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Table of Contents

FOREWORD	i
PREFACE	iii
INTRODUCTION	1
KEYNOTE SESSIONS	
Tropical Cyclone Surface Wind Structure and the Related Pressure-Wind Relationships	4
Tropical Cyclone Probabilistic Forecasting and Related Product Development Issues and Applications for User Risk Assessment.....	7
Tropical Cyclone Precipitation (QPE/QPF) and Related Inland Flood Modelling	8
WORKSHOP TOPICS	
Structure and Intensity Change.....	11
Tropical Cyclone Formation and Extratropical Transition.....	18
Tropical Cyclones in Intraseasonal to Climate Time Scales.....	23
Disaster Risks, Mitigation, Warning Systems and Socio-Economic Impacts	27
SPECIAL FOCUS SESSIONS	
Targeted Observations for Tropical Cyclone Track Forecasting	31
Ocean Field Experiments (ITOP, Gulf of Mexico) and New Research Findings	33
THORPEX/TIGGE Applications to Tropical Cyclone Motion and Forecasting	38
IBTracs Activities and Updates	40
PANEL DISCUSSION: Tropical Cyclones and Climate Change	45
RECOMMENDATIONS	46
Annex A - Workshop agenda	53
Annex B - List of participants	57

FOREWORD

The World Meteorological Organization (WMO) assigns a high priority to its World Weather Research Programme (WWRP), in particular with respect to high-impact weather systems such as tropical cyclones and the application by WMO Members of research results aimed at further improving early warning systems and reducing the impacts of these grave hazards.

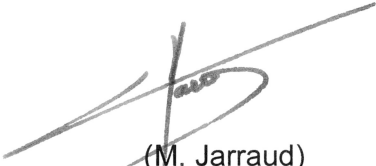
Since November 1985, WMO has organized a series of quadrennial International Workshops on Tropical Cyclones (IWTCs), the latest of which took place in La Réunion (France) from 10 to 15 November 2010. It is noteworthy that this seventh WMO International Workshop on Tropical Cyclones (IWTC-VII) has been the first held in WMO Regional Association I (Africa).

The Workshop primary objectives were to review progress in tropical cyclone research and operational practices since IWTC-VI and to contribute in identifying future research and operational priorities.

The six-day meeting set the scene for extensive in-depth discussions and resulted in a number of significant recommendations. A key Workshop outcome has been, in particular, the text book *“Global Perspectives on Tropical Cyclones: From Science to Mitigation”*, a completely rewritten, updated and expanded version of the 1995 original *“Global Perspectives on Tropical Cyclones”*.

I would like to thank France for hosting the event in La Réunion and to express my appreciation to Australia, Canada, China, Germany, Japan, Mexico, Spain, the United Kingdom and the United States of America, for providing the supplementary financial support which enabled so many participants to take part in this vital workshop, in particular from the developing world.

I also wish to express the appreciation of WMO to the International Organizing Committee, and in particular to its co-chairs, Messrs Jeffrey D. Kepert (Australia) and Chris Velden (USA), as well as the Local Organizing Committee and all workshop participants, for their invaluable contributions. I am confident that the present report will serve as a key information source for all those concerned with the tropical cyclone issue.



(M. Jarraud)
Secretary-General
World Meteorological Organization

PREFACE

The Seventh International Workshop on Tropical Cyclones (IWTC-VII) opened on 15 November 2010, marking the 25th year since the first workshop in the series was organized by the World Meteorological Organization (WMO) in Bangkok back in 1985. One hundred and thirty participants from 35 countries met in La Reunion, France to deliberate on ways to advance our understanding and forecasting to save lives threatened by tropical cyclones (TCs). The IWTC was conceived in the early eighties by a core group of tropical cyclone scientists, led by Professor William Gray. Unfortunately, the IWTC-VII marked the first workshop that Dr. Gray was unable to attend in person. However, we were greeted by our "creator" during the opening ceremony thanks to a videotape he prepared for us. In this greeting, Bill gave us a quick glance back on the inception and original intent of the IWTC, emphasizing that the goal was to bring together TC forecasters and researchers from all over the world to review the latest developments, to identify needs, and set requirements for progress to be made. He also touched upon the IWTC successes such as the channelling of scientific advances and emerging technologies into operational TC forecasting that has brought about very significant gains in terms of track forecasting and availability of new data and products. We have no doubt that the IWTC series has had a hand in these advances. And we also acknowledge that the strong support by WMO's World Weather Research Programme (WWRP) and Tropical Cyclone Programme (TCP) have contributed immensely to making the IWTC series such a success.

The opening ceremony also included several invited presentations. Johnny Chan, one of the co-directors of IWTC-VI, highlighted the major outcomes of the previous IWTC, and reviewed outcomes from the primary recommendations from that meeting. He proudly (being a co-editor) discussed one of the significant accomplishments; the publication of "Global Perspectives on Tropical Cyclones: From Science to Mitigation". This book is an update from previous volumes, but was published by a specialist company (World Scientific Publishing), in the hopes it would have a much wider circulation. A companion volume, "A Global Tropical Cyclone Forecast Guide II", is in preparation, and being led by Chip Guard. We expect this volume to be available in 2011.

Another important highlight of the previous IWTC was the formation of an expert panel to address the questions regarding TCs and climate change. Over most of the following four years, this panel debated the often contentious issues, and ultimately produced a statement that was published in an online review article in Nature Geoscience. Leads John McBride and Tom Knutson were invited to IWTC-VII to give a summary of the panel's agreed-upon stance on the issues. This briefing set the stage for a follow-on panel session on Thursday evening that picked up where the previous expert panel report left off by looking forward to ways in which the TC community can better resolve and address the remaining questions on this highly debated topic.

Two other presentations during the opening ceremony session addressed recent complementary workshops sponsored by WMO. Russ Elsberry gave an invited presentation summarising of the IWTC's sister workshop, the IWTC-Landfalling Processes (LP). The IWTC-LP-II was held in Shanghai, China in 2009. The purposes of the IWTC-LP-II are to assess the state-of-the-art in research (including field programmes) and forecast advances, and then determine what is required to improve the forecasts and early warnings of tropical cyclone landfall. It is also be a forum to transfer new science and technology to National Meteorological and Hydrological Services and thus contribute to the reduction of disaster risk through improved forecasts of tropical cyclone landfall events. The other workshop review presentation was given by Lianshou Chen, on tropical cyclone quantitative precipitation estimation and forecasting (QPE/QPF). The third workshop in this series was held in Nanjing, China in 2010. The overarching objective of this workshop series is to bring together researchers and forecasters to review the progress made towards improving QPF capabilities, and to advance the use of these fields in hydrological predictions with an emphasis on high-impact events. The workshops cover a wide range of issues relating to QPF including new observational approaches and technique development for QPE, advances in data assimilation, modelling and verification for QPF, user needs, and the challenges of operational QPF. Recommendations from that workshop are being provided to WMO.

The core programme for IWTC-VII followed the well-established model of previous IWTC's. Topic chairs and rapporteurs were selected, and assisted by working groups of volunteers, whom summarized the advances in TC forecasting and research over the previous four years. Their hard work culminated in the preparing of pre-workshop reports, which were made available to workshop participants just prior to the meeting. These reports, along with all of the IWTC-VII documentation and specifics, are now available online at:
<http://www.wmo.int/pages/prog/arep/wwrp/tmr/IWTC-VII.html>

IWTC-VII placed special emphasis on three aspects of TCs, which were presented as "keynote" sessions on the first day: (a) Surface Wind Structure & the Related Pressure-Wind Relationships, (b) Probabilistic Forecasting & Related Product Development Issues & Applications for User Risk Assessment, and (c) Precipitation (QPE/QPF) & Related Inland Flood Modelling. These topics were selected based on TC community perceptions, discussions and interactions in various venues (conferences, workshops, TC email list, publications, etc.) during the four years leading up to IWTC-VII. They were well-received by the delegates, and post-presentation discussions were lively. Several recommendations were spawned from these keynote sessions.

The following 4 days focused on four primary TC topics: (1) Structure and Intensity Change, (2) Formation and Extratropical Transition, (3) Intraseasonal to Climate Timescales, and (4) Disaster Risks, Mitigation, Warning Systems, and Socio-economic Impacts. Following the successful format of previous IWTCs, the mornings were devoted to rapporteur presentations on subtopics related to the main topic of the day. These presentations were basically synopses of the pre-workshop reports, highlighting some of the more interesting, contentious, and/or promising aspects that have come to light since the last IWTC. The afternoons were then spent in breakout groups, tasked to discuss the morning session issues and come up with recommendations focused on needs for further basic process observations and understanding, applied research, operational transition, or problems related to data access, communications, training, and mitigation strategies. The delegates were separated into 7-8 breakout groups with a chair and scribe. Care was taken to ensure that each breakout group had a good mix of forecasters and researchers, and active participation from the attending forecasters was strongly encouraged. Feedback from these breakout sessions helped form the basis for the nearly 200 recommendations that were originally delivered to the Recommendations Committee!

The various reports and presentations from these sessions, available on the website cited above, provide an excellent summary of progress over the past four years, while the workshop recommendations provide good guidance as to the needs and opportunities for further advancing tropical cyclone research and operations into the future.

Another trait of the IWTC series is the special focus sessions. These sessions, usually about an hour in length, are informal briefings and/or updates on specific topics of interest. For IWTC-VII, these included: Targeted Observations, Ocean Field Experiments, THORPEX/TIGGE Applications, IBTrACS Activities, HFIP Overview, and Dvorak Technique Issues. While these special sessions are primarily meant as informative and do not require reports or formal recommendations, the presentations can be found on the IWTC-VII web site cited above.

The final step in the workshop process is accomplished by the Recommendations Committee. For IWTC-VII, this committee was headed by Liz Ritchie. Liz and her small committee consisting of the topic chairs and a couple of others had the unenviable task of distilling all of the topic chair and breakout session recommendations down to a manageable number that could be shown and discussed in a plenary session on the final day. This included a loose prioritization of the recommendations, some of which were directed to WMO, and others that were directed to the forecast and research communities. There was considerable attendee discussion in the careful choosing of the final recommendations during the plenary; an indication that the assembly had a serious and vested interest in the formulation and follow-through of the workshop deliberations. The final set of prioritized recommendations from the committee was submitted to WMO, and is also available on the web site.

There was one major break from tradition with IWTC-VII. The meeting was shortened from covering almost two weeks, to one. The reasoning followed the line that many more attendees could stay through a full one-week meeting, as opposed to staying for only part of the previous two week scenario. There were obvious tradeoffs in this experiment. Most notably, a shortened meeting (from 9 to 6 working days) meant that the covered subject matter had to be reduced. For example, the traditional topic of TC Motion had to be eliminated as a primary topic. Other topics had to be somewhat compressed. The other factor was that the leads (chairs/rapporteurs) had less time to assimilate and prepare their recommendations for the Recommendations Committee, and in turn this committee had less time to distill these into a manageable list. But due to the great efforts by Liz and the topic chairs, the process worked. It is hoped that from lessons learned this can somehow be streamlined for the next IWTC and the time pressure on the recommendations committee and topic chairs thereby alleviated. On the plus side, the participants strongly indicated the preference for the one-week (6-day) workshop via a survey that was distributed on the last day. The results generally indicated that while the meeting at times felt a bit rushed and the material thus limited, it was the proper length for the meeting and the almost full attendance at the last day's plenary was testament to the shortened workshop attaining one of its important goals.

Another goal of IWTC-VII was to maintain the IWTC tradition of fostering interaction among delegates, both inside and outside of the meeting walls. Interaction during the meeting was facilitated by the generous allowance for question time, and by the breakout sessions. Outside the formal part of the meeting, interaction was accomplished through several social events/outings kindly provided by our Meteo-France (MF) hosts at Reunion, and by ensuring that participants ate together at breakfast and lunch. There was a nice Icebreaker on the first evening, and a wonderful workshop lunch which followed an excursion to the islands beautiful volcanic vistas as we took a half-day break in mid-week. There were also other excursions provided both before and after the meeting that were much appreciated by the attendees. We truly would like to recognize and thank our local hosts, in particular Philippe Caroff and his MF team, for their professional logistical support and wonderful hospitality during our stay on Reunion.

The multiple opportunities for interaction are one of the great features of the IWTC series. As co-directors, we were delighted to see conversations between forecasters and researchers, between people from developing and developed countries, and between senior folk with great experience and those relatively new to the field. We trust that these contacts will continue and be renewed into the future, and consider that furthering this mutual learning and understanding is a substantial benefit of the IWTC series.

Finally, we would also like to thank the participants, the topic chairs and rapporteurs, the discussion group leaders and scribes, the international programme committee (including a special thanks to WMO liaison Russ Elsberry), the local organizing committee and the staff of WMO's World Weather Research Programme and Tropical Cyclone Programme (TCP) for their collective effort which made this workshop a most fruitful event of learning and sharing. In particular, a special note of appreciation is extended to Nanette Lomarda, Koji Kuroiwa, Tetsuo Nakazawa, and Nathalie Tournier.

(Jeff Kepert)
(Chris Velden)
Co-chairs, IWTC-VII

INTRODUCTION

Background

The International Workshop on tropical Cyclones (IWTC) series started in 1985 following the proposal of WMO's Ninth Congress (Geneva, 1983) to organize a series of special tropical cyclone workshops as part of the activities relating to the WMO Commission on Atmospheric Science (CAS) Tropical Meteorology Programme and research aspect of the Tropical Cyclone Programme. The objective of the workshop was to examine current knowledge, forecasting, warning and research trends on tropical cyclones from an integrated global perspective, to report on these aspects and to offer recommendations for future forecasting studies and research with special regard to the varying needs of different regions; and to promote future collaboration between the research and forecasting communities.

The first workshop (IWTC-I) was held in Bangkok, Thailand from 25 November to 5 December 1985 under the direction of an International Programme Committee chaired by Professor William M. Gray. A major outcome of IWTC-I was the publication of a text book, *A Global View of Tropical Cyclones* (GVTC) based on the material prepared for the workshop. The workshop also made a number of recommendations for further WMO action, both for forecasting and for research.

Since then, an IWTC has been organized about every four years, each of which had one or more important accomplishments and all of which served as a special and unique gathering of tropical cyclone researchers and warning specialists from all regions affected by tropical cyclones. IWTC-II (Manila, 1989) initiated the preparation of the forecasting manual *Global Guide for Tropical Cyclone Forecasting* (GGTCF), which was published just before IWTC-III (Huatulco, 1993). A special session on global climate change and tropical cyclones was held during IWTC-III under the chairmanship of Sir James Lighthill of the International Council for Science (ICSU), a summary of which was subsequently published in the Bulletin of the American Meteorological Society (BAMS). A subsequent report was commissioned by CAS to provide a post-IPCC assessment of tropical cyclone climate change under a committee chaired by Ann Henderson Sellers. This report was presented to CAS-XII and published in the BAMS. In addition, the textbook GVTC was revised and later published under the title *Global Perspectives on Tropical Cyclones* (WMO/TD No. 693) (GPTC). At IWTC-IV (Hainan, 1998), participants discussed the revision of the forecasting manual GGTCF aside from reviewing the progress in tropical cyclone research and operational practices. An innovation in IWTC-IV was the holding of nine informal special focus groups outside the daily main session hours. At the IWTC-V held in Cairns (2002) a keynote session on the present, imminent and future satellite observations for tropical cyclones was organized and was very well received specially by tropical cyclone forecasters. A very important session during IWTC-VI (San Jose, 2006) was on the relationship between tropical cyclones and climate change. Extensive discussions were held, which resulted in the endorsement by workshop participants of a Statement on Tropical Cyclones and Climate Change. At the IWTC-VII, the recently published *Global Perspectives on Tropical Cyclones: From Science to Mitigation* (April 2010) was presented by Professor Johnny Chan, a co-editor of the textbook, which is an update of the 1995 GPTC. An evening panel/discussion session was organized, devoted to the question of how to make progress and come to a consensus on anthropogenic climate change and tropical cyclones. The session was moderated by John McBride and Tom Knutson, co-chairs of the World Weather Research programmes' Expert Team on Climate Impacts on Tropical Cyclones.

As in past workshops, IWTC-VII resulted in a number of recommendations addressed to WMO, tropical cyclone forecasters, research community on needed actions with the goal of improving tropical cyclone forecasting and warning systems and reducing the associated risk and damages caused by tropical cyclones. These workshops not only enhanced knowledge of the nature and behaviour of tropical cyclones it also provided opportunities for prioritizing new observational data and research requirements.

International Committee (IC)

The IC for IWTC-VII consisted of:

- Jeff Kepert (Australia) co-chairman
- Chris Velden (USA) co-chairman
- Lixion Avila (USA)
- BK Bandyopadhyay (India)
- Y Boodhoo (Mauritius)
- Johnny Chan (HK, China)
- Jim Davidson (Australia)
- Lianshou Chen (China)
- Russell Elsberry (USA)
- Masashi Kunitsugu (Japan)
- Rajendra Prasad (Fiji)

Messrs Boodhoo and Prasad both retired prior to the start of the workshop. The IC was responsible for the overall organization of the workshop including the choice of topics, selection of topic chairmen, rapporteurs and working group members, pre-workshop preparation and production of the topic rapporteur reports, conducting the workshop, preparation of the proceedings and arranging for additional funding for workshop participants.

Objectives of the IWTC-VII

- To examine current knowledge, forecasting and research trends on tropical cyclones from an integrated global perspective and
- To report on these aspects and to offer recommendations for future forecasting studies and research with special regard to the varying needs of different regions.

Workshop Sessions

Keynote sessions

- Tropical Cyclone Surface Wind Structure and the Related Pressure-Wind Relationships
- Tropical Cyclone Probabilistic Forecasting and Related Product Development Issues and
 - Applications for User Risk Assessment
- Tropical Cyclone Precipitation (QPE/QPF) and Related Inland Flood Modelling

Main Workshop Topics

- Structure and Intensity Change
- Tropical Cyclone Formation and Extratropical Transition
- Tropical Cyclones in Intraseasonal to Climate Time Scales
- Disaster Risks, Mitigation, Warning Systems and Socio-Economic Impacts

Special Focus Sessions

- Targeted Observations for Tropical Cyclone Track Forecasting
- Ocean Field Experiments (ITOP, Gulf of Mexico) and New Research Findings

- THORPEX/TIGGE Applications to Tropical Cyclone Motion and Forecasting
- IBTracs Activities and Updates
- Overview and Operational Products Expected from NOAA's Hurricane Forecast Improvement Programme (HFIP)
- Open Discussion on Application of the Dvorak Technique and Resolving Interagency Intensity Differences

Panel Discussion: Future Research Directions for Tropical Cyclones and Climate Change

Preparation of the Final Report

The summary reports in this report were provided by the session chairs. The workshop recommendations were collated by a small group chaired by Liz Ritchie. The editorial work was done at the WMO Secretariat.

