the major WMO recommendation already made on this topic at the previous IWTC-V meeting (refer to the related Proceedings), except that the chapter “The Total Warning System” should be expanded into “Effective Warning System and societal impacts”. A small multidisciplinary task force should be formed to prepare the new section.

IWTC-VI also asks WMO to rapidly initiate the process towards a follow on publication of an updated version of the Global Perspectives on Tropical Cyclones.

The IWTC-VI recognises that there should be inclusion in a coming WMO bulletin of a few articles coming from the IWTC-VI group.

11. DEFINITIONS

IWTC VI recommends that WMO be requested to provide agreed upon common definitions of:

1) *tropical cyclone coastal crossing;*
2) *tropical cyclone landfall and tropical cyclone landfall phase (for islands and continuous coastlines);*
3) *tropical cyclone strike;*
4) *tropical cyclone Impact;*
5) *tropical cyclogenesis;*
6) *extratropical transition (ET);*
7) *tropical transition (TT);*
8) *hybrid cyclone; and*
9) *subtropical cyclone.*

****

WORKSHOP PROCEEDINGS

CHAPTER 4

SPECIAL THEME: "QUANTITATIVE FORECASTS OF TROPICAL CYCLONE LANDFALL IN RELATION TO AN EFFECTIVE WARNING SYSTEM"

Jim Davidson (Australia)

0.1 **Track Forecasts (Lixion Avila)**
0.2 Observations and Forecasts of **Wind Distribution (Sai-Tick Chan)**
0.3 Observations and Forecasts of **Rainfall Distribution (Lianshou Chen)**
0.4 Observations and Forecasts of **Storm Surges (Shishir Dube)**
0.5 Observations and Forecasts of **Hydrology-related Issues (Kang Shong)**

Abstract

This Workshop report summarizes the presentations delivered and the issues addressed at IWTC-VI during the various sessions on the special theme: "Quantitative Forecasts of Tropical Cyclone Landfall in relation to an Effective Warning System". Here the landfall phase was defined as that period of a cyclone's lifecycle bounded by the immediate approach of the cyclone to the coast through to the early part of its transition over land.

Prospects for further improvements in quantitative forecasts of cyclone landfall appear to largely rest on greater access to multi-model consensus and single-model ensemble forecasts of not only track and intensity but also precipitation. Significant forecasting gains can also be realized through the continuing development and distribution of parametric models for a range of landfall parameters. As resources allow, these initiatives should be underpinned by field experiments, demonstration projects and various capacity building activities. Remote sensing data, especially from weather satellites, will remain critical to the forecast process.

One of the major recommendations from IWTC-VI is for greater effort to be directed by the research community into intensity and structure prediction, which continues to be a serious weakness in landfall hazard prediction. The other significant weakness identified was forecasting the spatial and temporal distribution of rainfall from a landfalling cyclone. It was also strongly recommended that more focus be placed at the next IWTC on water-related issues, including oceanic, coastal and inland flooding processes.

(A) Effective Warning System

An Effective Warning System was defined as "the targeted communication of timely, relevant, and understandable Warnings to a prepared, receptive and resourceful community – with the Warnings composed using a mix of the best available NWP guidance and forecasting skill". Alternatively, "**E**ffective Warnings **E**ngage and **E**mpower the **E**ndangered – and so **E**licit **E**vasive action".

(B) Established Facts

- Landfall hazard prediction is highly dependent on the cyclone's track. At a particular location, even small deviations in track can result in vastly different impacts from wind, storm tide, precipitation and flooding.

- Most deaths in tropical cyclones continue to be caused by flooding, landslips, mudslides and debris flows.
- With the steady growth in coastal population and infrastructure, we are witnessing what amounts to a quantum leap in vulnerability (and therefore risk) in many cyclone prone areas, irrespective of trends in cyclone numbers and intensities. Importantly, evacuation times have increased accordingly.
- Tropical cyclone speed at landfall is quite critical in terms of potential wind damage and rainfall/flooding. The faster the cyclone is moving, the lower the risk of wind and flood damage.

(C) Landfall Hazards

The following cyclone hazards were considered for discussion:

1. **WIND** – both temporal and spatial over varying terrain and topography
2. **RAINFALL** – both temporal and spatial
3. **FLOODS** – both riverine and localised
4. **LANDSLIPS & MUDSLIDES & DEBRIS FLOWS**
5. **STORM TIDE** (defined as being “storm surge + normal tide + wave setup”)
6. **WAVE ACTION** – including wave setup and wave runup

Note that 5 of the 6 hazards are water-related.
Tornadoes can obviously occur during the landfall phase but were not included for discussion in this particular exercise.

(D) Universally Accepted Definitions

The Workshop participants saw merit in better defining a number of terms used under the special theme. Appearing below are 4 of the key terms and suggested definitions for possible consideration by a (WMO) review panel.

TC Coastal Crossing
Eye passage partly or fully across the coast.

TC Landfall = TC Strike
Eye passage across the coast OR “glancing blows” (“glancing blows” defined as being wind gusts reaching at least 100 km/h).

TC Landfall Phase
That period of a cyclone’s lifecycle bounded by the immediate approach of the cyclone to the coast through to the early part of its transition over land.

TC Impact
Evidence of damaging TC-generated hazard(s) (may include large swells from distant cyclones).

(E) Strengths and Weaknesses

The following relative strengths and weaknesses in the landfall forecasting process were identified:

Relative Strengths

- Track forecasting (but small deviations in track do matter).
- Storm surge modelling (but also dependent on meteorological inputs).
- Hydrological modelling (but also dependent on meteorological inputs).
- NWP (including mesoscale/nested/coupled models).
- Remote sensing data (eg scatterometer, Doppler radars).
- Dvorak technique (although with some qualifications/reservations).

Relative Weaknesses

- Forecasting intensity, structure, structural change.
- Forecasting spatial and temporal rainfall distribution.
- Modelling wave action (including vicinity of small islands).
- Modelling the combination of "riverine flooding + storm tide + waves".
- Forecasting landslips, mudslides and debris flows.
- Defining Wind-Pressure relationships (which are cyclone dependent).
- Forecasting fine-scale wind features upon landfall.
- Estimating the wind decay rate in the transition over land.
- Surface and upper air observations networks in many areas.
- Quality of topographic and bathymetric data available for modelling.

(F) Discussion Topics

Workshop discussion was focussed in the following 4 areas:

1. MODELS
- SINGLE-MODEL ENSEMBLE PREDICTION SYSTEMS (including probabilities)
- MULTI-MODEL CONSENSUS FORECASTS (including probabilities)
- PARAMETRIC MODELS (including probabilities & "what if" scenarios)

2. WIND
- CYCLONE STRUCTURE (and structural change)
- WIND PROFILE
- PRESSURE PROFILE

3. WATER
- STORM TIDE
- WAVES
- RAINFALL
- FLOODING
- LANDSLIPS/MUDSLIDES/DEBRIS FLOWS

4. MISCELLANEOUS

(G) Key Discussion Points - MODELS

- Track forecasts are most important at longer lead-times but structure forecasts are nearly as important at shorter lead-times near landfall.

- Ensemble, consensus forecasting and parametric modelling techniques can be developed for many of the cyclone parameters and major hazards. However the continuing availability of high-resolution deterministic NWP modelling output is still seen to be critical in the forecast process.

- The full data set from ensemble and consensus runs should be made available to forecasters, so that they can readily examine the implications of different forecast scenarios for the various cyclone hazards. Forecaster training in the use of ensemble and consensus forecasts is essential.

- Consensus forecasts should be closely evaluated to identify: (1) the minimum number and optimal combination of forecast members that adds value to the forecast process; and (2) strategies to deal with situations when the consensus forecast does not work (e.g., bifurcation scenario when members are in two different track types).

- Probabilities/uncertainties can be derived from all 3 techniques – and “what if” scenarios operationally tested using parametric models.

- A continuing trend is evident towards more probability-type forecasts. Media specialists and social scientists should be closely involved in the creation of effective warning display formats involving probabilities. It is important too that real-life thresholds for response actions be considered in the process.

- Communicating RISK is not the same as communicating PROBABILITY. Besides, we must not overlook the need to convey probability (and risk) information over the radio as well as pictorially via the web and television. An extensive community-wide education campaign is required.

- A demonstrated need exists for a single password-protected repository for all global NWP forecast tracks and intensities, which preferably also includes ensemble and consensus forecasts.

(H) Key Discussion Points - WIND

- The time is opportune to recalibrate the Dvorak technique (for all basins), especially by incorporating remote sensing advances.

- A public domain parametric wind field model is required. This could then be used in conjunction with scatterometer data and the Dvorak technique to determine an individual cyclone’s wind and pressure profile.

- One of the challenges facing forecasters is how to operationally manage the fact that the pressure-wind relationship is essentially unique to each individual cyclone, being dependent on the “b” parameter. Put simply, it is recognized that no “one size” relationship fits all.

- Being developed under WMO sponsorship is a standard chart that will enable users to convert between different wind-averaging periods and gust factors. There is a corresponding need for improved modelling and representation of cyclonic winds over varying terrain and topography.

- Further studies are required into the asymmetry in cyclone structure at landfall, including developing a greater understanding of fine-scale transient features such as damaging wind streaks and roll vortices.

- Forecasters would benefit from knowing both the along-track and across-track forecast position errors, due to the obvious bearing they have on landfall timing and location.

- A global review of cyclone Category scales was considered desirable, with the particular objective of better defining the wind hazard to improve public understanding of the level of threat. For example, should it be clearly stated that the reference wind is at a height of 10 metres over open flat terrain? Is it more appropriate to use wind gusts in the Scale as they more closely relate to damage than the mean winds? Should storm surge/tide be in the Scale? Should there be a 1:1 correspondence with the maritime Beaufort scale? One must also consider that fact that relatively weak cyclones can produce torrential rainfall and significant floods. (Note that the Australian Cyclone Category Scale is wind gust based and is directly aligned with the Beaufort scale.)

(I) Key Discussion Points - <u>WATER</u>

- A primary need exists for improved rainfall forecasts – both spatial and temporal.

- The importance of wave action impact for small islands was again emphasized, together with the need to provide suitable operational forecasting techniques.

- A long-standing and important recommendation is to provide operational storm surge forecasting techniques for warning centres that currently do not have this capability.

- Further studies are required in to wave setup and techniques developed for providing more reliable operational estimates. Wave setup can often be an important component of storm tide. Wave runup is also significant in some locations and as such warrants further investigation.

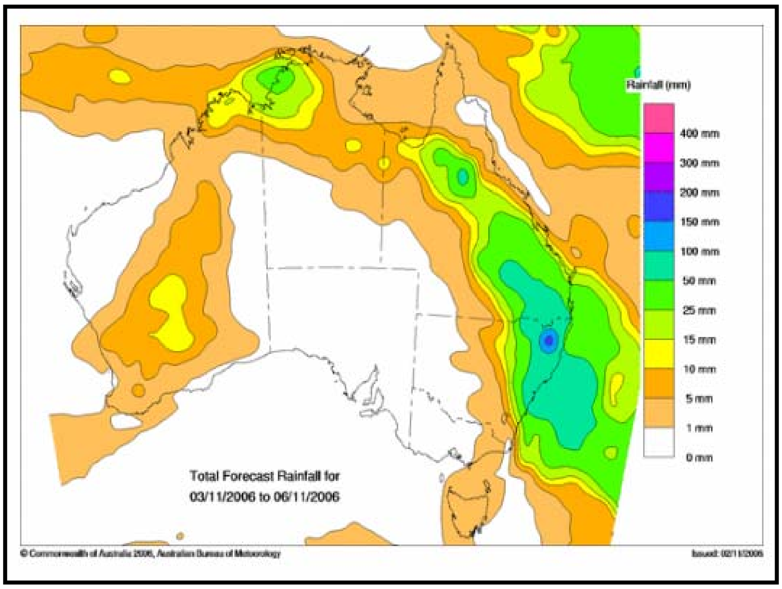
- Another major requirement is improved operational hydrologic/hydraulic flood modelling through tighter coupling with meteorological and tidal modelling outputs where appropriate. The best results are likely to be achieved through meteorological forcing by high-resolution NWP output.

- Allowance should be made for gridded rainfall inputs to hydrological models to take advantage of improved spatial and temporal rainfall analyses from high-resolution NWP models. Hydrological model domains are then best digitised to enable gridded rainfall inputs.

- A strong argument was put for greater use of radar-rainfall estimation techniques, especially for short lead times such as in flash flood, landslip and mudslide situations. Near real-time rainfall accumulation techniques are sorely needed. Even an indication of a “dry”, “average” or “wet” landfalling cyclone is considered useful.

- Continued development of the promising very short-range rainfall forecasting technique is required. The technique uses extrapolation for the first 0-3 hours followed by mesomodelling out to about 6 hours.

- Improved forecasting techniques for landslips, mudslides and debris flows are greatly needed. Forecasters are seeking either a "geological hazard map" for slopes at risk of landslips/mudslides and/or relevant expert operational assistance.



