Forecast Verification over north Indian Ocean

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भारत मौसम विज्ञान विभाग
INDIA METEOROLOGICAL DEPARTMENT
Need of Forecast Verification

- To monitor forecast quality
- To improve forecast quality
- To compare forecast of two systems and analyse of our strengths and weaknesses
- Confidence building among disaster managers, media and general public
- Plan for future
Forecast Verification over north Indian Ocean

i. Genesis forecast error

ii. Track forecast error

iii. Track forecast skill

iv. Landfall forecast error

v. Intensity forecast error

vi. Intensity forecast skill

vii. Annual average track forecast error

viii. Annual average track forecast skill

ix. Annual average intensity forecast error and skill

x. Error in Cone of Uncertainty forecasts

xi. Five year mean error & skill in track and intensity forecasts

xii. Heavy rainfall forecast error

xiii. Storm surge forecast errors

xiv. Probabilistic cyclogenesis forecast
GENESIS PROBABILITY: SHORT RANGE FORECAST

- **SOP for Genesis Forecast**
- **Input:**
  - Observations (mainly satellite based) for synoptic and environmental conditions
  - NWP models
  - Dynamical statistical guidance
- The official forecast is based on a consensus forecast determined from NWP, synoptic, environmental, statistical and dynamical-statistical inputs.
- **It provides probability of cyclogenesis during next 120 hrs based on the observations at 0300 UTC of everyday and issued at 0600 UTC.**
- **This probabilistic forecast is issued in terms of nil, low, fair, moderate and high probability corresponding to 0, 1-25, 26-50, 51-75 and 76-100% probability of occurrence.**
- **It commenced since 01 June 2014.**
- **Extended to 120 hrs since April 2018**
VERIFICATION OF CYCLOGENESIS FORECAST: METHODOLOGY

- Reliability Diagram

- Graphical method for assessing reliability, resolution, and sharpness of a probabilistic forecast.

- Plot between observed frequency & forecast probability.

- Reliability is the agreement between forecast probability and mean observed frequency.

- Realised curve closer to forecast curve indicate good forecast.

![Reliability Diagram](image.png)
Brier Score:

\[ BS = \frac{1}{n} \sum_{i=1}^{n} (f_i - o_i)^2 \]

Oi = 0: if event has not occurred and Oi= 1: if event has occurred
Fi is the probability of occurrence according to the forecast system
(Here taken Fi as 0.165 for LOW, 0.495 for Moderate and 0.83 for High categories)

Brier Score Reference:
Replaced the probability of occurrence with the climatological probability.

Note: BS can take on values in the range [0,1] For a perfect forecast BS = 0

Brier Skill:

\[ BSS = - \frac{BS - BS_{ref}}{BS_{ref}} \]

BSS can take value from 0-100%
DATA & METHODOLOGY: CYCLOGENESIS PROBABILITY

(a) Forecast frequency of different categories of probability and observed frequency over the NIO

WEEK-1, NIO

<table>
<thead>
<tr>
<th>Probability</th>
<th>High</th>
<th>Moderate</th>
<th>Low</th>
<th>Nil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecast</td>
<td>14</td>
<td>11</td>
<td>24</td>
<td>233</td>
</tr>
<tr>
<td>Observed</td>
<td>12</td>
<td>8</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

(b) Forecast frequency of different categories of probability and observed frequency over the BoB

WEEK-1, BoB

<table>
<thead>
<tr>
<th>Probability</th>
<th>High</th>
<th>Moderate</th>
<th>Low</th>
<th>Nil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecast</td>
<td>9</td>
<td>6</td>
<td>16</td>
<td>109</td>
</tr>
<tr>
<td>Observed</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

(c) Forecast frequency of different categories of probability and observed frequency over the AS

WEEK-1, AS

<table>
<thead>
<tr>
<th>Probability</th>
<th>High</th>
<th>Moderate</th>
<th>Low</th>
<th>Nil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecast</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>124</td>
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<tr>
<td>Observed</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

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EXTENDED RANGE FORECAST VERIFICATION FOR NIO

Week 1: Under warning for all categories. However, more prominent for Low & Moderate categories. Skillfull for Low & High category.

Week 2: Under warning in case of Nil, Low & Moderate categories. Over warning for High category.

Week 1 (46% skill) forecast (BS: 0.06) better than week 2 (11% skill) forecast (BS: 0.12)

#### WEEK 1

<table>
<thead>
<tr>
<th>BASIN</th>
<th>Bsi</th>
<th>BSr</th>
<th>BSS</th>
<th>BSS %</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIO</td>
<td>0.06013</td>
<td>0.11137</td>
<td>0.46014</td>
<td>46.0139</td>
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</table>

#### WEEK 2

<table>
<thead>
<tr>
<th>BASIN</th>
<th>Bsi</th>
<th>BSr</th>
<th>BSS</th>
<th>BSS %</th>
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</thead>
<tbody>
<tr>
<td>NIO</td>
<td>0.12502</td>
<td>0.13998</td>
<td>0.10689</td>
<td>10.68945</td>
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</table>
MEDIUM RANGE FORECAST VERIFICATION RESULTS FOR NIO

