交通部中央氣象局

委託研究計畫(期中/期末)成果報告

午後雷雨中長期展望整合預報技術之發展(2/2)

計畫類別：☑氣象　　□海象　　□地震

計畫編號：MOTC-CWB-102-M-03

執行期間： 102 年 3 月 20 日至 102　年 12 月 31 日

計畫主持人： Robert R. Gillies, Shih-Yu Wang

執行機構：Utah Climate Center / Utah State University, U.S.A

本成果報告包括以下應繳交之附件(或附錄)：

□赴國外出差或研習心得報告 1 份

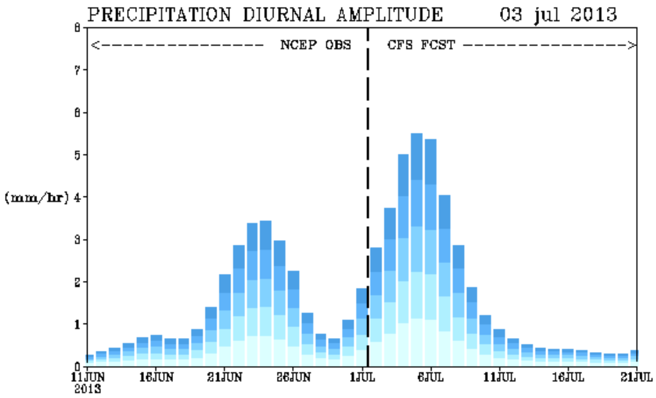
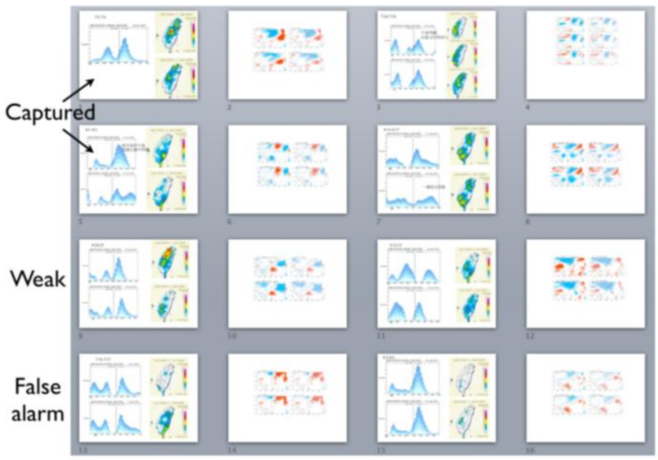
□赴大陸地區出差或研習心得報告 1 份

□出席國際學術會議心得報告及<u>發表之論文</u>各 1 份

中華民國　102　年　11　月　8　日

政府研究計畫(期中/期末)報告摘要資料表

計畫中文名稱	午後雷雨中長期展望整合預報技術之發展(2/2)		
計畫編號	MOTC-CWB-102-M-03		
主管機關	交通部中央氣象局		
執行機構	Utah Climate Center / Utah State University		
年度	102	執行期間	101 年 3 月 8 日-11 月 30 日
本期經費 (單位：千元)	$473 千元		
執行進度	預定（％）	實際（％）	比較（％）
	100	100	100
經費支用	預定(千元)	實際(千元)	支用率（％）
	473	473	100
研究人員	計畫主持人	協同主持人	研究助理
	Robert R. Gillies	**Shih-Yu Wang**	**Boniface Fosu**
報告頁數		使用語言	中文/English
中英文關鍵詞	午後雷雨、中長期展望、ＣＦＳ預報		
研究目的	本研究第一年計畫已運用美國 NCEP 第二代氣候預報系統(CFSv2)及再分析資料，獲得密集雷雨期及 10-20 天季內模的關係，並施用統計非線性方程及 CFSv2 流函數輸出值來表述這關係。第一年計畫也證實能有效預測台灣午後雷雨之活躍度的關係，並提供 3 周範圍內之長期展望。為了落實研究與作業相輔相成之目的，本期計畫把這動力-統計整合預報法技術轉移到氣象局， 建立作業流程，在夏季進行預報作業測試，再於秋季分析並探究此預報模組的表現及改進方案。主持人已和長期預報課會面及討論，分析本年夏季的預報表現及改進方法，並進一步研究跨尺度海陸風之交互作用對午後降雨的衝擊。		
研究成果	During this phase of the project, we explored the CFSv2 performance on such circulation setting and examined the forecast skill. The result indicates that CFSv2 is able to predict the occurrence of prolonged diurnal convection episodes as far out as 3 weeks ahead. This provides a potential for long-range “outlook” for persistent diurnal convection episodes at least two weeks in advance. This year, we also conducted an additional study		

