New Development on PMP Estimation in China

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Key issues in Engineering Hydrologic Studies

--Hydrologic frequency & PMP estimation in China

100 years of AMS rainfall data at a station in the U.S.

- (011901) 28-4229 ANMAX
- 100
- 3.46 2.60 5.65 4.90 3.02 7.15 2.97 2.86 2.70 3.18
- 3.39 2.13 2.34 2.61 4.39 2.04 3.06 3.92 3.00 3.67
- 1.97 1.45 2.78 2.73 3.98 1.98 2.17 2.00 1.80 2.08
- 1.72 2.61 3.10 3.73 2.82 2.17 2.10 6.78 6.05 4.55
- 1.92 3.20 3.50 3.45 2.78 3.33 1.42 2.62 3.23 4.20
- 2.42 3.23 2.22 4.25 3.21 4.02 1.37 4.16 1.81 5.05
- 2.44 3.84 2.80 2.29 3.35 3.18 5.06 2.41 3.58 2.10
- 4.29 3.80 3.78 6.63 2.77 3.42 2.25 2.71 2.84 2.35
- 2.83 1.90 2.63 2.46 4.68 4.10 2.51 1.95 2.59 4.71
- 4.94 3.88 2.81 2.51 2.85 3.72 2.91 2.26 4.88 2.63

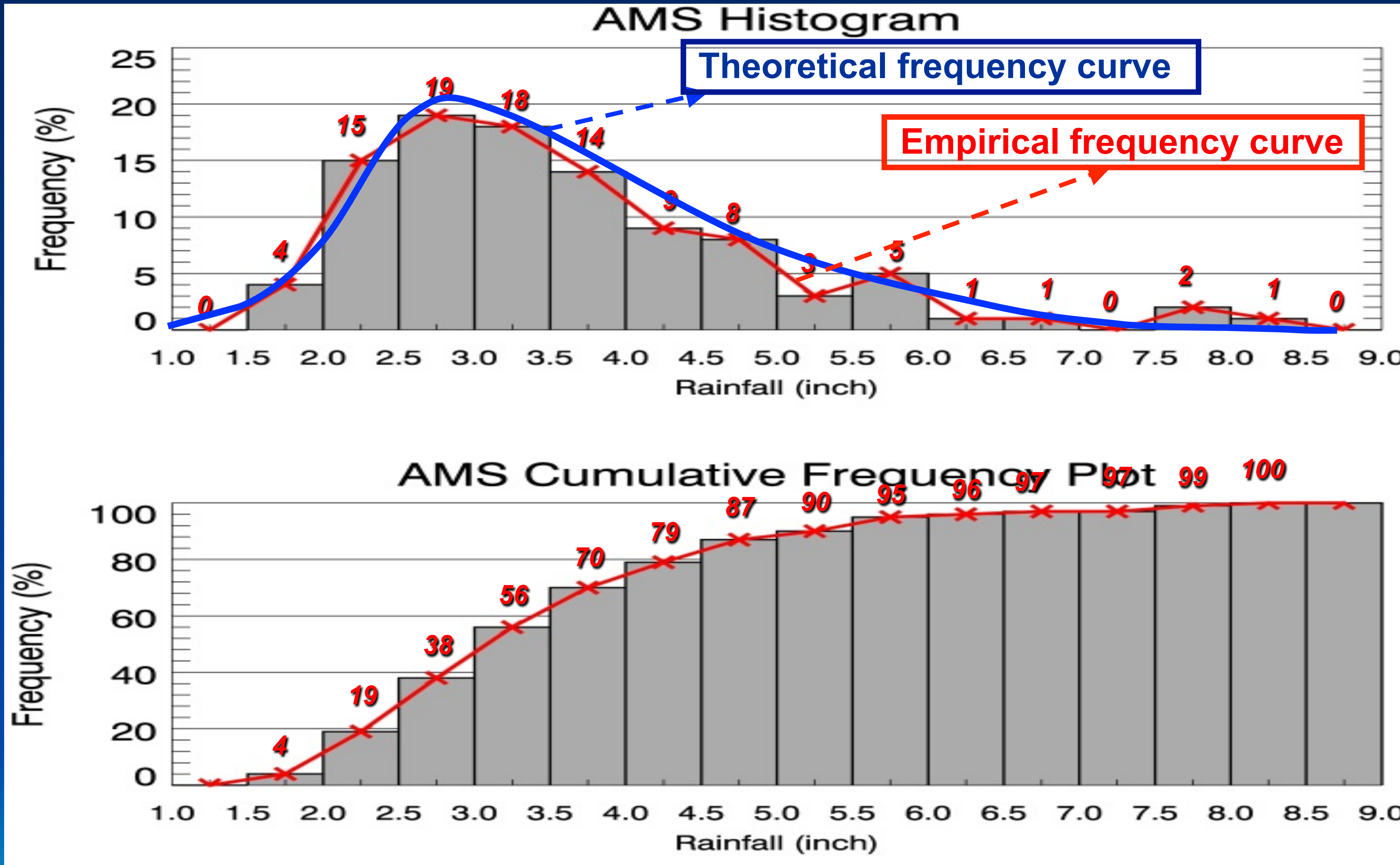
100 years of AMS rainfall data

（Sorted + Grouped）

(011901) 28-4229 ANMAX

100

1.55	1.61	1.64	1.95	2.04	2.05	2.15	2.18	2.21	2.23
2.25	2.27	2.31	2.36	2.38	2.38	2.42	2.46	2.46	2.52
2.55	2.56	2.60	2.65	2.66	2.73	2.74	2.77	2.79	2.85
2.85	2.94	2.95	2.96	2.96	2.97	2.98	2.98	3.06	3.07
3.10	3.14	3.15	3.15	3.18	3.19	3.20	3.21	3.22	3.23
3.24	3.30	3.37	3.40	3.42	3.47	3.52	3.61	3.61	3.63
3.64	3.66	3.66	3.78	3.80	3.84	3.88	3.91	3.92	3.97
4.06	4.16	4.22	4.23	4.29	4.31	4.35	4.40	4.45	4.51
4.56	4.65	4.72	4.76	4.82	4.86	4.98	5.16	5.31	5.34
5.53	5.56	5.60	5.73	5.74	6.41	6.86	7.52	7.69	8.11



(Increment = 0.5 in)

$$F(x)=\int_{-\infty}^{+\infty} f(x)dx=\int_{a}^{b} f(x)dx=\int_{?}^{?} f(x)dx=1$$

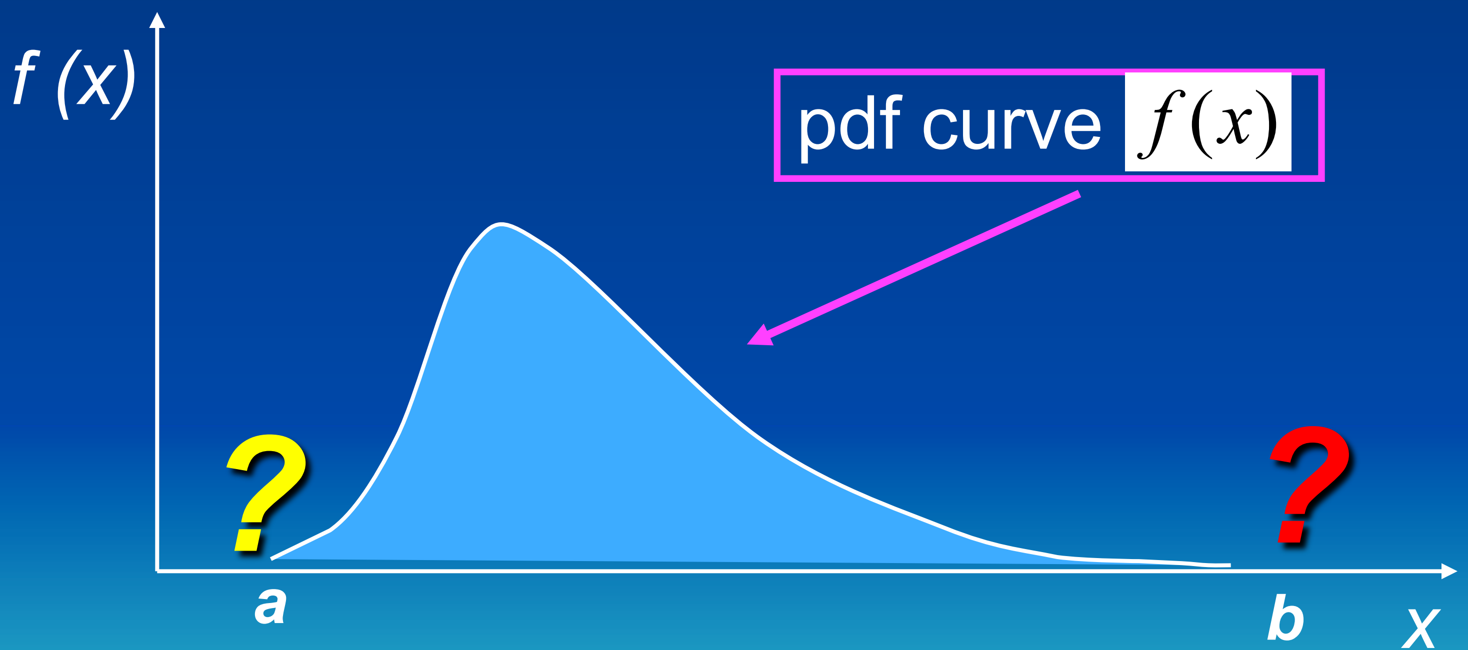


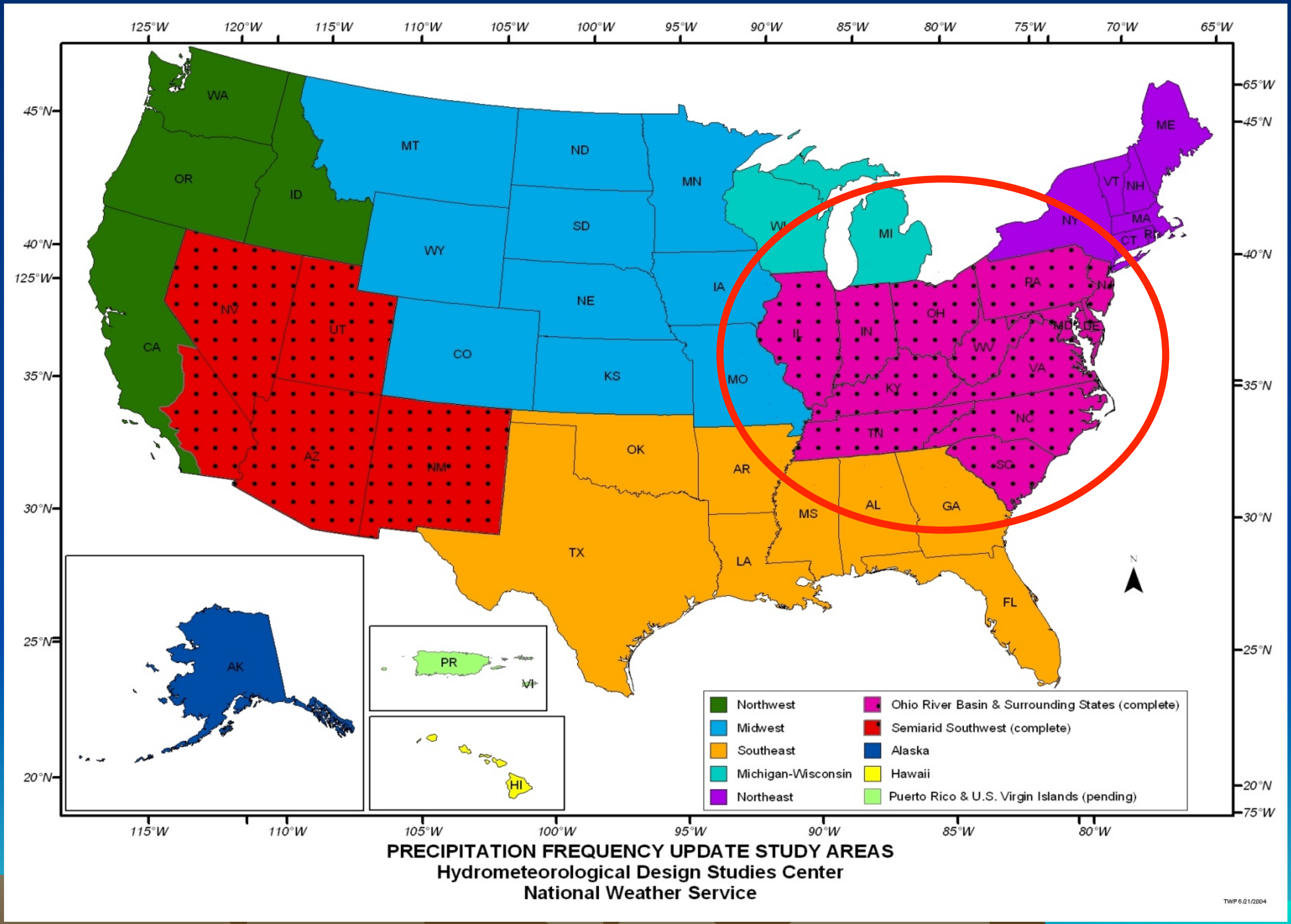
Fig. 2 Probability density function curve

Global Climate Change Makes the Issue more Complicated

Let data talk!

Linear Trend & *Shift* Study Area

-- Ohio River Basin



Location of Daily Stations in OH Study Area

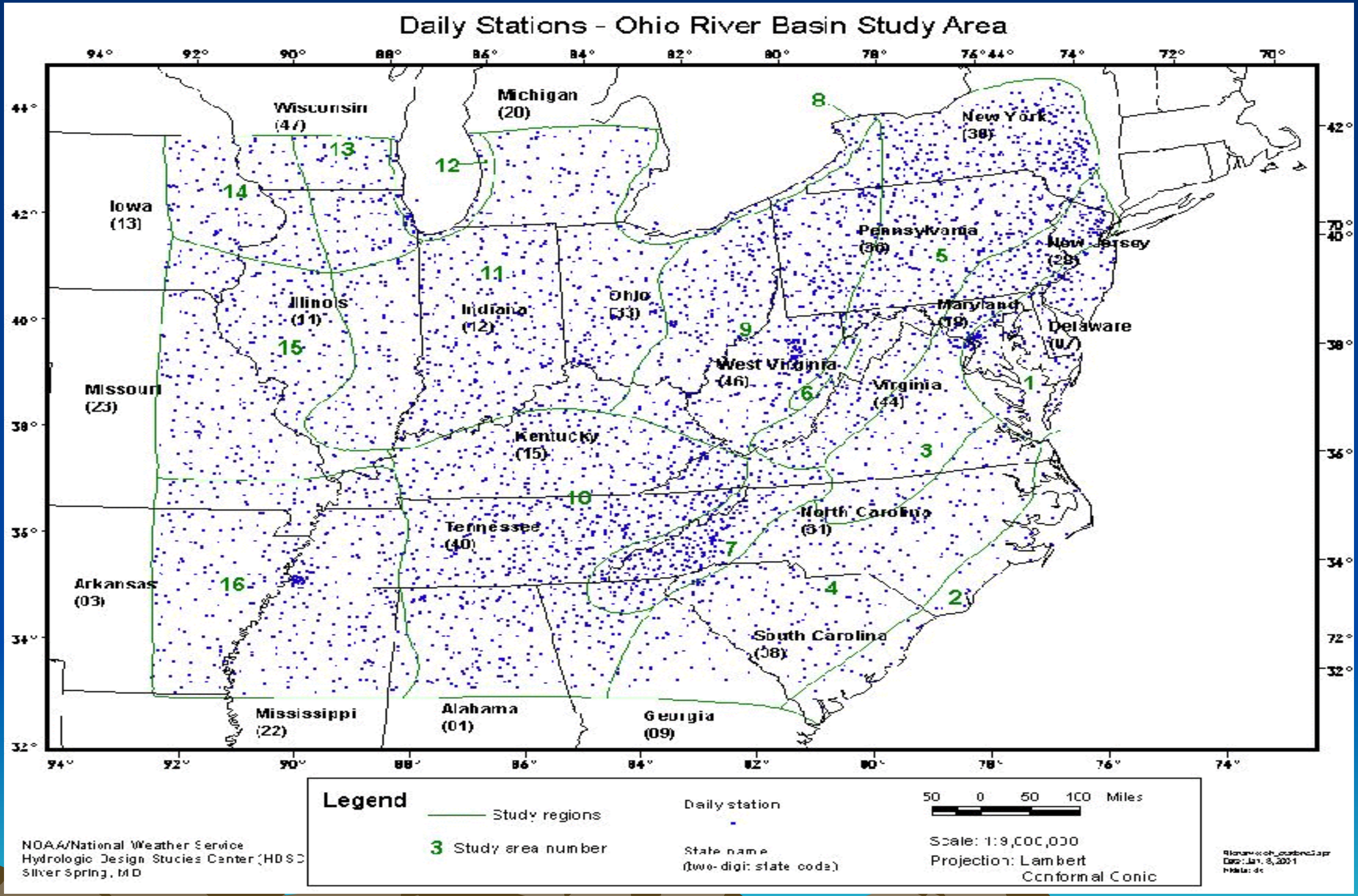


Fig. 3 Location of raingauges in Ohio River Basin

Only 16% or 1797 sites exhibited linear trend in mean for AMS in Ohio River Basin in past century

（1900 – 2000年）

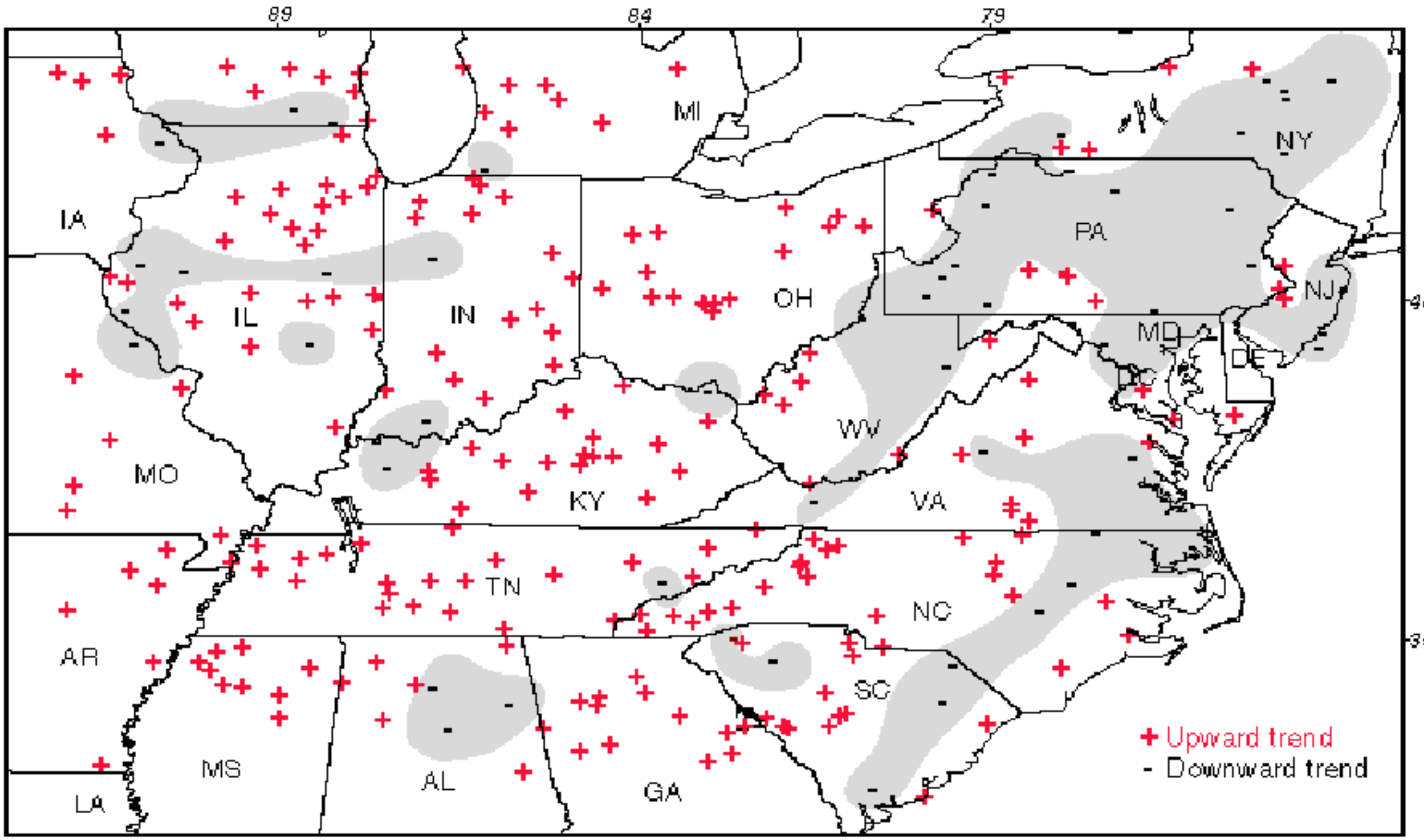


Fig. 4 Map of stations that exhibit linear trend in mean for AMP over 20th century