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BSi</th>
<th>BSr</th>
<th>BSS</th>
<th>BSS %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day-1</td>
<td>0.014</td>
<td>0.02</td>
<td>0.25</td>
<td>25.5</td>
</tr>
<tr>
<td>Day-2</td>
<td>0.018</td>
<td>0.04</td>
<td>0.50</td>
<td>50.1</td>
</tr>
<tr>
<td>Day-3</td>
<td>0.032</td>
<td>0.06</td>
<td>0.44</td>
<td>44.0</td>
</tr>
<tr>
<td>Day-4</td>
<td>0.030</td>
<td>0.06</td>
<td>0.53</td>
<td>53.1</td>
</tr>
<tr>
<td>Day-5</td>
<td>0.027</td>
<td>0.08</td>
<td>0.65</td>
<td>64.9</td>
</tr>
</tbody>
</table>

Results:
The BS for day1, day 2, day 3, day 4 and day 5 forecasts is 0.014, 0.018, 0.032, 0.030 and 0.027 respectively. The BSS varies from 25% to 65% during day1 to day5.
(i) Track forecast error

- Known as direct position error.
- It is calculated for each six hourly forecasts valid up 120 hrs during the life period of each cyclone.
- Then mean error is calculated for the given cyclone for 12, 24, 36, 48, 72, 84, 96, 108 and 120 hrs forecasts.

![Graph showing Track Forecast Errors of ESCS TAUKTAE in comparison to Long Period Average Errors (2016-20)]

- **24 hrs:** 73 km (77 km-LPA)
- **48 hrs:** 118 km (117 km-LPA)
(ii) Track forecast skill

- Track forecast skill is calculated for a given cyclone by comparing the six hourly operational track forecast errors with track forecast errors of a reference model. The climatology and persistence (CLIPER) model is used as a reference model.

- Track forecast skill (%) = \( \frac{\text{CLIPER track forecast error} - \text{Operational track forecast error}}{\text{CLIPER track forecast error}} \times 100 \)

- The average skill is calculated for 12, 24, 36, 48, 72, 84, 96, 108 and 120 hrs forecasts based on the life period of the cyclone.

- For a good forecast, skill should be at least positive.

- Higher the positive value of skill, better is the track forecast.
Scope for improvement in Track forecast skill

(i) Initial error / 00 hr forecast error is also calculated at present based on operational best track and the BT finalised at the time of verification.

(ii) BT data, which is the basis for track forecast verification, is prepared based on operational analysis. Due to absence of aircraft reconnaissance observations etc., the track in deep sea is mainly based on satellite based estimates. Goyal et al (2013) have shown that there can be an error of 0.5° (55 km) in such cases. Hence, reanalysis of best track can be carried out after the augmentation of observational network in sea areas.

(iii) The ensemble prediction system (EPS) which provides the strike probability and dynamical cone of uncertainty to be implemented.

(iv) CLIPER model to be updated with the latest past data to serve as a better reference model (Sharma et al, 2013 and Nayak et al, 2013).

(v) New approach like the Track Forecast Integral Deviation (TFID) integrates the track error over an entire forecast period (Yu et al., 2013). To be attempted over NIO.
iii. Landfall forecast error

Calculated as: (a) Landfall point forecast error (LPE) (km)
(b) Landfall time forecast error (LTE) (hrs)

(a) Landfall point forecast error
- defined as the direct position error between forecast landfall point & actual landfall point.
- forecast landfall point determined by applying linear interpolation to forecast location before & after landfall
- LPE is calculated for each six hourly forecasts valid upto 120 hrs

(b) Landfall time forecast error
- defined as difference in forecast landfall time and actual landfall time irrespective of landfall point.
Landfall forecast error - SuCS Amphan

Excellent demonstration of zero landfall point and time error

(a) Landfall Point Forecast Errors of SuCS AMPHAN in comparison to Long Period Average Errors (2015-19)

(b) Landfall Time Forecast Errors of SuCS AMPHAN in comparison to Long Period Average Errors (2015-19)
Landfall forecast error-SuCS Amphan

Excellent demonstration of zero landfall point and time error

Based on 17/0600 UTC (84 hrs prior to landfall)

Observed & forecast track along with COU and quadrant wind distribution based on 0600 UTC of 17th May (84 hrs prior to landfall) of SuCS AMPHAN indicating accuracy in landfall, track & intensity predictions
Landfall forecast error - SuCS Amphan

Excellent demonstration of zero landfall point and time error

- Based on 18/0300 UTC (60 hrs prior to landfall)

Observed & forecast track along with COU and quadrant wind distribution based on 0600 UTC of 17th May (84 hrs prior to landfall) of SuCS AMPHAN indicating accuracy in landfall, track & intensity predictions
Landfall forecast error-SuCS Amphan

Excellent demonstration of zero landfall point and time error

Based on 19/0300 UTC (36 hrs prior to landfall)
Landfall forecast error - SCS Shaheen

Landfall Point Forecast Errors of SCS SHAHEEN in comparison to Long Period Average Errors (2016-20)

Landfall Time Forecast Errors of SCS SHAHEEN in comparison to Long Period Average Errors (2016-20)
Scope for improvement in landfall forecast

(i) Improvements in observational network near the landfall locations and a denser network of HWSRs along the coast.

(ii) Use of mobile wind profilers, doppler on wheels etc. as being used in other parts of the globe for improving the accuracy in determination of landfall.

(iii) Determination of skill of the landfall forecasts using CLIPER.

(iv) Verification of probabilistic forecasts generated by models and strike probability generated by the EPS need to be verified.

(v) Currently, the landfall forecast is verified only for the cases for which actual landfall occurred. However, there are cases when there is forecast for landfall, but, landfall does not occur and vice versa. Verification of such cases to be carried out as per the methodology adopted by Dupont et al (2006).

