Targeted Observation in Tropical Cyclones

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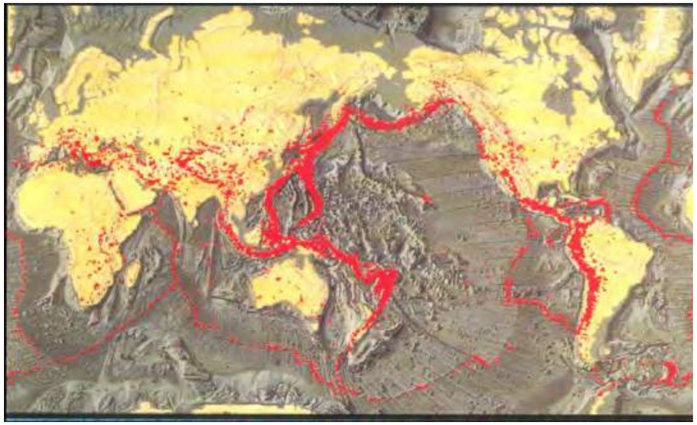
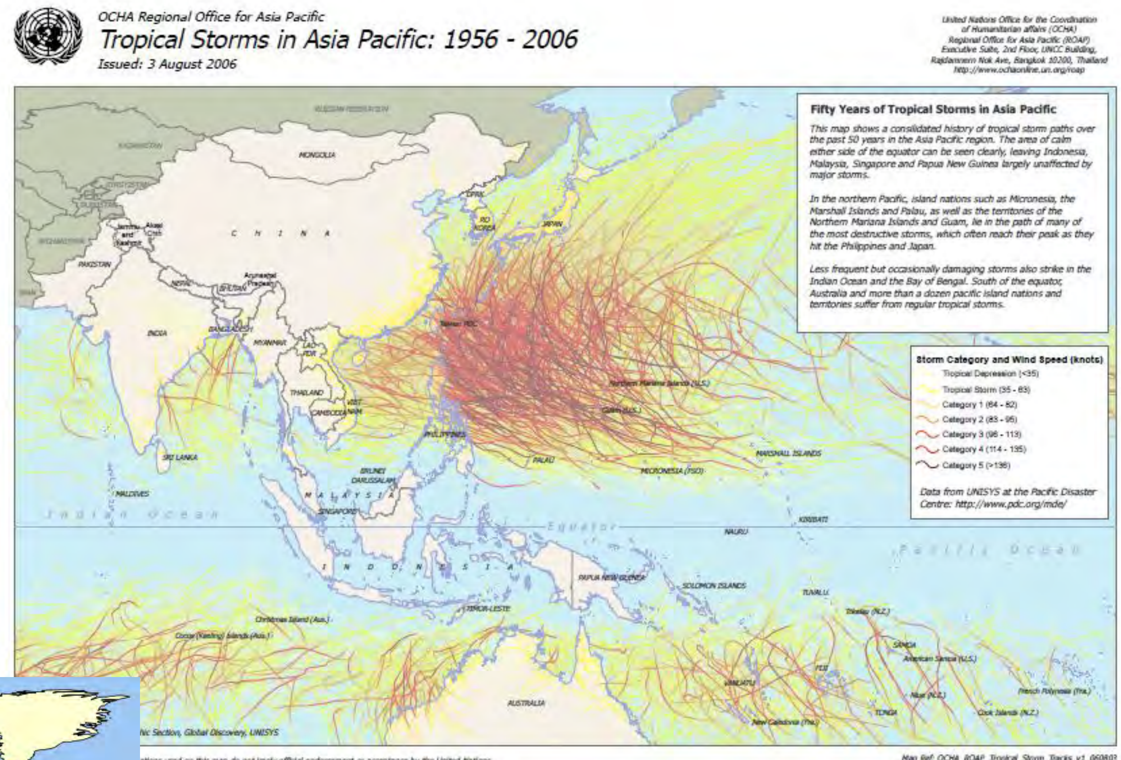
Grants: NSC, CWB, RCEC/Academia Sinica, ONR

易致災環境

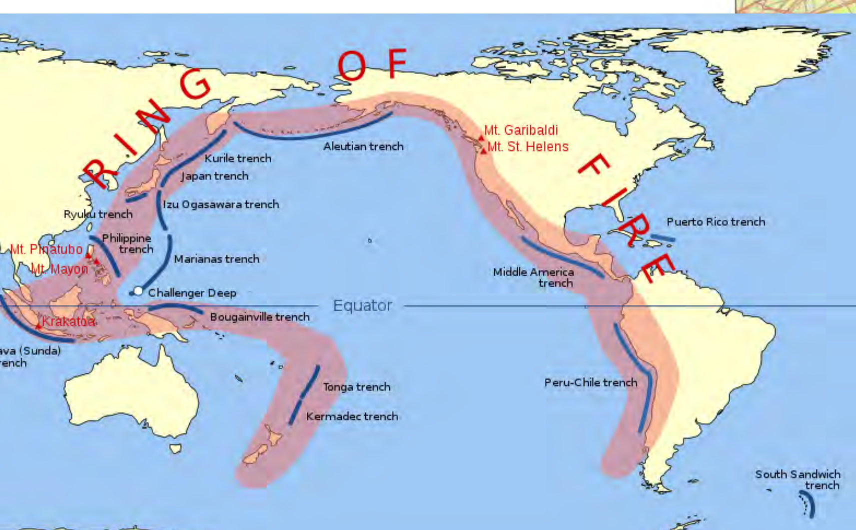


Pacific Ring of Fire

circum-Pacific seismic belt

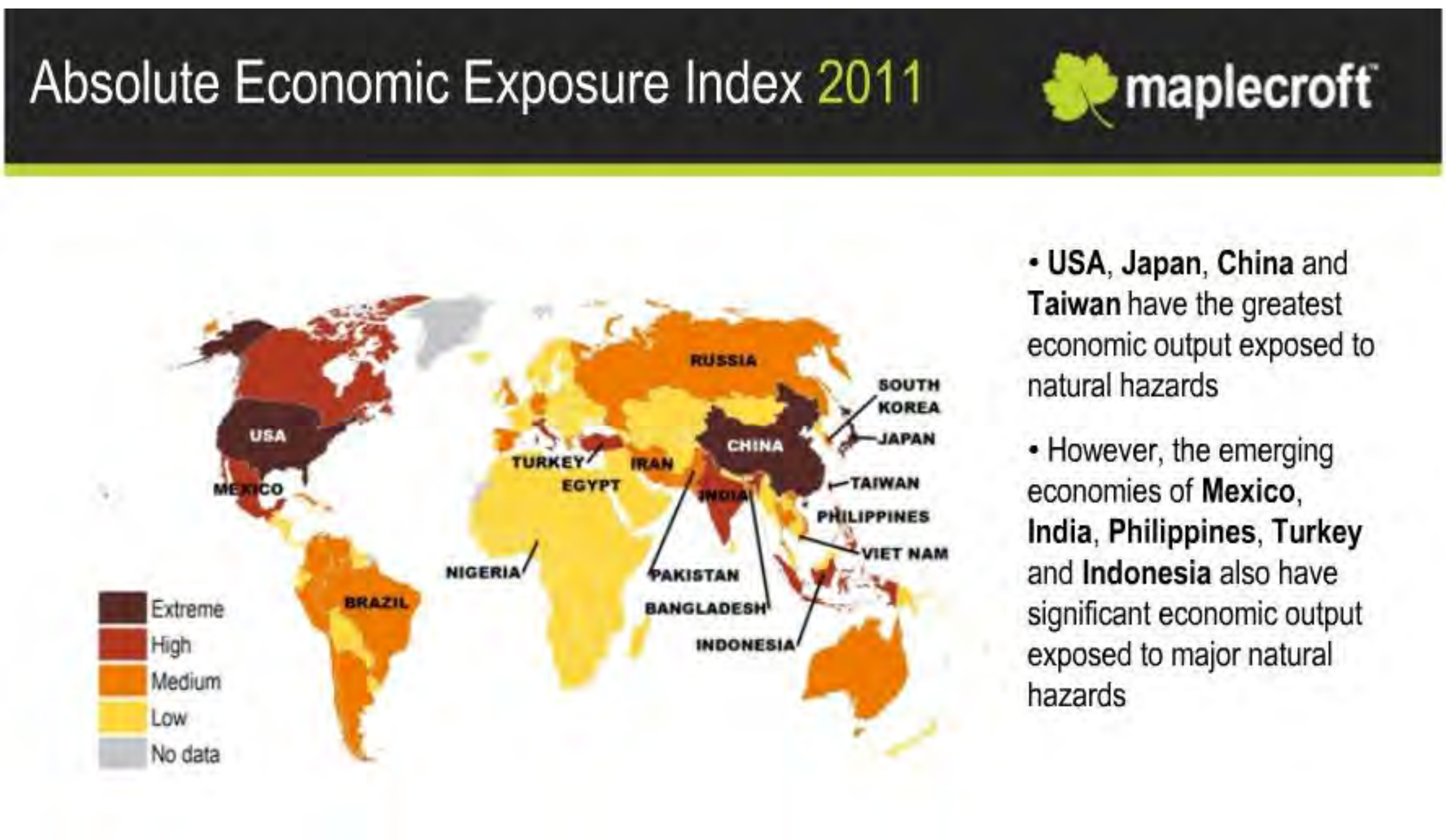


Typhoon Alley



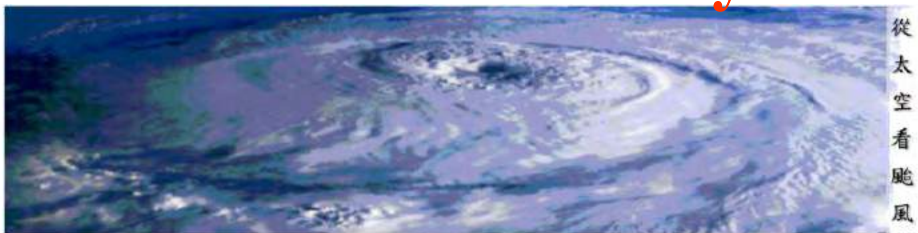
452 volcanoes, 75% of the world’s active and dormant volcanoes

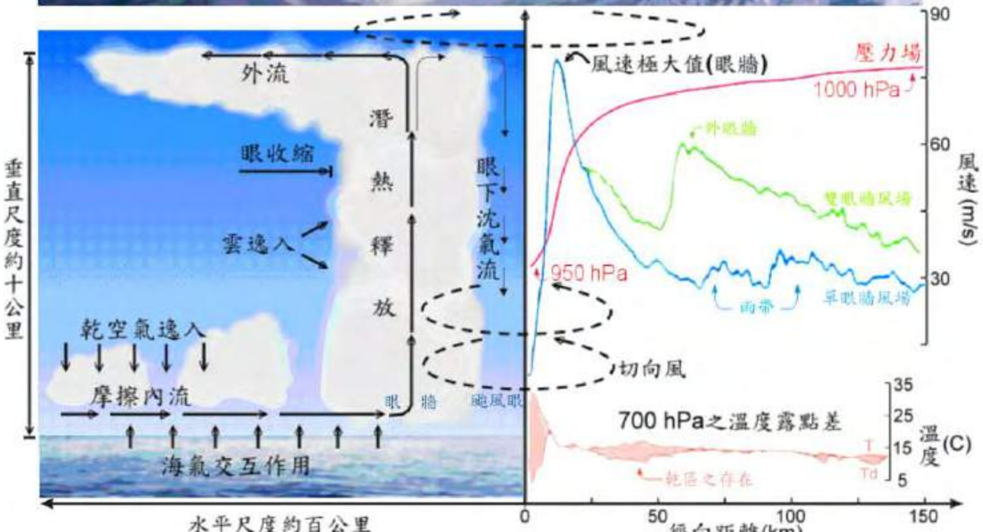
英國風險管理顧問公司Maplecroft於最新公布之“2011年天然災害風險圖輯(the Natural Hazards Risk Atlas 2011 NR)”台灣經濟活動之絕對災害風險指標(Absolute Economic Exposure Index)列為全球第四，與美國、日本與中國並列為具有極端風險之國家。



颱風 – 流體動力學在大自然所展現的絕妙實例

Beauty and the Beast

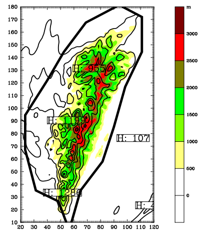


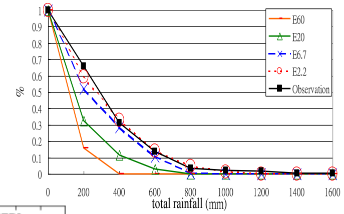


- 高速旋轉流
  (highly swirling)
- 強烈輻合輻散流
  (strong convergence)
- 劇烈濕對流
  (deep moist convection)
- 快速大氣—海洋交互作用
  (fast air-sea interaction)
- 多重尺度交互作用
  (multi-scale interaction)
- 地形效應
  (terrain effect)

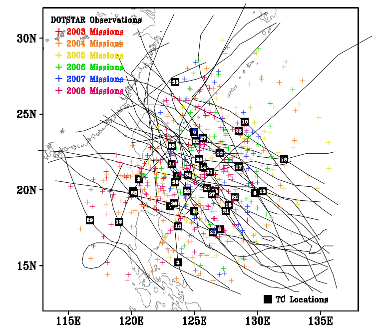
(Chun-Chieh Wu: 2002-2009)

(Wu et al. 2002, WF)

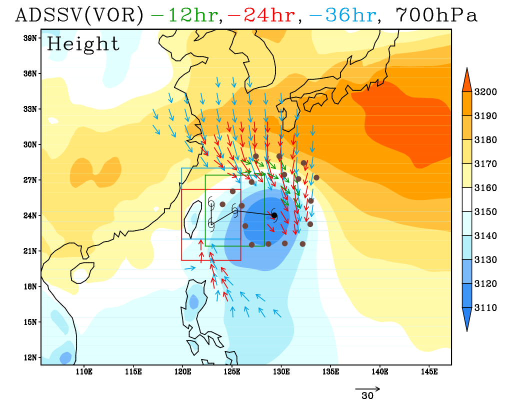




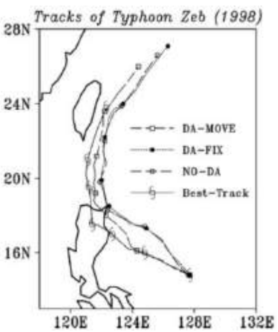
(Wu et al. 2009a, b, MWR)

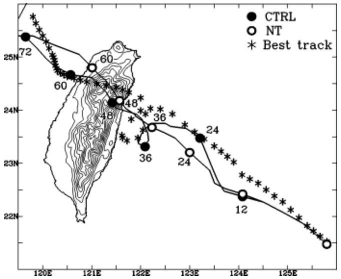


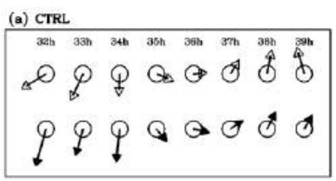
(Wu et al. 2007a JAS)



(Wu et al. 2006, JAS)







(Jian and Wu 2008, MWR)

Targeted observation in DOTSTAR

Typhoon intensity eyewall dynamics

Typhoon-terrain interaction

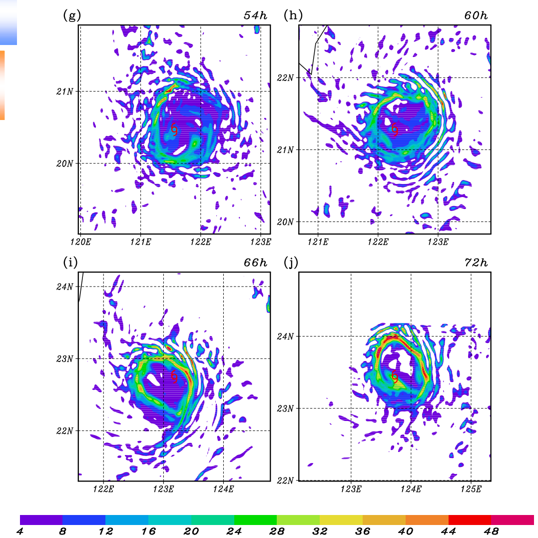
Typhoon movement

Typhoon rainfall

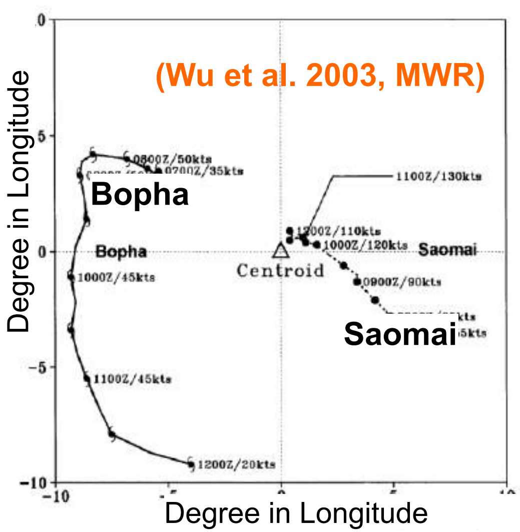
Typhoon-ocean interaction

Typhoon-climate

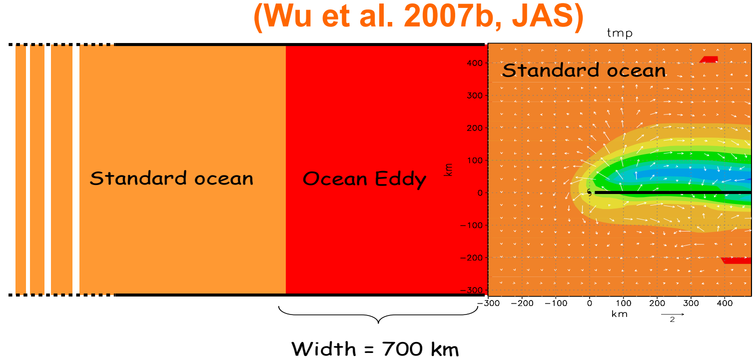
(Wu et al. 2009c, MWR)

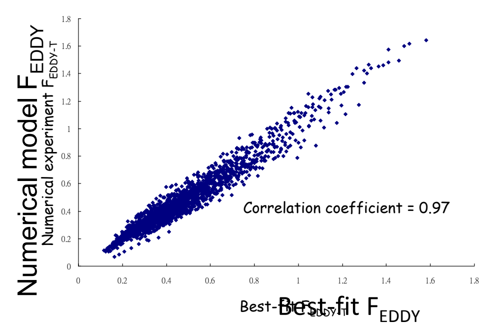


(Wu et al. 2003, MWR)

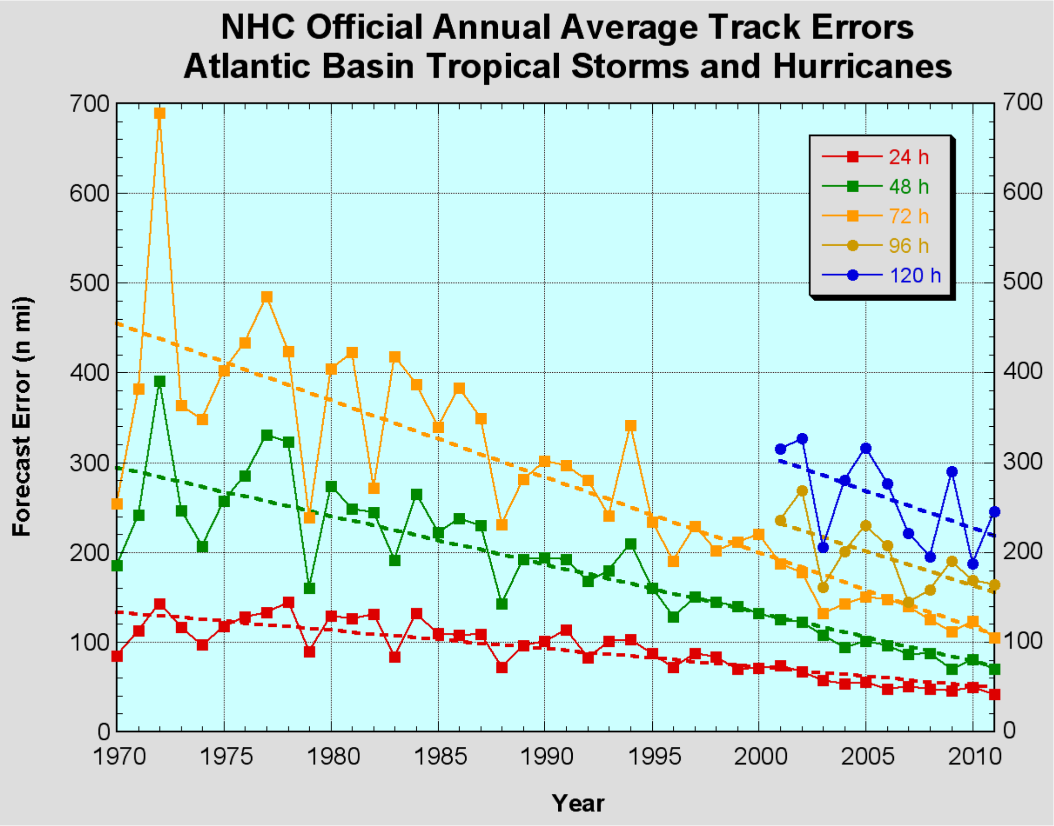


(Wu et al. 2007b, JAS)

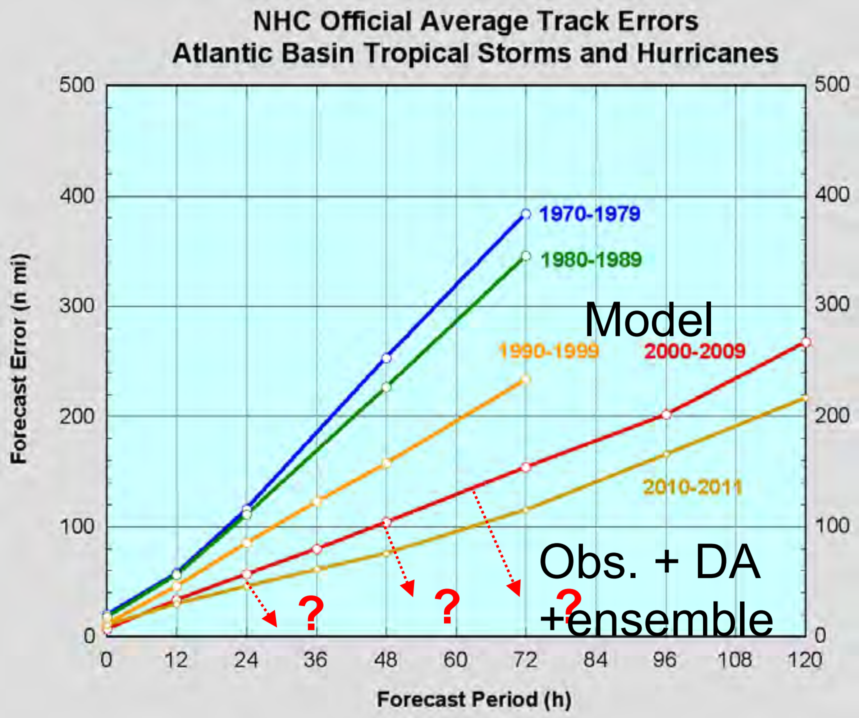




Long-term decreasing trend in TC track prediction errors



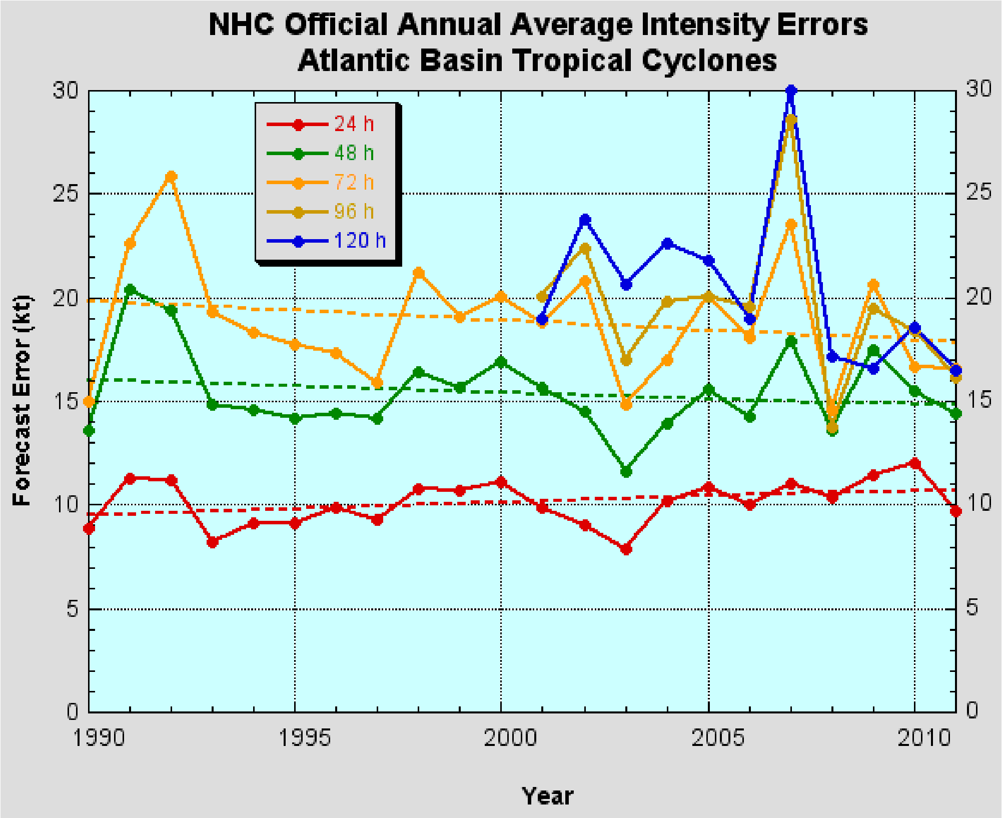
From NHC



Push the limit of predictability?

Very limited progress in TC intensity prediction

From NHC



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

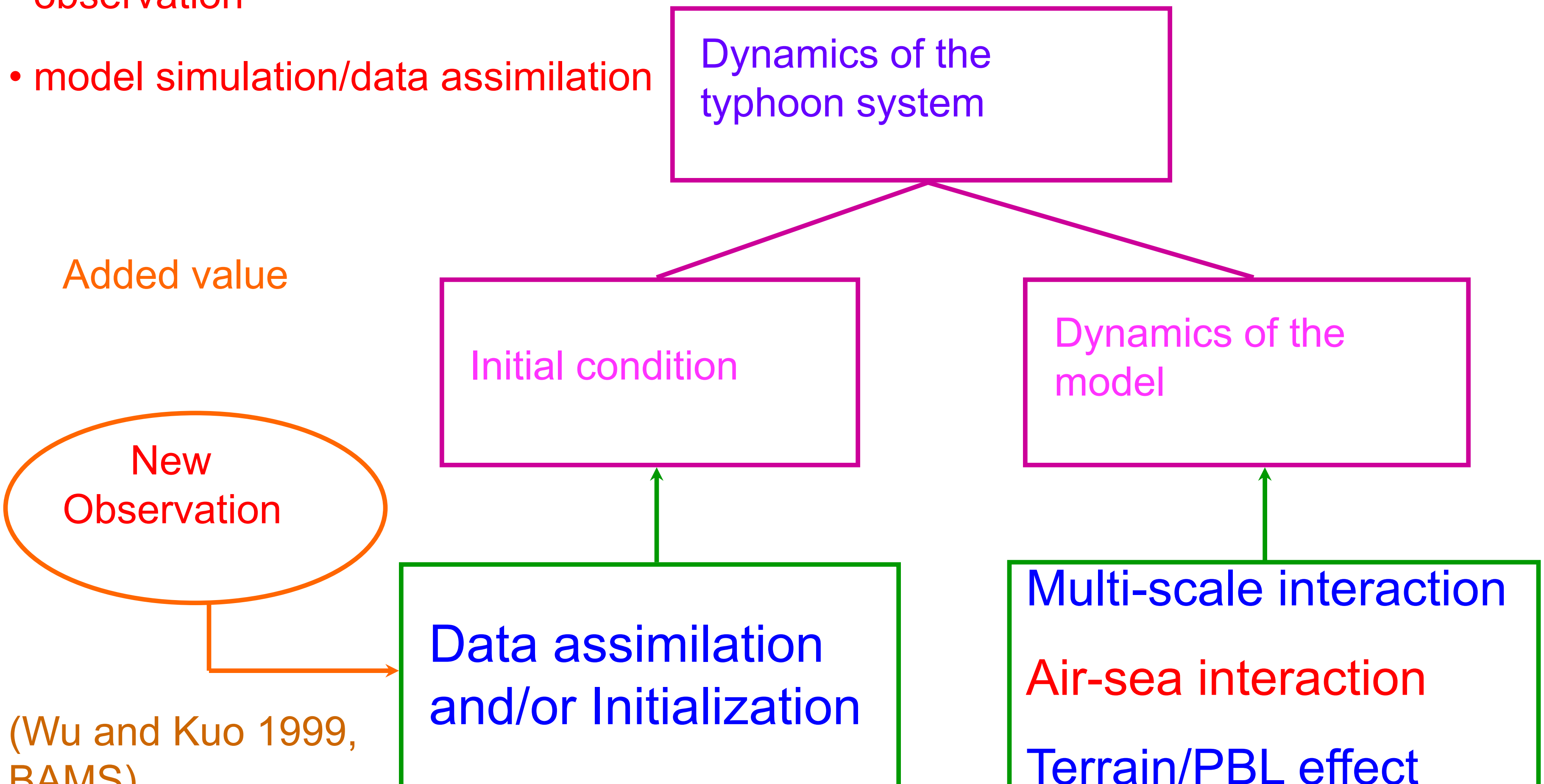
Environmental control – shear, trough-interaction (Wang and Wu 2004)

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

Improving the understanding and prediction of the TC systems

(in memory of Dr. Yoshio Kurihara)

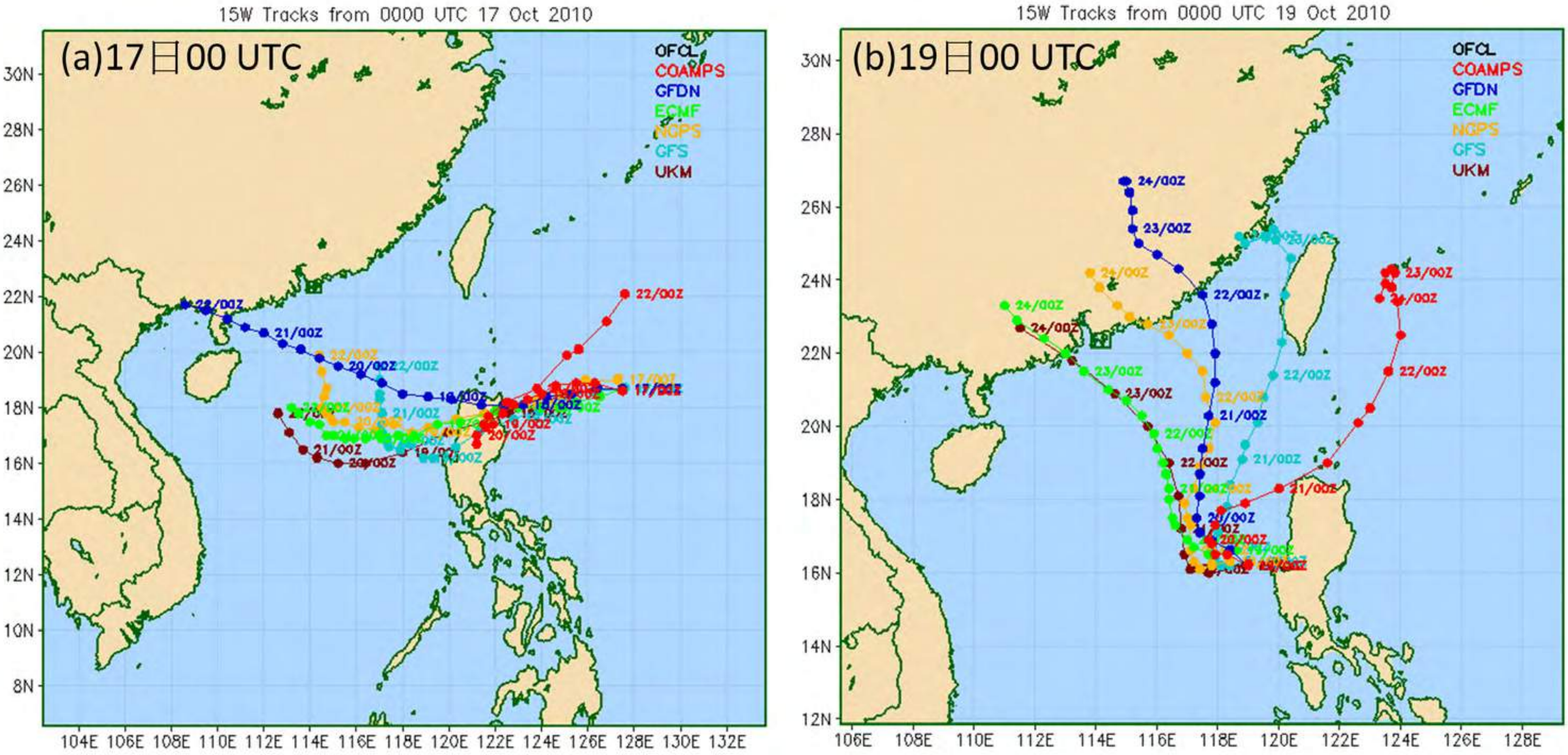
Key issues:
- dynamics
- observation
- model simulation/data assimilation



Forecast errors grow because of initial condition and model uncertainties, in the presence of chaos

- Initial condition uncertainties: better observations (e.g. satellites) and better data assimilation (e.g. EDA)
- Model uncertainties: better resolution/computing and better physical/dynamical understanding (forecasts right for the right reasons)
- Quantifying uncertainties is mainstream: using ensemble approach including predicting the predictability
- Predictability: what can be predicted out to which time ranges? Using re-forecasts to reduce systematic errors

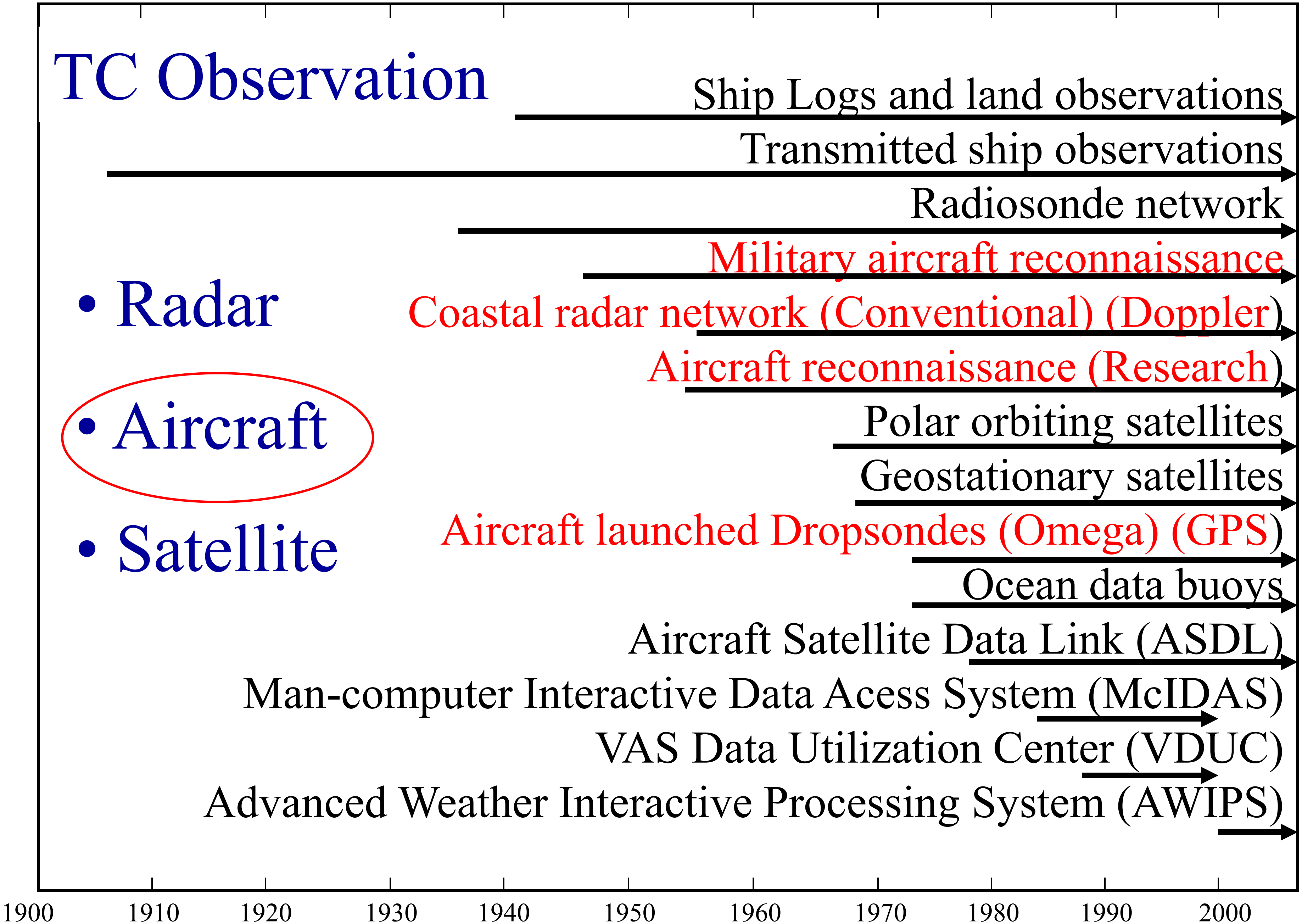
Challenge of TC prediction – Megi (2010)



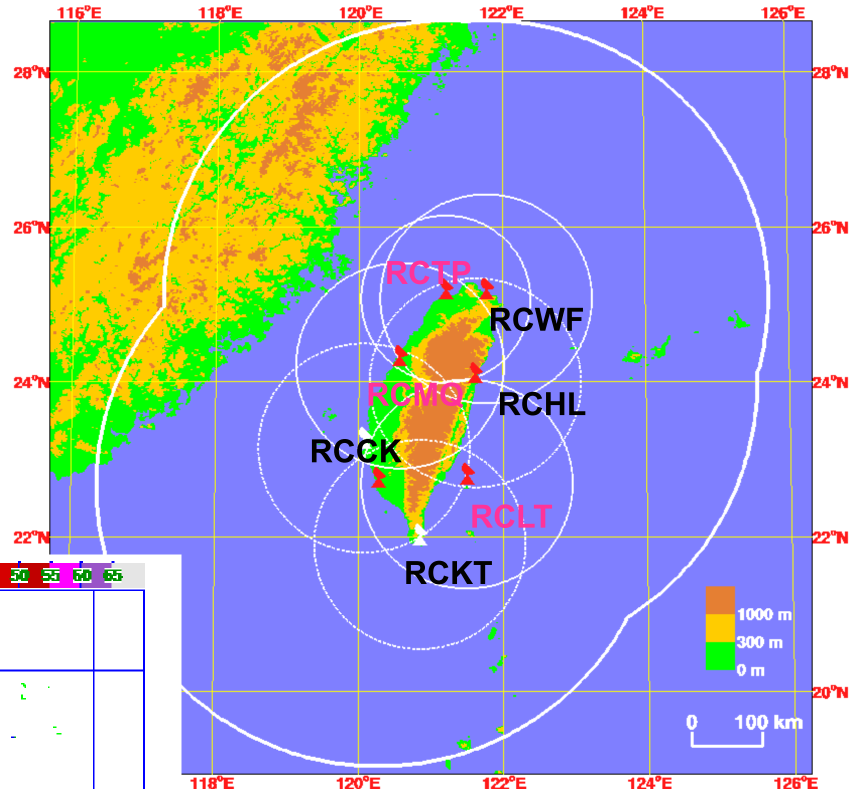
What is the minimum SLP in Megi as estimated by JMA?

Outline

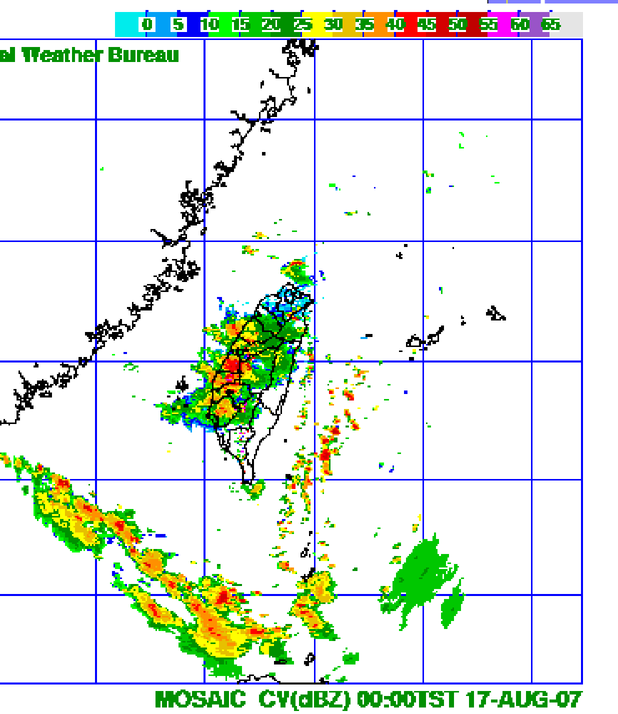
- Review of Targeted Observation
- DOTSTAR
- T-PARC
- ITOP
- Challenging issues

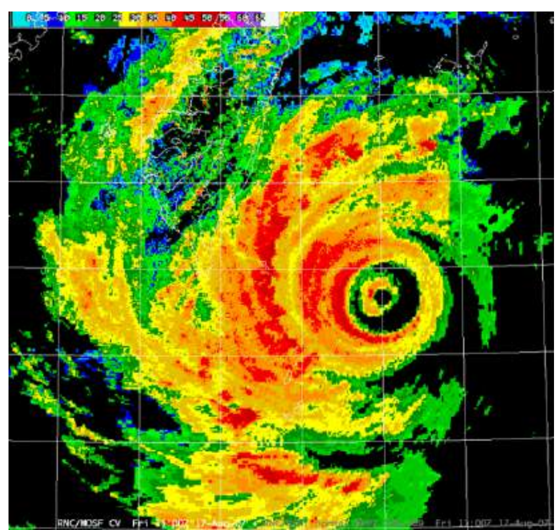

TC Observation
• Radar
• Aircraft
• Satellite
Ship Logs and land observations
Transmitted ship observations
Radiosonde network
Military aircraft reconnaissance
Coastal radar network (Conventional) (Doppler)
Aircraft reconnaissance (Research)
Polar orbiting satellites
Geostationary satellites
Aircraft launched Dropsondes (Omega) (GPS)
Ocean data buoys
Aircraft Satellite Data Link (ASDL)
Man-computer Interactive Data Acess System (McIDAS)
VAS Data Utilization Center (VDUC)
Advanced Weather Interactive Processing System (AWIPS)
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

Taiwan Doppler Radar Network

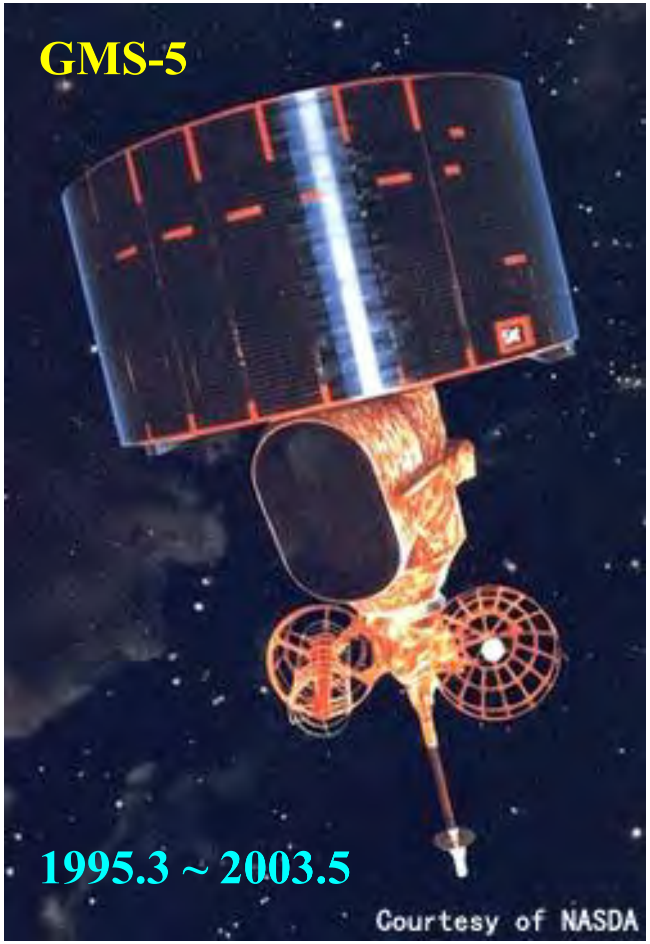


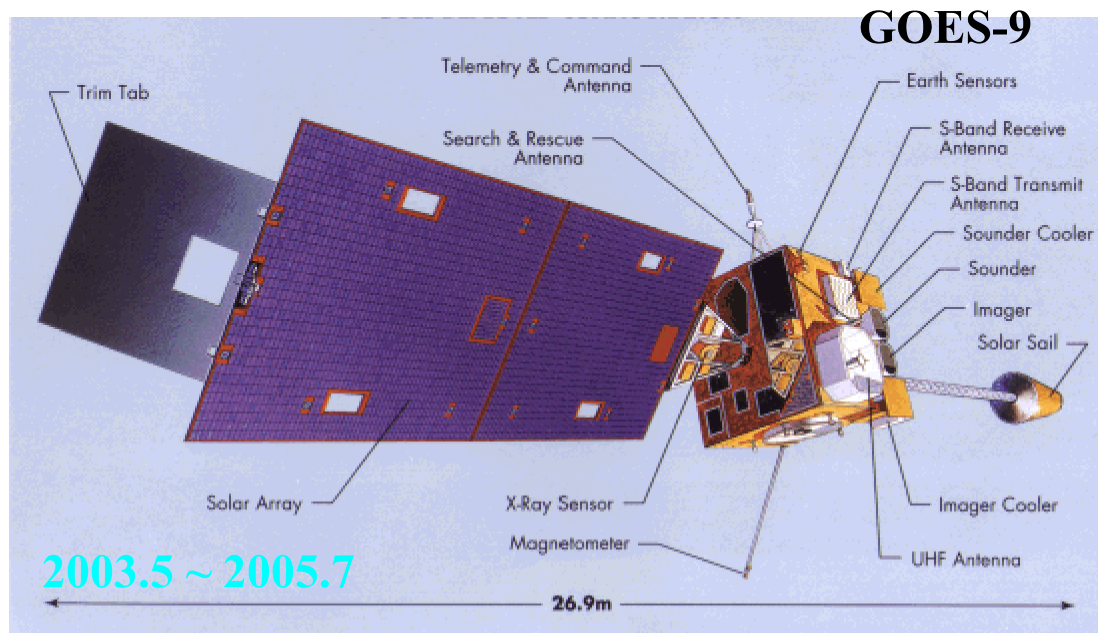
聖帕颱風
雙眼牆





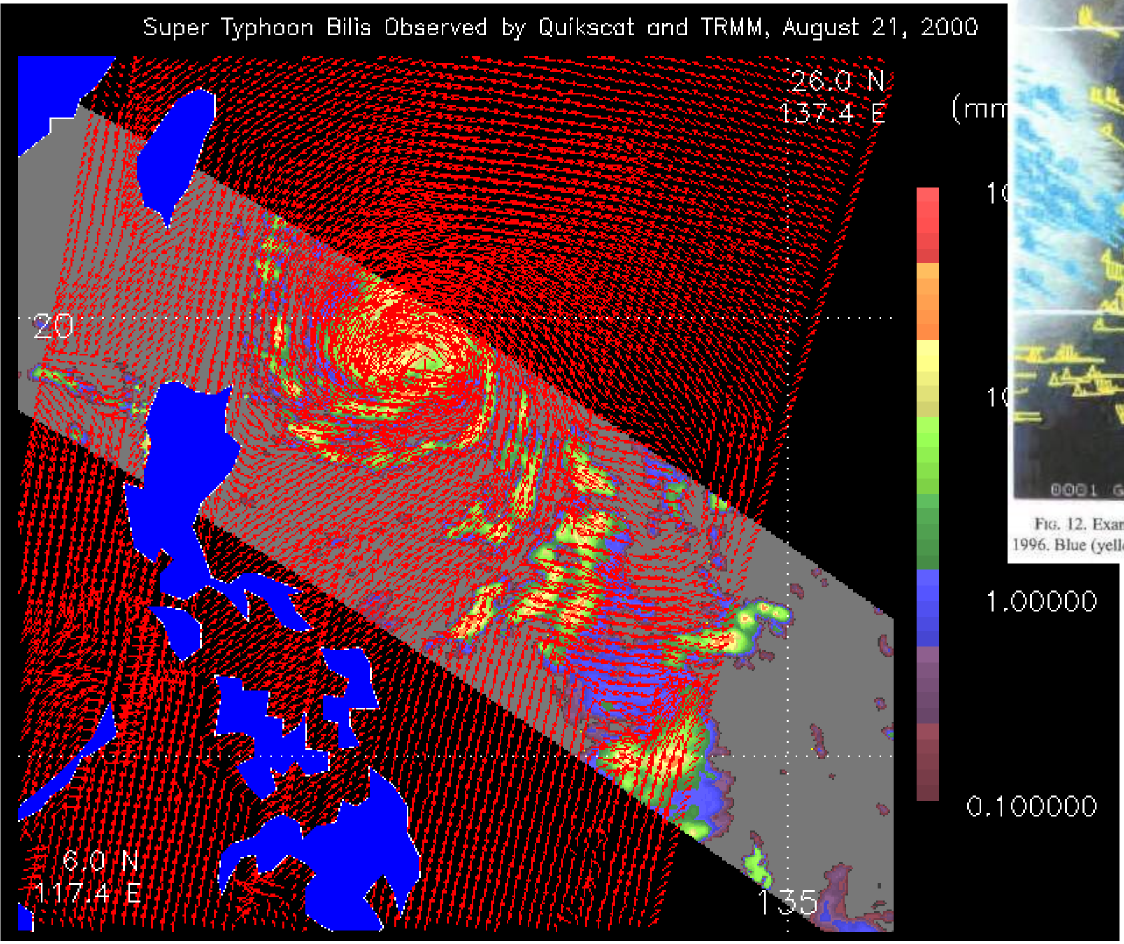
Geostationary Satellite





Cloud imagery

Satellite data – space look of typhoons



Typhoon Bilis (2000), QuikScat and TRMM

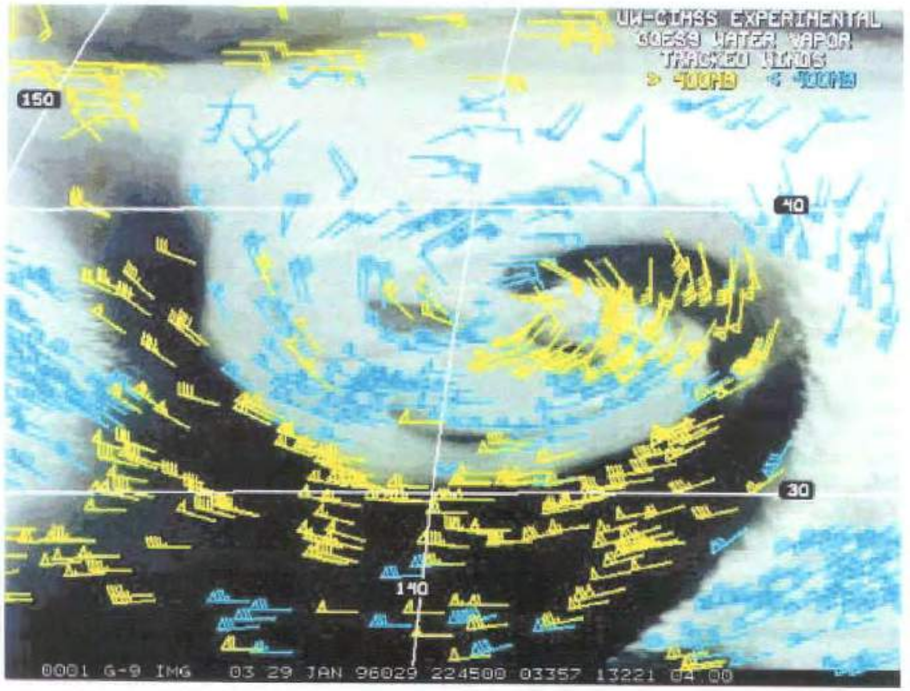


FIG. 12. Example of WVWV from *GOES-9* covering a strong extratropical cyclone in the eastern North Pacific on 29 January 1996. Blue (yellow) vectors (kt) indicate winds with assigned heights above (below) 400 mb.

WVWV from GOES-9
on 29 January 1996

After Velden et al. (1997)

Gone with the Wind

美國颶風穿越偵察(reconnaissance)和環境偵察(surveillance)

美國空軍/53WRS C-130 (10,000 ft.)

美國海洋大氣總署 Gulfstream- IV (40,000 ft.)

美國海洋大氣總署 P-3 (20,000 ft.)