Only 18% or 531 sites exhibited shift in mean for AMS in past century

（compression of prior- to post- 1958 ）

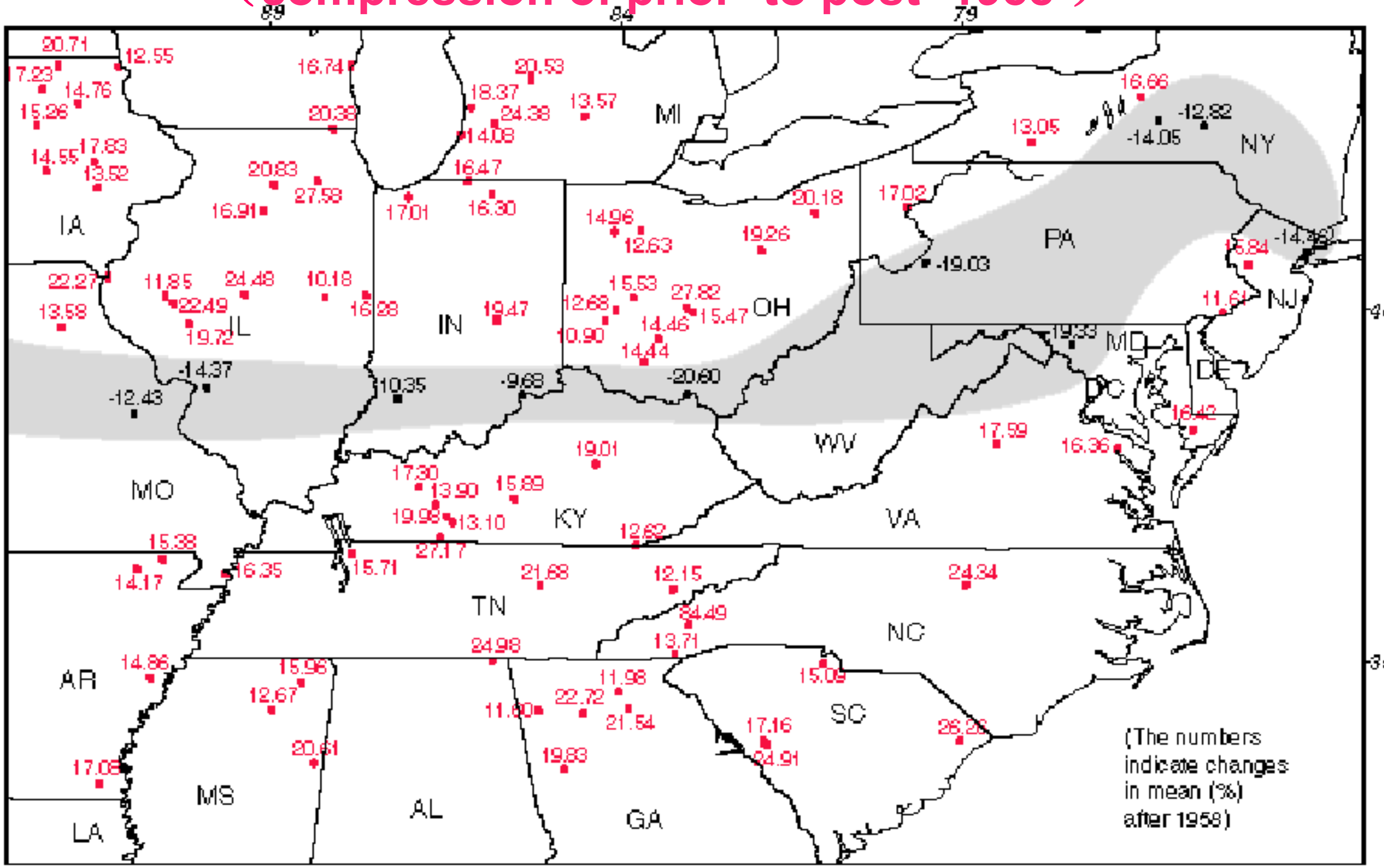


Fig. 5 Map of stations that exhibit shift in mean for AMP over the 20th century

Investigation of 1,741 daily AMS in Mainland China

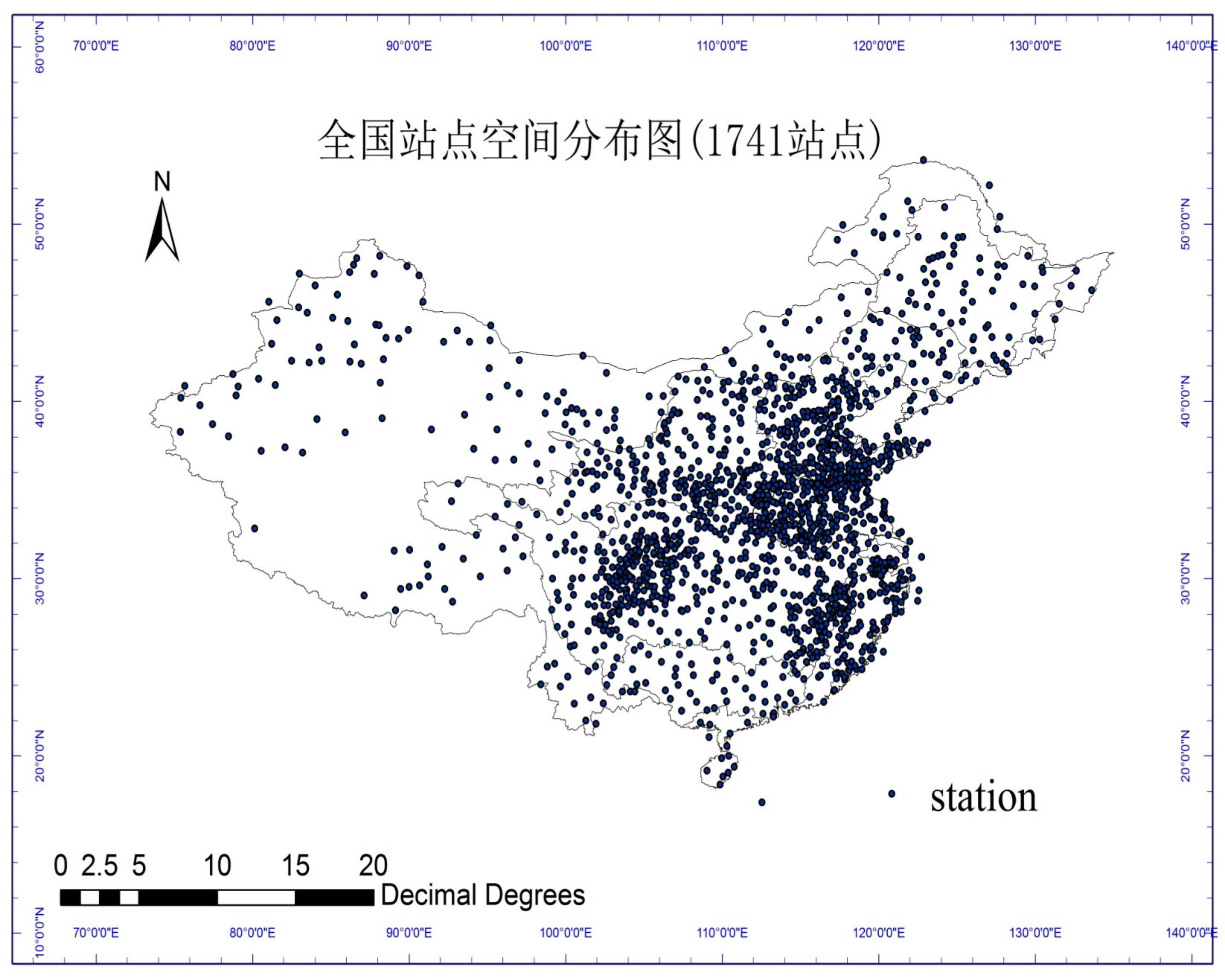


Fig. 6 Location of raingauges in China (partially)

Only 17.5% of 2,436 sites exhibited linear trend in mean of AMS in China

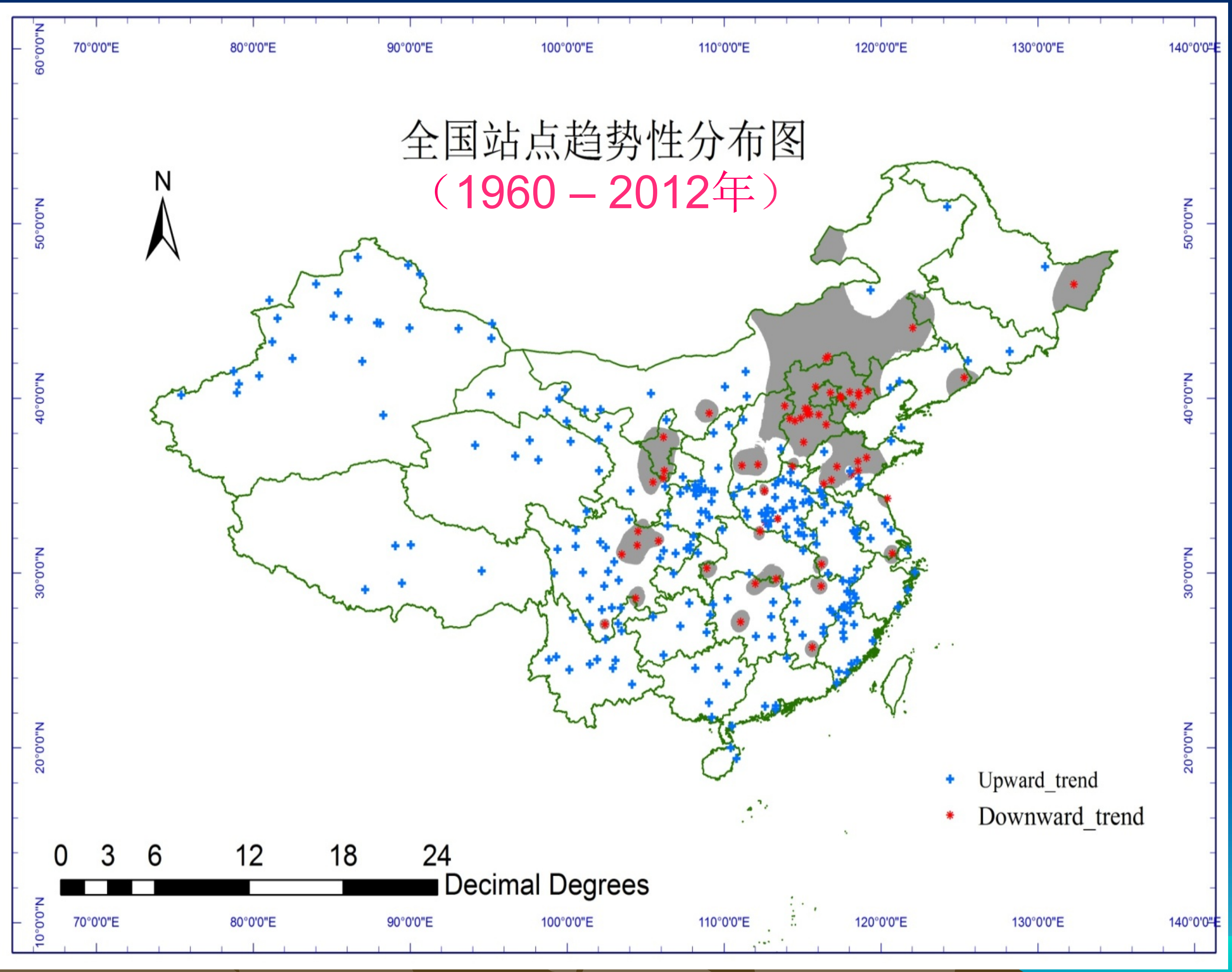


Fig. 7 Spatial distribution of raingauges with linear trend in China

Only 10.8% of 1,649 sites exhibited shift in mean for AMS in China

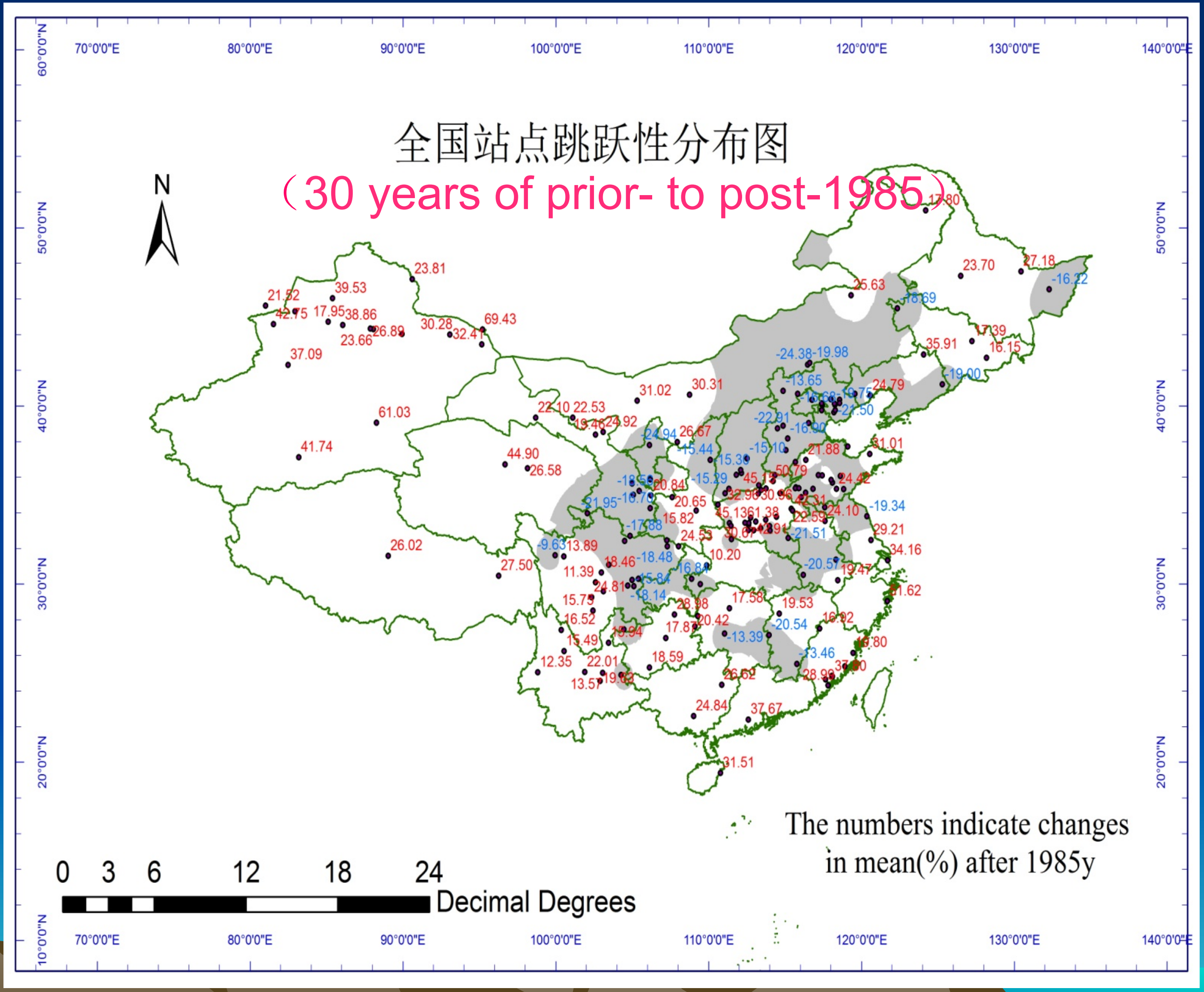


Fig.8 Spatial distribution of raingauges with shift in China

Findings

- **Generally speaking，there was no obvious linear trend and shift in mean for daily AMS in Ohio of the U.S. and in China in the past century；**
- **However，there was more than *50%* of tested sites that exhibited a clear increase in variance of daily AMS in OH River Basin， with SD increased by 23% for the latter half- to the former half- century。--- *What does it imply？***

It implies:

We may observe **more and more** extreme hydrometeorological events (**droughts or floods**) in the Ohio River Basin area in the near future than before though their mean does not change. ***So the world***.

Facing with the acceleration of climate change,

What is our job？

One of Our Mission

Exploration of a ***Robust*** ***and*** ***Reliable*** Approach to Performing Precipitation Frequency Analysis of Extreme Events。

Another Mission

--Explore a meaningful upper limit of rainfall

In China PMP estimation is required for design studies for large infrastructure（big dams、nuclear power stations）as regulatory standards in terms of flood-control, and flood-mitigation planning for large cities as well.

Probable Maximum Precipitation

-- Hydrometeorologically causal approach

Starting in 1930s – The U.S. Weather Bureau first introduced the upper limit to precipitation（*Late Prof. Ven Te Chow also used it*)

Maximum Possible Precipitation (MPP) → Probable Maximum Precipitation (PMP)

Definition of PMP

Probable maximum precipitation (PMP) is defined as the greatest depth of precipitation for a given duration meteorologically possible for a design watershed(1) or a given storm area(2) at a particular location ***at a particular time of Year***(3), with no allowance made for long-term climate trends.

(WMO No.-1045, *Manual on Estimation of PMP*, Geneva, 2009)

∗**Comments: (1) and (2) are not equivalent; (3) is irrelevant.**
--By Prof. B Lin

PMP Estimation Methodology -- International Practice

In general, mainly two types of approaches in design practice of PMP studies: I. Hydrometeorological (HYDROME) & II. Statistical (STAT)

(I-a) Moisture maximization	Maximum 12-hr persisting dew point (HYDROME)
(I-b) Storm transposition	Storm Separation + Adjustments (HYDROME)
(I-c) Use of D-A-D curves	Envelopment (HYDROME)
(II) Statistical approach	Modified frequency analysis (STAT)

<u>The most popular means – *Storm Transposition* (ST)</u>

The most difficult job is how to take ST in terrain area – <u>orographic effects?</u>

Key： **Storm separation**

- **Convergence component**
- **Orographic component**

Laminar Model

- R-Rainfall intensity (mm/s); v_1- Wind speed (m/s); △P-Difference In pressure (hPa); $\overline{q}_1$ & $\overline{q}_2$ - In & out specific humidity (g/kg)； g- Gravity acceleration (cm/s^2);ρ - Water density (g/cm^3)； Y- Horizontal distance (m).

$$R = \frac{\bar{v}_1 \Delta P_1 (\overline{q}_1 - \overline{q}_2)}{Y} \cdot \frac{1}{g\rho}$$

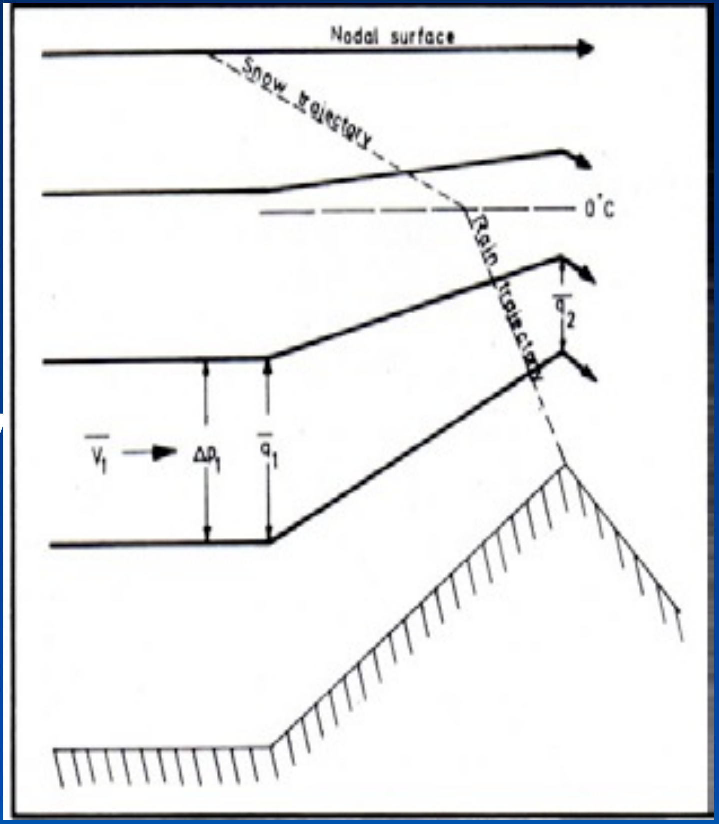


Fig. 28 Sketch of Laminar Model

（*NWS once applied unsuccessfully the Laminar Model to account the terrain effect on rainfall in a PMP study in 1961 and 1966)

Synoptic +Statistics+ Orographic

For a storm rainfall, the rainfall intensity for a given point P(x,y) in a drainage at any time can be defined by

$$I(x,y,t) = I_0(x,y,t) \times f(x,y,t)$$

（SDOIF method*）

Hence, the area-averaged rainfall R for the whole drainage area of A during the period of time is given below:

$$\overline{R}_{\Delta t,A} = \frac{\iint_A r_{\Delta t}(x,y)dxdy}{\iint_A dxdy} = \frac{\iint_A r_{0,\Delta t}(x,y) \times f_{\Delta t}(x,y)dxdy}{\iint_A dxdy} \approx \frac{\sum_i^m \sum_j^n r_{0,\Delta t}(x_i,y_j) \times f_{\Delta t}(x_i,y_j)dxdy}{\sum_i^m \sum_j^n \Delta x_i \Delta y_j}$$

（* Lin，Bingzhang， WMO NO-1045，Geneva，2009）

Assumption

The **SDOIF*** (***S****tep-****D****uration-****O****rographic-****I****ntensification-****F****actor*) method assumes that a rainfall could be decomposed into two component: Convergence component and Orographic component which is expressed in factor, *the Orographich Intensicication Factor* (OIF).

