Met Office

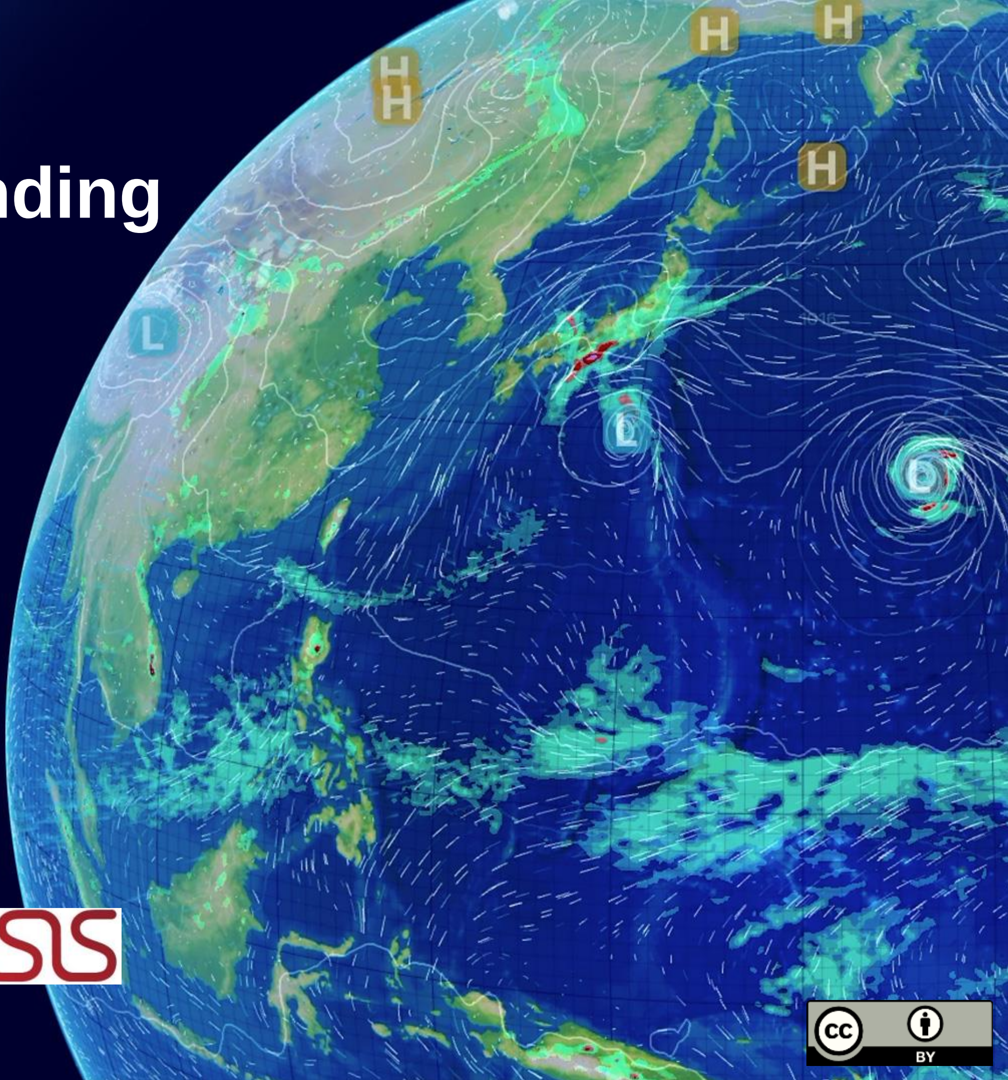
Improving our understanding of Bangladesh tropical cyclone risk

Decision making insights using kilometre-scale numerical modelling and Bayesian data analysis

Hamish Steptoe, Met Office UK

With Theo Economou, Saeed Sadri, Nick Savage, Zubair Maalick, Kate Salmon & others

EGU 2020, 7th May 2020



INTERNATIONAL CLIMATE INITIATIVE (IKI)

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the German Bundestag

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Headlines

Find out more

- 12 historical tropical cyclones impacting Bangladesh downscaled from ERA5. Each storm has a 9-member ensemble. Hourly fields at 4.4km and 1.5km resolution, some full 3D fields available.

Data Availability
Modelling Domain
Modelling Configuration
Data Resolution

- Downscaling resolves fine-scale structure of cyclones with more intense maximum wind speeds than ERA5.

Data Validation
Data Resolution
Data Resolution 2

- Chittagong and Cox's Bazar are particularly at risk of maximum tropical cyclone wind speeds exceeding 45 m/s and 60 m/s respectively, in 5% of tropical cyclones making landfall. A prototype warning model is produced by combining our Bayesian predictive hazard distribution with a loss function.

Hazard Analysis
Hazard to Decision Making

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Project Context

INTERNATIONAL CLIMATE INITIATIVE (IKI)

oasis LOSS MODELLING FRAMEWORK

P I K

The work in this presentation forms part of the International Climate Initiative (IKI) funded '*Oasis Platform for Climate and Catastrophe Risk Assessment – Asia*' led by Oasis LMF.

