Extreme wave observations in Deep Ocean

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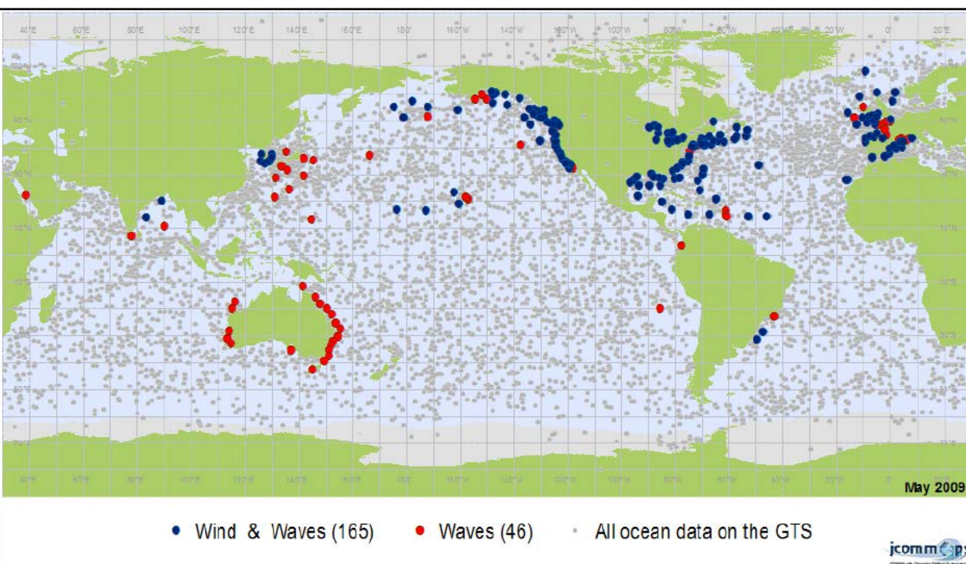
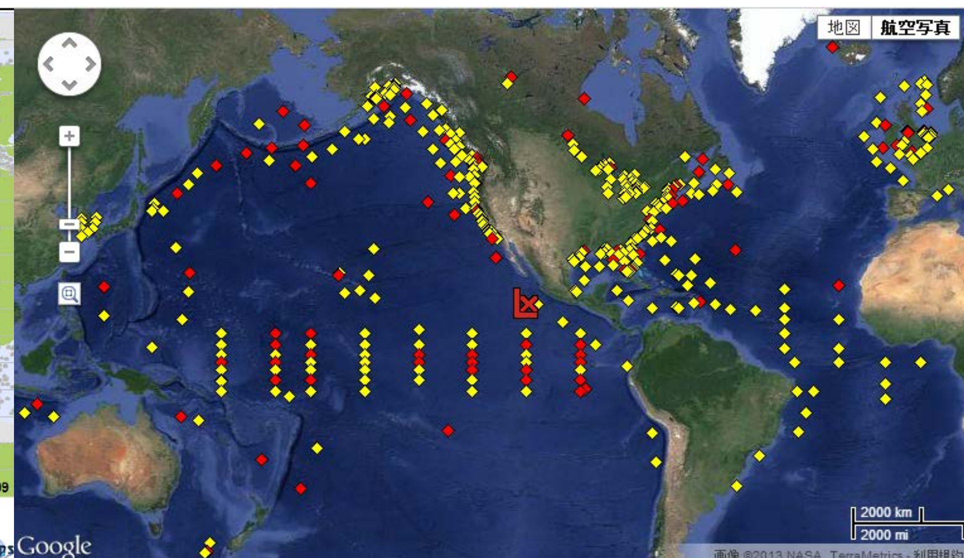
Brief description of motivation for study/application

- Extreme wave events occur in deep ocean but existing wave buoy networks are mostly confined to oceans in the vicinity of coast
- There are numerous moored buoys (DART, TAO/TRITON, NDBC-met buoys, etc.) and drifters (ARGO, etc.) without wave sensors that can be utilized to measure waves in the future
- Sensing buoy motion to detect mean wave properties seems feasible, but how about detecting extreme waves?



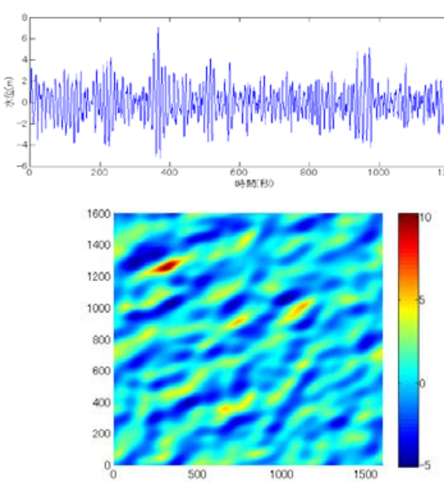
Swail et al. 2009

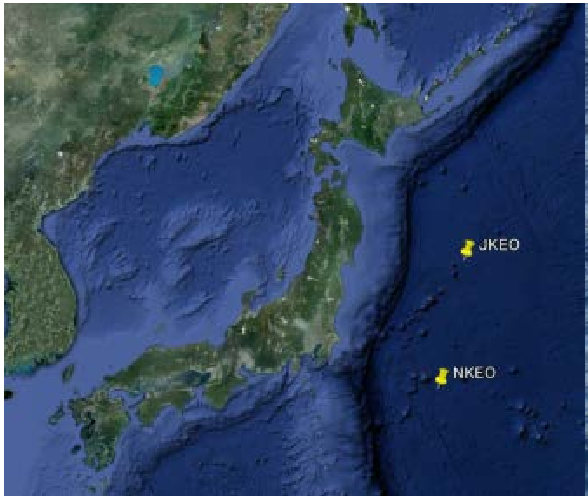


http://www.ndbc.noaa.gov/

Brief description of the methodology used in the study/application

- Attach a GPS wave sensor to an existing Met-Ocean moored buoy
  - K-TRITON buoys at JAMSTEC JKEO and NKEO stations
  - Validate wave observation with drifting wave buoy and 3G wave hind-cast simulations
- Estimate basic statistical properties of observed waves
- Case study of large amplitude waves – Horizontal motion
  - Freak waves over 10m (two events of 12 and 13 m wave height)
  - Extreme but not freak waves (three events around 20 m wave height)
- *Monte-Carlo simulation using High-Order Spectral Method*



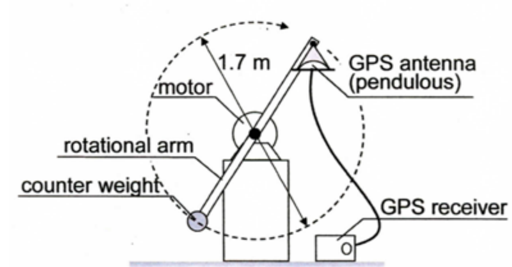


Summary of conclusions

- Wave was successfully observed attaching a point-positioning GPS sensor to existing deep ocean met-ocean mooring buoys in 2009 (3 months) and 2012-2013 (3 months and 9 months)
- Statistical properties of observed buoy motion after appropriate filtering conform with the classical description of ocean waves
- Extreme waves including freak waves were successfully observed demonstrating the feasibility of GPS sensor without reference point
- Horizontal movement of the buoy indicate orbital motion close to group velocity for some large waves

Principle of GPS wave sensing

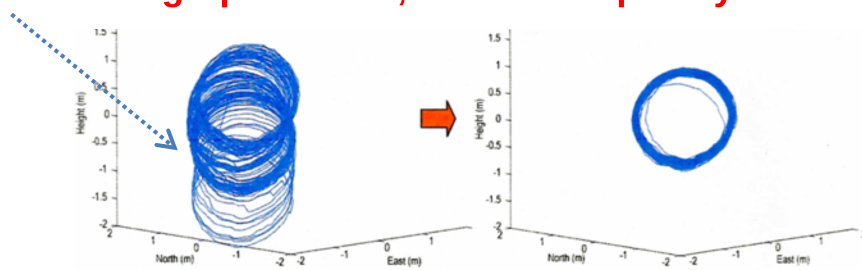
- Wave sensing with point-positioning GPS (JAXA: Yamaguchi et al, 2005)
  - High-pass filter: distinct frequency bands of wave and GPS noise spectrum (Harigae et al. 2005)
  - Noise due to change in number of satellites
  - Orbital motion simulator
  - Ocean testing off Shikoku Island



Orbital motion simulator

Error source	Range(1σ)	時定数
ephemeris	~3m	~1hr
Satellite clock	~3m	~5min
ionosphere	~9m	~10min
troposphere	~2m	~10min
multipath	~3m	~100sec
GPS receiver	~1m	white noise

High-pass filter; cut low frequency noise



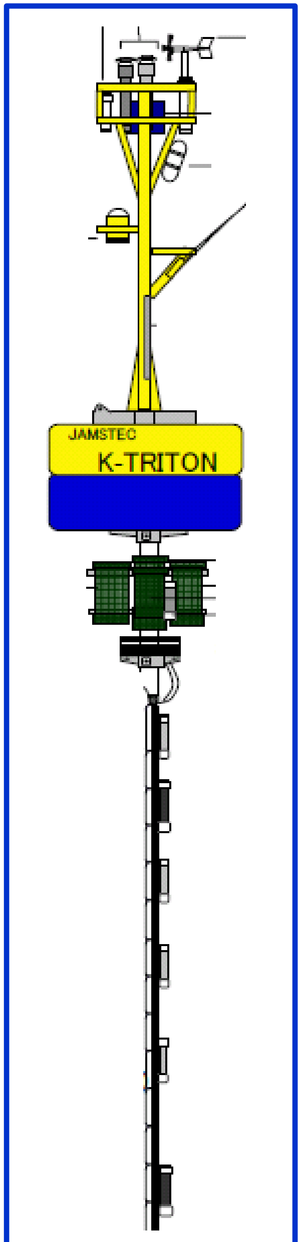
Parameter	Experiment result	True value
Wave height	167.5 cm	170 cm
Wave period	10.83 sec	11 sec
Wave direction	115.7 deg	114 deg

JAXA

Observation platforms – JAMSTEC K-TRITON Buoy

- Drifting buoy
  - Disk; reduce Roll by viscous effect (Katayama et al. 2007).
  - No.1 with wind sensor
  - No.3 & 6 improved stability

No.2
No.4

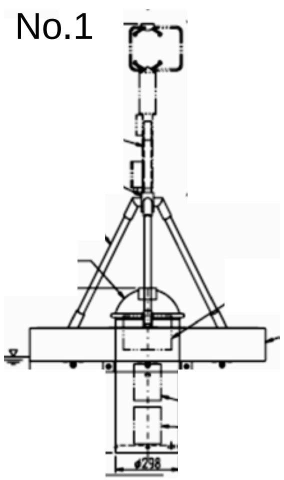


Moored buoy

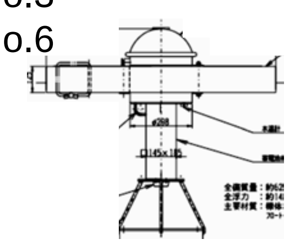
Influence of cable

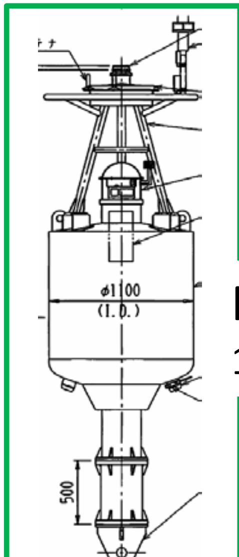
Buoy response

No.1



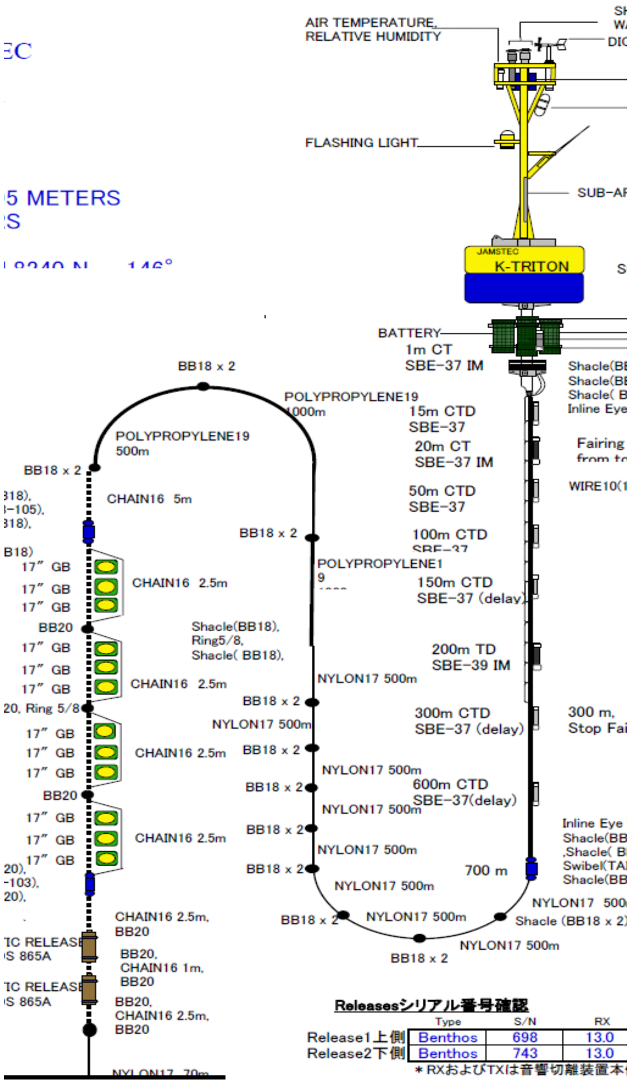
No.3
No.6





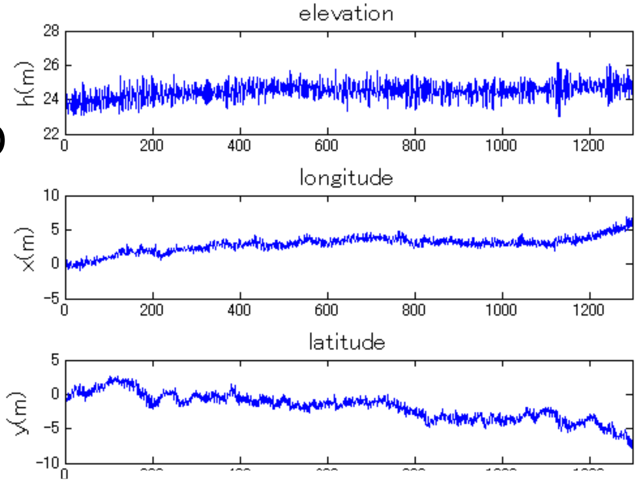
No.5

12th Wave WS

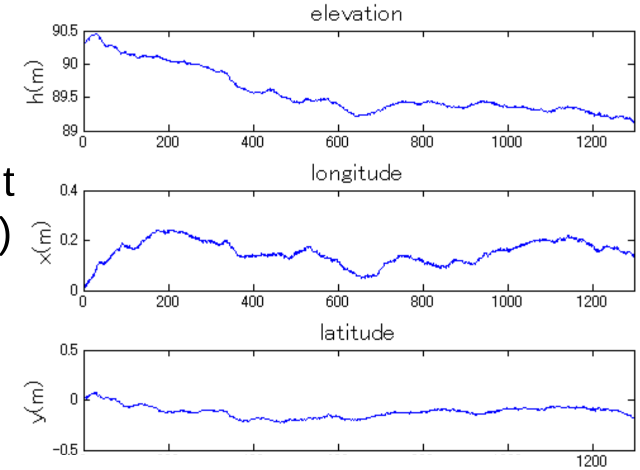


Extracting wave signal from point-positioning GPS

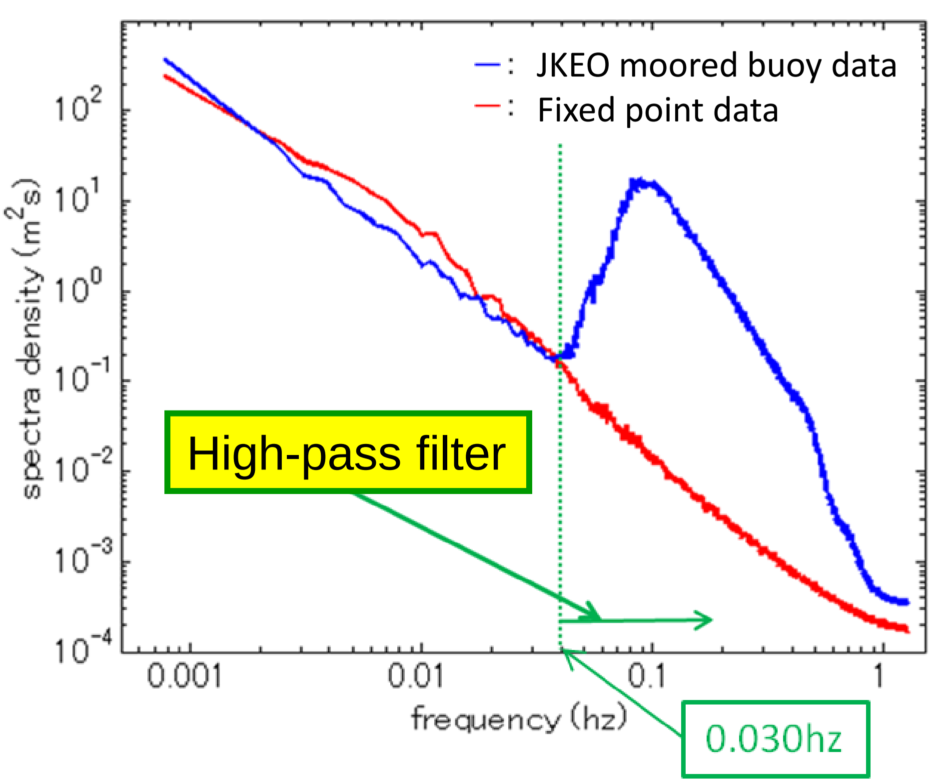
JKEO



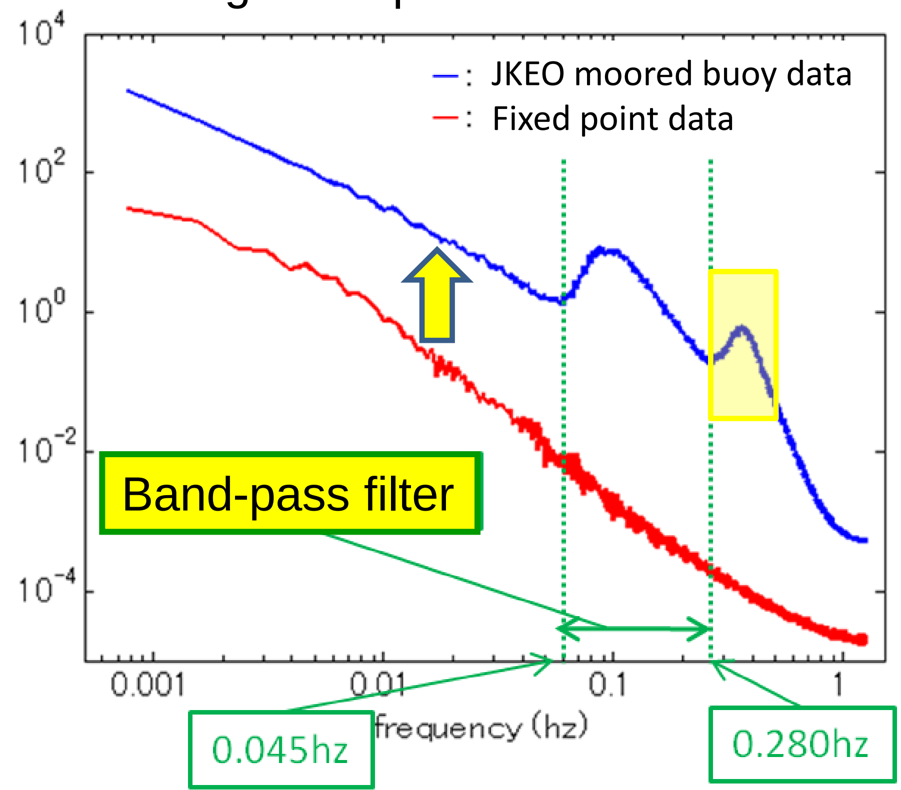
Stationary point
- Error large in height but relatively small O(10 cm) in horizontal position



