# Challenges of Tropical Cyclone Research - Targeted Observation, Data Assimilation, and Tropical Cyclone Predictability

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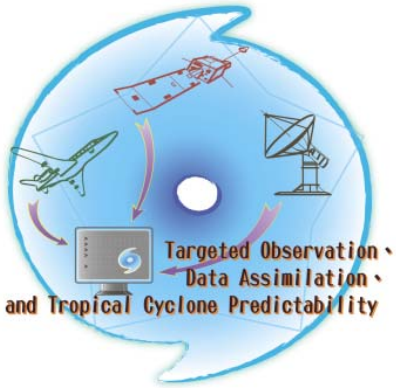
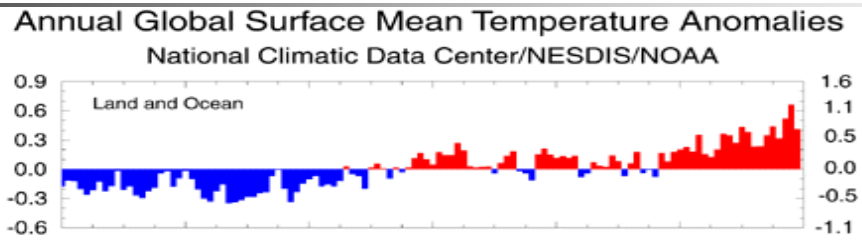
Outline

- Physics of Typhoons
- Current understanding
- Challenging issues

Acknowledging collaborators in DOTSTAR and T-PARC
Grants: NSC, CWB, RCEC/Academia Sinica, ONR



# 大氣現象與人類社會




- 全球暖化：二氧化碳，環境衝擊與生態丕變，「氣候公約」。
- 臭 氣 洞：氟氯碳化物，紫外線，「蒙特婁公約」。
- 聖嬰現象：1997/98年－印尼旱乾與森林大火，台灣暖冬與豐沛春雨。
- 颱　風：1996年7月賀伯（重創全島）。
  2001年6月奇比（重創澎湖）、
  7月下旬桃芝（重創花投）、
  9月中旬納莉（重創全台）。
  2004年6月底至7月初敏督利及伴隨之西南氣流（重創中台之七二水災；死亡33人、失蹤12人；農林漁牧損失超過89億元）。
  2005, 2006, 2007, 2008（卡枚基）, 2009(莫拉克)
- 梅　雨：豪雨。
- 龍捲風：美國大平原南部地區，每年春季。

1995/10/12

曉揭獎爾貝諾

# 加州兩教授共獲物理獎

## 荷、墨、美科學家分享化學獎

【綜合外電報導】瑞典皇家科學院十一日宣布，美國史丹福大學教授柏爾及加州大學歐文分校教授賴恩斯因爲發現兩種次原子粒子，共同獲得一九九五年諾貝爾物理學獎，將平分一百萬美元的獎金。

皇家科學院說，他們兩人得獎原因是「率先以實驗方式對輕子物理學作出貢獻」，發現了「大自然中最值得注意的兩種次原子粒子」。

柏爾生於一九二七年，一九七四至一九七七年間，他與史丹福大學直線加速器中心的研究同僚發現，電子有個比其重約三千五百倍的親戚，就是第三種輕子（TAU LEPTON）。

賴恩斯生於一九一八年，他在一九五〇年代與已故同事柯文合作，證實了微中子（NEUTRINO）的存在。

皇家科學院說，他們的上述重要發現有助於解答兩個重要問題：「宇宙的最小成分爲何，其性質如何？它們是否能告訴我們宇宙的歷史及其未來？」

加上柏爾及賴恩斯，諾貝爾物理學獎的美國籍得獎人增至六十一人，遠超過其他國家，排名第二的德國及英國都只有十九人得獎。

自第二次世界大戰以來，美國一直是諾貝爾獎科學獎項的主要贏家，這些年來的物理學及化學得獎人中有超過三分之一是美國人。

（法新社、斯德哥爾摩）今年的諾貝爾化學獎由荷蘭的克魯森，墨西哥的莫里納和美國的駱蘭共同獲得。

瑞典皇家科學院指出，六十一歲的克魯森、五十二歲的莫里納和六十八歲的駱蘭，「由於他們在大氣化學、尤其在有關臭氧的形成與分解方面的研究工作」而得獎。

頌詞中指出：「這三位科學家對影響臭氧層厚度的化學機能進行闡釋，而有助於使我們免於遭到一個可能造成嚴重後果的全球性環境問題。」

## The Nobel Prize in Chemistry 1995

"for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone"

**Paul J. Crutzen**

1/3 of the prize

the Netherlands

Max-Planck-Institute for Chemistry
Mainz, Federal Republic of Germany

b. 1933

**Mario J. Molina**

1/3 of the prize

USA

Massachusetts Institute of Technology (MIT)
Cambridge, MA, USA

b. 1943
(in Mexico City, Mexico)

**F. Sherwood Rowland**

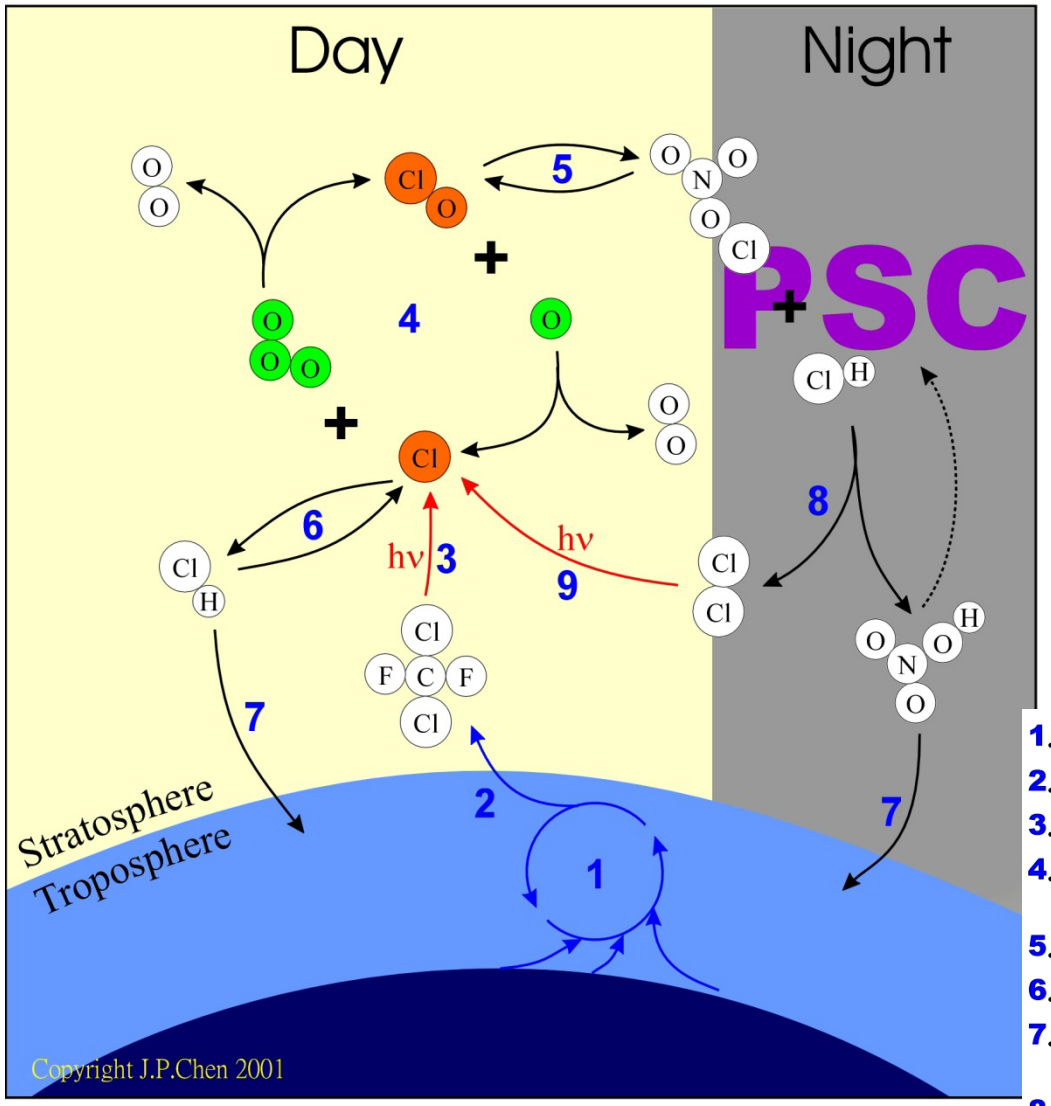
1/3 of the prize

USA

University of California
Irvine, CA, USA

b. 1927

# 臭氧洞形成機制




Why not over the Arctic region?

極地渦旋＋極地平流層雲

＋初春陽光的光化學作用

＋氯原子的催化作用

大氣動力學＋大氣化學

觀測＋理論＋

電腦模擬＋實驗室實驗

1. 地面釋放CFC，在對流層內迅速混合（約3～4年）。
2. 緩慢滲入平流層（約10年）。
3. 紫外線（以hν表示）將CFC分解，釋放出氯原子。
4. 快速摧毀臭氧的催化循環：氯原子摧毀臭氧，形成氧化氯；氧化氯摧毀氧原子，形成氯原子。註：氧原子是形成臭氧的原料。
5. $NO_2$可將活躍的氯原子轉換為不活躍的$ClONO_2$（儲存庫1）。
6. OH可將活躍的氯原子轉換為不活躍的HCl（儲存庫2）。
7. 可凝結的儲存庫2可以形成粒子而逐漸沉降回對流層，是真正能清除平流層內的氯之機制。
8. 極地平流層入冬時，氣溫會降得很低，於是形成由冰硝酸粒子組成的極地平流層雲（**P**olar **S**tratospheric **C**louds）；$ClONO_2$會在雲粒子表面與HCl進行異質反應，釋放出氯氣，但氯氣不會與臭氧發生反應。
9. 氯氣在初春陽光出現時，會被紫外線分解為氯原子，參與摧毀臭氧的催化循環，使得臭氧濃度迅速降低。

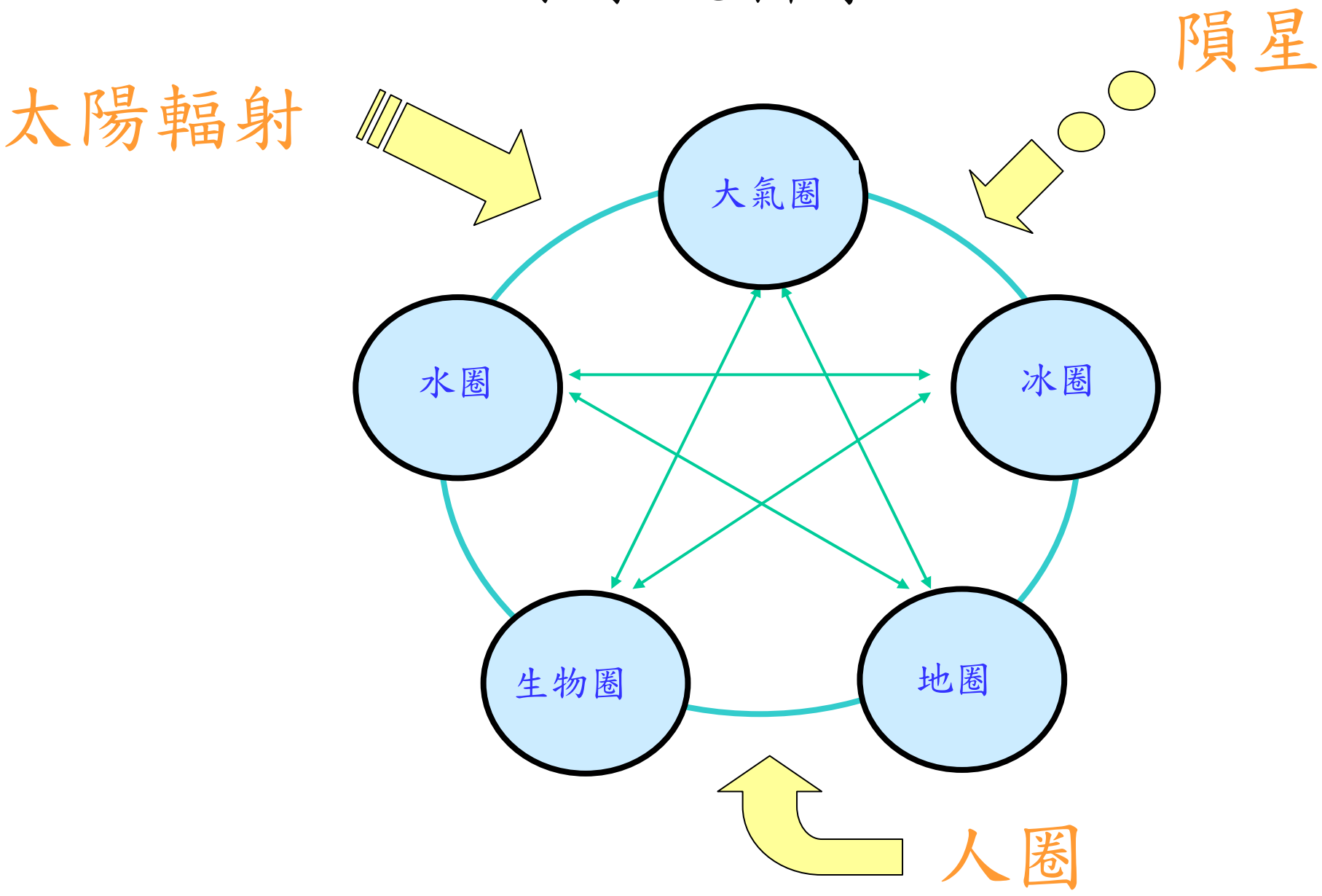
# 2009哥本哈根氣候變遷會議

2009　12.07～12.20

COP15
COPENHAGEN
UN CLIMATE CHANGE CONFERENCE 2009

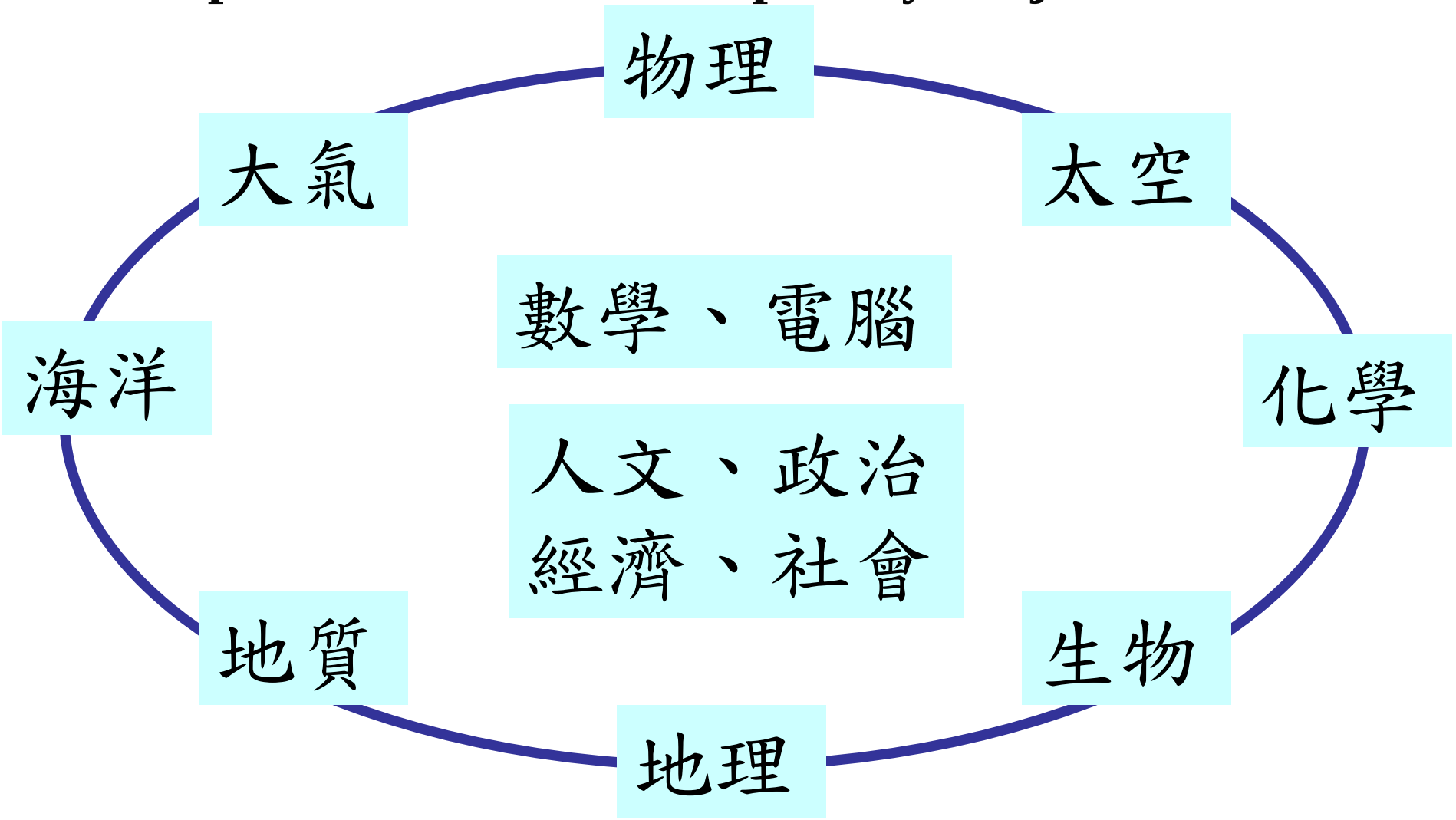
本次會議的主體是《聯合國氣候變化框架公約》第１５次締約方會議暨《京都議定書》第五次締約方會議，此外還有一系列附屬會議

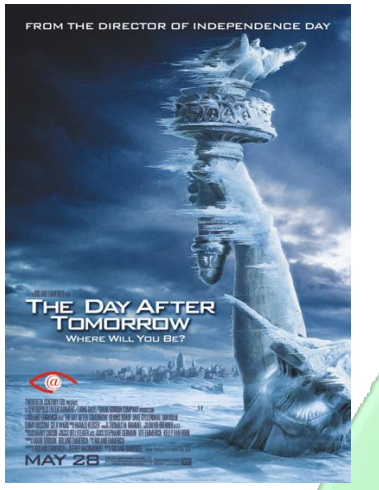
# 地球系統科學

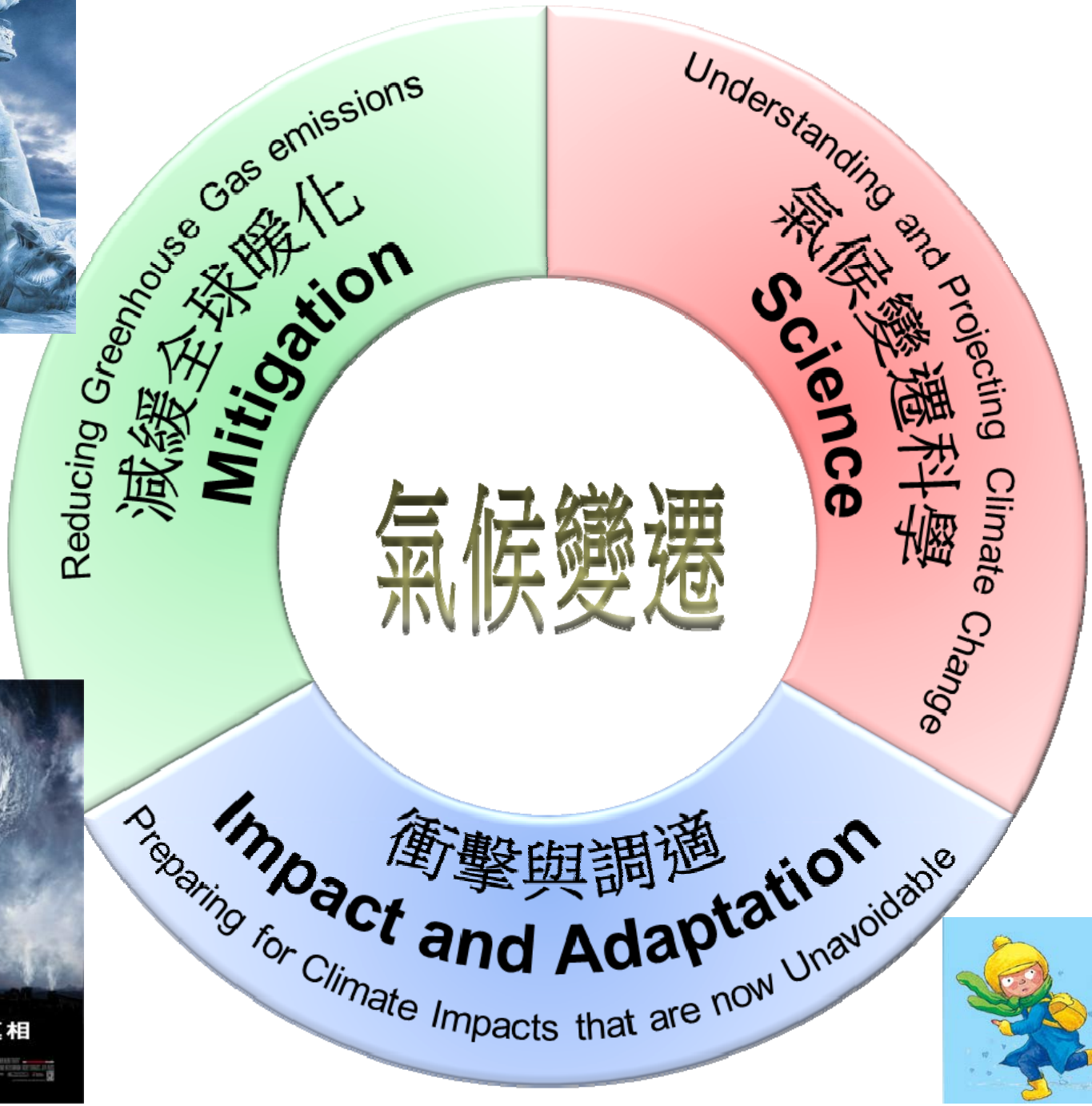


**Climate-change science**

**– a complicated and interdisciplinary subject**




FROM THE DIRECTOR OF INDEPENDENCE DAY
THE DAY AFTER TOMORROW
WHERE WILL YOU BE?
MAY 28

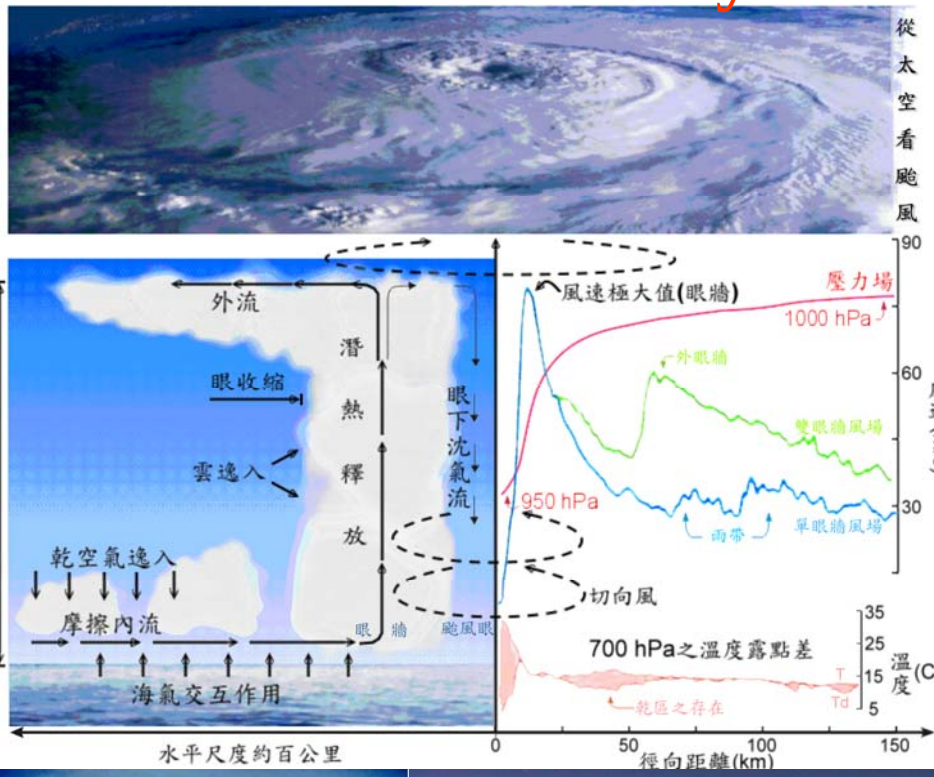

Reducing Greenhouse Gas emissions
減緩全球暖化
Mitigation
Understanding and Projecting Climate Change
氣候變遷科學
Science
氣候變遷
衝擊與調適
Impact and Adaptation
Preparing for Climate Impacts that are now Unavoidable


不願面對的真相


+2°C

# 颱風－流體動力學在大自然所展現的絕妙實例

## Beauty and the Beast

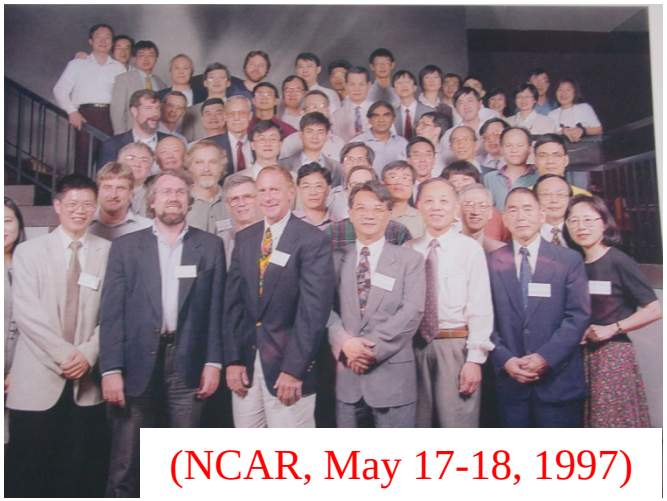




- 高速旋轉流
  (high rotation)
- 強烈輻合輻散流
  (strong divergence)
- 劇烈濕對流
  (severe moist convection)
- 快速大氣—海洋交互作用
  (fast air-sea interaction)
- 多重尺度交互作用
  (multi-scale interaction)
- 地形效應
  (terrain effect)

# Challenging scientific issues related to TCs

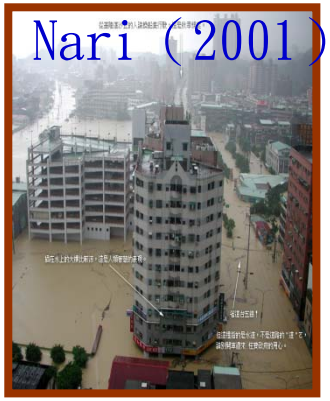
- TC movement
- TC genesis and intensity change
- TC-ocean-biogeochemistry interaction
- TC response and feedback to climate change
- TC-tectonics-geomorphology-seismology
  (Dadson et al. 2003, Nature, Links between erosion, runoff variability and seismicity in the Taiwan orogen)



(NCAR, May 17-18, 1997)