(vi) Improved intensity prediction could also reduce such cases in future.
(iv) Intensity forecast error

Intensity forecast error (kt):
• Calculated based on the forecast maximum sustained surface wind speed (MSW) and actual MSW.
• We calculate (a) absolute mean error and (AAE) (ii) Root Mean Square (RMSE) error.
• Data base includes six hourly forecasts with validity period of 120 hrs.
• We calculate intensity forecast errors for 12, 24, 36, 48, 60, 72, 84, 96, 108 & 120 hrs forecasts.
(v) Intensity forecast skill (%)

- Calculated by comparing the operational intensity forecast error like AAE & RSME with that of reference model.
- Forecast based on persistence method is used as reference model.
- Skill is calculated for 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hrs lead periods.
- Gain (loss) in skill (%) = Persistence Error - Operational Error

![Graphs showing intensity forecast skill]

**Graph (a)**: Intensity Forecast Skill based on AE of CS Gulab and Long Period Average Skill (2016-2020)

**Graph (b)**: Intensity Forecast Skill based on RMSE of CS Gulab and Long Period Average Skill (2016-2020)
Annual average track forecast error and skill are calculated by taking the track forecast errors of all the cyclones during the year.

It is calculated for 12, 24, 36, 48, 72, 84, 96, 108 and 120 hrs lead periods.

Annual average error = \( \frac{n_1E_1 + n_2E_2 + n_3E_3 + \ldots}{n_1 + n_2 + n_3 + \ldots} \)

where \( n_1, n_2, n_3 \ldots \) are number of six hrly forecasts verified for cyclone 1, 2, 3... and

E1, E2, E3... are the average error for cyclone n1, n2, n3....

Annual average track forecast skill = \( \frac{\text{weighted average CLIPER error-weighted average Operational error}}{\text{weighted average CLIPER}} \)
(vi) Annual average track forecast error & Skill

(a) Annual Average Track Forecast Error- 2021

(b) Annual Average Track Forecast Skill- 2021

[Graph showing annual average track forecast error and skill for different forecast lead times (12, 24, 36, 48, 60, 72, 84 hours)].

Operational Track Forecast Error: [Data for operational track forecast error for different forecast lead times.
LPA Track Forecast Error (km) 2016-20: [Data for LPA track forecast error for 2016-20 for different forecast lead times.]

Operational Track Forecast Skill: [Data for operational track forecast skill for different forecast lead times.
LPA (2016-2020) Track Forecast Skill (%): [Data for LPA track forecast skill for 2016-2020 for different forecast lead times.]}

[Graph showing operational and LPA track forecast error and skill for different forecast lead times.]

[Graph showing the improvement in track forecast skill for operational and LPA forecasts over the years 2016-20].
(vi) Annual average landfall point & time forecast error

- Annual average point & time forecast errors are calculated by taking the forecast errors of all the cyclones during the year.

- It is calculated for 12, 24, 36, 48, 72, 84, 96, 108 and 120 hrs lead periods.

- Annual average error = \( \frac{(E_1+E_2+E_3+\ldots)}{\text{total no. of cyclones}} \)

- \( E_1, E_2, E_3 \ldots \) are the average error for \( n \) cyclones
(vi) Annual average landfall point & time forecast error

Annual Average Landfall Point Forecast Errors during 2021 in comparison to Long Period Average Errors (2016-20)

Annual Landfall Time Forecast Errors during 2021 in comparison to Long Period Average Errors (2016-20)
Annual average intensity forecast error based on absolute error is calculated by taking the mean intensity forecast errors of all the cyclones during a year and the No. of observations verified.

It is calculated for 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hrs lead periods.

Annual average error based on absolute error = \[
\frac{(n1*E1+n2*E2+n3*E3+...)}{(n1+n2+n3+...)}
\]

\(n1, n2, ..\) are No. of six hrly forecasts verified for cyclone 1, 2, ... & \(E1, E2, ..\) are the mean intensity forecast errors for cyclone \(n1, n2,...\).

Similarly, annual average intensity forecast through persistence based on absolute error is calculated.

Skill in annual average intensity forecast based on absolute error is calculated w.r.t. persistence forecast for 12, 24, 36, 48, 60, 72, 84, 96, 108 & 120 as lead period.

\[
\text{Gain (loss) in skill (%) } = \frac{\text{Persistence Error} - \text{Operational Error}}{\text{Operational Error}}
\]

Similarly, annual average intensity forecast error and skill based on root mean square error are calculated.
(vii) Annual average intensity forecast error and skill

(a) Annual Intensity Forecast Error based on AE-2021

(b) Annual Intensity Forecast Skill based on AE-2021

(b) Annual Intensity Forecast Error based on RMSE-2021

(b) Annual Intensity Forecast Skill based on RMSE-2021
Five year mean error and skill in landfall, track & intensity forecasts

- Five year mean error in track forecast and intensity forecasts are calculated by the weighted mean approach.
- The annual average error are weighted by number of forecasts verified in the year for this purpose.
- Errors and skills are calculated for 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hour forecasts.
Advances in Cyclone Forecasting: Improvement in Track forecast accuracy

(a) Annual Average Track Forecast Error (km)

\[
y = -6.197x + 174.2 \\
R^2 = 0.752
\]

\[
y = -3.546x + 164.6 \\
R^2 = 0.708
\]

Average Track Forecast Error (km)