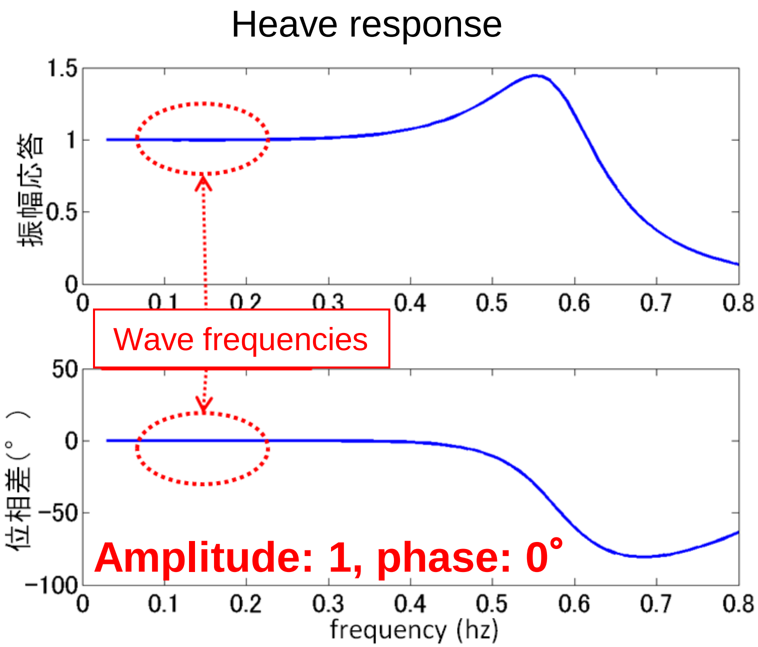
Heave spectrum

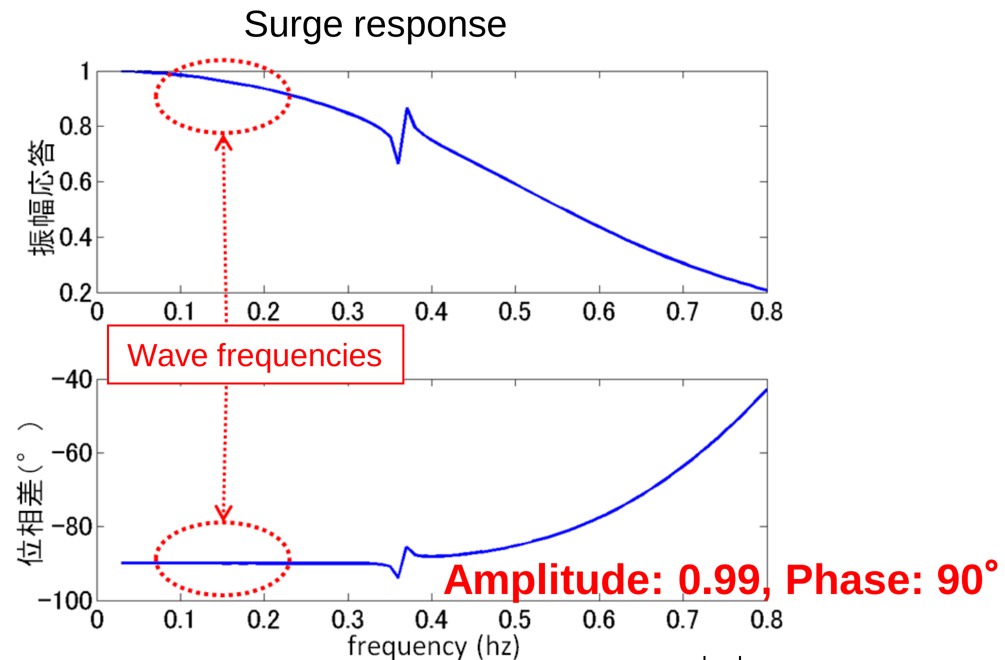


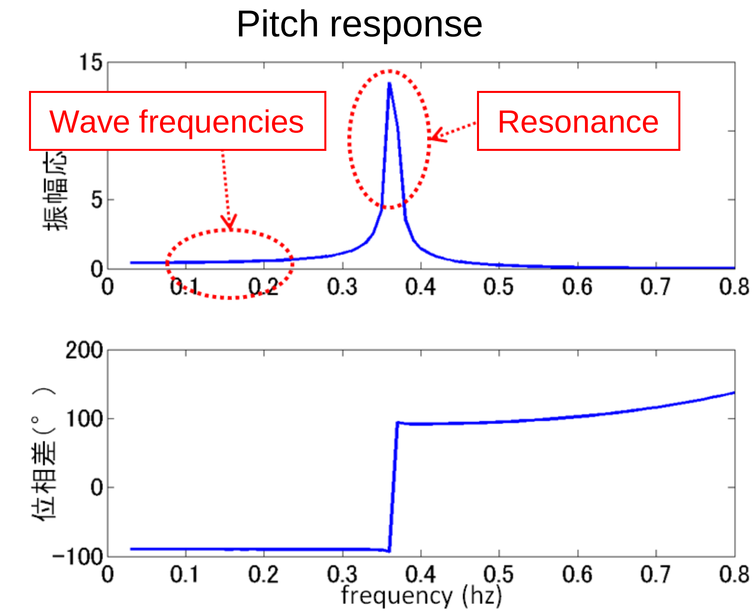
Longitude spectrum



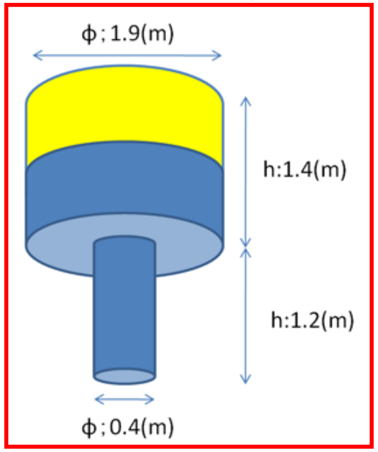
Response amplitude operator of K-TRITON buoy (heave, surge, pitch)

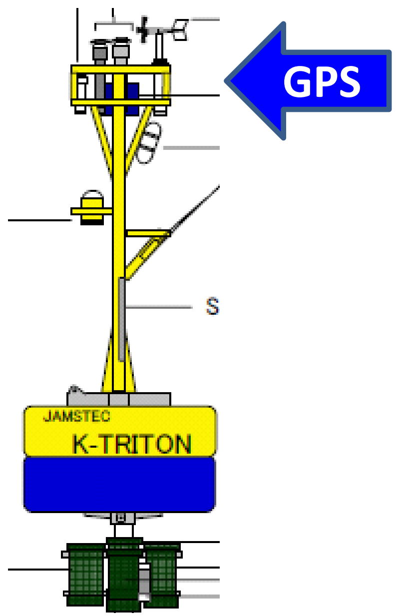






Simplified buoy geometry

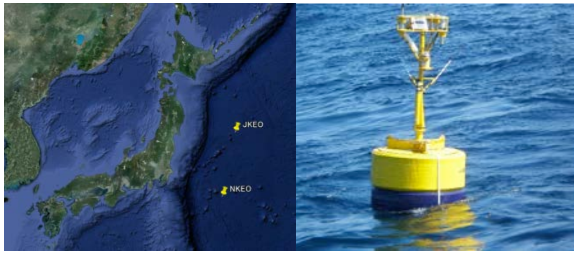




Radius of gyration → tuned

Observation points and periods

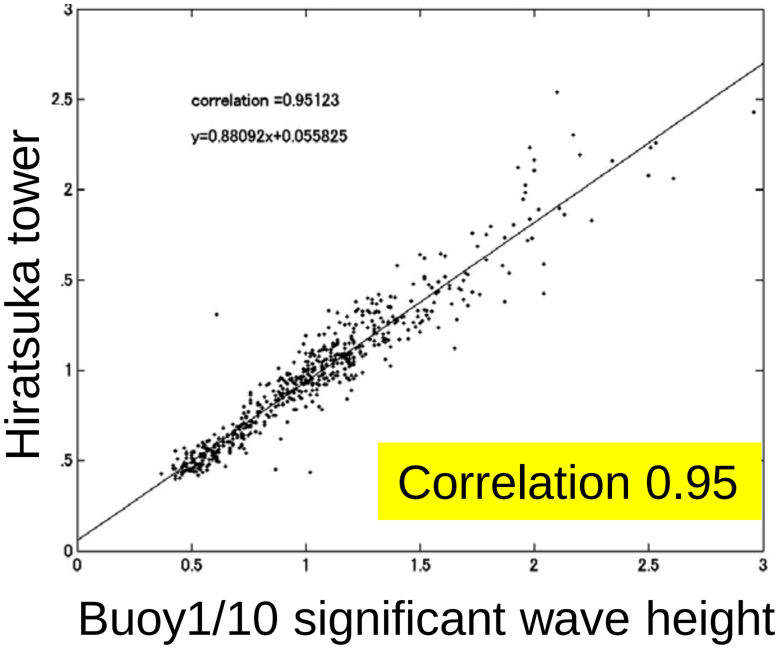
- **JKEO（JAMSTEC Kuroshio Extension Observatory)**
  - **Deep ocean (5400m); 38.1N, 146.4E, slack**
- **NKEO（New KEO）**
  - **Deep ocean (5700m); 33.8N, 144.8E, slack**
- Kouzu Island
  - Shallow (75m), slack
- Hiratsuka observational tower
  - Shallow (20m); tower (wave gauge, wind sensors)
- Kashiwa roof top
  - Fixed position

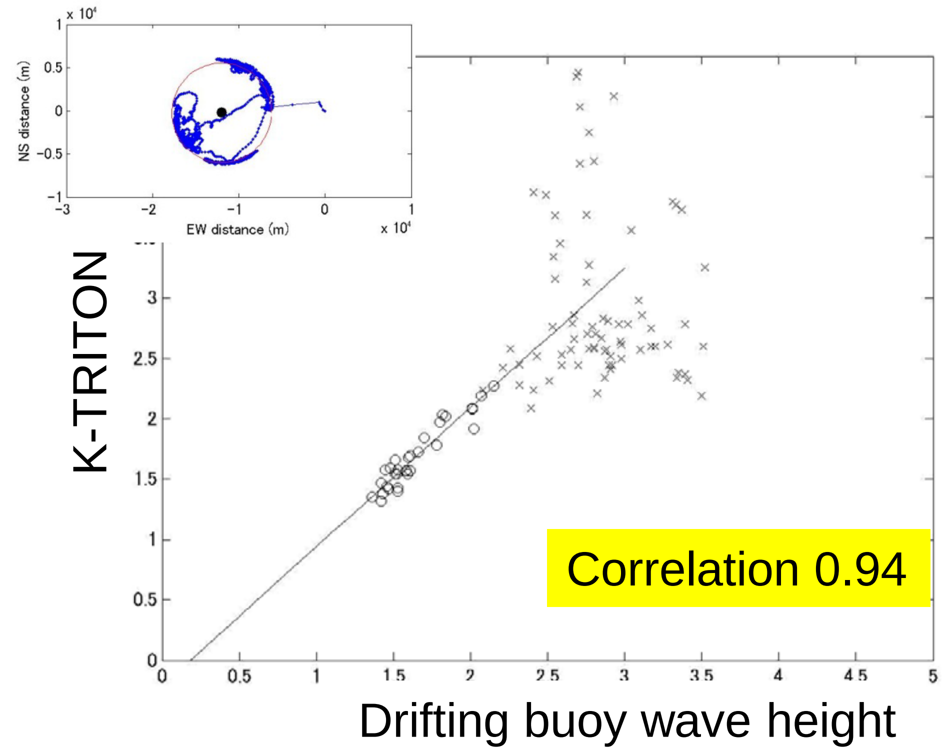


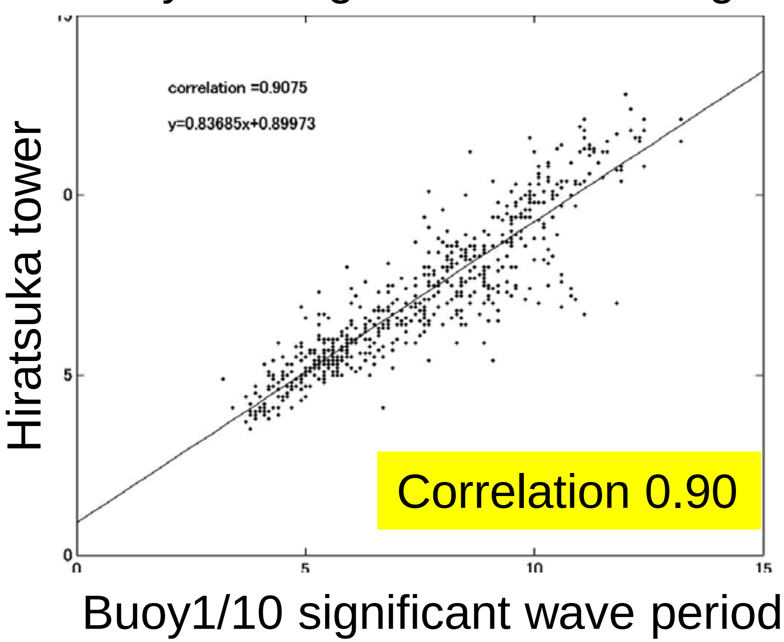
Google Earth From JAMSTEC

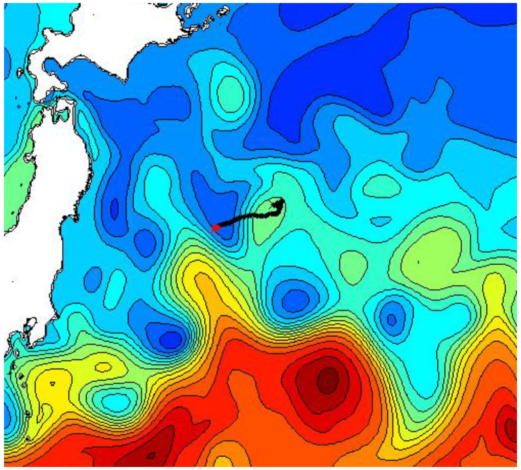
Buoy platforms	Location	Period	Status
Drifter No.1	Hiratsuka	2009/7/14-2009/8/10	Lost
	JKEO	2009/8/29-2009/9/2	
K-TRITON No.1	JKEO	2009/8/30-（12/6）2010/9/18	Retrieved
Drifter No.2	Kashiwa	2010/7/21-2010/8/11	Lost
	Hiratsuka	2010/8/23-2010/12/21	
	Mirai	2011/2/12-2011/2/23	
	JKEO	2011/2/23-2011/2/26	
K-TRITON No.2	Kashiwa	2010/11/5-2011/1/4	Retrieved
	Mirai	2010/2/12-2010/2/23	
	JKEO	2011/2/23-(3/3)　2012/6/22	
KOUZU	Nishichiba	2010/12/17-2010/12/24	Retrieved
	Kouzu-port	2011/1/11-2011/1/23	
	Kouzu	2011/1/23-2011/3/4	
	Kouzu	2011/6/31-2012/3末	
	Kouzu	2012/6/30-2012/3/12	
	Kouzu	2013/9/ -	In Operation
Drifter No.3	Kashiwa	2011/2/25-2011/3/2	retrieved
	Kouzu	2011/3/11-2011/4/26	
K-TRITON No.3	JKEO	2012/6/23-(2012/9/17)	Retrieved
K-TRITON No.4	NKEO	2012/6/20-2013/3/	Retrieved
	JKEO	2014/4/ -	Planned