"*The project goal is to strengthen capacities among-regional stakeholders to understand and develop transparent and standardised catastrophe models to simulate extreme weather event related damages that can be used to assess the likelihood and financial damage caused by extreme climate events and underpin information required by financial markets to invest in (Re-) insurance.*"

Our focus is on high resolution tropical cyclone modelling to better inform our understanding of wind hazards. Other project partners, Bangladesh University of Engineering and Technology (BUET) and Potsdam Institute for Climate Impact Research (PIK), are looking at storm surge and fluvial flooding associated with tropical cyclones.

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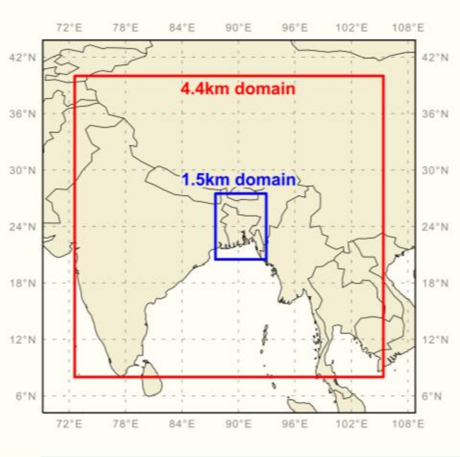
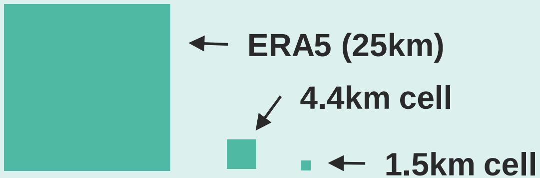
Modelling Domain



4.4km
(~ 800 x 800)
1.5km
(~ 550 x 400)

Grid cell comparison (to scale)



Our high-resolution convection-permitting modelling utilises the latest generation Met Office Unified Model v11.1, regional atmosphere configuration RA2-C. We run the regional model in a 'downscaling' configuration, using ERA5 data to initialise the model and provide boundary conditions.

Key Point (a) ► Model output is available at 4.4km (0.0405°) and 1.5km (0.0135°) over two nested domains: the 4.4km domain avoids placing model boundaries over the Himalayas and covers Nepal, Bhutan, Myanmar, most of India, and parts of the Tibetan plateau so as to facilitate hydrological modelling of the Ganges-Brahmaputra-Meghna river basins; the 1.5km domain is limited to Bangladesh only.

Due to the complex topography of the regional, numerically stable model runs required timesteps of 30 seconds at both resolutions, with additional orographic smoothing applied (using a 1-2-1 filter) to grid cells 1500m above mean sea level.

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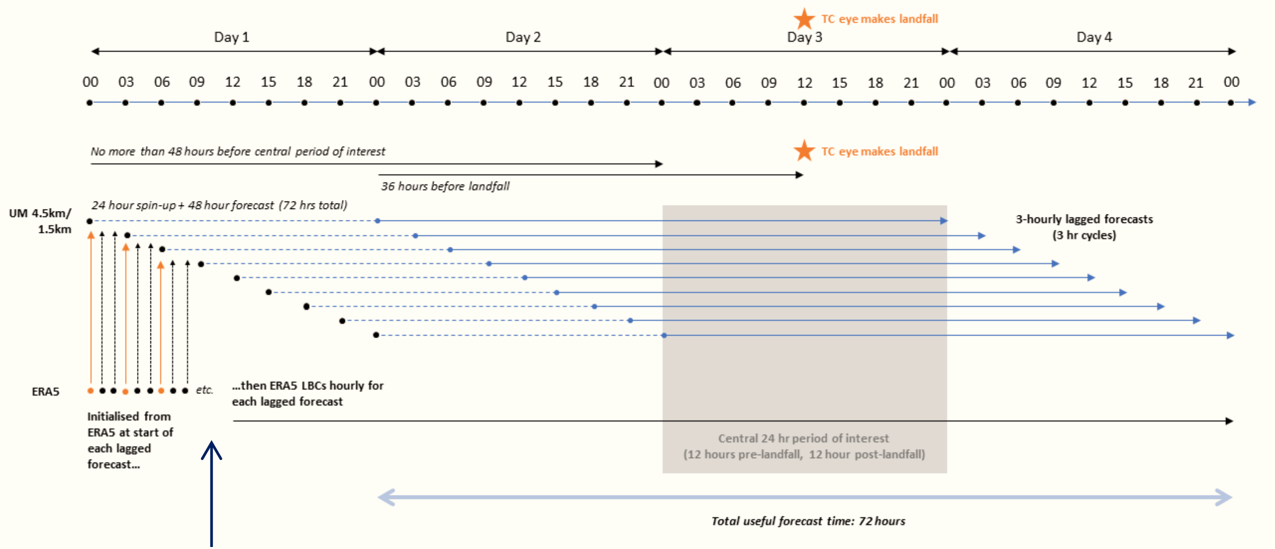
Modelling Configuration



Each run requires a 24 hour spin-up period as the regional model adjusts from the weak initial state inherited from the ERA5 driving global model. This initial 24 hours of model data is discarded in subsequent analysis and data files.