	(paper in review) exploring the interaction between large-scale flows and diurnal rainfall variability, as well as the land-sea breeze. We have partnered with the CWB Long Range Division in launching experimental forecast for the 2013 summer. Both the Utah Climate Center and the CWB produced operational outlook of diurnal potential as the following:  The CWB then discussed and reviewed each week how the model is performing. On Nov. 5, the two teams met and discussed the pros and cons of the current model setting and performance, while the Utah Climate Center PIs suggested improments for pattern recognition and spatial correlation.
具體落實應用情形	今年度的計畫內容乃發展科學並驗證模式，進度至今已（一）成功證實午後雷雨跟季內模的關係，（二）診斷ＣＦＳ對季內模的預報度，（三）於一〇二年夏季運用此預報度發展對持續性午後雷雨的中長期展望，完成『技術轉移』的工作。 **整體落實情況：**長期預報課監測本年預報表現後提出下列個案，分別表述（一）成功預報，（二）弱對流，（三）錯失個案的情況。計畫主持人則給與環流資料分析，發現預報成功的個案的確遵循之前所發現的季內模構造，但是預報失敗的個案則並不符合季內模的流場。解決方案為加入空間相關分析已調整模式的權重。 

計畫變更說明	(若有)
落後原因	(若有)
檢討與建議 (變更或落後 之因應對策)	預計模式改進將採用二步驟:先加入空間相關分析並測試模式表現(自動化),再輸出空間流場以供預報員診斷(人工)。

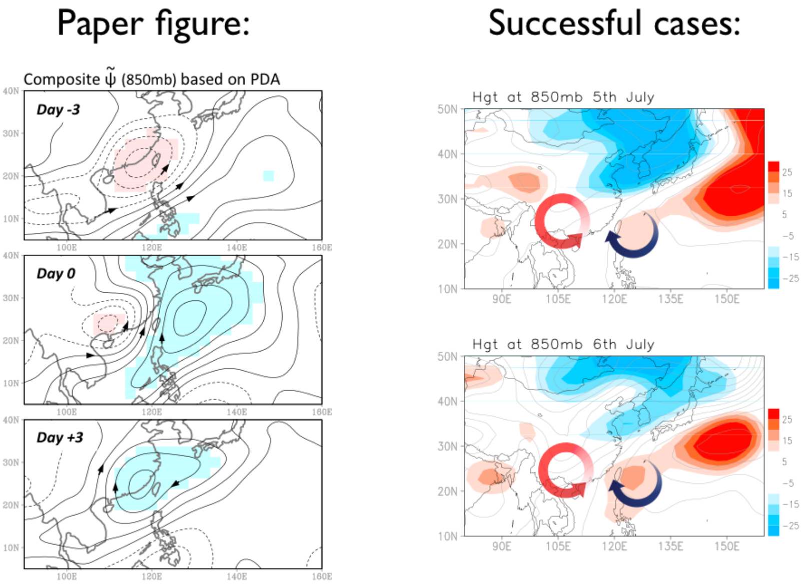
(以下接全文報告)

(一)預報實驗與改進

本年度夏季的預報實驗由氣象局長期預報課進行,採用UCC(猶他氣候中心)所製造的長期日對流展望來輔助每週的預報會議(http://cliserv.jql.usu.edu/data/wb_diurnal_fst.png)。本次實驗期間為六月中至九月中,結果指出(一)展望預報大體上具有一至二周的成功率,偶有三週成功的少數例子;(二)有時只有東半部產生午後對流,西半部微弱;(三)模式會產生假預報 — 預期日對流發生但實際上卻沒發生的例子。

經過主持人分析後,在預報成功與失敗的例子中我們發現季內環流的構造有所不同,其差異如下圖所示:

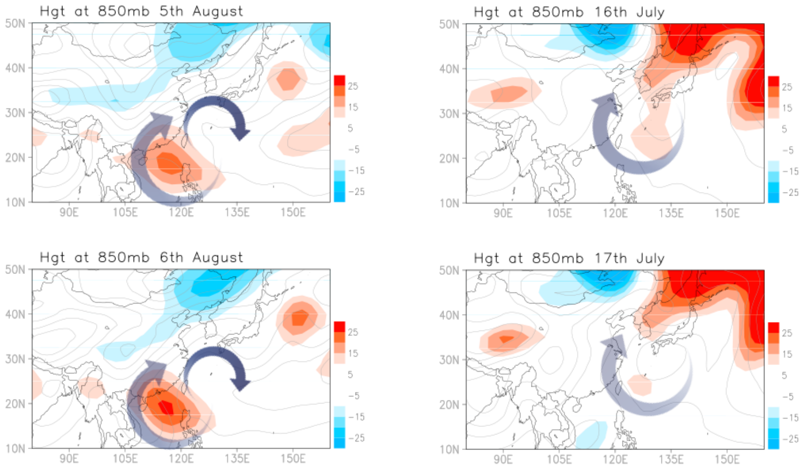
左:午後雷雨增強時的還流合成圖,及右:今年夏季成功預報的個案流場,彩色部分為雙周模.



