Cyclone Prediction System (CPS) for the North Indian Ocean

Dr. S. D. Kotal

भारत मौसम विज्ञान विभाग
INDIAN METEOROLOGICAL DEPARTMENT
Operational NWP Models at IMD

- GFS T1534L64 (12 km)
- WRF (3DVAR - 9 km, 3 km)
- HWRF (18 km, 6 km, 2 km)
- GEFS (T1534)
- GPP (Genesis Potential)
- SCIP (for cyclone intensity prediction)
- MME (for cyclone track)
- RI-Index (Rapid Intensification)
- Decay after landfall (Decay model)

NWP Model product from Other Centres

- ECMWF
- JMA
- NCEP GFS
- UKMO
- NCMRWF, IITM
Model configuration

HWRF:
- v3.7 with GFS T1534 initial and boundary condition
- Triple Nested (18 Km, 6 Km, 2 Km) - Vertical level 61
- Run time 00, 06, 12, 18 UTC

WRF:
- V3.6 with RADAR data assimilation using 3DVAR
- Horizontal resolution 9km & 3km
- Run time 00, 06, 12, 18 UTC

GFS:
- T1534L64 (12 Km)
- Run time 00, 06, 12, 18 UTC

GEFS
- Run time 00, 12 UTC
Dynamical models are providing very useful guidance to operational forecasters:

- Limitation of models.
- Variation of forecasts among NWP models.
- Requirements are also different for different forecast services.
- Need to generate more skillful, consensus, and requirement based products.
STEP-I : CYCLOGENESIS
STEP-II : TRACK
STEP-III : INTENSITY
STEP-IV : RAPID INTENSIFICATION
STEP-V : DECAY AFTER LANDFALL

Cyclone Prediction System

STEP-I
- Cyclogenesis Prediction
- GPP
  - Kotal et al., 2009

STEP-II
- Track Prediction
- MME
  - Kotal et al., 2011

STEP-III
- Intensity Prediction
- SCIP
  - Kotal et al., 2008

STEP-IV
- Rapid Intensification
- RII
  - Kotal et al., 2013

STEP-V
- Decay after Landfall
- Decay Model
  - Roy Bhowmik et al., 2005
GENESIS POTENTIAL PARAMETER (GPP)
STEP- I : Tropical Cyclogenesis

Kotal, S.D. and Bhattacharya S.K. 2013. Tropical Cyclone Genesis Potential Parameter (GPP) and its application over the North Indian Sea. Mausam, 64(1):149-170]

Objective:
To understand the potential zone of cyclogenesis and potential for intensification of a system at early stages of development
Formulation of the Genesis potential parameter (GPP):

**Two Dynamic variables:**
(i) Low level relative vorticity ($\zeta_{850}$)
(ii) Vertical wind shear (S)

**Two Thermo-dynamical variables:**
(i) Middle troposphere relative humidity (M)
(ii) Middle-trposospheric instability (I)
The GPP is defined as:
(Natural Hazards, 2009, 50,389-402)

\[ GPP = \frac{\zeta_{850} M I}{S} \]

if \( \zeta_{850} > 0, \ M > 0 \) and \( I > 0 \)

= 0 \hspace{1cm} \text{if} \hspace{1cm} \zeta_{850} \leq 0, \ M \leq 0 \) and \( I \leq 0 \)

Where, \( \zeta_{850} \) = Low level relative vorticity (at 850 hPa) in \( 10^{-5} \, \text{s}^{-1} \)

\( S \) = Vertical wind shear between 200 and 850 hPa (\( \text{ms}^{-1} \))

\( M = \frac{[RH - 40]}{30} \) = Middle troposphere relative humidity

Where \( RH \) is the mean relative humidity between 700 and 500 hPa

\( I = (T_{850} - T_{500}) \, ^{\circ}C \) = Middle-trpospheric instability (Temperature difference between 850 hPa and 500 hPa)
### Genesis potential parameter for developing versus non-developing systems:

<table>
<thead>
<tr>
<th>T.No.</th>
<th>Developing</th>
<th>Non-Developing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>11.1</td>
<td>3.4</td>
</tr>
<tr>
<td>1.5</td>
<td>12.3</td>
<td>4.2</td>
</tr>
<tr>
<td>2.0</td>
<td>13.3</td>
<td>4.6</td>
</tr>
<tr>
<td>2.5</td>
<td>13.5</td>
<td>2.7</td>
</tr>
<tr>
<td>3.0</td>
<td>13.6</td>
<td>-</td>
</tr>
</tbody>
</table>

**Threshold value of GPP => 8.0**
PHAILIN
(Bay of Bengal October 2013)
On 1 Oct. 2013: 168 hour forecast (7 days in advance) of GPP valid for 00 UTC 08 October 2013 correctly indicated the location of potential cyclogenesis zone, where Depression formed on that day.
On 3 Oct. 2013: 120 hour forecast (5 days in advance) of GPP valid for 00 UTC 08 October 2013 correctly indicated the location of potential cyclogenesis zone, where Depression formed on that day.
Grid Point Analysis of Genesis Potential Parameter (GPP)

On 6 Oct. 2013: 48 hour forecast (2 days in advance) of GPP valid for 00 UTC 08 October 2013 correctly indicated the location of potential cyclogenesis zone, where Depression formed on that day.
Inference: Analysis and forecasts of GPP show that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0).
Genesis forecasts by GPP FANI

