出國報告（出國類別：開會）

赴美國夏威夷州檀香山
參加世界氣象組織舉辦之
第 9 屆熱帶氣旋國際研討會

服務機關：交通部中央氣象局
姓名職稱：黃椿喜技正
連國淵副研究員
派赴國家/地區：美國
出國期間：107 年 12 月 2 日至 10 日
報告日期：108 年 2 月 12 日

摘要

颱風災害損失佔臺灣氣象災害之首，對經濟、民生影響甚鉅，因此颱風之觀測與預報為中央氣象局（以下稱氣象局）的重要業務之一，是以氣象局為掌握國際最新的颱風測報相關技術發展動態，須透過各種機會與國際各氣象機關及學研機構保持互動。本次氣象局氣象預報中心黃椿喜技正及氣象科技研究中心連國淵副研究員參加世界氣象組織（World Meteorological Organization）舉辦之「第 9 屆國際熱帶氣旋研討會」，和全世界熱帶氣旋領域最頂尖的科學家，以及各國或各區域最重要的作業中心之預報員進行交流研討，除了了解目前熱帶氣旋領域的最新進展以外，也透過交流的過程提供氣象局在熱帶氣旋預報上的做法及意見。

此次熱帶氣旋國際研討會安排「熱帶氣旋生成」、「熱帶氣旋路徑」、「熱帶氣旋強度變化」、「熱帶氣旋結構分析與變化」、「熱帶氣旋分析及遙測」、「熱帶氣旋預報不確定性及警特報之傳播與溝通」及「綜觀尺度以外的熱帶氣旋分析驗證」等 7 項子題。這些子題都是現行熱帶氣旋預報上最重要的議題，也是研究上亟待突破的重點，尤其是有關生成、強度、結構及新的觀測技術與策略等，需要更多的對話與區域合作才能有效提升預報能力。與頂尖科學家的討論除了可以強化我們對熱帶氣旋理論與作業更深入的理解外，也可以將預報上遇到的困難提供給科學家進行更基礎或深入的研究，最後再回饋到預報作業。在整個研討過程中，我國熱帶氣旋預報的現況大致都能與世界接軌，預報技術能力也處在相對較優國之一，但未來熱帶氣旋的預報仍有許多挑戰。

目次

一、目的

熱帶氣旋國際研討會（International Workshop of Tropical Cyclone；IWTC）是世界氣象組織（World Meteorological Organization；WMO）的世界氣象研究論壇（World Weather Research Programme；WWRP）與熱帶氣旋論壇（Tropical Cyclone Programme；TCP）之下每 4 年舉辦一次的主要工作會議。本次第 9 屆會議（ITWC-9）於美國夏威夷州檀香山凱薩飯店舉行，會議期間為 107 年 12 月 3 日至 7 日止，會議主席為 Mike Brennan 博士及夏威夷大學王玉清（Yuqing Wang）教授。這個會議第 1 次於 1985 年在泰國曼谷舉行，當時由 William M. Gray 擔任第 1 次會議的主席，第 8 屆會議則是在韓國釜山舉行。IWTC 會議透過邀請國際研究熱帶氣旋的專家學者與國家級作業中心之專業颱風預報資深預報員進行交流，主要目的是透過學界研究學者與作業單位預報員的對話過程，了解颱風預報作業上的實際需求，將最新的研究技術導入颱風預報作業，並透過預報作業的需求建議未來研究的方向。在這個理念下，會議訂定的主要目標為：

1. 檢驗目前全球熱帶氣旋的理論知識、預報技術與科學研究的趨勢及面向；
2. 找出熱帶氣旋作業與研究的的需求及機會；
3. 使作業單位與研究社群進行對話與交流；
4. 提供 WMO 建議、使預報作業與研究機構交流，進而改進全球對於熱帶氣旋的知識及預報工作。

在這個架構下，需要討論的面向涵蓋熱帶氣旋生成與環境，熱帶氣旋強度、結構與眼牆，熱帶氣旋路徑預報，熱帶氣旋與氣候變遷等。此次熱帶氣旋國際研討會預先安排進行報告與討論的子題共 7 項，分別是「熱帶氣旋生成」、「熱帶氣旋路徑」、「熱帶氣旋強度變化」、「熱帶氣旋結構分析與變化」、「熱帶氣旋分析及遙測」、「熱帶氣旋預報不確定性及警特報之傳播與溝通」及「綜觀尺度以外的熱帶氣旋分析驗證」。會議進行時每個子題下再細分為數個副子題，會議期間每半天討論 1 子題。進行方式首先由負責子題或副子題的學者，對所有參與者報告該子題近年來科學上的進展或預報作業上的重大需求。報告結束後，主席宣布將參與學者與預報員隨機分為 8 組人員，每組設立一位引言者及一位記錄員，每次分組人員皆不相同，但有一定比例的學者與預報員。分組討論時，由引言者帶領大家針對此次的子題進行發言討論，包括預先建議的議題或者經由討論得到的新議題，由記錄員將討論的重點摘要後提交到大會子題負責人，經過子題負責人統整後，最後一天在大會進行總結報告，經過大會討論後再提出給 WMO 的建議清單。

除了各子題的討論以外，每天也設定數個特別討論議題，包括「下個世代的氣象衛

星觀測系統」、「2017、2018 年的重要熱帶氣旋」、「風暴潮預報與警報」、「熱帶氣旋空間分析與遙測工具」、「新觀測策略」、「新無人飛機在熱帶氣旋研究的應用」、「國家層級氣象預報與警報服務之驗證與校驗」、「全球多重警報或特報系統」及「改進熱帶氣旋預報技術與資料庫」等。

此次會議邀請國際著名學者 Russell L. Elsberry 教授擔任焦點演講者，講述「改進熱帶氣旋結構分析與預報，並提供更有效的熱帶氣旋機率預警資訊或警報」。

中央氣象局（以下稱氣象局）氣象預報中心黃椿喜技正與氣象科技研究中心連國淵副研究員分別以資深預報員及研究員身份受邀參加會議，國內同行的學者有臺灣大學吳俊傑教授、黃怡瑄博士後研究員及李宗勇研究生等，另外臺大周仲島教授亦受邀參加會議。黃技正及連副研究員在這個會議中參與共同發表「近期熱帶氣旋運動之基礎與理論研究進展（Recent progress in fundamental and theoretical studies on TC motion）」報告，主筆為日本琉球大學地球物理所的 Kosuke Ito 教授與臺灣大學吳俊傑教授，其他共同作者有美國國家大氣研究中心（National Center for Atmospheric Research；NCAR）的 Chris Davis 博士、中國中山大學的 Kelvin Chan、英國帝國學院的 Ralf Toumi、臺灣大學李宗勇研究生、緬甸大氣水文部門的 War War Thein 等。

經由參加聯合國 WMO 的熱帶氣旋研討會，使我們能參與聯合國重要的國際氣象活動，增加臺灣在國際上的能見度，同時瞭解近年來熱帶氣旋預報上的重要進展與方向，使臺灣地區的颱風預報可以與國際接軌並與時俱進。另外，也可以透過國際會議的討論，將臺灣地區重要的颱風研究與預報作業推廣至國際，提升臺灣地區熱帶氣旋預報的影響力，對拓展我國國際空間有重要意義。

