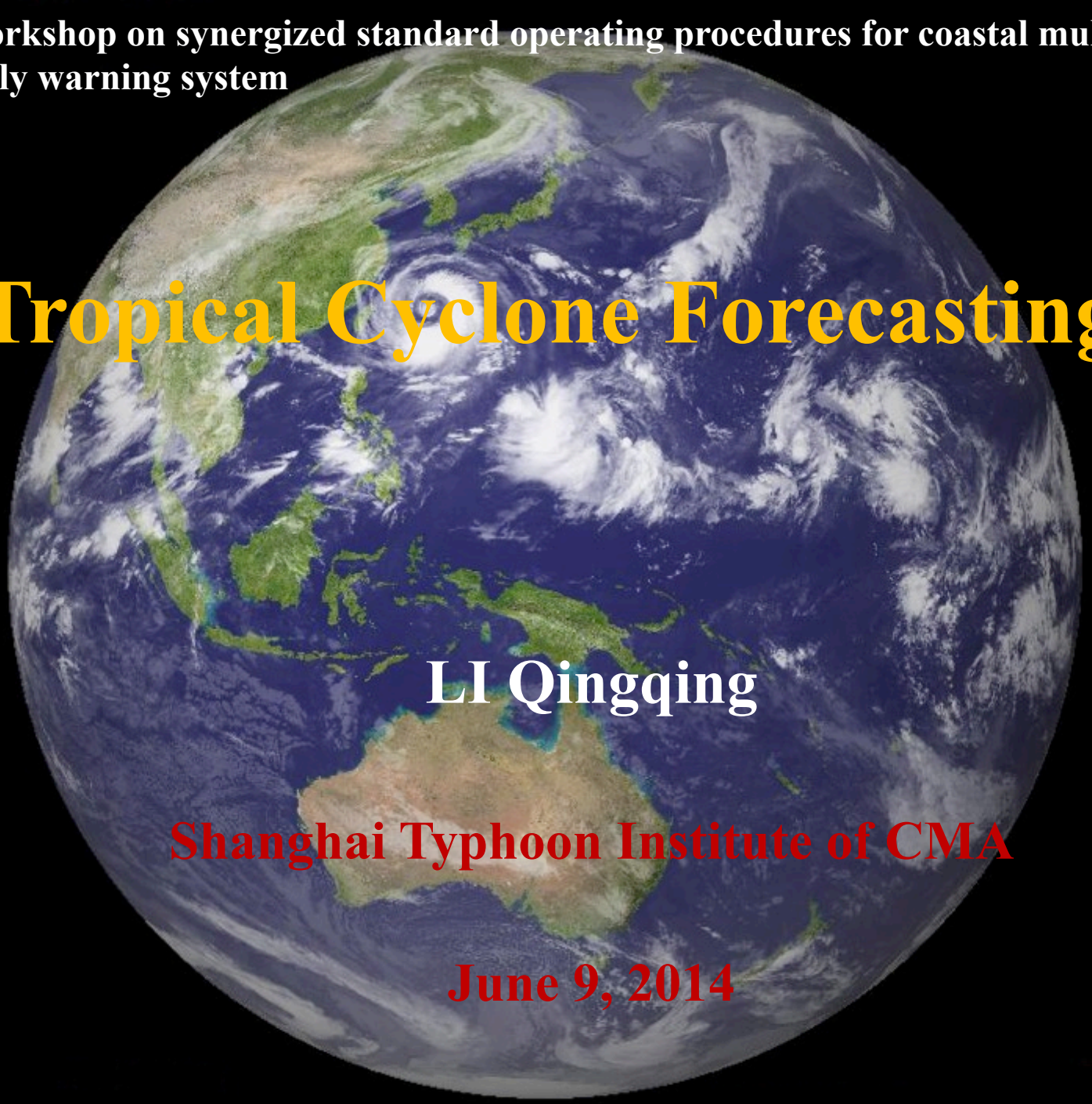
Training workshop on synergized standard operating procedures for coastal multi-hazards early warning system



Tropical Cyclone Forecasting

LI Qingqing

Shanghai Typhoon Institute of CMA

June 9, 2014

- **What is a tropical cyclone (typhoon)?**
- **What Hazards do a tropical cyclone may cause?**
- **What forecasts of tropical cyclones do we need?**
- **How do we make forecasts for mitigating tropical cyclone-related hazards?**
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Definition of tropical cyclones

A tropical cyclone is defined as

a warm-cored, non-frontal synoptic-scale cyclone, originating over tropical or subtropical oceans, with organized deep convection and a closed surface wind circulation about a well-defined center.

Once formed, a tropical cyclone is maintained by the extraction of heat energy from the ocean at high temperature and heat export at the low temperatures of the upper troposphere. In this way, tropical cyclones differ from extratropical cyclones, which derive their energy from horizontal temperature gradients (baroclinic effect) in the atmosphere.

Classification of tropical cyclone intensity

- *North Atlantic and Eastern North Pacific (Hurricanes)*

In USA, the hurricane categories are related to the maximum sustained 1-minute average 10-m wind speed and minimum central pressure below based on Saffir-Simpson Scale

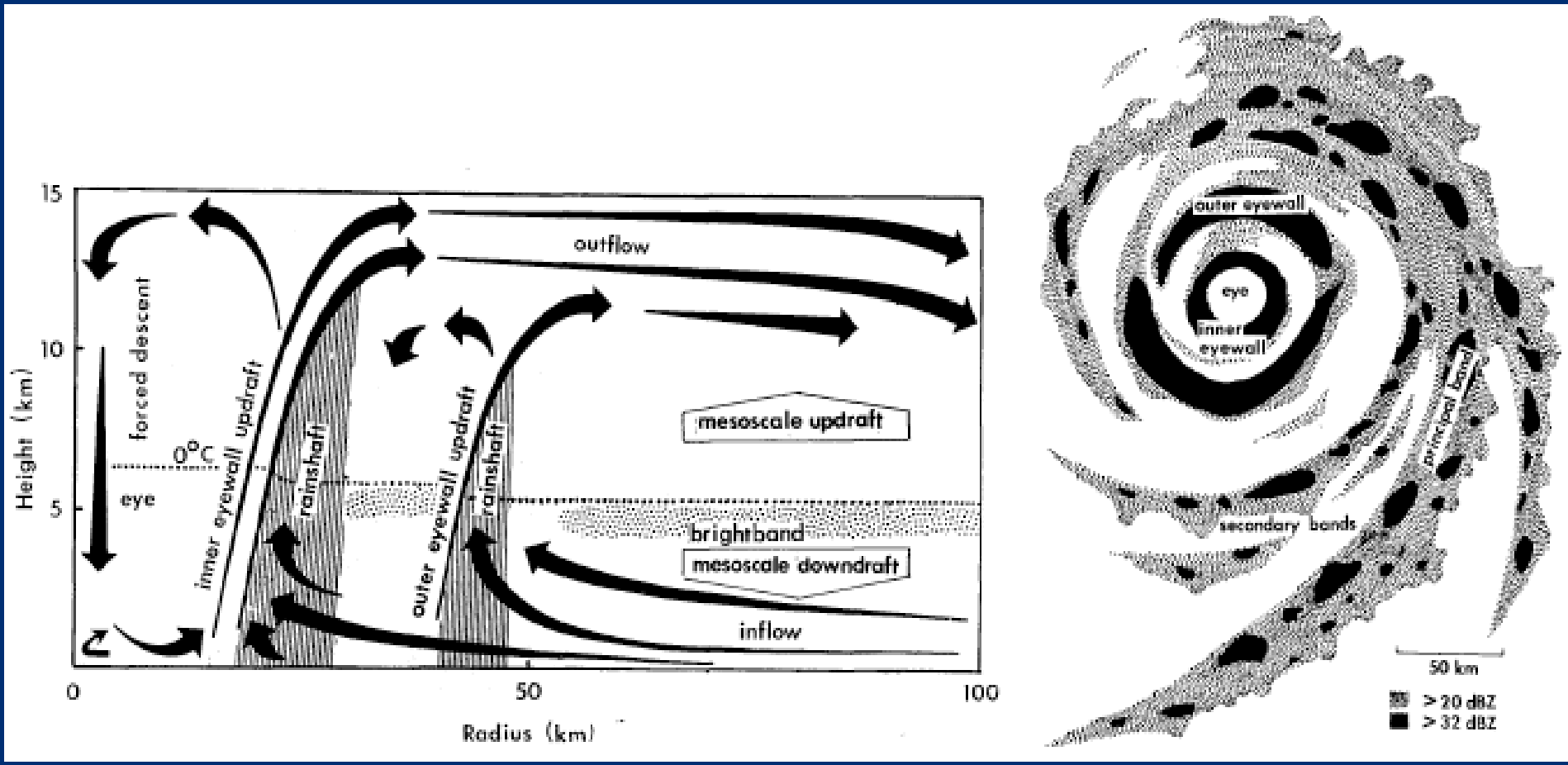
Saffir-Simpson category	Maximum sustained 1-minute average 10-m wind speed	Minimum central Pressure (hPa)
1	33-42 m/s (64-82 knots)	>980
2	43-49 m/s (83-96 knots)	979-965
3	50-58 m/s (97-114 knots)	964-945
4	59-69 m/s (115-135knots)	944-920
5	>70 m/s (136 knots)	< 920

•*CMA intensity categories for the Western North Pacific typhoons*

The tropical cyclone intensity scale is based on the maximum sustained (2-minute average 10-m) wind speeds

Category	maximum sustained 2-minute average 10-m wind speed (m s^{-1})
Tropical depression (TD)	10.8－17.1
Tropical storm (TS)	17.2－24.4
Severe tropical storm (STS)	24.5－32.6
Typhoon (TY)	32.7－41.4
Severe typhoon (STY)	41.5－50.9
Super typhoon (SuperTY)	≥51.0