<table>
<thead>
<tr>
<th>Lead Period (hrs)</th>
<th>2012-2016</th>
<th>2017-21</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>60</td>
<td>47</td>
</tr>
<tr>
<td>24</td>
<td>97</td>
<td>73</td>
</tr>
<tr>
<td>36</td>
<td>119</td>
<td>89</td>
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<tr>
<td>48</td>
<td>149</td>
<td>106</td>
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<tr>
<td>60</td>
<td>172</td>
<td>122</td>
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<tr>
<td>72</td>
<td>203</td>
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<tr>
<td>84</td>
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<td>96</td>
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<tr>
<td>108</td>
<td>281</td>
<td>240</td>
</tr>
<tr>
<td>120</td>
<td>316</td>
<td>306</td>
</tr>
</tbody>
</table>
Advances in Cyclone Forecasting: Improvement in Track forecast skill accuracy
Five Year Moving Average-Track Forecast Error & Skill

(a) Five Year Moving Average-Track forecast Error (km)

(b) Five Year Moving Average-Track forecast Skill (%)
Advances in Cyclone Forecasting:
Improvement in Landfall Point forecast

**Annual Average Landfall Point Error (km)**

- 12 hr
- 24 hr
- 36 hr
- 48 hr
- 60 hr
- 72 hr
- Linear (12 hr)
- Linear (24 hr)

**Comparative Average Landfall Point Error (km)**

- 2012-16: 27.2, 16.2, 35.9, 30.7, 92.3, 43.9, 58.5, 122.1
- 2017-21: 85.7

**Five Year Moving Average-Landfall Point Error (km)**

- 12-hours
- 24-hours
- 36-hours
- 48-hours
- 60-hours
- 72-hours

**Periods**
- 2003-07
- 2005-09
- 2007-11
- 2009-13
- 2011-15
- 2013-17
- 2015-19
- 2017-21
Advances in Cyclone Forecasting: Improvement in Landfall Time forecast

Annual Average Landfall Time Error (hrs)

- 12 hr
- 24 hr
- 36 hr
- 48 hr
- 60 hr
- 72 hr
- Linear (12 hr)
- Linear (24 hr)

Regression equations:
- $y = -0.2814x + 5.6289$, $R^2 = 0.3973$
- $y = -0.2236x + 6.1807$, $R^2 = 0.3608$

(b) Comparative Average Landfall Time Error (hrs)

- 2012-16: 2.4, 4.2, 4.3, 4.8, 4.3, 5.7, 3.8, 9.2
- 2017-21: 1.3, 2.2, 4.1, 4.3, 6.0, 7.2,

Five Year Moving Average-Landfall Time Error (hrs)

- 12-hours
- 24-hours
- 36-hours
- 48-hours
- 60-hours
- 72-hours
Advances in Cyclone Forecasting:
AE & RMSE of maximum sustained surface wind forecast

(a) Intensity forecast Error (kt) based on AE

(b) Intensity forecast Error (kt) based on RMSE

(c) Intensity Forecast Skill (%) based on AE

(d) Intensity Forecast Skill (%) based on RMSE

Graphical representations showing trends and relationships over time for AE and RMSE of maximum sustained surface wind forecast.
Advances in Cyclone Forecasting:
AE & RMSE of maximum sustained surface wind forecast
Advances in Cyclone Forecasting:
AE & RMSE of maximum sustained surface wind forecast

(a) Five Year Moving Average-Intensity forecast Error based on AE (kts)

(b) Five Year Moving Average-Intensity forecast Error based on RMSE (kts)

(c) Five Year Moving Average-Intensity forecast Skill based on AE (%)

(d) Five Year Moving Average-Intensity forecast Skill based on RMSE (%)

Period:
From 14th itself it was indicated that system would move parallel to west coast of India and affect all states from Kerala-Gujarat.

From 16th itself it was indicated that the system would cross south Gujarat coast between Porbander & Mahuva around 18th early morning.

<table>
<thead>
<tr>
<th>MSW (knot)/kmph</th>
<th>Impact</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>28-33 / (52–61)</td>
<td>Very rough seas.</td>
<td>Total suspension of fishing operations</td>
</tr>
<tr>
<td>34-40 / (62-74)</td>
<td>High to very high seas</td>
<td>Total suspension of fishing operations</td>
</tr>
<tr>
<td>41-63 / (75–117)</td>
<td>Very High seas</td>
<td>Total suspension of fishing operations</td>
</tr>
<tr>
<td>≥ 64 / (≥118)</td>
<td>Phenomenal</td>
<td>Total suspension of fishing operations</td>
</tr>
</tbody>
</table>

DATE/TIME IN UTC, IST = UTC + 0530 HRS, D: DEPRESSION, DD: DEEP DEPRESSION, CS: CYCLONIC STORM, SCS: SEVERE CYCLONIC STORM, VCS: VERY SEVERE CYCLONIC STORM, OBSERVED TRACK, FORECAST, CONE OF UNCERTAINTY
Forecast issued at 0830 hours IST of 17th May (about 18 hours prior to landfall) demonstrating accuracy in track, intensity and landfall.