Key Point (b) ▼

We run a 9-member ensemble, designed to limit the free-running model time to 72 hours, whilst ensuring that the central 24 hour period of interest (centred on the tropical cyclone landfall time) is sufficiently sampled.

Together the ensemble provides 9 simulations of the central 24 hours, but covers a period of 72 hours, centred on the TC landfall. After initialisation, each ensemble member is free running, constrained only at the boundaries by daily ERA5 data (i.e.. there is no data assimilation).

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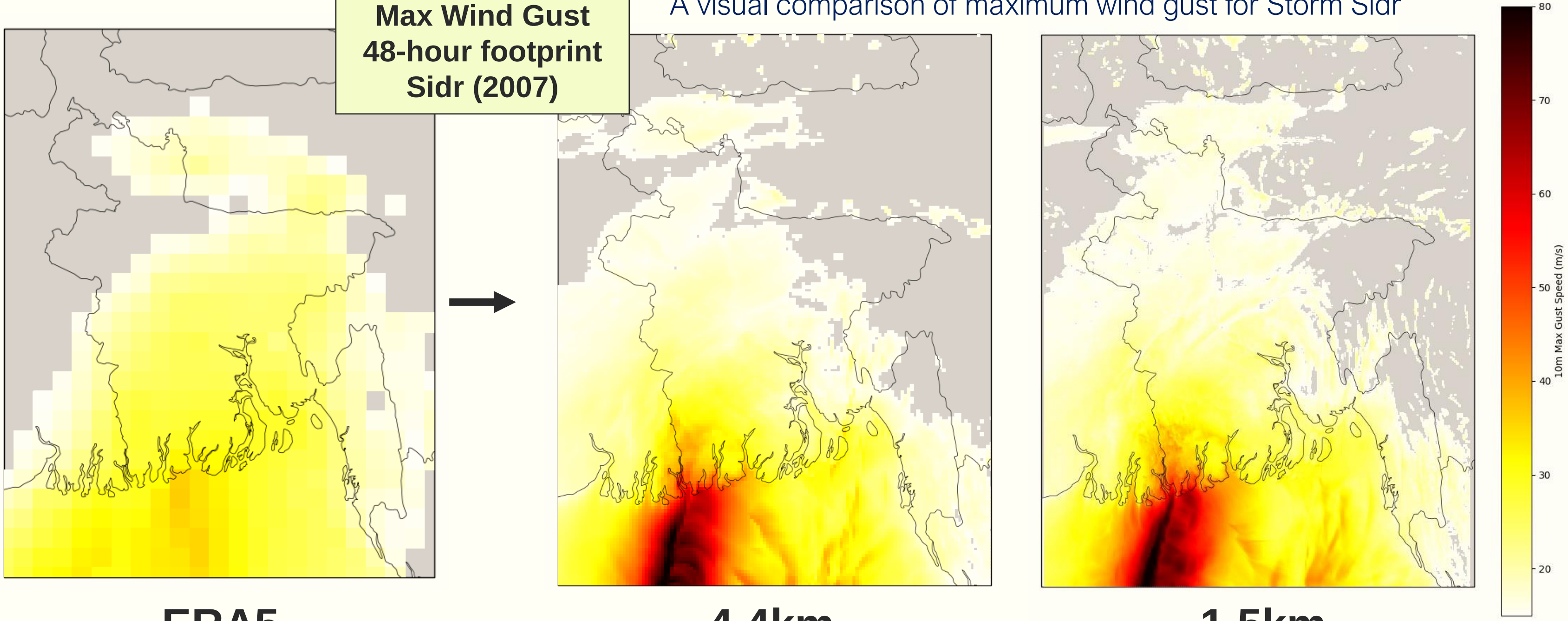
Data Resolution

Max Wind Gust 48-hour footprint Sidr (2007)