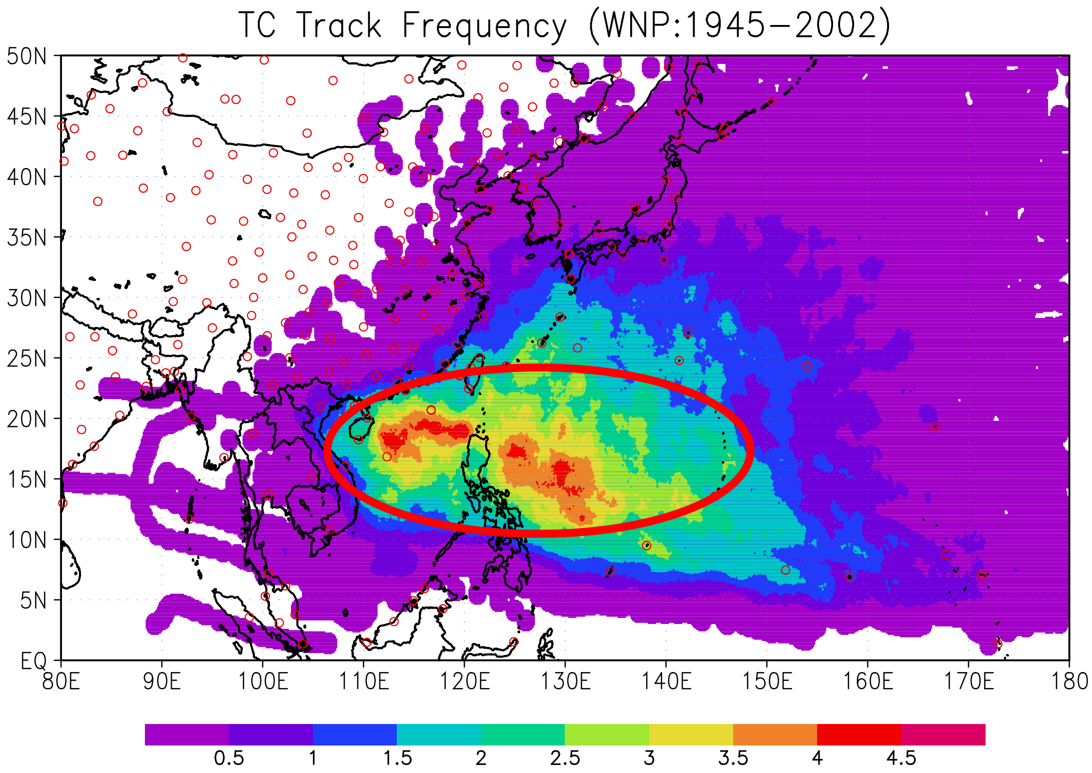
Vaisala RD-93投落送

Bottle-neck of typhoon research and forecast

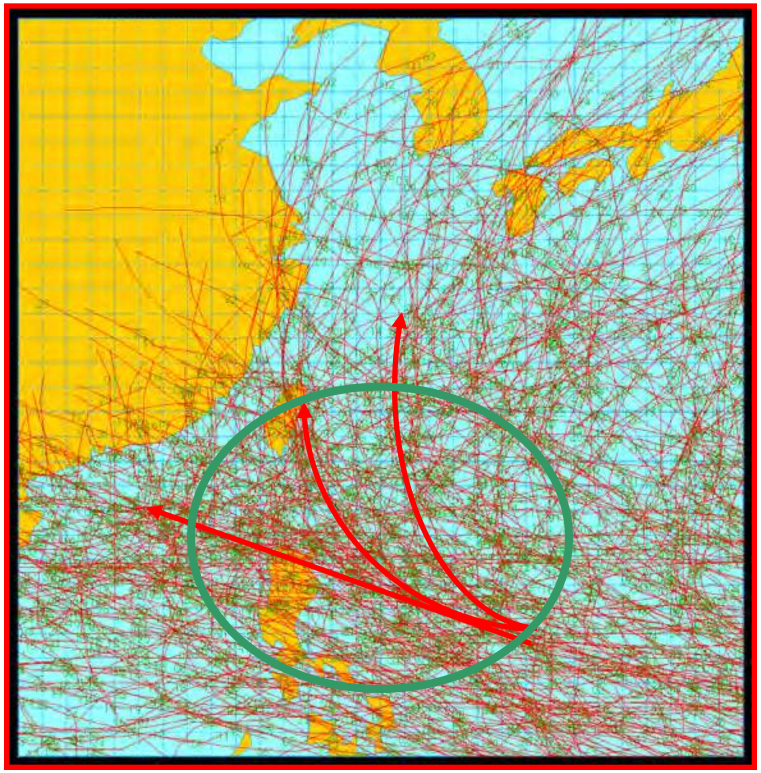
-- Lack of data (vortex and environmental scales)

(Wu and Kuo 1999, BAMS; Wu et al. 2003; 2004, MWR)

30 TCs per year!



TC tracks, 1989-2000

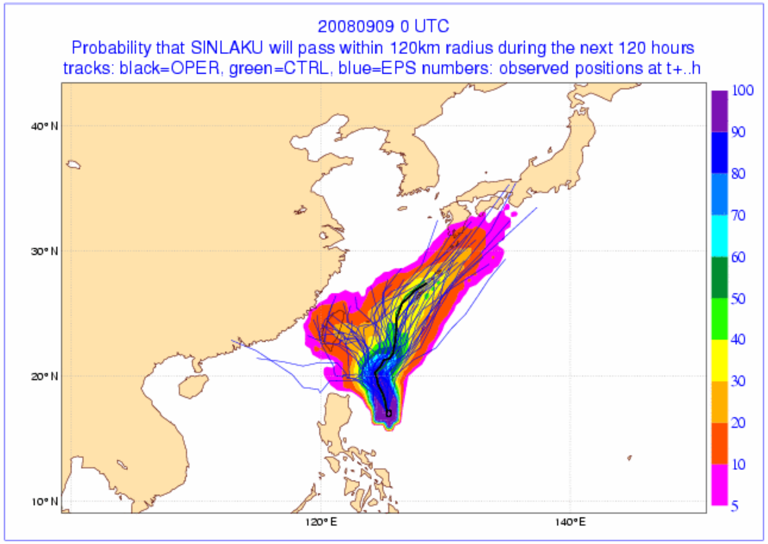


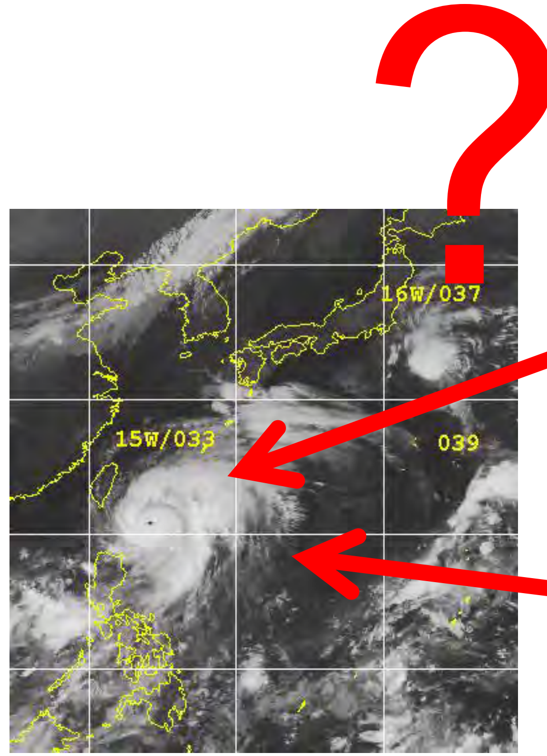
A unique spot as the base to conduct aircraft observations for typhoons in the NW Pacific

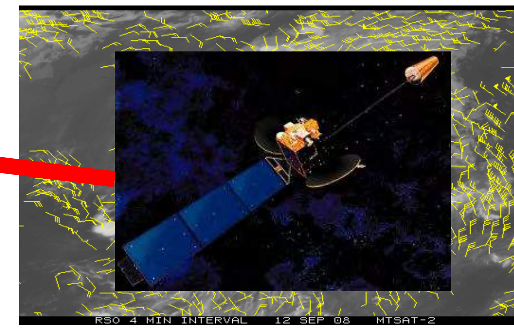
Purpose of this Special Lecture on Targeted Observation

- Review the topic
- Raise contentious issues
- Open up for debate and discussions
- Condense material and discussions into summary and short set of recommendations

The problem







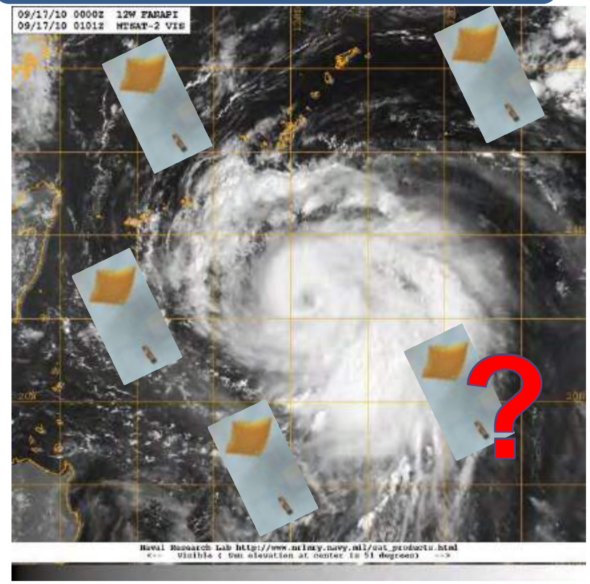
9th — t_i — Initialization

11th — t_a — Analysis (targeting)

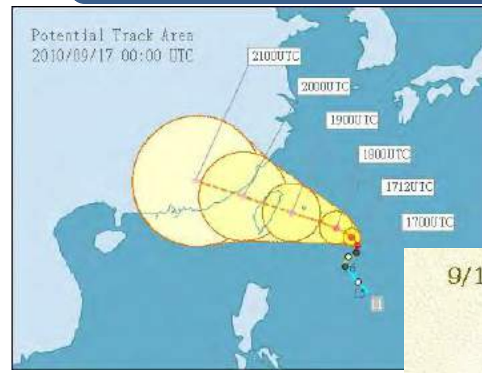
13th — t_v — Verification

What is adaptive (targeted) observations?

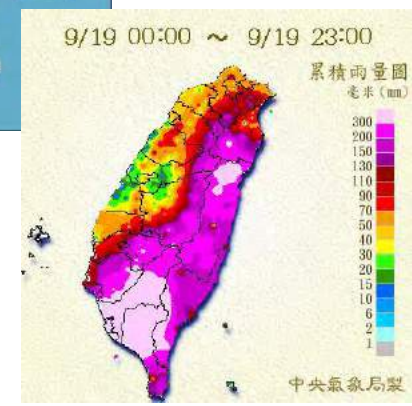
Observation (targeted) time → **Verification time**



Typically 48 h



Track forecasts



Rainfall rates

➢**Adaptive (targeted) observations**: extra observations made in sensitive regions to reduce initial condition errors and thereby improve numerical forecasts.

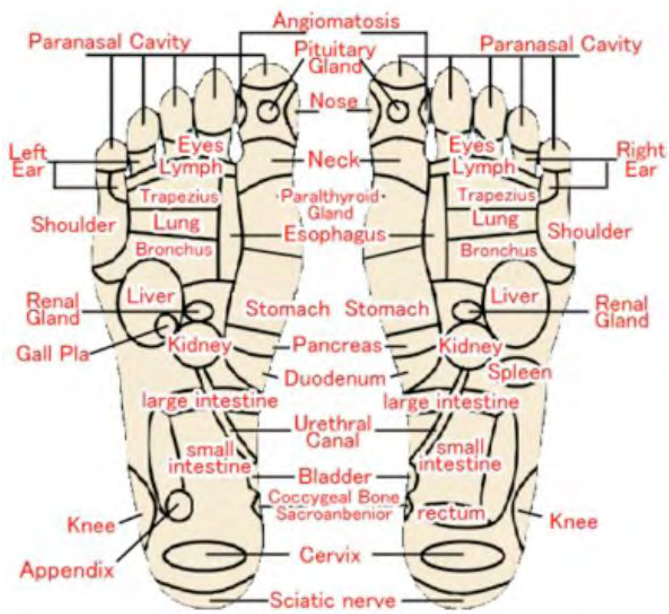
➢Targeted observation is an active research topic in NWP, with plans for field programs, tests of new observing systems, and application of new concepts in predictability and data assimilation. (Langland 2005)

Recent progress of targeted observations for tropical cyclones

Targeted Observation for Typhoon

"Tsubo(經穴)" for Observation

- analogy to therapeutic point for body
- "sensitive area" , where errors grow quickly, estimated by sensitivity analysis
- important area to improve typhoon forecast



(From T. Nakazawa)

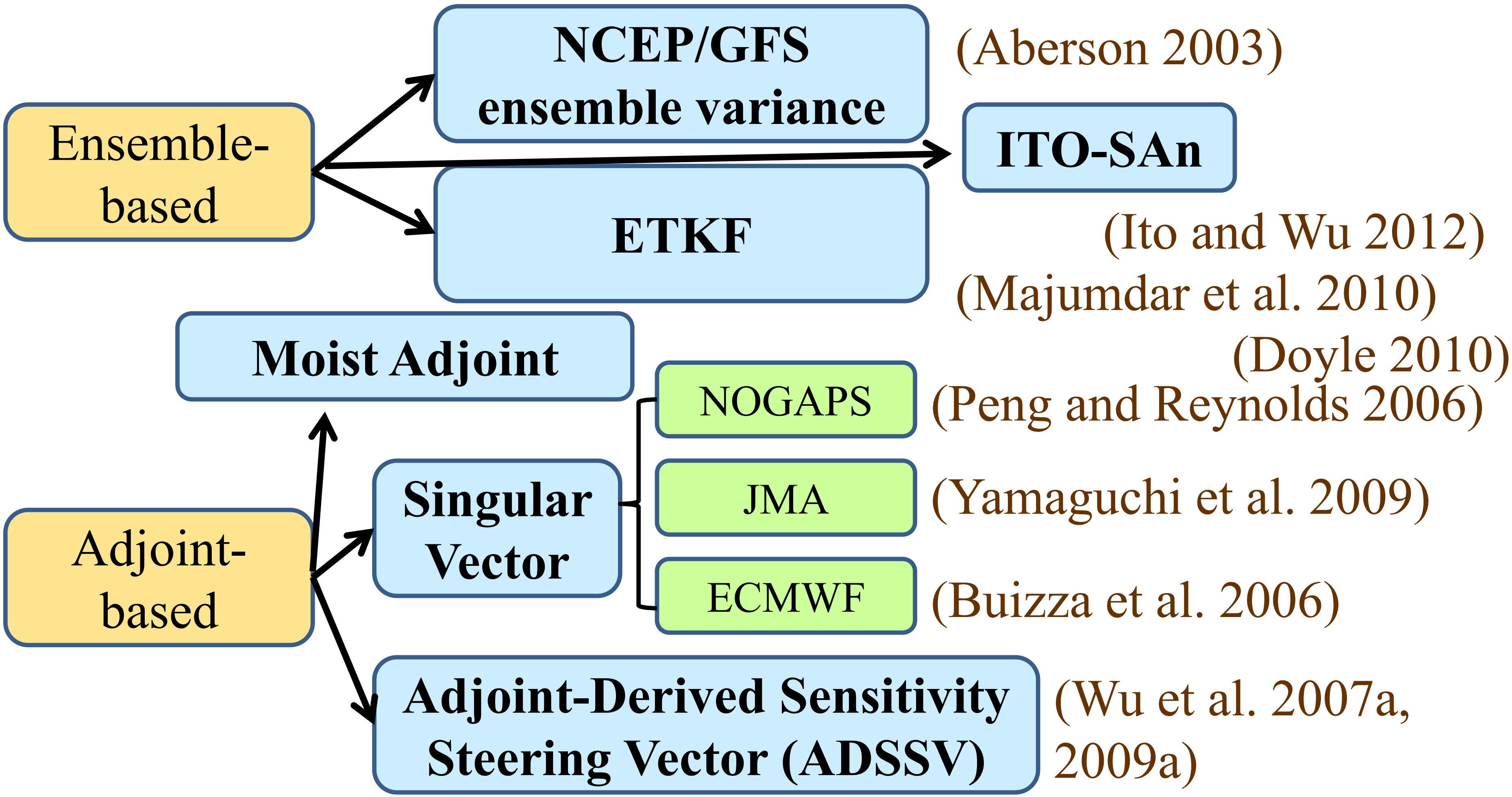
Background on targeted observations

- **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)**
- Factors associated with adaptive observations
  - Observation density, variables and errors
  - Magnitude of uncertainty
  - Data assimilation system
  - Growth of uncertainty

(Wu 2006, IWTC-VI, WMO, San Jose, Costa Rica)

Targeted observations in DOTSTAR and T-PARC

- Since 2003, several objective methods, have been proposed and tested for operational/research surveillance missions in the environment of Atlantic hurricanes conducted by HRD/NOAA **(Aberson 2003)** and NW Pacific typhoons by DOTSTAR (**Wu et al. 2005**).



Issues on targeted Observation

- *The sensitivity results of targeted methods can provide useful references for devising the targeted strategies.*
  - What is the impact to TC prediction after assimilating the data from the targeted observation?

→ *Atlantic Ocean:* TC track forecasts have been improved to 15-20% within the five-day forecast period for those missions designed by the targeted strategies (Aberson 2008).

→ *Atlantic Ocean:* **Majumdar et al. (2006), Reynolds et al. (2007)**

→ *Western Pacific Ocean:* An average 20% improvement for the 12-72h track forecasts over the NCEP-GFS, for 31 TCs during 2003-2008 **(Wu et al. 2009c).**

- *To*
  - ◎ – To identify the signal of binary interaction
  - ◎ – To identify the typhoon-trough interaction
  - ◎ – To investigate the extra-tropical transition
  - To show the seasonal variation of relationship b... c systems
  - To understand TC genesis
  - ….

NOGAPS SV:

Peng and Reynolds (2005)
Peng and Reynolds (2006)
Reynolds et al. (2009)

MM5 ADSSV:

Wu et al. (2007a, 2009a)

MM5 SV:

Kim and Jung (2009a)

Major collaborative efforts

- Operational Centers
  - ECMWF, UK Met Office, Meteo-France, JMA, Central Weather Bureau (Taiwan), NOAA/NCEP, NHC, United States Navy (NRL), JMA/MRI, KMA

- Research Groups
  - The above, plus DLR (Germany), U. Karlsruhe (Germany), National Taiwan U., Yonsei U., NOAA/AOML and NOAA/ESRL, U. Miami, SUNY Albany, U. Washington, U. Wisconsin, NPS, NCAR

- Informal “Targeting Consortium” established

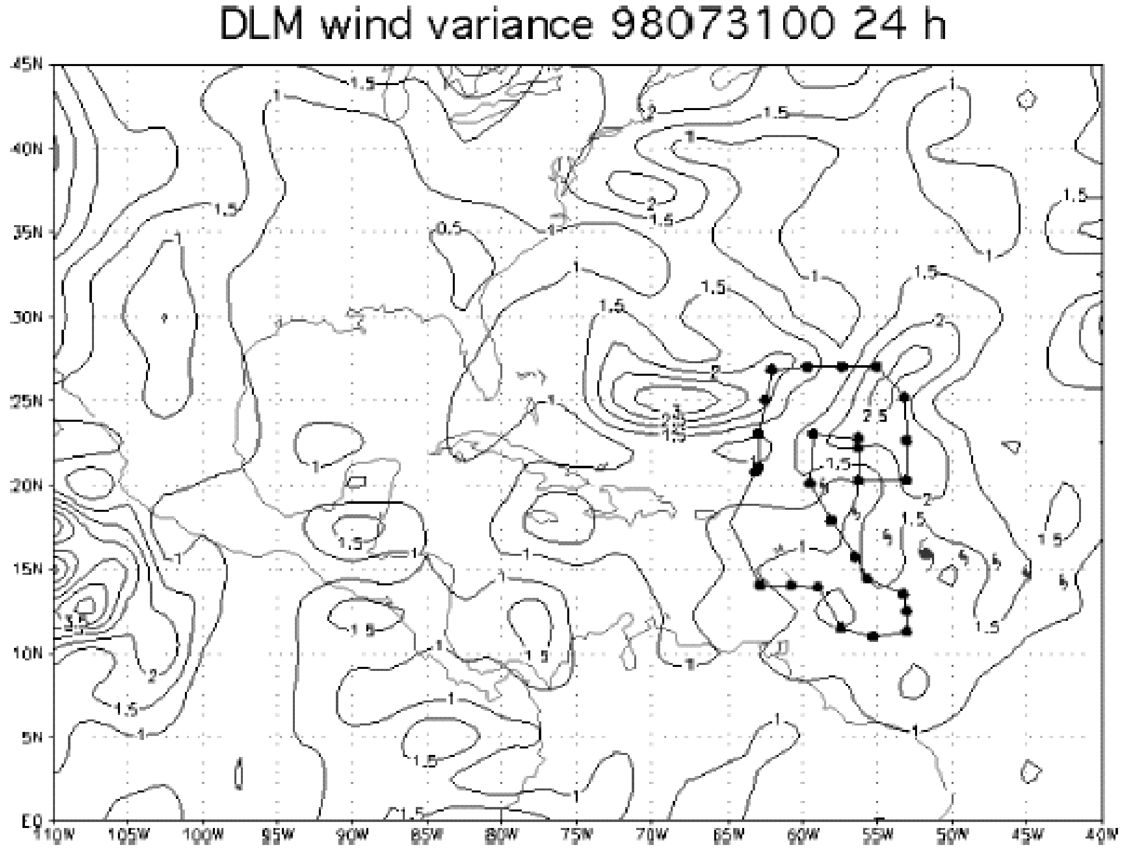
Facets of adaptive observing

- Forecasts of interest
- Types of observations available
- Adaptive observing strategies
- Decision on deployment
- Data assimilation / forecast model
- Evaluation of data impact

- Mostly performed through field campaigns

Deep-Layer Mean wind variance

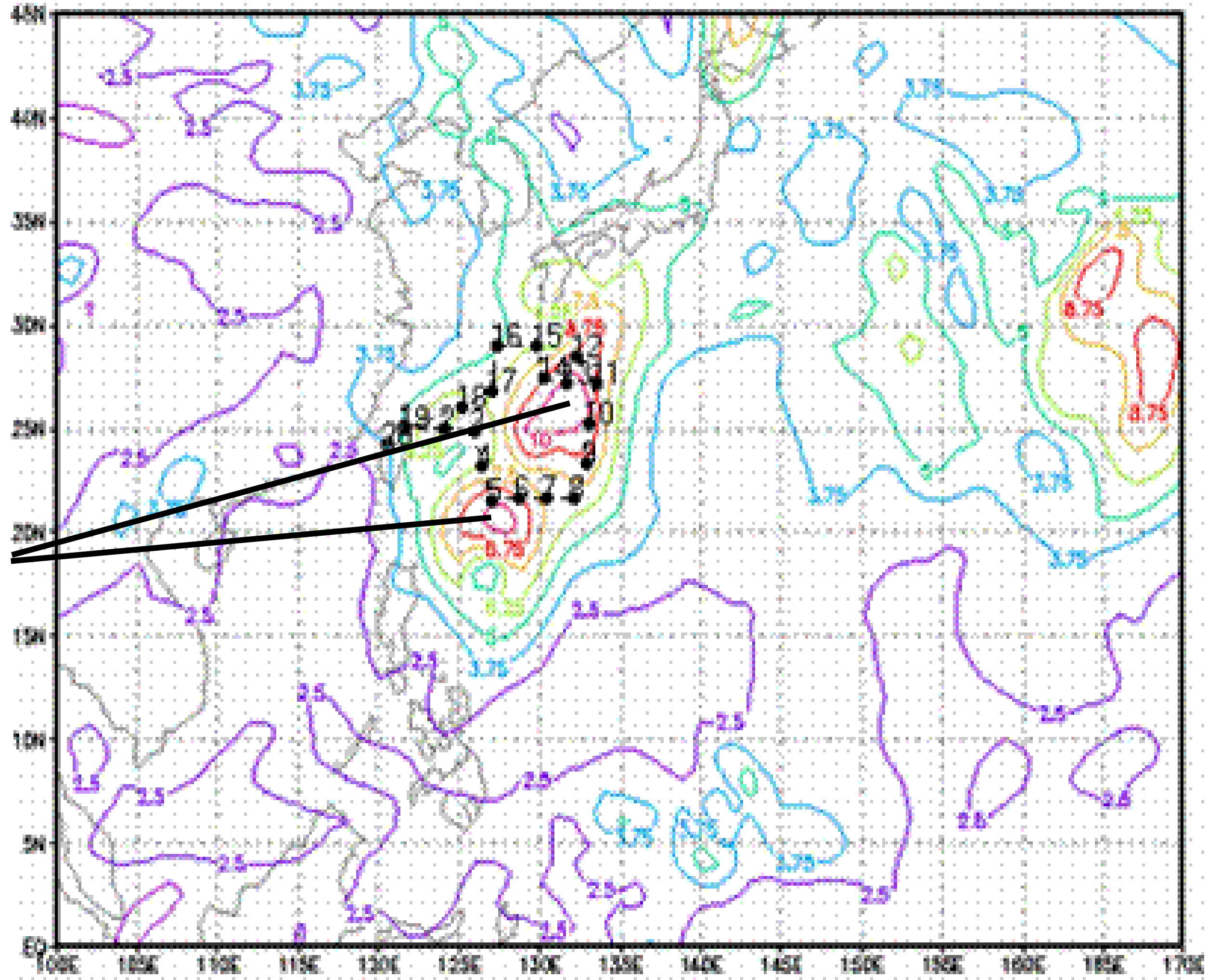
- The sensitive regions at the observing time are represented by locations containing the largest variance of the NCEP Global Forecast System (GFS) ensemble of deep-layer mean (DLM, 850-200 hPa) wind **(Aberson 2003).**
  - The DLM wind is chosen because tropical cyclones are generally steered by the environmental DLM flow
  - The dropwindsondes from the NOAA Gulfstream IV jet aircraft sample areas in which the uncertainty in this flow is predicted to be largest.
- **Aberson (2003)** demonstrated that the assimilation of only the subset of observations in areas of high NCEP DLM wind variance improved NCEP GFS TC track forecasts more than the assimilation of uniformly-sampled observations.



- Perturbation size at the nominal sampling time 0000 UTC 1 Aug 1998, from the previous day MRF ensemble forecast.
  - The large hurricane symbol is the location of Tropical Storm Alex at the nominal time.
  - The small hurricane symbols are the locations of Tropical Storm Alex at 12-h increments before and after the nominal time.
  - The black dots represent the locations of dropwindsonde observations.

- DLM wind variance for Typhoon Meari (2004)

- Observing time: 1200 UTC 25 Sep 2004



The sensitive areas are to the northeast and southwest of the center of Meari.

Singular Vector (SV) technique (I)

- The SV technique **(Palmer et al. 1998)** applied to date to tropical cyclones maximizes the growth of a total energy norm into a forecast verification region encompassing the tropical cyclone **(Peng and Reynolds 2006).**
- The leading singular vector (SV) represents the fastest growing perturbation to a given trajectory (such as a weather forecast) in a linear sense **(Peng and Reynolds 2006).**
- The theory of the SV:
  - A nonlinear model *M*, acting on a state vector **x**: $M(\mathbf{x}_0)=\mathbf{x}_t$
  - Let $\mathbf{x}_0'$ represent some perturbed initial state:

$$\mathbf{x}_0' - \mathbf{x}_0 = \mathbf{p}_0 \quad M(\mathbf{x}_0') - M(\mathbf{x}_0) = \mathbf{p}_t.$$

– For linear perturbation growth, the initial perturbation can be propagated forward in time using the forward-tangent propagator, **L**:

$$\mathbf{L}\mathbf{p}_0 \cong \mathbf{p}_t$$

– L can be represented by its singular values and initial- and final-time SVs

$$\mathbf{L} = \mathbf{E}^{-1/2}\mathbf{U}\mathbf{D}\mathbf{V}^T\mathbf{E}^{1/2}$$

V (U): matrices with columns composed of the initial (final) SVs

D: a diagonal matrix whose elements are the singular values of L.

E: matrix that defines how the perturbations are measured

– The SVs satisfy the eigenvector equation:

$\mathbf{L}^T\mathbf{E}\mathbf{L}\mathbf{y}_n = d_n^2\mathbf{E}\mathbf{y}_n$ ($\mathbf{y}_n = \mathbf{E}^{-1/2}\mathbf{v}_n$)

d_n: the nth singular value $\mathbf{v}_n$: initial-time SV

– The leading SV maximizes the ratio of the final perturbation energy to the initial perturbation energy:

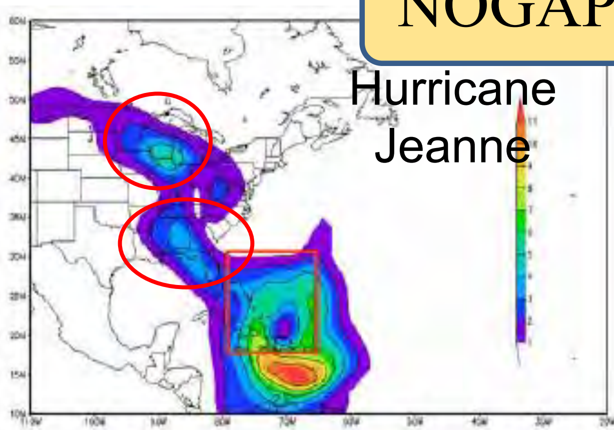
$$\frac{\langle \mathbf{p}_t ; \mathbf{E}\mathbf{p}_t \rangle}{\langle \mathbf{p}_0 ; \mathbf{E}\mathbf{p}_0 \rangle}$$

Singular Vector (SV) technique (II)

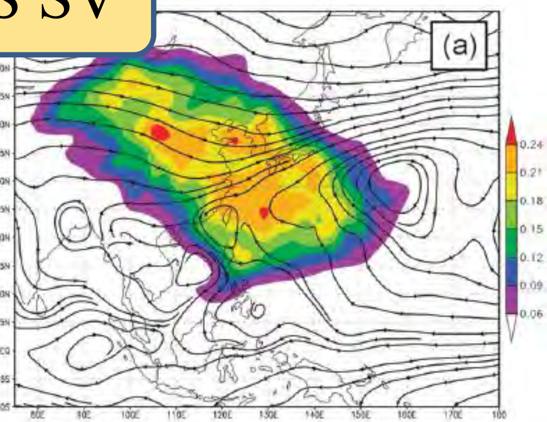
- Another singular vector method is calculated from the JMA EPS (Yamaguchi et al., 2009).
- Two kinds of singular vectors can be calculated:
  - Dry singular vectors: obtained using simplified physical processes that only include vertical diffusion.
  - Moist singular vectors:
    - full physics
    - require nearly twice as much computation costs as for the dry ones
    - capture of the uncertainty in areas such as a tropical region or typhoon surroundings where moist processes are dominant

Singular vectors

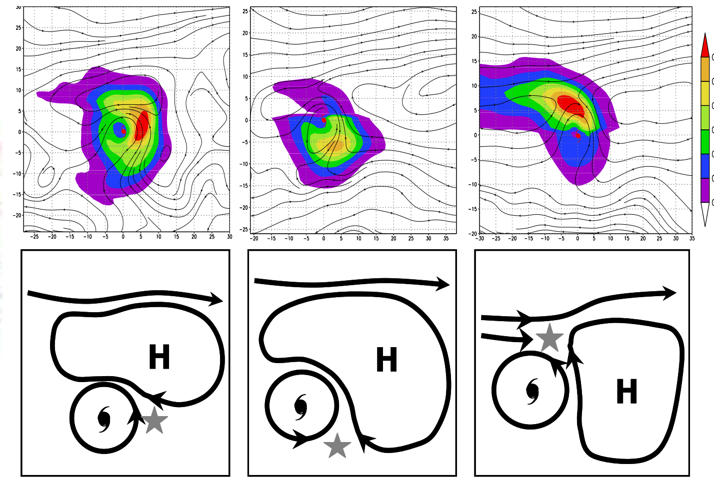
NOGAPS SV



(Peng et al. 2007)

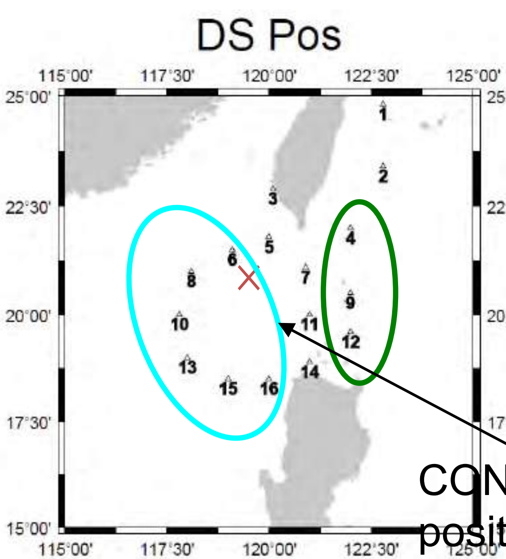


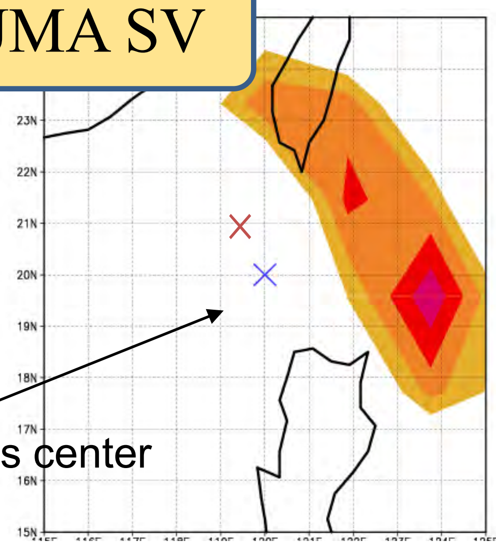
(Reynolds et al. 2009)



(Chen et al. 2009)

JMA SV

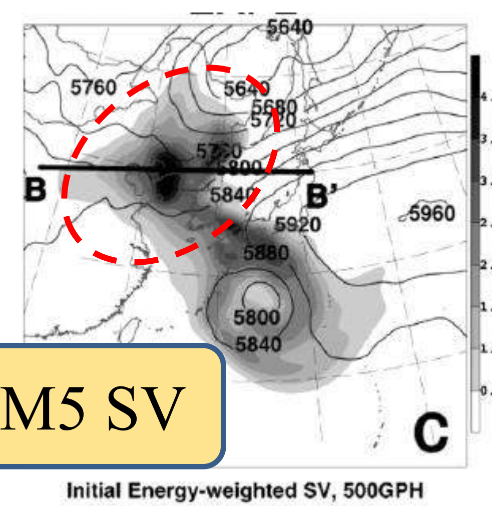




CONSON's center position

(Yamaguchi et al. 2009)

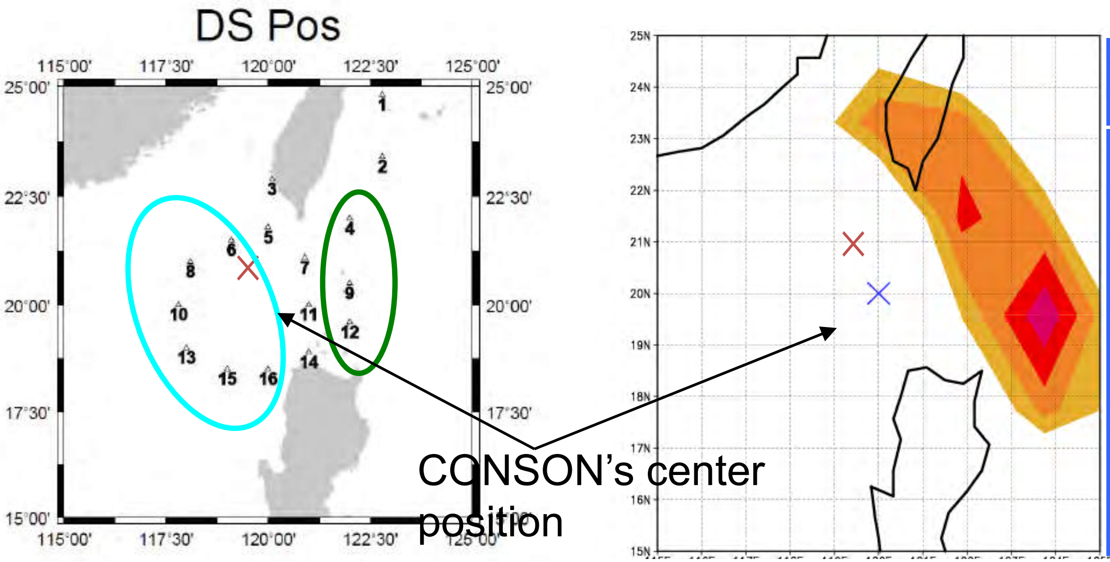
MM5 SV



Initial Energy-weighted SV, 500GPH

(Kim and Jung 2009)

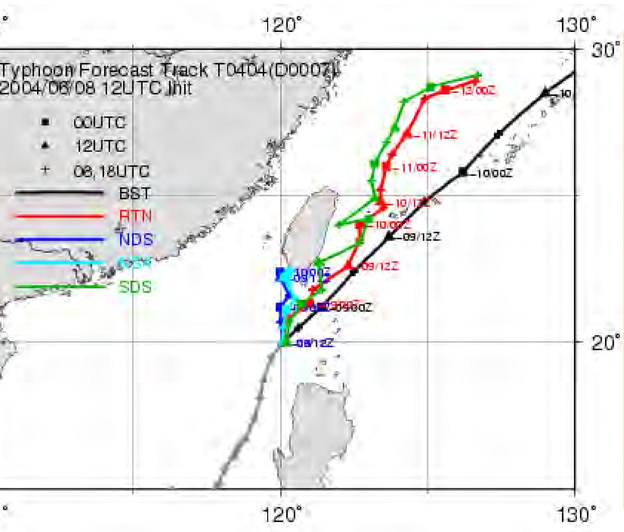
Impact of DOTSTAR data:



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



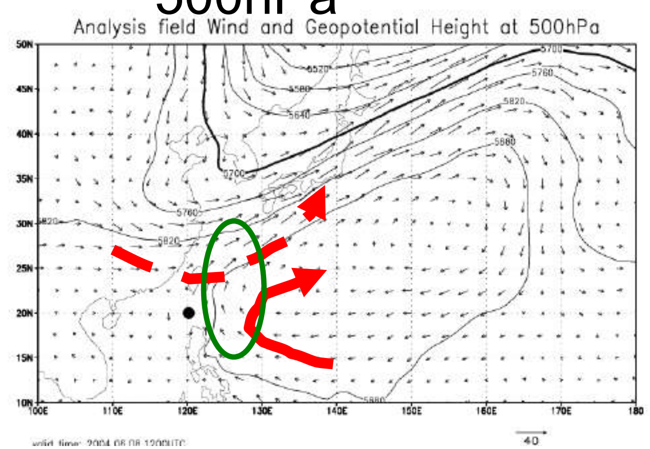
Red: (I) all dropsonde obs

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



(Yamaguchi et al. 2009, MWR)

ADSSV theory

- By defining the response function as a function of model output variables, one can use the adjoint model to calculate the sensitivity:

$$R = R(\mathbf{x}_{out})$$

$$\frac{\partial R}{\partial \mathbf{x}_{in}} = \mathbf{M}^* \frac{\partial R}{\partial \mathbf{x}_{out}}$$

$\mathbf{M}^*$: adjoint operator

(Errico 1997; Zou et al. 1997; Wu 2006)

- **Verification area**: square box (typically 600 km by 600 km) centered around the MM5-simulated storm location at the verification time.
- Define the **response function**: 0.875-0.225 σ deep-layer area-averaged zonal and meridional winds, respectively.

$$R_1 = \frac{\int_{0.875}^{0.225} \int_A u \; dxdyd\sigma}{\int_{0.875}^{0.225} \int_A dxdyd\sigma}$$

$$R_2 = \frac{\int_{0.875}^{0.225} \int_A v \; dxdyd\sigma}{\int_{0.875}^{0.225} \int_A dxdyd\sigma}$$

- Adjoint-Derived Sensitivity Steering Vector (ADSSV):

ADSSV w.r.t. vorticity= $\left(\frac{\partial R_1}{\partial \zeta}, \frac{\partial R_2}{\partial \zeta} \right)$

(Wu et al. 2007a)

There is a specific input perturbation (δX_{in})

What is **the impact** on R ($\frac{\partial R}{\partial \mathbf{X}_{in}}$) ?

Non-linear model : $X_{out}=m(X_{in})$

If there is a perturbation ΔX_{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

$R=R(X_{out})$ →

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

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

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

- Adjoint-Derived Sensitivity Steering Vector (**ADSSV**)
  - A new parameter to identify the sensitive (and targeted observing) areas to the steering flow **(R_1, R_2)** at the verifying time

$$R_1 = \frac{\int_{850hPa}^{300hPa}\int_A u\,dx\,dy\,dp}{\int_{850hPa}^{300hPa}\int_A dx\,dy\,dp} \qquad R_2 = \frac{\int_{850hPa}^{300hPa}\int_A v\,dx\,dy\,dp}{\int_{850hPa}^{300hPa}\int_A dx\,dy\,dp}$$

ADSSV w.r.t. vorticity : $\left(\frac{\partial R_1}{\partial \varsigma}, \frac{\partial R_2}{\partial \varsigma}\right)$

ADSSV w.r.t divergence : $\left(\frac{\partial R_1}{\partial D}, \frac{\partial R_2}{\partial D}\right)$

Magnitude – the degree of sensitivity

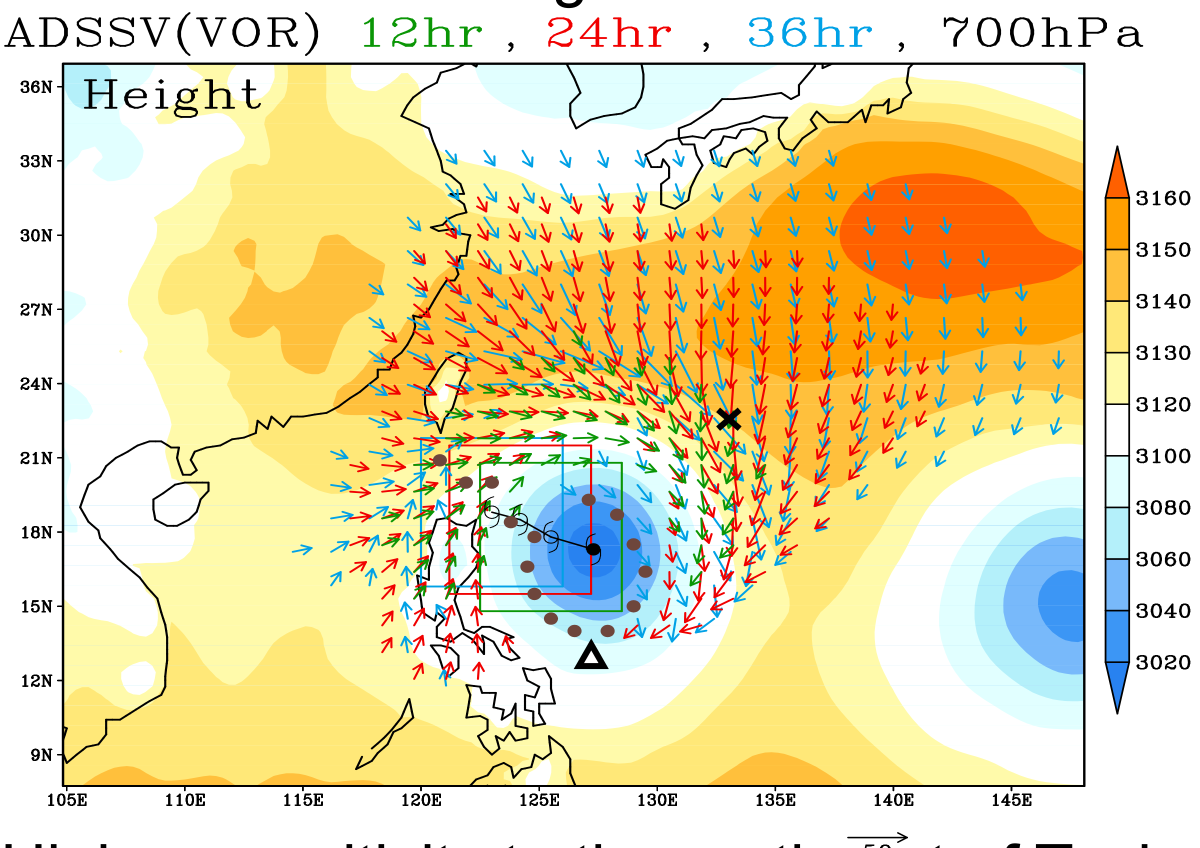
Direction – the change of the steering flow direction w.r.t. the vorticity or divergence variation.

(Wu et al. 2007b, JAS)

Application of targeted observations (ADSSV)

• ADSSV for Typhoon Mindulle

Observing time: 1200 UTC 27 Jun. 2004



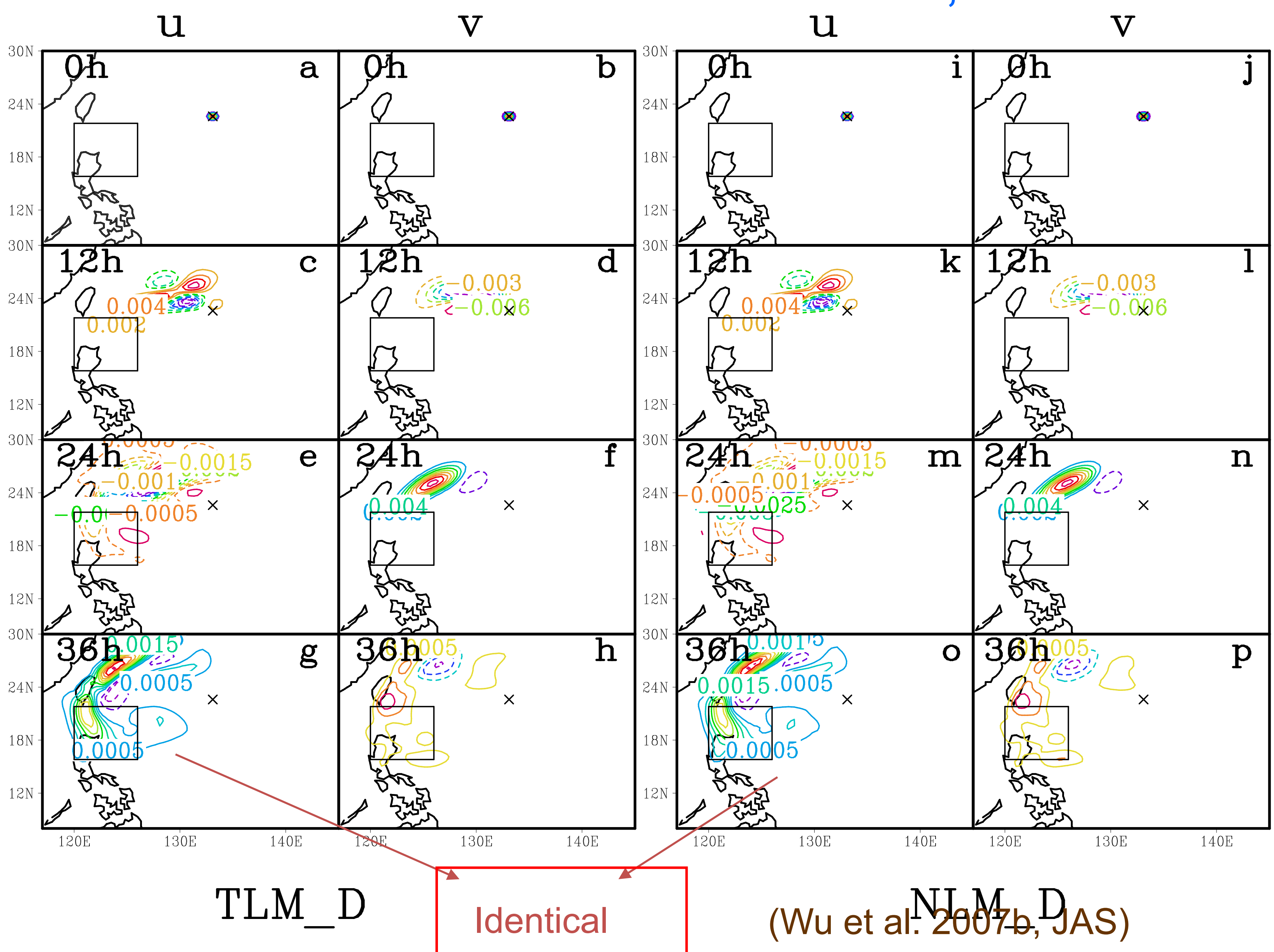
- Linearity test
- Impact study

- Higher sensitivity to the northeast of Typhoon Mindulle
- More impact on the meridional movement
- The sensitive areas does not match the deployment locations of the dropsondes in DOTSTAR (Wu et al. 2007a, JAS; Wu et al. 2009 MWR)

1 m/s, single point perturbation (multi-points, multi-level, larger pert.)

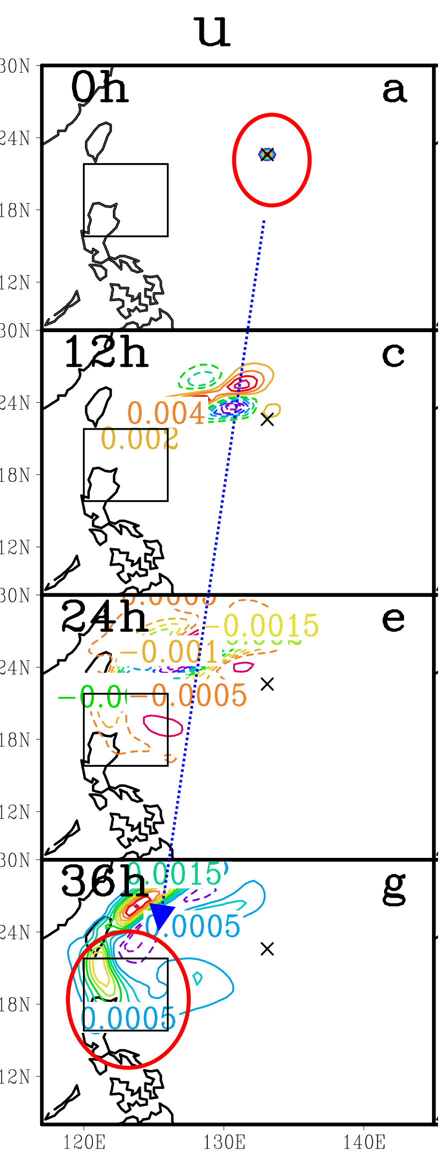
Linearity test

Mindulle, 2004



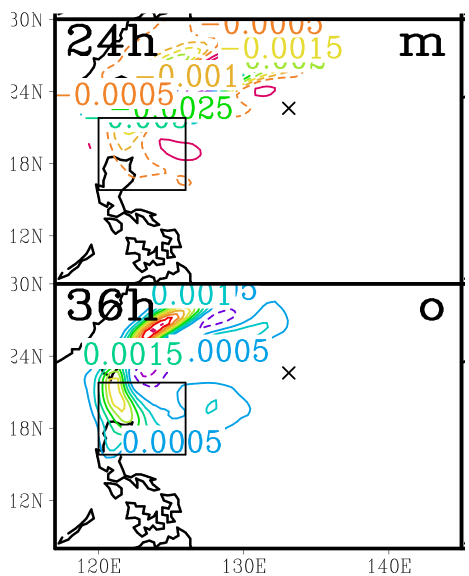
(Wu et al. 2007b, JAS)

Impact validation

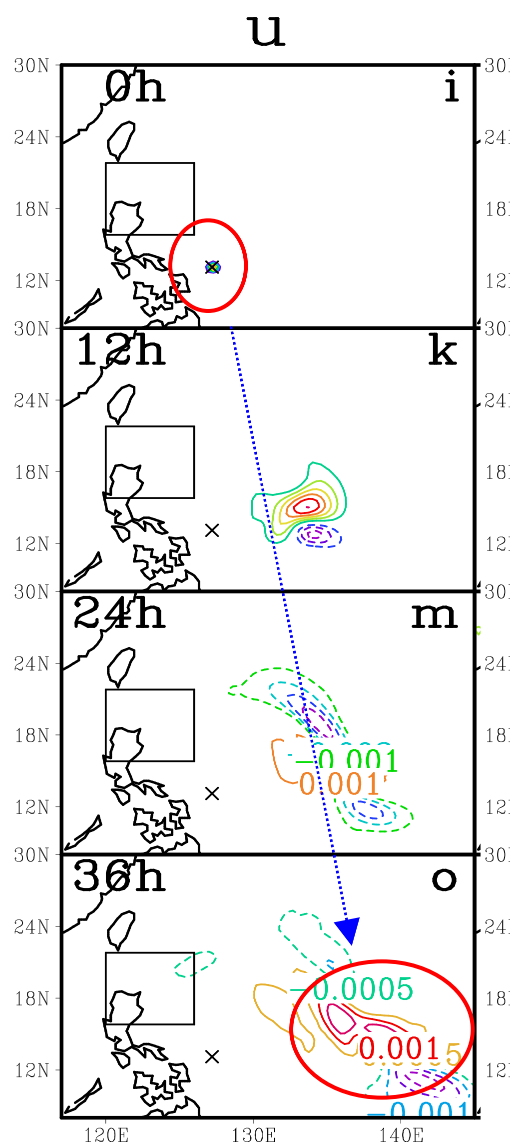


TLM-D

The perturbation starts at the ADSSV-sensitive location, and then it does grow and propagate into the verification region at 36h.

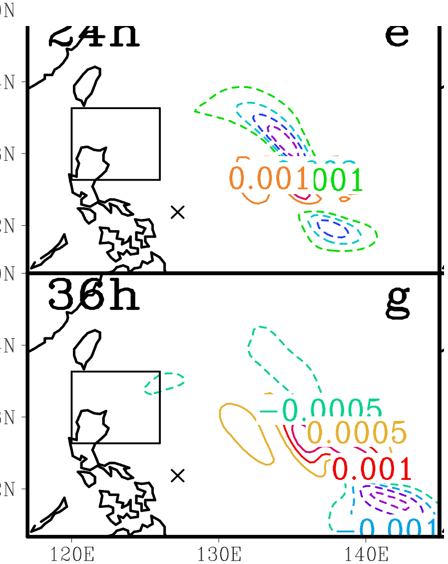


NLM-D



TLM-D

The perturbation starting at a non-sensitive region continues to grow and propagates eastward, and never shows any impact on the flow field in the verification region.

