# Possible Roles of the Indian Ocean in the Biennial Transitions between the Indian and Australian Summer Monsoons

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**Abstract**

The interannual variations of the Indian summer monsoon (ISM) and the Australian summer monsoon (ASM) display a pronounced biennial relationship, featuring an in-phase ISM-to-ASM transition and an out-of-phase ASM-to-ISM transition. Both the in-phase ISM-to-ASM and out-of-phase ASM-to-ISM transitions have occurred with and without the impacts of ENSO. The present study provides evidence for roles of ocean-atmosphere interactions in the tropical Indian Ocean in the biennial transitions between the ISM and ASM based on both observations and numerical model experiments. The in-phase ISM-to-ASM transitions can be accomplished through the monsoon-Indian Ocean interaction, including the ISM induced wind-evaporation effects on the SST and the SST influence on the ASM through an anomalous east-west circulation. The out-of-phase ASM-to-ISM transitions can occur through air-sea interaction in the tropical Indian Ocean. This interaction involves a sequence of processes, including wind-evaporation induced SST changes in the southwestern tropical Indian Ocean, the formation of a cross-equatorial SST gradient, the development of asymmetric wind and rainfall anomalies in the tropical Indian Ocean, and the appearance of SST anomalies in the North Indian Ocean due to wind-evaporation and cloud-radiation changes.

## 1. Introduction

The tropospheric biennial oscillation (TBO; Meehl 1994, 1997) is an important phenomenon involving the Indian summer monsoon (ISM) and the Australian summer monsoon (ASM). The TBO refers to a tendency for a relatively strong (weak) monsoon to be followed by a relatively weak (strong) monsoon and thus the TBO of the Indian-Australian monsoon system includes two key features: the in-phase ISM-to-ASM transition, i.e., a strong (weak) ISM is followed by a strong (weak) ASM, and the out-of-phase ASM-to-ISM transition, i.e., a strong (weak) ASM is followed by a weak (strong) ISM.

Since El Niño-Southern Oscillation (ENSO) events tend to develop from boreal spring and mature in boreal winter, they provide a similar impact on the ISM and ASM via a shift of the east-west Walker circulation. This shift in the Walker circulation is the traditional view of the role of ENSO in the in-phase ISM-to-ASM transitions (e.g., Meehl 1987; Meehl and Arblaster 2002; Yu et al. 2003). There are, however, in-phase ISM-to-ASM transitions that are not accompanied by ENSO. Then, what contributes to the in-phase ISM-to-ASM transitions? The present study provides evidence for the roles of the Indian Ocean in the in-phase ISM-to-ASM transitions without ENSO.

When ENSO switches its phase from boreal winter to boreal summer, it induces opposite sign ASM and ISM anomalies through anomalous Walker Circulation (Meehl and Arblaster 2002; Wu and Kirtman 2007b). This leads to an out-of-phase ASM-to-ISM transition. Analyses show that the out-of-phase transitions have also occurred when ENSO does not change its phase or has not completed its phase transition. In this case, what is the player for the transition? The present study shows that the out-of-phase ASM-to-ISM transitions can occur through air-sea interaction in the tropical Indian Ocean.

## 2. Two types of in-phase ISM-to-ASM transitions and two types of out-of-phase ASM-to-ISM transitions

The ISM is represented by June-September (JJAS) rainfall averaged over the region of 5°-25°N, 60°-100°E (IMR for short), and the ASM is represented by December-February (DJF) rainfall averaged over the region of 5°-20°S, 100°-150°E (AMR for short). The rainfall is from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997). The wet and dry monsoons are determined based on the criterion that the IMR or AMR anomalies exceed 0.43 times the corresponding standard deviation (i.e., upper and lower terciles). Warm and cold ENSO events are determined based on the NINO3.4 (5°S-5°N, 170°-120°W) SST anomalies, following the definition of CPC in ENSO monitoring. Specifically, warm and cold events are defined when 3-month running mean of ERSST v2 (Smith and Reynolds 2004) NINO3.4 SST anomalies with respect to climatology for the period 1971-2000 exceeds the threshold of 0.5°C for a minimum of 5 consecutive 3-month running means.