KEYNOTE SESSIONS

Tropical Cyclone Surface Wind Structure and Wind-Pressure Relationships

John Knaff (USA) and Bruce Harper (Australia)

This report summarizes the plenary and breakout discussions for Keynote Topic 1 of the WMO Seventh International Workshop on Tropical Cyclones, held in La Reunion, Nov 15-20, 2010. Here we mostly avoid restating the material prepared before the workshop and rather concentrate on our interpretation of the important items resulting from the questions, discussion following the keynote topic presentation and contained in the breakout discussions. We also reiterate our thanks to those that provided information for the keynote presentation. These include Dan Brown (NOAA/NHC, Miami), Sébastien Langlade (Météo-France, La Reunion), Joe Courtney (BoM, Perth), Derrick Herndon (CIMSS), Masashi Kunitsugu (JMA) and Eric Uhlhorn (NOAA/HRD, Miami).

It is now well recognized that the surface wind structure to a large extent determines the destruction potential of a given tropical cyclone, whereby larger storms of equal intensity will cause more destruction. The wind field is also the basis for the issuance of TC warnings and is a fundamental component in recently developed wind speed probabilities, which is discussed in another keynote topic. Accordingly, the traditional single-valued metric of TC intensity, the maximum surface wind (MSW), is increasingly insufficient to convey the information necessary for decision makers. Meanwhile, the associated TC Central Pressure or Minimum Sea Level Pressure (henceforth MSLP) is likely determined by the structure of the wind field, the latitude of the storm centre in a given basin, and the pressure of the surrounding environment. That being said, the organization of this short report seeks to identify cross-cutting issues associated with the keynote topic, which is to highlight recent work in two related areas of tropical cyclone (TC) research: wind structure and wind-pressure relationships (WPR).

Datasets and Observing Methods

Since IWTC-VI a number of datasets have become more readily available for studying tropical cyclone structure including historical QuikSCAT datasets and the stepped frequency microwave radiometer (SFMR). The operational use of QuikSCAT and ASCAT scatterometer has dramatically increased and these datasets often form the basis for tropical cyclone wind structure estimates. The historical record of these datasets have been used to study the factors that determine the TC wind structure and its evolution and as input for tools to estimate tropical cyclone structure. One issue made clear by attendees at the workshop is that while QuikSCAT data was much maligned by its shortcomings when it was available, it has been sorely missed in the current suit of operational products and has lead to a perceived degradation of operational capabilities. Thus the need for more instruments or techniques that can replicate the spatial and temporal coverage of QuikSCAT would be welcomed by the operational and research TC communities.

SFMR wind speed estimate technology, once only available on US NOAA research aircraft, is now available on the more numerous operational aircraft reconnaissance flights in the Atlantic Basin. This is a rich and unique dataset that provides for the first time coincident estimates of the surface wind structures. These data have already been utilized for understanding the relationships between flight-level winds and surface wind structures, which clearly show that the current flight-level-to-surface wind reductions are too simplistic and that boundary layer physics and tropical cyclone structure characteristics can be used to more accurately estimate surface winds from current and past flight-level data. It is expected that this will be an active area of future research.

Satellite methods remain the primary tropical cyclone observing tool and in the last four years new methods to estimate tropical cyclone surface wind structures have been developed. Two were highlighted in this meeting, namely the all-weather tropical cyclone surface winds that utilized the lower frequencies of the AMSR-E instrument to estimate the wind speed structure of

tropical cyclones and the multi-platform tropical cyclone surface wind analysis that combines various satellite measures and analogs to winds to provide an estimate of the surface wind field. Progress has also continued with a new scatterometer being launched by India, plans for a new A-SCAT in the next few years, and continued work on intensity estimation techniques, which were further highlighted in other topics. There was much interest in these being made available to operational centres as soon as possible.

There was also continued interest in the use of parametric wind models as operational tools to aid in the estimation of TC wind structure. Such efforts are currently underway at RSMC La Reunion and other TC warning centres may follow. This discussion also acknowledged that central pressure is a more stable metric for measuring intensity. The estimation of both wind and wind-pressure relationships are covered below.

Observation of Surface Wind

A number of issues were discussed in the context of recently published guidelines on conversions between various wind averaging periods that are in use by the TC warning centres. The discussions revolved around the suitability and representativeness of various averaging periods.

The Harper et al (2010) guidelines for converting between wind averaging periods were received without much enthusiasm and the breakout session discussions indicated that application of the techniques are likely not yet well understood by the TC community. Ironically, one of the criticisms levelled against the new recommendations were that they are dependent on the exposure – a physical reality largely ignored by the community to date. The consensus therefore appeared to be that these conversions were useful for “users”, but individual TC warning centres are likely to take a business-as-usual attitude. Thus the use of these conversions to assist in the exchange of information between centres and in improving the science basis, may not be realizable in the short term. One comment concerning the 0.93 conversion from 1-min to 10-min average peak winds would result in some operational changes in that warnings would be initiated at Dvorak $T=2.5$ instead of $T=3.0$ at the Australian TC warning centres - a point not reflected in the keynote presentation. It is therefore likely that, until more effort and importance is placed (or forced) on surface wind verifications, the TC warning centres will not feel the need to better define and improve the precision of their wind metrics. Meanwhile, the continued misuse of wind metrics will unfortunately maintain the avoidable legacy of unexplained variance in many products, tools and sensor systems. A major roadblock in this regard is the need to recalibrate the Dvorak method using a transparent and objective wind and pressure dataset, which would be acceptable to all TC warning centres. When completed, this would provide a new “level playing field” for the various agencies that would be better aligned with the developing advances in the science.

Evidence was also presented of the spectral makeup of the wind showing that 10-min and 3-sec averaged samples taken at random are expected to have less variance than, say, an equivalent 1-min averaged wind sample. In addition, the response/impacts of different wind speed metrics on a range of infrastructure elements was highlighted, showing that the shorter period gusts (e.g. 3-sec) are the principal cause of TC wind-induced damage, while storm surge is sensitive to the longer period (mean) forcing well estimated by a 10-min average. This was complemented by a study that utilized the wind field of a modelled TC and examined the representativeness of the sampled wind field using a 1-min and 10-min average wind. Findings of this study, currently in review, suggest that with current aircraft reconnaissance the peak 1-min wind is under-represented on the order of 10-15% while peak 10-min averages were under represented by ~ 2-3%. Despite this and similar evidence there was little consensus amongst attendees about which wind averaging strategies are likely best.

Wind-Pressure Relationships (WPRs)

In the past four years aircraft-based central pressure, coincident best track intensities and environmental and structural characteristics derived from numerical analyses were used to investigate the relationship between central pressure and maximum winds in tropical cyclones. These studies found that much of the observed variation could be explained by using additional

operational available data sets that provide the latitude, translation speed, environmental pressure and TC size. These methods were presented to the workshop and while they were generally well received, no consensus was arrived upon as to whether these methods should be employed or tested at the various warning centres. A consensus was however developed that more work was needed in this area and that better observations are ultimately needed to examine other important factors, particularly the radius of maximum wind, which plays a rather important role in WPRs, and also the radius to gales - another important forecast parameter and one which is quite sensitive to the assumed wind averaging period.

There was considerable discussion that WPRs could be used in combination with parametric TC models to reconcile the differences in existing observational datasets. It was thought that the improved WPRs could be used along with current estimates of intensity and TC location/translation to potentially fill in the gaps in the surface wind observations and provide additional and yet consistent estimates to TC wind structure. Some agreed that this should be pursued by the research community

Highlights of this keynote topic:

- SFMR surface wind estimates are improving our understanding of the structure of TC surface wind fields as they relate to flight-level wind fields.
- The need for observations of the wind fields associated with TCs was emphasized by the loss of the long-maligned, yet now appreciated QuikSCAT data.
- New conversions to account for differences between wind averaging periods were introduced and justified.
- Issues (representativeness, and stability) about the justification of peak 1-min wind speed metrics were raised.
- New WPRs were introduced that account for operationally available structural differences and environmental condition.
- The use of parametric models for use in operations was re-emphasized and with improved WPRs, the reduction in remotely sensed surface wind observation capabilities and the advantages of probabilistic wind field products, have become of more interest to the operational community.

Tropical Cyclone Probabilistic Forecasting and Related Product Development Issues & Applications for User Risk Assessment

Gary Foley (Australia) and Chris Landsea (USA)

The topic presentation reviewed progress made in respect of the development and availability of probabilistic forecasting products relating to tropical cyclones, particularly since the last international workshop, IWTC-VI (2006). Although both deliver probability forecasts as outputs, the distinction was drawn between statistical-dynamical techniques and ensemble methods from numerical weather prediction (NWP) models. It was also pointed out that ensemble methods vary fundamentally by the data on which they base the ensemble; either on multiple runs from a single model, model runs from an array of single models or model runs from an array of ensemble models.

Examples of forecast guidance products were presented and discussed with application to track prediction, intensity, wind speed distribution, heavy rainfall, storm surge and genesis. While the first part of the presentation looked at products available in most global basins, the second half of the presentation focussed on the experiences of the US National Hurricane Center where probabilistic forecast products are being used both internally to assist with the development of tropical cyclone warning policy and externally through a range of products available on their website.

Organizational aspects related to the promotion of product development from various centres and their assimilation into forecasting was also highlighted. The World Meteorological Organization (WMO), through its association with major scientific projects such as THORPEX; its coordination with other research organizations and government; and its sponsorship of forecast demonstration projects, was cited as taking a strong role in this area. The willingness of major NWP centres to support forecast demonstration projects was also seen as a positive for ongoing product development, as were the efforts being made by the THORPEX Interactive Grand Global Ensemble (TIGGE) to develop the Global Interactive Forecast System (GIFS). Through GIFS, probability products will be made widely and freely available to many countries affected by tropical cyclones.

A number of issues were presented that it was felt were needed to be addressed in order that increasing numbers of relevant tropical cyclone probability products can be successfully integrated into the forecasting and warning process. They concerned the need to ensure that users of probability products understand both their effectiveness and their limitations; that products are verified in a meaningful way; that there is a closer relationship between product developers and forecasters to achieve the best outcomes; and that, as a longer term goal, National Meteorological and Hydrological Services (NMHS) position themselves to further extend, in an ordered and systematic way, probability guidance to disaster reduction agencies and to the community.

Both the plenary and the smaller working group discussions expanded on the issues raised, particularly the current limitations in the understanding of ensemble probability and the difficulties in deriving meaningful verification of these products. Suitable training was seen as a significant issue, particularly when introducing probability products to smaller NMHS. Lively discussion ensued on the introduction of tropical cyclone probability products and concepts to the general community. It was widely agreed that any such moves should be made in consultation with social scientists and communication specialists to ensure the most effective community uptake and understanding possible.

The workshop participants generally recognized the potential of and increasing reliance on probability-based forecast products when dealing with the inherent uncertainty associated with tropical cyclones. It was also interesting to note the frequency that reference by other presenters to probability products arose as the workshop unfolded, suggesting the inevitability of incorporation of a more probabilistic approach to warning for tropical cyclones in the future.

Tropical Cyclone Precipitation (QPE/QPF) and Related Inland Flood Modelling

Yihong Duan and Jinping Liu, China

TC rainfall forecasting techniques are lagging behind those of the track forecast. However, significant progress has been made in recent years due to the advance in remote sensing observations and the improvement of mesoscale models and data assimilation techniques. Until relatively recently, TC rainfall prediction was carried out mainly using empirical speculation and subjective experience on the part of the forecaster. However, advanced techniques for quantitative precipitation estimation (QPE) and quantitative precipitation forecasting (QPF) are currently employed in operational applications in some major forecasting centres, which already have greatly improve the forecasting for LTC-related rainfall. Nevertheless, further improvements in QPF based on a better understanding of TC rainfall mechanisms are still required.

Quantitative precipitation estimation

Radar reflectivities have been widely used to estimate the rainfall rate and distribution of TCs. Rainfall can be calculated from certain algorithms from the relationship between radar reflectivities and observed rainfall, however the algorithms vary with different radar locations and rainfall properties.

Satellite measurements at microwave frequencies are key elements of present and future observing systems. Observation from both passive and active sensors have been widely used to estimate TC precipitation, including the NASA AMPR, altimeter dual-frequency measurements, TMI, SSM/I, AMSR-E, TRMM-PR, CloudSat-CPR, and so on. Available for more than 20 years, passive microwave measurements are very valuable but still suffer from insufficient resolution and poor wind vector retrievals in the rainy conditions encountered in and around tropical cyclones.

The combination of active and passive measurements offers much hope for improving cloud and precipitation retrievals. One example is TRMM Multisatellite Precipitation Analysis (TMPA). The dataset provides a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gauge analyses where feasible, at a spatial resolution of $0.25^\circ \times 0.25^\circ$. At finer scales the TMPA is successful at approximately reproducing the surface observation-based histogram of precipitation, as well as reasonably detecting large daily events.

There are several on-going projects aiming to set up precipitation datasets with a combination of measurements from radar, satellite and raingauge.

Quantitative precipitation forecast

Statistical models are found to be important in providing valuable guidance to forecasters, such R-CLIPER and PHRaM of NHC/USA. The most recent progresses are made by including parametric representations of the shear and topography effects. An analog scheme for TC QPF is being used in CMA, which statistically considered the similarity of TC features and associated environmental fields to history TCs.

Extrapolation based on satellite or radar QPE is heavily relied on in operation for TC precipitation nowcasting. NOAA NESDIS has been producing operational areal Tropical Rainfall Potential (TRaP) forecasts for landfalling tropical cyclones since the early 2000's. The system has been recently been upgraded to eTRaP, by which ensemble prediction of TC precipitation is produced by including different sensors and forecast latency. Example systems based on radar extrapolation including SWIRLS of HKO and the nowcasting system of JMA, which monitors and predicts local rainfall distribution trends within the next couple of hours. The TREC technique is being used in SWIRLS with echo intensity being calibrated dynamically in real time against surface rainfall as measured by a dense network of raingauges in Hong Kong.

Significant progresses have been made during the past four years in numerical weather prediction techniques, including vortex initialization scheme, radar data assimilation technique, PBL and microphysics scheme, air-sea-wave coupling scheme and ensemble technique.

The assimilation of Doppler reflectivity data was found to improve the inland short-range QPF skill, mainly in the first 3-h or 10-h forecast, as from different case studies. Large improvement in precipitation forecasts is found to occur along the path of the inner-core region during the hurricane landfall. Airborne Doppler radar data were also proposed to be important in improving the short-range numerical simulation of hurricane track, intensity changes, as well as rainfall.

Application of the superensemble technique to regional precipitation forecasts has shown the ability to generate more accurate forecasts pinpointing the exact locations and intensities of strong precipitation systems. The superensemble tended toward improving the member model forecasts by reducing the overestimation of light rain and adding a significant rain forecast that most of the member models miss.

Diagnostic indices are also very frequently used by forecasters, such as the turning of winds with height, which implies regions of thermal advection and thus ascent and descent. The anti-cyclonic turning of winds with height is found to be an important indicator for extreme tropical and sub-tropical rainfall by the forecasters in BOM of Australia. Distribution of vorticity, divergence, water vapour transportation, Q-vector, and so on, are some of the diagnostic indices being used by forecasters concerning TC precipitation.

Verification

It is generally accepted that QPFs must first be validated against observations to identify model limitations and biases and possible areas for improvement in the forecasts. Standard QPF validation techniques, such as bias and equitable threat scores (ETSs), can be used to assess some aspects of TC QPFs. A QPF validation scheme specifically designed to objectively evaluate model rainfall forecasts for landfalling TCs was proposed by Marchok et al. in 2007, which consists of pattern matching, mean rain and distribution of rain flux, and extreme rain amounts.

Recommendations

To meet the needs of TC-related disaster mitigation, observational and forecasting techniques relating to heavy rainfall caused by LTCs still require urgent improvements and significant development.

Heavy rainfall and flooding caused by LTCs are recognized as extreme weather events, but the science behind the behaviours of LTC rainfall is not currently understood to a great enough extent. Track prediction is still the most important to improve the forecast ability of extreme precipitation event.

There is a need to set up a database to study climate variation characteristics of rainfall at different time scales (hourly, daily, etc), to determine if there are multi-decadal changes or anthropogenic influences.

For numerical modelling, differences in the resolution and microphysical parameterization likely cause distinct QPFs. Further improvements in microphysical, boundary layer parameterization, and initial moisture field are required to obtain successful TC QPFs. Development in verification techniques is important for model improvement.

For data assimilation, more realistic microphysics scheme needs to be included in the radar data assimilation.

One of the major reasons for the slow pace of improvement in TC QPFs may be deficiencies in the collection and assimilation of real-time inner core data into numerical weather prediction models. Due to cloud and rain effect, satellite retrieved products usually have large uncertainties under cloudy and precipitating areas, thus most of the cloudy and rain-affected data are rejected during the quality control procedures in data assimilation.

There is a need to improve the pass-over of new QPE/QPF techniques to more WMO Members and to provide more rainfall data to more WMO Members. Related training activity is in urgent need.

WORKSHOP TOPICS

Topic 1 - Tropical Cyclone Structure and Intensity Change

Robert Rogers, USA

Introduction

During the IWTC-VII plenary session on Tropical Cyclone (TC) Structure and Intensity Change, rapporteurs presented recent progress on a variety of fronts, including environmental impacts, inner-core impacts, air-sea impacts, observational capabilities, operational advances, and subtropical and hybrid systems. In this Topic Chair summary, additional issues that arose during the discussions in the plenary session as well as the afternoon break-out session are presented.

There were several common subjects that arose during these discussions. These include concern about the demise of the QuikScat instrument; the potential utility of unmanned aerial systems (UASs); the need for continued research on factors important in tropical cyclone intensity change across multiple scales (environmental, oceanic, inner-core); the importance of predictability research; the expansion of training and sharing of forecasting techniques across regions, as well as the encouragement of forecaster/researcher interaction; continued development of coupled numerical models and the continued development of ensemble and consensus forecasting techniques using these models; and the need for the development of verification techniques for numerical model structure and intensity forecasts, especially for ensemble products. Specific areas of discussion and considerations for future efforts are summarized below. These are divided into four main sections: physical process research, observational capabilities, operational advances and needs, and transition of research to operations.

Physical process research

(a) *Environmental impacts*

The plenary session and subsequent discussions relating to physical process research were stratified based on spatial/temporal scales, with the first presentation focusing on environmental factors important in TC structure and intensity change. The dominant environmental factors that impact TC structure and intensity are well-known, i.e., vertical shear of the environmental wind, mid- and low-level humidity variations, sea-surface temperature (SST) and ocean heat content (OHC) variations, and outflow-layer interactions with the environment. Much of the research that has occurred on this topic since the last IWTC has focused on refining our knowledge of these impacts through a combination of case studies, compositing studies, and modelling investigations. Recent observational and modelling research on the impacts of vertical shear has identified a spectrum of shear values and TC intensities that permit continued intensification, contrary to conventional wisdom. While it is generally accepted that dry air in the middle and lower troposphere is detrimental to TC intensification, there is disagreement on the role of the Saharan Air Layer in the Atlantic basin on TC structure and intensity change. Continued research to further clarify the role of these processes seems warranted.

