JMA's Storm Surge Prediction for the WMO Storm Surge Watch Scheme (SSWS)

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1. Introduction

Storm surges are one of severe phenomena in coastal regions and sometimes generate dreadful inundation disasters. Even in recent years, heavy storm surge disasters occurred worldwide, such as the one in the coast of the Gulf of Mexico caused by Hurricane Katrina in 2005, the one in the coast of Bangladesh by Cyclone Sidr in 2007, and the one in the coast of Myanmar by Cyclone Nargis in 2008. By these storm surges more than thousands of people suffered. The countermeasures for storm surges and inundation are crucial.

In response to a request by the WMO Executive Council (60th session, June 2008), WMO initiated the development of a regional storm surge watch scheme (SSWS) in regions affected by tropical cyclones. In relation to the western North Pacific and the South China Sea, the ESCAP/WMO Typhoon Committee (41st session, January 2009) endorsed a commitment by the RSMC-Tokyo to prepare storm surge forecasts with the aim of strengthening the storm surge warning capabilities of National Meteorological and Hydrological Services (NMHSs) in the region.

JMA began development of a storm surge model for the Asian region in 2010, in collaboration with Typhoon Committee Members who provide tide observation and sea bathymetry data. Since 1 June 2011, horizontal distribution maps of predicted storm surges have been published on JMA's Numerical Typhoon Prediction website. The provision of time sequences showing selected points is also scheduled for 2012.

This paper gives an outline of the storm surge model and its performance. The model's numerical considerations are described in the next section, and its operation is covered in Section 3. In Section 4, details of related products, examples, and levels of performance are given. The final section provides a summary and briefly describes further development plans.

2. Model

2.1 Equations

Storm surges are mainly caused by the wind setup due to strong onshore winds over the sea surface and the inverse barometer effect associated with pressure drops in low-pressure systems. To predict temporal and spatial sea level variations in response to such meteorological disturbances, a linearized two-dimensional storm surge model is used. The basic equations of the model incorporate vertically integrated momentum fluxes and the continuity of the water mass under a rotating fluid with gravity acceleration:

$$\frac{\partial U}{\partial t} - fV = -g(D+\eta)\frac{\partial(\eta-\eta_0)}{\partial x} + \frac{\tau_{sx}}{\rho} - \frac{\tau_{bx}}{\rho} \quad (1)$$

$$\frac{\partial V}{\partial t} + fU = -g(D+\eta)\frac{\partial(\eta-\eta_0)}{\partial y} + \frac{\tau_{sy}}{\rho} - \frac{\tau_{by}}{\rho} \quad (2)$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0 \quad (3)$$

where U and V are mass fluxes in the x- and y-directions, defined as:

$$U \equiv \int_{-D}^{\eta} u dz \quad (4)$$

$$V \equiv \int_{-D}^{\eta} v dz \quad (5)$$

where f is the Coriolis parameter, g is the gravity acceleration, D is the water depth below mean sea level, η is the surface elevation, η_0 is the water column height corresponding to the inverse barometer effect, ρ is the density of water; τ_{sx} and τ_{sy} are the x- and y-components of wind stress on the sea surface; and τ_{bx} and τ_{by} the stress by bottom friction. The wind stresses are expressed as:

$$\tau_{(sx,sy)}=c_d \rho_a W(u_w, v_w) \quad (6)$$

where c_d is the drag coefficient, ρ_a is the density of air, $W \equiv \sqrt{u_w^2+v_w^2}$ is the wind speed, and $(u_{w,} v_w)$ is the wind velocity. The drag coefficient is set from the results of Smith and Banke (1975) and Frank (1984):

$$c_d=\begin{cases}(0.63+0.066W)\times 10^{-3} & (W<25m/s)\\ \left(2.28+0.033(W-25)\right)\times 10^{-3} & (\mathrm{W}\geq 25\mathrm{m/s})\end{cases} \quad (7)$$

The equations are solved by numerical integration using the explicit finite difference method.

2.2 Data

The bathymetry data for the storm surge model is mainly made from the 2-minute Global Gridded Elevation Data (ETOPO2) of NGDC/NOAA (Figure 1). The bathymetry data was partly modified with local bathymetry data provided by the Typhoon Committee Members, which enable more accurate forecast.