其他相關資訊可以參考 IWTC-9 的官方網頁，網址如下：
https://www.wmo.int/pages/prog/arep/wwrp/IWTC-9.html

二、過程

此次會議在夏威夷州檀香山市的凱薩飯店舉行，逐日行程如下：

第 1 天 12 月 2 日　搭機赴夏威夷檀香山市

此次參加會議一行人，由臺灣大學吳俊傑教授領隊，12 月 2 日上午在桃園機場集合後直飛夏威夷 Wakiki 國際機場 （Wakiki International Airport），當日下午入住位於 Wakiki 海灘附近的凱薩飯店。

第 2 天 12 月 3 日　國際熱帶氣旋研討會第 1 天會議

會議第 1 天早上 8 點開始進行註冊，開幕儀式由此次主辦人 Mike Brennan 博士與夏威夷大學王玉清教授致詞，之後進行拍照。

短暫休息後針對 William Gray 教授舉行特別的紀念議程，由曾經與其共事的學者及其學生說明他的生平事蹟、颱風研究上的重要貢獻及其他值得紀念的事蹟。

之後由 Russell L. Elsberry 教授擔任邀請焦點演講，其演講題目為「改進熱帶氣旋結構分析與預報，並提供更有效的熱帶氣旋機率預警資訊或警報（Toward improved analyses & forecasts of TC Structure & more effective probabilistic TC hazard information & warning）」。另由 Sarah Jones 博士報告「WWRP：推動並改進全球氣象科學（WWRP: catalyzing innovation in weather science internationally）」。

下午開始進行 7 個子題中的第 1 個子題「熱帶氣旋生成」討論，子題下另有 2 副子題分別是 1.1 「熱帶氣旋生成之綜觀、中尺度及對流尺度面向；Synoptic, Mesoscale and Convective Scale Aspects of Cyclogenesis」及 1.2 「熱帶氣旋生成之預報作業面向」。經過短暫休息後進行分組討論。

第 3 天 12 月 4 日 國際熱帶氣旋研討會第 2 天會議

第 2 天會議從早上 9 點開始，討論第 2 子題「熱帶氣旋路徑」。子題下共 3 個副子題，分別是 2.1 「近期熱帶氣旋運動之基礎與理論研究進展」報告，由日本琉球大學 Kosuke Ito 教授報告，討論近年來在颱風路徑預報上遇到的問題；2.2 是「近期在熱帶氣旋路徑預報與不確定性回顧之進展（Review of Recent Progress in TC Track Forecasting and Expression of Uncertainties）」；2.3 則是「了解高難度路徑預報之進展（Advances in Understanding Difficult Cases of Track Forecasts）」。報告完畢後進入分組討論。

下午是第 3 子題「強度變化」，此子題共 3 個副子題，分別是 3.1「強度變化：內部機制影響（Intensity Change: Internal Influences）」，3.2「強度變化：外部機制影響（Intensity Change: External Influences）」及 3.3「強度變化：作業面相（Intensity Change: Operational Perspectives）」。報告完後進入分組討論。

分組討論完畢後，另有 2 個特別議題，分別是「2017、2018 年重要的熱帶氣旋」及由日本琉球大學 Hiroyuki Yamada 博士報告「最新觀測策略（亞洲颱風飛機觀測）」，後者主要內容為介紹其近 2 年執行颱風投落送觀測計畫，並於 2018 年觀測颱風眼的過程。

第 4 天 12 月 5 日　國際熱帶氣旋研討會第 3 天會議

會議第 3 天上午進行第 4 子題「熱帶氣旋結構分析與演變」，此子題下共 3 個副子題，分別是 4.1「非對稱風場之分析與預報（Analysis & Prediction of Wind Field Asymmetry）」，4.2「熱帶氣旋結構分析與變化：雙眼牆形成與風場擴張（TC Structure Analysis & Change: Secondary Eyewall Formation & Expansion of the Wind Field）」及 4.3「溫帶變性氣旋（Extratropical Transition）」。報告完後進行分組討論。

下午進行第 5 子題「熱帶氣旋分析與遙測」，此子題下共 2 個副子題，分別是 5.1「現行與新發展偵測熱帶氣旋近地表風場結構之方法（New & Existing Methods to Estimate TC Surface Wind Structure）」及 5.2「新世代地球同步衛星與熱帶氣旋監測（New Generation Geostationary Satellites for TC Monitoring）」。報告完後進行分組討論。

分組討論完畢後，進行 3 個特別議題的討論，此 3 個特別議題分別是「下世代氣象衛星觀測系統（向日葵 8 號；低軌道衛星觀測）」、「熱帶氣旋預報的系統性校驗標準」及「改進熱帶氣旋預報技巧與熱帶氣旋資料庫」。

第 5 天 12 月 6 日　國際熱帶氣旋研討會第 4 天會議

當日上午進行第 6 子題「熱帶氣旋預報不確定性及警特報之傳播與溝通」之討論，該子題下分 3 個副子題，分別是 6.1「瞭解熱帶氣旋對社會之衝擊與進一步的全體警報系統概念（Understanding TC Impacts on Society for the Purpose of Advancing the Total Warning System Concept）」，6.2「風險之溝通與熱帶氣旋預報之不確定性（Communicating Risk & TC Forecast Uncertainty）」及 6.3「系集預報應用於熱帶氣旋預報作業之現行與潛在應用（Current & Potential Use of Ensemble Forecasts in Operational TC Forecasting）」，後進行分組討論。

下午進行第 7 子題「綜觀尺度以外的熱帶氣旋分析驗證」，此子題下共分 3 子題，分別是 7.1「熱帶氣旋與氣候變遷（TC and Climate Change）」，7.2「熱帶氣旋之季節預報（Seasonal TC Forecasting）」及 7.3「次季節尺度之熱帶氣旋預測與熱帶氣旋資料庫（TC Prediction on Subseasonal Timescales & the S2S Database）」，後進行分組討論。