Tropical Cyclone Genesis Potential Parameter (GPP ANALYSIS)
Based on 27–04–2019 valid for 0000 UTC of 27–04–2019
(Potential Cyclogenesis Zone for GPP =>30)

Tropical Cyclone Genesis Potential Parameter (GPP) (24 HR FORECAST)
Based on 27–04–2019 valid for 0000 UTC of 27–04–2019
(Potential Cyclogenesis Zone for GPP =>30)

Tropical Cyclone Genesis Potential Parameter (GPP) (48 HR FORECAST)
Based on 25–04–2019 valid for 0000 UTC of 27–04–2019
(Potential Cyclogenesis Zone for GPP =>30)

Tropical Cyclone Genesis Potential Parameter (GPP) (72 HR FORECAST)
Based on 24–04–2019 valid for 0000 UTC of 27–04–2019
(Potential Cyclogenesis Zone for GPP =>30)
Mean GPP forecasts based on 00 UTC of 25.04.2019 (FANI)

Mean GPP forecasts based on 00 UTC of 26.04.2019 (FANI)
Mean GPP forecasts based on 1200 UTC of 26.04.2019 (FANI)

Mean GPP forecasts based on 0000 UTC of 27.04.2019 (FANI)
Very Severe Cyclonic Storm ‘VAYU’
Arabian Sea during (10-17) June 2019
Genesis potential parameter (VAYU)

Tropical Cyclone Genesis Potential Parameter (GPP ANALYSIS)
Based on 10–06–2019 valid for 1200 UTC of 10–06–2019
(Potential Cyclogenesis Zone for GPP =>3G)

Tropical Cyclone Genesis Potential Parameter (GPP) (48 HR FORECAST)
Based on 09–06–2019 valid for 1200 UTC of 10–06–2019
(Potential Cyclogenesis Zone for GPP =>3G)

Tropical Cyclone Genesis Potential Parameter (GPP) (72 HR FORECAST)
Based on 07–06–2019 valid for 1200 UTC of 10–06–2019
(Potential Cyclogenesis Zone for GPP =>3G)
Area average Genesis potential parameter (GPP)

Based on 12 UTC of 09-06-2019

Based on 00 UTC of 10-06-2019
GENESIS POTENTIAL PARAMETER (GPP)
Based on 12 UTC of 10-06-2019

T.No.-2.0
DEPRESSION over the Bay of Bengal during 2-3 April 2021
DEPRESSION over the Bay of Bengal during 2-3 April 2021
Genesis forecasts by GPP (DEPRESSION)

Tropical Cyclone Genesis Potential Parameter (GPP ANALYSIS)
Based on 01–04–2021 valid for 0000 UTC of 01–04–2021
(Potential Cyclogenesis Zone for GPP = 30)

L (01.04.2021)

Tropical Cyclone Genesis Potential Parameter (GPP) (24 HR FORECAST)
Based on 01–04–2021 valid for 0000 UTC of 02–04–2021
(Potential Cyclogenesis Zone for GPP = 30)

(D) 24h

Tropical Cyclone Genesis Potential Parameter (GPP) (48 HR FORECAST)
Based on 01–04–2021 valid for 0000 UTC of 03–04–2021
(Potential Cyclogenesis Zone for GPP = 30)

(D) 48h

Tropical Cyclone Genesis Potential Parameter (GPP) (72 HR FORECAST)
Based on 01–04–2021 valid for 0000 UTC of 04–04–2021
(Potential Cyclogenesis Zone for GPP = 30)

72h
Genesis forecasts by GPP

**L(31.03.2021/12 UTC)**

**L(01.04.2021/00 UTC)**

**D(02.04.2021/00 UTC)**

**D(01.04.2021/12 UTC)**
DEPRESSION over the Bay of Bengal during (4-6) March 2022
Genesis forecasts by GPP (DEPRESSION)

Tropical Cyclone Genesis Potential Parameter (GPP) (ANALYSIS)
Based on 04-03-2022 valid for 0600 UTC of 04-03-2022
(Potential Cyclogenesis Zone for GPP = 30)

D (04.03.2022)

Tropical Cyclone Genesis Potential Parameter (GPP) (24 HR FORECAST)
Based on 04-03-2022 valid for 0000 UTC of 05-03-2022
(Potential Cyclogenesis Zone for GPP = 30)

24h

Tropical Cyclone Genesis Potential Parameter (GPP) (48 HR FORECAST)
Based on 04-03-2022 valid for 0000 UTC of 06-03-2022
(Potential Cyclogenesis Zone for GPP = 30)

48h

Tropical Cyclone Genesis Potential Parameter (GPP) (72 HR FORECAST)
Based on 04-03-2022 valid for 0000 UTC of 07-03-2022
(Potential Cyclogenesis Zone for GPP = 30)

72h
Forecast Skill of Genesis potential parameter (GPP) during 2021

Forecast Skill of Genesis potential parameter (GPP) during 2008-2020
STEP-II: TRACK PREDICTION BY MME


Objective: To generate a consensus track forecast of NWP models by collective bias correction
TRACK PREDICTION BY NWP MODELS AND MME