（* Lin，Bingzhang，1988 in Chinese, Nanjing; 1995 in Beijing; WMO NO-1045，Geneva，2009）

10 Tasks for the PMP Study in HK

Example

- Inception report
- Historical rainfall data acquisition (SE China)
- Storm survey/selection and analysis
- Transposition analysis of selected storms
- Synoptic analysis + apply the storm separation technique (SDOIFs)
- Statistical estimation
- Orientation + transposition adjustment
- Development of DAD with moisture maximization
- Impact of climate change/Long-term trends in rainfall extremes
- Comprehensive comparisons
- Final report

Procedures

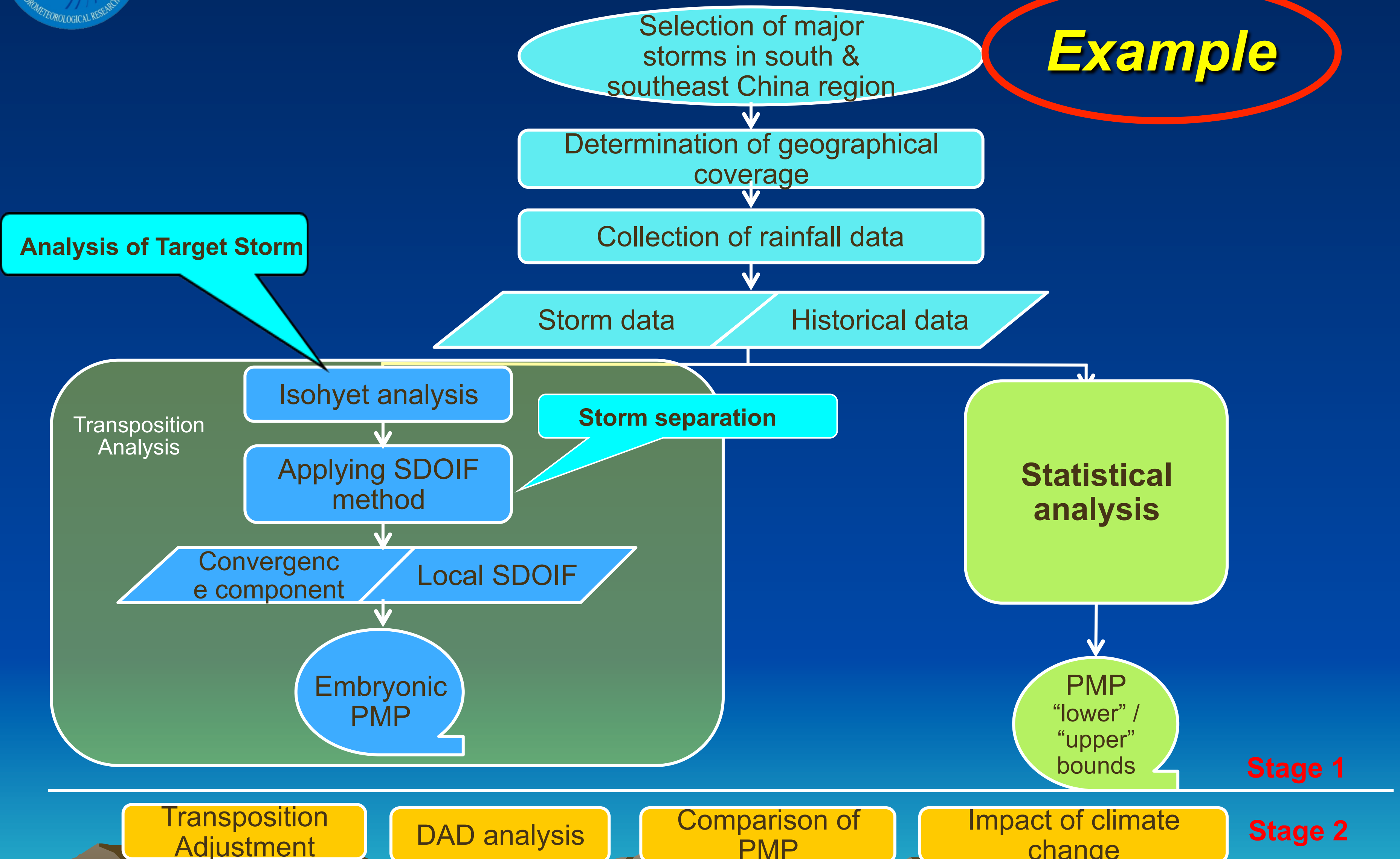


Fig. 29 Sketch of PMP estimation procedure for HK as example

Moving track of Morakot Typhoon

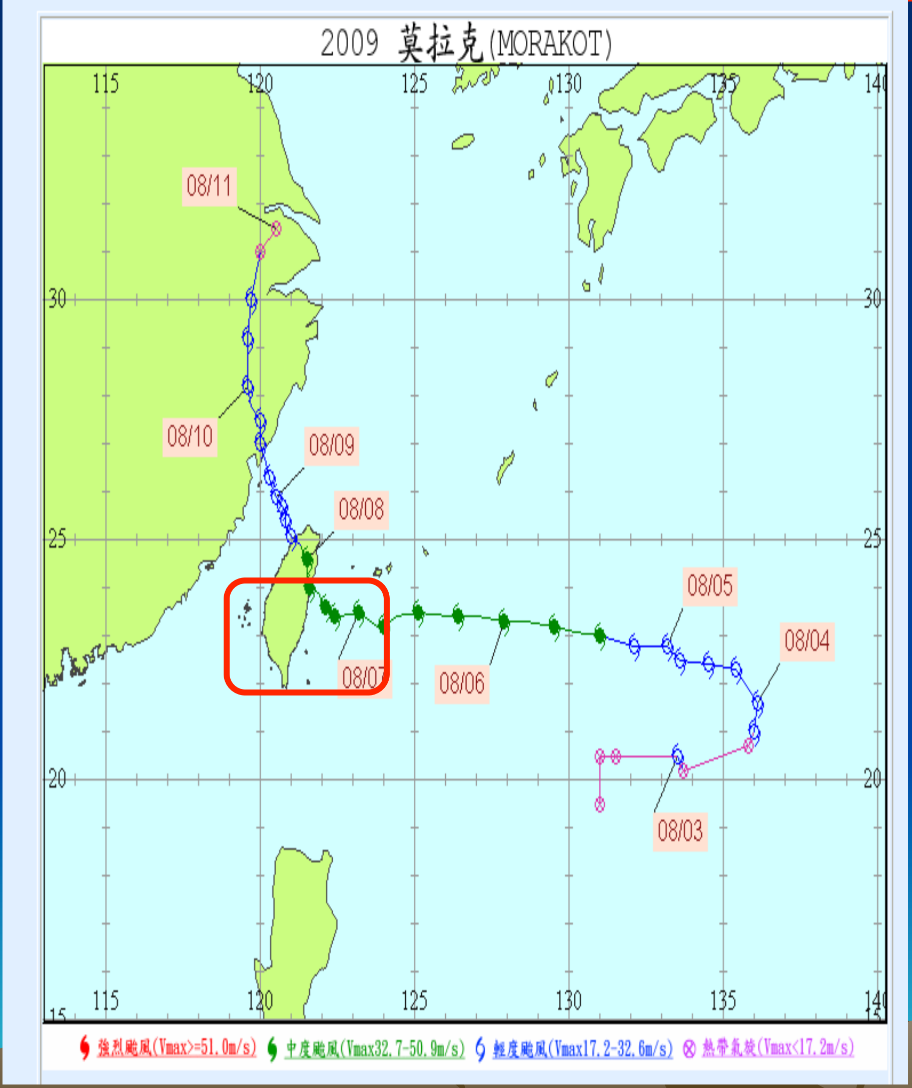


Fig. 30 Track of Morakot Typhoon, 2009-08-03~11

World, China mainland and Taiwan rainfall (By 2009)

Location	Date	Duration	Amount	Note
Shinliao, Taiwan (north)	October 17, 1967	24-hour	**1,672 mm**	**Taiwan record**
Jiayi Alishan, Taiwan	**August 8, 2009**	**24-hour**	**1,623 mm**	Typhoon Morakot
Linzhuang, China mainland	August 7, 1975	24-hour	1,060 mm	Sup. Typhoon Nina
Cilaos， La Reunion Island	March 15, 1952	24-hour	**1,870 mm**	Tropical Cyclone
Jiayi Alishan, Taiwan	**August 8-9, 2009**	**48-hour**	**2,361 mm**	**Typhoon Morakot**
Linzhuang, China mainland	August 7-8, 1975	48-hour	1,279 mm	Sup. Typhoon Nina
Cilaos， La Reunion Island	March 15-17, 1952	2-day	**2,500 mm**	Tropical Cyclone
Jiayi Alishan, Taiwan	**August 8-10, 2009**	**3-day**	**2,747 mm**	**Typhoon Morakot**
Linzhuang, China mainland	August 6-8, 1975	3-day	1,605 mm	Sup. Typhoon Nina
Cilaos， La Reunion Island	March 15-18, 1952	3-day	3,240 mm	Tropical Cyclone
Grand-llet, La Reunion Island	January 24-27, 1980	3-day	3,241 mm	Cyclone Hyacinthe
Commerson's Crater， La Reunion Island	February 24-26, 2007	3-day	**3,929 mm**	**Cyclone Gamede**

Issue of the Typhoon Morakot (1)

(1,000-year plus event?)

Lessons/findings learnt from the Morakot:

Total rainfall >> historical records in the Mainland China

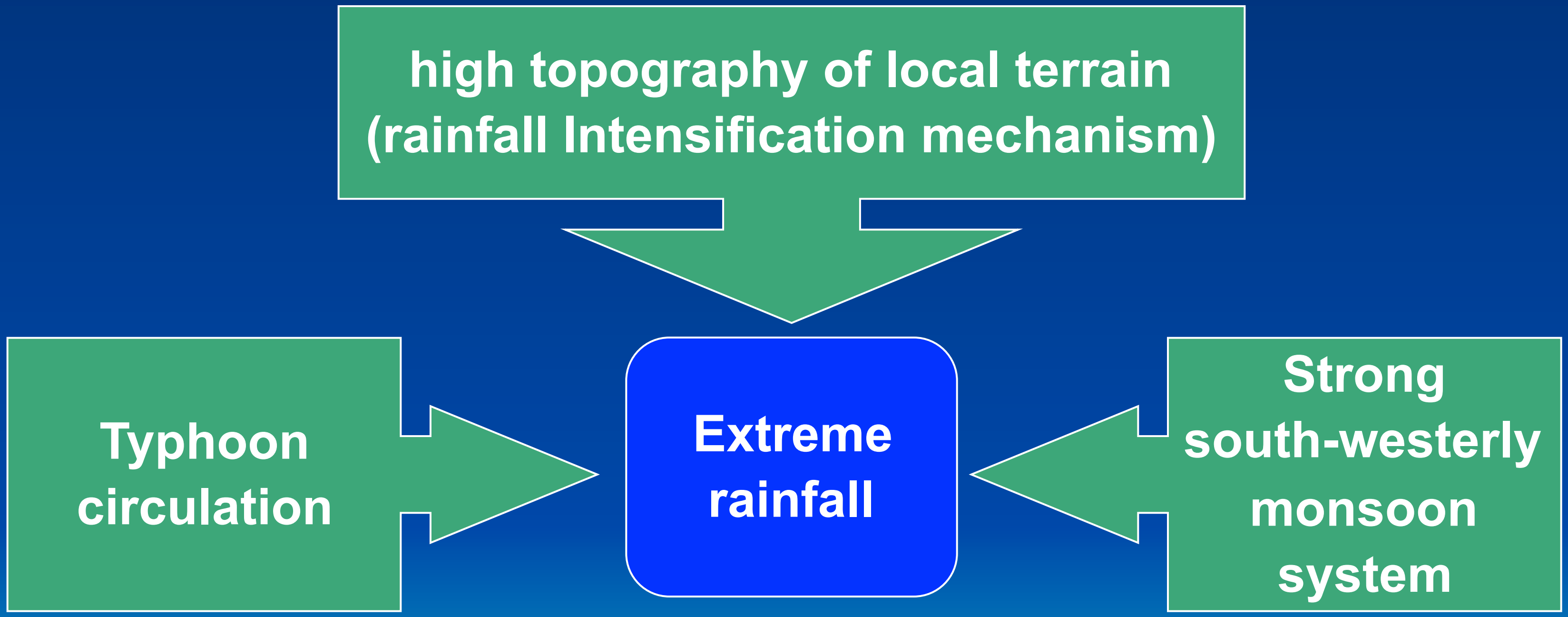
24-hr rainfall >> 1,000-year estimate in U.S. and PRVI

24-hr rainfall ~ 24-hr PMP estimate on Hainan Island

2-day rainfall ~ the world record

Issue of the Typhoon Morakot (2)

Possible causes:



However, current typhoon intensity forecast skill is still poor because of the lack of understanding on the complex interactions between ocean and typhoons

Fig. 31 Sketch of causes for Morakot Typhoon Storm

Isohyets of 24-hr for Morakot Typhoon

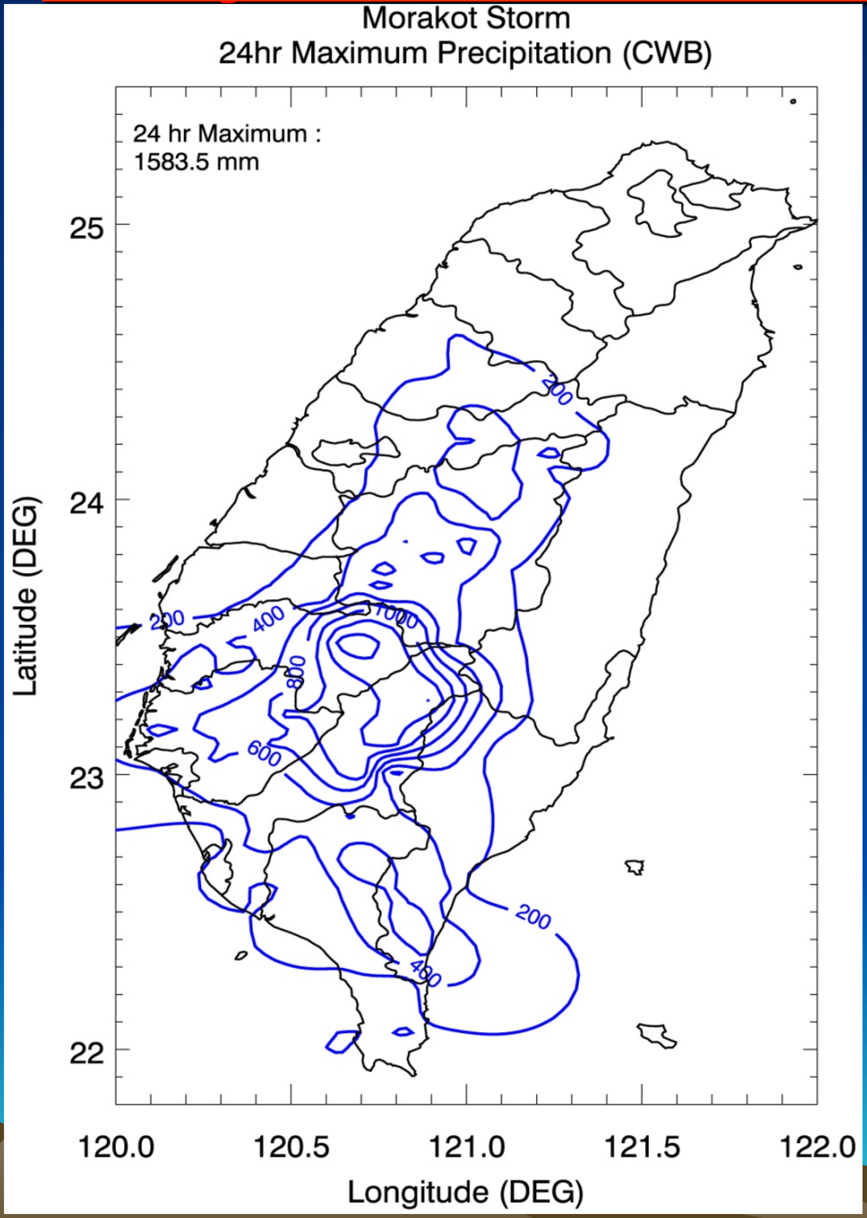


Fig. 32 24-hr isohyets of Morakot Storm

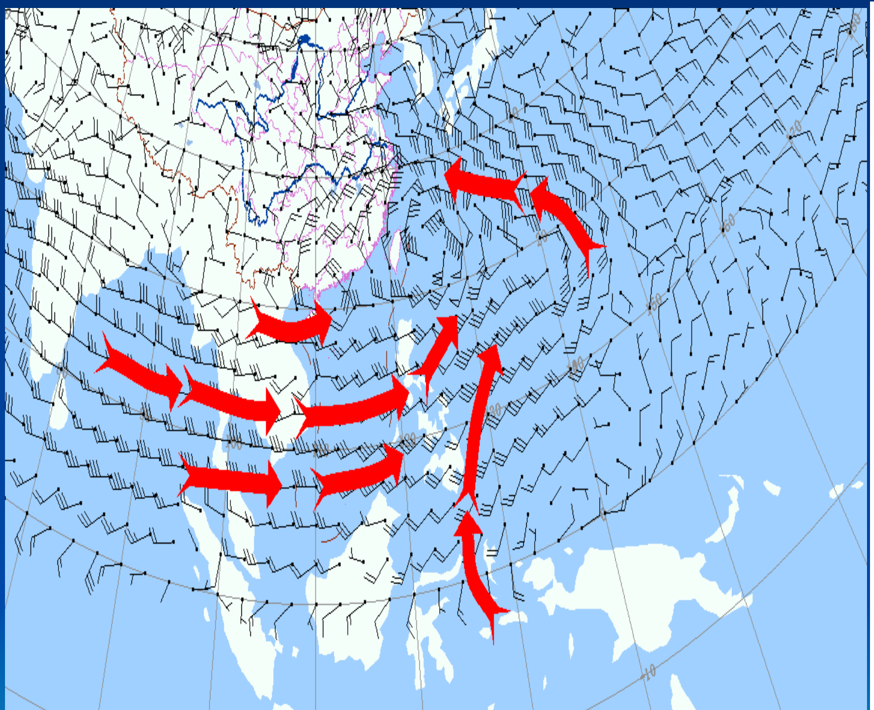
- **1,583mm / 24-hr**
- **2,372mm / 48-hr**
- **2,682mm / 72-hr**