完成分組討論後，另有 2 個特別議題，分別是「熱帶氣旋之新的無人飛機觀測策略」及「熱帶氣旋引起之風暴潮預報與警報」。

第 6 天 12 月 7 日　國際熱帶氣旋研討會第 5 天會議

最後一天的議程主要在大會上進行 7 個子題分組討論之結論與建議，中間穿插「數值天氣預報」的特別議題，進行總結會議後則是閉幕典禮。整個會議在下午 1 點左右結束。

此次總結會議主要討論的方向與最後提出的主要建議如下：

1. 建議作業單位進行颱風最大風速半徑分析及預報，並在最佳路徑預報中增訂此項目；
2. 建議作業中心增加路徑、強度、結構或特別難預報個案之熱帶氣旋資料庫；
3. 建議作業中心及研究單位提升颱風生成前的路徑、強度、結構等預報；
4. 建議作業單位利用系集預報估計路徑潛勢預報之不確定性範圍，取代靜態給定的不確定性範圍；
5. 建議提升系集預報及不確定性在社會科學方面的知識與應用；
6. 推廣國際 TIGGE（THORPEX Interactive Grand Global Ensemble）系集資料庫；
7. 建議增加雙眼牆生成與眼牆置換過程的研究及作業上之應用；
8. 建議作業中心與研究單位提升強度預報的能力及指引，並整合相關預報指引；
9. 建議增加發展或不發展的擾動資料庫，包括風暴的特性，如中心位置、德式分析指數等；
10. 建議研究學者、預報員與社會科學家共同進行早期預警系統之開發工作；
11. 建議未來應推廣更多的機率預報；
12. 建議各區域間合作，應用新型態的先進觀測技術，如多重觀測系統、無人飛機、衛星等，進行大型的區域熱帶氣旋觀測計畫；
13. 發展雷達、衛星等遙測反演近地表風場技術；
14. 建議在 IWTC 的架構下，舉行數個次領域研討會議。

第 7 天 12 月 8 日　休息日

由於當日沒有航班返回臺灣，因此 12 月 8 日暫時停留於夏威夷。

第 8、9 天 12 月 9、10 日　搭機返回臺灣

12 月 9 日中午前赴 Wakiki 國際機場搭機，隔日下午抵達桃園機場。

三、心得及建議

本次藉由參加 WMO 舉辦之「第 9 屆國際熱帶氣旋研討會」，可以和全世界在熱帶氣旋領域最頂尖的科學家，以及各國或各區域最重要的作業中心之預報員進行交流研討，除了可以了解目前熱帶氣旋領域的最新進展以外，也透過交流的過程，提供氣象局在熱帶氣旋預報上的做法及意見。

此次熱帶氣旋國際研討會所安排的 7 項子題為「熱帶氣旋生成」、「熱帶氣旋路徑」、「熱帶氣旋強度變化」、「熱帶氣旋結構分析與變化」、「熱帶氣旋分析及遙測」、「熱帶氣旋預報不確定性及警特報之傳播與溝通」及「綜觀尺度以外的熱帶氣旋分析驗證」。這些議題都是現行熱帶氣旋預報上最重要的議題，也是研究上亟待突破的重點，尤其是有關生成、強度、結構與新的觀測技術及策略等議題，需要更多的對話與區域合作才能有效提升預報能力。與頂尖科學家的討論除了可以強化我們對熱帶氣旋理論與作業更深入的理解外，也可以將預報上遇到的困難提供給科學家進行更基礎或深入的研究，最後再回饋到預報作業。在整個研討過程裡面，我國熱帶氣旋預報的現況大致都能與世界接軌，預報技術能力也處在相對較優的國家之一，但未來熱帶氣旋的預報仍有許多挑戰。

目前全世界颱風在路徑預報上的能力已經逐漸提升，但主要的困難大多數仍在颱風強度、結構變化等等議題，會議中討論比較熱烈的議題大致如下：

1. 颱風生成的預報問題；
2. 颱風形成前的路徑、強度及結構預報；
3. 颱風最大風速半徑之預報；
4. 風切對與颱風初生環境、生成、結構、強度及變性等影響；
5. 颱風強度預報，尤其是颱風快速增強之預報；
6. 颱風雙眼牆形成過程與眼牆置換機制對強度之影響；
7. 新的颱風觀測技術及應用；
8. 無人飛機觀測之應用；
9. 新世代衛星觀測之應用；
10. 衛星反演風場資料；
11. 強度預報指引之開發與整合；
12. 數值天氣預報或系集天氣預報之持續精進；
13. 機率預報與系集預報系統之推廣及應用。

參與研討會的過程，發現我國參與國際合作事務仍有諸多內外在的限制，外在的當然是臺灣的國際定位問題，導致官方機構參與全球性或區域性的國際合作事務上有很大的困難，可能不被邀請或只能用迂迴的方式參與。但在氣象的領域上，我國氣象局的預報技術其實並不低，尤其近年來，積極引進最新的預報技術、模式與分析，加上一些本土化預報技術的發展，教育訓練的持續進行，在某些預報領域上應有一定的優勢。往後仍應堅持發展自己的預報技術與能力，勇於突破這些困境，將臺灣的預報技術、能力或服務推廣至國際，甚至能進而產生一些影響力。內在的部分，主要是侷限於出國經

費的短缺及編列困難，有時需要額外的計畫支援，導致參與國際的過程產生諸多限制，減少相關人員出國意願或相對提高門檻，另外在語言的隔閡上也導致參加國際會議的門檻提高。

另一方面，近年來氣象局參與國際合作事務明顯增多，尤其是針對南向區域合作或針對友邦國家援助方面。在這個面向上，我國的預報能力通常優於這些國家，因此多以援助或教育訓練為主。然而進行援助或教育訓練，氣象局的預報能力仍要持續提升，而英文的讀寫與口說能力也要強化訓練才行。在對美、日、韓或中國等方面的合作，或有合作，或有競爭，也常需要培育更多的專業人才，並提升英文能力，才能使這些合作事務推展的更加順利，並有效提升我國在氣象預報上的能見度與影響力。

附錄 1 – 相關英文縮寫對應

IWTC: International Workshop of Tropical Cyclone （熱帶氣旋國際研討會）

NCAR: National Center for Atmospheric Research （美國國家大氣研究中心）

TCP: Tropical Cyclone Programme （熱帶氣旋論壇）

WMO: World Meteorological Organization （世界氣象組織）

WWRP: World Weather Research Programme （世界氣象研究論壇）

附錄 2 – 行程照片

第 9 屆國際熱帶氣旋研討會參與科學家合照

臺灣大學參加 IWTC-9 同行人員，由左至右分別為李宗勇研究生、本報告撰寫人氣象局連國淵副研究員、吳俊傑教授、本報告撰寫人氣象局黃椿喜技正及黃怡瑄博士後研究員。

黃椿喜技正及連國淵副研究員參加 IWTC-9 之會議名牌

IWTC-9 會議現場照片

IWTC-9 第 2 子題成員合影，前排左一為香港 Johnny Chen 博士，左二為日本 Munehiko Yamaguchi 博士；後排左二為本報告撰寫人氣象局連國淵副研究員，左三為本報告撰寫人氣象局黃椿喜技正，左四為臺灣大學吳俊傑教授，右一為日本 Kosuke Ito 教授。

IWTC-9 分組討論會議過程

IWTC-9 同行日本學者合影

IWTC-9 同行韓國氣象廳颱風中心合影

附錄 3 – 大會議程

	DAY 0 2 Dec 2018 (SUNDAY)
17:00-18:00	PRE-COORDINATION MEETING
18:00-19:00	INTRODUCTION TO IWTC-9

TIME	DAY 1 3 Dec 2018 (MONDAY)
8:00-9:00	REGISTRATION/ INFORMATION DESK OPENS at 8am
9:00-9:30	OPENING CEREMONY
9:30-10:00	ORGANIZATIONAL ARRANGEMENTS and ANNOUNCEMENTS (Co-chairs)
10:00-10:30	COFFEE BREAK/PHOTO
10:30-11:30	Prof William Gray Special Lecture
11:30-12NN	KEYNOTE 1 Prof R Elsberry
12NN-12:30	KEYNOTE 2 Dr S Jones
12:30-14:00	LUNCH
14:00-14:30	IWTCLP-4 Summary
14:30-16:00	TOPIC 1 CYCLOGENESIS
16:00-16:30	COFFEE BREAK
16:30-17:30	TOPIC 1 BREAKOUT
17:30	END of DAY 1