The in-phase ISM-to-ASM transition is determined when a wet (dry) ISM is followed by a wet (dry) ASM. Based on this, there are ten in-phase transitions for the period 1979-2005. Among them, there are five wet-to-wet and five dry-to-dry transitions, respectively. Among these transitions, five occurred in ENSO years (termed as Type A) and five in non-ENSO years (termed as Type B). In Type A transitions, SST anomalies persist from boreal summer to winter (Fig. 1a). In contrast, in Type B transitions, SST anomalies are weak in the NINO3.4 region (Fig. 1b).

The out-of-phase ASM-to-ISM transition is determined when a wet (dry) ASM is followed by a dry (wet) ISM. Based on this, nine out-of-phase transitions have been identified for the period 1979-2005. Among them, there are five wet-to-dry and four dry-to-wet transitions. All these cases accompany ENSO events in boreal winter with one exception during 1981-82. The Pacific SST anomalies in boreal summer, however, display important differences. According to these differences, the out-of-phase ASM-to-ISM transitions are classified into two types: Type A and B. In Type A transitions, NINO3.4 and/or NINO4 SST anomalies change to large opposite anomalies in boreal summer (Fig. 2a), and the boreal summer NINO3.4 SST anomalies (exceeding 0.5°C) and the IMR anomalies are of opposite signs. In contrast, in Type B transitions, NINO3.4 and NINO4 SST anomalies in boreal summer are weak (less than 0.5°C) or maintain anomalies of the same sign as in the preceding winter (Fig. 2b) and thus of the same sign as the IMR anomalies.

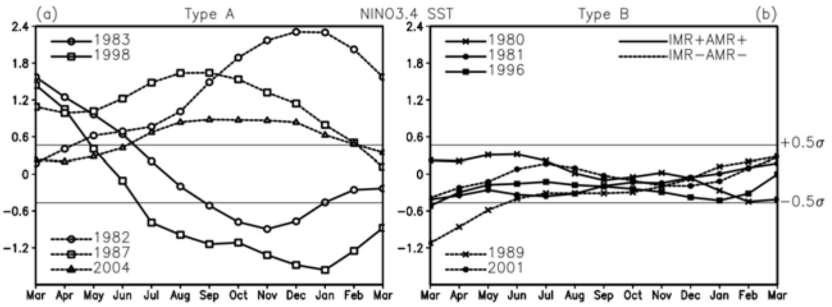


Fig. 1 3-month running mean NINO3.4 SST anomalies (°C) for Type A (a) and Type B (b) in-phase ISM-to-ASM transitions. Solid (dashed) lines are for wet-to-wet (dry-to-dry) transitions.

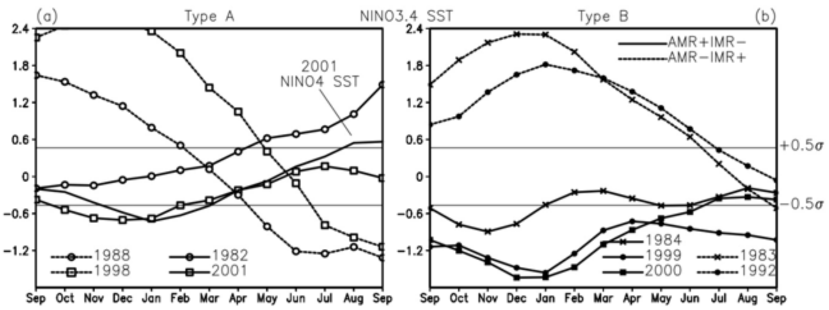


Fig. 2 3-month running mean NINO3.4 SST anomalies (ºC) for Type A (a) and Type B (b) out-of-phase ASM-to-ISM transitions. Solid (dashed) lines are for wet-to-dry (dry-to-wet) transitions. Also included in (a) are NINO4 SST anomalies for 2001.