- NCEP
- GFS
- JMA
- ECMWF
- UKMO

12 hrly F/C Lat.
12 hrly F/C Lon.
MME up to 120 h
12-hourly forecast latitude \((\text{LAT}_t^f)\) and longitude \((\text{LON}_t^f)\) positions at time \(t\) is defined as:

\[
\text{LAT}_t^f = a_0 + a_1 \text{NCEP}_t^{\text{lat}} + a_2 \text{GFS}_t^{\text{lat}} + a_3 \text{JMA}_t^{\text{lat}} + a_4 \text{ECMWF}_t^{\text{lat}} + a_5 \text{UKMO}_t^{\text{lat}}
\]

\[
\text{LON}_t^f = a'_0 + a'_1 \text{NCEP}_t^{\text{lon}} + a'_2 \text{GFS}_t^{\text{lon}} + a'_3 \text{JMA}_t^{\text{lon}} + a'_4 \text{ECMWF}_t^{\text{lon}} + a'_5 \text{UKMO}_t^{\text{lon}}
\]

for \(t = \text{forecast hour} 12, 24, 36, 48, 60, 72, 84, 96, 108\) and \(120\) h
VIYARU
(Bay of Bengal May 2012)
MME track forecasts based on different initial conditions
### Landfall point error (km) - VIYARU

<table>
<thead>
<tr>
<th>Model</th>
<th>FC based on 00 UTC/14.05.2013</th>
<th>FC based on 00 UTC/15.05.2013</th>
<th>FC based on 12 UTC/15.05.2013</th>
<th>FC based on 00 UTC/16.05.2013</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lead time: 56 h</td>
<td>Lead time: 32 h</td>
<td>Lead time: 20 h</td>
<td>Lead time: 8 h</td>
</tr>
<tr>
<td>IMD-GFS</td>
<td>NO LF</td>
<td>NO LF</td>
<td>136</td>
<td>-</td>
</tr>
<tr>
<td>IMD-WRF</td>
<td>NO LF</td>
<td>147</td>
<td>49</td>
<td>45</td>
</tr>
<tr>
<td>IMD-QLM</td>
<td>NO LF</td>
<td>63</td>
<td>137</td>
<td>243</td>
</tr>
<tr>
<td>JMA</td>
<td>137</td>
<td>63</td>
<td>98</td>
<td>49</td>
</tr>
<tr>
<td>NCEP-GFS</td>
<td>289</td>
<td>169</td>
<td>136</td>
<td>136</td>
</tr>
<tr>
<td>ECMWF</td>
<td>259</td>
<td>274</td>
<td>127</td>
<td>15</td>
</tr>
<tr>
<td>IMD-MME</td>
<td>63</td>
<td>63</td>
<td>63</td>
<td>25</td>
</tr>
<tr>
<td>IMD-HWRF</td>
<td>84</td>
<td>174</td>
<td>121</td>
<td>-</td>
</tr>
</tbody>
</table>
PHAILIN
(Bay of Bengal October 2013)
NWP model and consensus NWP (Multi-model ensemble) track forecasts based on 00 UTC of 08.10.2013 for cyclone PHAILIN

All model landfall point forecasts varied from north AP to Paradip(Odisha)

Consensus track forecast correctly predicted landfall at GOPALPUR(Odisha)
NWP model and Multi-model ensemble track forecasts based on 00 UTC of 09.10.2013

All model landfall point forecasts varied from North AP to Sagar Island (west Bengal)

Consensus track forecast correctly predicted landfall at GOPALPUR
NWP model and Multi-model ensemble track forecasts based on 00 UTC of 10.10.2013

All model landfall point forecasts varied from Kalingapattanam(North AP) to Paradip(Odisha)

Consensus track forecast correctly predicted landfall at GOPALPUR
NWP model and Multi-model ensemble track forecasts based on 00 UTC of 11.10.2013

All model landfall point forecasts varied from Kalingapattanam(North AP) to Paradip(Odisha)

Consensus track forecast correctly predicted landfall at GOPALPUR
NWP model and Multi-model ensemble track forecasts based on 00 UTC of 12.10.2013

All model landfall point forecasts varied from Kalingapattanam (North AP) to Gopalpur (Odisha)

Consensus track forecast correctly predicted landfall at GOPALPUR
Landfall Point Error (km) of NWP Models

**Average Landfall Point Error (km)**
- IMD-MME: 20
- NCEP-GFS: 36
- IMD-GFS: 41
- UKMO: 44
- IMD-WRF: 69
- JMA: 73
- HWRF: 144

**MME landfall forecast errors were consistently low at all lead time**

**Average landfall forecast error was lowest for MME**

Legend:
- UKMO
- NCEP-GFS
- JMA
- HWRF
- IMD-GFS
- IMD-WRF
- IMD-MME

*Positive for North of actual landfall*
*Negative for South of actual landfall*
Landfall Time Error of NWP Models (hr)

Negative for Early landfall
Positive for Delayed landfall

Forecast Lead Time (hr)

Average Absolute Landfall Time Error (hr)
MME forecasts track for cyclone HUDHUD

(Bay of Bengal October 2014)
NWP model and consensus NWP (Multi-model ensemble) track forecasts based on 12 UTC of 17.05.2016 and 00 UTC of 18.05.2016 for cyclone ROANU (Landfall Time-10 UTC 21.5.2016)

Landfall forecast Lead Time -94 h

Landfall forecast Lead Time -82 h
NWP model and consensus NWP (Multi-model ensemble) track forecasts based on 12 UTC of 18.05.2016 and 00 UTC of 19.05.2016 for cyclone ROANU

Landfall forecast Lead Time -70 h

Landfall forecast Lead Time -58 h
NWP model and consensus NWP (Multi-model ensemble) track forecasts based on 12 UTC of 19.05.2016 and 00 UTC of 20.05.2016 for cyclone ROANU