TIME	DAY 2 4 Dec 2018 (TUESDAY)	DAY 3 5 Dec 2018 (WEDNESDAY)	DAY 4 6 Dec 2018 (THURSDAY)
9:00-10:30	TOPIC 2 TRACK	TOPIC 4 TC STRUCTURE ANALYSIS & CHANGE	TOPIC 6: COMMUNICATION OF FORECAST UNCERTAINTY & WARNINGS GMAS
10:30-11:00	COFFEE BREAK	COFFEE BREAK	COFFEE BREAK
11:00-12NN	TOPIC 2 BREAKOUT	TOPIC 4 BREAKOUT	TOPIC 6 BREAKOUT
12NN-13:30	LUNCH	LUNCH	LUNCH
13:30-15:00	TOPIC 3 TC INTENSITY CHANGE	TOPIC 5 TC ANALYSIS & REMOTE SENSING	TOPIC 7 TC VARIABILITY BEYOND THE SYNOPTIC SCALE
15:00-15:30	COFFEE BREAK	COFFEE BREAK	COFFEE BREAK
15:30-16:30	TOPIC 3 BREAKOUT	TOPIC 5 BREAKOUT	TOPIC 7 BREAKOUT
16:30-18:00	SIGNIFICANT TROPICAL CYCLONES in 2017 and 2018	NEXT GENERATION METEOROLOGICAL SATELLITE SYSTEMS BASIC SET OF VERIFICATION METRICS FOR TC FORECASTS	NEW USES OF UAV IN TC RESEARCH STORM SURGE FORECASTS & WARNINGS
18:00-19:00	NEW OBSERVATION STRATEGIES	IMPROVING SKILL OF TC FORECASTS & THE S2S DATABASE END OF DAY 3	END OF DAY 4
19:00	END OF DAY 2		

TIME	DAY 5 7 Dec 2018 (FRIDAY)
8:30-10:15	SUMMARY OF BREAKOUT SESSIONS (Topics 1-7) 15 min per topic
10:15	COFFEE BREAK
10:30-11:30	SPECIAL TOPIC SESSION NWP
11:30-12:30	IWTC-9 RECOMMENDATIONS
12:30-13:00	CLOSING CEREMONY
13:00	END OF IWTC-9

附錄 4 – 大會 7 項子議題及報告

TOPIC 1 **3 DEC** **CYCLOGENESIS** **DJ Halperin** （p) **M Mohapatra** **F Roux** (p) (GROUP PHOTO)	T1.1 Synoptic, Mesoscale and Convective Scale Aspects of Cyclogenesis **(B Tang (p) & J Fang (p))** T1.2 Cyclogenesis: Operational Forecasting Perspectives **(E Blake & SD Kotal) ppt** (p) - presenting **BREAKOUT SESSION GROUPS for TOPIC 1**
TOPIC 2 **4 DEC** **TC TRACK** **K Cheung** (p) **H Eito** (GROUP PHOTO)	T2.1 Recent Progress in Fundamental & Theoretical Studies on TC motion **(K Ito (p) & CC Wu)** T2.2 Review of Recent Progress in TC Track Forecasting and Expression of Uncertainties **(J Heming (p) & F Prates)** T2.3 Advances in Understanding Difficult Cases of Track Forecasts **(L Magnusson) (J Doyle (p))** (p) - presenting **BREAKOUT SESSION GROUPS for TOPIC 2**
TOPIC 3 **4 DEC** **TC INTENSITY ver2** **J Courtney** (p) **E Hendricks**	T3.1 Intensity Change: Internal Influences **(J Vigh (p))** T3.2 Intensity Change: External Influences **(S Braun (p)) ppt** T3.3 Intensity Change: Operational Perspectives (ver5) **ppt** **(S Langlade) (J Courtney (p))**

(GROUP PHOTO)	(p) - presenting **BREAKOUT SESSION GROUPS for TOPIC 3**
TOPIC 4 **TC STRUCTURE ANALYSIS & CHANGE** **D Nolan** **M Yamaguchi** (GROUP PHOTO)	T4.1 Analysis & Prediction of Wind Field Asymmetry **(C Sampson (p))** T4.2 TC Structure Analysis & Change: Secondary Eyewall Formation & Expansion of the Wind Field **(DP Stern (p))** T4.3 Extratropical Transition **(R McTaggart-Cowan & C Evans (p))** (p) - presenting **BREAKOUT SESSION GROUPS for TOPIC 4**
TOPIC 5 **TC ANALYSIS & REMOTE SENSING** **J Knaff** **P Caroff** (GROUP PHOTO)	T5.1 New & Existing Methods to Estimate TC Surface Wind Structure **(T Meissner & L Ricciardulli)** T5.2 New Generation Geostationary Satellites for TC Monitoring **ppt** **(K Bessho & J Beven)** (p) - presenting **BREAKOUT SESSION GROUPS for TOPIC 5**

TOPIC 6 **COMMUNICATION OF FORECAST UNCERTAINTY & WARNINGS** **MC Monteverde** **C Qian** (GROUP PHOTO)	T6.1 Understanding TC Impacts on Society for the Purpose of Advancing the Total Warning System Concept **ppt** **(B Fakhruddin (p))** T6.2 Communicating Risk & TC Forecast Uncertainty **ppt** **(L Anderson-Berry)** (V Prasad (p)) T6.3 Current & Potential Use of Ensemble Forecasts in Operational TC Forecasting **ppt** **(M Yamaguchi (p), H Titley & L Magnusson)** (p) - presenting BREAKOUT SESSION GROUPS for TOPIC 6
TOPIC 7 **TC VARIABILITY BEYOND THE SYNOPTIC SCALE** **T Knutson** **TC Lee** (GROUP PHOTO)	T7.1 TC and Climate Change **(K Walsh)** T7.2 Seasonal TC Forecasting **ppt** **(P Klotzbach)** T7.3 TC Prediction on Subseasonal Timescales & the S2S Database **(S Camargo)** (p) - presenting BREAKOUT SESSION GROUPS for TOPIC 7

附錄 5 – 子議題 2.1 報告初稿

Topic 2.1
Recent progress in fundamental and theoretical studies on TC motion

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Working Group (in alphabetical order): Chris Davis (NCAR, United States), Guo-Yuan Lien (CWB, Taiwan), Kelvin Chan (Sun Yat-sen University, China), Ralf Toumi (Imperial College, United Kingdom), Treng-Shi Huang (CWB, Taiwan), Tsung-Yung Lee (NTU, Taiwan), War War Thein (Myanmar Department of Meteorology and Hydrology, Myanmar)

Abstract: This report summarizes the recent advances in the fundamental understanding of the movement of TC. Although this area is quite mature, there are still considerable progresses. This report summarizes new concepts and updates on existing fundamental theories on TC movement obtained from simplified barotropic models, full-physics models, and data analysis. It also reviews the interaction with environment and discusses the fundamental aspects of predictability related to the TC movement. The conventional concepts of the steering flow, β-gyre, and diabatic heating remain important. However, sophisticated understanding of various mechanisms serves as an important basis toward the further improvement of track forecast.