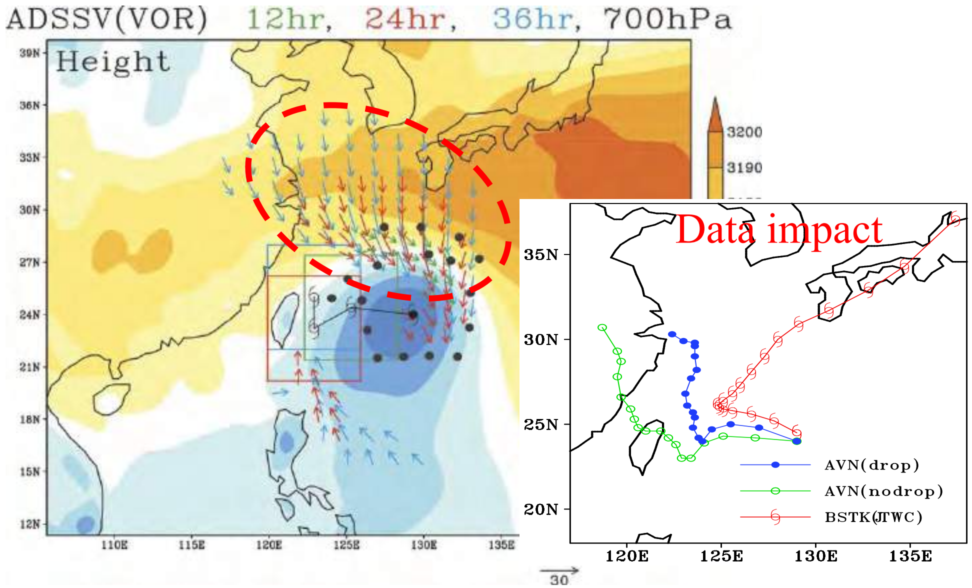


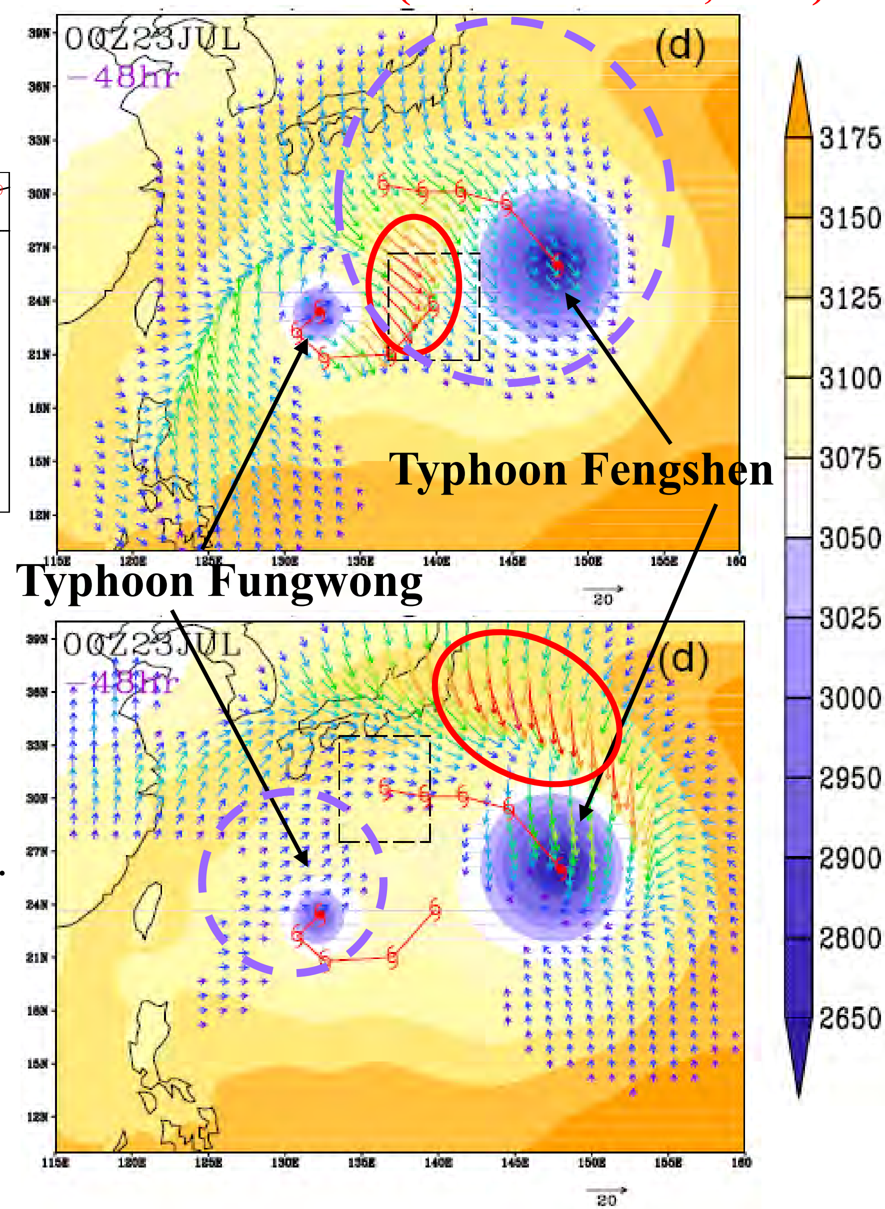
NLM-D

(Wu et al. 2007b, JAS)

- Wu, C.-C.*, J.-H. Chen, P.-H. Lin, and K.-S. Chou, 2007: Targeted observations of tropical cyclones based on the adjoint-derived sensitivity steering vector. *J. Atmos. Sci.*, **64**, 2611-2626.

(Wu et al. 2007, JAS)





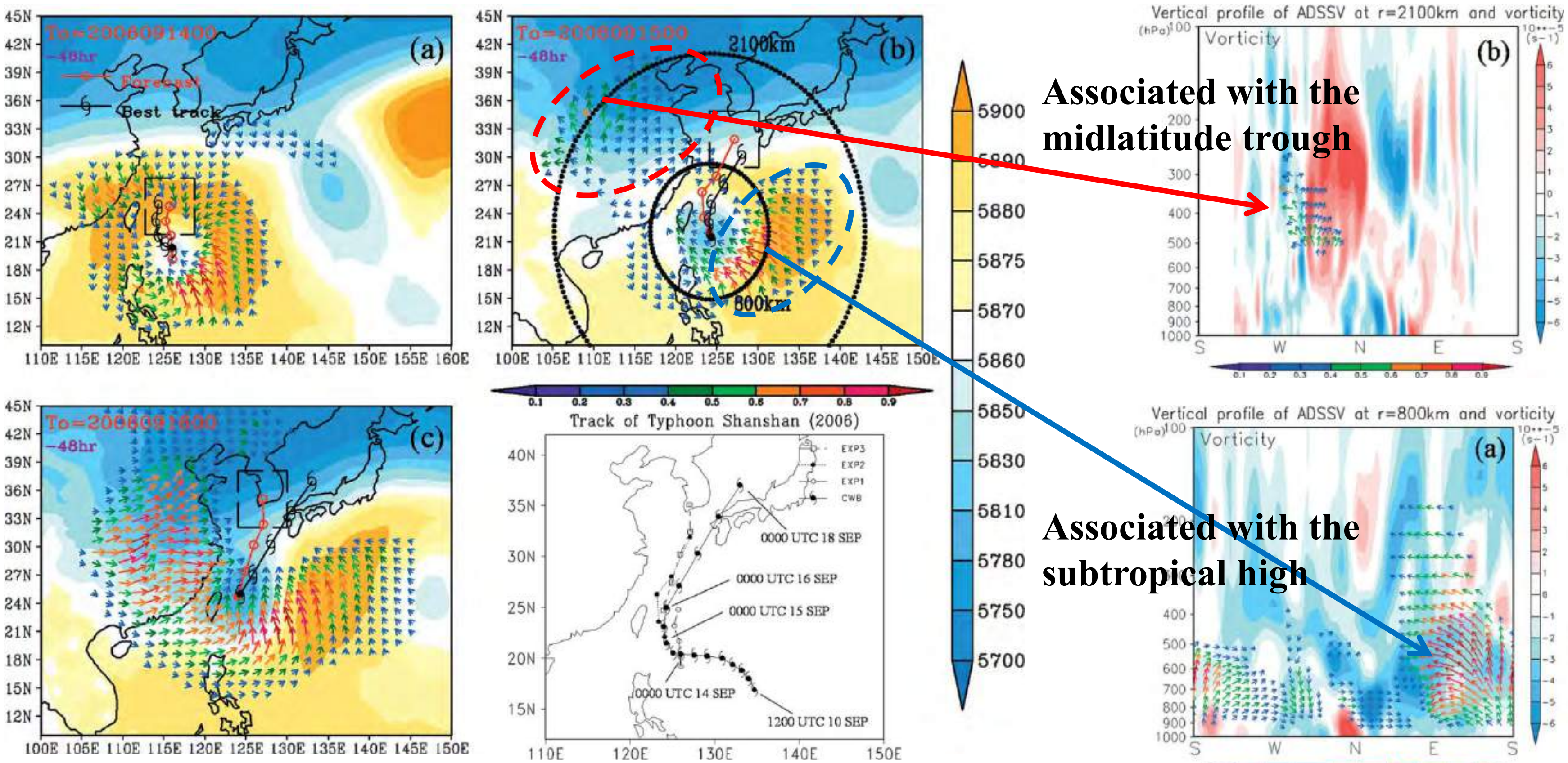
➢A new method for targeted observations is proposed and examined based on the adjoint sensitivity.

➢The locations of DOTSTAR's dropwindsondes well match the sensitive region. Dropwindsonde data have a positive impact on the track forecasts of Meari.

➢The ADSSV method is applied to identify the signals of the binary interaction. Typhoon Fengshen (2002) is sensitive to the steering flow of Typhoon Fungwong, but the sensitivity for Typhoon Fungwong to the steering flow of Typhoon Fengshen is rather insignificant. (one-way interaction)

- Wu C.-C.*, S.-G. Chen, J.-H. Chen, K.-H. Chou, and P.-H. Lin, 2009: Interaction of Typhoon Shanshan (2006) with the mid-latitude trough from both Adjoint-Derived Sensitivity Steering Vector and potential vorticity perspectives. *Mon. Wea. Rev.*, **137**, 852–862.

(Wu et al. 2009, MWR)



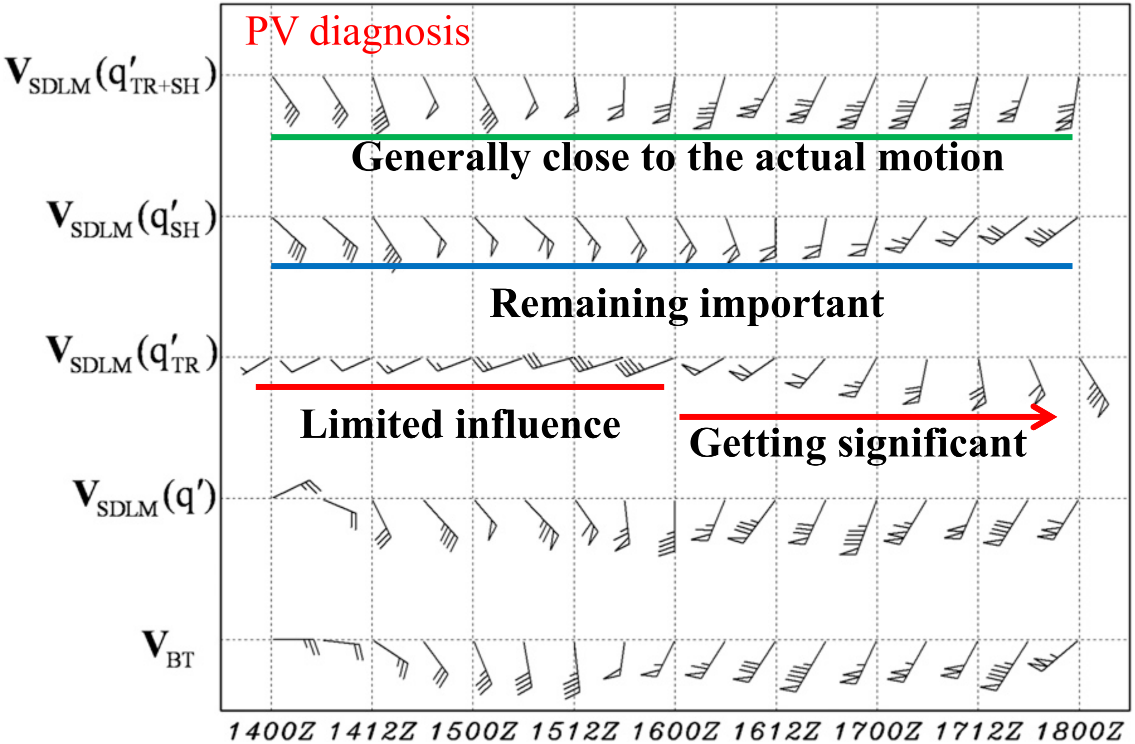
➢Two major ADSSV features can be identified for Typhoon Shanshan, associated with the midlatitude trough and the subtropical high.

➢The maximum ADSSV occurs at 800–500 hPa to the southeast of Shanshan (associated with the subtropical high).

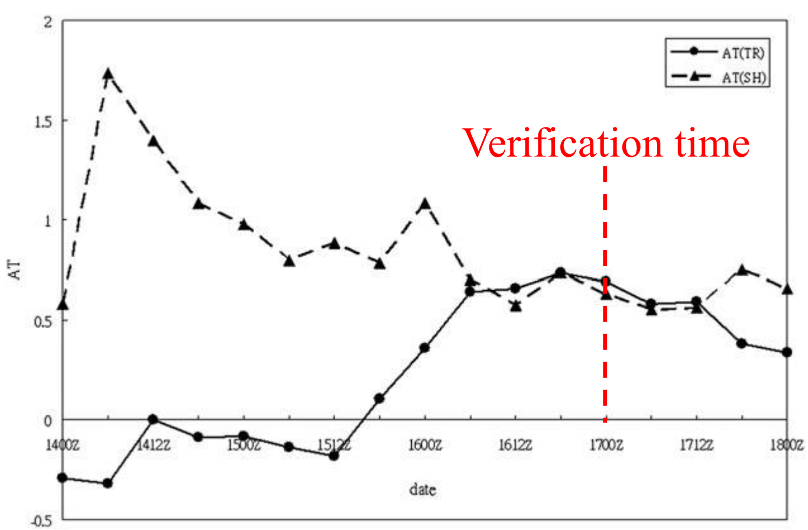
➢ADSSV signals are located upstream of the storm center at about 500–300 hPa (associated with the mid- to upper-tropospheric midlatitude trough).

- Wu C.-C.*, S.-G. Chen, J.-H. Chen, K.-H. Chou, and P.-H. Lin, 2009: Interaction of Typhoon Shanshan (2006) with the mid-latitude trough from both Adjoint-Derived Sensitivity Steering Vector and potential vorticity perspectives. *Mon. Wea. Rev.*, **137**, 852–862.

(Wu et al. 2009, MWR)



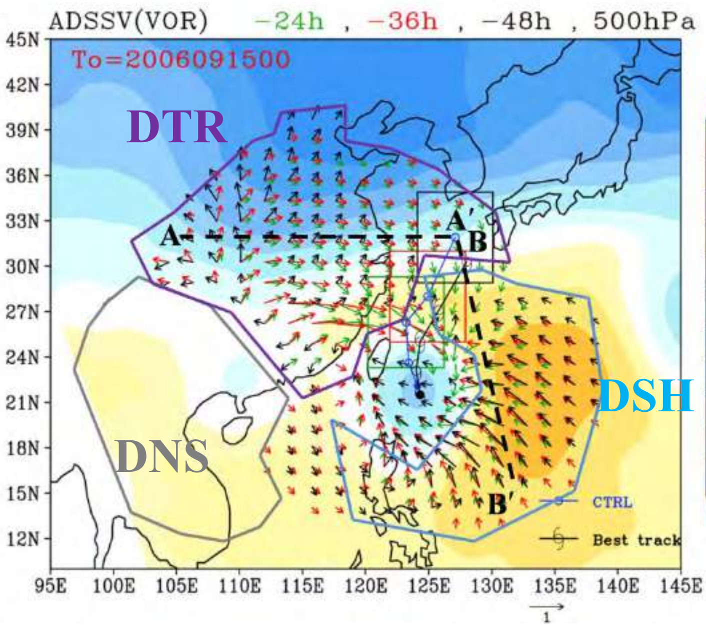
- The steering effect of the trough is getting significant after around 1200 UTC 16 September.
- Subtropical high remains important to advect Shanshan.



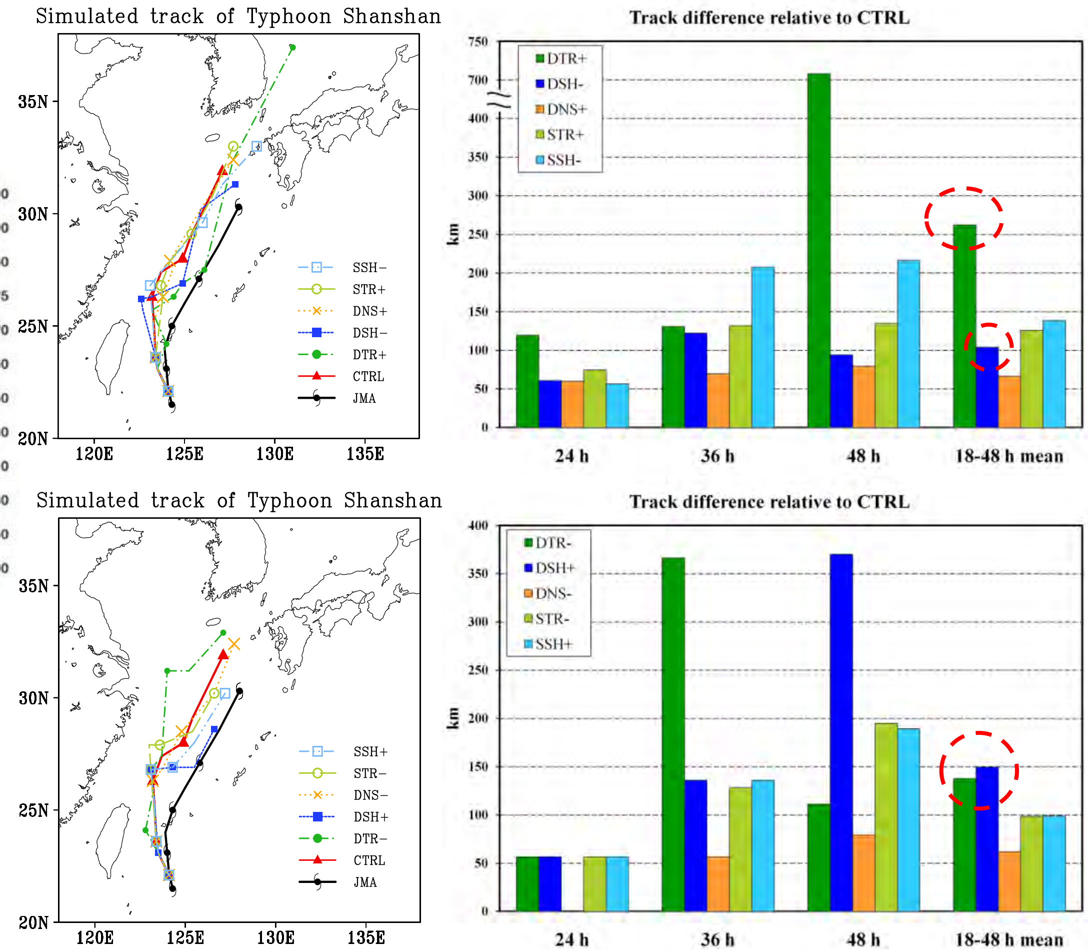
- The PV diagnosis indicates that the trough and the subtropical high equally contribute to the steering flow of Shanshan at the verification time, in accord with the ADSSV signals.

- Chen, S.-G., C.-C. Wu*, J.-H. Chen, and K.-H. Chou, 2011: Validation and interpretation of Adjoint - Derived Sensitivity Steering Vector as targeted observation guidance. *Mon. Wea. Rev.* **139**, 1608–1625.

ADSSV and perturbed area



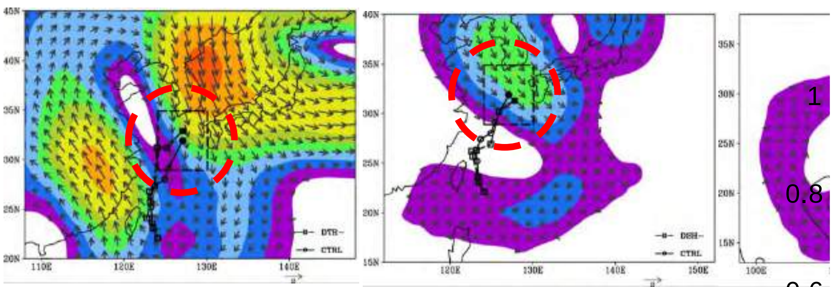
(Chen et al. 2011, MWR)



➢Perturbations associated with high ADSSV sensitivity lead to more track deflection than those with low ADSSV sensitivity.

- Chen, S.-G., C.-C. Wu*, J.-H. Chen, and K.-H. Chou, 2011: Validation and interpretation of Adjoint - Derived Sensitivity Steering Vector as targeted observation guidance. *Mon. Wea. Rev.* **139**, 1608–1625.

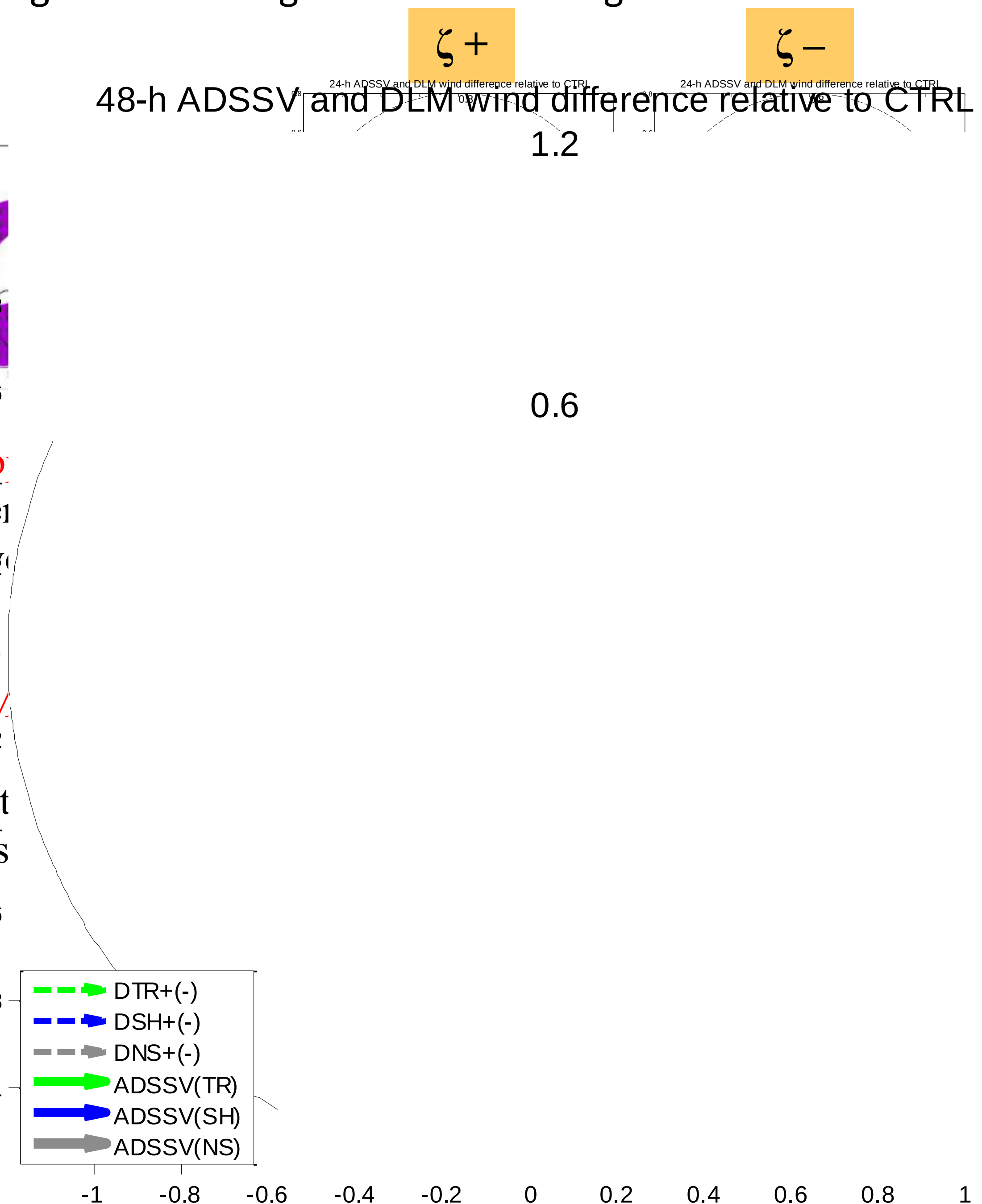
850-250-hPa DLM wind difference at 48 h



➢The signals of DLM wind difference pro verification area for perturbation in high se while it displays limited influence on the v for perturbation in low sensitivity region.

➢Comparison between ADSSV and DLM shows they are generally consistent with perturbing high sensitivity regions. It identified by ADSSV for results in low sens

(Chen et al. 2011, MWR)



Ensemble Transform Kalman Filter (ETKF)

- The ETKF **(Bishop et al. 2001)** uses data assimilation theory to predict the reduction in 200-850 hPa wind forecast error variance within a given ‘verification region’ for feasible deployments of targeted observations, based on any available operational ensemble forecast **(Majumdar et al. 2006).**
- The theory of the ETKF:
  - The analysis error covariance matrix $\mathbf{P}^r(t_o)$at the observing time (t_o) pertaining to the routine observational network is found by solving the Kalman filter error statistics equation:

$$\mathbf{P}^r(t_o)=\mathbf{P}^i(t_o)-\mathbf{P}^i(t_o)\mathbf{H}^{rT}(\mathbf{H}^r\mathbf{P}^i(t_o)\mathbf{H}^{rT}+\mathbf{R}^r)^{-1}\mathbf{H}^r\mathbf{P}^i(t_o)$$

$\mathbf{H}^r$: observation operator ; $\mathbf{R}^r$: error covariance matrices

$\mathbf{P}_i$: analysis error covariance matrix

ETKF theory

(Majumdar et al. 2010)

- The **transformation matrix** is solved by using the analysis error variance from NRL (**NAVDAS**) to obtain the routine analysis error covariance:

$$\mathbf{T}^{r\mathrm{T}}\mathbf{Z}^{i\mathrm{T}}[\mathbf{P}^{i}{}_{\mathrm{OPER}}(t_a\,|\,\mathbf{H}^i)]^{-1}\mathbf{Z}^i\mathbf{T}^r = \mathbf{I}$$

$$\mathbf{P}^r(t_a\,|\,\mathbf{H}^r) = \mathbf{Z}^i(t_a)\mathbf{T}^r\mathbf{T}^{r\mathrm{T}}\mathbf{Z}^{i\mathrm{T}}(t_a)$$

- ETKF predicted **reduction in forecast error variance** due to targeted observations ($\mathbf{H}^q$):

$$\mathbf{S}^q(t_v\,|\,\mathbf{H}^q) = \mathbf{Z}^r(t_v)\mathbf{Z}^{r\mathrm{T}}(t_a)\mathbf{H}^{q\mathrm{T}}[\mathbf{H}^q\mathbf{P}^r(t_a\,|\,\mathbf{H}^r)\mathbf{H}^{q\mathrm{T}} + \mathbf{R}^q]^{-1}\mathbf{H}^q\mathbf{Z}^r(t_a)\mathbf{Z}^{r\mathrm{T}}(t_v)$$

- ETKF **guidance**: the diagonal of $\mathbf{S}^q(t_v\,|\,\mathbf{H}^q)$ localized within the verification area is produced as a function of the q'th targeted observation ($\mathbf{H}^q$).

- Modifying observation errors of targeted observation ($\mathbf{H}^q$) by the inverse of a Gaussian function as in Gaspari and Cohn (1999).

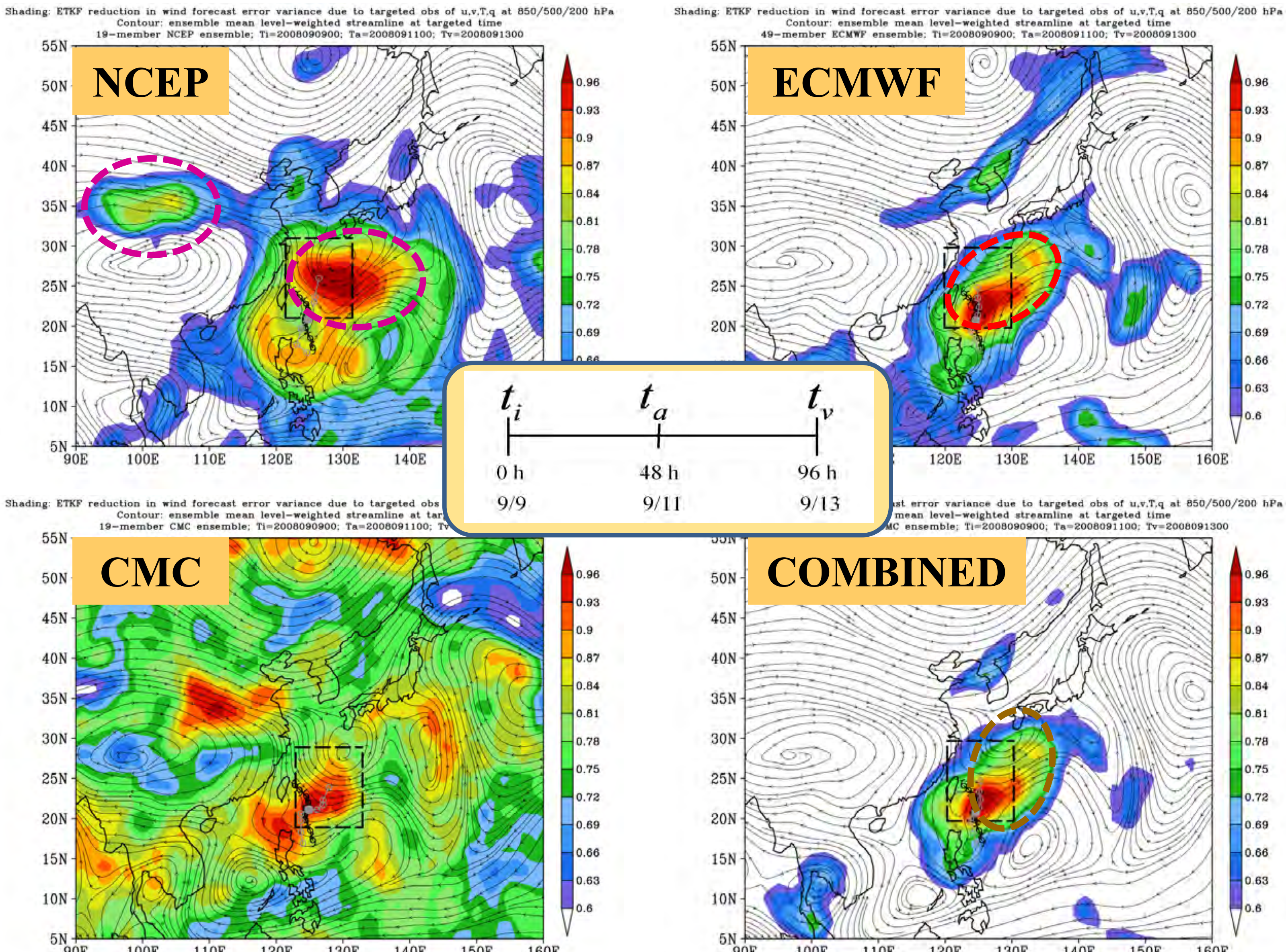
- Verification norm:

$$\frac{1}{p_1 - p_0}\int_{p_0}^{p_1}(u_s{}^2 + v_s{}^2)\frac{dp}{2}$$

Over 3 levels: 850, 500, and 200 hPa.

Application of targeted observations (ETKF)

ETKF – Typhoon Sinlaku (2008)

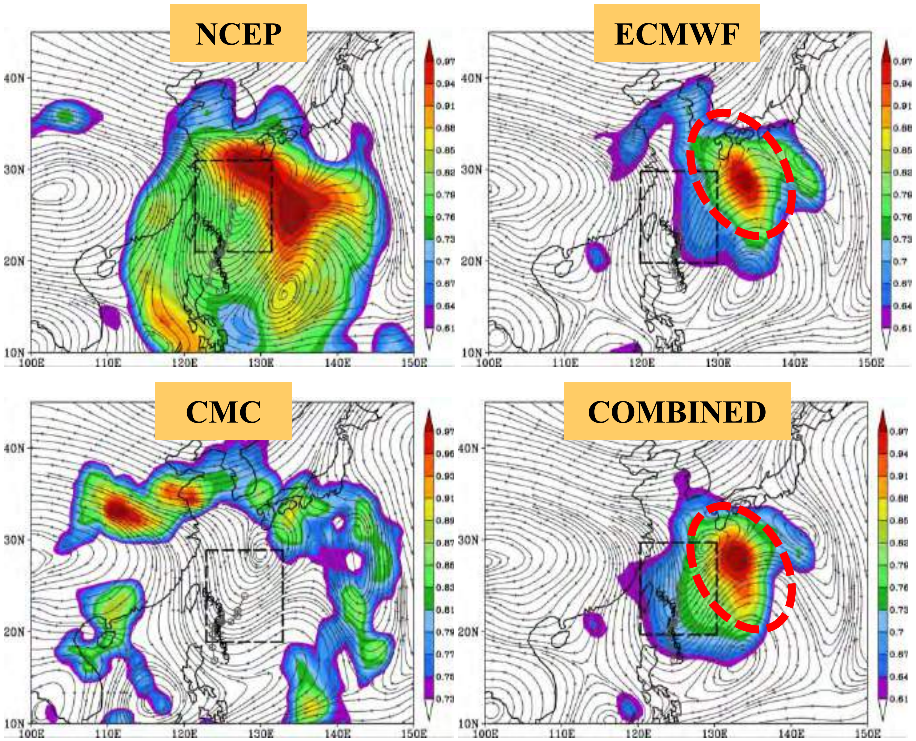


(Majumdar et al. 2010)

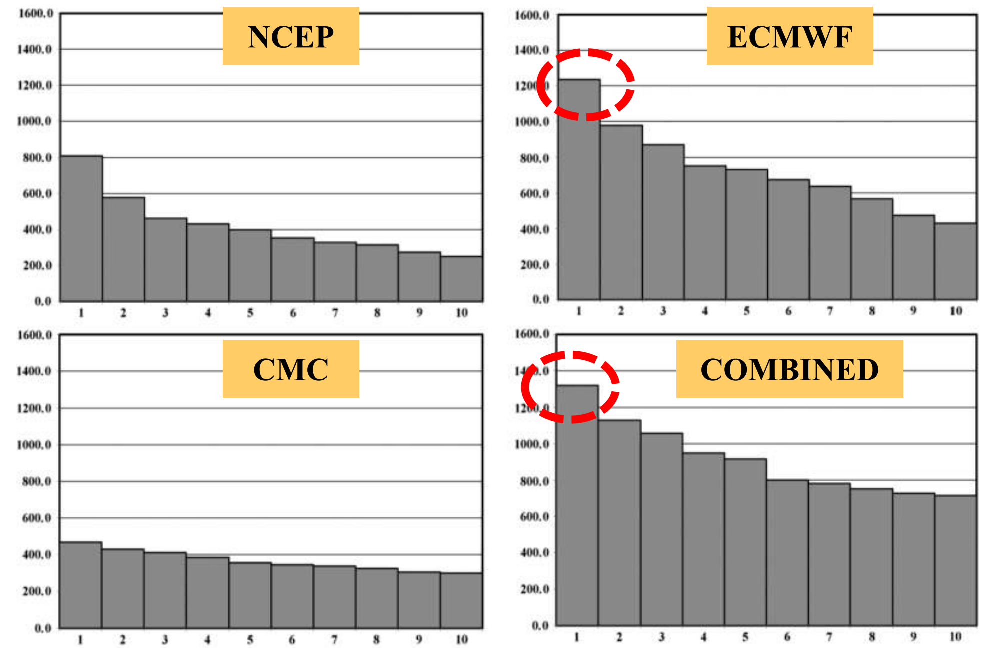
- Majumdar, S. J.*, S. -G. Chen, and C.-C. Wu, 2011: Characteristics of Ensemble Transform Kalman Filter adaptive sampling guidance for tropical cyclones. *Quart. J. Roy. Meteor. Soc.* **137**, 503-520.

(Majumdar et al. 2011, QJRMS)

ETKF guidance with TC removal



Eigenvalue of analysis error covariance matrix



- ➢Modified ETKF guidance by removing the TC components in each member is proposed.
- ➢Characteristics of ETKF targets show distinct feature between each model.
- ➢ETKF guidance with "COMBINED" ensembles is dominated by ECMWF due to rapidly amplifying perturbations by SV method and more spatially variable variance.

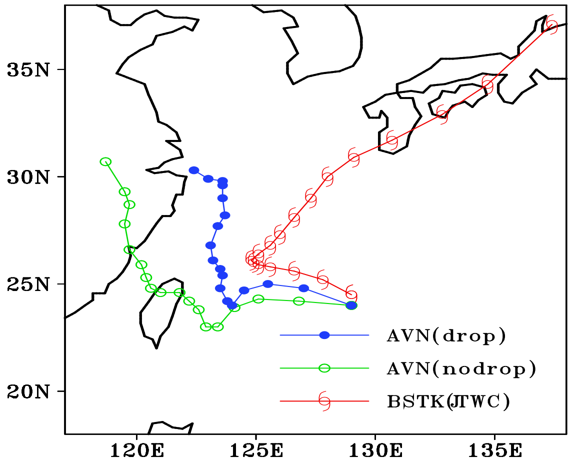
Main Recommendations from IWTC-VI (Wu; Elsberry, 2006)

IWTC-VI recognizes adaptive observations as a very promising way to improve TC track prediction and recommends:

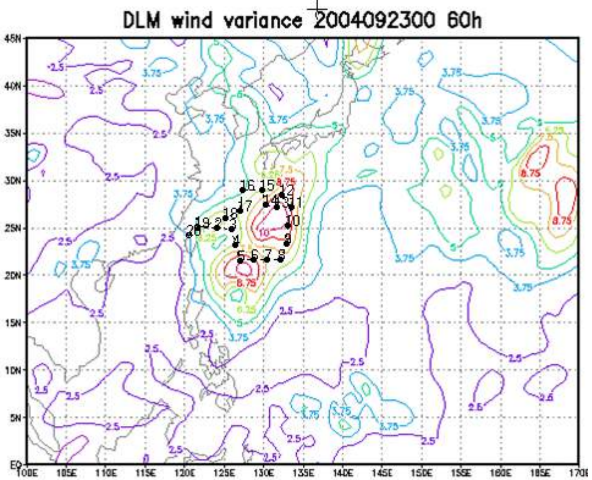
- Increased consideration given to targeted observations.
- WMO should encourage expansion of aircraft targeting capabilities in various tropical cyclone basins.
  → T-PARC under WMO/THORPEX
- Research on targeted data should be extended to other observing systems/data (e.g. satellite-derived soundings).
  → Limited progress: practical issues?
- Application of new concepts in predictability and data assimilation should be tested.
  → Several research papers published since 2006
- Further research should be undertaken to define the best way to optimize targeted observations.
  → Intercomparison between strategies was initiated at IWTC-VI. "Best way" depends on available observations and data assimilation scheme.

- **Etherton et al. (2006)** qualitatively discussed the observational sensitivity results in 2005 Atlantic season for three strategies: DLM wind variance, ETKF, and ADSSV.
  - The DLM wind variance approach usually produces sensitivity areas very near the center of the tropical cyclone.
  - The ETKF indicates secondary features other than the tropical cyclone that may be important to the track forecast.
  - The ADSSV rarely, if ever, selects targets in the immediate vicinity of the center of the tropical cyclone. Instead, a ring around the storm is usually the target area, although areas to the south, west, and east are more common than locations to the north of the center of a cyclone.

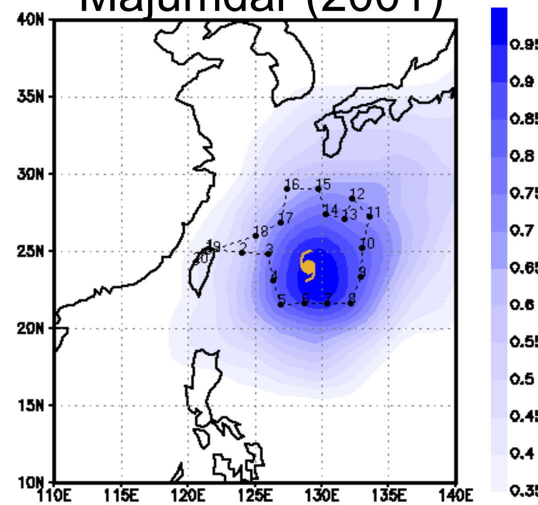
Comparison of targeted observations in DOTSTAR



Ensemble Variances, Toth and Kalnay (1993)

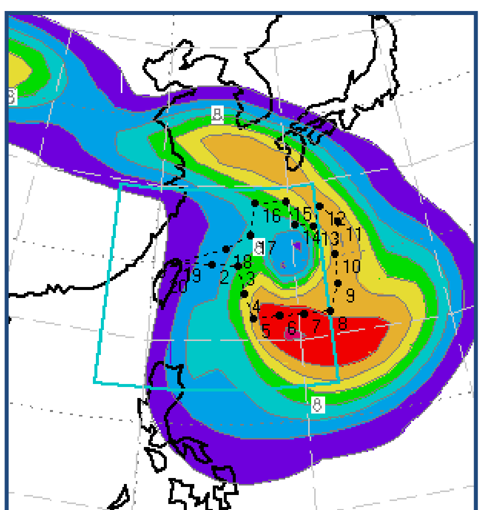


ETKF, Bishop and Majumdar (2001)

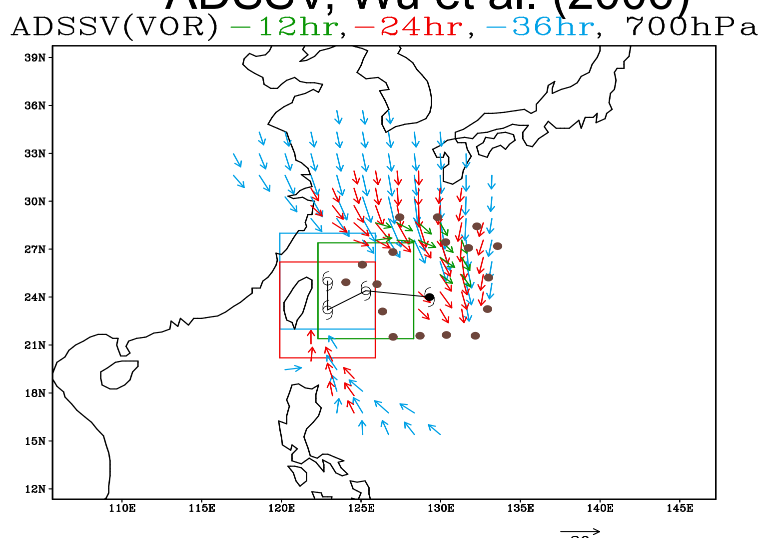


DOTSTAR
(Wu et al. 2006b)

FNMOC SV, Palmer et al. (1998)



ADSSV, Wu et al. (2006)



•G-IV surveillance
Comparison of
targeted techniques
(Etherton et al. 2006)
Maumdar et al. 2006
Reynolds et al. 2006

Comprehensive comparisons are needed (Wu 2006, IWTC-VI)

Inter-comparison of Targeted Observation Guidance for Tropical Cyclones in the Western North Pacific

- **Chun-Chieh Wu[1], Jan-Huey Chen[1], Melinda Peng[2], Sharan Majumdar[3], Carolyn Reynolds[2], Sim Aberson[4], Munehiko Yamaguchi[5], Roberto Buizza[6], Shin-Gan Chen[1], Tetsuo Nakazawa[7] and, Kun-Husan Chou[1]**

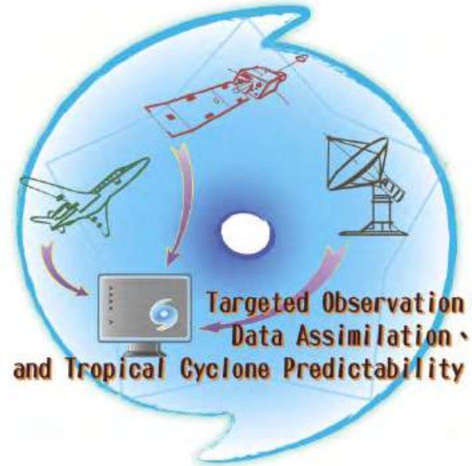
- To highlight the unique dynamic features in affecting the TC tracks, we compare six different targeted techniques based on 84 cases of two-day forecasts of the Northwest Pacific tropical cyclone in 2006.
- The six targeted methods:

  TESVs form ECMWF, NOGAPS, and EPS of JMA

  ETKF

  DLM wind variance

  ADSSV



Wu et al. (2009, MWR)

Objectives of comparison study

- To highlight the unique dynamics features in affecting the TC tracks, we compare six different targeted techniques based on 84 cases of two-day forecasts of the Northwest Pacific tropical cyclones in 2006.
- The six targeted methods:
  - TESVs form ECMWF, NOGAPS, and EPS of JMA (Ensemble Prediction System of Japan Meteorological Agency)
  - ETKF based on the multi-model ensemble members [ECMWF, NCEP and CMC (Canadian Meteorological Centre)],
  - DLM wind variance based on NCEP/EFS
  - ADSSV by MM5 adjoint modeling system
- Unlike the Atlantic Ocean, the Northwest Pacific regions have more complicated dynamical systems affecting the TC motion.
  - Mid-latitude trough
  - Subtropical jet
  - Southwesterly monsoon
  - Binary interaction
- Results from this work would not only provide better insights into the physics of the targeted techniques, but also offer very useful information to assist the future targeted observations, especially for the DOTSTAR, TCS-08 and TH08 (Typhoon Hunting 2008) in T-PARC, 2008.

Wu et al. (2009a, MWR)

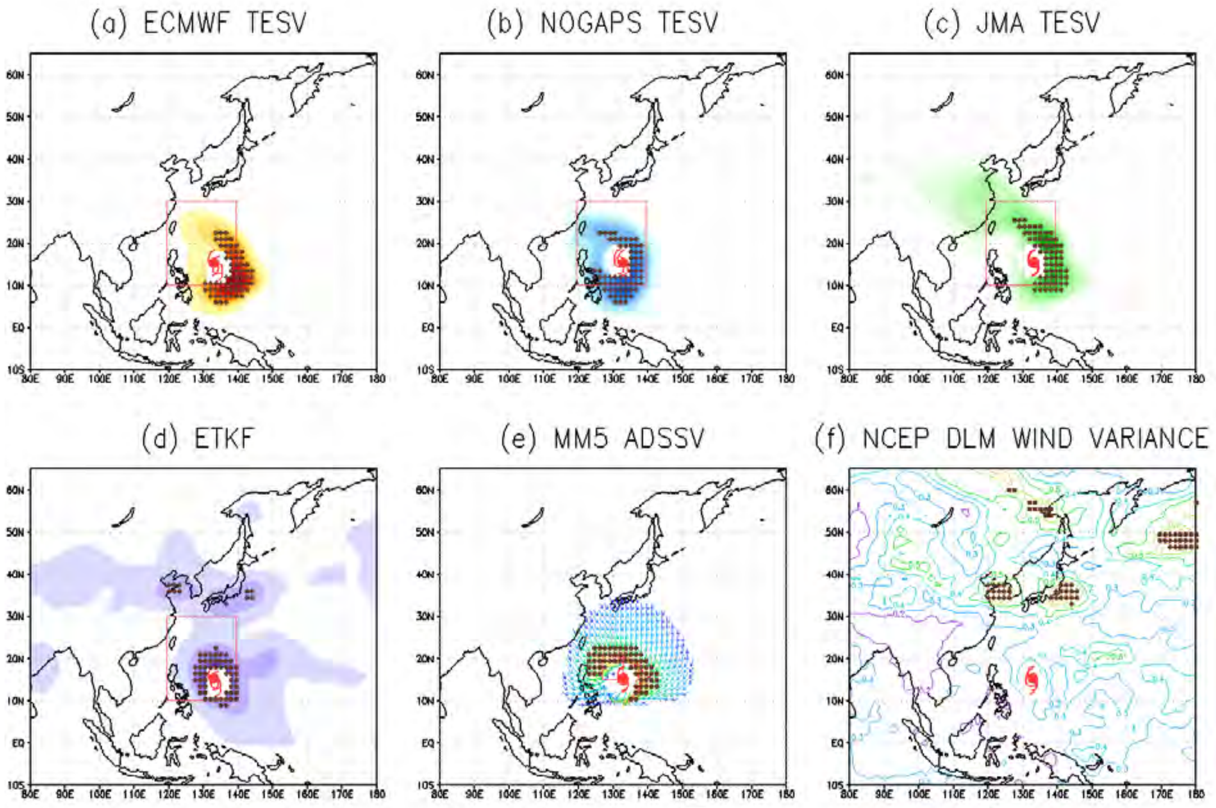
Inter-comparison of targeted guidance

- Common target locations
  - Modified Equitable Threat Scores (METS) (Majumdar et al. 2006)
    - *Provides the quantitative measure of how the leading targets of two sets of guidance are similar to each other.*

$$METS = \frac{c - E(c)}{2x - c - E(c)}$$

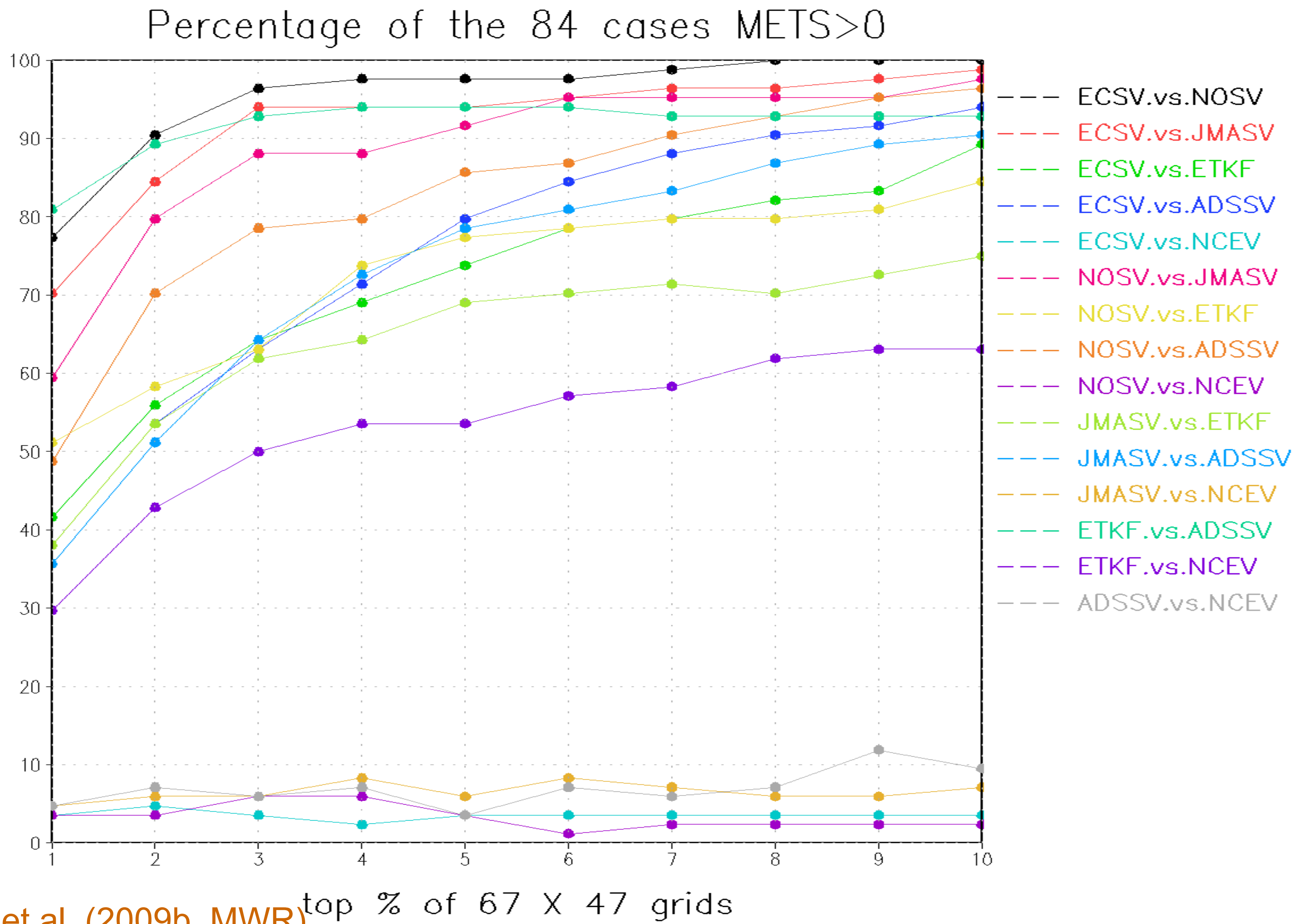
- c: number of common grid points between each pairs of guidance
- x: number of leading targets
- $E(c)$: expected number of common grid points between all feasible realizations of guidance

Leading targets = 2 % of total grid points in the domain



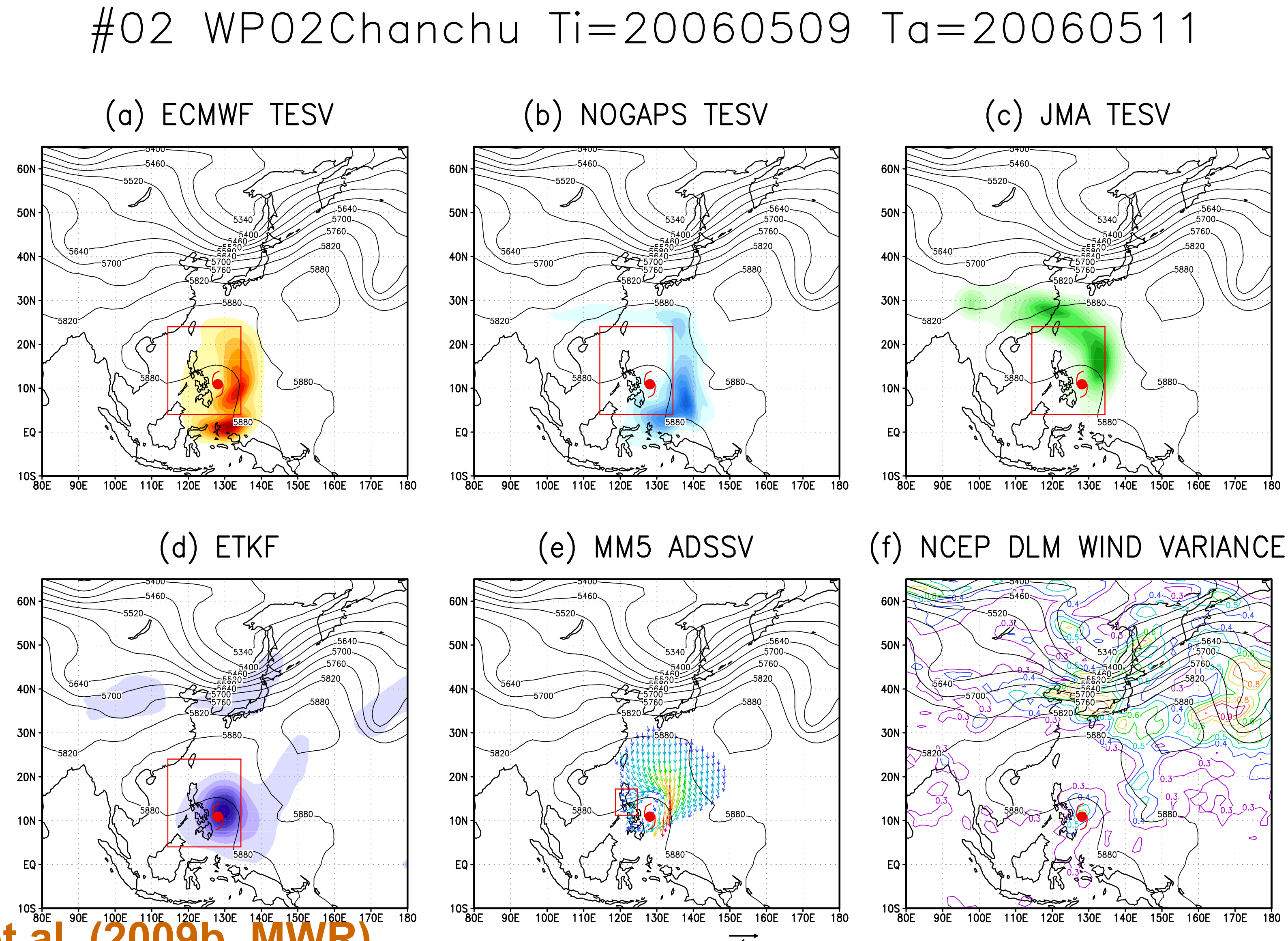
10 WP04 Ewiniar Ti=20060702 To=20060704

Wu et al. (2009b, MWR)