Cross validation: Hiratsuka Tower, Drifting buoy, K-TRITON



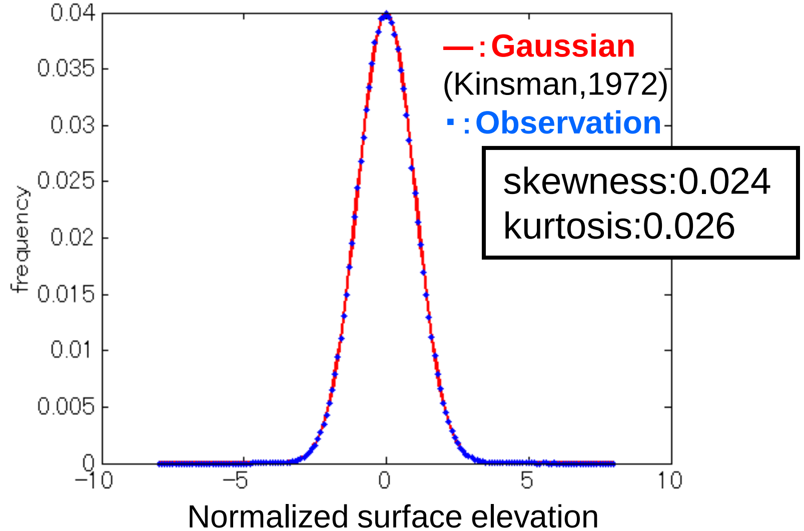




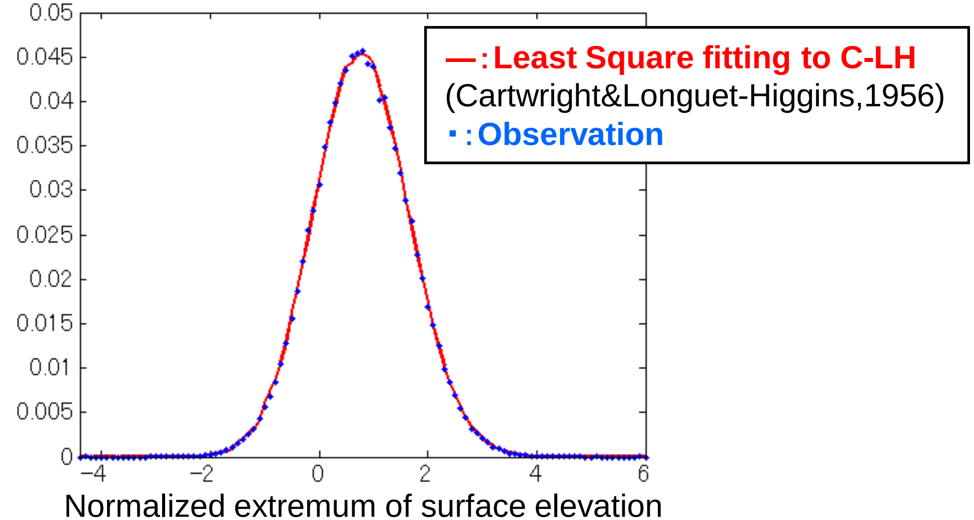


Statistics of wave measurements from the K-TRITON buoy

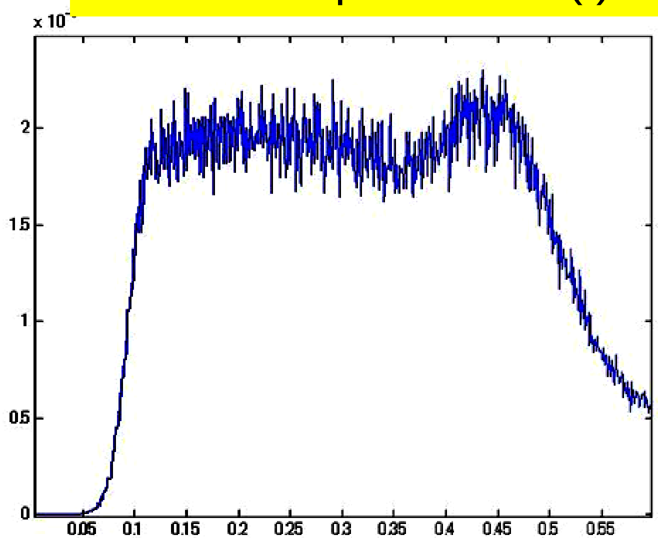
Elevation distribution: Gaussian



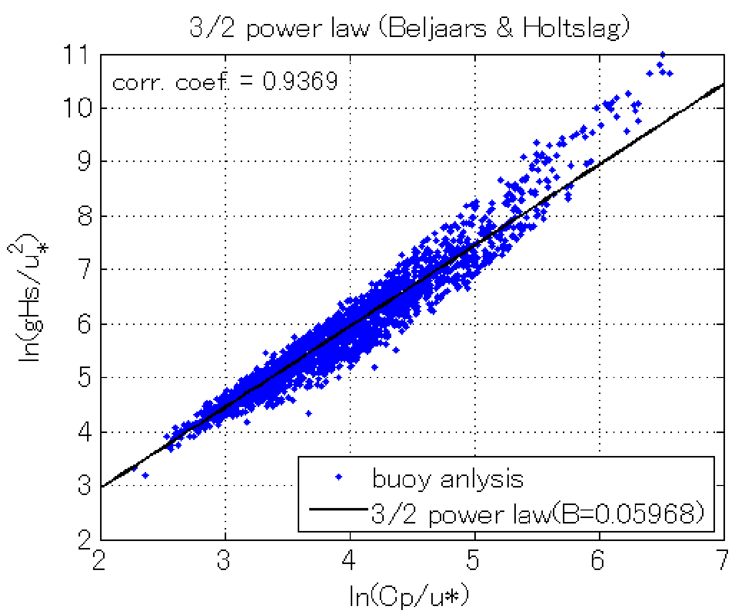
Extremum distribution: Longuet-Higgins



Saturated spectrum S(f)xf⁴

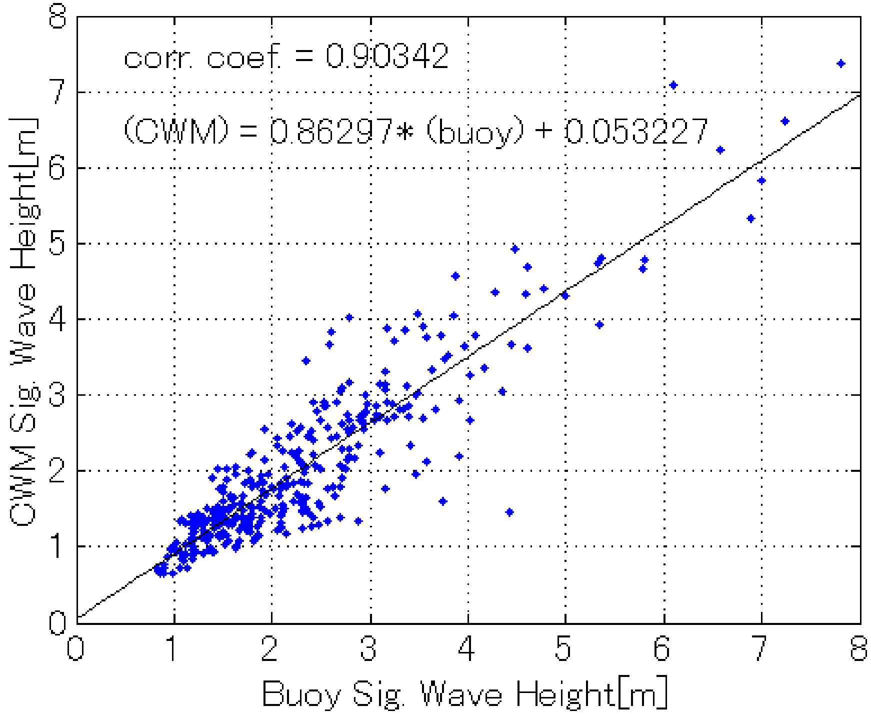


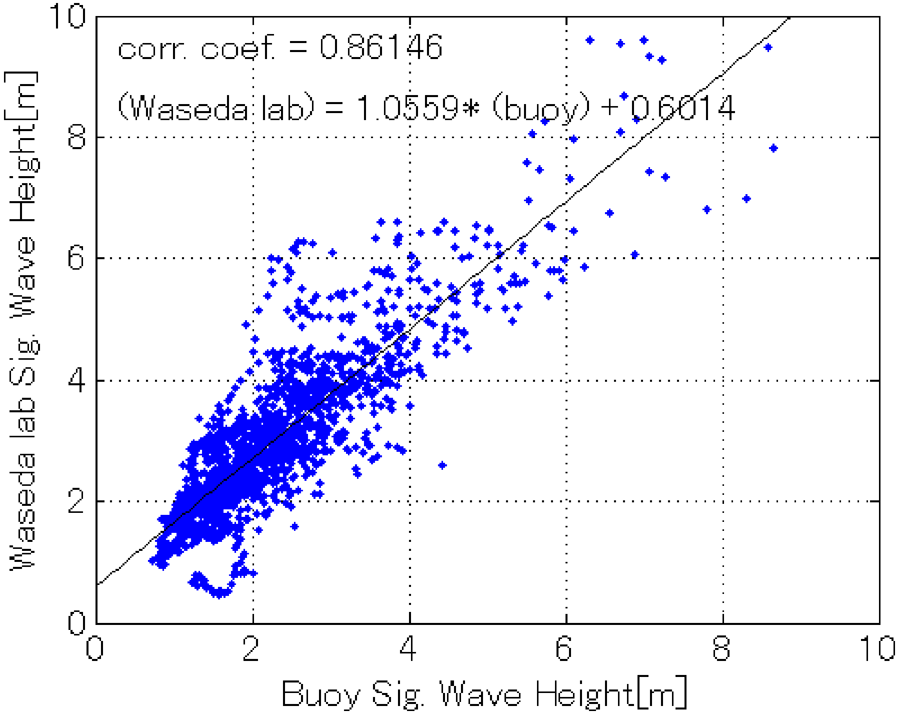
Toba 3/2 law

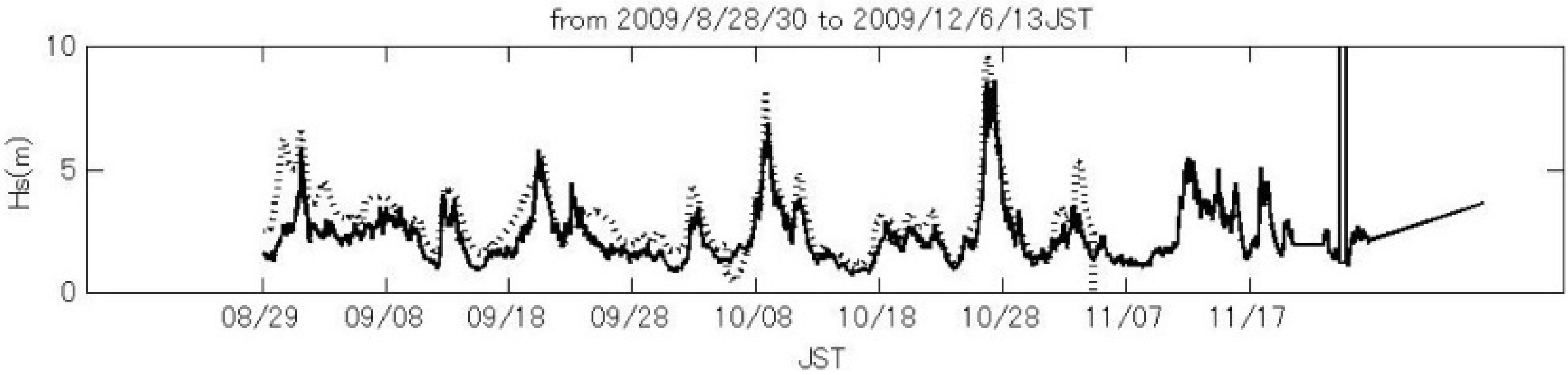


Observation-model comparison（JKEO）

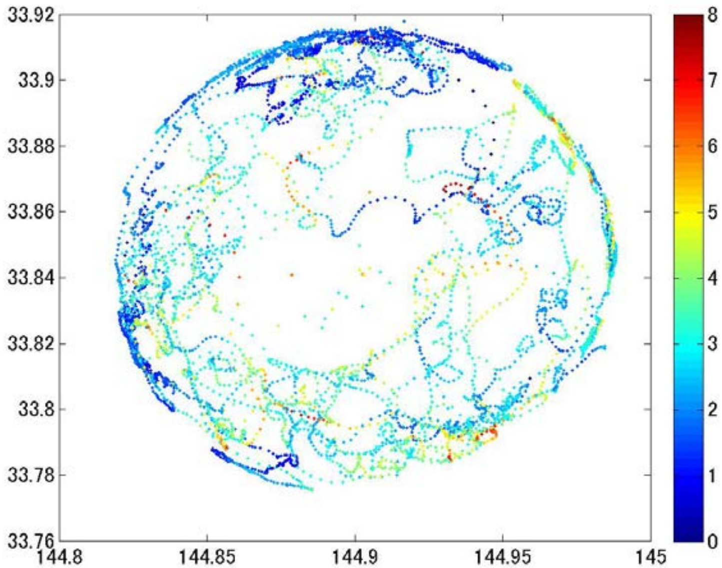
Moored buoy observation compares fairly well with the model