基本上預報成功的案例都具有類似左側合成圖的構造,也就是低壓CELL在西部而高壓CELL在東部的結構。這樣子的短波列同時具有向西移動的特徵。在比較預報失敗的個案後,我們發現那些例子的季內環流結構有顯著

的不同：若非是並排的低壓則是太過顯著的高低壓系統，如下圖所示．

False alarm 個案:



今年夏季午後雷雨“虛假預報”的個案流場，彩色部分為雙周模．

因此，我們建議在模式中加入空間相關系數（σ, spatial correlation coefficient），計算方式為比較每個預報季內模流場與合成資料流場的相關性，並用此相關系數來產生權重，乘上如下模式：

$$\mathrm{PDA}^{\mathrm{E}} = 0.16\Delta\tilde{\psi}^{2} + 0.96\Delta\tilde{\psi} + 1.14$$

weight it by spatial correlation x σ

此法可於明年夏季進行即時診斷，而更加完整的ＨＩＮＤＣＡＳＴ分析將需要更長期的計畫資源來進行。

（二）跨尺度海陸風交互作用

概述：The formation mechanism of diurnal rainfall in Taiwan is recognized as a result of solar thermal heating and island-scale land-sea breeze (LSB) interacting with orography. This study found that the diurnal variation of the large-scale circulation over the East Asia-Western North Pacific (EAWNP) modulates considerably the diurnal rainfall in Taiwan. It is shown that the interaction between the two LSB systems—the island-scale LSB and the large-scale LSB over EAWNP—facilitates the formation of the early morning rainfall in western Taiwan, afternoon rainfall in central Taiwan, and nighttime rainfall in eastern Taiwan. Moreover, the post-1998 strengthening of a shallow, low-level southerly wind belt along the coast of Southeast China appears to intensify the diurnal rainfall activity in Taiwan. These findings reveal the role of the large-scale LSB and its long-term variation in the modulation of local diurnal rainfall.

背景 : Local solar heating and the interaction between Taiwan's land-sea breeze (LSB) and orography are well-known mechanisms causing the late-afternoon rainfall maximum, which occures around 5 p.m. local time. In addition to the late-afternoon rainfall, an increase in the early-morning rainfall appears around 5 a.m. local time. This early-morning rainfall has been attributed to nocturnal drainage flows along the western slope of the mountains breaking the stable planetary boundary layer over the western plains of Taiwan.

The large-scale circulation covering the EAWNP region also exhibits a marked diurnal variation. Huang et al. (2010) found that the LSB circulation over much of the East Asian coastal areas is coupled with the global-scale atmospheric pressure tide; this produces a planetary-scale LSB with a spatial scale of ~1000 km. Later, Huang and Chan (2011, 2012) utilized a newer generation of global reanalysis, namely the Modern-Era Retrospective Analysis for Research and Applications (MERRA), to reveal further details of the large-scale LSB in EAWNP and the South China Sea. Huang and Chan (2011, 2012) showed that the interaction between the monsoonal southwesterlies and the continental LSB over East Asia contributes to the formation of morning convection in the South China Sea and afternoon convection in southern China. Because Taiwan is located within EAWNP's diurnal flow regime, it is possible that the formation mechanism of diurnal rainfall in Taiwan also undergoes certain modulation by such a large-scale LSB. This aspect has not been documented and is examined herein

It is anticipated that the much increased temporal and spatial resolutions of modern reanalyses like MERRA can provide an observational depiction of the interaction between the island-scale LSB (referred to as Taiwan-LSB) and the large-scale LSB (referred to as EAWNP-LSB), as well as their impact on the formation of local diurnal rainfall. Both the Taiwan-LSB and EAWNP-LSB exhibit a marked seasonal variation. Here, our season of interest is May and June (MJ), a time period when the diurnal rainfall in Taiwan experiences a strong interaction between Taiwan-LSB and EAWNP-LSB (explained later).