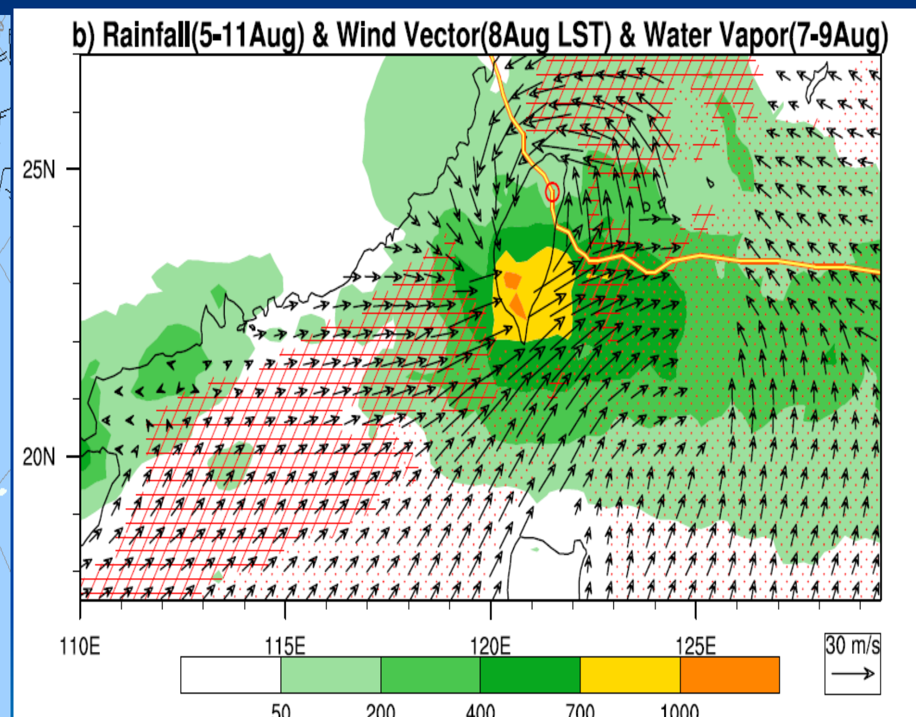
(based on hourly rainfall observations)

Moisture Flux of Morakot Storm

Development of the SDOIF for the Target Area

- Major Moisture Flux during Morakot (left)





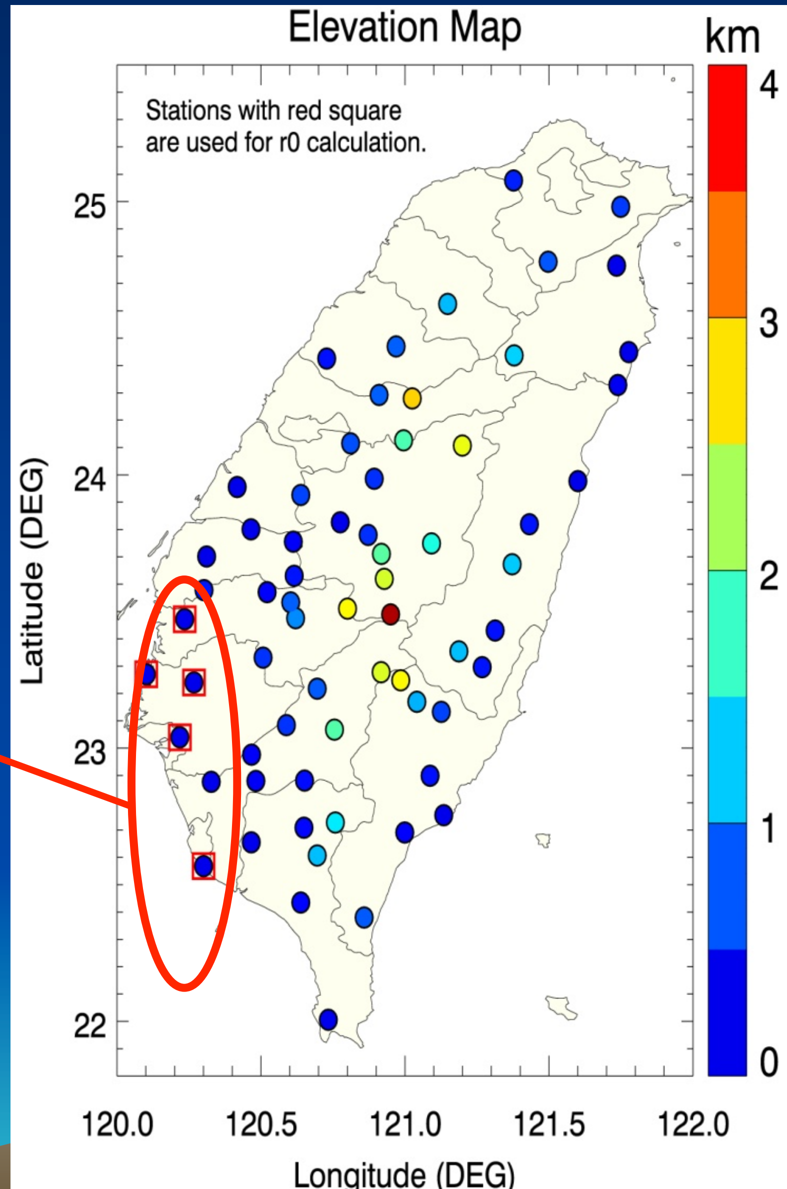
- Power Spectrum of the WNPSM Index (right)
- *(After Chi–Cherng Hong, Taipei Municipal University of Education, Taipei, Taiwan)*

Fig. 33 Model simulation of moisture flux for Morakot Typhoon

Locations of Key Raingauges in Taiwan

$$f_{\Delta t}(x,y) = \frac{r_{\Delta t}(x,y)}{r_{0,\Delta t}(x,y)}$$

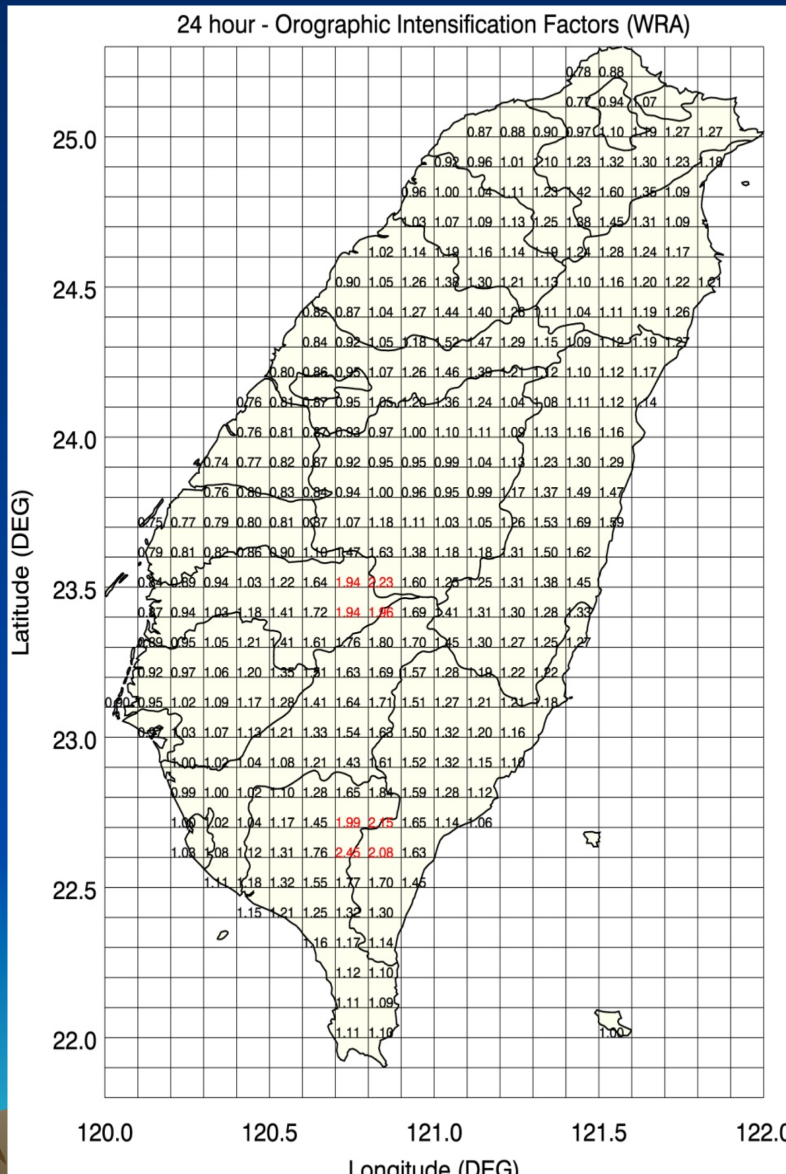
Base stations



AMS of rainfall at each of 66 stations are employed

Fig. 34 Location of raingauges in Taiwan for analysis of OIF

Gridded 24h OIF for Morakot (10kmx10km)



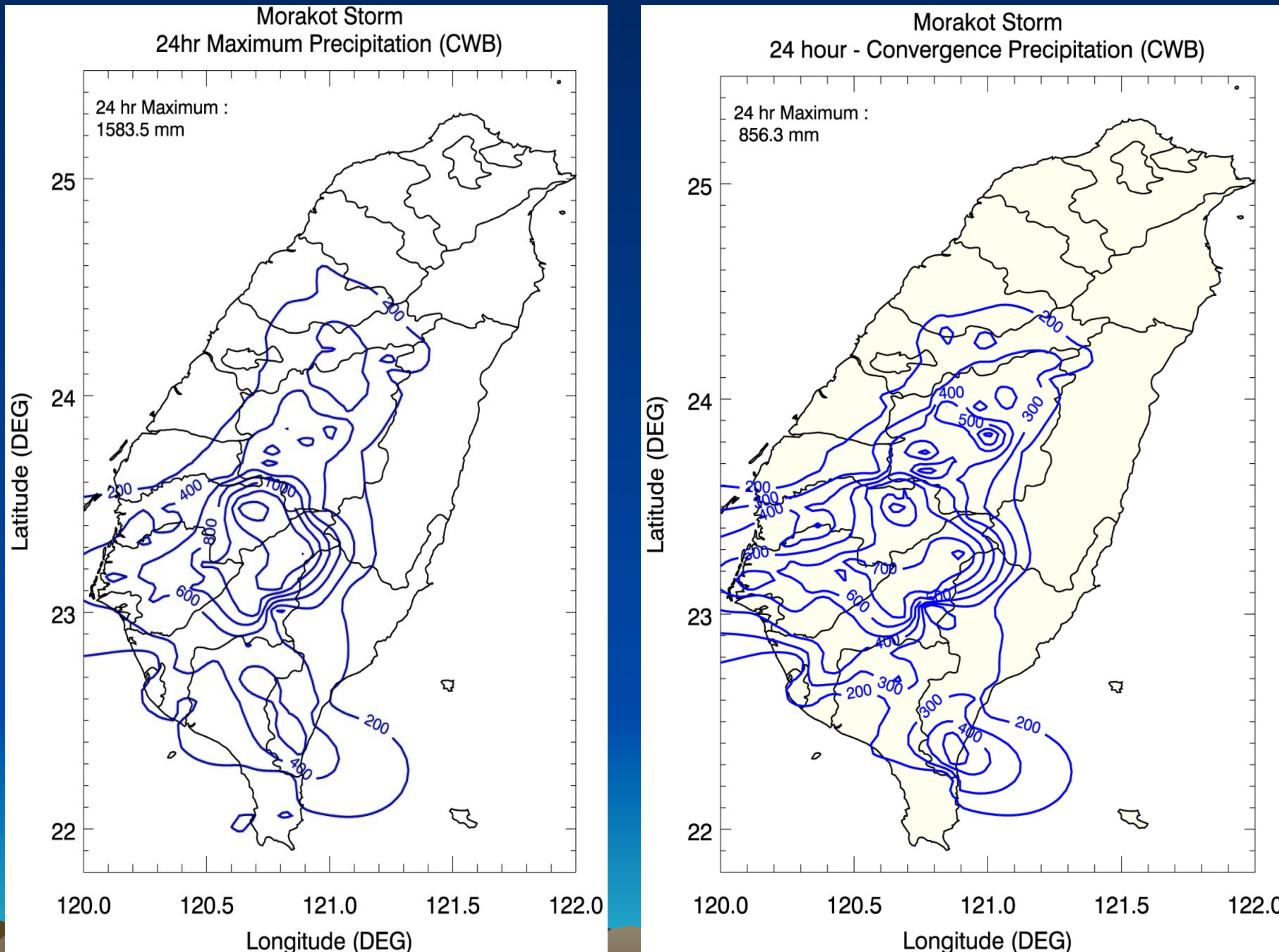
Orographic

Intensification

Factor

Fig. 35 Map of 24-hr gridded OIF for Morakot Storm

Before & After Storm Separation



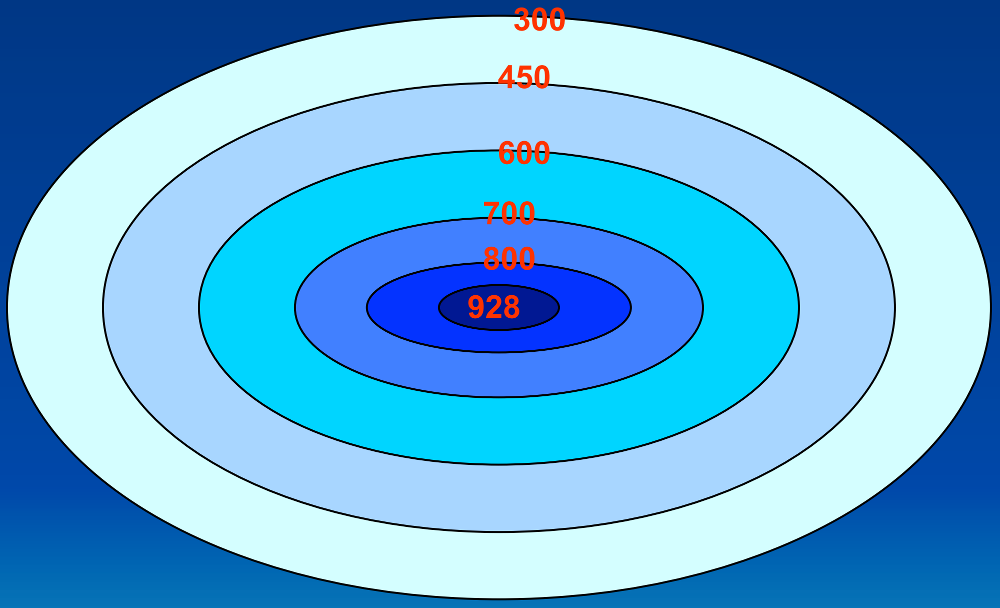
Before

After

Fig. 36 Before and after decomposition of 24-hr Morakot Storm rainfall

Generalized Convergence Component Pattern

(based on synoptic analysis of 4 major storms)