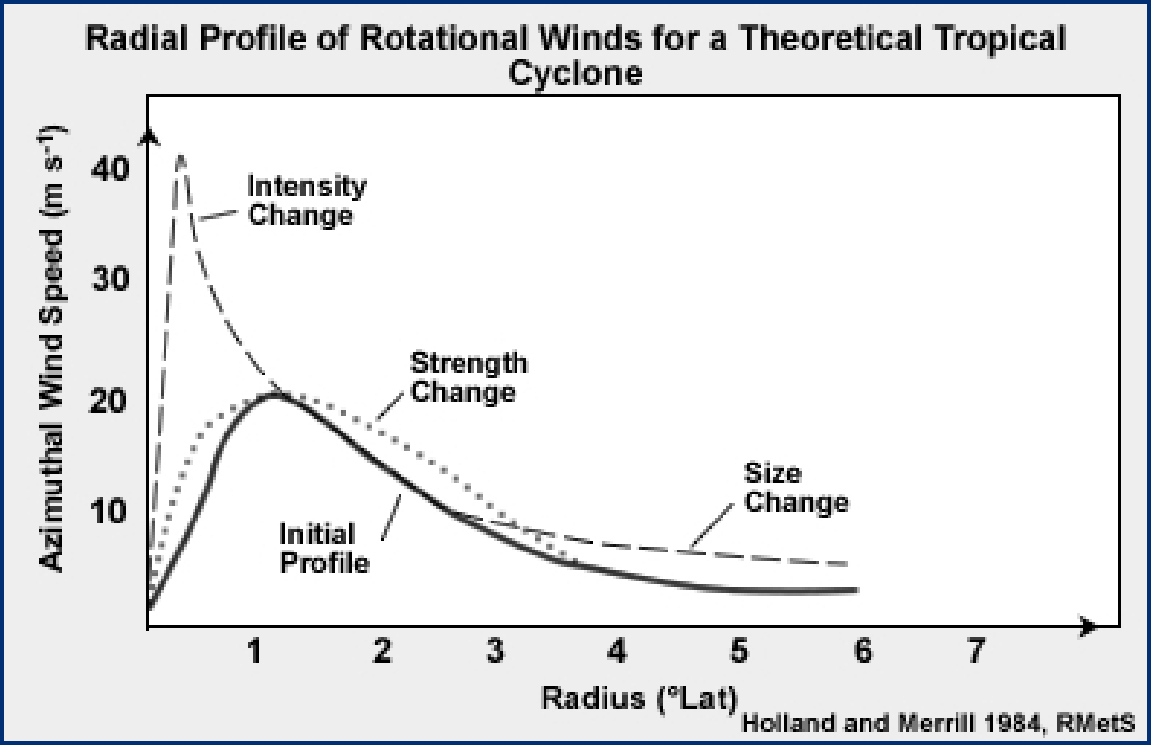
Basic structure of tropical cyclones

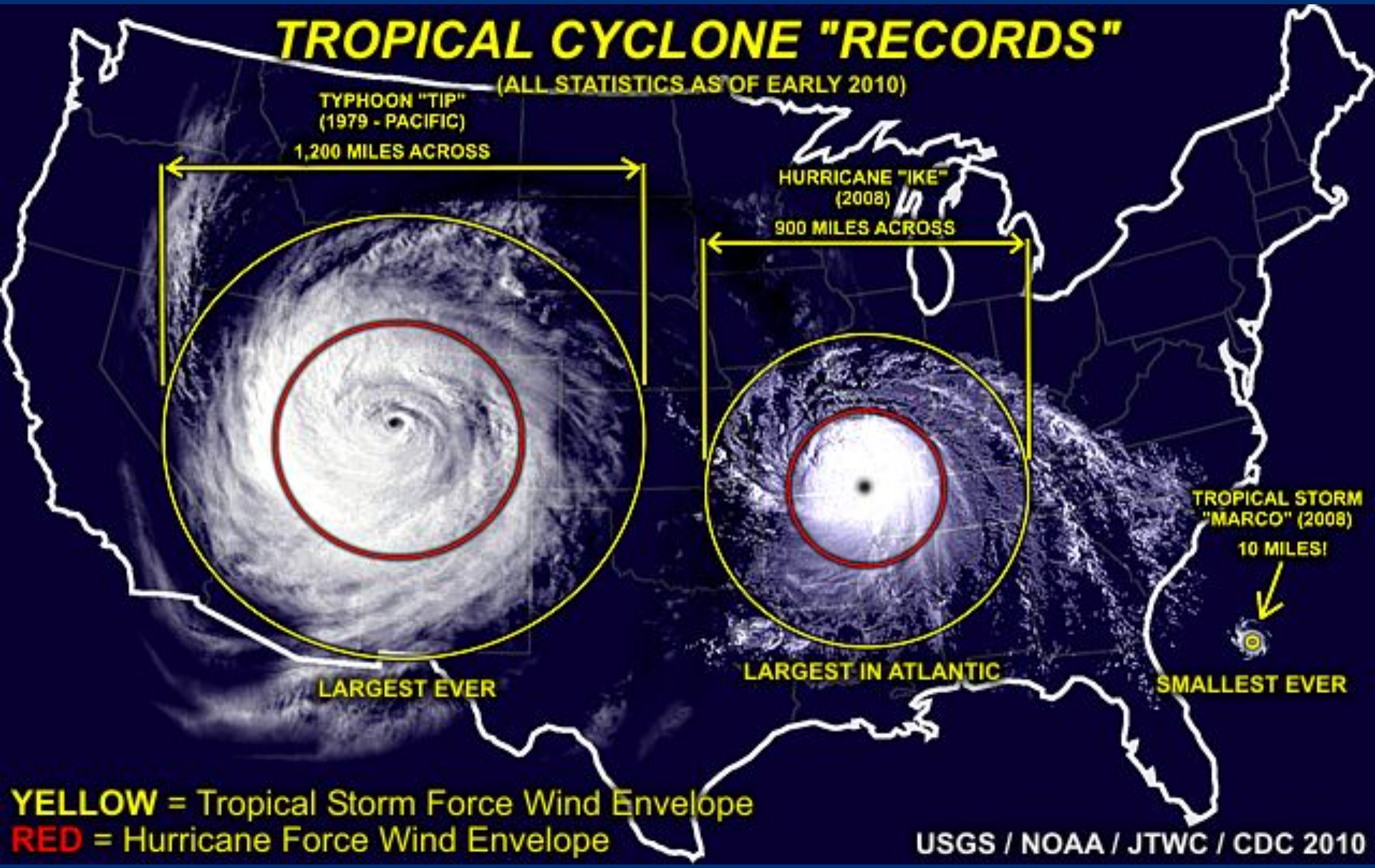


Willoughby 1990

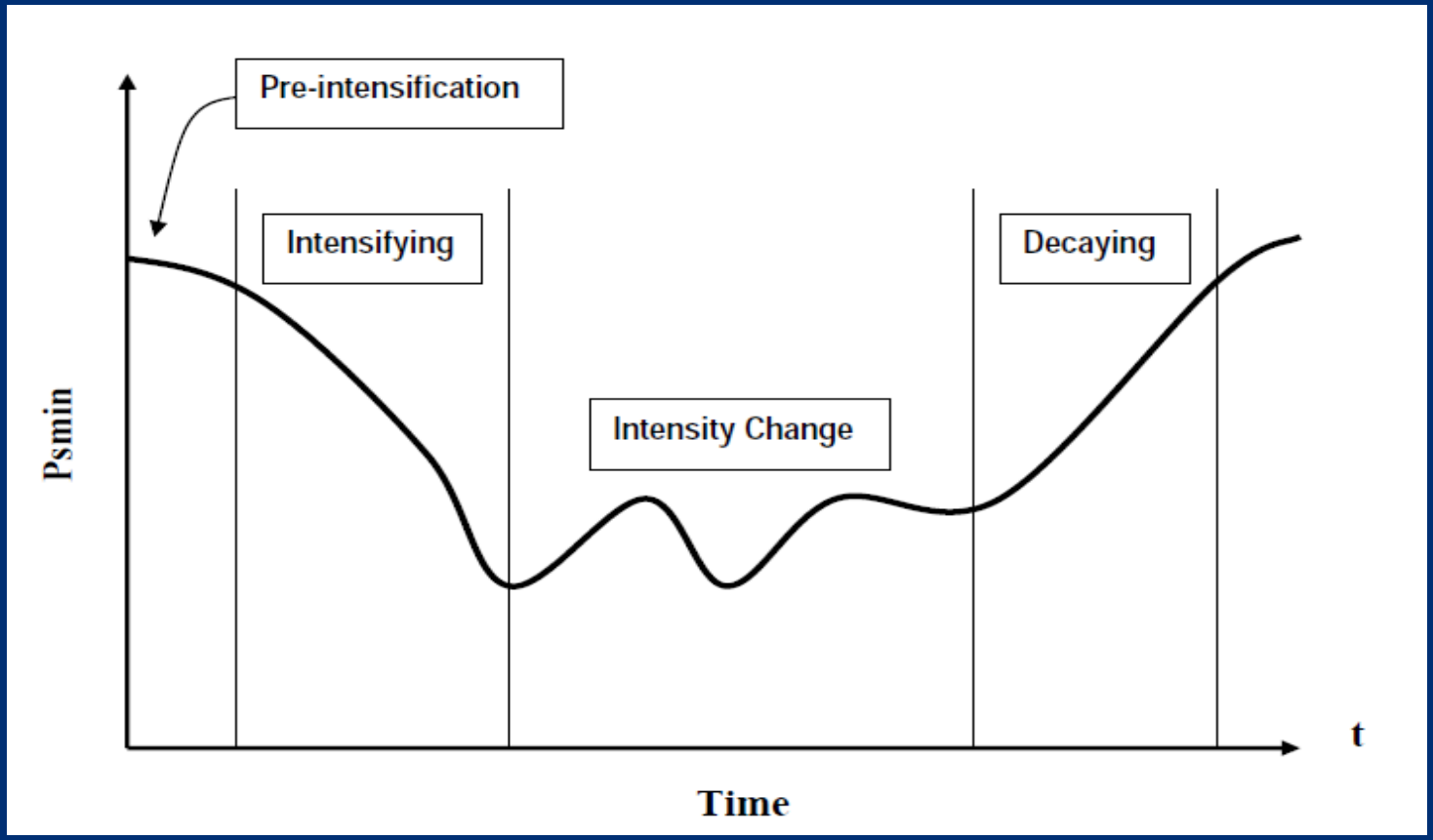
Tropical cyclone size parameters

Radius of eye (REYE)
Radius of maximum wind (RMW)
Radius of gale-force wind (17m/s)
Radius of damaging-force wind (25.7m/s or 50 knots)
Radius of hurricane-force wind (33m/s)
Radius of the outmost closed isobar (ROCI) in surface pressure field




TROPICAL CYCLONE "RECORDS"
(ALL STATISTICS AS OF EARLY 2010)
TYPHOON "TIP"
(1979 - PACIFIC)
1,200 MILES ACROSS
LARGEST EVER
HURRICANE "IKE"
(2008)
900 MILES ACROSS
LARGEST IN ATLANTIC
TROPICAL STORM
"MARCO" (2008)
10 MILES!
SMALLEST EVER
YELLOW = Tropical Storm Force Wind Envelope
RED = Hurricane Force Wind Envelope
USGS / NOAA / JTWC / CDC 2010

Lifecycle and rapid intensification of a tropical cyclone



Rapid intensification or deepening is defined as a decrease in the minimum sea-level pressure of a tropical cyclone of 1.75 hPa hr^{-1} or 42 hPa in 24 hours (Wang and Wu 2004)

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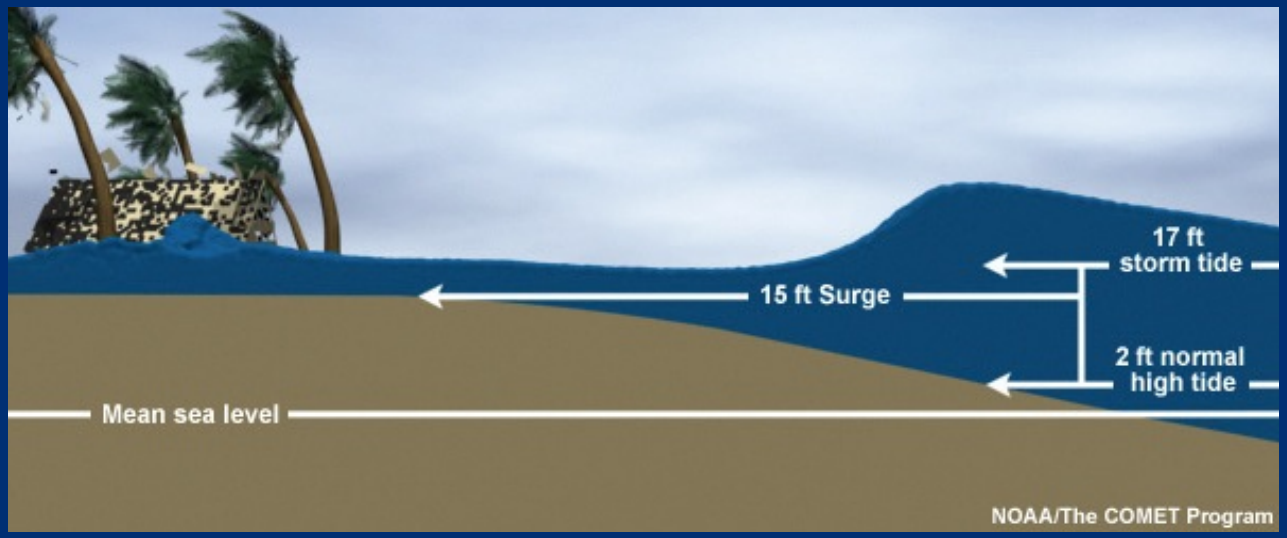
What hazards do a tropical cyclone may cause?

STORM SURGE **is an abnormal rise of water generated by a storm's winds.**

STORM TIDE **is the water level rise during a storm due to the combination of storm surge and the astronomical tide.**



What hazards do a tropical cyclone may cause?

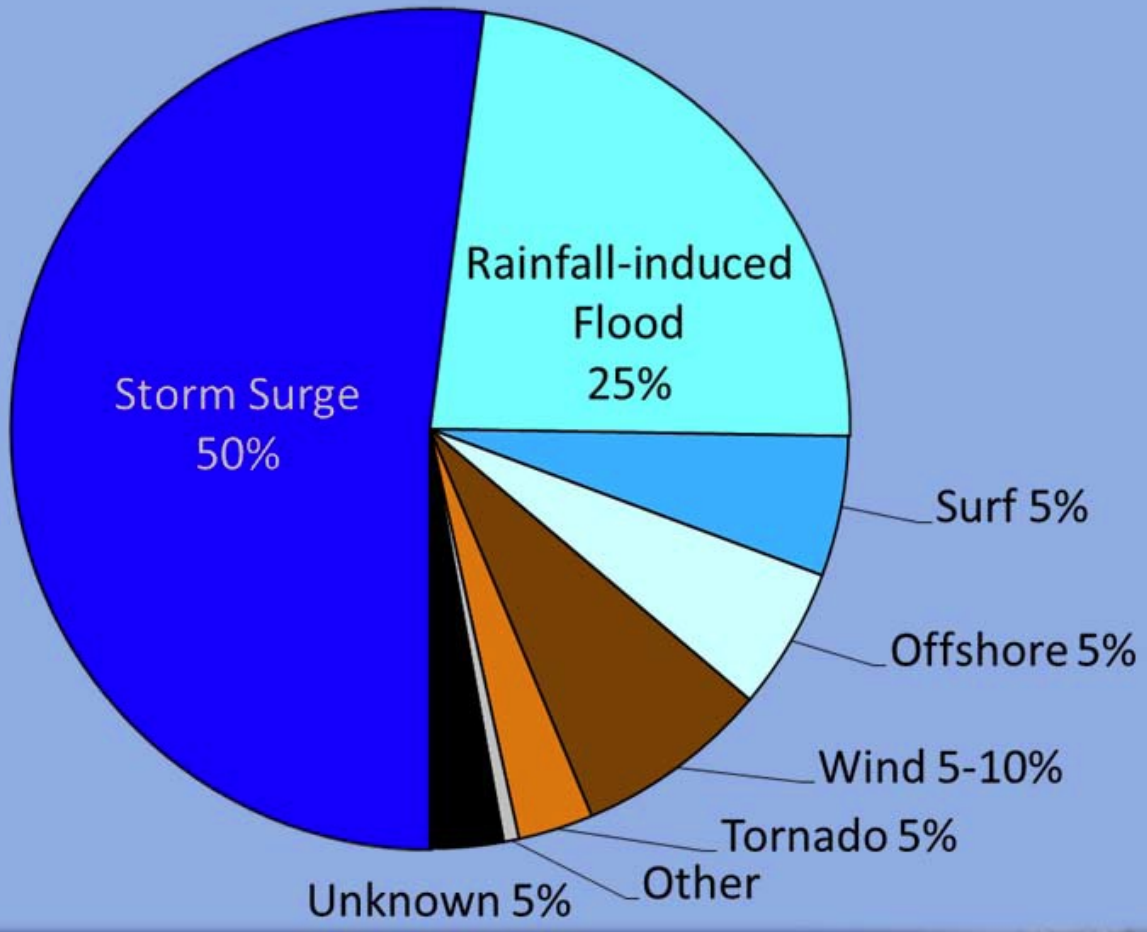
TORNADOES. **Tropical cyclones can also produce tornadoes.**

WINDS. **Hurricane-force winds, 74 mph or more, can destroy buildings and mobile homes.**

RAINFALL. **Tropical cyclones often produce widespread, torrential rains in excess of 6 inches, which may result in deadly and destructive floods. In fact, flooding is the major threat from tropical cyclones for people living inland. Flash flooding, defined as a rapid rise in water levels, can occur quickly due to intense rainfall.**

RIP CURRENTS. **The strong winds of a tropical cyclone can cause dangerous waves. When the waves break along the coast, they can produce deadly rip currents—even at large distances from the storm.**

U.S. Atlantic Tropical Cyclone Deaths, 1963-2012



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What forecasts of tropical cyclones do we need?

Track **and landfall location and timing if a tropical cyclone is forecast to make landfall**

Intensity

Wind **distribution (storm size) and duration**

Rainfall **distribution and its accumulated amount**

Storm surge

- **What is a tropical cyclone (typhoon)?**
- **What hazards do a tropical cyclone may cause?**
- **What forecasts of tropical cyclones do we need?**
- **How do we make forecasts for mitigating tropical cyclone-related hazards ?**

  — Computer models are the basis.

How does the NMC typhoon forecast process work?