Wu et al. (2009b, MWR)

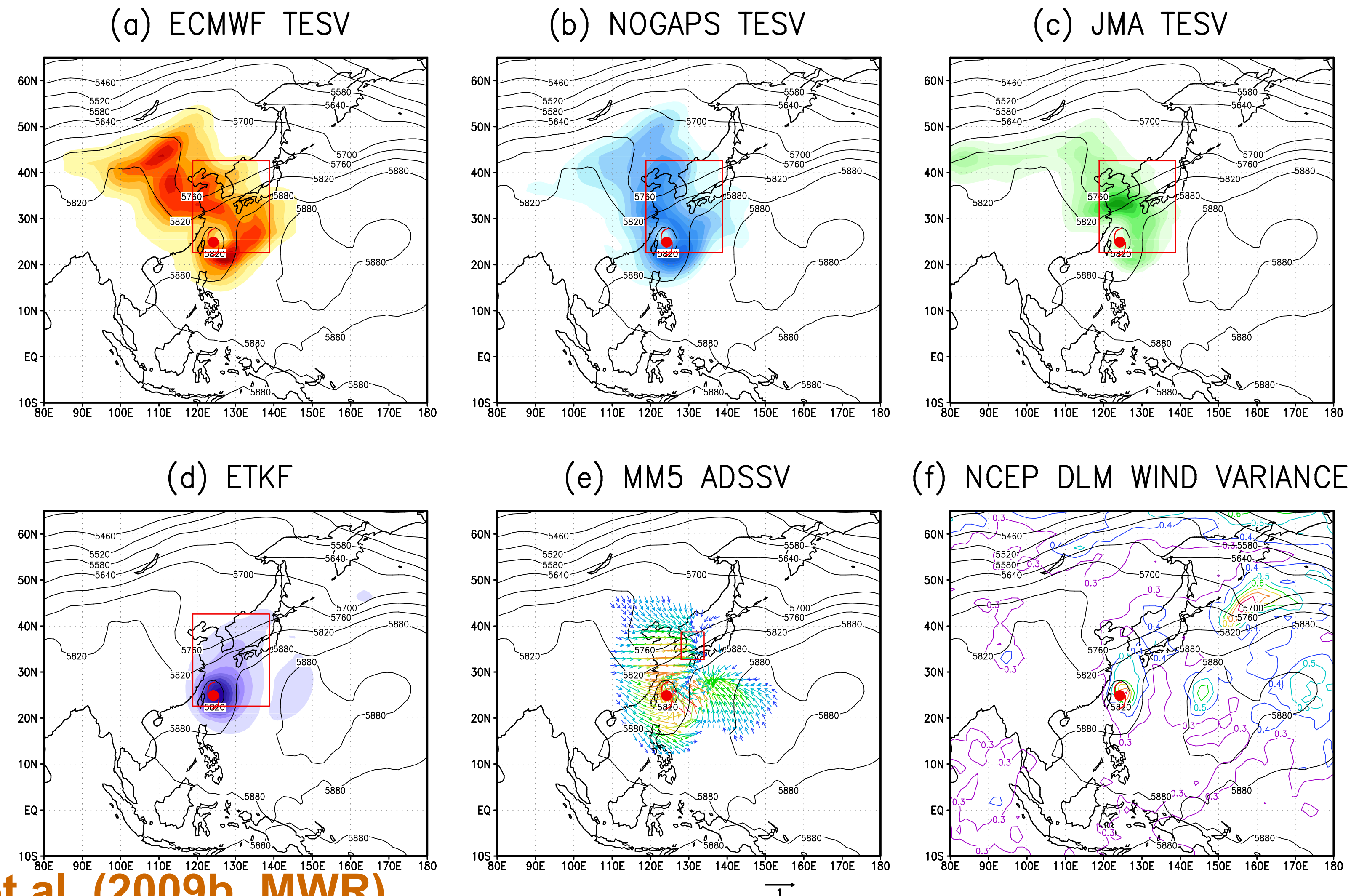
Common features: sub-tropical high



Wu et al. (2009b, MWR)

Common features: mid-latitude trough

#38 WP14Shanshan Ti=20060914 Ta=20060916



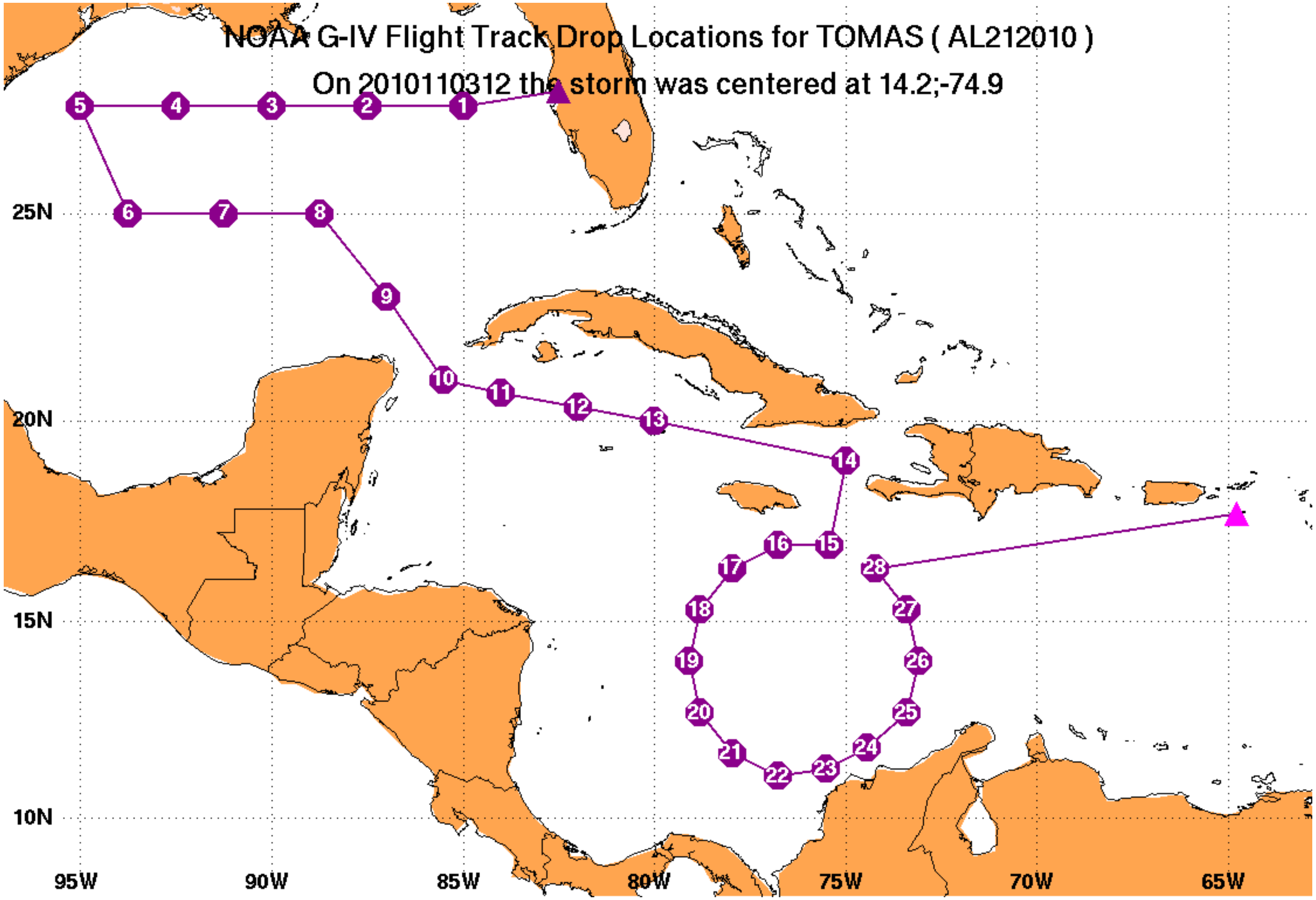
Wu et al. (2009b, MWR)

Outline of session

- History & Recommendations from IWTC-VI
- DOTSTAR & T-PARC
- Review of the different facets
- Recommendations

- Between 1982 and 1996, NOAA/HRD conducted 20 “synoptic flow” experiments.
  - Average error reductions in consensus forecasts from three dynamical models: 16-30%.
- In 1997, NOAA began operational synoptic surveillance with the G-IV jet aircraft.
  - 176 missions in first 10 years
  - 10-15% improvements in NCEP GFS track forecasts within the first 60 h (init. mission times)
  - Impact decreases after mission times
  - Fully operational since 2007
  - 10-year review in Aberson (MWR, 2010)

NOAA (US) Synoptic Surveillance



10-15% improvement of NCEP GFS track forecasts up to 60 h (Aberson 2010)

A brief history (NW Pacific)

- 2003: DOTSTAR began

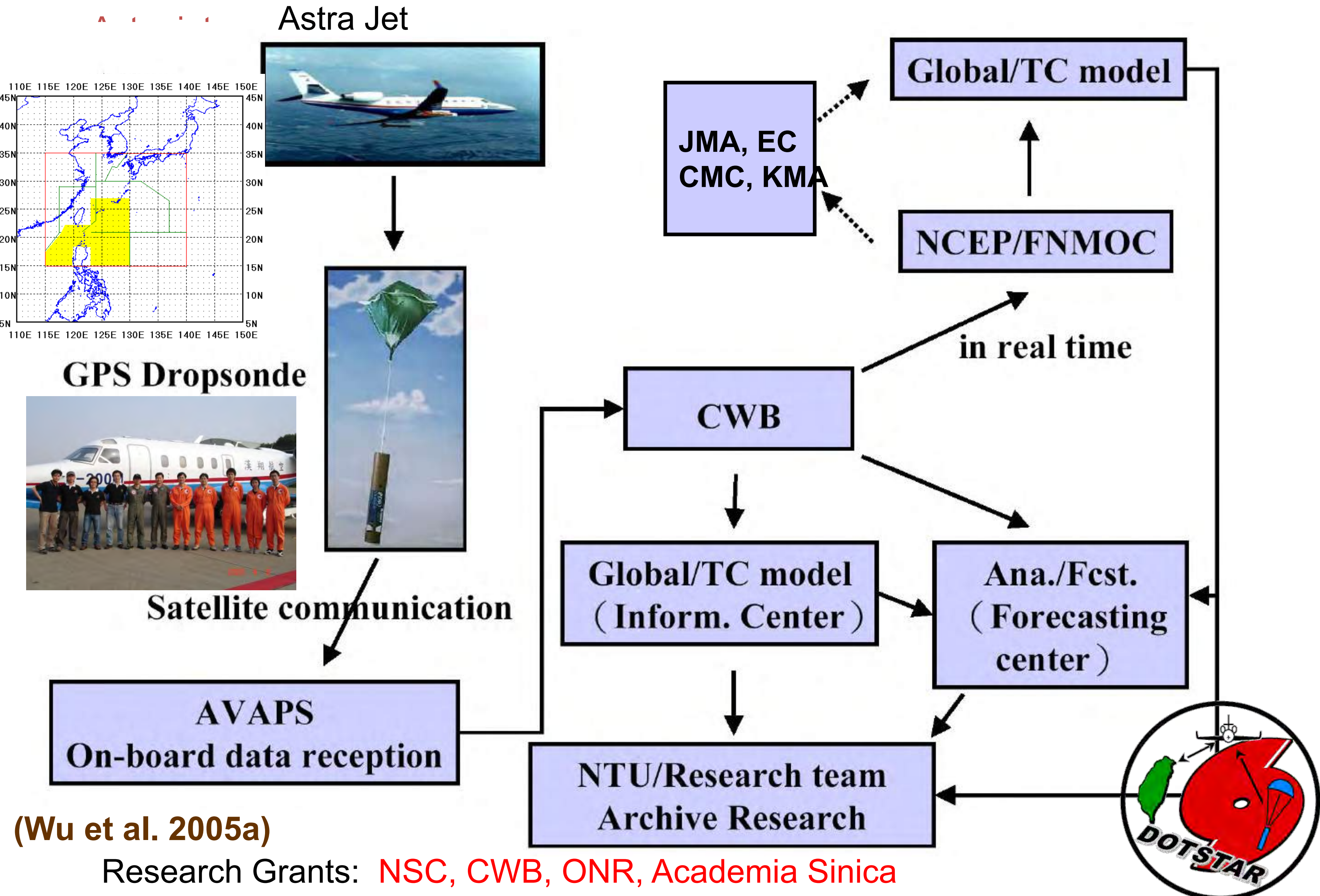
- 2008: THORPEX Pacific Asian Regional Campaign (T-PARC)

- 2010: ITOP

Dropwindsonde Observations for Typhoons near the Taiwan Region

(DOTSTAR)

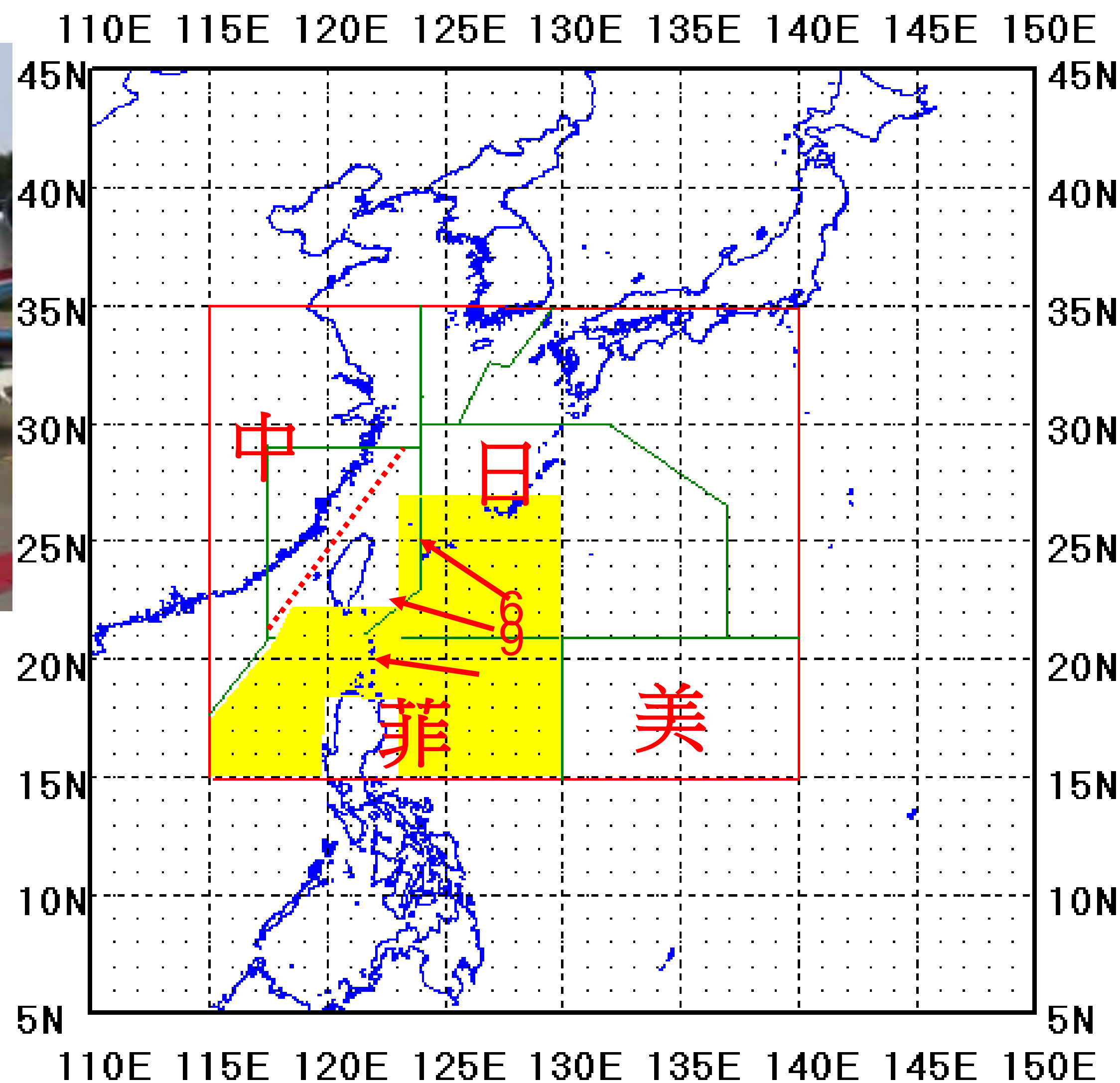
Dropwindsonde Observations for Typhoons near the Taiwan Region (DOTSTAR)



(Wu et al. 2005a)

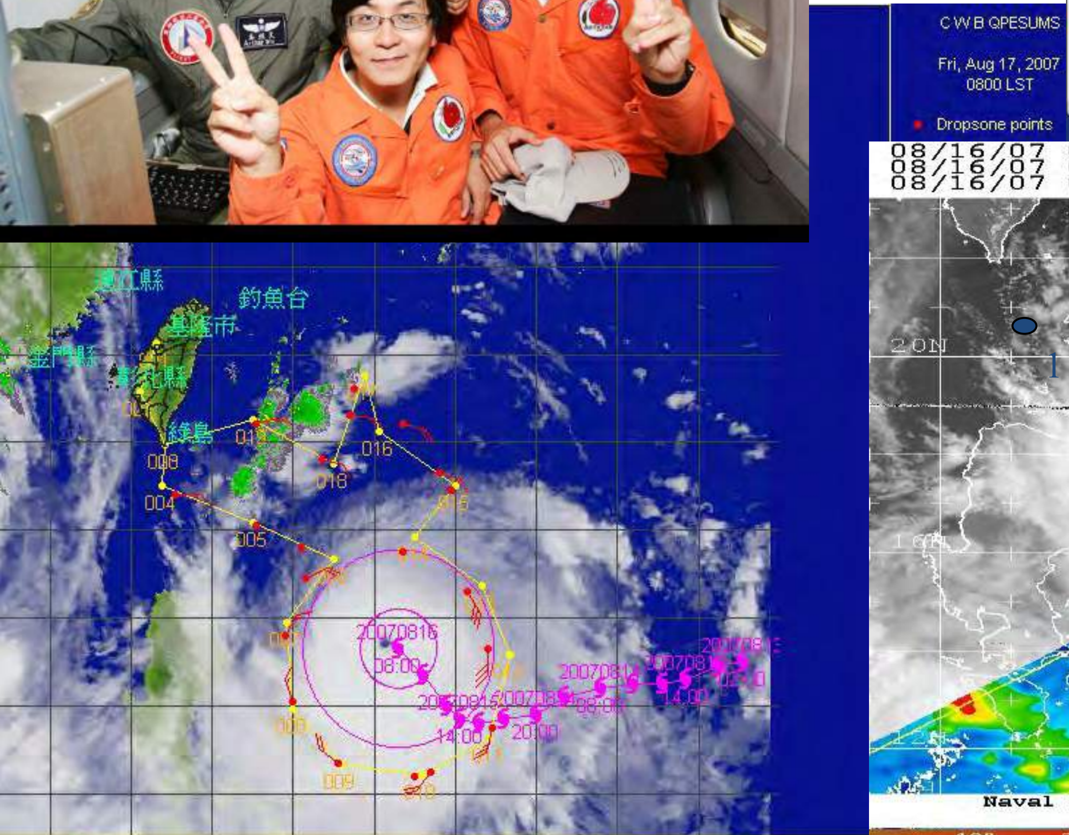
Research Grants: NSC, CWB, ONR, Academia Sinica

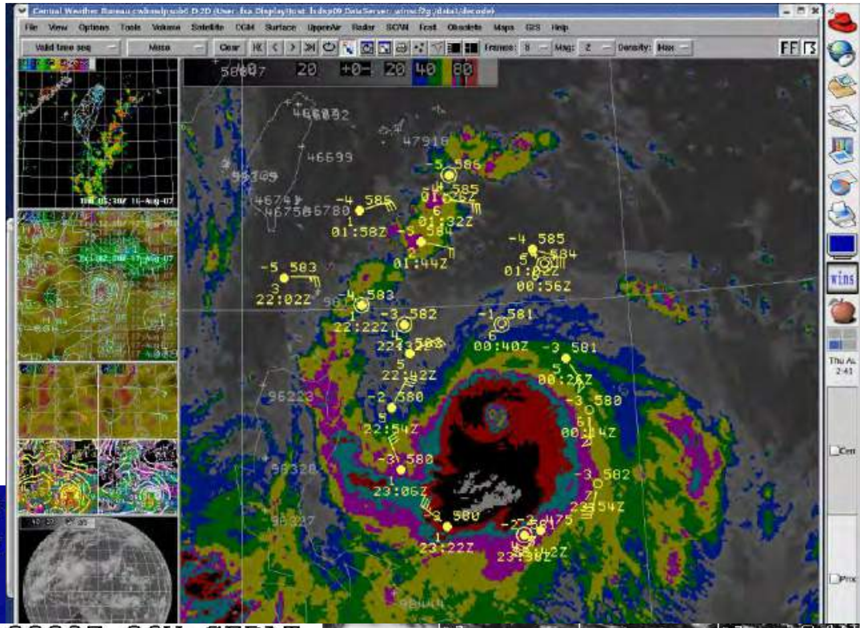
追風區域 – 航管問題 (FIR)

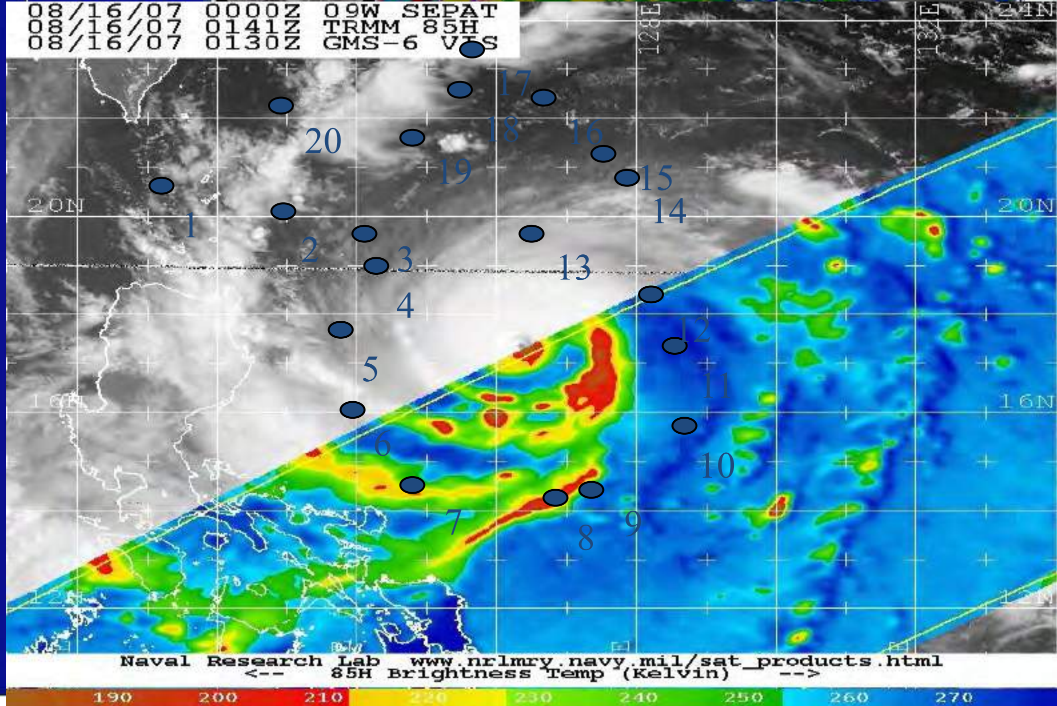


Real-time DOTSTAR data in CWB's WINS

Typhoon Sepat
2007/08/16/0000







摘自健康雜誌

標靶觀測

分鐘醫學教室：

什麼是標靶治療（Targeted Therapy）？

根據美國食品暨藥物管理局（FDA）對標靶治療的定義：使用標靶藥物的藥理機轉是針對某種已知並且確定的細胞標靶，或是介入訊息傳遞途徑，當拮抗這些標靶，或者是降低相關途徑活性後，可以減緩、甚至消除癌細胞及其進展惡化過程。

台北榮總胸腔腫瘤科陳育民醫師表示，標靶治療就像精確導彈，只鎖定癌細胞組織特有的作用機轉、療效增加、不傷害正常細胞，因此副作用較少。

原理大致可分三類：

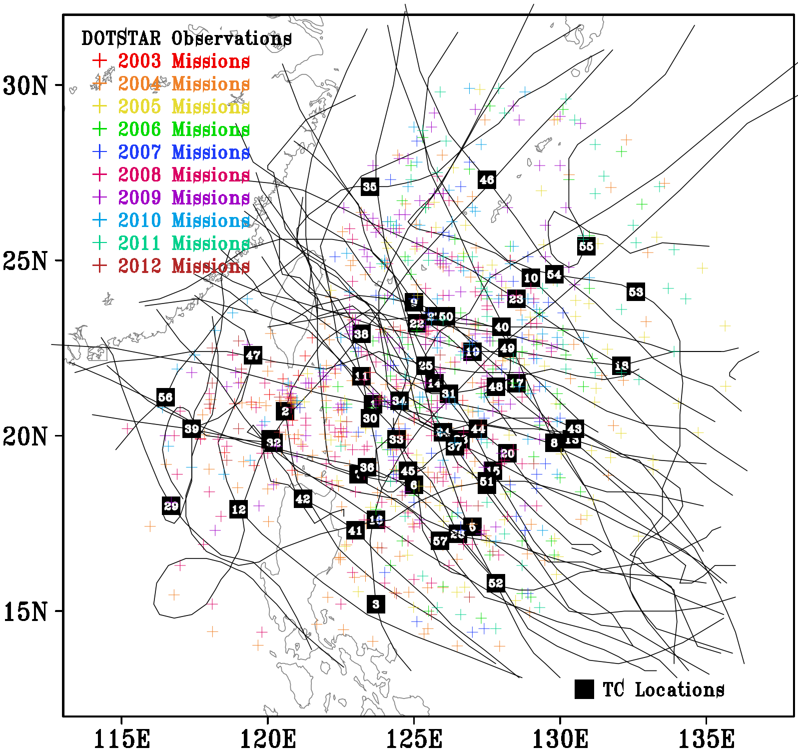
- **第一類是阻斷癌症訊息傳遞的小分子物質**，例如得舒緩（Tarceva）用於治療非小細胞肺癌，基利克（Glivec）用於治療慢性髓球性白血病與胃腸基質瘤，紓癌特（Sutent）用於腎細胞癌。
- **第二類是針對細胞表面抗原的單株抗體**，比如莫須瘤（Mabthera）用於CD20陽性惡性淋巴瘤，爾必得舒（Erbitux）用於頭頸癌、轉移大腸癌，癌思停（Avastin）用於大腸直腸癌，賀癌平（Herceptin）用於治療乳癌等。
- **第三類則是其他各類藥物**，如萬科(Velcade)是一種蛋白酶體抑制劑，可用於多發性骨髓癌。

醫生，我可以用標靶藥治癌嗎？

「我要標靶治療！」常是癌症病人急著跟醫生說的話。標靶藥物真能救命嗎？
在「命」與「錢」的拔河中，你該如何取得最佳效益？

文・張曉卉　攝影・[illegible]

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



Up to present, 61 missions have been conducted in DOTSTAR for 47 typhoons, with 993 dropwindsondes deployed during the 329 flight hours.

42 typhoons affecting Taiwan

32 typhoons affecting (mainland) China

9 typhoons affecting Japan

5 typhoons affecting Korea

14 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. (2010 JGR) Weissmann et al. (2010 MWR)

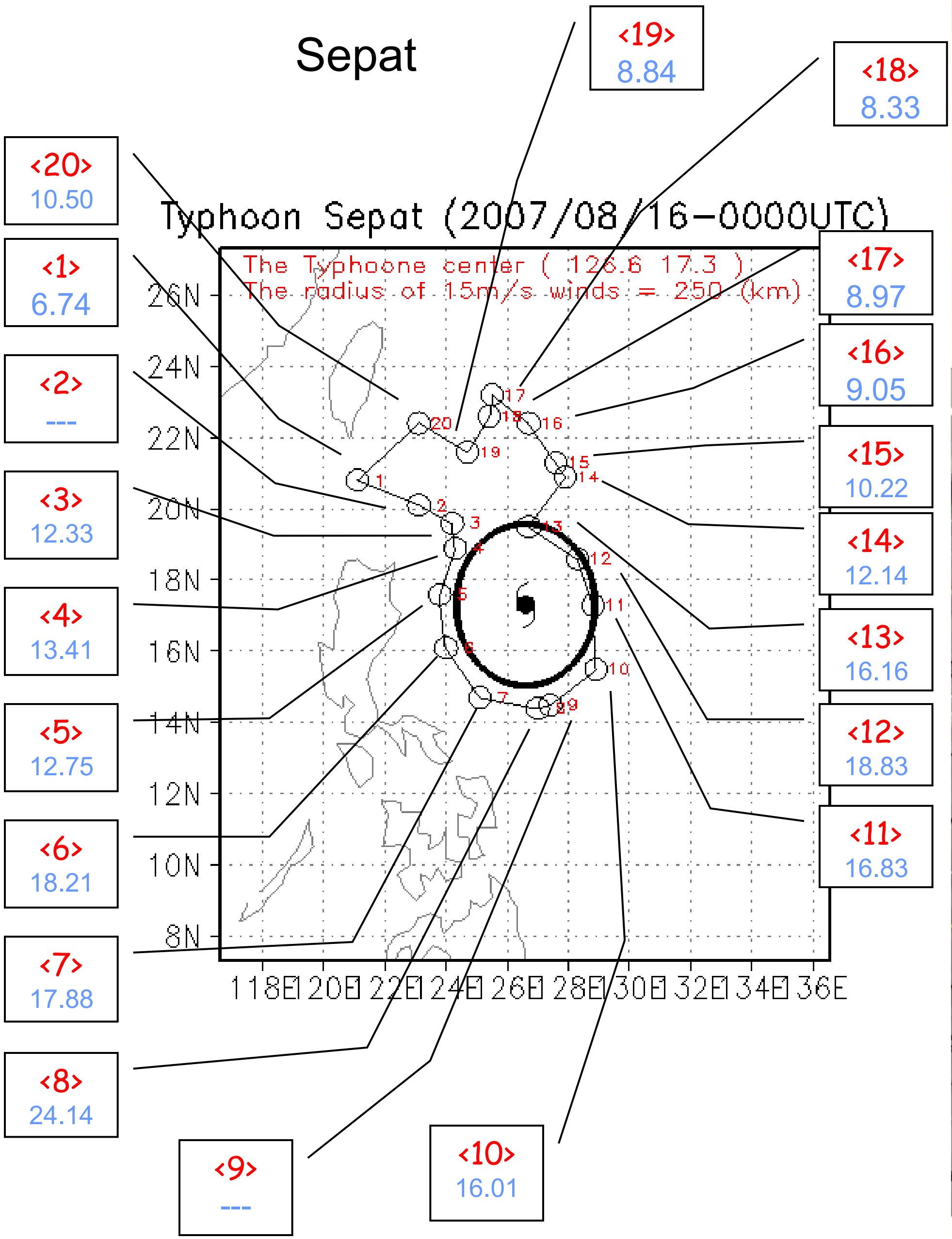
Biography:
Dotstar are a melodic indie/alt rock 4-piece based in Bridport, Dorset. We are currently on an ongoing tour the South West of England - check our website www.dotstarweb.com for tour dates, photos, mp3 demo downloads and more.

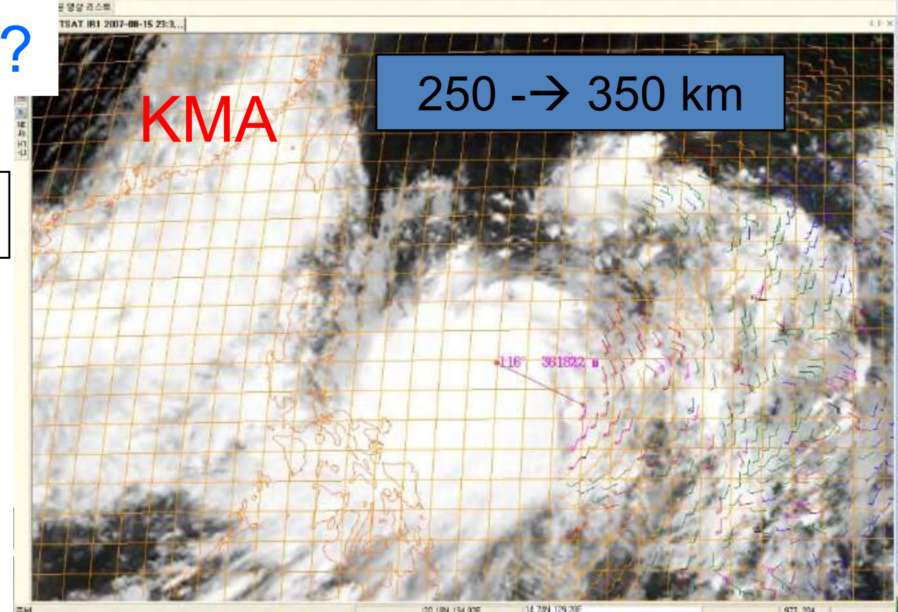
DOTSTAR team at NTU, 2007/10

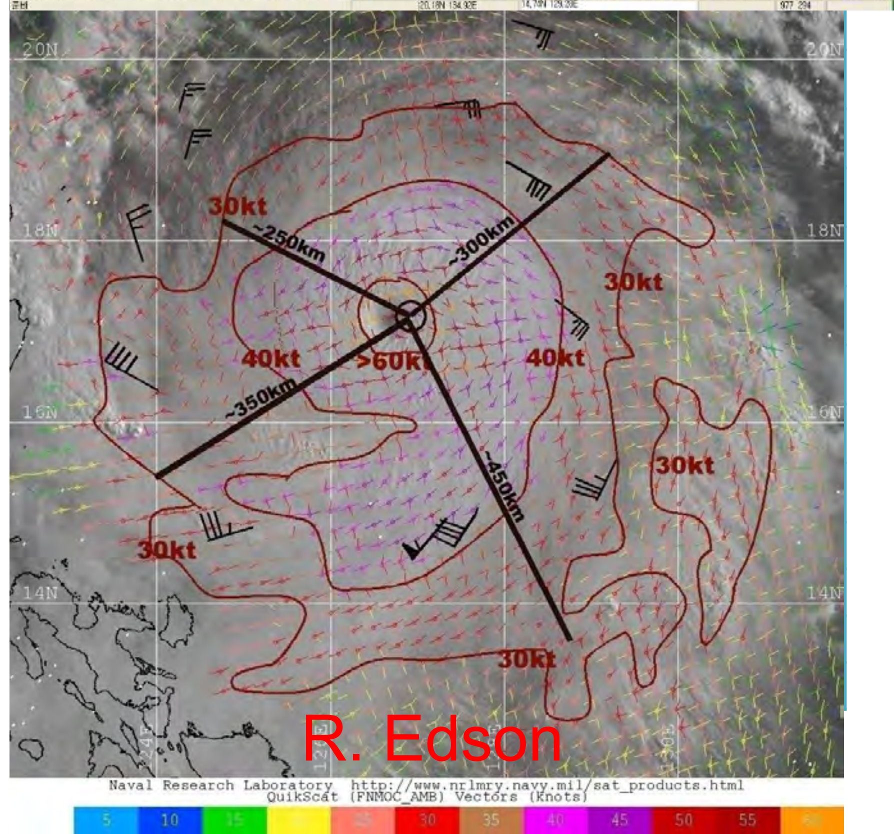
Photographed by Ya-Heng Lee

Team work in DOTSTAR

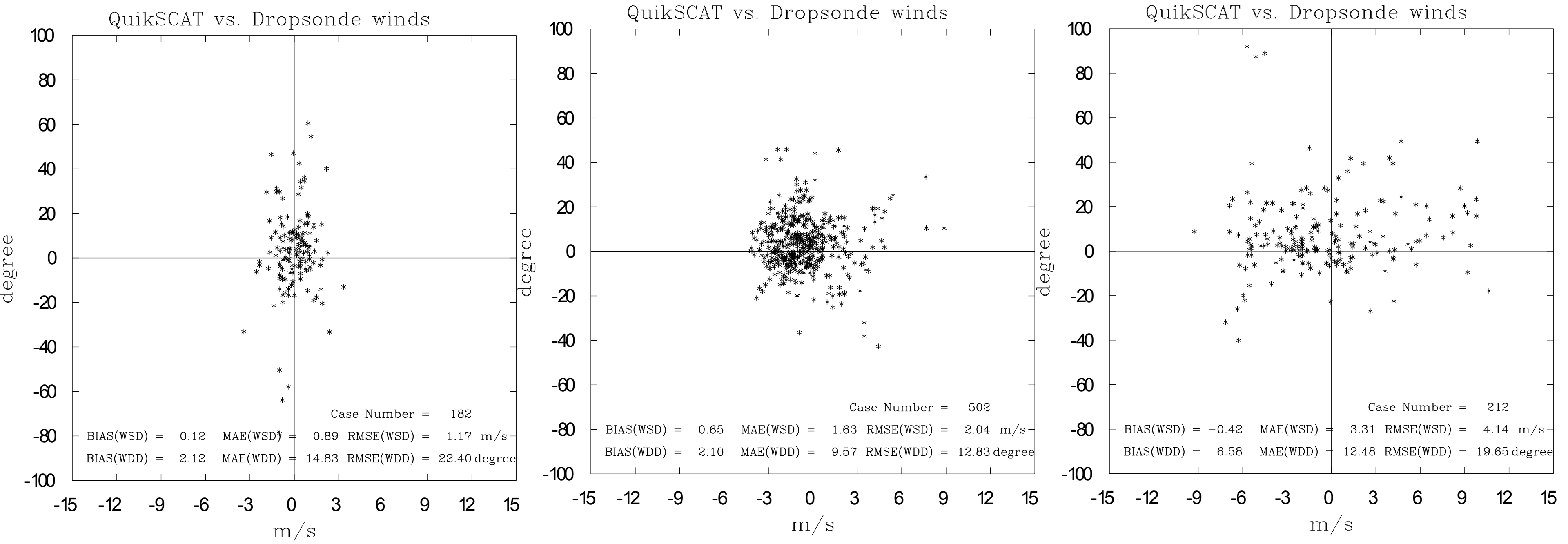
Radius of Gale-force wind?







Intercomparison of DOTSTAR data and QuikSCAT data Analysis of different wind regimes



V < 10.0 m/s	10.0 ≦ V < 17.2 m/s	V ≧ 17.2 m/s
RMSE: 1.2 m/s, 22.4˚	RMSE: 2.0 m/s, 12.8˚	RMSE: 4.1 m/s, 19.7˚

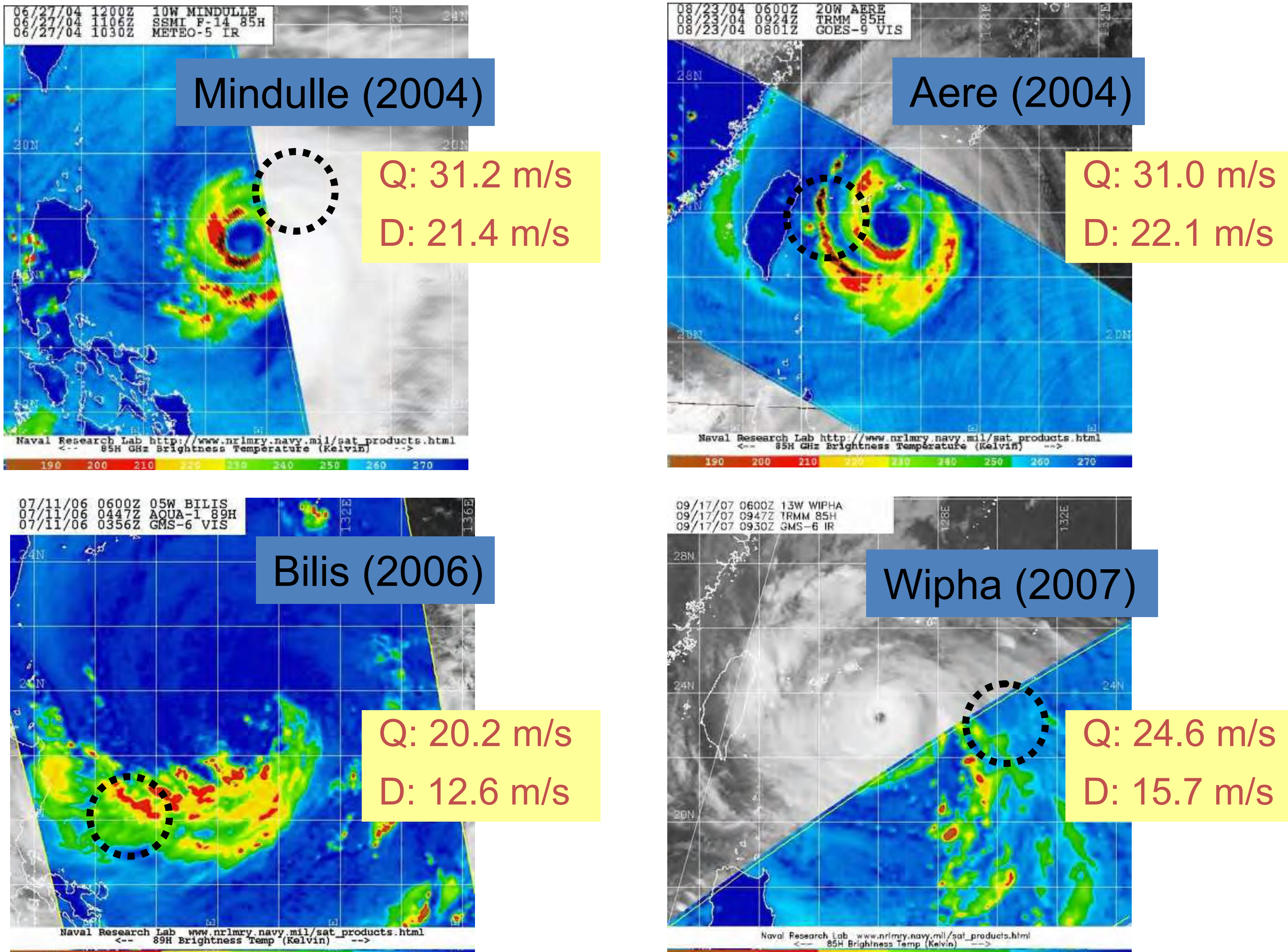
Large wind direction differences occur for low wind regimes, and large wind speed differences occur for higher wind regimes.

A systematic clockwise bias (~7˚) on wind direction can be found in locations of high wind; this result has not been discussed in literature.

Chou et al. 2010 JGR

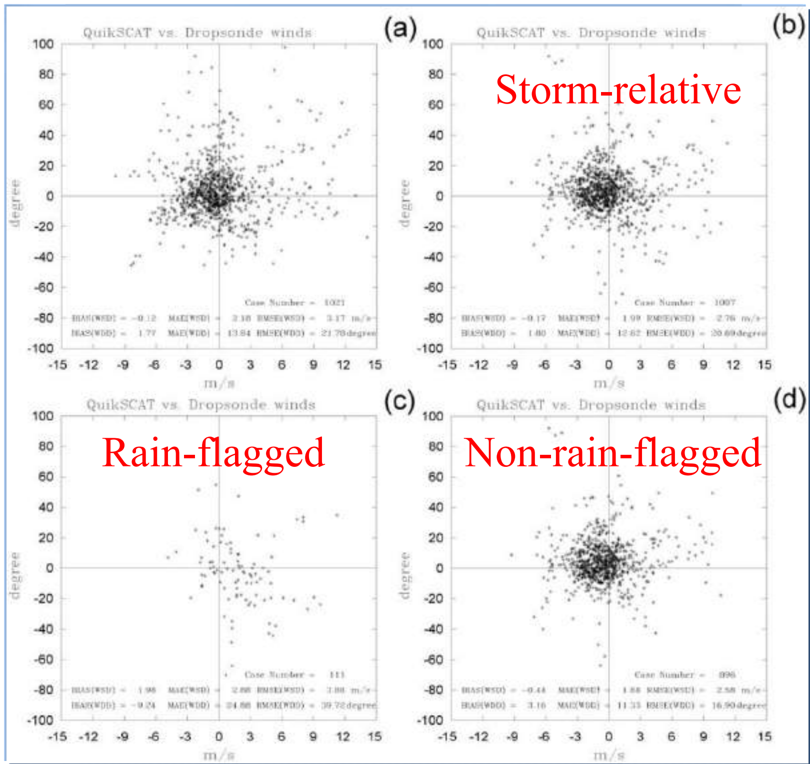
Intercomparison of DOTSTAR data and QuikSCAT data

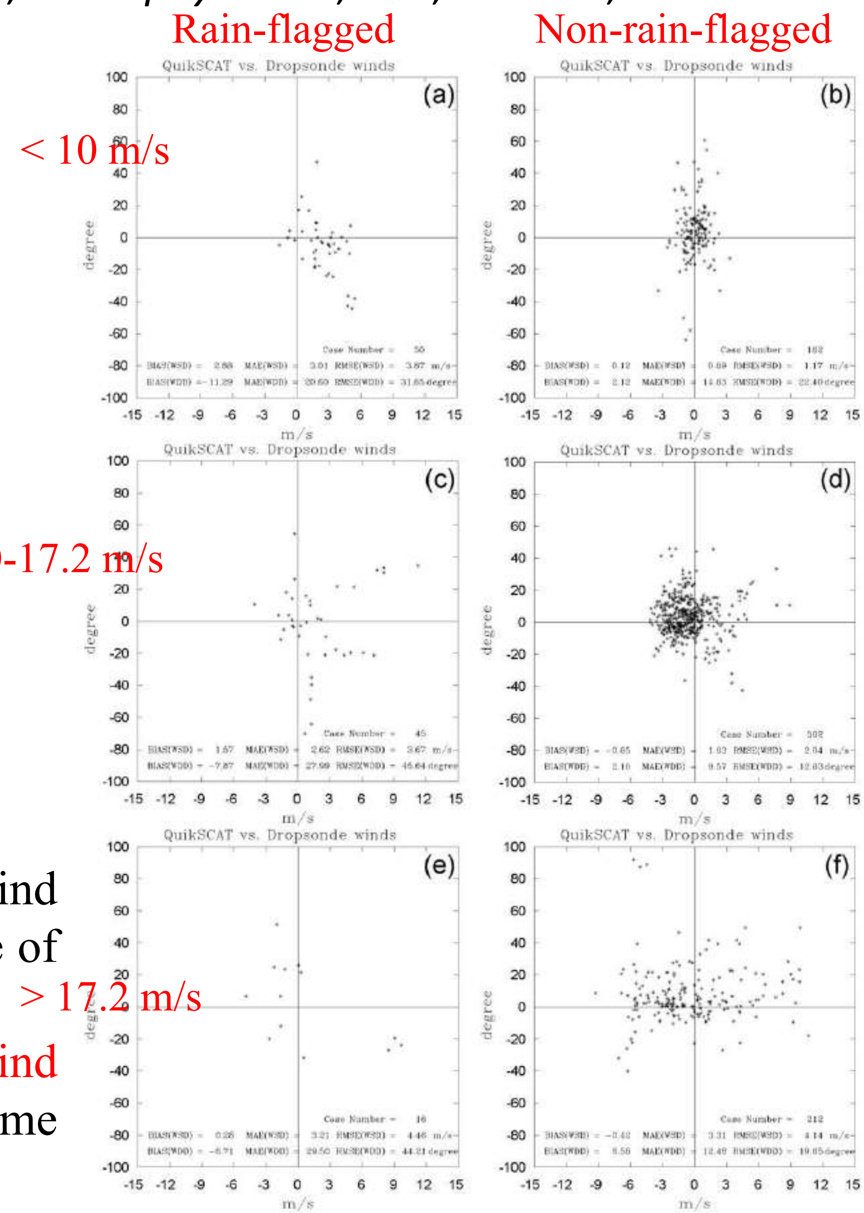
The current QuikSCAT processing algorithm did not effectively identify the narrow rain band structure is speculated.



Chou et al. 2010 JGR

- Chou, K.-H., C.-C. Wu*, P.-H. Lin, and S. Majumdar, 2010: Validation of QuikSCAT wind vectors by dropwindsonde data from Dropwindsonde Observations for Typhoon Surveillance Near the Taiwan Region (DOTSTAR), *J. Geophys. Res.*, **115**, D02109, doi:10.1029/2009JD012131.





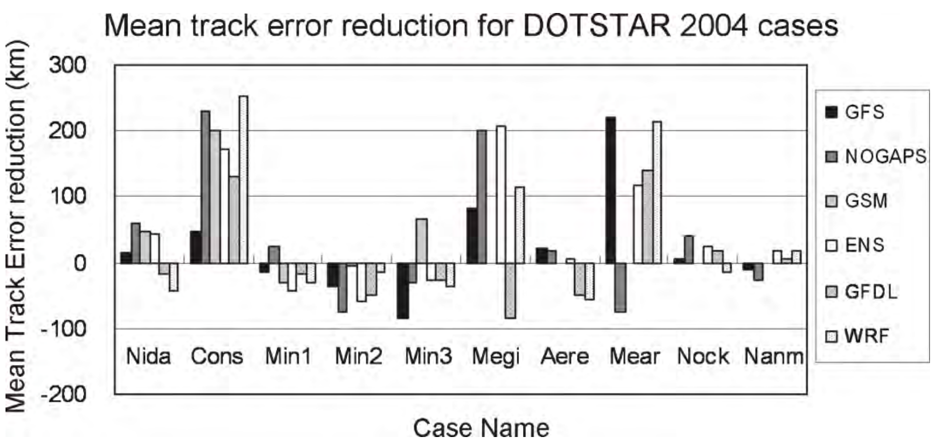
(Chou et al. 2010, JGR)

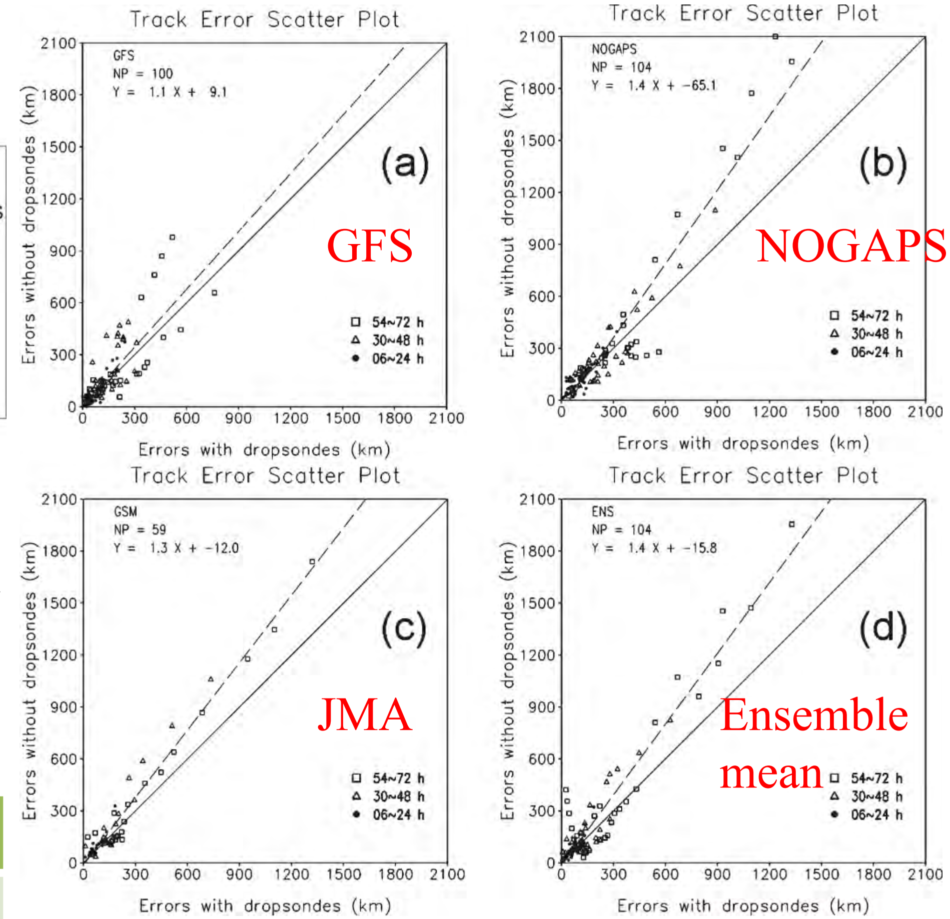
➢The absolute mean and RMS difference of wind speed are 2.2 and 3.2 m/s, respectively, while those of wind direction are 13.8° and 21.8°, respectively.

➢QuikSCAT data slightly underestimates the wind speed of medium-wind regime and possesses some clockwise directional bias in the high-wind regime.

- Wu, C.-C.*, K.-H. Chou, P.-H. Lin, S. D. Aberson, M. S. Peng, and T. Nakazawa, 2007: The impact of dropwindsonde data on typhoon track forecasts in DOTSTAR. *Weather and Forecasting*, **22**, 1157-1176.

(Wu et al. 2007, WF)





➢The impact of dropwindsonde data deployed in 10 missions for 8 typhoons during 2004 is evaluated with 5 models.

➢6–72-h mean track error reductions:

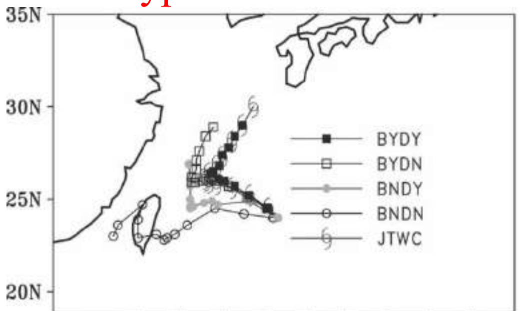
GFS	NOGAPS	JMA	WRF	GFDL
14%	14%	19%	16%	3%

➢Most of the points, as well as the regression line, are located to the upper left of the diagonal line, indicating that the model forecasts with the dropwindsonde data generally have smaller errors than do the denial runs, especially for points with large track errors.