Consensus rainfall forecasts out to 8 days are now being produced by the Australian Bureau of Meteorology.

Up to 8 global models are statistically combined using the "probability matched ensemble mean" technique.

Rainfall probability forecasts are also derived with the % chance being the proportion of available models predicting rain at or above the given threshold.

Web address: **http://www.bom.gov.au/watl/**

(J) Key Discussion Points - MISCELLANEOUS

- The ongoing need for Capacity Building, Training, Seminars, Workshops, and Symposia was featured in the Rapporteurs' Reports and in participant debate, and subsequently featured in the Workshop Recommendations.

- The benefit of conducting Field Experiments and Demonstration Projects was similarly raised and flowed through to the Workshop Recommendations.

- Requests were made for improved upper air observations in cyclone basins especially across the SW Pacific - and improved surface observational networks for forecast verification and model calibration.

- Very little discussion was held at IWTC-VI on the "hybrid" cyclone, where a system may still be warm-cored but the maximum winds are well removed from the centre. More attention could be given to this area.

- Transfer of techniques from research to operations is still rather piecemeal. Attempts should be made to better streamline the process.

****

CHAPTER 5

TROPICAL CYCLONE STRUCTURE AND STRUCTURE CHANGE

Jeffery D. Kepert (Australia)

This report summarizes the plenary and breakout discussions for topic 1 of the WMO Sixth International Workshop on Tropical Cyclones, held in Costa Rica, Nov 21-30, 2006. As such, it mostly avoids the material prepared by the original topic chair, Hugh Willoughby, and the subtopic rapporteurs contained in WMO TMRP 72. It draws upon the report of the topic rapporteur, Jenni Evans, and upon the recommendations arising from the working group discussions, as well as my own observations. I would like to thank Hugh Willoughby (who was unfortunately unable to attend) for his extensive work before the workshop. I also thank the subtopic rapporteurs (Liz Ritchie, Jeff Kepert, Nick Shay, Mark Lander, and John Knaff) and special focus rapporteurs (Chris Velden, Pete Black and Shuyi Chen) for their thorough preparation before the workshop and cooperation during it, Jenni Evans for her comprehensive notes, the working group leaders and rapporteurs for their diligence.

This report is organized differently to the pre-workshop reports, as I have attempted to identify cross-cutting issues from the original five subtopics, and draw these together.

Observations

The past decade or so can justifiably be regarded as a “golden era” in terms of the quantity, range and quality of the observational coverage. Twenty years ago in Australia, satellite coverage consisted of a taped-together photographic print every 3 hours. Now multiple satellites provide much more frequent coverage, and computer-based display systems facilitate manipulation and interpretation of the data. Currently, multiple low-earth orbiting satellites provide digital data in the infrared, near-infrared, visible, and passive microwave wavelengths. These are complemented by the global coverage of geostationary satellites that provide high temporal resolution digital data in the visible, near-infrared and infrared wavelengths, and by space-based polar-orbiting radars designed to detect clouds, rain and ocean surface winds.

A feature of this series of workshops has been the enthusiasm of the participants to learn how to better access and interpret these data, and the willingness of experts to provide relevant tuition. These and other efforts to extract the maximum from satellite data should continue, since such measurements constitute reality in most basins, and a detailed understanding of each instrument’s characteristics is necessary to best interpret the data. The work of several internet sites in providing ready access to imagery and derived products, such as those hosted by the US Naval Research Laboratories, the Cooperative Institute for Meteorological Satellite Studies, and the NOAA/NESDIS, is widely appreciated. However, some of these sites do not receive 24/7 support and the risk of relying on them for operations is recognized. To balance this disadvantage, their role as research institutions encourages the early development and operational use of products from research satellites such as CloudSat and WindSat.

Although the range of new data is impressive, the Dvorak technique for interpreting visible and infrared imagery remains the workhorse for intensity estimation in much of the world. Often the old and new are used in conjunction, for example in tracking eyewall cycles, and for locating the storm centre on microwave imagery prior to applying the Dvorak rules. The use of existing “best track" datasets for new applications, notably climate change studies, has emphasised the need for a consistent application of intensity estimation techniques.

Coupled with the increase in satellite data, it is encouraging to see Canada and Taiwan joining the United States in conducting aircraft reconnaissance of the core and/or environment of tropical cyclones. A recurring theme of the workshop was the need to assess the accuracy of the various satellite-based intensity estimation techniques, driven largely but not wholly by the increasing demands placed on the "best track" data by climate change studies. In situ measurements are a necessary part of such calibration, and properly equipped aircraft remain the best way of obtaining these. Meanwhile, the observational capability of these aircraft has been significantly extended in the past decade, with the introduction of the GPS dropsonde and stepped-frequency microwave radiometer (SFMR) improving the ability to measure surface winds in particular.

There exists, however, a risk that the golden era in satellite data may be drawing to a close. The scheduled replacement of passive microwave sensors may be delayed, while the QuikScat instrument is past its design life and no direct replacement is planned, although the ASCAT instrument is expected to provide valuable data for some years. Likewise, the number of satellite altimeters, crucial for ocean analysis, is projected to decline. Balancing this, there are the exciting possibilities of a geostationary-orbit Doppler radar, the planned global precipitation mission, and the possibility of an additional downlink station in southern latitudes to reduce the delay in accessing data.

Obtaining the best from the data remains of vital importance, especially if the coverage should decrease. Improvements in data assimilation technology, together with the current good level of satellite coverage, have lead directly to the substantial improvements in track prediction at all time scales. Direct prediction of size and intensity change has fared less well, partly due to limited model resolution introducing systematic biases in the depiction of these quantities, and partly because of the enormous technical difficulties associated with assimilating data in the tropical cyclone core. A precondition for improvements in these areas may be to persuade the major NWP centres to add measures of skill in these parameters to their usual tests, although this would likely require improved accuracy of estimation of storm size parameters in the best track analyses to deliver full benefit.

The challenges forecasters face in integrating data from a range of sources prompted requests for an automated global objective analysis of tropical cyclone surface wind fields. Such an analysis would be difficult to achieve in data-sparse areas. However, the use of scatterometer and passive microwave wind observations, combined with estimates of intensity derived by conventional means, and utilising advances in knowledge of the tropical cyclone boundary layer and parametric wind modelling, may produce an analysis of useful quality.

Ocean data availability is presently oriented more towards sea surface temperature (SST) than the more relevant oceanic heat content. The continuing development of oceanic data assimilation capability would seem to enable good estimates of the latter parameter by the responsible centres, which would be of considerable value to operational forecasting. Moored instruments deliver direct measurements of the vertical propagation of internal waves generated by the tropical cyclone passage, allowing the diagnosis of how the storm affects the ocean structure. The amount of heat lost during the storm passage is very variable, and depends on the storm wind forcing strength, area and duration, as well as on the initial strength and depth of the thermocline.

Two research observational field programmes were reported at the meeting. The high wind-speed component of the CBLAST (Coupled Boundary Layers and Air-Sea Transfer) experiment has yielded direct flux measurements at unprecedentedly high wind speeds. Such knowledge is fundamental to intensity forecasting, storm surge and wave prediction, potential intensity theories, and climate change projections. Key results include confirmation of laboratory and indirect field measurements showing that the drag coefficient levels off at high wind speeds, and extensions of the wind speed range over which the moisture flux coefficient is known to be constant. Thus the ratio of the drag to enthalpy exchange coefficients eventually levels off, rather than decreasing, at high winds, as required by Emanuel's potential intensity theory. The RAINEX (Rainbands and Intensification Experiment) delivered unique observations of the eyewall replacement cycle, and early results appear to help explain the differences between storms in the extent to which they undergo such cycles.

Numerical Weather Prediction

The substantial and continuing improvements in global and regional NWP have lead to substantial improvements in track prediction, and numerical forecasts have substantially overtaken statistical techniques. Skill in intensity and size prediction has improved more slowly, with statistical methods for intensity partly holding their own against NWP. Obstacles to progress include the biases due to model resolution, and the shortage of high quality storm size data for model verification. While large-scale NWP has considerable potential for forecasting genesis, intensification and size, it will require systematic verification of model forecasts of these parameters for good progress. Verification will in turn require bias-correction schemes to account for the resolution-induced bias. Such bias-correction would of course be valuable in its own right. Ideally, international agreement on verification schemes for tropical cyclone parameters would yield benefits similar to those obtained by the current internationally consistent verification of large-scale fields.

High-resolution research NWP for tropical cyclones is achieving impressive results, although operational implementation at these resolutions is a long way off. It is important to remember that these research simulations may have been subject to a certain amount of tweaking not possible in real-time. Data assimilation in the cyclone core remains a challenge, due to the tight gradients, the likelihood of small position errors in the background, and the difficulty of developing accurate forward models. The use of flow-dependent background error covariances is likely important, either through 4D-VAR or ensemble-based assimilation.

Ensembles, both single-model and multi-model, continue to grow in importance. Combining the information in forecaster- and user-friendly forms remains a challenge, but objective consensus forecasts of track have achieved a level of accuracy that is very hard for either the human, or single models, to beat. It is highly likely that they will prove to have similar benefits for other forecast parameters, including intensity and size. These parameters have been shown to be sensitive to (for example) the initial moisture field in idealised studies. As moisture is difficult to observe and may display marked small-scale variation, the use of perturbations that include moisture in an ensemble prediction system can help to ensure that the ensemble contains a realistic amount of spread.

Ocean eddies are of similar scale to 24 – 48 hour track forecast errors. Given their impact on intensity change, it may be necessary to consider intensity forecasts that are conditioned on the storm track. Of course, this presupposes that the ocean initial condition in coupled models is sufficiently accurate.

Intensity

Potential intensity models continue to underpin our understanding of intensity, with the difference between current and estimated potential intensity remaining a good statistical predictor for intensity change. While the principal potential intensity models produce similar answers and require similar inputs, their internal assumptions are very different, which leads to significantly different sensitivity to input parameters. Notably, these models have opposite response to eyewall boundary layer relative humidity changes. There does not yet exist a mature theory and further work is needed to resolve these differences, given the central role of these models in understanding tropical cyclones in both the current and future climate.

Recent work has demonstrated the possibility of so-called superintensity, where storms may exceed their potential intensity due to the mixing of high equivalent potential temperature air from the eye into the eyewall by small-scale vortices. Much of the associated work relies on models, but there is one observational paper suggesting the effect is real. This points to the need for further refinement of potential intensity theories, that they may include a less primitive depiction of the cyclone dynamics. There is also the issue that storms intensify at a finite rate and take time to achieve their potential intensity. Factors such as the favourability of the outflow environment determine how quickly, and whether, they get there.

Measuring and estimating intensity remains a challenge, given the limitations of the Dvorak technique. Changes in this technique with time are recognized as a serious problem for climate studies, and a lack of in situ calibration data in most basins continues to cast doubt on the absolute reliability of the technique. The case for a consistent reanalysis is compelling. Even in the North Atlantic, changes in instrumentation and practices in aircraft data have introduced inhomogeneities. For instance, the past decade has seen the introduction of GPS dropsonde data (1997), a change in the flight-level to surface wind reduction method (2003) and the operational introduction of the stepped-frequency microwave radiometer (partly available in 2005, and soon to be installed on all U.S. reconnaissance aircraft).

Intensity change (in both directions) is known to be sensitive to environmental moisture, trough interactions, shear, the ocean heat content, and internal processes within the storm. The complexity of integrating these factors is illustrated by the differences of opinion in the research literature as to the mechanisms governing the rapid intensification and weakening of Hurricane Opal (1995). It is unclear what the ultimate limits of intensity predictability are, and operational detection of rapid deepening remains a challenge. However, dynamical and statistical-dynamical schemes have supplanted the purely statistical intensity forecast schemes as the most skilful. Monitoring the eyewall replacement cycle is an important part of forecasting intensity change, which has been facilitated by the current wealth of satellite data, especially the passive microwave sensors. The identification of shear thresholds for weakening is important. There is a growing body of evidence that the response to shear depends upon storm intensity and size, as well as to other environmental aspects such as the detailed wind profile, the humidity and the ocean heat content. There is scope for further investigation here. A significant benefit of the recognition of “annular hurricanes” is the finding that these weaken much more slowly than average, thereby removing an occasional source of large intensity forecast errors.

None of the global NWP systems presently beat statistical forecasts of intensity, although there is anecdotal evidence that the forecasts of intensity tendency are useful. Given the coarse resolution of current operational models, this difference is perhaps not surprising. It appears that optimal use is presently not being made of the operational global models’ predictions of intensity change, and that work on some form of bias correction scheme would likely yield dividends.