Landfall forecast Lead Time -46 h

Landfall forecast Lead Time -34 h
NWP model and consensus NWP (Multi-model ensemble) track forecasts based on 12 UTC of 20.05.2016 and 00 TUC 21.05.2016 for cyclone ROANU

Landfall forecast Lead Time -22 h

Landfall forecast Lead Time -10 h
ESCS MEGH: 05-10 November 2015
(Arabian Sea)
TROPICAL CYCLONE "MEGH"
OBSERVED vs IMD-MME TRACK
(based on different initial conditions)
All Track forecasts by MME vs Observed Track (BULBUL) (Bay of Bengal November 2019)
All Track forecasts by MME vs Observed Track (FANI) (Bay of Bengal April 2019)
TCs (a) Phailin, (b) Hudhud, (c) Fani, (d) Mora, (e) Bulbul, and (f) Roanu.
Mean track forecast error (km) – 2009-2019

CYCLONE TRACK FORECAST ERRORS (2009-2019)
Mean MME track forecast error (km)

Mean MME Track Forecast Errors (DPE) (km) (2009-2019)

Track Error (km)

<table>
<thead>
<tr>
<th>Lead Time (hr)</th>
<th>12</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>60</th>
<th>72</th>
<th>84</th>
<th>96</th>
<th>108</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error (km)</td>
<td>54</td>
<td>69</td>
<td>85</td>
<td>105</td>
<td>123</td>
<td>147</td>
<td>160</td>
<td>186</td>
<td>220</td>
<td>246</td>
</tr>
</tbody>
</table>
Year wise MME track forecast error (km)
Landfall Point error (km)

MME Landfall Point Error (km)-2019

- 0-24: 15 km
- 24-48: 49 km
- 48-72: 54 km
- 72-96: 22 km

MME Landfall Point Error (km)-2009-2019

- 0-24: 42 km
- 24-48: 69 km
- 48-72: 86 km
- 72-96: 84 km
- 96-120: 127 km
STEP-III: Tropical Cyclone Intensity Prediction by SCIP model

Objective:
Intensity prediction at 12-hr interval up to 72 hours

Statistical Cyclone Intensity Prediction (SCIP) Model

Data sample: 62 Tropical Cyclones during the period 1981 to 2000
<table>
<thead>
<tr>
<th>S.No</th>
<th>Predictors</th>
<th>Symbol of Predictors</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Intensity change during last 12 hours</td>
<td>IC12</td>
<td>Knots</td>
</tr>
<tr>
<td>2.</td>
<td>Vorticity at 850 hPa</td>
<td>V850</td>
<td>$x\ 10^5\ s^{-1}$</td>
</tr>
<tr>
<td>3.</td>
<td>Storm motion speed</td>
<td>SMS</td>
<td>ms$^{-1}$</td>
</tr>
<tr>
<td>4.</td>
<td>Divergence at 200 hPa</td>
<td>D200</td>
<td>$x\ 10^5\ s^{-1}$</td>
</tr>
<tr>
<td>5.</td>
<td>Initial Storm intensity</td>
<td>ISI</td>
<td>Knots</td>
</tr>
<tr>
<td>6.</td>
<td>Initial Storm latitude position</td>
<td>ISL</td>
<td>°N</td>
</tr>
<tr>
<td>7.</td>
<td>Sea surface temperature</td>
<td>SST</td>
<td>°C</td>
</tr>
<tr>
<td>8.</td>
<td>Vertical wind shear</td>
<td>VWS</td>
<td>Knots</td>
</tr>
</tbody>
</table>
Formulation of the model:
The model is developed using multiple linear regression technique

\[ y = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_n x_n \]

The SCIP model estimates changes of intensity at 12, 24, 36, 48, 60 and 72 hours. Six separate regression analyses are carried out for forecast interval 12, 24, 36, 48, 60 and 72 hour.

12 hours intensity change by multiple linear regression technique is defined as:

\[ dv_t = a_0 + a_1 IC12 + a_2 SMS + a_3 VWS + a_4 D200 + a_5 V850 + a_6 ISL + a_7 SST + a_8 ISI \]

for \( t = \) forecast hour 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120h
CS VIYARU: May 10-16
Intensity Prediction by SCIP model for MAHASEN

Forecast Lead Time (h)

Forecast Intensity (kt)

- Observed
- FC1 (11May/00z)
- FC2 (12May/00z)
- FC3 (13May/00z)
- FC4 (14May/00z)
- FC5 (15May/00z)
- FC6 (16May/00z)
### Intensity forecast error (kt)- VIYARU

Average absolute errors (Number of forecasts verified is given in the parentheses)

<table>
<thead>
<tr>
<th>Lead time →</th>
<th>12 hr</th>
<th>24 hr</th>
<th>36 hr</th>
<th>48 hr</th>
<th>60 hr</th>
<th>72 hr</th>
<th>84 hr</th>
<th>96 hr</th>
<th>108 hr</th>
<th>120 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMD-SCIP</td>
<td>1.3 (6)</td>
<td>4.3 (6)</td>
<td>6.4 (5)</td>
<td>3.8 (4)</td>
<td>11.3 (4)</td>
<td>10.0 (3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IMD-HWRF</td>
<td>27.2(10)</td>
<td>21.3(9)</td>
<td>8.6(8)</td>
<td>10.9(7)</td>
<td>19.2(6)</td>
<td>23.0(5)</td>
<td>29.5(4)</td>
<td>14.0(3)</td>
<td>22.0(2)</td>
<td>29.0(1)</td>
</tr>
<tr>
<td>OFFICIAL</td>
<td>3.6 (24)</td>
<td>6.8(22)</td>
<td>8.7(20)</td>
<td>10.0(18)</td>
<td>13.0(16)</td>
<td>15.0(14)</td>
<td>14(10)</td>
<td>13(8)</td>
<td>17(6)</td>
<td>14(4)</td>
</tr>
</tbody>
</table>