Generalized convergence component pattern of Morakot Storm

Convergence Pattern can be Transposed in a Wider Region

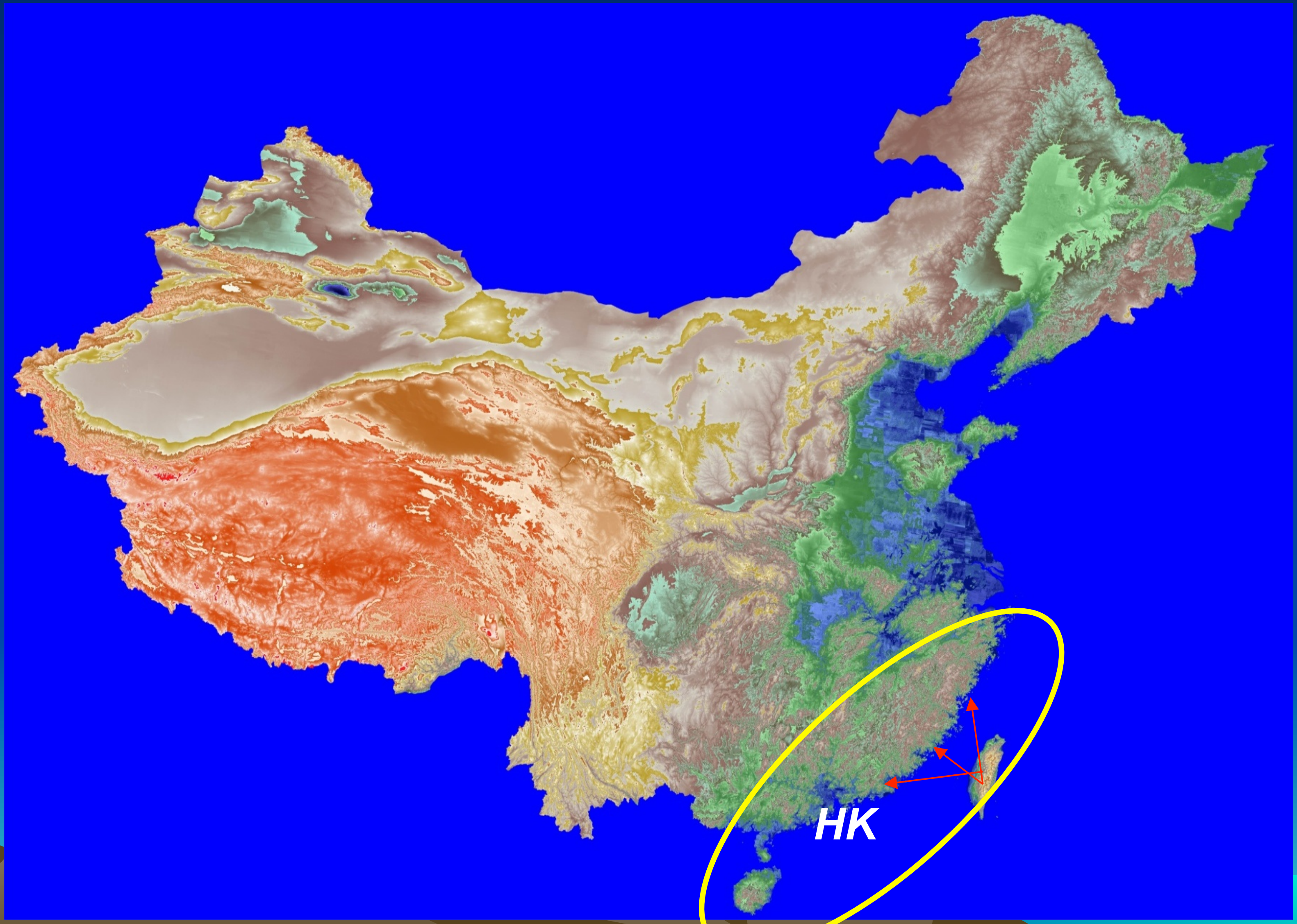


Illustration of transposition for convergence pattern of Morakot Storm

Application example: Transposed to HK

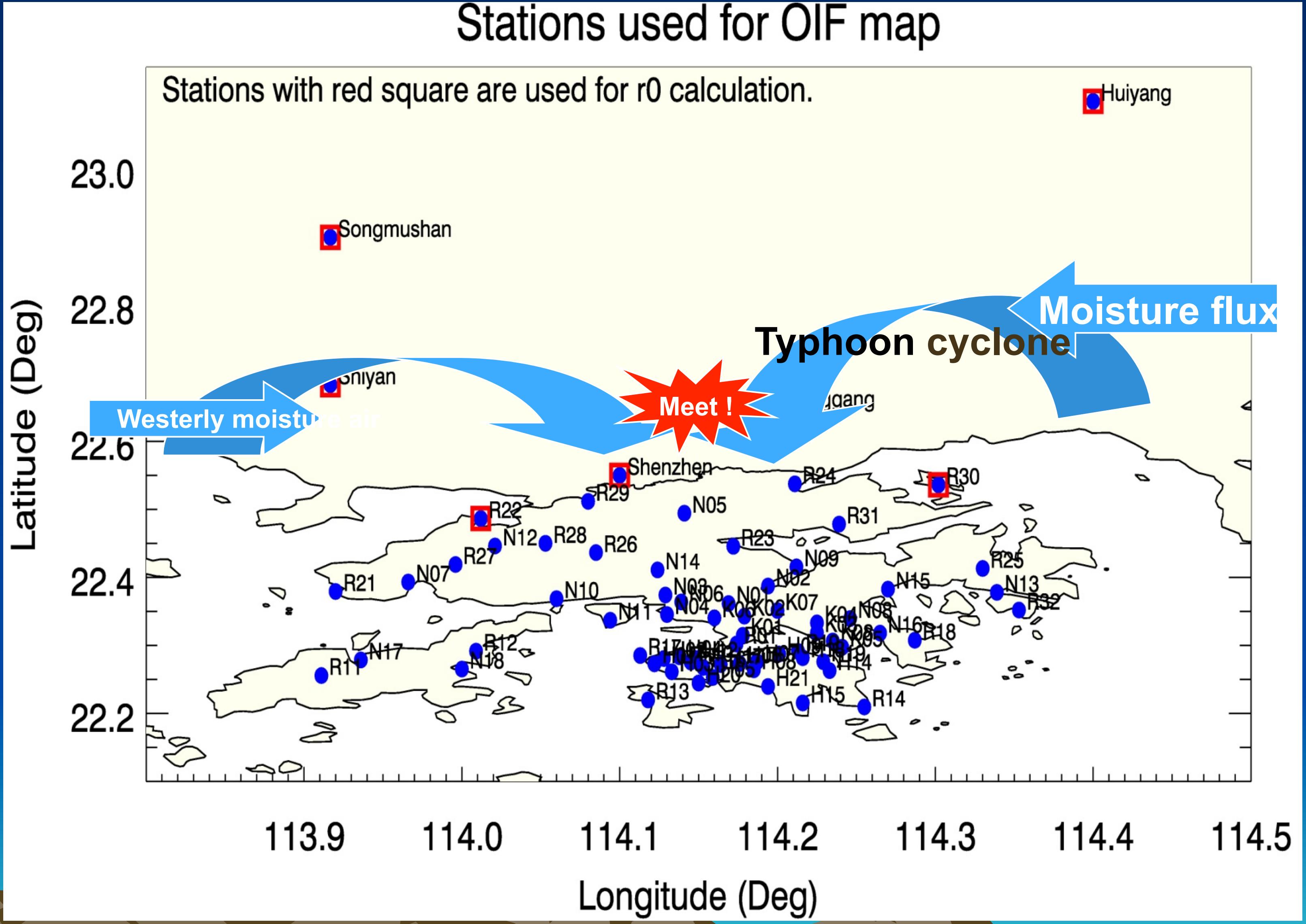
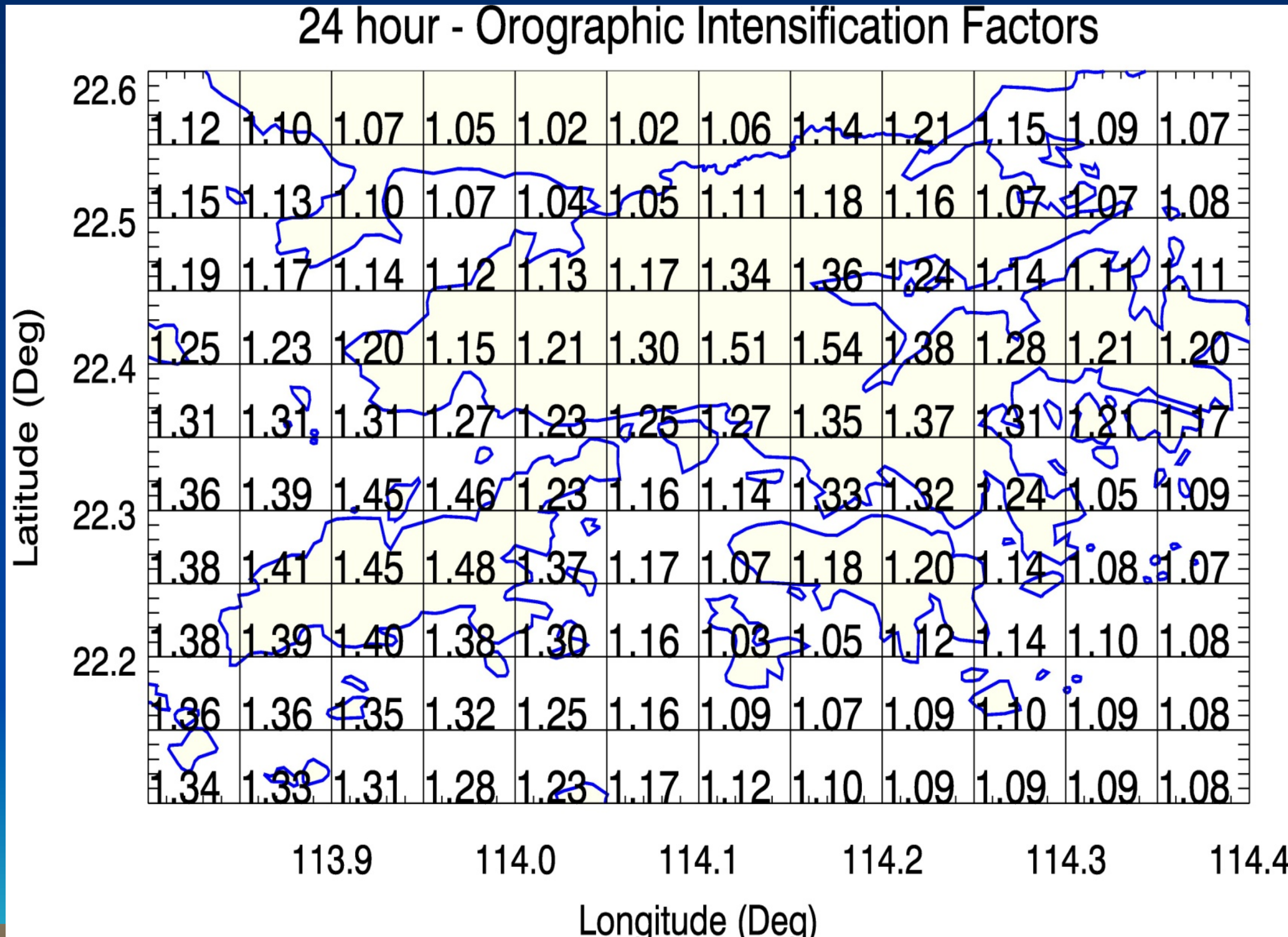


Illustration of synoptic analysis for HK in terms of moisture flux

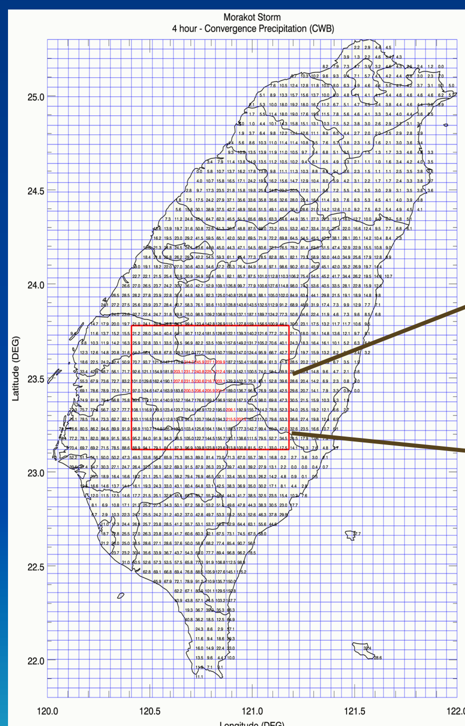
Development of OIF in Design Area, HK

(5kmx5km)

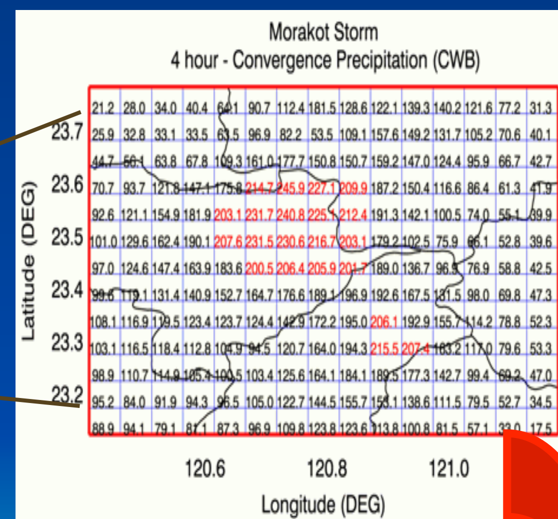


Convert the Convergence into gridded

- Convert the convergence component of Morakot into a gridded frame like the gridded SDOIF
- Then cut-off the center piece to match the HK area size



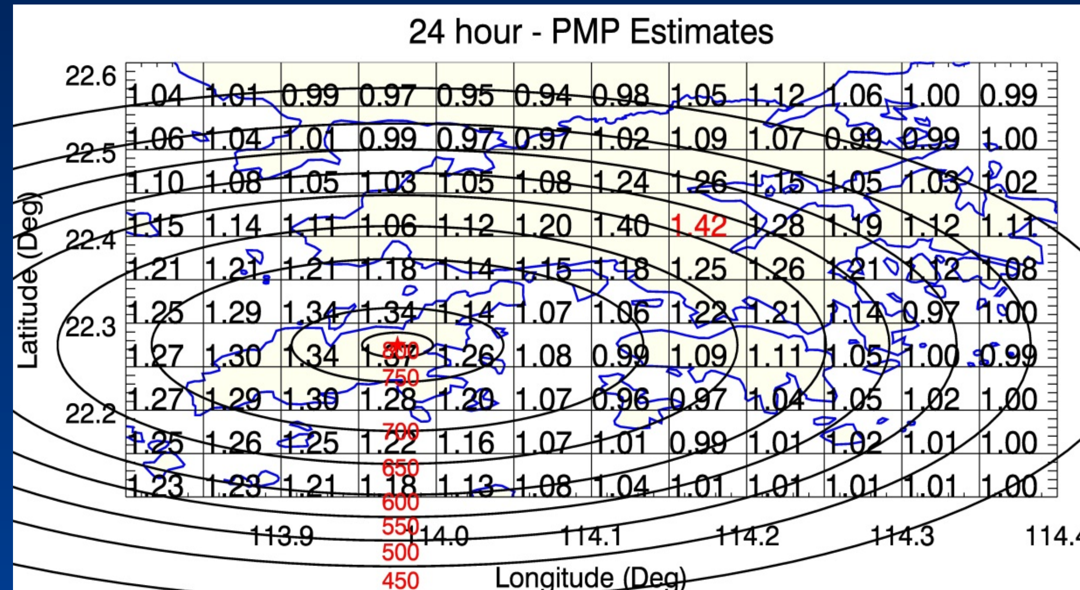
showing here is for the 4-hr Morakot pattern at resolution of 5kmx5km



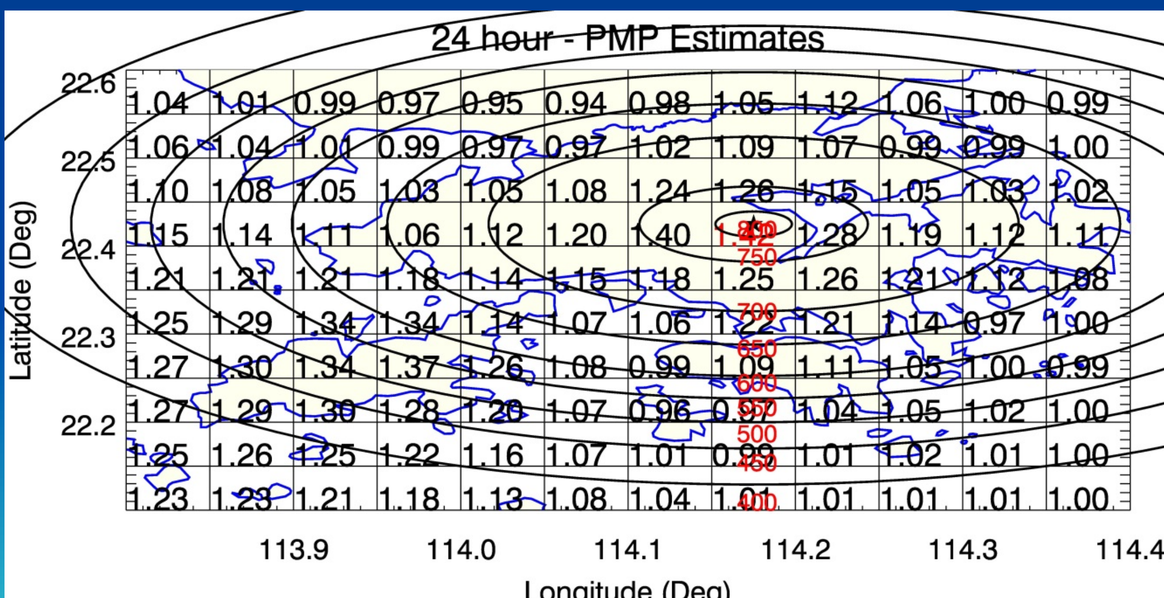
4-hr sub-mesh

Fig. 40 Illustration of cut-off sub-mesh of convergence pattern

E-W orientation with different center points （as example)



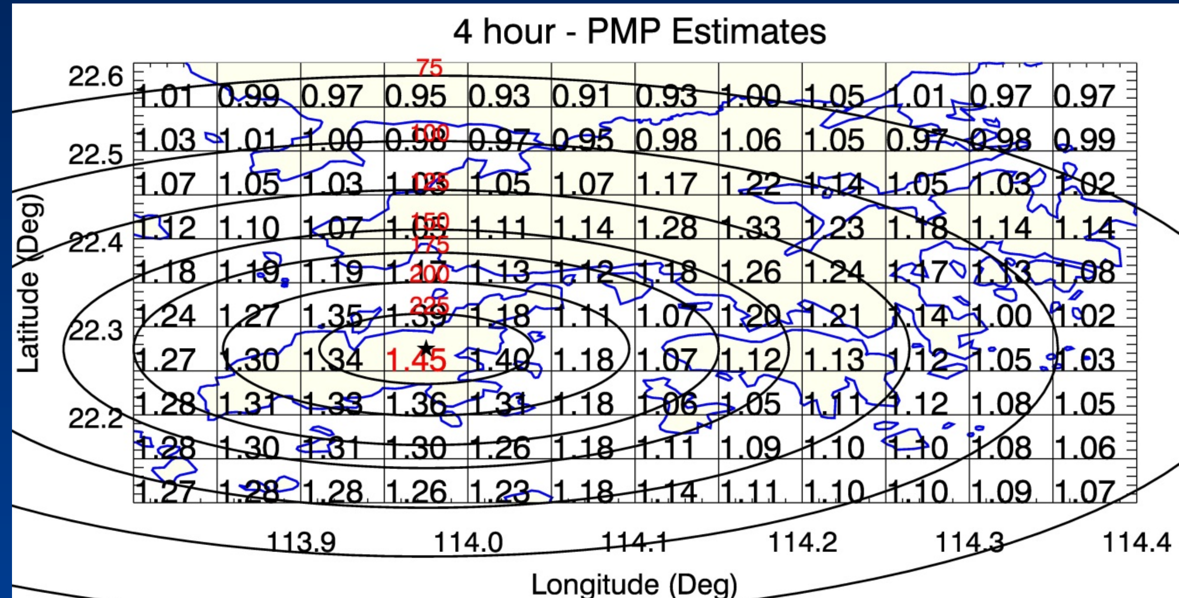
(Peak at Lantau)



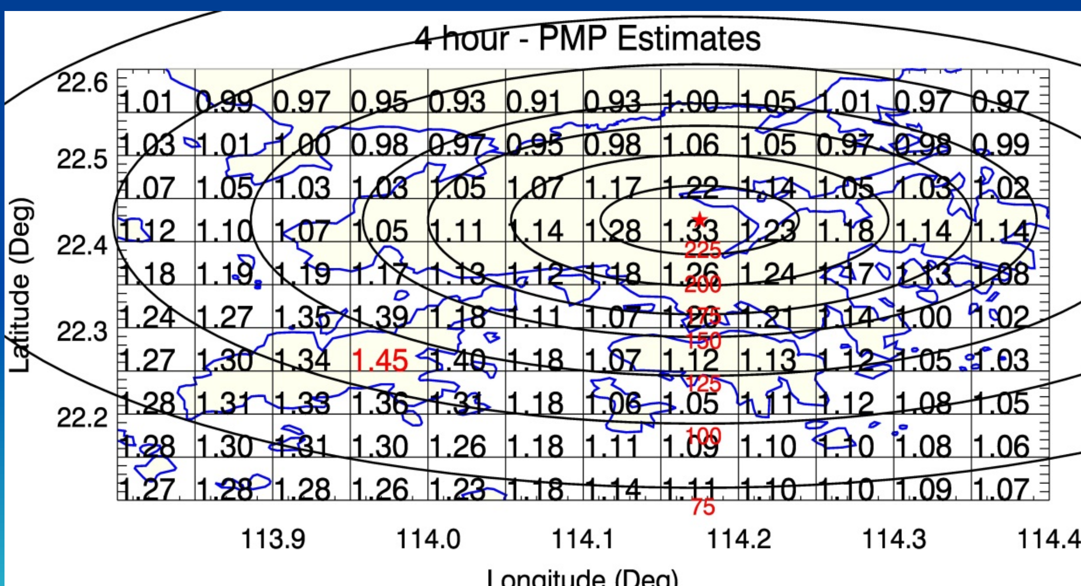
(Peak at Tai Mo Shan)

Fig. 41 Orientation of transposed convergence pattern (1)

E-W orientation with different center points （as example)



(Peak at Lantau)



(Peak at Tai Mo Shan)

Fig. 42 Orientation of transposed convergence pattern (2)

Calculation of Embryonic PMP

- Distribution of Gridded-average Embryonic PMP in HK

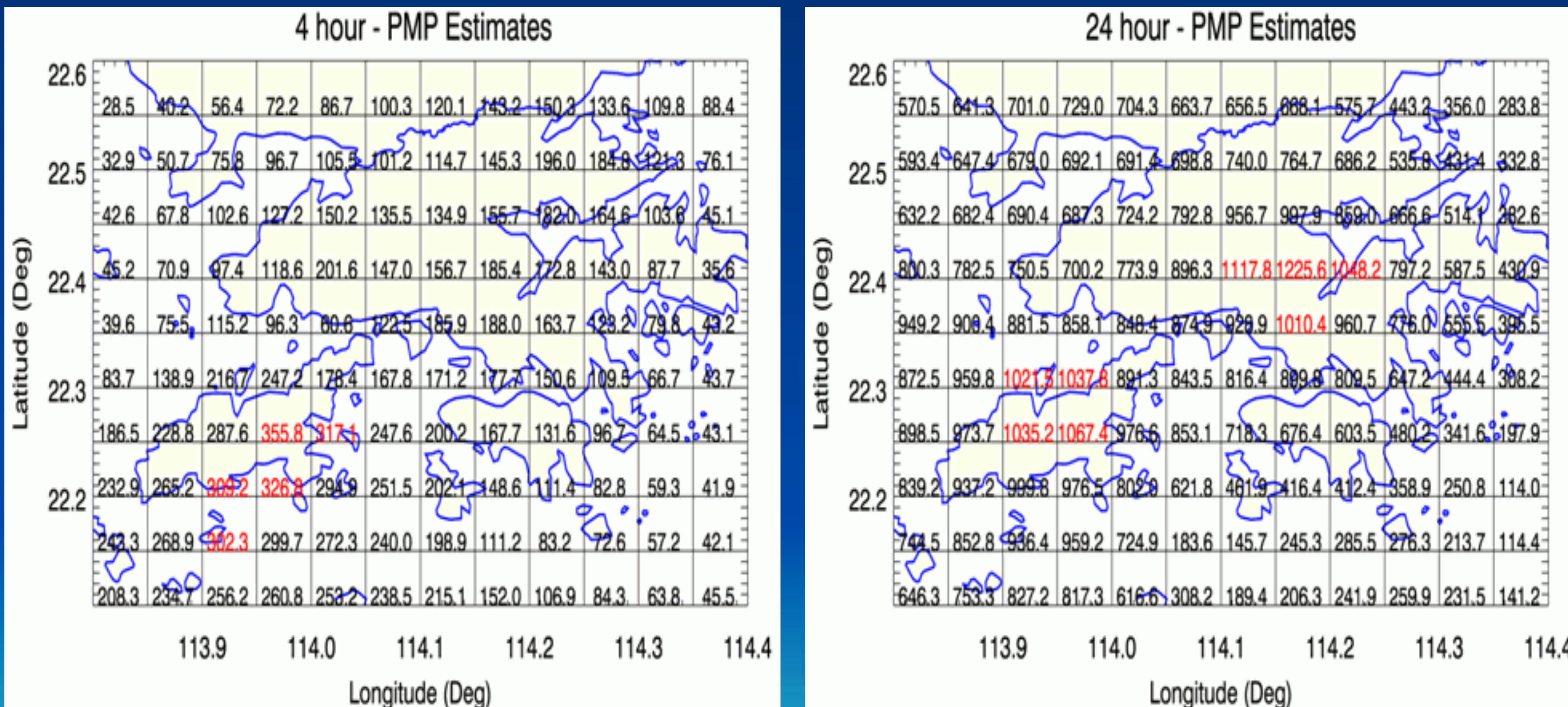
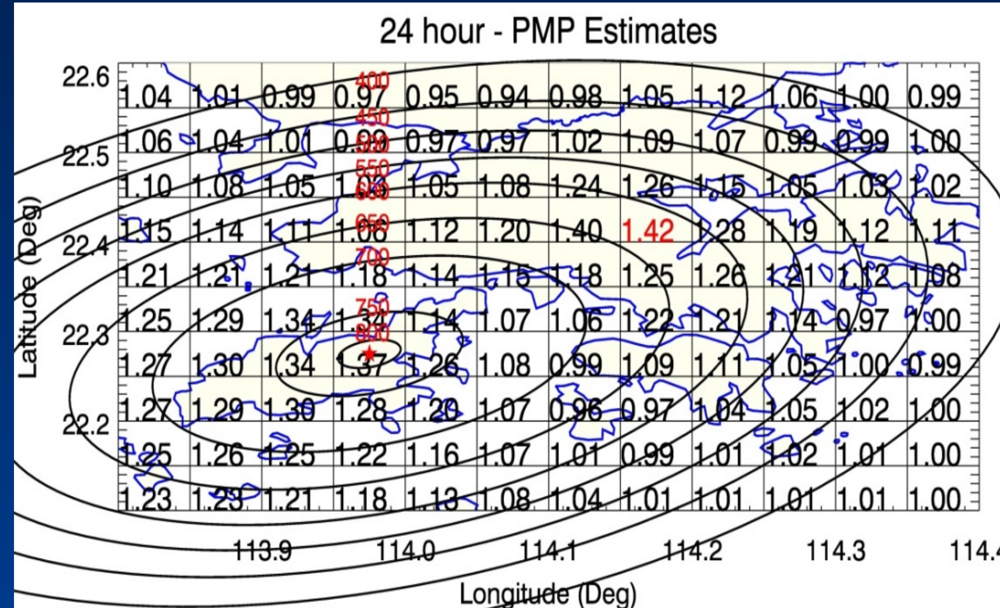