One subset of TC intensification, rapid intensification (RI), has received considerable attention due to its potential for significant impacts in landfalling scenarios. Many of the factors important in RI are similar to those that are known to be favourable for intensification generally (e.g., low wind shear, warm sea surface temperature and high ocean heat content). Composite studies of the large-scale environment associated with RI show that the environment for systems undergoing RI is not significantly different from the environment for systems intensifying more slowly. This suggests that what distinguishes a TC that undergoes RI from one that intensifies more slowly is not strongly dependent on the environment but may also depend on some other characteristic, such as the structure of the inner core.

Much of the discussion pertaining to TC structure emphasized the need to improve the understanding of the environmental processes that govern TC precipitation. This need is especially acute for regions significantly impacted by TC rainfall, e.g., in the west Pacific basin. The role of environmental humidity, low-level jets, monsoonal flow, and topography on determining TC rainfall have all been emphasized as important parameters for targeted future research. TC size and radial wind profiles are other significant parameters, especially with regard to storm surge forecasts that are reliant on the total (rather than just the peak) wind field. Forecasting tools for TC wind structure have recently been developed based on climatological and environmental factors (translational speed, intensity, latitude) and persistence (i.e. initial condition), but the lack of appropriate data for validation hampers progress on this front.

(b) Inner-core impacts

Much of the work on inner-core impacts has focused on convection and its role in TC intensification, including RI. Having said that, though, it is recognized that the structure of the inner-core within which convection occurs is crucial to determine the impact of that convection on the vortex. This recognition is reflected in the recent research that has considered the impact of static stability, eyewall slope, and tangential wind profiles on vortex heating efficiency. Additionally, barotropic instability and eyewall mesovortices that can arise along intense radial gradients of momentum, temperature, and moisture in the vicinity of the eyewall can also play a role in modulating both TC inner-core structure and intensity.

In terms of convection itself, convective bursts, and the subset of bursts that are co-located with high vorticity (termed vortical hot towers, VHTs), have been shown to be important in the intensification of simulated and observed TCs. The increase in inner-core convective coverage during intensification, and RI in particular, has also been shown from a mass flux perspective, and it is a large reason why several break-out sessions emphasized the importance of inner-core lightning as a proxy for convective activity and intensification. Clearly further research is needed on the exact role of convection, its structure and distribution, and the inner-core structure within which it occurs in governing TC intensification and RI. Research into the importance of inner-core processes in RI will complement well the research on environmental impacts mentioned above.

Recent studies have come to contradictory conclusions as to the important physical processes for supporting superintensity. One modelling study emphasizes area-integrated latent heat fluxes as being the important driver of storm intensity, also finding that surface fluxes radially far from the eyewall have an important contribution to the storm's θ_e budget. Another set of observational studies showed eye/eyewall mixing from mesovortices allowed a TC to maintain an intensity significantly above the theoretically predicted maximum potential intensity on three separate days as it crossed the cold wake left behind by a previous TC.

Modelling and observational studies of TC inner-core structure have advanced the understanding of eye and eyewall structure and dynamics and TC boundary layer structure. Eye formation has been attributed to detrainment of ascending air in the eyewall leading to subsidence warming. Other studies have found that intense mesoscale convective systems away from the vortex centre, expected when there is vertical shear, can lead to multiple regions of inner-core subsidence which can disrupt the eye formation process. However, other research has found cases where shear-induced subsidence near the core appeared to support a short-lived, hurricane-strength vortex. This apparent discrepancy highlights the uncertainty regarding shear impacts on vortex structure discussed above that should be further pursued.

Although the occurrence and behaviour of eyewall replacement cycles is well documented, the formation mechanisms are still debated with widely diverse explanations available. One study found that the secondary eyewall formed when there was an enhanced region of outer vorticity called a beta skirt around the tropical cyclone. The formation of moat regions, which are present between the inner and the outer eyewall, may be associated with rapid filamentation zones where the flow was dominated by strain. In these regions, the development of deep moist convection could be significantly distorted and even suppressed. Other work has suggested that the moat was mainly controlled by the subsidence associated with the overturning flow from eyewall

convection and downdraft from the anvil stratiform precipitation outside of the eyewall. High-resolution numerical model simulations have attained greater success in recent years at reproducing these eyewall replacement cycles; these simulations should serve as a foundation for resolving these questions.

Airborne Doppler radar measurements have been analyzed to document the slope of the radius of maximum winds, finding that the slope varies nearly linearly with radius so that a greater slope outward of the radius of maximum wind occurred for larger radii. Also, there was almost no relationship between intensity and radius of maximum wind. Another study using airborne radar has documented the structure of turbulent kinetic energy (TKE), finding that TKE is peaked within the TC boundary layer and along the eyewall. These studies have been facilitated by the recent capability to effectively and efficiently process airborne radar data in a fraction of the time that was previously required, providing a wealth of inner-core kinematic measurements that can and should be mined for years to come.

(c) *Air-sea impacts*

In the past fifteen years, there has been significant progress made in understanding the basic oceanic and atmospheric processes that occur during TC passage. The relevant physical processes span a multitude of domains and spatial/temporal scales: from the background oceanic state (temperature, current, and salinity profiles); to the oceanic thermal and current response to TC forcing; to processes at the air-sea interface such as the surface wave field, surface winds, surface drag coefficient, wind-wave coupling, enthalpy fluxes, and sea spray. There is a need to isolate fundamental physical processes involved in the interactions through detailed process studies using experimental, empirical, theoretical, and numerical approaches.

It is generally agreed that, in most scenarios, a measure of the integrated energy from the ocean surface and subsurface (such as ocean heat content) is a more useful measure of the air-sea response to TC forcing than sea-surface temperature alone. The challenge in using this information to improve forecasts of TC structure and intensity is properly representing the temperature, salinity, and current profiles in the initial conditions of numerical models, and then accurately representing the feedback between the atmosphere, ocean, and wave interface in a high-wind environment. The first challenge has its roots in the limited observations of ocean structure, along with limited capabilities to assimilate this data. For this reason many of the breakout groups emphasized the need to increase ocean observational capabilities and improve the assimilation of this data in coupled numerical models. The second challenge also is grounded in the limited observations of air-sea momentum and enthalpy fluxes in a high-wind environment. Recent laboratory work and field experiments such as CBLAST and ITOP have yielded useful data that have enabled a better specification of momentum and enthalpy exchange coefficients as a function of wind speed, as well as the dependence of drag coefficients on properties of the wave field. More work is needed on this, however, as well as on assessing the possible role of sea spray on modulating enthalpy and momentum fluxes. Other work using CBLAST data has examined the turbulent structure of the TC boundary layer using flight-level data in outer radii (i.e., between rainbands) and providing estimates of dissipative heating. This work should continue to improve the parameterization of air-sea momentum and enthalpy fluxes and dissipative heating in coupled numerical models. This was another topic that was emphasized by the discussion groups.

(d) *Subtropical and hybrid systems*

Since the IWTC in 2006, there has appeared increasing documentation and evidence in the refereed literature of extratropical processes occurring in association with named tropical cyclones. Such cases are typically classified as either subtropical (STC) or hybrid cyclones. Tropical cyclones whose development involves some baroclinic processes are more common than what may be otherwise assumed. For example, studies from the 1990's have shown that baroclinic processes were a factor in the development of almost 50% of all North Atlantic TCs.

Most of the research on STC and hybrid cyclones has looked at the environmental conditions associated with their development and the pathways that they follow to development. Environmental conditions include sea-surface temperature values less than the typical 26°C

needed for TC formation; an interaction between a baroclinic disturbance, such as an upper-level trough or cut-off low, and the preexisting subtropical or tropical system; and a low-level shallow warm core at some stage of the storm's life cycle. Pathways to development include non-baroclinic (40% in the North Atlantic), low-level baroclinic (13%), transient trough interaction (16%), trough induced (3%), weak tropical transition (13%) and strong tropical transition (16%). These percentages differ substantially for different basins.

Warning and response processes from operational centres are well-established for tropical cyclones, but they are not as centralized for non-tropical cyclones, despite the potential for impacts from them that can be as significant, in terms of high winds, heavy rains, and storm surge, as tropical cyclones. The black/white dichotomy of the warning/response process stands in contrast to the shade-of-gray continuum of cyclone types and their ability to change types. There is presently no single set of objective criteria that, if applied, would irrefutably support a forecaster's analysis of cyclone type (subtropical, hybrid or tropical). For this reason one of the common suggestions from the plenary and discussion sections was to continue the research of TC development pathways, and, in particular, to develop a "universal" cyclone classification methodology based on the latest research, operational forecasting capabilities, and real-time data availability. Once an accepted definition of subtropical cyclones is established, then an accepted, and maintained, database of STCs would allow for their analysis and diagnosis.

Enhanced communication of subtropical and hybrid system impacts to emergency managers is also necessary. In the absence of a more appropriate warning system, it may be preferable to continue to use TC warning systems for subtropical/hybrid systems.

Observational capabilities

Reliable observations are of course a crucial part of any forecasting and research effort for TC structure and intensity change. The vast majority of the ocean basins impacted by TCs rely on satellite data only for their observations. Fortunately, over the past few decades coverage by satellites has improved dramatically. Geostationary visible, infrared, and near-infrared imagers cover the entire globe, as do low-earth orbit (LEO) satellites carrying microwave imagers. The key advantage of geostationary imagers is the temporal continuity. Microwave imagers have long been recognized for their ability to sample TC structures not accessible to visible and infrared imagers due to cloud cover, but their temporal coverage is limited. With a multitude of microwave imagers having been launched since 2006, however, LEO satellites and their accompanying microwave imagers provide revisit times on the order of several hours now, as opposed to once or twice a day in earlier years.

Surface winds are estimated primarily in two ways: aircraft reconnaissance and satellite-based scatterometry. The use of the stepped-frequency microwave radiometer (SFMR), now placed on all U.S. Air Force TC reconnaissance aircraft, has provided a much better depiction of surface winds in the Atlantic basin, though errors in the estimate of peak surface wind remain due to sampling limitations. Recent research attempting to quantify this uncertainty has yielded promising results; it is recommended that this research continue. Elsewhere in the world, the primary tool for estimating surface winds is satellite-based scatterometry, with QuikScat having served as the primary tool for this effort. All operational centres have expressed concern over the loss of QuikScat in November 2009. The ASCAT scatterometer has filled some of the gap, but it has only 60% of the coverage of QuikScat. In addition, the optimum use of ASCAT remains uncertain. A key recommendation that arose from nearly all of the discussion groups was the need for a replacement capability, and for the WMO to strongly encourage those nations with the resources to fast-track such a replacement, or at least to ensure that planned timelines for launches are upheld.

Many products have been developed for structure and intensity estimation based on satellite observations. Prominent examples include the CIMSS Advanced Dvorak Technique (ADT), supplemented with microwave data using the Automated Rotational Center Hurricane Eye Retrieval (ARCHER), and the SATellite CONsensus (SATCON) algorithm, which combines estimates from three sources: the CIMSS ADT and the CIMSS and CIRA AMSU algorithms.

SATCON provides the TC forecaster with the ability to quickly reconcile differences in objective intensity methods, thus decreasing the amount of time spent on the analysis of current intensity. As was recognized by several groups, there is a crucial need to conduct basin-specific Dvorak validation.

A structural algorithm has also been developed that can predict eyewall replacement cycles with reasonable accuracy. This scheme uses geostationary satellite data plus information on the surroundings of the storm from the Statistical Hurricane Intensity Prediction Scheme to provide forecasters with a probability of imminent secondary eyewall formation. This provides an additional tool for evaluating tropical cyclone structure and its role on future intensity. Given the prominent role of satellite data for operational centres worldwide, research into this and similar types of techniques should continue.

Because of the resource limitations that preclude greater use of manned aircraft, one common recommendation from the discussion groups was to pursue the use of unmanned aircraft (though some unmanned systems can be quite expensive as well). Recent successes using the Aerocliipper, Aerosonde, and Global Hawk unmanned aerial systems indicate the potential for a bright future using these types of platforms. However, as is the case with any new observational platform, it is crucial that a robust method for assessing the potential impacts of a proposed observing system be employed prior to deploying the system. This can, and should, be accomplished through the careful use of observing system simulation experiments (OSSEs). Observing system experiments (OSEs) should also be performed on existing data sources to perform such tasks as identifying optimal mission profiles and sampling strategies.

Operational advances and needs

As mentioned above, the primary tool for analyzing TC structure in the majority of the TC forecasting centres is satellite data. Earlier techniques used geostationary visible and infrared imagery to infer wind radii, but this suffered from considerable uncertainty. Low-level atmospheric motion vectors have helped in this regard, but they are often obscured by middle- and high-level cloudiness to be effective. Microwave imagers have provided significant additions to the capability for structure and intensity analysis, in particular with such processes as eye formation and eyewall replacement cycles. The Advanced Microwave Sounding Unit (AMSU) has provided direct objective measurement of the thermal structure of tropical cyclones. Scatterometers have been an invaluable tool for the analysis of the surface wind field, in particular the outer wind field, but, as mentioned above, the loss of QuikScat in November 2009 has significantly degraded the ability to assess TC wind structure. The loss of this data and the need to replace it was identified by nearly all discussion groups as a key recommendation.

To address the variable temporal gaps in microwave coverage, CIMSS has developed a family of algorithms called Morphed Integrated Microwave Imagery at the Cooperative Institute for Meteorological Satellite Studies (MIMIC) to create synthetic "morphed" images that use the observed imagery to fill in the time gaps and present time-continuous animations of tropical cyclones and their environment. These images provide 15-minute resolution animations of microwave imagery in the ice-scattering range (MIMIC-TC) and the TC-retrieved precipitation field overlain on geostationary infrared imagery (MIMIC-IR). These tools allow forecasters and analysts to use microwave imagery to follow trends in a tropical cyclone's structure more efficiently and effectively, which can result in higher-confidence short-term intensity forecasts.

As mentioned above, the analysis of TC intensity, primarily using satellite data, includes the Dvorak technique, Automated Dvorak technique (ADT), and SATellite CONsensus (SATCON) methods. Despite the increasing reliability of these automated intensity estimation algorithms, there are still uncertainties and basin-to-basin variability in relating satellite-derived patterns with intensity estimates. For this reason continued efforts toward validating the Dvorak technique using aircraft data in multiple basins (where possible) was a common recommendation from the plenary and discussion groups.

For forecasting of TC structure, much less guidance is available compared with TC track and intensity. As a result the forecast process is very subjective, with little time to prepare an adequate forecast and little opportunity to validate the forecasts. These factors have tended to establish structure as the “poor cousin” of track and intensity, despite the critical dependence of storm surge on structure and the clear need to improve the quality of both observing systems and guidance in this area. One technique that has been developed, mentioned previously, uses a combination of persistence and climatological values modified by factors known to influence size, such as latitude and translational speed. Continued work in this area is clearly warranted.

Intensity forecasting continues to rely on a combination of statistical/dynamical and dynamical models. Statistical/dynamical models, the most well-known of which is the Statistical Hurricane Intensity Prediction Scheme (SHIPS), continue to show the greatest skill in forecasting intensity change. A scheme for predicting RI based on SHIPS predictors has also been developed that shows reasonable skill, especially compared with fully dynamical models. The success of the SHIPS algorithm, and its cousin for the western Pacific basin, STIPS, has prompted a universal request from the global TC forecasting community to adapt this algorithm to all basins.

While fully dynamical models still trail statistical/dynamical models in intensity prediction skill, some improvement has occurred over the past several years. As resolution continues to increase, physical parameterizations continue to be refined, and air-sea coupling is improved and implemented in global models, it is expected that these numerical models will approach and perhaps exceed the skill of the statistically-based models. One key area that needs continued development, however, is the assimilation of environmental and inner-core data (both satellite- and aircraft-based) into these models. Recent efforts at assimilating inner-core data, including flight-level, dropsonde, SFMR, and airborne Doppler radar, through variational and ensemble-based techniques have shown some promise, but more development and testing is needed and is clearly warranted.

Similar to TC track prediction, a consensus of intensity prediction algorithms, both statistical and dynamical, shows considerable promise, as do ensemble approaches using dynamical models. Continued development of these consensus and ensemble techniques has been advanced as an important goal by several of the discussion groups. A key step in this process is the development of robust diagnostic and verification techniques that go beyond simple metrics of position and intensity and incorporate structural information of the TC. This applies both for ensemble techniques as well as deterministic approaches.

To ensure a broad dissemination of new forecasting techniques around the world, all discussion groups recommended an expansion of training and sharing of forecasting techniques across regions. In addition, all groups recommended a concerted effort to encourage greater forecaster/researcher interactions to facilitate better interaction between the two communities. This could occur through a programme similar to the visiting scientist programme currently being employed by the U.S. National Hurricane Center.

Transition of research to operations

As indicated above, a great deal of research on advancing the understanding of TC structure and intensity change, the ability to observe these parameters, and their representation in numerical models, has occurred over the past several years. Clear paths to follow in these research efforts have also been identified. A crucial question to ask, however, is how best to ensure that these research efforts are effectively translated into advancements in operational forecasting techniques.

One key step in this process is identifying the existing research efforts and mapping these research efforts onto current operational needs. An interagency committee in the U.S. TC community has undertaken an effort to do just that. A list of operational needs has been created by the U.S. National Hurricane Center and Joint Typhoon Warning Center. This list consists of fourteen items, ranging from improved guidance for TC intensity change; to statistically-based real-time guidance for track, intensity, and precipitation; to improved utility of microwave satellite and

radar data in TC analyses, among other areas. A separate table encompassing all areas of TC research, including basic and applied research, has also been created. All TC-related research efforts being undertaken within the U.S. have been mapped onto this research table, which has then been mapped onto the list of operational needs. With such a mapping, areas of sufficient research efforts, as well as gaps in research efforts, become clear. This effort can be used to track TC research efforts in an aggregate sense, and point to areas where greater research emphasis can be focused to provide a greater benefit to operational forecasting. It is recommended that those nations with active TC research programmes engage in a similar exercise. This effort, combined with such programmes as the U.S. Joint Hurricane Testbed, Hurricane Forecast Improvement Project, and visiting scientist programme, holds the promise to accelerate improvements in the forecasting of TC structure and intensity change.

Topic 2 - Tropical Cyclone Formation and Extratropical Transition

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Introduction

During the plenary session on Tropical Cyclone Formation and Extratropical Transition, rapporteurs presented summaries on progress in research and operations related to the theory of tropical cyclone formation, forecasting tropical cyclone formation, recent field programmes on tropical cyclone formation and extratropical transition, and forecasting extratropical transition. In this Topic Chair Summary, the plenary sessions are summarized in conjunction with additional issues that were raised in discussion and within individual discussion groups.