The distinction between SST and ocean heat content is important, since deep warm-core rings may produce an order of magnitude increase in the latter parameter in the Gulf of Mexico. Such contrasts are rarer elsewhere in the ocean outside western-boundary currents, although the detailed oceanography of other tropical cyclone basins is not as well known in the tropical cyclone community. The magnitude of ocean heat content lost during the passage of a storm is very variable and depends both on storm characteristics (wind forcing strength, area and duration) and the ocean thermal structure (depth, strength of the thermocline). Completely representing this in coupled models requires close attention to the ocean initial condition, particularly in the most complex situations, although simpler models appear to satisfactorily represent the negative feedback of storm-induced upper ocean cooling in many cases.

However, while ocean heat content is now widely accepted as being a more relevant measure than SST, many of the key studies have been for relatively intense storms. It is not as clear whether tropical depressions, or even weak tropical cyclones, respond more to ocean heat content, SST, or perhaps even low-level atmospheric moisture. That is, at what stage in the development process do ocean mixing and WISHE assume the important role they have in a mature tropical cyclone?

Structure

Forecasts of storm size remain a challenge, not least because of significant deficiencies in the verification data – the available radii datasets often disagree, and contain systematic biases. Operational NWP forecasts of storm size at present seem to not be verified, with the possible exception of the US operational models.

There is some knowledge of situations in which the storm size can increase, such as during recurvature, extra-tropical transition and the transition to a monsoon gyre structure, but little is known about the dynamics of these wind-field expansions. This is a serious issue, given the tendency for large cyclones to produce catastrophic storm surge and wave fields. In designing a skill measure for size forecasts, it is necessary to bear in mind that the impact of forecast errors on storm impact may be highly nonlinear. Recent analyses of aircraft data have shown that the relative rate at which the wind decreases outside the radius of maximum winds is related to intensity, with intense storms having on average a more peaked profile than weaker storms. Examples of storms with “pinhole” and large eyes have emphasised that any single simple wind-pressure relationship will not fit all storms.

Recent years have seen significant advances in knowledge of boundary layer structure. Analytical and numerical idealised models have resolved the full 3-dimensional structure of the boundary-layer wind field. These models show that the tropical cyclone boundary layer contains substantial variability, due to the variation in the rotational constraint (measured by the inertial stability) within the storm, and to asymmetric frictional forcing. An alternative perspective on these results is that advection is important in determining the local vertical profile of wind, and that one-dimensional “column” models, in spite of their success elsewhere in the atmosphere, are inappropriate in the tropical cyclone boundary layer. Three-dimensional boundary layer models have made important prediction, including that the surface wind reduction factor increases towards the centre of the storm, and is higher on the left of track than on the right in the Northern Hemisphere. These have largely been confirmed by observational analyses. This new knowledge has resulted in changes in the way that surface winds are estimated from aircraft measurements.

The winds in the upper part of the boundary layer are supergradient in some storms, notably intense ones with “peaked” wind profiles. In the cases so far analysed, observations and model are in good agreement on the degree to which the winds are supergradient, and the wind returns to gradient balance above the boundary layer.

Observational and theoretical work has shown the presence of fine-scale spiral bands aligned nearly with the flow in the lower part of the tropical cyclone circulation. These bands are likely the manifestation of shear instability of the radial inflow in the boundary layer similar to that which causes boundary layer rolls in the general atmospheric boundary layer, although there are some discrepancies with scale and the role of latent heat release to be resolved. These streaks are associated with alternating bands of strong and weak near-surface winds, and may carry a significant fraction of the boundary layer fluxes of heat, moisture and momentum. They may thus impact the intensity of the storm, by enhancing the downwards flux of momentum to the surface and providing an additional gust-causing mechanism, and the upwards thermodynamic fluxes into the storm.

The eye and eyewall circulation is predominantly in one of two states: a barotropically stable quasi solid-body rotation, or an unstable circulation with a hollow tower of high vorticity located narrowly inwards of the radius of maximum wind. Transition from the first to the second proceeds via latent heat release in the eyewall and vortex stretching/squashing of the resulting secondary circulation. The reverse transition occurs through the release of the barotropic instability, resulting in the formation of eyewall mesovortices that efficiently mix momentum, heat and moisture between the eyewall and the eye. There is some evidence that a more baroclinic mode may also exist in the upper troposphere. This work represents an important advance in understanding eye dynamics, although there remain some interesting unanswered questions.

The near-surface air in the eye generally has higher equivalent potential temperature than that in and beneath the eyewall. The above mixing process can inject the high-entropy air into the eyewall, leading to a more intense storm. This process, known as superintensity, further indicates the need for better potential intensity models. Other mechanisms, including the boundary layer inflow that penetrates into the eye before turning and heading upwards and outwards, may also contribute to raise the potential intensity through this mechanism.

Boundary layer rolls and eyewall mesovortices affect the surface wind field, and hence potential danger, of the tropical cyclone. The former are likely often present, while the latter are a transient feature. Nevertheless, the possibility that these recently-discovered features alter the damage-causing potential of a tropical cyclone would seem to require a forecast policy decision. It would be strongly preferable that such a policy was internationally uniform. Rainbands of larger scale than those discussed above appear to be associated with vortex Rossby waves. Uncertainty as to the role of rainbands in tropical cyclone intensification continues. Competing contributions include the inwards transport of angular momentum and the consumption of high equivalent potential temperature air in the inflowing boundary layer. Further research is required.

A recently identified type of tropical cyclone, the annular hurricane, appears to rely on partial completion of the eye mixing process for its formation, which can occur only under certain specific environmental conditions, namely weak southeasterly (in the Northern Hemisphere) shear. The operational significance of such storms is that they are more intense, and weaken more slowly from their peak intensity, than average storms.

External Interactions

Further work on the response of tropical cyclones to shear has elucidated the effects of shear on rainfall and wind distribution, and on intensity change. Observational and modelling studies are in reasonable agreement on the shear threshold for weakening, that weakening may not occur immediately with the onset of shear, and that the detailed response depends on storm intensity and structure. Wind shear is not always linear with height, and the variety of patterns possible poses a difficulty in formulating general forecast rules, although there is some indication that lower-tropospheric shear may be more important, particularly in weak systems (including genesis). In diagnosing shear, different investigators have averaged over variously sized storm-centred domains, and there appears to be little consensus as to which possesses the most predictive skill.

Wind shear causes a substantial asymmetry in the storm's precipitation field. Whether this translates into an asymmetry in the precipitation swath depends on the shear-relative motion, with along-shear motion resulting in an asymmetric precipitation swath.

The environmental moisture around a storm can have a strong influence on its development. Observational evidence, including work on Saharan air layers, suggests that forecast skill can be increased based upon these considerations. This work is supported by idealized numerical simulations and by case studies.

Work has slowed on trough interactions, with the exception of extratropical transition studies, although this is a little puzzling, given that the problem of differentiating "good" from "bad" troughs remains.

While a number of important environmental influences have been identified, it is important to remember that in reality, several may operate simultaneously and determining the net effect of the combination can be complex. For instance, the effect of wind shear may be reduced if the storm is over a region of high ocean heat content, or increased if the environmental air is unusually dry, because enhanced deep convection helps intensify and realign a tilted vortex.

Conclusions

The topic has seen significant research progress in the past few years. The following represents a brief and incomplete list:

- Boundary layer
- Environmental moisture
- Field experiments
- Intensity, potential intensity and intensity change
- Numerical Weather Prediction
- Observations (in situ, remote, using)
- Ocean
- Size and size change
- Shear and upper troughs
- Small-scale features

As always, transforming the research progress into operational practice takes time, and contrasts abound. High-resolution models and observations are revealing important fine-scale structures, and an increasing range of satellite products is leading to steady improvements in our ability to diagnose the details of the storm lifecycle. Increased knowledge of tropical cyclone boundary layer structure has changed how flight-level winds are "reduced" to the surface. Yet the long-established Dvorak technique remains the dominant technique for intensity estimation in much of the world. Improvements in NWP have had a strong impact on track forecasting, particularly through the use of multi-model consensus techniques, yet intensity forecasts have just begun to use similar techniques. While these techniques presently use a few marginally skilful and independent members, more ensemble members may be available if suitable bias-correction was developed for coarse-scale NWP.

A strong driver of improved understanding and improved forecasts has been the need to protect vulnerable populations and infrastructure. With the increasing population and development of tropical coastal regions, this demand will continue to grow. The need to understand how climate change impacts upon tropical cyclone behaviour is another research driver. At the same time, advances in technology and the sheer fascination of tropical cyclones are enabling an ever deeper understanding. These factors have greatly influenced the impressive growth in understanding summarised in the topic chair and rapporteur reports for IWTC-VI. We look forward to similar growth in the next four years.

****

CHAPTER 6

TROPICAL CYCLONE FORMATION AND EXTRATROPICAL TRANSITION

Patrick A. Harr (USA)

1. Introduction

During the IWTC-VI plenary session on Tropical Cyclone Formation and Extratropical Transition, Rapporteurs presented summaries of progress on topics that addressed the external and internal influences on tropical cyclone formation, operational forecasting of tropical cyclone formation, observing and forecasting extratropical transition, and the physical processes associated with extratropical transition and the downstream impacts due to extratropical transition. In this Topic Chair Summary, additional issues that were identified during the plenary session and during individual Discussion Groups are summarized.

Some common themes were contained in discussions of tropical cyclone formation and extratropical transition. One theme stresses the need for increased understanding and awareness of interactions among a variety of space and time scales that range from global-scale interannual and intraseasonal circulations, synoptic-scale features over each basin, and mesoscale factors related to individual cloud clusters. Also, a strong need for consistent definitions of tropical cyclone formation and extratropical transition was identified. The definitions should provide a framework for construction of datasets that satisfy operational priorities and high-quality data sets will be defined based on physically relevant formation characteristics. Finally, a common requirement exists to establish the current levels of predictability associated with tropical cyclone formation and extratropical transition.

2. External Influences of Formation

The topic of tropical cyclone formation was discussed in a framework of a two-stage model. In stage one, the large-scale environment is conditioned for tropical cyclone formation through a variety of synoptic- and sub-synoptic-scale processes that enhance environmental factors that are favourable for formation. This stage is characterized by the external influences of tropical cyclone formation. In stage two, a concentration of environment vorticity occurs via mesoscale processes that act on the kinematic and thermodynamic fields. This stage is characterized by internal influences on tropical cyclone formation.

Discussions of the primary external influences of tropical cyclone formation concentrated on the role of tropical waves that propagate zonally along equatorial latitudes. These waves often perturb the large-scale environment such that it is more favourable to tropical cyclone formation. An important aspect of the influence of tropical waves on formation is that there is some indication that many wave characteristics are becoming more predictable with operational numerical forecast models. However, the predictability still exhibits a large degree of uncertainty that varies by model and wave phenomenon. The role(s) of tropical waves in perturbing the synoptic-scale flow of the monsoon trough/intertropical convergence zone (ITCZ) was discussed relative to factors that contribute to perturbations that may be due to instabilities in the ITCZ configuration. It was noted that tropical waves seem to perturb the large-scale factors favourable for tropical cyclone formation on time scales that are shorter than perturbations associated with internal characteristics of the ITCZ.

It was noted during discussion that external influences are important factors in the formation of subtropical or hybrid cyclones. These include formations influenced by the tropical upper-tropospheric trough, tropical transition due to equatorward extensions of midlatitude troughs. Furthermore, it was noted that predictability associated with these formations is often lower than the predictability associated with formation in tropical latitudes.

3. Internal Influences on Formation

As stressed in IWTC-V, the need for a physically realistic and consistent definition of tropical cyclone formation was recognized. Because of a variety of operational constraints, and the need to provide appropriate warning for protection of life and property, there are several regional differences in the definition of tropical cyclone formation. It was acknowledged that it would be extremely difficult to get all tropical cyclone warning centres to agree upon one definition that would preserve the practices of each region that have evolved to provide an optimum warning of a tropical cyclone threat. However, regional differences often cause deviations from standard physically-based definitions of tropical cyclone formation, because they have evolved to provide optimum utility to the respective tropical cyclone warning centre. A region-independent definition would be desirable as it would provide a consistency in several tropical cyclone-related data bases that are utilized for both policy and research. Therefore, the post-process by which assessment of tropical cyclone formation is made should be one that is basin-independent.

The definition of tropical cyclone formation particularly impacts the assessment of internal influences on formation. Because the internal influences are often dominated by mesoscale processes that occur over time periods of hours and space scales of 10-100 km, variability associated with the determination of formation will contribute to varying structural characteristics due to the rapid changes in internal influences.

4. Observations in Addition to Satellites

Both forecasters and researchers recognize the critical need for observations of tropical cyclone formation from a variety of platforms over a wide range of space and time scales. However, it is generally recognized that global conventional observing systems will not expand and that several factors are contributing to a reduction in standard atmospheric and oceanographic observations. Therefore, systematic studies are needed of the impact to the prediction (both numerical and non-numerical) of tropical cyclone formation due to reduced observations worldwide. Furthermore, a strong need exists to insure that current observational capabilities are utilized fully. This includes investigation of the utility of various observation types and locations to numerical weather prediction model predictions of the large-scale tropical environment that influences tropical cyclone formation. Factors important to the process of tropical cyclone formation should be examined carefully such that appropriate observation requirements are identified to resolve the important characteristics such that improved understanding of the formation process is achieved.