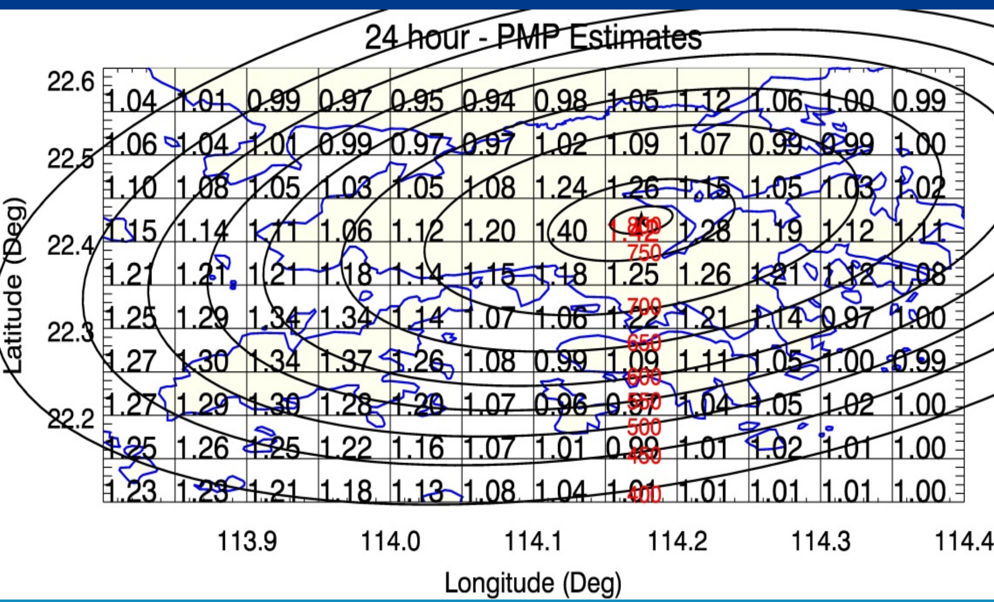
Fig. 43 Gridded embryonic PMP for HK (unfinished; example only)

Orientation 22.5° – 24hr

(Embryonic PMP)



Centered at Lantau



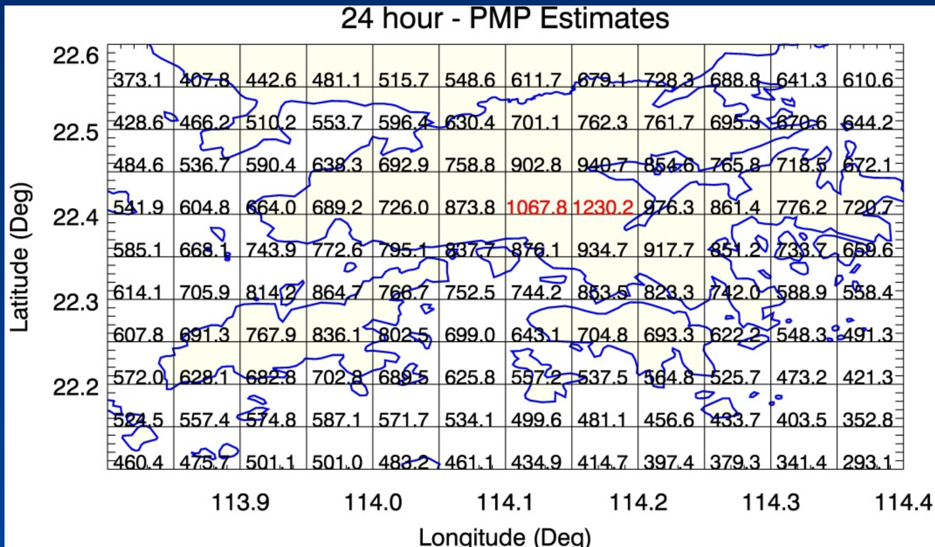
Centered at Tai Mo Shan

Fig. 44 Orientation of transposed convergence pattern (3)

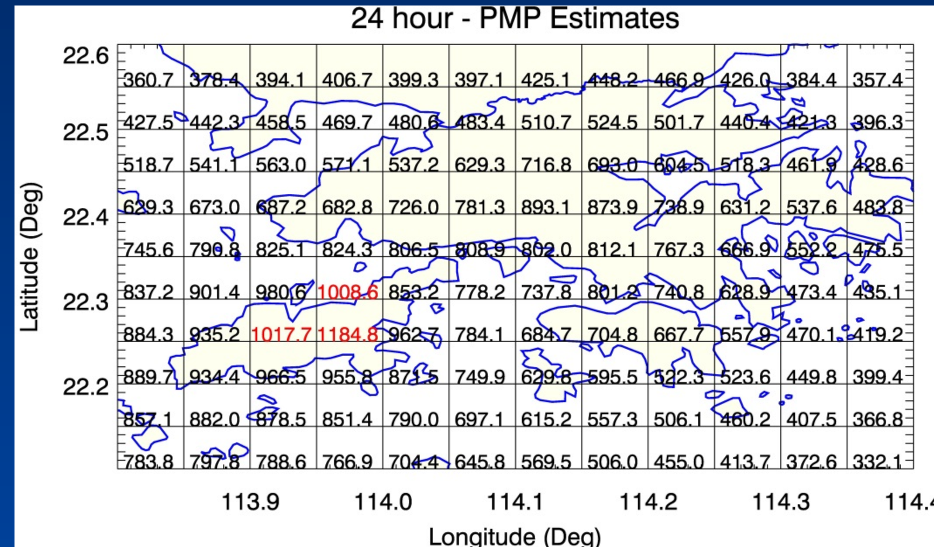
NE-SW orientation – 22.5°

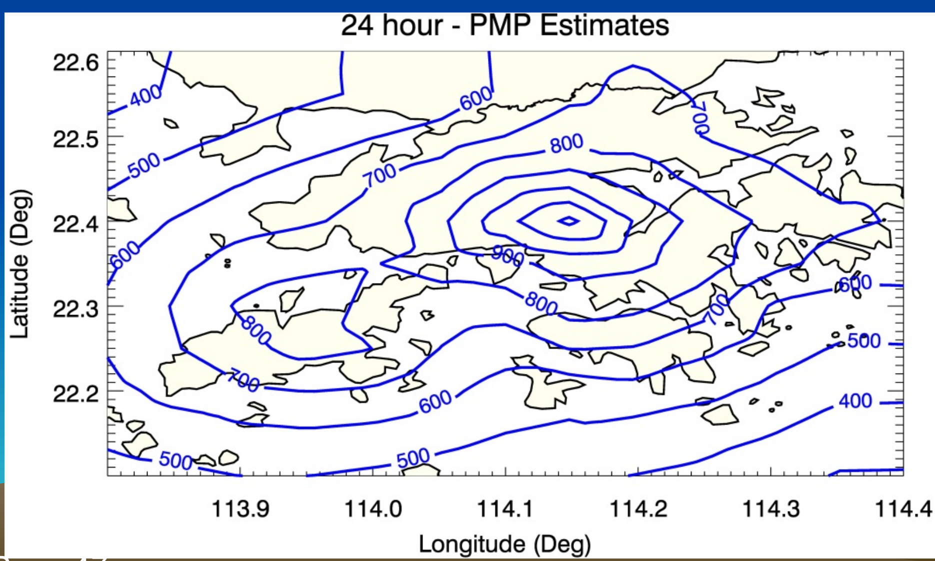
(Embryonic PMP)

Centered at Tai Mo Shan



Centered at Lantau





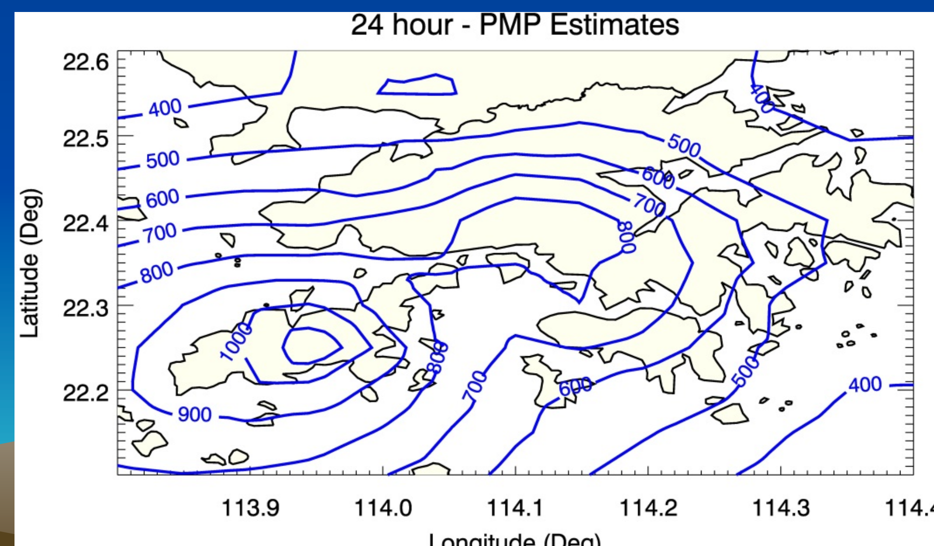
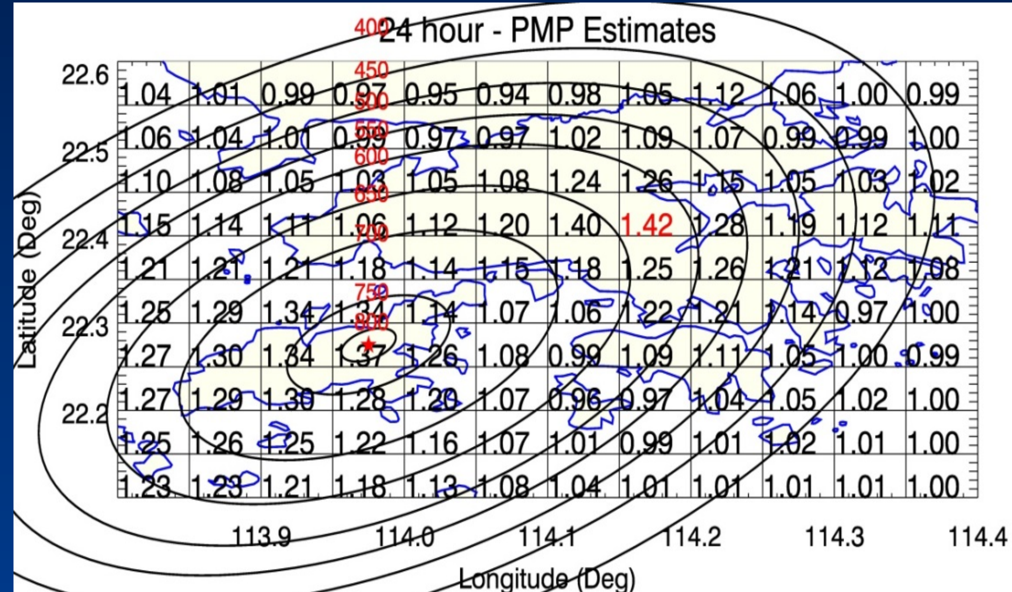


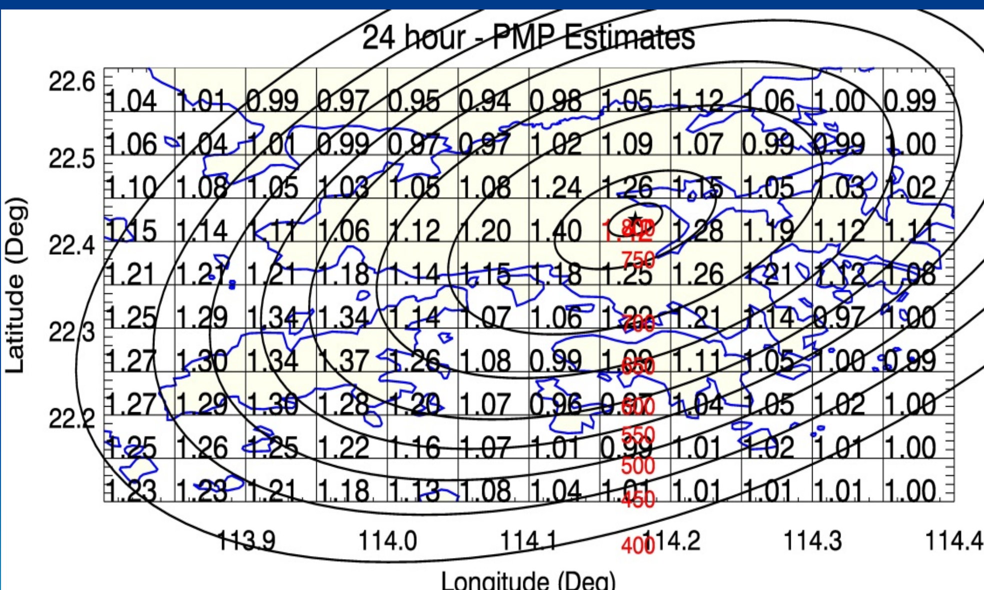
Fig. 45 Embryonic PMP for HK-1 (example only)

Orientation 45º – 24hr

(Embryonic PMP)



Centered at Lantau



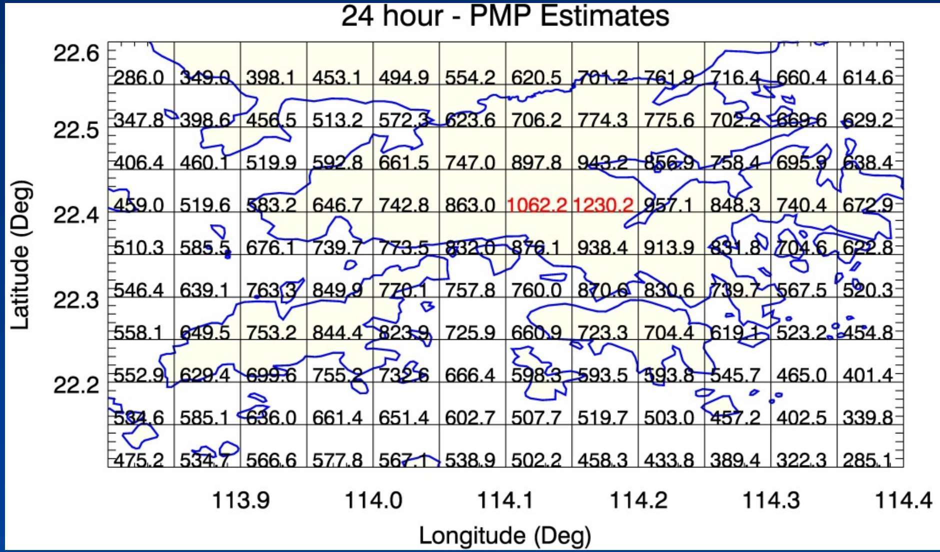
Centered at Tai Mo Shan

Fig. 46 Orientation of transposed convergence pattern (4)

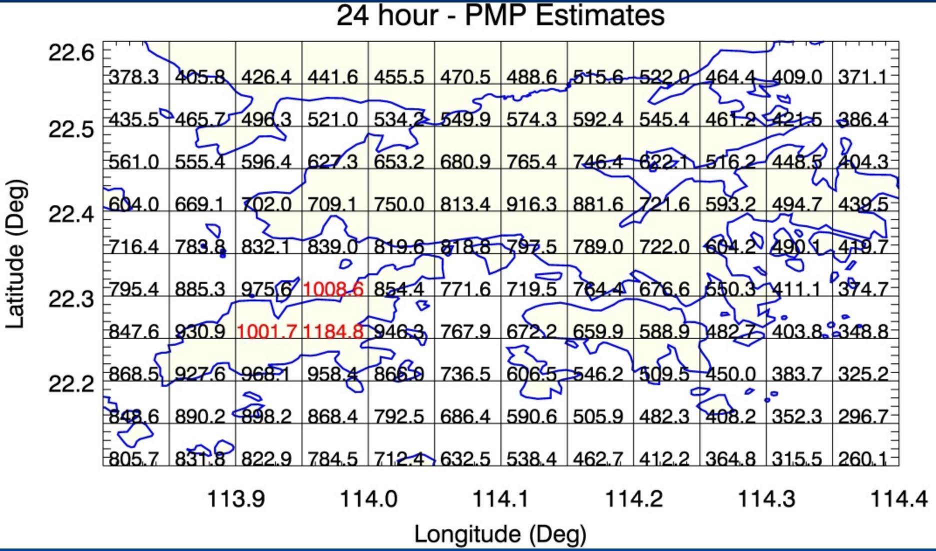
NE-SW orientation – 45°

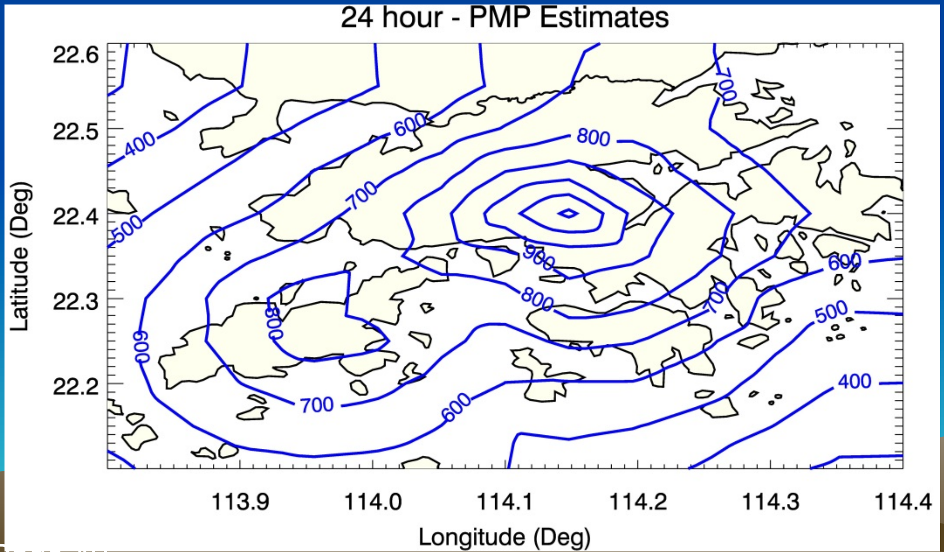
(Embryonic PMP)

