# Supporting Information for "Modeled and satellite-derived extreme wave height statistics in the North Atlantic Ocean reaching 20 m"

Kaushik Sasmal[1], Tsubasa Kodaira[1], Yuki Kita[2], Rei Miratsu[3], Tingyao Zhu[3], Tsutomu Fukui[3], Takuji Waseda[1]

[1]Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa, Chiba, Japan

[2]MS & AD InterRisk Research & Consulting, Inc., Chiyoda, Tokyo, Japan

[3]Nippon Kaiji Kyokai (ClassNK), Chiyoda, Tokyo, Japan

## Contents of this file

**Text S1.**

## 1. Model Set-up

TodaiWW3-NK is based on third–generation spectral wave model NOAA WAVEWATCH III version 6.07 (The WAVEWATCH III® Development Group (WW3DG), 2019). The model computational domain encompasses the Atlantic Ocean. The bathymetry data for the model was derived from ETOPO1 (Amante & Eakins, 2009). The spatial resolution of the model is $0.20^o \times 0.25^o$ (Lat $\times$ Lon). There are 35 frequency bins and 36 directional bins. The lowest and the highest frequencies were set to 0.04118 Hz and 1.1 Hz. For model physics, the ST4 package of Ardhuin et al. (2010) was used. The model was forced by NCEP/CFSR hourly wind (Saha et al., 2010, 2014). NCEP/CFSR daily sea ice concentration was provided to the model as a source of sea ice. A one-month spin-up run was carried out and the model was integrated for 25 years in hindcast mode (1994-2018). Significant wave height (Hs) was post-processed from model output for GWS areas 8,9,15, and 16. The Hs from the model is validated against satellite altimeter data (Ribal & Young, 2019) and UK Met Office buoy data.

### 1.1. Equations for statistics

$$\mathrm{CC} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}, \tag{1}$$

$$\mathrm{Bias} = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i), \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2}, \tag{3}$$

$$\mathrm{SI} = \frac{RMSE}{\bar{x}}, \tag{4}$$

where $x_i$ is the observed value, $y_i$ is the computed value of wave parameter, $n$ is the number of observations, $\bar{x}$ is the averaged observed value, $\bar{y}$ is the averaged computed value.

## References

Amante, C., & Eakins, B. (2009). ETOPO1 1 arc-minute global relief model: procedures, data sources and analysis. NOAA technical memorandum NESDIS NGDC-24. *National Geophysical Data Center, NOAA*.

Ardhuin, F., Rogers, E., Babanin, A. V., Filipot, J.-F., Magne, R., Roland, A., ... others (2010). Semiempirical dissipation source functions for ocean waves. part i: Definition, calibration, and validation. *Journal of Physical Oceanography*, *40*(9), 1917–1941.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., ... others (2020). The era5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*.

Rascle, N., & Ardhuin, F. (2013). A global wave parameter database for geophysical applications. part 2: Model validation with improved source term parameterization. *Ocean Modelling*, *70*, 174–188.

Ribal, A., & Young, I. R. (2019). 33 years of globally calibrated wave height and wind speed data based on altimeter observations. *Scientific data*, *6*(1), 1–15.

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., ... others (2010). The NCEP climate forecast system reanalysis. *Bulletin of the American Meteorological Society*, *91*(8), 1015–1058.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., ... others (2014). The NCEP climate forecast system version 2. *Journal of Climate*, *27*(6), 2185–2208.

The WAVEWATCH III® Development Group (WW3DG). (2019). User manual and system documentation of WAVEWATCH III® version 6.07. *Tech. Note 333*, *NOAA/NWS/NCEP/MMAB, College Park, MD, USA, 465 pp. +Appendices.*.

**Table S1.** Comparison of $H_s$ statistics between models and observations.

| Extreme event | Model | Statistics | | | |
|---|---|---|---|---|---|
| Date and time | | CC | Bias (m) | RMSE (m) | SI |
| 20140105 07:23:22 UTC | ERA5 | 0.97 | -1.79 | 2.45 | 0.22 |
| SARAL (Ka band) | IOWAGA | 0.98 | -0.02 | 0.98 | 0.09 |
| | TodaiWW3-NK | 0.98 | 0.18 | 0.93 | 0.08 |
| 20070209 21:30:40 UTC | ERA5 | 0.96 | -1.05 | 1.95 | 0.21 |
| JASON-1 (Ku C band) | IOWAGA | 0.99 | -0.25 | 0.85 | 0.09 |
| | TodaiWW3-NK | 0.99 | -0.18 | 0.76 | 0.08 |
| 20110214 11:03:10 UTC | ERA5 | 0.98 | -0.57 | 1.04 | 0.11 |
| JASON-2 (Ku C band) | IOWAGA | 0.99 | -0.36 | 0.78 | 0.08 |
| | TodaiWW3-NK | 0.98 | 0.10 | 0.75 | 0.08 |
| 20130204 06:00:00 UTC | ERA5 | 0.99 | -0.28 | 0.64 | 0.12 |
| K5 buoy | TodaiWW3-NK | 0.98 | 0.06 | 0.63 | 0.12 |