## Significant societal impact of TCs in Taiwan

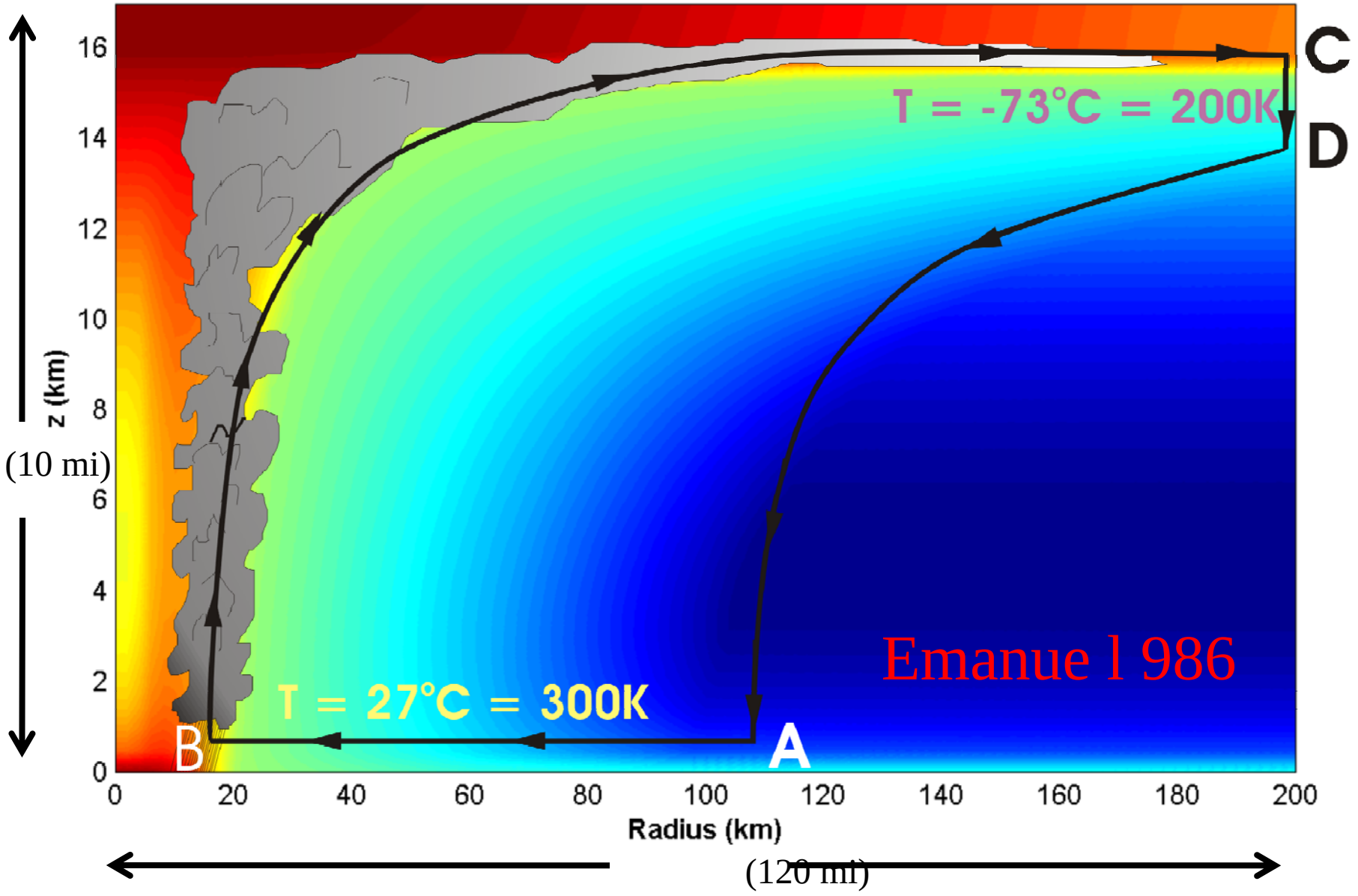
- Direct/indirect damages, losses, and casualties
- Cost of the false alarm or over-warning
- Impact on landscape: erosion/landslide/debris flow
- Management of water resources





- Intellectually challenging
- Significant contributions to the society

# Hurricane as a Carnot Heat Engine



# Theoretical Upper Bound on Hurricane Maximum Wind Speed

## 颶風最大風速之理論上限

$$|V_{pot}|^2 \simeq \frac{C_k}{C_D} \frac{T_s - T_o}{T_o} \left( k_0^* - k \right)$$

**Surface temperature**

**Ratio of exchange coefficients of enthalpy and momentum**

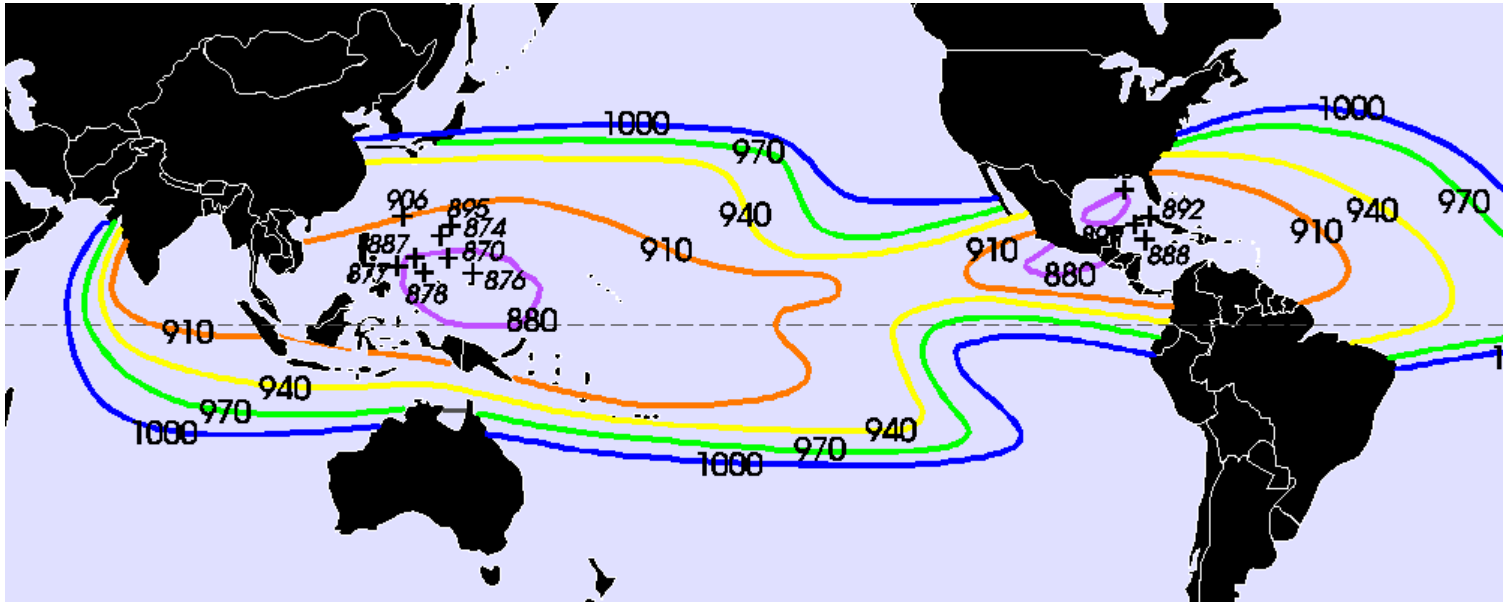
**Outflow temperature**

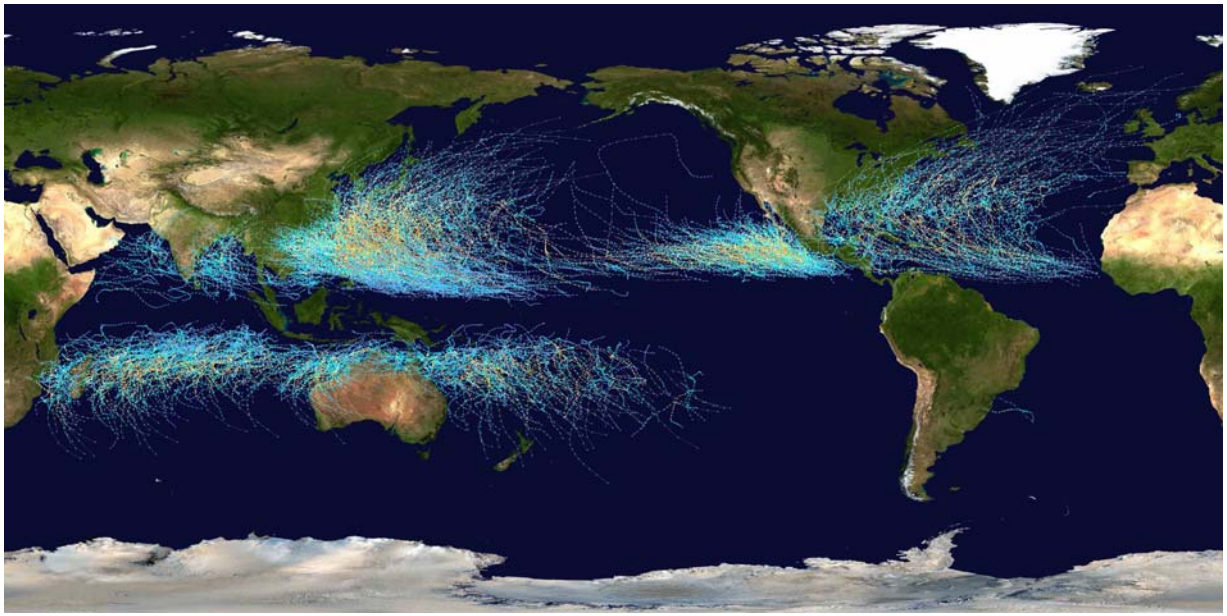
**Air-sea enthalpy disequilibrium**

Emanue l 995

It is important to have beauty in one's equation than to have them fit experiments. Paul Dirac (1902-1984)

# Climatological Theoretical MPI MAP



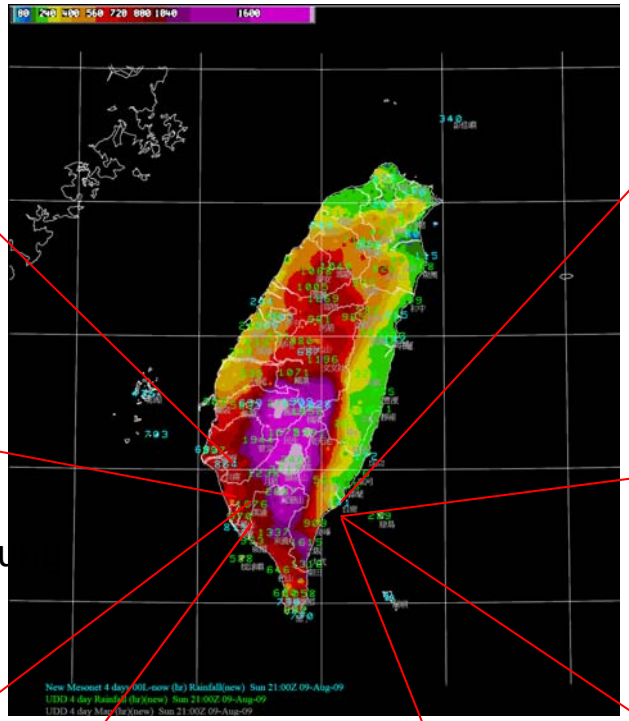
# Accumulated rainfall from Aug. 6 to 10 associated with Typhoon Morakot

Chiashien, Kaohsiung

A bridge linked Pingtung and Kaohsiu

An aerial view in Chiatu

Landslide in Pingtung



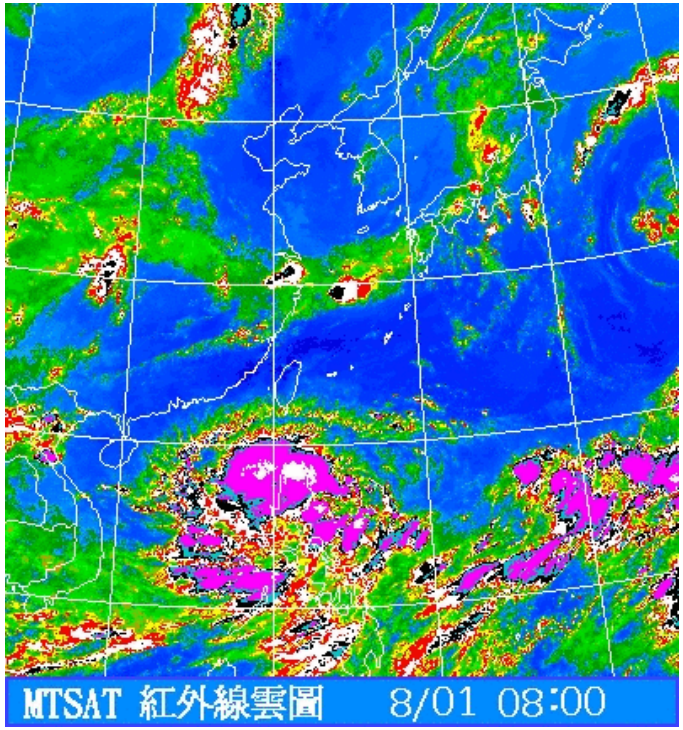
A hotel building fell into the river. (Taitung)

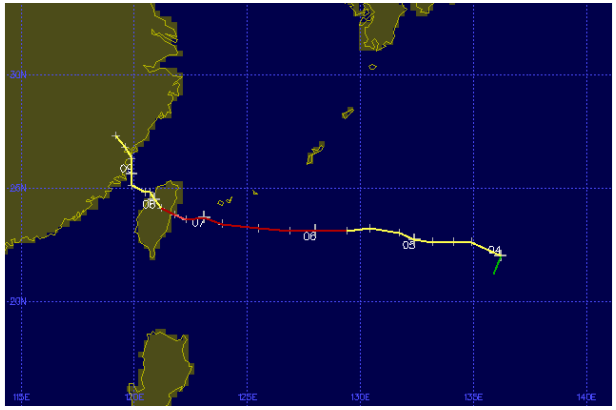
Taimali, Taitung

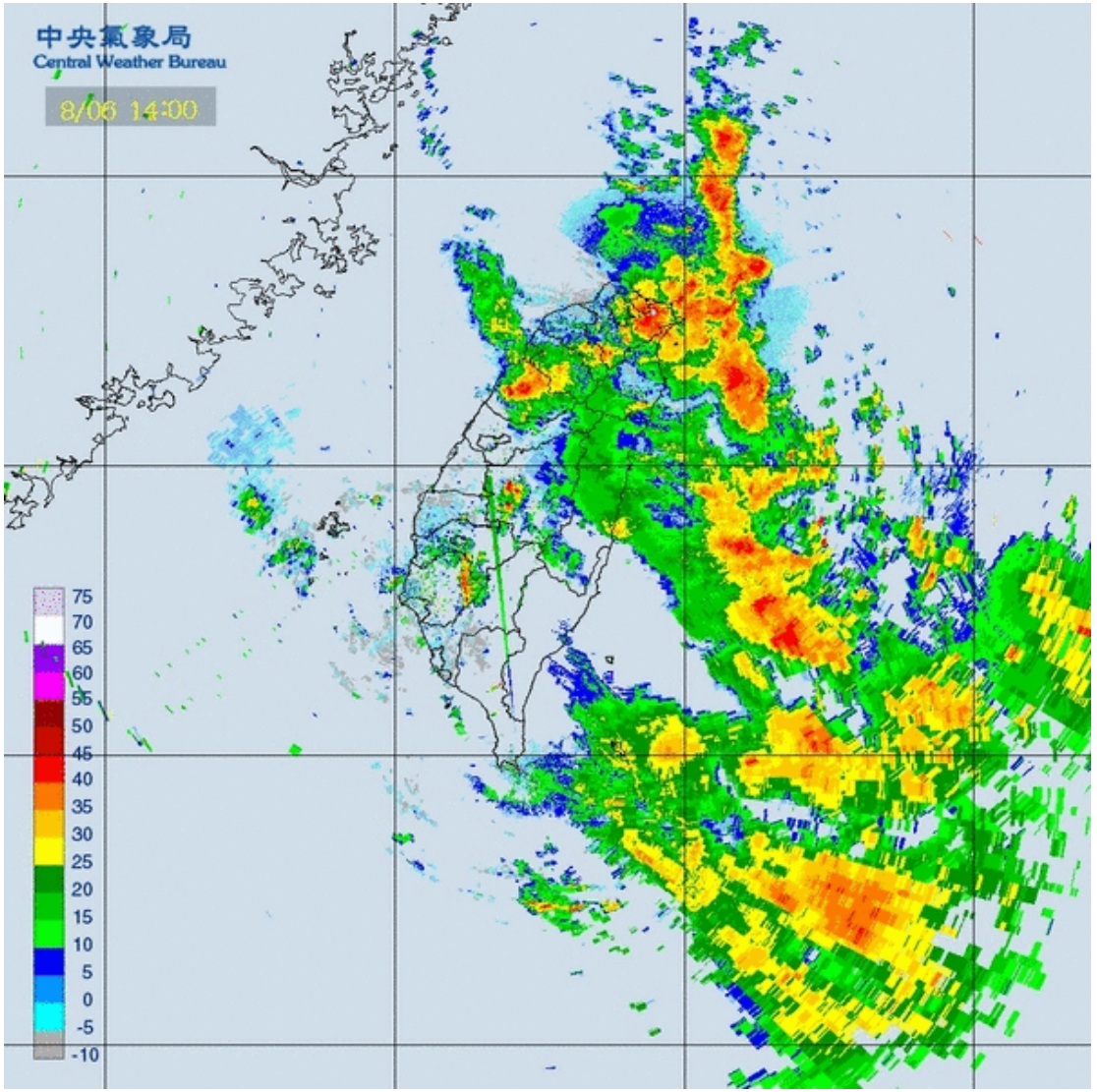
Taimali, Taitung

A railroad in Taitung

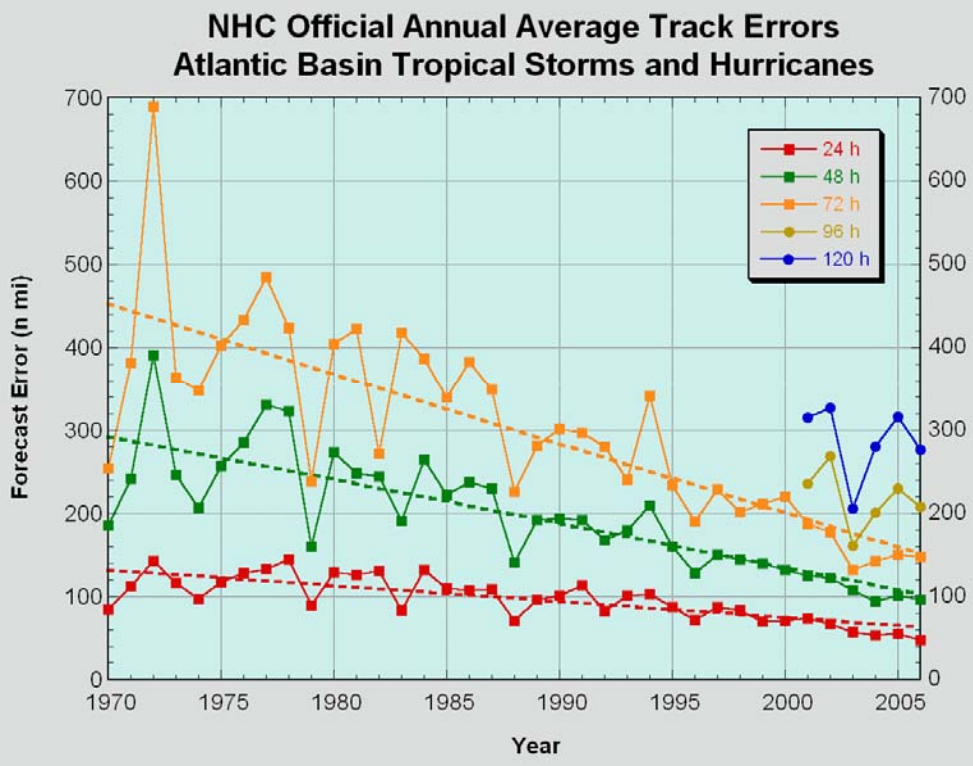
# Typhoon Morakot: Radar imageries during 0600 UTC 06 Aug ~ 1200 UTC 10 Aug (102 hours)



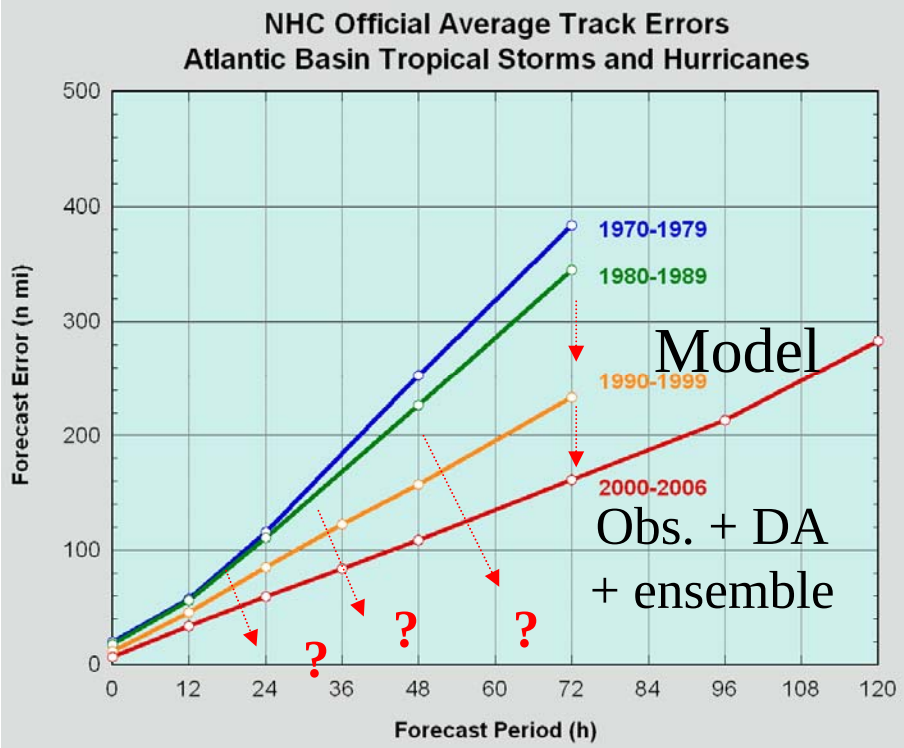





# Long-term decreasing trend in TC track prediction errors

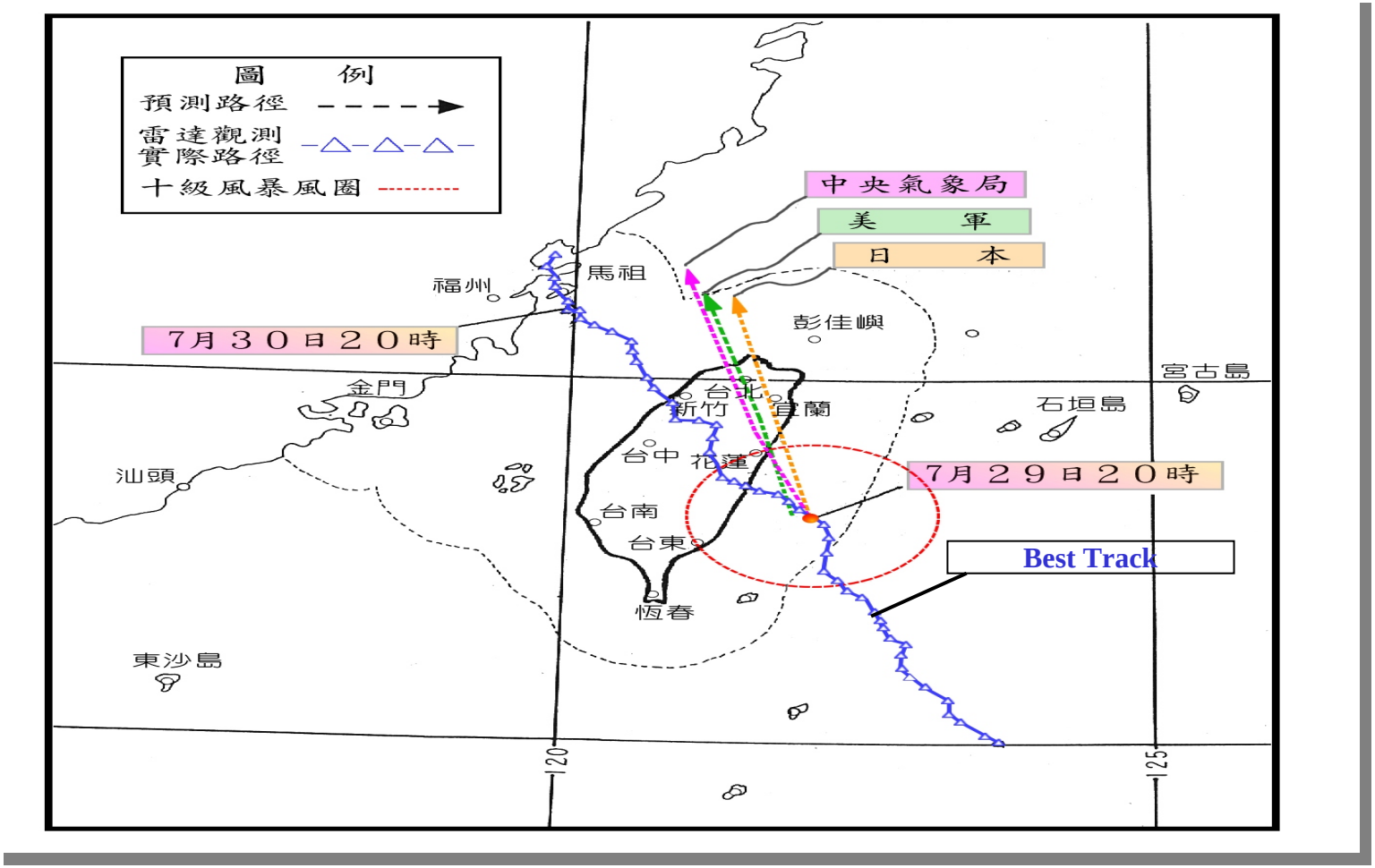



**From NHC**

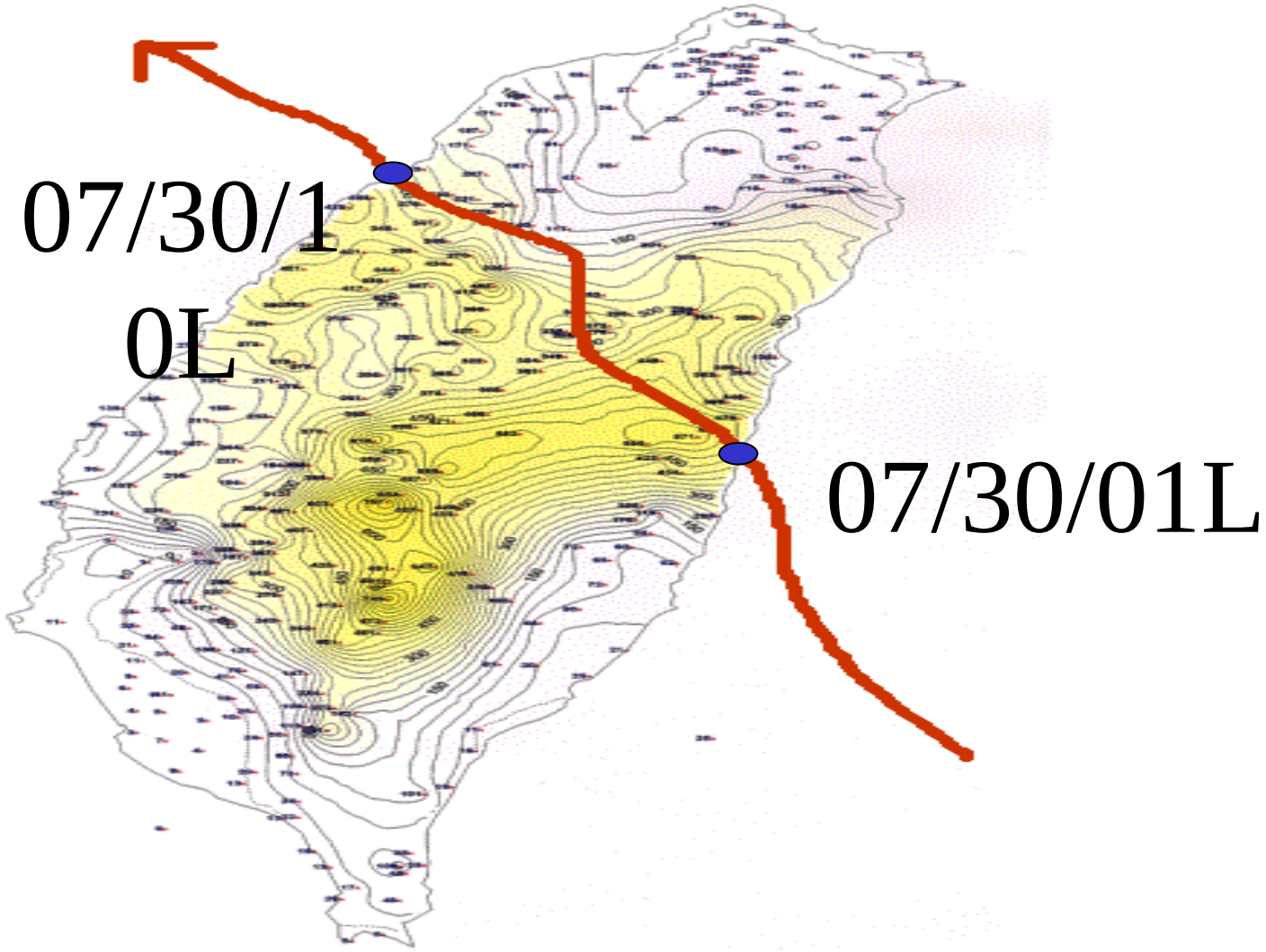



**Why?**

**Push the limit of predictability?**



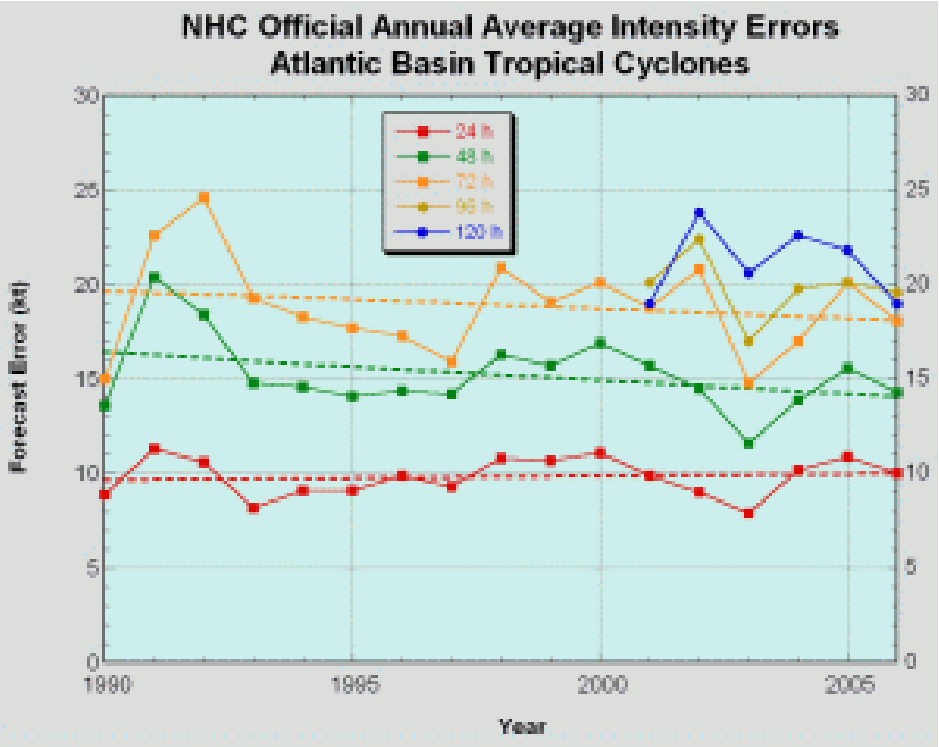

Track of Typhoon Torajie on July 29-July 31, 2001.




