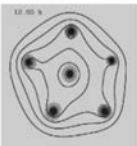
Cloud, Rainfall, and Typhoon

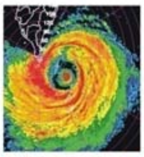
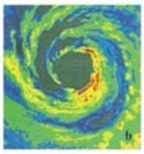
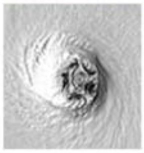




Hung-Chi Kuo

National Chair Professor
NTU Chair Professor
NTU Distinguished Professor

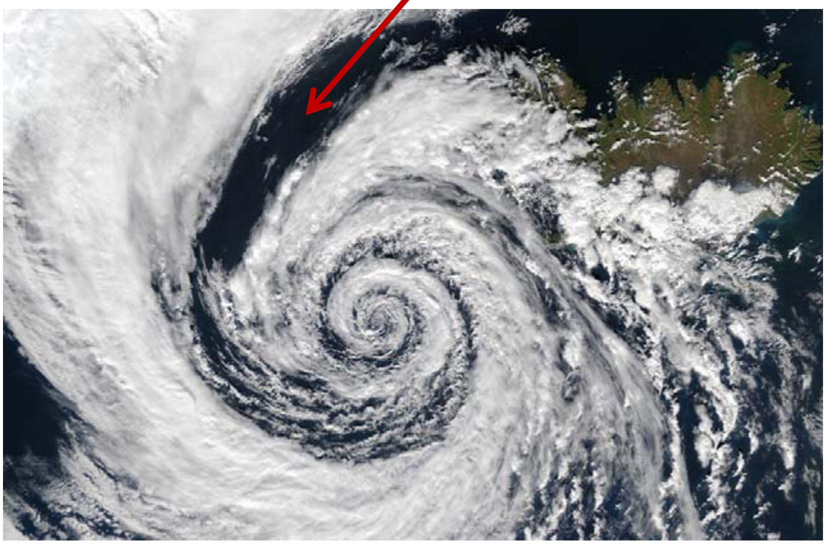
Department of Atmospheric Sciences
National Taiwan University
Taipei, Taiwan

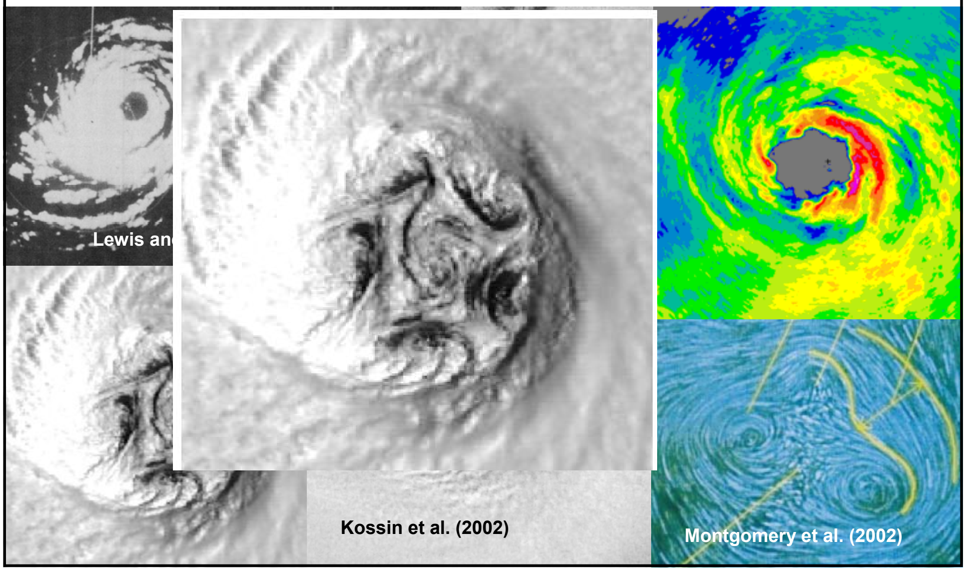
June 29 2010

Many spiral bands

Dry air intrusion



Polygonal eyewalls and eye mesovortices in hurricanes



象神颱風侵襲後的台北市Taipei city aftermath of a typhoon

Before

Aftermath (near 500 people got killed)

Typhoon Morakot 2009

Typhoon Research Topics

Track： Track error cut half since 1990
satellite data, model, ensemble
technique, data assimilation

Intensity and structure

wind shear, SST, ocean heat content,
land fall, internal dynamics

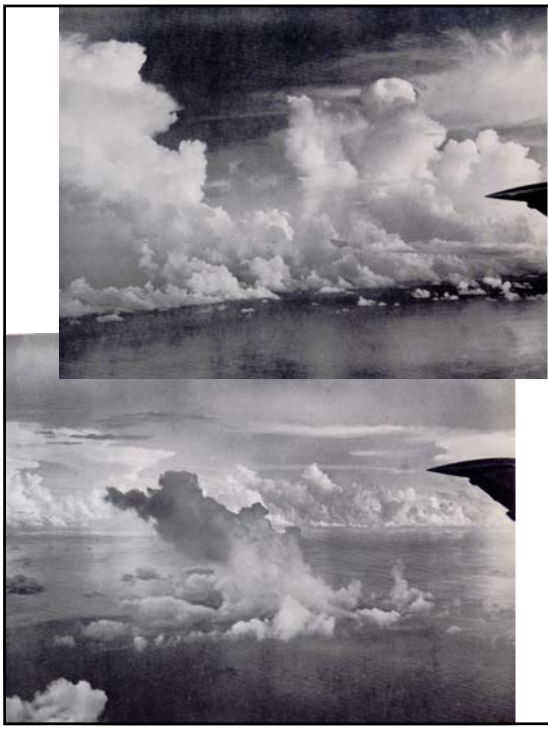
Genesis clustering (one after another)

Climate genesis frequency, area, track
decadal, global warming

Thermodynamics
Clouds and cloud systems

Quote from 1970 Tropical Conference by Bill Gray:

"If little cumulus weren't important, God wouldn't have made so may of them"



Photos from 1957 Pacific flights

Joanne Simpson at WHOI

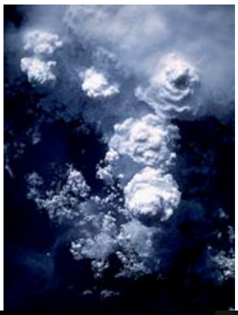
"So I was interested in clouds for just themselves because they were fascinating," explains Simpson. Rossby said that no one was very interested in them, so it was a good subject "for a little girl to study."

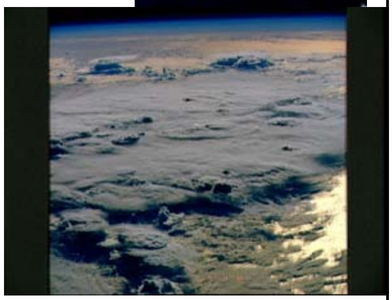
– U. Chicago, late 1940s

Riehl, H., and J. S. Malkus, 1958: On the heat balance in the equatorial trough zone. *Geophysica*, **6**, 503-538.

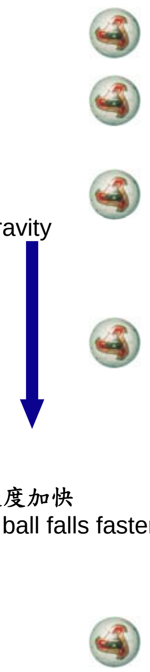
- Energy balance of equatorial trough zone requires undilute vertical transport through the θ_e or h minimum in the midtroposphere
- About 2,000 "hot towers" needed to satisfy the global balance

Update: Zipser (2003) provides evidence that undilute ascent over tropical oceans is relatively rare: freezing is important source of additional buoyancy





gravity



重力
球速度加快
The ball falls faster and faster

速度越下越快，變窄
The water speeds up and gets narrower.

浮力 向上速度越來越快
越強對流 越窄
Buoyancy makes the updraft narrower.

熱帶是條件性不穩定大氣 Conditional Unstable Atmosphere

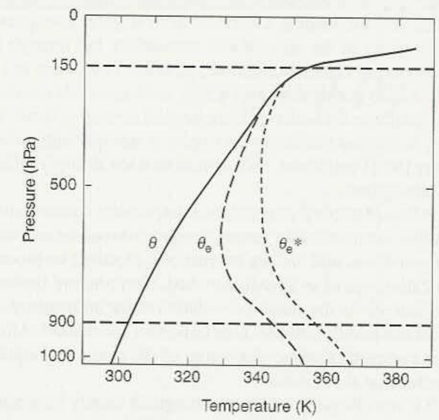


Fig. 11.1 Typical sounding in the tropical atmosphere showing the vertical profiles of potential temperature θ, equivalent potential temperature θ_e, and the equivalent potential temperature θ_e^* of a hypothetically saturated atmosphere with the same temperature at each level. This figure should be compared with Fig. 9.10, which shows similar profiles for a midlatitude squall line sounding. (After Ooyama, 1969. Reproduced with permission of the American Meteorological Society.)

Ooyama 1969

High θ_e for vigorous convection

Convection rooted in PBL

Finite amplitude forcing required

PBL structure is of vital importance for the air-sea interaction!

Up moist, down dry!

Convective Rain with large intensity

More condensation more latent heat

⇧

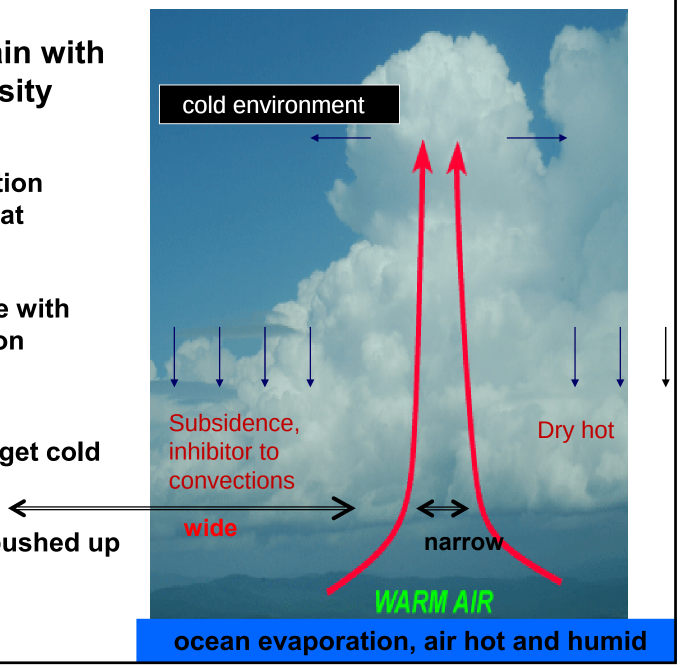
Latent heat release with Cloud condensation

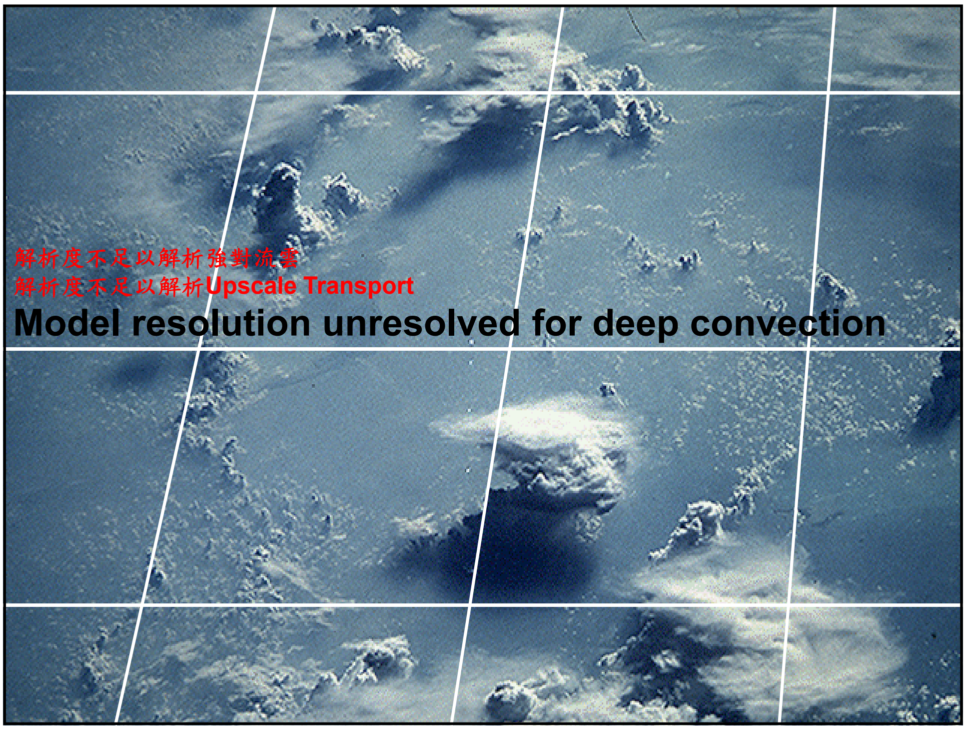
⇧

Expansion and get cold

⇧

Hot and moist air pushed up
High θ_e air





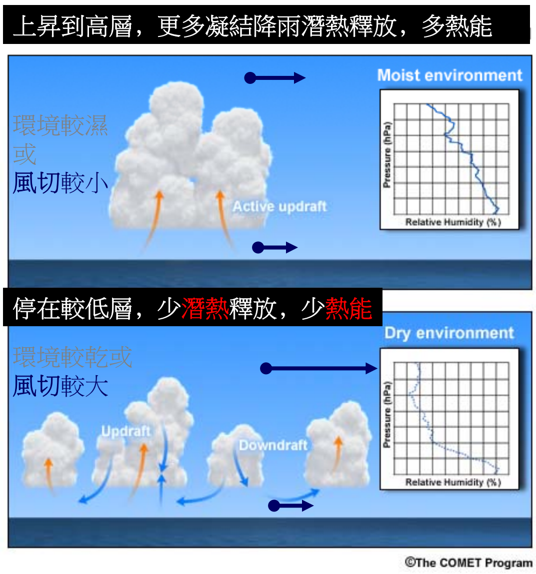
Water vapor and wind shear (wind speed difference)