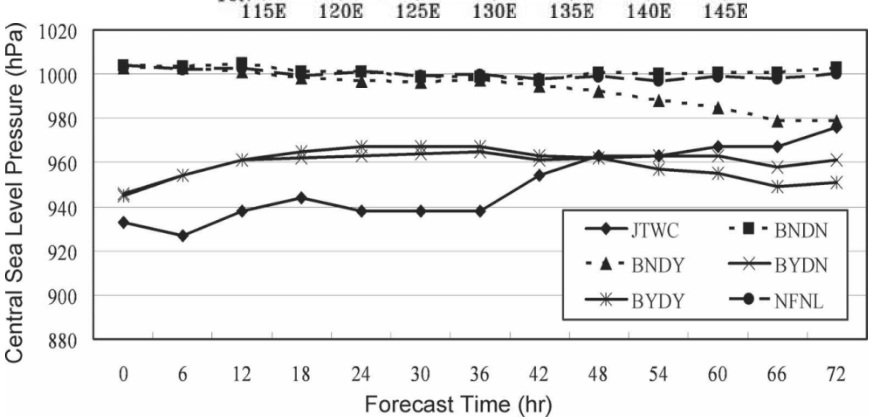
- Chou, K.-H., and C.-C. Wu*, 2008: Development of the typhoon initialization in a mesoscale model – Combination of the bogused vortex with the dropwindsonde data in DOTSTAR. *Mon. Wea. Rev.*, **136**, 865-879.

(Chou and Wu 2008, MWR)

Typhoon Meari

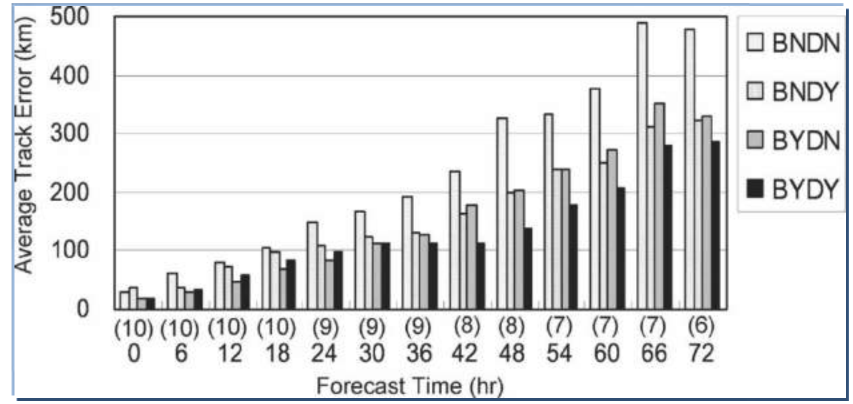


TIME	6h	12h	18h	24h	36h	48h	60h	72h	MEAN
BNDN(TE)	118	171	320	392	462	706	740	1263	576
BNDY(TE)	35	140	104	125	202	290	397	574	260
BNDY(TEI)	83	31	216	267	260	416	343	689	316
BYDN(TE)	25	25	25	45	91	145	237	311	130
BYDN(TEI)	93	146	295	347	371	561	503	952	446
BYDY(TE)	11	25	59	70	55	22	40	134	52
BYDY(TEI)	107	146	261	322	407	684	700	1129	524

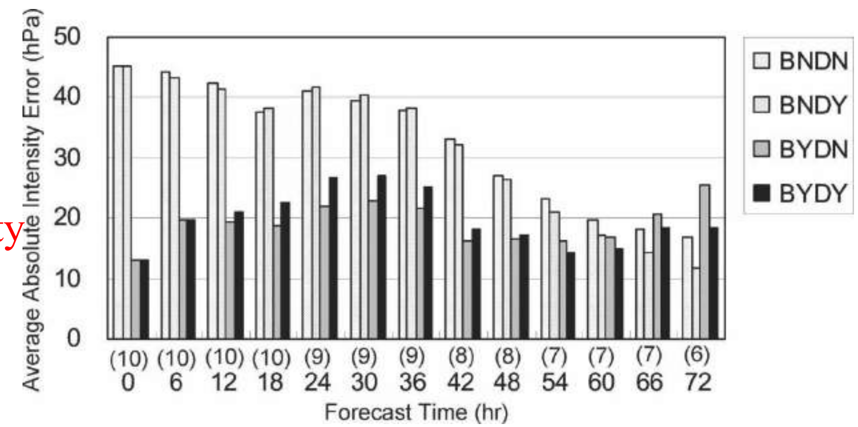


10 cases in 2004

Track



Intensity



➢The track and intensity forecasts for Typhoon Meari (also for Conson and Megi) are much improved by the proposed new method (with dropwindsondes and with the bogused vortex).

➢The average track and intensity error can be reduced by 40% and 30%, respectively, for all 10 cases in 2004 with using the bogused vortex and the dropwindsonde date.

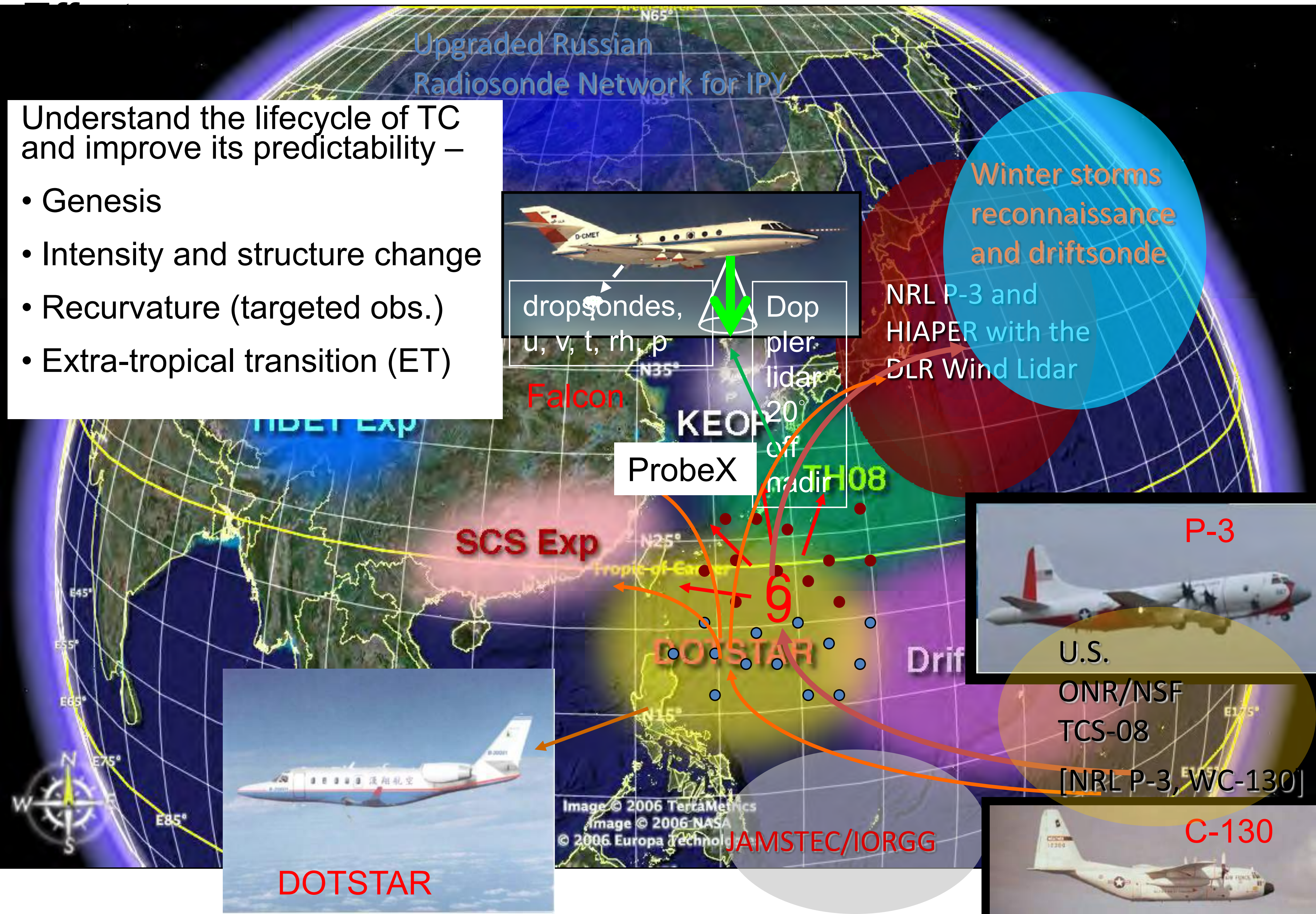
T-PARC:
DOTSTAR, TCS-08, TH-08

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

THORPEX-PARC Experiments (2008) and Collaborating

Understand the lifecycle of TC and improve its predictability –

- Genesis
- Intensity and structure change
- Recurvature (targeted obs.)
- Extra-tropical transition (ET)



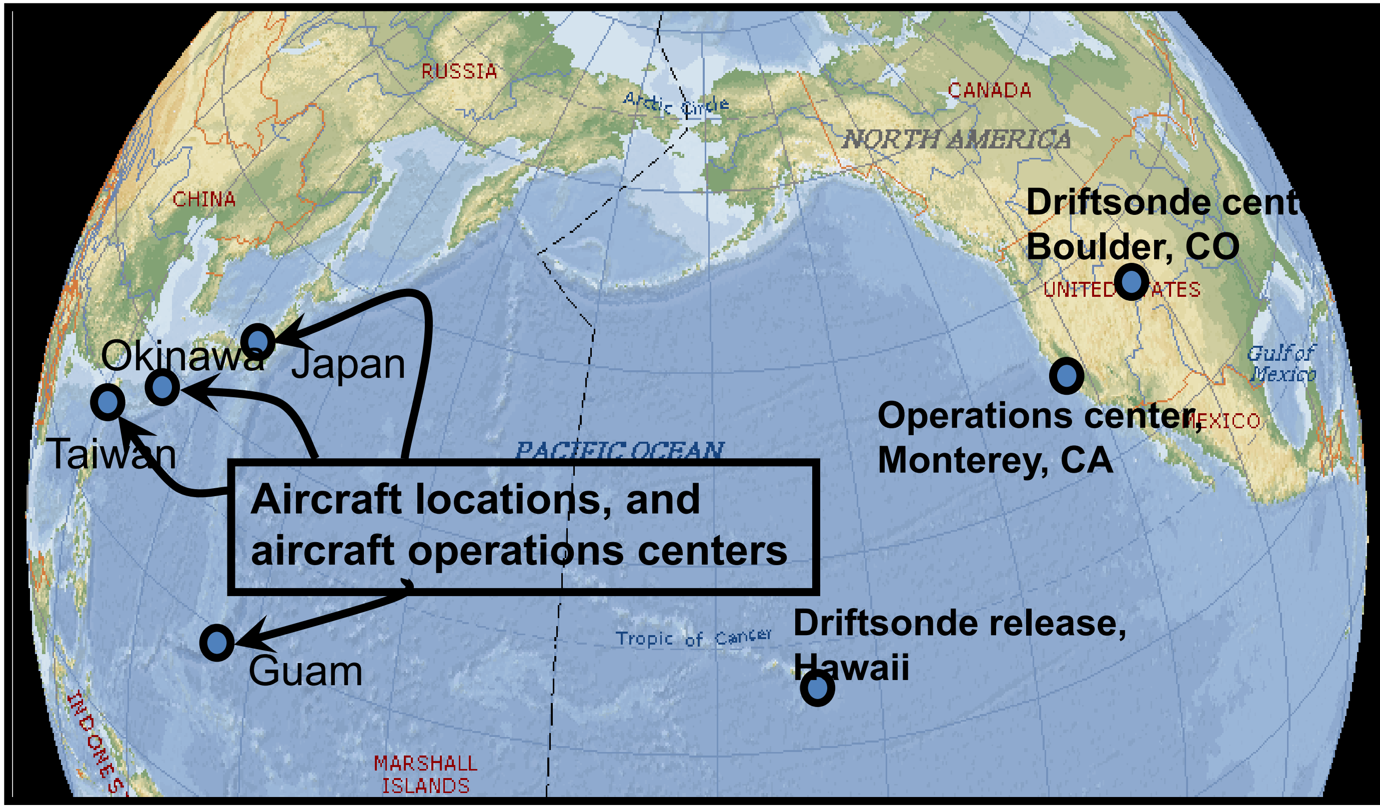
T-PARC Operations Support
Science Leadership

T-PARC planning meeting, Japan, 2008

Science Steering Committee (SSC)

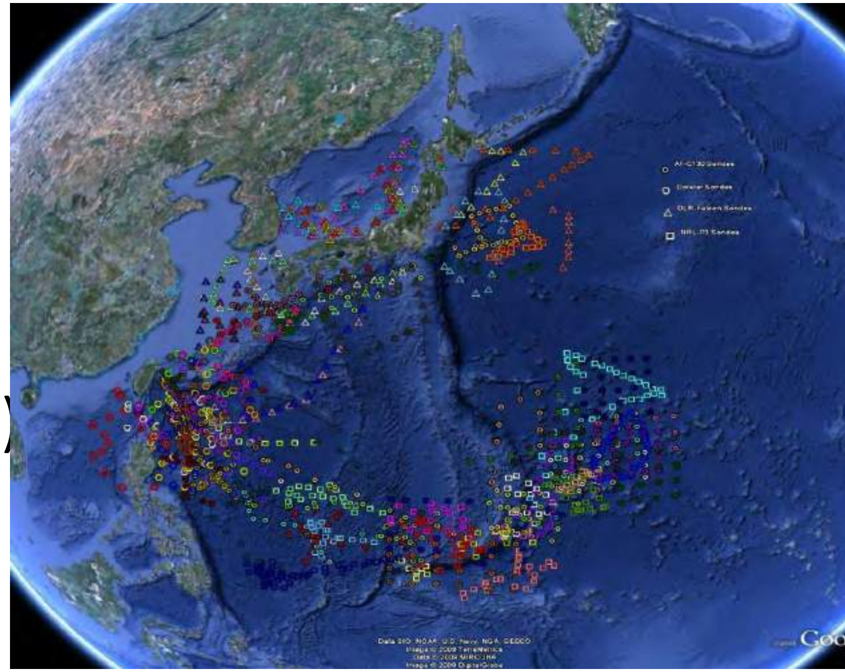
Chair: Harr (US), Co-Chairs: Nakazawa (Japan), Weissmann (German), TCS-08 Rep: Elsberry Korea: Lee, PRC: Chen, Canada: McTaggart-Cowan, Ex-Officio: Moore (NCAR), Parsons (WMO), Wu (DOTSTAR), Toth (NCEP).

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



Operations: Aircraft

- NRL P-3 (10 August – 3 October)
  - 23 missions
  - 165 hours
- WC-130J (1 August – 30 September)
  - 24 missions
  - 215 hours
- DLR FALCON (25 August – 1 October)
  - 24 missions
  - 10 single mission days
  - 7 days in which two missions were flown
  - 85 hours
- DOTSTAR (July – October)
  - 10 missions
  - 51.8 hours



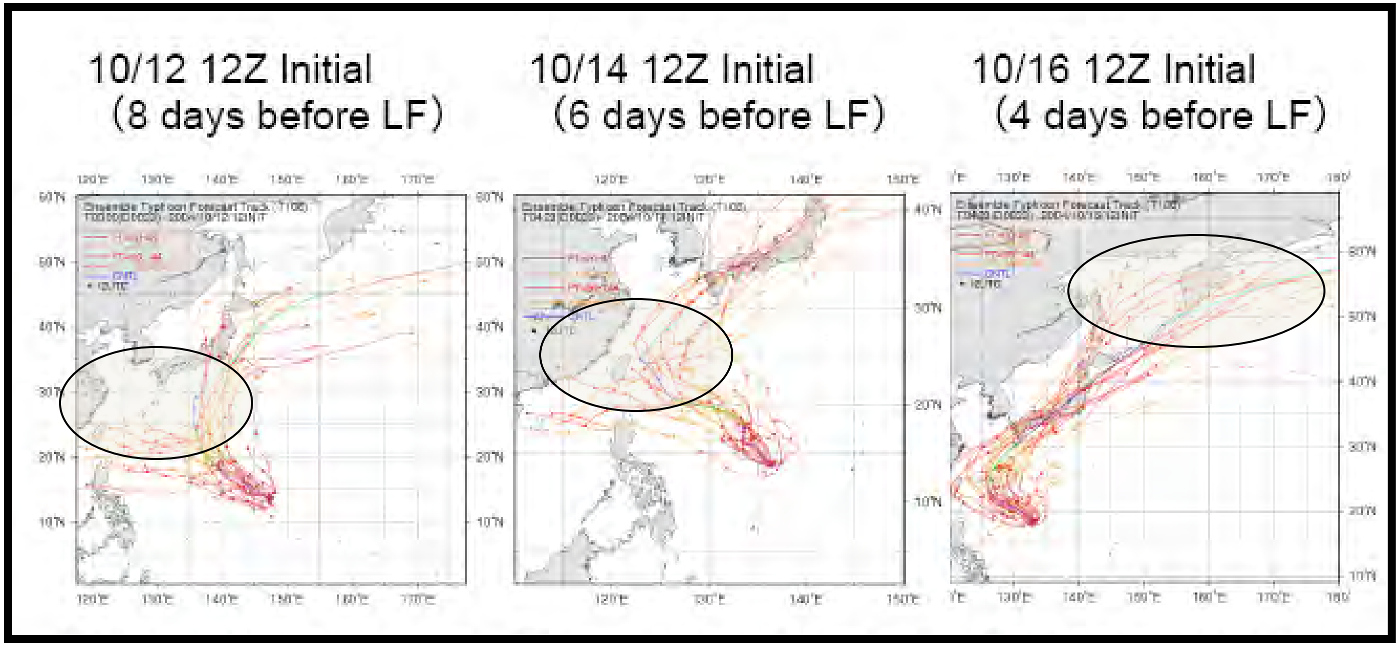
Courtesy of Blake Arensdorf

- **Total: 507 h, 81 missions, 1448 dropwindsondes**

What are the key structural aspects of the tropical cyclone and its environment that limit the predictability of recurvature and the start of extratropical transition over the subtropical western North Pacific?

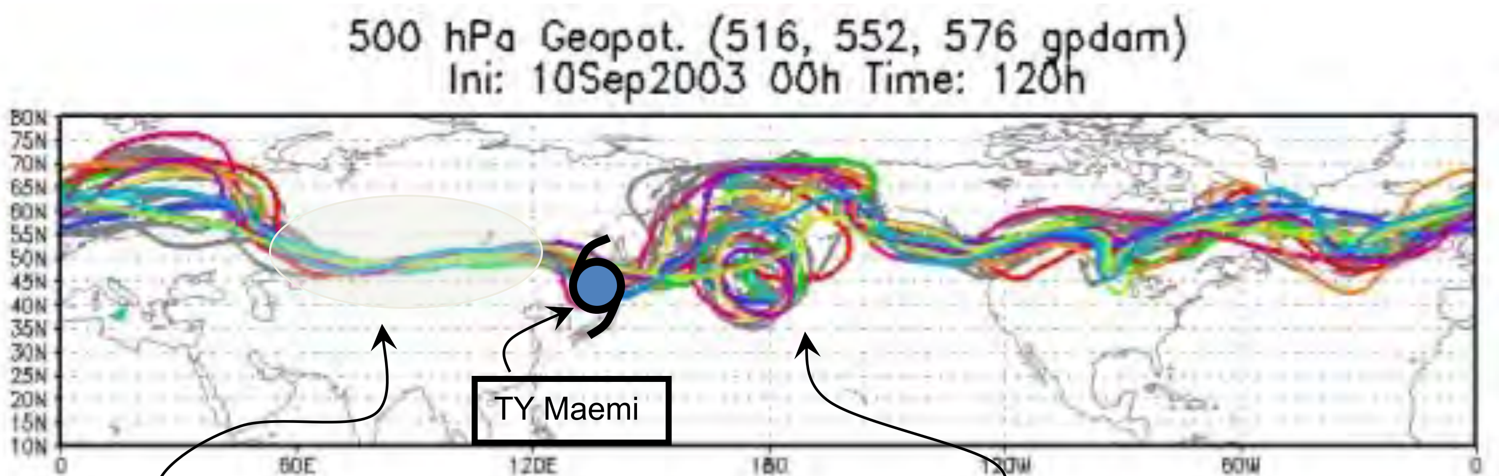
Increase in forecast uncertainty over tropical and midlatitude regions often occurs due to tropical cyclones and the movement of tropical cyclones into the midlatitudes

TY Tokage, October 2004
Tracks from the JMA ensemble prediction system



Tracks supplied by Dr. T. Nakazawa

Ensemble Prediction System from the European Center for Medium Range Weather Forecasts (ECMWF)
5-Day Forecasts associated with the Extratropical Transition of TY Maemi (2003)

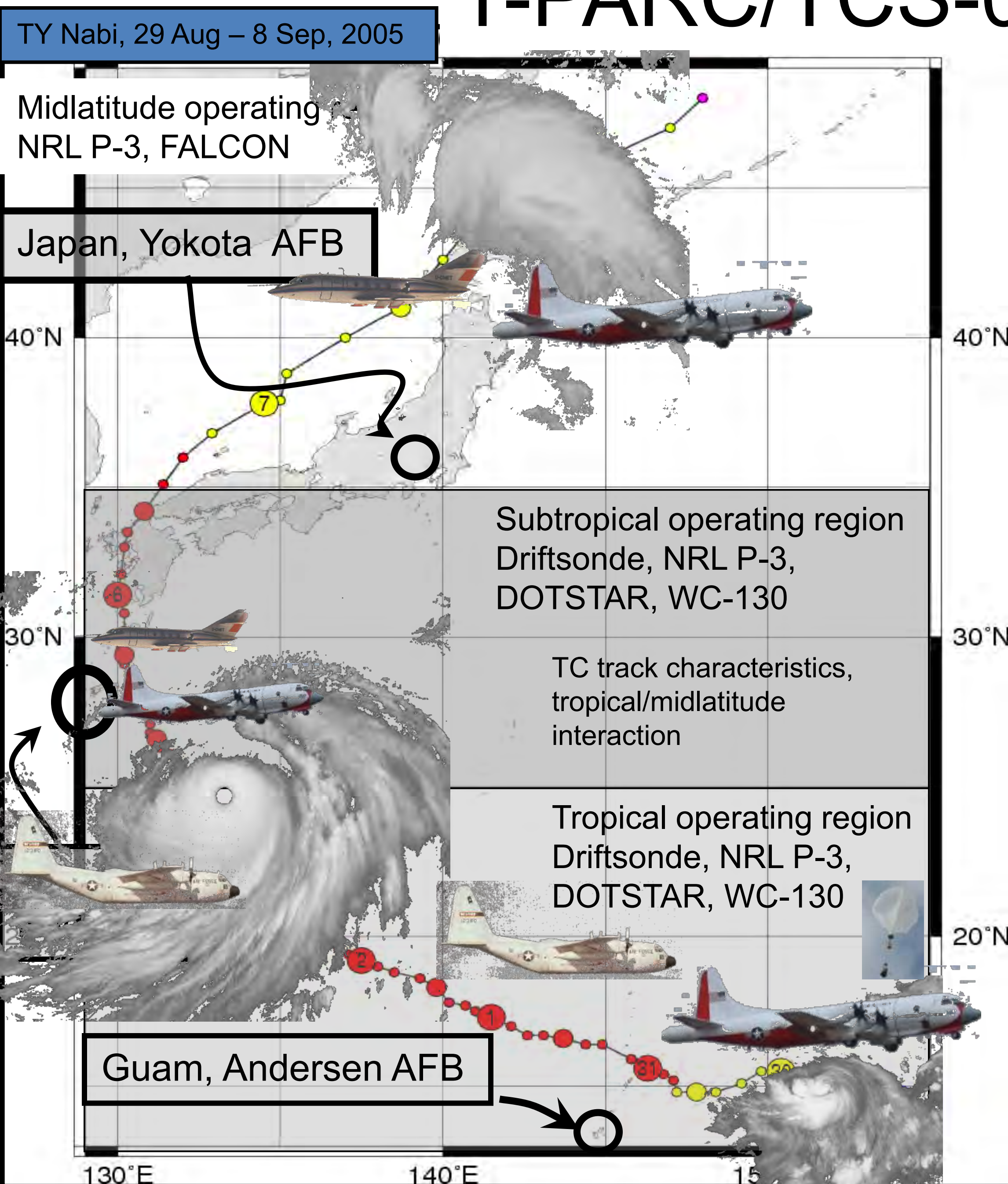


Agreement among members implies high predictability

Large spread among members implies decreased predictability

Graphic supplied by Prof. S. Jones and D. Anwender

T-PARC/TCS-08 Components



Extratropical Transition (ET – recurvature), Downstream Impacts

ET characteristics, forcing of downstream impacts, tropical/midlatitude interactions, extratropical cyclogenesis

TC Intensification and structure change

Recurvature, initiation of ET

Tropical Measurements

Large-scale circulation,
deep convection,
monsoon depressions,
tropical waves,
TC formation

From Pat Harr

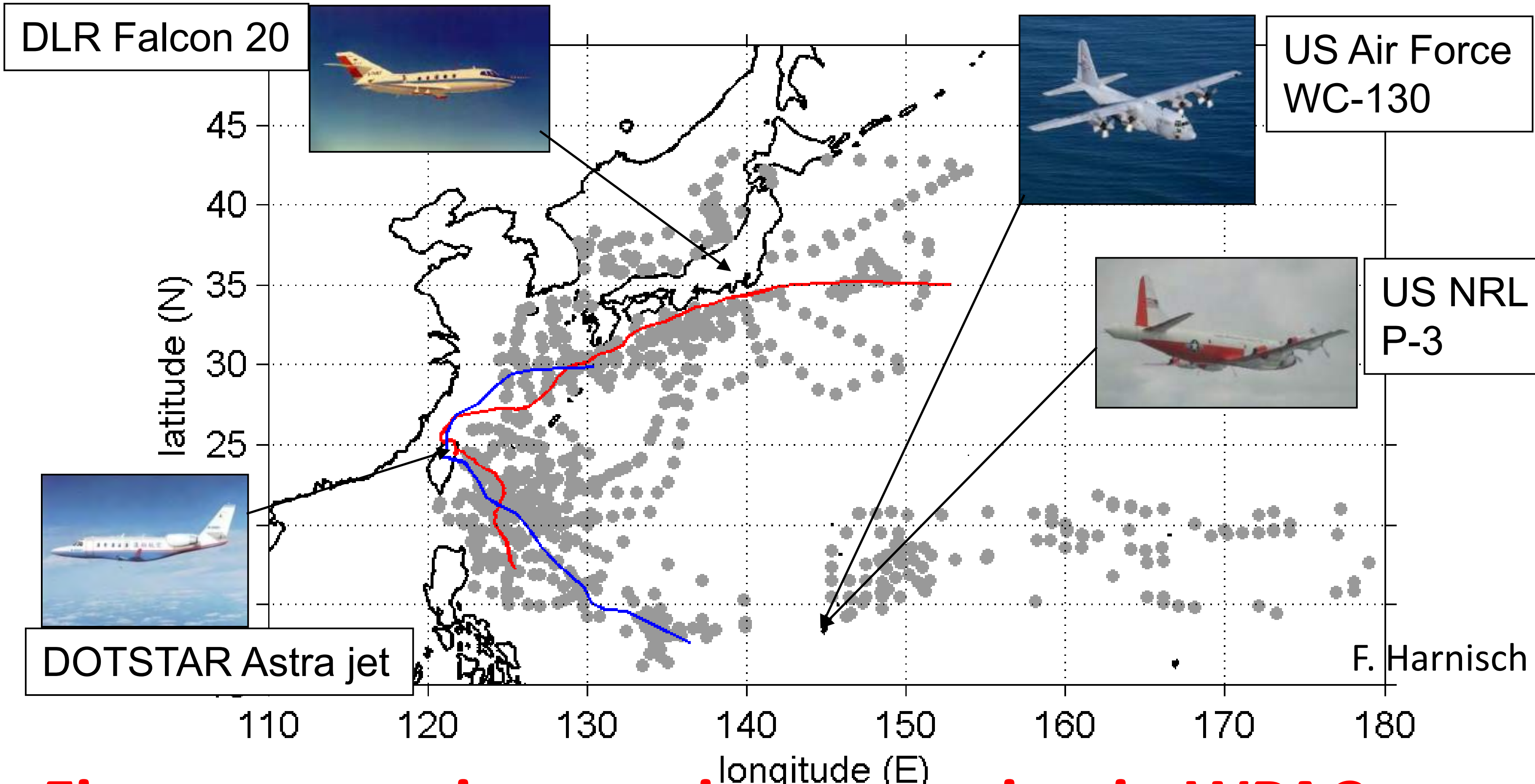
The Perfect Storm for Aircraft Obs

- Day 1 WC-130 and P-3 fly genesis
- Day 2 WC-130 and P-3 fly genesis
- Day 3 WC-130, P-3 and DOTSTAR intensification and structure
  - forward deploy to Okinawa
- Day 4 WC-130 and P-3 down time
- Day 4 Falcon and DOTSTAR fly recurvature and targeting
- Day 5 Falcon, WC-130 and P-3 fly ET
- Day 6 Falcon, and P-3 fly ET

From Pat Harr

Real time targeted observation guidance
For DOTSTAR, TH08, and T-PARC

http://typhoon.as.ntu.edu.tw/DOTSTAR/English/home2_english.htm

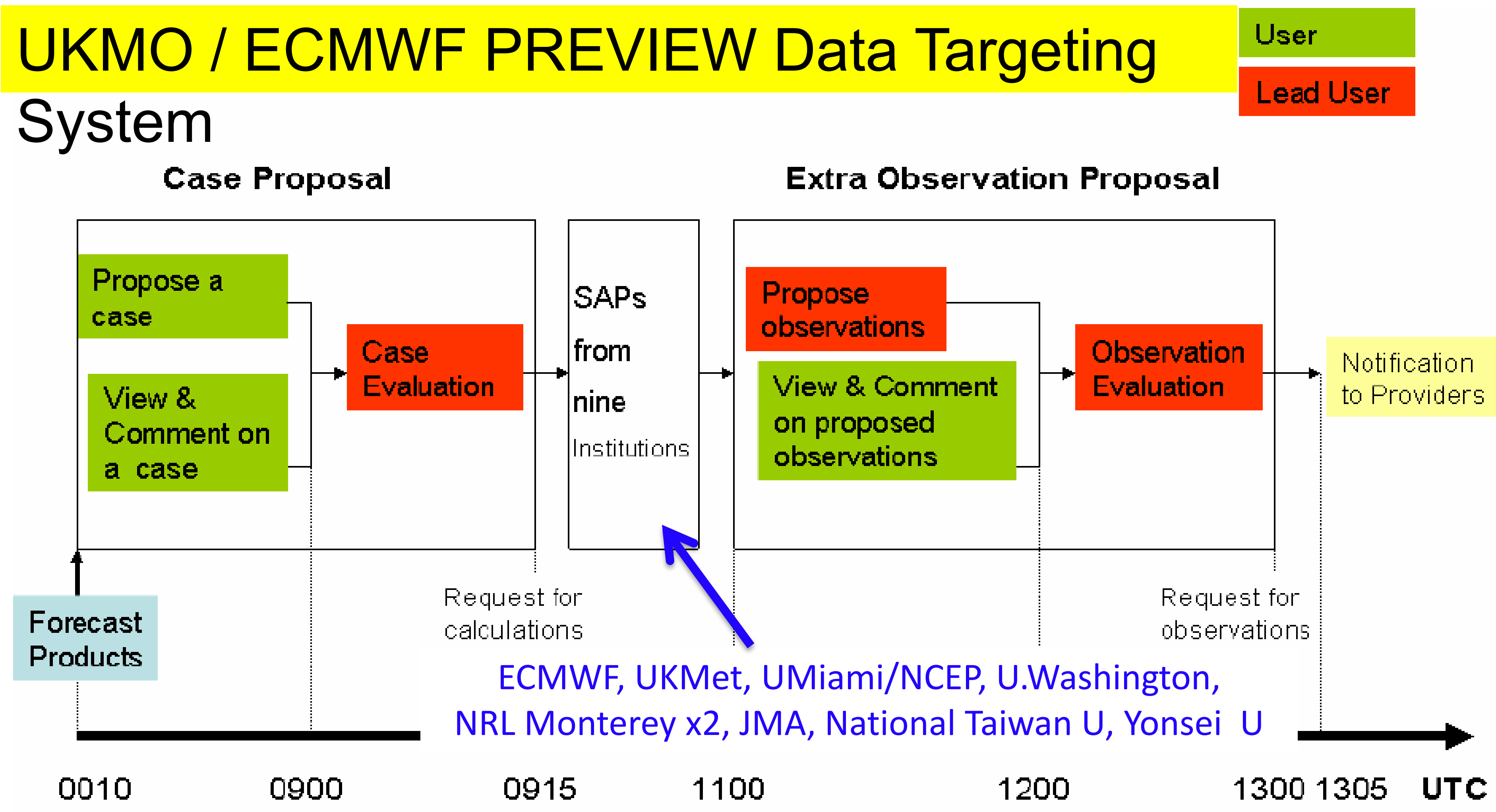


First systematic targeting operation in WPAC
1 August – 30 September 2008

Multiple aircraft (up to 2 for targeting + 2 for structure missions)
Comparison of several targeting methods
ECMWF/UKMO Data Targeting System

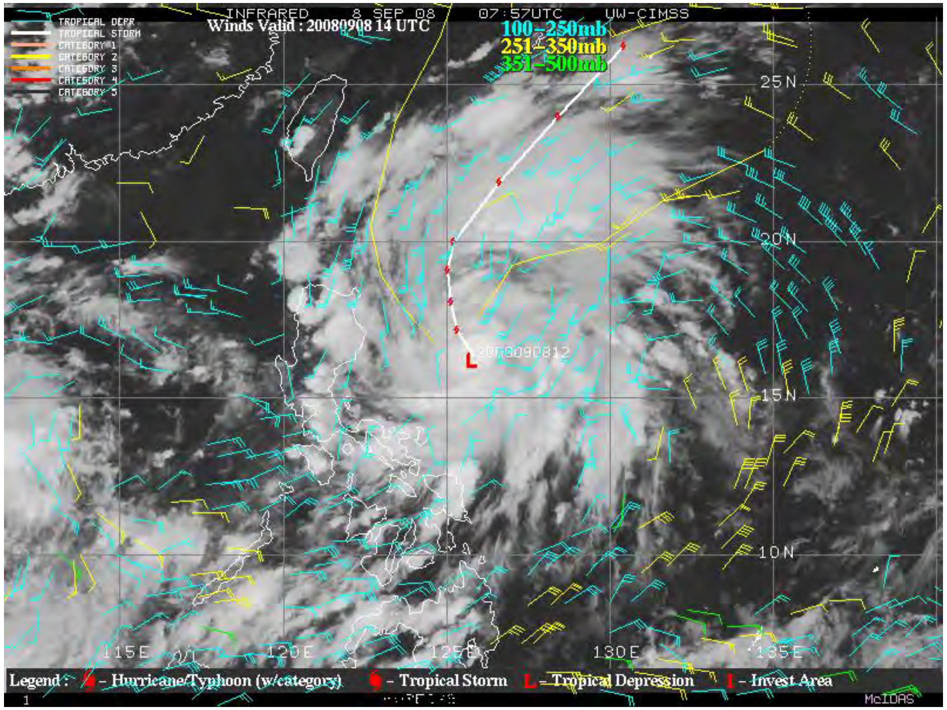
DOTSTAR + Falcon + P3 + C130,
52h + 85h + 165h + 215h = 507h flight hours, unprecedented!
173 + 328 + 604 + 343 = 1448 dropwindsondes

UKMO / ECMWF PREVIEW Data Targeting System



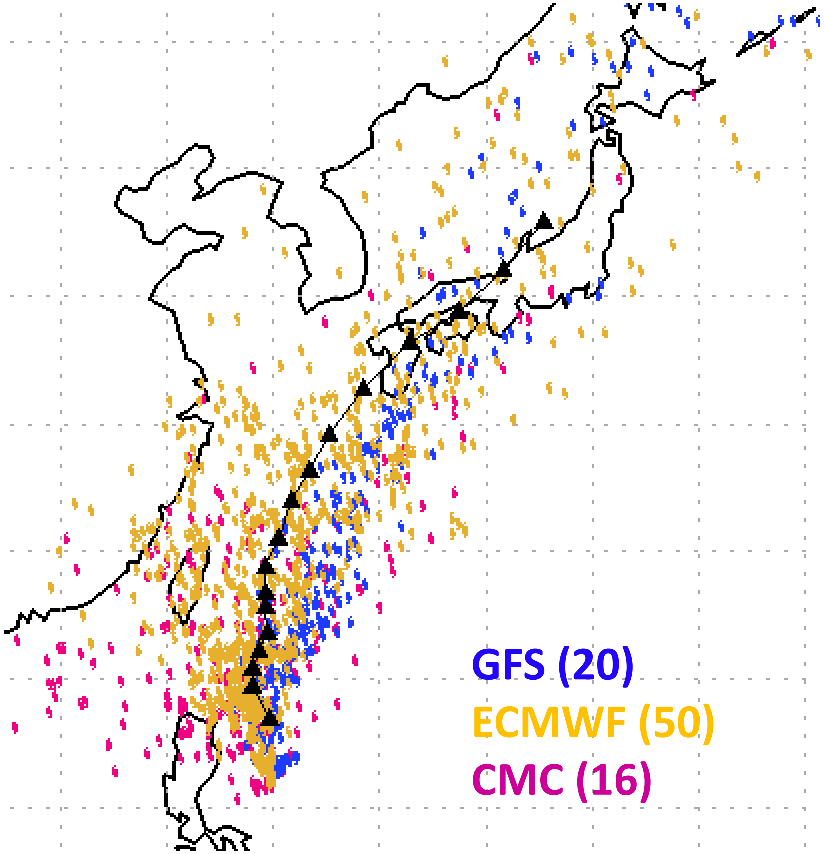
Sinlaku. Concept for Targeting Operations. 21 UTC, 20080908

Potential threat of TC to land

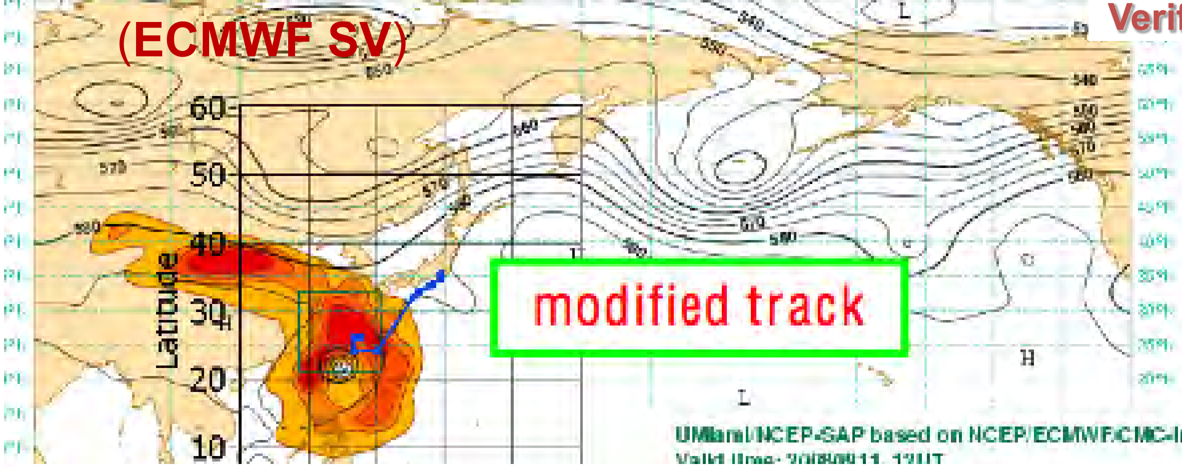


Courtesy CIMSS/U.Wisconsin

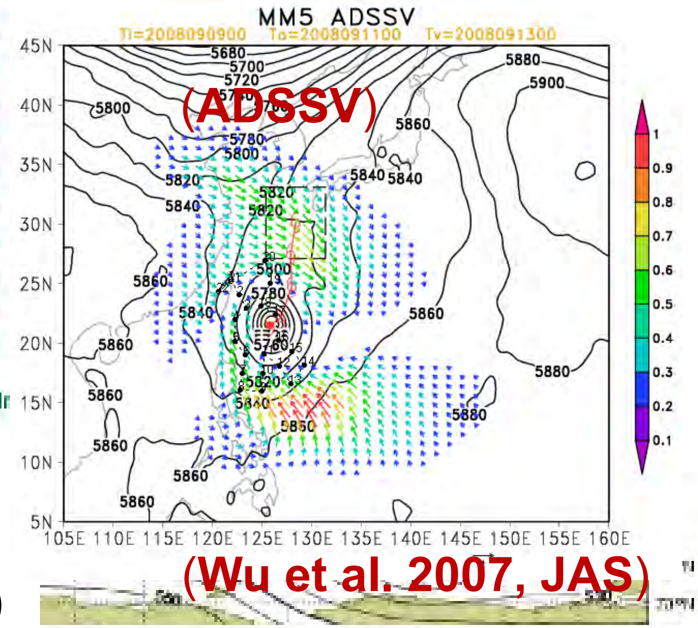
Uncertainty in ensemble track forecasts



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

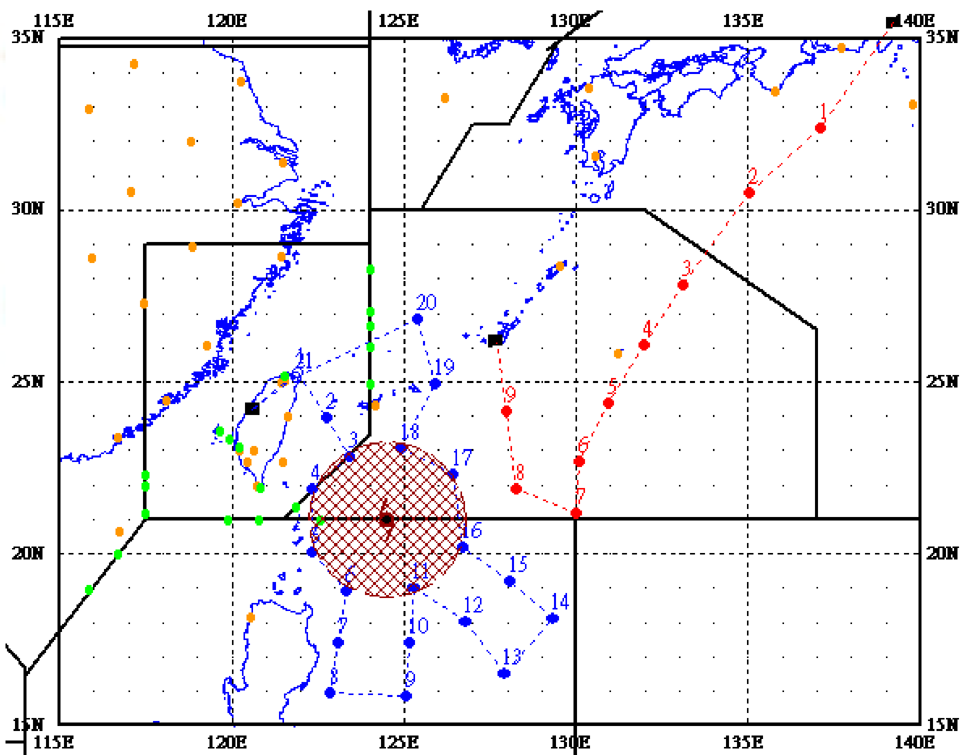


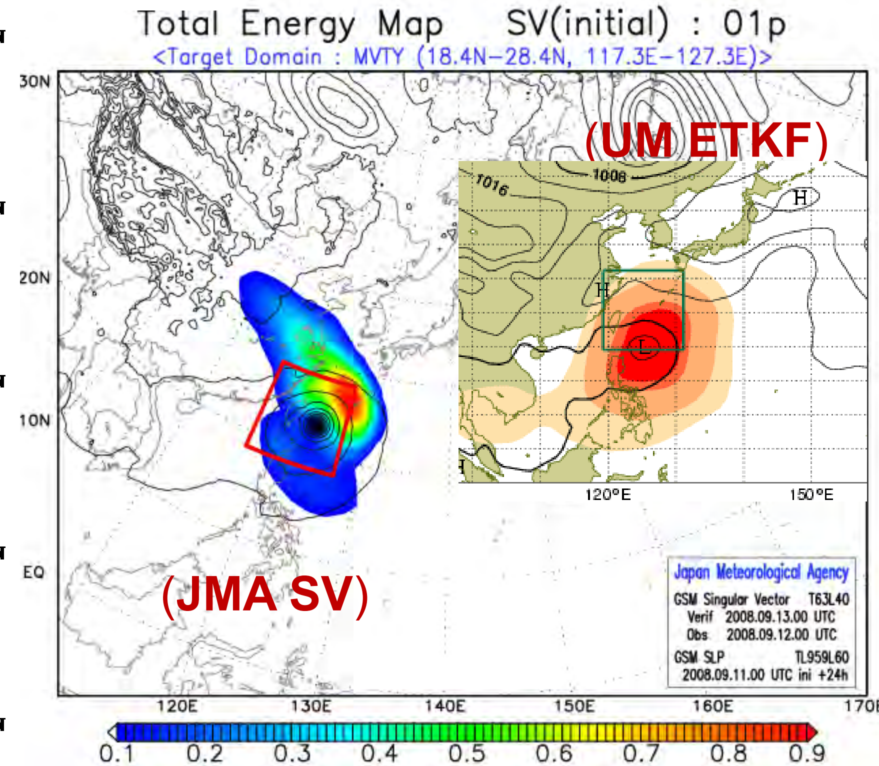
Verif. Time : 2008.09.13 00UTC



DOTSTAR Flight Plan (BLUE) and FALCON Flight Plan (1) (Red)

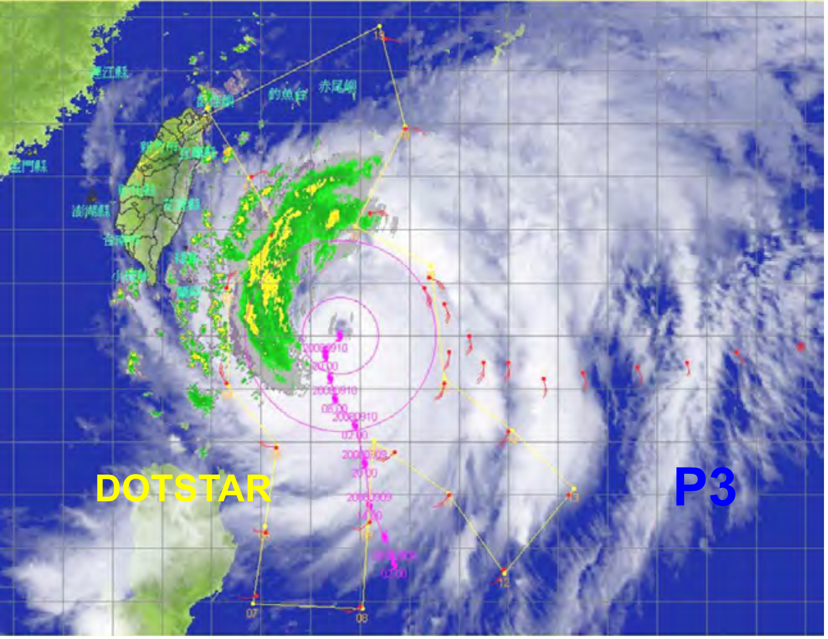
10-11 September 2008 (Targeted observation)



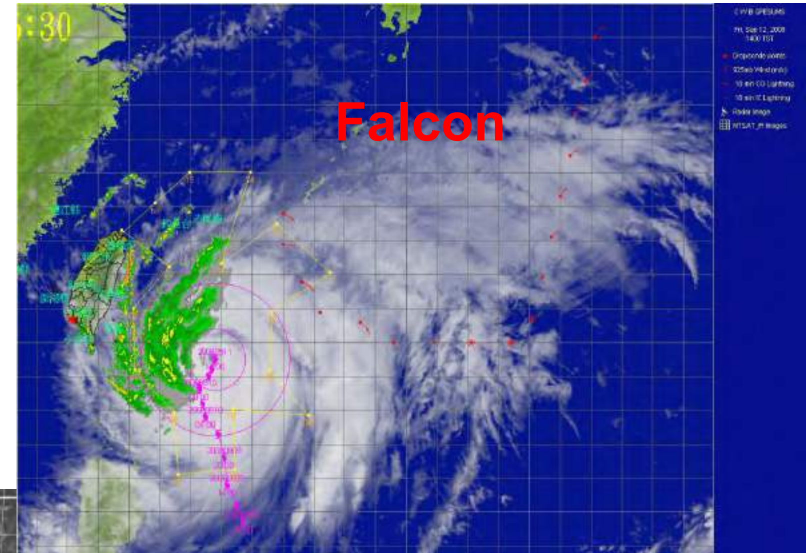


11 September, 2009, Typhoon Sinlaku

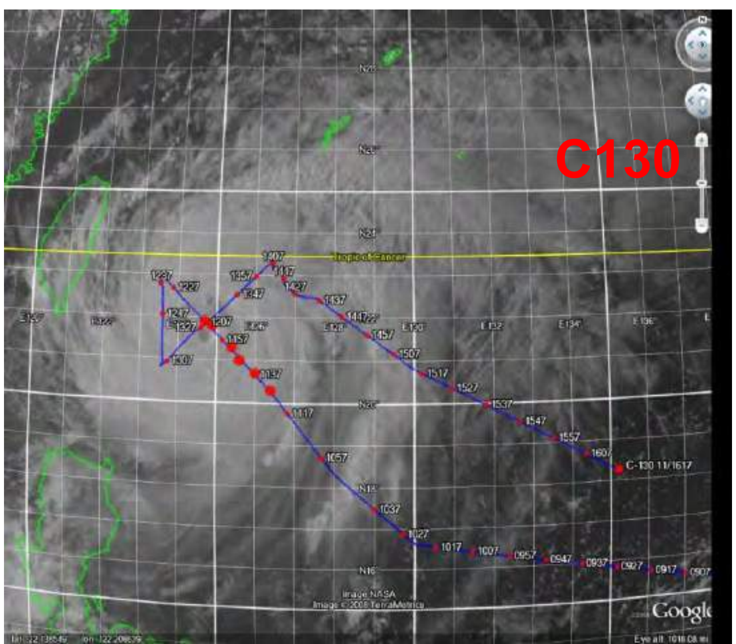
DOTSTAR + Falcon + P3 + C130 Flight tracks

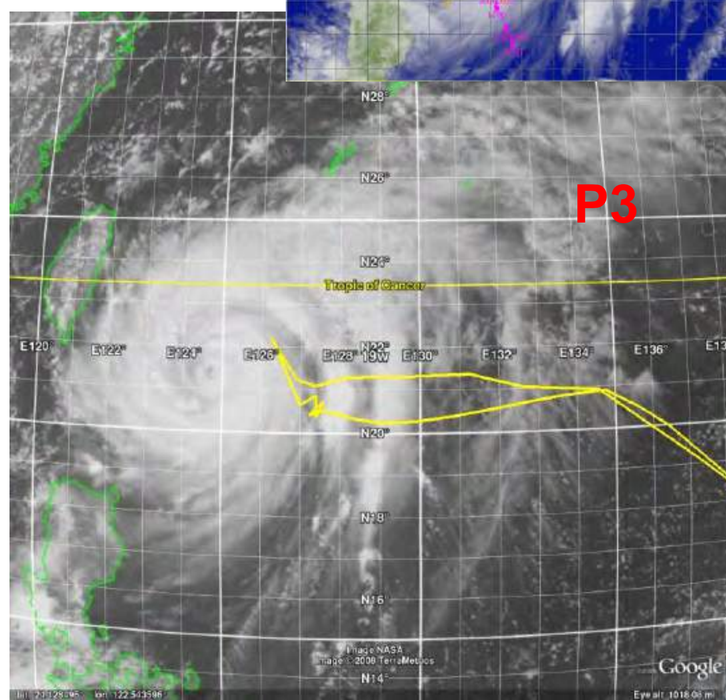


T-PARC



First time with four aircrafts observing typhoons over NW Pacific ocean





Data impact – track, structure and intensity

Impact of T-PARC observations: Three key papers (MWR 2011)

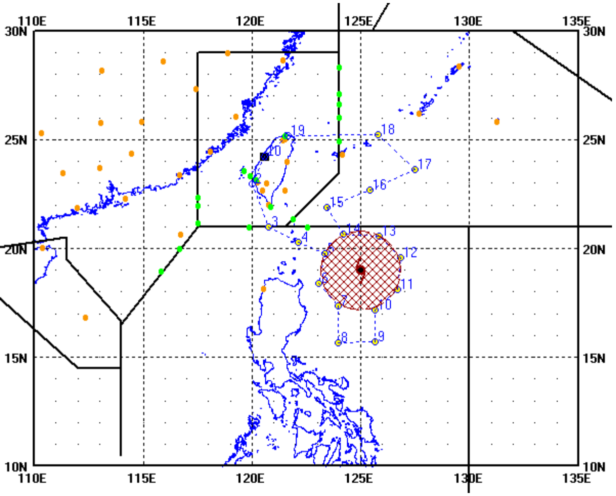
- **The influence of assimilating dropsonde data on typhoon track and mid-latitude forecasts**
  M. Weissmann, F. Harnisch, C.-C. Wu, P.-H. Lin, Y. Ohta, Koji Yamashita, Y.-H. Kim, E.-H. Jeon, T. Nakazawa, and S. Aberson

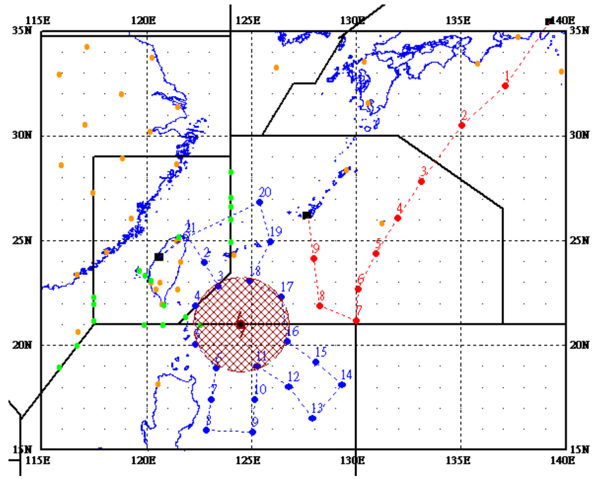
- **Sensitivity of typhoon forecasts to different subsets of targeted dropsonde observations**
  F. Harnisch and M. Weissmann

- **The impact of dropwindsonde observations on typhoon track forecasts in DOTSTAR and T-PARC.**
  Chou, K.-H., C.-C. Wu, P.-H. Lin, S. D. Aberson, M. Weissmann, F. Harnisch, and T. Nakazawa