It was indicated that the system would cross coast between Porbander & Mahuva between 2030-2230 IST of 17th with wind speed 155-165 gusting to 185 kmph.
OPERATIONAL FORECAST ACCURACY - TRACK, LANDFALL & INTENSITY

**Track Forecast Errors of ESCS TAUKTAE in comparison to Long Period Average Errors (2016-20)**

- **24 hrs:** 73 km (77km-LPA)
- **48 hrs:** 118 km (117 km-LPA)

**Intensity Forecast Errors based on AE of ESCS TAUKTAE and Long Period Average Errors (2016-20)**

- **24 hrs:** 4.4 kt (7.9 kt-LPA)
- **48 hrs:** 8.9 kt (11.4 kt-LPA)

**Landfall Point Forecast Errors of ESCS TAUKTAE in comparison to Long Period Average Errors (2016-20)**

- **24 hrs:** 27 km (32km-LPA)
- **48 hrs:** 71 km (62 km-LPA)

**Landfall Time Forecast Errors of ESCS TAUKTAE in comparison to Long Period Average Errors (2016-20)**

- **24 hrs:** 3.5 hrs (2.5 hrs-LPA)
- **48 hrs:** 6.5 hrs (5.0 hrs-LPA)
From 1st Bulletin it was indicated that system would intensify up to VSCS stage, affect Odisha-West Bengal States and cross North Odisha coast on 26th A/N.

Forecast issued on 24th morning demonstrating accuracy in track, landfall & intensity prediction.

<table>
<thead>
<tr>
<th>DATE/TIME IN UTC, IST = UTC + 0530 HRS</th>
<th>Impact</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>28-33 ((52–61)</td>
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<td>≥ 64 (≥118)</td>
<td>Phenomenal</td>
<td>Total suspension of fishing operations</td>
</tr>
</tbody>
</table>
OPERATIONAL FORECAST ACCURACY - TRACK, LANDFALL & INTENSITY

24 hrs: 24 km (77 km-LPA), 48 hrs: 58 km (117 km-LPA)

**Track Forecast Errors of VSCS YAAS in comparison to Long Period Average Errors (2016-20)**

- 24 hrs: 24 km
- 48 hrs: 58 km

**IntENSITY Forecast Errors based on AE of VSCS YAAS and Long Period Average Errors (2016-20)**

- 24 hrs: 13.7 kt (7.9 kt-LPA)
- 48 hrs: 12.9 kt (11.4 kt-LPA)

**Landfall Point Forecast Errors of VSCS YAAS in comparison to Long Period Average Errors (2016-20)**

- 8 km error in Landfall Point Forecast upto 48 hrs lead period

**Landfall Time Forecast Errors of VSCS YAAS in comparison to Long Period Average Errors (2016-20)**

- 0.5-2.5 hrs in Landfall Time forecast upto 48 hours lead period

**Legend**

- Operational Track forecast error
- Long Period Average Track Forecast Error
- AE
- LPA-AE

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The cone of uncertainty forecasts issued along with the track forecasts are also verified to find out the percentage of track forecasts lying within the forecast cone of uncertainty. It is calculated for each cyclone and also for the year as a whole.

Errors are calculated for 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hrs lead period.
## Verification of Cone of uncertainty forecast

<table>
<thead>
<tr>
<th>Lead Period (hrs)</th>
<th>Viyaru</th>
<th>Phailin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W</td>
<td>B</td>
</tr>
<tr>
<td>12</td>
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<td>14</td>
</tr>
<tr>
<td>24</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>36</td>
<td>13</td>
<td>7</td>
</tr>
<tr>
<td>48</td>
<td>15</td>
<td>3</td>
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<tr>
<td>60</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>72</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>84</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>96</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>108</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>120</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

W- within range, B- Beyond range, T- Total
## Verification of cone of uncertainty (COU) in track forecast issued by IMD during 2013

<table>
<thead>
<tr>
<th>Lead period (hrs)</th>
<th>Within COU</th>
<th>Outside COU</th>
<th>Total</th>
<th>Percentage Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>57</td>
<td>26</td>
<td>83</td>
<td>68.7</td>
</tr>
<tr>
<td>36</td>
<td>51</td>
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<tr>
<td>48</td>
<td>48</td>
<td>16</td>
<td>64</td>
<td>75.0</td>
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<tr>
<td>60</td>
<td>39</td>
<td>15</td>
<td>54</td>
<td>72.2</td>
</tr>
<tr>
<td>72</td>
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<td>65.1</td>
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<td>71.9</td>
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<tr>
<td>96</td>
<td>19</td>
<td>6</td>
<td>25</td>
<td>76.0</td>
</tr>
<tr>
<td>108</td>
<td>13</td>
<td>4</td>
<td>17</td>
<td>76.5</td>
</tr>
<tr>
<td>120</td>
<td>06</td>
<td>2</td>
<td>8</td>
<td>66.7</td>
</tr>
</tbody>
</table>

### Verification of COU during 2014-15

Mohapatra et al, 2017, Current Science
(ix) Heavy rainfall forecast error

Spatial distribution and intensity forecasts of heavy rainfall issued sub-division wise are verified in a tabular form for each date and time of forecast by comparing the actual occurrence of heavy rainfall.