A visual comparison of maximum wind gust for Storm Sidr



ERA5 → **4.4km** **1.5km**

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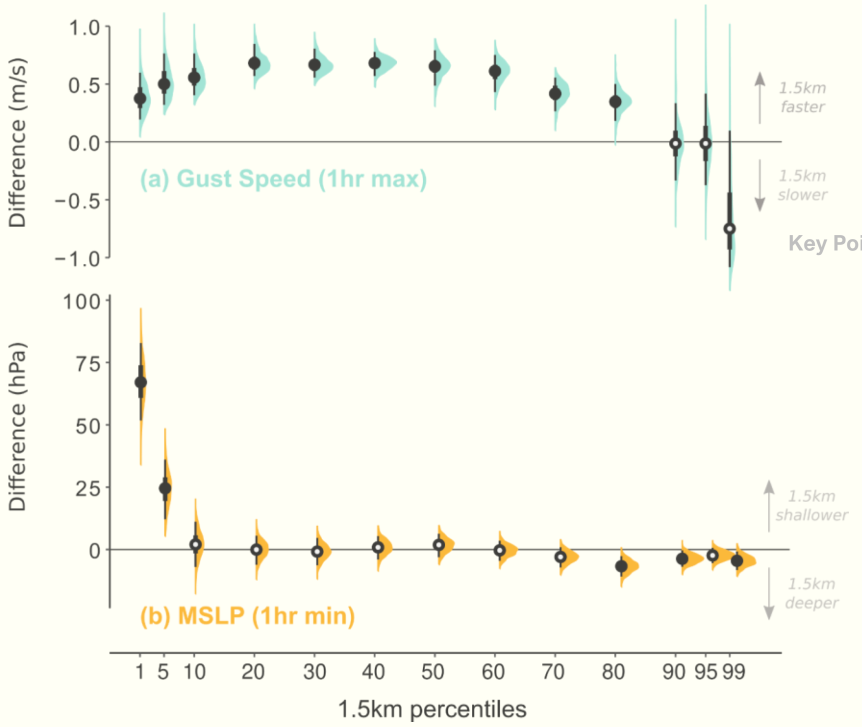
Data Resolution 2



All subsequent analysis presented here focuses on 4.4km data – mainly for computational reasons (further discussion of this later). But we also examine the difference between the two resolutions for two key variables: maximum gust speed and minimum mean sea-level pressure.

Key Point (c) ►

Differences in maximum gust speed footprints, for the 1st to 80th percentiles, of the 1.5km data are roughly O(0.5 m/s) faster than the 4.4km data. For the very highest gust speeds (90th, 95th and 99th percentiles of the 1.5km data) the differences with the 4.4km data shows much greater variability. We suspect that the minimal difference seen in the upper extreme percentiles results from under sampling rather than a systematic difference.

Key Point (d) ▼

For minimum MSLP footprints, extreme lows of the 1.5km data are [50, 87] hPa and [10, 37] hPa shallower for the 1st and 5th percentiles respectively (90% HDI). Given the relationship between central pressure deficit (i.e. the difference between the tropical cyclone central pressure and the environmental pressure outside the tropical cyclone), peak wind speed and tropical cyclone size, this comparisons suggests that 1.5km storms must also be smaller in size than the 4.4km storms.

Key Point (e) ▲

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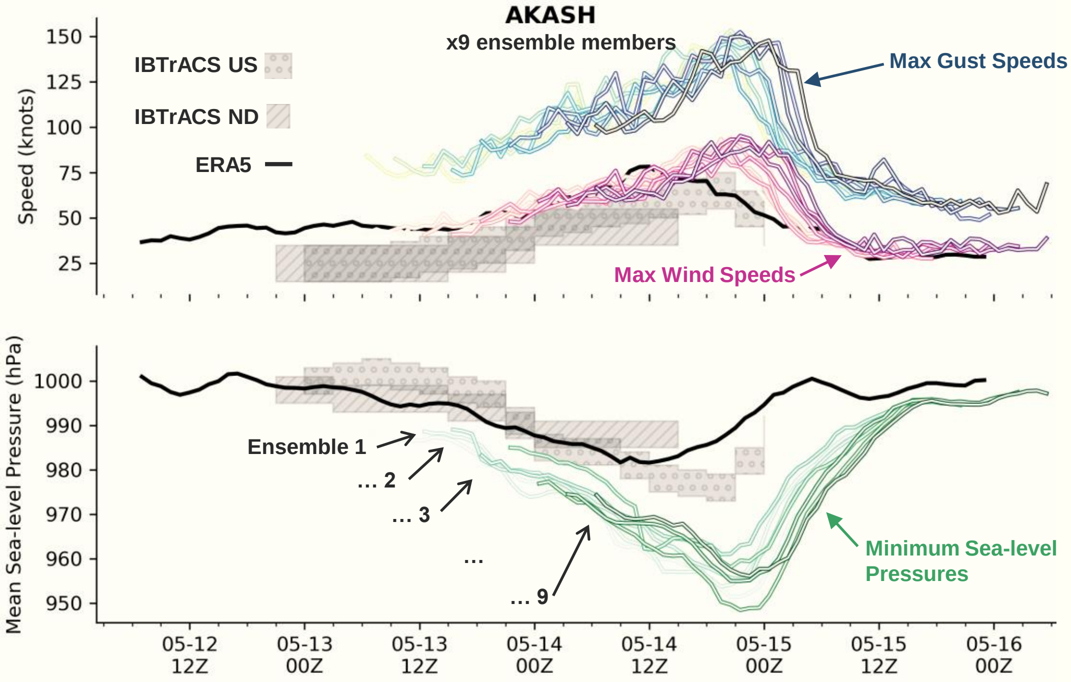
Data Validation



We compare our 4.4km data to ERA5 and IBTrACS New Delhi (ND) and US centre forecasts (including IBTrACS uncertainty information). Validation is very variable between storms. Agreement between ERA5 and IBTrACS is often poor.