Humid environment
Small wind shear

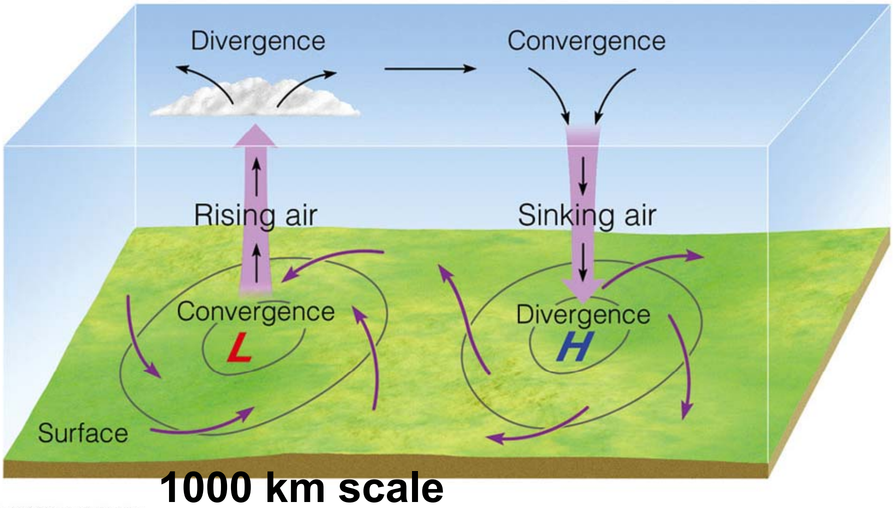
Convection deep

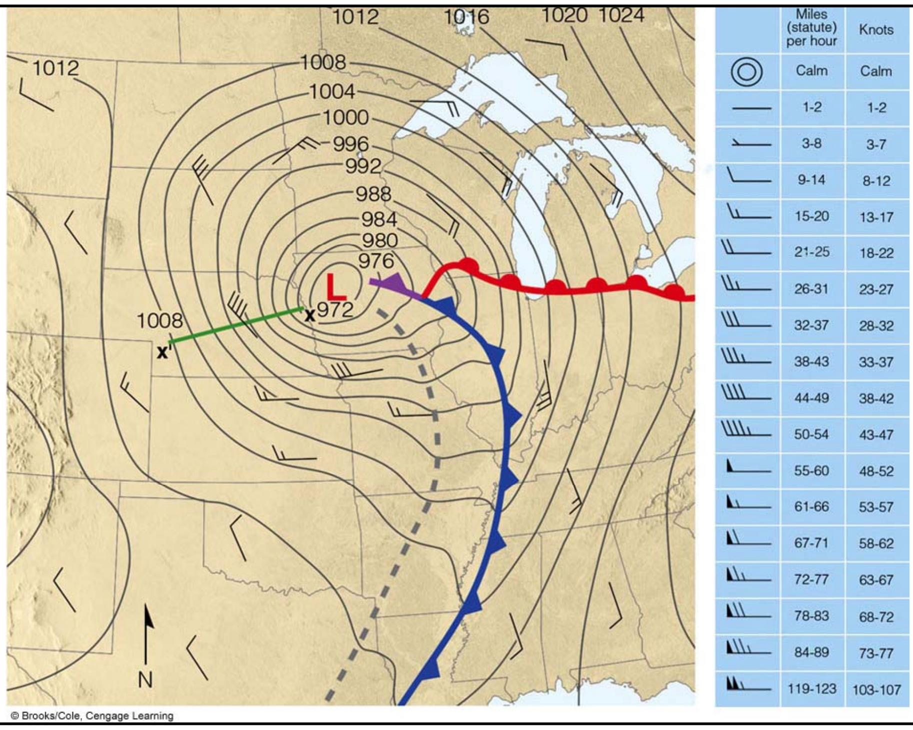
Dry environment
large wind shear

Convection shallow

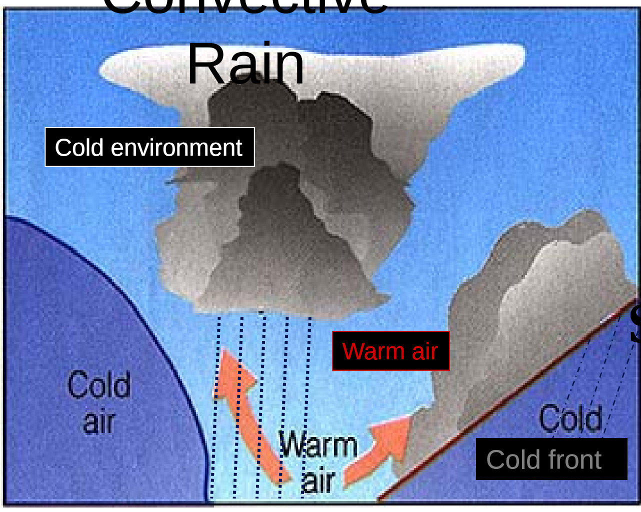


Mechanical lifting, system of cloud.
Conditional instability not necessary.





Convective Rain



Stable Rain

Federation of American Scientists

Early 70s: Development of Ideas Related to the Problem of Cumulus Parameterization (Arakawa, Yanai, Ooyama, Gray)

Yanai, Esbensen, and Chu (1973)

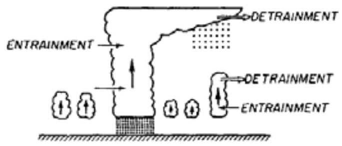
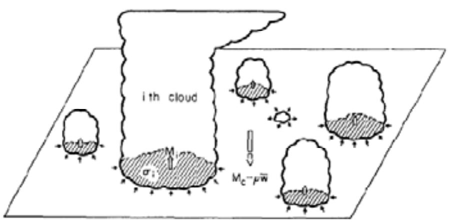
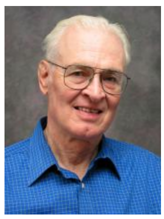


FIG. 1. Schematic view of an ensemble of cumulus clouds.

Arakawa and Schubert (1974)



Gray (1973)



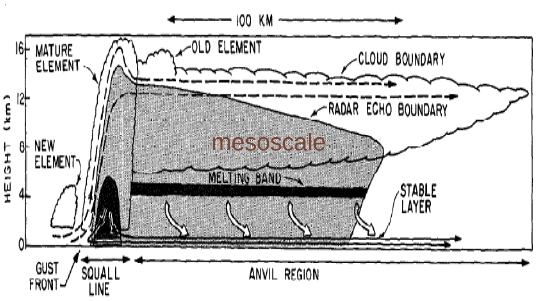
"Up moist – down dry"

Mesoscale Organization 中尺度對流

Line Islands, GATE, etc. – convection observed with distinct mesoscale organization

…and found that such systems (squall lines)

(Houze 1977)



Convective area
~ 10 km

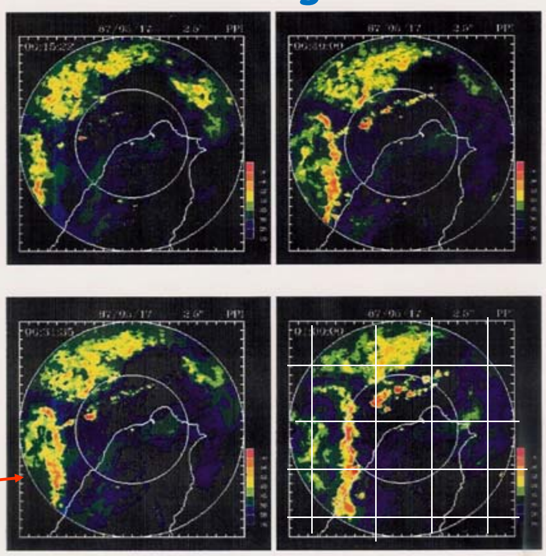
- were commonplace in the tropics
- contained convective-scale and mesoscale downdrafts
  中尺度下沈氣流
- enhanced the surface sensible and heat fluxes over large areas 海氣交互作用
- contained stratiform "anvil" regions that contributed ~40% of the total precipitation 40%層狀雨

Mesoscale Organization

狂風不終朝，
暴雨不終日，
孰為此者？
天地；
天地尚不能久，
而況人乎。

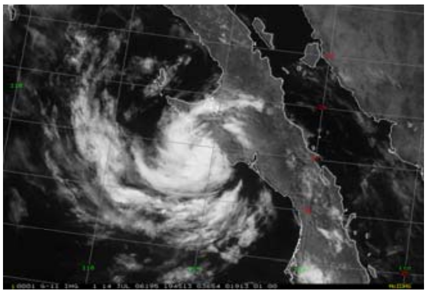
老子

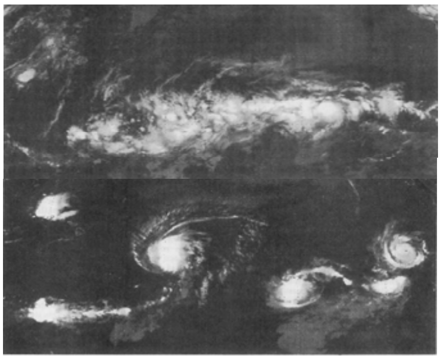
颮線
Squall line

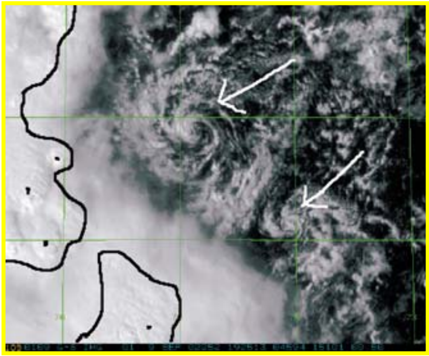


1987 年 5 月 17 日鋒前颮線之雷達回波圖

模式解析？

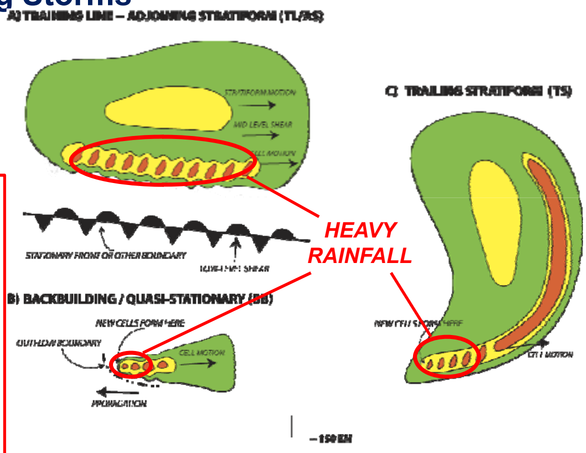






Flash-Flood-Producing Storms

- 184 cases from 1999-2003; 75% were MCSs.
- Three dominant patterns emerged.
- BB MCSs are more dependent on mesoscale and storm-scale processes, particularly lifting provided by storm-generated cold pools, than on preexisting synoptic boundaries.



Frequency

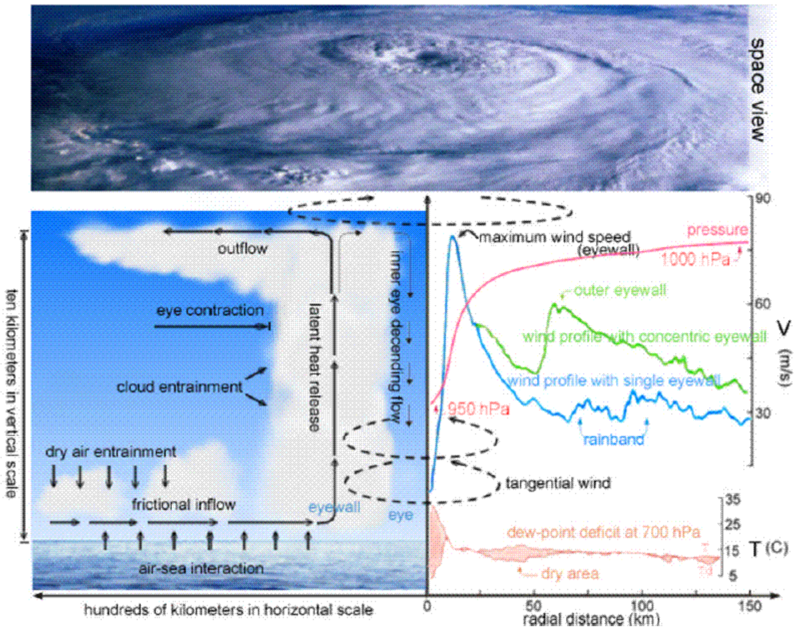
TL/AS	34%
BB	20%
TS	20%

Schumacher and Johnson (2005, 2006)

- 對流降雨： Convective rain
  - 低層熱、濕空氣 hot and humid air
  - 降雨率大 large rain intensity
  - 時間和空間尺度短 small spatial and time scale
- 穩定降雨： Stable rain
  - 需要推擠空氣上昇 lifting required
  - 降雨率小 rain intensity small
  - 時間和空間尺度長 large spatial and time scales
- 長時間降雨 ，需要水氣補給。 Long duration need water vapor supply.
- 中尺度降雨系統 Mesoscale system 。
- 系統降雨和對流胞降雨不同。System vs convective cell

Typhoon Basic Physics

Typhoon Structure



Latent Heat during typhoon made landfall

Precipitation ~1600*mm*

$1600\ mm = 1.6\ m$

$1.6\ m * 1000\ kg\ m^{-3} * 2.5\times10^{6}\ J\ kg^{-1}$

$= 4 \times 10^{9}\ J\ m^{2}$

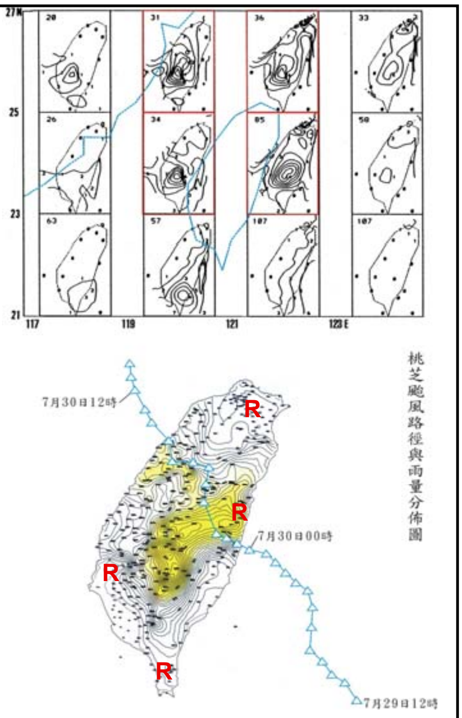
$4\times10^{9}\ J\ m^{2} * 2.5\times10^{9}\ m^{2}\ \sim10^{19} J$

Annual energy usage in Taiwan 10^{17}J (10^{18}J in States)

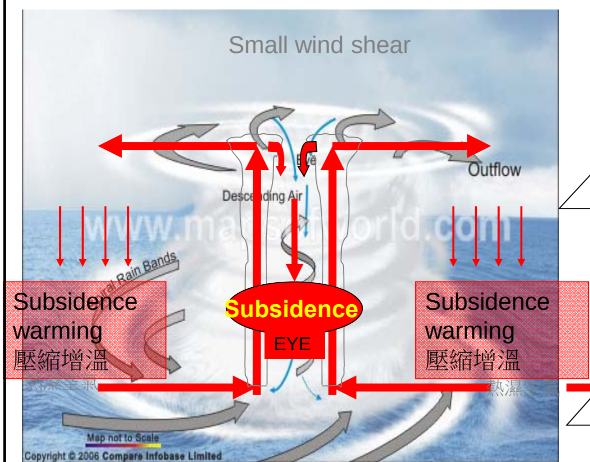
CWB is capable of 24 hr and 100km scale precipitation (phase locked with topography)

0 to 12 hr and 10 km ppn remain biggest challenges

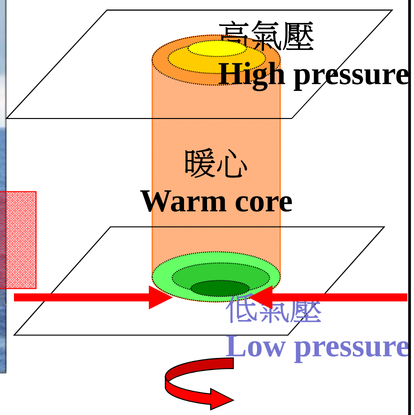
355mm in 5 hr in the city of KaoShung (5 pm to 10 pm at the beginning of the rush hour)



颱風結構和機制



海面溫度高 high sea surface temperature



Ooyama 1969

The important of *air-sea interaction* to the maintenance of tropical cyclone.

"Tritium measurement indicates 60%-80% of the water in the eyewall could have evaporated from the ocean not so long ago."

"Tropical cyclone consumes a great deal more latent heat than it can collect from the pre-existing atmospheric vapor."

Huge CAPE without air-sea interaction make NO tropical cyclone.

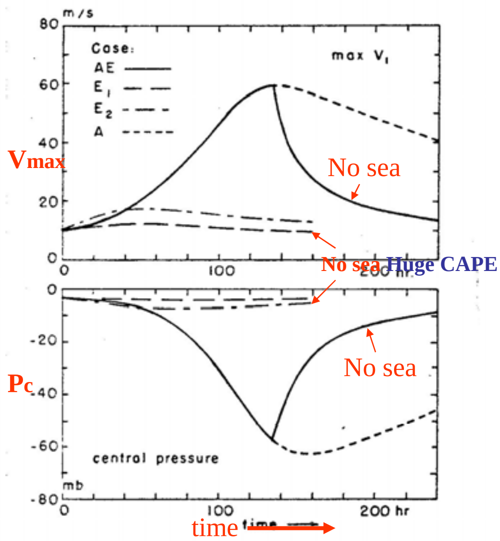


FIG. 15. Results of experiments demonstrating the importance of direct energy supply from the ocean to tropical cyclones. In Case AE, the energy supply to the Case A cyclone is suddenly stopped ($C_E=0$) at $t=134$ hr, to simulate landfall. In Cases E_1 and E_2, in which η is initially assumed to be 2.0 and 3.0, respectively, there is no energy supply from the ocean.

颱風大小與強弱無明顯關係

No relationship between size and intensity

What are the controls??