<table>
<thead>
<tr>
<th>Date/Time(UTC)</th>
<th>Forecast Rainfall in association with VSVS Hudhud</th>
<th>Observed Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>06.10.14/0300</td>
<td><strong>Andaman and Nicobar Islands:</strong> Isolated heavy to very heavy rainfall during the <strong>next 24 hours.</strong> Intensity would increase thereafter with heavy to very heavy rainfall at a few places and isolated extremely heavy falls (&gt;=25 cm) during <strong>subsequent 48 hours.</strong></td>
<td><strong>08 October 2014:</strong> Andaman &amp; Nicobar Islands: Isolated heavy to very heavy rainfall</td>
</tr>
<tr>
<td>07.10.14/0300</td>
<td><strong>Andaman and Nicobar Islands:</strong> Heavy to very heavy rainfall at a few places and isolated extremely heavy falls (&gt;=25 cm) would occur over during <strong>subsequent 48 hours.</strong></td>
<td></td>
</tr>
<tr>
<td>08.10.14/0300</td>
<td><strong>(i) Andaman and Nicobar Islands:</strong> Heavy to very heavy rainfall at a few places and isolated extremely heavy falls (&gt;=25 cm) during <strong>next 24 hours.</strong></td>
<td></td>
</tr>
<tr>
<td>Date/Time(UTC)</td>
<td>Forecast Rainfall</td>
<td>Observed Rainfall</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>08.10.14/0300</td>
<td><strong>(ii) North Andhra Pradesh and South Odisha:</strong> Heavy to very heavy falls at a few places with isolated extremely heavy falls over south Odisha from <strong>11th evening onwards.</strong> Heavy rain to very heavy rainfall would also commence at a few places over Visakhapatnam, Vizianagaram, Srikakulam districts of north coastal Andhra Pradesh and districts of north coastal Odisha <strong>during the same period.</strong></td>
<td>08 October 2014: Andaman &amp; Nicobar Islands: Isolated heavy to very heavy rainfall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 October 2014: North Andhra Pradesh: Heavy to very heavy rainfall at a few places. South Odisha: Isolated heavy to very heavy rainfall</td>
</tr>
<tr>
<td>09.10.14/0300</td>
<td><strong>(i) North Andhra Pradesh and South Odisha coasts:</strong> Heavy to very heavy falls at a few places and isolated extremely heavy falls over East Godavari, Visakhapatnam, Vizianagaram and Srikakulam districts of North Coastal Andhra Pradesh and South Odisha from <strong>11th evening onwards.</strong> Heavy to very heavy rainfall at isolated places over remaining districts of Andhra Pradesh and North Coastal Odisha <strong>during the same period.</strong></td>
<td></td>
</tr>
</tbody>
</table>
### (ix) Heavy rainfall forecast error

<table>
<thead>
<tr>
<th>Date/Time (UTC)</th>
<th>Forecast Rainfall</th>
<th>Observed Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.10.14/0300</td>
<td><strong>North Andhra Pradesh and South Odisha coasts:</strong> Heavy to very heavy falls at a few places and isolated extremely heavy falls would occur over West and East Godavari, Visakhapatnam, Vizianagaram and Srikakulam districts of North Coastal Andhra Pradesh and Ganjam, Gajapati, Koraput, Rayagada, Nabarangpur, Malkangiri, Kalahandi, Phulbani districts of South Odisha commencing from <strong>11th onwards.</strong> Heavy to very heavy rainfall at isolated places over Krishna, Guntur and Prakasham districts of Andhra Pradesh and North Coastal Odisha <strong>during the same period.</strong></td>
<td>12 October 2014: North Andhra Pradesh: Heavy to very heavy rainfall at a few places Odisha: Isolated heavy to very heavy rainfall</td>
</tr>
</tbody>
</table>
Heavy rainfall forecast is considered to be correct for a given subdivision, if there is occurrence of heavy rainfall over at least two stations in that sub-division. For the purpose of verification a 3X3 contingency table has been prepared namely for no heavy rainfall (≤ 64.4 mm), heavy to very heavy rainfall (64.5-244.4 mm) and extremely heavy rainfall (≥ 244.5 mm).

<table>
<thead>
<tr>
<th>24 hr observed class of heavy rainfall</th>
<th>24 hr forecast class of heavy rainfall</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No heavy rainfall</td>
<td>Heavy to very heavy Rainfall</td>
</tr>
<tr>
<td>No heavy rainfall</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Heavy to very heavy rainfall</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Extremely heavy rainfall</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>CSI (%)</td>
<td>27.3</td>
<td>47.6</td>
</tr>
<tr>
<td>PC (%)</td>
<td>57.7</td>
<td></td>
</tr>
<tr>
<td>HSS</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>
To find out the biases in the forecast, this 3X3 contingency table is reduced to 2X2 contingency table for verification of (i) heavy rainfall or higher intensity & no heavy rainfall and (ii) extremely heavy rainfall & no extremely heavy rainfall.

<table>
<thead>
<tr>
<th>Observed rainfall</th>
<th>24 hr forecast for heavy rainfall or higher and no heavy rainfall</th>
<th>Total</th>
<th>24 hr forecast for extremely heavy rainfall &amp; no extremely heavy rainfall</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YES</td>
<td>NO</td>
<td></td>
<td>YES</td>
</tr>
<tr>
<td>YES</td>
<td>15</td>
<td>6</td>
<td>21</td>
<td>2</td>
</tr>
<tr>
<td>NO</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>9</td>
<td>26</td>
<td>5</td>
</tr>
</tbody>
</table>

- **POD**: 0.7 | 1.0
- **FAR**: 0.1 | 0.6
- **MR**: 0.3 | 0.0
- **C-NON**: 0.6 | 0.9
- **CSI**: 0.7 | 0.4
- **BIAS Occ.**: 0.8 | 2.5
- **PC (%)**: 69.2 | 88.5
- **TSS**: 0.3 | 0.9
- **HSS**: 0.2 | 0.5
Scope for improvements in TC rainfall forecast verification

- Current procedure involved rigorous statistical verification procedure.
- Rainfall associated with a TC when it is out in the sea also needs to be understood for improving our warnings.
- Daily satellite gauge merged rainfall dataset is being generated since 2013 by IMD and NCMRWF.
- A rainfall forecast model such as R-CLIPER (based on rainfall climatology and persistence) using the satellite-based rain estimates could be developed for the NIO basin to serve as the baseline for verification of the skill of forecast.
- Verification of EPSgram is not carried out at present.
- Similarly, the location specific meteogram and local forecasts for TC related rainfall needs to be verified.
- NWP based QPFs could be verified based on errors in the location as well as in the intensity of rainfall.
Spatial distribution and intensity forecasts of gale wind issued sub-division wise are verified in a tabular form for each date and time of forecast by comparing the actual occurrence of gale wind.