### Root Mean Square (RMSE) errors (Number of forecasts verified is given in the parentheses)

<table>
<thead>
<tr>
<th>Lead time →</th>
<th>12 hr</th>
<th>24 hr</th>
<th>36 hr</th>
<th>48 hr</th>
<th>60 hr</th>
<th>72 hr</th>
<th>84 hr</th>
<th>96 hr</th>
<th>108 hr</th>
<th>120 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMD-SCIP</td>
<td>2.2 (6)</td>
<td>8.0 (6)</td>
<td>8.5 (5)</td>
<td>4.3 (4)</td>
<td>14.9 (4)</td>
<td>11.6 (3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IMD-HWRF</td>
<td>30.0(10)</td>
<td>24.3(9)</td>
<td>12.2(8)</td>
<td>12.8(7)</td>
<td>22.8(6)</td>
<td>28.0(5)</td>
<td>31.5(4)</td>
<td>14.3(3)</td>
<td>22.4(2)</td>
<td>29.0(1)</td>
</tr>
<tr>
<td>OFFICIAL</td>
<td>4.6 (24)</td>
<td>8.9(22)</td>
<td>10.8(20)</td>
<td>12.5(18)</td>
<td>16.1(16)</td>
<td>17.8(14)</td>
<td>16.1(10)</td>
<td>15.7(8)</td>
<td>17.5(6)</td>
<td>16.4(4)</td>
</tr>
</tbody>
</table>
Intensity Prediction by SCIP model for PHAILIN

![Intensity Prediction Graph]

- **Forecast Intensity (kt)**
- **Forecast Lead Time (h)**

- **Observed**
- **FC1(08oct/00z)**
- **FC2(09oct/00z)**
- **FC3(09oct/12z)**
- **FC4(10oct/00z)**
- **FC5(10oct/12z)**
- **FC6(11oct/00z)**
- **FC7(11oct/12z)**
- **FC8(12oct/00z)**
### Average absolute errors (PHAILIN)
(Number of forecasts verified is given in the parentheses)

<table>
<thead>
<tr>
<th>Lead time →</th>
<th>12 hr</th>
<th>24 hr</th>
<th>36 hr</th>
<th>48 hr</th>
<th>60 hr</th>
<th>72 hr</th>
<th>84 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMD-SCIP</td>
<td>10.4(8)</td>
<td>18.3(7)</td>
<td>23.7(6)</td>
<td>24.6(5)</td>
<td>31.5(4)</td>
<td>36.7(3)</td>
<td>-</td>
</tr>
<tr>
<td>IMD-HWRF</td>
<td>17.0(6)</td>
<td>21.0(5)</td>
<td>27.8(5)</td>
<td>30.5(4)</td>
<td>28.3(3)</td>
<td>19.5(2)</td>
<td>11.0(1)</td>
</tr>
</tbody>
</table>

### Root Mean Square (RMSE) errors
(Number of forecasts verified is given in the parentheses)

<table>
<thead>
<tr>
<th>Lead time →</th>
<th>12 hr</th>
<th>24 hr</th>
<th>36 hr</th>
<th>48 hr</th>
<th>60 hr</th>
<th>72 hr</th>
<th>84 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMD-SCIP</td>
<td>13.9(8)</td>
<td>23.3(7)</td>
<td>29.6(6)</td>
<td>32.3(5)</td>
<td>32.4(4)</td>
<td>37.2(3)</td>
<td>-</td>
</tr>
<tr>
<td>IMD-HWRF</td>
<td>19.0(6)</td>
<td>24.2(5)</td>
<td>31.7(5)</td>
<td>31.2(4)</td>
<td>28.6(3)</td>
<td>20.0(2)</td>
<td>14.9(1)</td>
</tr>
</tbody>
</table>
Landfall Intensity (kt) Prediction by SCIP model

Forecast Issue Time

<table>
<thead>
<tr>
<th></th>
<th>Predicted</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 UTC/09.10.2013</td>
<td>85</td>
<td>115</td>
</tr>
<tr>
<td>00 UTC/10.10.2013</td>
<td>90</td>
<td>115</td>
</tr>
<tr>
<td>12 UTC/10.10.2013</td>
<td>113</td>
<td>115</td>
</tr>
<tr>
<td>00 UTC/11.10.2013</td>
<td>131</td>
<td>115</td>
</tr>
<tr>
<td>12 UTC/11.10.2013</td>
<td>133</td>
<td>115</td>
</tr>
<tr>
<td>00 UTC/12.10.2013</td>
<td>126</td>
<td>115</td>
</tr>
</tbody>
</table>
SCS HELEN: Nov 19-23
Average absolute errors (HELEN)  
(Number of forecasts verified is given in the parentheses)

<table>
<thead>
<tr>
<th>Lead time →</th>
<th>12 hr</th>
<th>24 hr</th>
<th>36 hr</th>
<th>48 hr</th>
<th>60 hr</th>
<th>72 hr</th>
<th>84 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMD-SCIP</td>
<td>8.0(3)</td>
<td>11.3(3)</td>
<td>20.5(2)</td>
<td>24.5(2)</td>
<td>14.0(2)</td>
<td>25.0(1)</td>
<td>-</td>
</tr>
<tr>
<td>IMD-HWRF</td>
<td>5.3(4)</td>
<td>11.0(4)</td>
<td>7.0(3)</td>
<td>6.0(2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Root Mean Square (RMSE) errors  
(Number of forecasts verified is given in the parentheses)