資料： Observed precipitation is derived from (i) 21 conventional meteorological stations operated by Taiwan's Central Weather Bureau as indicated in Figure 1 and (ii) 3-hourly TRMM (Tropical Rainfall Measuring Mission) 3B42 satellite precipitation

(Simpson et al. 1996) beginning in 1998. The TRMM 3B42 dataset provides rain rate at the spatial resolution of 0.25° longitude × 0.25° latitude, comparable with the common spacing of meteorological station network in EAWNP. Meteorological data including wind fields, humidity, and vertical velocity are extracted from the 3-hourly MERRA reanalysis at the spatial resolution of 0.667° longitude × 0.5° latitude. MERRA's spatial and temporal resolutions represent a leap forward when compared to older reanalyses with the common 6-hourly, 2.5-deg resolutions. The analysis here covers the time period from 1998 to 2012 for the MJ months, when diurnal variation is becoming predominant in the region.

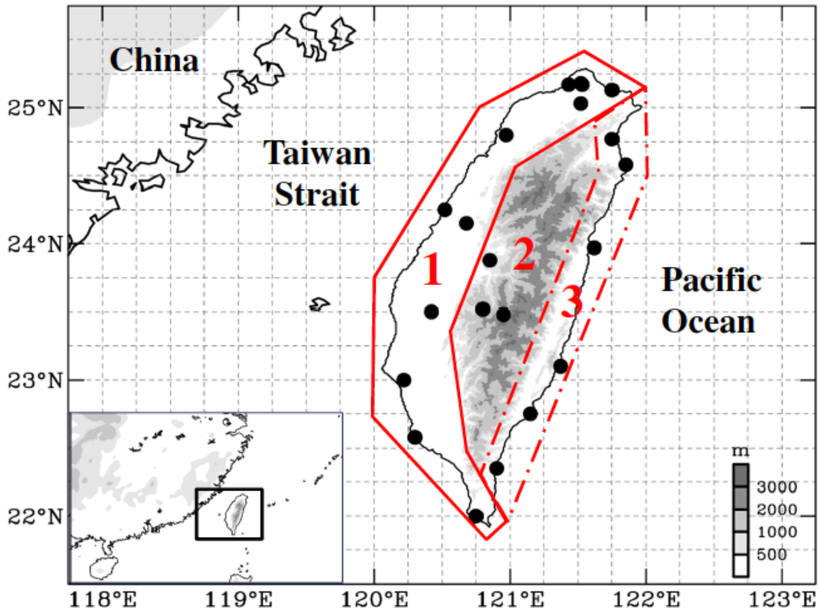


Fig. 1 The geography and location of 21 conventional surface observation stations in Taiwan (dots). Stations are separated into three groups for estimating rainfall variations in western Taiwan (domain 1), central mountain range (hereafter, CMR) of Taiwan (domain2) and eastern Taiwan (domain 3) for use in Fig. 2. The scale of stippled orography in Taiwan is given in the right bottom panel.

分析結果：

a. Rainfall characteristics

Based on the north-south oriented orographic features in Taiwan, we define three sub-regions consisting of western Taiwan with plains and foothills (domain 1 in Fig. 1), the central mountain range (CMR; domain 2), and eastern Taiwan with steep slopes (domain 3). The temporal evolution of the 3-hourly rainfall averaged from the 21 surface stations (Fig. 2a) shows a bimodal signal, with an early-morning peak at 0800 h and a late-afternoon maximum at 1700 h. In each sub-region, western Taiwan shows the pronounced bimodal signal (Fig. 2b) while the CMR and eastern Taiwan exhibit a single late-afternoon peak of diurnal rainfall (Figs. 2c and 2d). However, the timing of the rainfall peak is skewed towards the afternoon hours of 1400 ~ 1700 h in the CMR and the evening hours of 1700 ~ 2000 h in eastern Taiwan. In Fig. 2 we overlay the TRMM rain rate averaged over Taiwan and from the three sub-regions. The general resemblance between the station and TRMM observations indicates that TRMM indeed replicates the timing and amplitude of diurnal rainfall across Taiwan; although the actual rainfall values are underestimated.