2.1.1 Introduction

Amongst all the elements of TC forecasting, the track forecast has always been the most important, because the intensity, rainfall, and storm surge become less meaningful if the track forecast is wrong. Basically, a TC is influenced by the surrounding flow, but its motion is also modified by the β-gyre effect and the diabatic heating. Because of the importance of the TC track, the effects of topography, land-sea contrast and the interaction with other systems on the TC motion have also been intensively studied.

However, there are still considerable progresses in the understanding of the movement of the TC. With the errors in track forecast being decreased, the considerations of the physical processes that were previously thought of as "minor", have become more important. It is also worth mentioning that updated understandings of well-known mechanisms and the important target regions. This report does not repeat detailed discussions on the concepts mentioned earlier in Elsberry (1995), Chan (2010, 2017), and the latest one on the TC track in IWTC-VIII (Elliot and Yamaguchi, 2014). Rather, this report focuses on the recent findings from numerical models and data analysis.

2.1.2 Barotropic Models

Recently, Gonzalez et al. (2015) have shown that a barotropic non-divergent model has replicated the linear β-gyres as a stream function dipole with a uniform southeasterly ventilation flow across the vortex. The β-gyre effect can be interpreted in terms of a wave number-1 vortex Rossby wave. Because the positive mean radial gradient of the vorticity in the outer region constitutes an outer waveguide that supports very-low-frequency vortex Rossby waves, the reproduced structure of β-gyre clearly depends on the radial profile of the basic vorticity field. They also show that although the simulated storm with the linear model accelerates to unrealistically fast speed (8.5 m/s), the introduction of non-linearity yields the forced wavenumber-1 gyres, that have opposite phase of the linear gyres. In this way, their ventilation flow counteracts the advection by the linear gyres, to limit the overall vortex speed up to approximately 3 m/s.

Scheck et al. (2014) investigated the structure and evolution of SVs for stable TC-like vortex in background flows with horizontal shear using a non-divergent barotropic model (Fig. 2.1.1). In anti-cyclonic shear with westerly wind to the north, the leading initial SV for a stable TC-like vortex is aligned with streamlines connected to stagnation points. The singular value for the leading SV for anticyclonic shear is larger than that for the cyclonic shear. The evolved SV indicated a southwest-northeast displacement of the vortex. This is associated with the efficient advection by the outer perturbation.

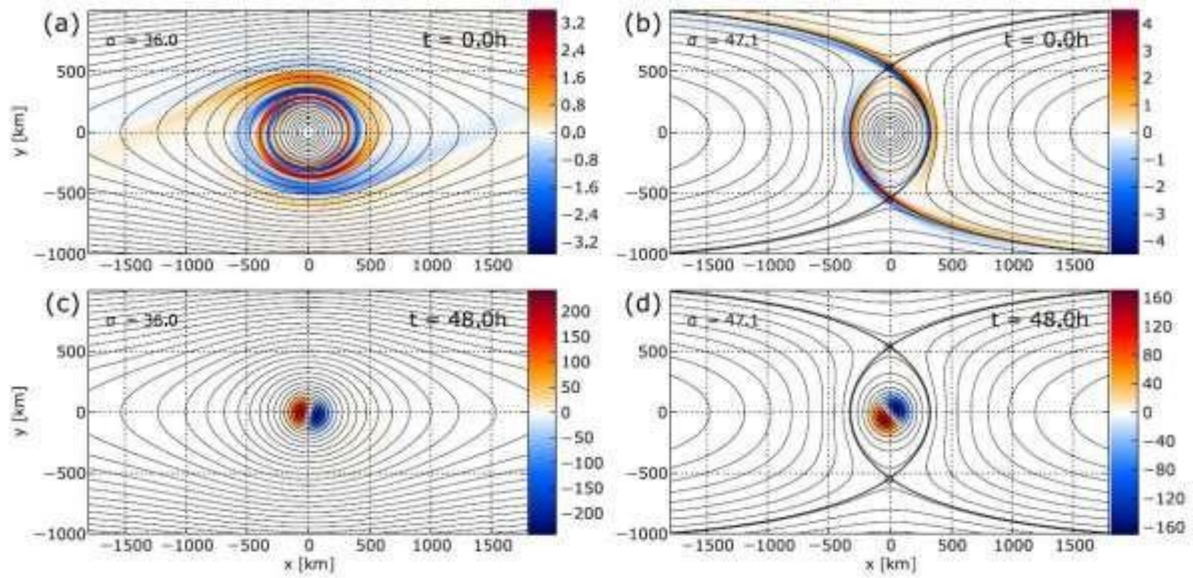

Fig. 2.1.1: Vorticity distribution of the initial (a),(b) and the evolved (c),(d) SVs for a single stable vortex: an optimization time interval of 2 days and background (left) cyclonic shears and (right) anticyclonic shears. The thin black contours are streamlines. In the anticyclonic shear case, the thick lines are the streamlines connected to the stagnation points (small circles) north and south of the vortex. The singular value is shown by sigma at the upper left in each panel. (after Scheck et al., 2014)

2.1.3 Recurvature

The recurvature is basically explained by the change of the environmental flow that steers the TC. Recent works have shown that the occurrence and location of the recurvature are sensitive to the SST field and the size of TC, as discussed in sections 2.1.5 and 2.1.7 below. Notably, it has been found that a TC initiated at a higher latitude can recurve by itself even in the absence of background flow (Chan and Chan, 2016; Fig. 2.1.2). Differential horizontal advection of the planetary vorticity by the TC circulation at different vertical levels leads to the development of vertical wind shear known as the β-shear. The flow associated with the upper tropospheric anticyclone on the equatorward side of the TC and the diabatic heating associated with the asymmetric convection combine to cause the intrinsic recurvature of the TC. The knowledge is important in forecasting the movement of the TC, when, in particular, the environmental flow is weak. The anticyclonic outflow in the upper troposphere and Rossby wave dispersion, gradually propagate the upper tropospheric anticyclone equatorward and westward such that it displaces from the southeast to southwest of the TC in general (Wang and Holland, 1996). Given that a TC located at a higher latitude has a slower