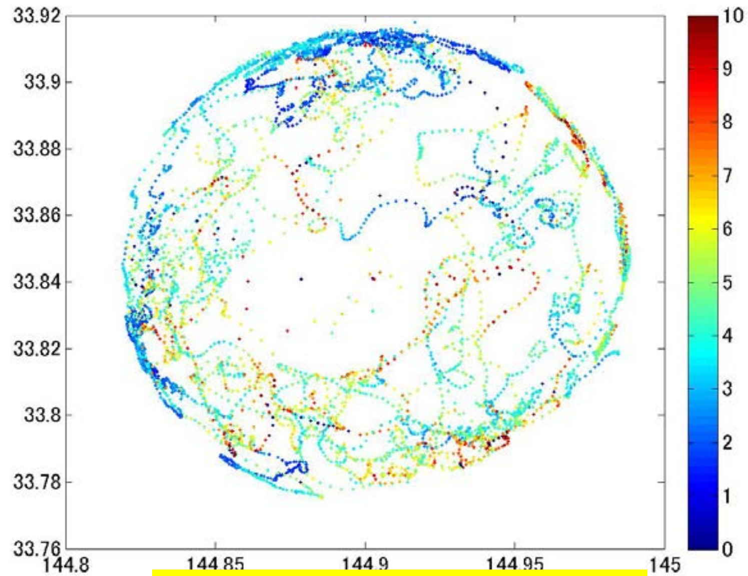




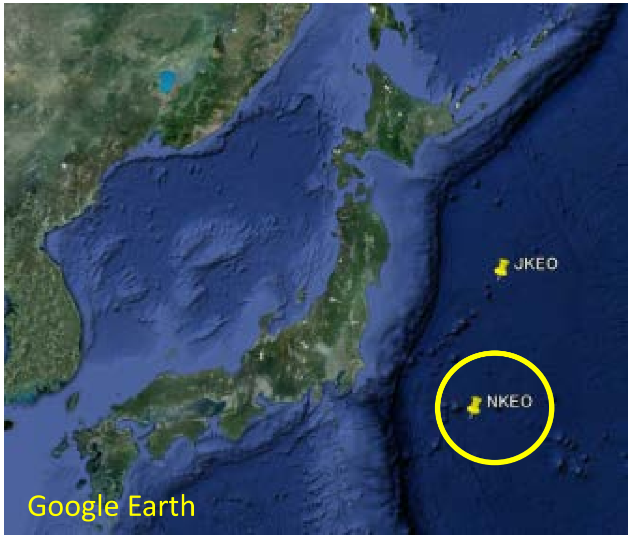
NKEO Observation 2012 June – 2013 March

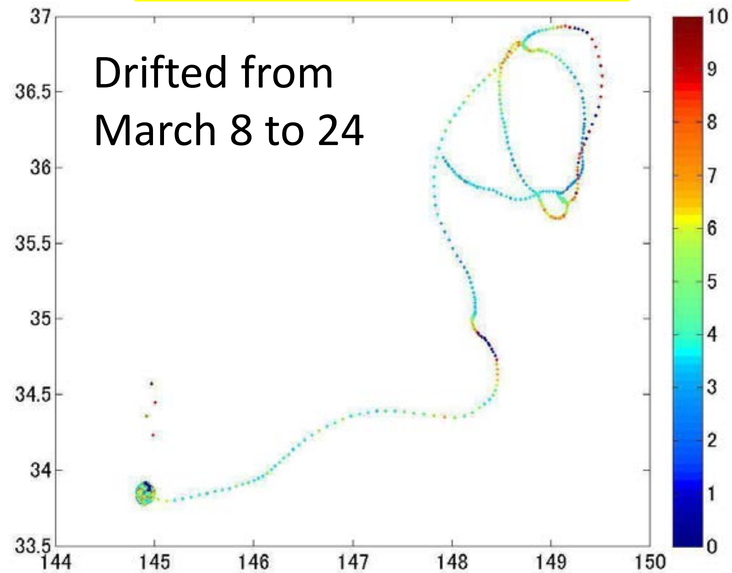


Significant Wave height

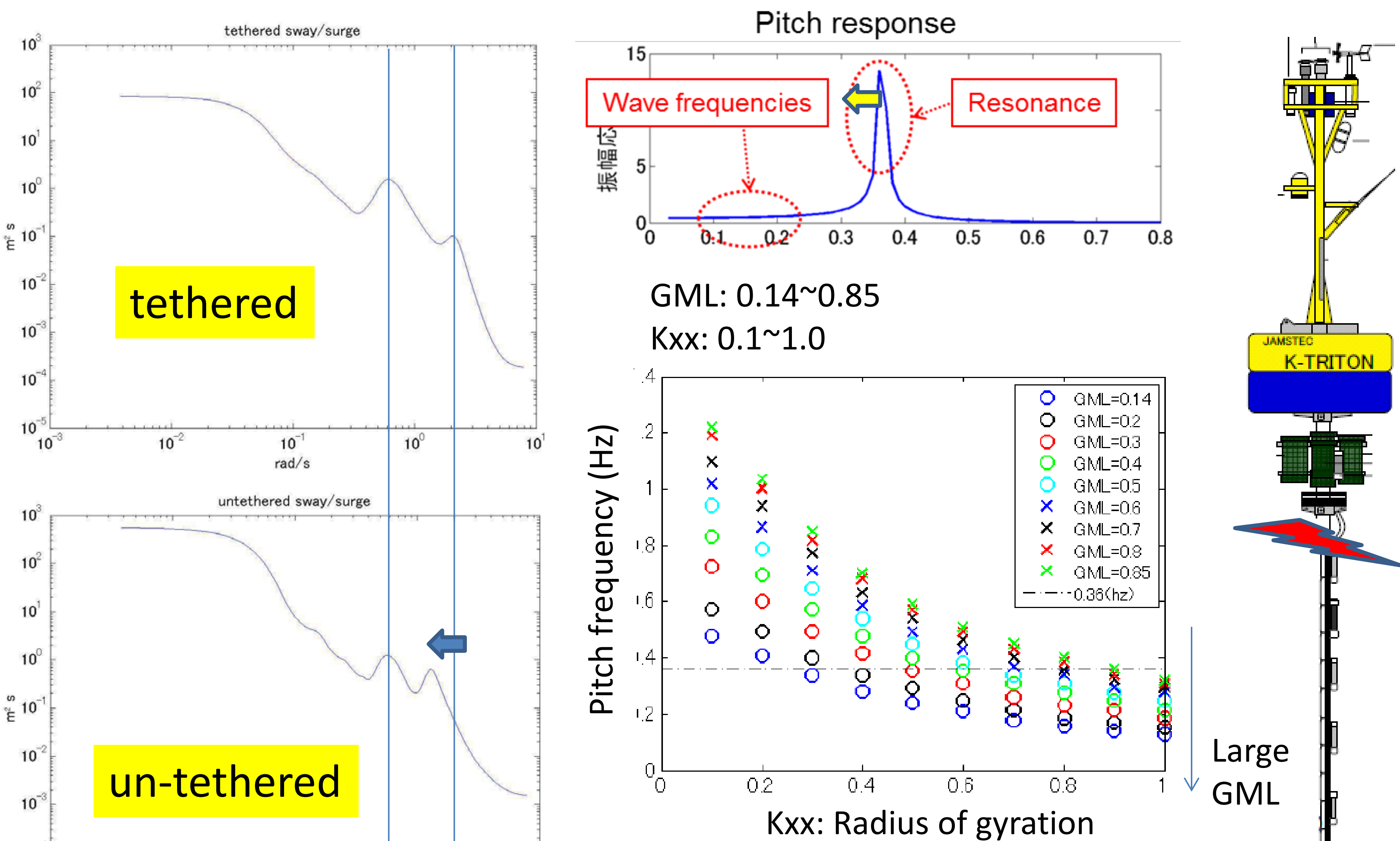


Maximum Wave height





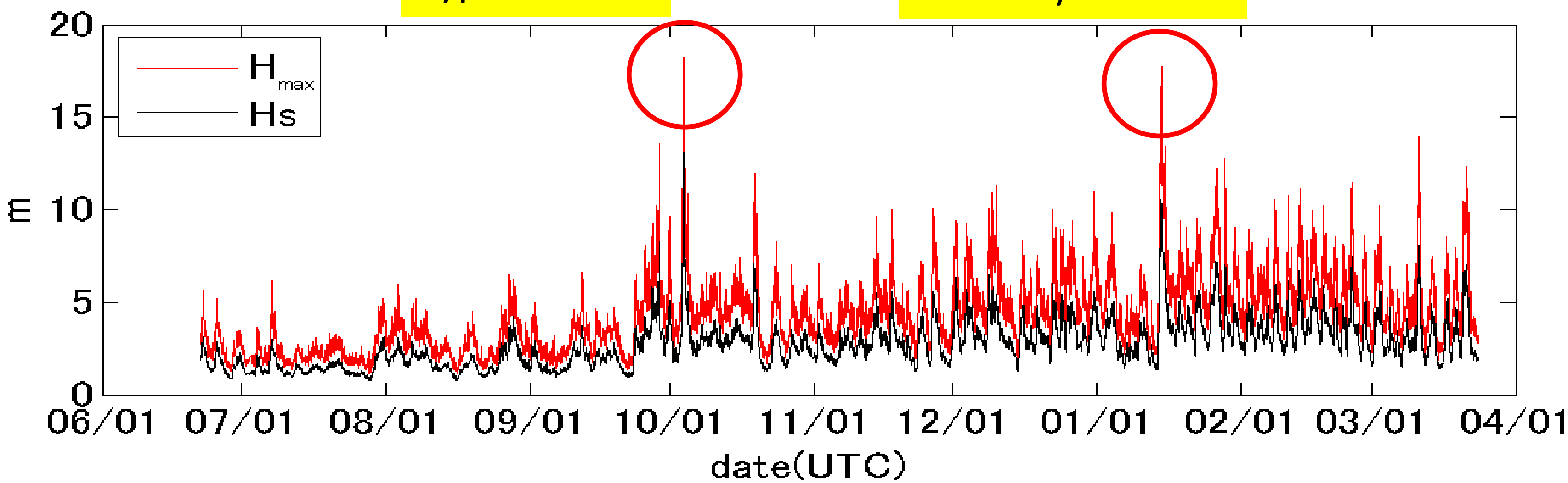
Effect of tethering on pitching/rolling motion

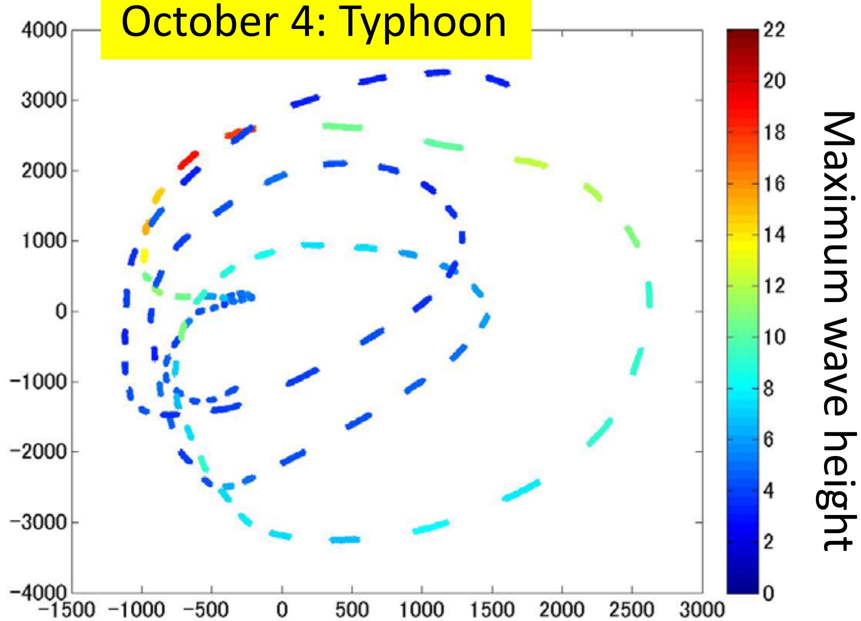


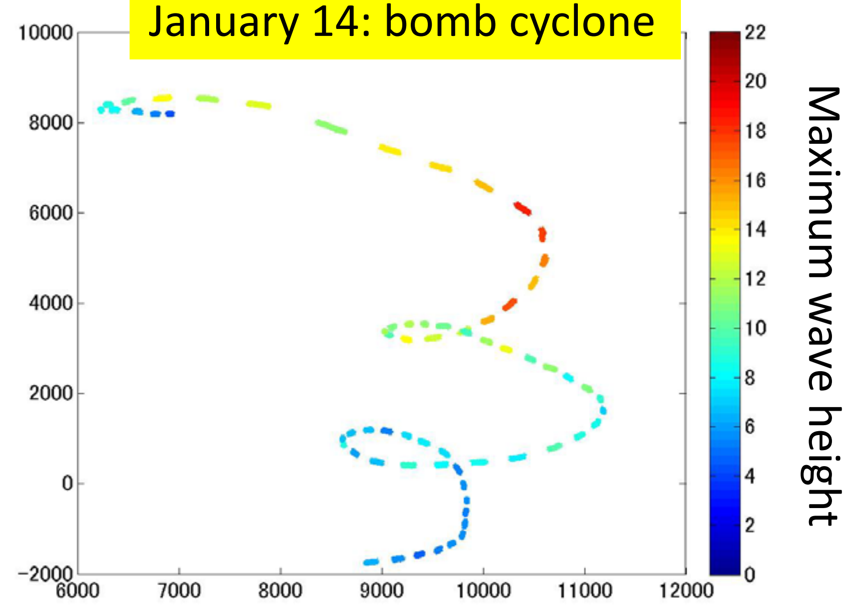
Without cable, center of gravity rises

→ Decrease GML → lower pitch frequency

NKEO ～20 m wave height events – ***horizontal motion***

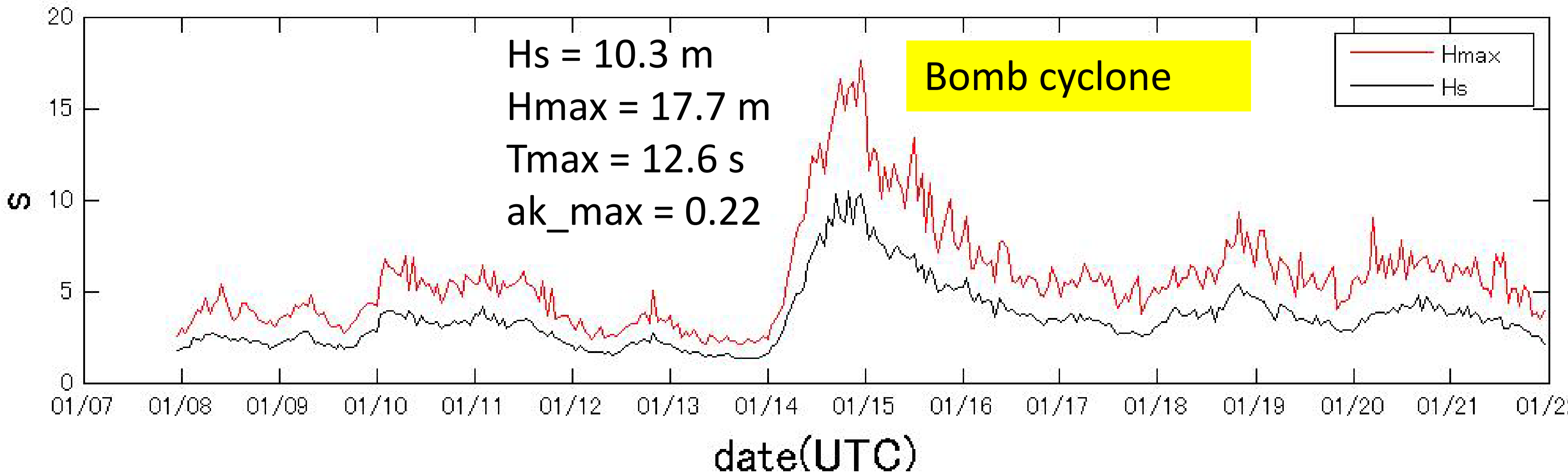


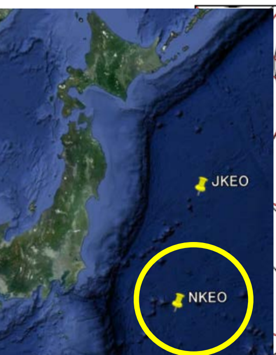


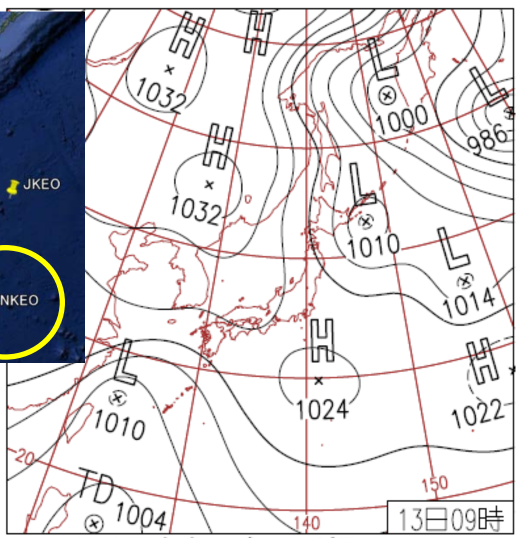


Line segments indicate 20-minute buoy tracks

2013.1.14 NKEO extreme wave observation

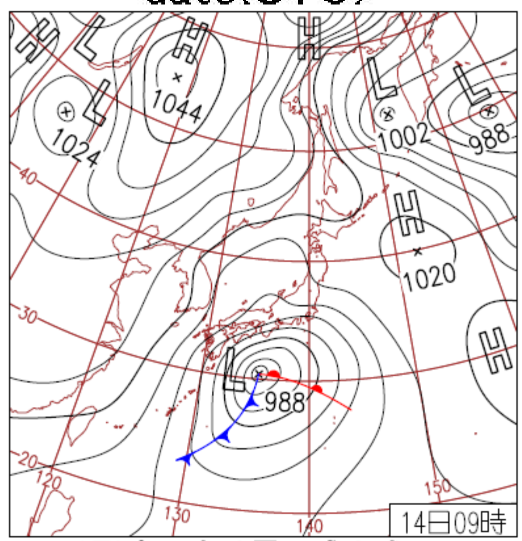






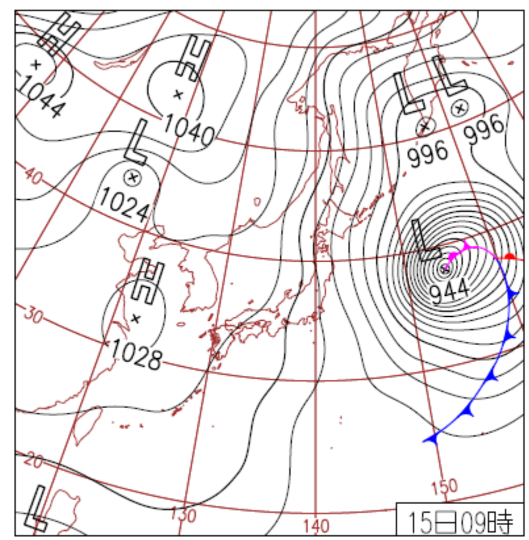
13日(日)西から天気下り坂

東シナ海の低気圧により、沖縄～九州は雨。沖縄で30mm/1h以上の雨となり1月の1位の値を更新した所も。東日本は高気圧圏内で晴れて気温が平年よりも高め。岩手県で震度4。



14日(月)東日本は雪の成人式

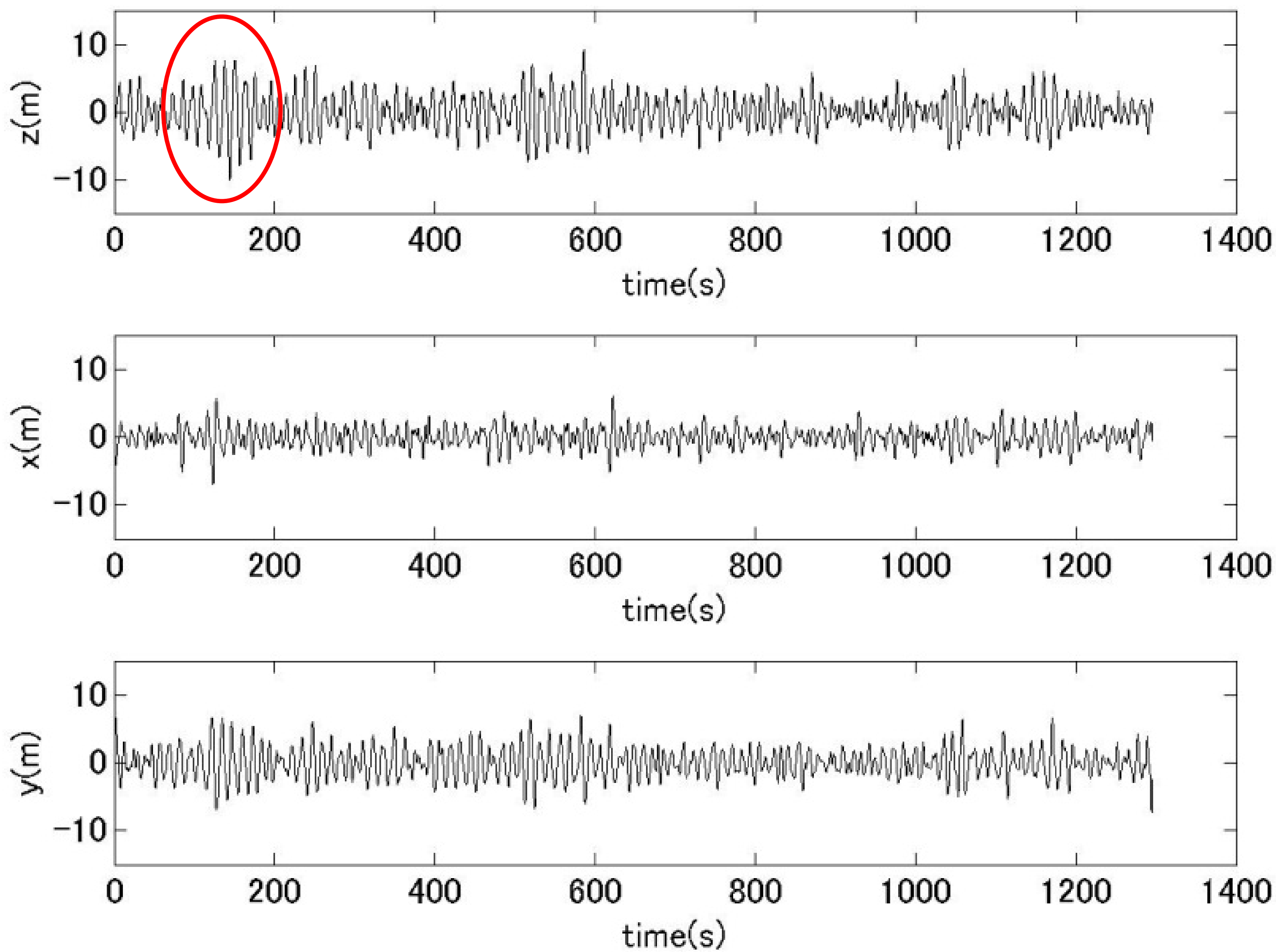
急速に発達した低気圧により太平洋側は風が強く、関東南部中心に雪。千葉県銚子で最大瞬間風速38.5m/s。横浜・東京で初雪。最深積雪は横浜13cm、東京8cm。