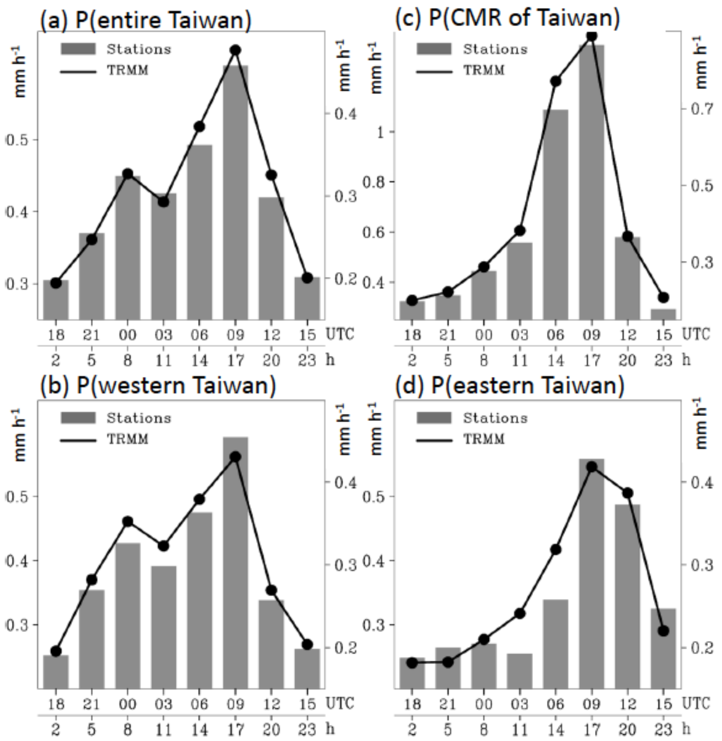


Fig. 2 Time evolution of 3-hourly precipitation (P) estimated from rain gauge stations (histogram) and TRMM 3B42 (solid line with dots) for (a) the entire Taiwan, (b) the western Taiwan (domain 1 in Fig. 1), (c) the CMR of Taiwan (domain 2) and (d) the eastern Taiwan (domain 3). The rainfall scale for rain gauge observation is shown in the left and for the TRMM observation in the right. The lower x-axis is local time in Taiwan, which is universal time (UTC) +8 h.

Next, the regional features of the TRMM precipitation over the EAWNP region are shown in Fig. 3, derived from the MJ climatology of 1998-2012. Rainfall first appears at 0200 h over the Taiwan Strait and develops along the western coast of Taiwan up to 0800 h (Figs. 3a-c). Beginning early afternoon (1400 h), heavy rainfall quickly develops over Taiwan through 1700 h (Figs. 3d-f). At 2000 h, rainfall dissipates over the island and yet, a narrow rainband develops over ocean along the eastern coast of Taiwan into midnight (Fig. 3g and 3h).

b. LSB scale interaction

To provide a quantitative measure of the diurnal wind variation in Taiwan, we compute the surface wind divergence (Ds) from stations:

$$D_s = \frac{1}{A}\int_L V_n \, dl, \qquad (1)$$

where A, Vn and *dl* indicate respectively the area of Taiwan encircled by the circumference connecting the selected stations (Fig. 4b), the surface wind velocity normal to the circumference and the distance increment along the circumference. It is expected that solar radiative heating drives the temporal evolution of the island-averaged Ds and its maximum convergence (i.e. –Ds > 0) at 1400 h, following the maximum surface temperature; this is confirmed in Fig. 4a. Next, DS is derived from MERRA's 10 m winds over the domain of 120^{o}-122^{o}E, 22^{o}-25.5^{o}N (surrounding Taiwan). As shown in Fig. 4a, MERRA's DS is in good agreement with that derived from surface stations. This resemblance of MERRA with the station-observed LSB is remarkable and thus builds confidence in our subsequent analysis for the scale interaction of LSBs.

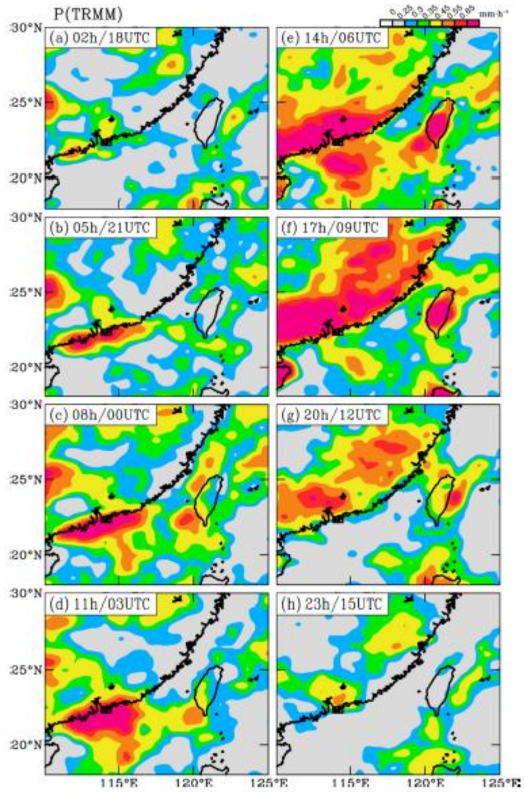


Fig. 3 Horizontal distributions of the TRMM 3B42 rain rate averaged during 1998~2012 May and June at (a) 0200, (b) 0500, (c) 0800, (d) 1100, (e) 1400, (f) 1700, (g) 2000 and (h) 2300 h (local time in Taiwan). The color scale of (a)-(h) is given on top of (e).