Centered at Tai Mo Shan



Centered at Lantau





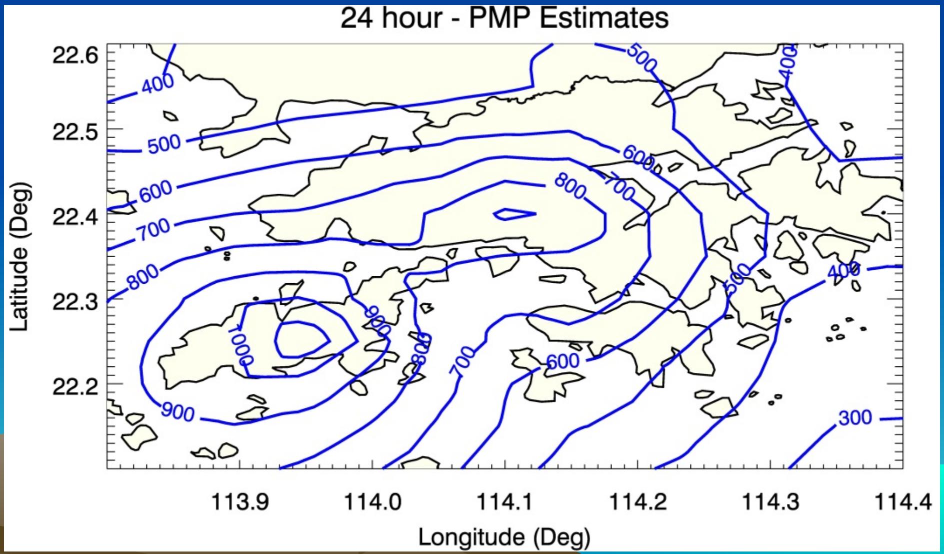


Fig. 47 Embryonic PMP for HK-2 (example only)

Depth-Area-Duration Curves （1）

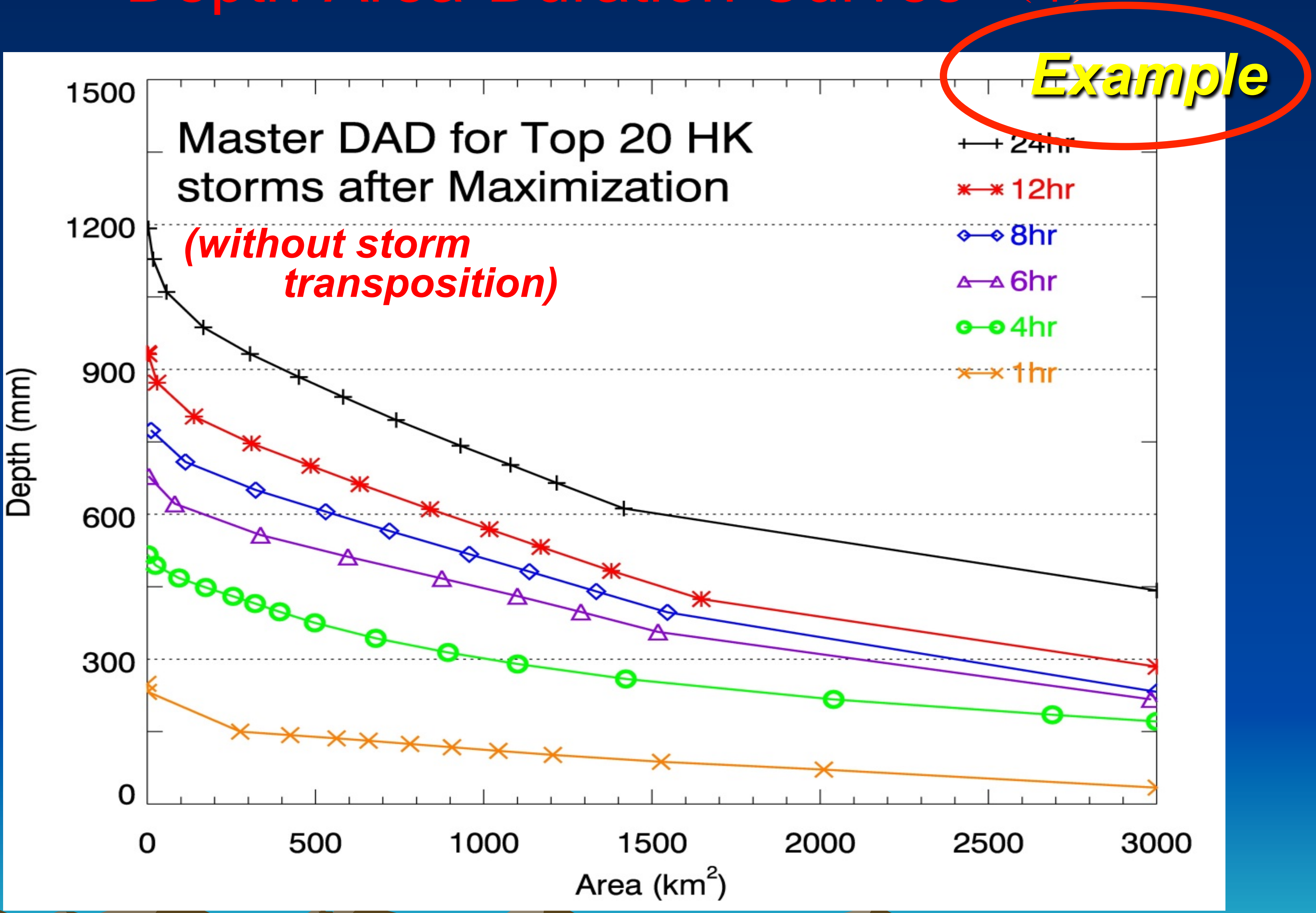


Fig. 48 DAD curve-1 (example only)

Depth-Area-Duration Curves （2）

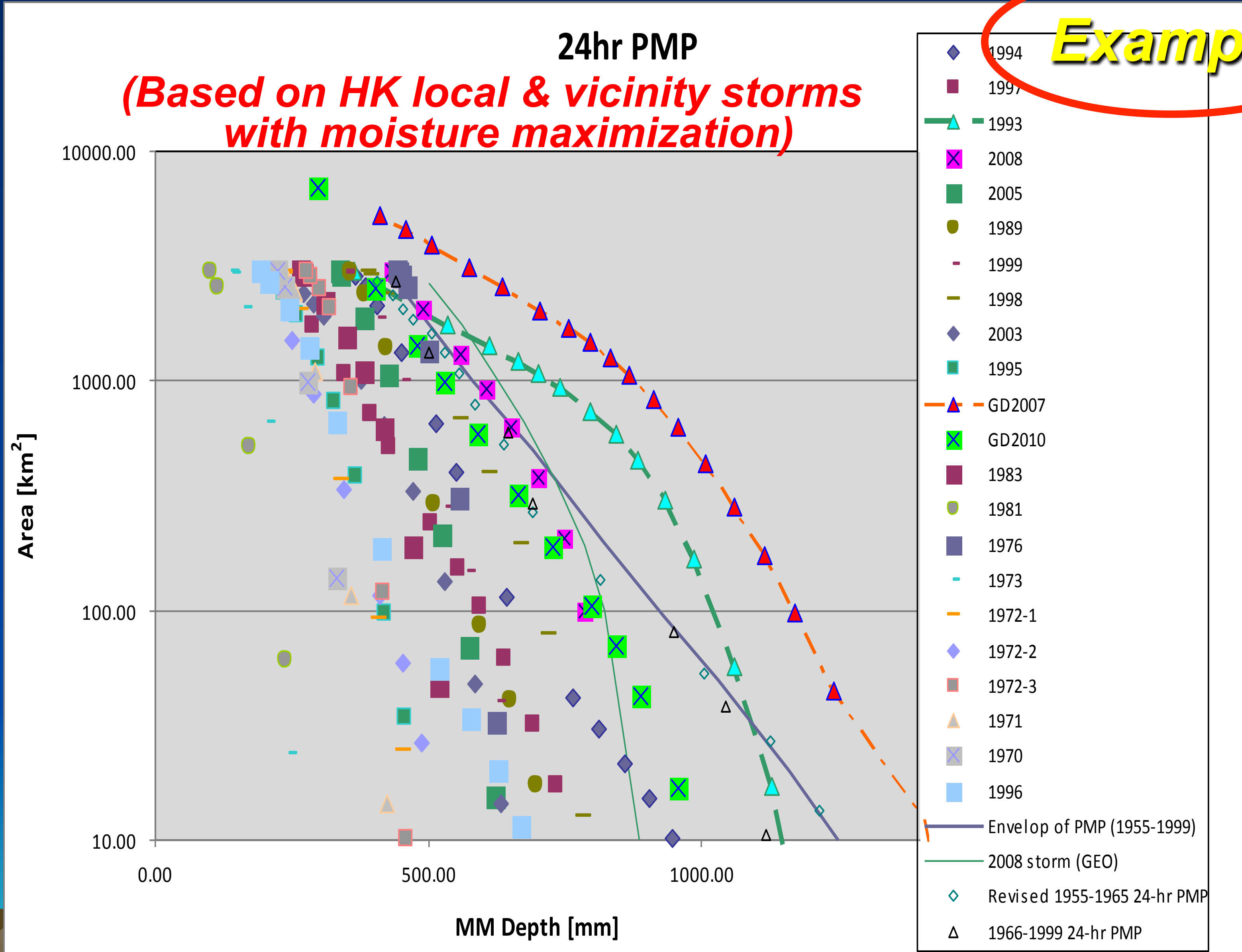


Fig. 49 DAD curve-2 (example only)

Moisture Maximization

Ratio of Moisture Maximization:

Ratio of moisture maximization for transposition

$$r = W_m / W_r = W_{27.17} / W_{24} = 99.48 / 74.0 = 1.304$$

in which, W_m is the historical maximum consistent dew point which is 27.17^{o}C *in design area* while the W_r is the representative dew point, 24.0^{o}C, for the Morakot storm *in target area*.

Estimated PMP in HK via *Storm Transposition*

Estimated PMP for Hong Kong:

4-hour:	406mm x 1.304	= 529 mm
24-hour:	1227mm x 1.304	= 1,600 mm

Statistical Approach (1)

PMP, X_{PMP}

$$X_{PMP} = \bar{X}_n + K_m \times S_n = (1 + K_m \times C_{vn}) \times \bar{X}_n$$

where $\bar{X}_n$ the mean of the n maxima

S_n the standard deviation of the n maxima

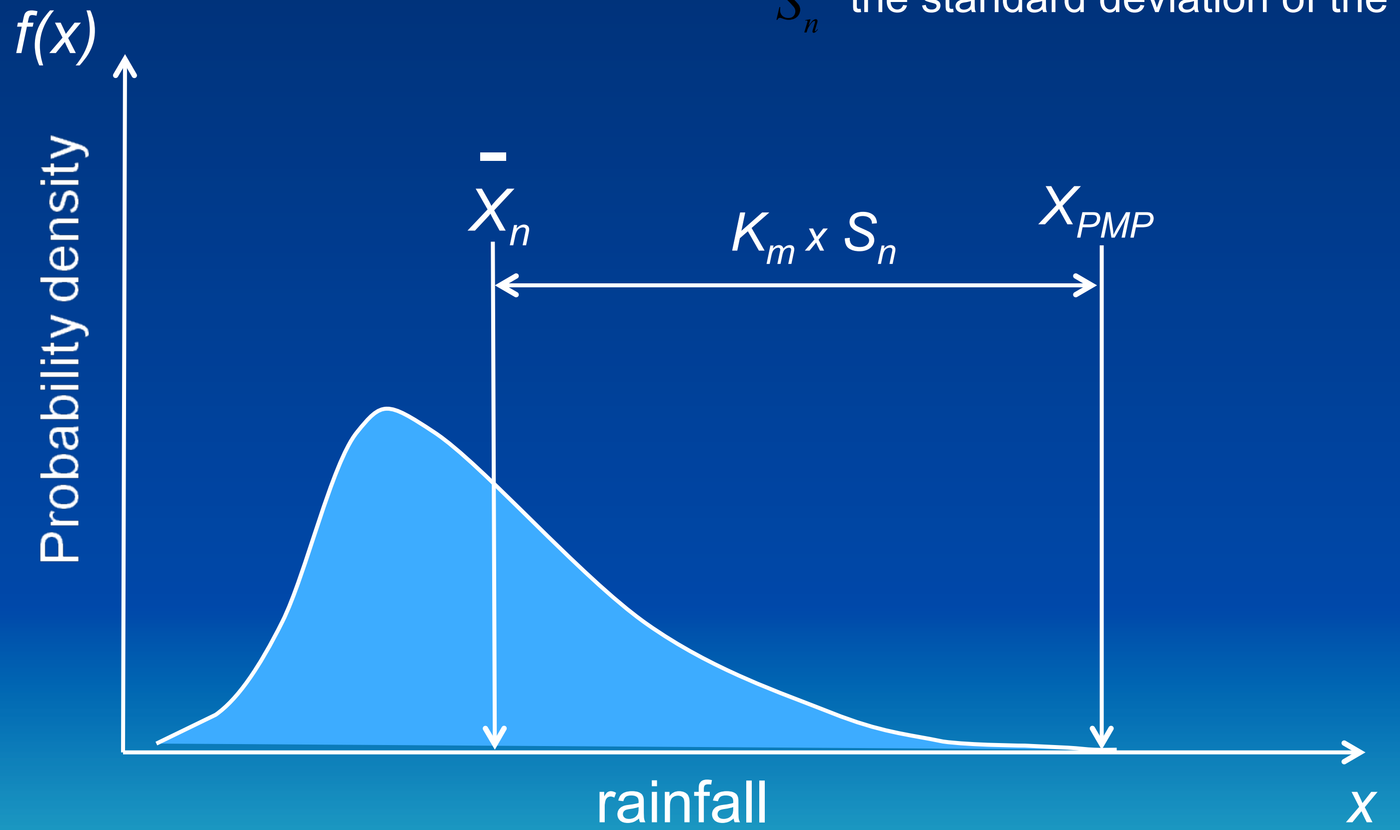


Fig. 50 Sketch for statistical approach to PMP (1)

Statistical Approach (2)

"Modified" Frequency Analysis

- "standard deviation", K_m, is added to the mean in the frequency equation

$$X_{PMP} = \bar{X}_n + K_m \times S_n = (1 + K_m \times C_{vn}) \times \bar{X}_n \longrightarrow X_{pmp} = \bar{X}_n + K_m \times S_n$$

where $\bar{X}_n$ and S_n are the mean and the standard deviation of the n maxima, C_{vn} is the coefficient of variation of the sample with n values

- calculated in a unique way that the maximum observed value ($K_m = \frac{(X_m - \bar{X}_{n-1})}{S_{n-1}}$) from the historical series will be omitted in the computation

$$K_m = \frac{(X_m - \bar{X}_{n-1})}{S_{n-1}} \longrightarrow X_m = \bar{X}_{n-1} + K_m \times S_{n-1}$$

Tricky

where $\bar{X}_{n-1}$ and S_{n-1} are the mean and the standard deviation of the rainfall series **from which the maximum record rainfall was omitted.**

Statistical Approach (3) – New development

Criteria to Check the Eligibility and Stability of Using the Method

- Beyond the WMO No. 1045
- The criterion of **minimum data size** of N_m

$$N_m = \phi_m^2 + 2$$

where ϕ_m is the maximum deviation from mean and is directly computed from the following equation,

$$\phi_m = \frac{(X_m - \overline{X}_n)}{S_n}$$

- The criterion of the **stable size** of N_s in terms of 10% relative error (*Lin, 1981; Lin & Vogel, 1993*)

$$N_s \geq 5.76 \times (\phi_m^2 + 2)$$

Statistical Approach (4)

The Table of K_m (Lin & Vogel, 1993)

Appendix 1 List of variations of K_m with variation of n under different values of T_m

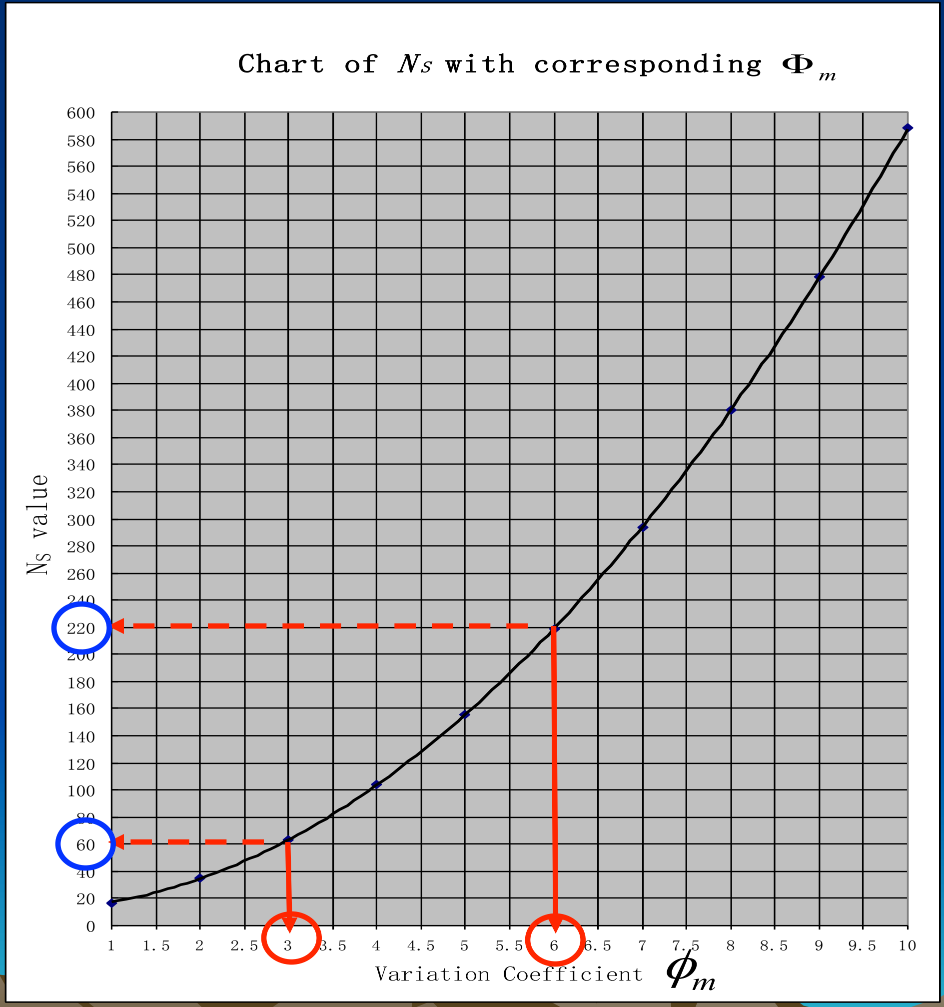
n	Tm 5	6	7	8	9	10	15
27	132.38						
38		224.90					
50	7.29						
51			353.41				
66				523.92			
83					742.43		
100		7.58	9.95	13.65			
102						1014.94	
150	**5.50**						
200		6.65			11.74	14.25	
219		**6.60**					
227							3397.46
294			**7.70**				
300			7.67			12.29	
380				**8.80**			
400				8.74			
478					**9.90**		
500	5.14	6.24	7.38	8.58	9.84		20.28
588						**11.00**	
600						10.97	
1000	5.07	6.11	7.18	8.27	9.39	10.55	17.05
1308							**16.50**
1500							16.28
5000	5.01	6.02	7.05	8.05	9.08	10.10	15.35
10000							15.17
Nm	27	38	51	66	83	102	227
Ns	**150**	**219**	**294**	**380**	**478**	**588**	**1308**

Notes: 1. N_m refers to the minimum number of data length required to make the K_m-value method reasonable.
2. N_s refers to the required number of data length to make a more statistically stable results.

10% in error

Statistical Approach (5)

- Relationship of Variation Coefficient ϕ_m with N_s



Take some stations out when

N_s > 3.5 n as it may cause

50% in error in terms of K_m.