<table>
<thead>
<tr>
<th>Date/Time</th>
<th>Gale wind Forecast</th>
<th>Recorded wind</th>
</tr>
</thead>
</table>
| 06.10.14 (0300) | Andaman and Nicobar Islands: Squally wind speed reaching 45-55 kmph during next 24 hours. The wind speed would increase gradually reaching gale wind speed upto 70-80 kmph on 8th October 2014. | 08 October 2014: Port Blair: 88 kmph  
09 October 2014: Port Blair: 60 kmph  
10 October 2014: Port Blair: 64 kmph |
| 07.10.14/08.10.14 (0300) | Andaman and Nicobar Islands: Squally wind speed reaching 45-55 kmph during next 12 hours. The wind speed would increase gradually reaching gale wind speed of 70-80 kmph by 8th morning, October 2014. | 11 October 2014: Machilipatnam: 88 kmph  
Visakhapatnam: 74 kmph  
12 October 2014: Visakhapatnam: 185 kmph |
| 08.10.14/12.10.14 (0300) | North Andhra Pradesh and Odisha coasts: Squally wind speed reaching 50-60 kmph gusting to 70 kmph would commence from 11th morning onwards. The wind speed would increase to 130-140 kmph gusting to 150 from 12th morning. |                                                                                                  |
(xi) Storm surge forecast error

Both spatial distribution and intensity forecasts of storm surge height issued district-wise are verified in a tabular form for each date and time of forecast by comparing with the actual storm surge, which is estimated by survey team or observed by tide gauge.

<table>
<thead>
<tr>
<th>Forecast Storm surge above astronomical tide and area to be affected</th>
<th>Actual Storm Surge</th>
</tr>
</thead>
</table>
| **09.10.14/0300 UTC**
Storm surge of about 1-2 meters above astronomical tide would inundate low lying areas of East Godavari, Visakhapatnam, Vizianagaram and Srikakulam districts of north coastal Andhra Pradesh at the time of landfall (12 Oct 2014/ Around noon) | Observed Storm Surge recorded by the tide gauge at Visakhapatnam was 1.4 m. |
| **10.10.14/0300 UTC**
Storm surge of about 1-2 meters above astronomical tide would inundate low lying areas of Visakhapatnam, Vizianagaram and Srikakulam districts of north coastal Andhra Pradesh at the time of landfall (12 Oct 2014/ Around noon) |   |
(xi) Storm surge forecast error (2009-14)

<table>
<thead>
<tr>
<th>Observed class of storm surge (m)</th>
<th>24 hour forecast class of storm surge (m)</th>
<th>0</th>
<th>0.1-1.0</th>
<th>1.1-2.0</th>
<th>2.1-3.0</th>
<th>3.1-4.0</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>11</td>
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<td>0.1-1.0</td>
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<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3.1-4.0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>CSI</td>
<td></td>
<td>0.46</td>
<td>0</td>
<td>0.20</td>
<td>0.20</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>PC (%)</td>
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<td>41.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HSS</td>
<td></td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mohapatra (2015), TCRR
Outcome

Due to above improvements, there has been increase in confidence of disaster managers and public leading to

i. Minimum loss of human lives (limited to double digits) in recent years (Amphan-76, FANI -64, Titli-85, Hudhud-46 and Phailin-21 against 10,000 deaths during Odisha Super Cyclone in 1999)

ii. Decrease in area of evacuation by 300 km in 20 years and hence evacuation cost by 60 percent.

iii. Decrease in ex-gratia paid by Govt. to survivors by 99% as compared to 1999.

iv. Significant gains to various sectors as power sector saved around 500 crores each from cyclone warnings during Phailin and Hudhud.
v. Thus around 1100 crores are saved due to accurate forecast of one cyclone (Rs 590 crores in ex gratia payments, 32 crores in evacuation and 500 crores by power sector) which is more than double the entire cost of modernisation programme of IMD during 2008 to 12 (about 437 crores).

vi. Accurate cyclone warnings have not only benefitted India, but also residents of 13 Bay of Bengal and Arabian Sea countries. The number of deaths due to cyclones hitting these countries in recent years is limited to less than 100 in recent years [Sagar-53 (Somalia), Mekunu-26 (Oman), Luban-14 (Yemen), Chapala-5 (Yemen), Megh-18 (Yemen), Bulbul-6 (Bangladesh), Amphan-18 (Bangladesh)] against deaths in lakhs ten years back (1,40,000 deaths due to Nargis that hit Myanmar in 2008).


viii. Awards and Appreciations to India and IMD from various national and international agencies.
Our advances in meteorology were evident during the recent cyclone in Odisha, when we received accurate forecasts of the landfall point that were more accurate than the forecasts of well known international bodies.
In this cyclone, India Meteorological Department made excellent utilisation of Technology and from 6th October itself, this cyclone was predicted. The actual wind speed due to cyclone was same as the predicted wind speed. The track of the cyclone was same as that predicted. The time of landfall of cyclone was also same as that predicted by IMD.
Appreciations Received

Excerpt of 294\textsuperscript{th} Report of the Department-related Parliamentary Standing Committee on Science & Technology.