Hierarchy of Tropical cyclone Track Models

- ***Statistical***

  CLIPER (Climatology-Persistence)

  - knows NOTHING about current state of atmosphere

- ***Simplified Dynamical (Trajectory)***

  BAMD, BAMM, BAMS

  - Follow cork in stream analogy, where the cork (the tropical cyclone) is not allowed to affect the stream

- ***Dynamical models***

  GFS, ECMWF, GFDL, HWRF, GRAPES

  - Most sophisticated models available

  - Solve fundamental physical equations of the atmosphere and include a variety of physical processes

Continued

- ***Consensus***

  TVCA, TVCE, FSSE

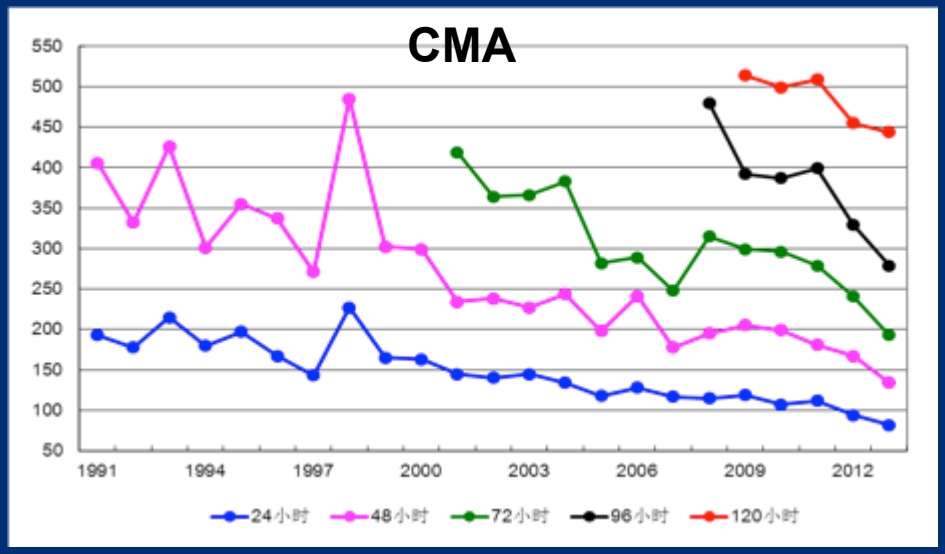
  - Not actual models, but combinations of other models

  *** Can be a simple average**

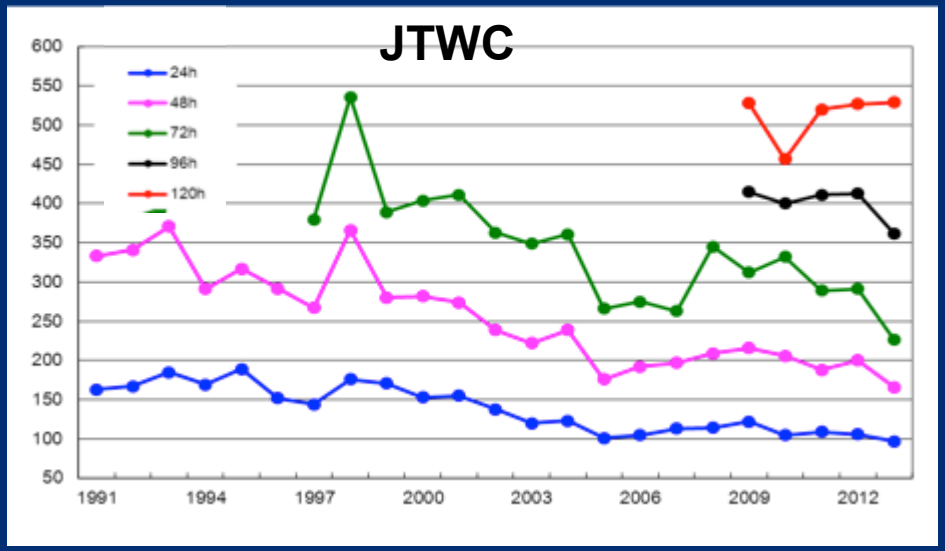
  *** Can be more complicated, where past performance is used to try to come up with an optimal combination and/or to correct model biases ("corrected consensus")**

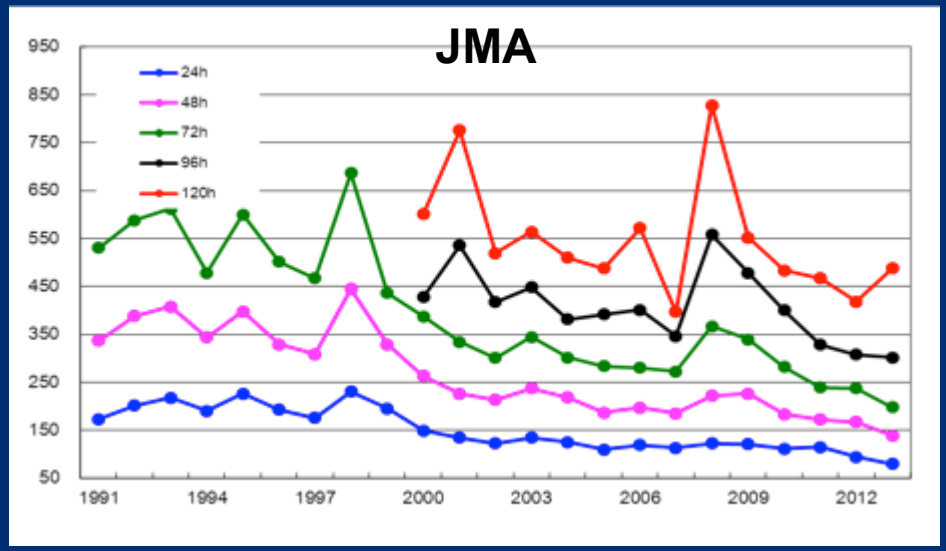
  - Consensus models generally outperform the individual models that make them up

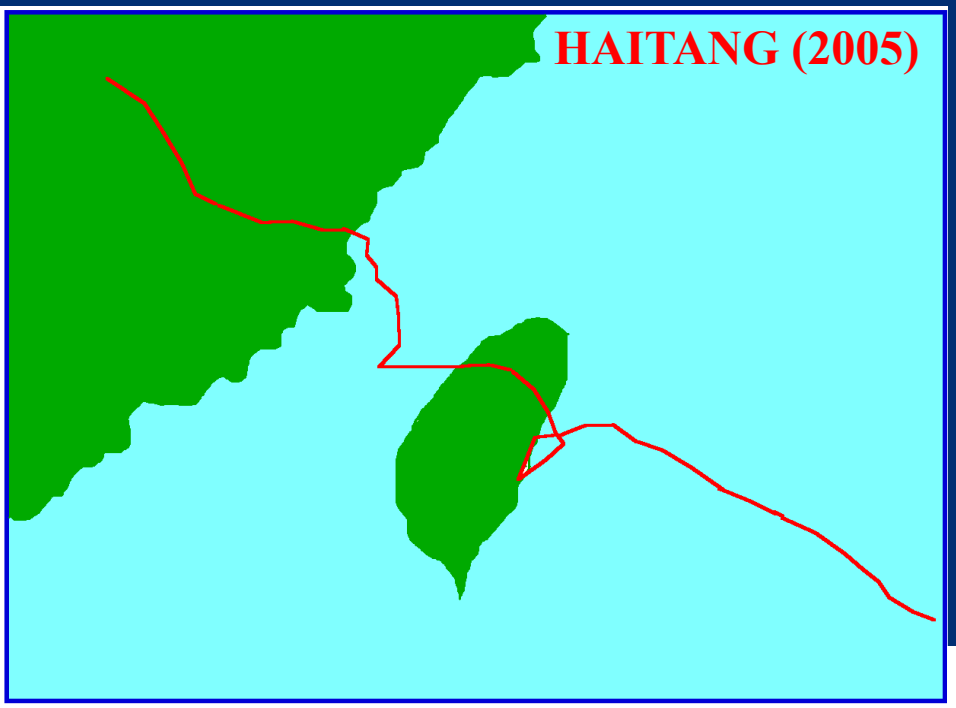
Official typhoon track forecast errors



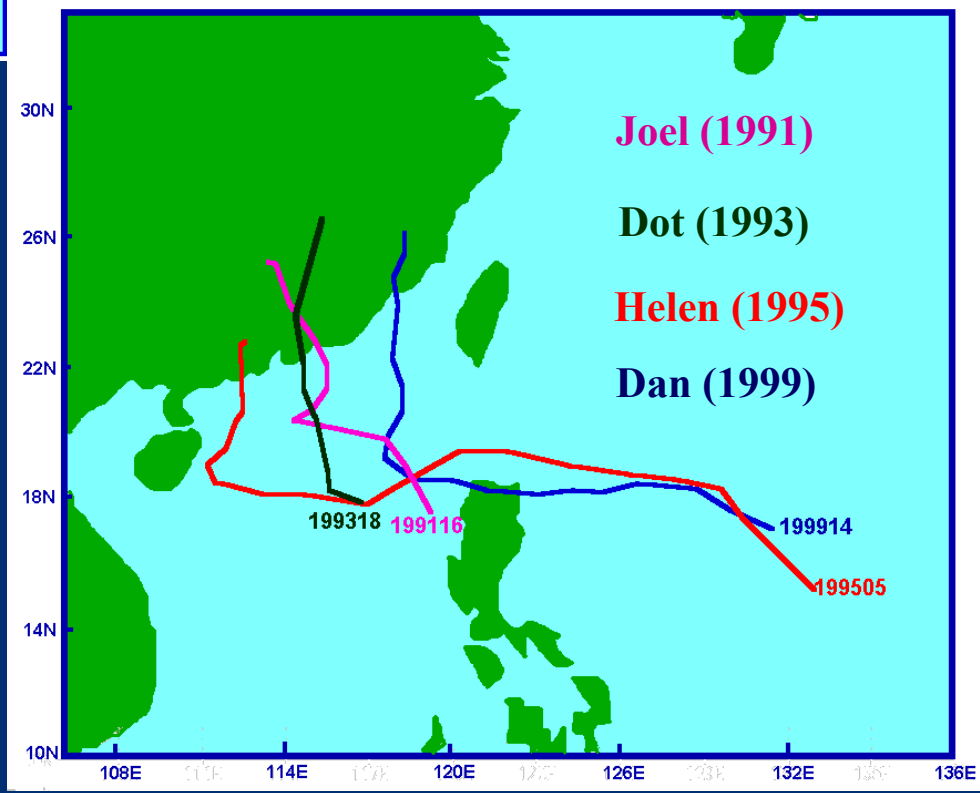
Operational track forecasts have improved dramatically in the last decade, resulting from the knowledge of mechanisms for controlling tropical cyclone movement and the significant improvement of numerical models.



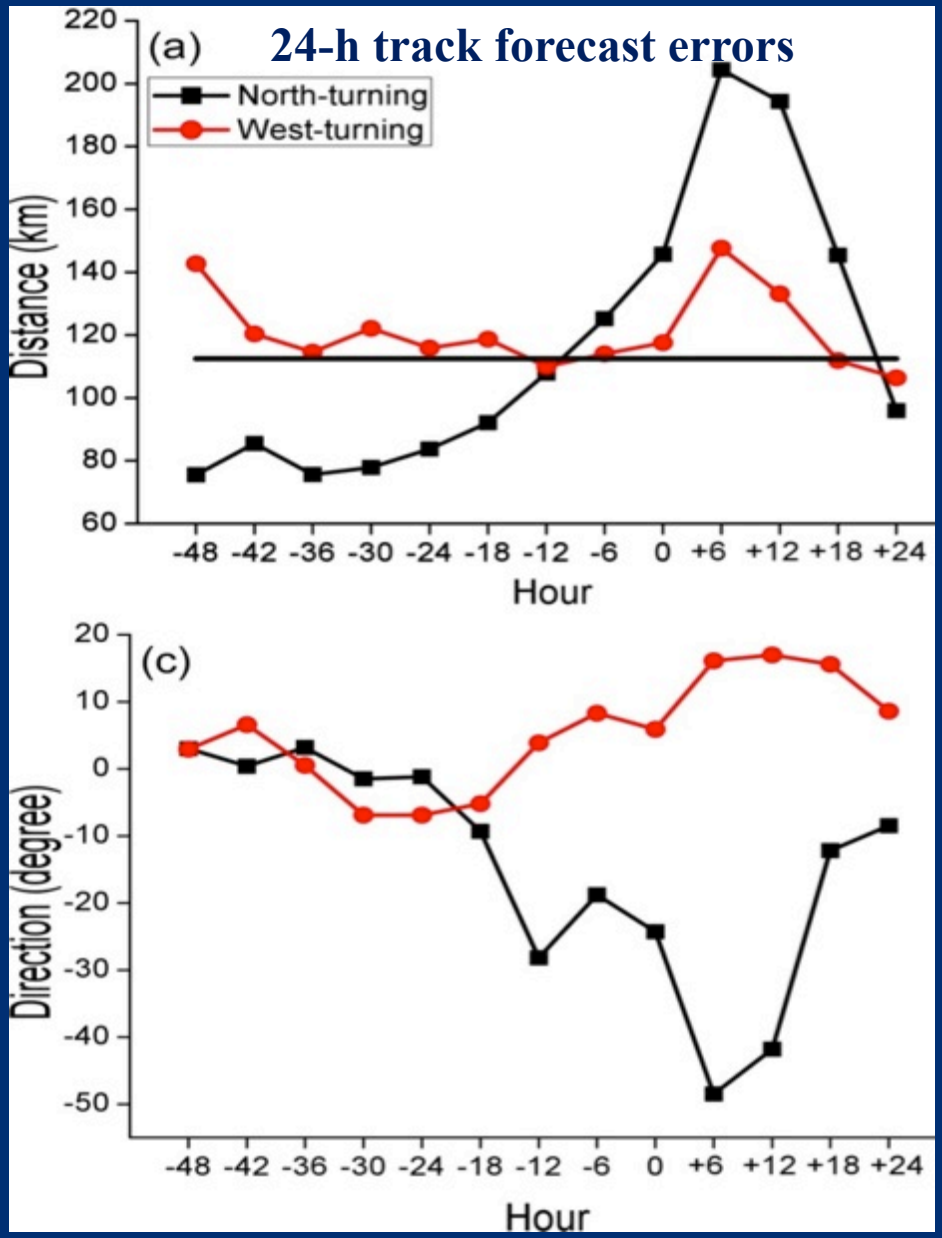




Sudden track changes



Huge track forecast errors



110 km

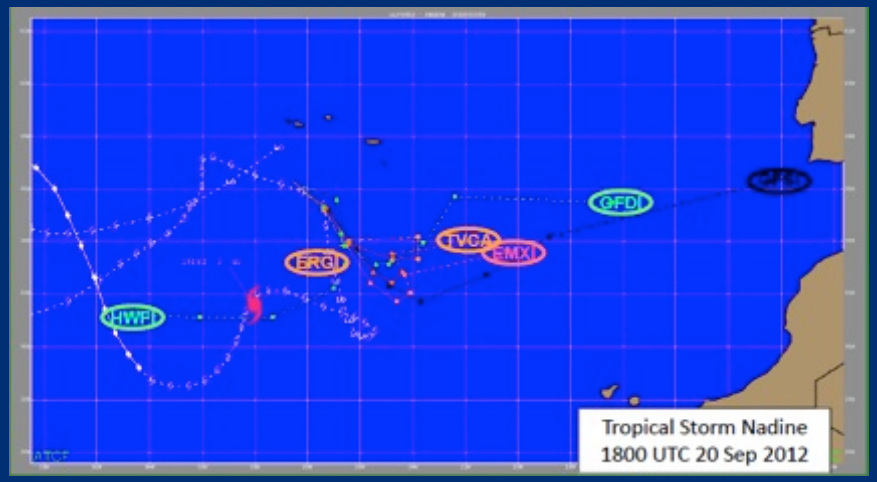
Considerations of subjective track forecasts

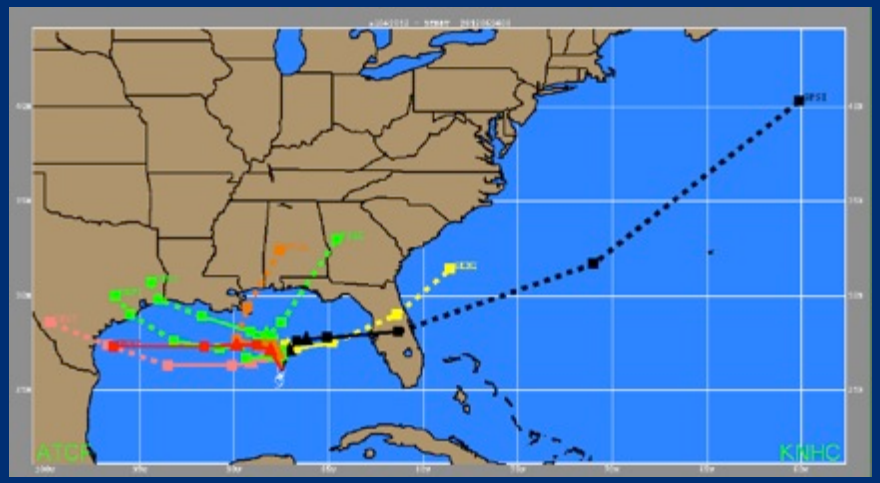
- **Previous forecast exerts a strong constraint on the current forecast.**