In IWTC-VI, the process of tropical cyclone formation was divided into two sections devoted to internal and external influences on formation. Recommendation from IWTC-VI pointed to the need for an increase in understanding of the relative roles of these influences. Since IWTC-VI, several major field campaigns have been designed and implemented with specific objectives related to an increase in understanding of scale interactions during the formation process. Presentation and discussion during IWTC-VII examined the processes associated with tropical cyclone formation and recommendations stress the continued need for increased observations and understanding of relevant processes. The ability to forecast tropical cyclone formation was discussed in relation to identification of a process by which forecasts could be constructed in a consistent manner. The synergy of factors that represent physical processes as forecast guidance products is critical to the forecast process. Furthermore, relevant factors vary based on the target forecast time interval.

Presentations and discussions of extratropical transition focused on themes that are similar to those examined with respect to tropical cyclone formation. Interactions among processes that vary over a wide range of space and time scales were highlighted as being critical to increased understanding and forecast skill of high-impact weather during extratropical transition events. The influence of extratropical transition over regions directly impacted by an event was examined in addition to downstream development that may influence near-hemispheric flow characteristics. Recommendations build on recent observation campaigns to allow for identification of factors that could increase predictability of the impacts that result from the extratropical transition of a tropical cyclone.

Tropical Cyclone Formation: Theory and Idealized Modelling

The theory of tropical cyclone formation continues to be discussed in relation to paradigms associated with the mesoscale organization of pre-existing disturbances. The pre-existing disturbance may originate from factors related to a variety of tropical circulations that often range from the cloud cluster to synoptic scale. Research efforts continue to focus on questions such as why so few pre-existing disturbances develop into tropical cyclones, what is fundamentally different about disturbances that do develop, can these differences be identified and on what time scale could differences be defined?

At IWTC-VII, it was stressed that the multi-stage aspect to tropical cyclone formation continues to be investigated. The initial stage is characterized by an aggregation process that moistens the mid-troposphere and leads to enhanced convection via a radiative-convective feedback mechanism. The second phase results in contraction of the pre-existing circulation with embedded convection. Within the organization stage, the “top-down” and “bottom-up” paradigms of mesoscale organization continue to be studied. Since IWTC-VI, the “bottom-up” way of thinking has been placed into the marsupial paradigm that encompasses the multi-scale nature of tropical cyclone formation from synoptic to cloud scales into a more unified framework. In this context, the steady growth of the convective and vorticity signature of the pre-existing disturbance proceeds in an environment that is protected from detrimental effects. The intensification of the pre-existing disturbance to tropical cyclone is defined as an evolution via a transfer of energy among scales.

The fundamental process by which the multi-stage aspect of formation is seen to be more of a unified view of formation was presented in term of deep convection that develops in an environment of vertical vorticity and amplifies the local vorticity via stretching. Additionally, the vorticity remnant is sustained beyond the lifetime of the originating deep convection. Throughout the process, vortical remnants combine and undergo additional intensification via continued convective development, in a manner that corresponds to an upscale cascade of energy. The amplification and combination of vorticity represents an increase in the relative circulation over a contained area that encompasses the deep convection. This unified view of tropical cyclone formation is put forward in contrast to theories related to finite amplitude disturbances and the role of a “trigger” mechanism that contributes to the evolution of a tropical wave to a tropical depression. In this view, the process of formation is often described as undergoing stages of development. The initial stage is one in which deep convection forms due to low-level moisture in a region of mean ascent due to decreased radiative cooling. There is some similarity between stage one and the aggregation process defined in the unified view.

Based on the review of recent research and discussion at the IWTC-VII, it is clear that future research on the theory and idealized modelling of tropical cyclone formation should be guided by several remaining over-arching questions on key physical mechanisms. A priority should be to examine the pathways by which a pre-existing disturbance evolves to a tropical cyclone. Furthermore, factors associated with the pathways to organization that are common or unique to each ocean basin should be identified.

Field Experiment Formation Studies

As defined above with respect to the theory of tropical cyclone formation, there is a strong need for increased observations of processes that lead to the intensification of a pre-existing disturbance to a tropical cyclone. During the period since IWTC-VI, several major field campaigns have been undertaken with specific objectives related to tropical cyclone formation. During 2008, the combined THORPEX Pacific Asian Regional Campaign (T-PARC) and Tropical Cyclone Structure-2008 (TCS-08) programme was conducted over the western North Pacific. The PRE-Depression Investigation of Cloud systems in the Tropics (PREDICT) programme over the tropical North Atlantic. In both of these projects, the experiment design was set to address many of the factors discussed with respect to models of tropical cyclone formation that were summarized in the previous section. Specifically, aircraft missions were designed to examine processes associated with relative contributions of low-level vorticity in deep convective towers versus mid-level circulations embedded in stratiform regions of mature mesoscale convective systems. These objectives address the predictability associated with the location, timing, and rate of tropical cyclone formation over the western North Pacific and the tropical North Atlantic.

The case of the formation of TY Nuri (2008) over the western North Pacific during TCS-08 was presented to highlight the utility of aircraft observations, aircraft-based Doppler radar data, and satellite data for examination of processes related to the development of a pre-cursor easterly wave that tracked across the western North Pacific over a period of days prior to intensifying to a tropical depression. Initial analyses have emphasized various aspects of the formation process such as vorticity dynamics, mid-level moisture, vertical profiles of latent heat release, environmental interactions, and specification of a region protected from environmental interactions detrimental to continuation of deep convection.

Another programme with a focus on tropical cyclone formation was the African Monsoon Multidisciplinary Analysis (AMMA) project and the U.S. component N-AMMA. Results were presented that highlighted the continued uncertainty in the role of the Saharan Air Layer (SAL) with respect to development of African Easterly waves (AEWs) and the amount of dust that actually penetrates into a convective region of an AEW. Additional cases for examination of factors related to formation of tropical cyclones over the tropical North Atlantic will be examined as part of the PREDICT programme.

Although initial analyses of cases from various field programmes related to tropical cyclone formation have led to varied results, the value of *in situ* measurements in many cases over multiple ocean basins has been made clear. The continued analysis of data from the many field programmes holds promise for increased understanding and forecast skill related to tropical cyclone formation. Continued comprehensive and detailed analysis of all collected data was strongly encouraged and recommended throughout the IWTC-VII.

Tropical Cyclone Formation Forecasting

The presentation and discussion of tropical cyclone formation forecasting concentrated on the process key to construction of forecasts based on physical processes related to the target time interval of the forecast. At long time ranges (e.g., monthly), formation forecast guidance is based upon statistical relationships, slowly-varying large-scale conditions [i.e., El Niño-Southern Oscillation (ENSO), Madden-Julian Oscillation (MJO)], and ensemble prediction systems. It was noted that while conditions that impact tropical cyclone formation at time scales of a month or longer, there are significant relationships to factors that affect shorter-range forecasts. At the medium range (e.g., 5-14 days), formation forecast guidance depends on factors such as short-term fluctuations in the MJO and convectively-coupled, equatorially-trapped waves. Over the medium range, the importance of numerical forecast guidance often increases over guidance based on statistical relationships. Furthermore, ensemble prediction systems (EPSs) become important for assessing and communicating uncertainty in forecasts of tropical cyclone formation. At short ranges (e.g., 0-5 days), tropical cyclone formation forecasts often depend on accurate assessment of the current conditions then utilizing numerical guidance to examine possible influences on the current conditions that will either inhibit or enhance the likelihood of the formation of a tropical cyclone. In both presentation and discussion, the continued value of EPS guidance over the shorter-range time intervals was stressed.

For all applicable forecast time intervals, there is a continued need for a structured process that will guide the construction of a skilful forecast of tropical cyclone formation. Key aspects of such a process would combine subjectively-defined indicators of tropical cyclone formation with objective numerical guidance. However, this requires comprehensive and current documentation of the known skill of operational numerical forecast systems with respect to tropical cyclone formation and environmental factors that relate to formation. Therefore, it is highly recommended that the research and operational forecast communities collaborate on systematic verification of tropical cyclone formation forecasts.

The understanding of the role(s) of large-scale factors in tropical cyclone formation and increased skill in guidance supplied from operational numerical models has contributed to some increase in skill of tropical cyclone formation forecasts. While operational global models do not typically have horizontal resolution capable of correct representation of mesoscale factors in formation, the increased skill with respect to large-scale factors that impact formation allows correct identification of formation cases at lead times that may extend beyond five days. While there are instances of extremely accurate extended-range forecasts of formation by operational numerical forecast models, it was noticed that there remain a significant number of instances in which formation is not well forecast. These missed forecasts are often associated with rapid formation, small circulations, hybrid circulations, or cases in which mesoscale factors dominate.

Tropical cyclone formation forecasts at extended ranges (i.e., 1-2 weeks) are becoming increasingly available and reliable. It is clear that planners for a wide variety of maritime activities have a demand for extended range forecasts of tropical cyclone formation. The increase in skill of predictions at extended ranges is due to increased understanding of synoptic-scale tropical wave activity that contributes to organization of convection. While initial forecast techniques at extended ranges were primarily statistical, numerical forecasts at extended ranges are now routine and exhibiting increased skill. However, a cost of increased probability of detection associated with tropical cyclone formation forecasts may be an increased false alarm rate.

The dependence of skillful formation forecasts on identification of dominant pathways to formation was discussed and led to a high-priority recommendation for the research community. Also, threshold parameter by which a definition of tropical cyclone formation could be defined for the purpose of verification was discussed. The proposed parameter would be based on the distribution of deep convection as represented in satellite. Finally, documented cases in which operational global numerical models successfully predict tropical cyclone formation days in advance were discussed. These cases should be examined to determine characteristics associated with these successful forecasts and compare with unsuccessful forecasts. Finally, many of the above factors and recommendations could be examined with respect to an examination of the limits of predictability with respect to tropical cyclone formation.

Extratropical Transition Research and Field Experiments

The presentation and discussion on research and field programmes associated with the extratropical transition of a tropical cyclone concentrated on structural changes associated with the change from tropical to extratropical cyclone and on the impact of the poleward-moving tropical cyclone on the midlatitude circulation into which it is moving. While the extratropical transition of a tropical cyclone is often associated with severe local weather conditions, the impact of an extratropical transition on the midlatitude flow has been shown to be directly linked to high-impact weather events far downstream of the original extratropical transition event. Therefore, there is a strong requirement to assess the extent of the sensitivity to various physical mechanisms during extratropical transition. These mechanisms include the impact of sensible and latent heat fluxes, precipitation distribution, frontogenesis, and baroclinic energy conversions. Finally, the character of the downstream response to extratropical transition should be placed in the framework of the mean environmental conditions (i.e., baroclinic wave guides) across the entire ocean basin in which the extratropical transition is occurring.

A key point of discussion related to the extratropical transition of a tropical cyclone is the lack of systematic observation programmes under which key data with respect to a rapidly-changing environment could be gathered. While current tropical cyclone observation programmes target pre-landfall storms at peak tropical cyclone intensity, it would be worthwhile to continue observations to increase the predictability of the extratropical transition and downstream impacts. Additionally, there was noted concern related to the lack of models under which objective assessment of storm intensity could be identified throughout the extratropical transition process. Key observations would allow validation of intensity against satellite-based estimates that could then lead to a type of pattern recognition technique for estimating storm intensity.

Following IWTC-VI, the THORPEX Pacific Asian Regional Campaign (T-PARC) was conducted to examine the lifecycle of a tropical cyclone over the western North Pacific. During the field phase of T-PARC, several tropical disturbances moved poleward to undergo a transition into the midlatitudes. The character of these disturbances included a weak circulation associated with widespread deep convection, a midlevel tropical cyclone, a typhoon, and a super typhoon. The extratropical transition of TY Sinlaku during T-PARC was presented as an example of the variability associated with the process of extratropical transition. While TY Sinlaku appeared to be entering the transformation stage from a highly sheared, decaying tropical cyclone to extratropical cyclone, a period of rapid re-intensification as a tropical cyclone occurred. Analysis of aircraft data obtained during the period of re-intensification identified the convective structures that contributed to the re-emergence of a vertically aligned convective system. These observations will provide a basis for examining the process of extratropical transition and the impact of the tropical circulations on the region of the midlatitudes into which they are moving.

A key recommendation to be carried forth from IWTC-VII is the need for increased understanding of factors that explain the variability associated with extratropical transition events and their impact on local and downstream high-impact weather. A critical component is the systematic quantification of the impact of extratropical transition on operational numerical prediction systems. Other factors relate to the definition of predictability as it relates to extratropical transition.

Forecasting Extratropical Transition

The presentation and discussions related to the forecasting of extratropical transition concentrated on factors common among ocean basins, direct and indirect impacts, and conveying uncertainty in forecasts related to weather associated with the extratropical transition of a tropical cyclone. During the poleward movement of a tropical cyclone, tropical cyclone force winds, rainfall, and ocean waves are often maintained far into the midlatitudes. Since official forecasts of the tropical cyclone may have been terminated, it is often difficult to convey the continued threat of severe weather elements.

Because of the wide variety of factors associated with the entire process of extratropical transition, the importance of increased observations was stressed as a means by which forecast skill related to important weather conditions (e.g., extreme precipitation, ocean waves, damaging winds) could be improved. Typically, an increase in variability among ensemble members is identified with an increase in forecast difficulty or uncertainty. These characteristics are often observed in ensemble prediction systems during extratropical transition events. However, it is not clear whether other measure would provide equally valid or better metrics of the impact of an extratropical transition event. Additionally, the communication of such metrics to the public is important as an extratropical transition often results in the movement of tropical cyclone-like wind and rain conditions into regions that do not normally experience these conditions during non-winter periods. The methods by which forecast information is communicated among tropical cyclone warning centres, midlatitude weather warning centres, and hydrological prediction centres was discussed. Even though an event may occur without threat of landfall, the impact on the midlatitude flow can be significant and influence weather patterns over downstream populated regions. The communication of warnings to the public should be enhanced. There is a tendency for complacency once the public perceives that the threat of a tropical cyclone has ended. New graphical forecast products are needed that could define and communicate weather parameters and regions in a probabilistic framework that would communicate uncertainty to the public.

To increase skill in prediction of high-impact weather events during extratropical transition, it is required that forecasts of past events be examined carefully. This requires detailed and current verification statistics and a database that would provide metrics for verification. It was highly recommended in discussion that current tropical cyclone best track products and extended best-track data bases be augmented with parameters associated with the extratropical transition of tropical cyclones. Recommendations that would contribute to improved skill in forecasting extratropical transition and its downstream impacts include increased understanding of factors that impact the extratropical transition process. There is a need for improved observation capability with respect to the rapidly-moving tropical cyclones that undergo extratropical transition.

Topic 3 - Tropical Cyclones in Intraseasonal to Climate Time Scales

Suzana J. Camargo, USA

Introduction

At the 7th International Workshop on Tropical Cyclones, the topic 3 was focused on tropical cyclones variability on various time-scales and their relationship with climate. The topic was subdivided in 3 sub-topics, according to the time-scales. The first one, on sub-seasonal time-scales had as rapporteur Frédéric Vitart from the European Center for Medium-Range Weather Forecasts. The second sub-topic rapporteur was Philip Klotzbach from Colorado State University, in USA, and the focus of the group was on seasonal time-scales. The last group focus was on climate time-scales, and was led by Thomas Knutson from GFDL, and most of the members of that working group were also members of the WMO expert group on tropical cyclones climate change.

In the intraseasonal and seasonal working groups, the operational tropical cyclone forecasts were also discussed, with a focus on the progress made in the operational forecasts in the last 4 years. In the case of climate time-scales, there were 2 additional events related to this topic in the workshop, which will be described in more detail below. Given the existence of these 2 additional events focusing on climate time-scales, the breakout groups after the topic 3 presentations were asked to focus their discussions on the intraseasonal and seasonal time-scales.

One of the points that was stressed in the breakout discussions of topic 3, as well in many other occasions during the IWTC-VII workshop was the importance of having reanalysis of the best-track datasets world wide. Given that all researchers that focus their work on the tropical cyclones and climate relationship used these datasets, it's fundamental for the progress of the field, that these datasets are as accurate and homogeneous as possible. An estimation of the uncertainties on these datasets would be a great improvement in determining the significance of trends in tropical cyclone activity. Furthermore, in basins where there are more than one best-track dataset available it would invaluable to reach a consistency among the different datasets, as well as consistency when the tropical cyclones cross regional borders. Homogeneity regarding intensity estimates and wind speed averaging should be a focal point in discussions on the future improvements in the best-track datasets. Finally, financial support for projects on the improvement and reanalysis of best-track datasets should be strongly supported by the WMO.

Intraseasonal time-scales

The working group on intra-seasonal time-scales that worked with Frédéric Vitart was composed of: P. Goswami, J. Gottschalk, P. Klotzbach, A. Leroy, K. Oouchi, P. Roundy, A. Sobel and M. Wheeler. In their report (Vitart, 2010), they describe in detail that the deeper understanding that occurred on how the Madden-Julian Oscillation modulates tropical cyclone activity. When the Madden-Julian Oscillation (MJO) is on its active phase on a certain region, i.e. when the convection frequency and intensity is enhanced compared to climatology, there is a higher likelihood of tropical cyclone formation. The relationship between tropical cyclones and the MJO is the main source of predictability of tropical cyclone activity in intra-seasonal time-scales. Besides tropical cyclone frequency, the MJO also affects tropical cyclone intensity, tracks and landfall.

There was a significant improvement in the simulation and prediction of MJO in the last few years which led to new and improved forecast schemes of tropical cyclone genesis on intra-seasonal time-scales. Statistical forecasts of the MJO typically still have more skill than dynamical ones after 10 days. One important factor for the progress in the intra-seasonal time-scales was the CLIVAR MJO working group and task force, which developed common diagnostics and skill measures to be used in evaluating the MJO in dynamical models and could potentially help in improving MJO in models and the simulation of the relationship between MJO and tropical cyclone activity.

There was great enthusiasm at IWTC-VII with the progress made in the intraseasonal dynamical forecasts, especially the ECMWF model products. Forecasters from many countries declared their interest in having access to this data on real-time. There was a great amount of discussion on the possible usage of these forecasts. The need to show the skill of these forecasts on real-time, using standardised skill measures was also expressed and it is a very important issue that needs be followed up.

The sub-seasonal working group expressed interest in having a WMO supported website for tropical cyclones subseasonal forecasts, similar to what was created for the seasonal forecasts, using the same format for all groups that issue those forecasts. Similarly to the case of the seasonal forecasts website, some rules will need to be developed for the groups contributing to such website.