Accumulated rainfall (with contour interval of 30 mm) during passage of Typhoon Toraji (July 29 – 31, 2001).

# Very limited progress in TC intensity prediction

From NHC




Internal dynamics – VRW, spiral rainbands, mesoscale vortices, eyewall processes

Environmental control – shear, trough-interaction

Boundary processes – sfc. fluxes, ocean mixing, sea spray, waves, land/topography

(Wang and Wu 2004)

物理、化學---實驗科學

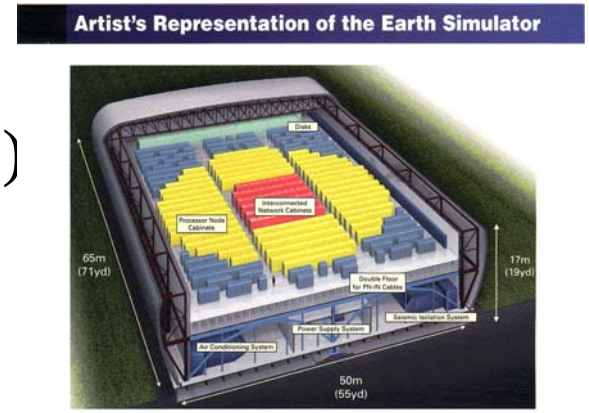
大氣科學---數值實驗

# Numerical Weather Prediction

Governing equations

- Momentum equation.(Newton's Law)
- Continuity equation.(Conservation of mass)
- Equation of state.
- Thermodynamic equation.
- Weather vapor equation.

(u, v, w, p, T, $\rho$ , r)




Difference equations + Numerical algorithm

Analytic I.C
Idealized I.C.

Real data

Numerical model

theory

prediction

大氣數值模式

# 混沌效應

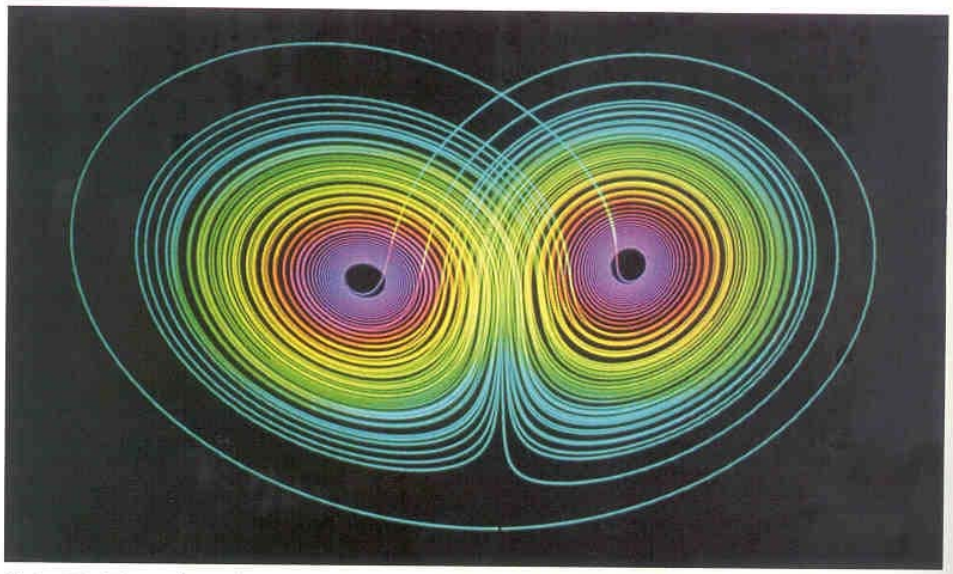


Plate 23: Two trajectories on the Lorenz attractor with color indicating distance to unstable steady states.

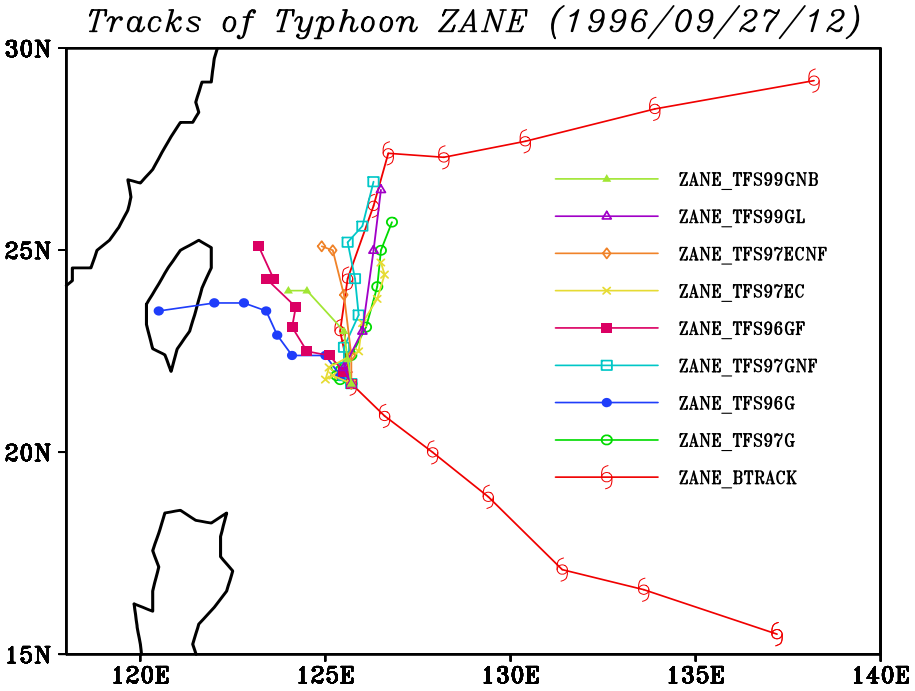

Prof. Edward Lorenz

The magic of coffee!

Chaos – butterfly effect –

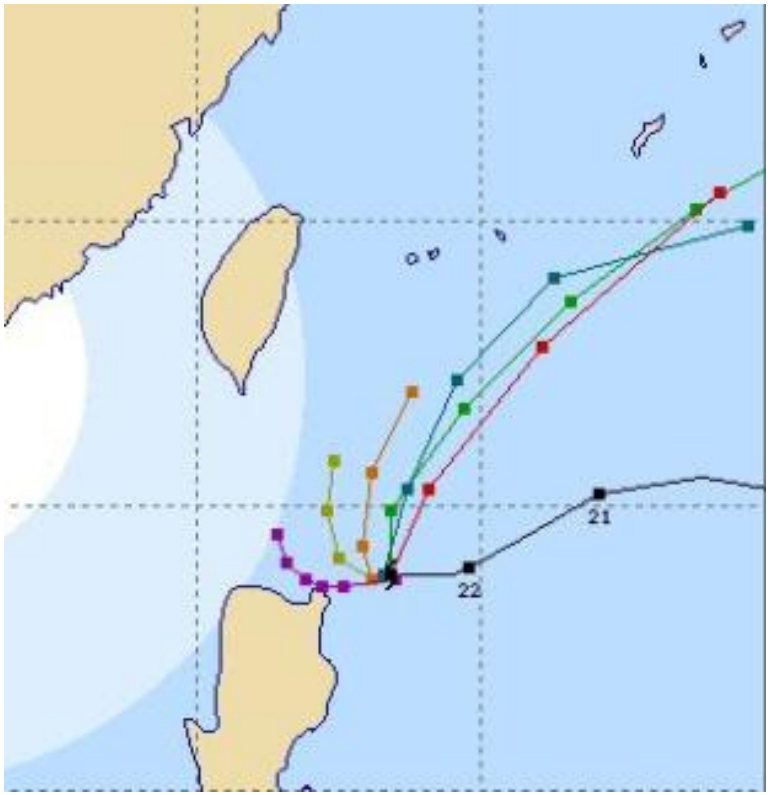
Sensitivity to initial conditions; nonlinearity; complexity; non-periodicity.

# *Sensitivity to Initialization*




Wu et al.
（2000）

Lupit, Oct. 2009

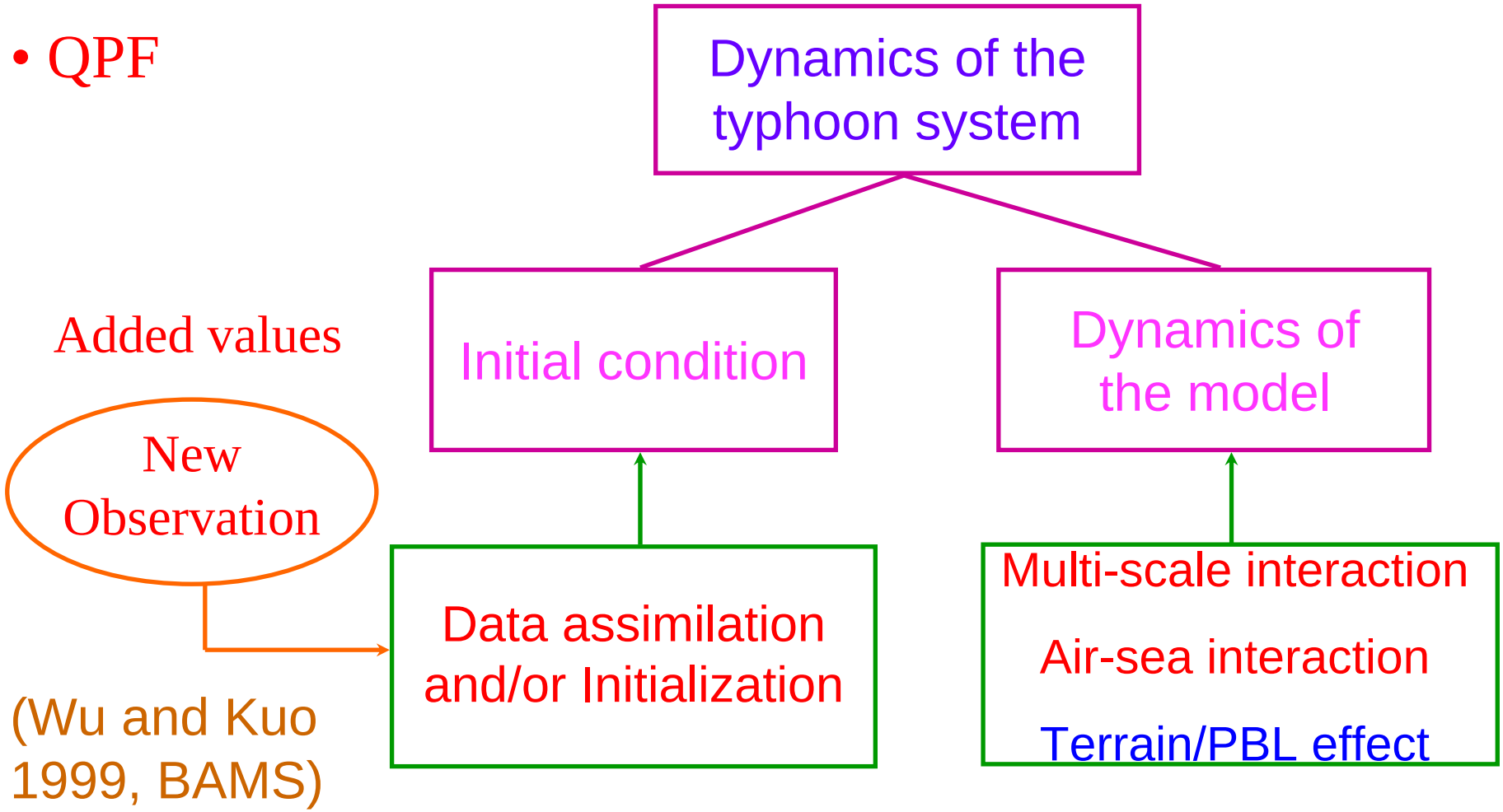


# Improving the understanding and prediction of the TC systems

(in memory of Dr. Yoshio Kurihara)

USWRP (1995-)

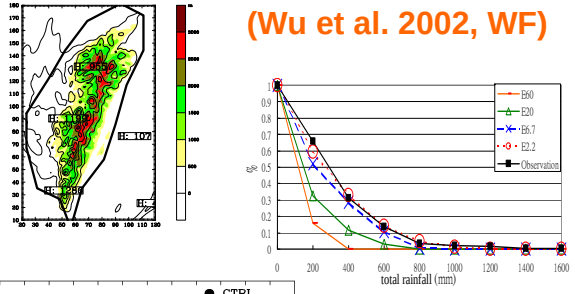
- Optimal mix of obs.
- Hurricane at Landfall
- QPF



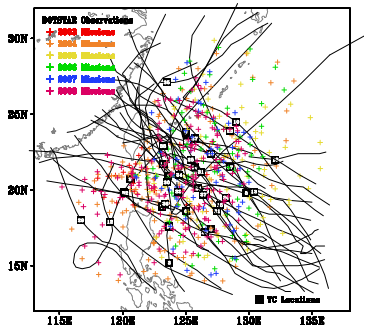

(Wu and Kuo 1999, BAMS)

*(Chun-Chieh Wu)*

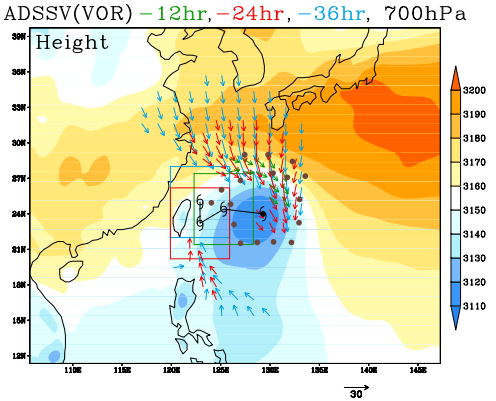
(Wu et al. 2002, WF)



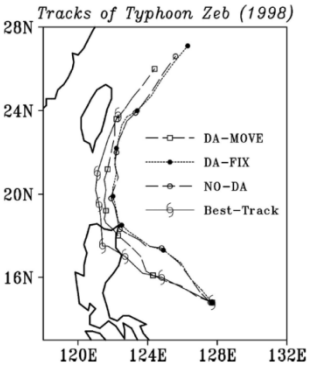
(Wu et al. 2009a, b, MWR)

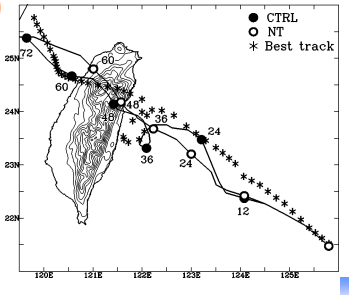


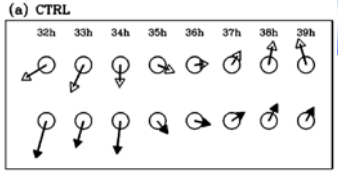
(Wu et al. 2007a JAS)




(Wu et al. 2006, JAS)




(Jian and Wu 2008, MWR)

**Targeted observation in DOTSTAR**

**Typhoon intensity eyewall dynamics**

**Typhoon-terrain interaction**

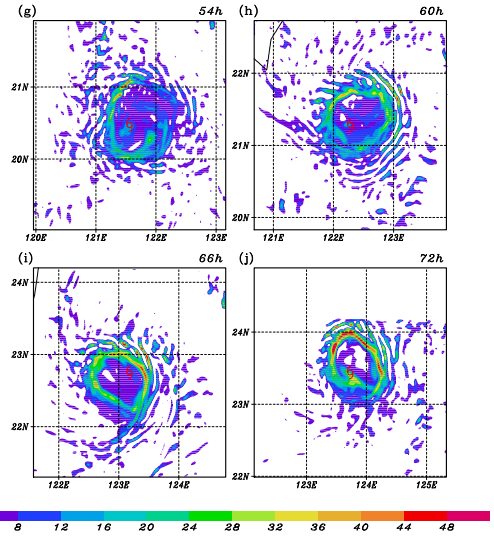
**Typhoon movement**

**Typhoon rainfall**

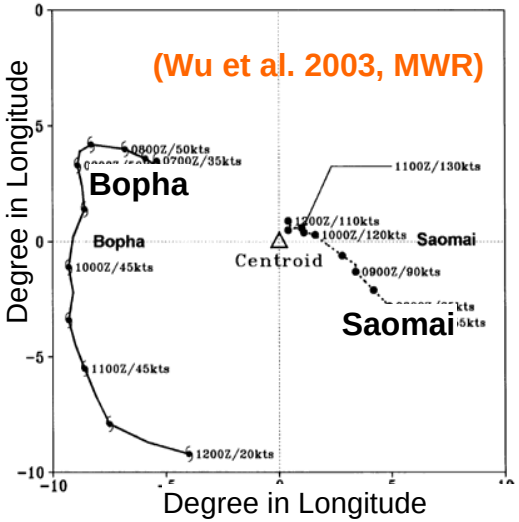
**Typhoon-ocean interaction**

**Typhoon-climate**

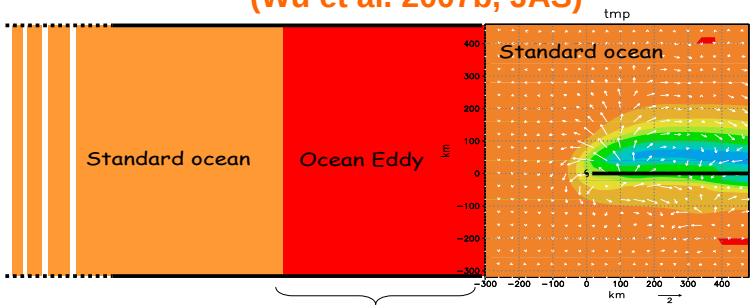
(Wu et al. 2009c, MWR)

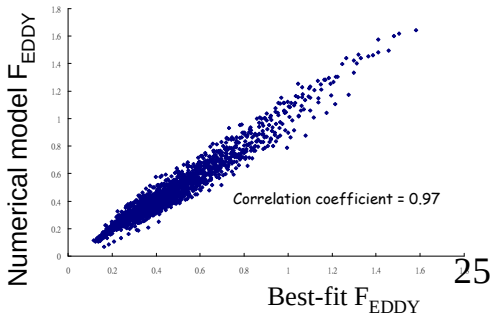



(Wu et al. 2003, MWR)



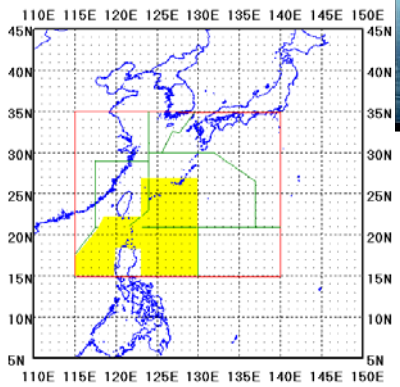

(Wu et al. 2007b, JAS)



# Dropwindsonde Observations for Typhoons near the Taiwan Region (DOTSTAR)

Astra Jet




GPS Dropsonde

Satellite communication

Global/TC model

JMA, EC
CMC, KMA

NCEP/FNMOC

in real time

CWB

Global/TC model
（Inform. Center）

Ana./Fcst.
（Forecasting center）

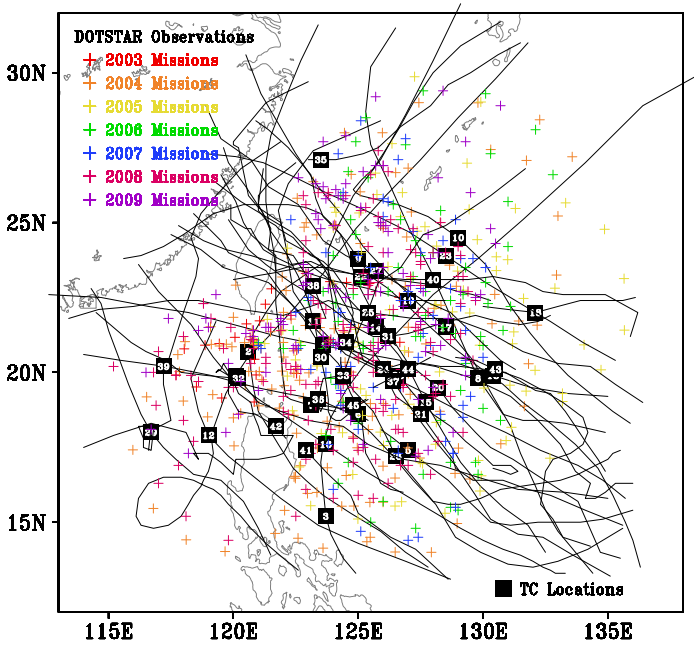
AVAPS
On-board data reception

NTU/Research team
Archive Research

(Wu et al. 2005a)

Research Grants: NSC, CWB, ONR, Academia Sinica

# Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR, 2003 – 2009)




Up to 2009, 45 missions have been conducted in DOTSTAR for 35 typhoons, with 751 dropwindsondes deployed during the 239 flight hours.