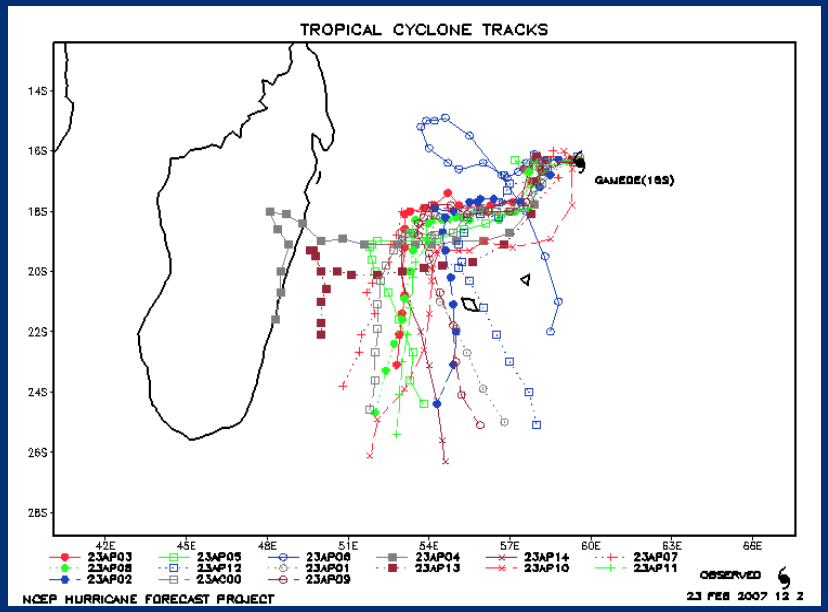
- Credibility can be damaged by making big changes for forecast to forecast, then having to go back to the original

- **Changes to track forecasts are typically made in small increments.**
- **Persistence or current motion has strong influence on the first 12 hours or so of the forecast track.**
- **Strive for continuity within a forecast; therefore, changes in direction and speed of the tropical cyclone movement from one forecast time to the next are also made gradually.**

Consensus example

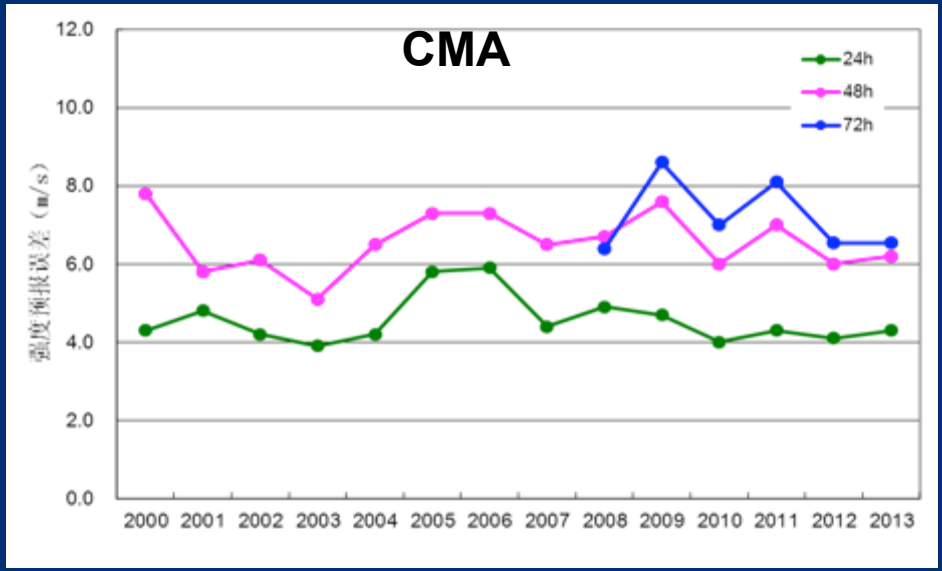




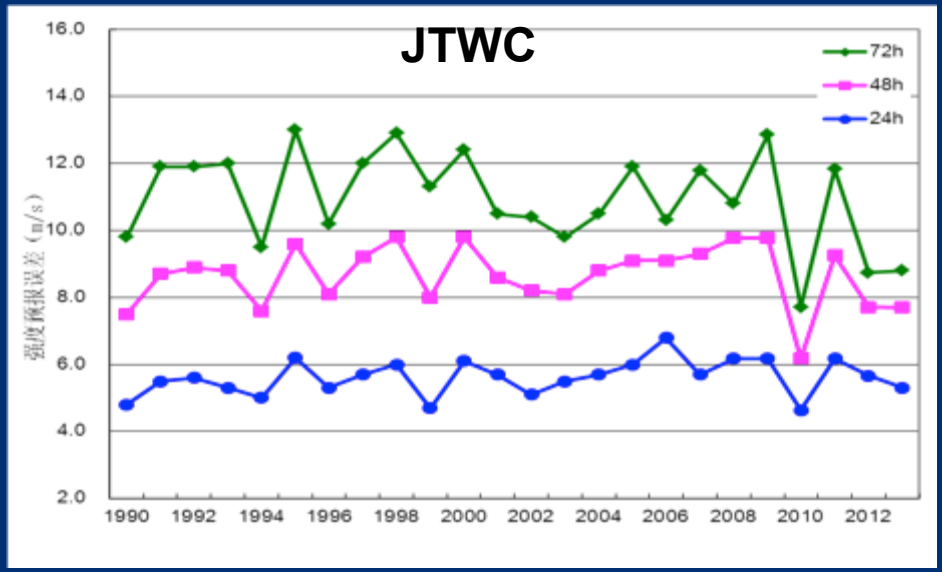


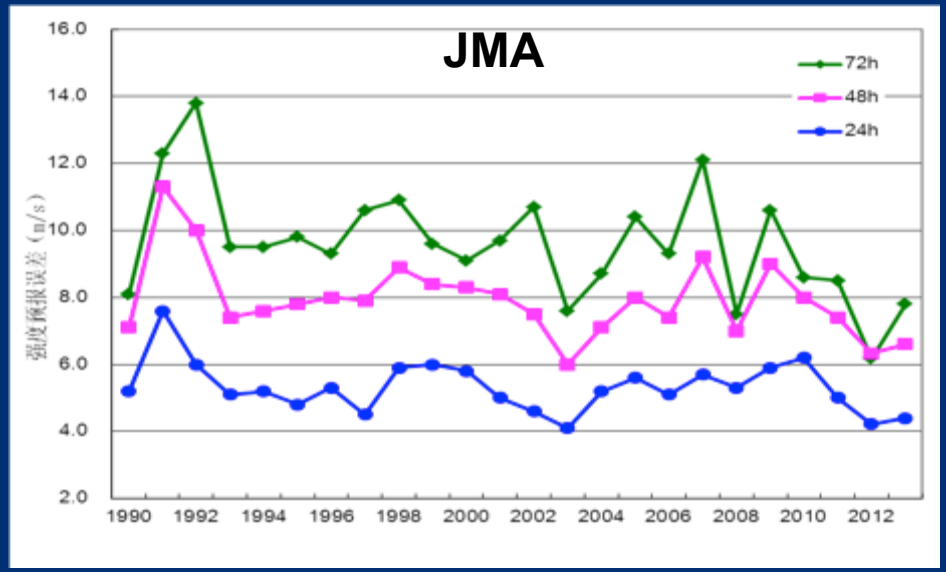
Consensus approach doesn't always work, especially when model scenarios are completely different.

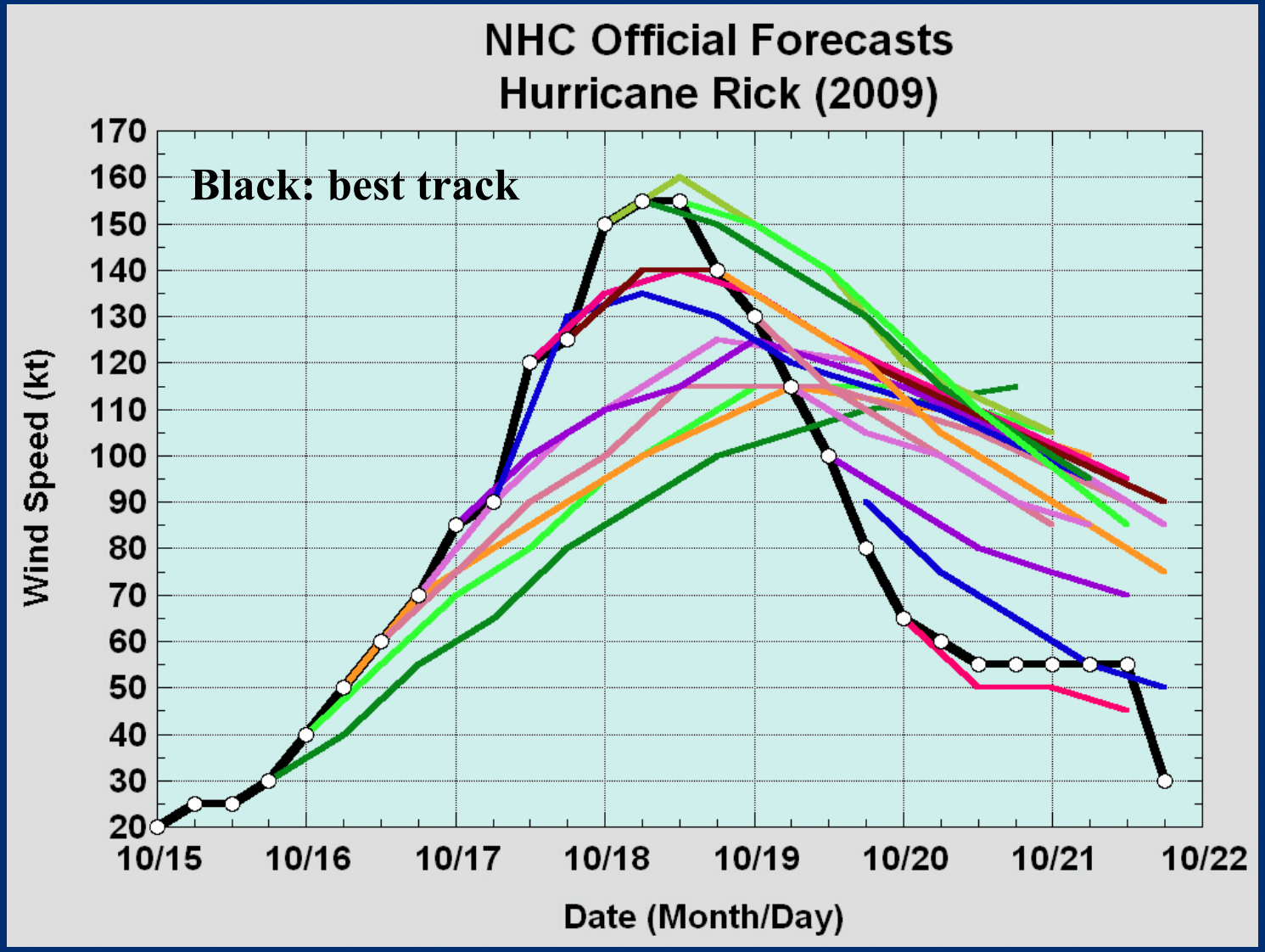
Tropical cyclone intensity forecasting



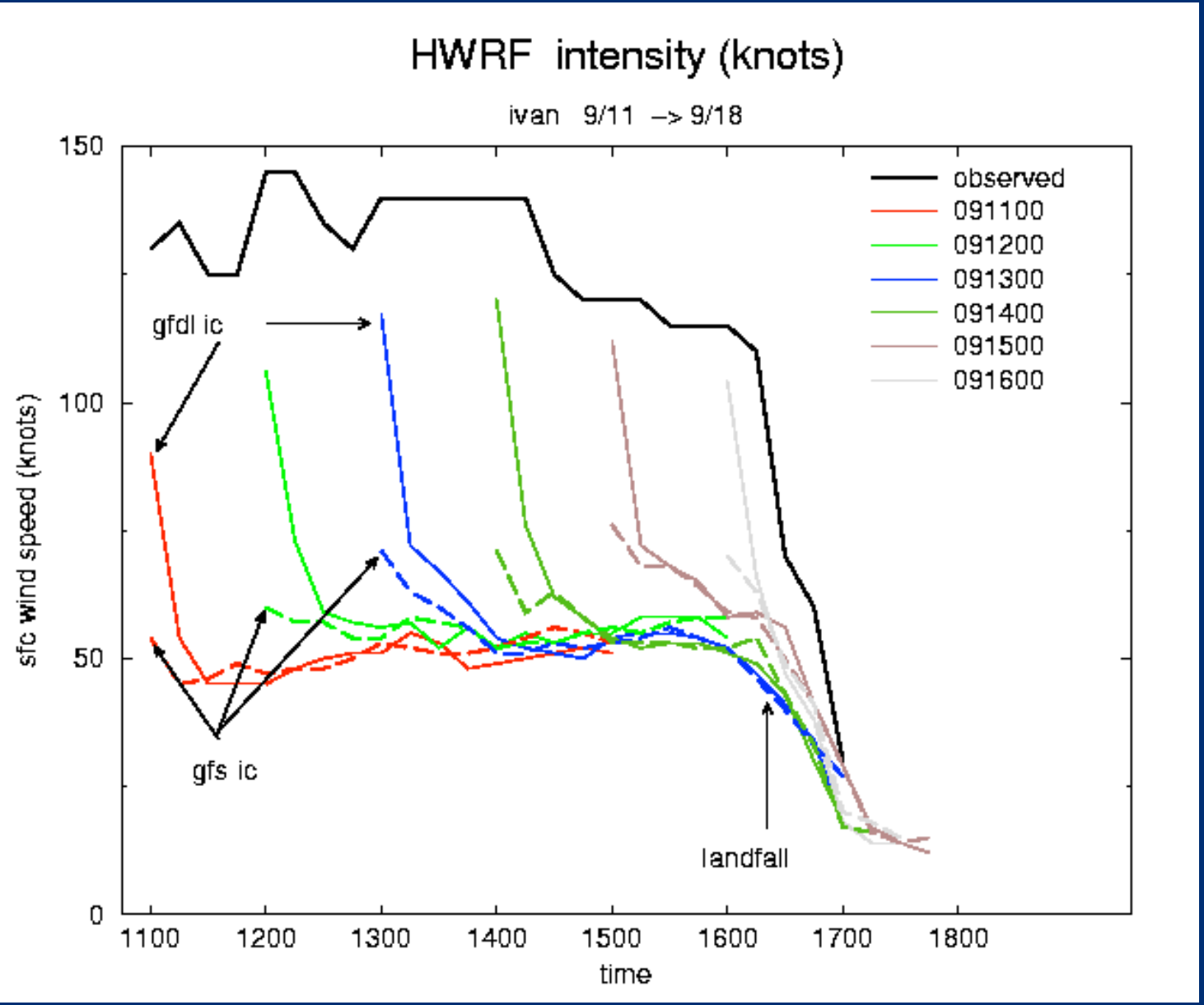
Official typhoon track intensity errors







The difficulty in predicting rapid changes in intensity



The difficulty in predicting rapid changes in intensity

- **Forecasting tropical cyclone intensity is a much more difficult problem than forecasting tracks.**
- **As a result, limited progress has been made in intensity forecasting over the past 20 years.**
- ***Dynamical* forecast models of TC intensity have never caught up with *statistical* models.**
- **The *statistical* models only tell you what *typically* occurs and have difficulty in forecasting rapid strengthening or weakening.**
- **Although the *dynamical* models can forecast rapid change in intensity, they are not reliable and have very little skill.**
- **Large improvements in intensity prediction will require increases in observations from the inner core of the storm, better computer models, and new ways to get high-density observations into the storms.**