Seasonal time-scales

The seasonal working group was led by Philip Klotzbach, with contributions from M. Ballester, A. Barnston, G. Bell, J. Camp, J. Chan, D. Jones, Y. Kuleshov, T. LaRow, M. Saunders, O.P. Singh and F. Vitart. On seasonal time-scales, the main source of predictability is El Niño-Southern Oscillation (ENSO) and in the last few years, a deeper understanding was achieved in how ENSO modulates tropical cyclone activity in all basins. Besides ENSO many other modes of variability influence the seasonal tropical cyclone activity, such as the Atlantic Meridional Mode (AMM), and the Atlantic warm pool, and these relationships have been further explored.

As happened in the past, most of the published papers focused on the North Atlantic variability on seasonal time-scales. Some basins have very few studies dedicated to them, such as the South Indian Ocean and should be the focus of the research on seasonal time-scales on the next years.

In the last few years, some modelling groups used high-resolution models to study tropical cyclone activity in seasonal time-scales and a few of them developed seasonal dynamical and statistical-dynamical forecasts of tropical cyclone activity, joining the two pioneering institutions in issuing dynamical seasonal tropical cyclone forecasts (namely ECMWF and IRI - International Research Institute for Climate and Society). Further improvement on tropical cyclone seasonal forecasts are dependent on improvement on ENSO forecasts, an area which has not have much progress in the last decade. Therefore, the research community should perform a better understanding of ENSO predictability and limitations of tropical cyclone seasonal forecasts predictability, due to its dependence on ENSO. More regional seasonal products are being developed, such as seasonal forecasts for specific areas, and landfall. However it is fundamental to understand the limits of their predictability and evaluate their real-time skill.

As a result of IWTC-VI recommendations, a few products were produced focused on seasonal tropical cyclone forecasts. A WMO publication did a review of the state-of-the-art of seasonal forecasts (Camargo et al. 2007). This review was the basis of the book chapter that appeared recently (Camargo et al. 2010). Another significant achievement was the development of a WMO supported website for tropical cyclone seasonal forecasts of different institutions on the same format. This website was first created with a few groups that were issuing tropical cyclone seasonal forecasts (statistical and dynamical) for many years and had peer-reviewed publications describing their forecasts and the skill of those forecasts. The next step will be to have common skill measures to evaluate the forecasts currently in the WMO website. Another important step will be to open the website to additional interested institutions that agree to follow the established rules for the website.

One of the questions discussed at IWTC-VII is the public misuse and misunderstanding of tropical cyclone seasonal forecasts, despite the effort that agencies and groups that issue those forecast put in explaining its use and validity. It is recommended to put additional effort in educating the public about the correct interpretation and usage of these forecasts.

Climate time-scales

As a consequence of the recommendations of IWTC-VI an expert group on climate change and tropical cyclones was created. This group stayed active throughout these 4 years and was responsible for 2 publications, one a book chapter reviewing the literature (Knutson et al. 2010a), and another recently published paper on the current understanding of this relationship (Knutson et al. 2010b). Due to the existence of this expert group, the working group of the climate time-scales was mostly comprised of members of the expert group. The climate change and tropical cyclones subtopic had Thomas Knutson as rapporteur and the working group members were J. McBride, C. Brueyere, J. Chan, J. Elsner, K. Emanuel, I. Held, G. Holland, J. Kossin, C. Landsea, A.K. Srivastava, M. Sugi and K. Walsh.

Because of the existence of the expert group at IWTC-VII the influence of climate change on tropical cyclone activity was discussed on 3 occasions during the workshop. First, one of the co-leaders of expert group (John McBride) presented a summary of the findings on the expert team, summarizing Knutson et al. 2010b. Then, the rapporteur and expert group co-leader Tom Knutson gave a complimentary talk with more technical details on how the conclusions of the expert team were reached. The third and final activity was a panel discussion on the future research directions of climate change and tropical cyclones. The panel was led by the expert group co-leaders (T. Knutson and J. McBride) and had participation of the other expert team members present at ITWC-VII: J. Chan, K. Emanuel, C. Landsea, G. Holland and M. Sugi.

The main conclusions of the expert team (Knutson et al. 2010b) are:

- The most robust projections are for an increase in tropical cyclone intensity and rainfall rates.
- The global frequency of tropical cyclones is expected to either decrease or remain similar to the present.
- Projections for individual regions are not very robust.
- Other aspects of tropical cyclone activity projection besides number and intensity - such as genesis, track, and duration - cannot be projected at this point with confidence.
- The attribution of recent observed trends to either anthropogenic or natural causes is still unclear.

Although there have been many studies with model simulations of TC climatology, variability and future projections using dynamical or statistical models or a combination of both, one issue in obtaining robust model projections is that dynamical models have different external forcings, resolutions, parameterizations. These differences among models make a clean assessment very difficult. There has been some effort to organize multi-model inter-comparisons in which forcings and boundary conditions would be uniform and these should be supported by the international research community.

Furthermore, future improvements and discontinuities in the observing system may continue to confound our ability to detect long-term trends. In order to avoid this problem, careful analysis needs to be taken to address these issues so that there is progress in analyzing the significance and the in the attribution of long-term trends.

Summary

Progress had been made in the understanding of the relationship of tropical cyclones and climate in all time scales. New products have been developed that forecast tropical cyclone activity in seasonal and intraseasonal time-scales. New groups developed seasonal dynamical and statistical-dynamical tropical cyclone forecasts. While only statistical subseasonal tropical cyclone forecasts existed during IWTC-VI, currently dynamical subseasonal tropical cyclones forecasts were developed with similar skill as the statistical forecasts.

On climate change time-scales the WMO expert group was instrumental getting experts to agree on the state-of-the art of the science and which aspect of the projections on tropical cyclone activity in the future are robust and which are still not well understood. Many modelling groups

world wide have dedicated enormous amount of human and computational resources to climate change simulations of tropical cyclone activity. These high-resolution simulations by many different groups were fundamental in clarifying the robust and less understood aspects of the field. These modelling studies have benefited the climate-tropical cyclone understanding in all time-scales, from intra-seasonal to multi-decadal time scales.

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Topic 4 - Disaster Risks, Mitigation, Warning Systems & Socio-Economic Impacts

Jim Davidson, Australia

Introduction

The following Rapporteurs presented at the Workshop and lead Breakout Discussion Groups:

- Rick Murnane – “Risk Assessment”
- Bill Read – “Disaster Mitigation Strategies”
- S.T. Chan – “Operational Warning Strategies”
- Linda Anderson-Berry – “Societal Impacts of Tropical Cyclones”
- Ryan Crompton – “Economic Impacts of Tropical Cyclones”

Risk Assessment

This is the first occasion that risk assessment has been included as a topic at an IWTC. Therefore, most of the discussion paper and the workshop presentation aimed to provide an overview of risk assessment using catastrophe risk models. Most catastrophe risk models (cat models) for TCs are proprietary and have been developed for use by the insurance industry. However, emergency managers, planners, and other public entities use similar models.

While cat models do not appear directly related to TC forecasting, the (re)insurance industry and the emergency management community have shared interests in cat model development and improvement. In addition, a range of societal activities use knowledge generated by cat models. For example, engineers (civil, wind, and coastal) use the hazard components of cat models to develop design codes for structures, master plans for land-use, and disaster mitigation works. Participants at the IWTC could be seen to have a common interest in better quantifying aspects of the exposure, hazard, and loss components of cat models.

One of the IWTC recommendations to the research community concerns the development of a global wind hazard return period map. These maps already exist for many regions. However, having an internally consistent, publicly available compendium of these maps would be a useful resource for many interests including the TC forecasting community. Another research community recommendation promotes the linkage of real-time meteorological data to TC risk models. Perhaps the best approach for this is the development of a parametric wind field model that can be validated for regional risk assessment. Finally, there is a recommendation to develop multi-hazard catastrophe risk models. This is a very involved exercise, but could be modelled in part after the Global Earthquake Model being developed by the seismological community. This work entails developing public databases on a variety of physical and social parameters such as bathymetry, topography, housing stock, occupancy, and construction.

Disaster Mitigation Strategies

Coastal population growth coupled with a lack of TC experience is driving ever higher the annual damage costs from TC impacts. At the same time, it is gratifying to note that fatalities are trending downward due to effective warnings and successful evacuation planning. Attention should be directed to managing the rarer TC events where the probability of occurrence is low but the impact is severe. If unprepared for such an event, the public is likely to respond in a reactive rather than proactive manner with less than optimal consequences.

Also to be considered are the inadequate building codes in many areas at risk from high winds, floods and/or storm surge. An option would be for planning authorities to define a higher return frequency for coastal development (eg 500 year rather than 100 year). In particular, critical facilities and infrastructure must be built outside the surge and flood zones. It was noted that the increased accuracy in track forecasts is being trumped to some extent by the population growth and the increased lead time required for evacuation decisions.

If mitigation strategies are to be successful, it will require the combined and sustained will and efforts of the TC forecast and research communities, government decision makers, emergency managers, the media and the wider community. Suggestions offered in the presentation included better land use policy, TC resistant building codes, joint multi-agency workshops on mitigation, and a fit-for-purpose mitigation resource guide for NMHSs.

Operational Warning Strategies

The end-to-end warning system was discussed at some length with constructive debate on the communication of warning information. Success stories such as that of Bangladesh in the implementation of an effective early warning system might be documented by WMO. The challenge of keeping up with emerging communication technologies is a universal one. In just the past decade the proliferation of mobile phones in developing countries has opened a warning communication pathway. If not done so already, NMHSs might explore the use of mobile phones to disseminate location-based warnings for individuals in the threatened area.

Communication through the media is considered critical for effective use of information by the public and for disaster preparedness. WMO is being requested to allocate resources to provide training in this area to developing countries through initiatives such as SWFDP. Wherever possible, NMHSs should also upgrade their communication systems in the more remote communities, which is essential to the timely communication of TC warnings.

Workshop participants highlighted the benefits of deploying reconnaissance flights for improved TC monitoring, as well as validation and development of satellite-based techniques to assess both TC structure and intensity (including Dvorak and its extension based on the microwave sensors). Considering the profound vulnerabilities and rapid economic development of the Asia-Pacific region, it is being recommended that the countries in this region organize regional co-operation efforts to initiate aircraft reconnaissance.

More reliable probabilistic products of TC motion can now be generated with the recent advances in NWP models. It is generally felt that further development work should be carried out on the provision of TC probability/uncertainty forecasts in both textual and graphical format, in concert with the creation of suitable community education programmes to assist in interpreting these products.

As requested by the host of the Severe Weather Information Centre (SWIC), it is being recommended that a standardized format for TC Advisories by RSMCs/TCWCs be developed to facilitate data exchange and product generation for consumption by the global community. Apart from standardization of common content, the template might also accommodate regional variations to account for specific needs.

Societal Impacts of Tropical Cyclones

The IWTC focus has always been to provide “better” information to the community to support their general safety and well-being, informed decision-making, and to minimise the socio-economic costs of TC impacts. Of particular note, this IWTC and the previous two workshops addressed to varying degree the end-to-end warning system and related concepts. Societal Impacts is now an integral part of IWTCs (and should remain so) in providing the link between the science, warning systems and public safety.

During the presentation, the changing paradigm in Disaster Risk Management was traced from the early 1980s when the focus was on the hazard, through the 1990s where the emphasis shifted to understanding vulnerability and mitigating the consequences of natural hazards, and then on to the 2000s when mainstreaming Disaster Risk Reduction came to the fore. Today we see a focus more on community resilience and capacity building with climate variability and climate change factored in to the decision-making process.

Discussed at some length was the subject of effective communication and the various elements essential to its success. The role of the media was highlighted – not just the traditional

media such as radio, television and the internet but also the newer opportunities offered by the social networks such as Facebook and Twitter. Social media can foster timely and repetitive messaging thereby encouraging the public to take even more protective action.

Economic Impacts of Tropical Cyclones

From a future loss sensitivity perspective, the main influences are expected to be anthropogenic climate change and exposure which is tied to changes in coastal population and wealth. Vulnerability (eg building codes) is usually held constant in such analyses. Leading studies show that by 2050 the total economic loss from TC impacts, at least in the US, could be several times that of the early 2000s. Private and public insurance is critical in both providing incentives for disaster mitigation by pricing according to risk and in providing funds for economic recovery after a catastrophe.

The conclusions reached in the presentation included recognition of the increasing global trend in TC losses with the main drivers being socio-economic factors and the expectation that losses will increase in the future. Although anthropogenic climate change can not be detected in loss analyses to date, it is more than likely to exacerbate future losses. There is also a benefit on all time scales in reducing societal vulnerability to counter exposure growth.

Financial solutions encouraging vulnerability reduction are an effective tool to minimise future losses. Sustainable development rests with disaster risk financing and mitigation.

Summary and Closing Remarks

The most common theme across all Topic 4 rapporteur reports is that unless appropriate action is taken around the world to address the growing concentration of people and wealth in TC-prone coastal areas, the potential for loss of life and high damage costs will greatly increase with time, perhaps more so under a climate change scenario. At the same time an effective TC warning service, combined with a range of non-meteorological disaster mitigation strategies and attractive financial incentives, are clearly the most potent mechanisms by which to achieve risk reduction.

The role of NMHSs arguably extends through the full disaster (risk) management cycle – prevention, preparation, response and recovery. Here we might include capacity building, hazard assessments, partnership development, stakeholder engagement, community awareness and the central TC warning service. Even following a significant event, NMHSs need to be involved in field and community surveys of the impact zone so valuable lessons can be learnt.

In regards to Topic 4, related publications and WMO initiatives include (1) the recent release of “Global Perspectives on Tropical Cyclones From Science to Mitigation” with a chapter devoted to disaster mitigation and societal impacts, (2) the soon-to-be-published “Guidelines on Early Warning Systems and Application of Nowcasting in Warning Operations” authored by a WMO Public Weather Services Expert Team, and (3) various projects under the WMO Disaster Risk Reduction Programme. Synergistic gains will be realised through collaboration.

Whereas IWTC-VI had as a special theme “Quantitative Forecasts of TC Landfall in relation to an Effective Warning System” and a dedicated Topic on “Disaster Mitigation, Warning Systems and Societal Impact”, TC impacts did not feature at IWTC-VII (along with TC motion). The parallel International Workshops on TC Landfall Processes could be at least partly responsible for the decision not to include TC impacts as a separate Topic. Forecasters indicated that they would prefer that more prominence be given to TC impacts at IWTC-VIII.

From feedback received during the course of the workshop, the presentations on catastrophe risk models and loss normalisation techniques were found to be quite useful but need not be included at all IWTC, especially if the 6 day format is retained. Instead, forecasters could be provided an opportunity in plenary to share relevant experiences and case studies as they did so successfully but to a smaller audience in the Breakout Discussion Groups

Two workshop recommendations are particularly welcome. The first is that WMO establish an expert group (comprising forecasters and researchers) on each of the IWTC-VII Topics to facilitate the implementation of recommendations. Hopefully, this will increase the likelihood that important Topic 4 recommendations are duly followed up. The second is that WMO organizes a specialised workshop on societal impacts for the purpose of advancing the Total Warning System concept. TC forecasters and society as a whole will be beneficiaries.

Finally, it is important to adopt a multi-disciplinary approach to most Topic 4 pursuits with meteorologists, climate change scientists, engineers, economists, social scientists, media and emergency managers working in partnership towards the common goal of reducing the global impact of TCs. In fact it could reasonably be said that “**Reducing Impacts Matters Most**” and therefore should underpin the aspirations and work programmes of all participating partners.

SPECIAL FOCUS SESSIONS

1A - Targeted Observations for Tropical Cyclone Track Forecasting

Chun-Chieh Wu (NTU) and Sharanya J. Majumdar (USA)

Premise

The assimilation of extra in-situ and remotely sensed observations, possibly targeted in “sensitive” areas, is expected to improve numerical forecasts of tropical cyclone track (and eventually structure).

Progress since 2006

At the WMO Sixth International Workshop on Tropical Cyclones (IWTC-VI) in 2006, several recommendations were made on Topic 3.3, entitled “Targeted observations and data assimilation in track prediction”. Additionally, the presence of interested scientists at IWTC-VII led to the initiation of international collaborations to pursue these recommendations. Under the general recommendation that “increased consideration should be given to targeted observations”, the following key accomplishments have been made since 2006:

- Expansion of aircraft targeting capabilities via the WMO/THORPEX Pacific Asian Regional Campaign (T-PARC) in 2008.
- Publication of numerous peer-reviewed articles on targeted observing techniques and sensitivity studies specifically for tropical cyclones.
- Evaluation of the impact of targeted observations on tropical cyclone track forecasts.

Main conclusions

The assimilation of dropwindsonde data in the near environment of tropical cyclones in the Atlantic and western North Pacific basin has led to improved operational track forecasts on average. These improvements have been adjudged to be sufficiently significant to justify the continuation of aircraft surveillance missions in both basins.

The degree of improvement varies significantly depending on the numerical model and data assimilation scheme.

Preliminary evaluations on the assimilation of targeted satellite data have also yielded a positive influence on track forecasts.

In addition to the tropical cyclone track, improvements to forecasts of mid-latitude systems and remote tropical cyclones have also been realized in a limited number of cases.

In a few cases, the assimilation of dropwindsonde data in the inner core of the tropical cyclone have led to degraded forecasts in global models.

The respective sensitive areas for targeted observations selected by the different techniques often disagree.

It is still unclear whether observations assimilated in areas deemed sensitive by the targeted observing techniques provide more benefit to forecasts than those in non-sensitive areas. The relatively short range of aircraft compared with the size of the sensitive areas limits the scope of such evaluations.

Recommendations

Given the limited availability and range of aircraft observations, an emerging consensus is that improved use ought to be made of existing observations. These include the targeting and optimal treatment of available satellite radiance data, and atmospheric motion vectors.

Additionally, special radiosonde launches could be considered, although their effectiveness has not yet been proven.

Targeted observing programmes are costly. The effectiveness of existing strategies may change as the observational network, numerical models and data assimilation schemes evolve. It is therefore imperative to frequently review the targeted observing programmes, by evaluating the impact of the targeted observations using a variety of models and data assimilation schemes.

New strategies, such as the optimal radius of aircraft circumnavigation around the cyclone, and the various sensitivity techniques, require evaluation. While this is often impractical in operations, research is necessary via basic scientific investigations, Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs)

New observing platforms such as unmanned aircraft and wind lidars require consideration.

As more observations become available globally for adaptive use, the coordination of the use of observations for tropical cyclones is worth investigating. An example of such a system is the EURORISK PREVIEW data targeting system used during T-PARC.

Investigations into the mechanisms by which data are assimilated into the models, particularly in the inner-core, are necessary to improve both the data assimilation and the targeting strategies.

As had been evident in several other sessions during IWTC-VII, more focus is being placed on high-resolution numerical predictions of tropical cyclone formation, structure and intensity. The expansion of targeted observations, where applicable, to these metrics is worth exploring.