## 3. Roles of the Indian Ocean in the in-phase ISM-to-ASM transitions

The Type A in-phase transitions occur due to the similar impacts of ENSO on the ISM and ASM through a shift of the Walker circulation. For Type B in-phase transitions, no obvious SST anomalies are present in the eastern equatorial Pacific. Then, what is responsible for the in-phase ISM-to-ASM transitions? Figure 3 shows the evolution of composite SST, rainfall, and surface wind anomalies for Type B transitions. In these composites, the anomalies in dry monsoon years are reversed and grouped together with those in wet monsoon years. The evolution of composite anomalies in the tropical Indian Ocean indicates that the in-phase ISM-to-ASM transitions are due to monsoon-Indian Ocean interaction, which consists of the following two-step processes.

In the first step, anomalous ISM contributes to tropical Indian Ocean SST changes through wind-evaporation effects. From Fig. 3d, a strong ISM is associated with anomalous southwesterly winds over the Arabian Sea and easterly winds over the equatorial Indian Ocean during JJA. These anomalous winds are in the same direction as climatological mean winds and surface winds are thus enhanced. The stronger winds drive a greater evaporation and stronger vertical Ekman pumping, which contributes to the SST cooling. Indeed, negative SST anomalies develop over the tropical Indian Ocean in SON and DJF (Figs. 3b-c). The effects of the ISM on surface wind speed and associated surface evaporation and consequently SST have been confirmed by analysis of lag-lead correlation with the IMR after removing the ENSO impacts based on observations and simulations of an AGCM forced by climatological SST (Wu 2008).

In the second step, the tropical Indian Ocean SST anomalies induce local anomalous heating in the atmosphere and an anomalous east-west circulation over the tropical Indian Ocean-northern Australia, and thus lead to an anomalous ASM. As seen in Fig. 3f, negative rainfall anomalies develop above negative SST anomalies in the equatorial Indian Ocean in DJF. This is accompanied by anomalous westerlies at lower-level (Fig. 3f) and anomalous easterlies at upper-level (Wu 2008) over the eastern tropical Indian Ocean through northern Australia. This results in anomalous convergence at lower-level and anomalous ascent over northern Australia and thus leads to a weak ASM. Numerical experiments of an AGCM forced by specified SST anomalies support the impacts of the Indian Ocean SST anomalies on the ASM variability (Wu 2008).