The model calculates only storm surge values. Storm tide levels are calculated as the sum of storm surges and astronomical tides, the latter of which are determined by harmonic analysis using the past observational tide data provided by the Members.

2.3 Meteorological forcing

The storm surge model requires fields of surface wind and atmospheric pressure as external forcing, and these fields – especially winds – are the key factors in storm surge prediction performance. In the operation of the SSWS storm surge model, two kinds of meteorological forcing field are used. One is a simple parametric TC model, and the other is the products of the JMA operational Global Spectral Model (GSM).

The parametric TC model is considered superior to the NWP model in terms of TC track and intensity forecast accuracy because its meteorological field is provided by RSMC TC advisories. The simple parametric TC model used by Konishi (1995) based on Fujita's empirical formula (Fujita, 1952) is adopted. The radial pressure distribution of the simple parametric TC model is represented as follows (Figure 2):

$$P=P_\infty-\frac{P_\infty-P_c}{\sqrt{1+(r/r_0)^2}} \quad (8)$$

From the pressure profile, the gradient wind speed is calculated with the following relation (Figure 3):

$$-\frac{v^2}{r} - fv = -\frac{1}{\rho}\frac{\partial P}{\partial r} \quad (9)$$

In equations (8) and (9), P is the atmospheric pressure at distance r from the center of the TC, P_∞ is the environmental atmospheric pressure at a sufficiently distant point, P_c is the TC central pressure, r_0 is the scaling factor of the radial distribution of pressure, and v is the gradient wind speed. The wind vectors are rotated inward 30 degrees to express inflow to the TC center. To express the asymmetry of the wind field in a TC, the movement velocity vector of the TC multiplied by a weight that decays exponentially with distance from the TC center is added to the wind vector. The resulting wind and pressure fields are applied to the storm surge model as external force. These formulae diagnose wind and pressure fields at each point in time using the necessary input of forecast values as follows:

- TC center location (longitude and latitude)
- Minimum pressure at the TC center
- Maximum sustained wind speed
- Radius of the 50-kt wind speed area (if present)
- Radius of the 1,000-hPa isobar

These values are obtained from tropical cyclone advisories issued by the RSMC Tokyo – Typhoon Center.

The SSWS storm surge model also uses wind and pressure fields predicted by the GSM, which is a hydrostatic numerical weather prediction model with 0.25 x 0.2-min horizontal grid resolution. It runs four times a day and provides 216-hour (9-day) forecasts covering the globe. As typhoon intensity is often underestimated by the GSM, and typhoon track by the parametric TC estimates better intensity than GSM, the GSM meteorological fields around TCs are implanted by the parametric TC model.

3. Operation

Table 1 shows the outline of the specifications of the SSWS storm surge model. The horizontal grid resolution is 2 minutes, corresponding to a distance of about 3.7 km. The model covers almost all coastal areas in the RSMC Tokyo area of responsibility (Figure 4). It runs four times a day (every 6 hours) on the JMA supercomputer system, and calculates storm surge predictions up to 72 hours ahead.

Each calculation takes about 10 minutes, and storm surge distribution maps are created using the results. When no typhoon is expected during the forecast time, the model calculates data only for the next run, and no distribution maps are produced.

4. Products

JMA began issuing storm surge distribution maps for Typhoon Committee Members via JMA's Numerical Typhoon Prediction Website (https://tynwp-web.kishou.go.jp/) on 1 June 2011 (Figure 5). Maps of the whole computational domain and enlarged versions showing only the areas around typhoons are available on the website. The data can also be downloaded up to 72 hours ahead in ZIP compressed format. It is important to evaluate the performance of the storm surge model, and an example of storm surge simulation results is given in this section.

Case study: Typhoon Koppu (T0915)

Figure 6 shows a storm surge distribution map for Typhoon KOPPU (T0915), which generated extremely high storm surges in Hong Kong and Macao and made landfall on the coast of southern China. Although the time of the predicted peak surge was slightly later than the observed one, the heights of the predicted peak surges are quite comparable to the observed values (Figure 7).