15日(火)冬型の気圧配置へ

低気圧が東海上で発達し、日本付近は冬型の気圧配置となって日本海側では雪。太平洋側は東海・関東を中心に概ね晴れ。北日本を中心に293地点で真冬日。

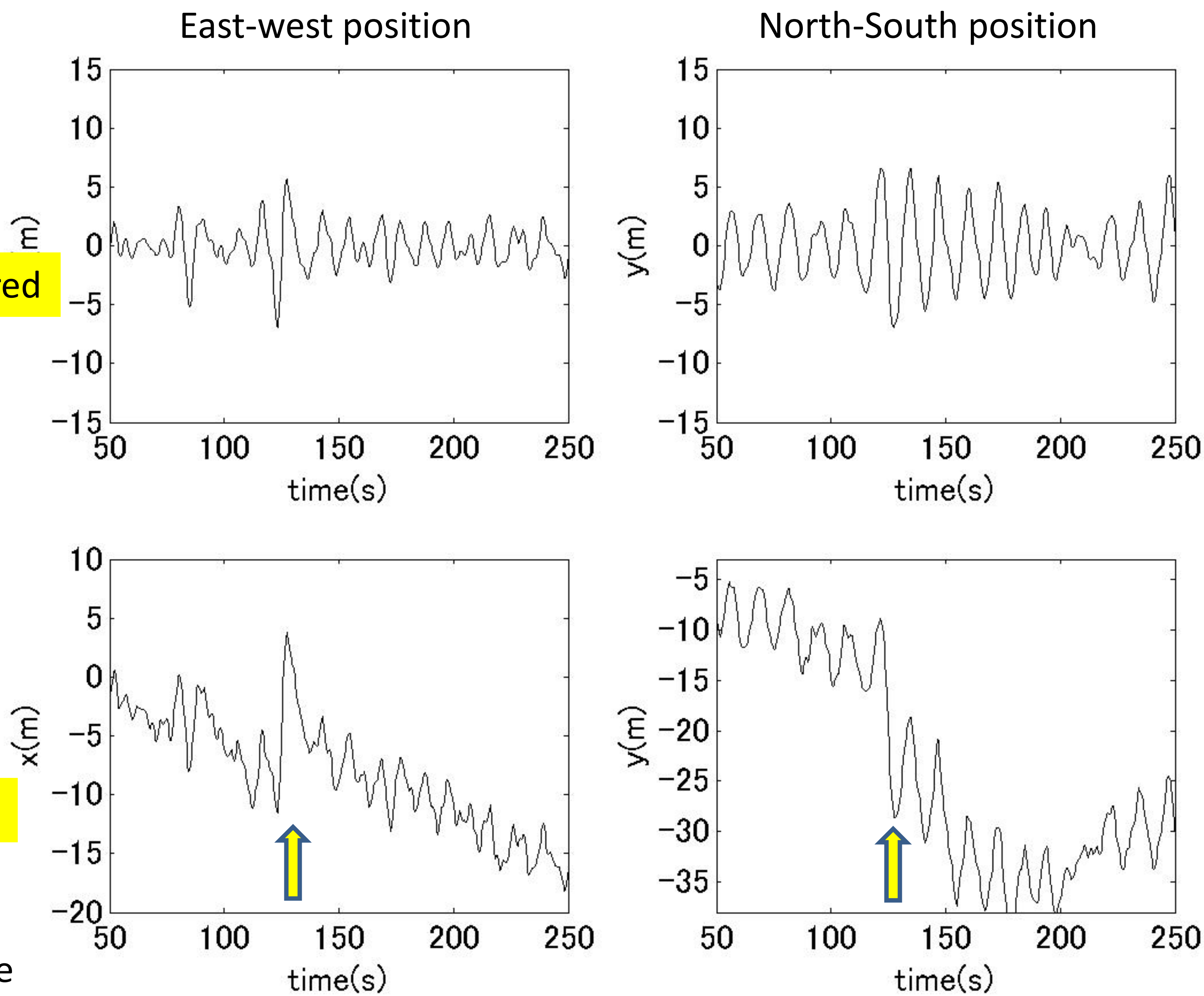
2013.1.14 Hmax=17.7m; time-series (filtered)



Horizontal motion; filtered vs. un-filtered records

Hmax = 17.7 m
Tmax = 12.6 s
Cp=19.7 m/s
Cg=9.8 m/s

High-pass filtered



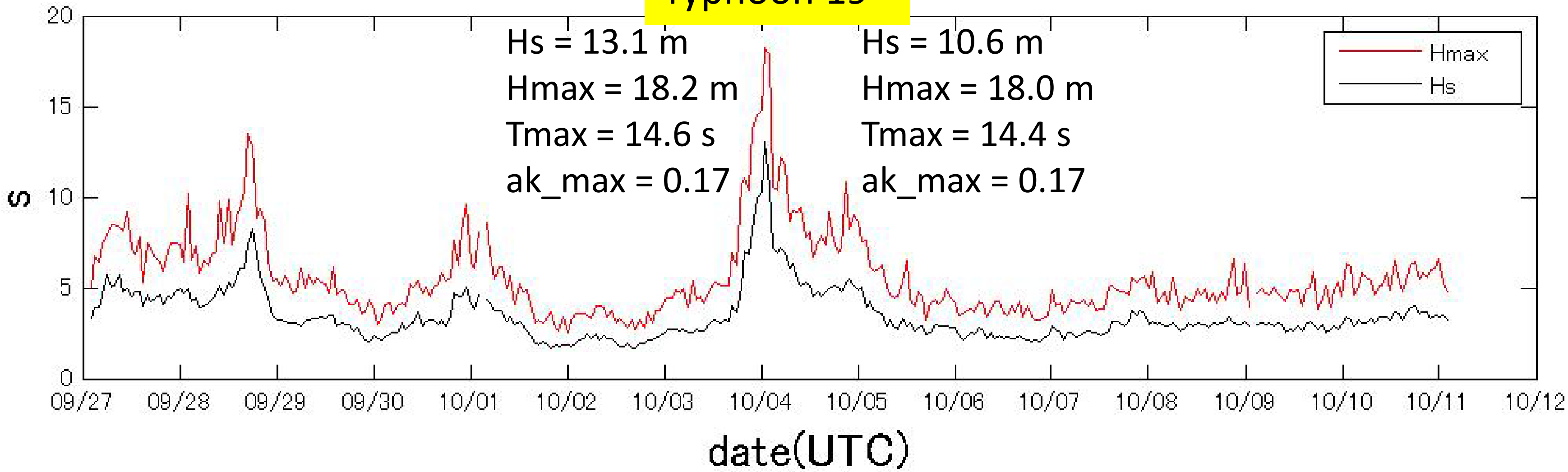
Estimated maximum orbital speed
～7 m/s

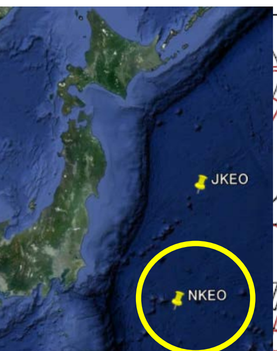
Original record

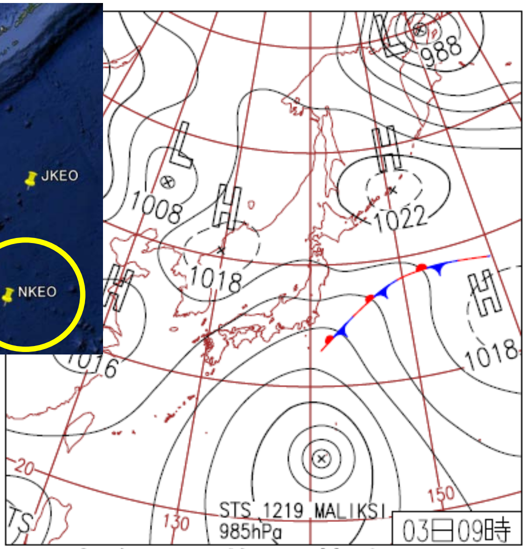
NO influence of number of satellite

2012.10.4 NKEO extreme wave obseravtion

Typhoon 19

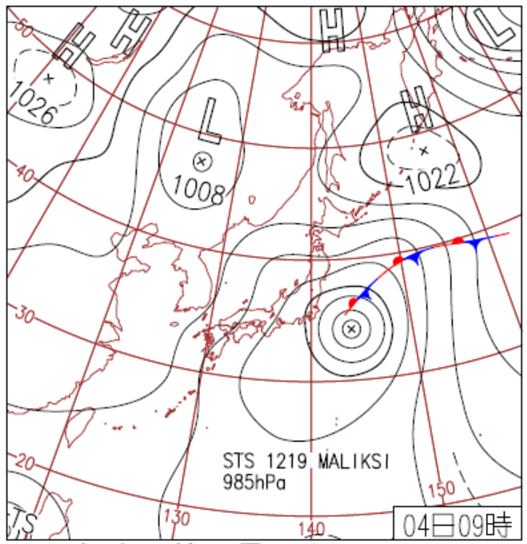






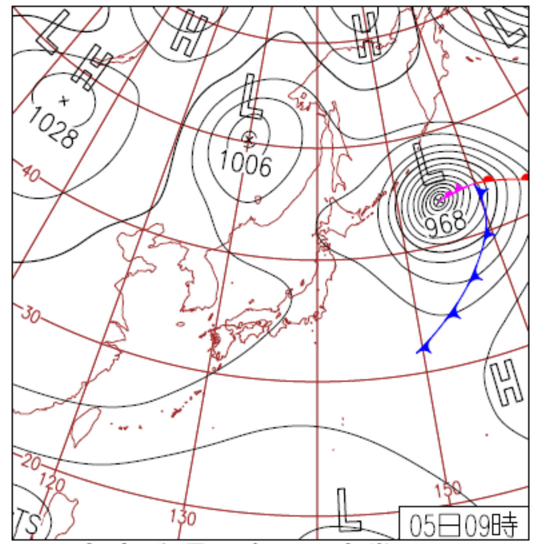
3日(水)台風、小笠原に接近

台風第19号の北上に伴い、八丈島西見で最大瞬間風速30.5m/s、57mm/1hの雨。関東は南岸の前線により雨、西日本は移動性高気圧に覆われ晴れ。東海と北海道の一部で気温上昇。



4日(木)台風第19号 温低化

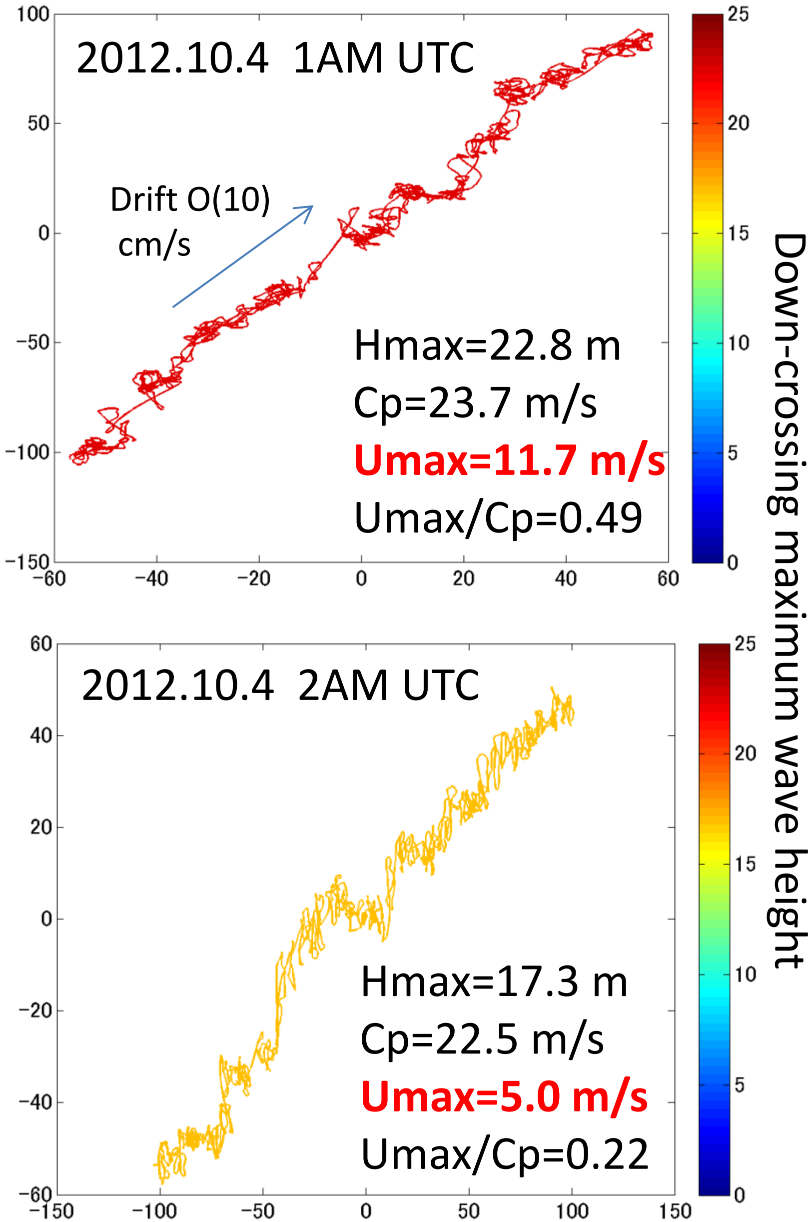
台風第19号は北上を続け温帯低気圧に。関東～東北の太平洋岸は台風の北上に伴って風が強まり千葉県銚子で最大風速20.7m/s。晴れた東海を中心に21地点で真夏日。

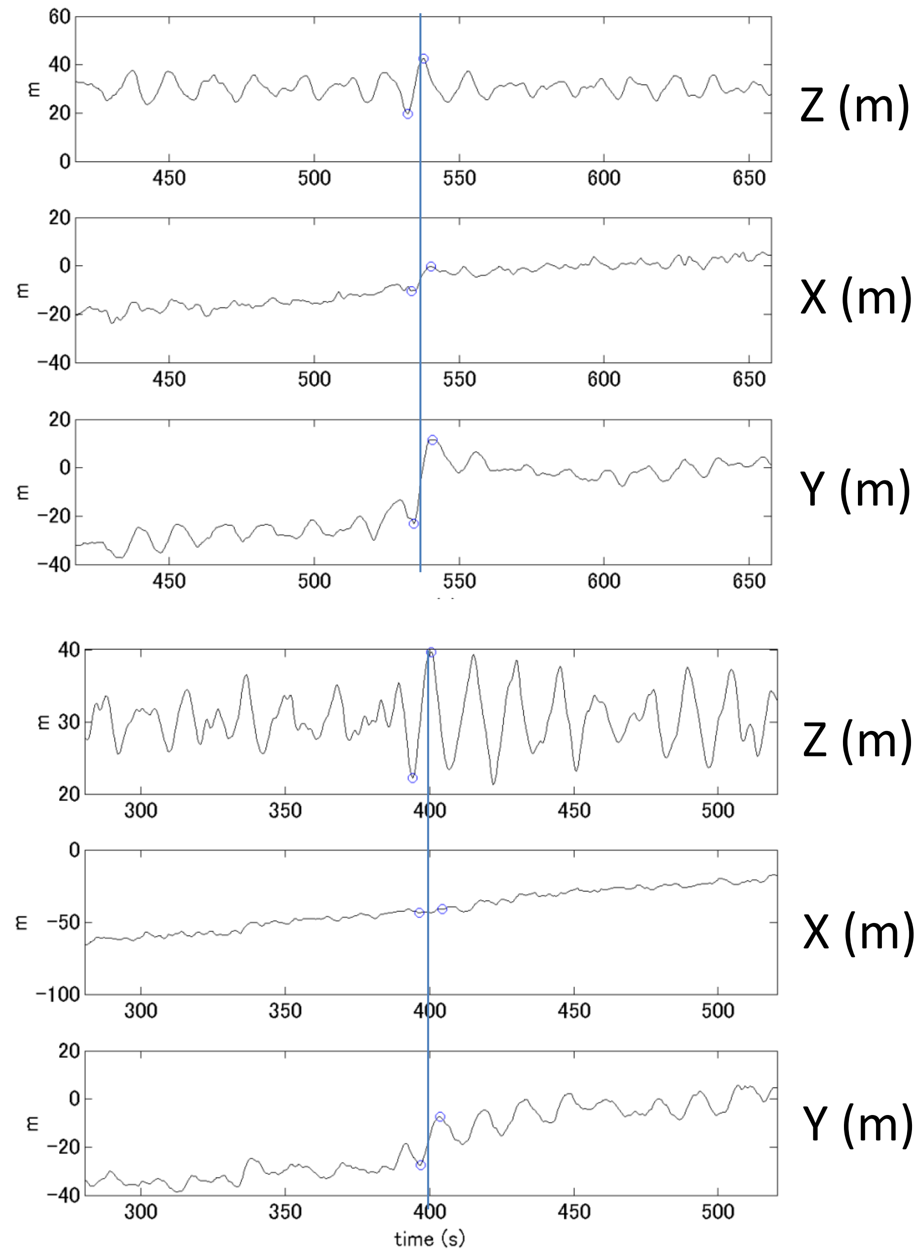


5日(金)新潟県の海上で竜巻

北日本上空に寒気を伴った気圧の谷が通過し、大気の状態が不安定。北陸～東北では積乱雲が発達し、秋田県で突風、新潟県の海上で竜巻発生。山形県鶴岡市荒沢で59mm/1hの雨。