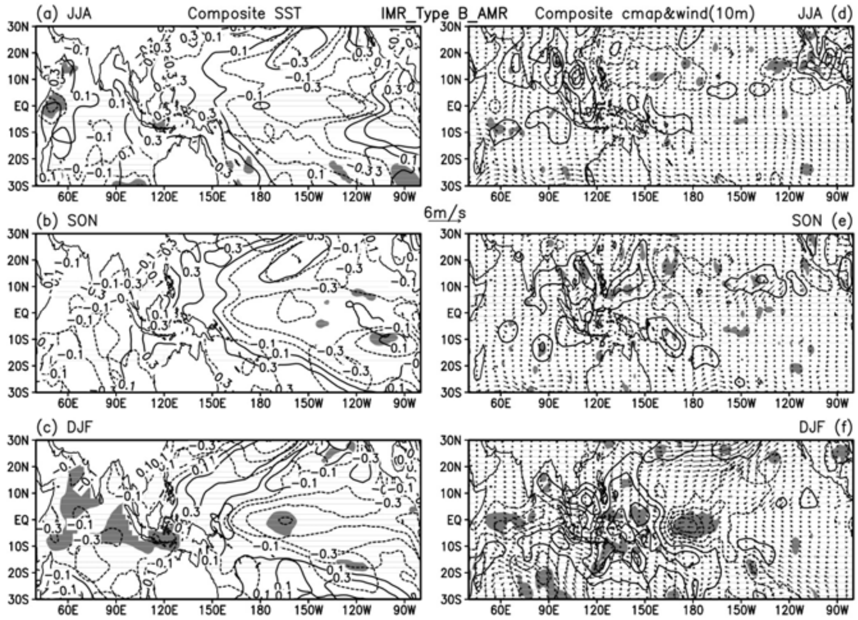


Fig. 3 SST anomalies (°C) (left) and CMAP rainfall (mm/day, contour) and NCEP-DOE reanalysis 10-m wind (m/s, vector) anomalies (right) for Type B in-phase ISM-to-ASM transitions during JJA (a, d), SON (b, e), and DJF (c, f). The contour interval for SST (rainfall) is 0.2°C (0.8 mm/day) starting from 0.1°C (0.4 mm/day). Shading denotes regions where the SST and rainfall differences between the wet-to-wet and dry-to-dry transitions are significant at the 95% confidence level according to the two-tailed Student-t test. The wind scale is denoted by the arrow.

## 4. Roles of the Indian Ocean in the out-of-phase ASM-to-ISM transitions

For Type A out-of-phase transitions, the equatorial central-eastern Pacific SST anomalies change their sign in JJA. As such, they lead to an ISM anomaly of the sign opposite to the previous ASM anomaly. This suggests that ENSO plays an important role in the out-of-phase ASM-to-ISM transition. For Type B out-of-phase transitions, the direct effects of ENSO on the ASM-to-ISM transition via large-scale circulation changes are weak. Then, what are the factors and processes leading to the transition from the ASM to the ISM? Figure 4 shows the evolution of composite SST, rainfall, and surface wind anomalies for Type B transitions. In these composites, the anomalies in dry-to-wet transitions are reversed and grouped together with those in wet-to-dry transitions. The evolution of composite anomalies in the tropical Indian Ocean indicates that the out-of-phase ASM-to-ISM transitions are accomplished through a sequence of processes that are similar to those for the evolution of a tropical Indian Ocean asymmetric mode (Wu et al. 2008), which is elaborated below.

First, negative SST anomalies are induced in the southwestern tropical Indian Ocean due to wind-evaporation effects. In SON and DJF, there is a large anomalous cyclone over the South Indian Ocean (Figs. 4e-f), which is a response to the remote ENSO forcing and the local air-sea interaction (Huang and Kinter 2002; Xie et al. 2002; Wang et al. 2003). Correspondingly, anomalous southwesterlies develop over the southwestern tropical Indian Ocean. These anomalous winds enhance surface wind speed and surface evaporation, leading to SST cooling there (Figs. 4a-b).

Second, the SST cooling in the southwestern tropical Indian Ocean establishes a cross-equatorial SST gradient (Figs. 4b-c). This SST gradient induces lower-level divergence south of the equator and convergence north of the equator and cross-equatorial flows through its hydrostatic effects on sea level pressure (Lindzen and Nigam 1987). These flows are deflected by the Coriolis effects. Thus, asymmetric rainfall and wind anomalies are seen in MAM (Fig. 4g).

Third, rainfall and wind anomalies over the North Indian Ocean contribute to the SST change through cloud-radiation and wind-evaporation effects. The anomalous westerlies enhance surface wind speed and surface evaporation. Above-normal rainfall reduces the incoming shortwave radiation. These changes contribute to SST cooling in the North Indian Ocean (Fig. 4d).

Fourth, the negative SST anomalies in the North Indian Ocean induce negative rainfall anomalies in boreal summer (Fig. 4h). The negative SST anomalies in the South Indian Ocean weaken due to the cloud-radiation feedback in relation to the suppression of convection there.