Verification

To examine the performance of the SSWS storm surge model, we verified the model accuracy by comparing predicted values with observed ones. In this verification, hourly storm surge predictions were compared with observations at seven tide stations. The predictions are calculated by the GSM analysis data (Sep. 2007 – Dec. 2010) and the parametric TC model with typhoon best track data (RSMC Tokyo). Figure 8 shows a scatter diagram of the predicted storm surges against the observed values. The predicted values include all those for 1-hour through 72-hour forecast time. The figures show that the surge predictions lie in the range of ±100 cm.

To quantitatively evaluate the accuracy of the model, bias score (BS), false alarm ratio (FAR), threat scores (TS) and probability of detection (POD) values were also calculated for verification (Figure 9). The definitions of these scores are found in the appendix. The bias scores slowly decrease to zero with a storm surge threshold of over 90 cm. The FAR scores decrease with a threshold of less than 140 cm and increase with thresholds over this value. Both TS and POD decrease with a threshold of over 90 cm. These scores indicate that the SSWS model tends to underestimate large storm surges.

5. Summary

JMA is expected to provide Typhoon Committee Members with storm surge information within the framework of the WMO Storm Surge Watch Scheme (SSWS), and began the development of a storm surge model for Asian areas in 2010. The setup of the system was completed in 2011, and JMA started issuing storm surge predictions on 1 June of the same year.

The model runs four times a day and predicts storm surge conditions up to 72 hours ahead. Horizontal distribution maps of surges are uploaded to the Numerical Typhoon Prediction Website provided by RSMC Tokyo - Typhoon Center in real time. JMA plans to start providing storm surge time-series charts in 2012 at one point for each TC Member, with possibly more points to be added in later years (Figure 10).

Appendix: Verification score definitions

This appendix gives the definitions of the verification scores used in this paper, which are based on Jolliffe and Stephenson (2003). All pairs of predicted and observed values are divided into four categories as shown in Table A1, and the frequencies of each category are used to calculate the verification scores.

(1) Bias score

The bias score is the ratio of the number of forecasts of occurrence to the number of actual occurrences. Scores range from 0 to infinity and the perfect score is 1.

$$BS = \frac{(Hits) + (False\ alarms)}{(Hits) + (Misses)} \quad \text{(A1)}$$

(2) Probability of detection (POD)

This quantity is defined by:

$$POD = \frac{(Hits)}{(Hits) + (Misses)} \quad \text{(A2)}$$

It represents the total number of correct event forecasts (hits) divided by the total number of events observed. It ranges from 0 to 1, and the perfect score is 1.

(3) False alarm ratio (FAR)

FAR is defined by:

$$FAR = \frac{(False\ alarms)}{(Hits) + (False\ alarms)} \quad \text{(A3)}$$

It is the number of false alarms divided by the total number of event forecasts. It can vary from 0 to 1. A FAR value of 0 represents perfect skill.

(4) Threat score (TS)

TS is defined by:

$$TS = \frac{(Hits)}{(Hits) + (False\ alarms) + (Misses)} \quad \text{(A4)}$$

It can vary from 0 to 1. A TS value of 0 represents perfect skill.

References

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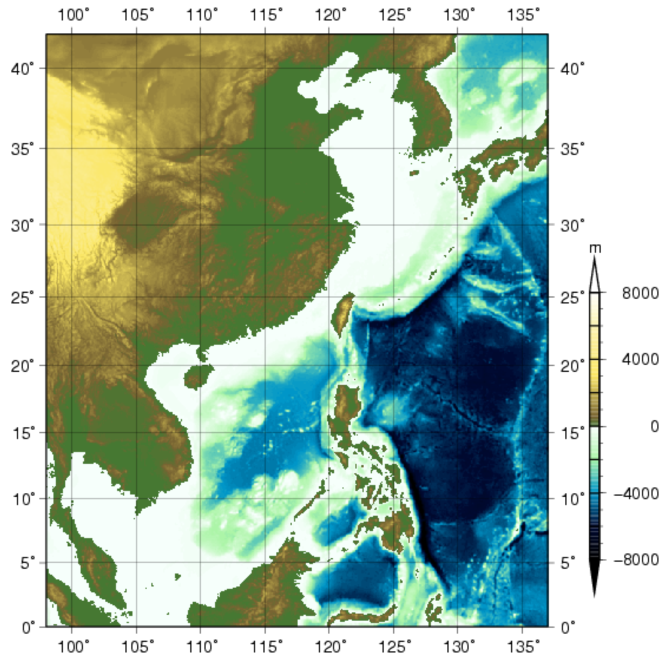