5. Large-scale Control and Mesoscale Influences; Intraseasonal

It has become clear that the large-scale influence on tropical cyclone formation is dependent on interactions among a variety of space and time scales. Researchers stressed the need to define factors that would provide diagnostic evaluation of potential tropical cyclone formation, which should include the systematic examination of tropical cyclone formation in numerical prediction models.

Furthermore, it is imperative that the examination address a measure of uncertainty in the ability for tropical cyclone formation to be related to large-scale factors in numerical model simulation. This may also be examined with ensemble techniques to assess relative roles of important environmental factors that may be associated with tropical cyclone formation. Furthermore, the increased use of re-analysis data to identify large-scale influences on tropical cyclone formation was advocated. However, caution is advised because of potential problems associated with data assimilation aspects of re-analyzed data sets.

While recognizing the importance of the above research, forecasters stressed that transition of research findings on large-scale factors in tropical cyclone formation to operational forecast centres has been slow. Significant training is required to move new research findings to the operational forecast process.

6. Prediction of Tropical Cyclone Formation with Numerical Models

In recent years, significant effort has been expended to examine factors associated with tropical cyclone formation through numerical simulation. Both researchers and forecasters recognized that collection of high-resolution (spatial and temporal) observations is critical to evaluate numerical results. However, questions were raised as to whether there has been adequate use of data sets from operational analyses and previous field programmes. These sources should be exploited before additional specialized programmes are initiated.

The ability of operational numerical models to forecast tropical cyclone formation must be systematically identified. Furthermore, the ability of a numerical model to forecast tropical cyclone formation must be represented in factors that have operational relevance, and should include the rates of false alarms, hits, and misses in terms of the forecasts of tropical cyclone formation at various time intervals.

The use of ensemble techniques associated with operational global numerical prediction models should be increased to identify areas where tropical cyclone formation is likely. Regional models should then be utilized to examine the timing of imminent tropical cyclone formation.

7. Seasonal Prediction

While seasonal prediction of tropical cyclone formation presents an interesting and challenging scientific problem, forecasters stressed that prediction of just the seasonal number of tropical cyclones in a particular basin may not have operational significance to the forecaster. However, these seasonal forecasts may have a high degree of significance for certain industries and the general public, because release of the seasonal forecasts increases public awareness of the tropical cyclone threat. To be more effective, education of the general public is needed on what the seasonal forecast means to them.

In the research community, debate continues as to what methodology provides the most promise of accurate seasonal prediction. Currently, statistical methods, dynamical models, and combinations of statistical methods and dynamical models are being used to produce seasonal forecasts. Statistical models require identification of specific factors that may be related in a predictive manner to seasonal formation characteristics. Researchers generally agreed that if there is hope for dynamical model-based seasonal predictions, the models must include a coupling of the atmosphere and ocean.

8. Extratropical Transition

Because of the severe impacts associated with expanded precipitation, wind, and wave fields during the transition of a tropical cyclone to an extratropical cyclone, researchers and forecasters both agreed that a need exists for a focused research programme that examines the important physical characteristics associated with extratropical transition. This research programme should promote analysis of existing observations, analyses, and forecast data sets. In particular, uncertainties associated with predictions of extratropical transition should be examined to identify specific physical characteristics that impact the numerical prediction of extratropical transition. Furthermore, the overall research programme should be coordinated with existing programmes (e.g., operational field programmes, planned specialized field programmes) to obtain detailed observations of the evolutionary structure of extratropical transition. Studies such as these would identify optimal observation types, locations, and densities to map the extratropical transition process.

Finally, it was recognized that the role of the ocean in extratropical transition may be highly variable and is not understood. A severe lack of observations of atmospheric and oceanic characteristics in the environment exists during extratropical transition events. More observations are needed to specify the sensitivity of the transition process to changes in the overall environment.

****

CHAPTER 7

TROPICAL CYCLONE MOTION

Russ Elsberry (USA)

1. Importance of Tropical Cyclone Motion

It is frequently stated that great advances have been made in tropical cyclone motion prediction (see Topics 0.1 and 3.1), so that one might infer that tropical cyclone motion has decreased in importance. The Keynote theme of IWTC-VI on requirements for an effective warning system for tropical cyclones provided strong evidence that much remains to be done with tropical cyclone motion prediction related to landfall impacts. First, examples of the dispersion of the numerical model guidance tracks for critical landfall forecasts were presented in Topic 0.1, which has led to probability products that convey tropical cyclone forecast uncertainty to various types of users. The tropical cyclone rainfall distribution discussed in Topic 0.3 depends critically on the track – both the specific path and the translation speed, since even tropical storms moving slowly over an area can lead to extreme rainfall accumulations. Whether (and the degree) a tropical cyclone will interact with topographic features and lead to local maxima in precipitation depends on the motion. Similarly, a relatively small shift in the landfall track can mean the difference between a disastrous storm tide (Topic 0.4) at a coastal location or an extreme low tide on the opposite side of the track where offshore winds exist. Finally, the occurrence and magnitude of the hydrological-related disasters covered in Topic 0.5 depend as much (or more) on the tropical cyclone path and translation speed as on the rainfall distribution.

A strong input from the forecast community arose from these presentations at IWTC-VI – whereas the primary focus in tropical cyclone track prediction has been on improving 72-h forecasts and extension to 120 h (see discussion below), the forecasters require greater track accuracy for shorter range landfall position forecasts. It is this broader context that the presentations and discussions of tropical cyclone motion at IWTC-VI are summarized here. Recommendations related to improved tropical cyclone track predictions will also be mentioned.

2. Advances and Requirements for Operational Track Prediction

As indicated above, Topics 0.1 and 3.1 documented the great improvements in 72-h track predictions that have been achieved in the past few years. These improved 72-h track predictions have been achieved in all tropical cyclone basins, such that the operational forecasts are both more accurate and more consistent from year-to-year. Several countries have extended the length of the forecast from 48 h to 72 h during the past four years, and the Australian Bureau of Meteorology has announced plans to extend the length from 24 h to 48 h, and then to 72 h. In the U.S., the warning centres have extended the forecast interval from 72 h to 120 h during the past four years (Topic 3.2). These 120-h track forecasts are accurate as 72-h forecasts of a decade ago, which represents a great advance in the ability to provide longer-range warnings of tropical cyclones. The Korea Meteorological Administration is considering an extension to 120 h forecasts by the 2008 season.

Two major developments have contributed to these track prediction improvements: (i) Numerical model track guidance has been improved; and (ii) Adoption of the consensus approach for track prediction. The numerical model guidance has been improved by better observations of the environment and the tropical cyclone structure, and better use of existing observations (especially satellite-based winds) in improved data assimilation systems. Greater horizontal resolution in both global models and regional models, and better physics representations of the environment and the tropical cyclone structure, have also contributed to improved track guidance. These developments led to the major recommendations related to maintaining and even increasing the remote sensing data, and especially the microwave data and scatterometer data.

The second major development in the past four years related to consensus forecasting was documented in Topics 3.1 and 3.2, and this led to an organization of a special focus session "Sharing Experiences in Operational Consensus Track Forecasting." The forecaster interest demonstrated at this special focus session led to the major recommendation to "facilitate the dissemination of all tropical cyclone-related numerical weather prediction (NWP) products" so that consensus forecasting can be applied at more tropical cyclone warning centres. Topic 3.2 included a listing of the global and regional models that might be used for tropical cyclone track prediction, and an indication of future plans for these models. The Japan Meteorological Agency has made available to the WMO Typhoon Committee members a password-protected website that contains tracks and fields from a number of NWP centres.

Further improvements are considered to be possible by continuing activities related to the two major developments above that have already contributed to track prediction improvements: (i) Further advancements in numerical model guidance via observations, data assimilation, and numerical model improvements; and (ii) Addition of more skilful models, and optimum use of consensus guidance when few models are available. For the first item, more advanced global models are being developed in several countries, so that insertion of initial conditions that represent tropical cyclones in all basins in which they exist could result in more skilful models for use in consensus track forecasting. Characterization of when each of these models is likely to be erroneous is necessary for optimum use of the consensus approach, and especially when only a few models are available. These requirements for future improvements are included in the major recommendations. Another recommendation is for WMO to develop training programmes for consensus forecasting.

3. Future Track Prediction Emphases

The forecast community requirement for greater track accuracy for 12- to 36-h landfall positions requires special attention. First, high temporal resolution tropical cyclone centre fixes are required for short-term forecasts. Second, vortex wind structure and precipitation observations (e.g., Doppler radar) are needed to initialize the numerical model, which also implies advanced data assimilation technologies. Third, high-resolution, mesoscale models will be needed that include air-sea-land coupled models. Better forecasts of the tropical cyclone impacts of damaging winds, precipitation, and storm surge during landfall will result from better 12-36 h track forecasts. Some nowcasting techniques to update the longer track guidance with local observations will also be required.

In Topic 0.2, L. Avila of the U. S. National Hurricane Center (NHC) compared the average track forecast errors for landfalls during 2001-2005 versus all storms during that period. The 24-h and 48-h landfall forecast errors were about 40% smaller than for all storms, with values of about 35 n mi and 60 n mi, respectively. Specific aircraft radar observations inserted into advanced data assimilation systems, and higher resolution models, are planned to further improve U.S. landfall forecasts.

As indicated above, the longer-term track guidance from the various numerical models can vary widely at times. In some cases, an outlier track may indicate an error in the initial conditions. In other cases, the variability is an indication of large uncertainty in the forecast situation. A new method by J. Goerss of the Naval Research Laboratory-Monterey for determining the track forecast confidence based on the spread of the dynamical model guidance was described in the special focus session 3a. Whenever the spread is small, a smaller circle can be drawn around the consensus mean position to indicate the likelihood that about 72-74% of the time the storm centre will be inside the circle. This representation of the track forecast confidence takes into account the degree of difficulty of the forecast, as opposed to drawing the same confidence circle in every situation.

An ensemble prediction system (EPS) is another tool to estimate this uncertainty for different situations. Generally the average of the EPS member tracks is not better than the corresponding deterministic model track for that NWP centre since the numerical model used for the EPS has to be a degraded version of the deterministic model in order for the EPS to be integrated with many members in a limited time. Thus, the primary objective of the EPS for tropical cyclones is to estimate the track uncertainty from the spread of the EPS forecast tracks. As of 2005, the track spreads calculated from the European Center for Medium-range Forecasts (ECMWF) and the National Centres for Environmental Prediction (NCEP) EPSs were not a good indicator of the track forecast error. Some post-processing of the EPS tracks is required, perhaps along the lines for the conditioned strike probability maps for Typhoon Songda mentioned in Topic 3.1 The WMO World Weather Research Programme (WWRP) THORPEX Interactive Grand Global Ensemble (TIGGE) programme will greatly increase the number of EPS tracks. This led to the two major recommendations regarding facilitating dissemination of ensemble forecasts and the development of probabilistic forecast products from the NWP centres and the TIGGE.

Recent progress in the use of targeted aircraft observations to improve tropical cyclone track predictions was summarized in Topic 3.3. Whereas the capability to deploy dropsondes in the environment of tropical cyclones has previously been limited to the U. S., the Dropwindsonde Observations for Typhoon Surveillance near Taiwan Region (DOTSTAR) programme has expanded the use of targeted observation. Four techniques for determining the most sensitive regions at the observation time are described in Topic 3.3. Sometimes the sensitive areas are in the region of the tropical cyclone and other times the sensitive areas are remote from the cyclone. Whereas only preliminary comparisons of the forecast errors for analyses based on different targeted techniques were presented at IWTC-VI, a planning session was held to develop a strategy for a broader evaluation of the various techniques.

4. Concluding Remarks

The importance of the track forecasts was emphasized. Because dramatic improvements in 72-h track forecasts have been achieved from improved numerical guidance and consensus approaches, extensions were made to 120-h forecasts that are accurate as 72-h forecasts just a decade ago. WMO needs to facilitate the transfer of this technology to developing nations, including training, appropriate workstations, and necessary communication capability. The forecast community also stated a requirement for improved landfall position forecasts for improving warnings of the regions of damaging winds, heavy precipitation, and storm tides. A likely focus will be on probabilistic forecasts to assist in risk assessment.

****

CHAPTER 8

CLIMATE VARIABILITY AND SEASONAL PREDICTION OF TROPICAL CYCLONE ACTIVITY/INTENSITY

Chris Landsea (USA)

Incorporating:

Topic 4.0: The **2004 and 2005 Atlantic Hurricane Seasons**
Rapporteur: Max Mayfield (NHC, USA)

Topic 4.1: **Variability of tropical cyclone activity/intensity on intraseasonal and interannual scale**
Rapporteurs: Joo-Hong Kim (SNU, South Korea), Chang-Hoi Ho (SNU, South Korea)

Topic 4.2: **Possible relationships between climate change and tropical cyclone activity**
Rapporteur: Tom R. Knutson (GFDL, USA)

Topic 4.3: **Short-term climate (seasonal and intra-seasonal) prediction of tropical cyclone activity and intensity**
Rapporteur: Suzana J. Camargo (IRI, USA)

Special Topic 4a: **Updated Statement on the Possible Effects of Climate Change on Tropical Cyclone Activity/Intensity**
Rapporteur: John McBride (BMRC, AUS)

4.0: The 2004 and 2005 Atlantic Hurricane Seasons

Max Mayfield provided an overview of the extremely active hurricane seasons during 2004 and 2005 for the Atlantic basin.