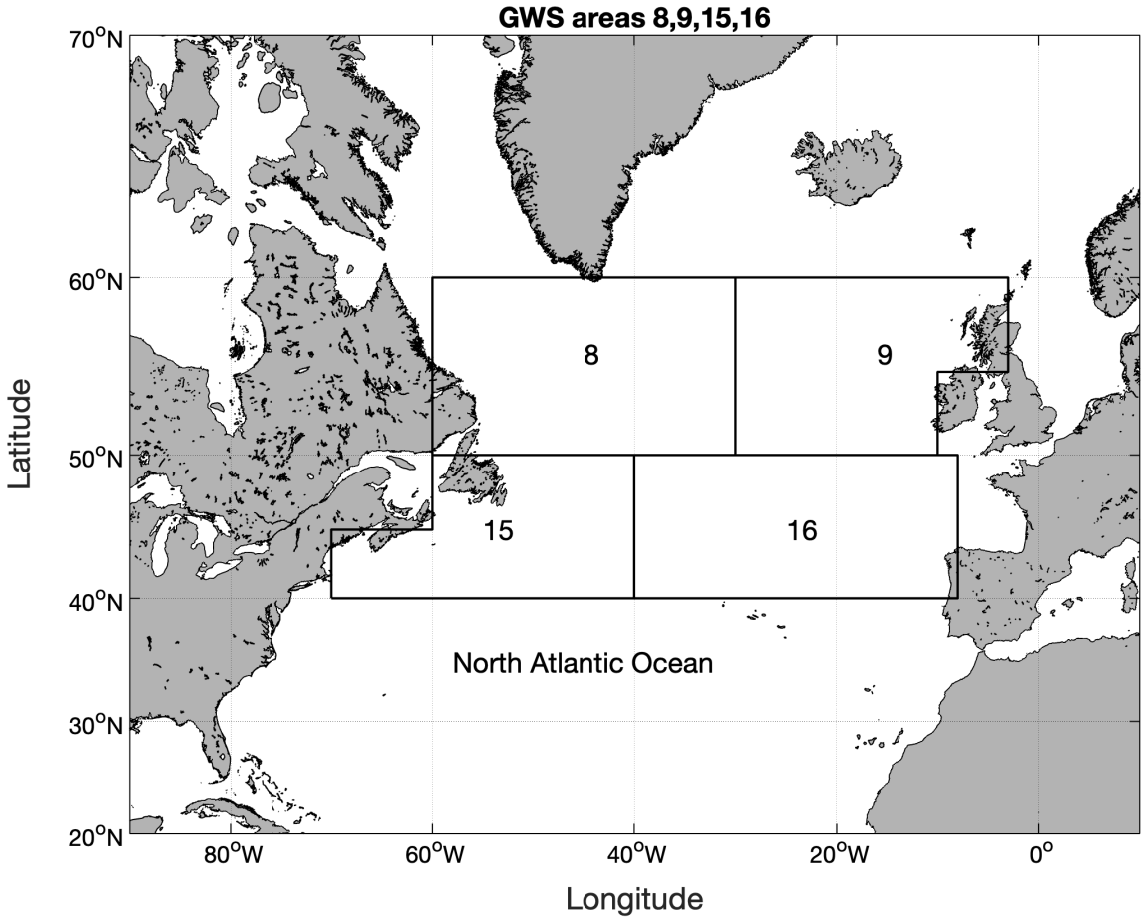


**Figure S1.** Map of study region and the Global Wave Statistics (GWS) areas 8,9,15,16 are shown.

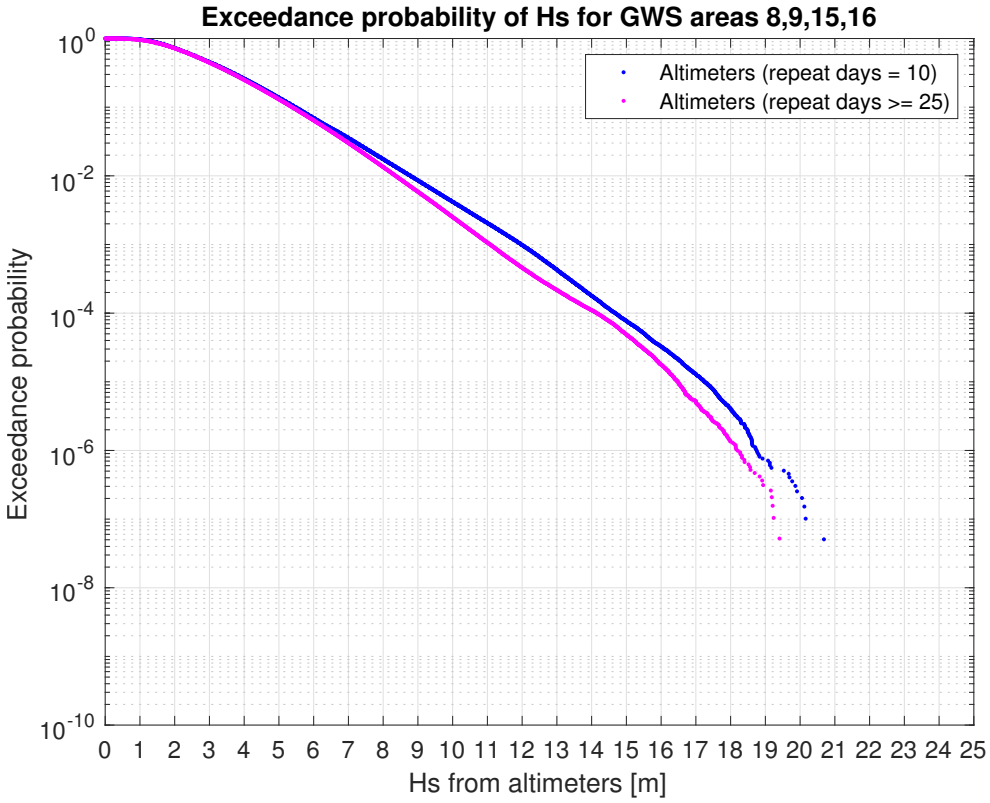


**Figure S2.** Comparison of exceedance probability of significant wave height between altimeters with repeat cycle=10 days and repeat cycle >=25 days. The altimeters with repeat cycle=10 days are TOPEX, JASON-1, JASON-2, and JASON-3. The altimeters with repeat cycle >=25 days are ERS-2, ENVISAT, CRYOSAT-2, SARAL, and SENTINEL-3A. The comparison is made for GWS areas 8,9,15 and 16 using 25 years data from 1994 to 2018.