Figure 1 The SSWS model region and topography

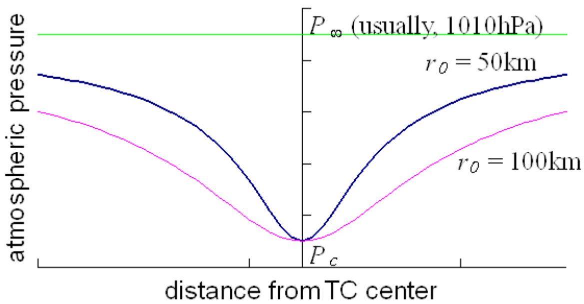

Figure 2 Distributions of surface atmospheric pressure against the distance from the TC center based on Fujita's formula

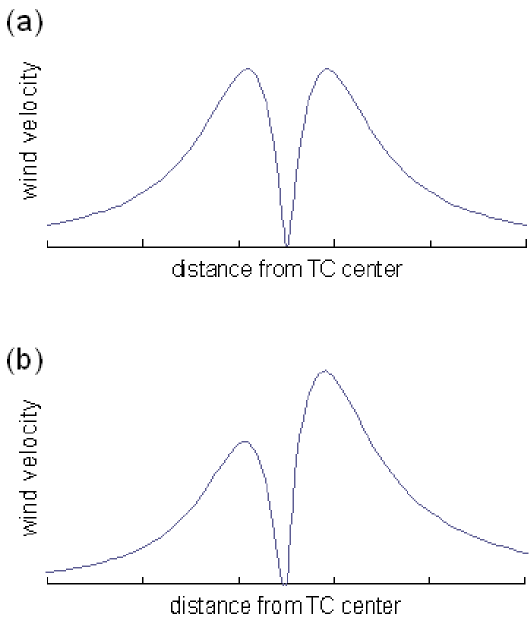

Figure 3 Distributions of surface wind speed against the distance from the TC center by gradient wind and movement velocity

(a) Gradient wind

(b) Gradient wind with movement velocity for asymmetry

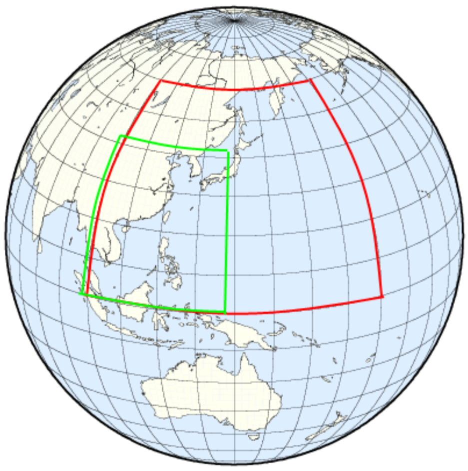

Figure 4 RSMC Tokyo region and SSWS model region

The red and green lines show RSMC Tokyo region and SSWS model region, respectively.

Table 1 SSWS model specifications

Model	2-dimensional linear model
Grid	Lat-Lon grid
Region	0 – 42ºN, 98ºE – 137ºE
Resolution	2’ x 2’, 1,171 x 1,261 (– 3.7 km)
Time step	8 seconds
Forecast time	72 hours
Cycle	4/day (every 6 hours)
Initial time (UTC)	00, 06, 12, 18
Member	1 member (no-typhoon case: model GPV; typhoon case: model GPV + bogus (center))
Model GPV forcing	GSM (Asian region, 0.25º x 0.2º)
Typhoon forcing (bogus)	Pressure: Fujita’s formula Inflow angle: 30º Movement velocity for asymmetry