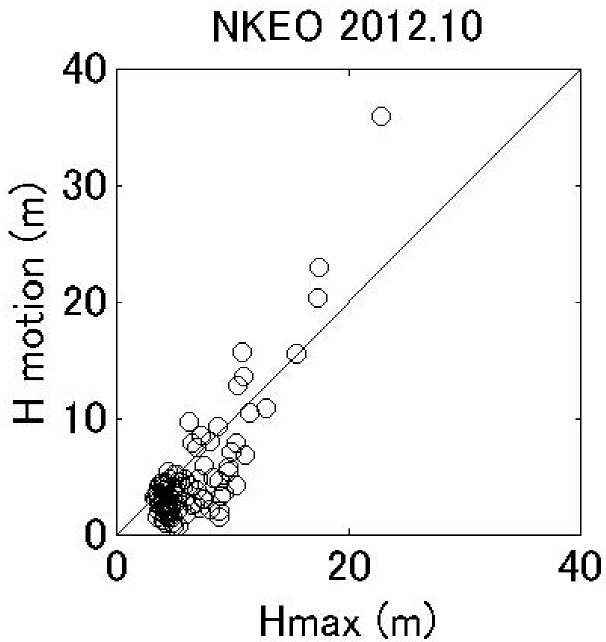
Waves of 20 m height; *horizontal motion*

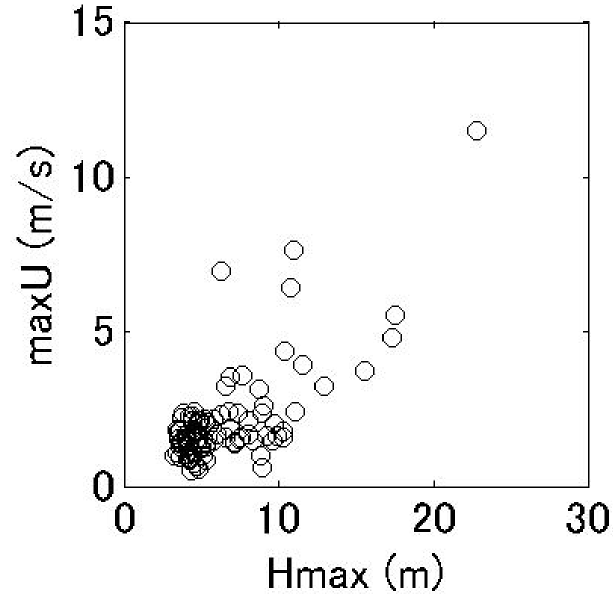




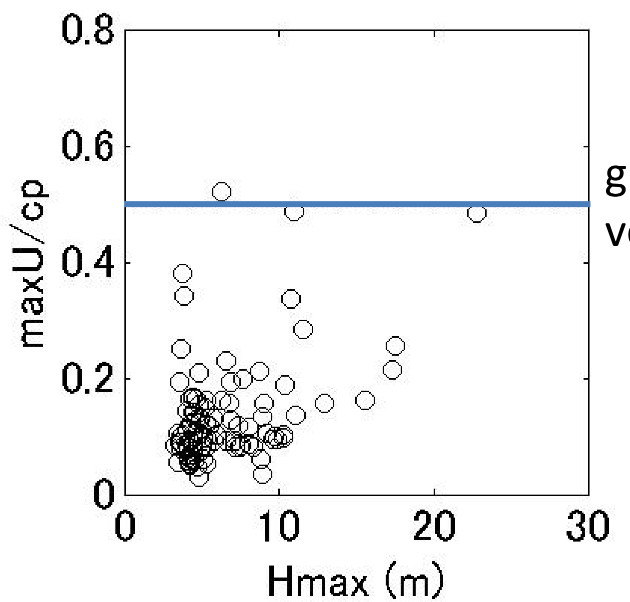
NKEO 2012.10.3 – 10.6 : 95 x 20min records

Down-crossing maximum waves

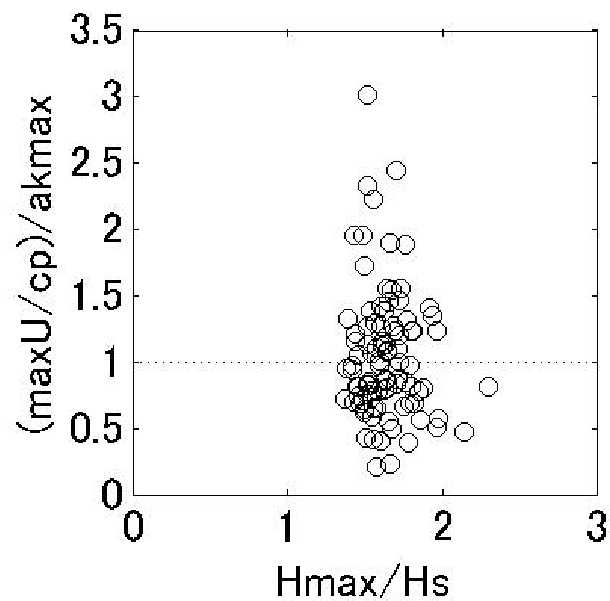




Buoy velocity exceeds group velocity



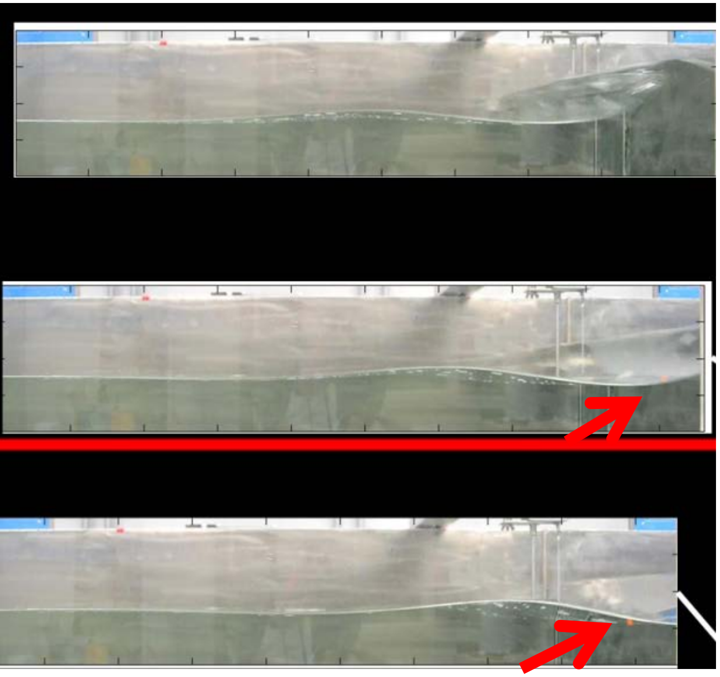
group velocity



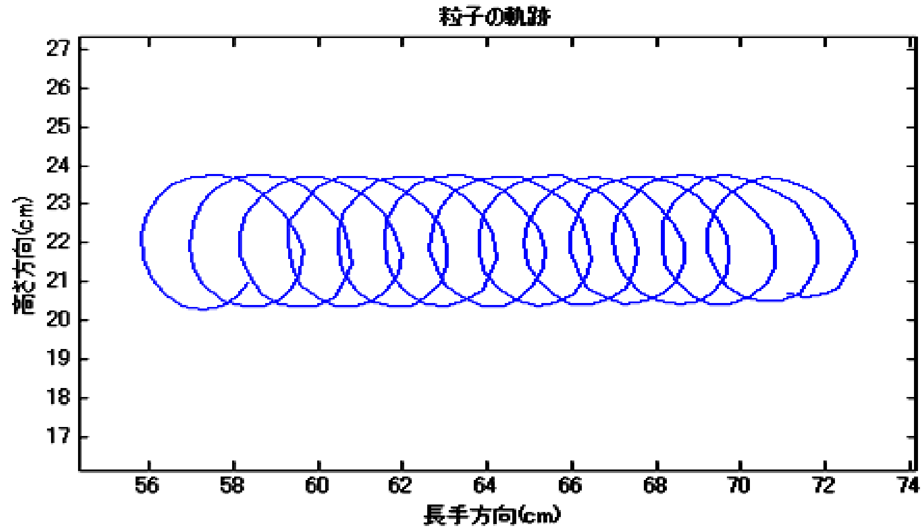
Airy wave orbital speed

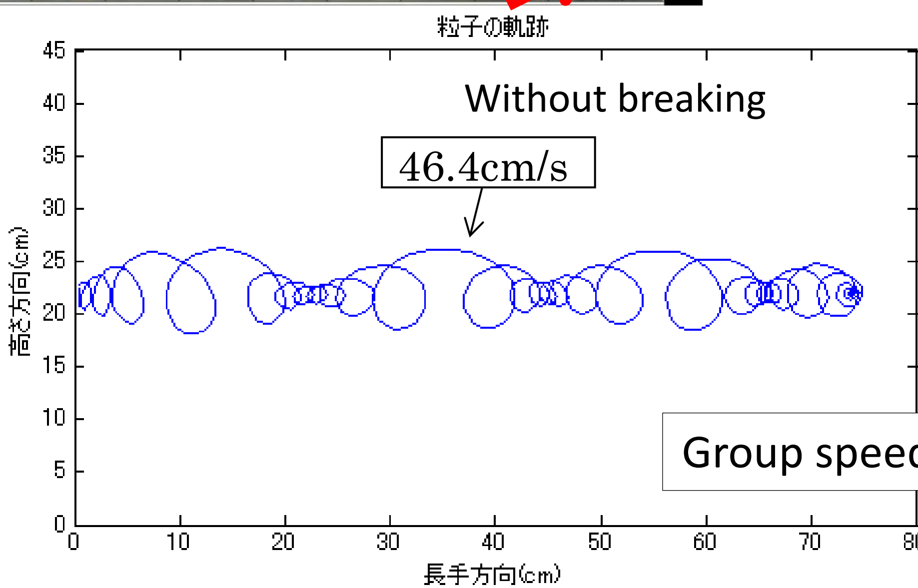
Particle motion at the free surface（Tank：L10m,D60cm,W80cm)

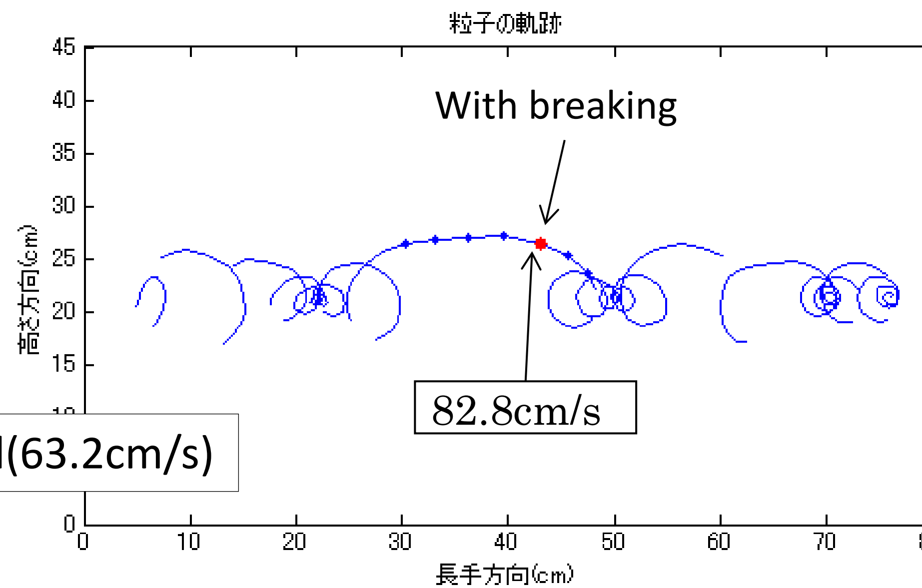
2012 Takahashi, thesis U-Tokyo



Stokes Drift



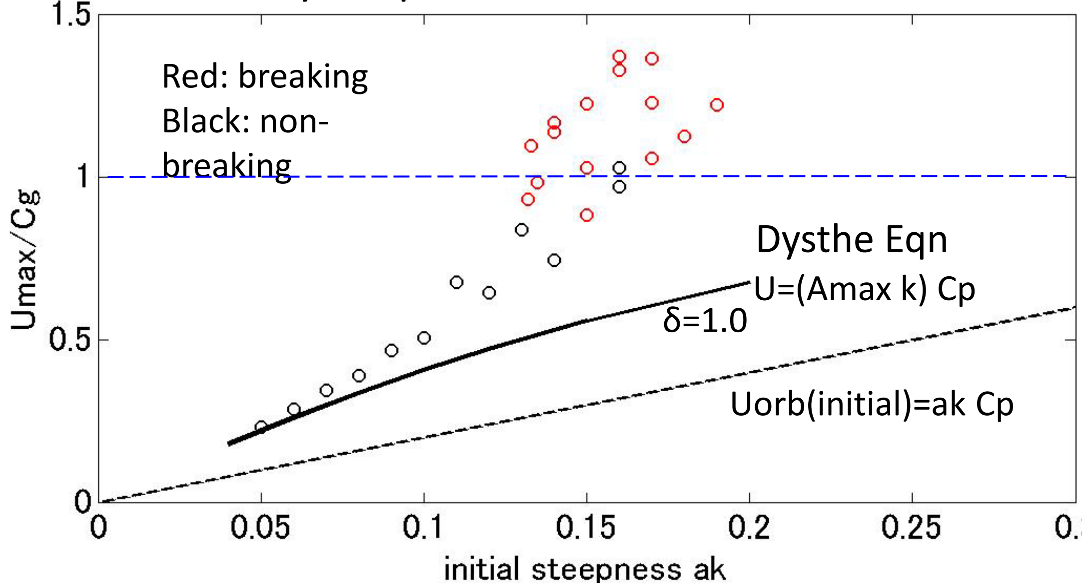




Group speed(63.2cm/s)

Modulational instability and particle velocity

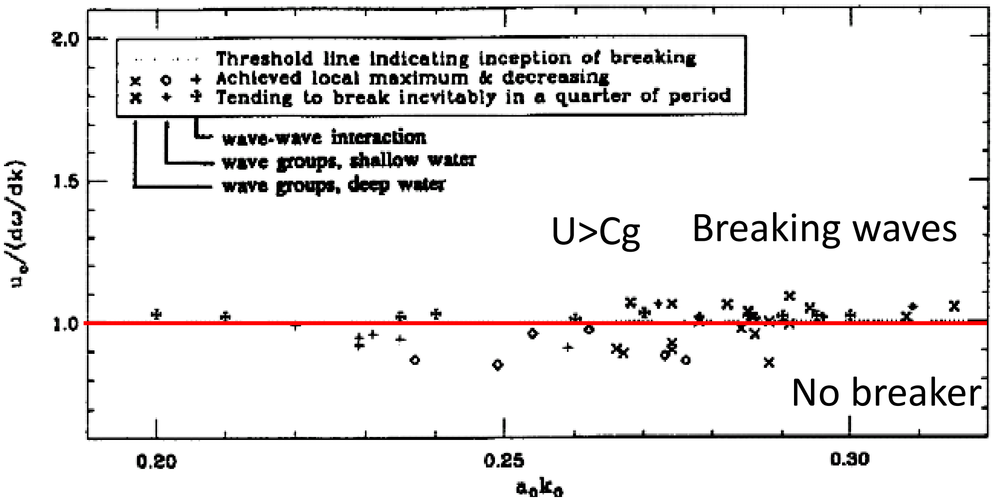
UTokyo Experimental result



Particle velocity based on weakly nonlinear theory

$$u_{orb} = Ak\frac{g}{\omega}$$

At most, 0.7 times group velocity; if the wave is breaking, it should reach the phase speed