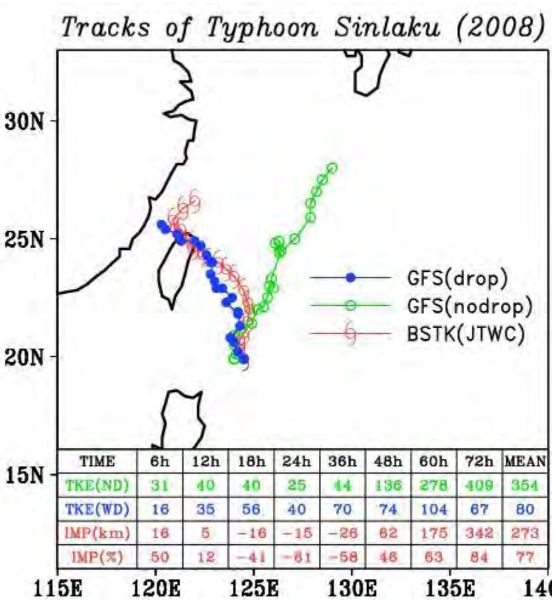
Impact of dropwindsondes to NCEP GFS forecasts of Sinlaku

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

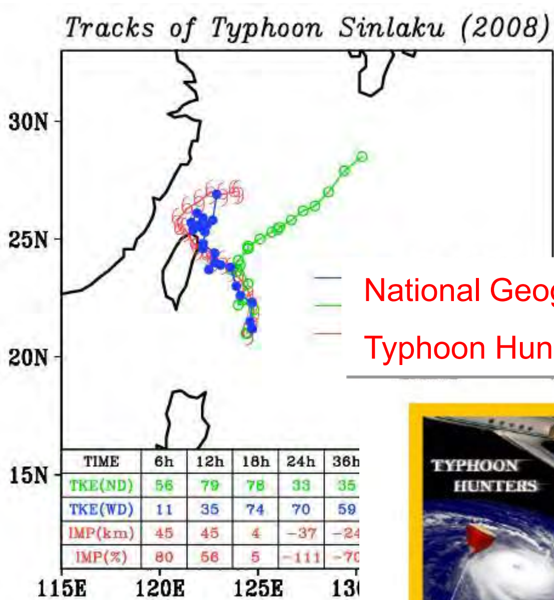




Degradation due to the inner-core dropsonde data (Aberson 2008)



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

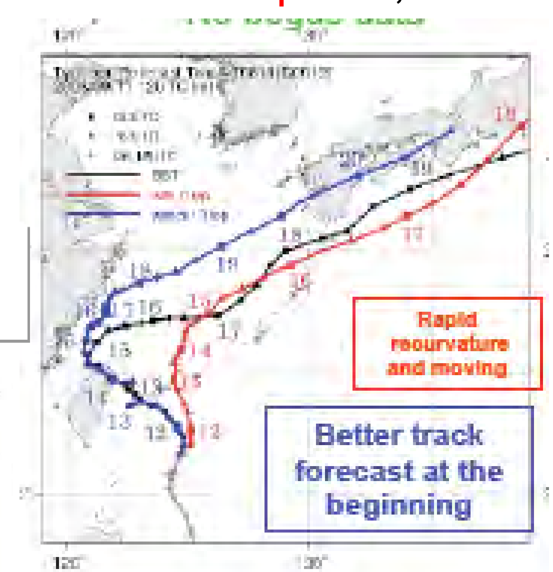


TIME	6h	12h	18h	24h	36h
TKE(ND)	56	79	78	33	35
TKE(WD)	11	35	74	70	59
IMP(km)	45	45	4	-37	-24
IMP(%)	80	56	5	-111	-70

National Geographic

Typhoon Hunters

12 UTC Sept. 11, 2008

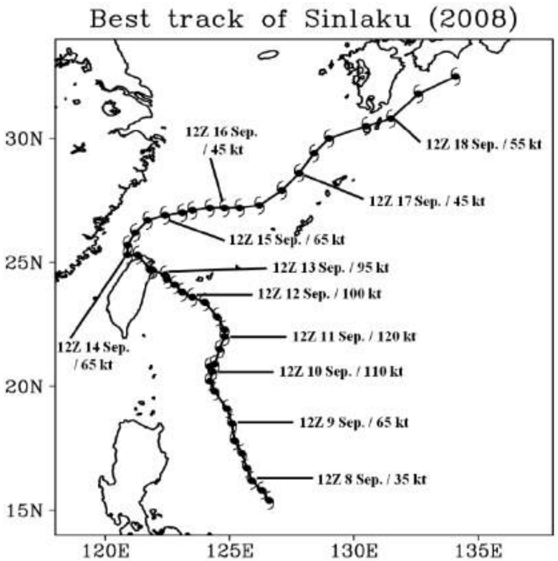


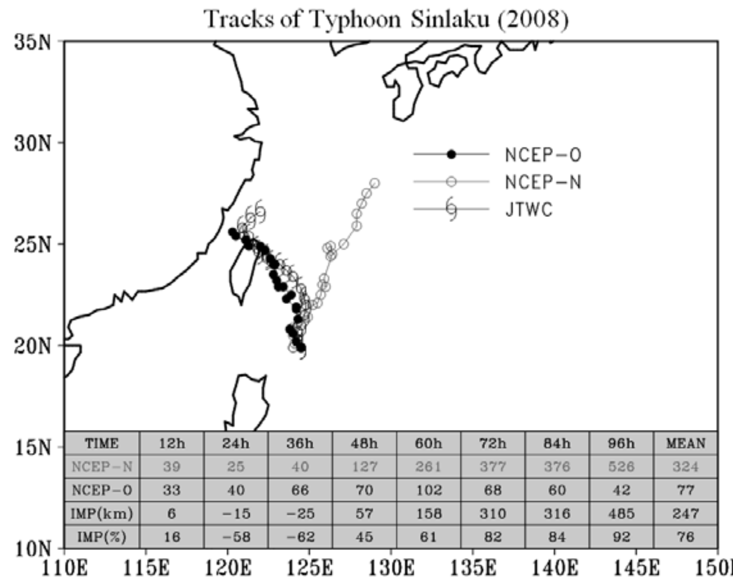
JMA/GSM, from Nakazawa)

(Wu et al. 2012, MWR)

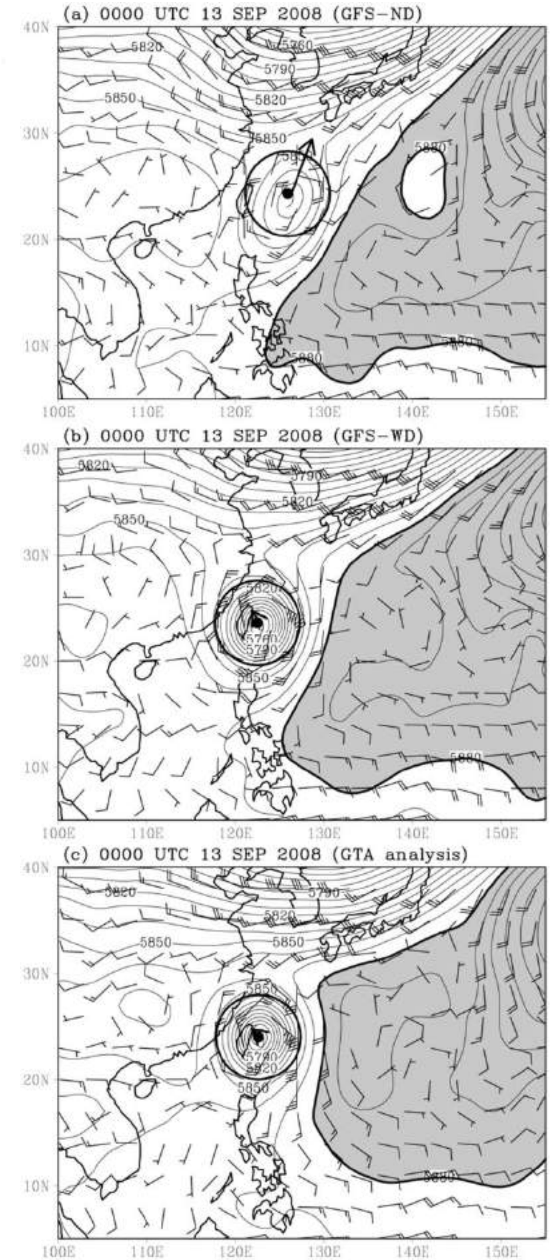
- Wu, C.-C.*, S.-G. Chen, C.-C. Yang, P.-H. Lin, and S. D. Aberson, 2012: Potential vorticity diagnosis of the factors affecting the track of Typhoon Sinlaku (2008) and the impact from dropwindsonde data during T-PARC. *Mon. Wea. Rev.*, **140**, 2670-2688.

(Wu et al. 2012, MWR)





TIME	12h	24h	36h	48h	60h	72h	84h	96h	MEAN
NCEP−N	39	25	40	127	261	377	376	526	324
NCEP−O	33	40	66	70	102	68	60	42	77
IMP(km)	6	−15	−25	57	158	310	316	485	247
IMP(%)	16	−58	−62	45	61	82	84	92	76

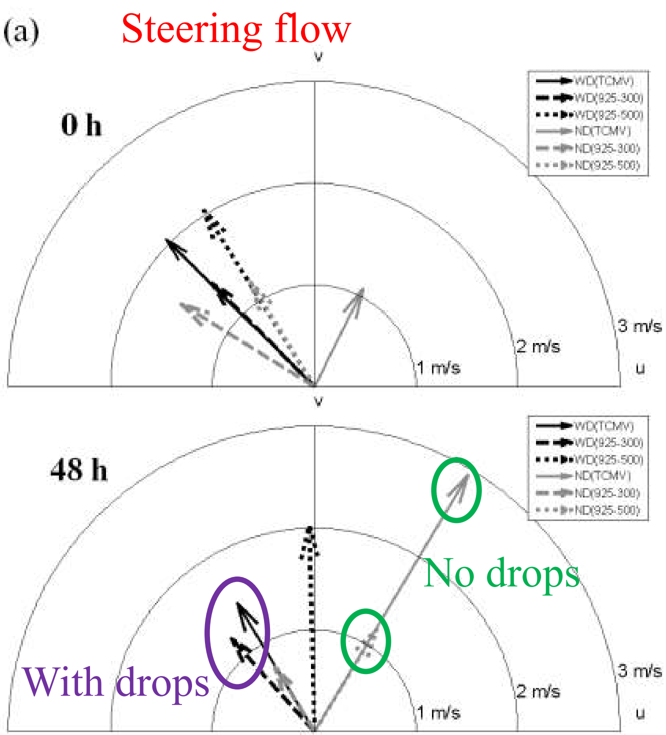


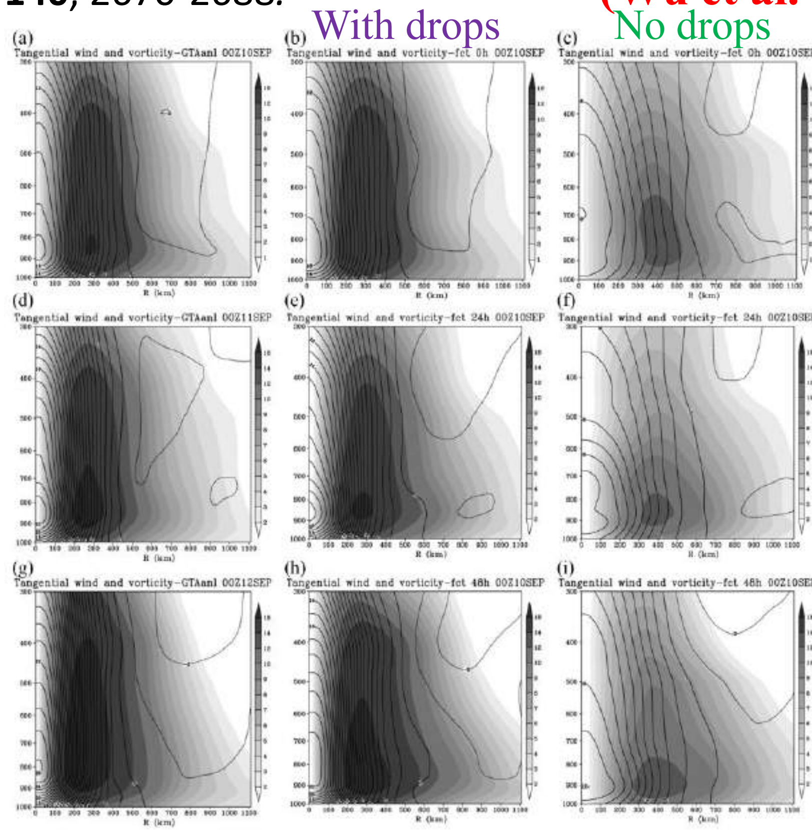
➢In the NCEP GFS model, the assimilation of dropwindsonde data leads to an improvement in the 12–96-h mean track forecast of up to 76%.

➢The subtropical high to the northeast of Sinlaku in GFS-ND is weaker and smoother than that in GFS-WD. The geopotential height associated with the midlatitude trough in GFS-ND appears deeper than that in GFS-WD.

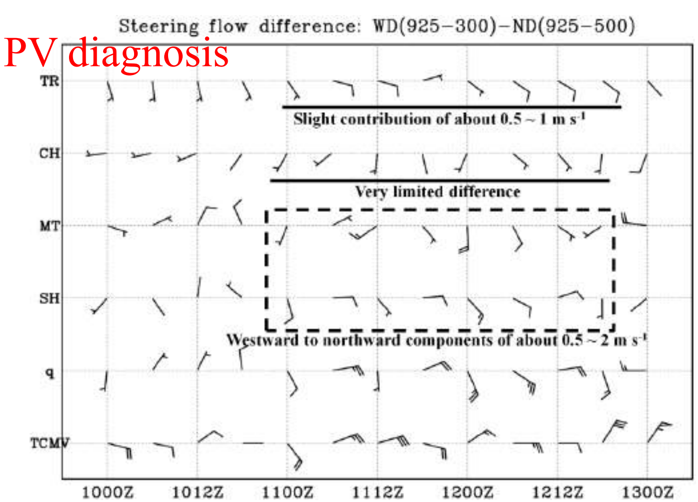
- Wu, C.-C.*, S.-G. Chen, C.-C. Yang, P.-H. Lin, and S. D. Aberson, 2012: Potential vorticity diagnosis of the factors affecting the track of Typhoon Sinlaku (2008) and the impact from dropwindsonde data during T-PARC. *Mon. Wea. Rev.*, **140**, 2670-2688.

(Wu et al. 2012, MWR)





Vertical vortex structure

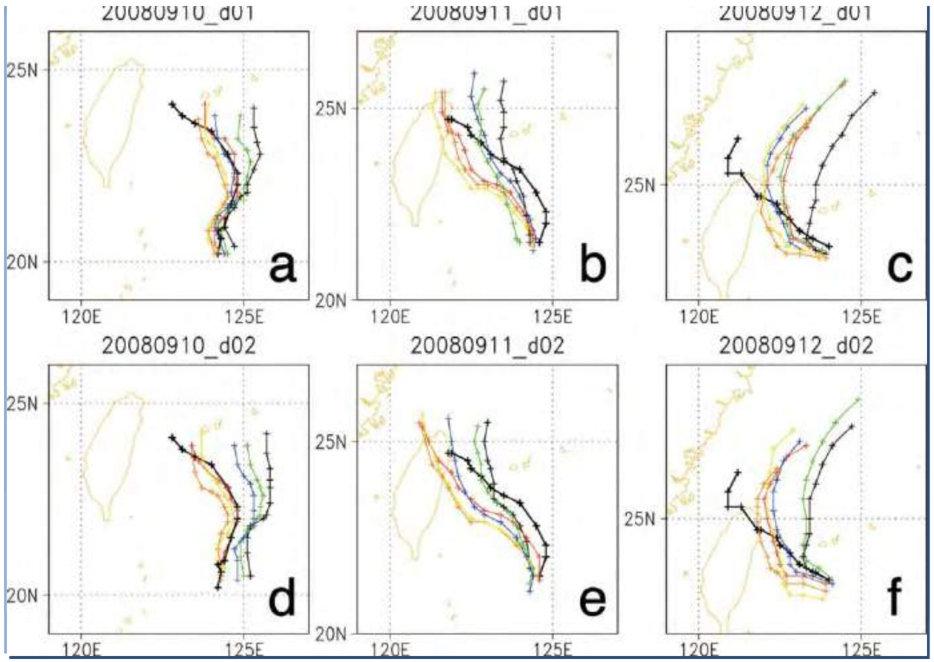


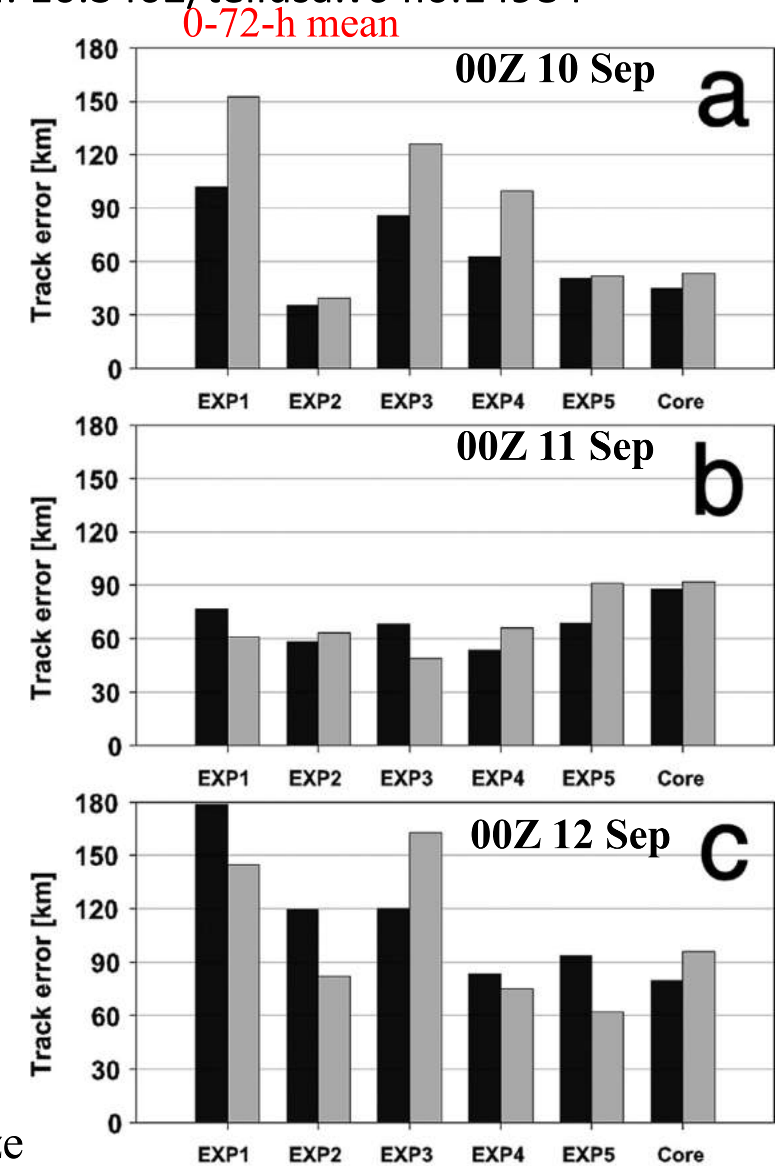
- The TC in GFS-WD is advected under the influence of the 925–300-hPa steering flow, whereas the TC motion in GFS-ND appears closer to the 925–500-hPa mean flow.
- This discrepancy can be explained by the difference in the vertical structure.
- The model steering flow associated with the subtropical high and monsoon trough is modified by the assimilation of dropwindsonde data contributing to the northwestward motion of Sinlaku.

- Jung, B.-J., H. M. Kim, F. Zhang, and C.-C. Wu, 2012: Effect of targeted dropsonde observations and best track data on the track forecasts of Typhoon Sinlaku (2008) using an ensemble Kalman filter. *Tellus A.*, **64**, 1-19. doi: 10.3402/tellusa.v64i0.14984

Table 2. Description of numerical experiments

Experiment	Description
EXP1	Assimilate the conventional observations.
EXP2	Assimilate the conventional observations and the targeted dropsonde observations.
EXP3	Assimilate the conventional observations and the TC position information.
EXP4	Assimilate the conventional observations, the TC position, and TC minimum SLP information.
EXP5	Assimilate the conventional observations, the targeted dropsonde observations, the TC position and TC minimum SLP information.
CORE	Same as EXP2, except that the dropsonde observations near the TC core regions are also assimilated here.



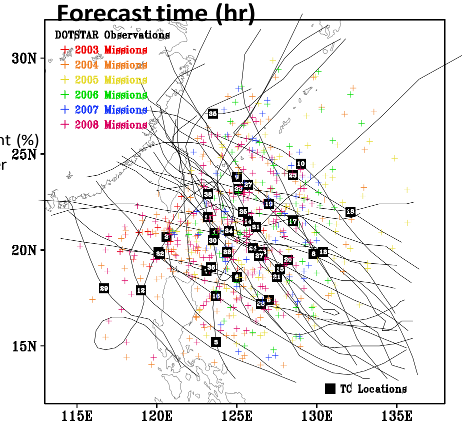


➢Assimilation of dropsondes leads to improved initial position and subsequent track forecast compared with experiments that only assimilate conventional obs.

➢Assimilation of SLP information is efficient to analyze the strong vortex structures of TC and reduces track forecast errors.

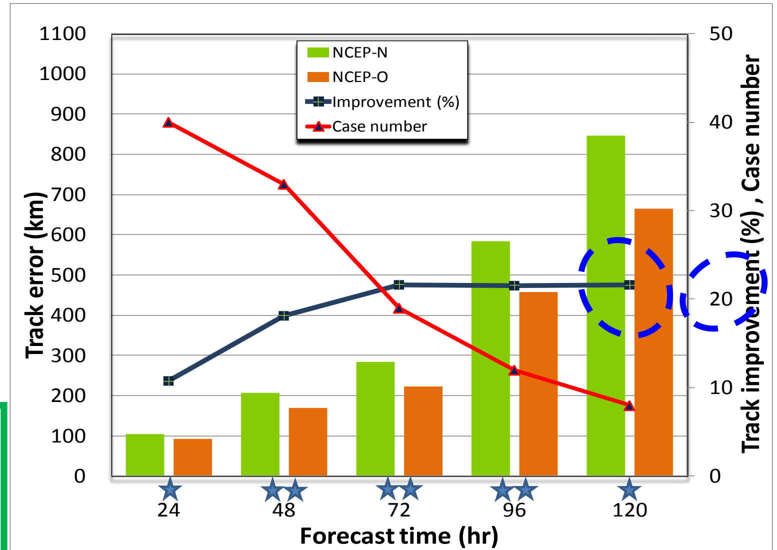
(Jung et al. 2012, Tellus A)

- Chou, K.-H., C.-C. Wu*, P.-H. Lin, S. D. Aberson, M. Weissmann, F. Harnisch, and T. Nakazawa, 2011: The impact of dropwindsonde observations on typhoon track forecasts in DOTSTAR and T-PARC. *Mon. Wea. Rev.* **139**, 1728–1743.

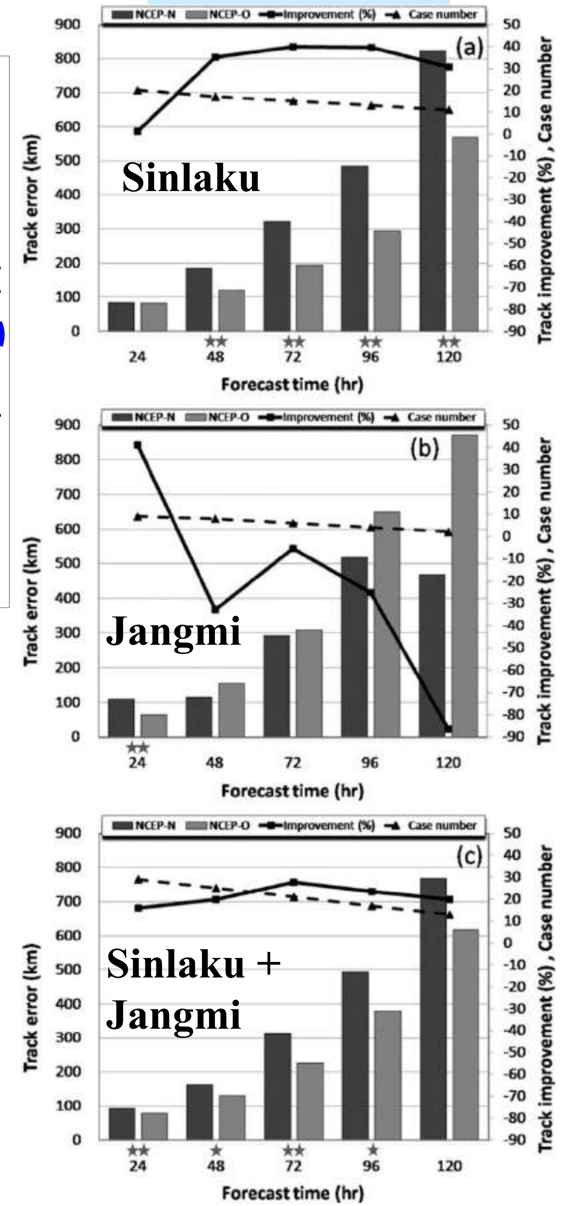


Paired t-test statistical examination: statistically significant at the 90% (*) and 95% (**) confidence level

GFS Impact from 2003 to 2009 (DOTSTAR)



2008 (T-PARC)



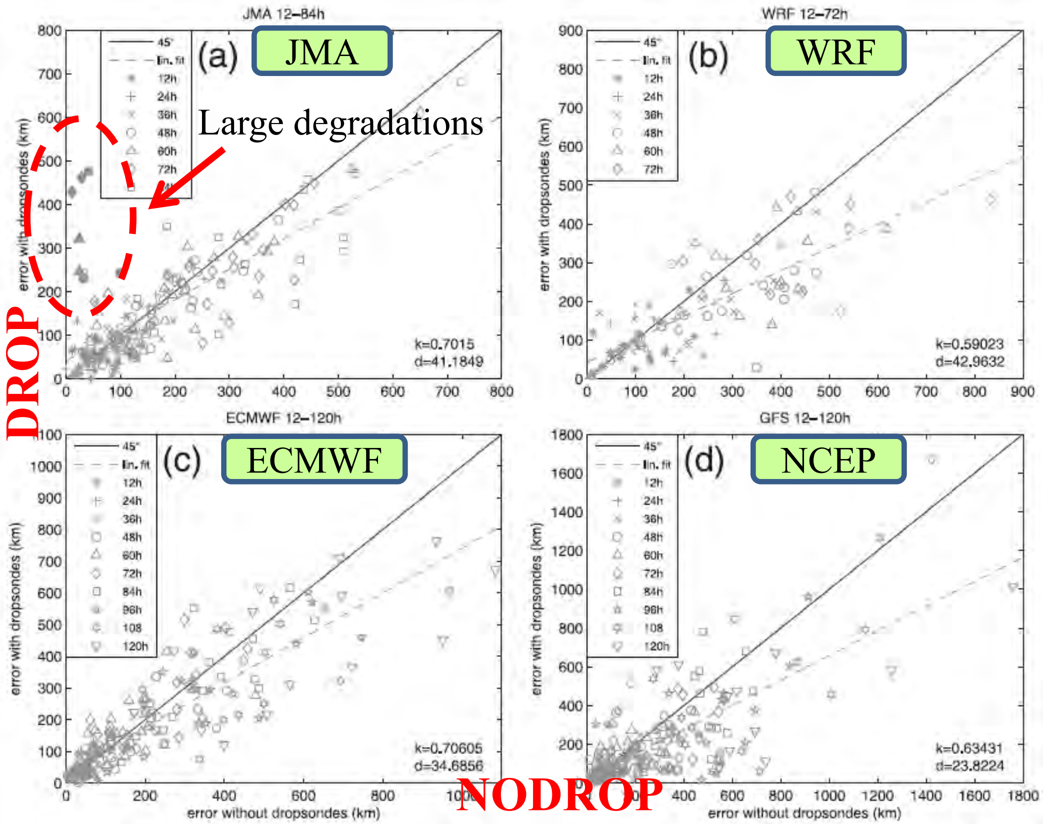
➢The mean 1- to 5-day track forecast error is reduced by about 10%–20% for both DOTSTAR and T-PARC cases in the NCEP system.

➢The impact in the ECMWF system is not as beneficial as in the NCEP system, likely because of more extensive use of satellite data and more complex data assimilation.

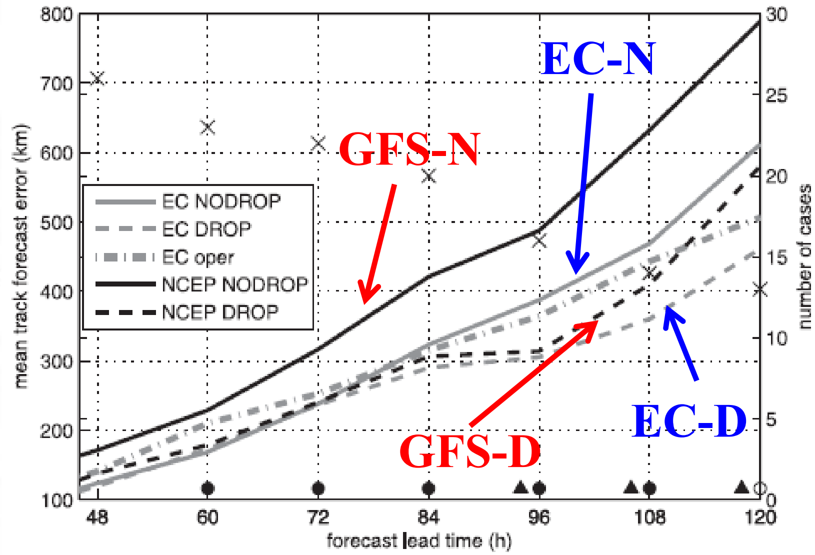
(Chou et al. 2011, MWR)

- Weissmann M.*, F. Harnisch, C.-C. Wu, P.-H. Lin, Y. Ohta, K. Yamashita, Y.-K. Kim, E.-H. Jeon, T. Nakazawa, and S. Aberson, 2011: The influence of dropsondes on typhoon track and mid-latitude forecasts. *Mon. Wea. Rev*. **139**, 908-920.

(Weissmann et al. 2011, MWR)



Sinlaku + Jangmi

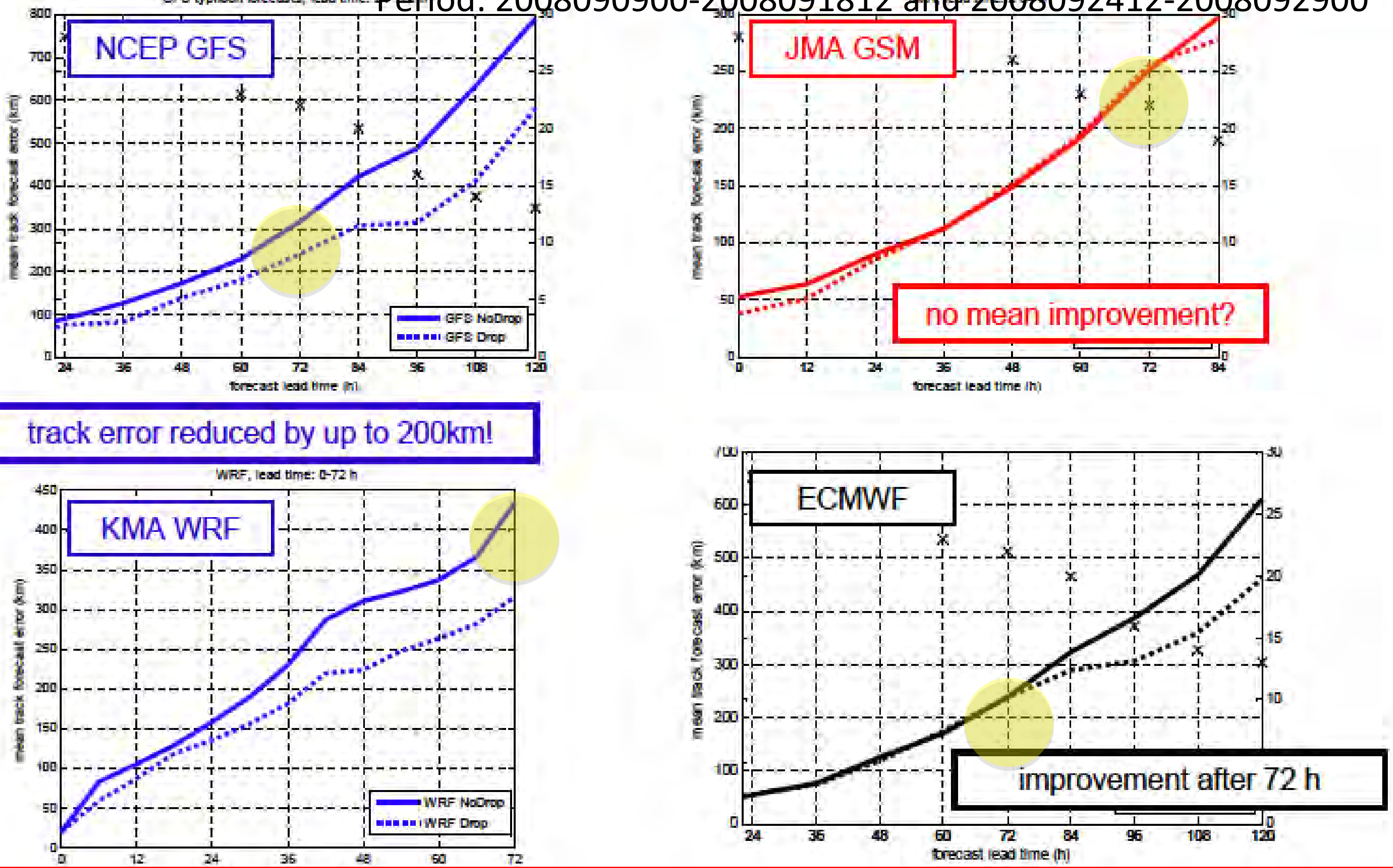


➢All models show an improving tendency of track forecasts, but the improvement varied from about 20% to 40% in NCEP and WRF to a comparably low influence in ECMWF and JMA.

➢The influence of targeted dropsondes on typhoon track forecasts strongly depends on the modeling system. 4DVAR likely leads to better analyses without dropwindsondes, thus limiting the influence of additional observations.

Influence of T-PARC observations on typhoon track forecast

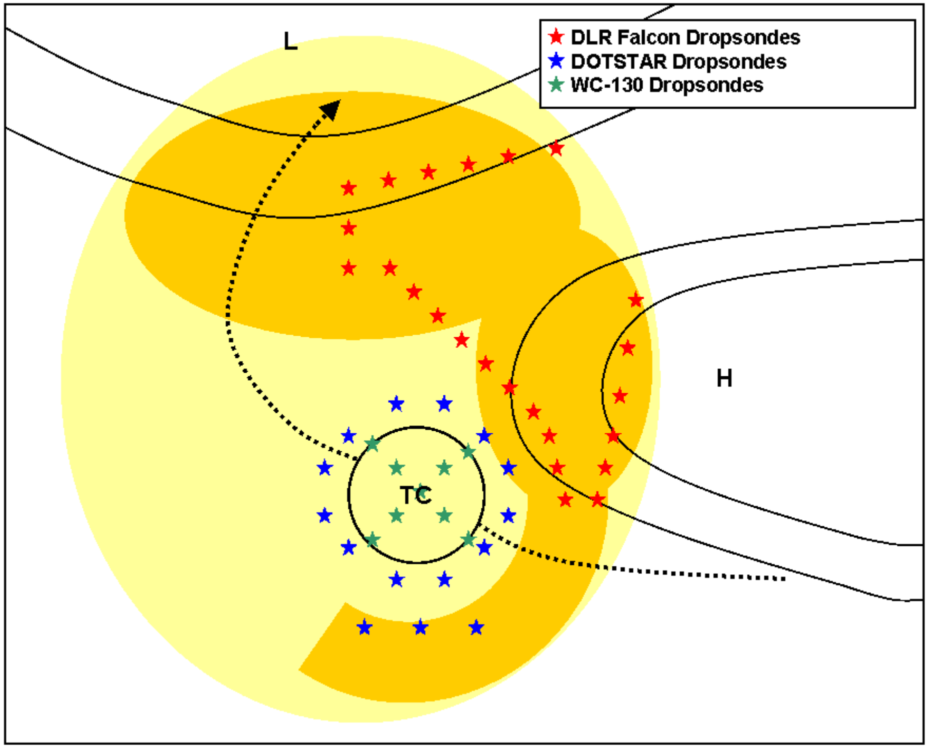
Period: 2008090900-2008091812 and 2008092412-2008092900

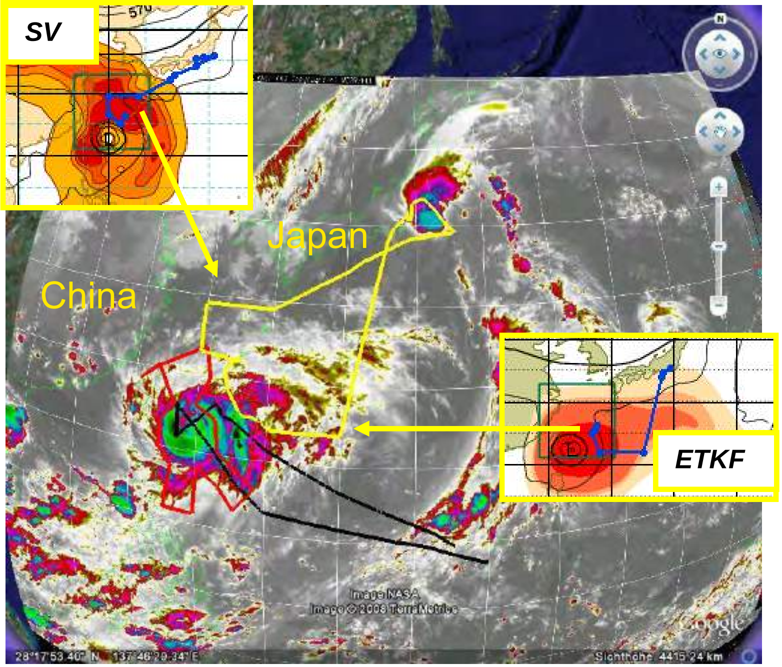


The influence strongly depends on the modeling and DA system
--> need for comparison of models to draw conclusions on targeting!

(Weissmann et al. 2011, MWR)

T-PARC:Joint missions for typhoon targeting (TY center, surrounding and sensitive area)





Separation of dropwindsondes into 3 subsets

Concept for ideal mission:

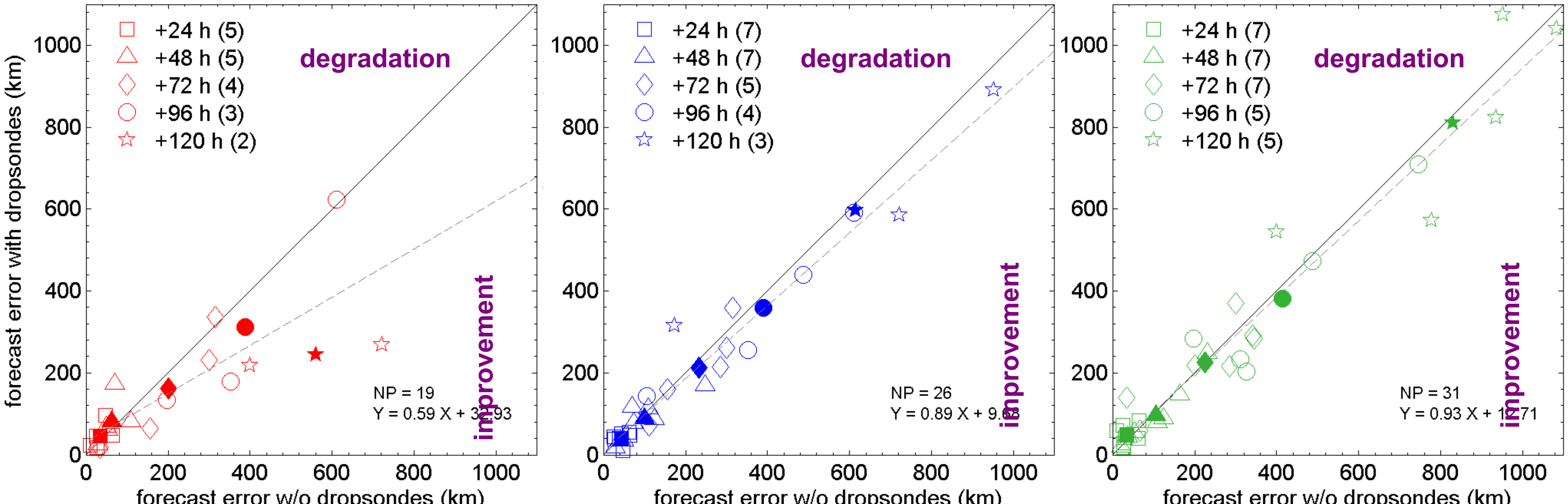
- WC-130 observations in typhoon center (green)
- DOTSTAR observations in typhoon surrounding (blue)
- Falcon obs. in sensitive area highlighted by e.g. SV, ETKF (red)

Joint mission on 11 September

(Harnisch and Weissmann 2011, MWR)

Which subset of dropsondes improves the typhoon track forecast the most?

typhoon vicinity | **remote sensitive regions** | **typhoon center and core**



1

typhoon vicinity:
improvement of the track forecast

2

'remote' sensitive regions
small positive to neutral impact on the track forecast error

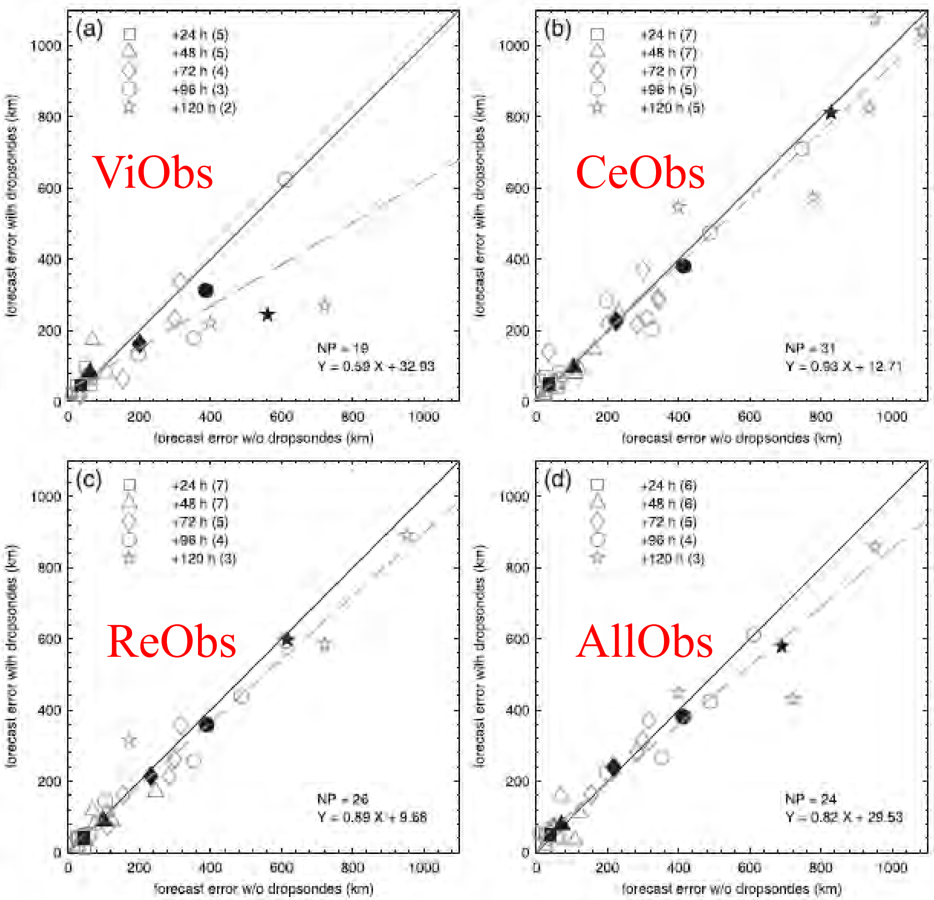
3

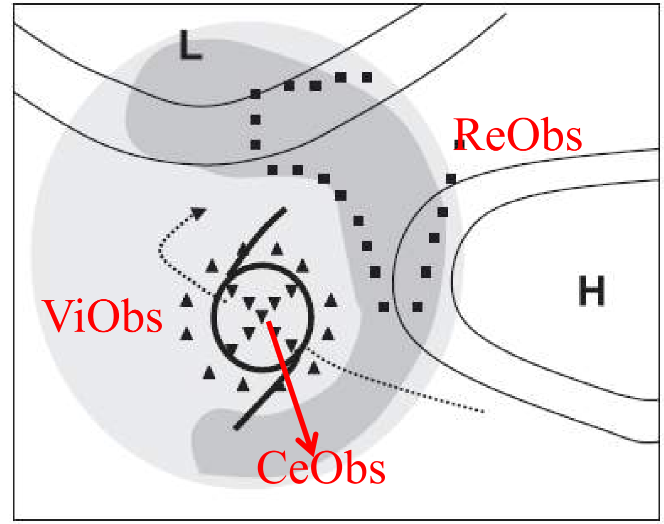
typhoon center and core:
overall neutral impact, with positive and negative outliers

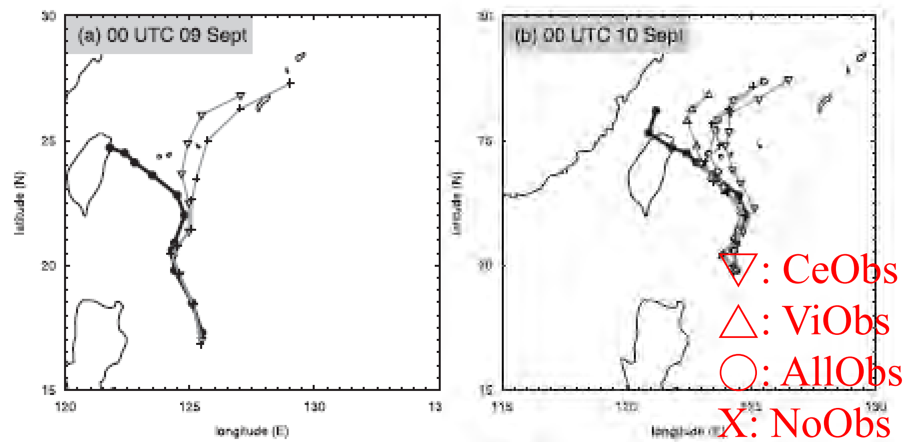
(Harnisch and Weissmann 2011, MWR)

- Harnisch, F., and M. Weissmann, 2010: Sensitivity of typhoon forecasts to different subsets of targeted dropsonde observations. *Mon. Wea. Rev.*, **138**, 2664–2680.

(Harnisch and Weissmann 2010, MWR)







➢Observations in the vicinity of the TC ("ViObs") lead to the largest track error reduction.

➢Results in "ReObs" do not show a large improvement.

➢The influence in "CeObs" on track forecasts is neutral on average.

Other key findings

- Improve track forecasts from targeted observations can lead to improvement in
  - Mid-latitude forecasts.
  - Tropical cyclone forecasts in different basins.

- The average cumulative impact over a whole field program (cycling) exceeds that without cycling.

- Sometimes degradation or neutral impact due to the inner-core dropwindsondes.

Other studies

- Aberson
  - Global effects of dropwindsondes
- Wu, Kim, Hakim, Torn, NCAR
  - EnKF assimilation of T-PARC data
- Reynolds, Langland, Doyle, Chen
  - Data denial, observation sensitivity, moist adjoint
- Majumdar, Wu, Weissmann, Harnisch
  - ETKF signal variance versus 4d-Var / EnKF data impact

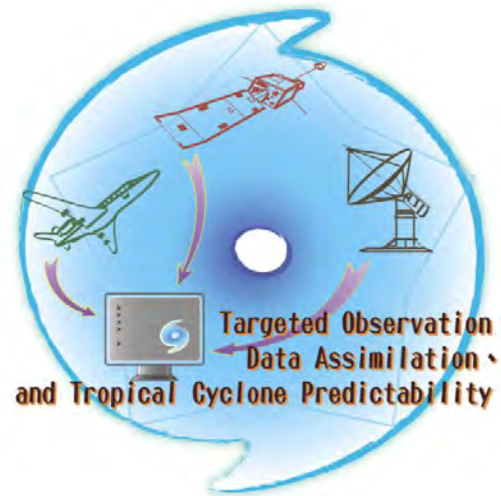
SPECIAL
Tropical Cyclone Predictability
COLLECTION

Special Collections in *Mon. Wea. Rev.*: Targeted Observations, Data Assimilation, and Tropical Cyclone Predictability

- Chun-Chieh Wu, Sharanya J. Majumdar, Sim D. Aberson, Tetsuo Nakazawa, and Carolyn Reynolds

18 papers published

Theme: Accurate tropical cyclone track forecasts are of foremost importance to the increasing population in coastal areas worldwide, necessitating advances in all facets of the numerical prediction process. These include the observational network, the data assimilation schemes that blend these observations with the numerical first guess field, the vortex initialization schemes and the dynamics, physics, and resolution of the models themselves, and methods to target observations to optimize the reduction in forecast error. During the past 30 years, the forecast skill for tropical cyclone track has increased steadily because of improvements in all of these areas. In particular, advances have been made in targeted observations and data assimilation over the past decade. This *Monthly Weather Review* special collection gathers together a series of timely papers on these topics, many of which have resulted from multinational collaborations.



http://journals.ametsoc.org/page/Cyclone_Predictability

Recommendations at IWTC-VII

- Need to assess thoroughly the impact of the targeted observations on models with high performance and advanced data assimilation system (e.g., ECMWF).

- Evaluate relative impact of observations in target areas versus those in non-target areas.

- Make improved use of existing observations:
  - Targeting and thinning of available satellite data
    - Radiance data
    - Atmospheric motion vectors (rapid-scan)
  - Special radiosonde launches
- For practical operation, need to identify the most appropriate radius for the surveillance flights to circumnavigate TCs.

(Wu and Majumdar 2010)

Recommendations at IWTC-VII

- Targeted observations to improve forecasts of TC formation, structure and intensity
- Observing Systems Simulation Experiments (OSSEs) to evaluate the respective merits of different targeting methodologies, observing platforms and data assimilation schemes.
- Annual evaluations of targeted observing programs.

(Wu and Majumdar 2010)

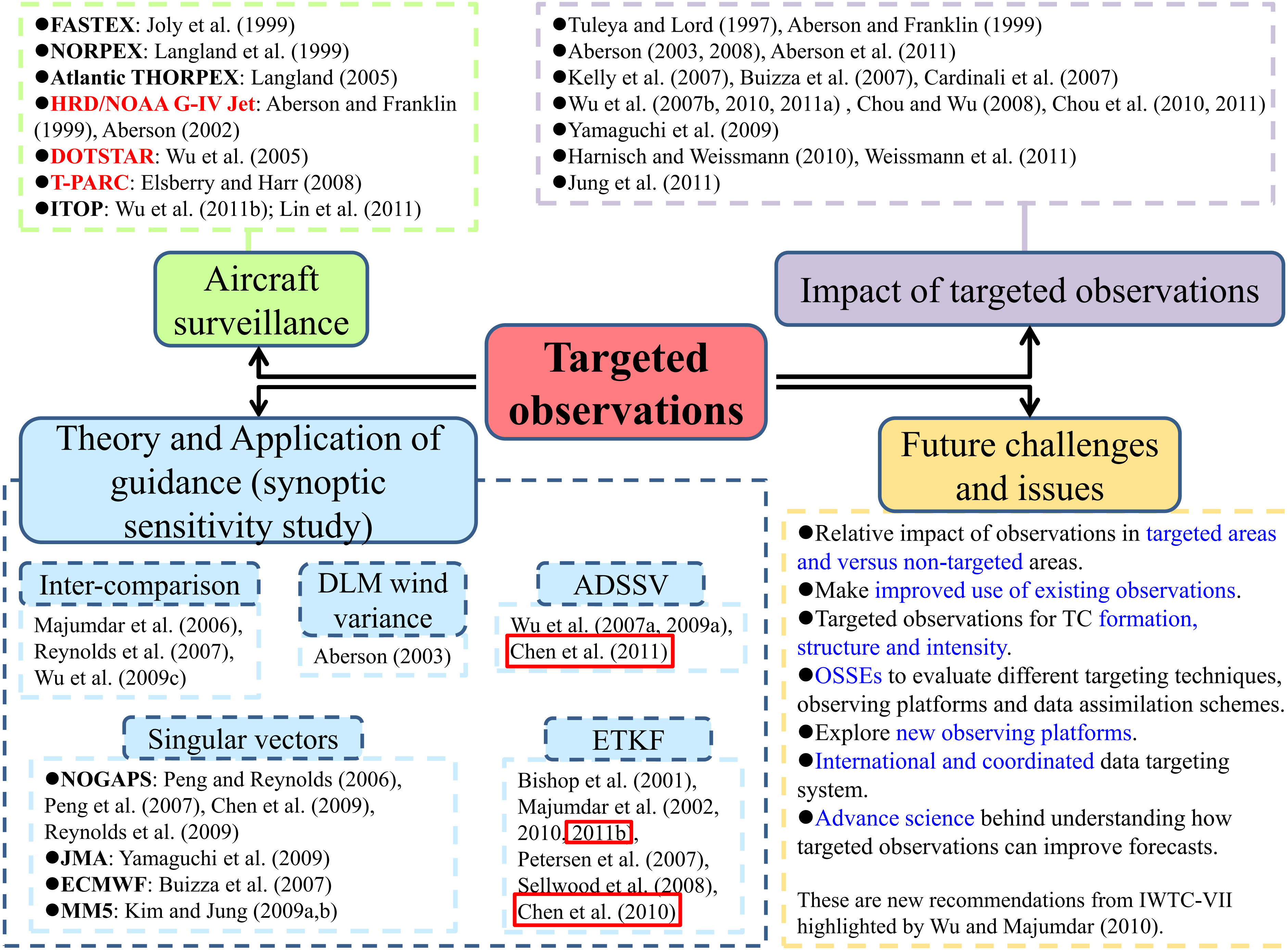
Recommendations at IWTC-VII

- Explore new observing platforms
  - Unmanned aircraft (high- and low-level)
  - Doppler Wind Lidar

- Move towards an international, centralized and coordinated data targeting system for global tropical cyclones, winter storms etc?