The diurnal variation of the surface circulation over EAWNP is shown in Fig. 5 and applied with the first harmonics (S1), using the Fourier analysis in order to isolate the diurnal component (i.e. the S1 component of surface winds explains 90% of the diurnal variance in EAWNP). Between 0800 h (Fig. 5c) and 2000 h (Fig. 5g), the diurnal variation of lower-tropospheric winds reveals a reversal of the large-scale LSB over the EAWNP region. At 0200 h (Fig. 5a), land breezes from western Taiwan and southeastern China collide and form an apparent convergence line along the Taiwan Strait and coastal southern China. By 0800 h the local land breeze in western Taiwan has weakened while the land breeze in southeastern China persists (Fig. 5c), which later dissipates in the early afternoon. Such a continental land breeze is part of EAWNP-LSB. From 0200 to 1100 h, the interaction of land breezes between Taiwan and southeastern China migrates eastward and displaces the early morning convergence over the Taiwan Strait and then over Taiwan. The initiation of the relatively strong island convergence at 1100 h occurs soon after this regional-scale convergence zone propagates through. The propagating convergence is indicated by the white dashed lines in Fig. 5, from which the location are based upon the maximum center of S1 of the 925-hPa vertical velocity (see next).

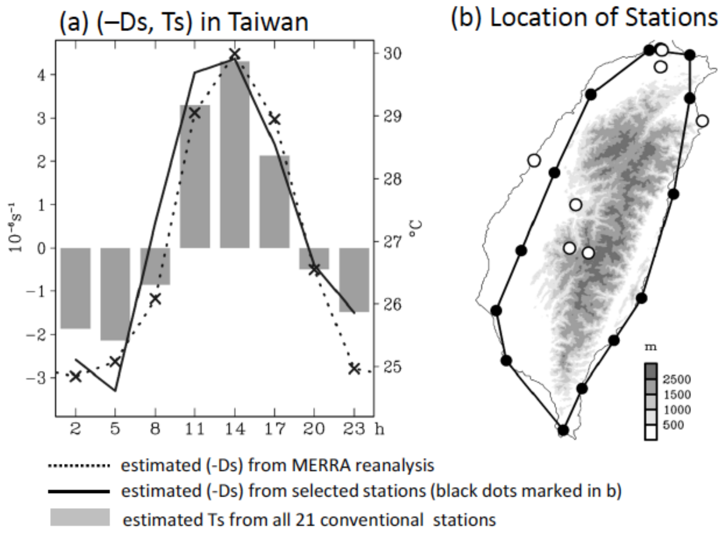


Fig. 4 (a) Time evolution of 3-hourly surface wind convergence (-Ds) estimated from selected surface stations (solid line) and the MERRA reanalysis (dotted line). In (a), time evolution of 3-hourly surface temperature averaged from all 21 stations [black + white dots marked in (b)] is overlaid as histogram. The methodology used for the estimation of (-Ds) from selected surface stations (black dots with solid line linked) is explained in (b). The scale of stippled orography in (b) is given in the right.

c. Impact on diurnal rainfall

The consequence from such a scale interaction between the local and regional LSBs can be visualized by the 925-hPa vertical motion superimposed with Fig. 5. Overall, areas with surface convergent anomalies are associated with ascending motion with the strength corresponding to the magnitude of convergence; areas of divergence are association with descending motion. Using MERRA and based upon the regional perspective, we find that the early morning convergence initiated in the Taiwan Strait also plays a role as it propagates over coastal western Taiwan, forming the morning convergence there and the subsequent morning rainfall (Fig. 2b).

The formation mechanism of Taiwan's afternoon convection is rather straightforward, i.e. sea breeze interacting with terrain in conjunction with heated slopes creating thermal lifting. However, additional effect of EAWNP-LSB on Taiwan's afternoon convection can be observed from Figs. 5c-e, in which the development of the local convergence in Taiwan is coupled with the passage of the regional surface convergence zone. Soon after the regional surface convergence zone propagates over Taiwan, a relatively strong island convergence is initiated at 1100 h (Fig. 5d) and persists through 1700 h under the strong local thermal lifting. As the surface convergence zone moves away from Taiwan (Figs. 5e-f), easterly winds develop over the ocean as part of the sea breeze of EAWNP-LSB and encounter the land breeze in eastern Taiwan; this forms a subsequent narrow band of convergence offshore eastern Taiwan (~ 0200 h, Fig. 5a).