30 **typhoons affecting Taiwan**

23 typhoons affecting (mainland) China

7 typhoons affecting Japan

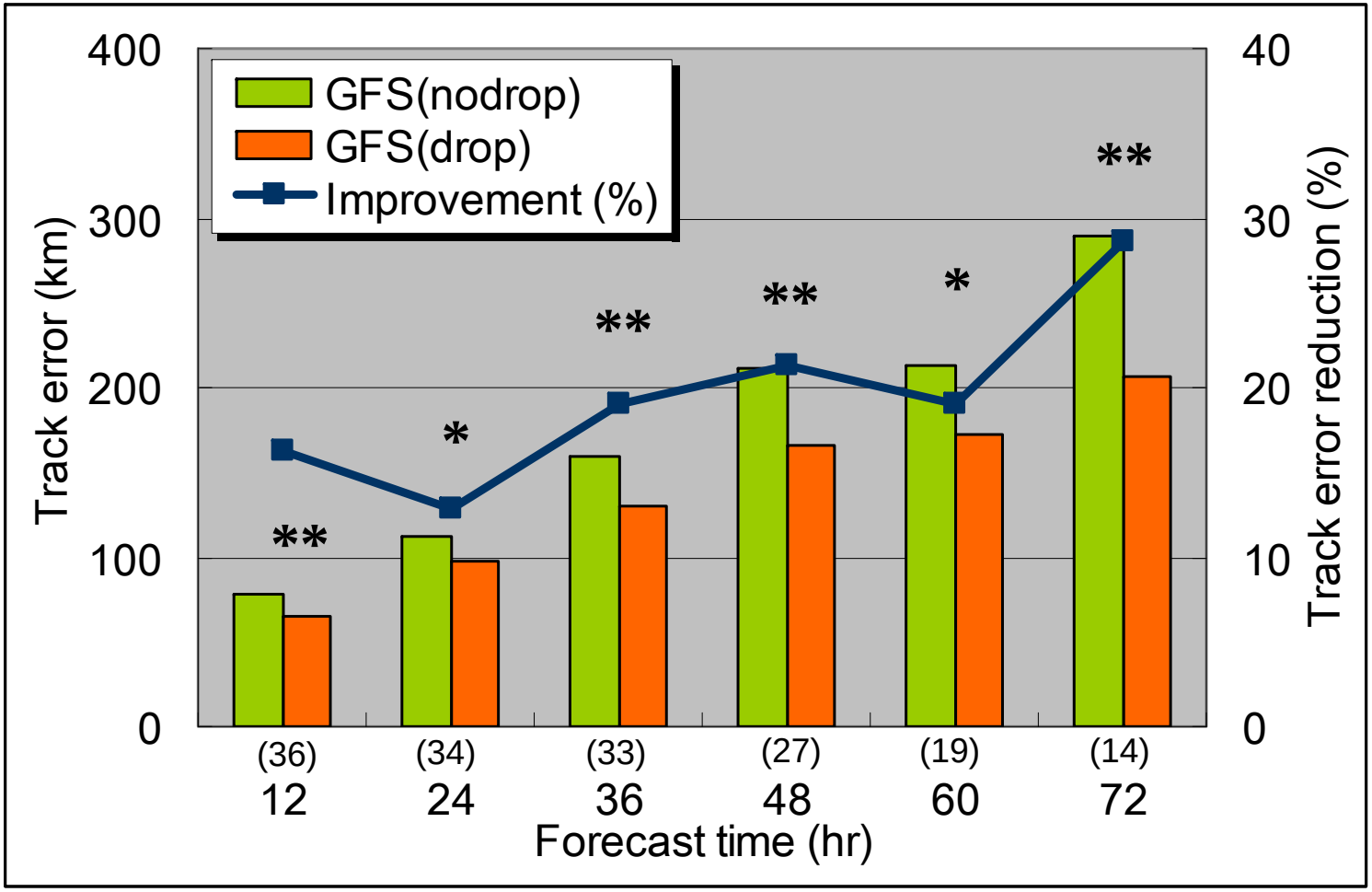
3 typhoons affecting Korea

10 typhoons affecting Philippines

- Useful real-time data available to major operational forecast centers
- Positive impact to the track forecasts to models in major operation centers (NCEP/GFS, FNMOC/NOGAPS, JMA/GSM)
- Targeted observation

Wu et al. (2005 BAMS, 2007a JAS, 2007b WF, 2009a,b,c MWR), Chou and Wu (2008 MWR), Chen et al. (2009 MWR, JAS), Yamaguchi et al. (2009 MWR), Chou et al. (2009 JGR)

# NCEP GFS Impact from 2003 to 2008 (All 36 cases)




**Paired t-test statistical examination**

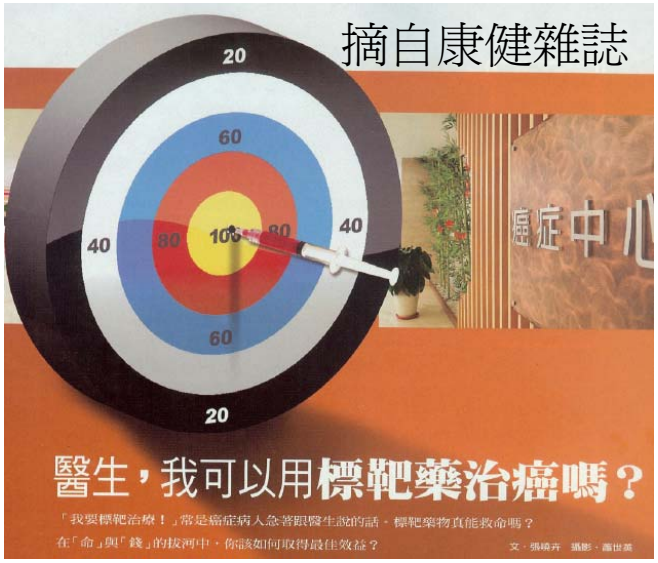
*** : statistically significant at the 90% confidence level**

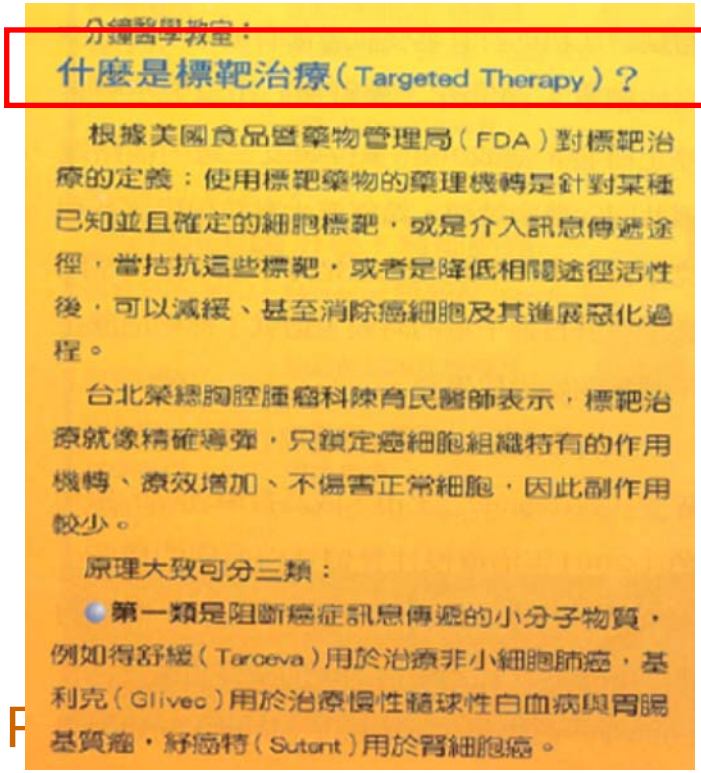
**** : statistically significant at the 95% confidence level**

Wu et al. 2010a

# Background on targeted observations

- **Adaptive observations** : observations targeted in sensitive regions can reduce the initial condition's uncertainties, and thus decrease forecast error.
- **Targeted observation** is an active research topic in NWP, with plans for field programs, tests of new observing systems, and application of new concepts in predictability and data assimilation. **(Langland 2005)**




(Wu et al. 2006, IWTC-VI, San Jose, Costa R

# What means “sensitivity”?

- Direct sensitivity – very inefficient.

$X_{in}$ → model → $X_{out}$

- Adjoint sensitivity: an estimate of sensitivity of model output with respect to input based on the adjoint model (Errico 1997).

Given R=R($\mathbf{X}_{out}$) what initial perturnation ( $\delta \mathbf{X}_{in}$ ) would exert the most impact on **R** ( $\frac{\partial R}{\partial \mathbf{X}_{in}}$ ) ?

$$\underset{\sim}{\mathbf{x}} = \begin{bmatrix} u \\ v \\ w \\ p \\ \vdots \end{bmatrix}$$

Wu et al. (2007a JAS)

# Adjoint Sensitivity

**Non-linear model：$\mathbf{X}_{out}=m(\mathbf{X}_{in})$**

If there is a perturbation $\Delta \mathbf{X}_{in}$, we can use a first-order Taylor series approximation to get：

$$\delta \mathbf{X}_{out} \approx \frac{\partial m(\mathbf{X}_{in})}{\partial \mathbf{X}_{in}} \delta \mathbf{X}_{in} = \mathbf{M}\,\delta \mathbf{X}_{in}$$ **--- Tangent linear model**

$R=R(\mathbf{X}_{out})$ ⟶

$$\delta R = \left\langle \frac{\partial R}{\partial \mathbf{X}_{out}}, \delta \mathbf{X}_{out} \right\rangle = \left\langle \frac{\partial R}{\partial \mathbf{X}_{out}}, \mathbf{M}\,\delta \mathbf{X}_{in} \right\rangle$$

$$\left\langle \frac{\partial R}{\partial \mathbf{X}_{in}}, \delta \mathbf{X}_{in} \right\rangle$$

**Adjoint relationship**

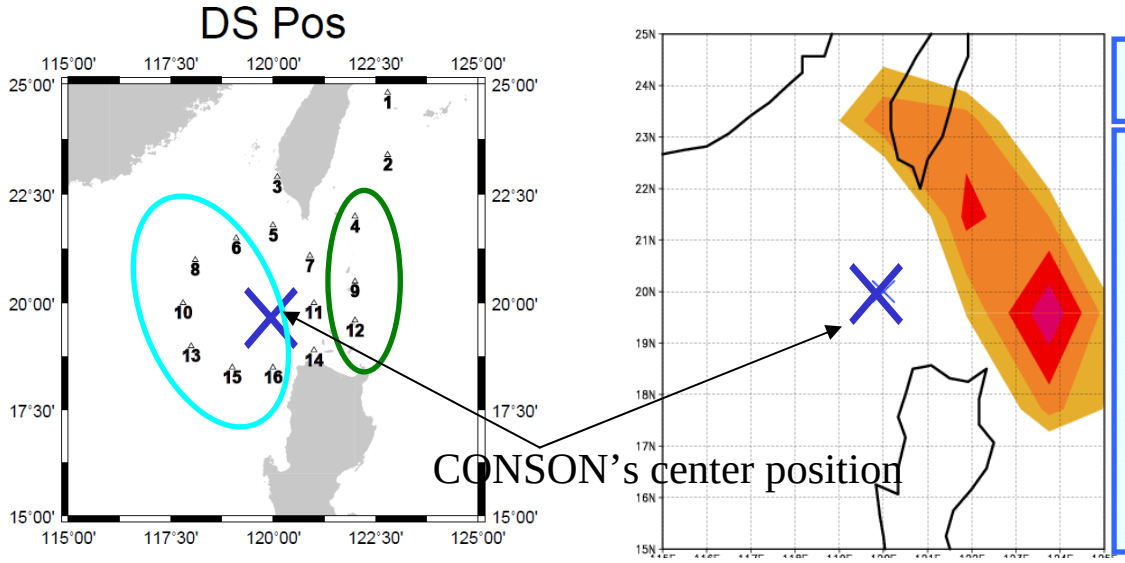
$$= \left\langle \mathbf{M}^{T} \frac{\partial R}{\partial \mathbf{X}_{out}}, \delta \mathbf{X}_{in} \right\rangle$$

$$\frac{\partial R}{\partial \mathbf{X}_{in}} = \mathbf{M}^{T} \frac{\partial R}{\partial \mathbf{X}_{out}}$$

**Adjoint model**

Wu et al. (2007a JAS)

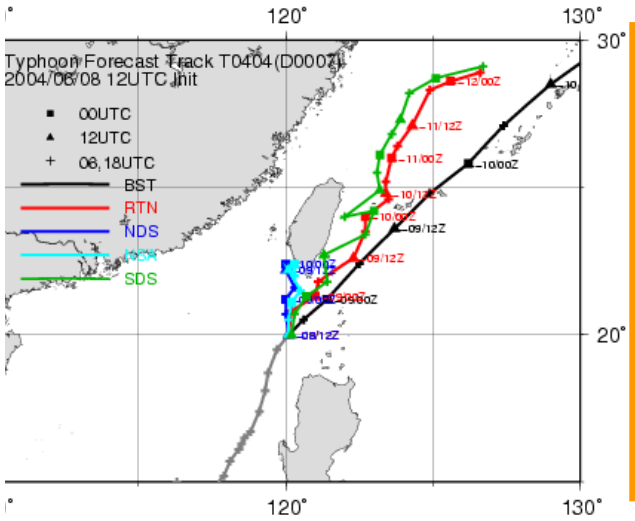
# Impact of targeted observation in DOTSTAR :




## Sensitive analysis result

- Sensitive region shows vertically accumulated total energy by the 1st moist singular vector.
- Targeted area for the SV calculation is 25N-30N, 120E-130E.

## OSE result on CONSON's (2004) track forecast



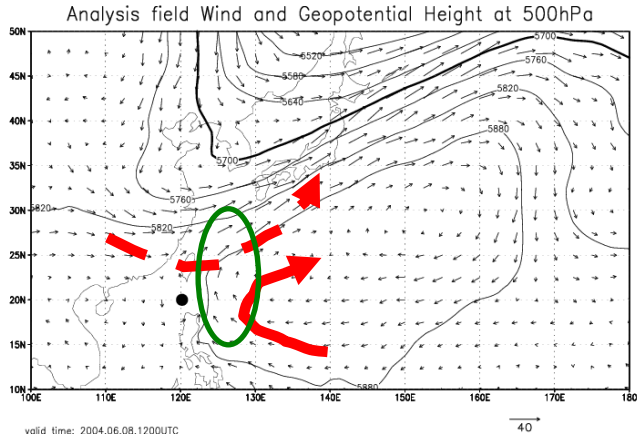

Red: (I) all dropsonde obs

Blue: (II) no dropsonde obs

Green: (III) Three dropsonde obs within the sensitive region

Light blue: (IV) Six dropsonde obs outside the sensitive region

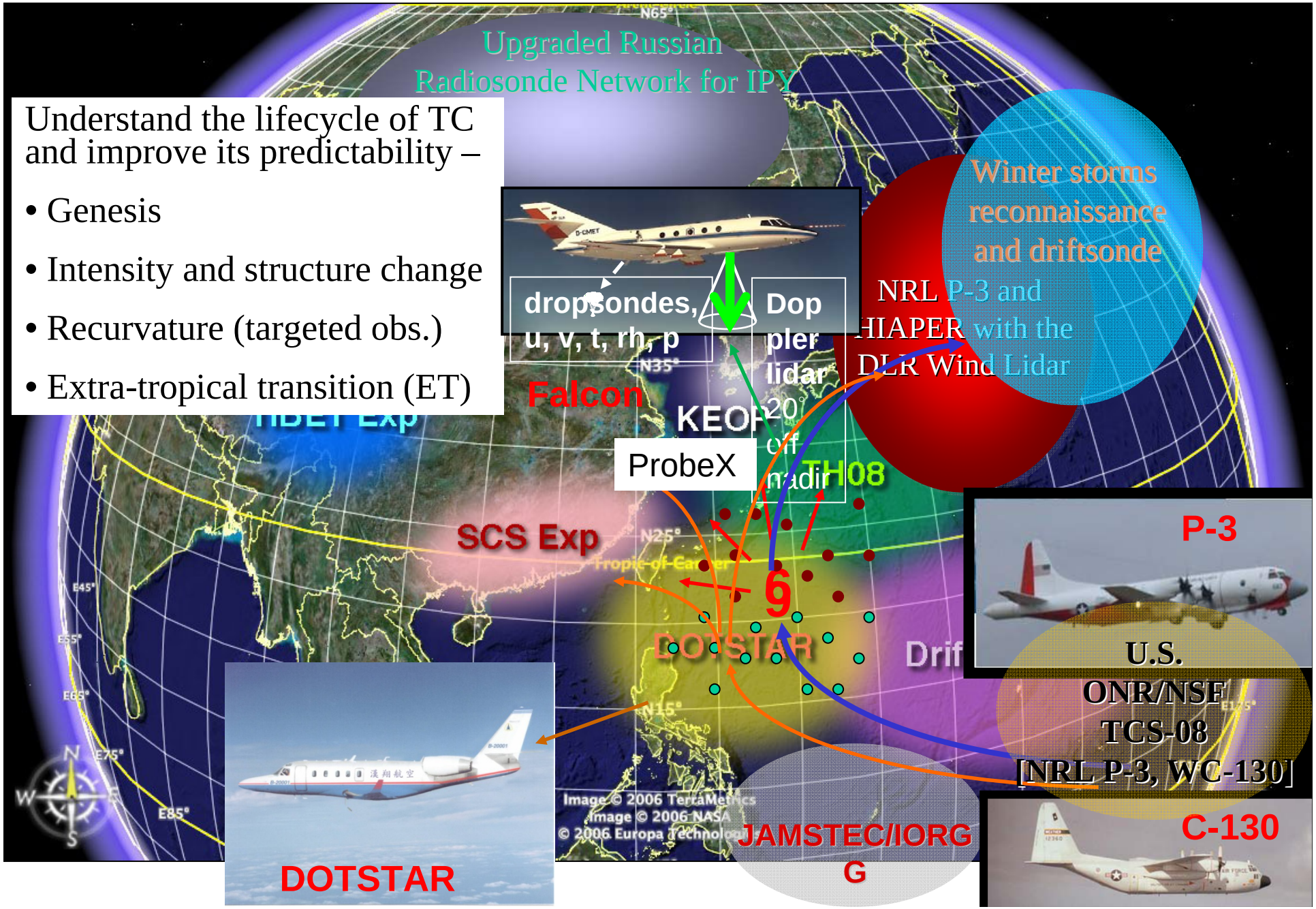
## Wind & Z at 500hPa




Significant improvement of a "bust" case

**(Yamaguchi et al. 2009, MWR)**

# THORPEX-PARC Experiments (2008) and Collaborating Efforts



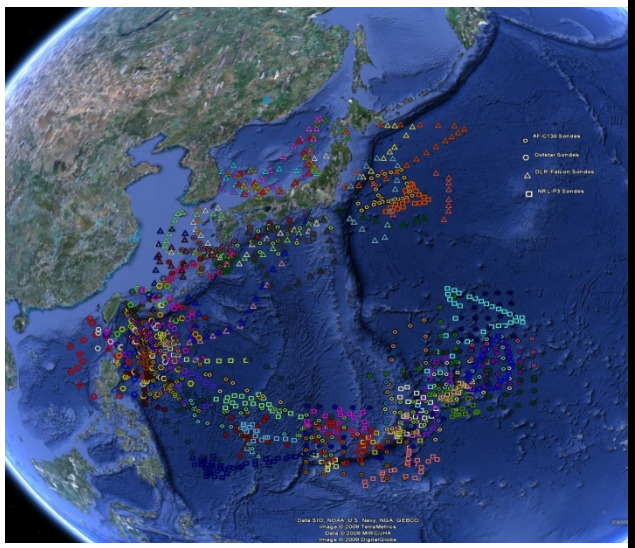
THORPEX
Pacific Asian Regional Campaign
ProbeX TCS-08 TH-08
DOTSTAR
T-PARC

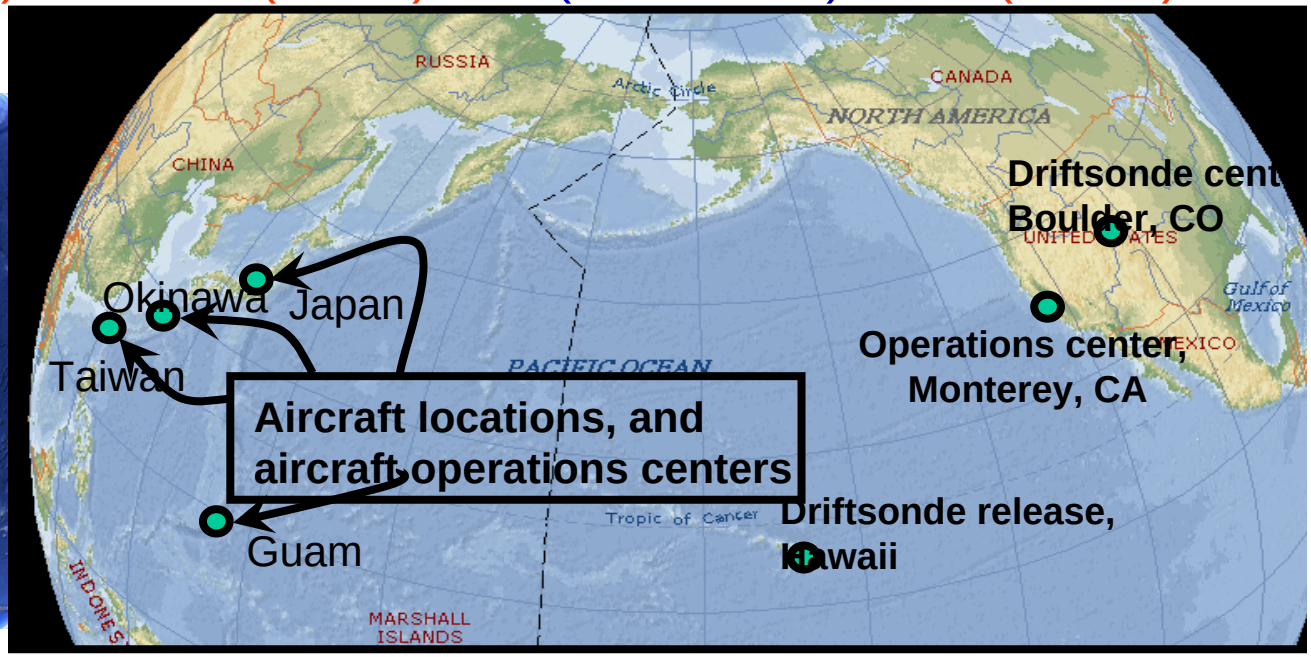
# T-PARC Operations Science Leadership

T-PARC planning meeting, Japan, 2008

## Science Steering Committee (SSC)

Chair: Harr (US), Co-Chairs: Nakazawa (Japan), Weissmann (German),
TCS-08 Rep: Elsberry Korea: Lee, PRC: Chen, Canada: McTaggart-Cowan,
Ex-Officio: Moore (NCAR), Parsons (WMO), Wu (DOTSTAR), Toth (NCEP).



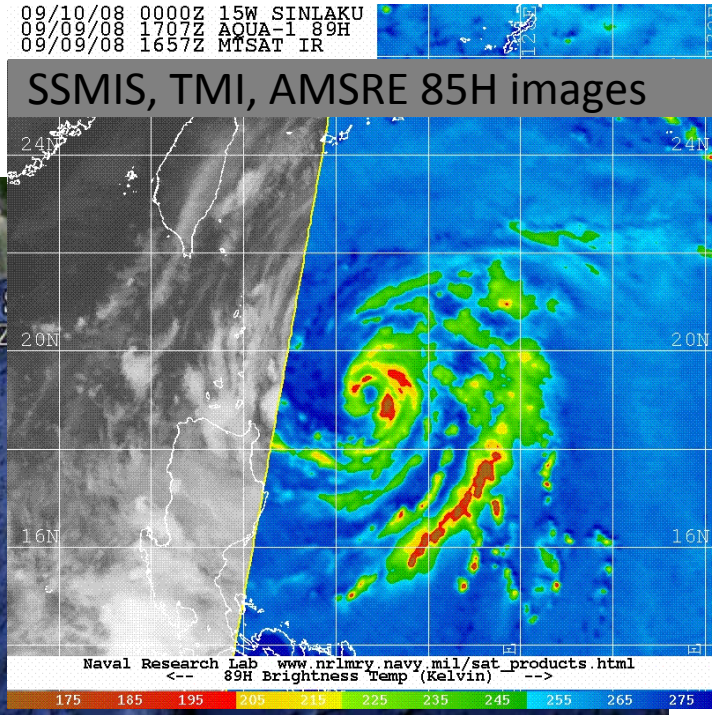



DOTSTAR + Falcon + P3 + C130,

52h + 85h + 165h + 215h = 507h flight hours, unprecedented!

173 + 328 + 604 + 343 = 1448 dropwindsondes

# Typhoon Sinlaku



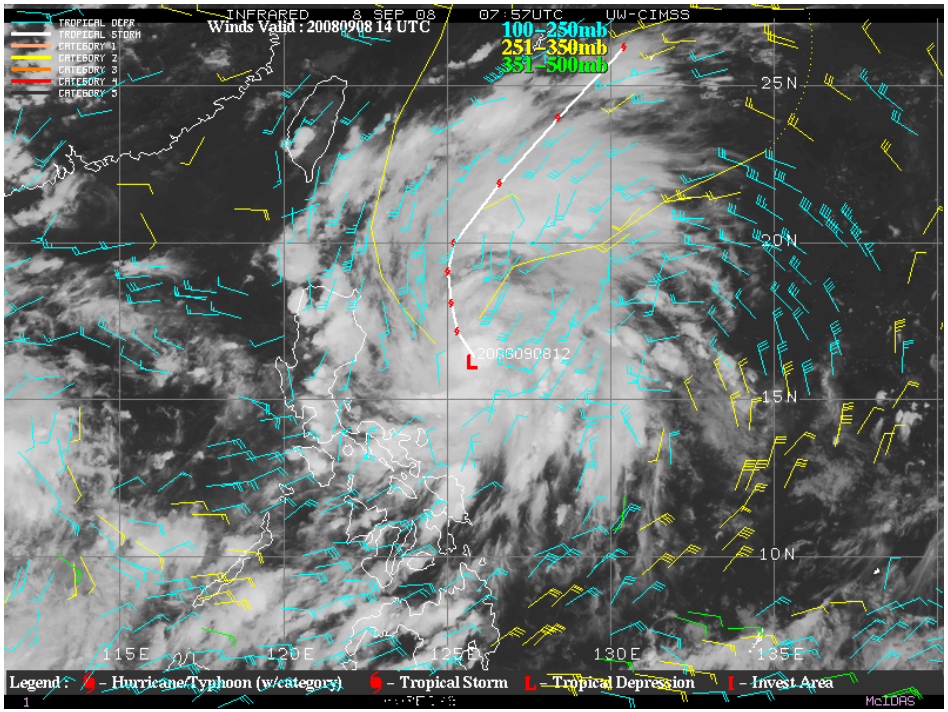




- The concentric eyewall structure can be clearly viewed from the satellite images at 0445Z , 0900Z, and 1134Z on September 11.
- When Sinlaku went through an eye wall replacement cycle on September 11, it started to weaken.
- The new primary eyewall formed at 2132Z 11 SEP.