Tulin & Landrini 2001

Tulin's (2001) breaking criterion: u>cg

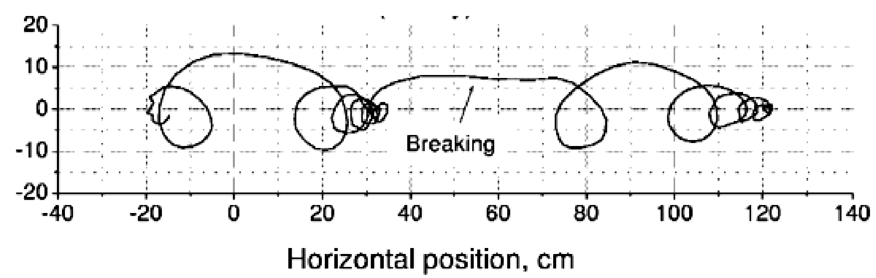
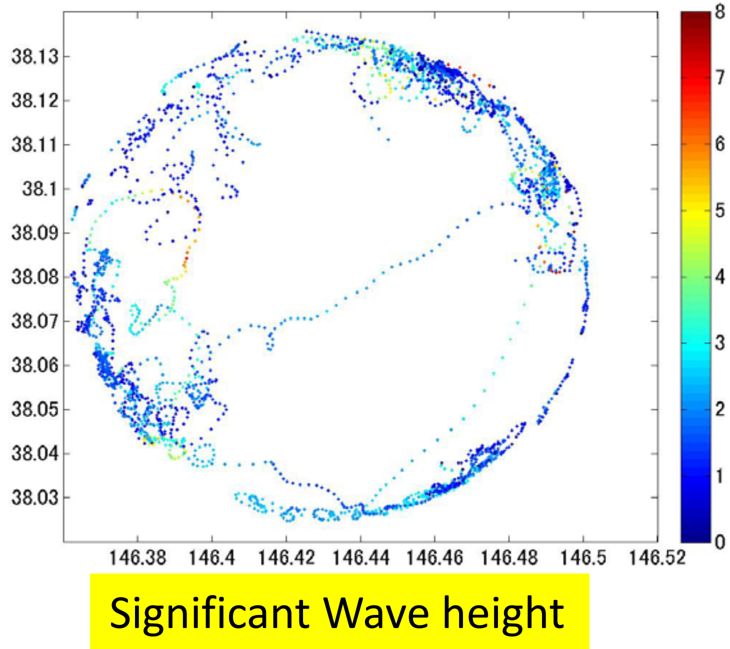
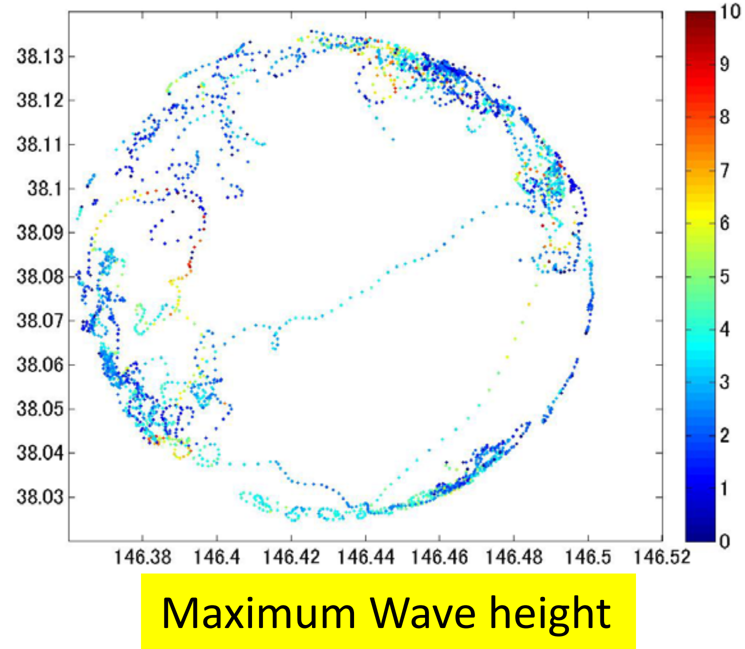


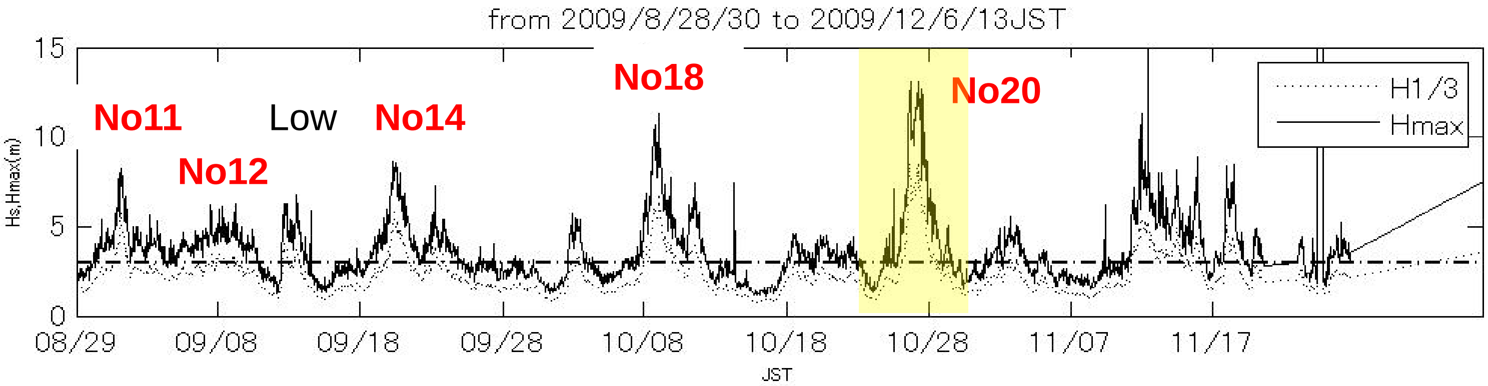
Figure 18: Orbital trajectories in both phase and physical space for different wave conditions.

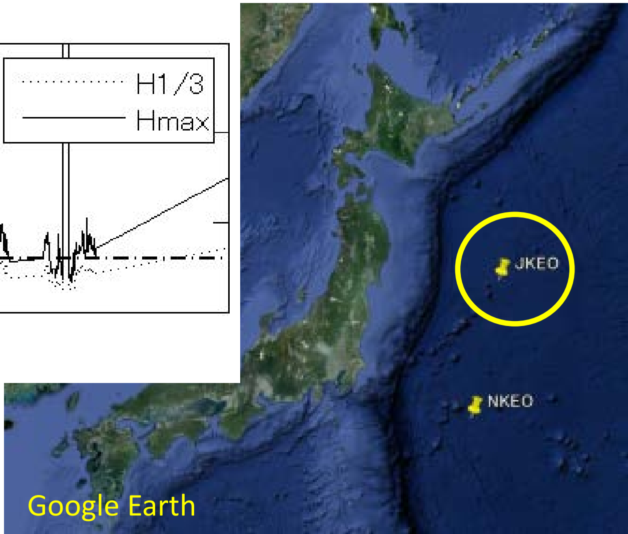
Tulin & Landrini 2001

JKEO Observation 2009 August - December



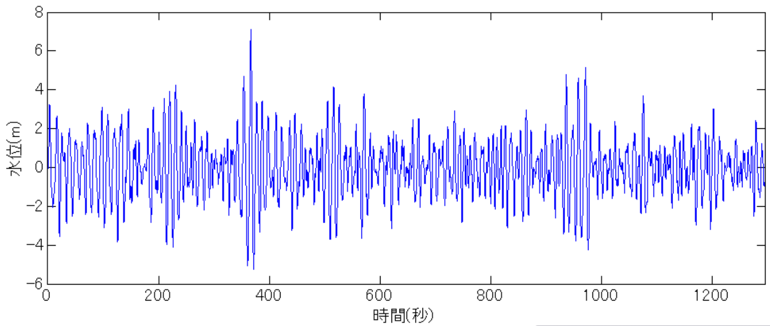




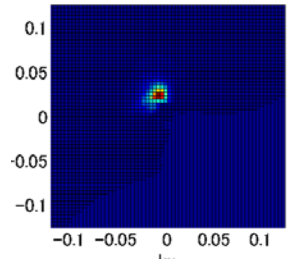


JKEO 2009.10 freak wave – Freakish Sea Index

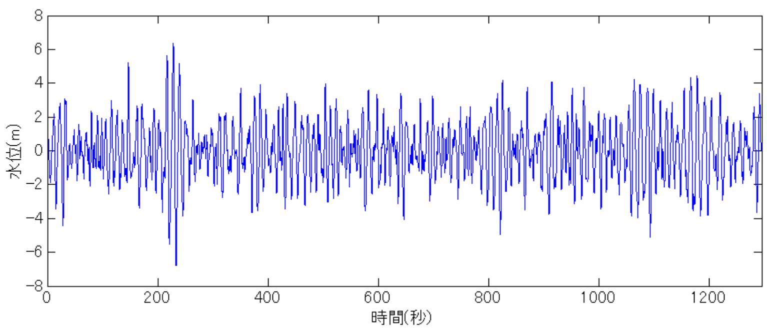
2009.10.26 19:00 (UTC)



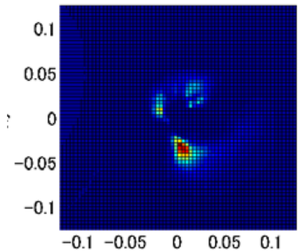
Hs = 5.79m
Hmax = 12.33m
AI=Hmax/Hs = 2.13



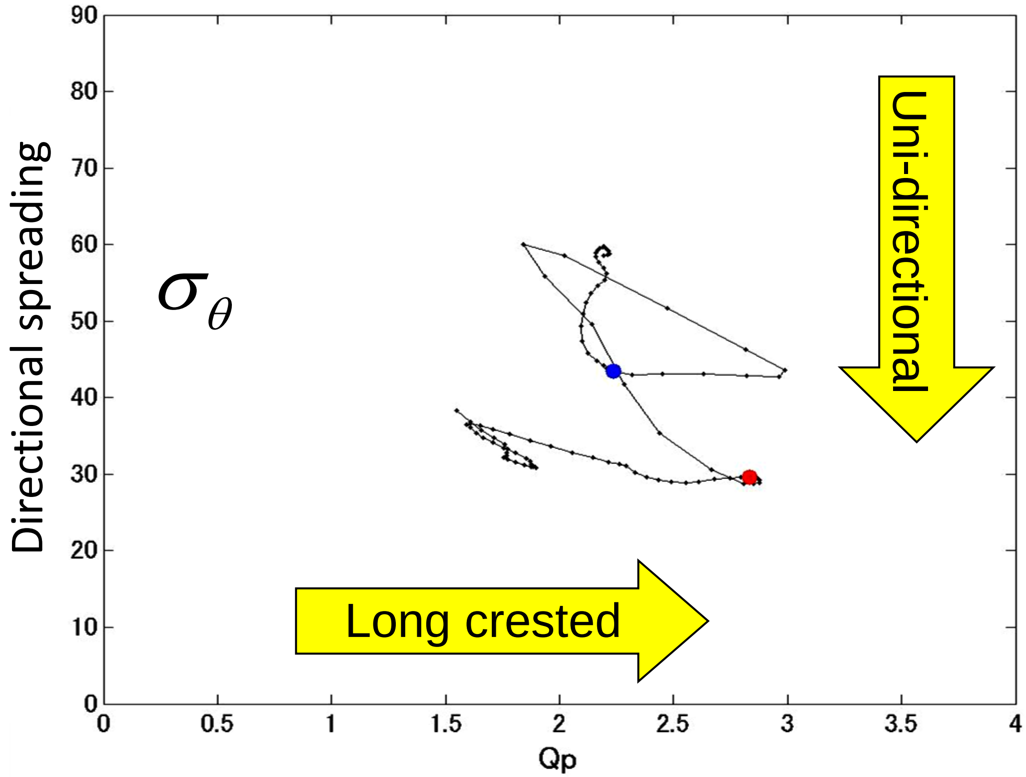
2009.10.27 16:00 (UTC)



Hs = 6.56m
Hmax = 13.19m
AI=Hmax/Hs = 2.01



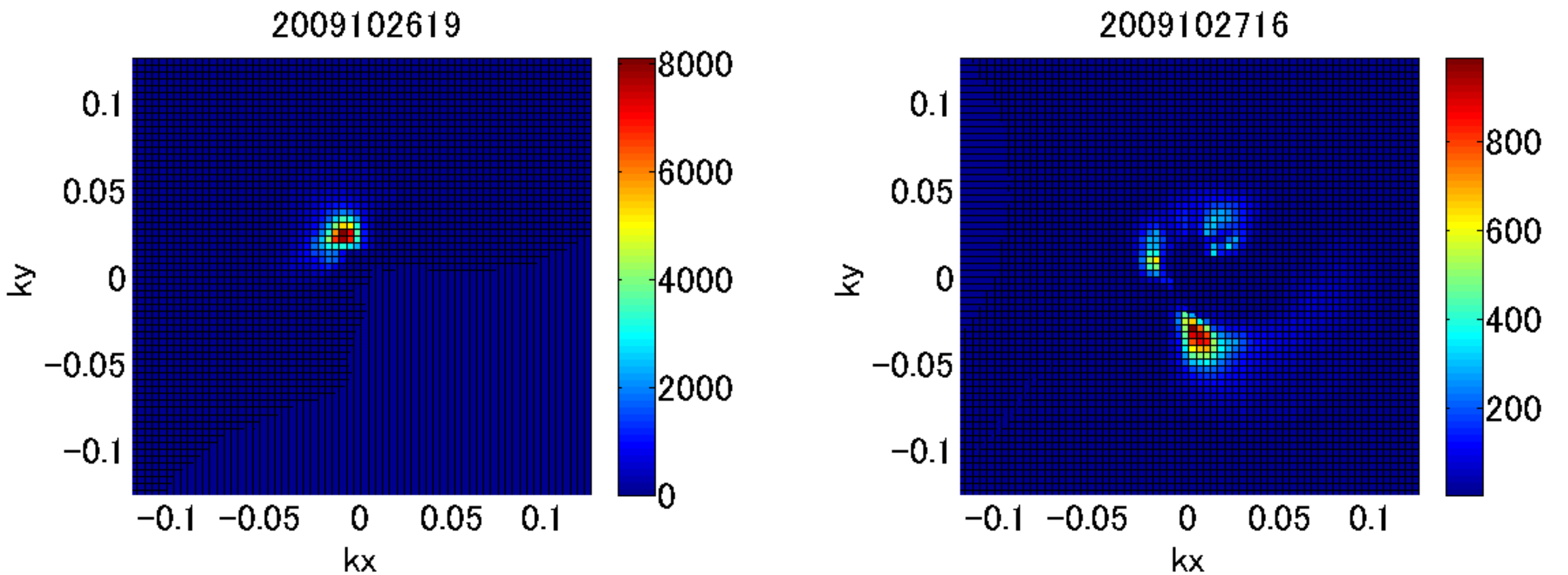
2009.10.27 13 m wave was observed at JKEO (red dot)
2009.10.28 12 m wave was observed at JKEO (blue dot)



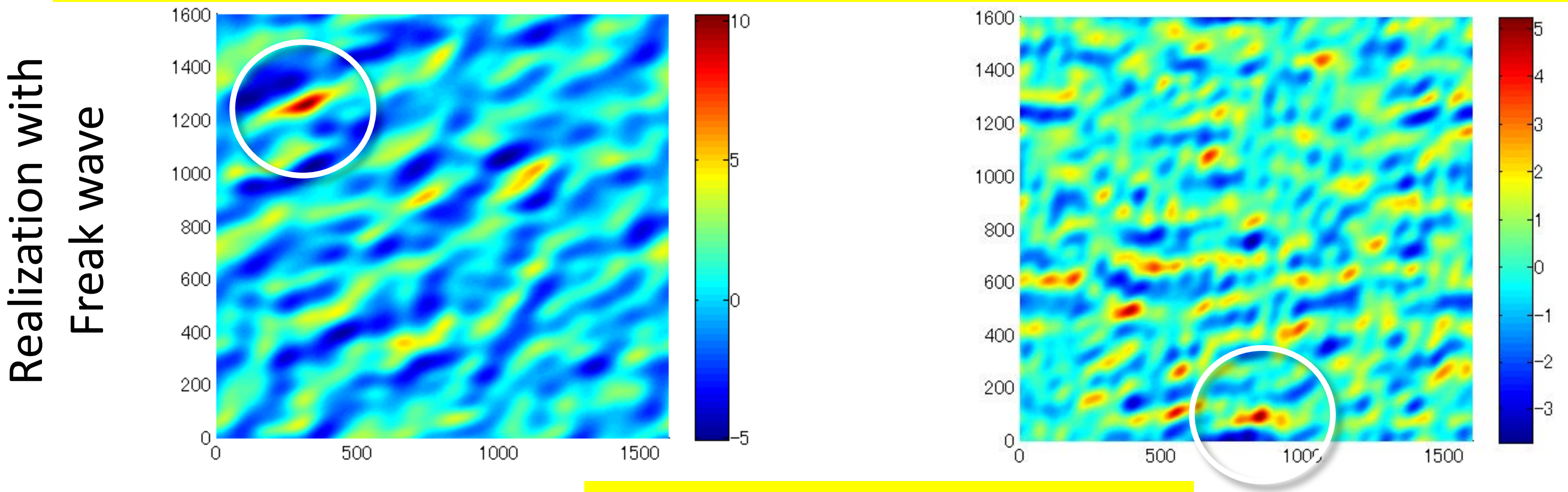
Q_p Frequency bandwidth

e.g. Tamura et al. 2009, Waseda et al. 2012,2013

Surface elevation from directional spectrum



Monte Carlo Simulation (100 periods x 10)with High-Order Spectral Method

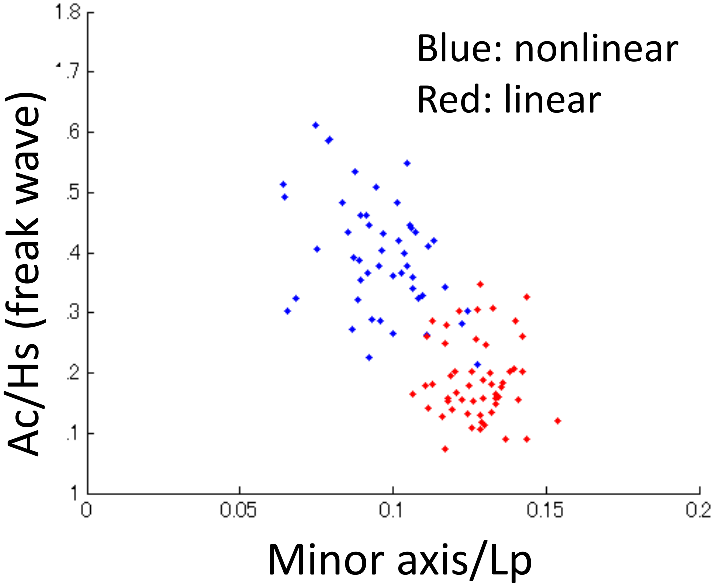


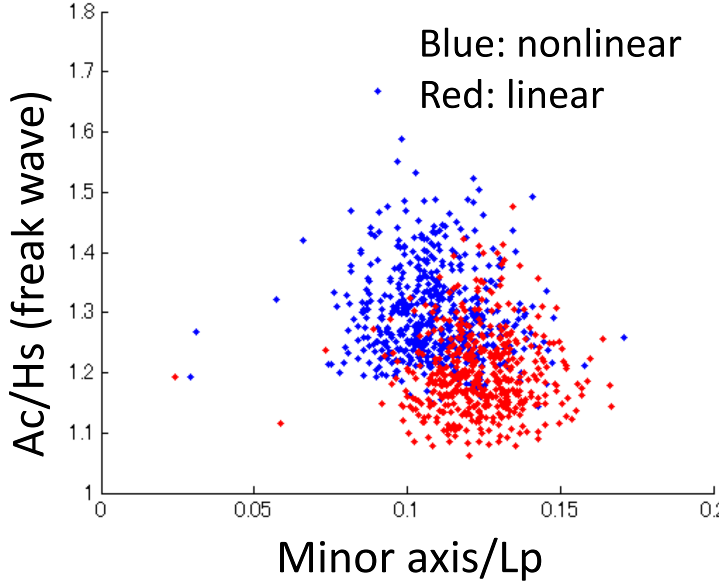
2013 Fujimoto, thesis UTokyo

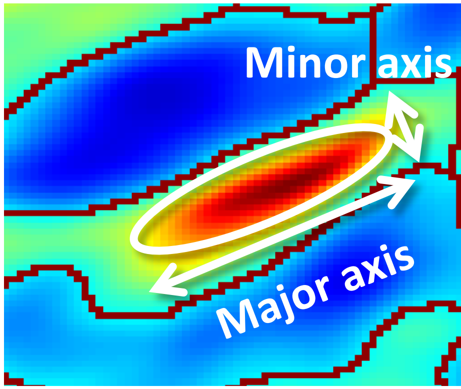
Geometry of freak waves – linear vs. nonlinear