Factors Influencing Intensity
(what we have known is still limited)

Sea surface temperature - tropical cyclones generally need deep warm water to strengthen

Vertical wind shear – tropical cyclones require low vertical wind shear (little change in wind speed or direction with height) to strengthen

Temperature and moisture patterns in the storm environment – tropical cyclones need an unstable atmosphere (decreasing temperatures with height) and a moist atmosphere for strengthening

Interaction with land – tropical cyclones that interact with land weaken

Internal structural changes – eyewall replacements typically cause fluctuations in intensity in strong tropical cyclones

Considerations of subjective intensity forecasts

- **Continuity also applies to intensity forecasting. Changes from advisory to advisory and from one forecasting time to the next within a forecast are gradual.**
- **Intensity forecasts tend to be conservative; rapid intensity changes are rarely forecast unless you have solid evidence.**
- **Modest changes in track can result in different predicted environmental factors and land interaction which can affect intensity.**

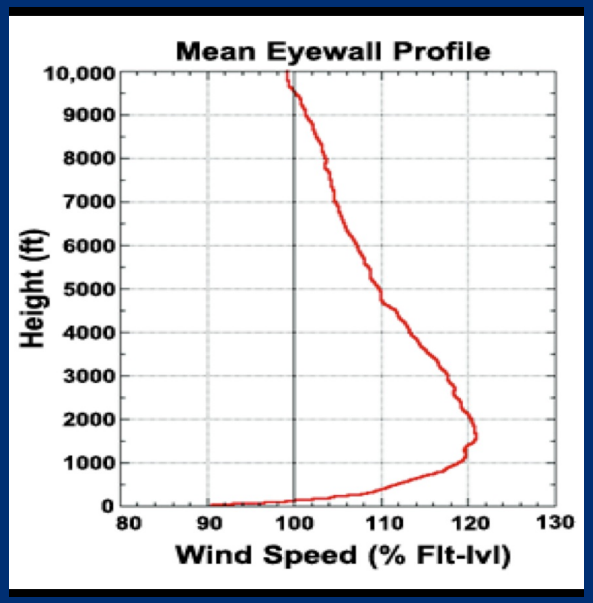
Tropical cyclone wind forecasting (very little guidance available)

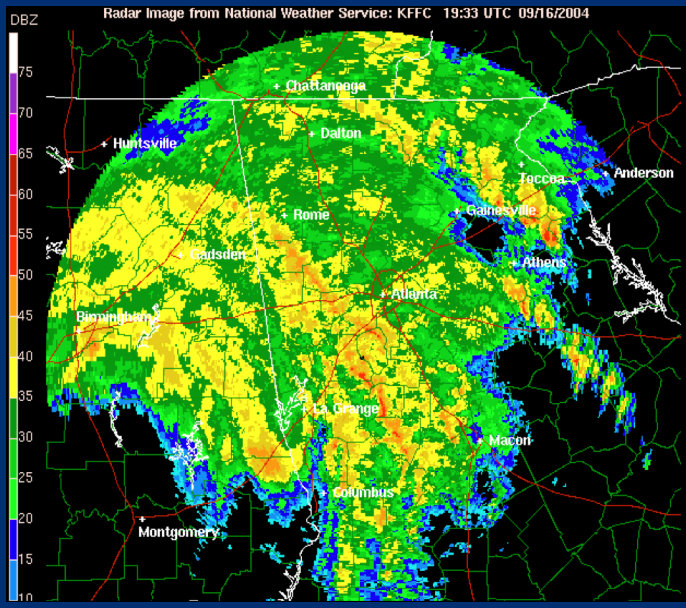
Factors that determine the inland wind threat

- Tropical cyclone intensity at landfall and the rate of weakening
- Forward speed of motion
- Size of the wind field
- Low-level stability
- Interaction with other meteorological phenomena

How do tropical cyclone winds change?

- Wind speeds aloft are typically higher in a tropical cyclone.
- Gusts over land are often much higher than sustained winds. Over land, a typical gust factor is 1.3. So a 30 m s^{-1} wind could have a corresponding gust of 40 m s^{-1}.
- Over complex terrain (e.g., mountains) and in the tropical cyclone eyewall, this gust factor may be higher at 1.65. So a 30 m s^{-1} wind could have a gust as high as about 50 m s^{-1}.
- Strong winds tend to occur in regions of stronger thunderstorms.
- Winds in rainbands tend to occur during the daytime when stronger winds aloft are more effectively transported to the surface.
- When tropical cyclones interact with fronts, winds and gusts can decrease on the cold side of the front.



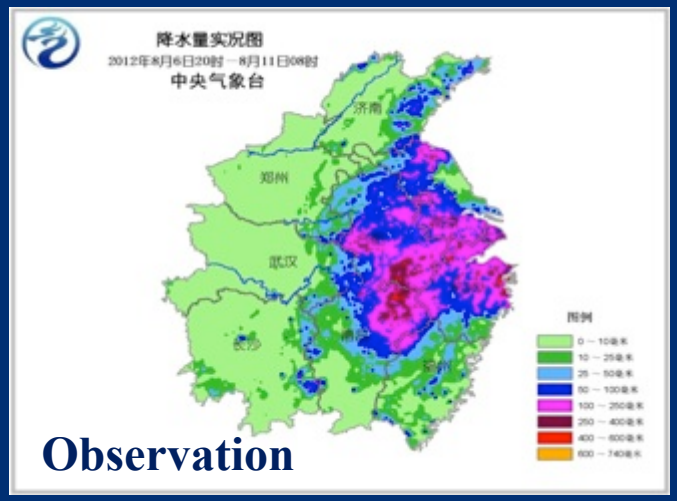


Considerations of subjective wind forecasts

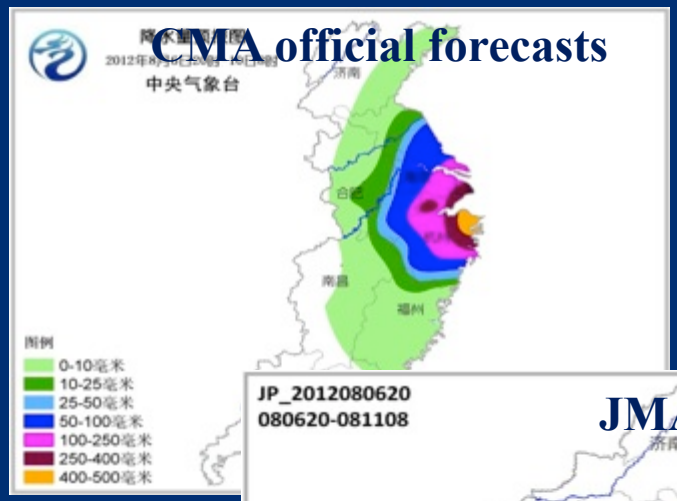
- Wind radii graphics are crude depictions of the extent of winds of various thresholds in the four cyclone quadrants.
- Wind radii specify the **maximum** extent over which winds of a certain threshold are occurring. They should not be interpreted to mean that winds of a given strength are occurring everywhere in the specified area.
- Wind radii estimates are usually less reliable over land.
- Best if used as a **rough guide** to estimate the arrival of wind fields of various thresholds.
- Using wind radii to gauge arrival and end times of the winds at various thresholds should be done with caution, since there are substantial errors with the estimates of theses radii.

Tropical cyclone rainfall forecasting (again, very little guidance available)

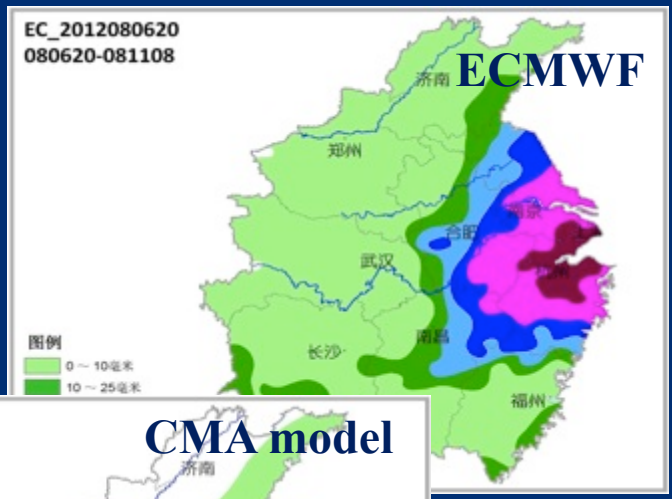
Typhoon Haikui (2012)



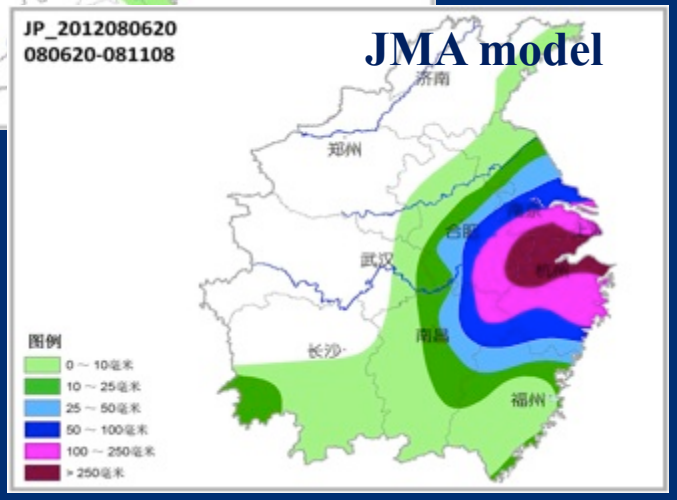
Observation



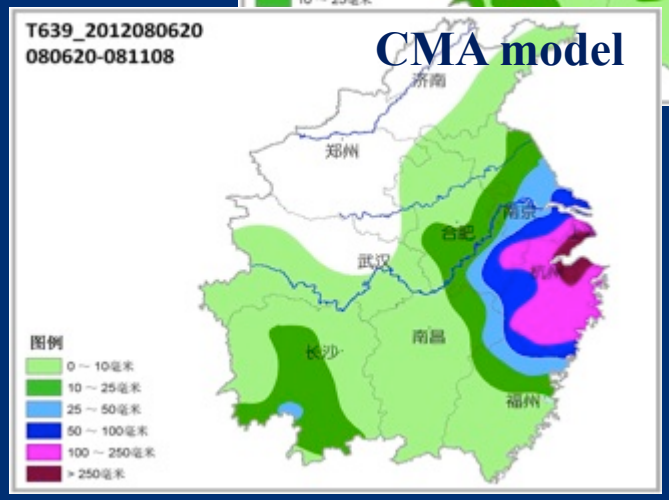
CMA official forecasts



ECMWF



JMA model



CMA model

What factors govern how much rain falls?

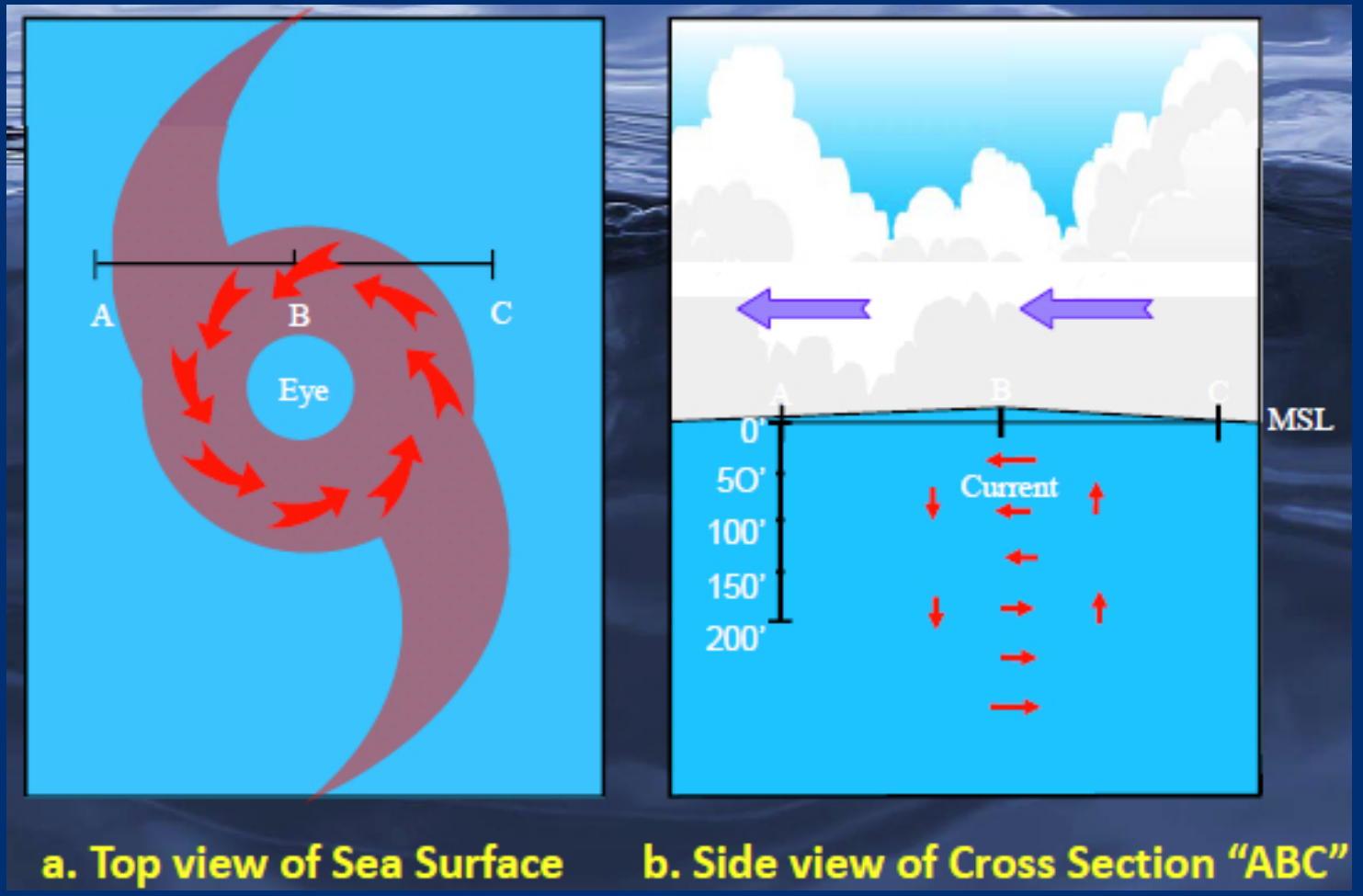
- Bigger tropical cyclones tend to produce more rainfall.
- Slower tropical cyclones can produce substantially more rainfall.
- A more unstable atmosphere will enhance the overall rain rate.
- More rainfall generally occurs on the downshear left side.
- More rain falls on the windward side of elevated terrain, with less rain on the leeward side.
- The proximity of a tropical cyclone to frontal boundaries or upper-level troughs tends to enhance the rainfall potential.