- Continue to advance science behind understanding how targeted observations can improve forecasts

(Wu and Majumdar 2010)


●FASTEX: Joly et al. (1999)
●NORPEX: Langland et al. (1999)
●Atlantic THORPEX: Langland (2005)
●HRD/NOAA G-IV Jet: Aberson and Franklin (1999), Aberson (2002)
●DOTSTAR: Wu et al. (2005)
●T-PARC: Elsberry and Harr (2008)
●ITOP: Wu et al. (2011b); Lin et al. (2011)
●Tuleya and Lord (1997), Aberson and Franklin (1999)
●Aberson (2003, 2008), Aberson et al. (2011)
●Kelly et al. (2007), Buizza et al. (2007), Cardinali et al. (2007)
●Wu et al. (2007b, 2010, 2011a) , Chou and Wu (2008), Chou et al. (2010, 2011)
●Yamaguchi et al. (2009)
●Harnisch and Weissmann (2010), Weissmann et al. (2011)
●Jung et al. (2011)
Aircraft surveillance
Impact of targeted observations
Targeted observations
Theory and Application of guidance (synoptic sensitivity study)
Future challenges and issues
Inter-comparison
Majumdar et al. (2006), Reynolds et al. (2007), Wu et al. (2009c)
DLM wind variance
Aberson (2003)
ADSSV
Wu et al. (2007a, 2009a), Chen et al. (2011)
Singular vectors
●NOGAPS: Peng and Reynolds (2006), Peng et al. (2007), Chen et al. (2009), Reynolds et al. (2009)
●JMA: Yamaguchi et al. (2009)
●ECMWF: Buizza et al. (2007)
●MM5: Kim and Jung (2009a,b)
ETKF
Bishop et al. (2001), Majumdar et al. (2002, 2010, 2011b), Petersen et al. (2007), Sellwood et al. (2008), Chen et al. (2010)
●Relative impact of observations in targeted areas and versus non-targeted areas.
●Make improved use of existing observations.
●Targeted observations for TC formation, structure and intensity.
●OSSEs to evaluate different targeting techniques, observing platforms and data assimilation schemes.
●Explore new observing platforms.
●International and coordinated data targeting system.
●Advance science behind understanding how targeted observations can improve forecasts.
These are new recommendations from IWTC-VII highlighted by Wu and Majumdar (2010).

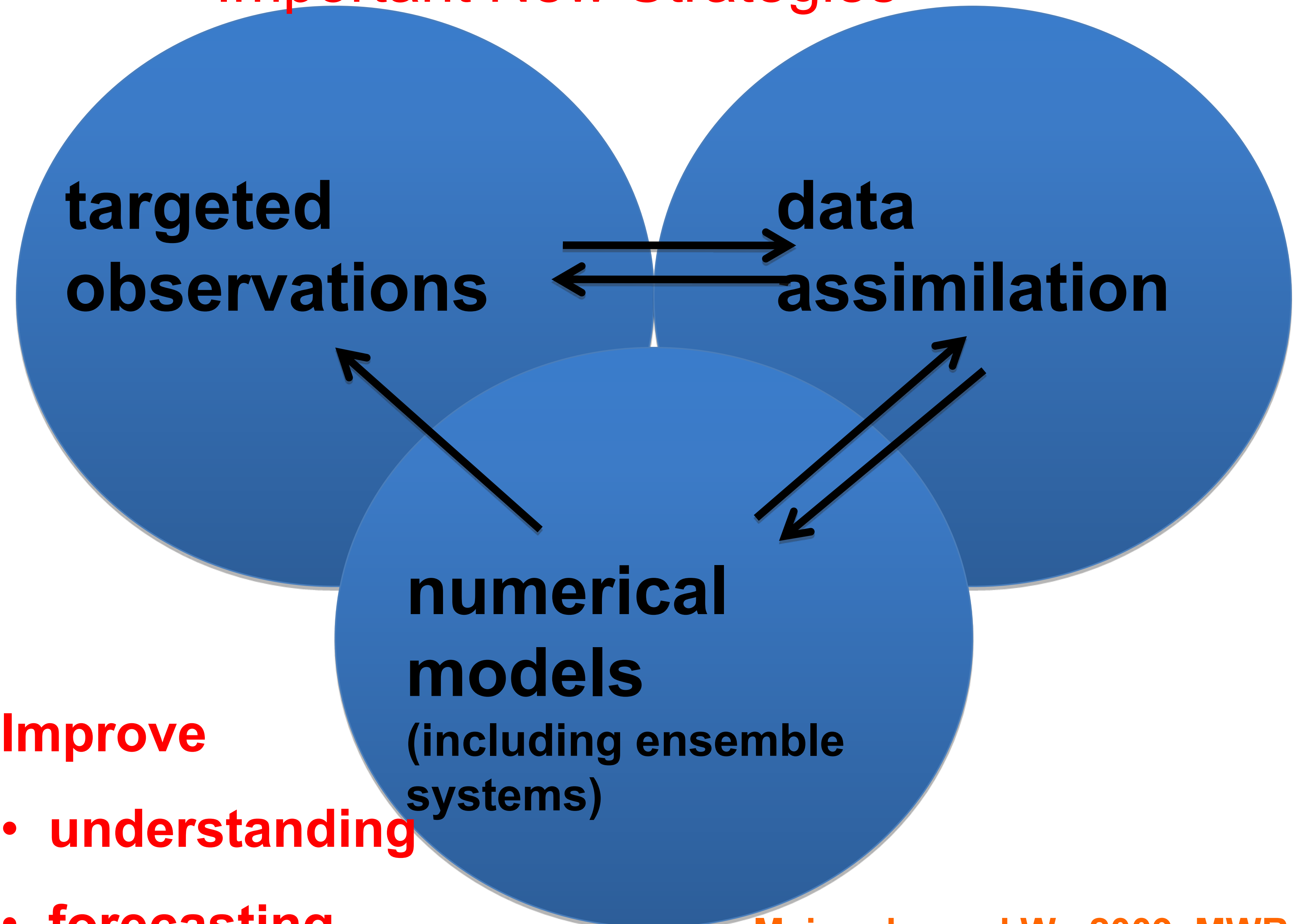
Publications

- Wu, C.-C.*, S.-G. Chen, C.-C. Yang, P.-H. Lin, and S. D. Aberson, 2012: Potential vorticity diagnosis of the factors affecting the track of Typhoon Sinlaku (2008) and the impact from dropwindsonde data during T-PARC. *Mon. Wea. Rev .*, **140**, 2670-2688.
- Jung, B.-J., H. M. Kim, F. Zhang, and C.-C. Wu, 2012: Effect of targeted dropsonde observations and best track data on the track forecasts of Typhoon Sinlaku (2008) using an ensemble Kalman filter. *Tellus A.,* **64**, 1-19. doi: 10.3402/tellusa.v64i0.14984.
- Huang, Y.-H., M. T. Montgomery, and C.-C. Wu*, 2012: Concentric eyewall formation in Typhoon Sinlaku (2008) – Part II: Axisymmetric dynamical processes. *J. Atmos. Sci.,* **69**, 662-674.
- Wu, C.-C.*, Y.-H. Huang, and G.-Y. Lien, 2012: Concentric eyewall formation in Typhoon Sinlaku (2008) – Part I: Assimilation of T-PARC data based on the Ensemble Kalman Filter (EnKF). *Mon. Wea. Rev.,* **140**, 506-527.
- Chou, K.-H., C.-C. Wu*, P.-H. Lin, S. D. Aberson, M. Weissmann, F. Harnisch, and T. Nakazawa, 2011: The impact of dropwindsonde observations on typhoon track forecasts in DOTSTAR and T-PARC. *Mon. Wea. Rev.* **139**, 1728–1743.
- Chen, S.-G., C.-C. Wu*, J.-H. Chen, and K.-H. Chou, 2011: Validation and interpretation of Adjoint - Derived Sensitivity Steering Vector as targeted observation guidance. *Mon. Wea. Rev.* **139**, 1608–1625.
- Majumdar, S. J.*, S. -G. Chen, and C.-C. Wu, 2011: Characteristics of Ensemble Transform Kalman Filter adaptive sampling guidance for tropical cyclones. *Quart. J. Roy. Meteor. Soc.* **137**, 503-520.
- Weissmann M.*, F. Harnisch, C.-C. Wu, P.-H. Lin, Y. Ohta, K. Yamashita, Y.-K. Kim, E.-H. Jeon, T. Nakazawa, and S. Aberson, 2011: The influence of dropsondes on typhoon track and mid-latitude forecasts. *Mon. Wea. Rev*. **139**, 908-920.
- Wu, C.-C**.***, G.-Y. Lien, J.-H. Chen, and F. Zhang, 2010: Assimilation of tropical cyclone track and structure based on the Ensemble Kalman Filter (EnKF). *J. Atmos. Sci.*, **67**, 3806-3822.
- Chou, K.-H., C.-C. Wu*, P.-H. Lin, and S. Majumdar, 2010: Validation of QuikSCAT wind vectors by dropwindsonde data from Dropwindsonde Observations for Typhoon Surveillance Near the Taiwan Region (DOTSTAR), *J. Geophys. Res*., **115**, D02109, doi:10.1029/2009JD012131.
- Wu, C.-C.*, J.-H. Chen, S. J. Majumdar, M. S. Peng, C. A. Reynolds, S. D. Aberson, R. Buizza, M. Yamaguchi, S.-G. Chen, T. Nakazawa , and K.-H. Chou, 2009: Inter-comparison of targeted observation guidance for tropical cyclones in the North western Pacific. *Mon. Wea. Rev*., **137**, 2471-2492.
- Yamaguchi M., T. Iriguchi, T. Nakazawa, and C.-C. Wu, 2009: An observing system experiment for Typhoon Conson (2004) using a singular vector method and DOTSTAR data. *Mon. Wea. Rev*., **137**, 2801-2816.
- Wu C.-C.*, S.-G. Chen, J.-H. Chen, K.-H. Chou, and P.-H. Lin, 2009: Interaction of Typhoon Shanshan (2006) with the mid-latitude trough from both Adjoint-Derived Sensitivity Steering Vector and potential vorticity perspectives. *Mon. Wea. Rev*., **137**, 852–862.
- Chou, K.-H., and C.-C. Wu*, 2008: Development of the typhoon initialization in a mesoscale model – Combination of the bogused vortex with the dropwindsonde data in DOTSTAR. *Mon. Wea. Rev*., **136**, 865-879.
- Wu, C.-C.*, K.-H. Chou, P.-H. Lin, S. D. Aberson, M. S. Peng, and T. Nakazawa, 2007: The impact of dropwindsonde data on typhoon track forecasts in DOTSTAR. *Weather and Forecasting*, **22**, 1157-1176.
- Wu, C.-C.*, J.-H. Chen, P.-H. Lin, and K.-S. Chou, 2007: Targeted observations of tropical cyclones based on the adjoint-derived sensitivity steering vector. *J. Atmos. Sci.,* **64**, 2611-2626.
- Wu, C.-C.*, P.-H. Lin, S. Aberson, T.-C. Yeh, W.-P. Huang, K.-H. Chou, J.-S. Hong, G.-C. Lu, C.-T. Fong, K.-C. Hsu, I-I Lin, P.-L. Lin, C.-H. Liu, 2005: Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR): An overview. *Bulletin of Amer. Meteor. Soc*., **86**, 787-790.

Publications

- Kunii,M., T.Miyoshi, and E. Kalnay, 2012: Estimating the impact of real observations in regional numerical weather prediction using an ensemble Kalman filter. *Mon. Wea. Rev.*, **140**, 1975–1987.
- Harnisch, F., and M. Weissmann, 2010: Sensitivity of typhoon forecasts to different subsets of targeted dropsonde observations. *Mon. Wea. Rev.*, **138**, 2664–2680.
- Peng, M. S., and C. A. Reynolds, 2006: Sensitivity of tropical cyclone forecasts as revealed by singular vectors. *J. Atmos. Sci.*, **63**, 2508–2528.

Important New Strategies



Improve

- **understanding**
- **forecasting**

Majumdar and Wu 2009, MWR

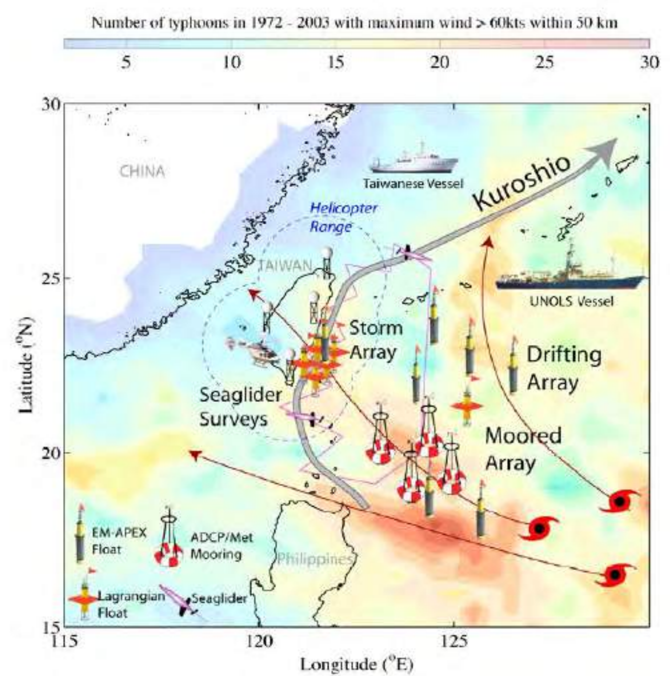
Impact of Typhoons on the Oceans in the Pacific (ITOP, 2010)

ITOP planning meeting, Taipei, 2008

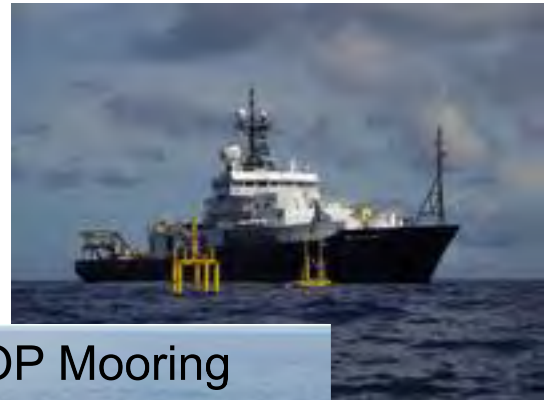
International collaboration:

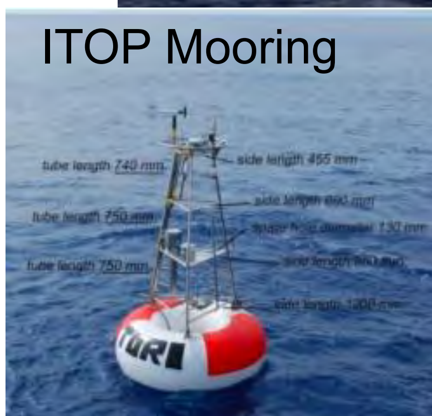
ITOP operation, Guam, 2010

- **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 (coupled model) with ITOP data.

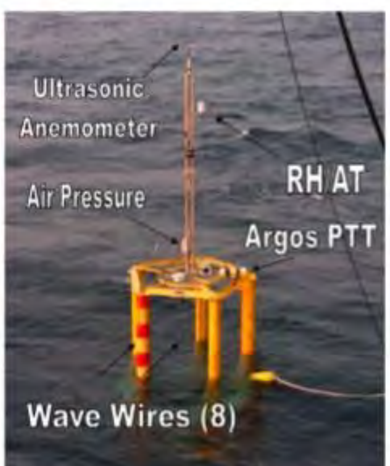


ITOP Facilities



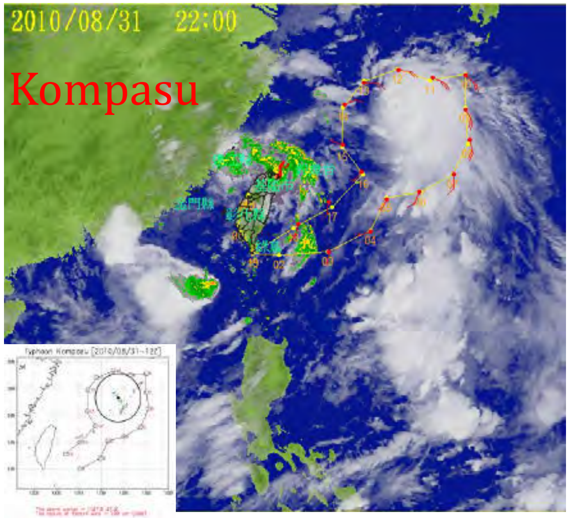


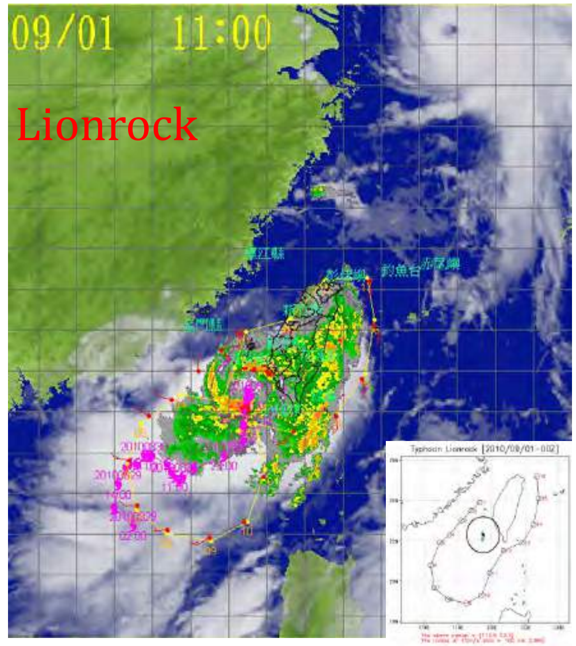
Air-Sea Interaction Spar (ASIS) Buoy

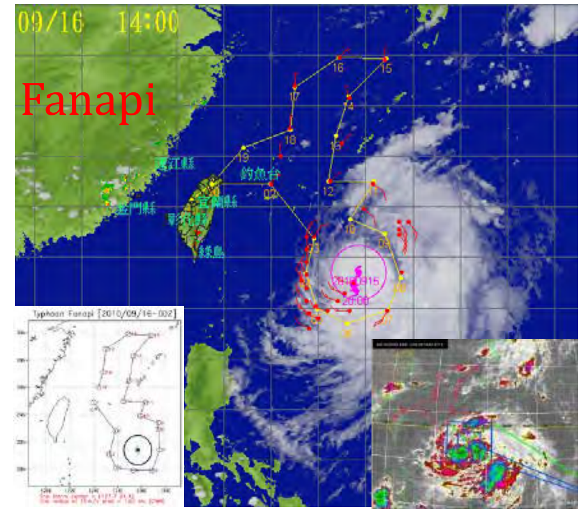


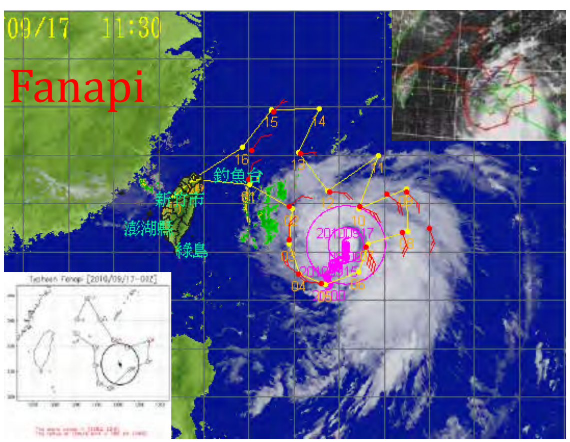
EASI-ASIS Buoys in tandem mooring

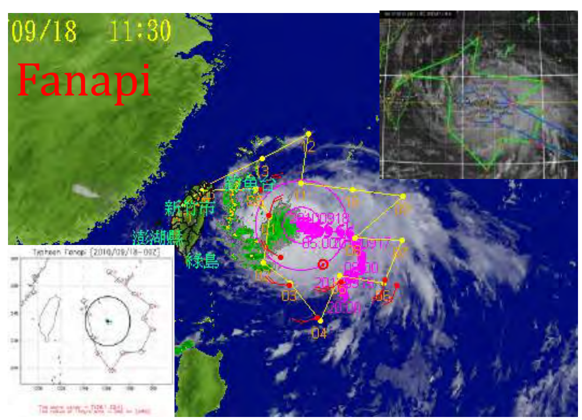
DOTSTAR observations during ITOP 2010

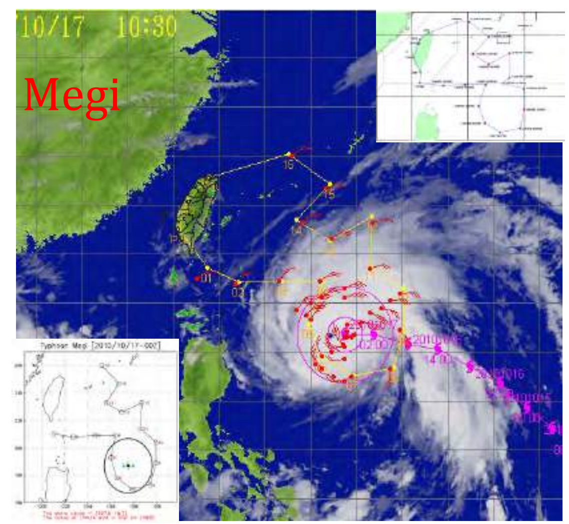








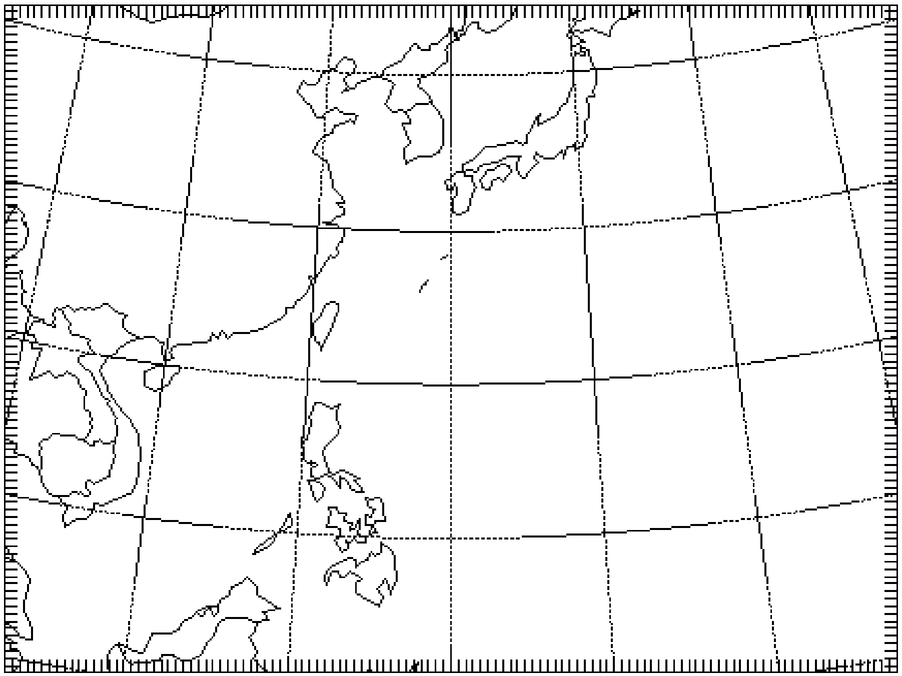




ITOP ensemble reanalysis based on EnKF (*ITOP_EnKF*)

EnKF data assimilation method revised from Wu et al. (2010 JAS)

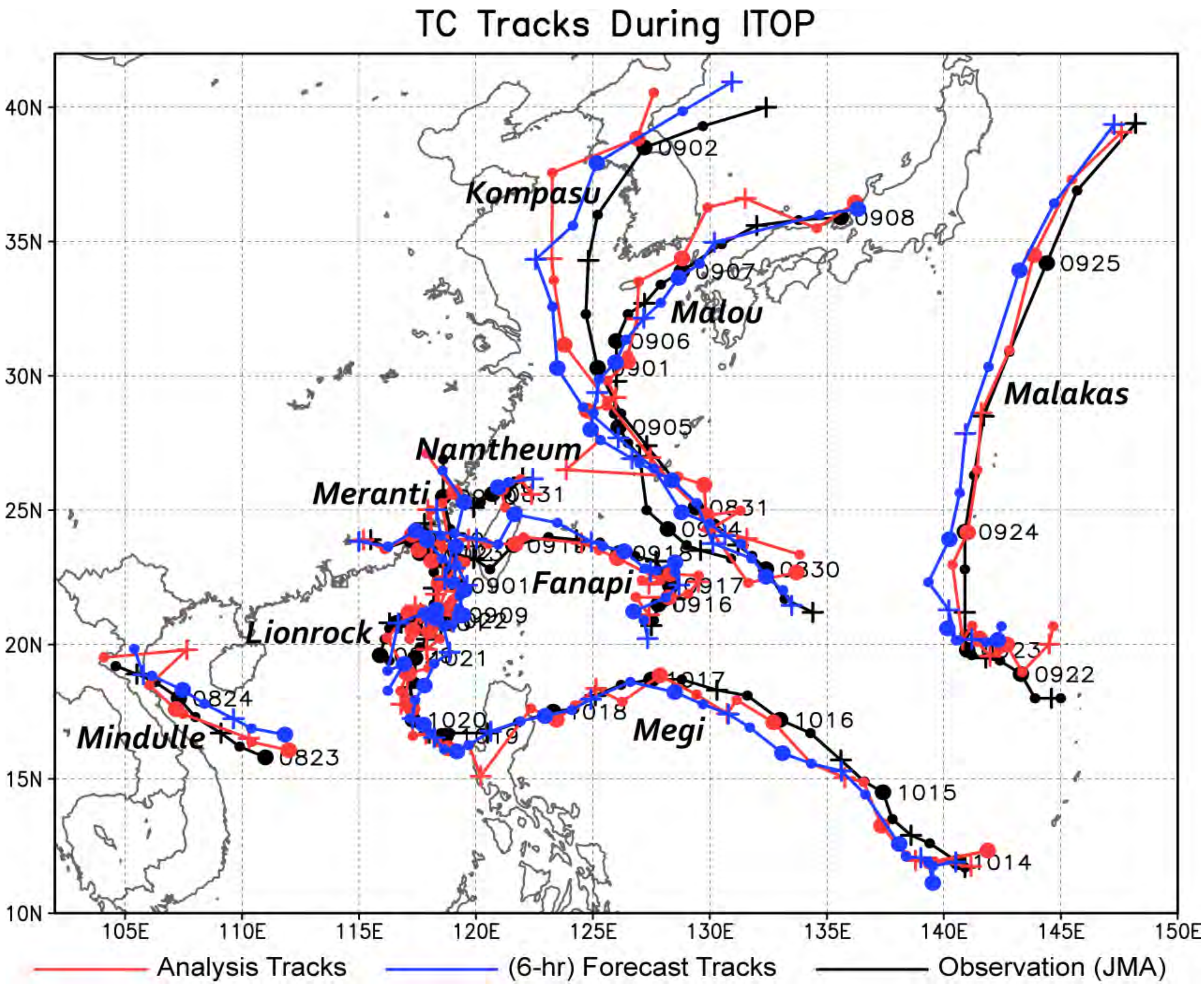
EnKF system based on WRF V2.2.1
(Zhang et al. 2006; Meng et al. 2007)



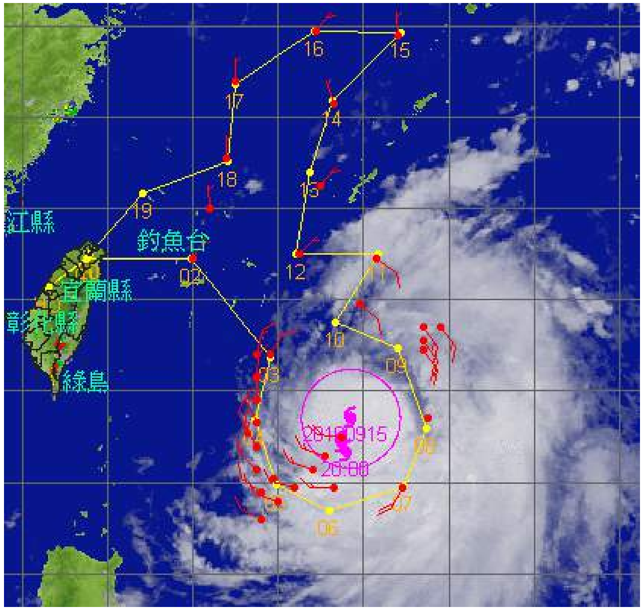
Model domain

- 18 Aug. ~ 25 Oct. 2010
- 45 ensemble members
- Single domain: 121*91 grids with (coarse) 54-km resolution
- Initial ensemble generated from NCEP FNL at 1800 UTC 17 Aug.
- Boundary conditions are also from NCEP FNL over the whole analysis.
- 6-hour cycling assimilation
- Observations assimilated: radiosonde, dropwindsonde data, surface station data, cloud motion vectors, and aircraft reports.

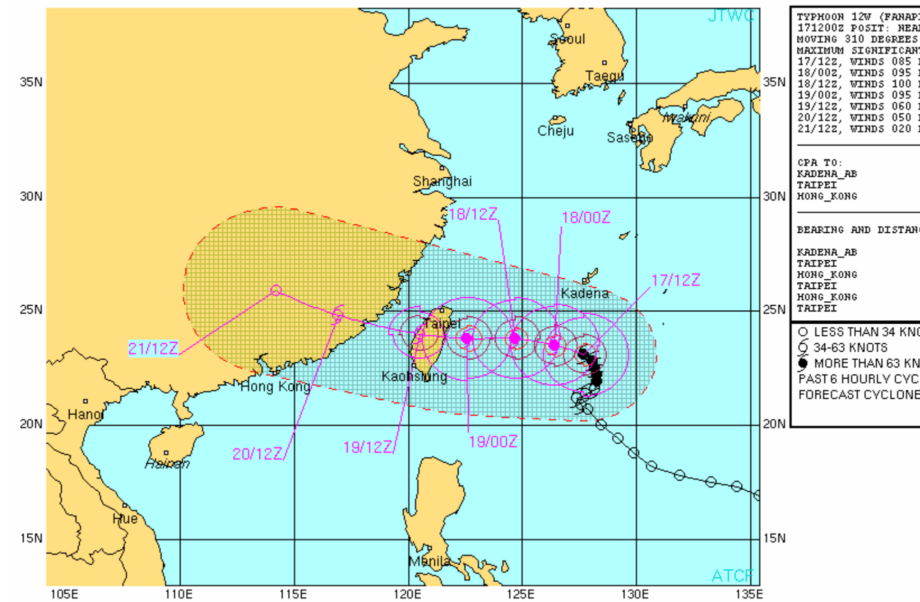
ITOP ensemble reanalysis based on EnKF (*ITOP_EnKF*)

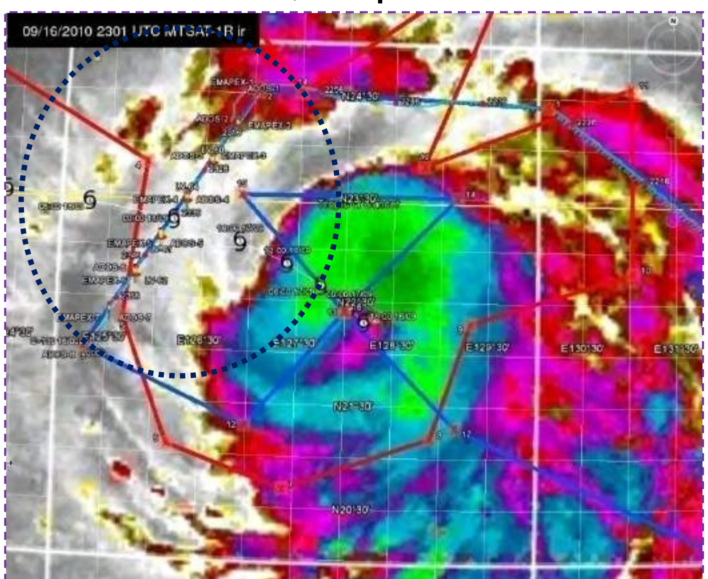


ITOP DOTSTAR/C130 joint observations: Fanapi (2010)

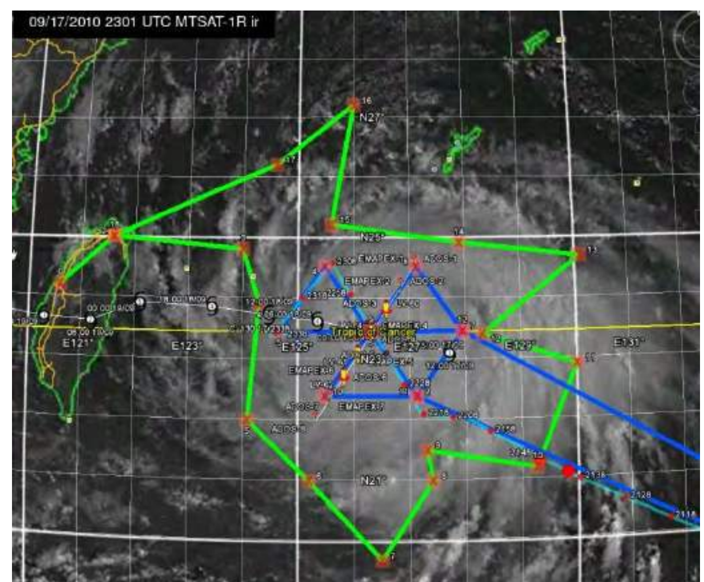


0000 UTC, Sept. 16th



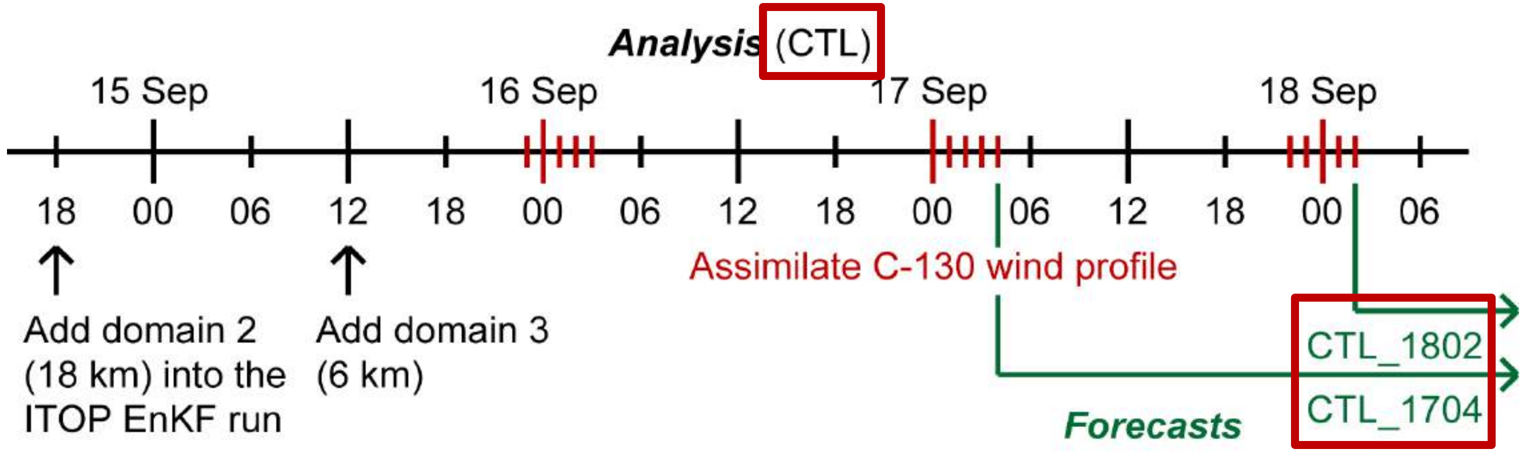


0000 UTC, Sept. 17th



0000 UTC, Sept. 18th

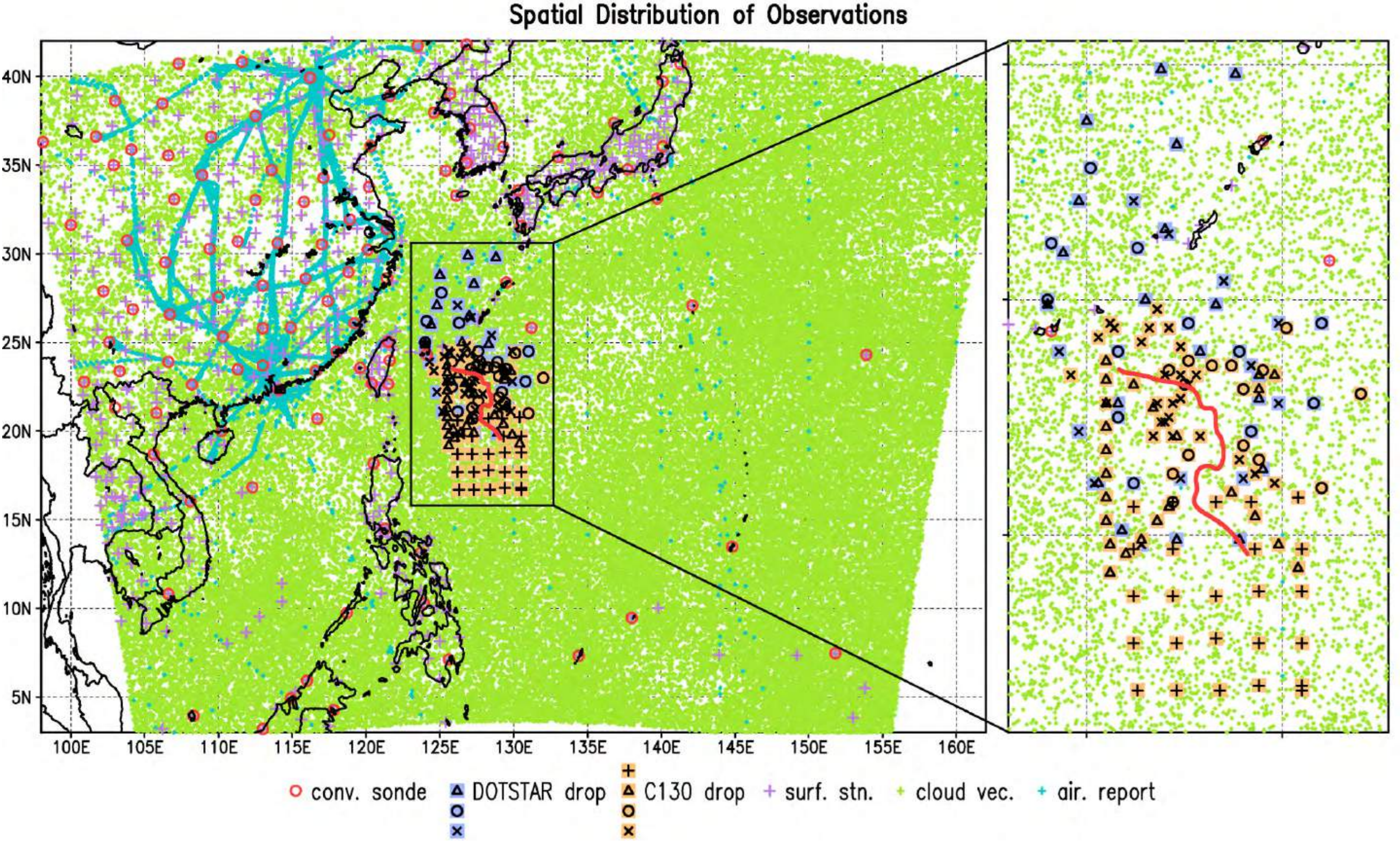
High-resolution analysis and forecast of Typhoon Fanapi



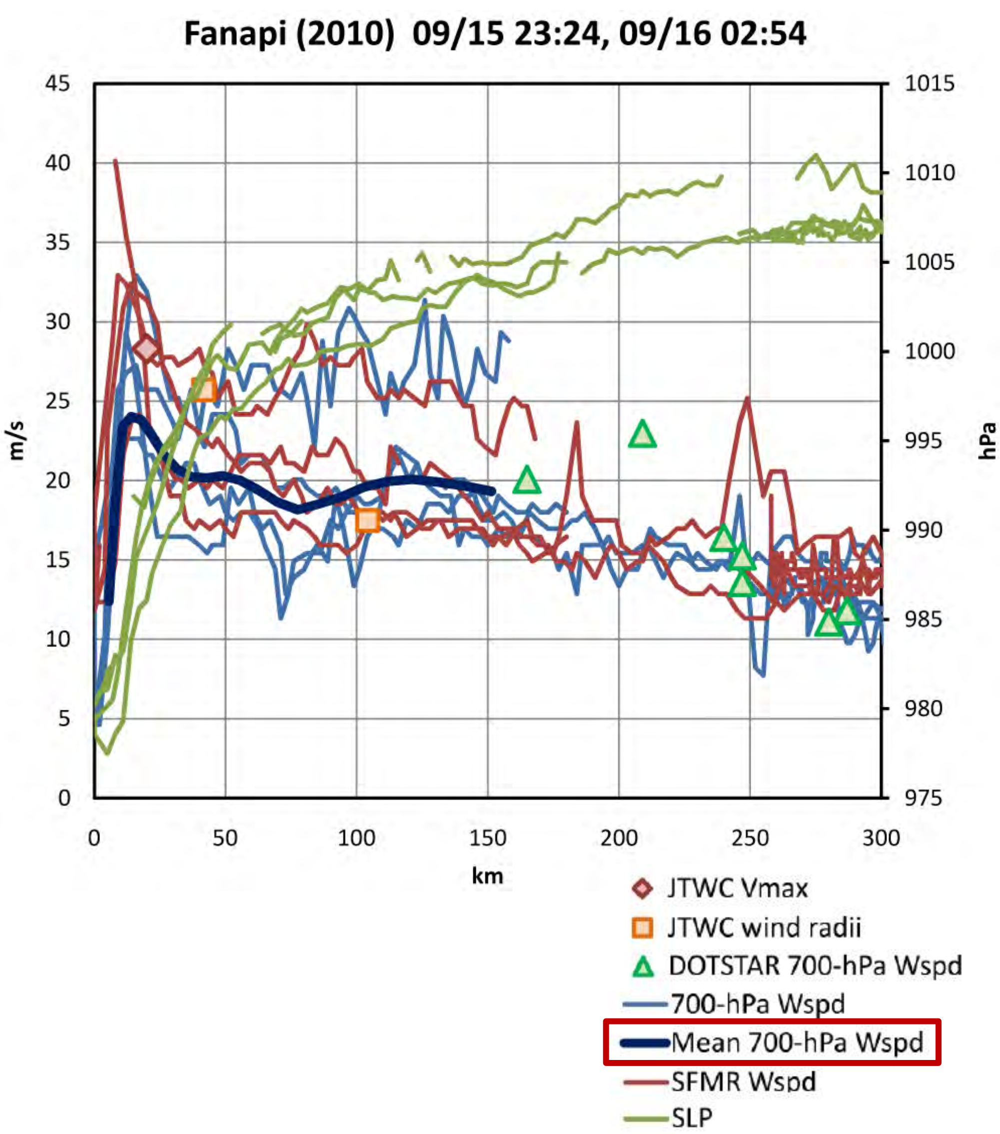
- 1- hour Cycling run from its genesis, initialized with low-resolution ITOP_EnKF run at 1800 UTC 17 Sept.
- Add two additional vortex-following domains (18- and 6-km resolutions).
- Use the same 45-member ensemble.
- Use the same data stream for assimilation, but also include few additional special parameters for TCs (methodology modified from Wu et al. 2010, 2012):
  - TC center position (every hour).
  - Minimum central SLP (every hour).
  - Azimuthal-mean 700-hPa tangential wind profile from 3 C130 missions (when available; using the same composite data for each mission).

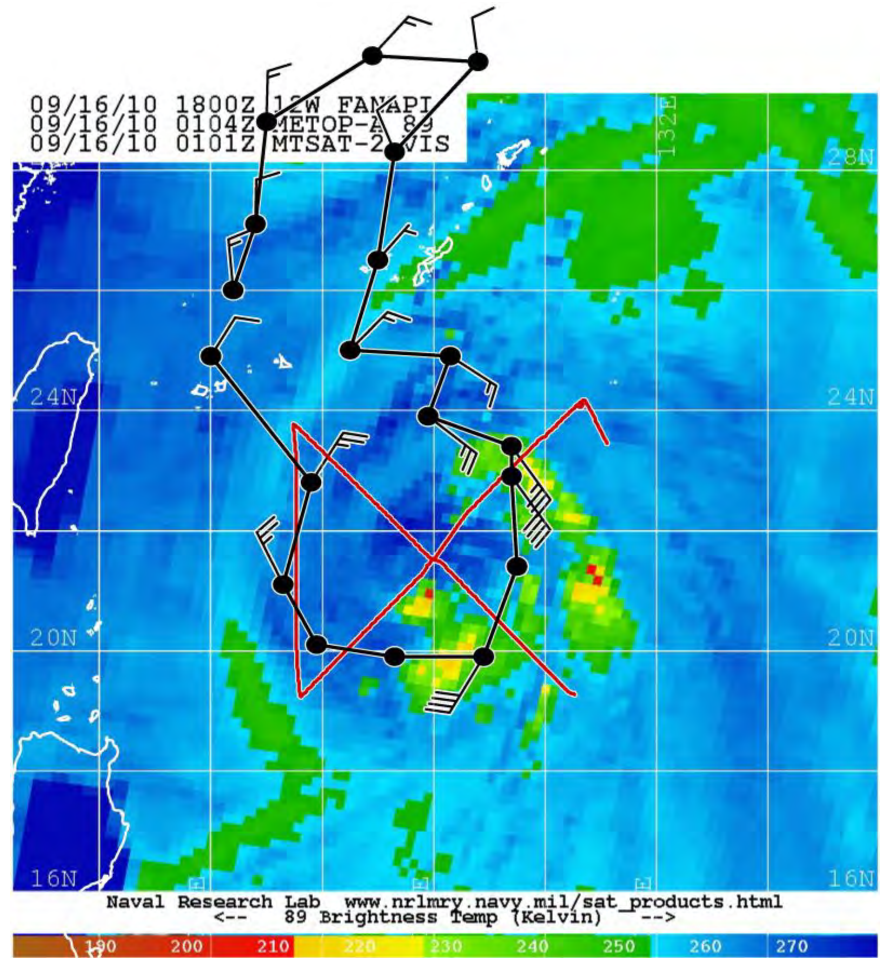
Data distribution in Fanapi

From 1730 UTC 14 Sept to 0230 UTC 18 Sept

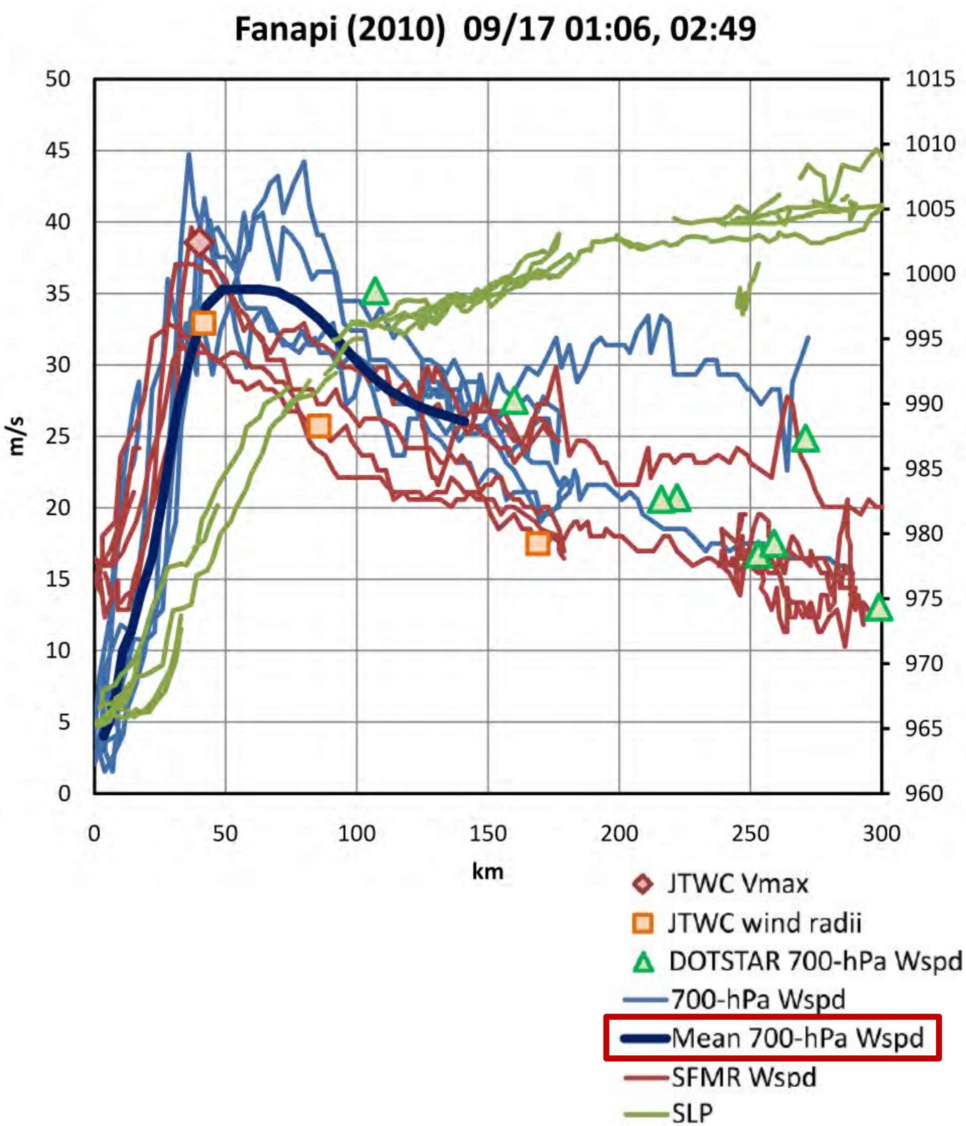


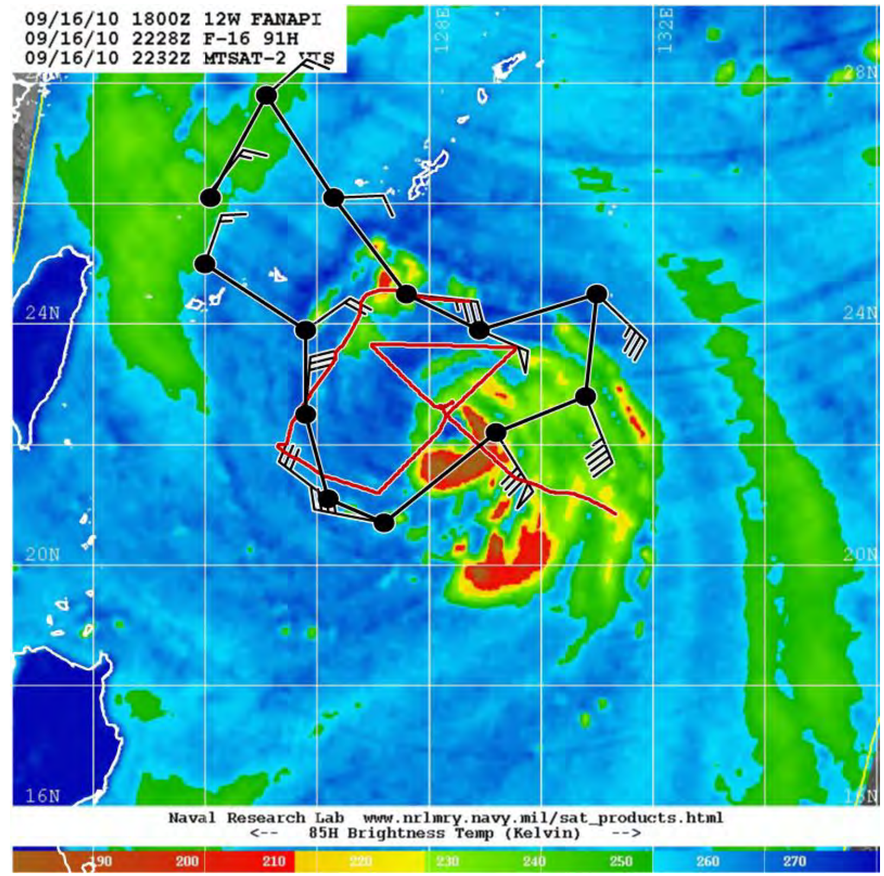
3 consecutive C130-DOTSTAR joint fight missions (I)