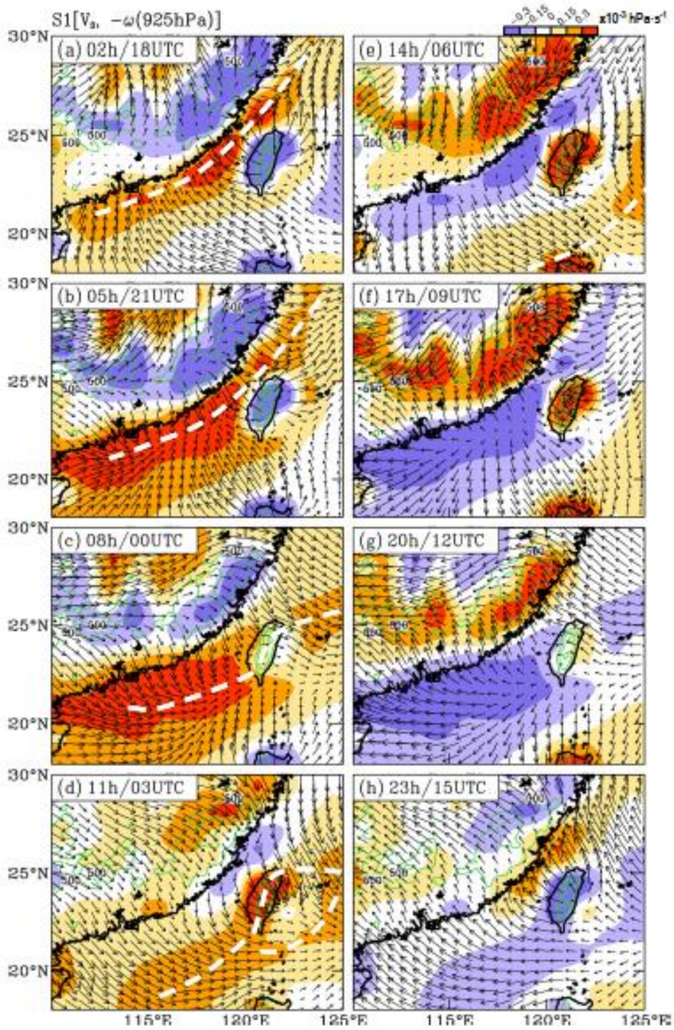


Fig. 5 The diurnal harmonic (S1) of 925 hPa vertical motion (-ω) superimposed with 10 m wind field. The color scale of (-ω) is given on top of (e). The topography with altitude at 500, 1000, 2000 and 3000 m are marked by the green lines. The white dashed line indicates the movement of the regional convergence zone that located based on the maximum centers of S1(-ω) at 925 hPa.

d. Change in the recent decade

Given the connection of EAWNP-LSB with Taiwan-LSB, as well as the changing circulation/sea surface temperature pattern observed in the region, the long-term change of diurnal rainfall in Taiwan is examined here based on the available TRMM 3B42 data during the 1998-2012 MJ seasons. The circulation change is shown in Fig. 6 through the comparison between two eras: 2006-2012 and 1998-2004. Over the entire Taiwan (Fig. 6a) the daily rainfall has increased by about 25% while the morning (0800 h) and afternoon (1700 h) rainfall has increased more than that at other hours, suggesting an amplification of the diurnal cycle. This overall change in diurnal rainfall consists of sharp increases in the morning rainfall over western Taiwan (Fig. 6b), afternoon rainfall in central Taiwan (Fig. 6c), and evening rainfall in eastern Taiwan (Fig. 6d).