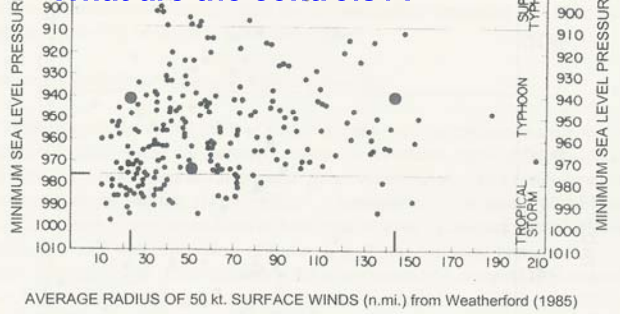


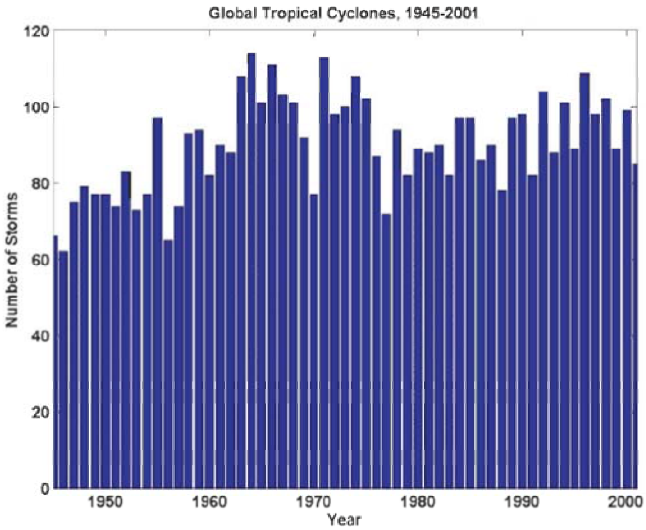
Figure 13. Intensity (minimum sea-level pressure) versus the radial extent of 50 kt (60 miles/hour) winds in nautical miles (n mi) for northwest Pacific typhoons as measured by reconnaissance aircraft [Weatherford and Gray 1988]. One n mi is equal to 1.85 km. Large dots illustrate the large differences that can exist for cyclones of the same minimum sea-level pressure (MSLP) of 940 mb, 23 kt versus 144 kt. Note also that the cyclones of similar outer radius of 50 knot winds can have MSLP differences as great as 890 versus 975 mb. These measurements are also typical of the Atlantic.

Weatherford and Gray 1988

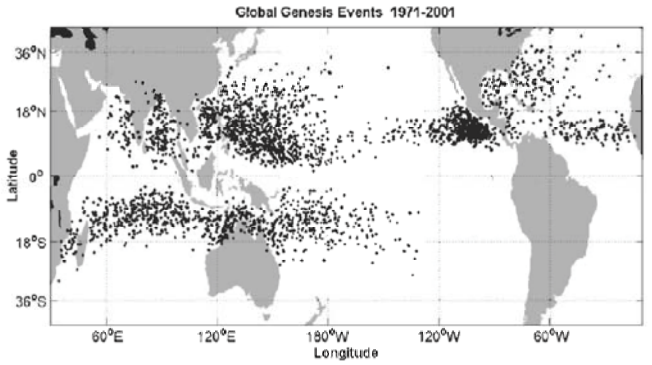
Gray (1968) identified 6 necessary (not sufficient) conditions of tropical cyclone genesis. They are

- Pre-existing synoptic disturbance with convection;
- Significant planetary vorticity (means some distance away from the equator);
- Favorable vertical shear pattern;
- Moist mid-troposphere;
- Warm ocean (SST> 26.5°C) with deep mixed layer;
- Conditionally unstable atmosphere.

The annual global tropical cyclones from 1945~2001.



The annual number of tropical cyclone has not changed much globally.
The annual number seems to be around 90 with about +/- 15.



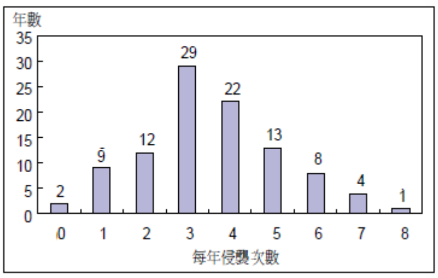
Global distribution of tropical cyclongenesis during 1971~2001

- Taiwan is usually attacked by an average of three to four typhoons every year.

- 50 percentage TYs which attacked Taiwan occurred in JUL.,AUG. & SEP. About 10% occurred in OCT.,NOV, & DEC.

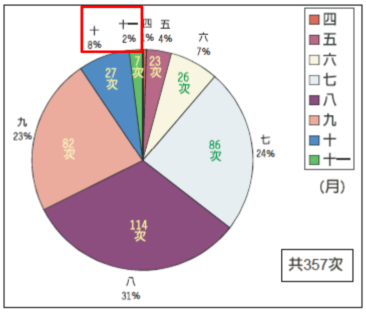
- Summer Monsoon (South-westerly flow) (July & Aug & early-Sep)

- Winter Monsoon (East-northerly flow) (late-Sep,Oct,Nov,Dec)

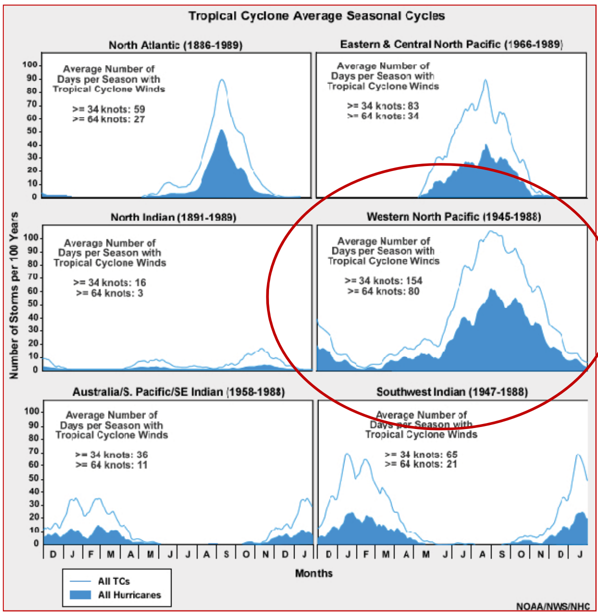


圖六　百年來侵台颱風之次數統計，平均每年約三至四次。

Kuo, Wu & Lee (2001)



圖五　百年（一八九七至一九九六）來侵台颱風於各月之次數統計，可以發現颱風的侵台主要在七、八及九月份，十二月至三月沒有颱風侵台。



Average annual cycle of tropical cyclone occurrence for each ocean basin.

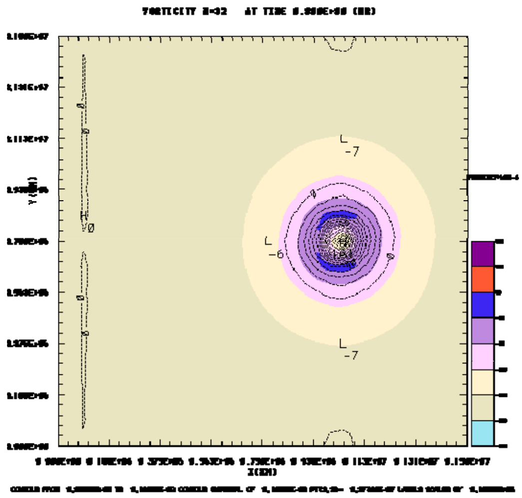
The abscissa spans the months of the year and the ordinate is the number of storms per hundred years. The blue line represents all tropical cyclones (surface winds greater than 17 m/s or 34 knots) and shading represents tropical cyclones of hurricane strength (surface winds greater than 33 m/s or 64 knots).

The averaging time for the mean surface wind speeds varies across basins

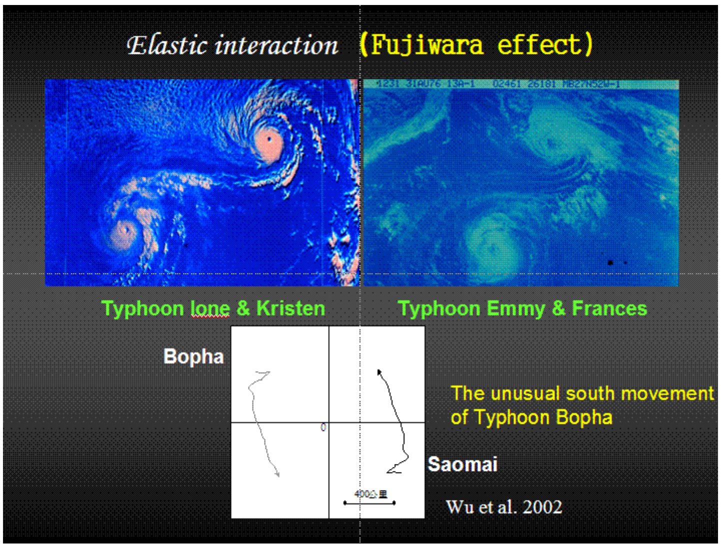
Typhoon motion affected by

- Steering flow
- Beta-drift
- Shear
- Drag effect
- Fujiwhara effect
- Topography effect

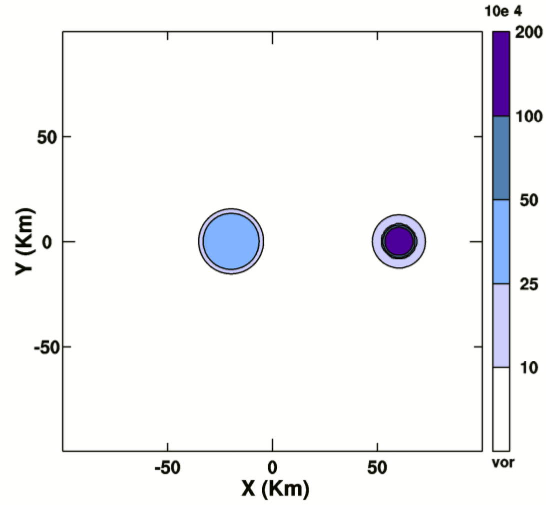
Beta Drift



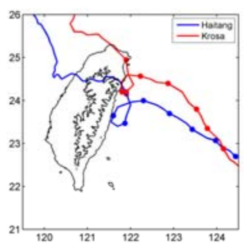
Simulation of Fujiwhara effect



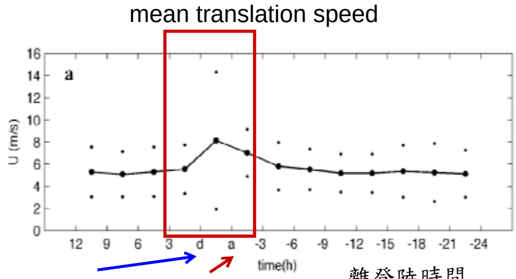
Simulation of Fujiwhara effect



颱風接近陸地時路徑偏折及移速改變

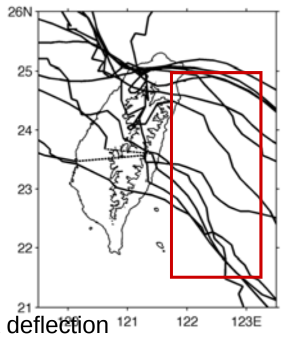


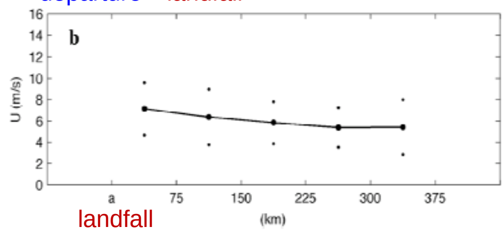
mean translation speed



departure landfall

離登陸時間



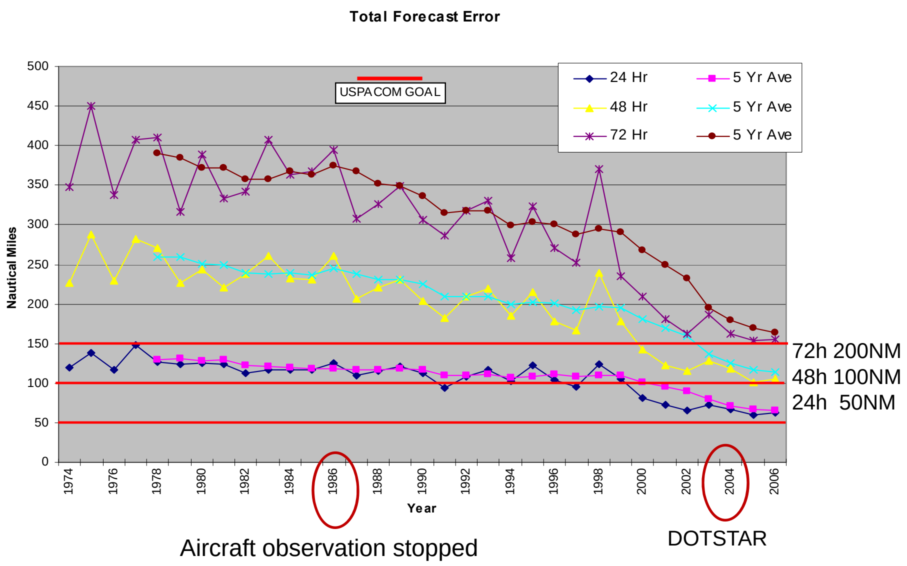


landfall

離陸距離

Track deflection
(cyclonic path = topographic strectching?)

West Pac Track Errors cut in half since 1990



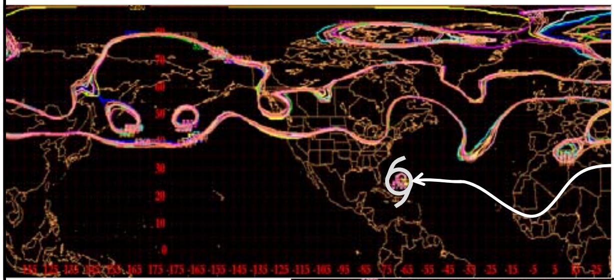
Edward Fukada

JTWC

Typhoon Intensity and Structure

The Downstream Influences of the Extratropical Transition of Tropical Cyclones

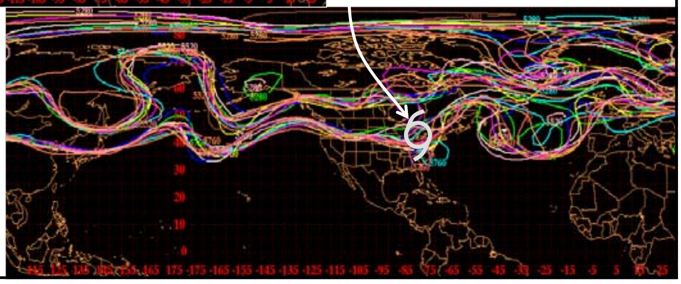
Patrick Harr
Naval Postgraduate School



0000 UTC 16 Sep 2003
GFS Ensembles +00

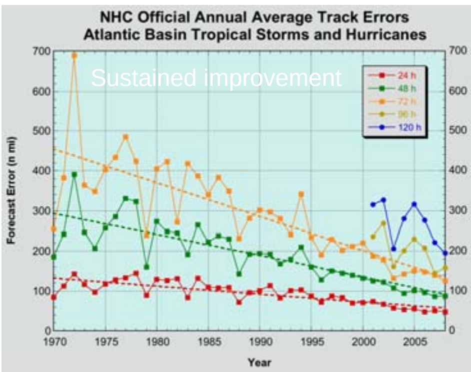
Hurricane Isabel

GFS 500 hPa Ensembles +108 h
VT 1200 UTC 20 Sep 03

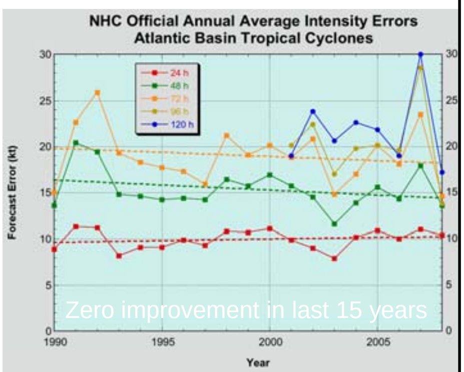


Acknowledgment: Office of Naval Research, Marine Meteorology Program

Error cut in half since 1990



No progress in the last 20 years



www.nhc.noaa.gov/verification/verify5.shtml

Why such a big difference between track and intensity?

Courtesy of Dr. G. Holland

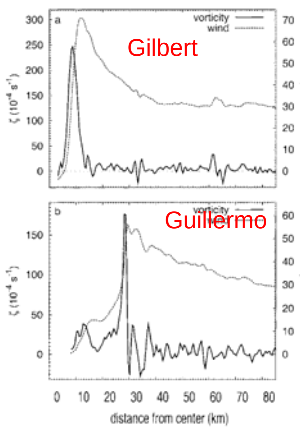
Environmental Factors

Typhoon weakens
over region of cold water or low ocean heat content,
over land or region of decreased humidity,
over region of strong vertical wind shear.