1B - Ocean Field Experiments and New Research Findings Examples from CBLAST, TPARC/ TCS-08, ITOP/ TCS10*

Peter Black, Jeff Hawkins and Eric D'Asaro, USA

Over the past seven years, three major field projects have been organized to study the impact of air-sea interaction on TC genesis, structure and intensity change in addition to the yearly Hurricane Research Division's (HRD) Air-Sea interaction module. These were the Coupled Boundary Layer Air Sea Transfer (CBLAST) experiment, the THORPEX Pacific Asia Regional Campaign (TPARC)/Tropical Cyclone Structure 2008 (TCS08) experiment and the project, Impact of Typhoons on the Ocean in the Pacific (ITOP)/ Tropical Cyclone Structure 2010 (TCS10). The scientific results from the HRD work done in collaboration with the University of Miami (UM) and the preliminary results from the CBLAST experiment were summarized by Shay in the final report from the IWTC-VI meeting in Costa Rica (2006), edited by Johnny Chan and published in 2010. The HRD/UM efforts focused on two major topics: 1) understanding the nature of ocean response in the presence of the Gulf Loop Current and associated eddies and 2) the impact of evolving eddy structures on TC intensity. The CBLAST effort focused on obtaining high wind flux observations in the TC environment and relating those to new bulk aerodynamic observations and improved TC numerical model simulations for the boundary layer. The TPARC/TCS08 objectives were more focused on TC genesis, rapid intensity change and Extratropical Transition (ET), while ITOP/TCS10 objectives were focused on the evolution of the cold wake in the ocean generated by typhoons, its impact on TC intensity change and WPAC TC life cycle. While the HRD/UM and CBLAST observations and science results were summarized by Shay as mentioned, the special focus session on TC Ocean Field Experiments in IWTC-VII reviewed the latest results from CBLAST03-04 by way of comparison with more recent observations and scientific results from TPARC/TCS08 and ITOP/TCS10, just completed in October, 2010. All three projects were sponsored by the Office of Naval Research (ONR). The CBLAST project was jointly supported by NOAA, while TPARC/TCS08 was jointly supported by the U.S. National Science Foundation and ITOP/TCS10 was jointly supported by the Taiwan National Science Council.

The statistics for these three projects indicated that 17 flights consuming 123 flight hours were flown in the Atlantic basin during CBLAST over two years from 2003-2004, compared with roughly 33 flights and 300 flight hours flown in the Western Pacific Basin in each of two years during 2008 and 2010, respectively. Each project investigated 3-4 mature TC events. During CBLAST, six stepped-descent, low-level flights were conducted in the TC boundary layer making direct momentum and enthalpy flux observations while in TPARC/TCS08 and ITOP/TCS10, half of approximately 24 science flights per year were made at 300 mb in TC genesis and pre-genesis situations, developing a new observing strategy of 'combo' dropsonde and AXBT deployments to observe the atmosphere and ocean simultaneously from 10 km altitude in the atmosphere to 1 km depth in the ocean. While 330 GPS dropsondes and only 7 AXBTs were deployed during CBLAST03-04, 1074/250 sondes/AXBTs were deployed in TPARC/TCS08 and 828/822 sondes and AXBTs were deployed during ITOP/TCS10 (plus 43 AXCTDs and AXCPs). One NOAA WP-3D aircraft was available for use during CBLAST with occasional support from the second NOAA WP-3D and the NOAA G-IV (in the TC environment). For TPARC/TCS08 two Air Force Reserve WC-130J aircraft (one full crew) were utilized plus an NRL P-3C, German Falcon and Taiwan ASTRA/DOTSTAR. And for ITOP/TCS10 two WC-130J aircraft were again utilized (two full crews) in collaboration with ship-based observations, Taiwan and UM moored buoy arrays and the Taiwan ASTRA/DOTSTAR aircraft for TC environment flights, including the first joint, simultaneous ASTRA/WC130J flights.

In CBLAST, three drift buoy and float deployment flights were conducted over two years deploying 54 drifters and 20 floats, while in TPARC/TCS08, two drift buoy deployments were

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conducted, deploying 24 drifters, and in ITOP/TCS10, seven drift buoy and float deployment flights were made deploying 65 drifters and 24 floats, a record number for TC deployments.

The fundamental new observational advancement from CBLAST was the direct eddy correlation observations of momentum and enthalpy flux made possible by a new generation of instrumentation, i.e. the Best Atmospheric Turbulence (BAT) probe developed by Tim Crawford (who passed away at the apex of the CBLAST-low experimental observation period) and Jeff French from NOAA Field Research Facility and the modified LICOR high-frequency water vapour probe developed by Will Drennan at UM, which succeeded in making eddy flux observations to approximately 30 m/s, near hurricane force for the first time, and augmenting the dropsonde-inferred results from Powell (2003) and wave tank results from Donelan (2004). This instrumentation led to the fundamental new science result (French et al 2008 and Black et al 2007) indicating that the drag coefficient (C_d) approaches a constant value near 27 m/s, just below hurricane force, reversing the belief held prior to 2003 that the drag coefficient increased linearly with wind speed indefinitely despite historical direct eddy correlation observations to slightly above gale force (Smith, 1980; Large and Pond, 1980), i.e. approximately 20 m/s. In addition Drennan et al 2007 and Zhang et al 2008 showed that the enthalpy flux remains constant above gale force winds to hurricane force winds.

Most recently in 2010, using the multi-sonde deployment strategy for detailed eyewall vertical/horizontal structure observation developed by Black together with Doppler radar eyewall observations and the budget technique originally suggested by Emanuel, Bell (2010) has shown that C_d appears to remain constant with wind speed to over 70 m/s from earlier reported CBLAST values, a result partially substantiated by recent sonde-based C_d estimates of Vickery et al, 2010. Further, Bell (2010) shows that 50-60 m/s C_k values appear to decrease from earlier reported CBLAST values, but increase again above 60 m/s, a result partially substantiated by wave tank measurements of Haus et al, 2010.

Other notable CBLAST science results include directional wave spectral observations from the Scanning Radar Altimeter (SRA) which show that TCs generally exhibit three azimuthal regions characterized by three differing alignments of local wind and swell, a result that may play a role in modulating exchange coefficients by storm quadrant for the same wind speed. These regions are 1) the right two-thirds sector where the local wind and swell are generally aligned with each other in a region of growing waves (small wave age), but exhibit a tri-modal characteristic, 2) the left two-thirds sector where local wind and swell directions deviate from each other by 45-90 degrees (wave age is large, but steady with azimuth) and 3) the rear sector where swell spectra broaden and decrease over a large range of directions, but maintain separation from local wind direction by 45-90 degrees (large but decreasing wave age).

The existence of roll vortices was confirmed in TCs by momentum flux observations from the middle of the boundary layer at 250 m on one penetration that exhibited strong vertical/horizontal wind covariances that peaked at the same wavelength of 900 m as streaks observed in Synthetic Aperture Radar (SAR) images from various satellite platforms in various TCs (Zhang et al, 2009). The roll of these features in modulating and augmenting boundary layer fluxes has been discussed by Foster (2005), Morrison et al (2005) and Lorsolo et al (2008).

The principal air-sea interaction results from TPARC/TCS08 included the development of the NRL Mobile Ocean Observing System (MOOS) which provided for launching, processing, recording and near real-time processing of more than 250 AXBT observations from the WC-130J aircraft. It also included the deployment of 24 drifting buoys ahead of two typhoons, Hagupit and Jangmi, which moved along parallel track separated by less than one degree latitude. The principal scientific results that have come about so far from these observations are the excellent agreement between AXBT and NRL Stennis ocean model estimates of Ocean Heat Content and the ability to use the AXBT observations to adjust locations of important ocean feature boundaries in the ocean model to their actual position. This capability allowed for more precise location of eddy boundaries with respect to intensity changes observed by WC-130J aircraft as TC's passed over these features, especially Super Typhoon (STY) Jangmi. AXBT, buoy and model predictions showed

STY Jangmi passing over a warm and cold eddy pair a day prior to landfall on Taiwan. This was correlated with observed Rapid Intensification (RI) over the warm eddy followed by Rapid Filling (RF) over the cold eddy. During the RF process over the cold eddy, satellite microwave, airborne radar and Taiwan ground-based radar all documented a drying of the NW quadrant and total evaporation of rainbands in this region as landfall approached. The rapid deepening and filling was modelled by NRL COAMPS-TC with and without ocean coupling. It was found that the coupled version of COAMPS-TC more accurately represented the RI than did the uncoupled version, and was able to replicate a cessation of RI offshore prior to landfall as the RF event began (although it did not replicate the RF process itself) as opposed to the uncoupled version which maintained peak STY intensity up to the point of landfall. Coupled COAMPS-TC also represented the development of a dry slot (although not the complete deterioration of rainband activity) in the NW quadrant of Jangmi during the RF process prior to landfall.

The AXBT MOOS development undertaken for TPARC/TCS08 also allowed for first time implementation of a high altitude (10 km, 300 mb) observing strategies employing 'combo' deployments of dropsondes and AXBTs simultaneously over a 'square spiral' pattern that could be adjusted in size and location depending on the evolving convective and dynamic fields observed during the course of the flight. This first time ever observing strategy allowed for a more detailed observational input into initial experiments with TC coupled model efforts to simulate TC genesis and subsequent development.

The ITOP/TCS10 experiment was only recently completed. However, the primary objective of observing TC-generated cold wakes and their recovery with an array of airborne-deployed drifting buoys, ocean floats and AXBTs coordinated with ship-based observations, including a fleet of AUV's, was accomplished in great detail for one typhoon (Fanapi) with drifters and floats deployed both ahead and behind Fanapi, a moderate CAT2 TC with a somewhat small inner, high-wind core. However, the aircraft based observations were expertly coordinated with ship based observations from the R/V Revelle and from Taiwan and UM moored buoys located just south (left) of the track. Four surveillance flights in the developing system utilizing the high altitude sonde/AXBT combo observing strategy developed during TPARC/TCS08 led to extremely accurate predictions of the complex S-shaped track followed by Fanapi just before the planned drifter and float deployments. The NRL MOOS system was expanded to two independent systems with major hardware and software upgrades, one for each WC-130J aircraft, and was a major factor in the 100% success rate of the processing, recording and real time data transmission that was accomplished. The ocean surface forcing of the cold wake by Fanapi and environmental conditions around the TC were further mapped by the first-ever series of synchronous Taiwan ASTRA/DOTSTAR flights in coordination with inner core SFMR-equipped WC-130J flights on 2 days. A 3C cold wake approximately 100 km in width was observed over an approximately 500 km long swath from initiation by the TC throughout its subsequent warming period over the following two weeks. The vastly improved microwave SST products developed at National Taiwan University and NRL, and run in real time, provided the capability to track cold wake formation in real time and provide proper siting for post TC airborne and surface ship sampling patterns.

Two subsequent storms were subsequently observed providing a wide range in TC ocean forcing conditions. Malakas, a slow, very large northward-moving TC produced a large 5C cold wake that was mapped in detail by AXBTs and AXCTDs as well as a line of floats and drifters. After a three week lull in activity, the final TC, Megi, formed and underwent RI into a tiny STY with record high SFMR surface winds of 75 m/s, but a max wind radius of only 6 km. Megi's inner core and subsequent wake was also observed floats, AXBTs and AXCTDs. The width of the wake was about the same as Fanapi, but its magnitude of only 1.5C was less owing to the deeper initial mixed layers of 80m in the more southerly track. Another coordinated Taiwan ASTRA/DOTSTAR and WC-130J flight day was conducted which thoroughly documented the TC structure and intensity and provided the basis for very accurate landfall of Megi on Luzon as a STY. Coincidentally a spectacular COSMO/ SKYMED3 SAR pass occurred during the coordinated ASTRA/ WC-130J flight with overpass time within 20 min of one of the eye penetrations, at coincident within 10 min of two 91 GHz microwave imagers, which should allow for detailed comparison of rainband and eyewall surface wind features.

Two additional special flights helped complete a large array of inter-calibration observations. On one flight, a record 85 AXBTs were launched over a grid 300 km on a side to observe the phase and amplitude of internal tides in the central Philippine Sea in a space-time domain, showing excellent agreement with model predictions and peak to peak amplitudes of 100 m near the 20C isotherm at 200 m depth. A second flight prior to the Megi flights was conducted over the R/V Revelle where 20 AXBT's from the two AXBT manufacturers were dropped near the ship coincident with CTD casts. This proved to be a key observation for final QC and correction of AXBT profiles for the entire ITOP observing period.

In conclusion:

- Oceanic eddies (warm/cold) interact with many tropical cyclones in the western Pacific (during all phases, genesis, mature, and decay) and require real-time monitoring to forecast intensity trends well.
- Both IR and microwave SST products need to be used in conjunction with satellite altimeter and ocean model data sets to provide ocean front and eddy locations and to map the OHC signal.
- SST wake signals can be rapidly modified while subsurface thermal structure persists for weeks, potentially impacting subsequent TCs, thus the SST signal can be grossly misleading when trying to factor in oceanic impact on TC intensity.
- Storm track through the 3-D thermal structure plays key role in TC intensity changes.

And finally:

- We are at an historic potential turning point in history for improving TC intensity observation and forecasting where the capability to observe the TC surface and the mid-level wind domain concurrent with subsurface ocean thermal structure matches the improved coupled model capabilities to assimilate and model the total TC environment.
- This alignment could provide the next best opportunity for improving TC intensity and structure forecasting.

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2A – THORPEX/TIGGE Applications to Tropical Cyclone Motion and Forecasting

R. Swinbank, T. Nakazawa and H. Yu

Overview of TIGGE and plans for GIFS (*R. Swinbank, UK Met. Office*)

RS gave an overview of TIGGE and its relationship to THORPEX and GEO. TIGGE has been operating since Oct 2006 with 10 operational NWP centres contributing global ensemble forecasts to the database. Interested people can register for access at the TIGGE website (<http://tigge/ecmwf.int>).

An important application of TIGGE is the development of a prototype Global Interactive Forecast System (GIFS). RS described plans for developing and evaluating TIGGE products in conjunction with the WMO SWFDP (Severe Weather Forecast Demonstration Project) and other regional projects. SWFDP regional projects were integral to the process of cascading ensemble and probabilistic products to users. There was an invitation to forecasters for feedback on what types of products should be developed.

Questions/Comments

Météo France: noted problems with CXML datasets from some centres.

TN noted there had been some problems but they should be fixed now.

Pakistan: asked for comment on relative skill between ensembles and deterministic models.

Based on Met Office experience, RS suggested ensembles showed better skill after Day 3.

Australia: welcomes this opportunity to provide products for use by the community in decision making (especially through SWFDPs)

RS made the point that the TIGGE WG plans to work very closely in conjunction with the SWFDP which has developed good links with operational forecasters and users.

Australia: commented that estimating probabilities from the proportion of the ensemble that forecast a particular event was not satisfactory when the ensemble is under-spread (e.g. if track forecasts are not diverse enough).

Meteo France: asked if model data was under the same resolution from each contributing member.

RS answered no – each centre decided what resolution to run their model.

New Zealand: could not access ECMWF data through the SWFDP website but had to go separately to the ECMWF site for those products.

RS was not sure how access to data for SWFDPs worked.

The TC formation products shown earlier looked useful and asked if they could be made available through the SWFDP.

RS asked that he be sent a reminder to follow-up this up.

NW Pacific Ensemble Forecast Project (*T. Nakazawa, WMO/WWRP*)

TN explained the background behind the development of cxml file format for data transfer of TC information and showed products developed at JMA for the NW Pacific TC ensemble forecast project, including some examples taken from the TC forecast website developed by MRI/JMA (<http://tparc.mri-jma.go.jp/cyclone/>) for the NW Pacific.

Questions/Comments

Australia: Are these products available in real-time? (yes)

Is there an intention to add formation oriented guidance products? (maybe)

Can a similar domain be built for the SW Pacific area?

TN said that MRI would be happy to make the software available, so similar websites could be set up for other regions.

US: Is CXML data available for 10 days for the ECMWF model?

RS acknowledged that they run the model for 15 days but only presently make 5 days available via CXML. He will raise this with ECMWF.

China: Probability type products were helpful but asked if this could be extended to other products such as precipitation fields.

USA: Could cyclone phase space products be provided? (yes)

Hong Kong: track data in CXML only goes to 4 days (TN can change to 5 days)

Ensemble Products in Shanghai Meteorological Bureau (*H. Yu Shanghai Typhoon Institute*)

These were developed and tested during the Shanghai EXPO period. There has been increased usage of consensus and EPS products since 1996 in SMB. HY showed the array of model members used. They also placed a researcher in the forecast office to advise on product choice.

Forecaster feedback from the trial indicated that they favoured deterministic forecasts and noted resistance to ensemble products by decision makers. Ensemble products were helpful to express confidence however overall there was considered to be too much uncertainty and the products were not effective (and so forecasters were not confident to use them). They considered products like the Extreme Forecast Index were useful.

Questions/Comments

US: noted that ensemble verification was tricky.

Australia: followed up by suggesting that once forecasters started using probability numbers then there was an obligation to verify the forecast.

Pakistan: noted low public opinion for a 50% chance type forecast – RS noted that in some situations a 50% chance of precipitation was quite high.

Pakistan: enquired about probability products for storm surge.

HY said that SMB used deterministic models for storm surge.

(This report is based on notes originally taken by Gary Foley during the session. We thank Gary for taking the notes)

2B - International Best Track Archive for Climate Stewardship (IBTrACS): Activities and Update

Kenneth R. Knapp (USA)

Introduction

This session focused on the International Best Track Archive for Climate Stewardship (IBTrACS), which is a collection of global best track data from agencies worldwide. The goal was to present the current status of IBTrACS activities and generate discussion related to issues in best track data. Three discussion topics were introduced:

- Best track parameters and data quality
- Best track data continuity
- Global reanalysis

The following is a summary of the presentation and discussion topics.

IBTrACS Overview

A recommendation from the IWTC-VI was that the WMO incorporate the numerous best track (BT) datasets into a unified dataset. In short, the IBTrACS effort completed this requirement. IBTrACS began as a project in 2007 as part of the World Data Center for Meteorology – Asheville. The goal was to collect, in one location, all publicly-available estimates of a tropical cyclone's position and intensity.

IBTrACS was developed toward user requirements. The initial requirement being the format should be similar to other formats in use by the tropical cyclone research community. While formats like comma separated variables (CSV) and netCDF are more versatile, the community was already using some specific formats (Figure 1) such as the HURDAT, ATCF and cXML formats. The limitation on the latter is that they allow only one reported intensity per position. However, with many agencies reporting intensities, it is impossible to report all available intensities in these formats.

The first dataset release (version 1) was made public in 2008. The collection and combination of the data from many the many sources into one dataset is described by Kruk et al. (2010). For version 1, the intensity reports [that is, minimum central pressure (MCP) and maximum sustained winds (MSW)¹] were combined using a mathematical average of all available reports (Figure 1). User feedback and discussions at the IBTrACS workshop (Levinson et al. 2010) recommended not using the mean as a representative intensity, but a satisfactory alternative was not provided. The second version was released in 2009, when IBTrACS began to report the intensities as originally reported by the source agency in the CSV and netCDF formats (Knapp et al. 2010). The mean was still used for restrictive formats (right column of Figure 1). Version 3 of IBTrACS – released in 2010 – represents the first version not to use the mean intensity as the source of intensity for any format. The official WMO position and intensity – as reported by the responsible RSMC/TCWC – is used in the restrictive formats. Conversely, all reported intensities are still available in the CSV and netCDF formats.