Key Point (f) ▼

Peak gust speeds are typically 50 – 150 knots (25 – 80 m/s) faster than ERA5 & minimum MSLP is typically 20 – 50 hPa deeper than ERA5 in the 4.4km model.

In general, most peak wind/gusts and minimum MSLP lags ERA5 & IBTrACS by 4-12 hours. The speed of travel of tropical cyclones over the ocean appears slower in the 4.4km model. Longer ocean transition time appears to result in more delayed landfall.

Key Point (g) ▼

Unfortunately there are no reliable source of observational data in this region to verify these results against.

Validation of storm tracks is in progress.

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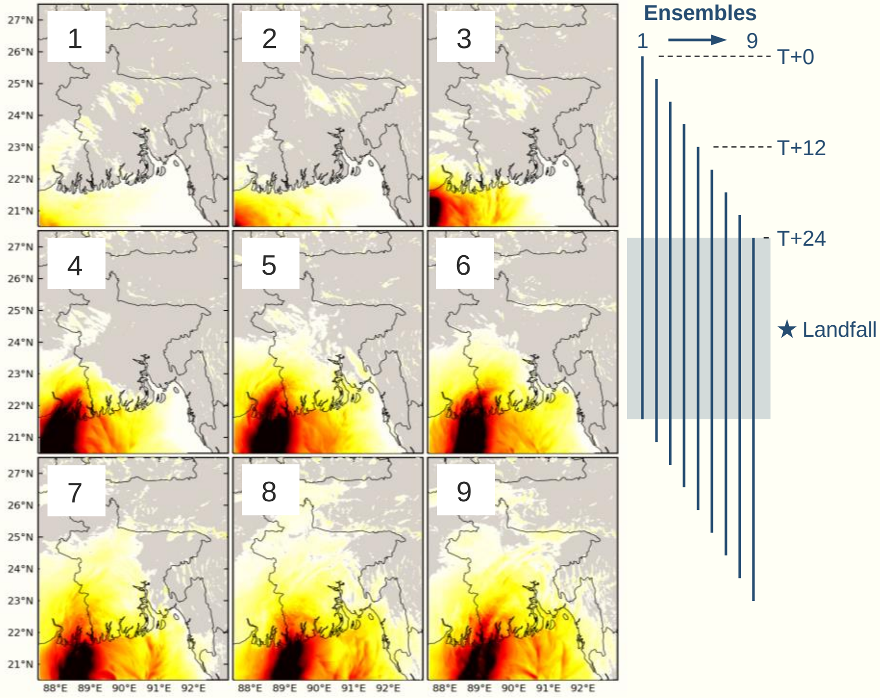
Footprint Ensemble



For our use case, we collapse our variables over the time-dimension to create a hazard ‘footprints’. This is a common view of hazard within the (re)insurance industry, representing the maximum (or minimum) values associated with an event.

Key Point (h) ▼

Initialisation time has significant influence on storm track. Lack of data assimilation within each ensemble run means they can diverge significantly from driving ERA5 data within a period of 48 hours.

Key Point (i) ▼

However each footprint is a physically plausible realization of how the storm could have evolved. We can use these alternative (or counterfactual) simulations to explore the range of tropical cyclone scenarios in greater detail than if we were relying on observations alone.

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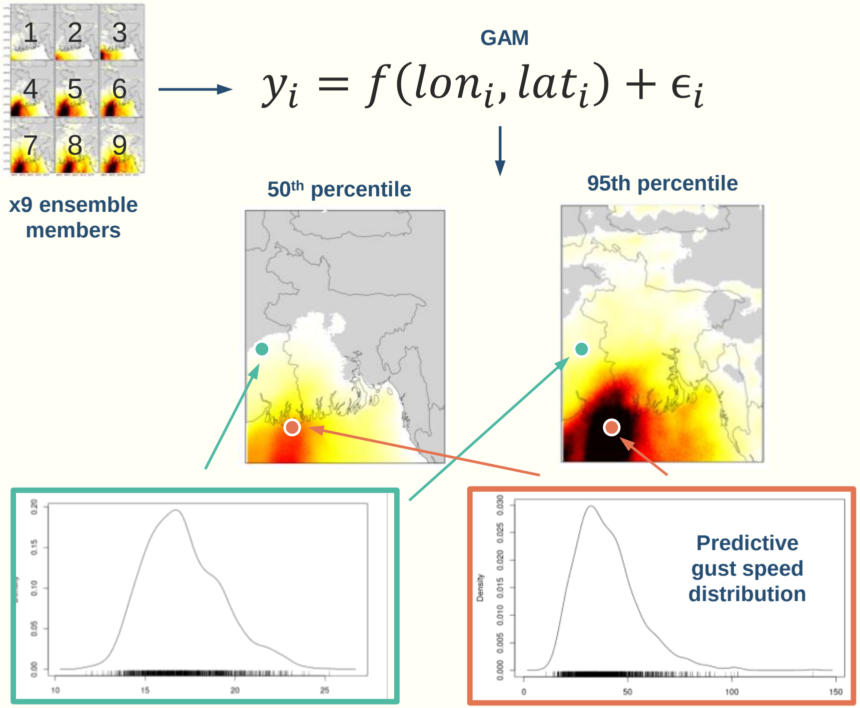
Generalised Additive Modelling



To integrate information from all 9 ensemble members into a coherent spatial prediction we use a generalise additive models (GAM) as a flexible spatial regression framework.