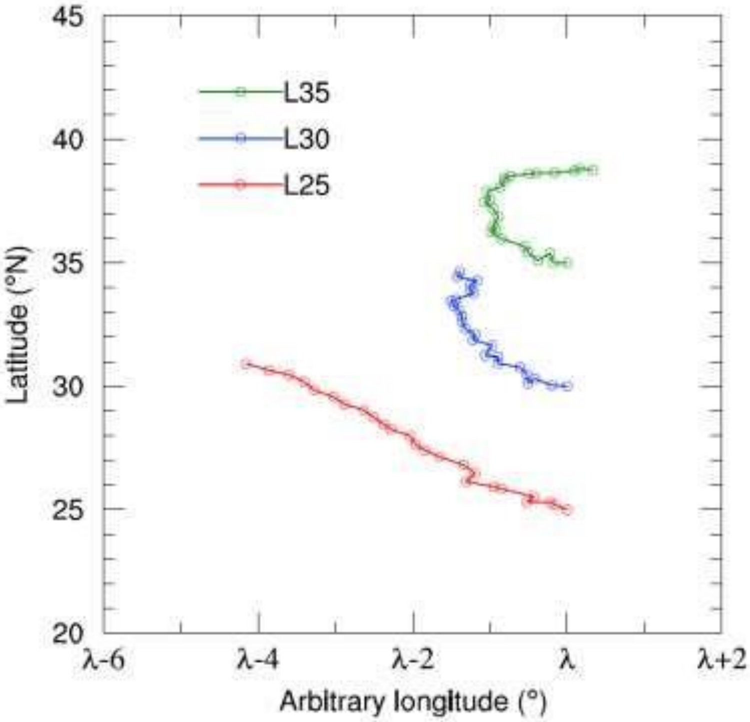

Fig. 2.1.2: Six-day TC tracks a symmetric spun-up vortex initially at 25°N, 30°N, and 35°N with no background flow. The time interval between markers of each track is 6 hrs. The tracks are drawn based on the central minimum sea level pressure of the vortex (after Chan and Chan, 2016).

development (Li et al., 2012) and a greater Coriolis force, the anticyclonic outflow of a higher-latitude TC therefore advects the upper tropospheric anticyclone less outward (see Fig. 3 of Chan and Chan (2016)). As a result, the upper tropospheric anticyclone of a TC at higher latitude is located closer to the vortex and thus has a greater influence on the TC movement through the horizontal advection of potential vorticity. It subsequently leads to the diabatic heating asymmetries to cause the intrinsic recurvature at higher latitudes.

2.1.4 The Influence of Topography

The interaction between terrain, basic flow and the TC is non-linear. Recent studies have made efforts in further understanding of the mechanisms leading to TC track deflection (Lin et al., 2016). The following mechanisms have been proposed to explain the upstream track deflection: (1) Advection by orographically blocking basic flow, (2) Channeling effect, (3) Asymmetric latent heating, (4) Asymmetric steering flow in middle levels, (5) Terrain induced gyres, (6) Approach angles and landing location.

Tang and Chan (2014) analyzed the terrain effect in the Taiwan and the Philippines. The terrain induced gyres are found over both Central Mountain Range of Taiwan and the mountains of Luzon. A pair of terrain-induced gyres rotate cyclonically around the TC, and the flow associated with the gyres starts to push the TC northward. As the TC is about to make landfall, the anticyclonic gyre is located north and the cyclonic gyre south of the TC. Furthermore, the height of a terrain controls the strength of the terrain-induced gyre, with weaker gyre in the Philippines terrain simulation. PVT diagnosis showed that while horizontal advection played a major role, the importance of diabatic heating became comparable during the landfall period.

Different from the mechanism of track deflection proposed by Jian and Wu (2008) and Huang et al. (2011), which had suggested that low-level channeling effect is the main contribution of the track deflection. Wu et al. (2015) investigated the effect of sudden track changes of TCs approaching Taiwan. An important finding in this study, is that the robust flow characteristics identified during the southward turn of a TC is the azimuthal asymmetric tangential wind at middle levels, but not the channeling winds at low levels. The azimuthal changes in the wind speed is connected to the changes in vertical velocity. Sensitivity experiments with respect to different parameters are also conducted in this study. The results demonstrate that the southward track deflection of the TC, is a common phenomenon prior to landfall. The results also suggest that when the altitude is higher, the TC approaches the northern part of the terrain, or when the translation speed is lower, the track deflection of the TC, would be prominent. Other parameters such as the width and length of the mountain, and the RMW have limited effects on the track of the TC.

Lin et al. (2016) investigated a series of idealized experiments to examine the influences of orography on TC track. These influences include mean flow advection, cyclonic circulation, channeling, asymmetric flow steering, asymmetric latent heating, and vertical wind shear effects. The VT is utilized to examine the southward deflection of TC. When the TC was upstream the mountain, the easterly basic flow became sub-geostrophic as a result of orographic blocking. The TC decelerated and deflected to the south, with the VT primarily dominated by the horizontal advection. After that, the TC passes over the mountain clockwise, steered by the orographically generated high-pressures. During this time period, the VT is mainly contributed by horizontal advection and stretching term. The diabatic heating is linked with the northwestward movement over the lee-ward slope. The enhanced advection of eyewall convective clouds associated with diabatic heating contributes to the abrupt turning of the TC, to the northwest.

Both the channeling effect and the asymmetries in the mid-levels, contribute to the southward track deflection of a TC. Huang and Wu (2018) investigates the motion of a TC that is deflected southward while moving westward toward an idealized terrain similar to that in Taiwan. The analyses of both the flow asymmetries and the PVT demonstrate that horizontal advection contributes to the southward movement of the TC [see Fig. 9 of Huang and Wu (2018)]. The track deflection is examined in two separate time periods, with different mechanisms leading to the southward movement. The changes in the background flow induced by the terrain, first cause the large-scale steering current to push the TC southward, even the TC is still far from the terrain. As the TC approaches the idealized topography, the role of the inner-core dynamics becomes important, and the TC-terrain-induced channeling effect results in further southward deflection of the track. The asymmetries in the mid-level flow also develop during this period (Fig. 2.1.3), in part associated with the effect of vertical momentum transport. The combination of the large-scale environmental flow, low-level channeling effect and the asymmetries in the mid-level flow all contribute to the southward deflection of the TC track.

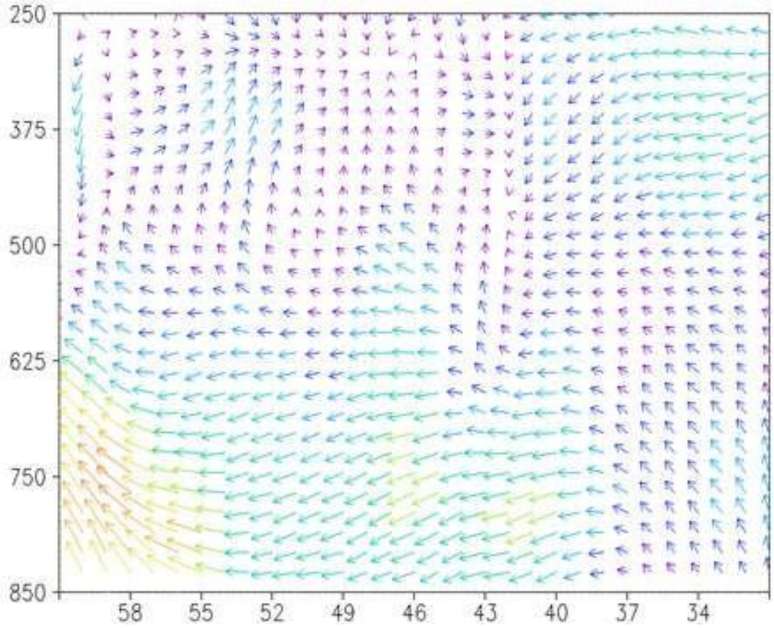

Fig. 2.1.3: Asymmetric flow at different levels calculated within 100 km of the vortex. The x-axis shows the integration time (h), and y axis is the vertical levels in terms of atmospheric pressure (hPa) (after Huang and Wu 2018).