2004 and 2005 together were among the most devastating Atlantic hurricane seasons on record. Over 4800 lives were lost from tropical cyclone impacts in the Caribbean Islands, Central America and North America, with the largest losses of lives in Haiti (over 3000 fatalities from 2004's Jeanne) and in the United States (around 1500 people killed from 2005's Katrina). While difficult to quantify in many other regions, direct damages in the United States were over $45 billion in 2004 and over $100 billion in 2005. These values are the highest recorded, likely due to the combination of increased population and infrastructure in hurricane vulnerable coastal regions.

With regards to measures of tropical cyclone activity, both 2004 and 2005 stand out as being extremely busy and in some cases record-setting. Fifteen named storms developed in 2004, including Nicole, a subtropical storm. Nine of the named systems became hurricanes, and of these, six became major hurricanes. These totals are considerably above the long-term means of 11 named storms, 6 hurricanes, and 2 major (Category 3, 4 or 5 on the Saffir-Simpson Hurricane Scale) hurricanes. The season also featured intense and long-lived hurricanes. Ivan, a category 5 storm, twice reached a minimum pressure of 910 mb, a value surpassed by only five other previous tropical cyclones in the Atlantic basin historical record. In addition, Ivan was a major hurricane for a total of 10 days, a new record for a single storm since reliable records began. In terms of “accumulated cyclone energy” (ACE; the sum of the squares of the maximum wind speed at 6-h intervals for tropical storms and hurricanes), overall activity this year was 234% of the long-term mean. Only two seasons since 1944 (1950 and 1995) have had higher ACE values.

By almost all standards of measure, the 2005 Atlantic hurricane season was the most active of record. Twenty-eight storms – twenty-seven tropical and one subtropical – formed during the year. This broke the record of 21 set in 1933. Fifteen of the storms became hurricanes, breaking the record of twelve set in 1969. Seven hurricanes became major hurricanes. This was just short of the record of eight major hurricanes set in 1950. Four hurricanes reached category 5 strength [maximum 1-min winds greater than 135 kt], which was the first time this had been observed in one season. In terms of “accumulated cyclone energy”, overall activity this year was the highest of record, about 256% of the long-term mean. The previous record was about 249% of the long term mean set in 1950. A record seven named storms formed before the end of July, including Hurricane Emily, the earliest category 5 hurricane on record in the basin. The season also ran late, as Tropical Storm Zeta was the second latest developing storm of record and lasted into January 2006.

4.1 Variability of Tropical Cyclone Activity/Intensity on Intraseasonal and Interannual Scale

Joo-Hong Kim reviewed the current status of the understanding on variability of tropical cyclone activity/intensity on intraseasonal to interannual time scales around the globe.

Annually, approximately 80−90 tropical cyclones occur over the tropical oceans. The tropical cyclone activities depend on thermodynamic parameters (e.g., sea surface temperature (SST), atmospheric stability, and mid-tropospheric moisture) and dynamic parameters (e.g., low-level vorticity and vertical wind shear). In many cases, thermodynamic parameters are closely linked with each other in the tropics; the atmosphere overlying high SSTs tends to be humid, and humid air with high atmospheric temperature inevitably becomes unstable

Over the tropical oceans prone to frequent tropical cyclones, the thermodynamic factors for tropical cyclone formation are most often satisfied. Also, the dynamic parameters—positive low-level vorticity and weak vertical wind shear—give rise to environments favourable for the generation of tropical cyclones. In the case of changes in the large-scale circulation in the tropical oceans, the thermodynamic and/or dynamic parameters may be modified. These modifications, in turn, may alter the tropical cyclone activity/intensity.

The variation of the tropical cyclone activity is to some extent associated with the El Niño–Southern Oscillation, quasi-biennial oscillation, Arctic Oscillation, North Atlantic Oscillation, Antarctic Oscillation, Madden–Julian Oscillation, etc., depending on the ocean basin. Subsequently, the discussion will be involve several ocean basins such as the western North Pacific, the North Atlantic, the eastern and central North Pacific, the Indian Ocean, and Australia and South Pacific.

4.2 Possible Relationships Between Climate Change and Tropical Cyclone Activity

Tom Knutson reviewed the current science on possible relationships between climate change and tropical cyclone activity/intensity on different time scales.

The report first discusses observed tropical climate trends and multi-decadal variability that are relevant to tropical cyclone activity, including in SSTs, water vapour, atmospheric stability, and atmospheric circulation. Investigations into observed trends and low-frequency variability of tropical cyclone activity are reviewed, which cover all tropical cyclone basins but most focus upon the Atlantic tropical cyclone records. An overview is provided of paleotempestology – the study of pre-historic tropical cyclones using geological proxy evidence or historic documents – which provides localized estimates of tropical cyclone variations on the order of century and millennium timescales. Theoretical studies and numerical models (both coupled global climate models and downscaled regional models) have been utilized extensively to research past tropical cyclone behaviour (climatology, seasonal cycles, interannual, decadal and multidecadal variability). These tools have also been instrumental in making projections of future greenhouse gas warming impacts (into tropical cyclone frequency, intensity, and rainfall) as well as allowing assessments of how these changes compare with studies of recent tropical cyclone observations. Finally, the role that tropical cyclones may have in actively forcing the climate system is discussed.

There are substantial roadblocks both in making reliable future projections about tropical cyclone activity and in determining whether a trend can be detected in historical tropical cyclone data. For the climate change detection problem, a large hurdle is the quality of the tropical cyclone historical databases. Several recent studies report strong increasing trends in several tropical cyclone metrics. However, the databases used in these studies were unfortunately populated over time without a focus on maintaining data homogeneity, a key requirement for databases which are to be used to assess possible climate-related trends. Additionally, improved understanding of the causes of past variations or trends in tropical cyclone activity will depend on the existence of reliable climate-quality data sets for related variables, such as SST, atmospheric temperature, moisture, wind shear, etc. However, data quality and data inhomogeneity issues with datasets such as the NCAR/NCEP and ERA reanalyses remain as an important roadblock for further advancement. Climate (global and regional) models are another important tool for investigating tropical cyclone climate variability and change. These contain hypotheses for how the climate system works in a framework which allows experiments to be performed to test various hypotheses or compare the model's historical simulations against historical observations. Nonetheless, there are important uncertainties in climate models and the radiative forcings used for such experiments. Finally, in contrast to the theory of potential intensity of tropical cyclones, which is more well-established, a comparable theory of tropical cyclone frequency is not well-developed at this time. The lack of theoretical underpinning of tropical cyclone genesis and frequency of occurrence remains as an important roadblock to progress in this area, apart from global model limitations.

In general, hurricane-climate research is expected to progress most rapidly when a combination of theory, modelling, and observations are brought to bear on the problem. The need for improved climate-quality tropical cyclone databases seems clear. These will provide better information for assessing future changes, and more reliable statistical assessments of past changes in hurricane activity, including landfall, in all basins. Tropical cyclone/climate modelling studies will benefit from efforts to improve global climate modelling in general. In addition, studies which focus on simulation or downscaling of tropical cyclones could benefit from more rigorous testing of model performance with simulating a wider range of tropical cyclone metrics. Finally, exploration of empirical approaches, such as seasonal genesis parameters, should be encouraged, including testing/evaluation and improvements aimed at reproducing characteristics of historical tropical cyclone activity in different basins from both observations and climate model simulations. Based on these results, these approaches may be useful for making climate change projections of tropical cyclone activity.

4.3 Short-term Climate (seasonal and intra-seasonal) Prediction of Tropical Cyclone Activity and Intensity

Suzana Carmago discussed the state of the science in seasonal and sub-seasonal tropical cyclone prediction.

Seasonal tropical cyclone forecasts are currently produced using statistical and dynamical methods in various centres and for different regions. Statistical seasonal tropical cyclone prediction was first conducted in the Atlantic basin at Colorado State University using statistical relationships between Atlantic tropical cyclone activity and predictors such as the El Niño – Southern Oscillation (ENSO), the Quasi-Biennial Oscillation (QBO) and Caribbean basin sea level pressures. Statistical forecast techniques have continued to develop since these early forecasts began in the mid-1980s and have spread to several tropical cyclone basins. Some groups are issuing seasonal forecasts up to almost a year in advance of the season. Verifications of some of the seasonal prediction efforts have demonstrated that substantial skill exists, especially at the shortest lead times. Additionally, recent statistical predictions have been attempting to regionalize the forecasts to impacts along specific coastal zone.

Two groups are now issuing seasonal forecasts of tropical storm frequency based on dynamical models. The skill of some dynamical models to predict the frequency of tropical storms over the Atlantic can be comparable to the skill of statistical models. Over the other ocean basins, dynamical models can also display some robust skill in predicting the frequency of tropical storms, but they usually perform poorly over the North and South Indian Oceans. The seasonal prediction of the risk of tropical storm landfall still represents a challenge for dynamical models, as track produced tend to be unrealistically poleward in most modelling systems

Interest in the prediction of atmospheric variability on the intra-seasonal timescale has recently blossomed. On this timescale, the Madden-Julian Oscillation (MJO), with its 30- to 80-day period, provides the greatest prospects for tropical prediction given its large scale, tendency to persist for at least an additional cycle, and its moderate to strong relationship to tropical cyclone activity in some basins. MJO prediction has so far been approached using mainly empirical methods, owing to the difficulty that global numerical models have in its simulation and prediction. While there is much room for improvement in the skill and application of empirical/statistical methods of intra-seasonal tropical cyclone prediction, the greatest hope for improvement lies with dynamical/numerical models. Indeed, numerical studies using twin-experiment methodology in which the model employed is assumed to be perfect, indicate useful predictability of the MJO may extend to 25-30 days, 10 days longer than that currently derived from empirical methods.

4a. Updated Statement on the Possible Effects of Climate Change on Tropical Cyclone Activity/Intensity

John McBride led development efforts for an updated statement on tropical cyclones and climate change.

This work was begun months in advance and was based in large part upon the summarization of Rapporteur Report 4.2 by Tom Knutson. Writing (and rewriting) were accomplished during the two weeks of the meeting based upon three full-workshop sessions and several smaller group interactions. On the last day of the workshop, the attendees voted to endorse the final statement (which includes a one-page summary, the detailed statement itself, and several recommendations). These are included in Chapter 2 of this report.

Summary

Below are comments and suggestions that were compiled from feedback with the Rapporteurs, working group leaders and individual workshop attendees. These are stratified first into items that are relevant to all primary topics (4.1, 4.2, and 4.3), then for items that are relevant to topic 4.2 singly, then for items that are relevant for topics 4.1 and 4.3 together. No attempt has been done here to prioritize these comments.

- Reanalyzing existing tropical cyclone "best track" datasets is of paramount importance for conducting reliable climate variability and change studies, along with other meteorological and applied purposes. Where there exist multiple "best tracks" for a specific basin, these need to be incorporated into a unified, reanalyzed tropical cyclone database. Given that these databases were developed at operational centres, there should be significant interaction with tropical cyclone forecasters in the reanalysis methods/process. Meta-information about why changes were introduced from the original databases is crucial in re-analysis work. While such reanalysis efforts will by nature still generally create a heteorogeneous timeseries because of differing available observations, it is also crucial that homogeneous tropical cyclone climate databases (i.e., the Kossin satellite approach) be developed (4.1, 4.2, 4.3).

- Many tropical cyclone databases currently contain insufficient meta-information on how intensity estimates have been obtained and what pressure-wind relationships were used. It is recommended that there be widespread adoption of the WMO format for best track databases and greater inclusion of metadata relating to how intensity estimates have been made (4.1, 4.2, 4.3).

- There is a very large inconsistency between global warming modelling/theory (which suggests small changes in intensity several decades from now) versus some observational studies (which suggest that large changes have already occurred). Further global warming modelling/theory studies are needed to better understand the sensitivity to greenhouse forcing (4.2).

- Research should be supported on a better understanding of the role of tropical cyclones in the general circulation of the atmosphere and ocean (4.2).

- There is a large need to understand tropical cyclone climate variability on the century timescale. Various methods for extending tropical cyclone databases back in time from both historical reconstructions (e.g., Chinese and Cuban documents) and from paleotempestology (e.g., sediment layers, tree rings, cave deposits) are strongly encouraged (4.2).

- There is a strong need for continued research into the multidecadal variability of tropical cyclones in all basins to understand the relative role of natural (e.g., ocean circulation) and anthropogenic (e.g., greenhouse gas and aerosol forcing) (4.2).