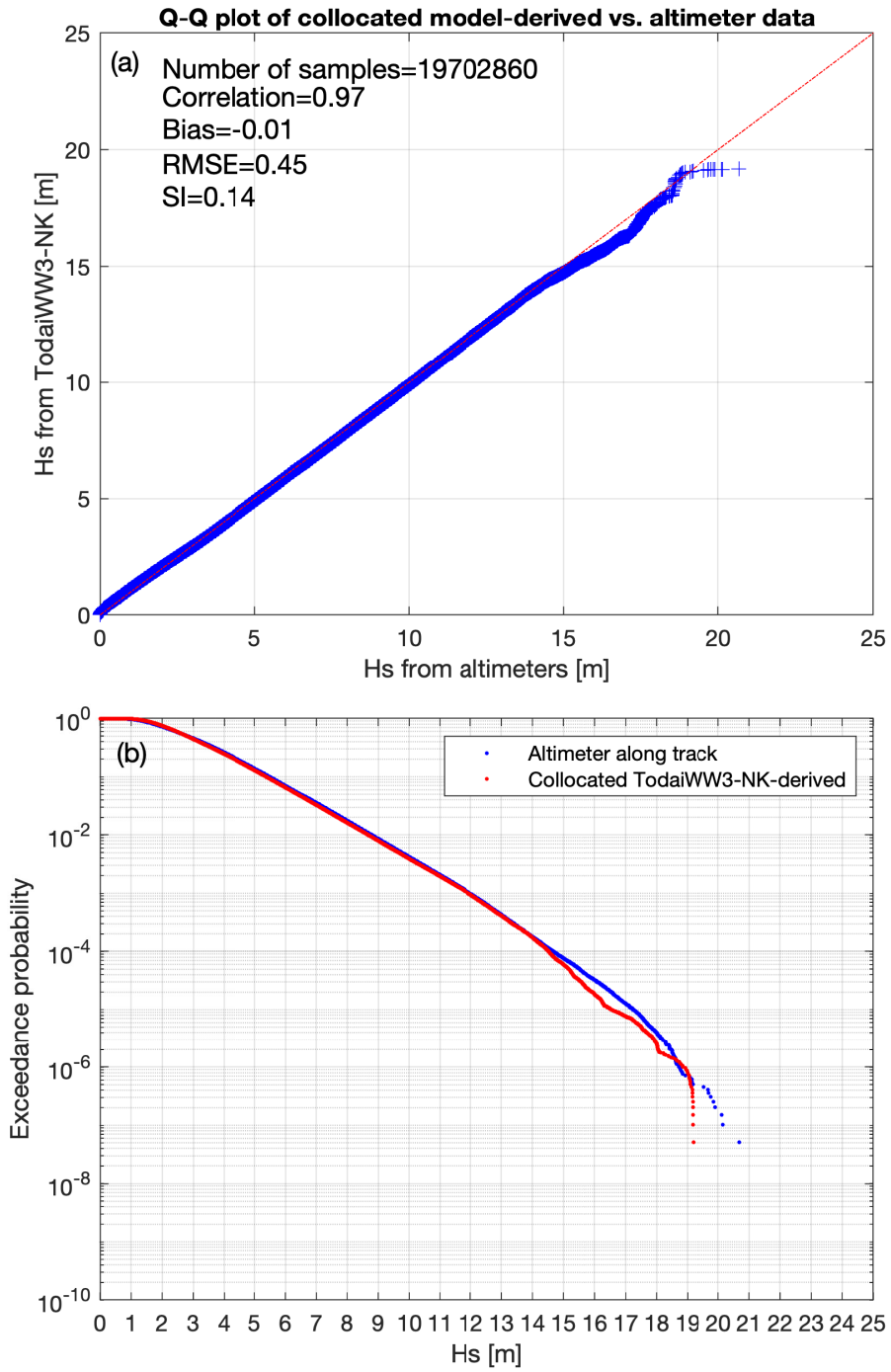


**Figure S3.** (a) Q-Q plot of Hs between TodaiWW3-NK and altimeter derived data for the GWS 8,9,15,16. (b) Comparison of exceedance probability of Hs between TodaiWW3-NK and altimeter derived data. Here the collocated model derived and