<table>
<thead>
<tr>
<th>Lead time →</th>
<th>12 hr</th>
<th>24 hr</th>
<th>36 hr</th>
<th>48 hr</th>
<th>60 hr</th>
<th>72 hr</th>
<th>84 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMD-SCIP</td>
<td>8.8(3)</td>
<td>14.1(3)</td>
<td>21.2(2)</td>
<td>25.1(2)</td>
<td>16.6(2)</td>
<td>25.0(1)</td>
<td>-</td>
</tr>
<tr>
<td>IMD-HWRF</td>
<td>7.9(4)</td>
<td>11.6(4)</td>
<td>8.2(3)</td>
<td>6.7(3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
VSCS LEHAR: Nov 23-28
Intensity Prediction by SCIP model for LEHAR

Forecast Lead Time (h) vs Forecast Intensity (kt)

- OBSERVED
- FC1(00Z/23NOV2013)
- FC1(12Z/23NOV2013)
- FC1(00Z/24NOV2013)
- FC1(12Z/24NOV2013)
- FC1(00Z/25NOV2013)
- FC1(12Z/25NOV2013)
- FC1(00Z/26NOV2013)
- FC1(12Z/26NOV2013)
- FC1(00Z/27NOV2013)
- FC1(12Z/27NOV2013)
### Average absolute errors (LEHAR)
(Number of forecasts verified is given in the parentheses)

<table>
<thead>
<tr>
<th>Lead time →</th>
<th>12 hr</th>
<th>24 hr</th>
<th>36 hr</th>
<th>48 hr</th>
<th>60 hr</th>
<th>72 hr</th>
<th>84 hr</th>
<th>96 hr</th>
<th>108 hr</th>
<th>120 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IMD-SCIP</strong></td>
<td>5.6 (10)</td>
<td>13.0 (9)</td>
<td>16.9 (8)</td>
<td>19.6 (7)</td>
<td>20.3 (6)</td>
<td>19.6 (5)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>IMD-HWRF</strong></td>
<td>23.4 (9)</td>
<td>12.9 (8)</td>
<td>12.4 (7)</td>
<td>12.7 (7)</td>
<td>7.3 (6)</td>
<td>13.6 (5)</td>
<td>21.3 (4)</td>
<td>22.7 (3)</td>
<td>30.5 (2)</td>
<td>57 (1)</td>
</tr>
</tbody>
</table>

### Root Mean Square (RMSE) errors
(Number of forecasts verified is given in the parentheses)

<table>
<thead>
<tr>
<th>Lead time →</th>
<th>12 hr</th>
<th>24 hr</th>
<th>36 hr</th>
<th>48 hr</th>
<th>60 hr</th>
<th>72 hr</th>
<th>84 hr</th>
<th>96 hr</th>
<th>108 hr</th>
<th>120 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IMD-SCIP</strong></td>
<td>6.6 (10)</td>
<td>16.6 (9)</td>
<td>19.7 (8)</td>
<td>22.1 (7)</td>
<td>24.0 (6)</td>
<td>22.9 (5)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>IMD-HWRF</strong></td>
<td>25.7 (9)</td>
<td>17.1 (8)</td>
<td>15.5 (7)</td>
<td>13.6 (7)</td>
<td>9.7 (6)</td>
<td>19.2 (5)</td>
<td>28.3 (4)</td>
<td>29.5 (3)</td>
<td>31.2 (2)</td>
<td>57 (1)</td>
</tr>
</tbody>
</table>
VSCS MADI: Dec 6-13
INTENSITY FORECASTS BY SCIP (MADI)

Intensity Prediction by SCIP model

<table>
<thead>
<tr>
<th>Forecast Lead Time (h)</th>
<th>0</th>
<th>12</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>60</th>
<th>72</th>
<th>84</th>
<th>96</th>
<th>108</th>
<th>120</th>
<th>132</th>
<th>144</th>
<th>156</th>
<th>168</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity (kt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VSCS(65 kt)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Lead time → 12 hr | 24 hr | 36 hr | 48 hr | 60 hr | 72 hr |

| AAE       | 5.2 (10) | 6.4 (10) | 12.8 (10) | 15.3 (9) | 16.9 (8) | 15.7 (7) |
| RMSE      | 6.4 (10) | 8.2 (10) | 15.3 (10) | 18.2 (9) | 20.3 (8) | 20.3 (7) |
INTENSITY FORECASTS BY SCIP (AMPHAN)
MEAN FORECAST ERRORS : 2008-2021
LANDFALL INTENSITY FORECASTS BY SCIP

(a) Phailin

(b) Hudhud

(c) Fani

(d) Bulbul

[Bar charts showing predicted and observed intensities for each storm at different forecast numbers and lead times]
Landfall intensity forecast by SCIP versus Observed intensity during 2010-2019

Mean landfall intensity error(h) of SCIP model during 2010-2019
STEP-IV: Rapid Intensification (RI)