Discussion on best track parameters and data quality

Best track data reporting is a three way balancing act between:

- Data availability – Forecasters and analysts can only provide parameters for which an estimate is available. Different agencies have various sources of data (satellite, aircraft reconnaissance, buoys, radars, etc.) which have all varied in time.
- User needs – In the past, use of tropical cyclone data has focused on intensity. But as interest has grown, other parameters of the storm – such as wind structure, rain features, etc – are needed by users.

¹ Where necessary, winds were converted to a 10-min maximum sustained wind prior to averaging.

- Analyst resources – Lastly, analysts do not have unlimited resources. In particular, the time spent reanalyzing a storm (“best tracking”) can vary by agency.

Currently, nearly all agencies provide the minimal reporting criteria for a storm – storm name, time, position and intensity in MSW and/or MCP. While the WMO format allows other data to be reported, few follow this convention or report the full suite of WMO format variables (e.g., wind radii, position quality, intensity source, etc.). In some cases, data are available that have not been “best tracked”. That is, the data derive from operational data feeds that have not undergone post-storm quality checks and may be of limited accuracy.

Based on these considerations, we asked three questions:

- Based on the WMO best track format parameters, which parameter could be most easily added to the BT record from your agency?
- What next parameter would be of the most use for users? (researchers, etc.)
- What would it take to add confidence flags or quality indicators to the best track record?

The following is a summary of the ensuing discussion:

- It was suggested that at some previous meeting, that the RSMCs agreed to follow WMO format and that agencies should start providing the parameters described in that format. In some respects, the format is irrelevant (since IBTrACS can reformat) but the reporting of the parameters by the agencies is necessary to start.
- There is a need for high precision – spatially and temporally – by some user communities (e.g., the ocean engineering). One participant noted that it was “embarrassing that we only offer 6 hr data.” When more precise observations are possible, then such observations should be reported. To this end, it was suggested that agencies make their “fix” data (those raw observations that record instantaneous position/intensity reports) might meet the needs of those needing higher temporal resolution.
- Based on the discussion, the parameter in highest demand that is not currently best track by all agencies was the TC structural parameters, such as radius of maximum winds and other wind radii.
- Landfall is another critical piece of information that is not really recorded by most agencies in the best track data, but should be.
- One RSMC asked that the IBTrACS or WMO poll users to identify the gaps to provide better guidance to RSMCs on which parameters should be best tracked that aren’t already.
- Agencies should not limit best track data that to those parameters that will always be reported. For instance, if some parameter is not available, then report as missing. It is better to have experts estimate (i.e., best track) parameters instead of users deriving their own parameters that may not be valid. Users will find some source of data if they need to and it is best if the experts derive those parameters.

Discussion on best track continuity

Best track dataset reliability is not well documented by source agencies. Nevertheless, users are interested in the continuity of the data in time. For instance, the following short question posed by an IBTrACS user has a complex answer: “When should I start trusting storm frequency?” The user needed to compare modelled frequency against observations. The dataset developers – the source agencies – are best suited to answer this question, but such documentation is often not available.

Two agencies have reported the results of analyses of time series of their best track data. JTWC analyzed their storm reports. The resulting study (Chu et al. 2002) reported in the summary: “The authors rate the 1985-2000 best-tracks to be of high quality and urge users to use older data with caution.” However, users of JTWC best track data often use intensities prior to 1985 for

climatological studies. The Australian Bureau of Meteorology (BoM) has also reported on the quality of best track data counts and intensities. The unpublished report² (presented at the 1st IBTrACS Workshop 2009) provided a summary of best track data reliability for different periods in the Southern Hemisphere. They conclude by stating: “There is evidently a considerable need for re-analysis of the historical TC data in order to obtain globally homogeneous records, something required to address the important question of how TC activity is changing and its possible relationship to global climate change more generally.” The topic of a global reanalysis is discussed in the next section. We propose, however, that an independent panel assess the best track data quality for each basin and provide steps for improvement, where needed.

For the discussion, we proposed the same question from the user, and variants of it that included:

- What criteria are used to decide an appropriate starting year?
- What is a good starting year for analyzing TC frequency? That is, when do counts become reliable?
- What is a good starting year for analyzing TC intensity? That is, when do intensities become reliable?
- What’s the best road forward to analyze continuity in each basin?

To be clear, we pose our questions as users of the data to the agencies. IBTrACS is not currently in the position to accomplish large-scale data quality analyses. Instead, we hoped to encourage each agency to investigate and document their best track data. The following is a summary of the ensuing discussion:

- The Holland (1981) study was mentioned as another analysis of dataset quality.
- Some work has been done to quantify the impact of changing observing systems (e.g., changes in ship tracks) on the quality of best track data. Perhaps similar studies could be performed in other basins.
- It was questioned whether users or providers should assess data quality. To some extent, each user should assess data quality and determine which periods of record can and cannot be used in their analysis. Conversely, the experts that provide the data need to provide as much metadata on data quality as possible for the users to make an accurate quality assessment. To that end, data providers could report the WMO quality parameters and let users decide on which data to include.
- Some agencies already record “best tracking” procedures and changes to them in time. Such information should be made public. Furthermore, agencies are encouraged to participate in the IBTrACS Community Survey³ which is aimed toward recording in a central location practices from each agency and how they have changed through time.

Discussion on a global reanalysis

Understanding the current tropical cyclone extent, frequency, and intensity is a key part in understanding how future changes will affect mankind. The recent study by Knutson et al. (2010) concludes that a future climate will likely have fewer TCs but be slightly more intense. Yet, if TCs will increase in intensity, then to what level will they increase if we don’t truly understand their current intensity? For instance, there are conflicting studies regarding north West Pacific Ocean activity over the last 30 year (Emanuel 2005; Wu et al. 2006). Knapp et al. (2010) also showed differences for some storms and notably: significant differences occur in recent years and can account for 50% of the annual PDI in any basin. An effort is underway to understand the best track practices through time at various agencies in order to understand how changes in these practices have impacted frequency or intensity. However, it is questionable whether understanding the differences between agencies will allow corrections to be made to reduce the interagency differences in best track intensity and number (Knapp and Kruk 2010). Therefore, a global reanalysis of tropical cyclone intensity should be the next step.

² Available at: <ftp://eclipse.ncdc.noaa.gov/pub/ibtracs/workshop/Day-1/1045-Australian-BoM-Kuleshov.ppt>

³ Available through Spring 2011 at: <http://www.surveymonkey.com/s/ibtracs>

Reanalyses are currently underway in two basins: the North Atlantic and the South Indian Oceans. The Atlantic hurricane database reanalysis project (Landsea et al. 2004) began with 1851 and is working forward chronologically. Conversely, Meteo-France La Réunion will begin reanalysis in 1998 (which is the first year of Meteosat geostationary coverage of the Indian Ocean) and move backward chronologically performing satellite reanalysis using the Dvorak technique (Dvorak 1984) and HURSAT-AVHRR data (Knapp and Kossin 2007).

To stimulate discussion, we asked:

- What data could be prepared to aid a global reanalysis?
- How could the TC community start the process of a global reanalysis?
- Are there overlaps/synergies that can be exploited?
- How would a reanalysis best be coordinated?

The ensuing discussion discussed:

- As to differences in the Western North Pacific, a meeting was already planned for December 2010 to discuss similarities and differences in best tracking practices for four of the agencies in the region: the Japan Meteorological Agency (as RSMC Tokyo), the China Meteorological Administration, the Hong Kong Observatory and the U.S. Joint Typhoon Warning Center. Results of this meeting may help alleviate some of the interagency differences in the region.
- The need for centralized datasets was clear. Whether it is satellite data, aircraft recon or *in situ* data, there is a need for a centralized archive of tropical cyclone related data. Some needs include: quick browsing of satellite data for looking at potential storms, a centralized aircraft reconnaissance repository, expanding HURSAT to other microwave data and collocation of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) with TC tracks. Such tools would facilitate a global reanalysis.

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IBTrACS Data Formats

		Multiple intensities possible	1 intensity per report
		<ul style="list-style-type: none"> ▶ netCDF ▶ CSV 	<ul style="list-style-type: none"> ▶ WMO ▶ HURDAT ▶ ATCF ▶ cXML ▶ GIS shapefile
Ver. 1	Mean position Mean intensity		Mean position Mean intensity <i>JAOT</i> Kruk et al., 2010
Ver. 2	Mean position Mean intensity Original positions & intensity		Mean position Mean intensity <i>BAMS</i> Knapp et al., 2010
Ver. 3	Original positions & intensity Other parameters as available		WMO position WMO intensity <i>In prep.</i>

Figure 1 - Summary of IBTrACS Dataset formats and versions, showing the transition away from reporting the mean intensity toward the practice of reporting TC parameters as reported by the source agency

PANEL DISCUSSION

Tropical Cyclones and Climate Change

Summary

At the IWTC-VII, an evening panel/discussion session was organized, devoted to the question of how to make progress and come to consensus on anthropogenic climate change and tropical cyclones. The session was moderated by John McBride and Tom Knutson. The session began with each of the five panelists and the two moderators presenting a very brief summary of their ideas on the key gaps and ways of progressing toward a better scientific understanding of the issue.

Greg Holland showed global temperature 20th century hindcasts from an NCAR study suggesting that the anthropogenic component of the global warming did not become substantial until beginning in the 1970s. He questioned the use of century-scale linear trends to search for an anthropogenic signal in tropical cyclones. Johnny Chan showed timeseries of TC landfall in different regions of the NW Pacific basin for the past 60 years and some even longer landfalling records from historical archives in China. None of these showed the recent few decades to have unusually high TC activity compared to the past levels. Kerry Emanuel maintained that a better theoretical understanding of the TC/climate change problem was needed, including contributions from paleotempestology. He showed that a strong ~6 deg C cooling of the Atlantic MDR outflow temperatures in recent decades was not captured by current AGCMs. This cooling was important for producing the rise in tropical storm counts in the North Atlantic basin since 1980 using his statistical/dynamical downscaling technique. Chris Landsea showed a time series of observed Atlantic category 5 hurricane occurrence since 1900 which exhibited a large upward trend over time. He concluded that this trend was not reliable and that one must first account for changing observing capabilities over time in such trend analyses. Masato Sugi updated the session on the latest 20km mesh GCM runs at JAMSTEC, showing some capability of simulating very intense typhoons. Future work will involve higher resolution models, better physics (cumulus parameterization) and larger ensembles, with a need to better understand TC formation and development processes to improve models. Tom Knutson maintained that having more confidence in future TC activity projections would first require more reliable projections of SST patterns, of the vertical profile of temperature change in the tropics, and an assessment of the implications of using fixed SST experiments vs coupled models for the TC climate simulations. He stated that for detection/attribution studies of TCs, there is a need for long control runs of TCs to estimate internal climate variability, and a need for improved observational data sets of TCs and of historical temperature trends ranging from the surface to the tropopause transition layer (TTL). John McBride recommended that the IWTC-VII endorse the WMO expert team's *Nature Geoscience* paper as being a true representation of the current state of the science on this topic.

A question and answer period followed, with substantial audience participation. While there were no notable new consensus recommendations emerging from the presentations or question and discussion period, a number of ideas were brought forth in the session that will be followed up on by the various research groups.

During the final session of the meeting, the IWTC-VII attendees voted to endorse the WMO expert team's assessment report from *Nature Geoscience* as being a fair representation of the current state of the science.

RECOMMENDATIONS

Recommendations to WMO

1. (High Priority) The IWTC-VII strongly recommends that WMO encourages the maintenance of existing observing systems that pertain to the tropical cyclone and its environment, the development and transition of new observing systems to operations, and the expansion of surface observing systems along coastal areas worldwide by respective partner nations. These observing systems include: 1) Remote sensing, including scatterometer, geostationary microwave sounder, geostationary Doppler radar, scanning radar altimeter, lidar; and 2) *in situ*, including unmanned aerial systems, and expansion of aircraft reconnaissance. IWTC-VII notes the importance of documenting uncertainties related to these systems.
2. (High Priority) Recognising the importance of the concept of an end to end warning system, the IWTC-VII recommends that the WMO encourage nations to upgrade communication systems in more isolated communities, which is essential to the timely communication of tropical cyclone warnings. This includes:
 - Providing guidelines for effective communication between tropical cyclone forecasters and disaster managers, government entities, the public, and media; and
 - Communicating the differences between tropical cyclones and midlatitude cyclones and their associated impacts for better public preparedness.
3. (High Priority) As a major initiative in the tropical cyclone landfall emphasis of the WWRP/Working Group on Tropical Meteorology Research Tropical Cyclone Panel, an expert team should be formed that will focus on the capability, gaps, and requirements needed to better understand, observe, forecast, and mitigate both the direct and remote rainfall associated with landfall events. An overall objective is to develop a multi-national Research Development Project or a Forecast Demonstration Project.
4. The IWTC-VII recommends that WMO encourage the inter-comparison, calibration, maintenance, and documentation of existing platforms for tropical cyclone wind measurements (i.e., remote sensing/satellite, SFMR, dropsondes, and land-based surface winds suitably adjusted to standard exposure).
5. The IWTC-VII recommends that the WMO, via coordination of the WWRP/TCP and WGNE assist in defining standard metrics by which operational centres classify tropical cyclone formation, structure, and intensity, and that these metrics serve as a basis to collect verification statistics. These statistics could be used for purposes including objectively verifying numerical guidance and communicating with the public.
6. The WMO should continue to support the regional tropical cyclone-related work of THORPEX to assist in the further development of a comprehensive suite of probabilistic forecast products targeting tropical cyclone track, intensity, genesis, and impacts on land and at sea.
7. There is concern that tropical cyclone seasonal forecasts are used inappropriately by users outside the tropical cyclone community. The IWTC-VII requests that WMO encourage the continued education of the media and the general public to the limitations of seasonal forecasts and assesses how the public responds to seasonal forecasts in different regions.
8. The IWTC-VII recommends that the WGTMR establish an expert group on each of the IWTC-VII topics to facilitate the implementation of recommendations. The expert groups should include a suitable mix of forecasters and researchers.
9. The IWTC-VII recommends that the WMO should promote the running of specialized workshops on IWTC themes. These include:

- The resumption of the International Workshop on Extratropical Transition (IWET) to examine results and define improvements since T-PARC;
- An international workshop on tropical cyclone formation that coordinates results from recent field programmes (e.g., TCS-08, GRIP, IFEX, PREDICT, and TCS-10); and
- A workshop on societal impacts for the purpose of advancing the Total Warning System concept and for the sharing of relevant experiences.

10. The IWTC-VII encourages the WMO to continue support of training programmes for forecaster development, which should include researcher participation and collaboration. Training should include new research developments, updates to current processes and products, and interaction between forecasters and researchers via visiting scientist programmes and exchanges among RSMCs.

11. Due to the vulnerabilities, rapid economic development, and rising economic status of the Asia-Pacific region, it is recommended that the countries of this region organize a regional co-operation to initiate aircraft reconnaissance for the purpose of supporting: 1) improved forecasts of intensity, size, and structure; and 2) validation and development of satellite-based techniques to assess both structure and intensity (including Dvorak new microwave-based methods). The WMO should encourage all countries in the region to contribute resources and/or assets towards this effort, as they are able. Data gathered should be disseminated in real-time in WMO-approved formats to all stakeholders.

12. The IWTC-VII recommends that the WMO encourages real time communication between forecasters and researchers through a private email list with the purpose of assisting RSMCs / TCWCs during specific TC forecast events.

13. The IWTC-VII recognizes the value of tropical cyclone disaster mitigation. Because of this, the WMO should encourage communication and education between forecasting and disaster management communities globally. In addition, the WMO should assist developing countries to engage in hazard assessment, risk mapping, and tropical cyclone simulation exercises, especially in highly vulnerable coastal and island areas.

14. The IWTC-VII recommends that the WMO encourage existing efforts within the UN to systematically track the loss of human life, socio-economic impacts, and direct and indirect costs associated with TC warning and other disaster mitigation initiatives globally.

15. The IWTC-VII recommends that WMO facilitates the development of a standardised template for detailed tropical cyclone bulletins as requested by the SWIC hosts. This template should be passed by WMO to the RSMC/TCWC Technical Coordination Committee for action.

16. IWTC-VII endorses the Knutson et al Nature Geosciences (2010) as being a fair assessment of the current state of the science of climate change impacts on tropical cyclones and encourages the WMO to also endorse this article.

Recommendations for forecast agencies and operational centres

Topic 1- TC structure and intensity change

1. (High Priority) The IWTC-VII encourages the expansion of, and training in, forecast aids from the Atlantic basin (e.g., SHIPS, secondary eyewall formation index) to the remainder of the global tropical cyclone warning centres and the provision of these forecast aids in standard formats.

2. (High Priority) IWTC-VII encourages the continued development of probabilistic guidance, and consensus guidance for formation, intensity, and track forecasting of tropical cyclones.

3. The IWTC-VII encourages the validation of basin-specific Dvorak intensity estimates. As part of this effort, researchers and operational centres should share any available validation data.

4. The IWTC-VII encourages an examination of differences in intensity forecasts among forecast agencies.
5. The IWTC-VII encourages the continued development and improvement of numerical weather prediction to study genesis, intensity and predictability. These outputs should be archived for the research community.
6. The IWTC-VII recommends that RSMCs contribute their challenging TC forecast cases to an international site that is made available to the research community. This database of TC forecasts could be used to baseline development of new forecast guidance products.

Topic 2 - Tropical Cyclone Formation and Extratropical Transition

7. (High Priority) The IWTC-VII recommends that the operational community examine the manner in which the high-impact weather that occurs during extratropical transition process can be effectively communicated. Examples include maintenance of the tropical cyclone name, forecast graphics that are consistent with those produced for the tropical cyclone phase, use of probabilistic products, and public perception of the post-tropical impacts. This should be accompanied by augmenting existing tropical cyclone training to include topics related to extratropical transition.
8. The IWTC-VII recommends that RSMCs consider whether a standard definition of tropical cyclone formation is desired and feasible. While difficult to encompass all regional factors, a common definition of formation will aid in research and in the examination of operational practices associated with tropical cyclone formation.
9. The IWTC-VII recommends that RSMCs contribute to the establishment of an extratropical transition best-track database to facilitate examination of the post-extratropical transition evolution and downstream development.
10. The IWTC-VII recommends that researchers and forecasters work together to systematically verify forecasts of tropical cyclone formation and extratropical transition in global operational numerical weather prediction models. Additionally, the verification results should be reported in a consistent manner that includes metrics related to operational forecast products such as time of formation, time of extratropical transition, etc.
11. The IWTC-VII recommends that operational numerical weather prediction centres systematically define the impact of extratropical transition on the global forecast skill of the operational models. Additionally, the impacts should be reported using metrics that have relevance to operational parameters such as wave activity, cyclone characteristics, etc.