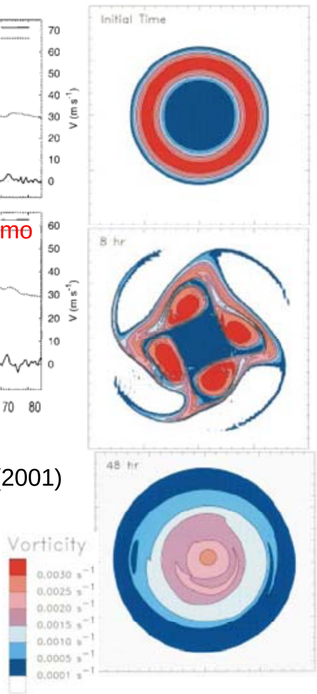
However, the variance of typhoon intensity change from climatology is not explained well by the synoptic-scale environmental conditions.

It is fairly typical for typhoons to strengthen or weakens rapidly without any clear commensurate changes in the environment.

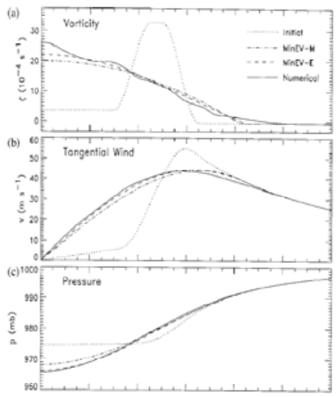
Internal meso-scale processes matter!



Kossin and Schubert (2001)

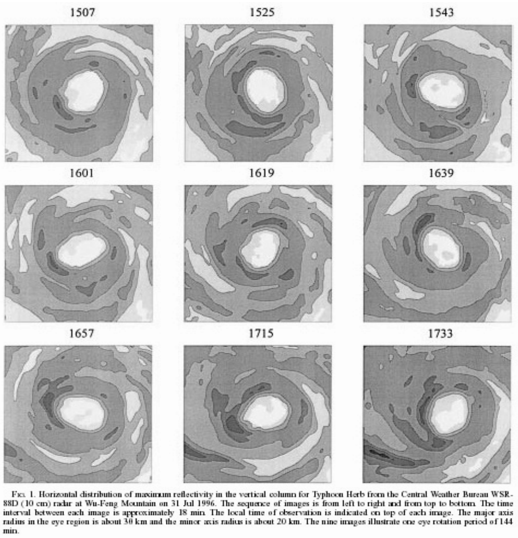


Schubert et al. (1999)



Vorticity mixing leads to Rapid Intensification !

賀伯颱風的橢圓形眼 Elliptical Eye Kuo et al. 1999 JAS



144 min rotation period

Lamb, 1932

Kirchhoff vortex (nonlinear)

$$\zeta \frac{ab}{(a+b)^2} = \omega$$

rotating period **P** = $\frac{2\pi}{\zeta}\frac{(a+b)^2}{ab}$

Kelvin PV wave (linear)

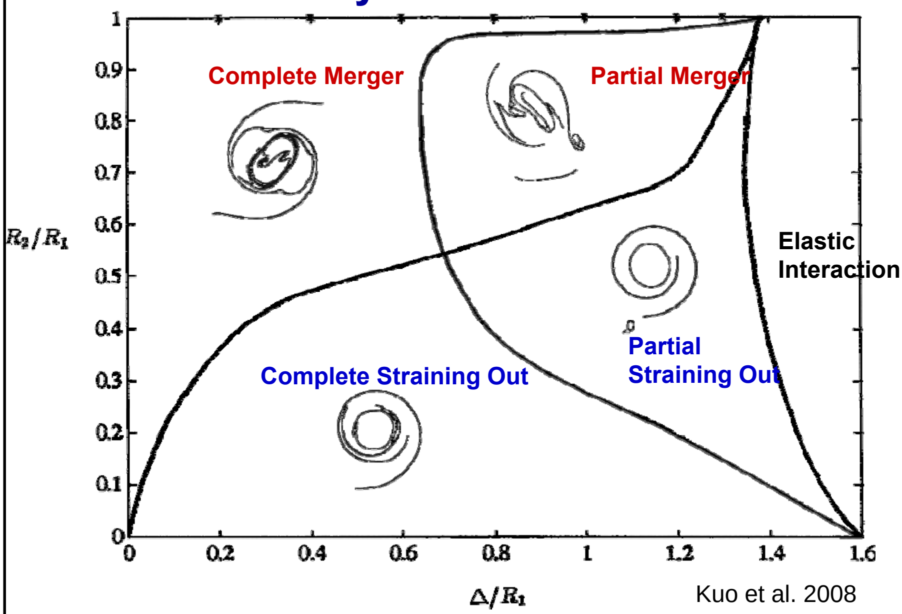
$$c = V_{max}(1-\frac{1}{m}) \qquad m = 2$$

$$\sim \frac{2\pi}{\omega} = \frac{2\pi}{2\frac{V_{max}}{r}} * 4 = \frac{2\pi}{\zeta} * 4$$

Vortex Rossby Waves

Deep convections rotation 144 min

Binary vortex interaction

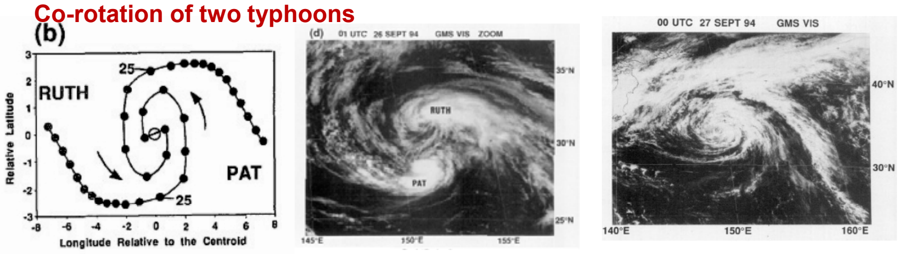


Kuo et al. 2008

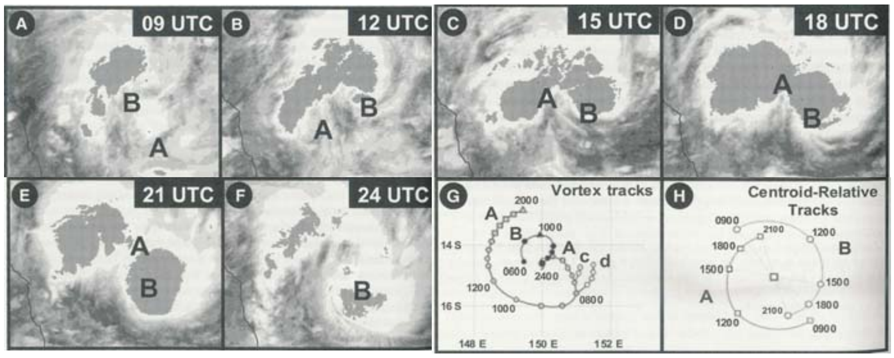
(Adapted from Dritschel and Waugh 1992.)

雙颱風互繞（藤原效應）合併 ---- 颱風 PAT 與 RUTH

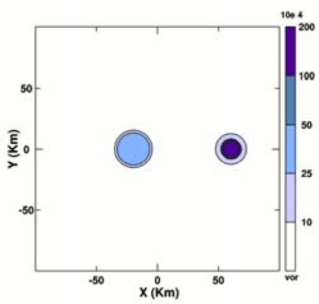
Co-rotation of two typhoons



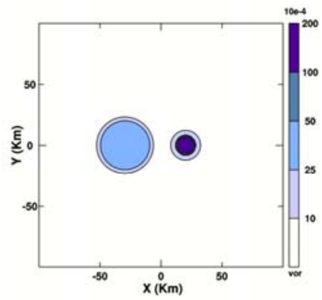
中尺度對流系統互繞 mesoscale convections Simpson et al. 1998



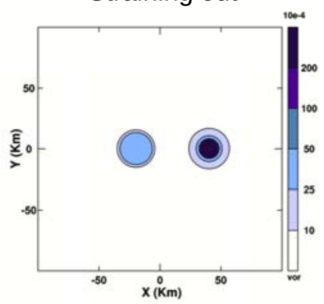
Elastic Motion



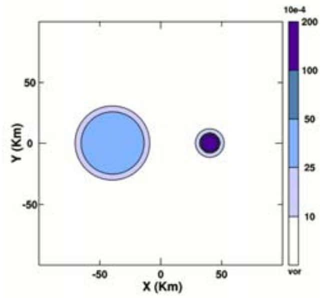
Merger



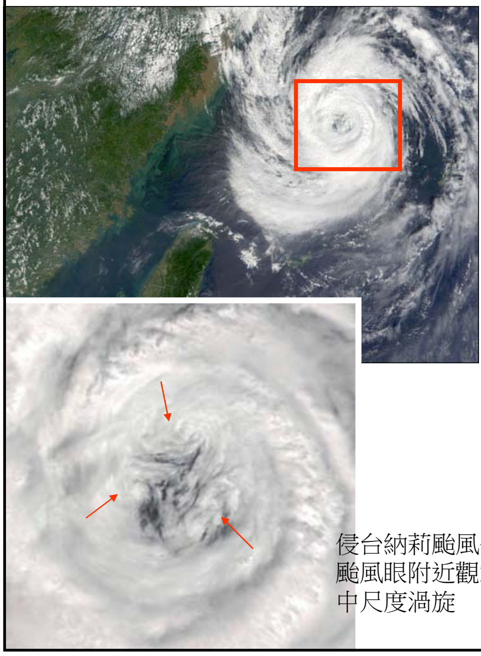
Straining out



Tripole



納莉颱風眼附近的中尺度渦旋



侵台納莉颱風登陸前
颱風眼附近觀測到3 個
中尺度渦旋

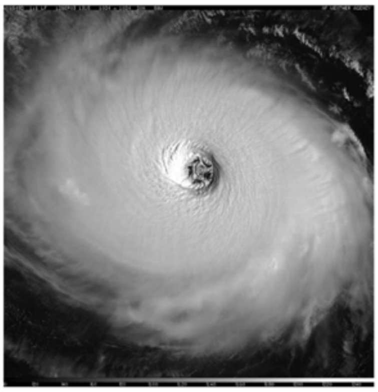
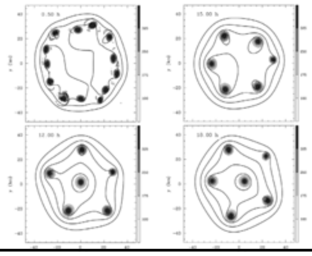
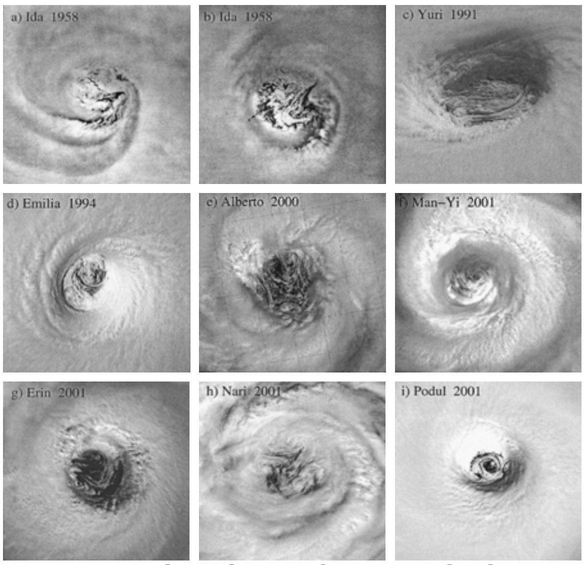


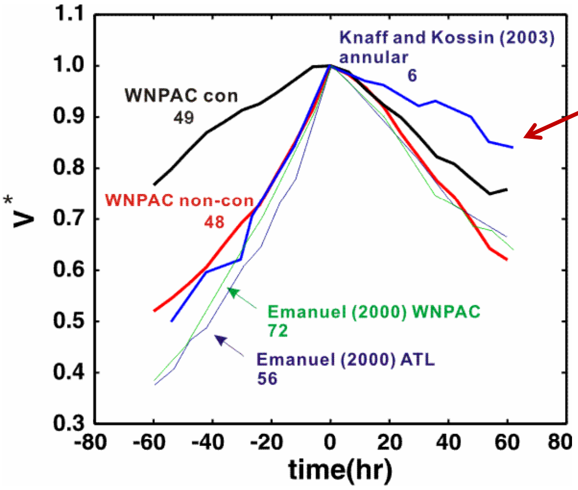
Fig. 1. Defense Meteorological Satellite Program (DMSP) image of Hurricane Isabel at 1315 UTC 12 Sep 2003. The starfish pattern is caused by the presence of six mesovortices in the eye—one at the eye center and five surrounding it.

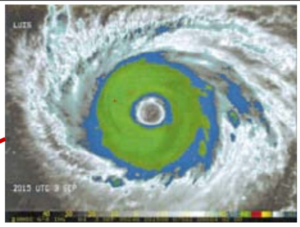




Vortical Swirls in Typhoon Eye Clouds

Kossin and Schubert 2002



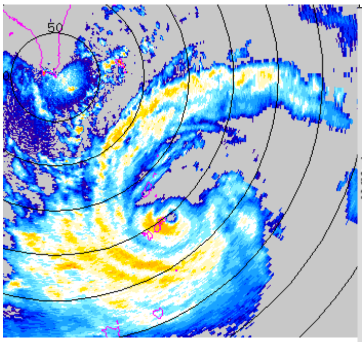


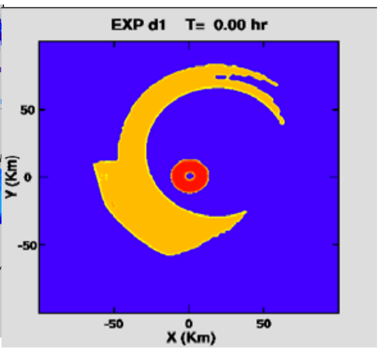
Key feature of concentric eyewall formation appears to the maintenance of a relative high intensity for a longer duration prior to formation, rather than a rapid intensification process that can reach a high intensity.

Kuo et al. 2009

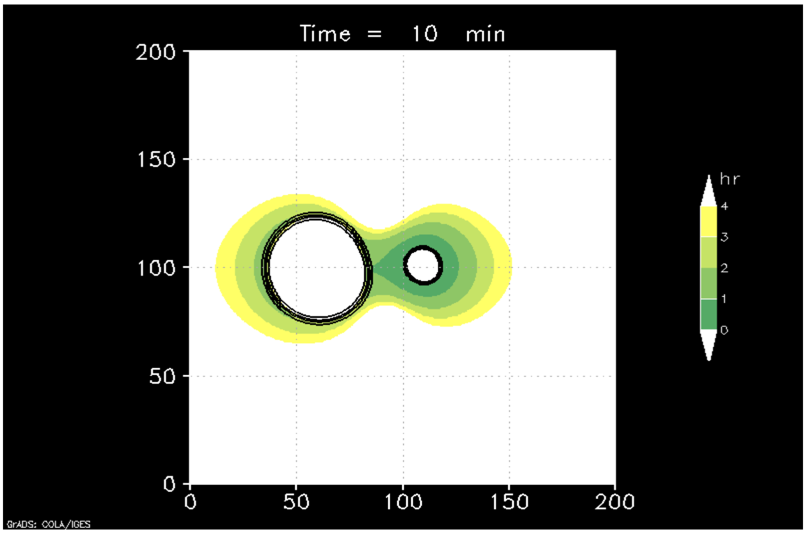
Concentric Eyewall formation

Kuo, H.-C., L.-Y. Lin, C.-P. Chang, and R. T. Williams, 2004: The formation of concentric vorticity structure in typhoons. *J. Atmos. Sci.*, **61**, 2722-2734.
Kuo, H.-C., W. H. Schubert, C.-L. Tsai, and Y.-F. Kuo, 2008: Vortex interactions and barotropic aspects of concentric eyewall formation. *Mon.Wea. Rev.,* **136,** 5183–5198.