**Objective:** Probability forecast of Rapid Intensification

**Rapid Intensification:** Increase of intensity by 30 kt during 24 h

**Data sample:** 88 Tropical Cyclones during the period 1981 to 2010
## Rapid Intensification

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Variables</th>
<th>Symbol of Variables</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Previous 12-h intensity change</td>
<td>IC12</td>
<td>kt</td>
</tr>
<tr>
<td>2.</td>
<td>Vorticity at 850 hPa</td>
<td>V850</td>
<td>$10^{-5}$ s$^{-1}$</td>
</tr>
<tr>
<td>3.</td>
<td>Storm motion speed</td>
<td>SMS</td>
<td>ms$^{-1}$</td>
</tr>
<tr>
<td>4.</td>
<td>Divergence at 200 hPa</td>
<td>D200</td>
<td>$10^{-5}$ s$^{-1}$</td>
</tr>
<tr>
<td>5.</td>
<td>Initial Storm intensity</td>
<td>ISI</td>
<td>kt</td>
</tr>
<tr>
<td>6.</td>
<td>Initial Storm latitude position</td>
<td>ISL</td>
<td>°N</td>
</tr>
<tr>
<td>7.</td>
<td>850-700 hPa average relative humidity</td>
<td>LTRH</td>
<td>%</td>
</tr>
<tr>
<td>8.</td>
<td>850-200 hPa vertical wind shear</td>
<td>SHR</td>
<td>ms$^{-1}$</td>
</tr>
<tr>
<td>9.</td>
<td>Sea Surface Temperature</td>
<td>SST</td>
<td>°C</td>
</tr>
</tbody>
</table>
Rapid Intensification Index (RII)

- Data Period - 1981-2010
- No. of TC - 88
- No. of data sample - 483
- No. of parameter - 8

### Predictors and Thresholds

- **IC12**: $\geq 8.2$ kt
- **ISI**: $\geq 41.2$ kt
- **SMS**: $\geq 3.8$ m/s
- **ISL**: $\geq 13.1$ N
- **IC12**: $\leq 10.9$ m/s
- **SHR**: $\geq 1.6$ s
- **D200**: $\geq 1.6$ s
- **V850**: $\geq 4.5$ s
- **LTRH**: $\geq 85.8$%
Composite probability of Rapid Intensification

The composite probability of RI ($P_n$) is defined as:

$$P_n = \left( \frac{n_1}{(n_1 + n_2)} \right) \times 100\%$$

Where,

$P_n =$ RI probability for $n$ number of variables that satisfied their respective thresholds

$n_1 =$ Number of RI cases that satisfied the $n$ number thresholds

$n_2 =$ Number of non-RI cases that satisfied the $n$ number thresholds

$n = 0, 1, 2, 3, 4, 5, 6, 7, 8$ (number of variables)
Composite probability of Rapid Intensification

**Graph:**
- Probability of RI (%)
- Total number of RI thresholds satisfied
- No. of RI- Indices satisfied: 0, 1, 2, 3, 4, 5, 6, 7, 8
- Probability (%): 0.0, 2.6, 5.2, 9.4, 22.0, 32.0, 72.7, 100.0

**Table:**
- No. of RI- Indices satisfied: 0, 1, 2, 3, 4, 5, 6, 7, 8
- Probability (%): 0, 0, 2.6, 5.2, 9.4, 22.0, 32.0, 72.7, 100.0
- Chances of occurrence: NIL, NIL, VERY LOW, VERY LOW, VERY LOW, LOW, MODERATE, HIGH, VERY HIGH

**Climatological Probability of RI=9.5%**
**Probability of Rapid intensification (by RI-Index)**

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour.

<table>
<thead>
<tr>
<th>Forecast based on</th>
<th>Probability of RI predicted</th>
<th>Chances of occurrence predicted</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>00 UTC/11.05.2013</td>
<td>9.4 %</td>
<td>VERY LOW</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/12.05.2013</td>
<td>5.2 %</td>
<td>VERY LOW</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/13.05.2013</td>
<td>2.6 %</td>
<td>VERY LOW</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/14.05.2013</td>
<td>5.2 %</td>
<td>VERY LOW</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/15.05.2013</td>
<td>9.4 %</td>
<td>VERY LOW</td>
<td>NO</td>
</tr>
<tr>
<td>12 UTC/15.05.2013</td>
<td>22.0 %</td>
<td>LOW</td>
<td>NO</td>
</tr>
</tbody>
</table>

Inference: RI-Index could able to predict non-occurrence of Rapid Intensification of cyclone VIYARU during its lifetime.
**Probability of Rapid intensification (by RI-Index)-PHAILIN**

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour.

<table>
<thead>
<tr>
<th>Forecast based on</th>
<th>Probability of RI predicted</th>
<th>Chances of occurrence predicted</th>
<th>Intensity changes (kt) in 24h</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>00 UTC/08.10.2013</td>
<td>9.4 %</td>
<td>VERY LOW</td>
<td>5</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/09.10.2013</td>
<td>9.4 %</td>
<td>VERY LOW</td>
<td>15</td>
<td>NO</td>
</tr>
<tr>
<td>12 UTC/09.10.2013</td>
<td>9.4 %</td>
<td>VERY LOW</td>
<td>40</td>
<td>YES</td>
</tr>
<tr>
<td>00 UTC/10.10.2013</td>
<td>72.7 %</td>
<td>HIGH</td>
<td>65</td>
<td>YES</td>
</tr>
<tr>
<td>12 UTC/10.10.2013</td>
<td>72.7 %</td>
<td>HIGH</td>
<td>40</td>
<td>YES</td>
</tr>
<tr>
<td>00 UTC/11.10.2013</td>
<td>72.7 %</td>
<td>HIGH</td>
<td>5</td>
<td>NO</td>
</tr>
<tr>
<td>12 UTC/11.10.2013</td>
<td>32.0 %</td>
<td>MODERATE</td>
<td>0</td>
<td>NO</td>
</tr>
</tbody>
</table>