- In-depth observational and modelling research needs to be conducted on the interannual variations of tropical cyclone genesis locations and tracks/prevailing steering flow. Such work is crucial for determining whether true skill can exist in downscaling basin-wide predictions to specific coastal regions (4.1, 4.3).

- Encourage the development of a uniform set of forecast quantities with regards to seasonal tropical cyclone forecasting and uniform metrics for skill evaluation. With regards to forecast quantities, these could include number of tropical cyclones with 34 kt wind, number of tropical cyclones with 64 kt wind, and a combined index such as Accumulated Cyclone Energy. With regards to metrics for skill evaluation, these could include correlations and mean square error against a baseline of climatology and short-term (1-5 year) persistence (4.3).

- Given the importance of El Nino-Southern Oscillation for seasonal predictions of tropical cyclones globally and that little to no skill currently exists in predicting the onset, magnitude and decay of ENSO, research is strongly encouraged into better understanding and predictions of the phenomenon (4.3).

- There is a lack of understanding concerning inter-basin variability, which may hamper efforts to improve forecasting on a seasonal timescale. Further studies on inter-basin variability and establishing causal links for any identified correlations are urgently needed (4.1, 4.3).

****

CHAPTER 9

DISASTER MITIGATION, WARNING SYSTEMS AND SOCIETAL IMPACT

M. C. Wong (Hong Kong, China)

1. Introduction

This report summarizes additional issues raised at the IWTC-VI during the Plenary and Discussion Group Sessions that reviewed the Rapporteurs and Topic Chair reports. The discussions were focused around 6 major areas:

(a) Tropical Cyclone Forecasting;
(b) Human and Economic Losses;
(c) Warning Dissemination;
(d) Disaster Mitigation, Prevention and Preparedness;
(e) Education and Outreaching; and
(f) IWTC arrangements.

Details are given in the following sections.

2. Tropical Cyclone Forecasting

Verification is an essential part of tropical cyclone forecasting. The meeting recommended that verification of tropical cyclone forecasts should be extended to intensity, high winds, rainfall and sea waves related to tropical cyclones. It was proposed that responses to storm surge could be enhanced by identifying local areas more sensitive to storm surges. It was also noted that there was a lack of proper definition for wind averaging for warning and wind damage investigation. It was suggested for WMO to conduct a worldwide survey relating tropical cyclone wind speeds to damages. The meeting highlighted the importance of making near real-time information available to forecast centres for proper decision-making, and recommended that measures be taken by National Meteorological and Hydrological Services (NMHSs) to combat bottlenecks in the data-flow

3. Human and Economic Losses

While assessing the impact of tropical cyclones, it would be important to focus on the number of casualties. In particular, poorer communities would be more vulnerable to the perils of tropical cyclones. The meeting considered that there was a lack of comprehensive information on the impact caused by tropical cyclones in terms of human and economic losses, and recommended the establishment of an international disaster database, compatible with GIS, to document these impacts. In order to facilitate implementation of the proposed “Disaster Database”, it was recommended that a Working Group be set up to oversee the project.

It was recommended that societal (social and economic) impact studies of landfalling tropical cyclones be conducted on a periodic basis. The results of such studies would be published to promote a culture of awareness as advocated by WMO. Also, economists would be engaged to work with the meteorological community in conducting a cost-benefit analysis of disaster mitigation policy.

4. Warning Dissemination

It was recommended to use SMS messages for the dissemination of warning/information to target users proactively. For better communication, NMHSs should be encouraged to improve relations with the media and disaster management agencies. WMO should also be encouraged to organize regional workshops bringing together forecasters and other appropriate stakeholders (disaster management experts, meteorological researchers, economists, social scientists and media) to share experience of successful and not-so-successful cases on warning dissemination.

It was noted that the existing WMO Media Working Group had already published guidelines in support of public education for media strategies. The weakest link in warning dissemination would be communication infrastructure at remote and vulnerable areas. The development of reliable communication systems for such purposes should be encouraged. The public might not be aware of the threat posed by weak or distant storms. RSMC/NMHSs were urged to warn the public that such storms could bring serious impacts as a result of associated heavy rainfall causing floods and landslides.

5. Disaster Mitigation, Prevention and Preparedness

In order to properly document the social and economic impact of tropical cyclones, it was recommended that expert teams be dispatched to survey the affected areas after the passage of a tropical cyclone. The teams would gather reliable information on the degree of damage and help people understand what the risks would be.

Improper land use in vulnerable areas was considered to be a major cause of disaster, especially, in coastal areas. It was recommended that appropriate regulatory framework on land use in such areas be developed and enforced.

It was suggested that countries that had low probability of tropical cyclone hits but high impact should conduct proper risk assessment and introduce suitable disaster preparedness programmes.

It was also suggested that WMO should target resources to support multi-disciplinary teams to undertake case studies on the effectiveness of warning systems and produce a catalogue for publication.

6. Education and Outreaching

An effective public education on tropical cyclone awareness and mitigation should best start at school. In this respect, NMHSs were encouraged to establish partnership with local education authorities to develop programmes to enhance the knowledge of local environmental hazards and warning systems. This knowledge should also be incorporated into school curricula.

In order to raise public awareness to natural hazards, a good way would be to add local flavour to the presentations on hazard risk such as videos showing of local historical damages as well as stories of people suffering from disasters.

In educating the public, there would be a need to educate not only the men-on-the-street but all levels of people including those holding resources and high-ranking government officials.

NMHSs should include in their education programmes a list of "do's and don'ts", including what to do during the perceived lower-threat periods before and after the storm passage and inside the "eye" of a typhoon.

There should be a certification requirement for disaster management personnel undertaking meteorological training.

7. IWTC Arrangements

For the IWTC-VII, it was recommended that :

(a) The topic on "Disaster Mitigation, Warning Systems and Societal Impacts" should be scheduled for the first day of the Workshop to emphasize and focus on societal issues, rather than at the end;
(b) A session/topic on public education be introduced; and
(c) Enhanced involvement of sociologists, economists and disaster management experts be encouraged.

8. Concluding Remarks

Disaster management is a multi-disciplinary task involving experts in weather observation and forecasting, education and outreach, communications and disaster response, etc. In order to achieve success in disaster mitigation, it is essential to get all stakeholders to play an active part and act as a team.

Disaster management is also an end-to-end mission. It starts with weather monitoring and forecasting, through issuance of hazard warnings and communication to the public, and ends with emergency response and recovery. Weather forecasting is, by itself, a very challenging task requiring many data input source as well as day-to-day verification and feedback. At the other end, the last and most critical link is effective communication so that the community can take the most appropriate response action. The focus of successful disaster management should be to improve on both of these critical issues.

All disasters would result in high to phenomenal social and economical consequences. There is presently no official database to systemically archive these events. Therefore, it is high time to pursue development of such a database in order to be able to truly reflect the consequences of natural disasters in quantitative terms.

Last but not least, I would like to give my special thanks to the Topic 5 rapporteurs Dr Woo-jin Lee, Dr Roger A. Pielke, Mr Joel Gratz and Dr Linda Anderson-Berry. I would also like to thank my colleague Dr T.C. Lee for presenting the Topic Chair Report at the Workshop on my behalf.

****

ANNEX A

SIXTH WMO INTERNATIONAL WORKSHOP ON TROPICAL CYCLONES (IWTC-VI)

SAN JOSE, COSTA RICA, 21-30 NOVEMBER 2006

Agenda

20 November 2006 (Monday)

1900-2000	Pre-registration
2000-2100	Pre-workshop orientation session

21 November 2006 (Tuesday)

0800-0900	Registration
0900-0930	Opening Ceremony

Plenary Session – Max Mayfield, Session Chair

Topic 0 : Special Theme: Quantitative Forecasts of Tropical Cyclone Landfall in relation to an Effective Warning system

0930-1000	Lixion Avila (USA) Topic 0.1 : Track forecasts
1000-1030	Morning coffee break
1030-1100	Sai Tick Chan (Hong Kong, China) Topic 0.2 : Observations and forecasts of wind distribution
1100-1130	Lianshou Chen (China), presented by Yihong Duan (China) Topic 0.3 : Observations and forecasts of rainfall distribution
1130-1200	Shishir Dube (India), presented by Bruce Harper (Australia) Topic 0.4 : Observations and forecasts of storm surges
1200-1330	Lunch
1330-1400	Kang Thean Shong (Malaysia), presented by Regina Cabarez (USA) Topic 0.5 : Observations and forecasts of hydrology-related issues
1400-1445	Jim Davidson (Australia) Topic 0 Chair summary
1530-1600	Afternoon coffee break
1600-1730	Breakout discussion groups – Topic 0

22 November 2006 (Wednesday)

Plenary Session – Jose Rubiera, Session Chair

Topic 1 : Tropical cyclone structure and structure change

0830-0900	Liz Ritchie (USA) Topic 1.1 : Environmental Effects on Tropical Cyclone Structure and Structure Change
0900-0930	Jeffrey D. Kepert (Australia) Topic 1.2 : Tropical cyclone inner-core dynamics influences
0930-1000	Nick Shay (USA) Topic 1.3 : Air-sea interface and oceanic influences
1000-1030	Morning coffee break

1030-1100	Mark Lander (USA) Topic 1.4 : Operational techniques in defining tropical cyclone structure John Knaff (USA)
1100-1130	Topic 1.5 : Operational guidance and skill in forecasting structure change
1130-1215	Hugh Willoughby (USA), presented by Jeff Kepert (Australia) Topic 1 Chair Summary
1215-1330	Lunch
1330-1530	Breakout discussion groups – Topic 1
1530-1600	Afternoon coffee break
1600-1630	Group Photo
1630-1800	Chris Velden (USA) Special Focus Topic 1a : Tutorial on the use of satellite data to define tropical cyclone structure
1630-1800	Peter Black & Shuyi Chen (USA) Special Focus Topic 1b : Field experiments related to tropical cyclone structure (CBLAST & RAINEX)

Evening Cocktail Reception

<u>23 November 2006 (Thursday)</u>

Plenary Session – Fred Sambula, Session Chair

Topic 2 : Tropical cyclone formation and extratropical transition

0830-0900	Bill Frank (USA) Topic 2.1 : External influences on formation
0900-0930	Mike Montgomery (USA), presented by Kevin Tory (Australia) Topic 2.2 : Internal influences on tropical cyclone formation
0930-1000	Jeff Callaghan (Australia) Topic 2.3 : Operational forecasting of tropical cyclone formation
1000-1030	Morning coffee break
1030-1100	Jenni Evans (USA) Topic 2.4 : Observing and forecasting of extratropical transition
1100-1130	John Gyakum(Canada), presented by Pat Harr (USA) Topic 2.5 : Physical processes and downstream impacts of extratropical transition
1130-1215	Pat Harr (USA) Topic 2 Chair summary
1215-1330	Lunch
1330-1530	Breakout discussion groups – Topic 2
1530-1600	Afternoon coffee break
1600-1730	Pedro Silva Dias(Brazil) Special Focus Topic 2a : The Catarina phenomenon
1600-1730	Jim Abraham (Canada), presented by Pat Harr (USA) Special Focus Topic 2b : THORPEX: a focus on tropical cyclone related research

<u>24 November 2006 (Friday)</u>

Plenary Session – Lianshou Chen, Session Chair
Topic 3 : Tropical cyclone motion

0830-0900	Tsz-Cheung Lee (Hong Kong, China) Topic 3.1 : Advances and requirements for operational track prediction
0900-0930	Sim Aberson (USA) Topic 3.2 : Improvements in understanding and prediction of tropical cyclone motion
0930-1000	Chun-Chieh Wu (PSA) Topic 3.3 : Targeted observation and data assimilation in track prediction
1000-1030	Morning coffee break
1030-1115	Russ Elsberry (USA) Topic 3 Chair summary
1200-1330	Lunch
1330-1530	Breakout discussion groups – Topic 3
1530-1600	Afternoon coffee break
1600-1730	Andrew Burton (Australia) Special Focus Topic 3a : Sharing experiences in operational consensus forecasting
1600-1730	Greg Holland & Roger Lukas (USA) Report to the IWTC-VI on the PROGRAMME FOR IMPROVEMENTS TO HURRICANE INTENSITY FORECASTS AND IMPACTS PROJECTIONS (HiFi)
1930-2130	Informal discussion on “Statement on Tropical Cyclones and Climate Change”

<u>27 November 2006 (Monday)</u>

Plenary Session – Gary Foley, Session Chair
Topic 4 : Climate variability and seasonal prediction of tropical cyclone activity/intensity

0830-0900	Max Mayfield (USA) Topic 4.0 : The recent active Atlantic hurricane seasons
0900-0930	Chang-Hoi Ho (Republic of Korea), presented by Jo-Hong Kim (Republic of Korea) Topic 4.1 : Variability of tropical cyclone activity/intensity on intraseasonal and interannual scales
0930-1000	Tom Knutson (USA) Topic 4.2 : Possible relationships between climate change and tropical cyclone activity
1000-1030	Morning coffee break
1030-1100	Suzana Camargo (USA) Topic 4.3 : Short-term climate (seasonal and intraseasonal) predictions of tropical cyclone activity/intensity
1100-1145	Chris Landsea (USA) Topic 4 Chair summary
1200-1330	Lunch