altimeter along track derived data for 25 years from 1994-2018 are used for the comparson.

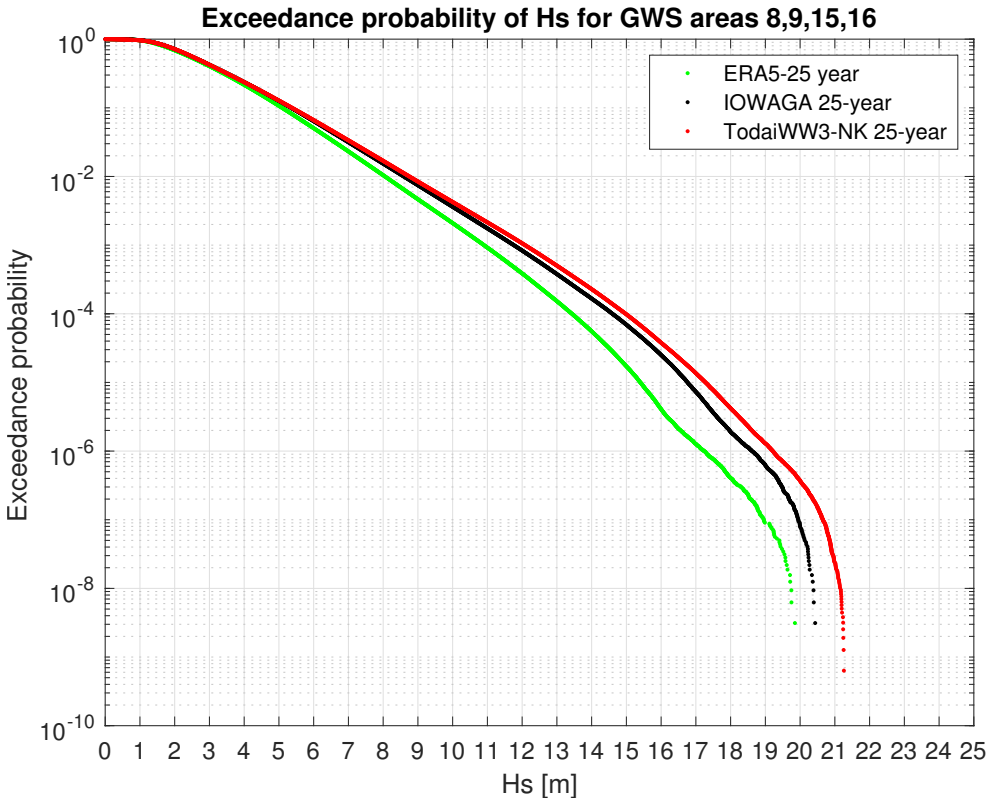


**Figure S4.** Comparison of exceedance probability of Hs between models for the GWS 8,9,15,16. Here 25 years of data from 1994-2018 are used.