Inference: RI-Index could able to predict OCCURRENCE as well as NON-OCCURRENCE of Rapid Intensification of cyclone **PHAILIN** during its lifetime except forecast for 12 UTC of 09.10.2013 and 00 UTC of 11.10.2013.
Probability of Rapid intensification (by RI-Index)-HELEN

<table>
<thead>
<tr>
<th>Forecast based on</th>
<th>Probability of RI predicted</th>
<th>Chances of occurrence predicted</th>
<th>Intensity changes (kt) in 24h</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>00 UTC/19.12.2013</td>
<td>5.2 %</td>
<td>VERY LOW</td>
<td>5</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/20.12.2013</td>
<td>9.4 %</td>
<td>VERY LOW</td>
<td>20</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/21.10.2013</td>
<td>9.4 %</td>
<td>VERY LOW</td>
<td>5</td>
<td>NO</td>
</tr>
</tbody>
</table>

Inference: RI-Index was able to predict NON-OCCURRENCE of Rapid Intensification of cyclone HELEN during its lifetime.
### Probability of Rapid intensification (by RI-Index)-LEHAR

<table>
<thead>
<tr>
<th>Forecast based on</th>
<th>Probability of RI predicted</th>
<th>Chances of occurrence predicted</th>
<th>Intensity changes (kt) in 24h</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>00 UTC/23.11.2013</td>
<td>5.2 %</td>
<td>VERY LOW</td>
<td>5</td>
<td>NO</td>
</tr>
<tr>
<td>12 UTC/23.11.2013</td>
<td>5.2 %</td>
<td>VERY LOW</td>
<td>20</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/24.11.2013</td>
<td>22.0 %</td>
<td>LOW</td>
<td>20</td>
<td>NO</td>
</tr>
<tr>
<td>12 UTC/24.11.2013</td>
<td>22.0 %</td>
<td>LOW</td>
<td>15</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/25.11.2013</td>
<td>32.0 %</td>
<td>MODERATE</td>
<td>15</td>
<td>NO</td>
</tr>
<tr>
<td>12 UTC/25.11.2013</td>
<td>9.4 %</td>
<td>VERY LOW</td>
<td>10</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/26.11.2013</td>
<td>9.4 %</td>
<td>VERY LOW</td>
<td>5</td>
<td>NO</td>
</tr>
<tr>
<td>12 UTC/26.11.2013</td>
<td>5.2%</td>
<td>VERY LOW</td>
<td>-15</td>
<td>NO</td>
</tr>
<tr>
<td>00 UTC/27.11.2013</td>
<td>9.4%</td>
<td>VERY LOW</td>
<td>-45</td>
<td>NO</td>
</tr>
<tr>
<td>12 UTC/27.11.2013</td>
<td>0.0%</td>
<td>NIL</td>
<td>-30</td>
<td>NO</td>
</tr>
</tbody>
</table>

Inference: RI-Index was able to predict NON-OCCURENCE of Rapid Intensification of cyclone LEHAR during its lifetime.
Rapid Intensification and Rapid Decay of TC CHAPALA over Arabian Sea
(28 October - 4 November 2015)


CHAPALA: Track & Intensity
Vertical cross section plots of axisymmetric specific humidity flux (shaded in g m\(^{-2}\) s\(^{-1}\)) at

(a) 0000 UTC 29 October 2015,
(b) 0000 UTC 30 October 2015,
(c) 1200 UTC 29 October 2015,
(d) 1200 UTC 30 October 2015,
(e) 0000 UTC 2 November 2015,
(f) 0000 UTC 3 November 2015.
Potentially vorticity (shaded in PVU) at 850 hPa

Mathematically, Ertel's (1942) form of potential vorticity (PV) is given by the equation:

$$ PV = \frac{1}{\rho} \zeta^a \cdot \nabla \theta $$

PV is a measure of the intrinsic cyclonicity of an air parcel. It can be shown through a combination of the first law of thermodynamics and momentum conservation that the potential vorticity can only be changed by diabatic heating (such as latent heat released from condensation) or frictional processes.
Vertical cross section plots of diabatic heating (shaded in °C)

(a) from 0000 UTC 28 October 2015 to 0000 UTC 29 November 2015,
(b) from 0000 UTC 29 October 2015 to 0000 UTC 30 November 2015,
(c) from 1200 UTC 29 October 2015 to 1200 UTC 30 October 2015,
(d) from 0000 UTC 2 November 2015 to 3 November 2015.
Vertical cross section plots of potential vorticity (shaded in PVU) at

(a) 0000 UTC 29 October 2015,
(b) 0000 UTC 30 October 2015,
(c) 1200 UTC 29 October 2015,
(d) 1200 UTC 30 October 2015,
(e) 0000 UTC 2 November 2015,
(f) 0000 UTC 3 November 2015.
Time series from 0000 UTC 28 October 2015 to 0000 UTC 03 November 2015 of the temperature at the centre of the storm at different vertical levels.

RI indicates Rapid Intensification phase and RD indicates Rapid Decay phase.

Time series from 0000 UTC 28 October 2015 to 0000 UTC 03 November 2015 of the temperature at the centre of the storm at different vertical levels (RI indicates Rapid Intensification phase and RD indicates Rapid Decay phase).
Thank you