1330-1530	Breakout discussion groups – Topic 4
1530-1600	Afternoon coffee break
1600-1730	John McBride (Australia) Special Focus Topic 4a : Updated statement on the possible effects of climate change on tropical cyclone activity/intensity

Gala Dinner

28 November 2006 (Tuesday)

Plenary Session – Shishir Dube, Session Chair

Topic 5 : Disaster mitigation, warning systems and societal impacts

0830-0900	Woo-Jin Lee (Republic of Korea) Topic 5.1 : Evaluating the effectiveness of warning systems
0900-0930	Roger Pielke Jr. (USA), presented by Joel Gratz (USA) Topic 5.2 : Factors contributing to human and economic losses
0930-1000	Linda Anderson-Berry (Australia) Topic 5.3 : Mitigation strategies and community capacity building for disaster reduction
1000-1030	Morning coffee break
1030-1115	MC Wong (Hong Kong, China), presented by TC Lee (Hong Kong, China) Topic 5 Chair summary
1200-1330	Lunch
1330-1530	Breakout discussion groups – Topic 5
1530-1600	Afternoon coffee break

29 November 2006 (Wednesday)

Plenary Session : Recommendations

0830-1000	Summary of individual topics
1000-1030	Morning coffee break
1030-1200	Presentation of recommendations
1200-1330	Lunch
1330-1530	Discussion of recommendations
1530-1600	Afternoon coffee break
1600-1730	Discussion of recommendations
1730-2000	Discussion on “Statement on Tropical Cyclones and Climate Change”

30 November 2006 (Thursday)

Plenary Session : Workshop Proceedings

0900-1130	Review of finalized recommendations
1130-1200	Closing Ceremony

ANNEX B

SIXTH WMO INTERNATIONAL WORKSHOP ON TROPICAL CYCLONES (IWTC-VI)

SAN JOSE, COSTA RICA, 21-30 NOVEMBER 2006

List of Participants

Title	First name	Family name	Address	Country	e-mail
Dr	Linda	ANDERSON-BERRY	Bureau of Meteorology Research Center 700 Collins St. GPO Box 1289 K MELBOURNE, Vic 3001	Australia	l.anderson-berry@bom.gov.au
Dr	Mike	BERGIN	Manager, Weather Services Bureau of Meteorology 295 Ann Street GPO Box 413 BRISBANE QLD 4001	Australia	m.bergin@bom.gov.au
Mr	Andrew	BURTON	Bureau of Meteorology P.O: Box 1370 6872 WEST PERTH	Australia	a.burton@bom.gov.au

Dr	Jeff	CALLAGHAN	Bureau of Meteorology 700 Collin street GPO Box 1289 K MELBOURNE, Vic 3001	Australia	j.callaghan@bom.gov.au
Mr	Jim	DAVIDSON	Commonwealth Bureau of Meteorology GPO Box 413 BRISBANE, QLD 4001	Australia	j.davidson@bom.gov.au
Dr	Gary	FOLEY	Bureau of Meteorology Research Center 700 Collins St. GPO Box 1289 K MELBOURNE, Vic 3001	Australia	G.Foley@bom.gov.au
Dr	Bruce	HARPER	Systems Engineering Australia pty ltd 7 Mercury Briidgeman Downs QLD 4035	Australia	seng@uq.net.au
Dr	Jeff	KEPERT	Bureau of Meteorology Research Center 700 Collins St. GPO Box 1289 K MELBOURNE, Vic 3001	Australia	j.kepert@bom.gov.au

Dr	John	MCBRIDE	Bureau of Meteorology Research Center 700 Collins St. GPO Box 1289 K MELBOURNE, Vic 3001	Australia	J.McBride@bom.gov.au
Mr	Todd	SMITH	Bureau of Meteorology Research Center 700 Collins St. GPO Box 1289 K MELBOURNE, Vic 3001	Australia	todd.smith@bom.gov.au
Dr	Kevin	TORY	Bureau of Meteorology Research Center 700 Collins St. GPO Box 1289 K, MELBOURNE, Vic 3001	Australia	k.tory@bom.gov.au
Mr	Trevor	BASDEN	Department of Meteorology Seaban House Crawford street P.O. Box 8330 NASSAU, NP	Bahamas	tbasden@gmail.com
Dr	Samarendra	KARMAKAR	Bangladesh Meteorological Department Abhava Bhawan Agargaon 1207 DHAKA	Bangladesh	directorbmd2005@yahoo.com

Prof.	Alimullah	MIYAN	South Asian Disaster Management Center IUBAT 4 Embankment Dive Road, Sector 10 Uttara Model Town, DHAKA 1230	Bangladesh	miyan@iubat.edu
Mr	Dennis	GONGUEZ	National Meteorological Service Philip Godar International Airport Box 717 BELIZE CITY	Belize	meteo@hydromet.gov.bz
Dr	Mark	GUISHARD	Bermuda Weather Service BAS-Serco Limited P.O. Box GE 123 ST GEORGE's GEBX	Bermuda	mguishard@bas-serco.bm
Prof.	Pedro	SILVA DIAS	University of Sao Paulo Rua do Matao 1226 05508-900 SAO PAULO SP	Brazil	pldsdias@master.iag.usp.br
Ms	Kathy Ann	CAESAR	Carribean Institute for Meteorology and Hydrology ST JAMES	British Carribean Territories	caesar@sunbeach.net kathy_annc@hotmail.com
Mr	Jim	ABRAHAM	Canadian Hurricane Center 45 Alderney Drive DARMOUTH, Nova Scotia	Canada	jim.abraham@ec.gc.ca

Mr	Peter	BOWYER	Canadian Hurricane Center 45 Alderney Drive DARMOUTH, Nova Scotia	Canada	peter.bowyer@ec.gc.ca
Dr	Christopher	FOGARTY	Canadian Hurricane Center 45 Alderney Drive DARMOUTH, Nova Scotia	Canada	chris.fogarty@ec.gc.ca
Prof.	John	GYAKUM	Mc Gill University Department of Atmospheric and Oceanic Sciences Mc Gill University 805 Sherbrooke Street West MONTREAL, QC H3A 2K6	Canada	john.gyakum@mcgill.ca
Dr	Fred	SAMBULA	National Weather Service PO Box 10098 APO GRAND GAYMAN KY1 1001	Cayman Islands	fred.sambula@caymanairports.com
Prof.	Lianshou	CHEN	Chinese Academy of Meteorological Sciences China Meteorological Administration 46 Zhong Guan Cun South Street BEIJING	China	lianshouchen@yahoo.com lschen@cams.cma.gov.cn

Ms	Ziying	CHU	China Meteorological Administration 46 Zhong Guan Cun Nan Da Jie BEIJING	China	chuzy@cma.gov.cn
Dr	Yihong	DUAN	Shanghai Typhoon Institute 166 Puxi Road SHANGHAI 200030	China	duanyh@mail.typhoon.gov.cn
Dr	Xiaotu	LEI	Shanghai Typhoon Institute 166 Puxi Road SHANGHAI 200030	China	leixt@mail.typhoon.gov.cn
Ms	Ying	LI	Chinese Academy of Meteorological Sciences China Meteorological Administration 46 Zhong Guan Cun South Street BEIJING	China	liying@cams.cma.gov.cn
Mr	Aiming	LIU	Chinese Academy of Meteorological Sciences China Meteorological Administration 46 Zhong Guan Cun South Street BEIJING	China	amil@163.com
Mr	Wenquan	LIU	China Meteorological Administration 46 Zhong Guan Cun Nan Da Jie BEIJING	China	liuwq@cma.gov.cn

Mr	Xuexin	NIU	Chinese Academy of Meteorological Sciences China Meteorological Administration 46 Zhong Guan Cun South Street BEIJING	China	xxniu827@163.com
Dr	Tao Yong	PENG	Guangzhou Central Meteorological Observatory 6 Fujin Road GUANGZHOU 510080	China	typeng@cma.gov.cn
Mr	Chuanhai	QIAN	National Meteorological Center CMA 46 Zhongguancun Nandajie BEIJING 100081	China	chqian@cma.gov.cn
Mr	Fumin	REN	Chinese Academy of Meteorological Sciences China Meteorological Administration 46 Zhong Guan Cun South Street BEIJING	China	fmren@163.com
Mr	Donghai	WANG	Chinese Academy of Meteorological Sciences China Meteorological Administration 46 Zhong Guan Cun South Street BEIJING	China	wangdh@cams.cma.gov.cn

Ms	Jing	XU	Chinese Academy of Meteorological Sciences China Meteorological Administration 46 Zhong Guan Cun South Street BEIJING	China	xujing@cma.gov.cn
Dr	Ming	XU	Shanghai Typhoon Institute 166 Puxi Road SHANGHAI 200030	China	xum@mail.typhoon.gov.cn
Mr	Xiangde	XU	Chinese Academy of Meteorological Sciences China Meteorological Administration 46 Zhong Guan Cun South Street BEIJING	China	cep99@cams.cma.gov.cn
Dr	Hui	YU	Shanghai Typhoon Institute 166 Puxi Road SHANGHAI 200030	China	yuh@mail.typhoon.gov.cn
Mr	Ibrahim	KASSIM	Comores Met Services	Comores	kassim@snpt.km
Dr	Maritza	BALLESTER PEREZ	Institute de Meteorology	Cuba	maritza@met.inf.cu

Mr	Omar	GARCIA	Instituto de Astronomia y Meteorologia Ave. Vallarta 2602 Esq Emilio Castelar Col Arcos Vallarta GUADALAJARA, CP 44130	Cuba	o_garcia_1998@yahoo.com
Dr	Ramon	PEREZ SUAREZ	Institute de Meteorology	Cuba	ramon@met.inf.cu
Dr	Jose	RUBIERA	Institute de Meteorology	Cuba	rubiera@met.inf.cu
Mr	Rajendra	PRASAD	Fiji Meteorological Service Ministry of Communications and Civil aviation Private mail bag NAP 0351 NADI AIRPORT	Fiji	rajendra.prasad@met.gov.fj
Mr	David	BARBARY	DIRRE/CRC/ Météo France BP 4 97491 SAINTE CLOTHILDE	La Réunion France	david.barbary@meteo.fr
Mr	Philippe	CAROFF	Meteo-France, RSMC 97 491 SAINTE CLOTHILDE	La Réunion France	philippe.caroff@meteo.fr
Mr	Jean Noel	DE GRACE	Météo France Aeroport du Lamentin BP 379 97288 LE LAMENTIN 2	France	jean-noel.degrace@meteo.fr

Dr	Samuel	WESTRELIN	Météo France 50 bd du Chaudron BP 4 97491 SAINTE CLOTILDE Cedex	La Réunion France	samuel.westrelin@meteo.fr
Dr	Harry	WEBER-PHILIPP	Meteorological Institute University of Munich Theresienstrasse 37 D-80333 MUNICH	Germany	harry@meteo.physik.uni-muenchen.de
Mr	Esterlin	MARCELIN	Service National des Ressources en Eau PORT-AU-PRINCE	Haiti	esterlinm@yahoo.fr
Prof.	Johnny	CHAN	Department of Physics and Material Science City University of Hong Kong 83 Tat Chee Avenue Kowloon Tong HONG KONG	Hong Kong, China	Johnny.chan@cityu.edu.hk
Dr	Sai Tick	CHAN	Hong Kong Observatory 134 A Nathan Road KOWLOON	Hong Kong, China	stchan@hko.gov.hk
Mr	Chiu Ying	LAM	Hong Kong Observatory 134 A Nathan Road KOWLOON	Hong Kong, China	chiuylam@hko.gov.hk

Dr	Tsz Cheug	LEE	Hong Kong Observatory 134 A Nathan Road KOWLOON	Hong Kong, China	tclee@hko.gov.hk
Mrs	Brenda Lai Yee	TONG	Hong Kong Observatory 134 A Nathan Road KOWLOON	Hong Kong, China	sps@hko.gov.hk
Prof.	Shishir	DUBE	Indian Institute of Technology KHARAGPUR 721 303	India	skdube@iitkgp.ernet.in
Dr	Thakur	PRASAD	India Meteorological Department PUNE	India	tprasad@imdmumbai.gov.in
Dr	Omprakash	SINGH	Indian Meteorological Department RSMC Tropical Cyclone Mausam Bhawan, Lodi Road 11003 NEW DELHI	India	opsingh@imdmail.gov.in
Dr	Evan	THOMPSON	Meteorological Service 65 3/4 Half-Way-Tree Road, KINGSTON 19	Jamaica	metservice.wbh@jamweb.net