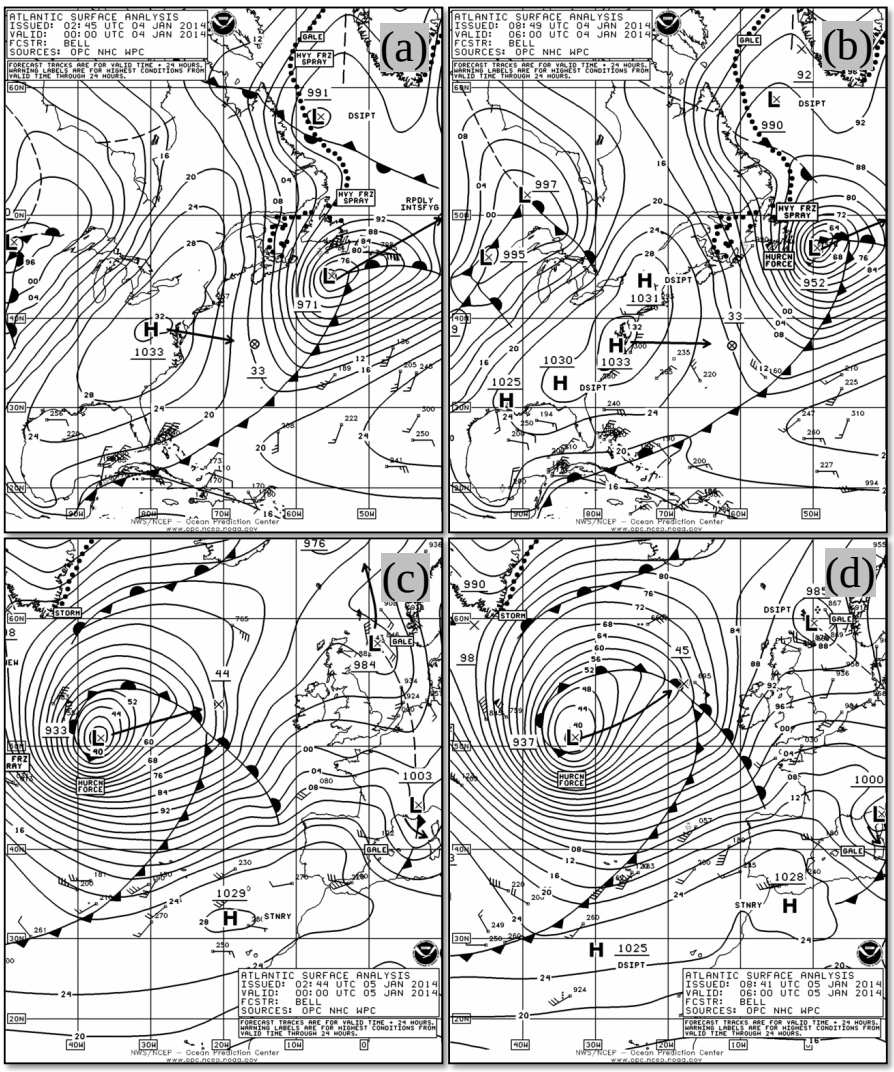


**Figure S5.** NOAA OPC synoptic analysis charts for 00:00 UTC and 06:00 UTC on 04 Jan 2014 (a,b) and for 00:00 UTC and 00:06 UTC on 05 Jan 2014 (c,d). On 04 Jan, the storm was near 44°N, 55°W with a SLP of 971 hPa at the center. It was expected to track northeast (shown by the arrow) and rapidly intensify to hurricane force. By 0000 UTC on 05 Jan, the storm had intensified with SLP of 933 hPa at the center of the storm with hurricane-force winds and moved



to 51°N, 38°W.