Key Point (j) ▲

We use a Gaussian location-scale model with smoothing parameter estimation by marginal likelihood maximisation so we can adopt a naïve Bayesian interpretation of the GAM with uninformative (improper) priors for each smooth model term. Other model families were trialed (e.g. GEV and gamma models), but the Gaussian location-scale family was found to have the best trade-off between computational efficiency and model fit.

Trial and error shows that $O(600)$ knots are required to represent thin-plate basis functions, given the resolution of the model data. Model fitting can take up to c. 10 hours and c. 100 GB memory for 4.4km data.

Key Point (k) ▼

Model fits are done for each named storm, and a posterior predictive distribution for each cell obtained by simulating random deviates with a mean and standard deviation based on 1000 simulations of the posterior distribution of the model parameters. These simulations are used to establish Bayesian credible intervals based percentile intervals.

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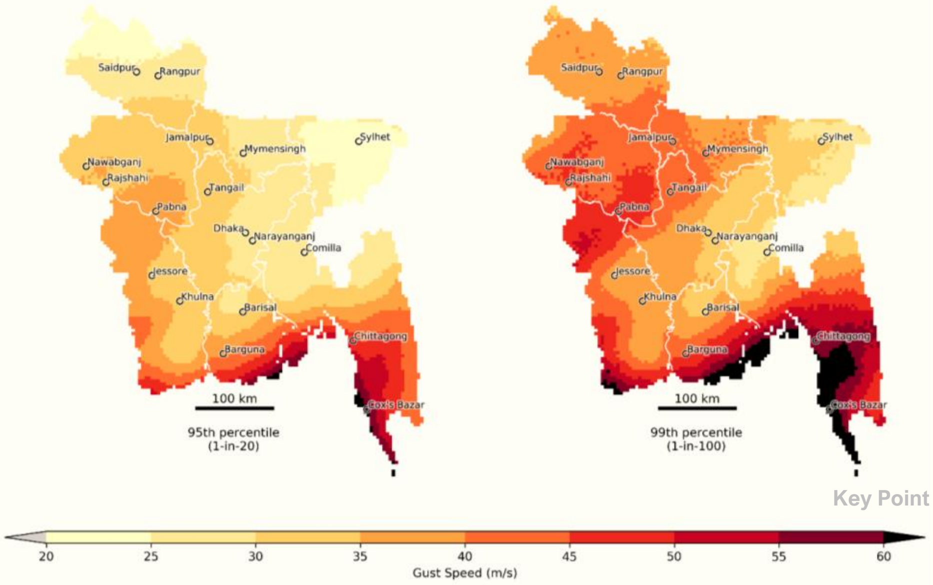
Hazard Analysis



Key Point (I) ►

To aggregate information from all ensembles of all named storms, we pool each of the 1000 simulations into a grand ensemble for gust speed hazard analysis.

The 95th and 99th percentiles represent the maximum gust speeds expected from a 1-in-20 and 1-in-100 event respectively. These credible intervals are based on the posterior model distribution derived from all 12 named tropical cyclones, conditional on a tropical cyclone making landfall in Bangladesh. The 20 – 60 m/s gust speed range roughly corresponds to a range of 39 – 117 kts, equivalent to the cyclonic to super cyclonic storm classification used in Bangladesh.

Based on historical cases, the provinces of Chittagong, Barisal and Khulna are most exposed of high wind speed associated with tropical cyclone gusts, whilst Sylhet and Rajshani are least exposed. The cities of Chittagong and Cox's Bazar are particularly at risk of maximum tropical cyclone wind speeds exceeding 45 m/s (87 kts) and 60 m/s (116 kts) respectively, in 5% of tropical cyclones making landfall. Maximum gust speeds in Dhaka are likely to reach 35 m/s (68 kts) in 1% of events, and 25 m/s (48 kts) in 5% of events.