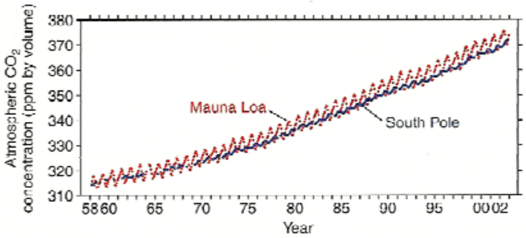


Typhoon Lekima (2001)



Climate and Typhoons

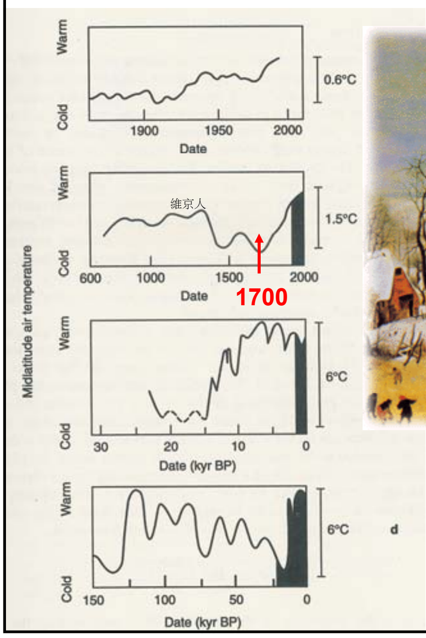
Keeling Curve (1958-)



Charles Keeling (left) at the dedication of the Keeling Building at the Mauna Loa Observatory, Hawaii (1997)

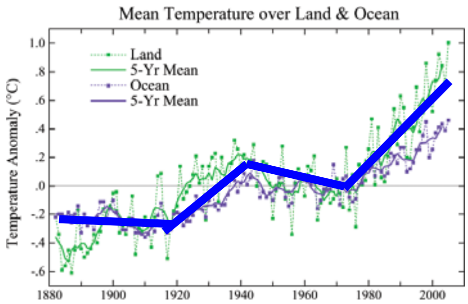
氣候變遷

Warming trend begins 1700A.D.



Bruegel, Pieter, the Younger
< Winter Landscape (1601) >

自然？？　　人為？？

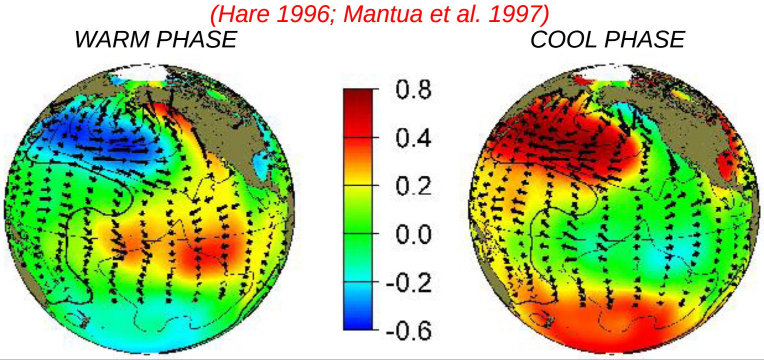


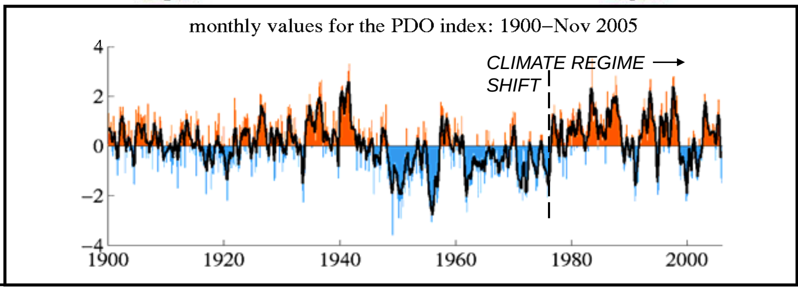
A New York Times-line

"MacMillan Reports Signs of New Ice Age"	"America in Longest Warm Spell Since 1776; Temperature Line Records a 25-Year Rise"	"Scientists Ponder Why World's Climate is Changing; A Major Cooling Widely Considered to Be Inevitable"	"Past Hot Times Hold Few Reasons to Relax About New Warming"
Sept. 18, 1924	March 27, 1933	May 21, 1975	Dec. 27, 2005
-	+	-	+

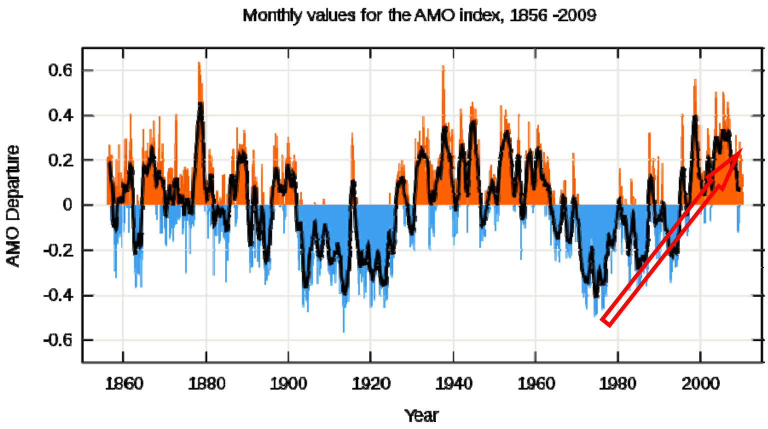
The Pacific Decadal Oscillation (PDO)

(Hare 1996; Mantua et al. 1997)



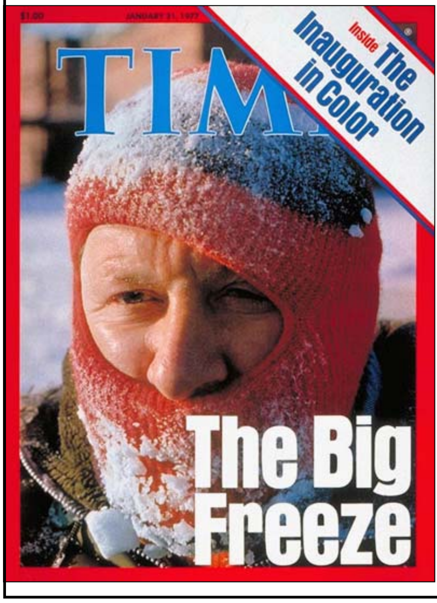


大西洋多年代海洋擾動



The 1970s cooling scare

January, 1977



April, 2006

風雨之不時，是無世而不常有之。 荀子天論

1988　　年際變化 季節預報　　1993

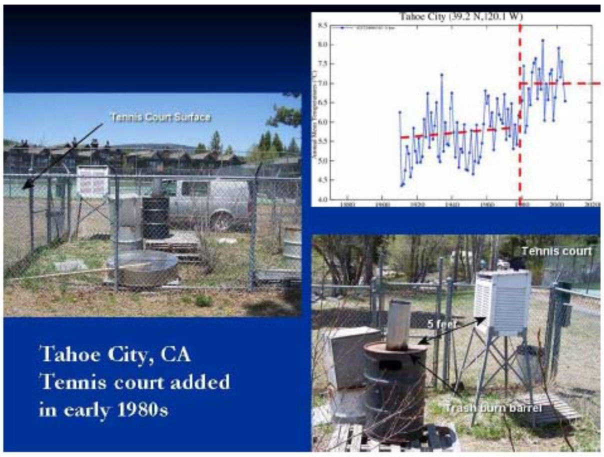
7. 4. 1988　　7. 18. 1993

Heavy rains in the summer of 1993 produced floods along most of the Mississippi River in the central United States, as shown in these Earth satellite photographs of St. Louis, Missouri on July 4, 1988 (left) and July 18, 1993 (right). Extreme climatic events may be increasing in frequency as a consequence of added radiative absorbing gases in the atmosphere.

Annual Variability

局部變化 Local Change

Temperatures rose at this station
when the nearby tennis court was built



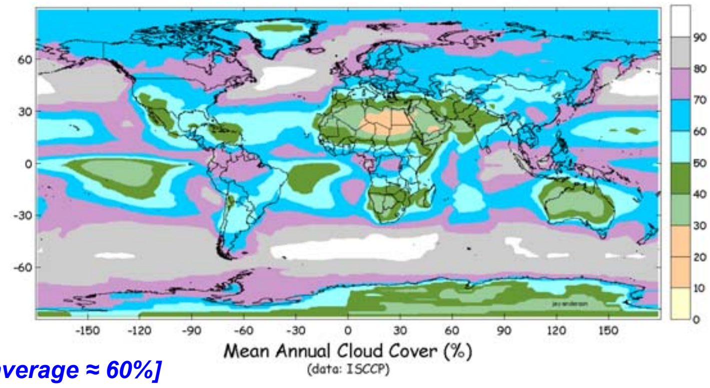
凝結尾 人為

Fig. 10.43 Condensation trails. [Photograph courtesy of Art Rangno.]

During the 3 days after the 9/11 /2001, statistical significant increase of 1.1C in the average diurnal temperature range for ground station across US.

911恐怖攻擊後，3天飛機停航其間，美國日夜溫差平均值增加1.1C。

雲量、雲類是影響氣候最大因素，現況與未來仍不清楚。



[average ≈ 60%]

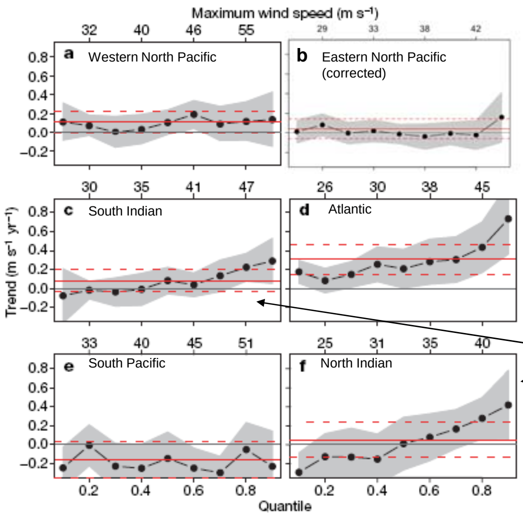
(1982-2001)

- *The climate system is sensitive to cloud cover and cloud type*
- *There is conflicting evidence on changes in global cloud cover over past 2-3 decades; reported trends vary by cloud type*
- *Deep convection impacts cirrus cloud coverage*

卡翠那颶風　Hurrican Katrina

- 任何獨立天氣事件都不應直接被歸因於全球暖化，IPCC也接受這個觀點
- Any extreme weather event should not be blamed on the global warming. (IPCC)
- 暖化對颱風的影響到現在還沒有觀測證據　(2010)
- There is no direct evidence of global warming has impact on tropical cyclone.

Regional Structure of Tropical Cyclone Intensity Trends



北大西洋1981-2006颶風變強

There statistical evidence that the strongest hurricanes are getting stronger is most convincing for the Atlantic (1981-2006).

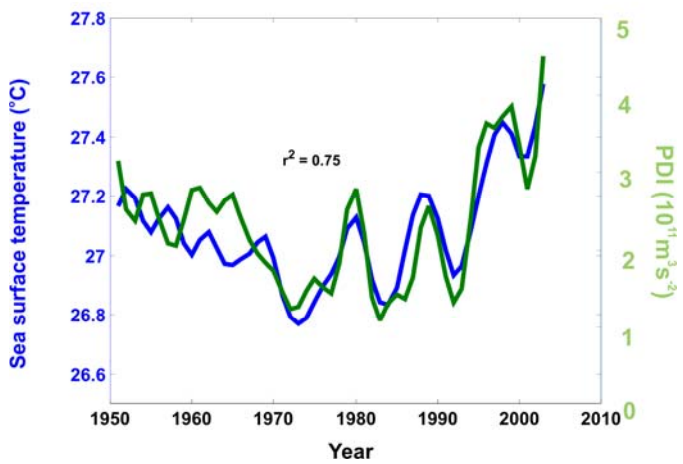
The North and South Indian Ocean data also suggest increased intensity, but data homogeneity concerns are still being debated for those regions.

The intensity change signal is quite weak for the Pacific basin.

Source: Elsner et al., *Nature,* 2008.

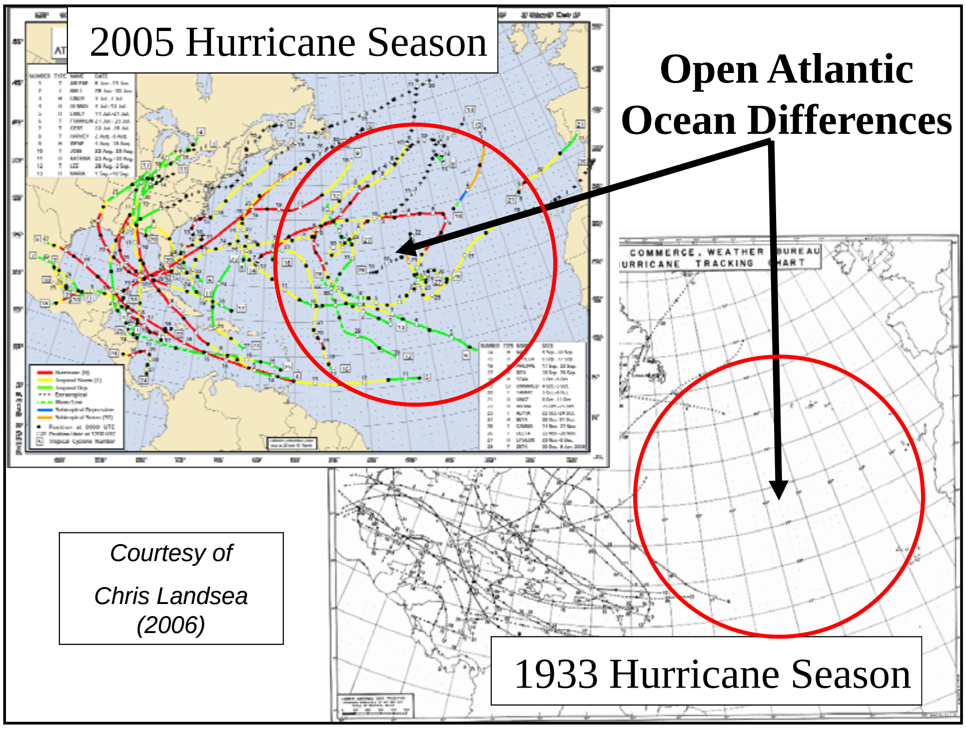
72

There is some recent evidence that overall Atlantic hurricane activity may have increased since in the 1950s and 60s in association with increasing sea surface temperatures…



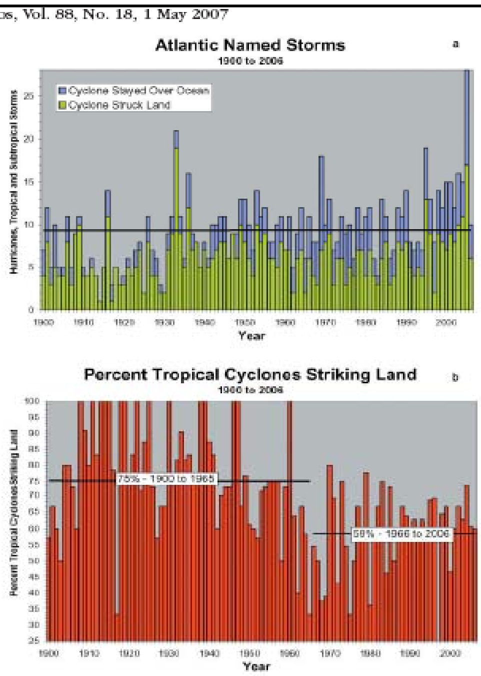
PDI is proportional to the time integral of the cube of the surface wind speeds accumulated across all storms over their entire life cycles.

Source: Kerry Emanuel, J. Climate (2007).

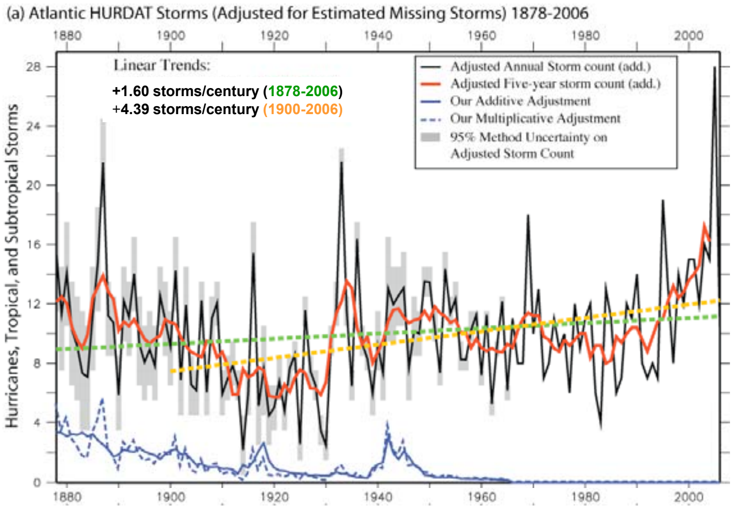


歷史資料的不確定性！
Data uncertainty!