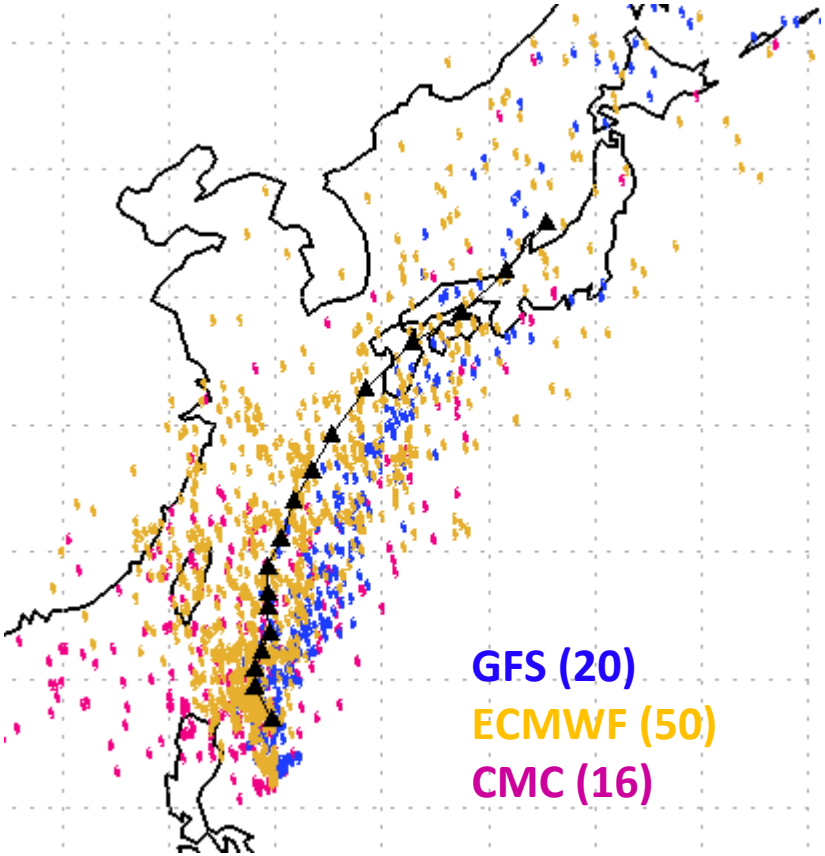
# Sinlaku. Concept for Targeting Operations. 21 UTC, 20080908

## Potential threat of TC to land

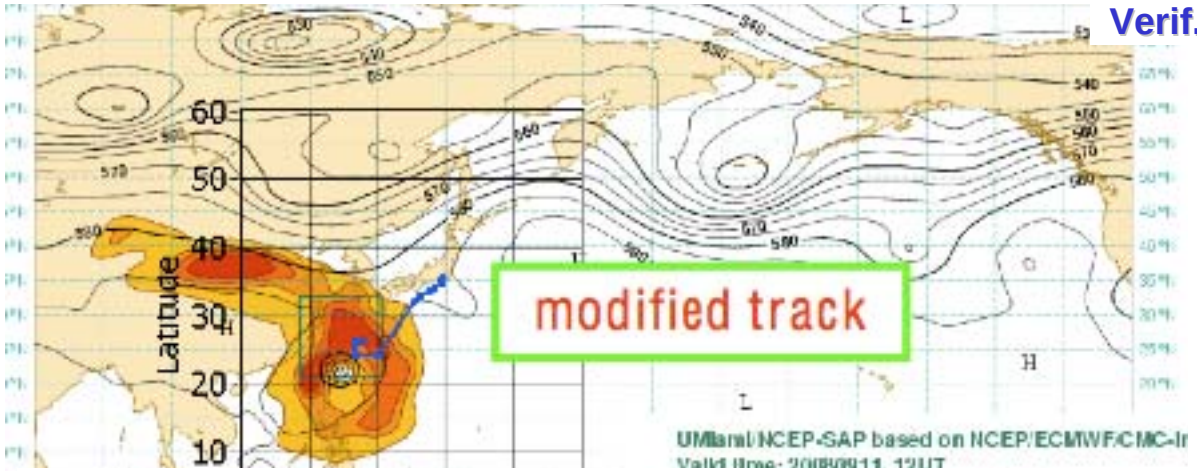



Courtesy CIMSS/U.Wisconsin

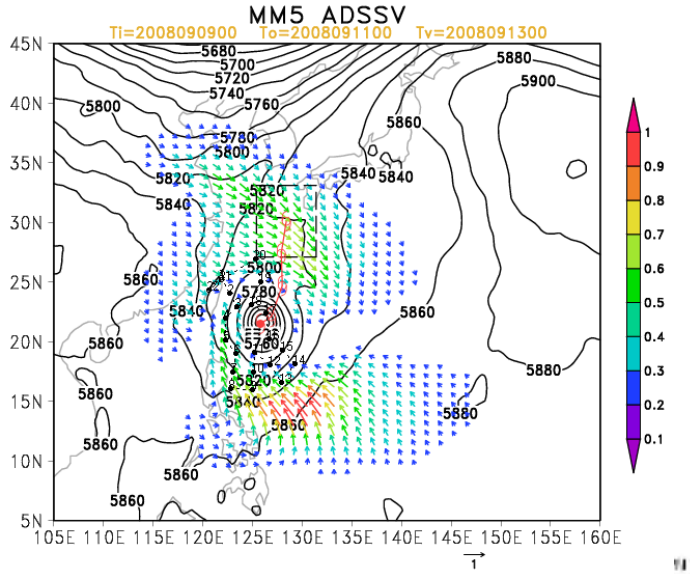
## Uncertainty in ensemble track forecasts



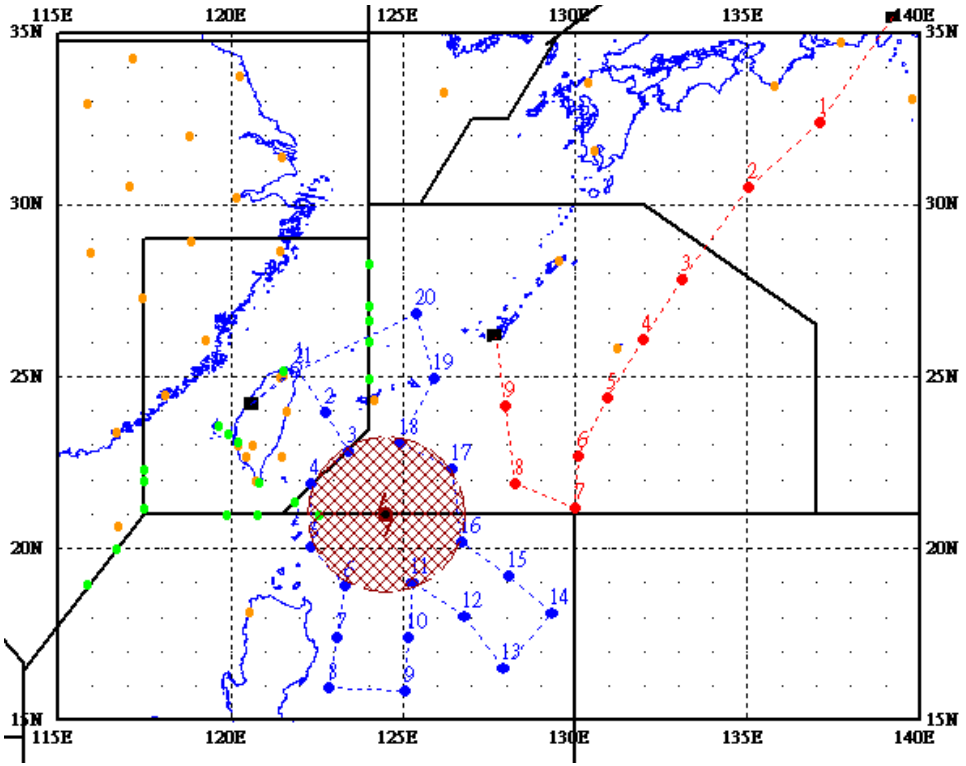

Uncertainty about strength of steering flow, and landfall location (if any)

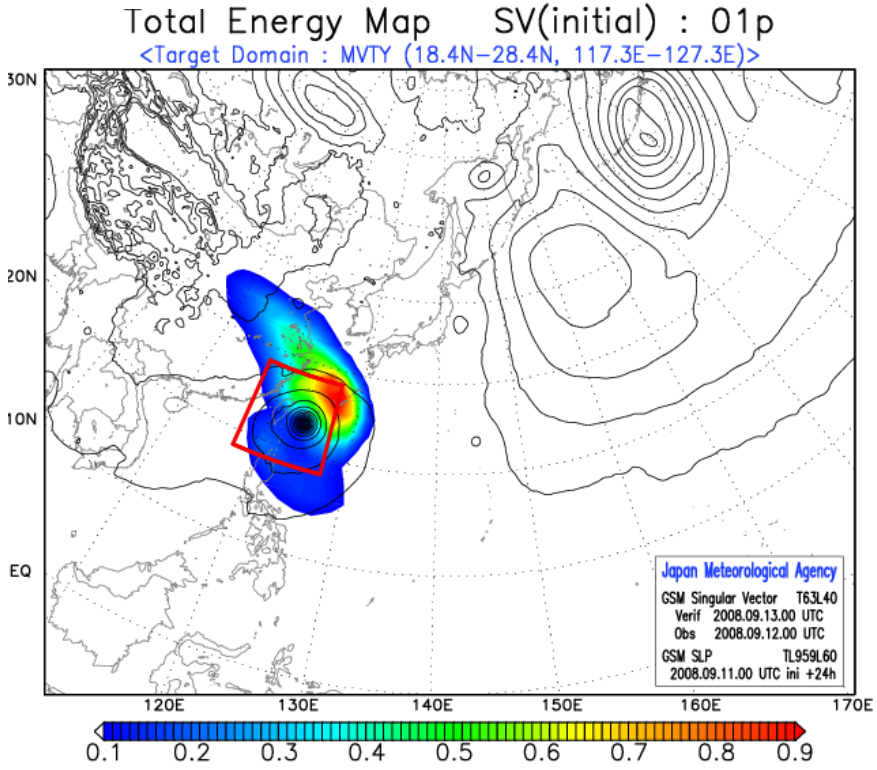


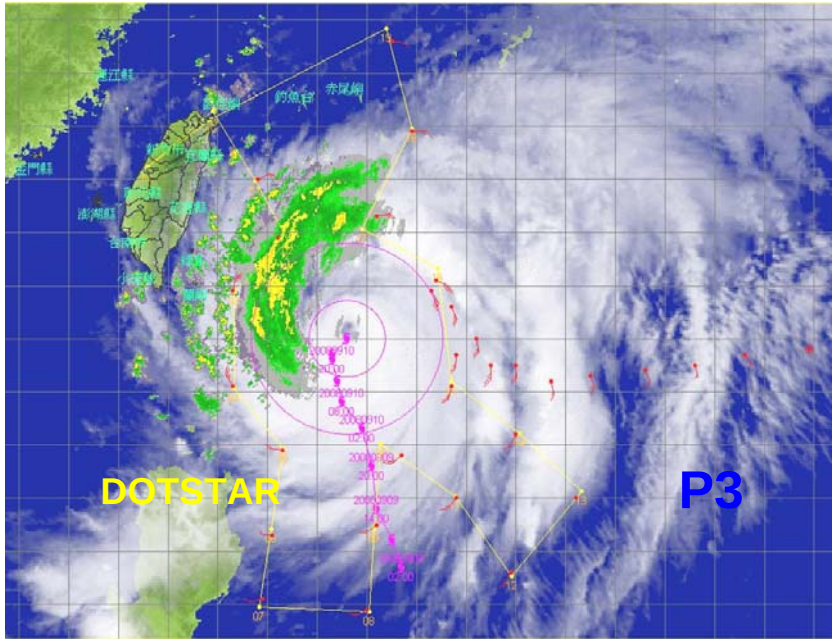

**Verif. Time : 2008.09.13 00UTC**




# DOTSTAR Flight Plan (BLUE) and FALCON Flight Plan (1) (Red)
# 10-11 September 2008 (Targeted observation)



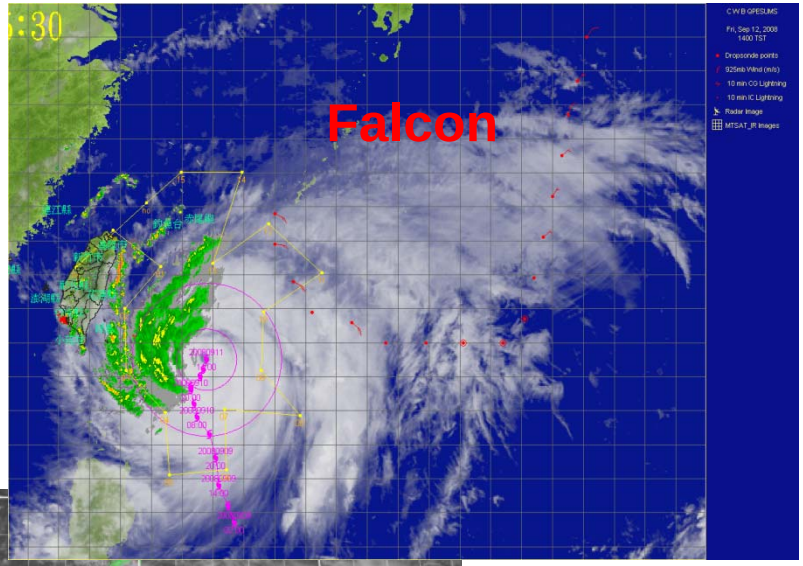






11 September, 2009, Typhoon Sinlaku

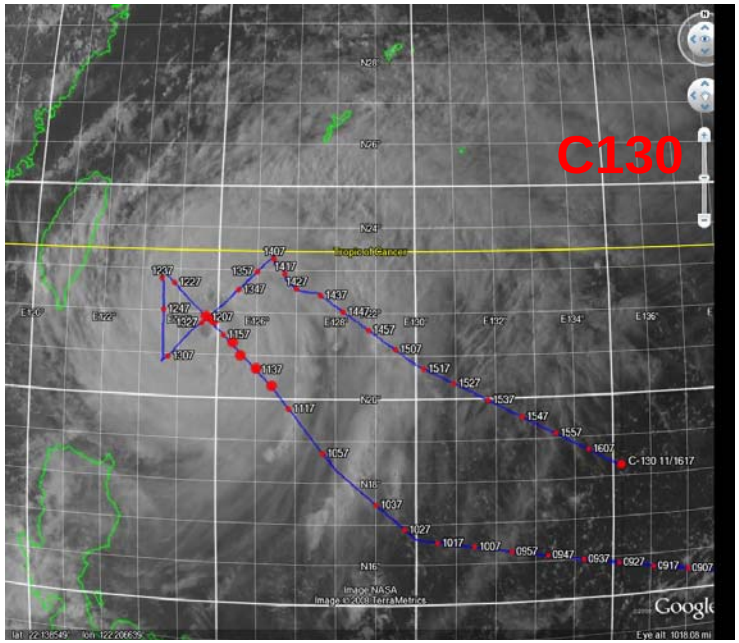
DOTSTAR + Falcon + P3 + C130 Flight tracks

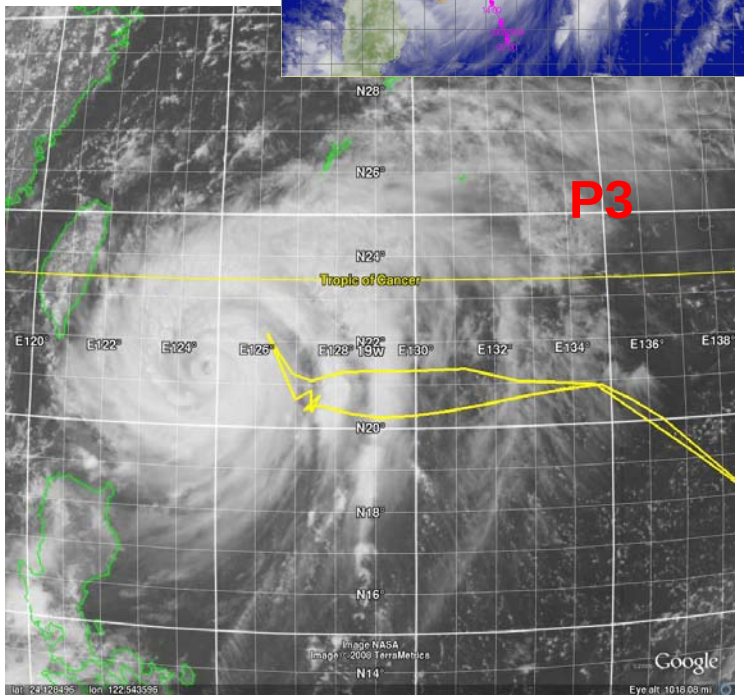
T-PARC




First time with four aircrafts observing typhoons

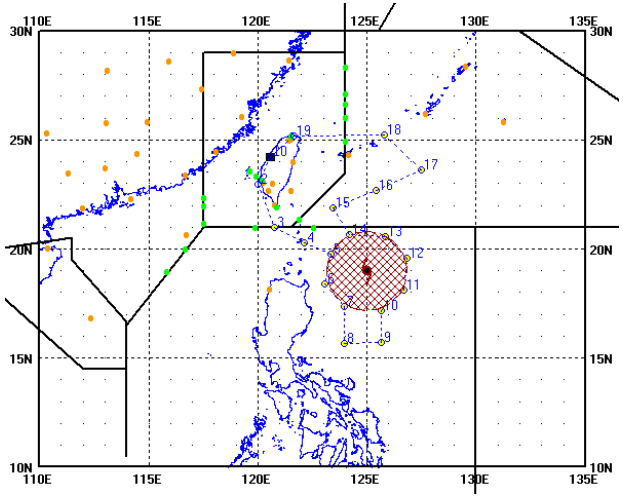
over NW Pacific ocean

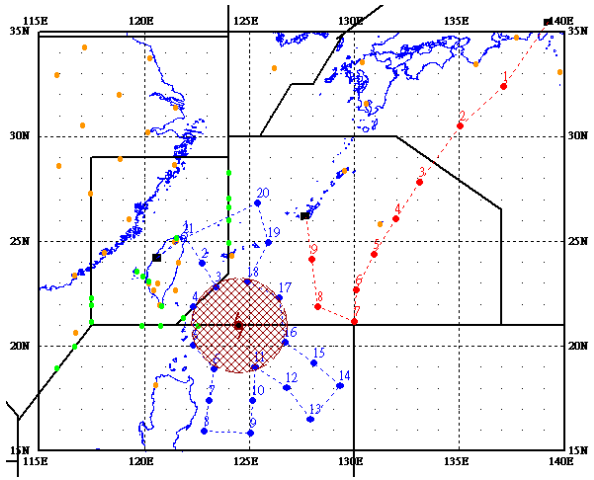


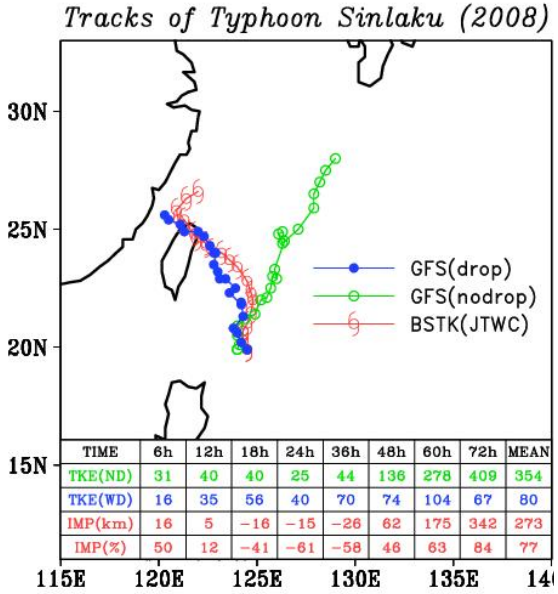



# Impact of dropwindsondes to NCEP GFS forecasts of Sinlaku

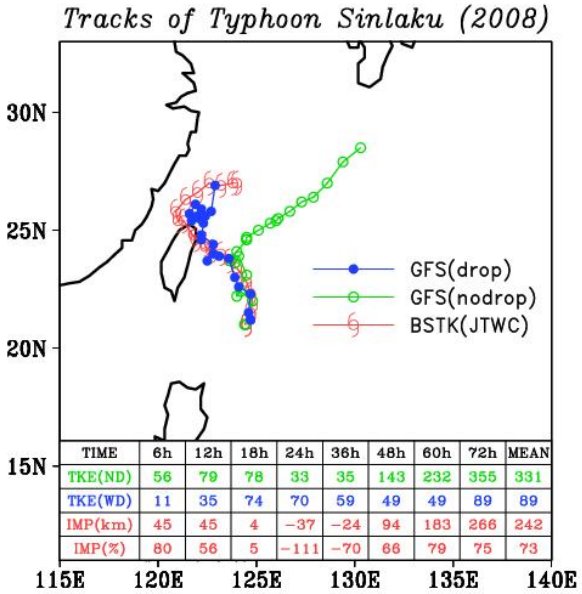
00 UTC Sept. 10, 2008; 00 UTC Sept. 11, 2008




| TIME | 6h | 12h | 18h | 24h | 36h | 48h | 60h | 72h | MEAN |
|---|---|---|---|---|---|---|---|---|---|
| TKE(ND) | 31 | 40 | 40 | 25 | 44 | 136 | 278 | 409 | 354 |
| TKE(WD) | 16 | 35 | 56 | 40 | 70 | 74 | 104 | 67 | 80 |
| IMP(km) | 16 | 5 | −16 | −15 | −26 | 62 | 175 | 342 | 273 |
| IMP(%) | 50 | 12 | −41 | −61 | −58 | 46 | 63 | 84 | 77 |




| TIME | 6h | 12h | 18h | 24h | 36h | 48h | 60h | 72h | MEAN |
|---|---|---|---|---|---|---|---|---|---|
| TKE(ND) | 56 | 79 | 78 | 33 | 35 | 143 | 232 | 355 | 331 |
| TKE(WD) | 11 | 35 | 74 | 70 | 59 | 49 | 49 | 89 | 89 |
| IMP(km) | 45 | 45 | 4 | −37 | −24 | 94 | 183 | 266 | 242 |
| IMP(%) | 80 | 56 | 5 | −111 | −70 | 66 | 79 | 75 | 73 |

(Wu et al. 2010b)

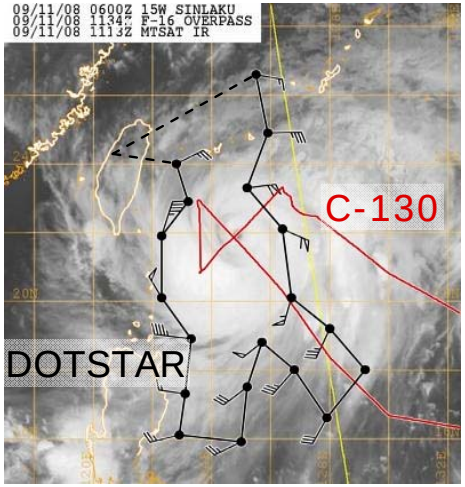
From National Geographic Channel

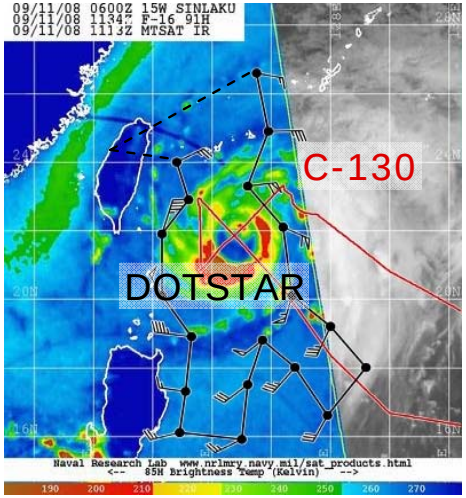
# Data

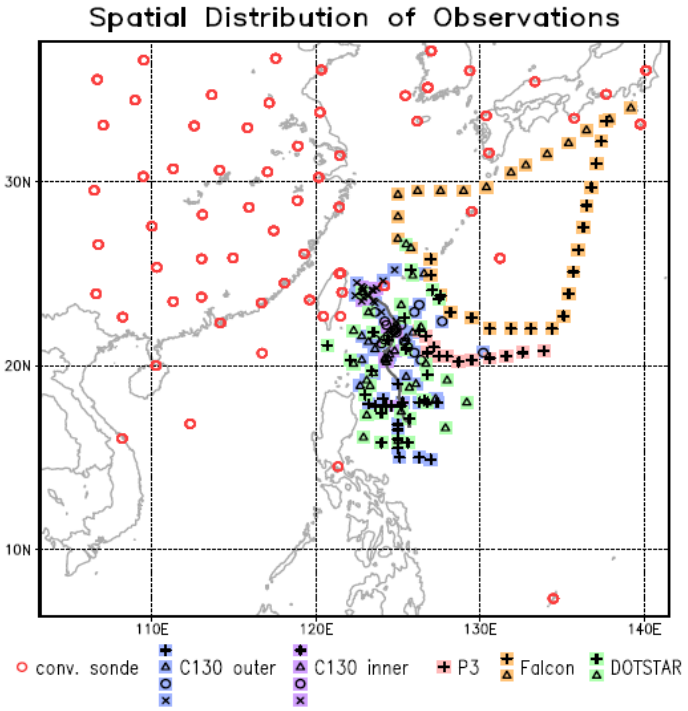
## THORPEX Pacific Asian Regional Campaign

## ( *T-PARC* )

- 2008/09/08 17:00 ~ 09/13 03:00 UTC




**9 flight missions with 159 dropwindsondes**

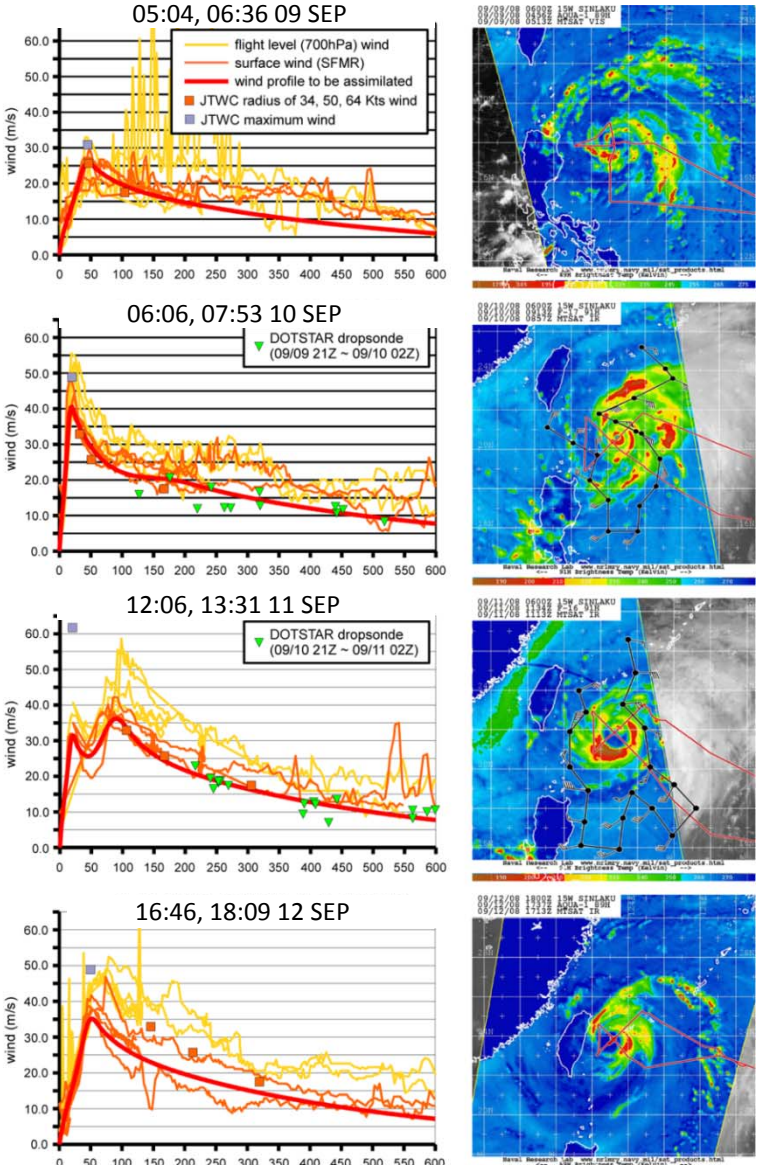
| | Conv. radiosonde | Dropwindsondes | | | | |
|---|---|---|---|---|---|---|
| | | DOTSTAR ASTRA | DLR Falcon | NRL P-3 | USAF C-130 | |
| | | | | | Inner core | Others |
| Total available | 623 | 36 (2 flights) | 34 (2 flight) | 12 (1 flight) | 20 | 57 |
| | | | | | (4 flights) | |

# Methodology

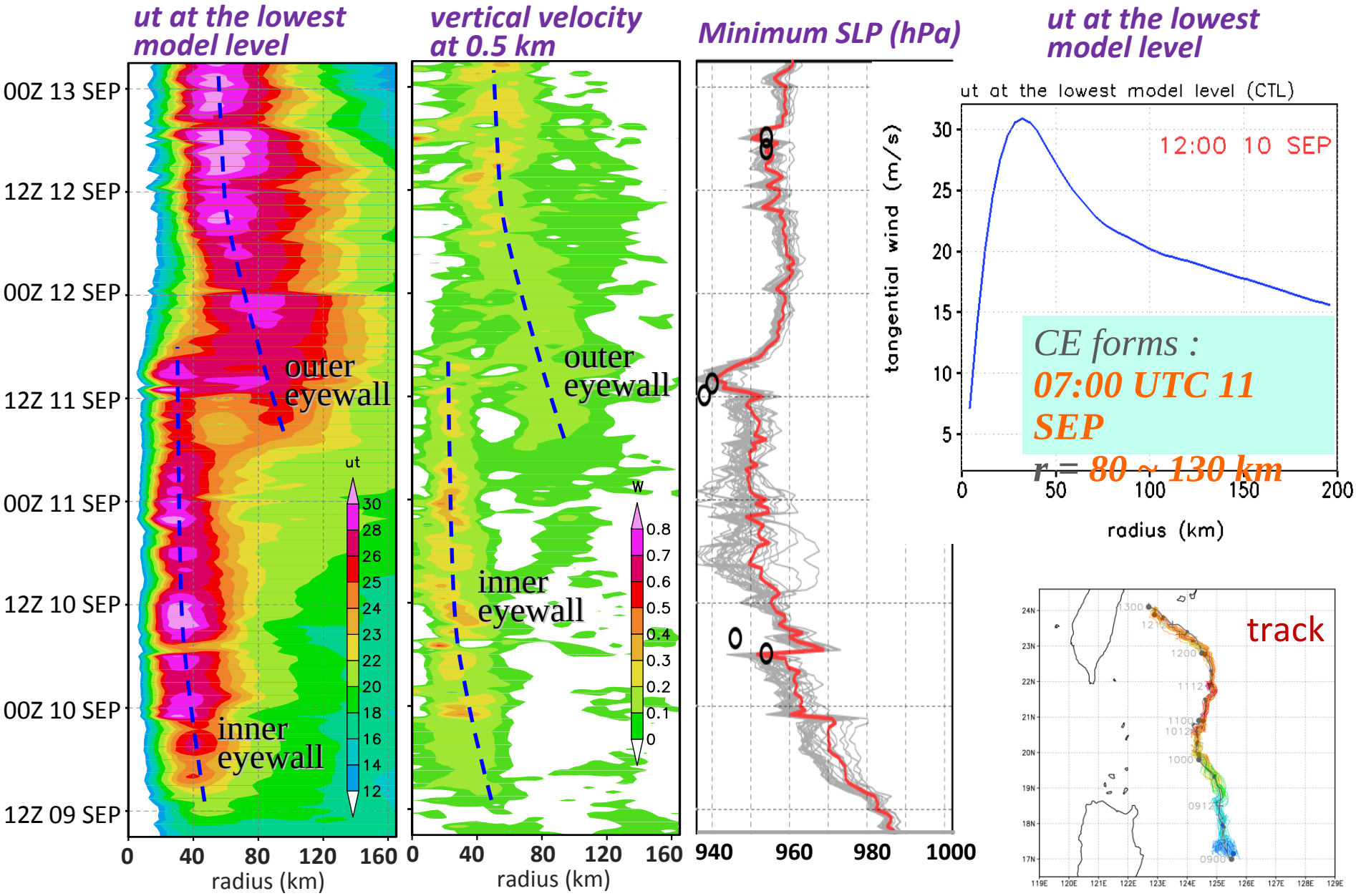
## EnKF data assimilation/ WRF model

- Observation operators related to TCs (Wu et al. 2010a, Lien et al. , 4:30pm, 11C.5)
  *center position / motion vector/*
  ***axisymmetric wind structure***
  - 3 hour best track data
  - TC radius (34, 50 kts) data from JTWC.
  - Surface wind from the T-PARC data (dropsondes and SFMR)