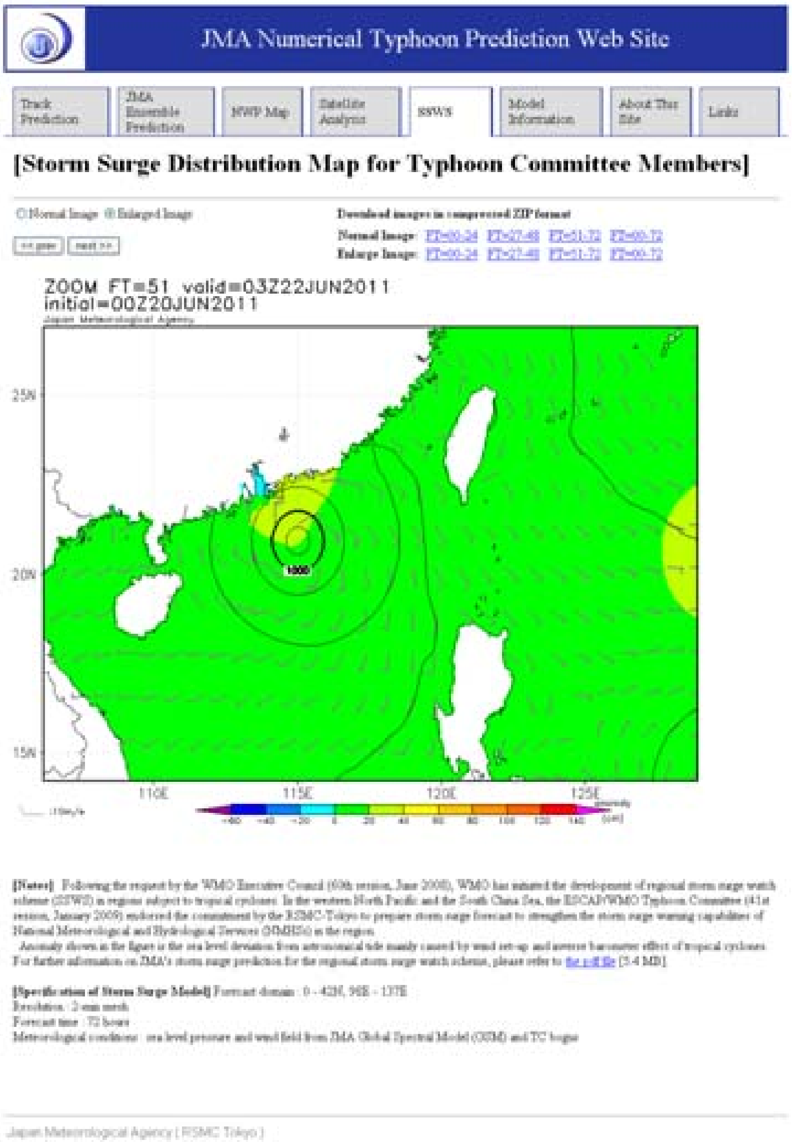

Figure 5 JMA Numerical Typhoon Prediction Website

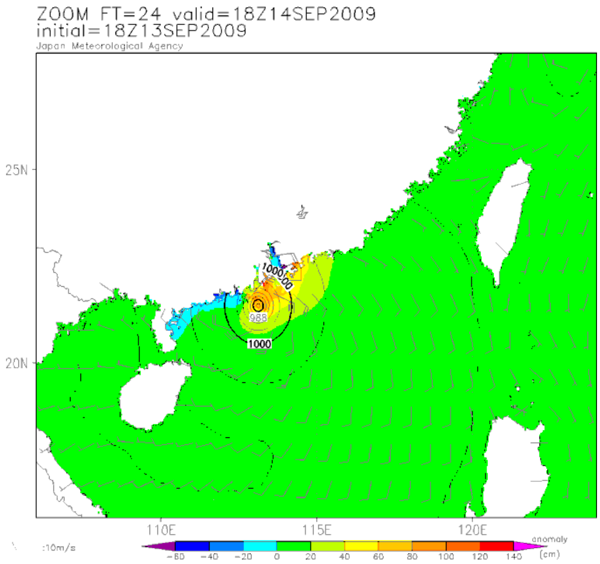

Figure 6 Storm surge distribution map for Typhoon Koppu (T0915)

The colors show storm surge height (cm), the contours show surface pressure (hPa), and the barbs show surface wind. The initial time is 18 UTC on 13 Sep., 2009.