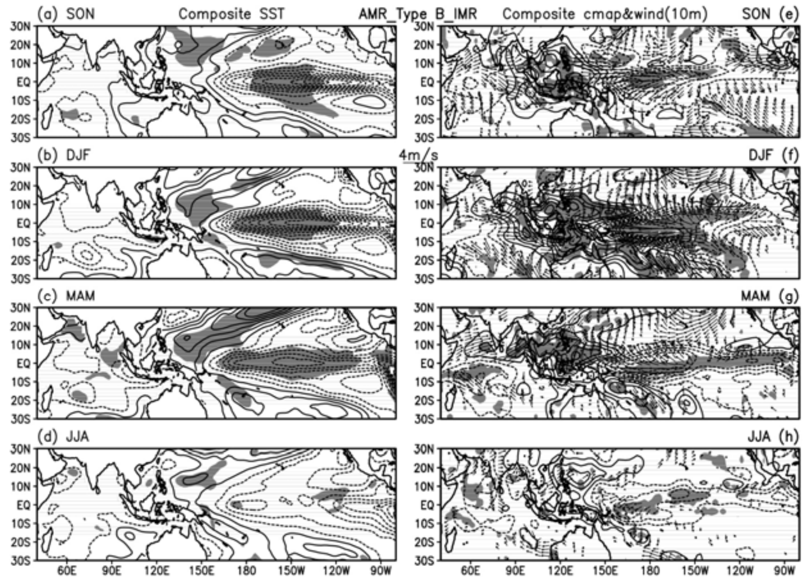


Fig. 4 SST anomalies (°C) (left) and CMAP rainfall (mm/day, contour) and NCEP-DOE reanalysis 10-m wind (m/s, vector) anomalies (right) for Type B out-of-phase ASM-to-ISM transitions during SON (a, e), DJF (b, f), MAM (c, g), and JJA (d, h). The contour interval for SST (rainfall) is 0.2°C (0.8 mm/day) starting from 0.1°C (0.4 mm/day). Shading denotes regions where the SST and rainfall differences between the wet-to-wet and dry-to-dry transitions are significant at the 95% confidence level according to the two-tailed Student-t test. The wind scale is denoted by the arrow; only those wind vectors whose corresponding t-values exceed the 90% confidence level are plotted.

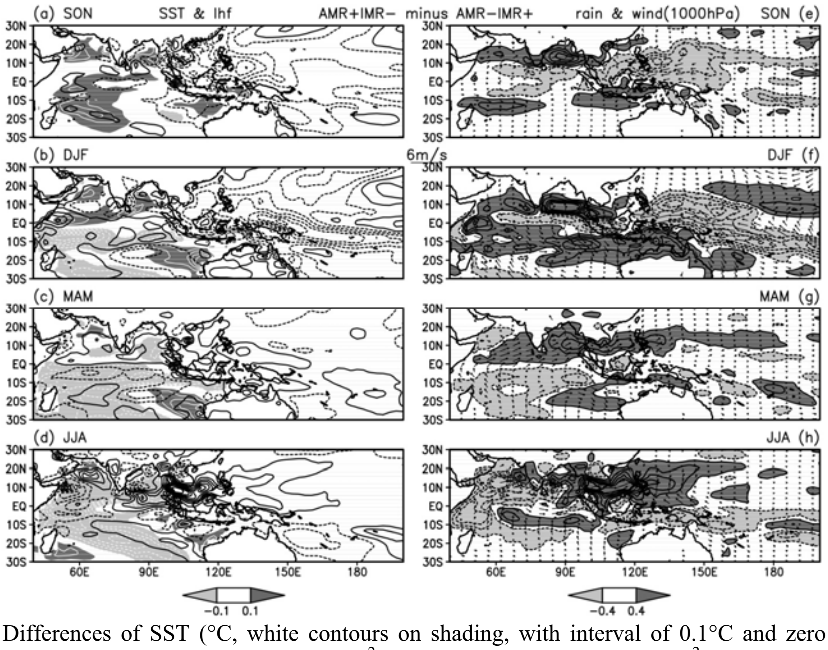


Fig. 5 Differences of SST (°C, white contours on shading, with interval of 0.1°C and zero contours suppressed) and surface latent heat flux (Wm$^{-2}$, contours with interval of 8 W/m$^2$ starting from 4 W/m$^2$) (left), rainfall (mm/day, contours on shading with interval of 0.8 mm/day starting from 0.4 mm/day) and 1000 hPa wind (m/s, vector) (right) anomalies obtained as composite wet-to-dry minus dry-to-wet ASM-to-ISM transitions during SON (a, e), DJF (b, f), MAM (c, g), and JJA (d, h). The wind scale is denoted by the arrow.