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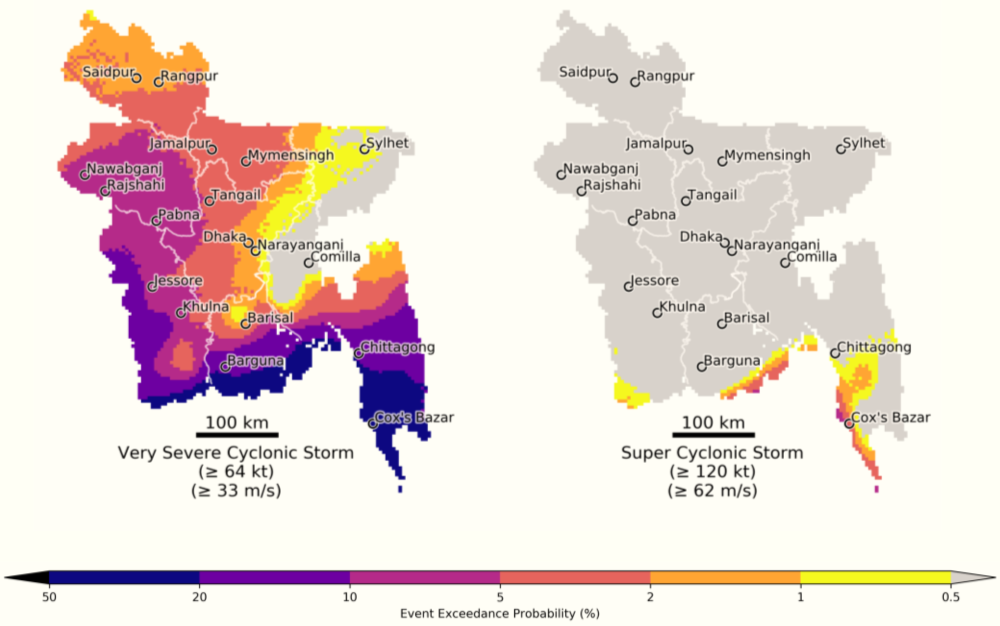
Hazard Analysis



The same data can be interpreted in terms of event exceedance probability. Here we show the 'per event' exceedance probability for the top 2 WMO tropical cyclone hazard levels used in Bangladesh. A 'Super Cyclonic Storm' warning is generally used as the basis for triggering evacuations.

Key Point (m) ▼

Areas within 30 km of the coastline of southern provinces (Khulna, Barisal and Chittagong) will experience maximum windspeed in excess of very severe cyclonic storm condition ≥ 33 m/s (64 kts) with a likelihood of 20-50% per tropical cyclone event (i.e. every 1-in-5, to 1-in-2 events).

Windspeeds in excess of super cyclonic conditions ≥ 62 m/s (120 kts) will be exceeded with a likelihood of 0.5-5% per event in limited areas south of Chittagong, with a small area in the vicinity of Cox's Bazar seeing exceedances of 5-10% per event (1-in-20 to 1-in-10).

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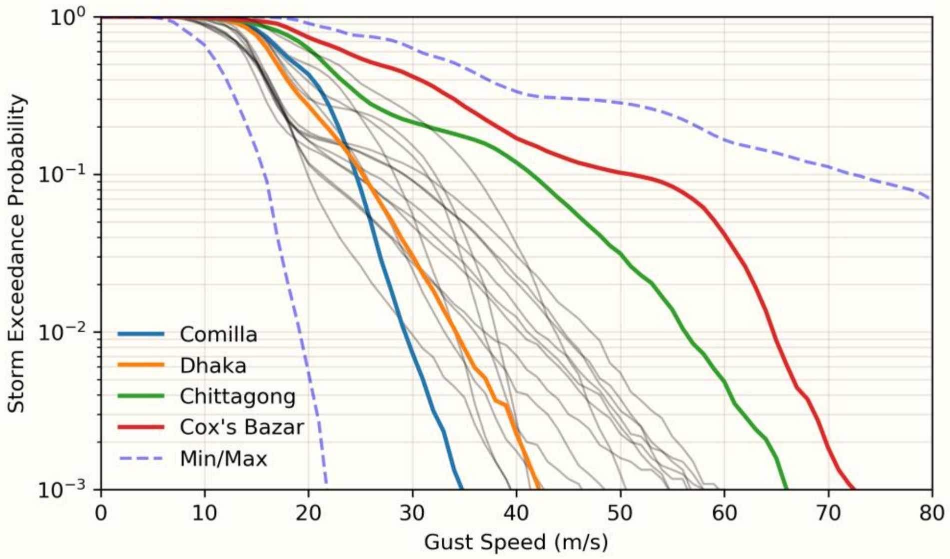
Hazard Analysis



Exceedance probability curves summarise information for gust speeds up to 80 m/s (155 kts) for 18 of the most populated towns and cities in Bangladesh (grey lines) with 4 key cities highlighted. The min and max range of exceedance probabilities (across all of Bangladesh) are represented by the dashed lines.

Coastal cities of Cox's Bazar and Chittagong are unsurprisingly the most exposed population centres to high gust speeds.

Chittagong and Cox's Bazar are roughly x2.5 and x4.8 more likely to experience tropical cyclones exceeding Very Severe cyclonic storm conditions than Dhaka, for a landfalling cyclone.

Key Point (n) ▲

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Hazard to Decision Making

Loss Function		Warning Level			
		OK	Warning	Disaster	Great Danger
Event	< 50 km/h	0	5	15	20
	50 ≥ km/h < 61	50	10	20	25
	61 ≥ km/h < 89	80	50	25	30
	≥ 89 km/h	100	100	80	40

PROOF OF CONCEPT ONLY!