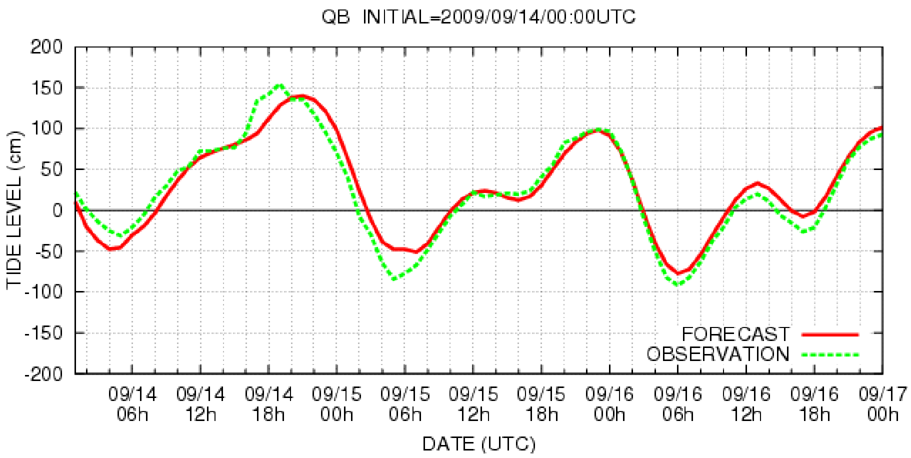

Figure 7 Time-series chart of predicted and observed tides at Quarry Bay (Hong Kong) for Typhoon Koppu (T0915)

The red and green lines show forecast and observed tides, respectively (cm). The initial time is 00 UTC on 14 Sep., 2009.

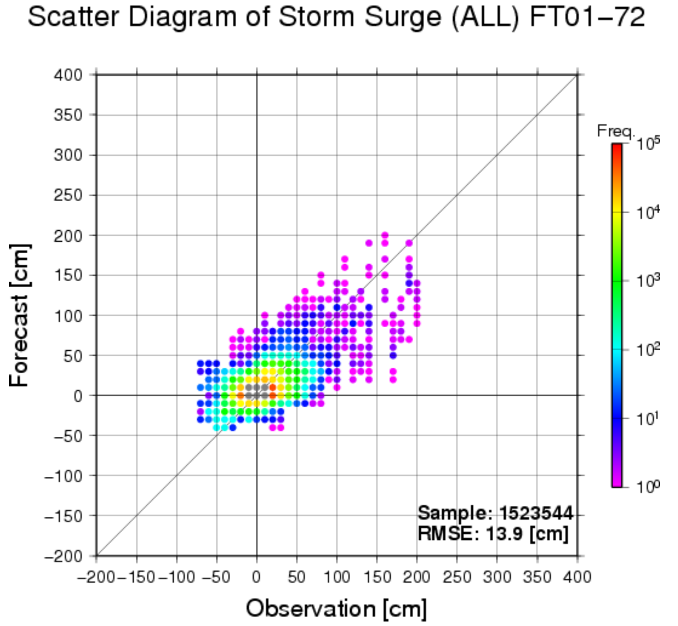

Figure 8 Scatter diagram of predicted storm surges against observed values

The statistical period is Sep. 2007 – Dec., 2010. The stations used were Quarry Bay (Hong Kong), Manila South Harbor (Philippines), Mariveles Harbor (Philippines), Macao, Tanjong Pagar (Singapore), and Huahin (Thailand).