In observations, most of the out-of-phase transitions are preceded by ENSO events. Can the out-of-phase ASM-to-ISM transitions occur without ENSO? If so, what are the processes leading to the out-of-phase transitions? These questions are difficult to answer based on observations. Numerical experiments of CGCMs indicate that the out-of-phase ASM-to-ISM can occur without ENSO (Yu et al. 2003; Wu and Kirtman 2007a). Figure 5 shows anomalies of SST, surface latent heat flux, rainfall, and surface wind anomalies as obtained for wet-to-dry minus dry-to-wet transitions based on a 50-year simulation of a CGCM with climatological SST in the Pacific Ocean (Wu 2009).

The SST anomalies show an obvious cooling in the southwest tropical Indian Ocean from SON to DJF (Figs. 5a-b). This cooling is associated with an increase in upward surface latent heat flux (Fig. 5b) due to enhanced surface wind speed in association with cyclonic wind anomalies over the tropical South Indian Ocean (Fig. 5f). This anomalous cyclone appears to be a Rossby wave type response to anomalous heating of the ASM. As a result, a cross-equatorial SST gradient forms in DJF (Fig. 5b). This SST gradient persists through MAM (Fig. 5c) although the North Indian Ocean SST anomalies become negative. This cross-equatorial SST gradient contributes to the development of a south-north contrast in rainfall and wind anomalies in MAM (Fig. 5g). The atmospheric changes lead to further cooling of the North Indian Ocean (Fig. 5c) through wind-evaporation and cloud-radiation effects. With the development of negative SST anomalies in the North Indian Ocean, negative rainfall anomalies start to appear in JJA (Fig. 5h). These features are similar to those seen in the observations for Type B transitions (Fig. 4). The model results suggest that the out-of-phase ASM-to-ISM transition can be accomplished by air-sea interaction processes in the tropical Indian Ocean triggered by anomalous ASM.

## 5. Summary

Analysis of observations reveals that the in-phase ISM-to-ASM transitions have occurred both in ENSO years and in non-ENSO years. In the former, Pacific SST anomalies associated with ENSO play a primary role. These SST anomalies persist from boreal summer to winter and exert similar impacts on the ISM and the ASM, leading to same sign ISM and ASM anomalies. The present study demonstrates roles of the Indian Ocean for the in-phase ISM-to-ASM transitions in non-ENSO years. A wet ISM induces SST cooling in the tropical Indian Ocean through wind-evaporation effects. The SST cooling in the tropical Indian Ocean in turn leads to anomalous atmospheric heating, which affects the ASM variability via an anomalous east-west circulation. The results suggest that without ENSO the in-phase transition from the ISM to the ASM can be accomplished by monsoon-Indian Ocean interaction.

Analyses of observations reveal two types of out-of-phase ASM-to-ISM transitions. In the first type, the out-of-phase transitions are accompanied by a phase switch of ENSO from boreal winter to boreal summer. For this type of transitions, the direct ENSO forcing plays a primary role. In the second type of transitions, ENSO maintains its phase during the monsoon transition. For this type of transitions, air-sea interaction in the tropical Indian Ocean plays an important role in generating the North Indian Ocean SST anomalies that leads to the monsoon transition. The air-sea interaction is initiated in the southwest tropical Indian Ocean by remote ENSO forcing and the Indian Ocean Dipole Mode and involves the wind-evaporation feedback. A numerical simulation of a CGCM shows that the out-of-phase ASM-to-ISM transitions can occur without ENSO. Analyses of the model simulation suggest processes similar to those Type B transitions identified in observations. The model results indicate that the tropical Indian Ocean air-sea interaction can be triggered by an anomalous ASM.