Topic 3 - Tropical Cyclones and Climate

12. The IWTC-VII recommends that there be continued effort placed into reducing the uncertainty in climate change projections of tropical cyclones. A continued effort to improve the models and reduce uncertainty in projections of the spatial distributions of SST, upper tropospheric structures and mid-tropospheric humidity from global climate models is needed. There is also a need for very long control runs of TC activity to monitor and understand internal variability in various basins.

Topic 4 - Disaster risks, mitigation, warning systems, and socio-economic impacts

13. (High Priority) The IWTC-VII recommends that nations share real-time observed data across operational centres to enable flood forecasts in cross-country basins.

Keynote Sessions

14. The IWTC VII recommends that numerical prediction centres that provide probabilistic or ensemble products should extend their lead time forecast beyond the 5-day period to facilitate longer-lead forecast utility of this crucial forecast information and be made more widely available to the RSMCs and NMHSs.

Recommendations to the Research Community

Topic 1 - TC structure and intensity change

1. The IWTC-VII encourages research towards improving the understanding of the impact of various environmental parameters on TC structure and intensity. These include vertical shear, humidity, water vapour advection, dust, topography, ocean heat content, boundary-layer fluxes, and upper-level outflow among others.

2. The IWTC-VII encourages research into the role of inner-core processes, such as barotropic instability, eye-eyewall mixing, and convection and its organization, on TC intensification. This research is especially important for rapid intensification.

3. The IWTC-VII encourages research into predictability limits for structure, intensity, and track forecasting.

4. The IWTC-VII encourages the collection of adequate real-time observations globally, including atmospheric, surface, and sub-surface oceanic observations. Research should be undertaken to optimize the utility from new observing systems and quantify the degree of gain to forecasts possible by using these observing systems.

5. The IWTC-VII encourages the development of a universal cyclone classification system for tropical, sub-tropical, and hybrid cyclones and guidance to discriminate between developing and non-developing baroclinic to tropical systems.

6. The IWTC-VII encourages the continued development and improvement of satellite-based analysis tools for TC intensity and structure estimation and prediction.

Topic 2 - Tropical Cyclone Formation and Extratropical Transition

7. (High Priority) The IWTC-VII recommends that a systematic effort be put forward to analyze factors related to tropical cyclone formation that are common among ocean basins and those that are unique to individual regions.

8. The IWTC-VII recommends that research on tropical cyclone formation address factors that govern the rate at which a tropical disturbance intensifies to a tropical cyclone. This should include patterns associated with specific synoptic scale and mesoscale regimes.

9. The IWTC-VII recommends that a type of best-track database be initiated and maintained for tropical systems that have a potential to develop into a tropical cyclone (i.e., INVESTS). This database will facilitate the statistical analysis of false alarm rates and time to formation.

10. The IWTC-VII recommends that development of a statistical-dynamical (i.e., SHIPS-type) feature-based product for tropical cyclone formation be pursued.

11. The IWTC-VII recommends that current operational field programmes and modelling efforts systematically address the role of ocean features during tropical cyclone formation and extratropical transition. This should include the collection and transmission of ocean data in real time as done with aircraft dropwindsonde data.

12. The IWTC-VII recommends that a field campaign be conducted in the South Indian Ocean region to study tropical cyclone formation, intensity and structure change, and extratropical transition or dissipation in that region.

13. The IWTC-VII recommends systematic observation of extratropical transition events in existing observing programmes to aid in the establishment of forecast thresholds for high-impact weather events and identification of factors that define the variability of such events.

14. The IWTC-VII recommends that research be conducted on satellite pattern-recognition techniques for classification of wind and precipitation distributions during extratropical transition to aid in the establishment of advisories.

Topic 3 - Tropical Cyclones and Climate

15. (High Priority) There is value in seasonal probabilistic prediction of tropical cyclone occurrence. The IWTC-VII recommends continued research and development of seasonal forecast systems for all basins and sub-regions where predictability has been demonstrated relative to a baseline skill level and supported by a standardized verification process.

16. (High Priority) There is considerable value in prediction of tropical cyclone activity on intra-seasonal time scales. The IWTC-VII recommends continued research and development on dynamical extended-range forecasts of tropical cyclone activity that is also supported by standardized verification. The IWTC-VII also recommends that a website be created with the existing operational sub-seasonal tropical cyclone forecasts, following the same guidelines for the existing WMO-supported tropical cyclone seasonal forecast website.

17. The IWTC-VII recommends that researchers work to better relate short-term climate variability and tropical cyclone activity, which should include inter-basin variability and encourage further exploration on the seasonal and intra-seasonal predictability (and limits of predictability) of tropical cyclogenesis, tropical cyclone activity, tropical cyclone tracks, landfall, and the extratropical transition of tropical cyclones.

18. Because of the strong dependence of seasonal tropical cyclone activity on the state of the El Niño-Southern Oscillation (ENSO), it is recommended that the skill of seasonal forecasts relative to the ENSO state, and prediction of the ENSO state, be documented.

19. Additional research into the potential influence of various large-scale climate modes (e.g., the North Atlantic Oscillation, Arctic Oscillation, Pacific Decadal Oscillation, Interdecadal Pacific Oscillation, and Indian Ocean Dipole) on tropical cyclone activity globally and regionally is recommended.

20. The IWTC-VII recommends that there be continued effort placed into reducing the uncertainty in climate change projections of tropical cyclones. This includes:

- Theory: A greater emphasis on theoretical understanding of TC formation and the relationship of tropical cyclones to climate
- Observations: Homogeneous TC data sets, construction and interpretation of historic TC data sets compiled from numerous sources and further research into the nature, causes and impact of inhomogeneities in historic tropical cyclone data sets from all cyclone basins

Topic 4 - Disaster risks, mitigation, warning systems, and socio-economic impacts.

21. The IWTC-VII recommends that researchers develop and validate tropical cyclone (multi-hazard) catastrophe models for all tropical cyclone regions. Researchers should investigate methods to link real time meteorological data to tropical cyclone risk models.

22. The IWTC-VII recommends that socio-economic impact studies of significant landfalling tropical cyclones be conducted and published. A particular aim of these studies could be to assess the impacts of social media on warnings and mitigation. To achieve this goal, adequate resources should be identified to support the deployment of multi-disciplinary teams to survey the TC impact area.

23. The IWTC-VII recommends that economists be encouraged to work with the meteorological community to conduct a cost-benefit analysis of disaster mitigation strategy and initiatives (including warning systems).

Keynote Sessions

24. (High Priority) The global best track database of tropical cyclone position, intensity, size, and other metrics, is an extremely valuable and important resource for all aspects of tropical cyclone research from daily to seasonal and climate time scales. The IWTC-VII encourages the continued reanalysis and improvement of the quality of the global tropical cyclone best track database in the following ways:

- A survey of users should be conducted to determine which metrics or parameters are needed from the global tropical cyclone best track dataset including documentation of the uncertainties in the historical tropical cyclone databases along with quality control flags for all derived quantities and a record of how they were derived.
- A working group of experts who will oversee the database should be established. This working group should ensure the homogeneity and long-term reliability of the database examining such issues as 10-min versus 1-min mean wind; consistency across regional borders; and consistency among datasets within the same region.
- An online clearinghouse for the global tropical cyclone best track database should be hosted in a central location to facilitate access.

25. (High Priority) High winds and heavy rainfall and flooding caused by landfalling tropical and extratropical cyclones are recognized as extreme weather events. However, the physical mechanisms associated with these processes are not currently well understood. Therefore, the IWTC-VII recommends that research efforts should be enhanced in this area. In addition, the research community should develop strategies to improve community preparation for such events via increased observations, improved forecast tools, adequate training, and threat communication.

26. The IWTC VII encourages research that improves the quantification of the relationship between the variations of radius of maximum winds and minimum sea-level pressure.

27. The ITWC VII encourages research on the reliability of rainfall measurements in the high-wind environment of a tropical cyclone.

28. The IWTC-VII recommends that efforts in improving radar and satellite data assimilation techniques and microphysical and boundary layer parameterizations should continue for numerical modelling of quantitative precipitation.

29. The IWTC VII encourages collaboration between hydrologists and precipitation researchers to develop and improve coupled hydrological–meteorological models that permit prediction of the temporal and spatial distribution of both the rainfall and the resultant flooding.

Seventh International Workshop on Tropical Cyclones (IWTC-VII)

(La Réunion, France, 15-20 November 2010)

Workshop Agenda

Sunday 14 November

- 14:00 16:00 Registration
- 16:30 18:00 Briefing Session for IC, LOC, Session Chairs and Rapporteurs
- 21:00 21:30 Pre-workshop Orientation Session

Monday 15 November

Opening Ceremony

- 09:00 09:40 Welcome, introductions, logistics and expectations
- 09:40 10:00 Review IWTCVI & Global Perspectives book (Johnny Chan)
- 10:00 10:10 Update on Global Forecast Guide (Chip Guard)
- 10:10 10:20 Review of IWTCLP-II (Russ Elsberry)
- 10:20 – 10:30 Review of QPE/QPF III (Chen Lianshou)
- 10:30 10:50 Expert Team Statement on TCs and Climate Change
(Tom Knutson and John McBride)
- 10:50 – 11:00 Workshop Logistics (Philippe Caroff)
- 11:00 11:30 Morning tea

Keynote Sessions

- 11:30 12:30 Keynote 1: TC surface wind structure, and the related pressure wind relationships
(John Knaff and Bruce Harper)
- 12:30 14:00 Lunch
- 14:00 15:00 Keynote 2: TC probabilistic forecasting and related product development issues
and applications for user risk assessment
(Gary Foley and Chris Landsea)
- 15:00 16:00 Keynote 3: TC precipitation (QPE/QPF) and related inland flood modeling
(Yihong Duan and Jinping Liu (Presented by Hui Lu))
- 16:00 16:30 Afternoon tea

- 16:30 18:00 Breakout discussion groups for keynote topic sessions
- 18:30 Icebreaker

Tuesday 16 November

Topic 1: Structure and Intensity Change

Plenary Session (Chairs: Rob Rogers and Lixion Avila)

- 08:30 09:00 Environmental impacts on tropical cyclone structure and intensity change (Jenni Evans)
- 09:00 09:30 Innercore impacts (Elizabeth Ritchie)
- 09:30 10:00 Airsea interface and oceanic influences (L. K. (Nick) Shay)
- 10:00 10:30 Observation capabilities and opportunities (Edward Fukada and John Molinari)
- 10:30 11:00 Morning tea
- 11:00 11:30 Structure and intensity change: Operational guidance (Andrew Burton)
- 11:30 12:00 Subtropical and hybrid systems (John R. Gyakum)
- 12:00 12:30 Topic chair summary (Robert Rogers)
Instructions for breakout sessions (Chris Velden and Jeff Kepert)
- 12:30 14:00 Lunch
- 14:00 16:00 Breakout Discussion Groups for Topic 1
- 16:00 16:30 Afternoon tea

Special Focus Session 1 (Parallel)

- 16:30 18:00 Special Focus 1a: Targeted observations for TC track forecasting (C.C. Wu and Sharan Majumdar)
- 16:30 18:00 Special Focus 1b: Ocean field experiments (ITOP, Gulf of Mexico) and new research findings (Nick Shay and Jeff Hawkins)

Wednesday 17 November

Topic 2: TC formation and extratropical transition

Plenary Session (Chairs: Pat Harr and Russ Elsberry)

- 09:00 09:30 TC formation: Theory and idealized modeling (Michael T. Montgomery and Roger K. Smith (Presented by Pat Harr))
- 09:30 10:00 Field experiment formation studies (Russ Elsberry and Chris Davis)

- 10:00 10:30 Formation forecasting (Grant Elliott (Presented by Pat Harr))
- 10:30 11:00 Morning tea
- 11:00 11:30 Extratropical transition research and field experiments (Sarah Jones)
- 11:30 12:00 Forecasting extratropical transition (Chris Fogarty)
- 12:00 12:30 Topic chair summary (Pat Harr)
- 12:30 14:00 Lunch
- 14:00 16:00 Breakout Discussion Groups for Topic 2
- 16:00 16:30 Afternoon tea
- Special Focus Session 2 (Parallel)***
- 16:30 18:00 Special Focus 2a: THORPEX/TIGGE applications to TC motion and forecasting (Tetsuo Nakazawa)
- 16:30 18:00 Special Focus 2b: IBTrACS activities and updates (Ken Knapp)

Thursday 18 November

- 09:00 12:30 Group Excursion
- 12:30 14:00 Conference Lunch

Topic 3: TCs in intraseasonal to climate time scales

Plenary Session (Chairs: Suzana Camargo and Johnny Chan)

- 14:00 14:30 TC activity on intraseasonal time scales (Frédéric Vitart)
- 14:30 15:00 TC variability on seasonal time scales (observations and forecasting) (Philip J. Klotzbach)
- 15:00 15:30 TC activity on climate time scales (Tom Knutson)
- 15:30 16:00 Topic chair summary (Suzana Camargo)
- 16:00 16:30 Afternoon tea
- 16:30 18:00 Breakout Discussion Groups for Topic 3
- 18:00 20:00 Dinner (own arrangement)
- 20:00 21:30 Panel discussion: Future research directions for TCs and climate change. Moderators: John McBride and Tom Knutson. Panel: Kerry Emanuel, Chris Landsea, Greg Holland, Johnny Chan, Masato Sugi

Friday 19 November

Topic 4: Disaster risks, mitigation, warning systems and socioeconomic impacts

Plenary Session (Chairs: Jim Davidson and Masashi Kunitsugi)

- 09:00 09:30 Risk assessment (Richard J. Murnane)
- 09:30 10:00 Disaster mitigation strategies (Bill Read)
- 10:00 10:30 Operational warning strategies (S. T. Chan)
- 10:30 11:00 Morning tea
- 11:00 11:30 Societal impacts of TCs (David King and Linda AndersonBerry)
- 11:30 12:00 Economic impacts of TCs (Ryan P. Crompton)
- 12:00 12:30 Topic chair summary (Jim Davidson)
- 12:30 14:00 Lunch
- 14:00 16:00 Breakout Discussion Groups for Topic 4
- 16:00 16:30 Afternoon tea

Special Focus Session 3 (Parallel)

- 16:30 18:00 Special Focus 3a: Overview and operational products expected from HFIP (Rob Rogers)
- 16:30 18:00 Special Focus 3b: Open discussion on application of the Dvorak technique and resolving interagency intensity differences (John Knaff and Chris Velden)

Saturday 20 November

Recommendations and Close Plenary Session (Chair: Lianshou Chen)

- 09:00 11:00 Topic summaries and presentation of recommendations. Topic and keynote chairs (Liz Ritchie)
- 11:00 11:30 Morning tea
- 11:30 14:00 Recommendation committee meets (with working lunch) (Free time for others)
- 12:30 14:00 Lunch
- 14:00 16:00 Recommendations committee summary (Liz Ritchie)
- Closing ceremony (Chair: Lianshou Chen)

Seventh International Workshop on Tropical Cyclones (IWTC-VII)

(La Réunion, France, 15-20 November 2010)

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Group photo of Participants attending the 7th International Workshop on Tropical Cyclones (IWTC-VII), Saint-Gilles-Les-Bains, La Réunion, France, 15-20 November 2010

World Weather Research Programme (WWRP) Report Series

Sixth WMO International Workshop on Tropical Cyclones (IWTC-VI), San Jose, Costa Rica, 21-30 November 2006 (WMO TD No. 1383) (**WWRP 2007 - 1**).

Third WMO International Verification Workshop Emphasizing Training Aspects, ECMWF, Reading, UK, 29 January - 2 February 2007 (WMO TD No. 1391) (**WWRP 2007 - 2**).

WMO International Training Workshop on Tropical Cyclone Disaster Reduction (Guangzhou, China, 26 - 31 March 2007) (WMO TD No. 1392) (**WWRP 2007 - 3**).

Report of the WMO/CAS Working Group on Tropical Meteorology Research (Guangzhou, China, 22-24 March 2007) (WMO TD No. 1393) (**WWRP 2007 - 4**).

Report of the First Session of the Joint Scientific Committee (JSC) for the World Weather Research Programme (WWRP), (Geneva, Switzerland, 23-25 April 2007) (WMO TD No. 1412) (**WWRP 2007 - 5**).

Report of the CAS Working Group on Tropical Meteorology Research (Shenzhen, China, 12-16 December 2005) (WMO TD No. 1414) (**WWRP 2007 - 6**).

Preprints of Abstracts of Papers for the Fourth WMO International Workshop on Monsoons (IWM-IV) (Beijing, China, 20-25 October 2008) (WMO TD No. 1446) (**WWRP 2008 - 1**).

Proceedings of the Fourth WMO International Workshop on Monsoons (IWM-IV) (Beijing, China, 20-25 October 2008) (WMO TD No. 1447) (**WWRP 2008 - 2**).

WMO Training Workshop on Operational Monsoon Research and Forecast Issues – Lecture Notes, Beijing, China, 24-25 October 2008 (WMO TD No. 1453) (**WWRP 2008 - 3**).

Expert Meeting to Evaluate Skill of Tropical Cyclone Seasonal Forecasts (Boulder, Colorado, USA, 24-25 April 2008) (WMO TD No. 1455) (**WWRP 2008 - 4**).

Recommendations for the Verification and Intercomparison of QPFS and PQPFS from Operational NWP Models – Revision 2 - October 2008 (WMO TD No. 1485) (**WWRP 2009 - 1**).

Strategic Plan for the Implementation of WMO's World Weather Research Programme (WWRP): 2009-2017 (WMO TD No. 1505) (**WWRP 2009 - 2**).

4th WMO International Verification Methods Workshop, Helsinki, Finland, 8-10 June 2009 (WMO TD No. 1540) (**WWRP 2010 - 1**).

1st WMO International Conference on Indian Ocean Tropical Cyclones and Climate Change, Muscat, Sultanate of Oman, 8-11 March 2009 (WMO TD No. 1541) (**WWRP 2010 - 2**).

Training Workshop on Tropical Cyclone Forecasting WMO Typhoon Landfall Forecast Demonstration Project, Shanghai, China, 24-28 May 2010 (WMO TD No. 1547) (**WWRP 2010 - 3**) (CD only).

2nd WMO International Workshop on Tropical Cyclone Landfall Processes (IWTCLP-II), Shanghai, China, 19-23 October 2009 (WMO TD No. 1548) (**WWRP 2010 - 4**).

5th WMO Symposium on Data Assimilation, Melbourne, Australia, 5-9 October 2009 (WMO TD No. 1549) (**WWRP 2010 - 5**).