- Rapid update Cycle (RUC): 30 mins
- horizontal resolution : 5 km
- 35 vertical layers
- 30-min output interval
- 28 ensemble members

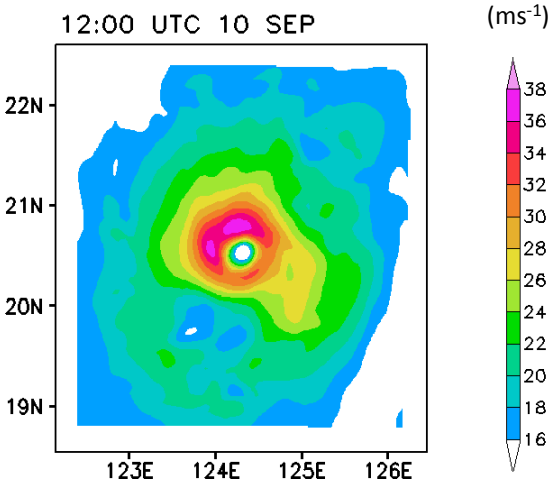


# CTL Experiment - hovemoller diagram

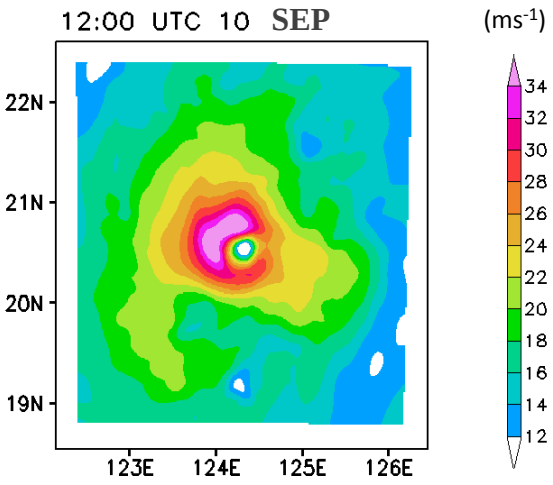


# CTL Experiment - *plan view*

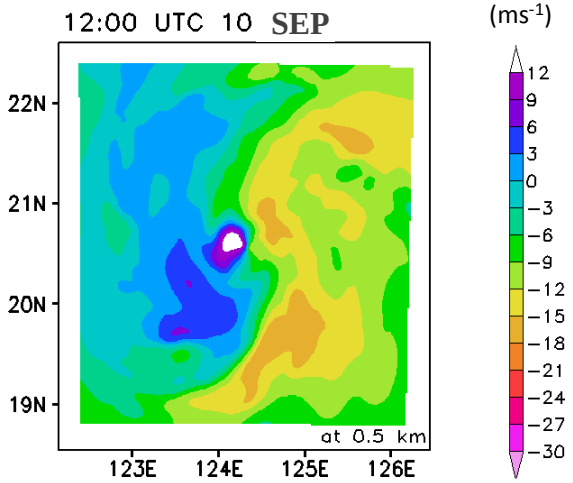
***Horizontal wind speed at the lowest model level***



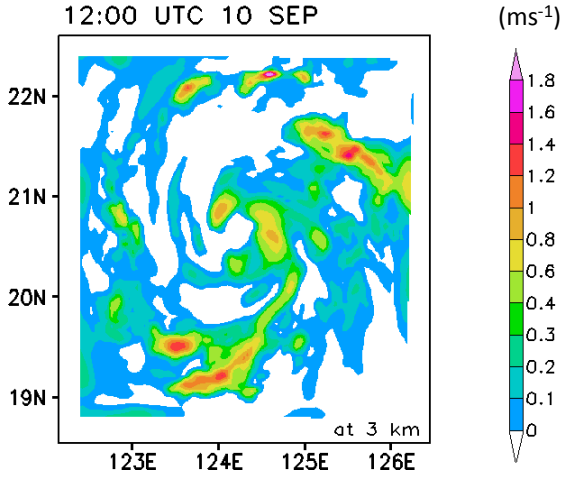

***Tangential winds at the lowest model level***



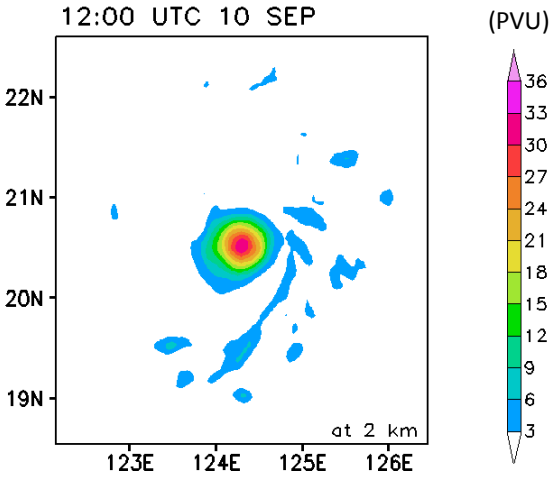

***Radial winds at the lowest model level***




***Vertical velocity at 2 km***



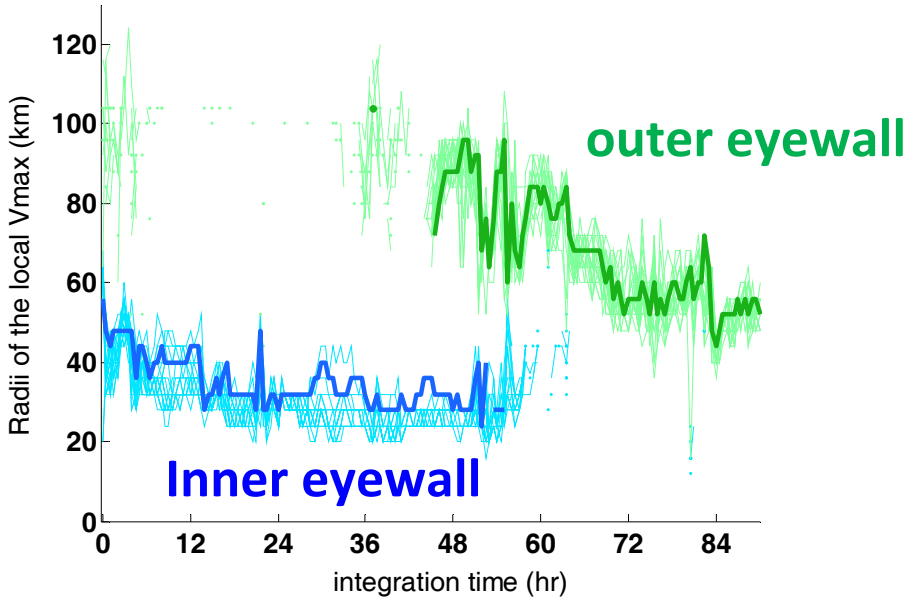

***Potential vorticity at 2 km***

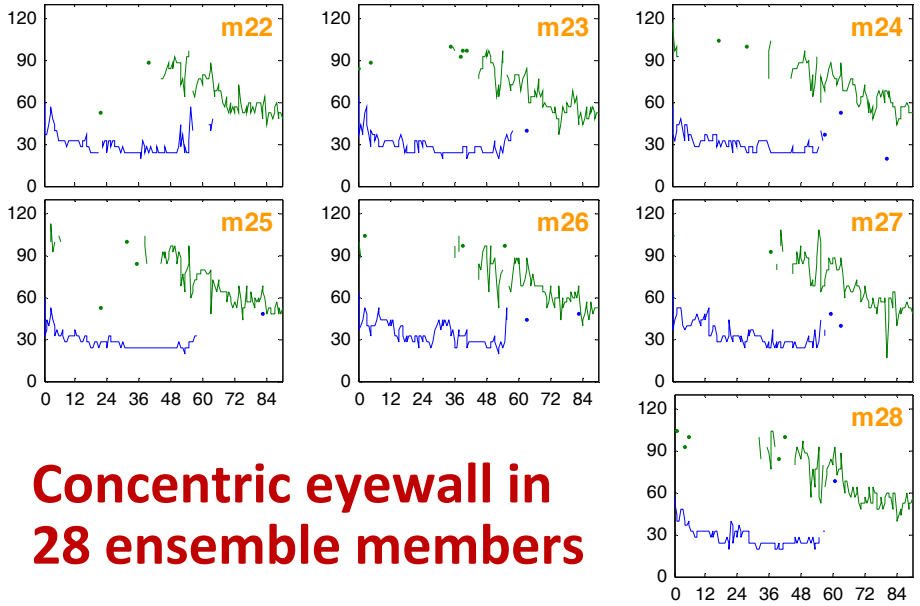



***07:00 UTC 11 SEP:***

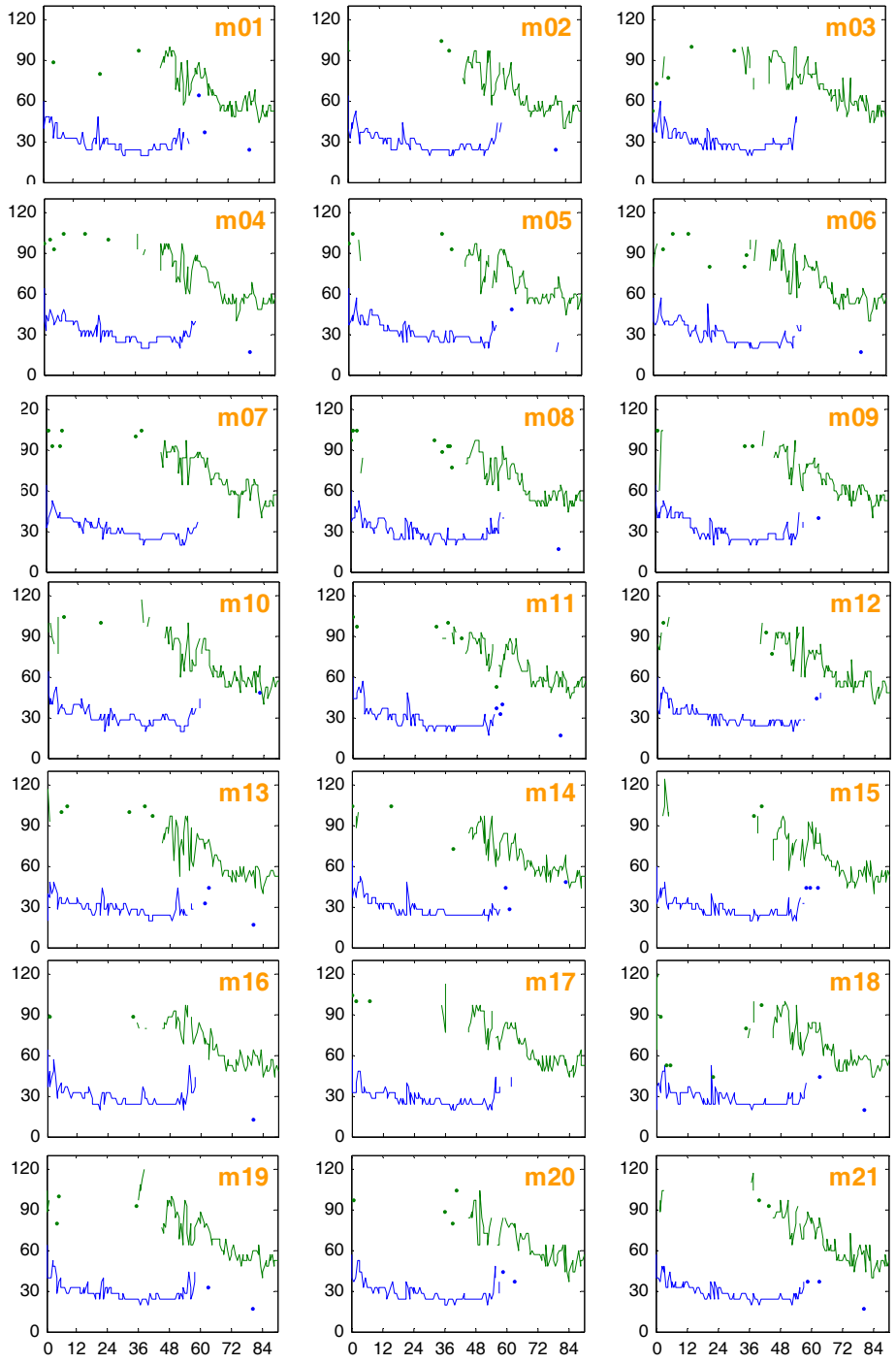
time when the secondary eyewall forms.

# CTL Experiment -
## Radii of local $V_{max}$



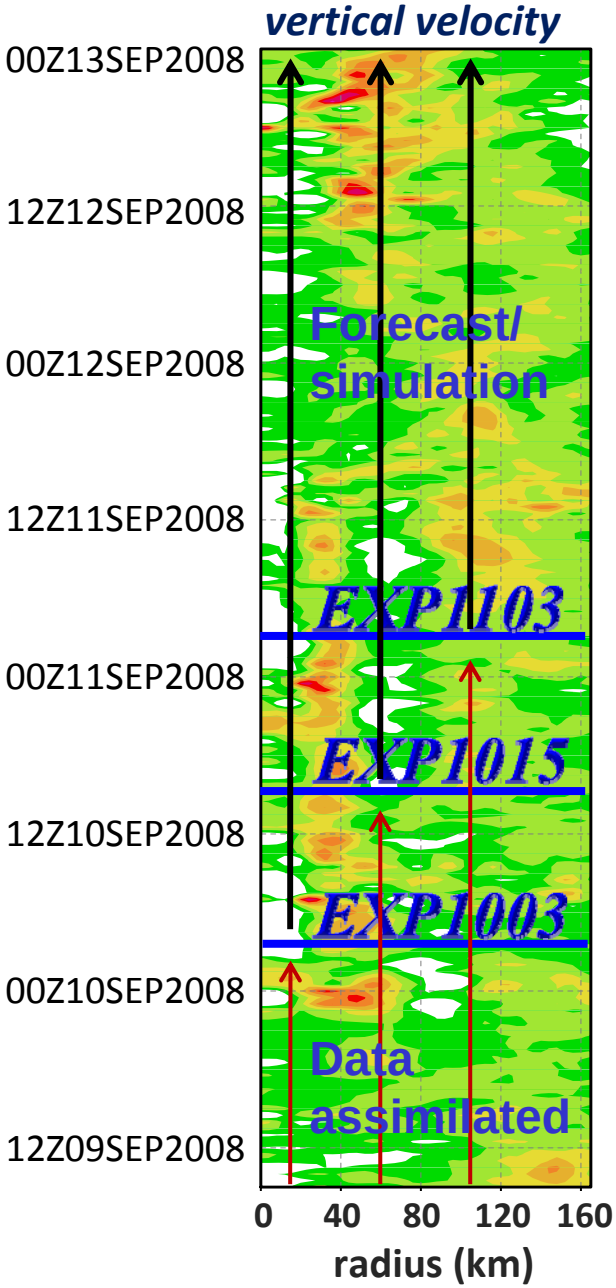




**Concentric eyewall in 28 ensemble members**



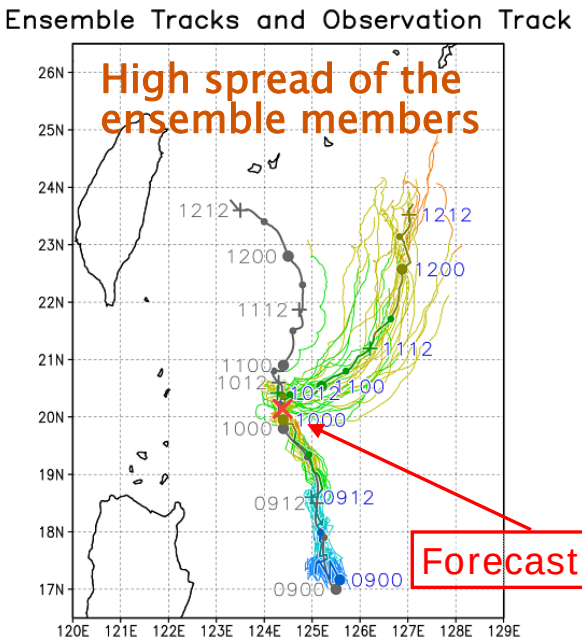
# Experimental design

| Exp. | EnKF assimilation | formation time (concentric eyewall ) |
|---|---|---|
| *CTL* | throughout the integration | 0700 UTC 11 SEP |
| *EXP1103* | until 0300 UTC 11 SEP | 0700 UTC 11 SEP |
| *EXP1015* | until 1500 UTC 10 SEP | 0730 UTC 11 SEP |
| *EXP1003* | until 0300 UTC 10 SEP | No concentric eyewall |

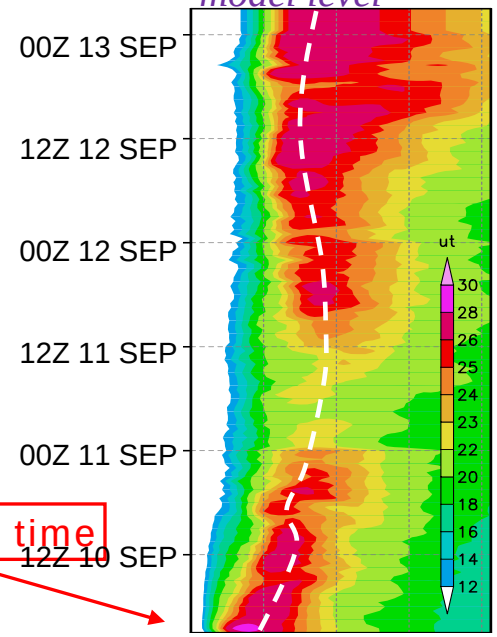


# EXP1003 - Forecast at 1003Z

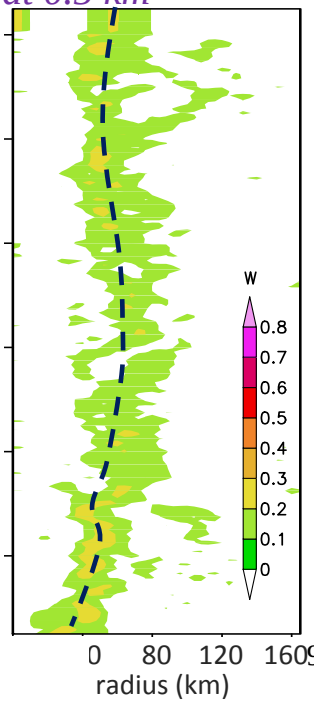
Ensemble forecast started from 2008/09/10 03:00 UTC.



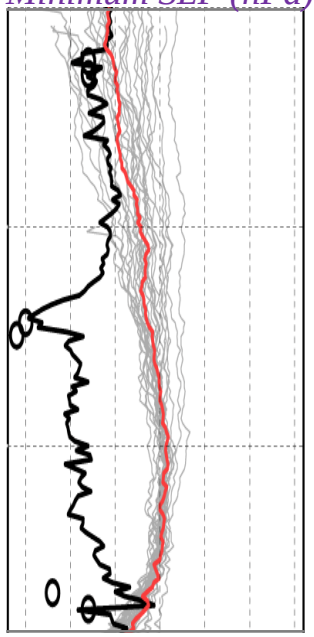

*ut at the lowest model level*

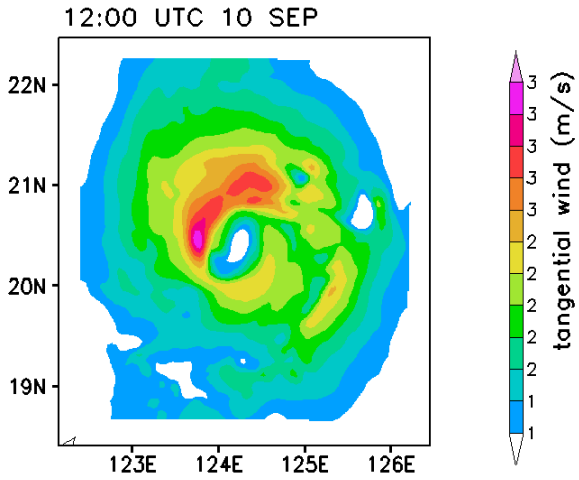


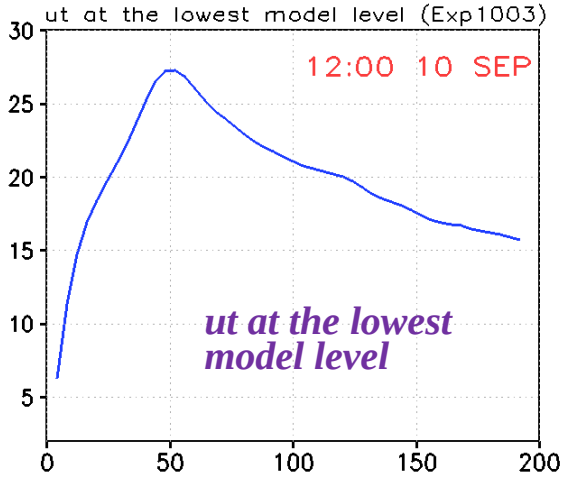

*vertical velocity at 0.5 km*




*Minimum SLP (hPa)*





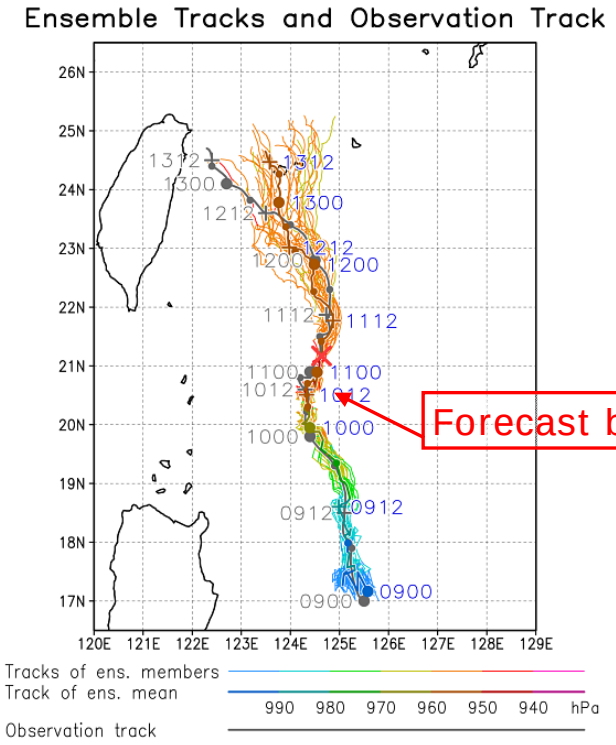

**No double eyewall**

# EXP1103 - Forecast at 1103Z

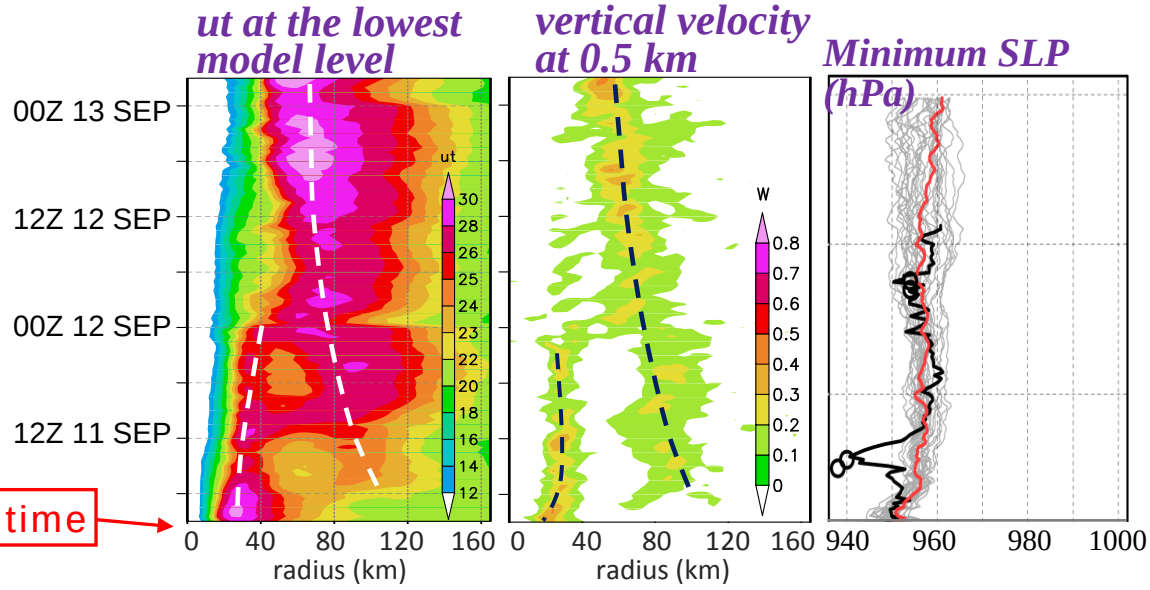
Ensemble forecast started from 2008/09/11 03:00 UTC.