2.1.5 The role of atmosphere-ocean interaction

Recent researches suggest that initial SST can affect TC tracks. Katsube and Inatsu (2016) and Sun et al. (2017) have shown that the warm SST tends to yield the earlier northward recurvature of the TCs in some cases in WNP. Sun et al. (2017) ascribed this result to the retreat of the subtropical high in their warm run. With a simplified linear baroclinic model, Katsube and Inatsu (2016) interpreted this track change as the well-known subtropical thermal response documented by Hoskins and Karoly (1981).

The coupling of the atmospheric model with the ocean model has become more common in recent years, because atmosphere-ocean coupling can be an important factor in intensity forecasts. The impact of the oceanic feedback on the track is less obvious. However, secondary influences of ocean coupling on the track via changes in intensity may be possible. For example, the coupling could change the vertical extent of the tropical cyclone, so that it is sensitive to different steering flow. A weakening and shallower cyclone may be more sensitive to lower level flow so that the effective steering flow may change (to lower height) as the coupling reduces the intensity (Lin et al., 2018). Coupling with the ocean could indirectly change the cyclone upper level anticyclone through intensity (diabatic heating) changes and the symmetry of the convection which could also have an impact on the flow.

Model studies do not show a strong impact of atmosphere-ocean coupling on the track of tropical cyclones. There have been a range of studies showing a marginal or no effect: idealized tropical cyclone studies with and without ocean coupling (e.g. Zhu et al, 2004, Duan et al., 2013), the role of adding wave coupling (Liu et al. 2011), individual case studies in the Atlantic (e.g. Winterbottom et al., 2012). Ito et al. (2015) examined 34 TC cases (281 runs) near Japan and found a minor effect of the atmosphere-ocean coupling. They report that the atmosphere-ocean coupling slightly (of the order of 20 km) deflects the TC position to the left because sea surface cooling on the right-hand side is not favorable for the storm (Fig. 2.1.4). A study of six tropical cyclones for the Bay of Bengal showed some improvement in the track forecast in the coupled model of less than 14% for the best initial SST distribution (Srinivas et al. 2016). They attributed the improved track to improved location of net vorticity generation to which cyclones tend to move. A more recent complete climatological study of the entire Indian Ocean shows no significant impact of coupling on track density (Lengaigne et al. 2018).

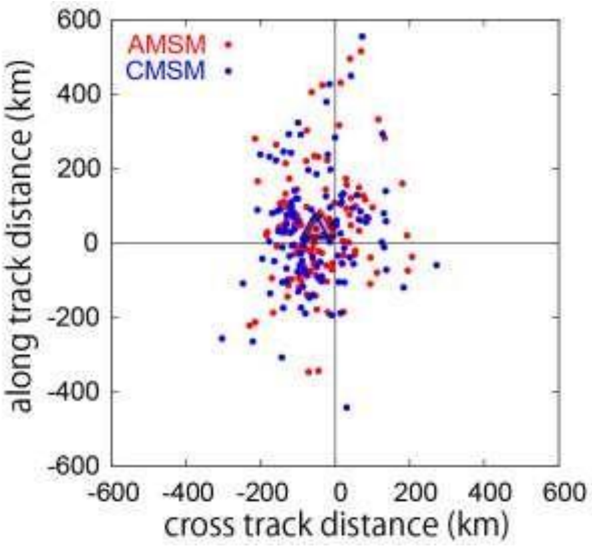

Fig. 2.1.4: TC center position at T+36 h for each experiment with the non-hydrostatic atmospheric (red) and coupled (blue) models relative to the RSMC best track. Vertical axis is

the along-track distance in the direction of the modeled TC motion from T+ 30 to 36 h, while the horizontal axis is the cross-track distance. Triangles indicate the mean positional bias in the same color (adopted and modified after Ito et al., 2015).

It is important to distinguish among the role of coupling in short-term weather forecasts, the initial condition of SST and its impact on the longer seasonal or climate time-scale. In addition to the recent works mentioned above regarding to the impact of initial SST, there is no doubt that coupling with the ocean can modify the large-scale SST patterns and hence the winds of the steering flow on longer time scales (e.g. Ogata et al. 2016; Sun et al. 2017). The seasonal forecast and climate projections of track densities will therefore be sensitive to atmosphere-ocean coupling.

2.1.6 Dynamics of Low-Predictability TC Tracks

There remain occasional stark disruptions in forecast skill in which ensemble spread is abnormally large, but only for a limited window of initialization times. The theoretical reasons behind such large track errors were explored by Torn et al. (2018). Using ensemble sensitivity analysis, the authors concluded that the foremost factor in creating large ensemble spread was a steering flow pattern with a saddle point of strong deformation (Fig. 2.1.5) downstream of the current location of the TC. In this pattern, small perturbations to the initial state have drastic consequences for the track prediction 2-4 days later.

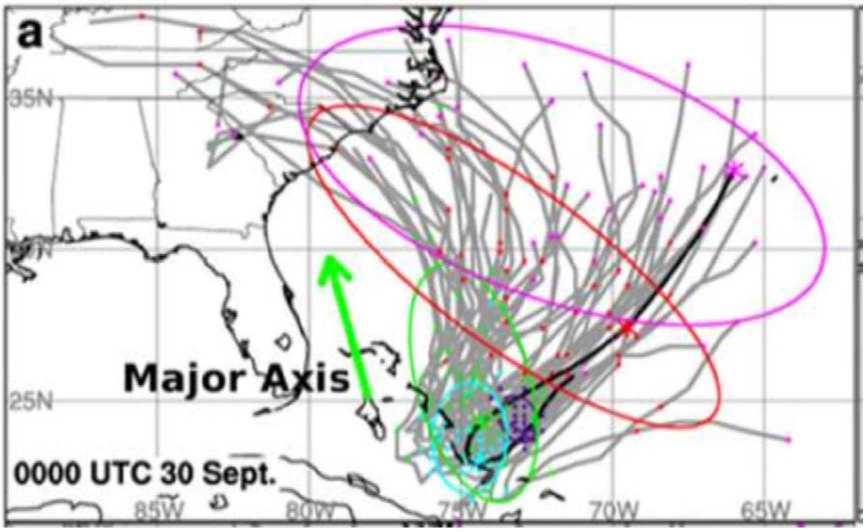

FIG. 4. ECMWF ensemble forecasts of Tropical Storm Joaquin initialized at (a) 0000 UTC 24 Jun, (b) 1200 UTC 24 Jun, and (c) 0000 UTC 25 Jun 2012 (gray lines). The dots indicate the location of each ensemble member at 24-h intervals, while the colored circles show a bivariate normal fit to the positions each 24 h, as in Hamill et al. (2011). Purple denotes 24-h locations,

cyan denotes 48-h locations, and green denotes 72-h locations. The thick black line denotes the NHC best track positions, while the stars indicate the corresponding best track position each 24 h. The direction of the 48-h major axis is denoted by the cyan vector. Fig. 2.1.5: ECMWF ensemble-mean 24-h forecast of steering winds initialized at 0000UTC 24

June 2012 for tropical storm Debby. The red dot and blue dot show the mean positions of the 10 ensemble members farthest east, and west, respectively at the 48-h position. (after Torn et al., 2018).