Storm surge forecasting

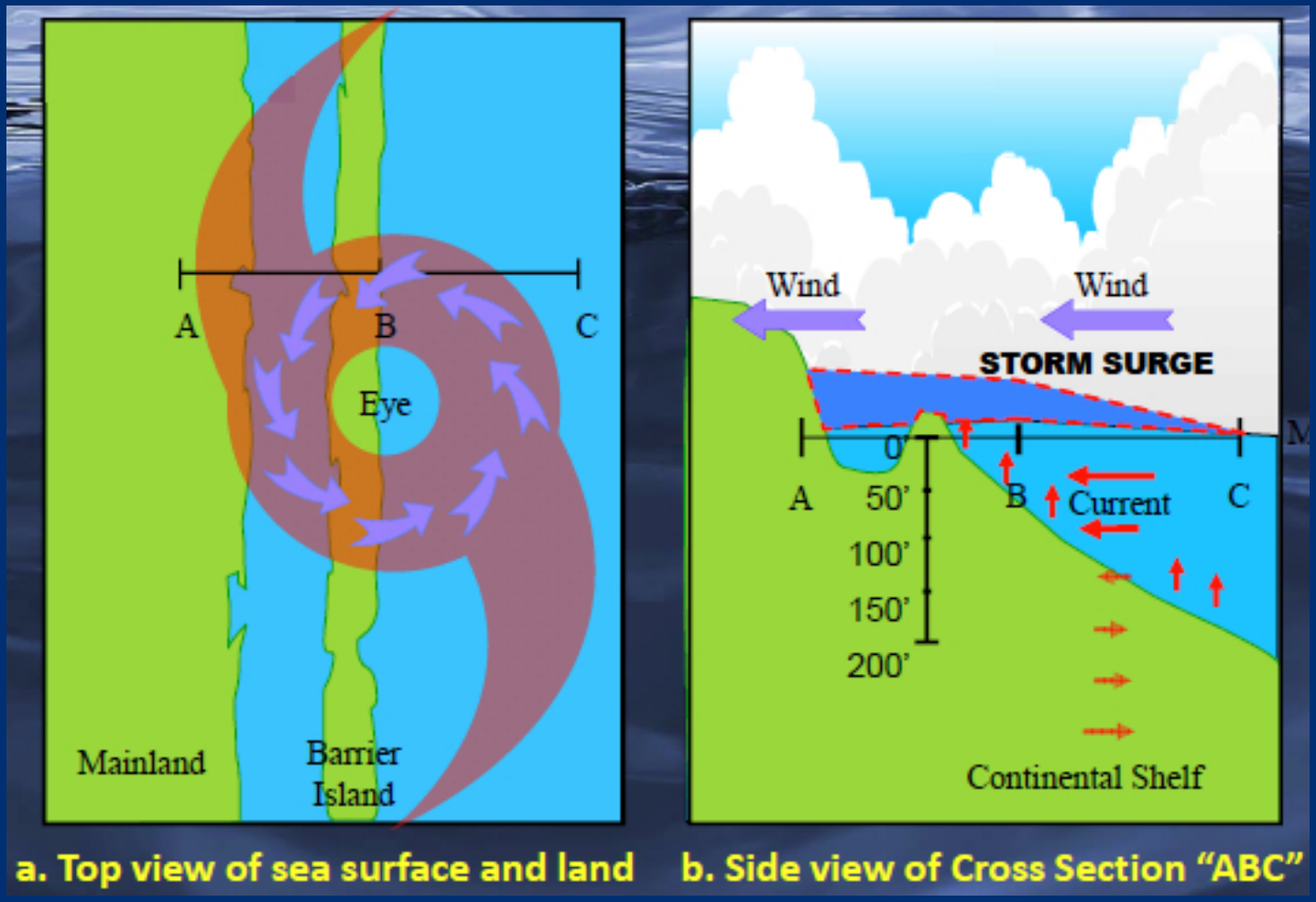
Hurricane Sandy (2012)

Hurricane Ike (2008)

Deep water

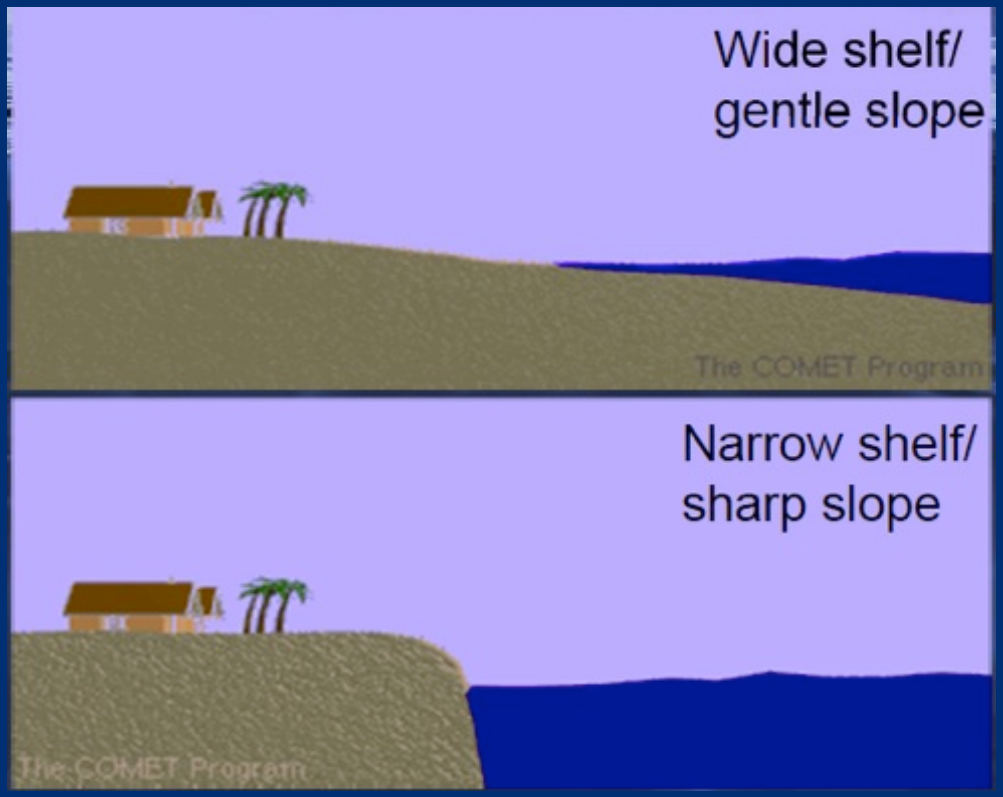

A
B
C
Eye
A
B
C
MSL
0'
5O'
100'
150'
200'
Current
a. Top view of Sea Surface
b. Side view of Cross Section "ABC"

Landfall


A
B
C
Eye
Mainland
Barrier Island
a. Top view of sea surface and land
Wind
Wind
STORM SURGE
0'
A
50'
100'
150'
200'
B
Current
C
Continental Shelf
b. Side view of Cross Section "ABC"

Factors affecting storm surge

- Central pressure
- Intensity (wind speed)
- Forward speed
- Size
- Angle of approach
- Width and slope of shelf



- Local features – concavity of coastlines, bays, rivers, headlands, or islands

Modeling surge

- ***Statistical***

  - Utilize historical data to develop statistical relationships

  - Necessary data is non-existent

- ***Deterministic Numerical Models***

  - Forecast surge based on solving physical equations

  - Strongly dependent on accurate meteorological input

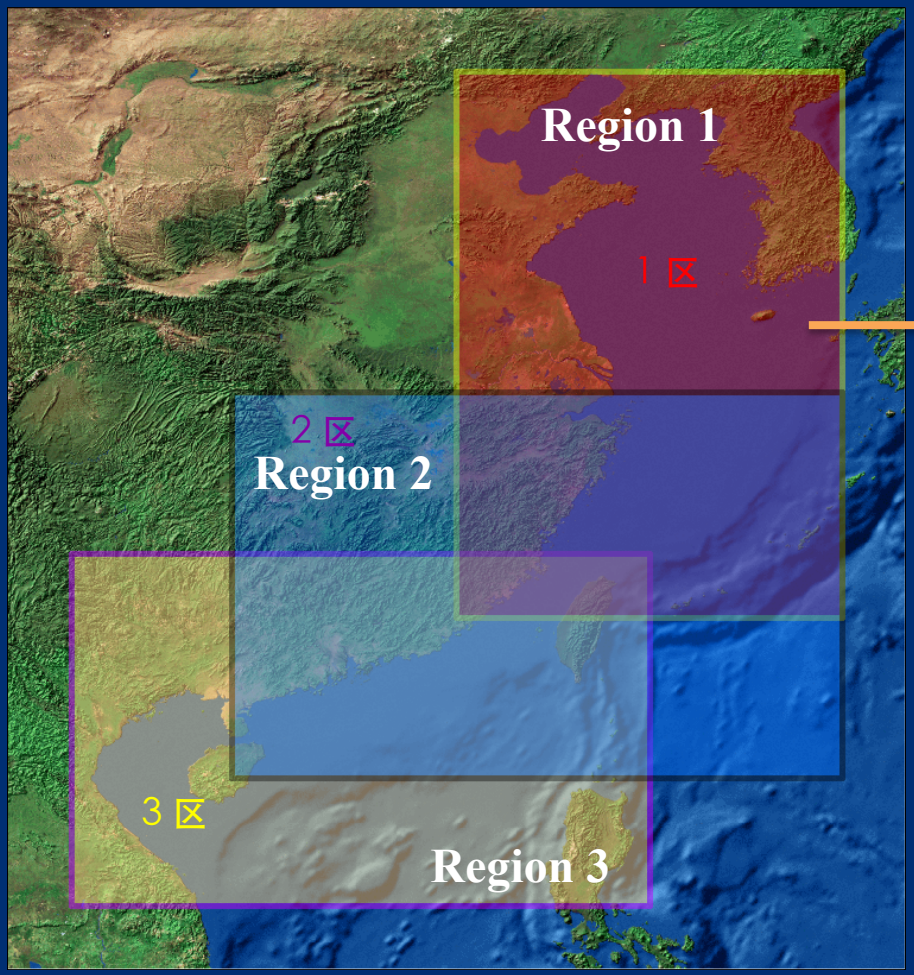
  - Current uncertainties in tropical cyclone forecasts render such methods inaccurate

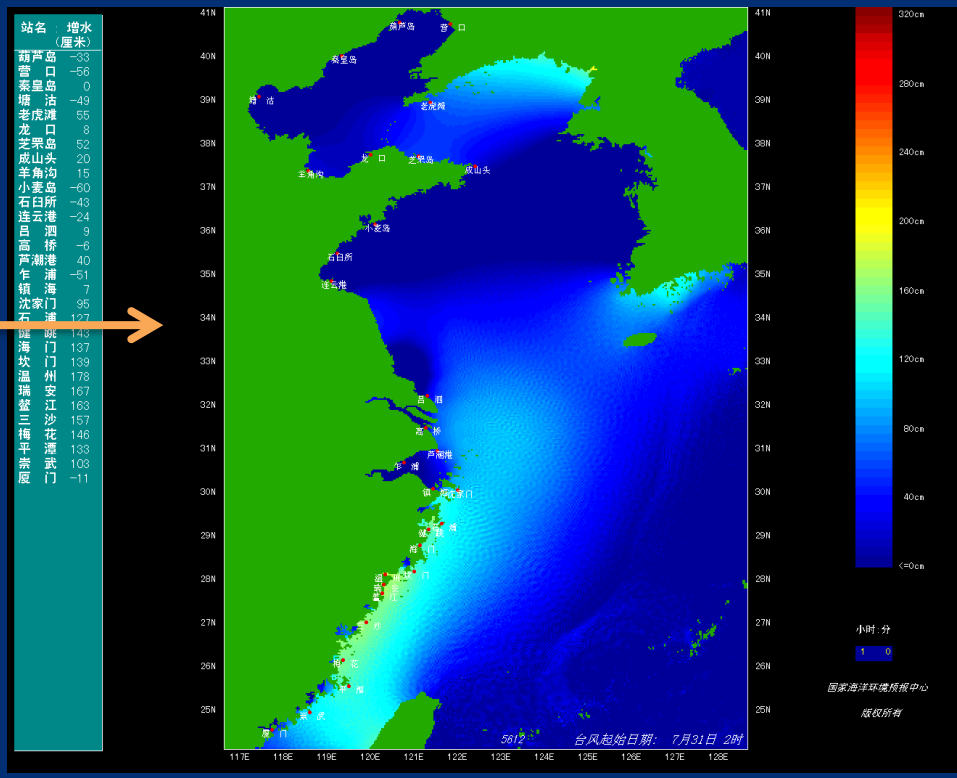
- ***Numerical Model Ensemble***

  - Many different runs of the same model but with different conditions (family of storms)

  - Best approach for determining storm surge vulnerability for an area since it takes into account forecast uncertainty

Storm surge model of the National Marine Environmental Forecasting Center





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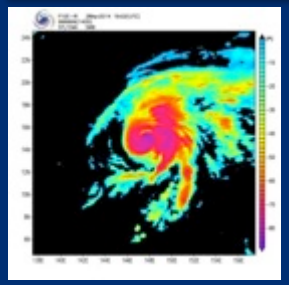
Workflow of chief typhoon forecasters in the National Meteorological Center (NMC) of CMA

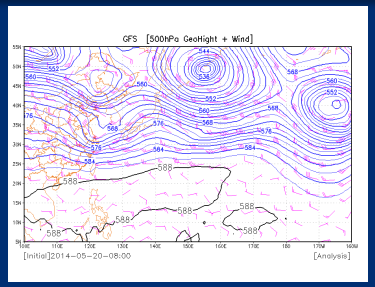
Day shift (Beijing time)

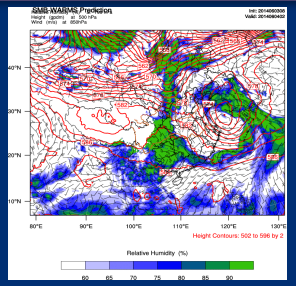
04:00 – 04:15 View hand-over notes

04:15 – 05:00 Synoptic and numerical guidance analysis

Wind and precipitation observation and disaster analysis







05:00 – 06:00

If a typhoon is forecast to strike the coasts of China, issue tropical depression and typhoon forecast products, and assist in issuing Typhoon Blue, Yellow, Orange, or Red Warnings at 6:00.