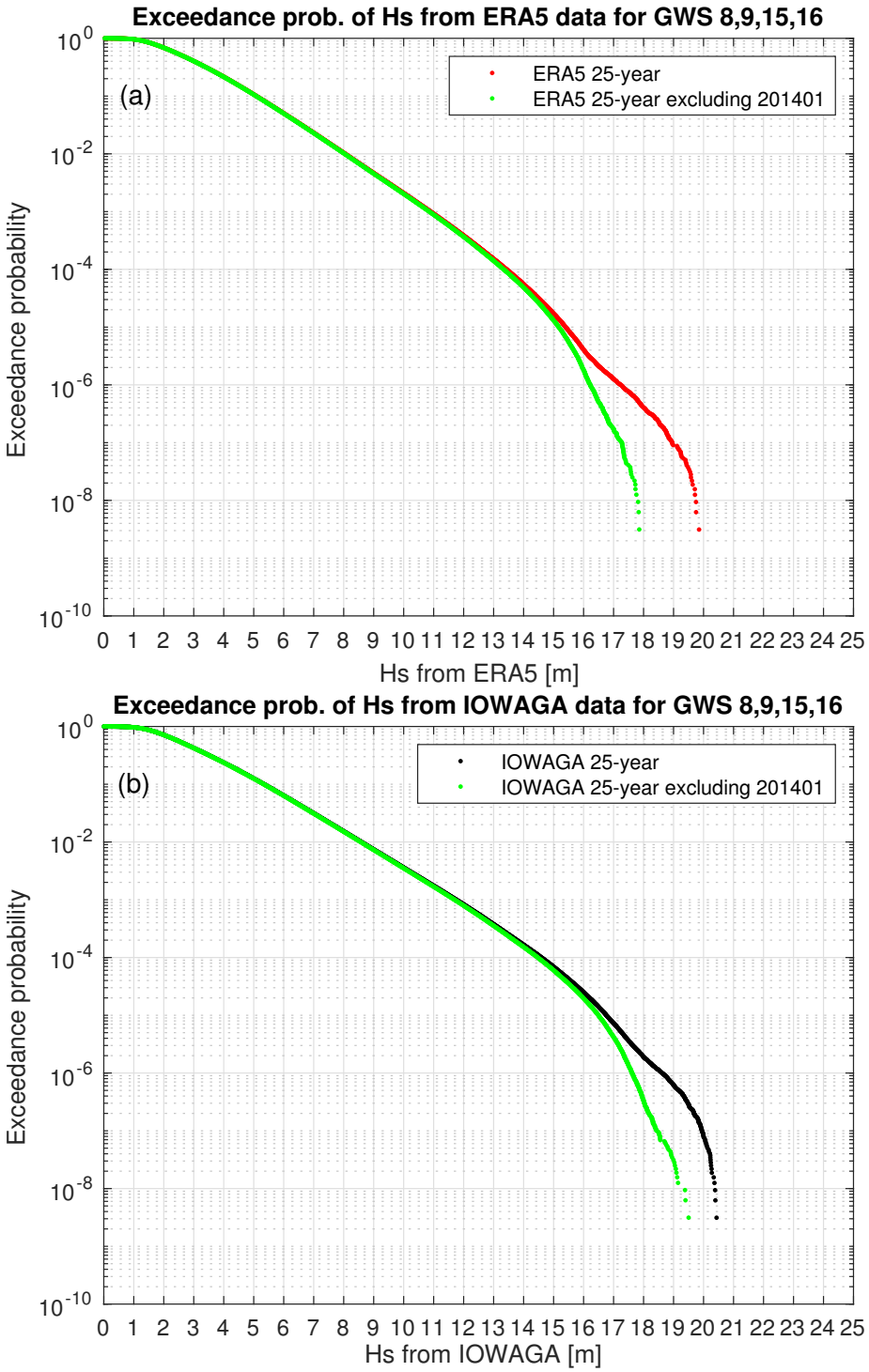


**Figure S6.** The exceedance probability of Hs is compared with and without January 2014 data. (a) Exceedance probability of significant wave height from ERA5 using 25 year 3-hourly data from 1994 to 2018 for GWS areas 8,9,15 and 16. (b) Exceedance probability of significant wave height from IOWAGA using 25 year 3-hourly data from 1994 to 2018 for GWS areas 8,9,15 and 16.