**Predict the double eyewall evolution**

## Consistency of the ensemble members

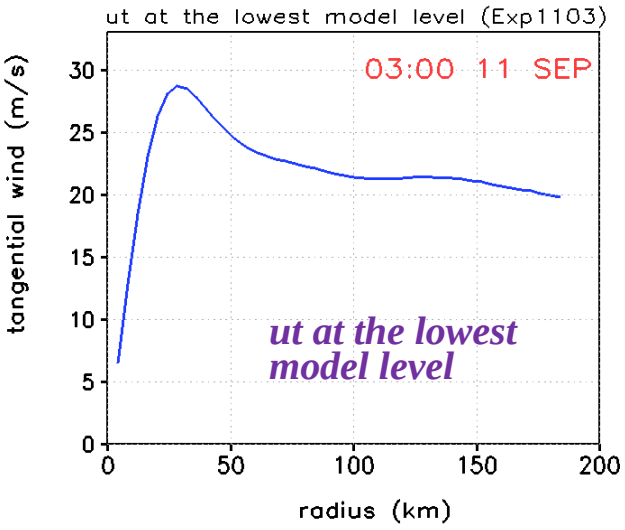


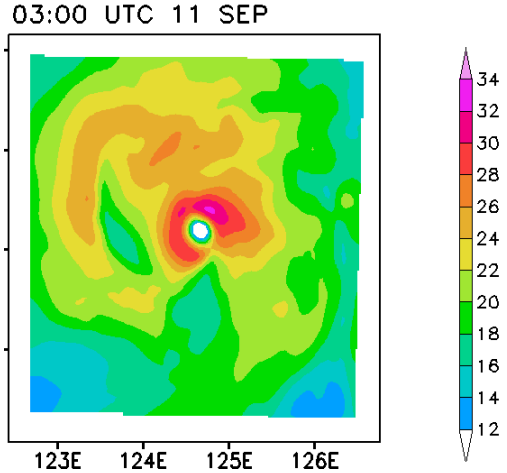

Forecast base time



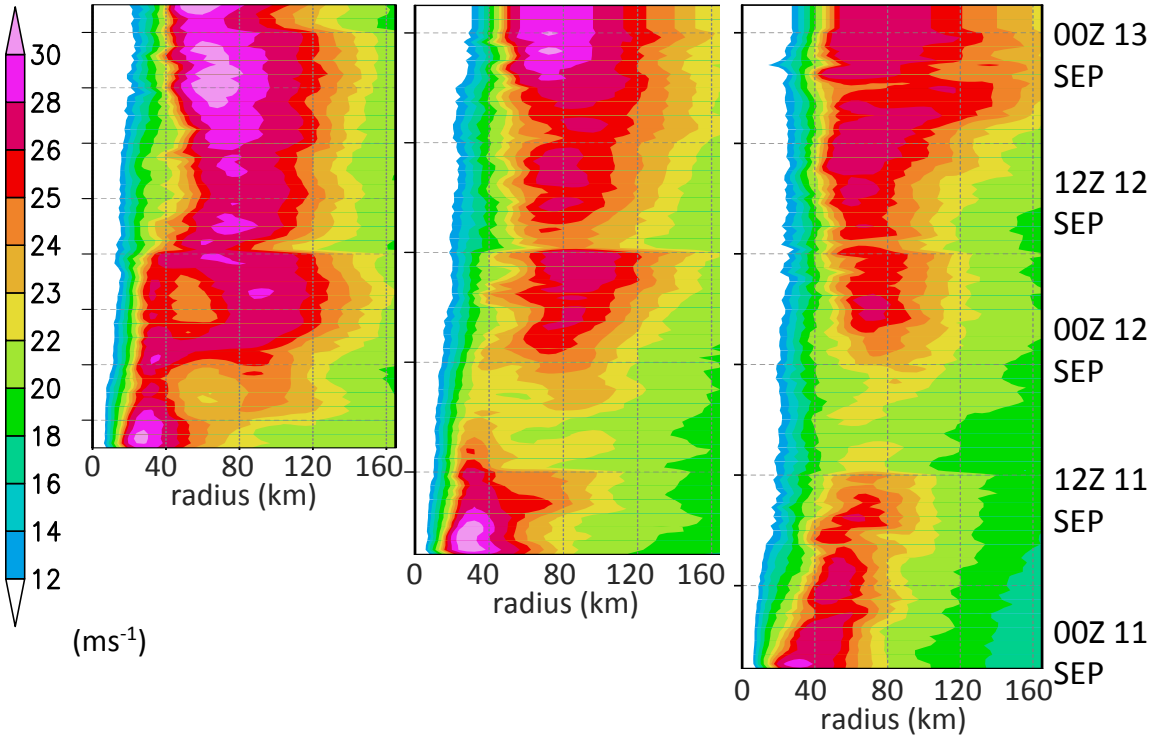

**Mechanisms and Predictability of concentric eyewall formation?**

**Physical insights?**



## *ut at the lowest model level* ($ms^{-1}$)



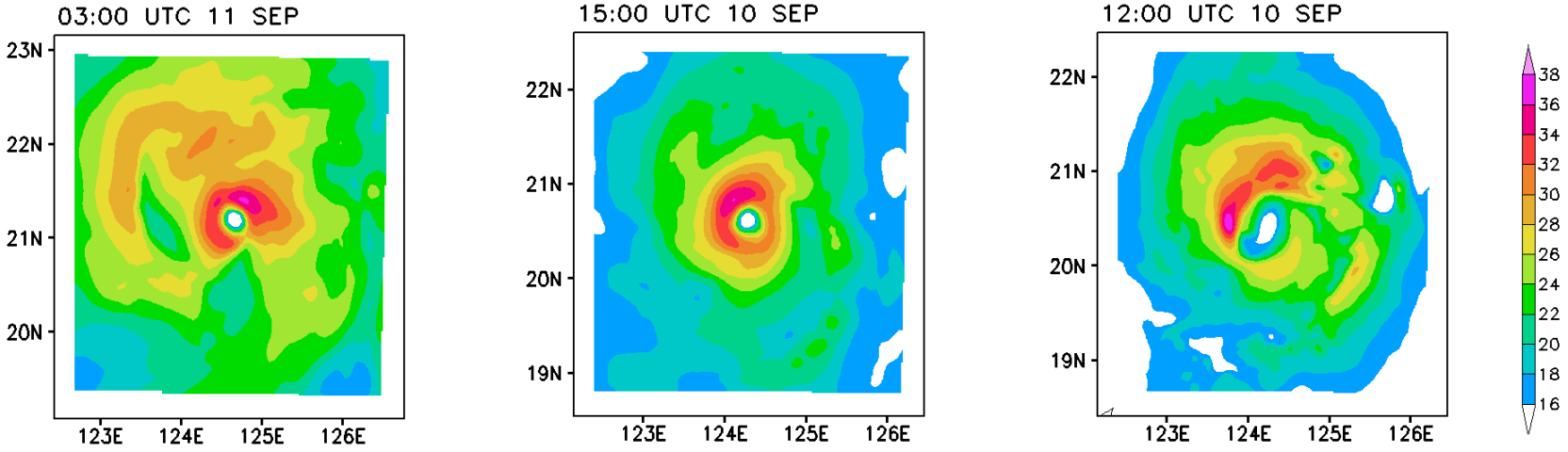

***EXP1103*** : CE forms

***EXP1015*** : Weaker CE

***EXP1003*** : No CE

***Why ?***

***EXP1103*** ***EXP1015*** ***EXP1003***



# Typhoon-ocean interaction in Sinlaku (2008)

In positive SSHA region:

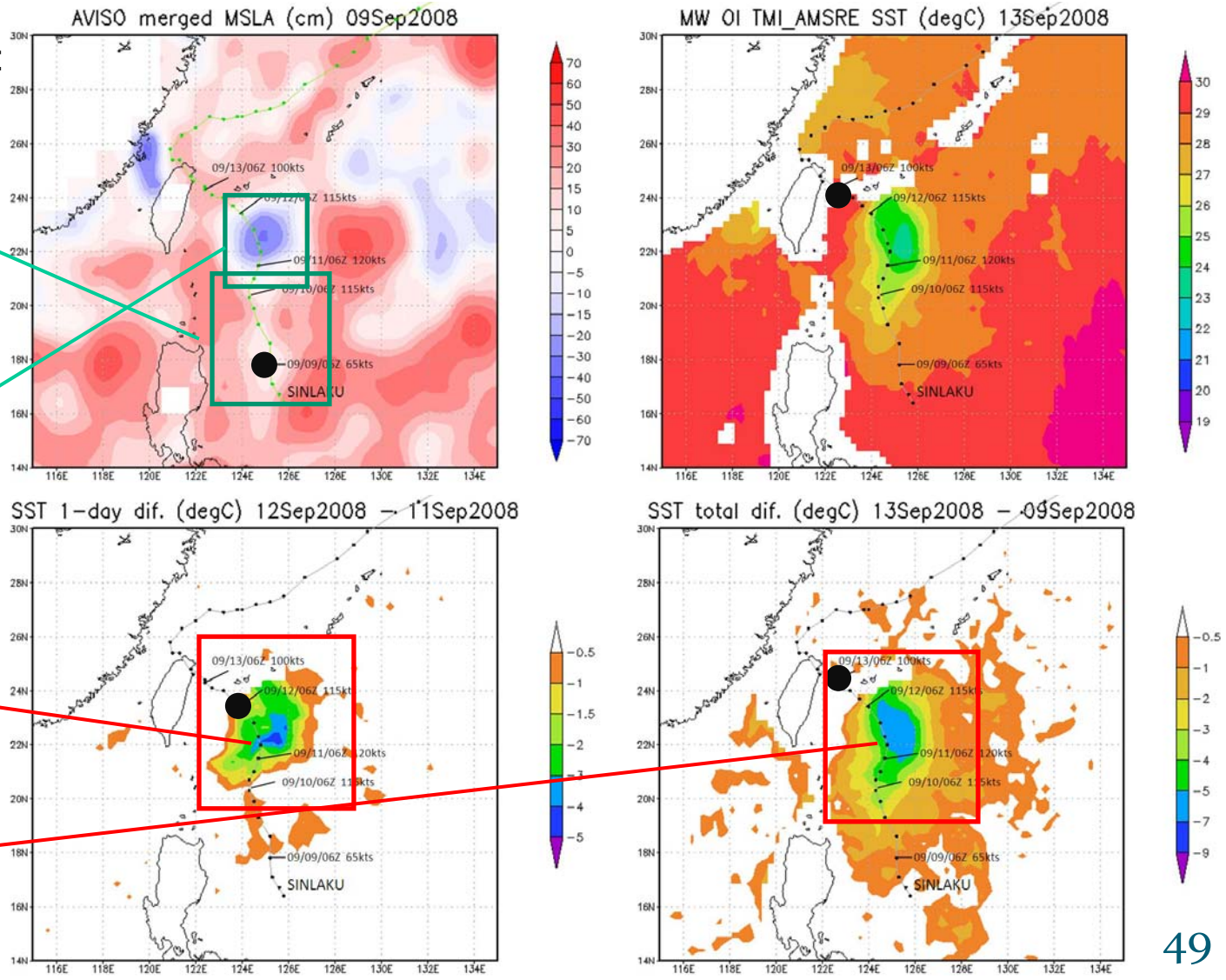
09/09 06Z ~ 09/10 06Z
+50kts/24hrs

09/09 12Z ~ 09/10 12Z
+50kts/24hrs

Cold Eddy
(09/11 06Z ~ 09/12 06Z)

SST cooling in one day:
> 4 ℃ (09/11 ~ 09/12)

Total SST cooling:
> 5 ℃ (09/09 ~ 09/13)

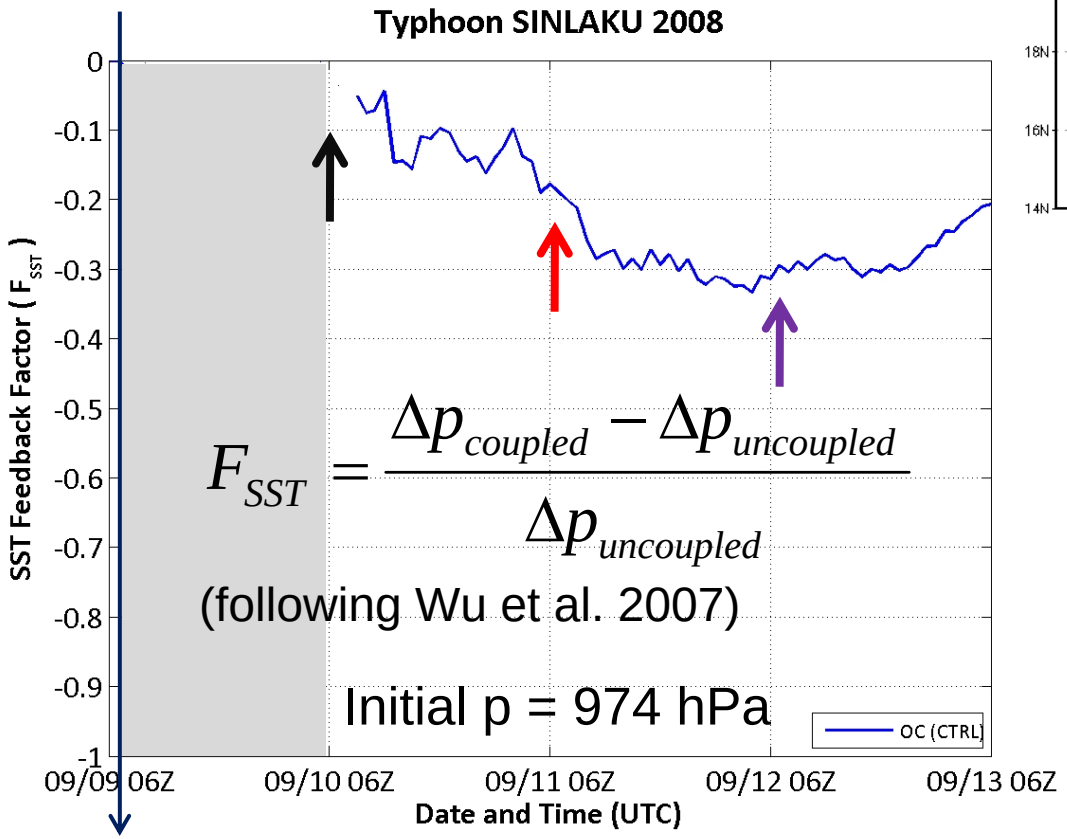



(Sung and Wu 2010)

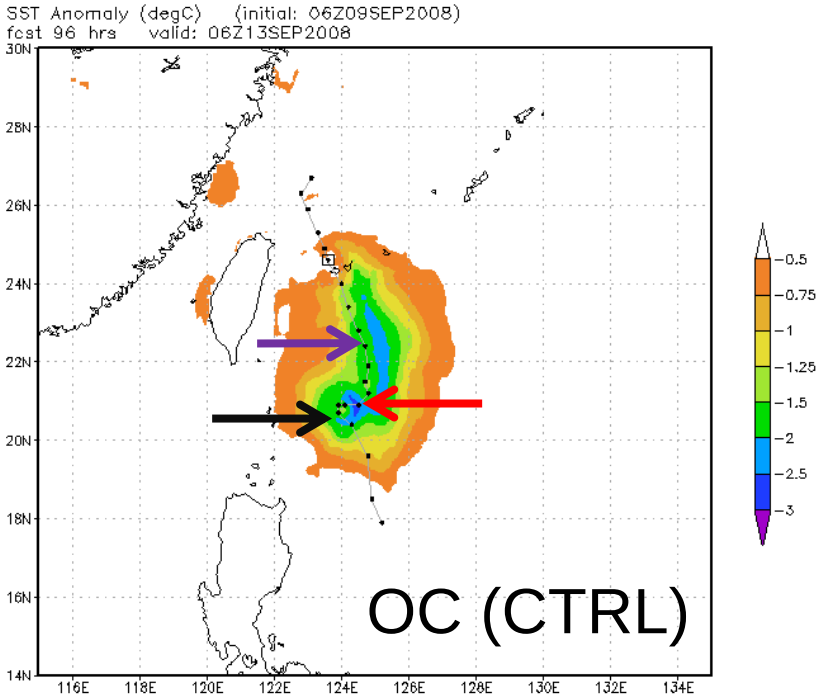
# EnKF + coupled model

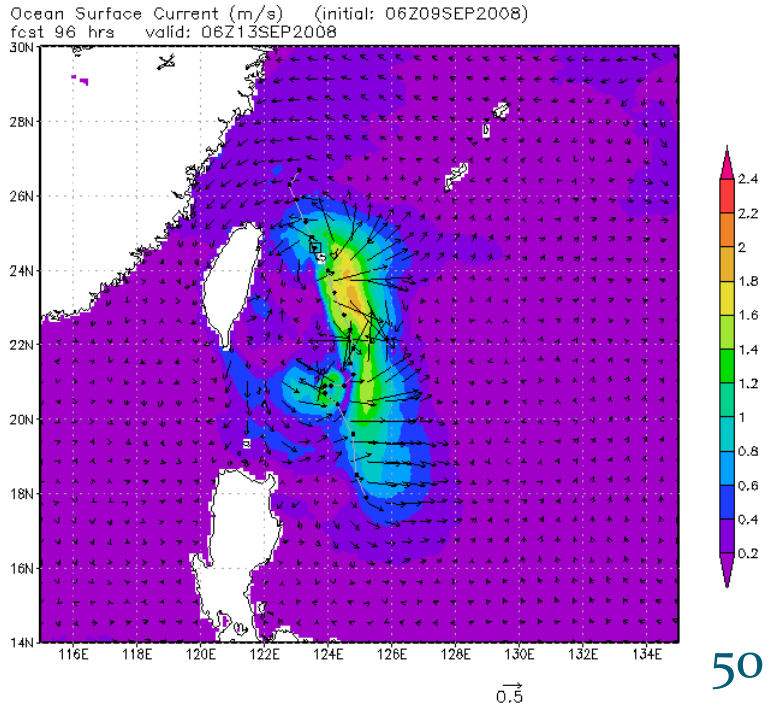
## CTRL: Uncoupled and Coupled ($F_{SST}$)

0: No SST feedback




-1: Strong SST feedback

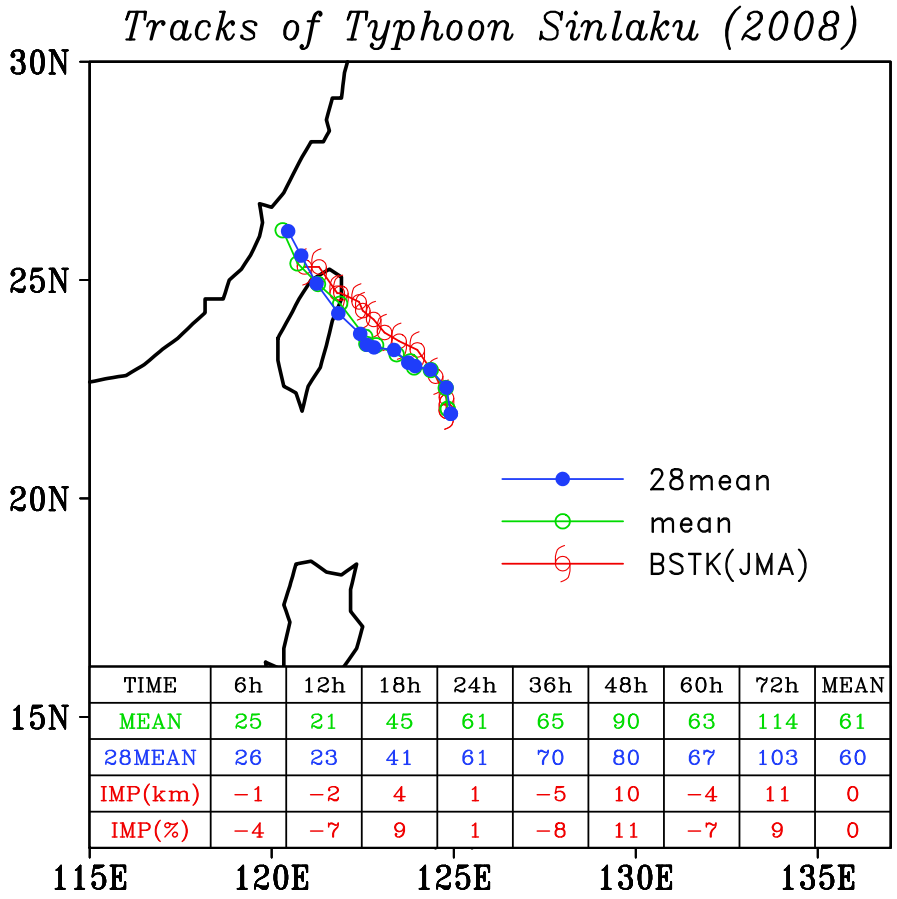



**(Sung and Wu 2010)**

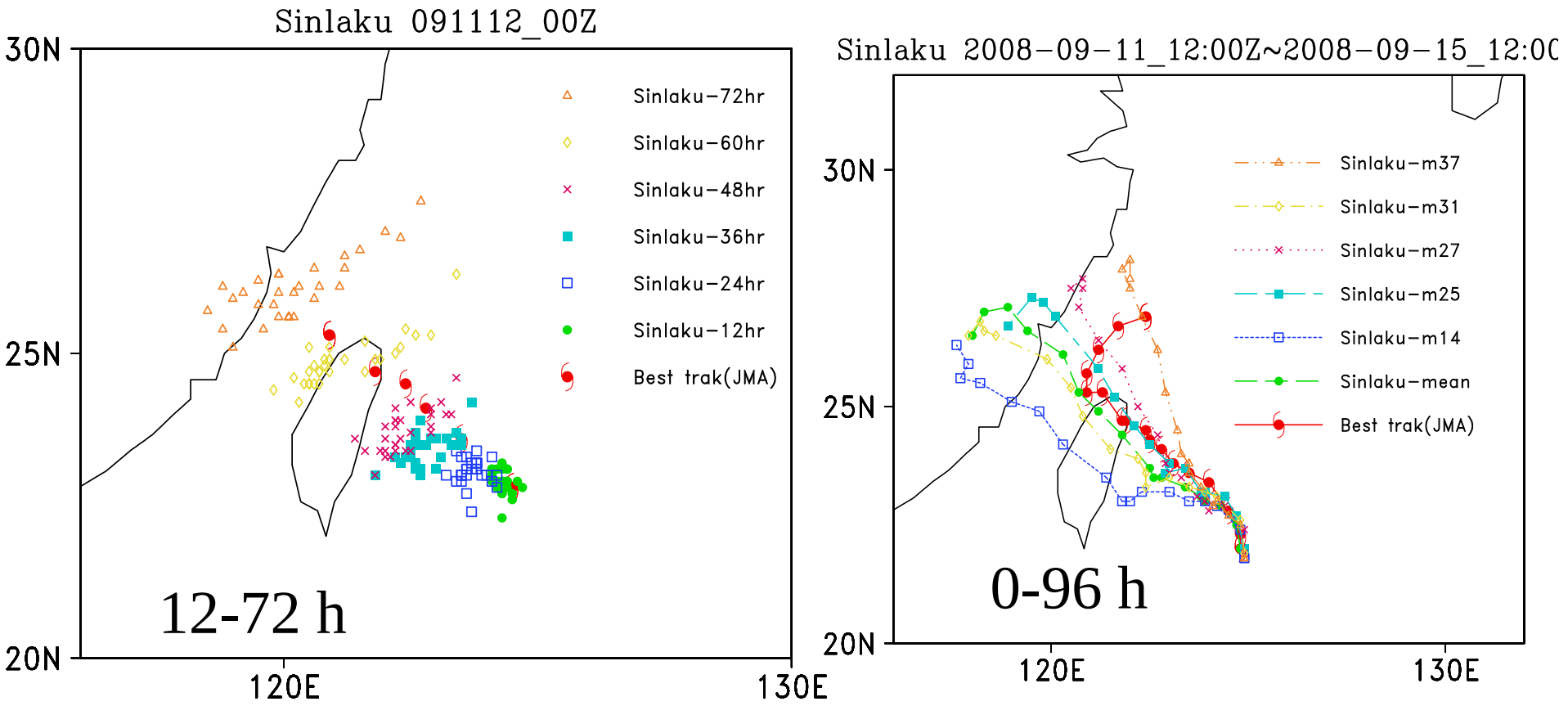
# Track forecast – EnKF ensemble mean

| hour | mean | 28mean |
|---|---|---|
| 12 | 21 | 23 |
| 24 | 61 | 61 |
| 36 | 65 | 70 |
| 48 | 90 | 80 |
| 60 | 63 | 67 |
| 72 | 114 | 103 |




Lin and Wu 2010

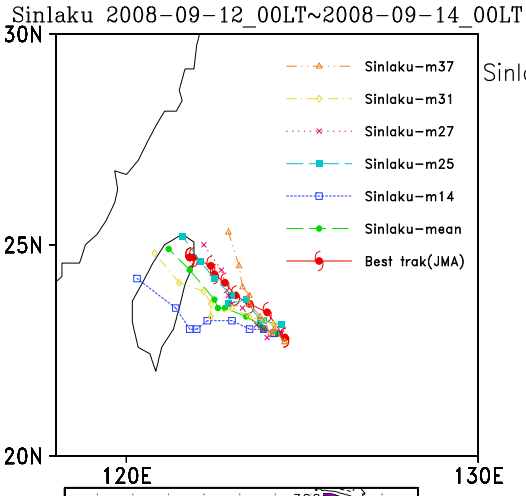
# Ensemble spread

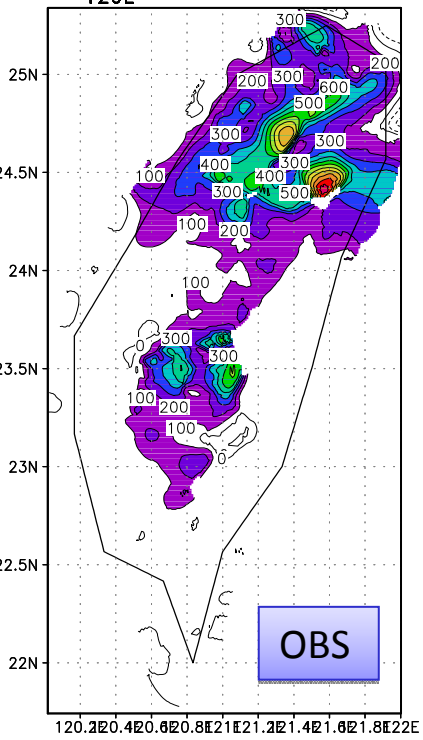


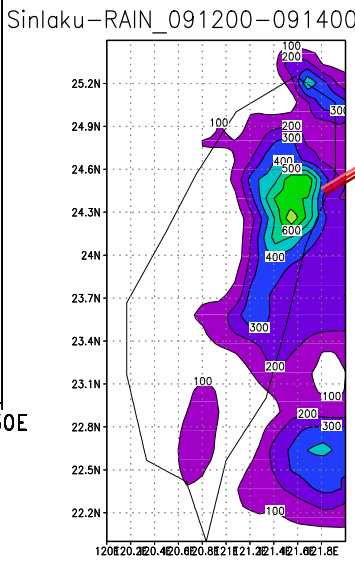

Lin and Wu 2010

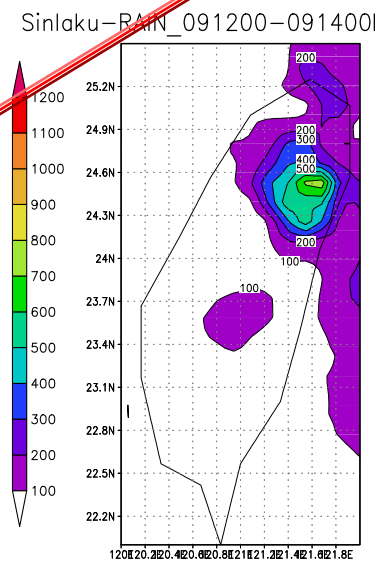
# 48-h accumulated rainfall 091200~091400LT associated with Sinlaku(2008)