Pre 1965 75%
Post 1965 59%



It is premature to conclude that human activity--and particularly greenhouse warming--has already had a discernible impact on Atlantic hurricane activity. 2009



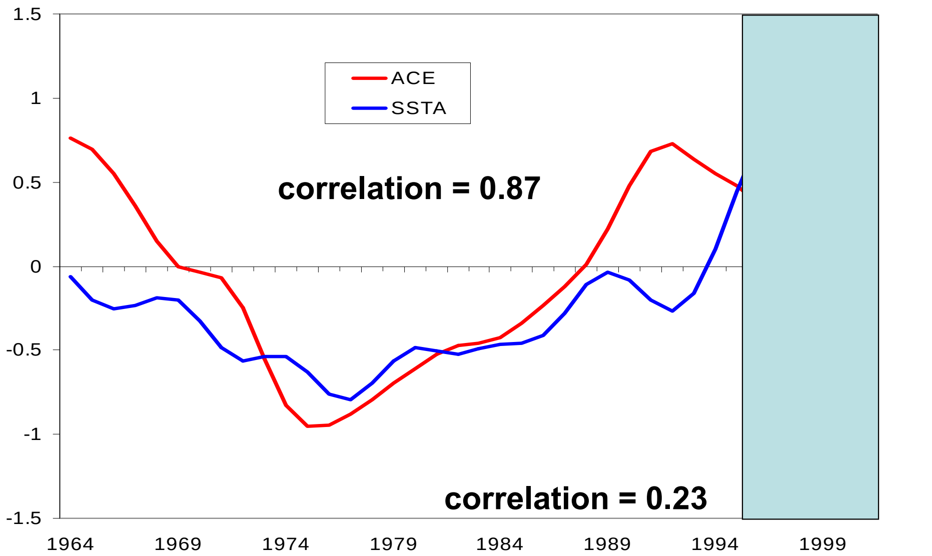
Trend from 1878-2006: Not significant (p=0.05, 2-sided tests, computed p-val ~0.2)
Trend from 1900-2006: Is significant at p=0.05 level

Source: Vecchi and Knutson, J. Climate, 2008.

Typhoon in Taiwan Region

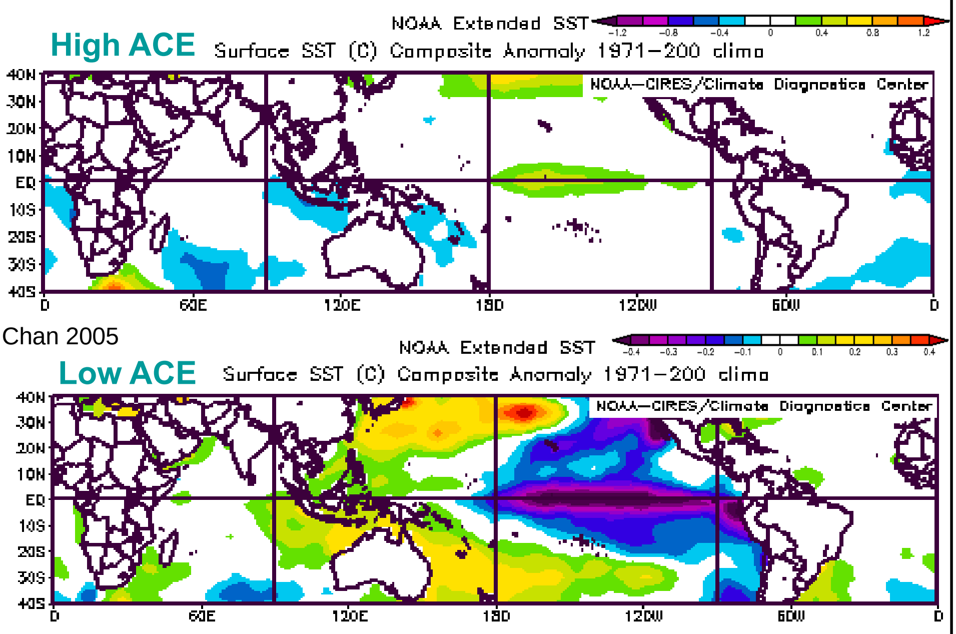
Monsoon and Typhoon

ACE vs May-Nov SSTA (5-30^{o}N, 120-180^{o}E) [10-year Gaussian-filtered; standardized]



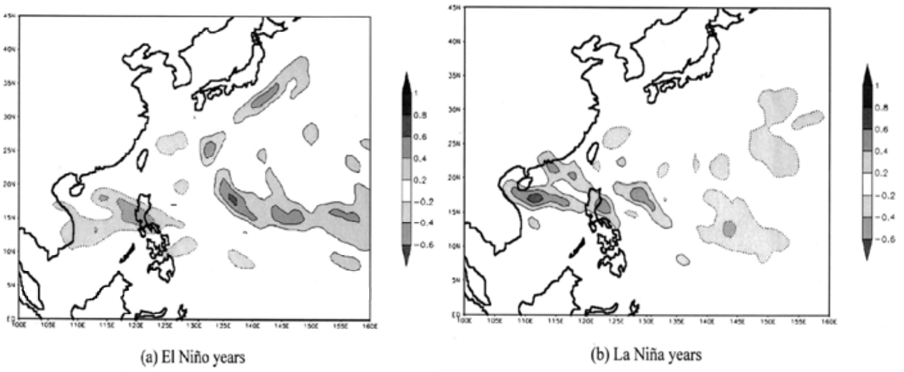
Chan 2005

May-Nov SSTA; High vs. Low ACE (≥|0.5σ|)



反聖嬰年九月或十月容易有強颱侵襲中國東南沿海

Tropical Cyclone Track Density

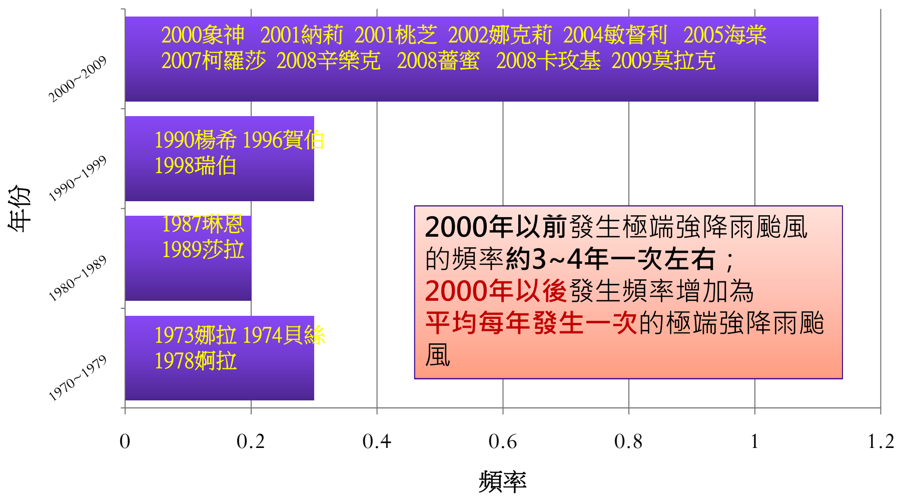


Fall of La Nina years more typhoons make landfall SE of China coast.

< ***Wu et al. 2004*** >

極端強降雨颱風發生頻率統計

（依據1970~2009年排名前20名之綜合降雨指標）



More frequent heavy Typhoon rainfall after 2000

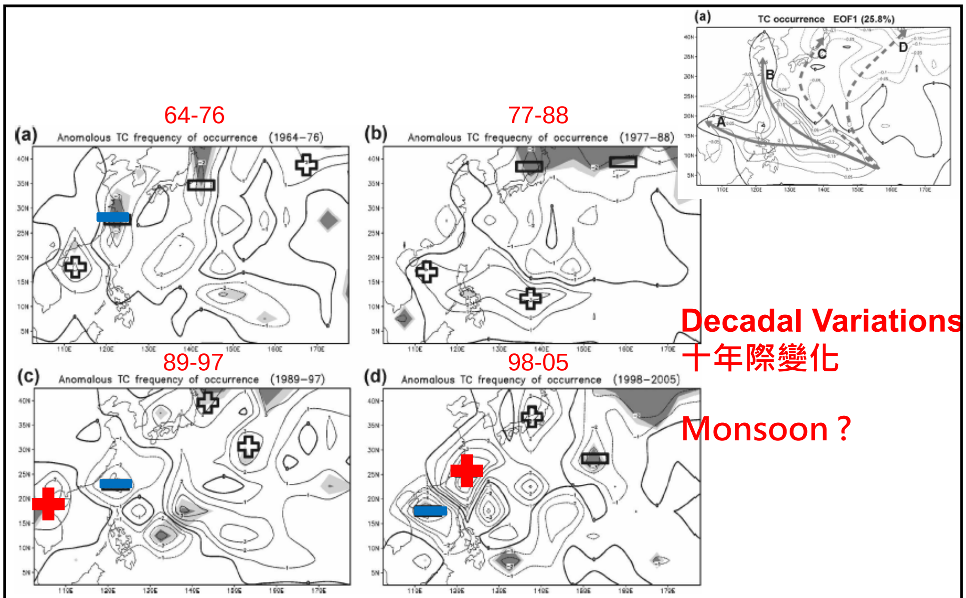
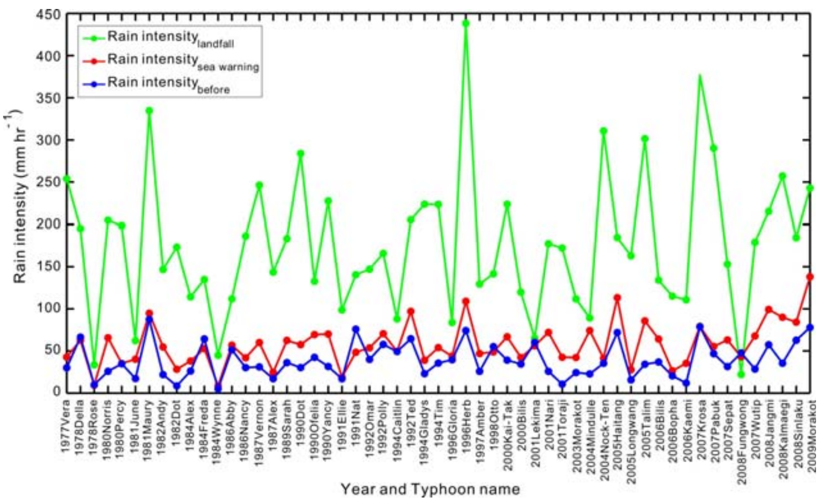


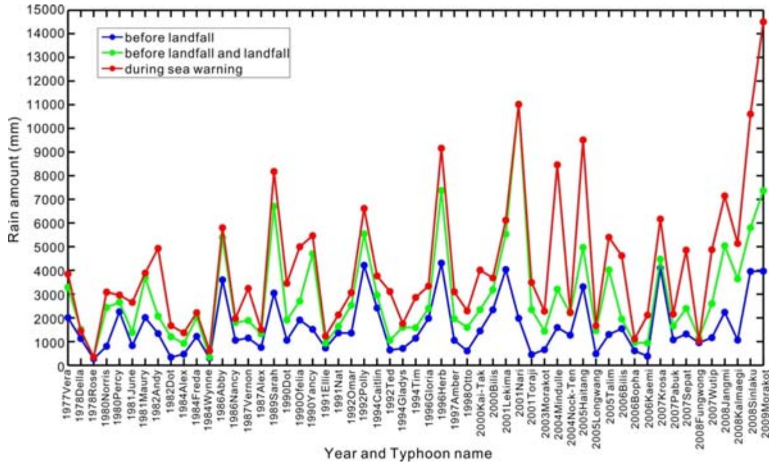
FIG. 2. Anomalous TC frequency of occurrence during the periods of (a) 1964–76, (b) 1977–88, (c) 1989–97, and (d) 1998–2005. Dark and light shadings indicate the areas with anomalies significant at the 95% and 90% confidence levels, respectively. Plus-shaped boxes (rectangular-shaped) indicate the areas with higher (lower) TS frequency of occurrence.

Liu and Chan 2008

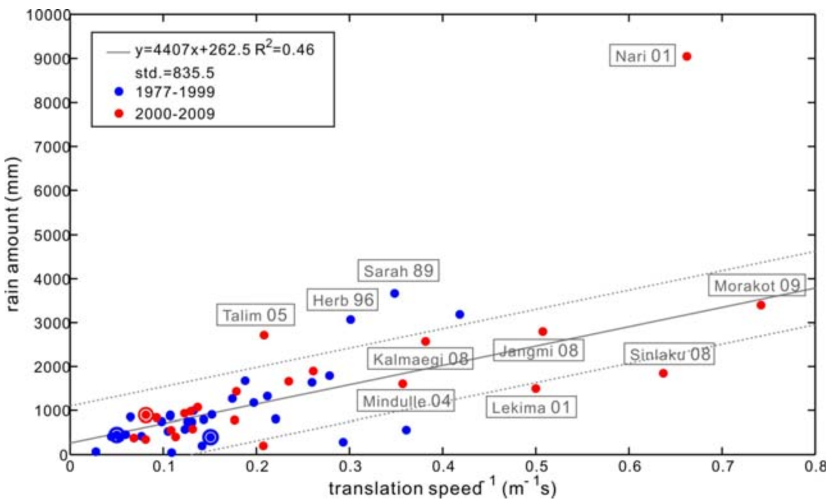
Much larger precipitation intensity during the landfall.



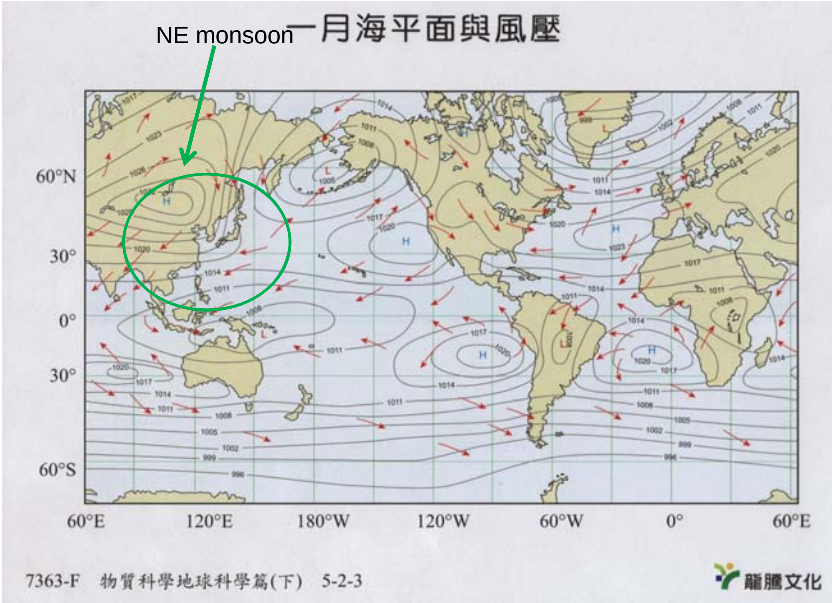
Rain amount before and after the landfall may be larger than rain amount during the landfall.



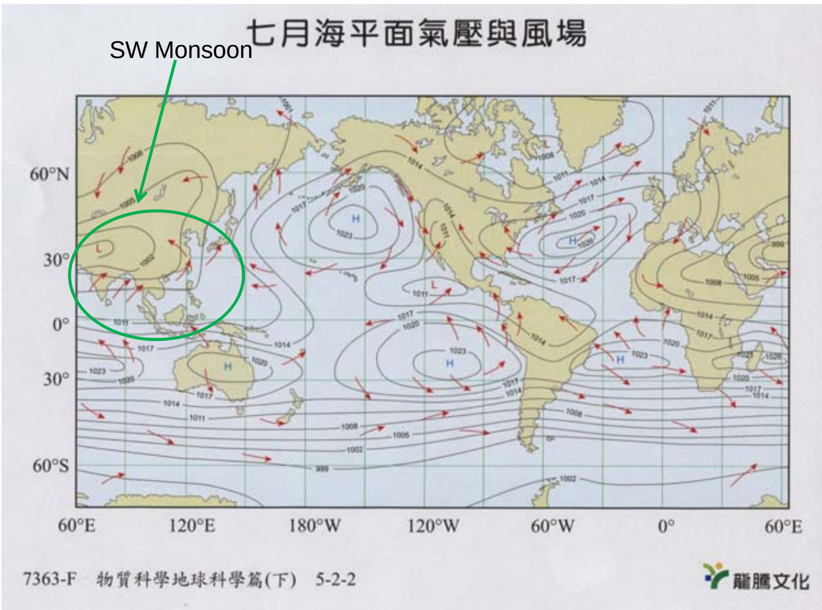
The amount of rainfall depends heavily on the speed of typhoon.