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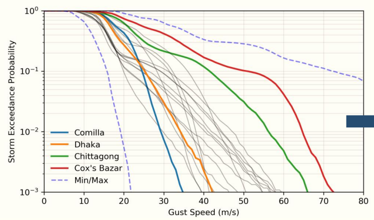

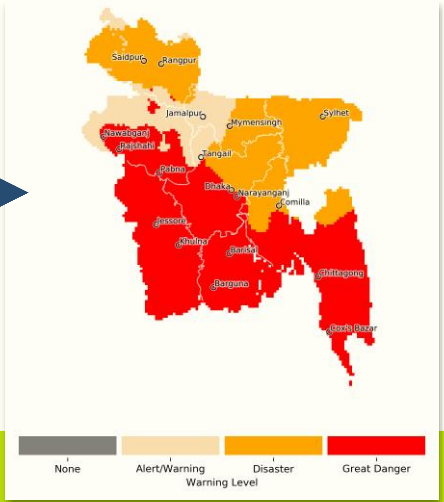

Key Point (o) ▶ Combing our Bayesian predictive hazard distribution with a loss function (describing the relative loss experienced for different actions and magnitude of event) we can create a warning model based on decision theory.

In each case, different levels of action are associated with each warning level. Evacuation typically takes places at the 'Great Danger' level. Each warning level has an associated range of wind speeds, that we define as the 'event'.

In this case, this map represents the default most effective action to minimising expected loss. This would be updated when specific forecast data becomes available for cyclone.

This is a coherent and transparent data-to-decision framework, but defining the loss function is crucial and hard!

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Data Availability

https://oasishub.co/dataset/bangladesh-tropical-cyclone-historical-catalogue

Available Variables
Net Down Surface SW Flux Corrected
Wet Bulb Potential Temperature
Air Pressure At Sea Level
Air Temperature
Geopotential Height
Relative Humidity
Stratiform Rainfall Amount
Stratiform Snowfall Amount
Surface Downwelling SW Flux in Air
Wind Speed of Gust
X Wind
Y Wind

→ wind on pressure levels & model turbulent kinetic energy also available on request

BOB01 (30/04/1991)
BOB07 (25/11/1995)
TC01B (19/05/1997)
Akash (14/05/2007)
Sidr (15/11/2007)
Rashmi (26/10/2008)
Aila (25/05/2009)
Viyaru (16/05/2013)
Roanu (21/05/2016)
Mora (30/05/2017)
Fani (04/05/2019)
Bulbul (09/11/2019)

All our data associated with this project will be made available under cc-by 4.0.

Key Point (p) ▲

Some data is already available on Oasis Hub (link above). Additional data compatible with the Oasis open-source loss model framework will be available on Oasis Hub soon.

Further netCDF data and code will be made available via Zenodo in conjunction with papers [in prep].

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Summary of Key Points

a) Model output is available at 4.4km (0.0405°) and 1.5km (0.0135°) over two nested domains

b) We run a 9-member ensemble, designed to limit the free-running model time to 72 hours

c) Differences in maximum gust speed footprints, for the 1st to 80th percentiles, of the 1.5km data are roughly O(0.5 m/s) faster than the 4.4km data

d) Extreme lows of the 1.5km data are [50, 87] hPa and [10, 37] hPa shallower for the 1st and 5th percentiles

e) This comparisons suggests that 1.5km storms must also be smaller in size than the 4.4km storms.

f) Peak gust speeds are typically 50 – 150 knots (25 – 80 m/s) faster than ERA5 & minimum MSLP is typically 20 – 50 hPa deeper than ERA5 in the 4.4km model.

g) Unfortunately there are no reliable source of observational data in this region to verify these results against.

h) Initialisation time has significant influence on storm track.

i) However each footprint is a physically plausible realization of how the storm could have evolved.

j) To integrate information from all 9 ensemble members into a coherent spatial prediction we use a generalise additive models (GAM)

k) Model fits are done for each named storm, and a posterior predictive distribution for each cell obtained by simulating random deviates with a mean and standard deviation based on 1000 simulations of the posterior distribution of the model parameters.

l) Chittagong and Cox's Bazar are particularly at risk of maximum tropical cyclone wind speeds exceeding 45 m/s (87 kts) and 60 m/s (116 kts) respectively, in 5% of tropical cyclones making landfall

m) Areas within 30 km of the coastline of southern provinces (Khulna, Barisal and Chittagong) will experience maximum windspeed in excess of very severe cyclonic storm condition ≥ 33 m/s (64 kts) with a likelihood of 20-50% per tropical cyclone event

n) Chittagong and Cox's Bazar are roughly x2.5 and x4.8 more likely to experience tropical cyclones exceeding Very Severe cyclonic storm conditions than Dhaka, for a landfalling cyclone.

o) Combing our Bayesian predictive hazard distribution with a loss function (describing the relative loss experienced for different actions and magnitude of event) we can create a warning model based on decision theory

p) All our data associated with this project will be made available under cc-by 4.0.

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Questions?

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