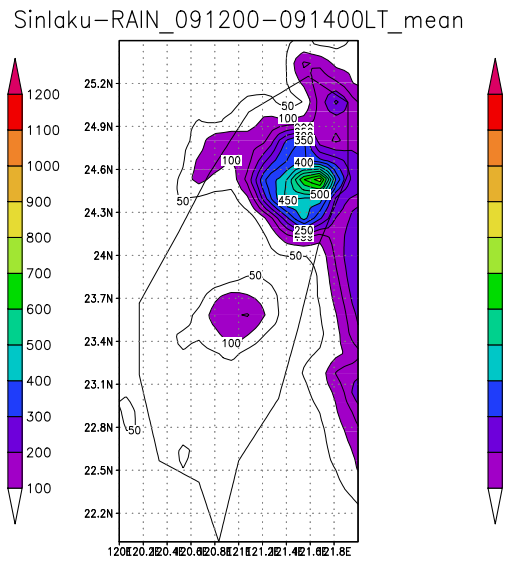
High predictability

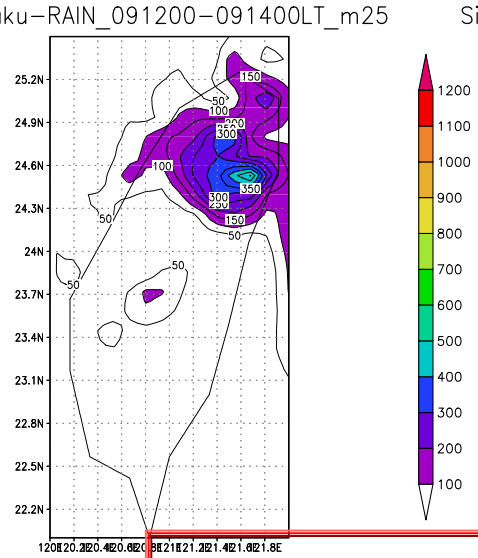


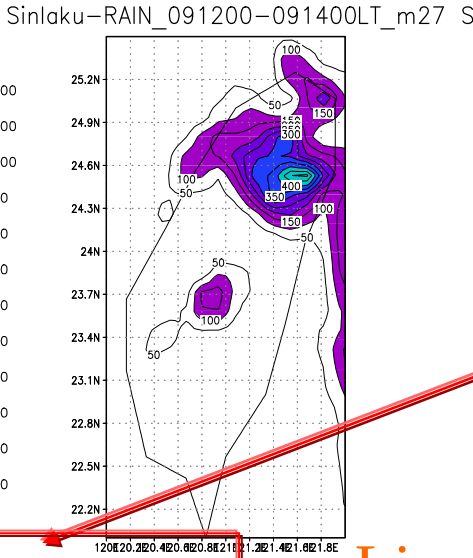



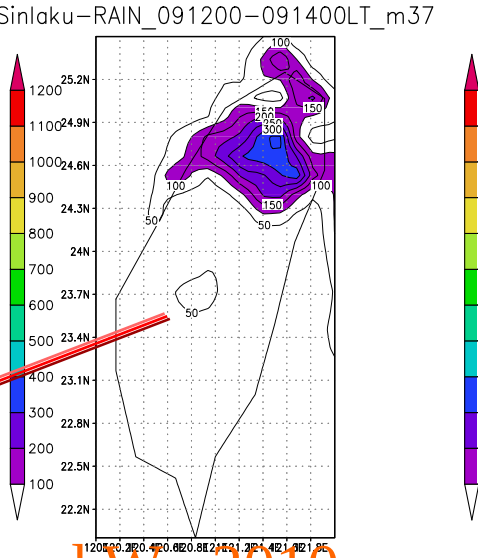



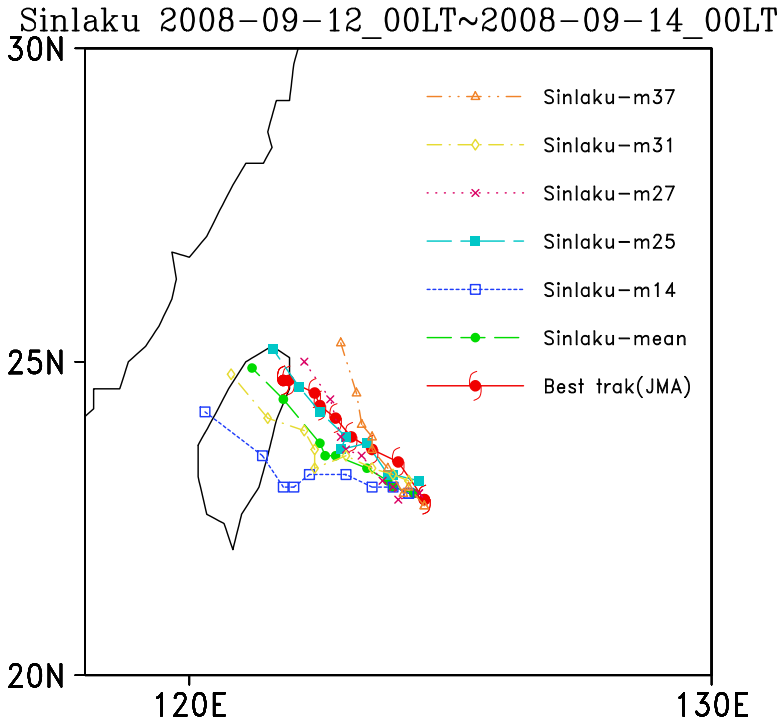



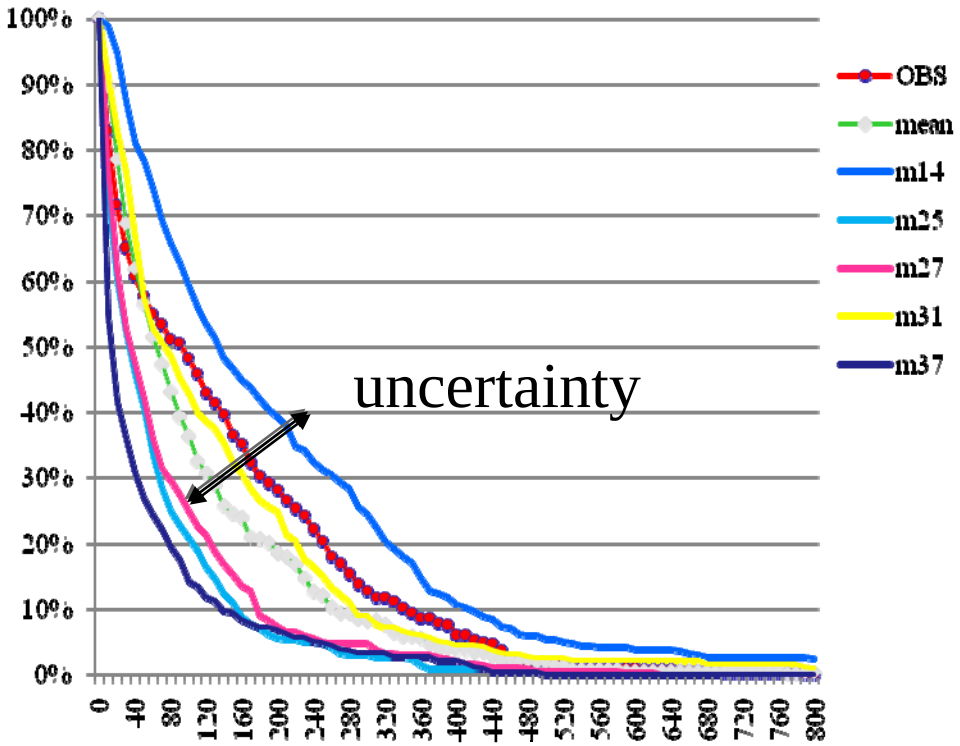

Low predictability

Lin and Wu 2010

# 48h-rainfall PDF over Taiwan

## 091200~091400LT




Following Wu et al. (2002)

Lin and Wu 2010

Next → Morakot (Yen)

## Summary

- ***DOTSTAR (2003-2009)***
- ***T-PARC (2008)***
- ***Targeted observations: theories and intercomparison***
- ***Impact of Targeted observations***
- ***EnKF data assimilation for TC***
- ***Sinlaku:  Targeted observation and impact***

  ***Internal dynamics (concentric eyewall)***

  ***TC-ocean interaction (cold eddy and wake)***

  ***TC-terrain interaction (track and rainfall)***

  ***Predictability (ensemble spread)***
- ***Future challenges***

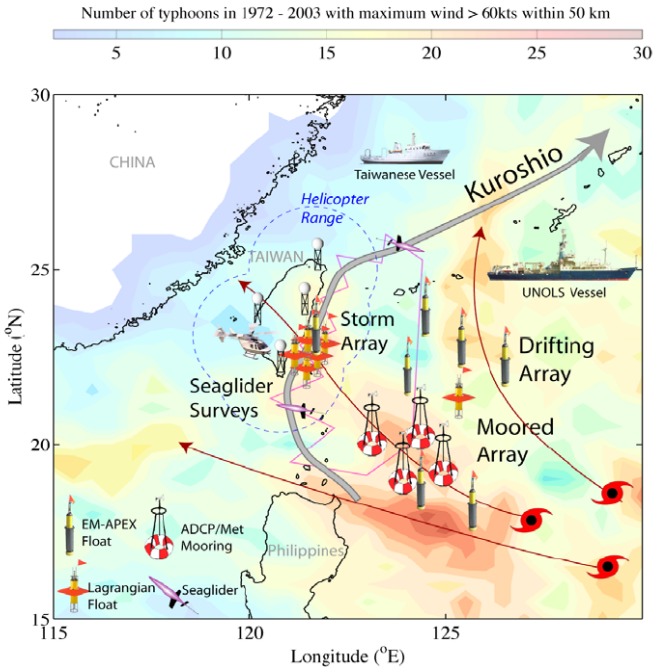
# Internal wave and Typhoon-Ocean interaction Project in the Western North Pacific and Neighboring Seas (ITOP, 2010)

International collaboration:

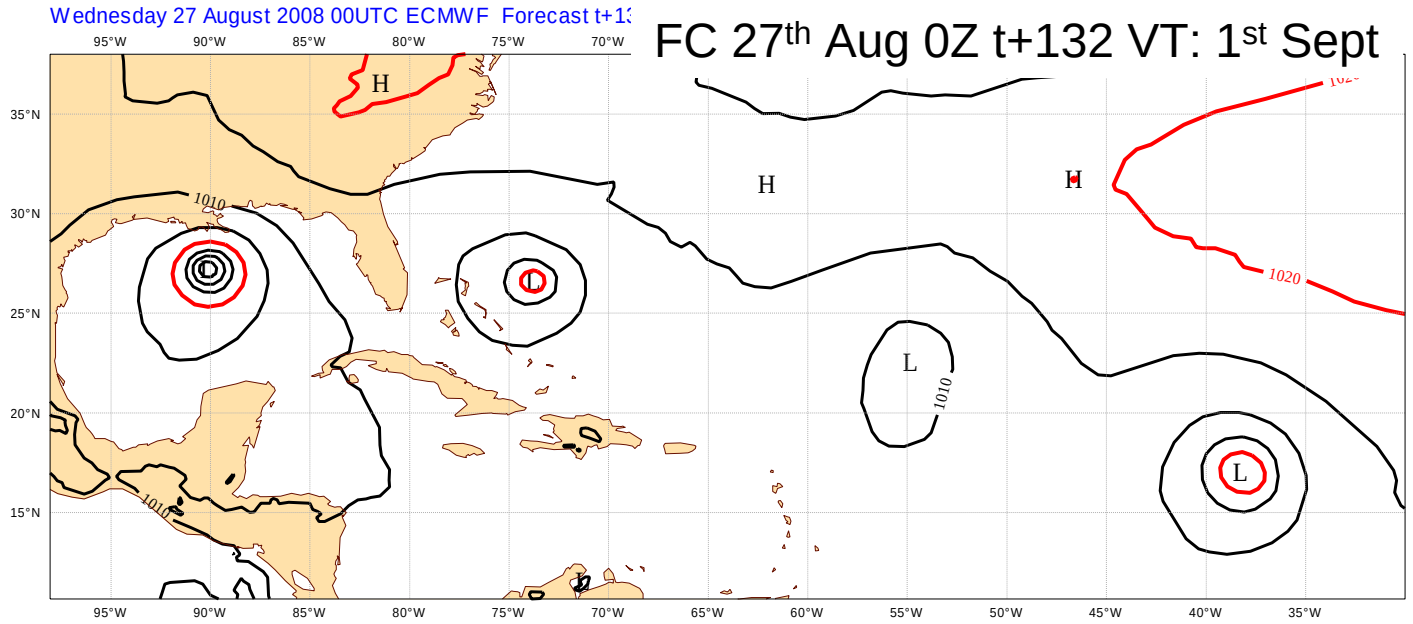


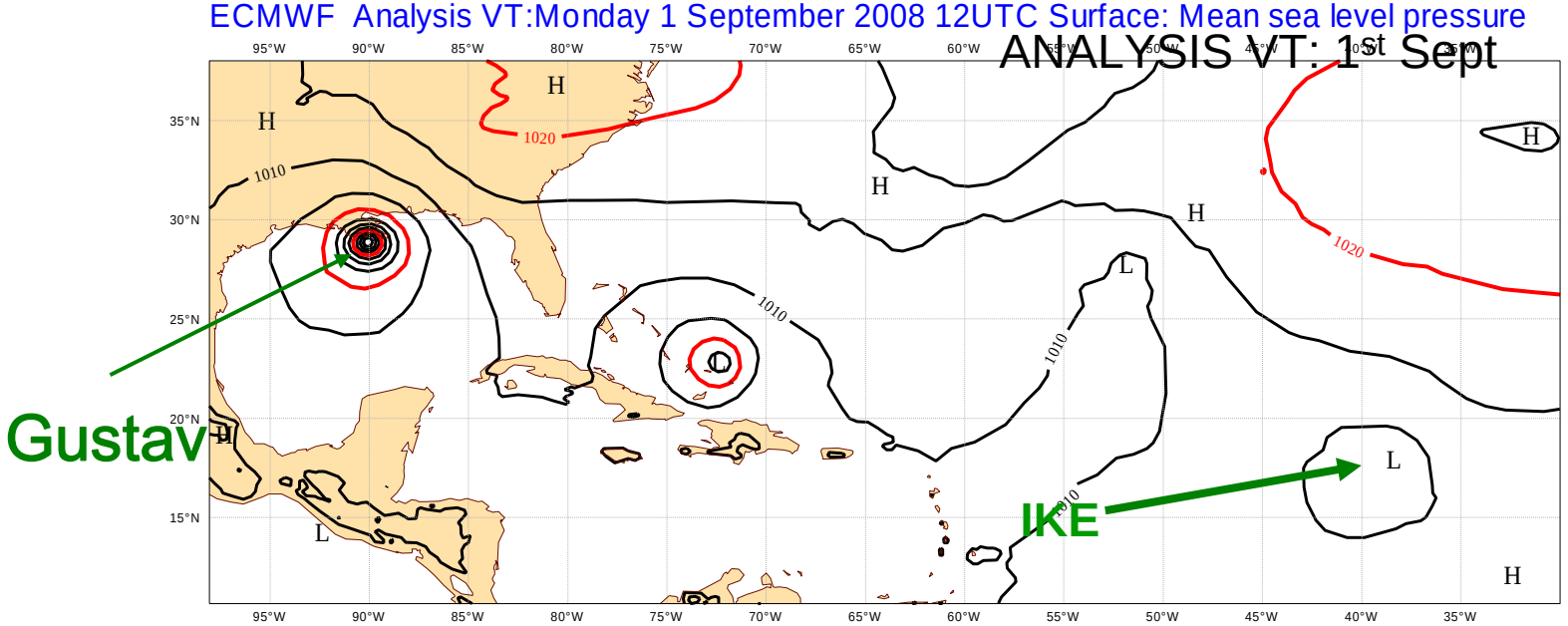
ITOP planning meeting, Taipei, 2008

- DOTSTAR, TCS-10, and ITOP coordination
- Investigation of the roles of upper ocean thermal structures (eddies and/or wakes) on typhoon-ocean interaction.
- Understanding the feedback of the typhoon-ocean interaction to typhoon intensity and structure evolution.
- Numerical simulation experiments (WRF-PWP coupled model) with the T-PARC (and TCS-10) and ITOP data.

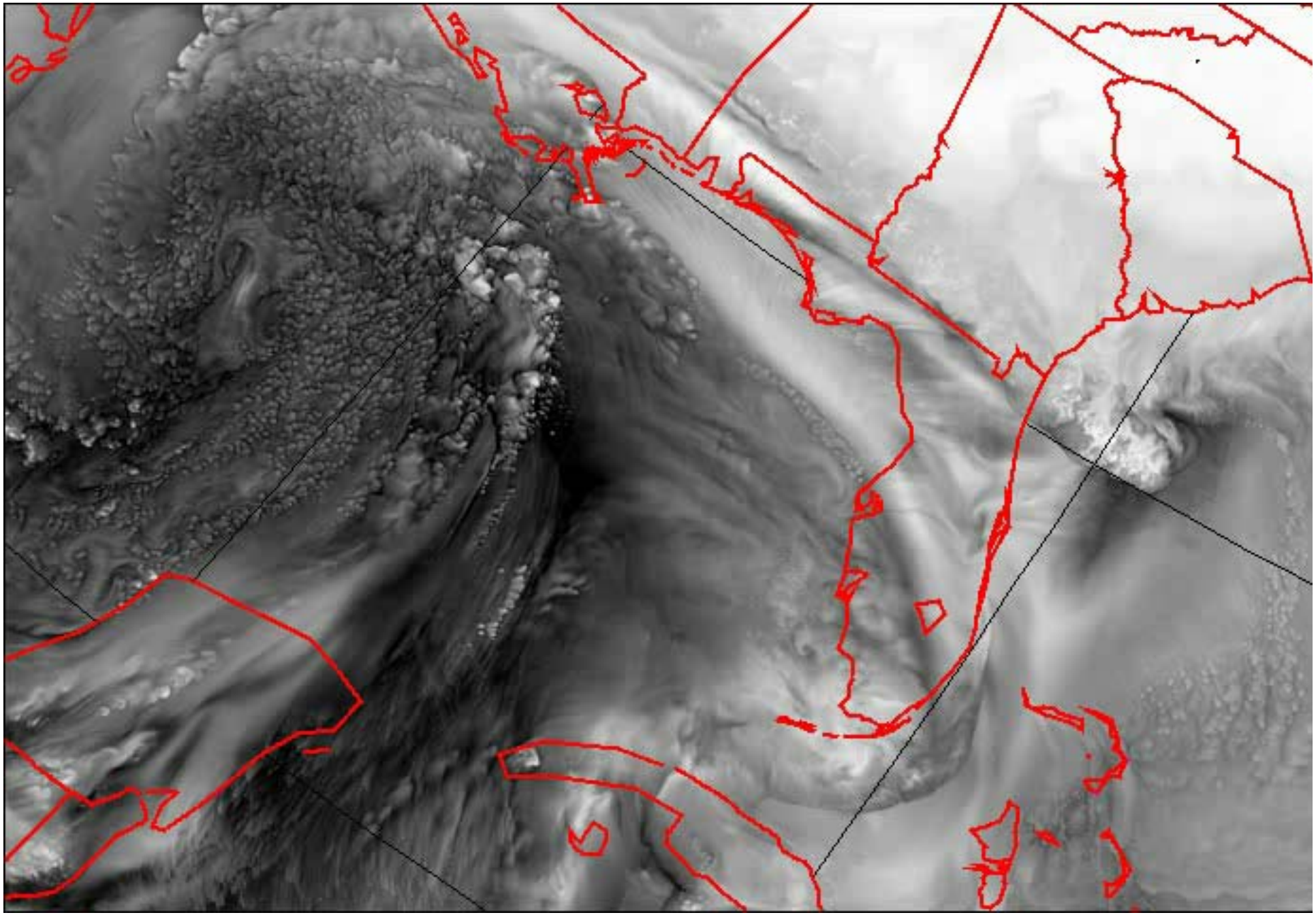


# Potential break-through from numerical models



# Next-generation numerical modeling system from ECMWF



# Vision: Pushing the envelope of predictability of typhoons

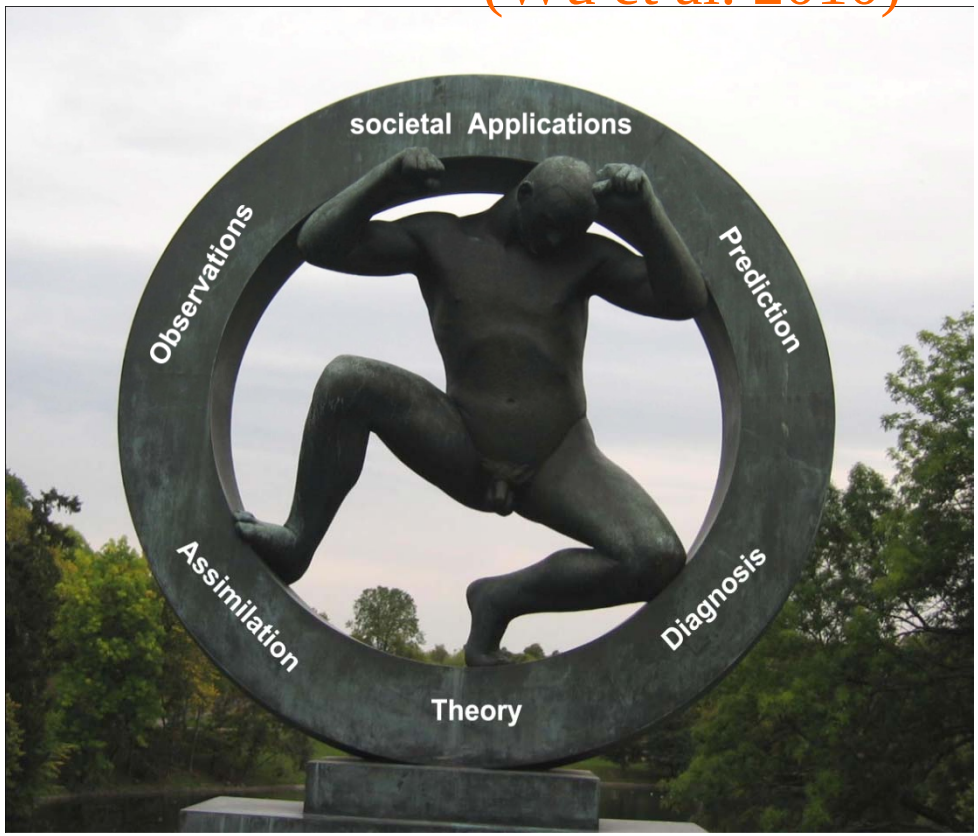
– **Predictability** and **dynamical processes**

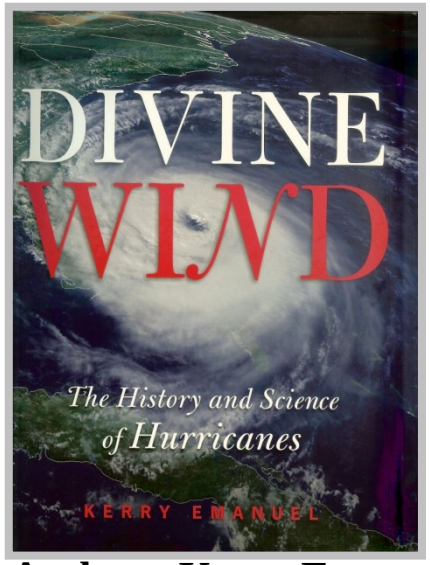
– **Observing systems**

– **Modeling, data assimilation** and **observing strategies**

Collaboration between **basic-research** and **operational-forecasting** communities, as well as **domestic** and **international** communities

(Wu et al. 2010)



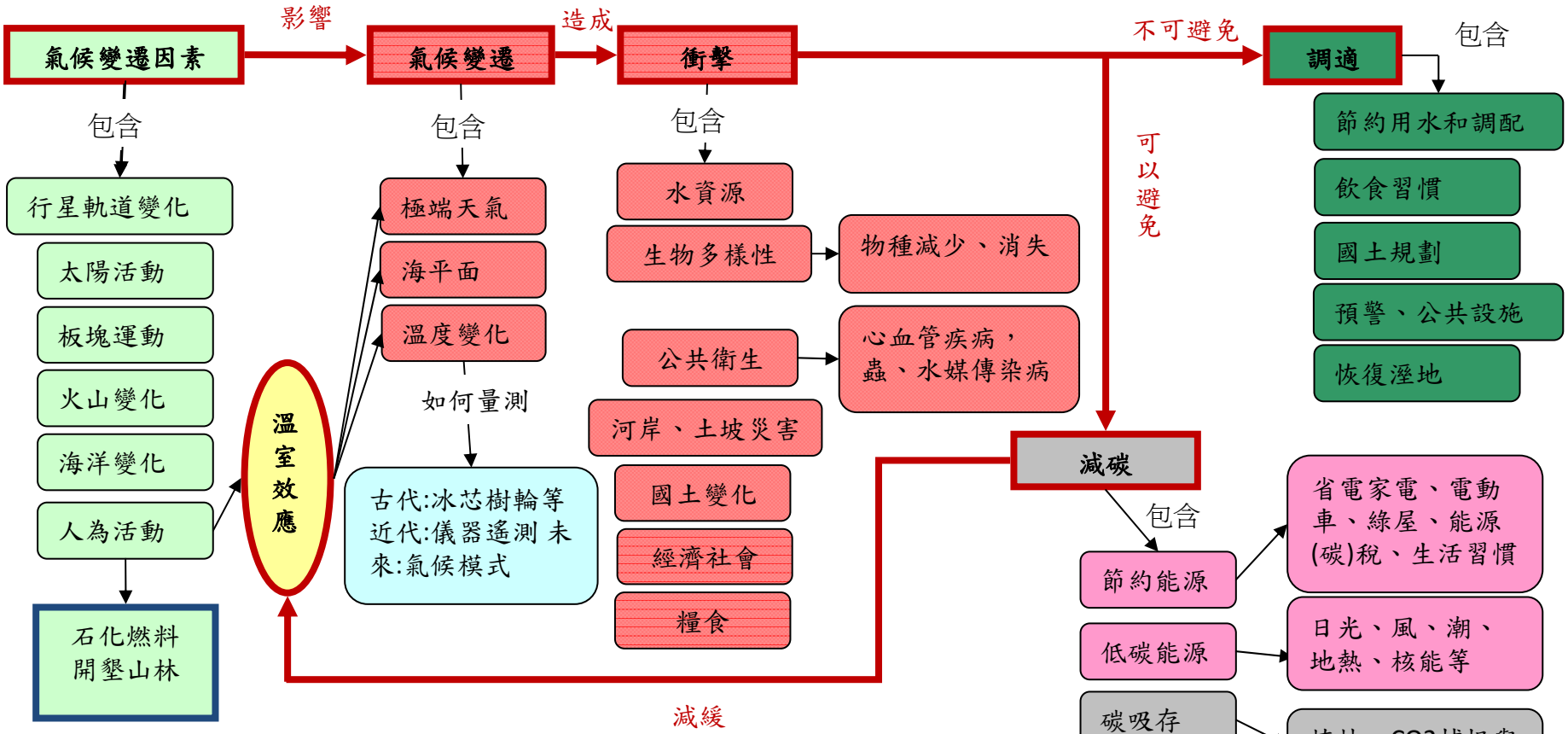




Author : Kerry Emanuel
Press : Oxford University


作者 ：Kerry Emanuel
譯者 ：吳俊傑、金棣
出版者：天下文化

| | | | |
|---|---|---|---|
| 科學間奏 | 1. 剖析氣象界的龐然大物 | 章節 | 1. 東洋神風 |
| | 2. 熱帶溫室 | | 2. 風暴之神 |
| | 3. 熱帶的傾盆豪雨 | | 3. 探險家與颶風的邂逅 |
| | 4. 信風 | | 4. 法國於1565年棄守佛羅里達 |
| | 5. 自然界的蒸汽機 | | 5. 暴風雨 |
| | 6. 颶風強度知多少 | | 6. 1780年颶風三部曲 |
| | 7. 生成 | | 7. 1900年的加爾維斯敦市 |
| | 8. 消散與變性 | | 8. 1926年的邁阿密 |
| | 9. 瞄準目標：颶風如何移動 | | 9. 凝望上帝：1928年聖費利佩與歐基求碧的浩劫 |
| | 10. 暴潮 | | 10. 1935年勞動節颶風 |
| | 11. 波浪 | | 11. 1938年新英格蘭大颶風 |
| | 12. 雨 | | 12. 海上悍將海爾賽力抗強颱 |
| | 13. 颶風預報 | | 13. 颶風追追追 |
| | 14. 颶風與氣候 | | 14. 卡米爾颶風 |
| 颱風吹到台灣 | 1. 可以無人觀測，也可以追風而行 | | 15. 深入渦漩：攝影記事 |
| | 2. 颶風名稱從何來、吹得多狂以及有用的颱風資訊 | | 16. 1970年11月東巴基斯坦大氣旋 |
| | | | 17. 崔西氣旋 |
| | 3. 近十年影響台灣地區的重大颱風 | | 18. 1992年安德魯颶風 |
| 附錄一 | | | 歷史上著名的熱帶氣旋 |
| 附錄二 | | | 颶風的各項紀錄 |
| 附錄三 | | | 晶片上的旋風 |

# 科學背景認知與主題安排




- 必須面對的真相
- 溫室效應
- 地球氣候
- 科學氣候量測
- 與自然共舞
- 「源」來如此
- 低碳生活