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# 利用分析場資料協助颱風氣候降雨預報之可行性研究

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## 摘　要

本研究開發客觀比對歷史颱風個案之方法。在颱風預報作業採用歷史個案做為參考案例的搜尋過程中，除了考慮颱風中心座標、強度…等颱風特性是否相近之外，亦將大尺度資料之特性亦納入颱風歷史個案之類比搜尋程序。採用NCEP Reanalysis資料之大尺度環流分析場，計算環流特徵做為分類指標，協助預報人員藉由歷史個案判別未來可能的風場與降雨型態。

初步研究結果顯示，本研究之颱風比對方式可客觀搜尋出路徑相似之個案，此外，配合日期差異、西南氣流指標、環流特徵..等，可進行個案二次篩選。未來此方法將併入中央氣象局發展之互動式智慧型天氣辨識系統，輔助預報人員進行相關預報評估作業。

## 一、前言

目前颱風氣候降雨預報的方法多採用颱風中心位置和中心最大風速為預報因子，以建立測站降雨量的統計預報模式(王時鼎1983; 張志琳1998; 葉天降等人1999; 蔡孝忠2000; Lee et al. 2006)。此類方法假設颱風環流與台灣地形具有鎖定效應，中心位置類似之颱風個案，伴隨的風場和降雨分佈往往也相近。實際資料分析指出，颱風中心位置相似，風場與環流型態並不一定完全相同；中心位置不同的颱風個案，也可能在台灣地區產生相似的風場環流型態。颱風氣候法推估測站降雨的作法，可概似但不能正確表現不同環流型態的風雨特徵差異，尤其是有明顯不同於的大尺度環流特徵，如東北季風和西南氣流。

Lin et al.(2001; 2002)的研究指出，山區降雨主要是由地形強迫氣流舉升效應所主控，在颱風登陸前，甚至颱風距離台灣仍遠時，只要氣流狀況符合產生地形雨的條件，山區就會發生強降雨。Lin et al. (2001) 提出一簡單指標協助豪大雨事件的研判，該指標考慮了3個影響因子：(i) 與地形走勢垂直的風速分量；(ii) 地形坡度；(iii) 水氣混合比。其中，經由台灣颱風降雨的案例分析顯示，與地形走勢垂直之風速分量為主要影響因子。

Tsai and Lee (2009)分析颱風時期之台灣測站風雨特徵及關聯性，利用MCA法(Maximum Covariance Analysis)，分析中央氣象局氣象觀測站之風速風向、雨量資料，找出風雨偶合場 (coupled fields)的主要對應特徵分量。該研究指出，風雨MCA分析以及特徵分類的邏輯和成果，可辨別不同風場環流型態下所對應的降雨型態，應適合做為颱風氣候降雨的輔助估計指標。

此外，由於地形的因素，台灣地區災害和颱風路徑走向有一定之關聯性，因此颱風警報期間，作業單位常會以類似路徑之歷史颱風個案做為決策參考。然而過去數十年之歷史颱風個案數量龐大，常要依賴經驗豐富人員之記憶，或是以人工搜尋比對，將可能使得參考資訊不夠客觀和完整。

為了將上述概念應用至實際預報作業，本研究將開發客觀比對颱風個案特性之方法。在颱風降雨預報作業採用歷史個案做為參考案例的搜尋過程中，除了考慮颱風中心座標、強度…等颱風特性是否相近之外，亦將大尺度資料之特性亦納入歷史颱風個案之類比搜尋程序。擬採用NCEP Reanalysis資料(簡稱R1；Kalnay et al. 1996)之大尺度分析場(例如海平面氣壓、500百帕高度場、地面風場…等)，做為颱風侵台期間之環流特徵分類指標，協助預報人員藉由歷史個案判別可能之風場與降雨型態，提供颱風警報期間參考。

此外，若作業期間之模式預報路徑及環流型態，與官方預報相近，則可利用全球預