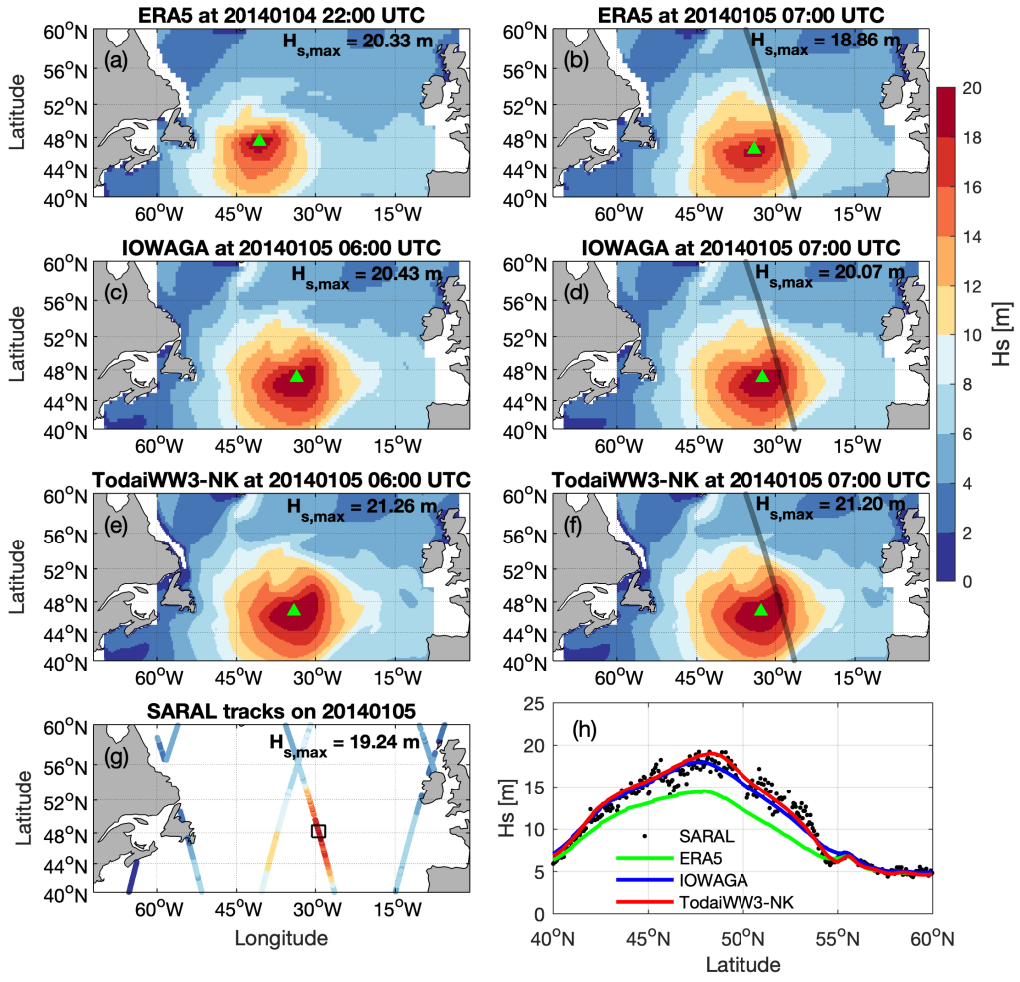


**Figure S7.** Spatial distribution of Hs from ERA5, IOWAGA and TodaiWW3-NK data during the extreme event in January 2014. The subplots (a) and (b) show the snapshots of Hs from ERA5 data. The subplots (c) and (d) show Hs from IOWAGA, and subplots (e) and (f) illustrate Hs from TodaiWW3-NK data. The Hs,max in the IOWAGA and TodaiWW3-NK dataset is found to occcur at 20140105 0600 UTC, whereas, Hs,max from ERA5 data is identified at 20140104 22:00 UTC. The values of the Hs,max are highlighted. Subplot (g) shows segments of altimeter tracks from SARAL on 20140105 and the rectangle in solid black line points to the location of Hs,max in the altimeter data. The subplot (h) shows a comparison of Hs between models and altimeter for a particular segment of the track shown in subplot (g) that passed close to the storm centre.

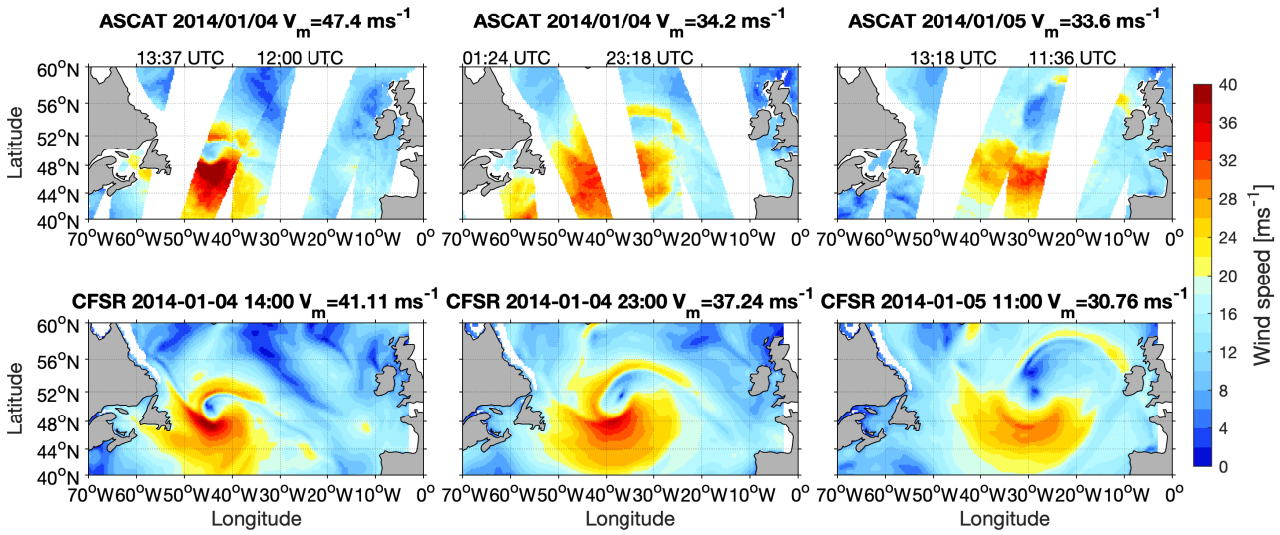


**Figure S8.** Comparison of wind speeds between ASCAT scatterometer and CFSR during January 4-5, 2014. The ASCAT 0.25° × 0.25° gridded data were obtained from http://www.remss.com/missions/ascat/.