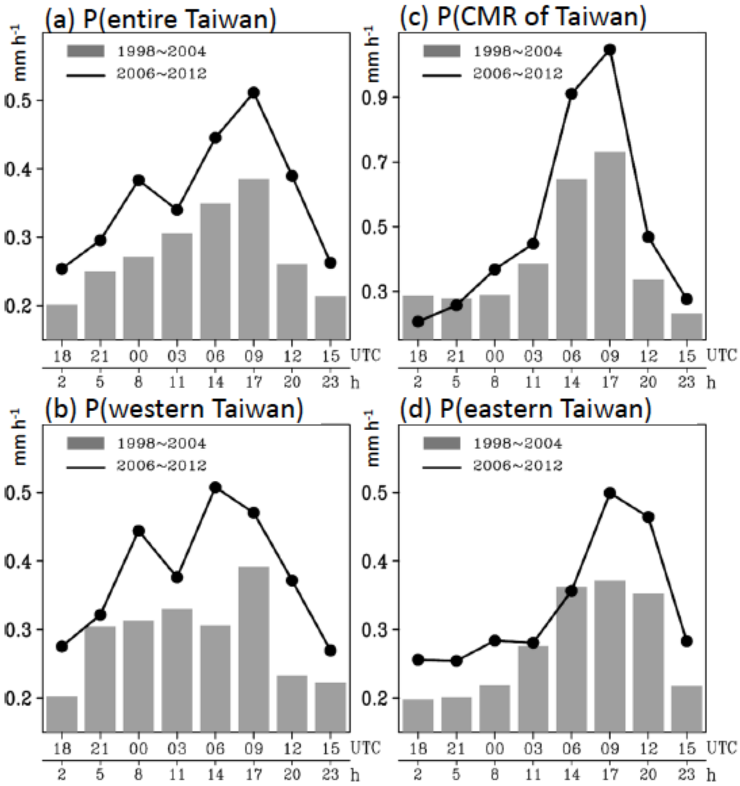


Fig. 6 Similar to Fig. 2 but for the 3-hourly precipitation estimated from TRMM 3B42 averaged during 1998~2004 (histogram) and 2006~2012 (solid line with dots).

We show in Fig. 7 the surface wind and regional precipitation changes between the two eras to inspect the large-scale circulation change associated with the diurnal rainfall change. There is an apparent narrow band of southwesterly winds formed along southeastern China, accompanying the rainband that extends over to southern Japan. Such wind and precipitation anomalies signify a possible intensification of the low-level jet (LLJ), a regional circulation feature critical to rainfall formation in Taiwan during the MJ season. The LLJ in this region brings the monsoon moisture from the South China Sea to the Taiwan Strait and, when encountering the mountain range in Taiwan, forms a localized jet core over the western slopes fueling local convection.

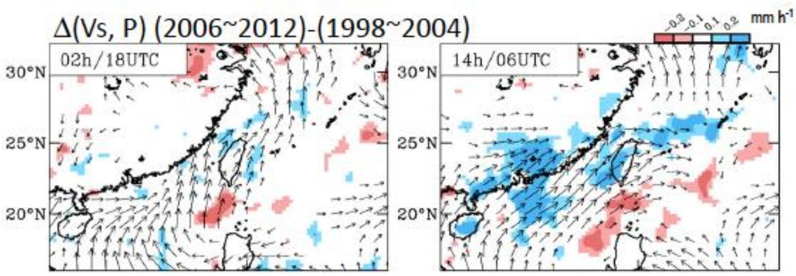


Fig. 7 The composite differences of (Vs, P) between the 2006~2012 and 1998~2004 eras. Only the value exceeding the 90% confidence level are shown.

未來研究：We will examine the surface wind and regional precipitation changes between the two eras in order to inspect the large-scale circulation change associated with the diurnal rainfall change. This analysis will reveal the long-term change of surface wind field in relation with the synoptic setting for active or inactive diurnal activity in Taiwan. We will also examine the possibility of any enhancement of southwesterly winds along southeastern China, as well as any intensification in both Taiwan-LSB and EAWNP-LSB and the precipitation response.

分析結論：The impact of the large-scale diurnal circulations on Taiwan's diurnal rainfall formation was examined for the MJ seasons during 1998-2012 using satellite data and the high-resolution MERRA reanalysis. The analyses showed that the diurnal rainfall in Taiwan consists of three regimes: a noticeable early-morning rainfall in western Taiwan, a predominant afternoon rainfall in central Taiwan, and a marked nighttime rainfall in eastern Taiwan. Analyses conducted by MERRA suggested that such sub-island differences are caused by the interaction between the two land-sea breeze systems: Taiwan-LSB (i.e. island-scale LSB) and EAWNP-LSB (i.e. large-scale LSB). In the early morning, easterly winds from the land breeze of Taiwan-LSB meet the westerly winds from the large-scale land breeze of EAWNP-LSB; their interaction initiates surface convergence in the Taiwan Strait. When coupled with the large-scale land breezes that migrate eastward across the Taiwan Strait, the shallow convergence facilitates the formation of early morning rainfall in western Taiwan. Later in the day, the late-afternoon rainfall in central Taiwan coincides with the passage of the large-scale surface convergence zone, which contributes to the local thermal forcing in the initiation of diurnal convection. At the nighttime, the shallow outflows in eastern Taiwan collide with easterly winds from the remnant of the large-scale sea breeze of EAWNP-LSB, triggering the formation of nighttime rainfall over the coastal ocean.

參考文獻：

Huang WR, Chan JCL (2011) Maintenance mechanisms for the early-morning maximum summer rainfall over Southeast China. Q J R Meteorol Soc 137: 959-968.

Huang WR, Chan JCL (2012) Seasonal variation of diurnal and semidiurnal variation of rainfall over Southeast China. Clim Dyn 39: 1913-1927.

Huang WR, Chan JCL, Wang SY (2010) A planetary-scale land–sea breeze circulation in East Asia and the western North Pacific. Q J R Meteorol Soc 136: 1543–1553.