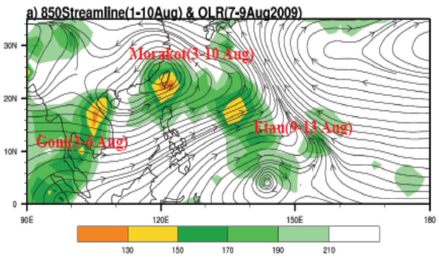


January Sea level Pressure and Wind

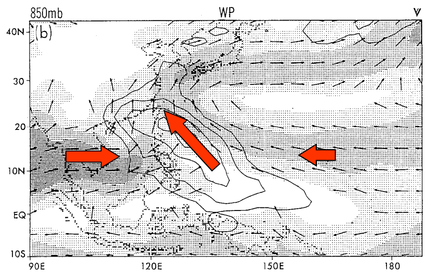


July Sea level Pressure and Wind

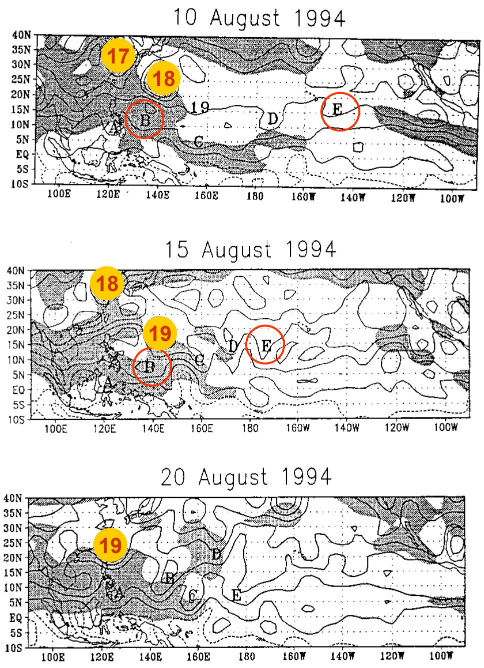




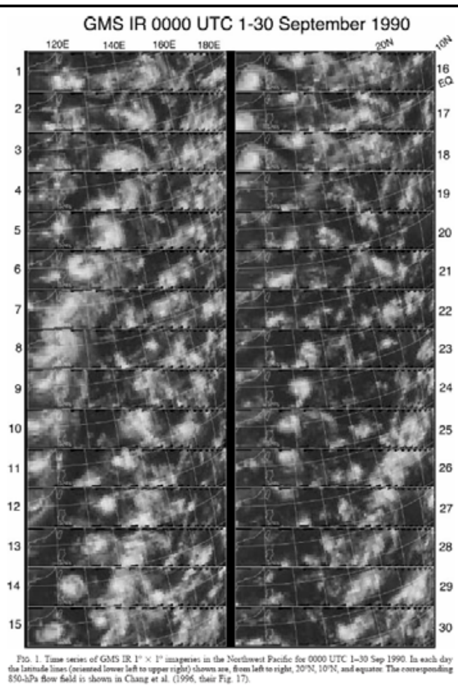
Hong et al.(2010)



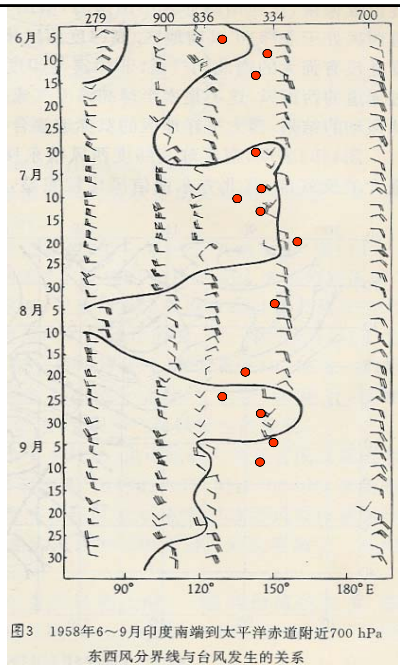
Lau and Lau(1990) JJA 1980-1987



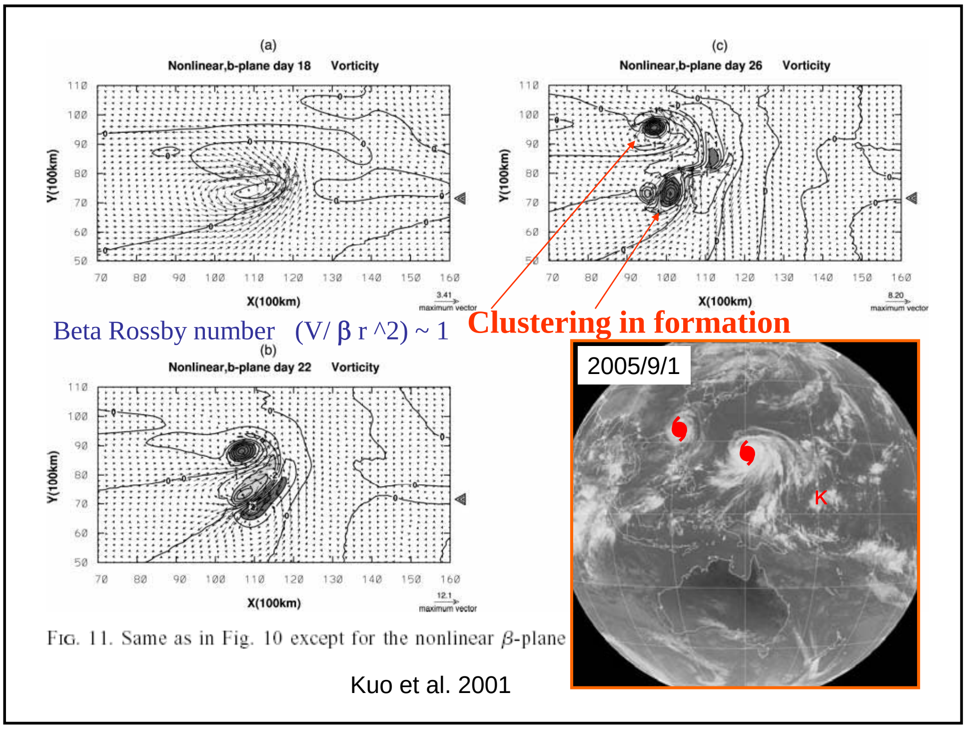
Sobel and Bretherton(1998)

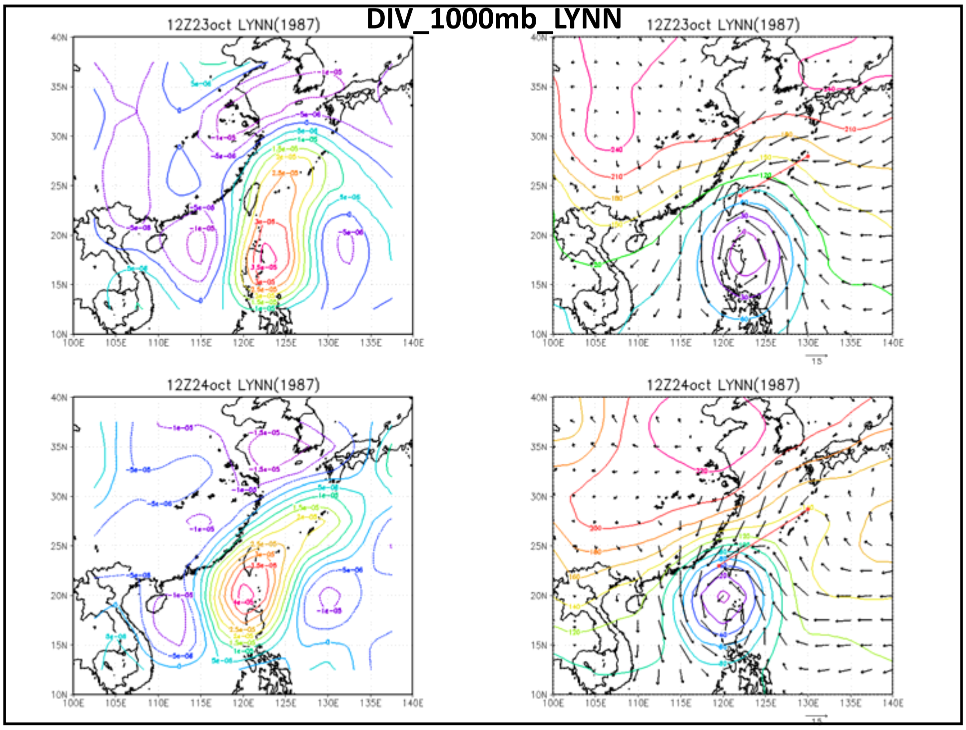


Kuo et al.(2001)

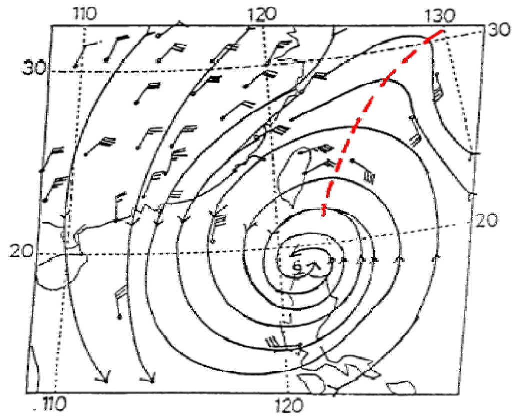


謝與陳(1963)


(a)
Nonlinear,b-plane day 18 Vorticity
(b)
Nonlinear,b-plane day 22 Vorticity
(c)
Nonlinear,b-plane day 26 Vorticity
Beta Rossby number (V/ β r ^2) ~ 1
Clustering in formation
2005/9/1
FIG. 11. Same as in Fig. 10 except for the nonlinear β-plane
Kuo et al. 2001


DIV_1000mb_LYNN
12Z23oct LYNN(1987)
12Z23oct LYNN(1987)
12Z24oct LYNN(1987)
12Z24oct LYNN(1987)

東北季風與秋季颱風共伴環流



Northeast Monsoon surge

Typhoon Lynn (1987)

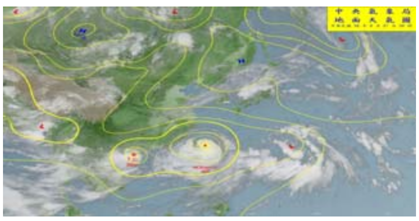
Flood in Taipei city

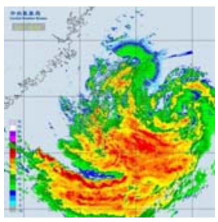
颱風位於巴士海峽，北部東北部持續降雨

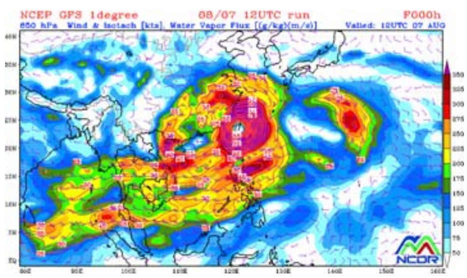
中尺度對流系統與地形作用

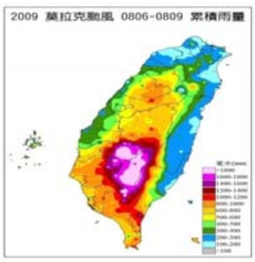
Typhoon Morakot (2009)

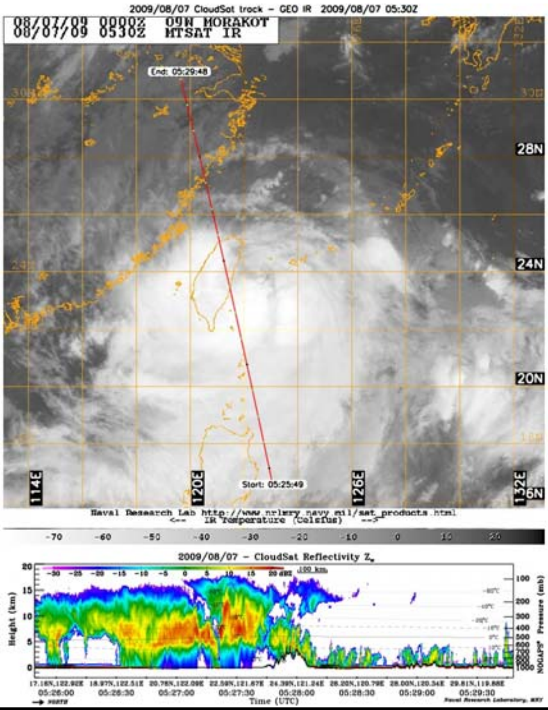
Interplay of Southwest Monsoon, Terrain, and Mesoscale Convection