Example:

220 >3.5x60 causes 50% in

K_m (3 / 6 = 0.5)

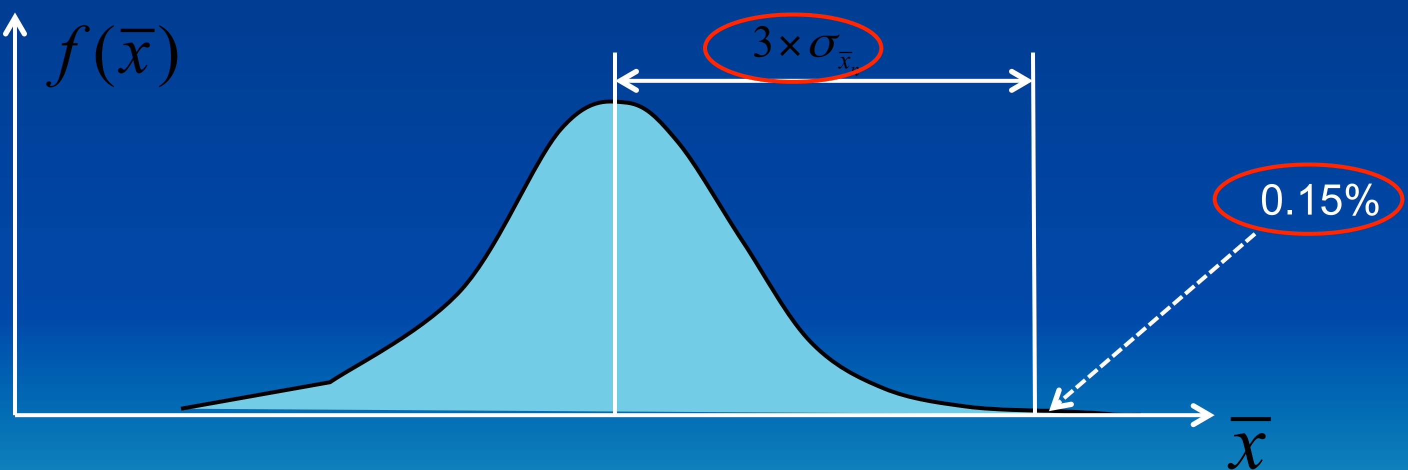
Statistical Approach (6)

Probable maximum adjustment of sample mean $\overline{x}$

PMP, X_{PMP}

$$\overline{X}_n' = \overline{X}_n + 3\times\sigma_{\overline{x}_n} \approx \left(1+\frac{3\times C_{vn}}{\sqrt{n}}\right)\times\overline{X}_n$$

where $\sigma_{\overline{x}_n}$ is the standard deviation of the mean $\overline{x}_n$



(Covering 99.7% of the probability area)

Fig. 51 Sketch for statistical approach to PMP (2)

$$\overline{X}'_{n,24} + K_{m,24} \times S_{n,24} = (1 + K_{m,24} \times C_{vn,24}) \times \overline{X}'_{n,24}$$

Equation of Statistical Approach

$$X_{PMP,24} = \overline{X}'_{n,24} + K_{m,24} \times S_{n,24} = (1 + K_{m,24} \times C_{vn,24}) \times \overline{X}'_{n,24}$$

$$X_{PMP,4} = \overline{X}'_{n,4} + K_{m,4} \times S_{n,4} = (1 + K_{m,4} \times C_{vn,4}) \times \overline{X}'_{n,4}$$

Regionalization

Estimated PMP in HK via Statistical Approach

1) The regionalized 24-hour PMP estimates are:

Employing HK data:	1650 mm / 24-hour	(regionalized)
Employing S.GD data:	1453 mm / 24-hour	(regionalized)

Suggested 24-hour PMP falls between 1453 mm ~ 1650 mm.

2) The regionalized 4-hour PMP estimates are:

Employing HK data:	628 mm / 4-hour	(regionalized)
Employing N14 data only:	533 mm / 4-hour	(N14 only – for reference and comparison)

Suggested 4-hour PMP falls between 533 mm ~ 628 mm.

Quality of PMP Estimates

It depends upon:

1) Availability of data;

2) Depth of the study.

How to determine the upper limit of the integration of the pdf ?

$$F(x)=\int_{-\infty}^{+\infty} f(x)dx=\int_{a}^{b} f(x)dx=\int_{?}^{?} f(x)dx=1$$

$$P_{Ex}=P(X>b)=\int_{b}^{+\infty} f(x)dx=0$$

It means: the pdf should converge at b.

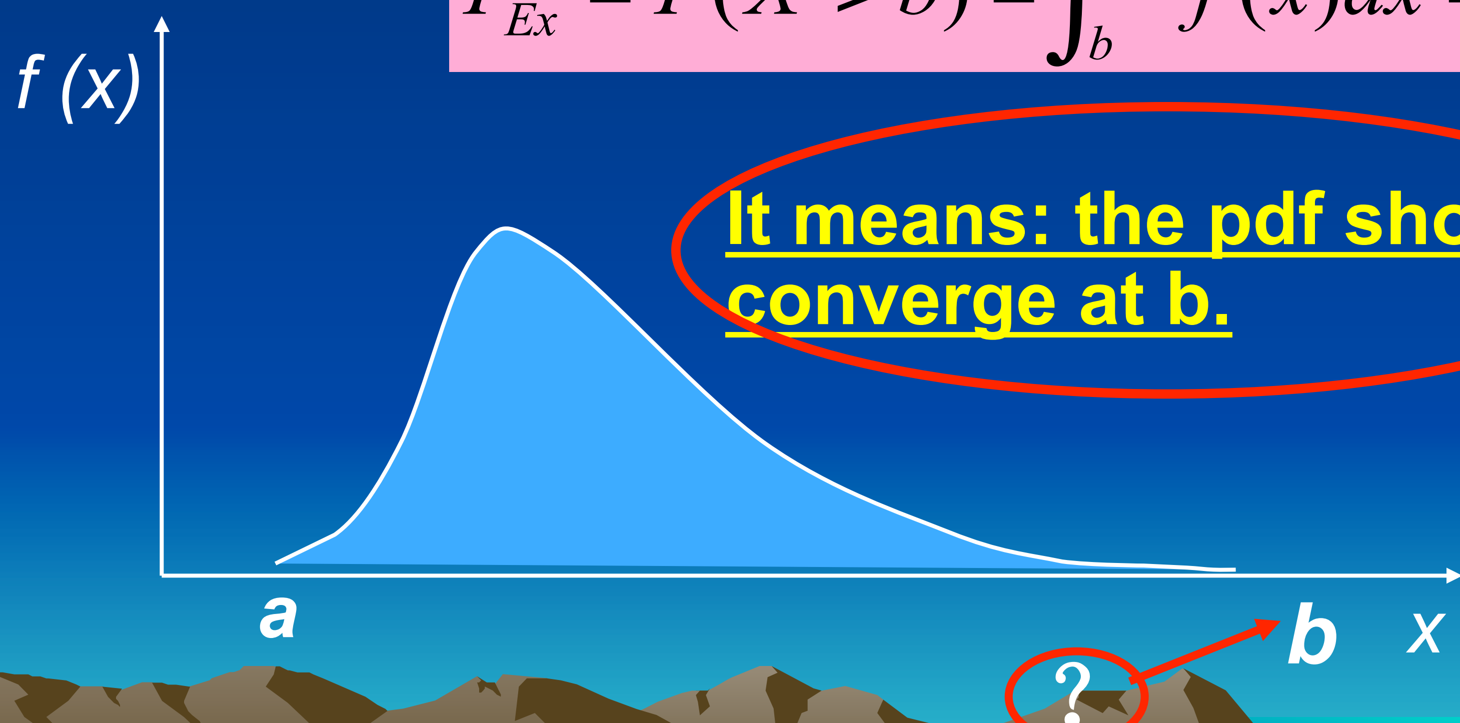


Fig. 55 Illustration of pdf curve (2)

In other words:

What is the probability of an estimated PMP?

In current textbooks it assumes:

- All quantiles are normally distributed ➔ *leading to divergence of upper tail*

Against reality

However， my studies say:
"No, not the case!"

1. Quantiles vary asymmetrically
2. Around 25-50yr – symmetrical variation
3. Quantiles < 25-50yr – positively skewed
4. Quantiles > 25-50yr – negatively skewed

➔*leading to convergence of upper tail*

（My investigations of a great number of AMS precipitation data in the U.S. and China support my findings; see below Figs. 56、57、58）

Findings (Results) over 84 Regions, OH

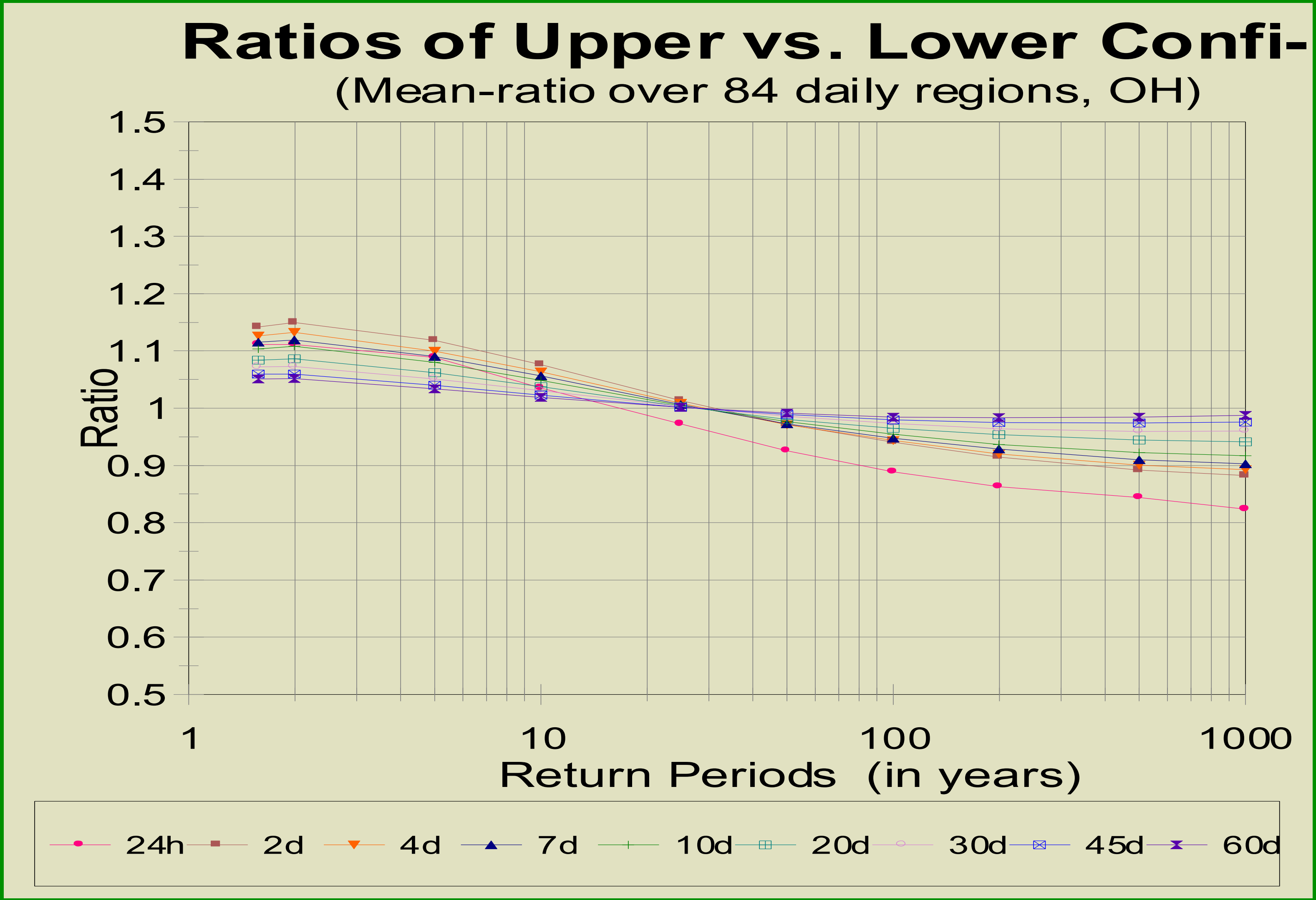


Fig. 56 Rations of (upper vs lower) for Ohio River Basin

Findings (Results) over 59 Regions, SA

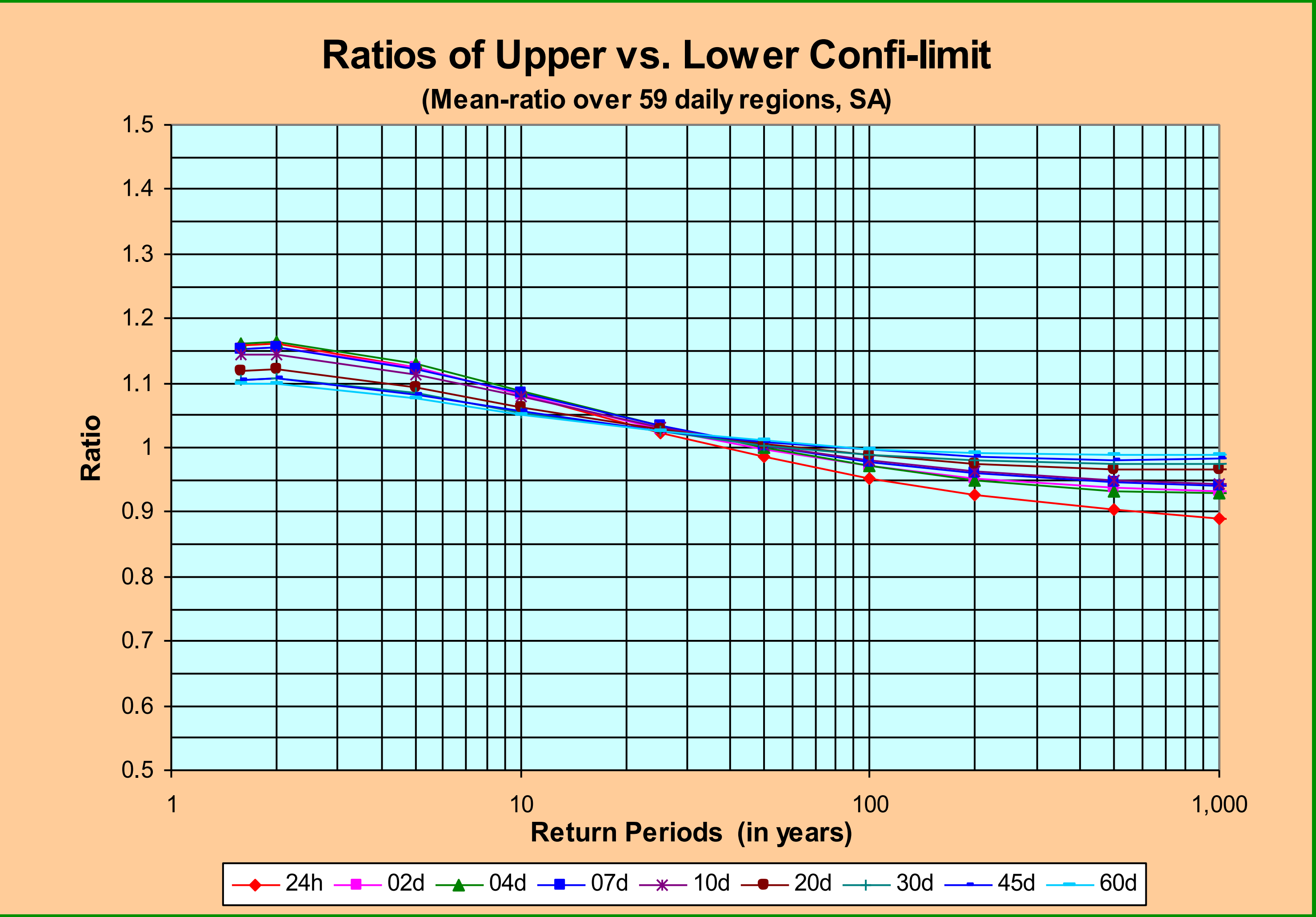
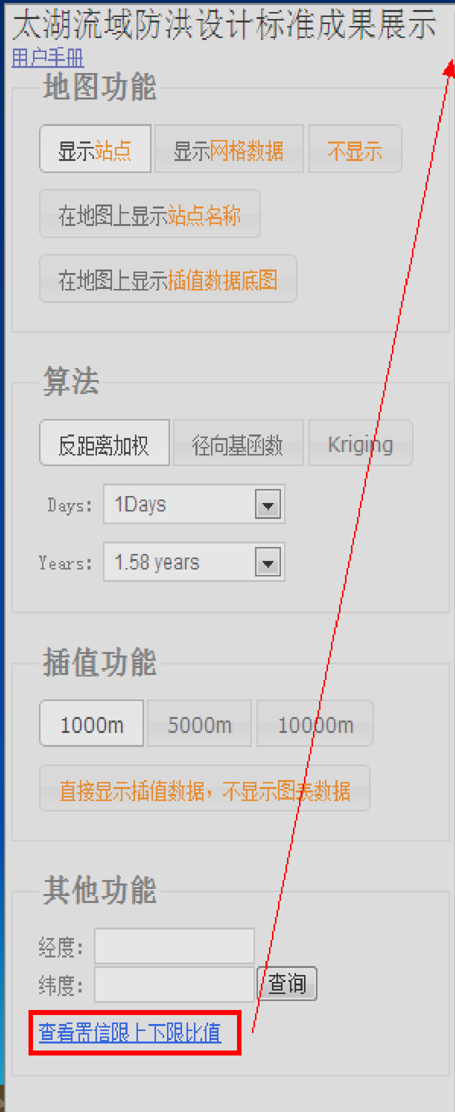


Fig. 57 Rations of (upper vs lower) for SW Semiarid U.S.

Findings (Results) over 8 Regions, Taihu



置信限上下限比值

时段长	重现期(Y)mm									
	Y1_58	Y2	Y5	Y10	Y25	Y50	Y100	Y200	Y500	Y1000
1天	1.24	1.24	1.19	1.11	1.03	0.98	0.95	0.92	0.90	0.90
3天	1.22	1.22	1.16	1.10	1.04	1.00	0.97	0.96	0.96	0.96
7天	1.21	1.21	1.16	1.10	1.03	1.00	0.98	0.97	0.97	0.97
10天	1.17	1.17	1.12	1.08	1.02	0.99	0.98	0.98	0.99	1.00
太湖流域平均	1.21	1.21	1.16	1.10	1.03	0.99	0.97	0.96	0.95	0.96

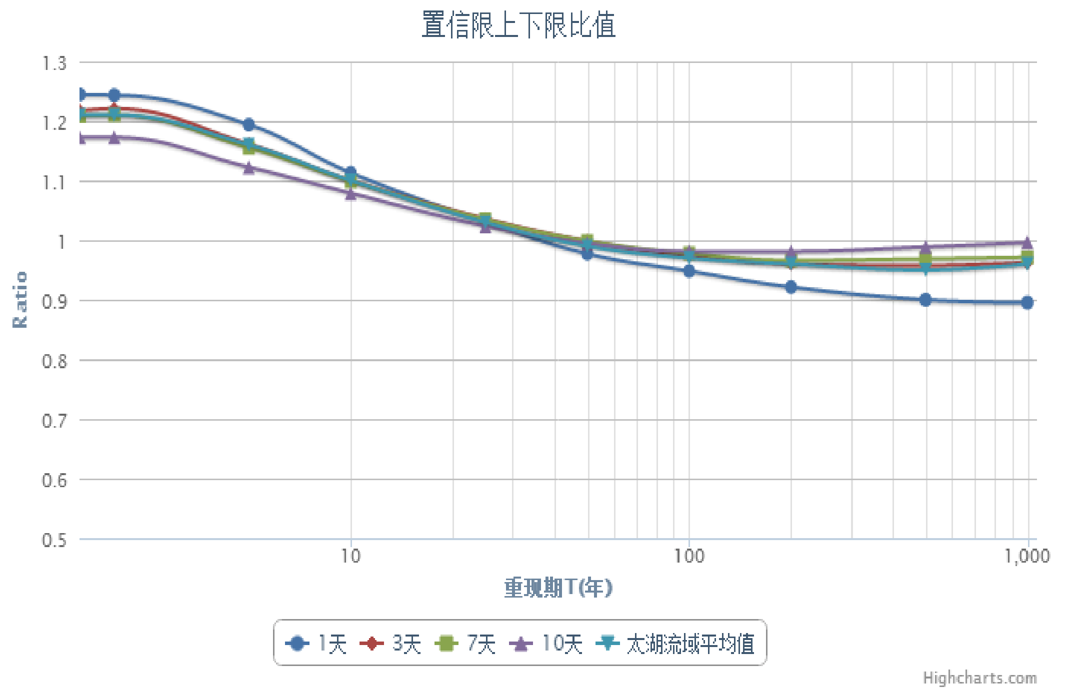


Fig. 58 Rations of (upper vs lower) for Taihu Lake

These Studies indicate that：

Upper tail of frequency distribution tends to converge

These evidences suggest that

the upper tail of the probability distribution should converge to a certain value by an asymptote.

Conclusion: Estimation of the upper limit of integration of the PDF is *doable*

$$\int_{-\infty}^{+\infty} f(x)dx = 1$$

$$\int_{?}^{?} f(x)dx = 1$$

$$\int_{a}^{b} f(x)dx = 1$$ → **OK**

Uncertainties of quantiles

Thus, ***the frequency analysis and the PMP study can be unified***, *tested each other*, complemented and no longer fighting against each other – **this may change the entire world of the hydrologic design studies.** ***Amazing!***

Wow !

It's exciting, but not easy!

There is still a long way to go.

However, the direction to go is certain. ***It's doable!***

Acknowledgements

1. NOAA of the U.S.: *Precipitation Frequency Atlases Update project*；
2. MWR of China: *Application of Regional L-Moments Method to Flood-Mitigation Planning* (#201001047, ongoing);
3. MWR of China: *Impact of Climate Change on PMP Estimation and the Countermeasures to Flood-Mitigation* (#201101033, ongoing);
4. HKSAR Government GEO: *PMP Estimation for Hong Kong* (ongoing);

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The End

Thank you