Long crested wave field

Short crested wave field

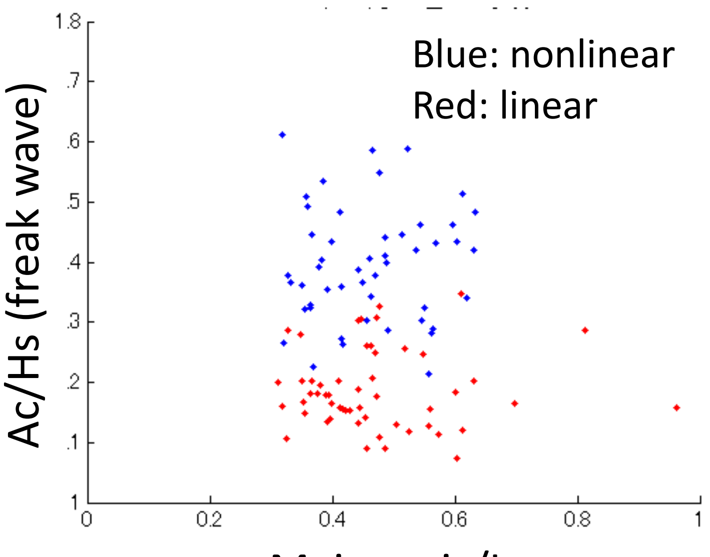


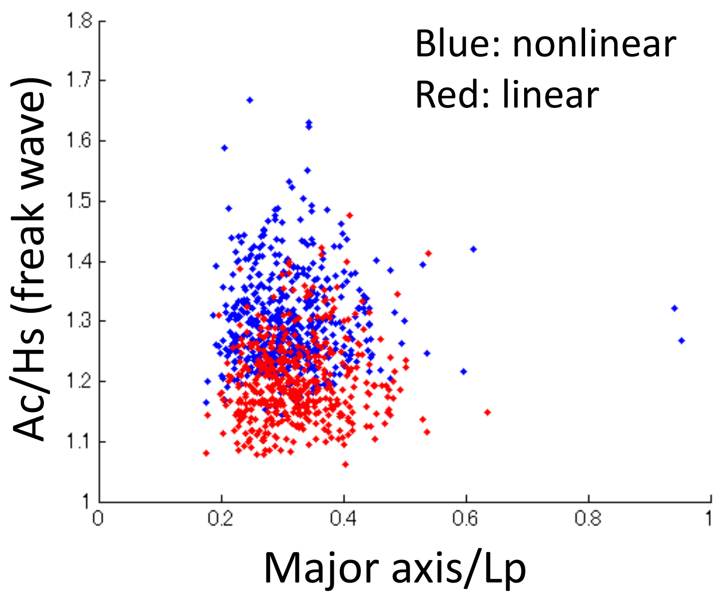




Threshold :
½ crest height

Minor axis reduces due to nonlinearity





The tendency is more evident with long crested waves

Nonlinear freak wave generation mechanism is more dominant with long crested wave field

2013 Fujimoto

Concluding remarks

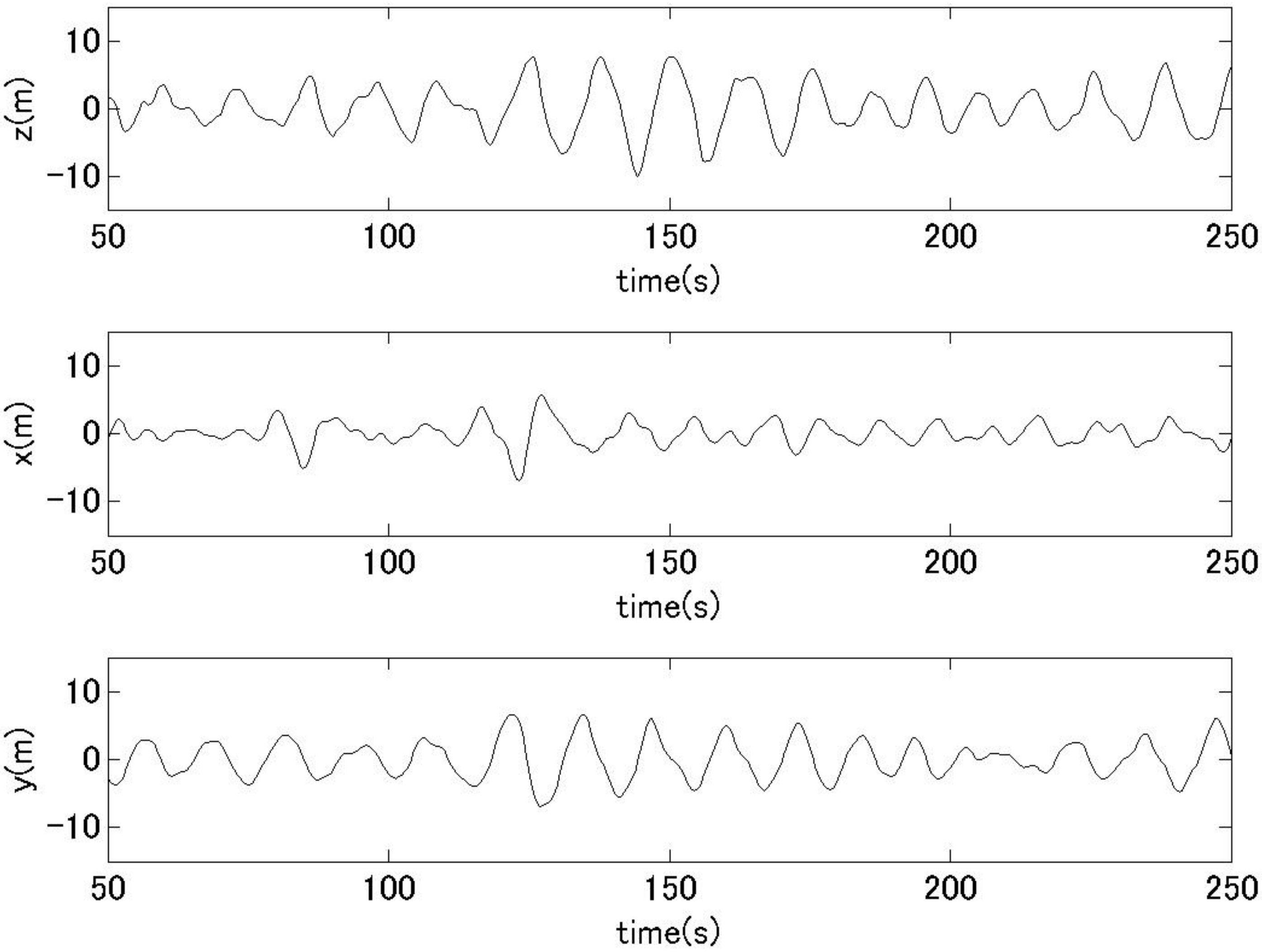
- Wave was successfully observed attaching a point-positioning GPS sensor to existing deep ocean met-ocean mooring buoys in 2009 (3 months) and 2012-2013 (3 months and 9 months)
- Statistical properties of observed buoy motion after appropriate filtering conform with the classical description of ocean waves
- Extreme waves including freak waves were successfully observed demonstrating the feasibility of GPS sensor without reference point
- Horizontal movement of the buoy indicate orbital motion close to group velocity for some large wave
  - Simultaneous accelerometer based observation will complement the GPS observation (see Collins' presentation in this WS)
- HOSM realization revealed relationship between nonlinearity and directional spreading

Wave shape around peak records   ak=0.22

Elevation

Zonal position

Meridional Position



Regional Operational Wave Model

WAVEWATCHIII™

- Sin, Sds: Tolman-Chalikov, Snl: DIA
- 2 tiered nested model

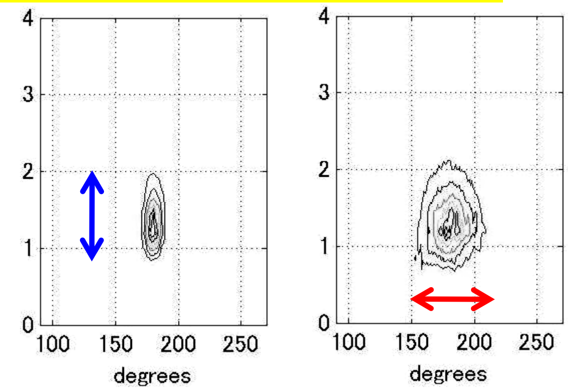
  1degree（Pacific）→ 1/4度（East of Japan）

  1degree (Pacific) → 1/10度（NKEO）

Wind

  NOGAPS（Pacific）→MSM（Regional）

In operation since 2009 April



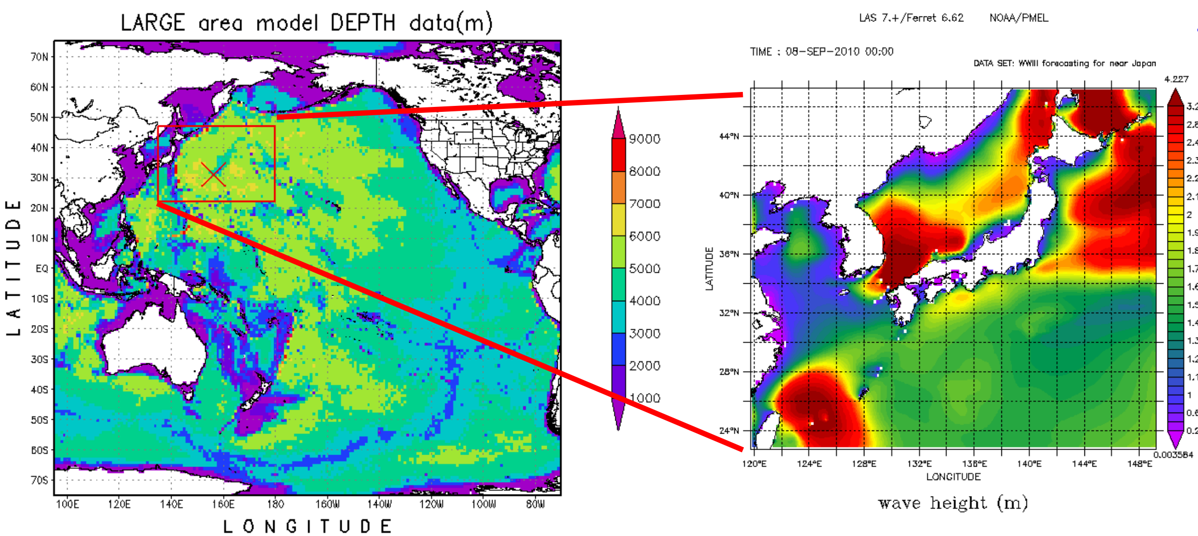
$$Q_p = 2m_0^{-2}\int_0^{\infty}\sigma\left[\int_0^{2\pi}F(\sigma,\theta)d\theta\right]^2 d\sigma$$

$$m_0 = \int_0^{2\pi}\int_0^{\infty}F(\sigma,\theta)d\sigma d\theta$$

$$\sigma_\theta = \left[2\left\{1-\left(\frac{a^2+b^2}{E^2}\right)^{\frac{1}{2}}\right\}\right]^{\frac{1}{2}}$$

$$a = \int_0^{2\pi}\int_0^{\infty}\cos(\theta)F(\sigma,\theta)d\sigma d\theta$$

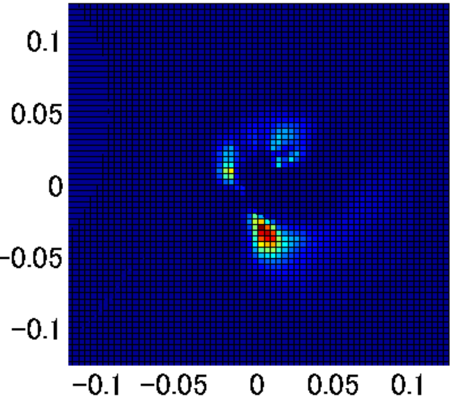
$$b = \int_0^{2\pi}\int_0^{\infty}\sin(\theta)F(\sigma,\theta)d\sigma d\theta$$



Tier 1

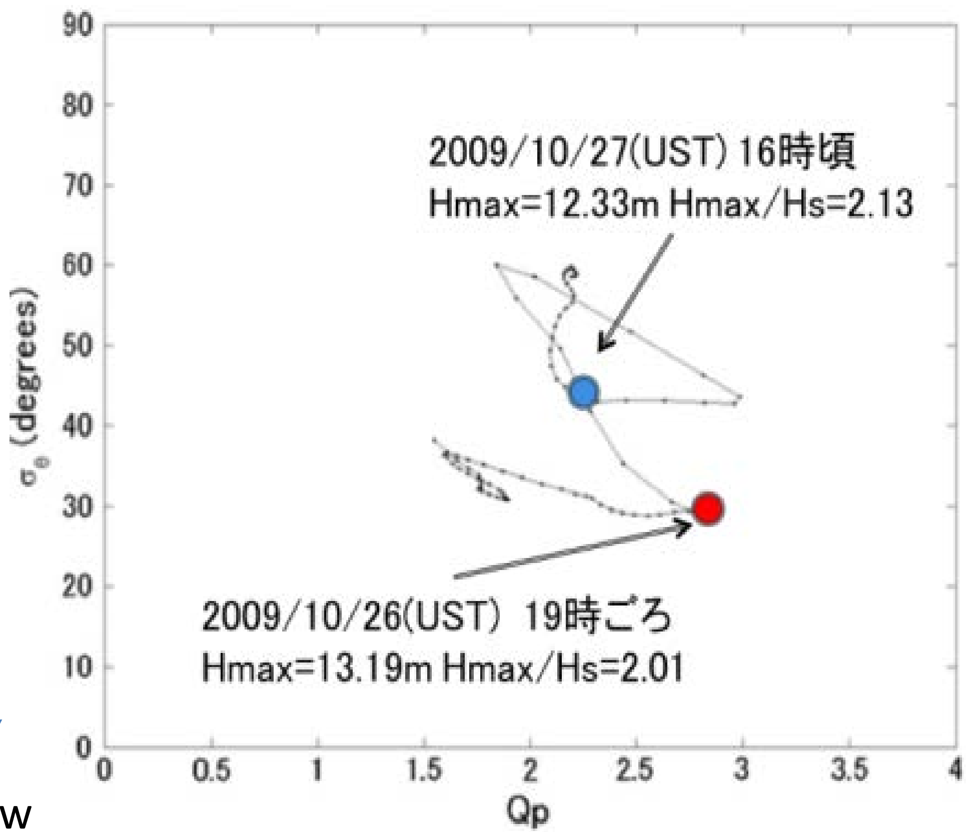
Tier 2

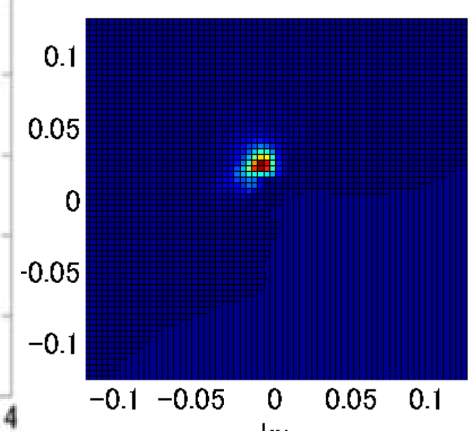
Observed Freakish Sea Index and directional spectrum from WW3



Directional
Spread

narrow





narrow

Frequency bandwidth