06:00 – 08:00

Preparations for the video conference

08:00 – 08:30

Video conference between the NMC and local forecast centers

08:40 – 09:20

Produce morning decision and service advisory

台风服务材料

2011 年第 1 期

2011 年 5 月 7 日下午

在菲律宾以东近海活动的热带低压已于5月7日14时发展为今年第1号热带风暴“艾利”（Aere，名字来源：美国，名字意义：风暴）。7日14时其中心位于菲律宾马尼拉东偏南方大约565公里的海面上，就是北纬13.1度、东经126.0度，中心附近最大风力有8级（18米/秒），中心最低气压为998百帕。

预计，未来两天“艾利”将以每小时 15 公里左右的速度向西北或西偏北方向移动，强度还将有所增强，主要影响菲律宾群

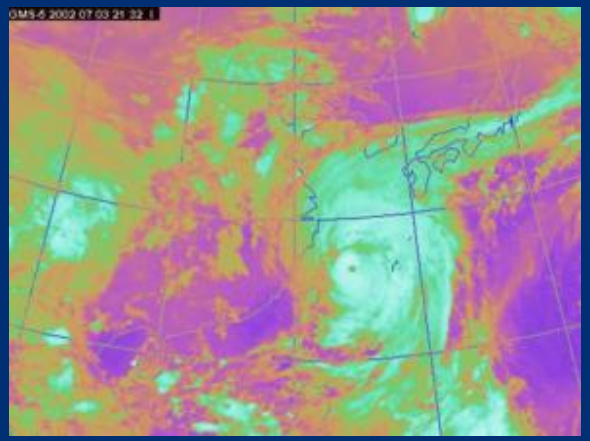
09:20 – 09:50

If a typhoon is forecast to strike the coasts of China, issue tropical depression and typhoon forecast products, and assist in issuing Typhoon Blue, Yellow, Orange, or Red Warnings at 10:00.

10:00 – 11:30

Typhoon monitoring and media interviews

14:00 – 14:20	The transaction of temporal work
14:20 – 14:40	Produce afternoon decision and service advisory
14:40 – 16:20	Preparations for the video conference (if needed)
16:30 – 17:00	Synoptic and numerical guidance analysis
	Wind and precipitation observation and disaster analysis



17:00 – 17:50	If a typhoon is forecast to strike the coasts of China, issue tropical depression and typhoon forecast products, and assist in issuing Typhoon Blue, Yellow, Orange, or Red Warnings at 18:00.
18:00 – 18:10	Hand-over notes
	Another chief typhoon forecaster goes on the night shift at 18:15.
19:00 – 20:00	Synoptic and numerical guidance analysis
	Wind and precipitation observation and disaster analysis

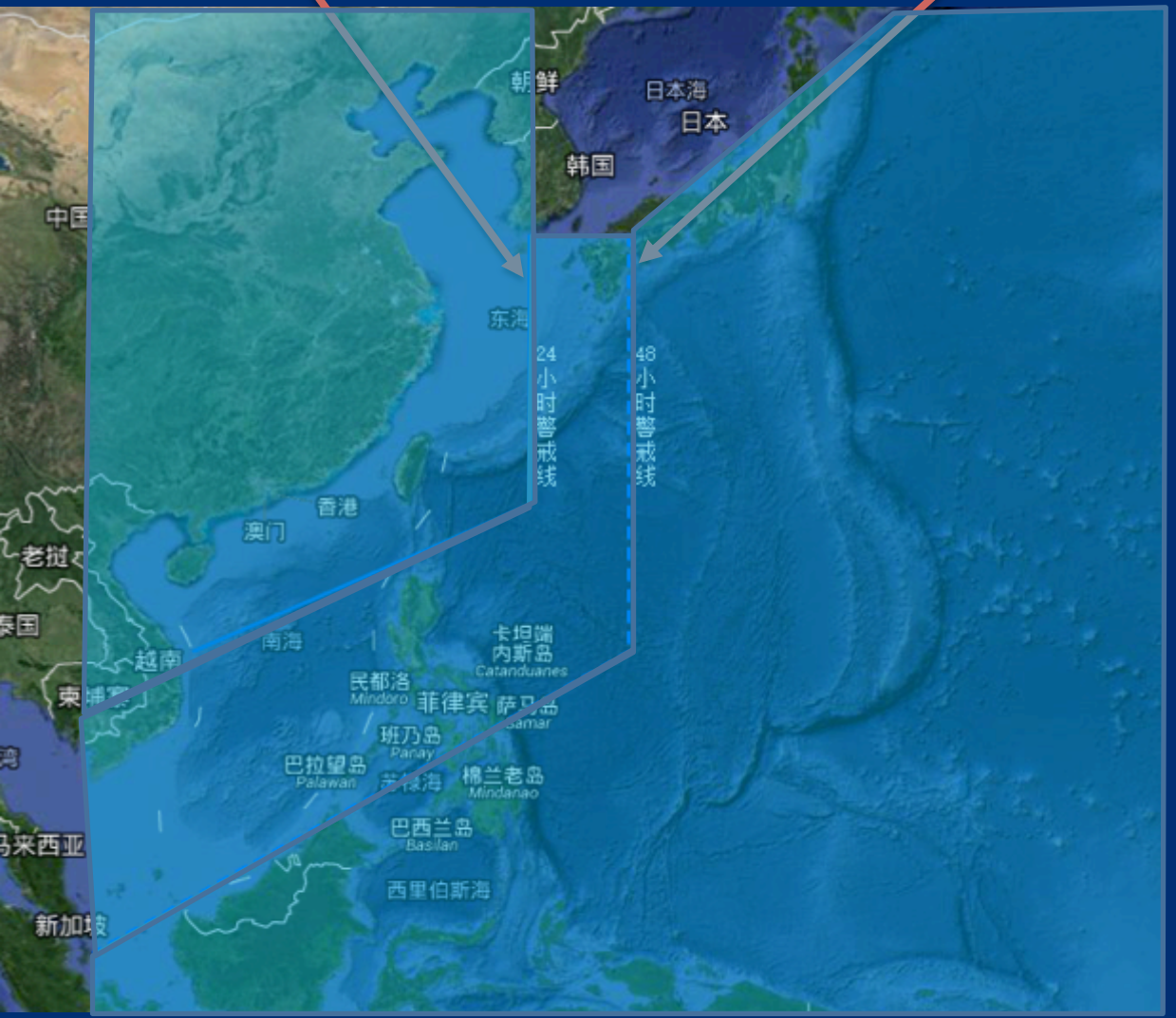
20:00 – 22:30	Preparations for the video conference (if needed)
	Media interviews (if needed)
22:45 – 23:00	Hand-over notes

Heavy workload and a lot of pressure!

Typhoon warning lines

24-h typhoon warning line

48-h typhoon warning line



Determine the typhoon position and intensity every hour, and make 120-h forecasts every 3 hours.

20:00.

Typhoon warning signals

A typhoon will have effect within 24 hours or has had effect; averaged wind speed greater than 10.8 m s^{-1} or gusts greater than 17.2 m s^{-1} will stay.

A typhoon will have effect within 24 hours or has had effect; averaged wind speed greater than 17.2 m s^{-1} or gusts greater than 24.5 m s^{-1} will stay.

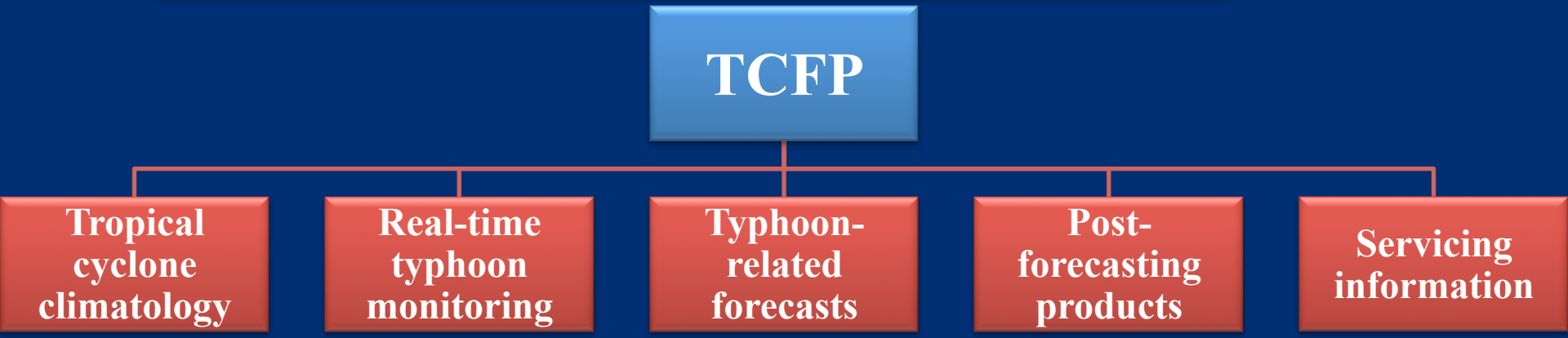
A typhoon will have effect within 12 hours or has had effect; averaged wind speed greater than 24.5 m s^{-1} or gusts greater than 32.7 m s^{-1} will stay.

A typhoon will have effect within 6 hours or has had effect; averaged wind speed greater than 32.7 m s^{-1} or gusts greater than 41.5 m s^{-1} will stay.

Expert system for typhoon forecasting

The tropical cyclone forecast platform (TCFP) is a web-based platform as the leading operational tool for typhoon forecasting in the Shanghai Typhoon Institue, furnishing informative typhoon monitoring and forecast products and tools for the forecasters.

Structure and basic features of the TFP



Comprehensiveness + Practicality + Controllability → Forecasters

Real-time typhoon monitoring

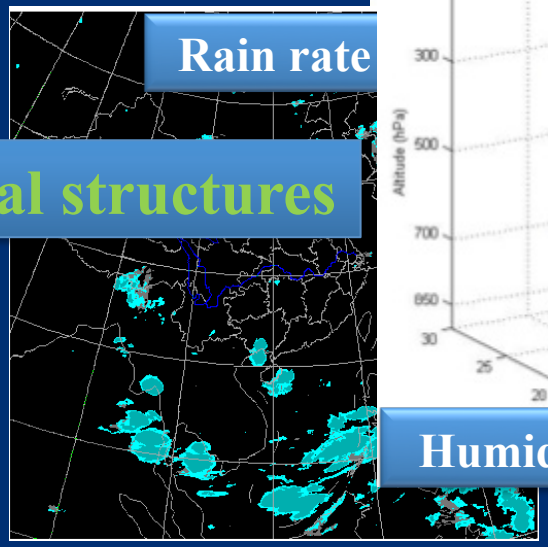
When a TC in the WNP is designated, we have

TC positions and intensities reported in differing warning centers

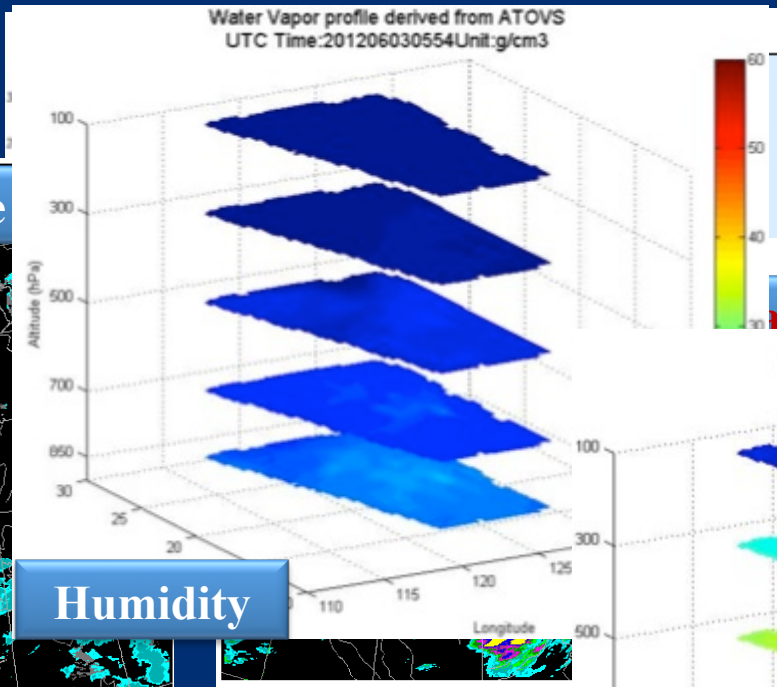
Satellite imagery

QPE

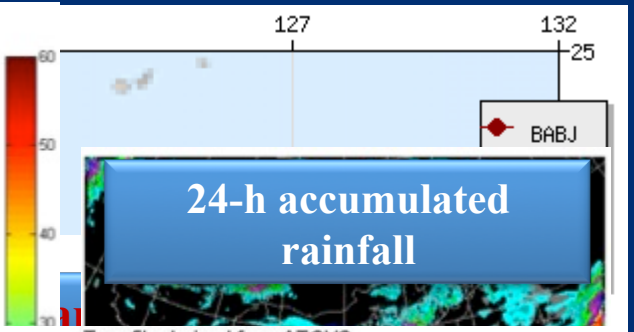
Rain rate



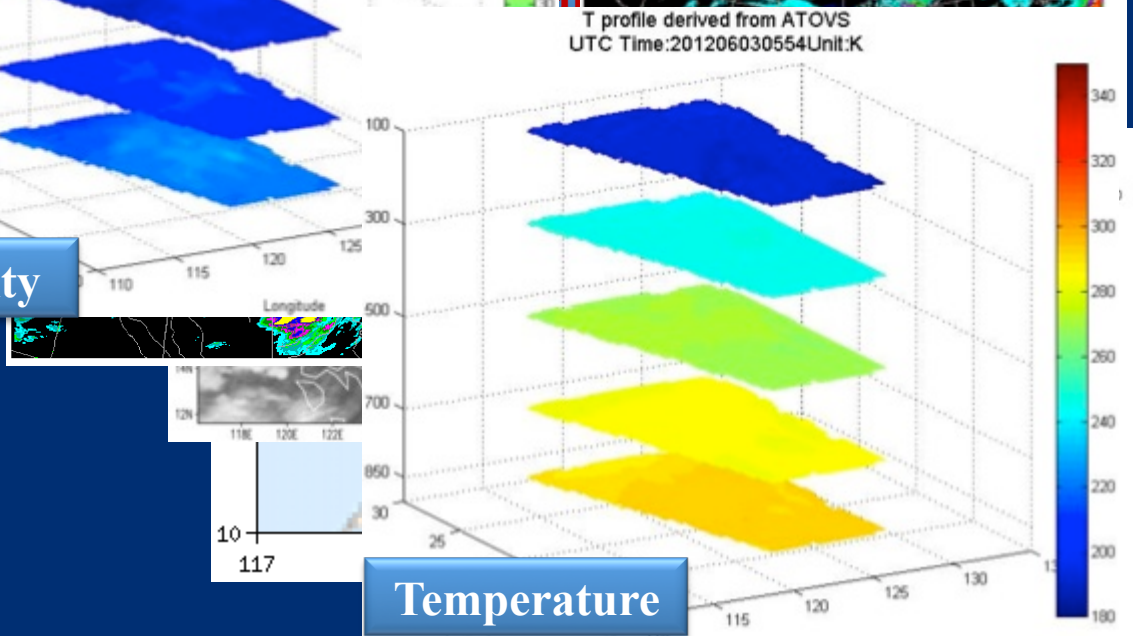
Vertical structures



Humidity



24-h accumulated rainfall



Temperature

Typhoon forecasts and products

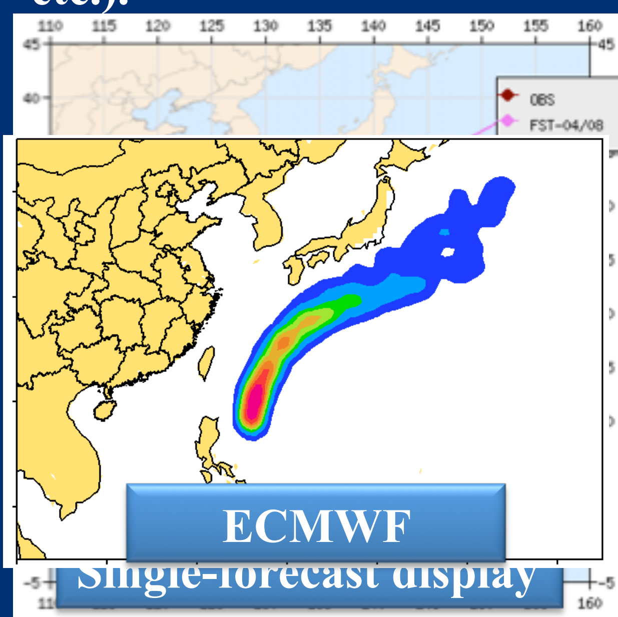
Typhoon forecasts and products (1)