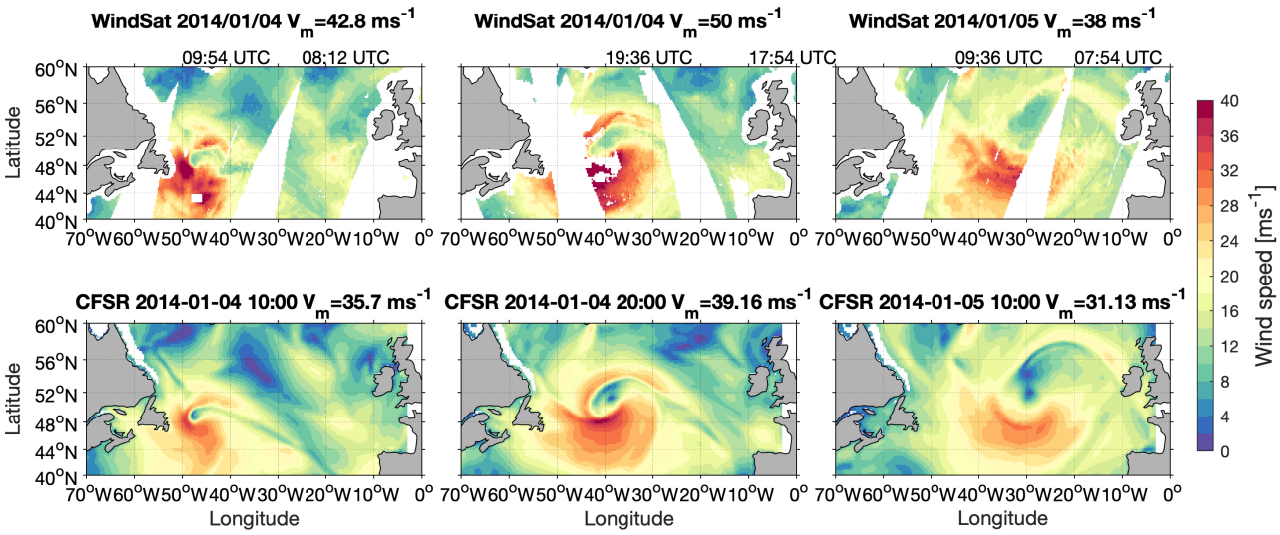


**Figure S9.** Comparison of wind speeds between WindSat radiometer based measurements and CFSR during January 4-5, 2014. The WindSat 0.25° × 0.25° gridded data were obtained from http://www.remss.com/missions/windsat/.

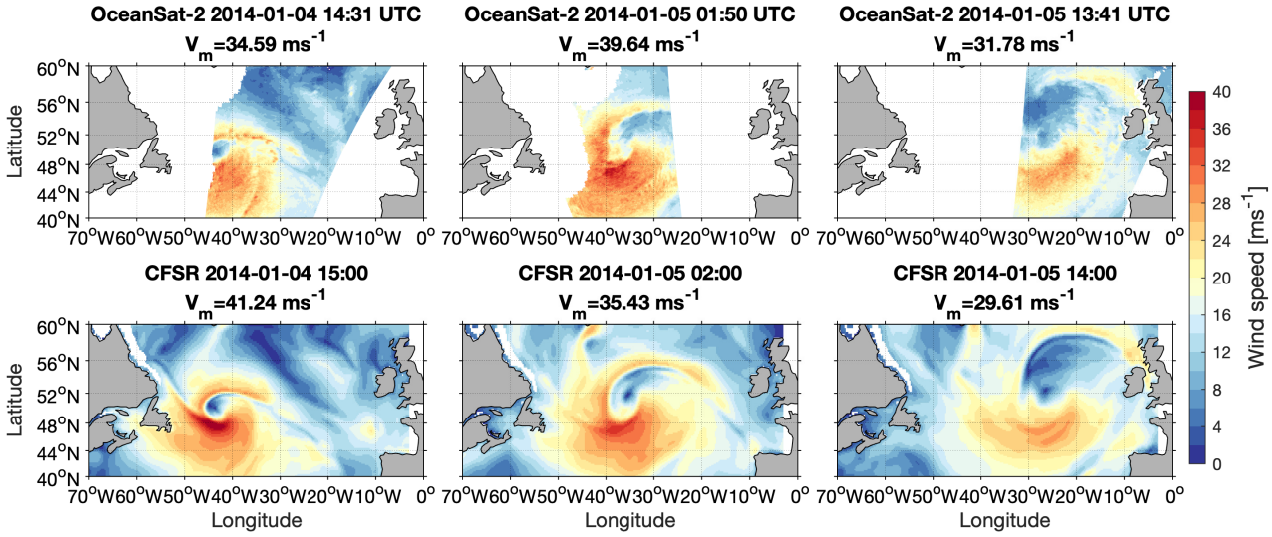


**Figure S10.** Comparison of wind speeds between OceanSat-2 scatterometer based measurements and CFSR during January 4-5, 2014. The OceanSat-2 L2 data were obtained from PODAAC/NASA.

**Table S2.** Data used in this paper and their sources

| Data | URL |
|---|---|
| **Reanalysis and hindcast** | |
| ERA5/ECMWF | https://cds.climate.copernicus.eu/cdsapp#!/home |
| IOWAGA/IFREMER | ftp://ftp.ifremer.fr/ifremer/ww3/HINDCAST/GLOBAL/ |
| **Satellite altimeter** | |
| Ribal and Young (2019) | https://portal.aodn.org.au/ |
| Globwave/IFREMER | http://globwave.ifremer.fr/ |
| PODAAC/NASA | https://podaac.jpl.nasa.gov/ |
| **In-situ** | |
| UK Met Office buoy | http://www.marineinsitu.eu/dashboard/ |
| **Satellite wind products** | |
| Widsat | http://www.remss.com/missions/windsat/ |
| ASCAT | http://www.remss.com/missions/ascat/ |
| OceanSat-2 | https://podaac.jpl.nasa.gov/ |
| **Wind and sea ice concentration** | |
| CFSR/NCEP | https://rda.ucar.edu/datasets/ds093.1/ |
| CFSv2/NCEP | https://rda.ucar.edu/datasets/ds094.1/ |