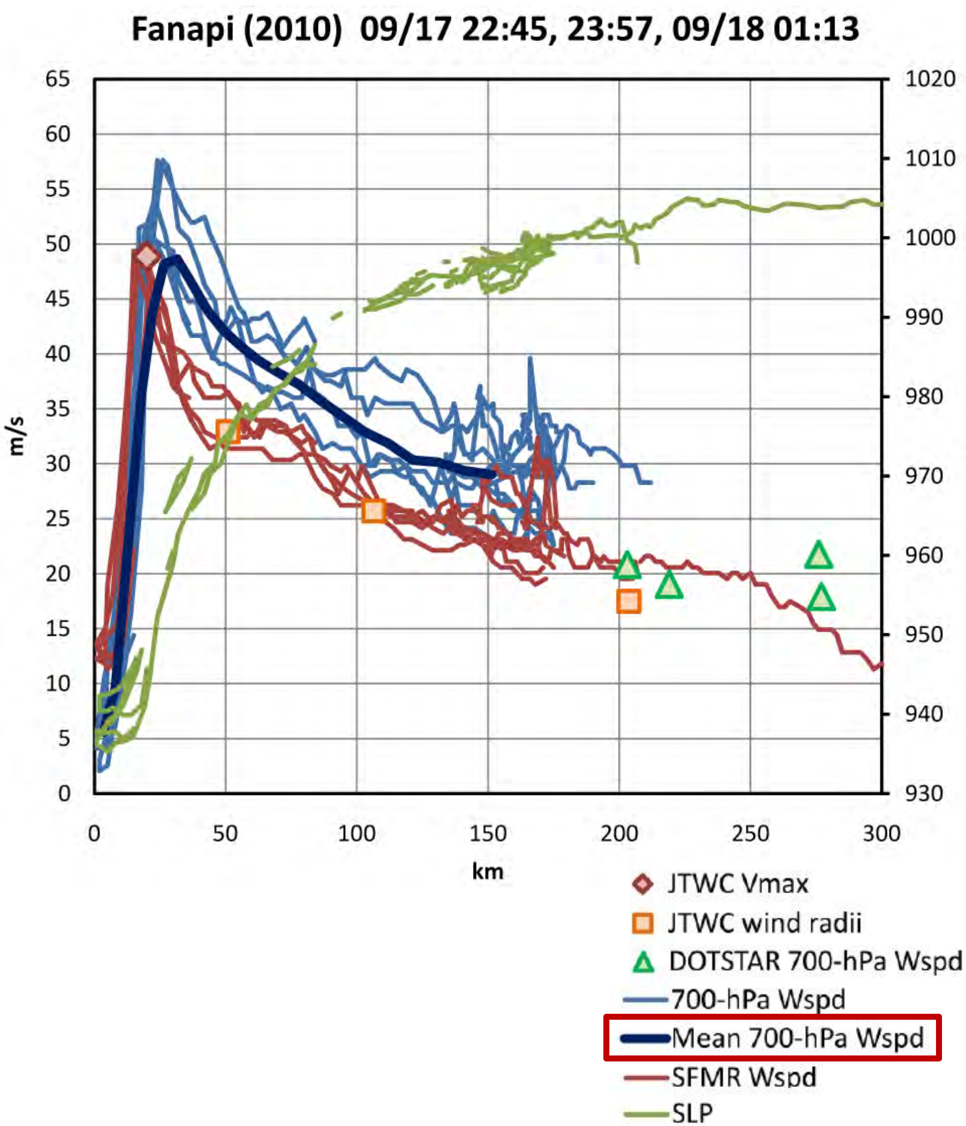


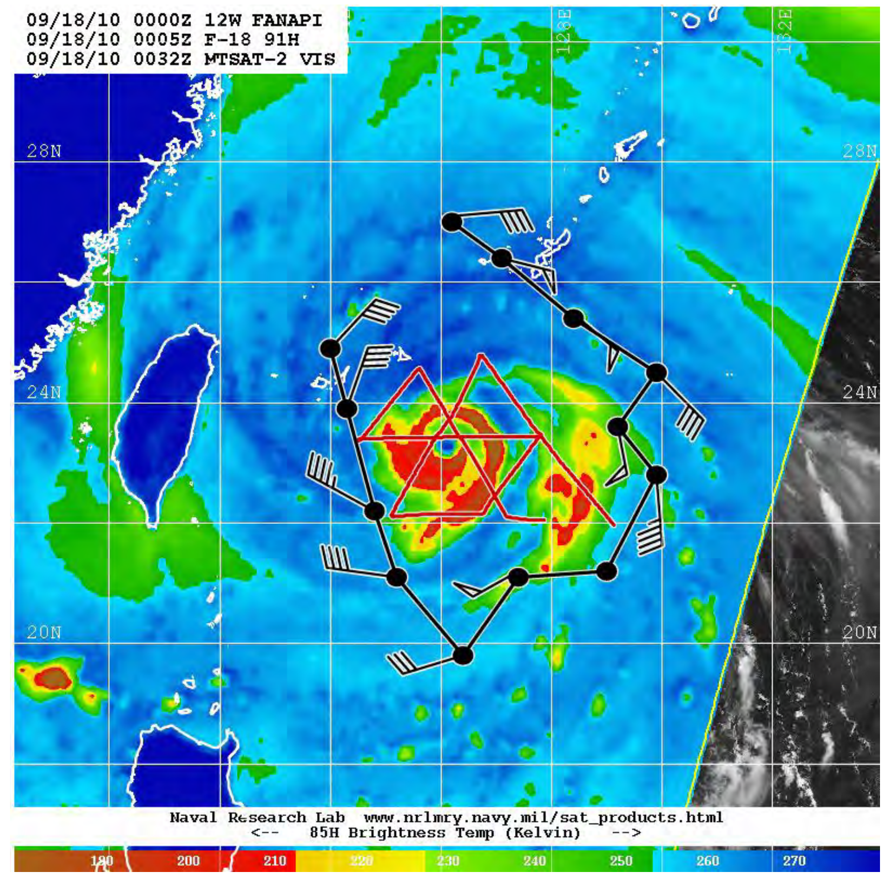
3 consecutive C130-DOTSTAR joint fight missions (II)



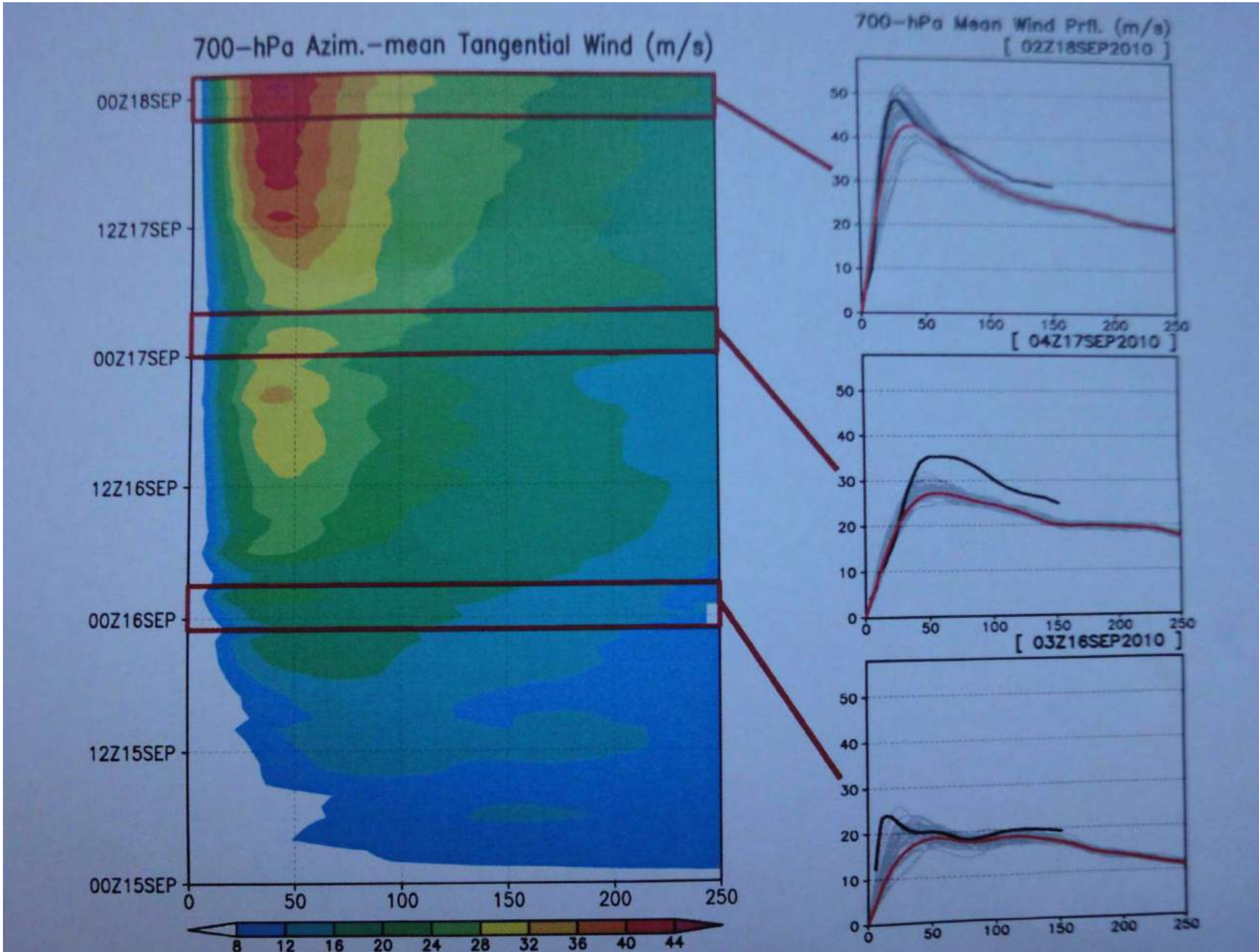


3 consecutive C130-DOTSTAR joint fight missions (III)

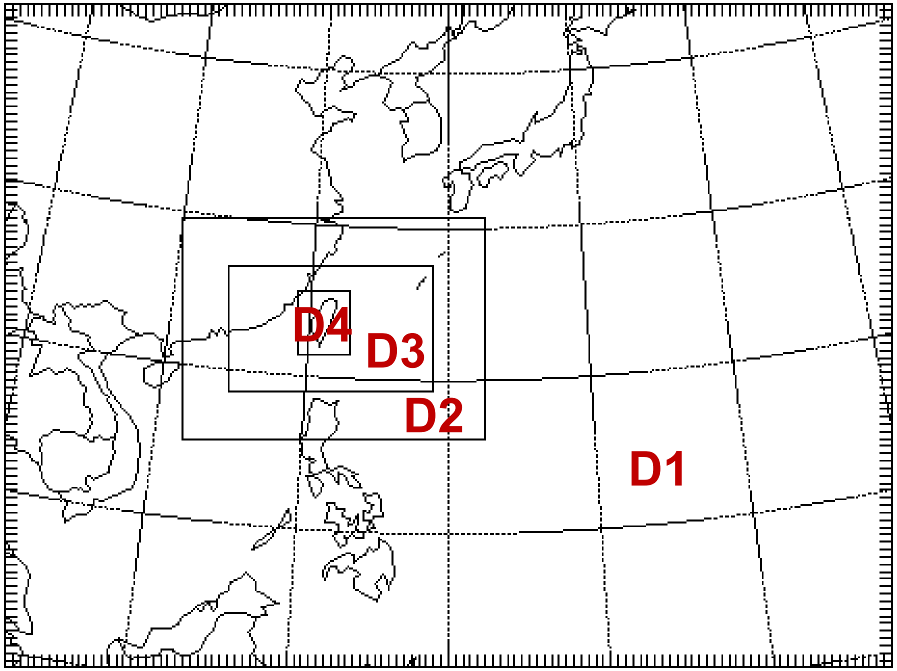




700-hPa azimuthal tangential wind profile

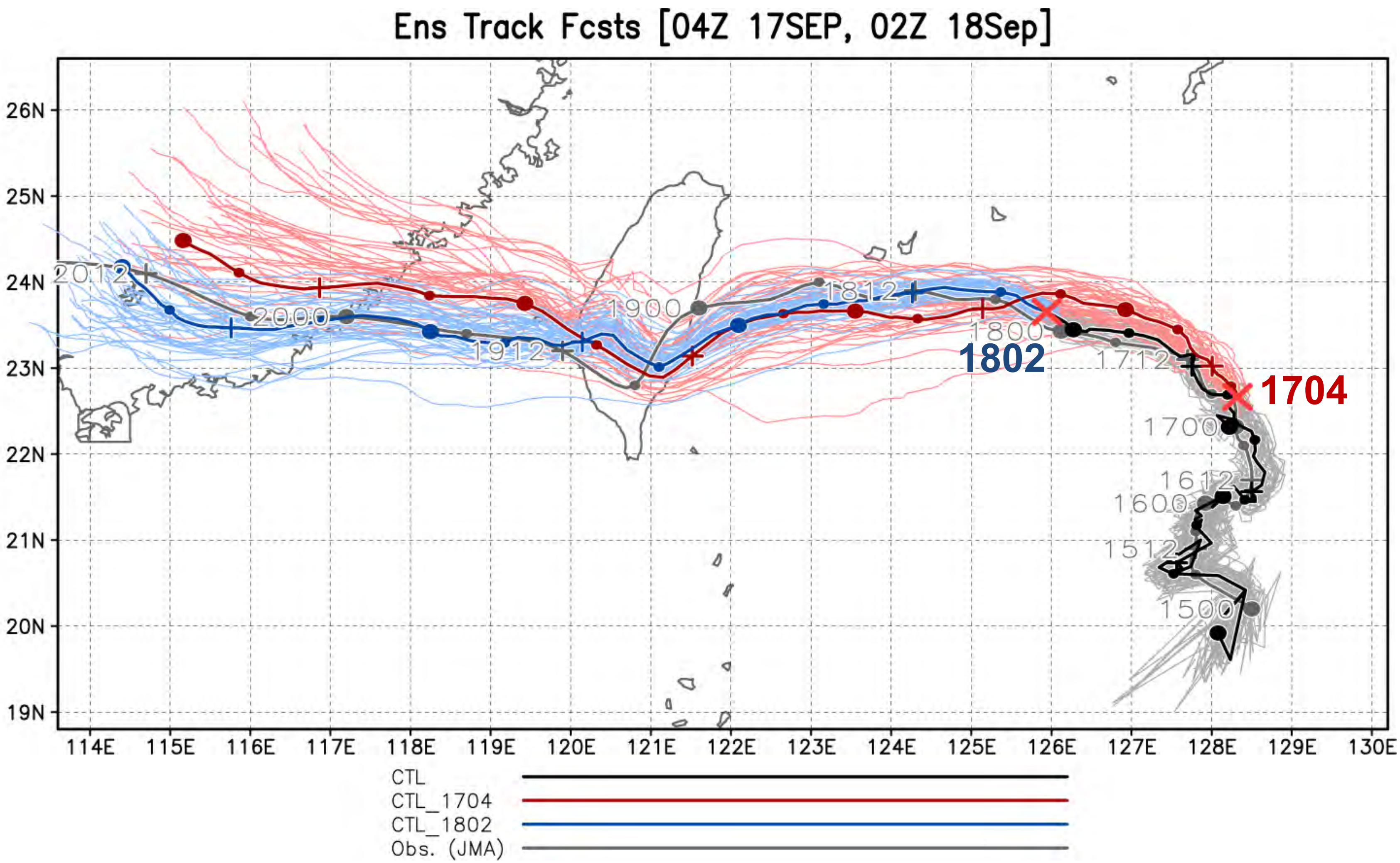


2-km resolution run initialized from ensemble mean (*CTL_1802_2km*)



- Use larger fixed domains in this simulation (data interpolated from the original moving domains).
- Add additional domain 4 covered Taiwan island with 2-km resolution.
- The track of Fanapi is nearly the same as that in *CTL_1802* (6 km / moving domain).

Forecasts : Ensemble tracks (*CTL_1704*, *CTL_1802*)

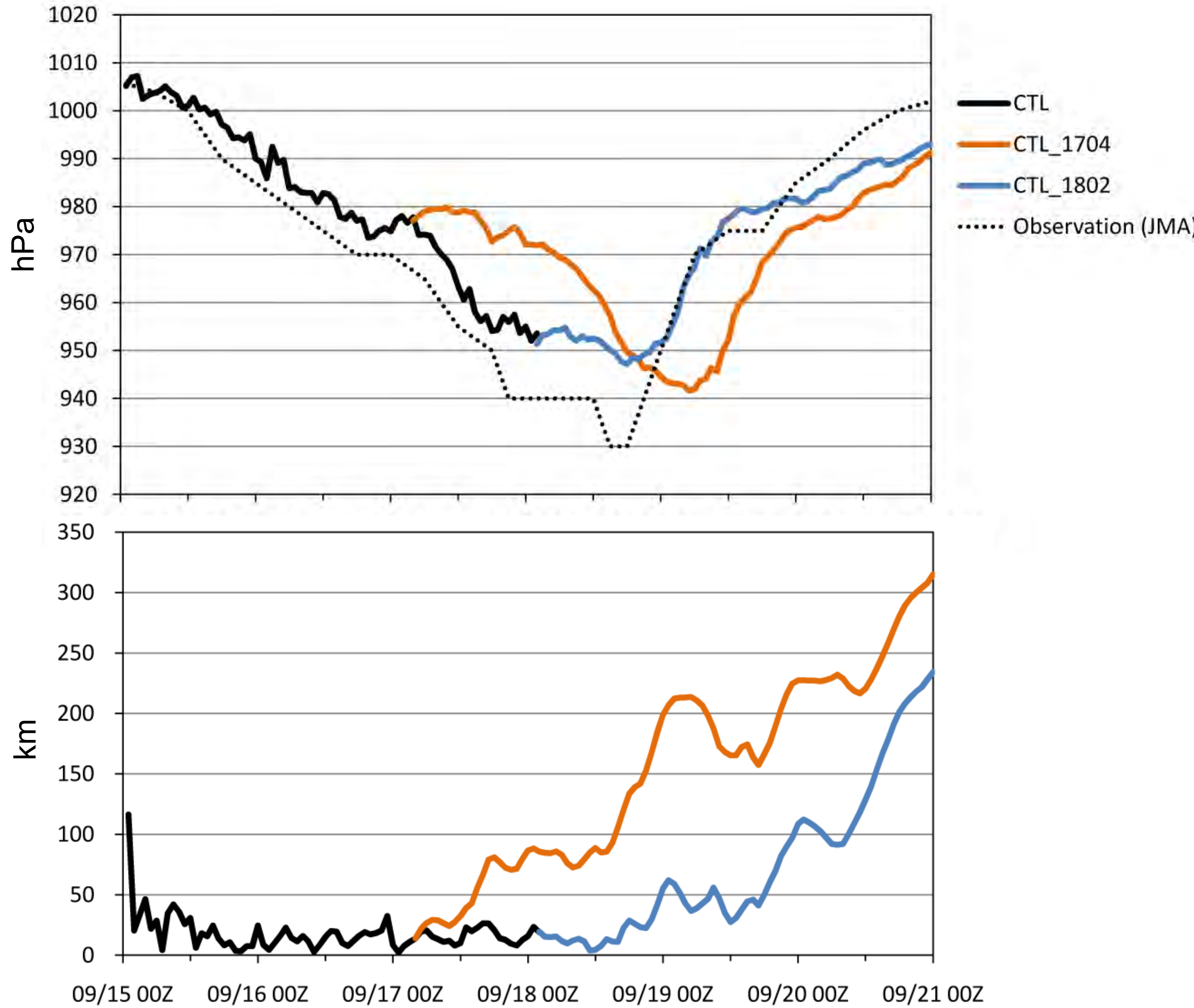


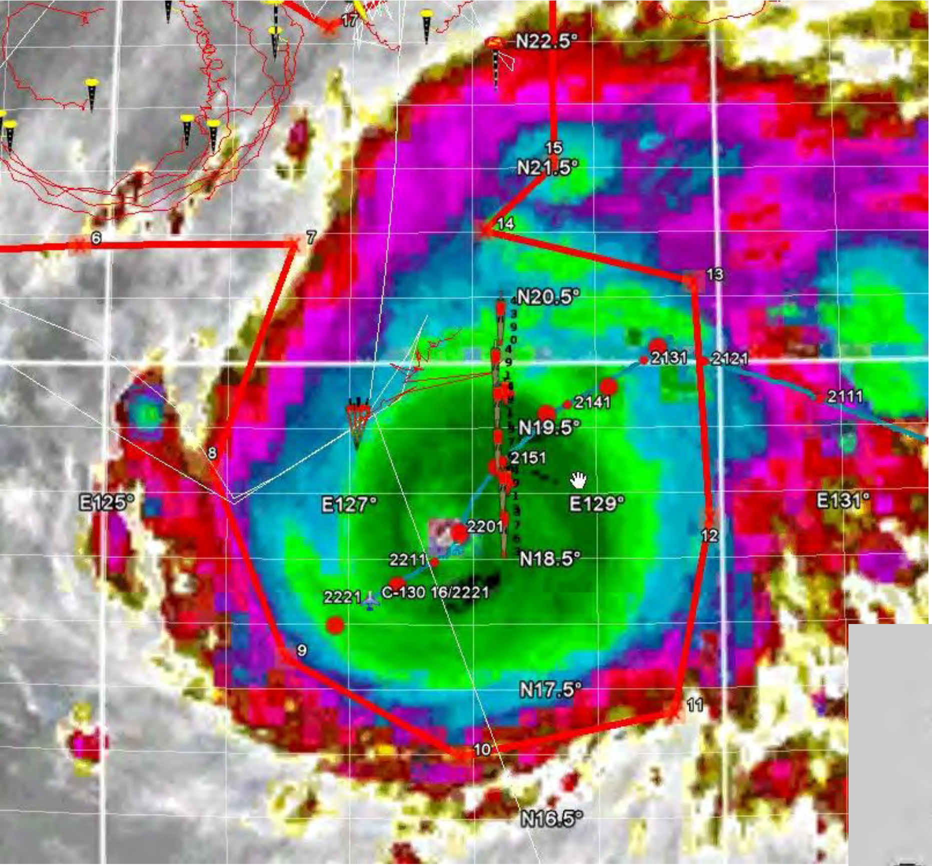
- The simulated Fanapi in *CTL_1704* moves slower than the observed track.

Forecasts : Track errors and intensities

Intensity

Track error





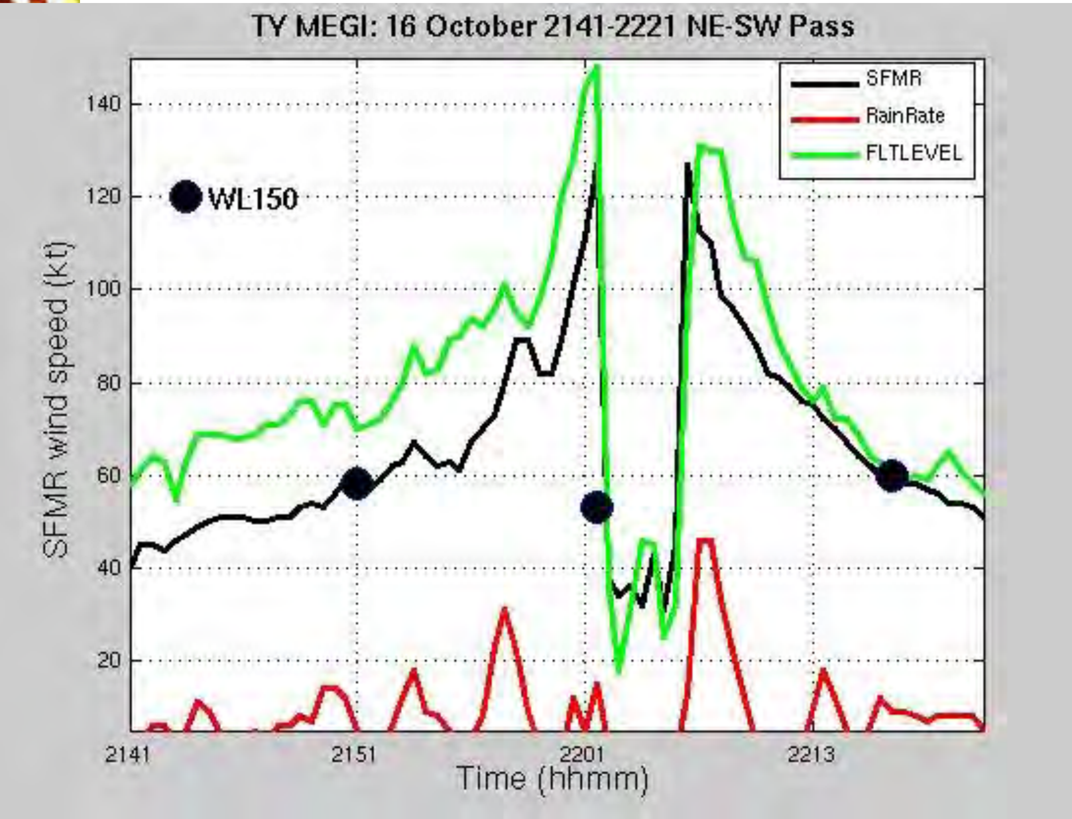
STy Megi 16 Oct

-

(C-130 (blue)and DOTSTAR tracks (red), float line (N-S near 128E) Dropsonde and AXBT (big red dots), HDobs (small red dots)

C-130 cross-section 16 Oct (2141-2221 UTC)

Flight level winds (green), SFMR derived surface winds (black), surface rain rate (red) and dropsonde derived lowest 150m wind speed (black dot)



Model setup of Typhoon Megi

- Time period: 2010.10.13_00:00 to 2010.10.24_06:00
- Domains
  - Domain 1: 121*91 grids, 54-km
  - Domain 2: 73*73 grids, 18-km, moving nested
  - Domain 3: 97*97 grids, 6-km, moving nested
- Assimilation data
  - General parameters:
    - Radiosonde and dropwindsonde data, surface station, cloud motion vectors, and aircraft reports
  - Special parameters for TCs:
    - TC center position
    - Minimum central SLP
    - Azimuthal-mean 700-hPa tangential wind profile from C130 missions (when available)

High-resolution reanalysis of Typhoon Megi

From 2010.10.13_00:00

Oct.13_00:00 Add domain 2 (18 km)
Oct.13_12:00 Add domain 3 (6 km)

C130 flight missions:

Oct.14_00:00-Oct.14_04:00

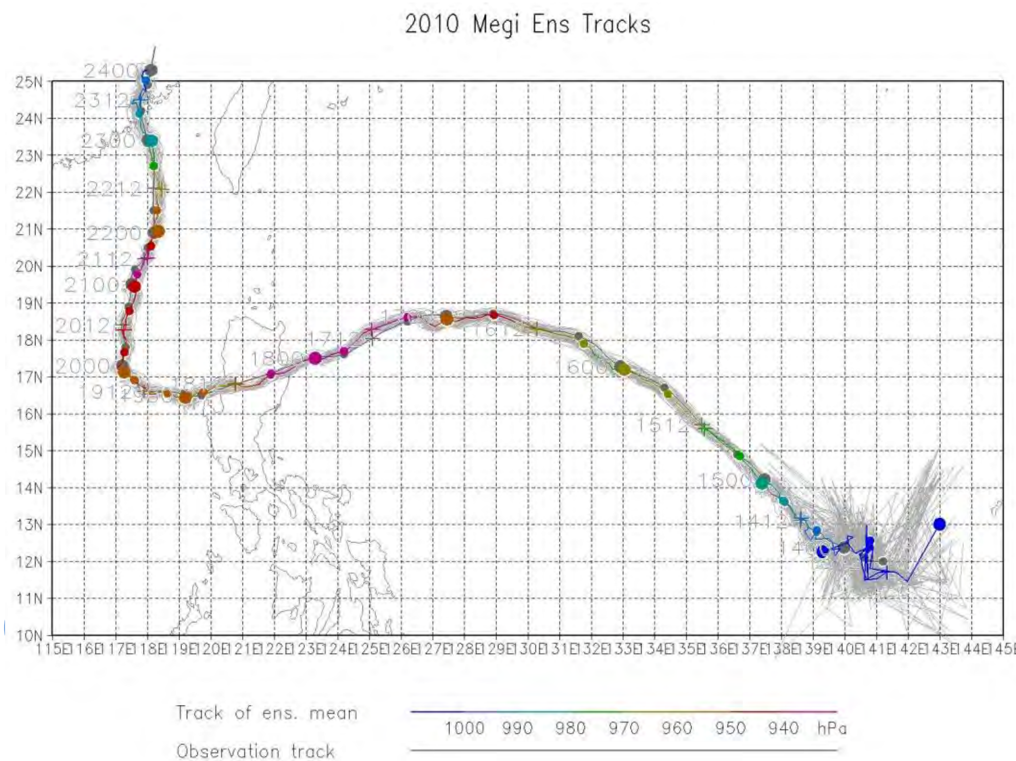
Oct.14_19:00-Oct.14_23:00

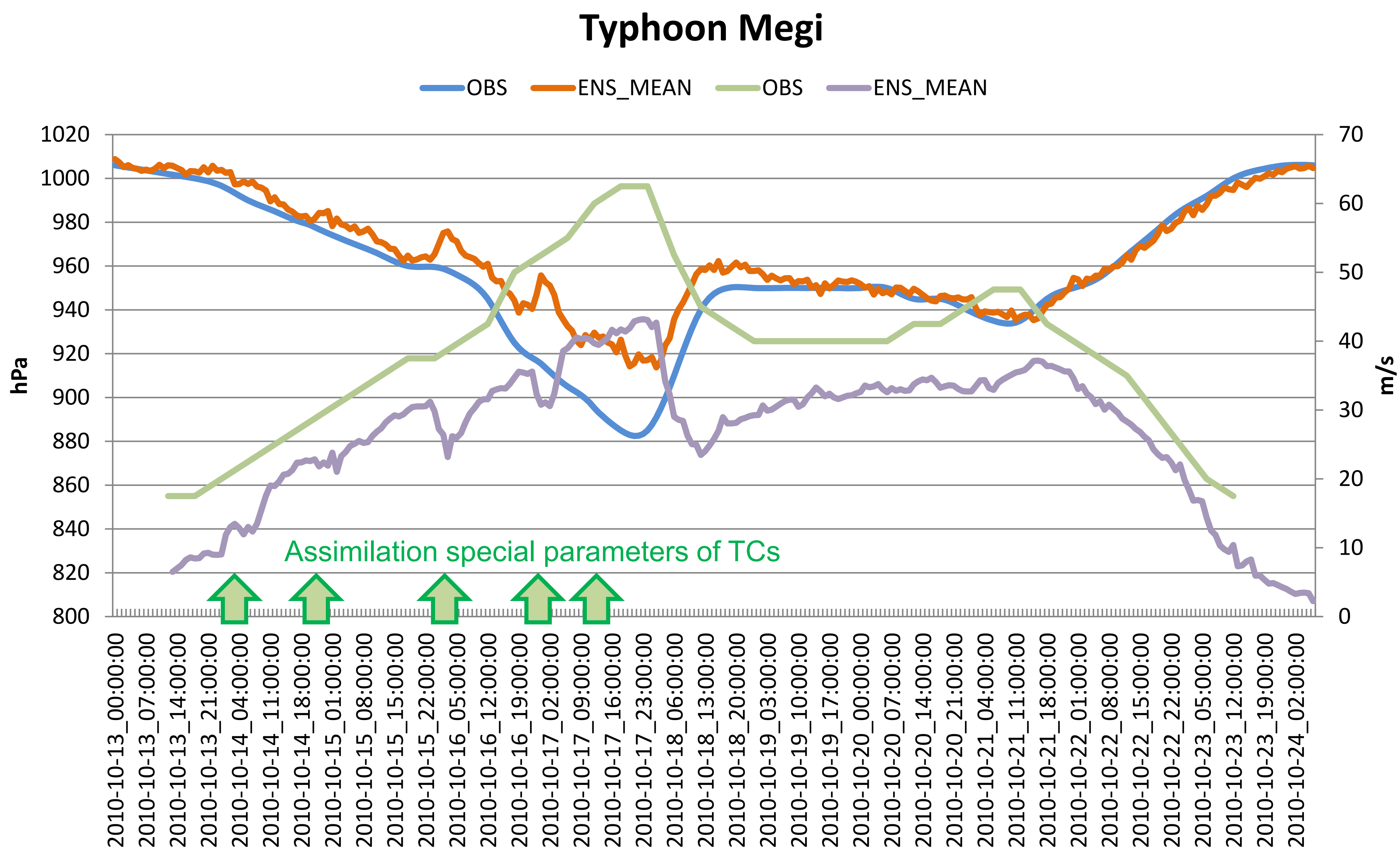
Oct.16_00:00-Oct.16_04:00

Oct.16_22:00-Oct.17_02:00
Oct.17_10:00-Oct.17_14:00

Oct.14
Oct.15
Oct.16
Oct.17
Landfall
Oct.19

To 2010.10.24_06:0




Typhoon Megi
OBS
ENS_MEAN
OBS
ENS_MEAN
hPa
m/s
Assimilation special parameters of TCs
1020
1000
980
960
940
920
900
880
860
840
820
800
70
60
50
40
30
20
10
0
2010-10-13_00:00:00
2010-10-13_07:00:00
2010-10-13_14:00:00
2010-10-13_21:00:00
2010-10-14_04:00:00
2010-10-14_11:00:00
2010-10-14_18:00:00
2010-10-15_01:00:00
2010-10-15_08:00:00
2010-10-15_15:00:00
2010-10-15_22:00:00
2010-10-16_05:00:00
2010-10-16_12:00:00
2010-10-16_19:00:00
2010-10-17_02:00:00
2010-10-17_09:00:00
2010-10-17_16:00:00
2010-10-17_23:00:00
2010-10-18_06:00:00
2010-10-18_13:00:00
2010-10-18_20:00:00
2010-10-19_03:00:00
2010-10-19_10:00:00
2010-10-19_17:00:00
2010-10-20_00:00:00
2010-10-20_07:00:00
2010-10-20_14:00:00
2010-10-20_21:00:00
2010-10-21_04:00:00
2010-10-21_11:00:00
2010-10-21_18:00:00
2010-10-22_01:00:00
2010-10-22_08:00:00
2010-10-22_15:00:00
2010-10-22_22:00:00
2010-10-23_05:00:00
2010-10-23_12:00:00
2010-10-23_19:00:00
2010-10-24_02:00:00

Model setup of Typhoon Malakas

- Time period: 2010.09.20_06:00 to 2010.09.28_00:00
- Domains
  - Domain 1: 121*91 grids, 54-km
  - Domain 2: 73*73 grids, 18-km, moving nested
  - Domain 3: 97*97 grids, 6-km, moving nested
- Assimilation data
  - General parameters:
    - Radiosonde and dropwindsonde data, surface station, cloud motion vectors, and aircraft reports
  - Special parameters for TCs:
    - TC center position
    - Minimum central SLP
    - Azimuthal-mean 700-hPa tangential wind profile from C130 missions (when available)

High-resolution reanalysis of Typhoon Malakas

From 2010.09.20_06:00

Sep.20_06:00 Add domain 2 (18 km)

Sep.21

C130 flight missions:

Sep.22_00:00 Add domain 3 (6 km)

Sep.22_20:00-Sep.23_00:00

Sep.23

Sep.23_17:00-Sep.23_21:00

Sep.24

Sep.24_16:00-Sep.24_20:00

Sep.25_00:00 Close domain 3, stop assimilate TC special para

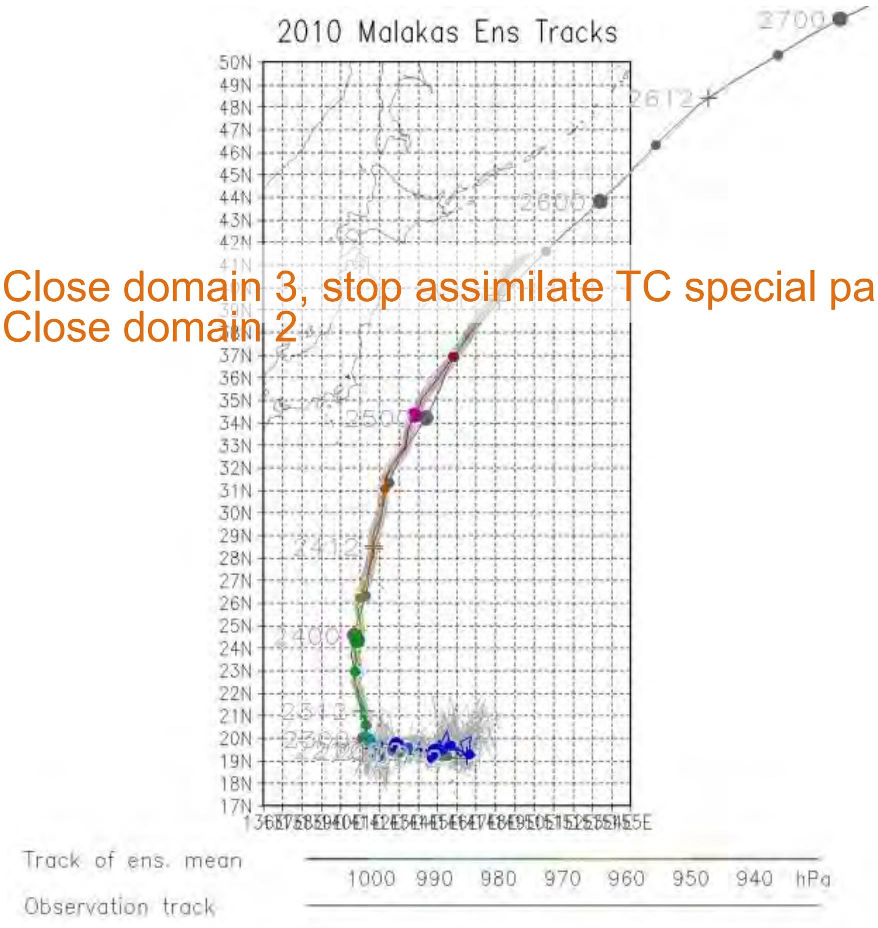
Sep.25_06:00 Close domain 2

Sep.26

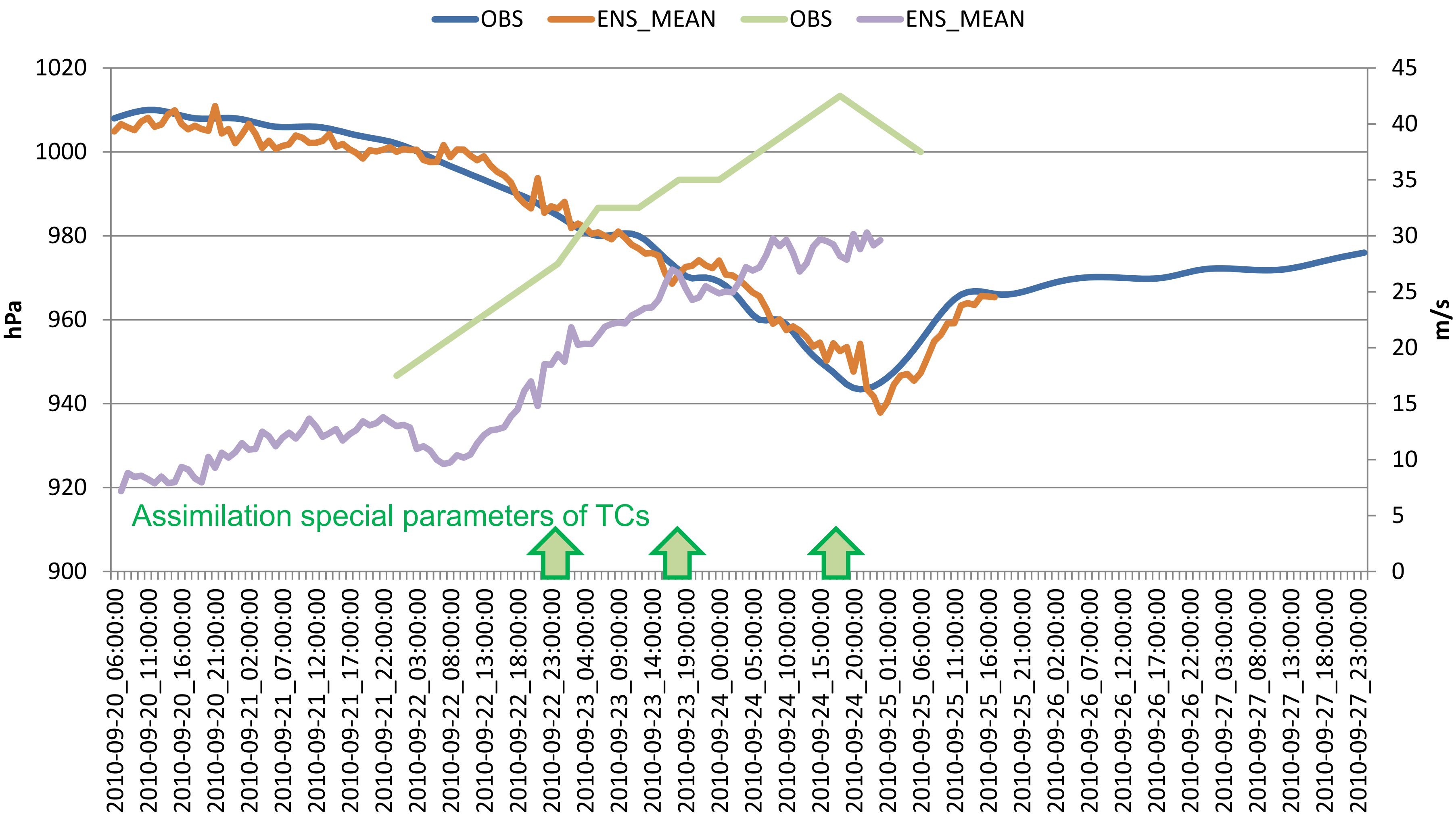
Sep.27

Sep.28

To 2010.09.28_00:00



Typhoon Malakas



Ongoing works

- **Typhoon-ocean interaction in Fanapi**
  – *Coupled model simulation*
  – *Cold wake (model vs. ITOP observation)*
    How it formed, sustained and decayed?
  – *Feedback to intensity*
  – *Provide the surface wind and SLP data for the ocean modeling and analysis*

- **High-resolution dataset for Megi**

  -- *What lead to such a supertyphoon?*

- **High-resolution dataset for Malakas**

  -- *Ocean (eddy) vs. atmosphere (vertical shear)*

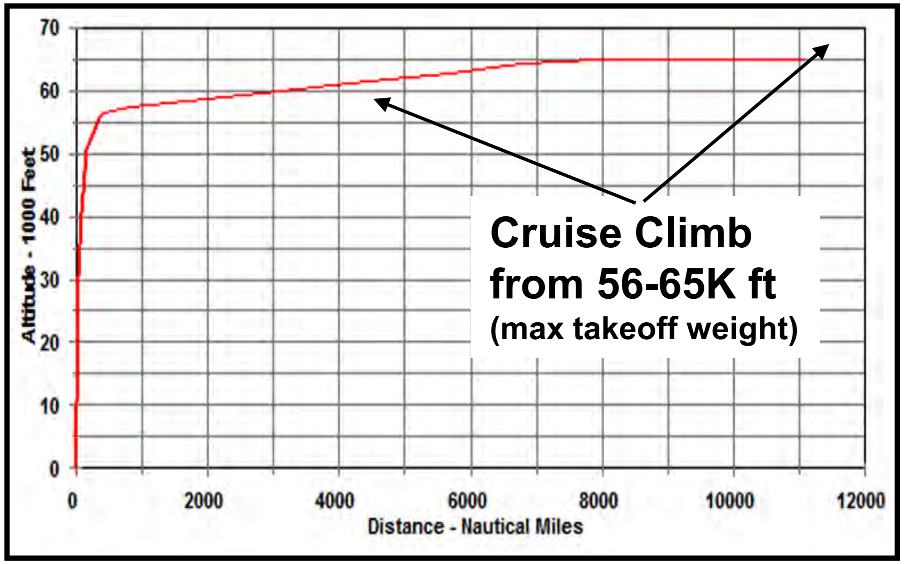
風中的答案

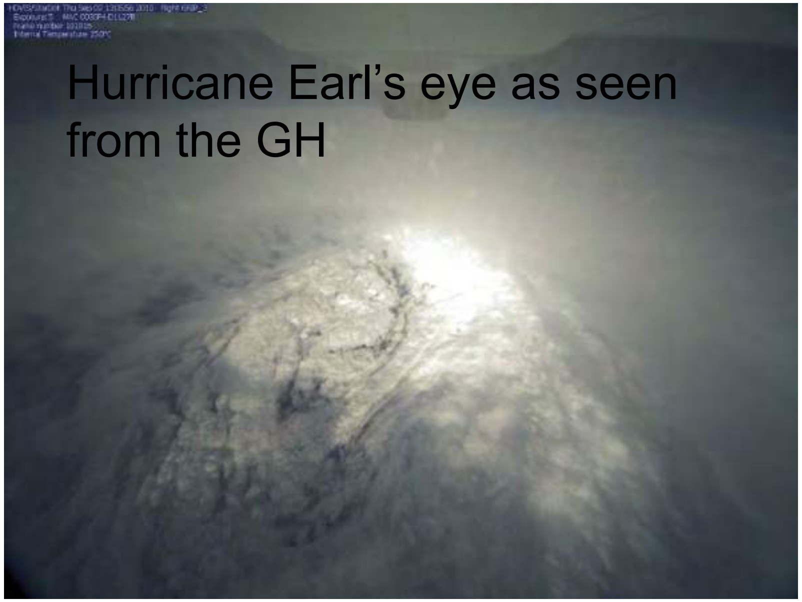
- 風中的答案（完整MV版）

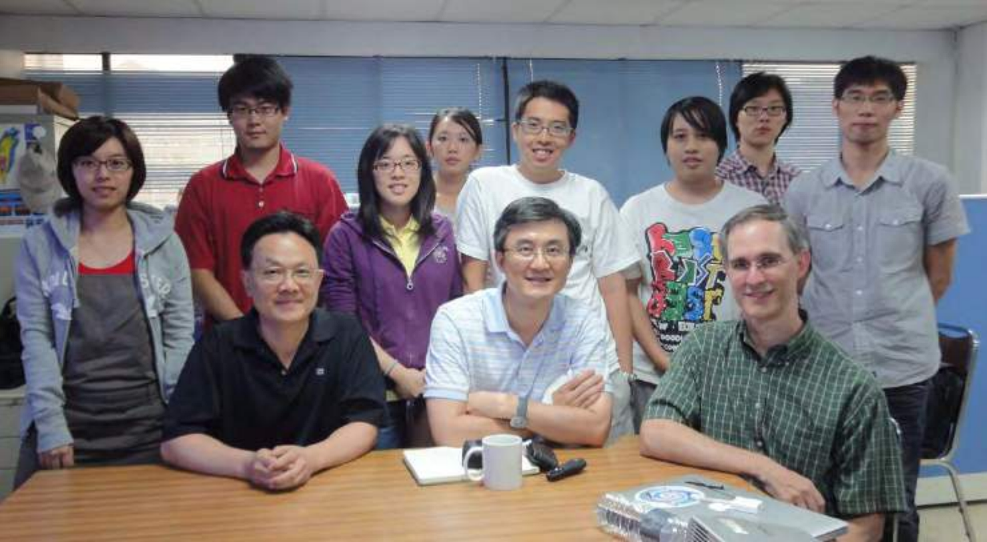
  http://www.youtube.com/watch?v=SoSm8ImP7tw

NASA's Global Hawk Unmanned Airborne System

Endurance	> 30 hours
Range	>11,000 nmi
Service Ceiling	65,000 ft
Airspeed (55K+ ft)	335 KTAS
Payload	1,000-1,500 lb
Length	44 ft
Wingspan	116 ft








NASA
NORTHROP GRUMMAN
DRYDEN FLIGHT RESEARCH CENTER

Cost-effectiveness

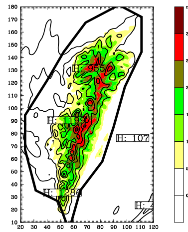
From Aberson (2010)

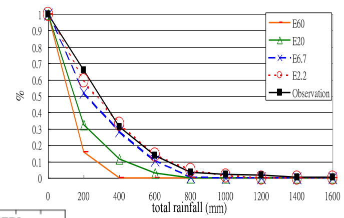
- One complete G-IV flight and required dropwindsondes: US $40,000.
- Average cost to evacuate one mile (1.6 km) of United States coastline: US $1,000,000.

- Have similar cost-benefit analyses been done elsewhere?

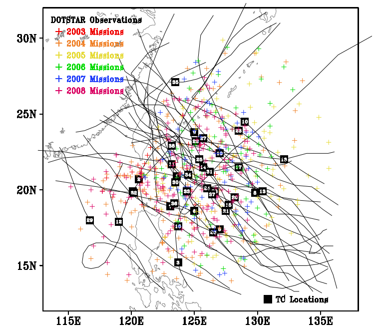
(Chun-Chieh Wu: 2002-2009)

(Wu et al. 2002, WF)

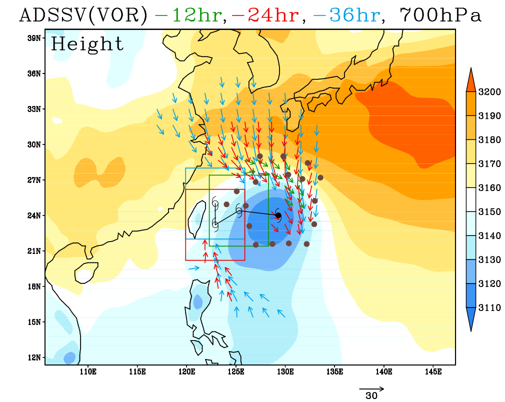




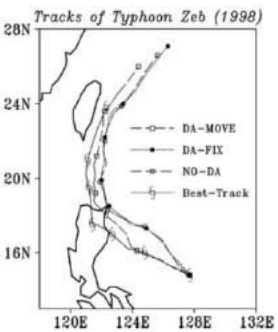
(Wu et al. 2009a, b, MWR)

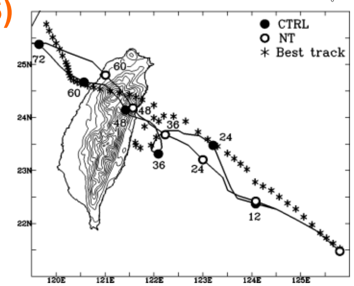


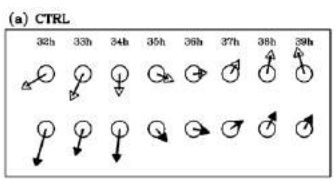
(Wu et al. 2007a JAS)



(Wu et al. 2006, JAS)

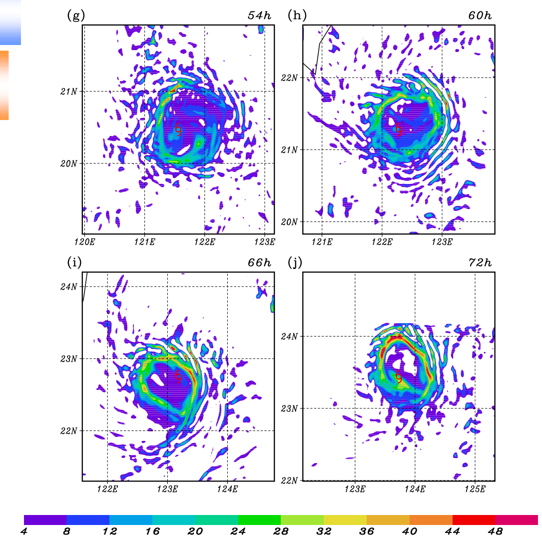






(Jian and Wu 2008, MWR)

(Wu et al. 2009c, MWR)



Targeted observation in DOTSTAR

Typhoon intensity eyewall dynamics

Typhoon-terrain interaction

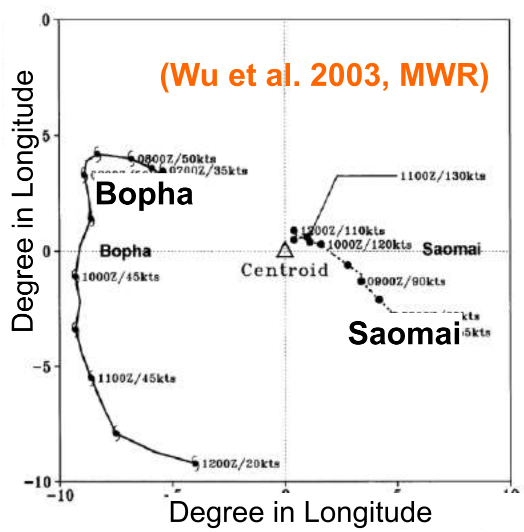
Typhoon movement

Typhoon rainfall

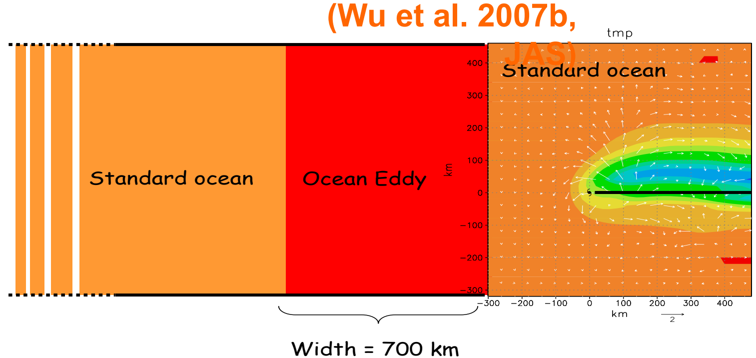
Typhoon-ocean interaction

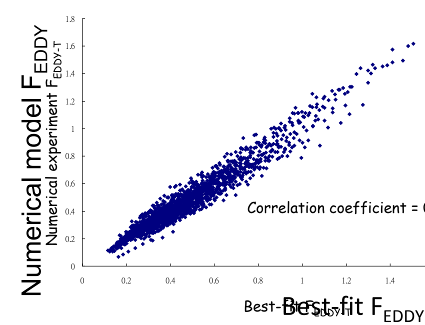
Typhoon-climate

(Wu et al. 2003, MWR)

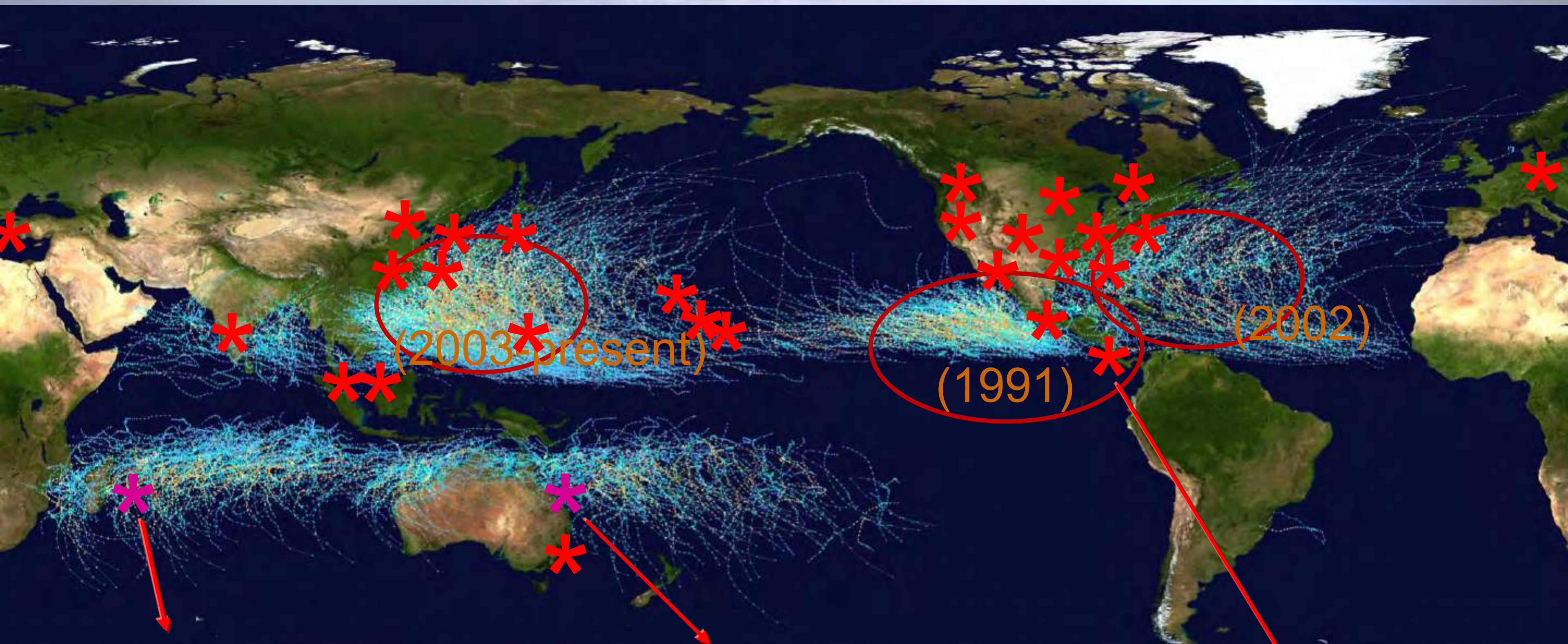


(Wu et al. 2007b, JAS)





Tracks of all tropical cyclones, 1985-2005
(1985-2005年所有熱帶氣旋的路徑)



Vision of the international Typhoon Research Center

Pushing the envelope of predictability of typhoons

- **Theory, predictability** and **dynamical processes**
- **Observing systems**
- **Modeling, data assimilation** and **observing strategies**
- **Societal applications**

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

THANKS FOR LISTENING

Q and A (break)