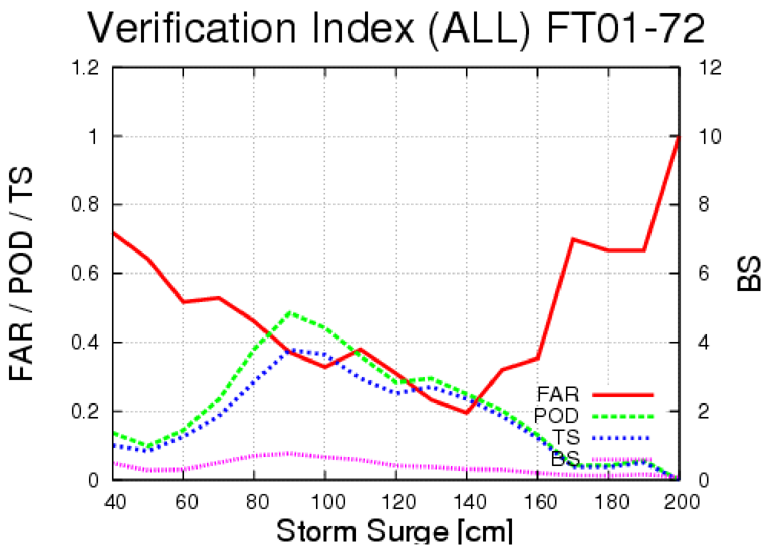

Figure 9 Verification scores

FAR: False Alarm Ratio; POD: Probability Of Detection;

TS: Threat Score; BS: Bias Score

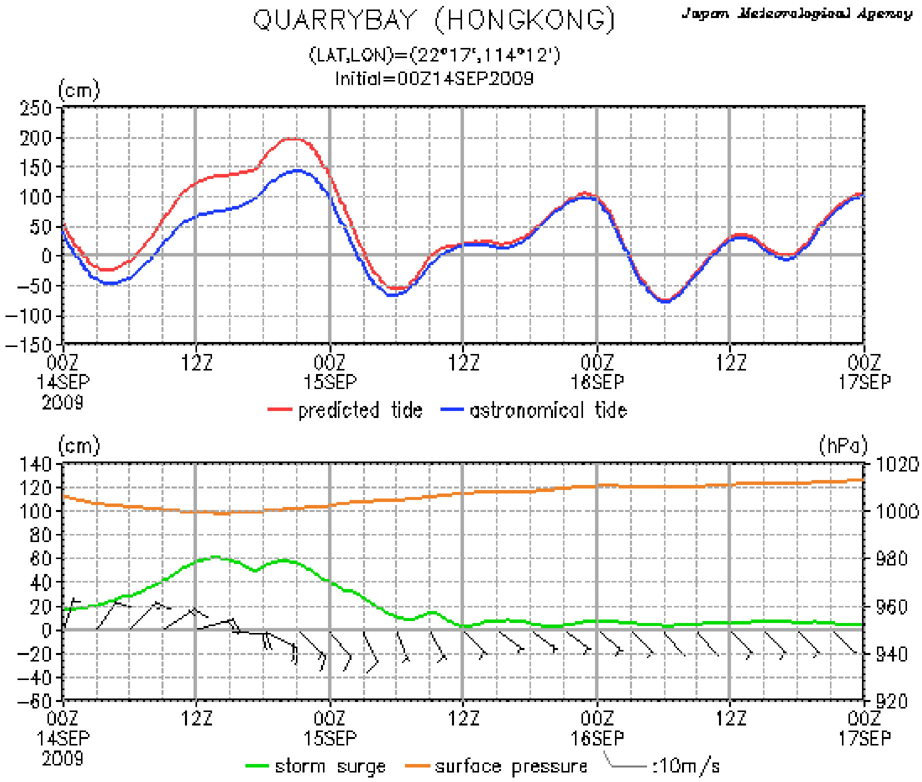

Figure 10 Time-series chart of predicted/astronomical tides and storm surge at Quarry Bay (Hong Kong)

The upper figure shows a time-series of predicted (red line) and astronomical (blue line) tides (cm). The lower figure shows a time-series of the predicted storm surge (cm), with barbs showing the wind speed and direction. The initial time is 00 UTC on 28 Jul., 2011.

Table A1 Contingency table

		Observed	
		Yes	No
Forecast	Yes	Hits	False alarms
	No	Misses	Correct negatives