Dr	Naoko	KITABATAKE	Meteorological Research Institute Japan Meteorological Agency 1-1 Nagamine TSUKUBA 3050052	Japan	nkitabat@mri-jma.go.jp
Mr	Nobutaka	MANNOJI	Japan Meteorological Agency Forecast Department 1-3-4 Ote machi, Chiyoda-ku TOKYO 100 8122	Japan	mannoji@met.kishou.go.jp
Dr	Munehiko	YAMAGUCHI	Japan Meteorological Agency Forecast Department 1-3-4 Ote machi, Chiyoda-ku TOKYO 100 8122	Japan	m-yamaguchi@met.kishou.go.jp
Mrs	Sahondranlala	RAVELOARISOA	Direction générale de la météorologie BP 1254 ANTANANARIVO 101	Madagascar	meteo@simicro.mg
Mr	Satyabhama	CAHOOLESSUR	Mauritius Meteorological Services Saint Paul Road VACOAS	Mauritius	meteo@intnet.mu

Dr	Michel	ROSENGAUS	Permanent Representatie of Mexico with WMO Comision Nacional del Agua Avenida Observatorio 192 Colonia Observatoio Delegacion Miguel Hidalgo 11860 MEXICO DF	Mexico	michel.rosengaus@cna.gob.mx mickros@prodigy.net.mx
Mr	Jose Antonio	SALINAS PRIETO	Mexican Institute of Water Technology Paseo Cuauhnahuca 8532 Col Progreso Jiutepec MEXICO	Mexico	jsalinas@tlaloc.imta.mx
Mr	Ricardo	PRIETO GONZALES	Servicio Meteorologico Nacional Comision Nacional del Agua MEXICO DF	Mexico	alberto.hernandez@cna.gob.mx
Mr	Alfredo	CAPELLO	Meteorological Service Seru Mahuma z/n CURACAO	Netherlands Antilles and Aruba	cur-met@meteo.an
Mr	Roy Denny	VAN OMMEN	Meteorological Service Netherlands Antilles Seru Mahuma zn CURACAO	Netherlands Antilles and Aruba	okki@meteo.an

Mr	Bejamin	MALAI	PNGNWS P.O. Box 1240 BOROKO	Papua New Guinea	binn_malai@hotmail.com
Dr	Prisco	NILO	PAGASA Science Garden Complex Agham Road QUEZON CITY 1100	Philippines	pdnilo@pagasa.dost.gov.ph
Dr	Rosa	PEREZ	PAGASA, 2/F Weather and Flood Forecasting Center Agham Road QUEZON CITY 1104	Philippines	rtperez1@yahoo.com
Prof.	Jae-young	BYON	Typhoon research team, Meteorological Research Institute Korea Meteorological Administration 460-18 Shindaebang-dong Dongjak-gu SEOUL	Republic of Korea	byonjy@kma.go.kr
Dr	Woo-Jin	LEE	Korean Meteorological Administration 460-18 Shindongbang-dong SEOUL 156-720	Republic of Korea	wjlee@kma.go.kr

Dr	Joo-Hong	KIM	Seoul National University 56222 Dept of Atmospheric Sciences School of Earth and Environment Gwanak-gu, Shilim-dong SEOUL	Republic of Korea	jhkim@cpl.snu.ac.kr
Mr	Sagato	TUIAFISO	Miniistry of Natural Resources, Environment and Meteorology	Samoa	info@mnre.gov.ws
Mr	Fermin	ELIZAGA RODRIGUEZ	INM Spanish Meteorological Service Leonardo Prieto Castro 8 28040 MADRID	Spain	std@inm.es
Mr	Gunavi Baladeva	SAMARASINGHE	Department of Meteorology Bauddhaloka Mawatha COLOMBO 07	Sri Lanka	sbaladev_24@yahoo.com
Mr	Moleni	TUUHOLOAKI	Tonga Meteorological Service Ministry of Transport	Tonga	mtuuholoaki@mca.gov.to
Mr	Julian	HEMING	Met Office Fitzroy Road EXETER, Devon Ex1 3PB	United Kingdom	julian.heming@metoffice.gov.uk

Dr	Manuel	LONFAT	Risk Management Solutions Ltd. Penisular House 30 Monument street LONDON 5NS EC3R	United Kingdom	manuel.lonfat@rms.com
Dr	Sim	ABERSON	Hurricane Research Division, NOAA 4301 Rickenbacker Causeway, Miami FL 33149	USA	sim.aberson@noaa.gov
Dr	Lixion	AVILA	Tropical Prediction Center National Hurricane Center 33165-2149 MIAMI	USA	lixion.a.avila@noaa.gov
Dr	Peter	BLACK	NOAA/AOML Hurricane Research Division 4301 Rickenbacker Cswy MIAMI, FL 33149	USA	peter.black@noaa.gov
Mr	Wes	BROWNING	NOAA/NWS Central Pacific Hurricane Center 2525 Correa Road Suit 250 HONOLULU, HI 96822	USA	wes.browning@noaa.gov
Dr	Reggina	CABRERA	NOAA/NWS/HQTR, Route W/OHD12, Washington, DC	USA	reggina.cabrera@noaa.gov

Prof.	Suzana	CAMARGO	International Research Institute for Climate and Society The Earth Institute at Columbia University P.O. Box 1000 PALISADES, NY 10964-8000	USA	suzana@iri.columbia.edu
Dr	Shuyi	CHEN	RSMAS/MPO University of Miami 4600 Rickenbacker cswy MIAMI, FL 33 149	USA	schen@rsmas.miami.edu
Dr	Kevin	CHEUNG	Pacific Sciece Association c/o Naval Postgraduate School, Monterey, CA 93943	USA	cpchang@nps.edu
Prof.	William	DRENNAN	University of Miami RSMAS/MPO 4600 Rickenbacker Causeway MIAMI, FL 33149	USA	wdrennan@rsmas.miami.edu
Dr	Kerry	EMANUEL	Dept. Earth Atmosphere & Planetary Sciences, MIT Bldg 54-1620, Cambridge MA	USA	emanuel@texmex.mit.edu
Prof.	Russell	ELSBERRY	US Naval Postgraduate School 589 Dyer Road MONTEREY, CA 93943-5114	USA	elsberry@nps.edu

Prof.	Jenni	EVANS	The Pennsylvania State University 503 Walker Building UNIVERSITY PARK, PA 16802	USA	jle7@psu.edu
Prof.	Chris	FAIRALL	NOAA Earth System Research Laboratory 325 Broadway BOULDER, CO 80305	USA	chris.fairall@noaa.gov
Prof.	William	FRANK	Pennsylvania State University Department of Meteorology 503 Walker Building UNVERSITY PARK, 16802	USA	frank@ems.psu.edu
Mr	Jeffrey	FRENCH	University of Wyoming Dpt 3038 1000 E. University Avenue LARAMIE, WY 82070	USA	jfrench@uwyo.edu
Dr	Edward	FUKADA	Joint Typhoon Warning Center 425 Luapele Road PEARL HARBOR, Hawaii 96860-3103	USA	edward.fukada@navy.mil
Prof.	Isaac	GINIS	Universtity of Rhode Island Graduate School of Oceanography 165 South Ferry Rd NARRAGANSETT, RI 02882	USA	iginis@gso.uri.edu

Dr	Joel	GRATZ	ICAT Managers LLC 3665 Discovery Drive, Suite 300 BOULDER, CO 80303	USA	gratzo@gmail.com
Prof.	Bill	GRAY	Colorado State University Department of Atmospheric Sciences	USA	amie@atmos.colostate.edu
Mr	Chip	GUARD	US NOAA/NWS Forecast Office 3232 Hueneme Road Barrigada GUAM 96913	USA	chip.guard@noaa.gov
Dr	Patrick	HARR	US Naval Postgraduate School 589 Dyer Road MONTEREY, CA 93943-5114	USA	paharr@nps.edu
Prof.	Robert	HART	Florida State University 404 Love Building Department of Meteorology TALLAHASSEE, FL 32306-4520	USA	rhart@met.fsu.edu
Prof.	Jeffrey	HAWKINS	Naval Research Laboratory NRL 7 Grace Hopper avenue MS 2 MONTEREY, CA 93943	USA	jeff.hawkins@nrlmry.navy.mil

Dr	Greg	HOLLAND	NCAR/MMM P.O. Box 3000 BOULDER, CO 80307-300	USA	gholland@ucar.edu
Mrs	Penelope	JONES	Naval Postgraduate School Department of Meteorology 589 Dyer Road, Room 254 MONTEREY, CA 93943-5114	USA	pjones@nps.edu
Mr	Phil	KLOTZBACH	Department of Atmospheric Science Colorado State University BOULDER, CO	USA	philk@atmos.colostate.edu
Prof.	John A.	KNAFF	Cooperative Institute for Resarch in the Atmosphere Colorado State University FORT COLLINS, CO 80523-1375	USA	knaff@cira.colostate.edu
Mr	Tom	KNUTSON	Geophysical Fluid Dynamics Lab NOAA P.O. Box 308 Forrestal Campus PRINCETON, New Jersey 08542	USA	tom.knutson@noaa.gov
Dr	Chris	LANDSEA	Tropical Prediction Center National Hurricane Center 33165-2149 MIAMI	USA	chris.landsea@noaa.gov

Dr	Kam-biu	LIU	Louisiana State University Department of Oceanography and Coastal Sciences School of coast and environment BATON ROUGE, LA 70803	USA	kliu1@lsu.edu
Prof.	Carlos	LOZANO	Environmental Modelling Center NOAA(NCEP 5200 Auth Road CAMP SPRINGS, MD 20746	USA	carlos.lozano@noaa.gov
Mr	Sharanya	MAJUMDAR	RSMAS/MPO University of Miami 4600 Rickenbacker cswy MIAMI, FL 33 149	USA	smajumdar@rsmas.miami.edu
Mr	Max	MAYFIELD	Tropical Prediction Center National Hurricane Center 33165-2149 MIAMI	USA	max.mayfield@noaa.gov
Dr	Michael T	MONTGOMERY	Naval Postgraduate School Department of Meteorology 589 Dyer Road, Room 254 MONTEREY, CA 93943-5114	USA	mtmontgo@nps.edu
Dr	Michael	MORGAN	University of Wisconsin 1225 W Dayton Street MADISON, WI 53706	USA	mcmorgan@wisc.edu

Prof.	David	NOLAN	University of Miami RSMAS/MPO 4600 Rickenbacker Causeway MIAMI, FL 33149	USA	dnolan@rsmas.miami.edu
Dr	Melinda	PENG	Naval Research Laboratory NRL 7 Grace Hopper avenue MS 2 MONTEREY, CA 93943	USA	melinda.peng@nrlmry.navy.mil
Dr	Elizabeth	RITCHIE	University of Arizona Department of Atmospheric Sciences P.O. Box 210081 University of Arizona TUCSON, AZ 85721 0081	USA	ritchie@atmo.arizona.edu
Dr	Lynn	SHAY	University of Miami RSMAS/MPO 4600 Rickenbacker Causeway MIAMI, FL 33149	USA	nshay@rsmas.miami.edu
Prof.	Alexander	SOLOVIEV	Nova Southeastern University's Oceanographic Center 800 N. Ocean DANIA BEACH, FL 33004	USA	soloviev@ocean.nova.edu

Mr	Chung-Hsiung	SUI	Pacific Sciences Association Meteorology Committee c/o Code MR/CP Department of Meteorology Naval Post Graduate School MONTEREY, CA 93943	USA	cpchang@nps.edu
Prof.	Naomi	SURGI	NOAA/NCEP/Environmental Modelling Center 5200 Auth Road wwBG Room 207 CAMP SPRINGS, MD 20746-4304	USA	naomi.surgi@noaa.gov
Dr	Zoltan	TOTH	NOAA	USA	zoltan.toth@noaa.gov
Prof.	Gregory	TRIPOLI	University of Wisconsin 1225 West Dayton Street MADISON, Wisconsin 53706	USA	tripoli@aos.wisc.edu
Dr	Yuqing	WANG	IPRC/SOEST University of Hawaii 1680 East West Road HONOLULU, HI 96822	USA	yuqing@hawaii.edu
Dr	Chris	VELDEN	University of Wisconsin-Madison	USA	chrisv@ssec.wisc.edu

Dr	Chun Chieh	WU	Pacific Science Association c/o Naval Postgraduate School, Monterey, CA 93943	USA	cpchang@nps.edu
Dr	Ray	ZEHR	NOAA/NESDIS, RAMM Team CSU 1375 Campus Delivery FORT COLLINS, CO 80523	USA	ray.zehr@noaa.gov
Mr	Alvaro	PALACHE	Servicio de Meteorologia Av. Bolivar Este No 76 El Prado	Venezuela	alvaropalache@hotmail.com
Mrs	Duong Lien	CHAU	Hydrometeorological Service 4 Dong Thai Than street HANOI	Viet Nam	dlchau@nchmf.gov.vn
Dr	Zhaochong	LEI	WMO		Zlei@wmo.int
Mrs	Nanette	LOMARDA	WMO		Nlomarda@wmo.int