The track record of the Ministry has been above par in the case of cyclone predictions which has been seen in the case of Hudhud and Vardah.
Among our many-sided advances in meteorology, important outcomes during the recent cyclones in Odisha, Andhra Pradesh and Tamilnadu, when we received accurate forecasts of landfall points that were more accurate than the forecasts of international agencies are notable.
Weather forecasts are available these days and the concerned technology has become so advanced these days, and space science also plays a very big role, that these weather forecasts turn out to be mostly accurate now. We should also gradually make it our nature to set our work patterns according to the weather predictions, which could safeguard us against losses.
Appreciation

from WMO for
Sagar and
Mekunu in 2018

Subject: Severe Tropical Cyclone "Sagar" and Extreme Severe Tropical Cyclone "Mekunu"

Dear Dr Ramesh,

I wish to refer to the recent severe tropical cyclone "Sagar" and the extreme severe tropical cyclone "Mekunu", which happened consecutively in the Arabian Sea, from 17 to 28 May 2018.

I wish to express my sincere gratitude and appreciation to the RSMC Tropical Cyclone Centre, New Delhi, India that provided its advisory bulletins every three hours, during these two events.

The advisory bulletins were well distributed to all Members of the WMO/ESCAP Panel on Tropical Cyclones (PTC) and Somalia, for their early preparedness. They were also distributed to WMO Secretariat in Geneva, and forwarded to WMO Regional Offices in Bahrain and New York.

In addition to benefiting PTC Members and Somalia, those bulletins were well utilized by WMO Regional Office in Bahrain, to communicate and coordinate with both PTC and other Members neighboring Oman for their early preparation and necessary actions in response to the tropical cyclones. At the same time, all members of the Inter-Agency Standing Committee (IASC) with the key UN and non-UN humanitarian partners were informed and WMO representative in New York used the bulletins to provide a daily briefing to the United Nations (UN) Operations and Crisis Center at UN Headquarter, and informed the UN Secretary-General’s Executive Office on the development of the tropical cyclones and their potential impacts.

It is vitally important and effective practice to distribute and communicate RSMC Dew Delhi’s advisory bulletins with Members, WMO, UN and its humanitarian agencies in a timely manner, to enable all those concerned to take necessary and appropriate actions. I shall appreciate it very much if such a practice will be continued and strengthened.

I look forward to your continued support to the WMO Tropical Cyclone Programme and activities to reduce risks of disasters by tropical cyclones.

Yours sincerely,

(P. Talaas)
Secretary-General
Our expertise in accurate weather forecast has improved. This was evidenced during the recent #CycloneFani that struck the eastern coast of the country. Due to accurate information and timely preparation, large scale destruction to life and property was averted #PresidentKovind
Appreciation from United Nations for FANI in 2019

Excerpt of Appreciation from United Nations Office for Disaster Risk Reduction

The government’s zero casualty policy for natural disasters and the near accuracy of the India Meteorological Department’s early warning system have helped reduce the possibility of deaths from cyclone “FANI”.
Appreciation from WMO for Amphan

Excerpt of Appreciation from World Meteorological Organisation

The accurate prediction of Super Cyclonic Storm “AMPHAN” immensely helped in early response & actions. The services provided by the India Meteorological Department/Regional Specialised Meteorological Centre, New Delhi showcased excellent lesson and best practices in tropical cyclone forecasting & warning services and response actions for effective mitigation of disaster.
Excerpt of Survey by NCAER, 2015

Based on independent Survey by National Centre for Applied Economic Research (NCAER) in Andhra Pradesh and West Bengal in 2015, more than 95 percent population believe and appreciate cyclone warnings by IMD.
Minimum annual socioeconomic benefits of weather prediction amounts to at least US$160 billion and going to go more in years to come.
Death Toll over India

Death toll due to landfalling cyclones over Indian region (2010-2020)

- AP: Andhra Pradesh
- TN: Tamil Nadu
- ODS: Odisha
- WB: West Bengal
- MAH: Maharashtra

TCs not shown: Bandu, Phet & Jal (2010), Lehar & Madi (2013), Ockhi (2017), Burevi (2020) due to weakening prior to landfall. Death due to landfalling TCs (MSW ≥ 34 knot)
Death Toll over Member Countries

Death toll due to landfalling cyclones

- BNG: Bangladesh
- MYN: Myanmar
- SL: Sri Lanka

<table>
<thead>
<tr>
<th>Year</th>
<th>OMAN</th>
<th>YEMEN</th>
<th>MYN</th>
<th>BNG</th>
<th>SOMALIA</th>
<th>OMAN</th>
<th>YEMEN</th>
<th>OMAN</th>
<th>BNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011-Keila</td>
<td>14</td>
<td>64</td>
<td></td>
<td></td>
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<tr>
<td>2013-Viyaru</td>
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<td>2015-Chapala</td>
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<td>2015-Megh</td>
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<td>2017-Marutha</td>
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<td>135</td>
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<td>2017-Mora</td>
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<td>2018-Sagar</td>
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<tr>
<td>2018-Mekunu</td>
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<tr>
<td>2019-Hikaa</td>
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<tr>
<td>2019-Bulbul</td>
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</tr>
</tbody>
</table>

Number of Deaths

- BNG + SL + MYN

- Oman: 25
- Yemen: 18
- Myanmar: 7
- Bangladesh: 3
Thank you