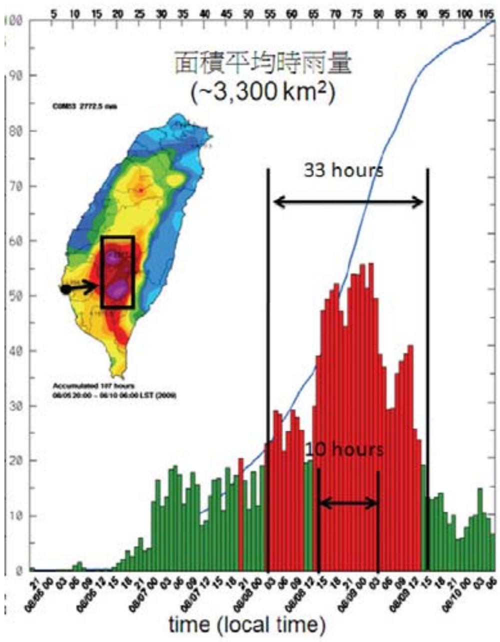


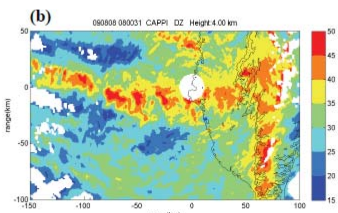




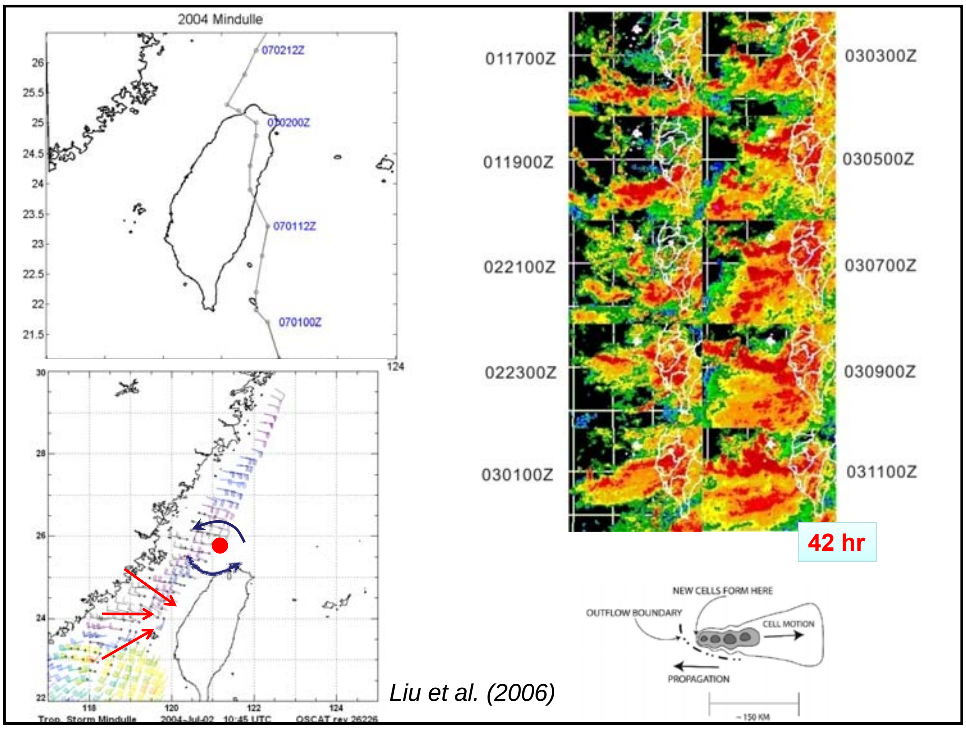
2009/8/7 CloudSat

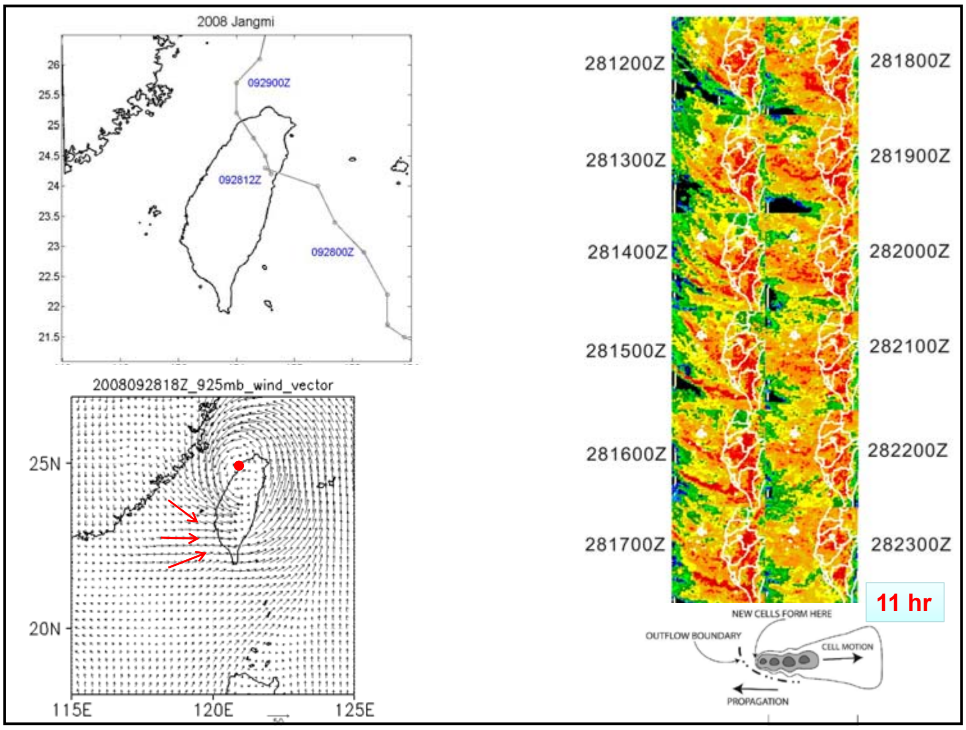
Courtesy of CloudSat web

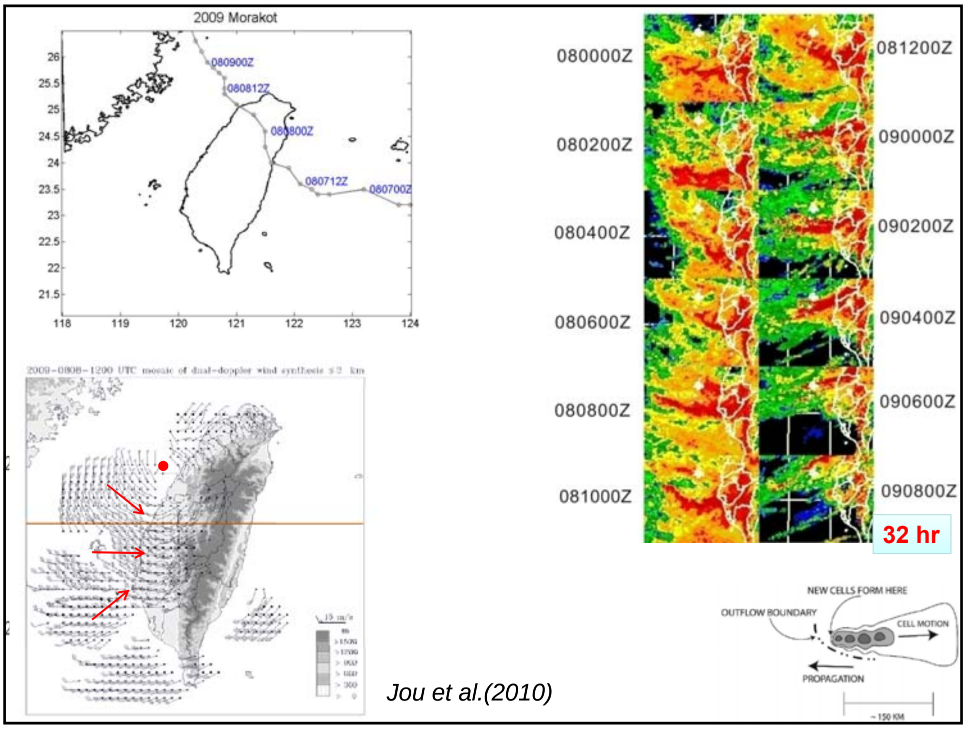


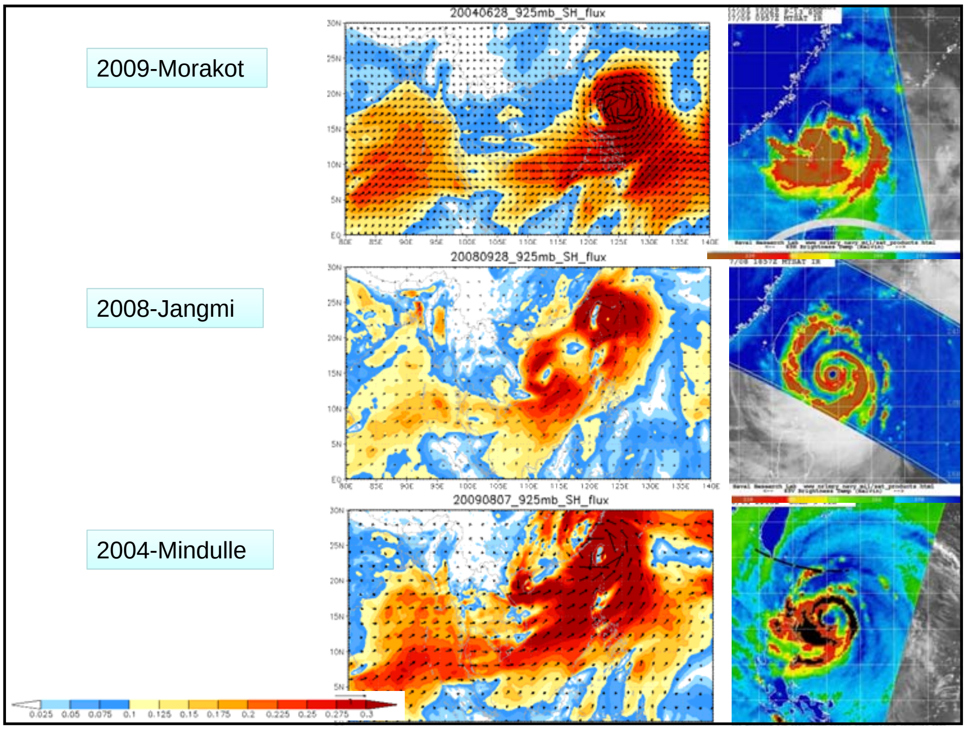


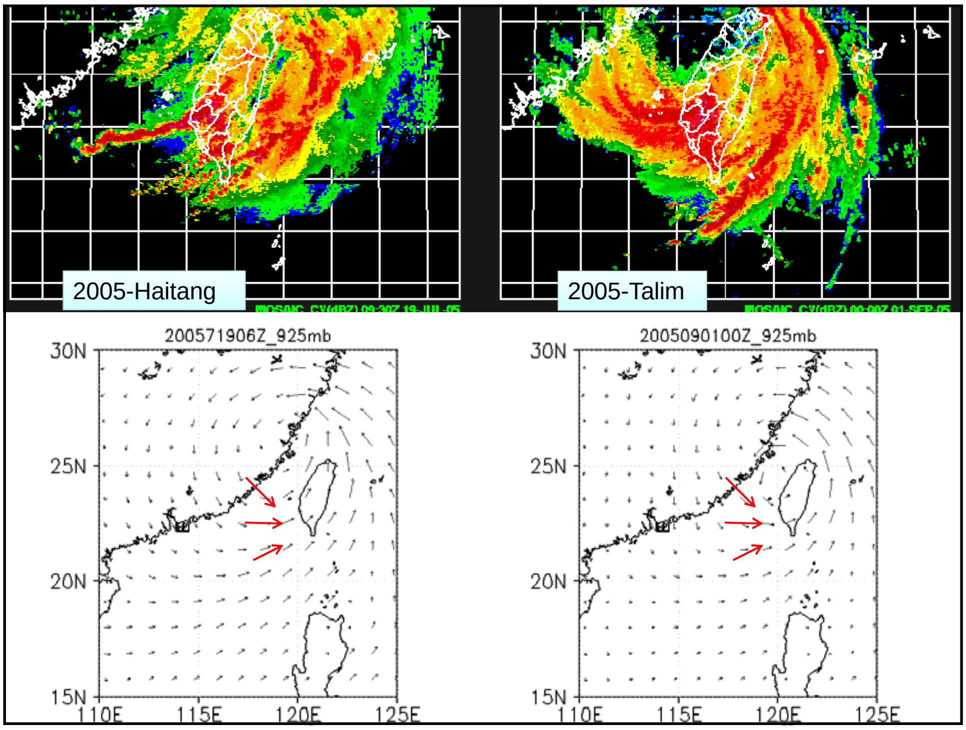
Chen et al. 2010
陳台琦等

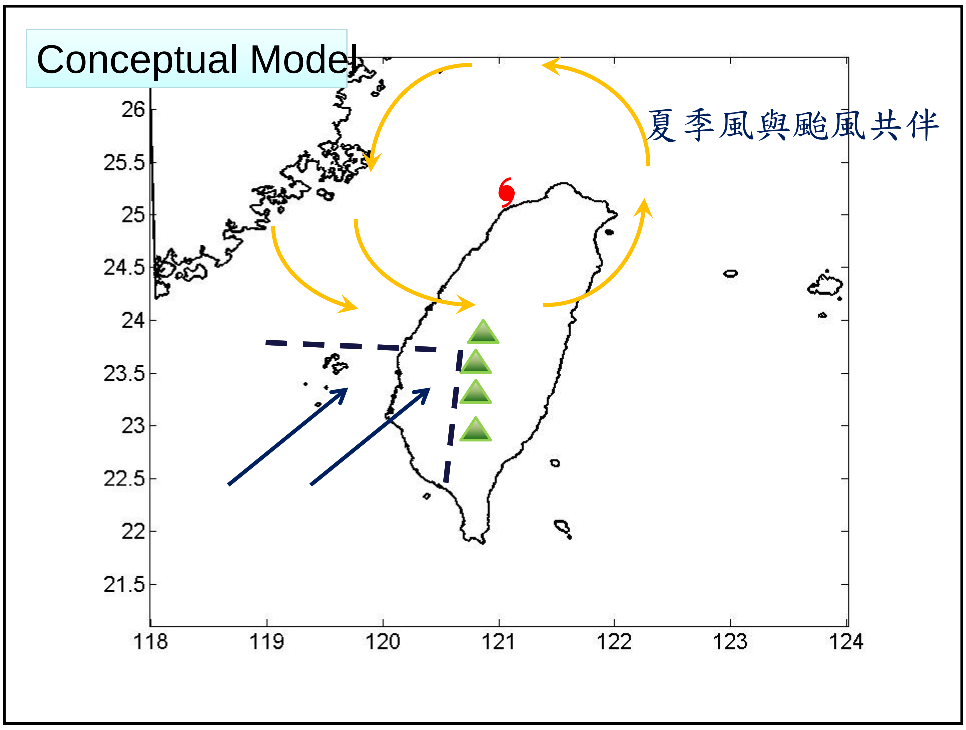

2004 Mindulle
070212Z
070200Z
070112Z
070100Z
011700Z
011900Z
022100Z
022300Z
030100Z
030300Z
030500Z
030700Z
030900Z
031100Z
42 hr
NEW CELLS FORM HERE
OUTFLOW BOUNDARY
CELL MOTION
PROPAGATION
Liu et al. (2006)


2008 Jangmi
092900Z
092812Z
092800Z
2008092818Z_925mb_wind_vector
25N
20N
115E
120E
125E
281200Z
281300Z
281400Z
281500Z
281600Z
281700Z
281800Z
281900Z
282000Z
282100Z
282200Z
282300Z
11 hr
NEW CELLS FORM HERE
OUTFLOW BOUNDARY
CELL MOTION
PROPAGATION

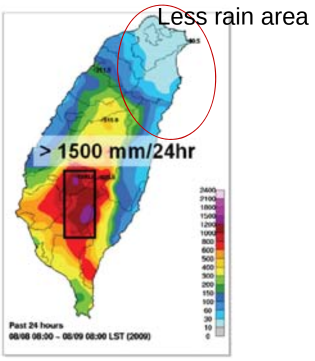

2009 Morakot
080900Z
080812Z
080800Z
080712Z
080700Z
080000Z
080200Z
080400Z
080600Z
080800Z
081000Z
081200Z
090000Z
090200Z
090400Z
090600Z
090800Z
32 hr
NEW CELLS FORM HERE
OUTFLOW BOUNDARY
CELL MOTION
PROPAGATION
~150 KM
Jou et al.(2010)

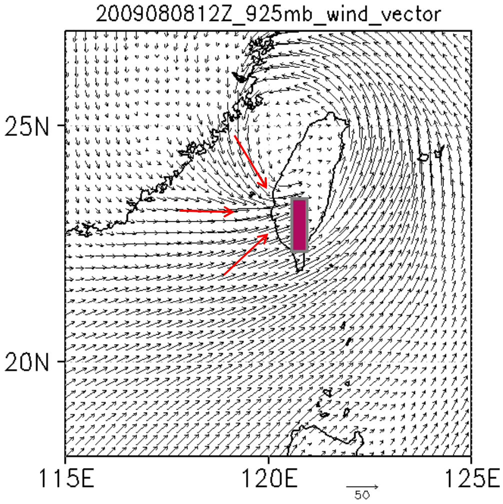

2009-Morakot
2008-Jangmi
2004-Mindulle
20040628_925mb_SH_flux
20080928_925mb_SH_flux
20090807_925mb_SH_flux
0.025 0.05 0.075 0.1 0.125 0.15 0.175 0.2 0.225 0.25 0.275 0.3


2005-Haitang
2005-Talim
200571906Z_925mb
2005090100Z_925mb
30N
25N
20N
15N
110E
115E
120E
125E


Conceptual Model
夏季風與颱風共伴
26
25.5
25
24.5
24
23.5
23
22.5
22
21.5
118
119
120
121
122
123
124

Typhoon-monsoon-topography interaction
颱風-季風-地形交互作用





Slow movement (long duration time)

Mesoscale convection

Southwest monsoon surge

Asymmetry in convection

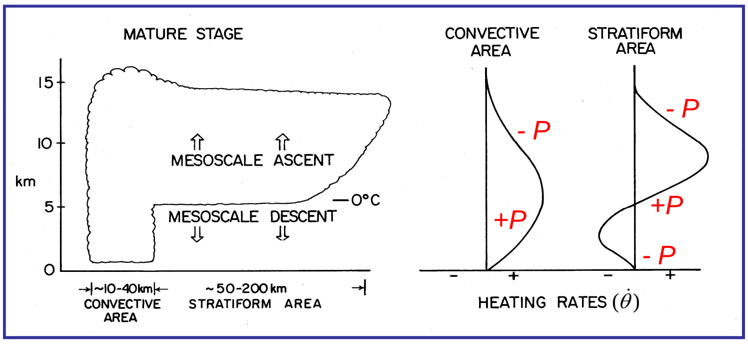
Terrain

Dynamical Implications of Heating Profiles

$$P = -(\zeta_\theta + f)\frac{\partial \theta}{\partial p} = potential\ vorticity$$

$$\frac{dP}{dt} = -(\zeta_\theta + f)\frac{\partial \dot{\theta}}{\partial p} + \cdots$$

P is created by vertical gradients in heating



Key point: if the diagnosed Q_1 profile is incorrect, it will feed back to contaminate the dynamics and energetics.