2.1.7 Large Scale Features

An MG is identified as a low-frequency cyclonic (or anticyclonic) circulation in the lower (or upper) troposphere with the diameter of about 2000-2500 km. When a TC is initially located in the eastern semicircle of an MG, several types of TC tracks can be identified (Liang and Wu, 2015). Liang and Wu (2015) showed that the different structure and relative distance affect the track pattern. Bi et al. (2015) showed that the sharp northward turn of the Typhoon Megi (2010) was induced by the strength of the TC in the initial field, as no sharp turn was observed when the initial TC was weakly implemented. Ge et al. (2018) indicated that the sharp northward turn can also be influenced by the vertical structure and the intensity of an MG. In their idealized simulation with a deeper and stronger MG, the total vorticity tendency of

TC’s wavenumber-1 component has become almost absent by the vorticity advection of the MG and the TC has exhibited a sharp northward turn (Fig. 2.1.6). In contrast, a TC experiences nearly constant northwestward track with a shallower MG. They also showed, that the differences in the radial gradient of the relative vorticity also yield the similar track differences in a simple barotropic model.

Wei et al. (2016) statistically investigated the relationship between the UTCL and the TC tracks over the WNP during 2000-2012. They found that for all the TCs and the UCTLs within the 15-degree interaction distance, there is little impact of the UTCL on the average directional change of the TC track, unlike the results obtained by the previous case studies. Albeit with the lower frequency, most of the left-turning TCs within a 5-degree distance experienced abrupt left-turning as much as 50 degrees in 12 hours. The TCs tended to be slowed down when undergoing abrupt directional changes.

Sun et al. (2015) investigated the interaction between a TC and a subtropical high on the WNP, focusing on the initial size of the TC for the case of TC Songda (2004) and the Megi (2010). With the increase of initial storm size, the main body of subtropical high tends to withdraw, and the TCs, which are initially located on the south western edge of the subtropical high, tend to turn northwards earlier. The increase in the mass flux with the larger vortex, decreases the geopotential height of the middle troposphere in the outer region of the TC and thus it leads to a break of the subtropical high on the WNP.

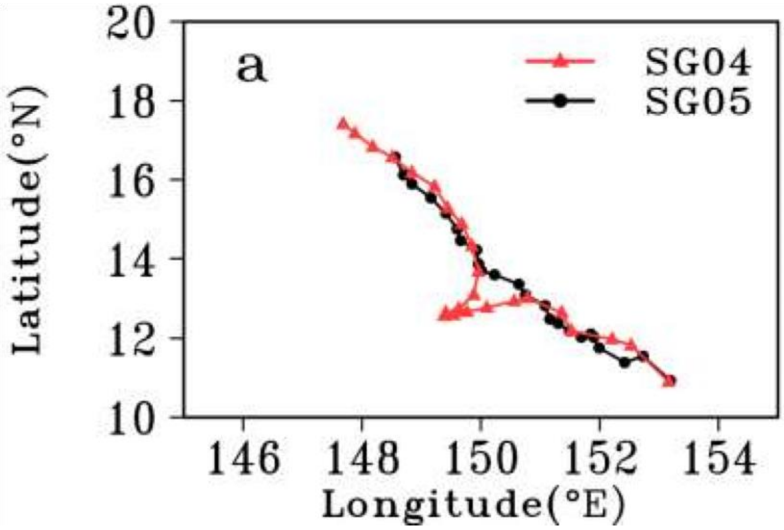

Fig. 2.1.6: Simulated 3-hourly TC tracks with a deep intense MG (SG04) and a shallow weak MG (SG05). (Ge et al. 2018)

2.1.8 Summary and Recommendation

The highly idealized models still provide an important perspective for the forecasting of the TC track. Recent works suggest that the TC track forecasting is sensitive to the radial profile of the relative vorticity in the outer region of the TC because it is related to the β-gyre and the faster developing mode. Recent idealized simulations with a full-physics model have brought the deeper understanding of the existing mechanisms and the finding of previously known mechanisms: the intrinsic recurving nature, the channeling effect in the middle troposphere, the atmosphere-ocean interaction and the impact of large-scale features. They suggest that the horizontal and vertical structure of a TC can impact on their own track through the interaction with other systems or as its own nature. It seems that the state-of-the-art models have, to some extent represented some of these effects. However, these findings are important for understanding the mechanism of the change of the TC tracks, particularly, when TC track was changed according to the use of finer mesh, new physical scheme, topography and coastal line. More accurate implementation of these components is highly desirable.

The fundamental aspects of the movement of the TC, are also important because it can facilitate the design of observations and data assimilation systems. Recent works suggest that the uncertainties along streamlines connected to stagnation points for TCs in a cyclonic shear should be reduced. The realistic-model-based ensemble sensitivity analysis detected the foremost factor in large track forecast errors was a steering flow pattern with a saddle point of strong deformation. These locations presumably correspond important regions to watch in terms of the track forecast.

Thanks to the sophisticated numerical model and observations, the TC position forecast errors have been decreasing to <100 km for T+24 and 200-300 km for T+72. In turn, the physical processes that were previously considered to be “minor” have become “substantial” in importance, as the required accuracy has become higher than ever. Although the conventional concepts of the steering flow, the β-gyre, and the diabatic heating remains important, the better understanding of various physical processes should be regarded as an important step for disentangling the complicated dynamics associated with the movement of the TC in the real world.

Acronyms used in the report:

CWB - Central Weather Bureau
ECMWF - European Centre for Medium-Range Weather Forecasts
IWTC - International Workshop on Tropical Cyclones
MG - Monsoon Gyre
NCAR - National Center for Atmospheric Research
NTU - National Taiwan University
PVT - Potential Vorticity Tendency
RSMC – Regional Specialized Meteorological Center
SST - Sea Surface Temperature
SV - Singular Vector
T+XX - Forecast time of XX hours
TC - Tropical Cyclone
UTCL - Upper Tropospheric Cold-Low
VT - Vorticity Tendency
WNP – Western North Pacific

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