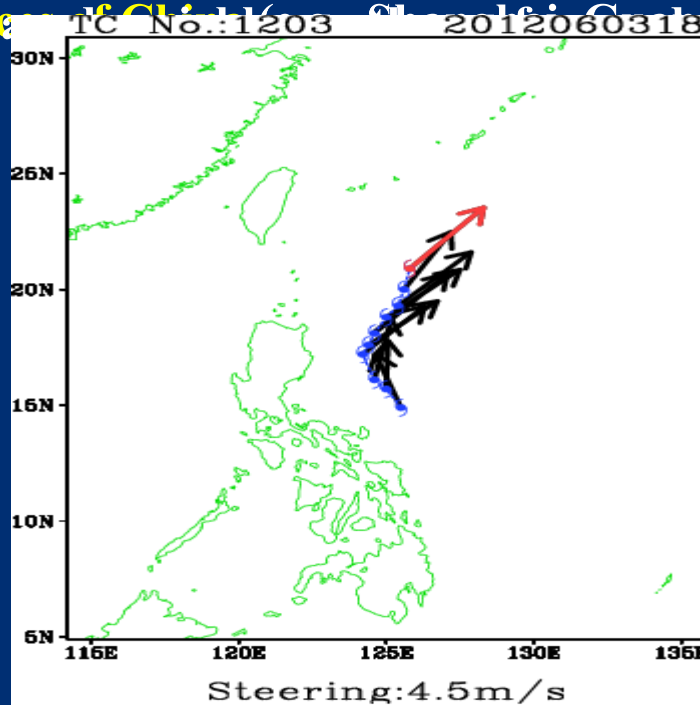
Typhoon track forecasts

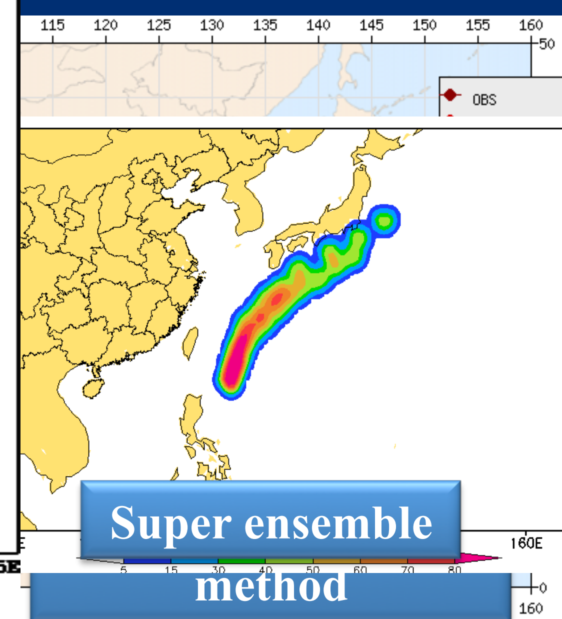
- Subjective predictions
- Dynamical forecasts
- Ensembles
- Pilot technique products
- Steering flow analysis

The subjective and dynamical predictions gather numerical track forecast results from the international TC warning centers (e.g., CMA, ECMWF, NCEP, JMA, JTWC, KMA, etc.) and the regional meteorological services of China (e.g., Shanghai, Guangdong, Fujian, HKO, etc.).

The TC track ensemble forecasts collect results of numerical ensemble prediction systems of … representative levels.

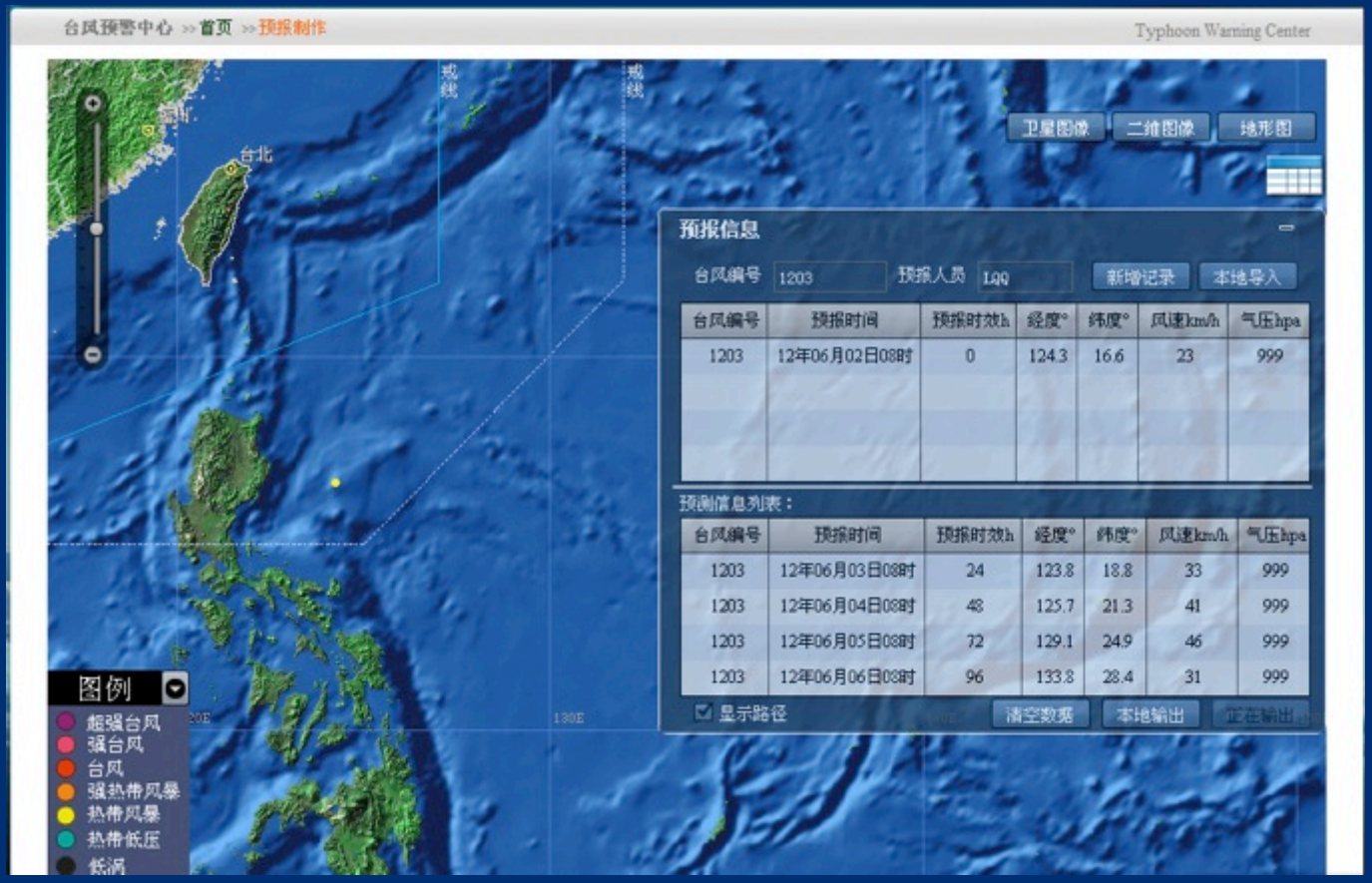






Typhoon forecasts and products (2)

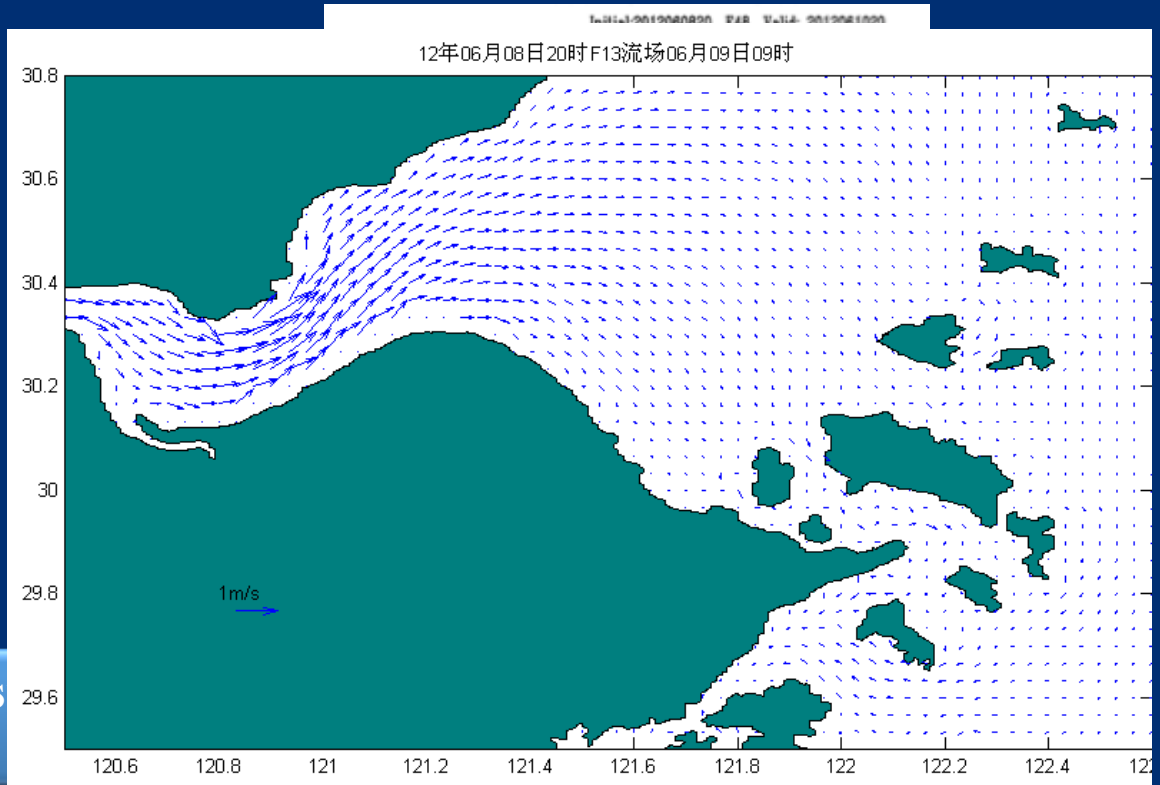
A latest **interactive** system/submodule of typhoon track and intensity forecasting based on the **Geographic Information System** is developed and provided for the forecasters. Forecasters can interactively record and graphically view their forecasts as well as forecast error statistics.



Typhoon forecasts and products (3)

Wave and storm surge forecasts

- **Wave forecasts**
- **Water level increment forecasts**
- **Sea surface current forecasts**



Sea s
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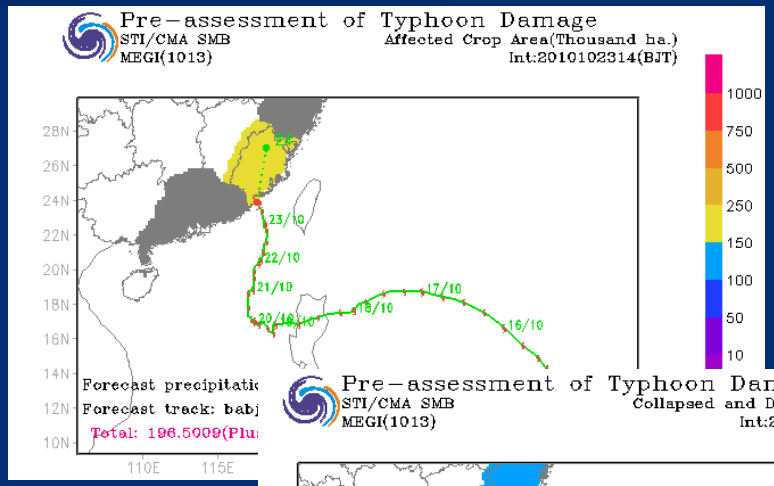
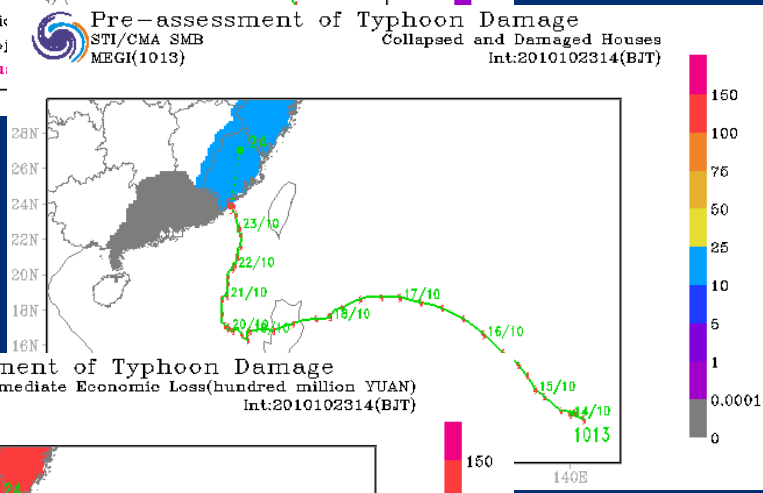
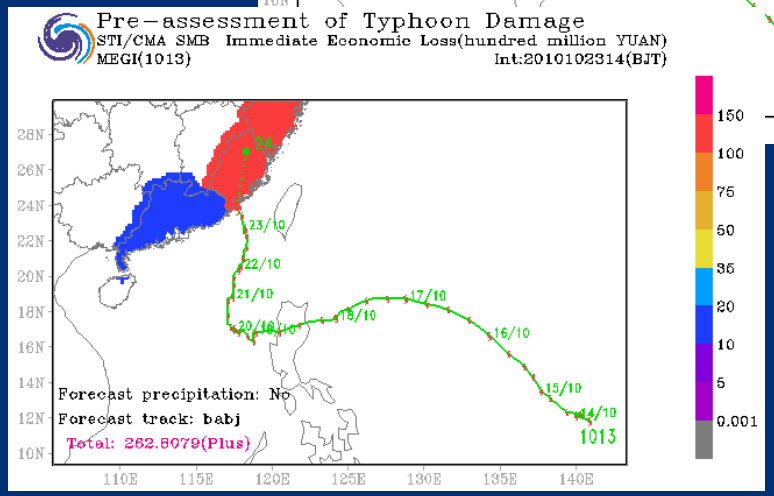
Typhoon forecasts and products (4)

TC-induced disaster pre-estimates

- Areas of stricken crops
- Numbers of collapsed and damaged houses
- Immediate economic losses
- Disaster ranks
- …







Thank you very much !

Email: liqq@mail.typhoon.gov.cn