Large Scale features (ENSO, IOD, MJO) and Seasonal Prediction of Tropical Cyclones

D. R. Pattanaik
IMD New Delhi
Email *- drpattanaik@gmail.com
Collaborator : Dr. M. Mohapatra, head RSMC, New Delhi

भारत मौसम विज्ञान विभाग
INDIA METEOROLOGICAL DEPARTMENT

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Topics to be covered

- **Part –I**
  - Tropical Cyclones over Different Ocean Basins
  - ENSO and Tropical Cyclone
  - Indian Ocean Dipole and Tropical Cyclone
  - Madden Julian Oscillation (MJO) and Tropical Cyclone

- **Part -II**
  - Forecasting of Tropical Cyclone
  - Extended Range and Seasonal Forecast Models
  - Verification over Bay of Bengal
Cyclonic Disturbances in all Ocean Basins (Landsea 1993, 2000)

Atlantic: Hurricane season (June to November) 97% of annual (August to October).


Central Pacific Basin: Hurricane season June to Nov (August - September).

Northwest Pacific Basin: Tropical cyclones occurring all year round. The main season from July to November (late August/early September).

North Indian Basin: Double peak of activity in May and November though tropical cyclones are seen from April to December.

Southwest Indian and Australian/Southeast Indian basins: have very similar annual cycles with tropical cyclones beginning in late October/early November, reaching a double peak in activity - one in mid-January and one in mid-February to early March, and then ending in May.

Australian/Southwest Pacific basin: Begin TC activity in late October/early November, reaches a single peak in late February/early March, fades out in early May.
Fig. 1. Plot of Julian Day versus IH activity (9-day running mean) using data for 1986–1989. Note that nearly all IH activity occurs between 1 August (Julian Day 213) and 1 November (Julian Day 305).
Monthly total number of Cyclonic Disturbances (CDs) including depressions (DD) and cyclonic storms formed during Oct-Dec (1971-2014)
TC and Large Scale Variables
ENSO and TROPICAL CYCLOGEBESIS

Pacific Annual SST

December 1982 SST

December 1982 SST Anomaly
Southern Oscillation Index (SOI)

SOI: Tahiti and Darwin as "centers of action", mslp correlations between two locations

Tahiti and Darwin are at opposite ends of the Southern Oscillation's seesaw, and so the difference in pressure between them is used to measure the Southern Oscillation. The numbers represent a statistical measure called the correlation coefficient. The figure shows that the pressure variation at Tahiti is as closely related to Darwin as are locations near to Darwin, but with the opposite sign (i.e., if the pressure is high at Darwin, it is low at Tahiti and vice versa). (After Rasmusson, 1984.)
During ENSO events, the atmospheric response to SST anomalies (SSTA) in the equatorial Pacific perturbs the Walker Circulation (an east–west circulation pattern produced by the zonal distribution of tropical surface heating) [Walker and Bliss, 1932] and it greatly influences the oceanic and atmospheric condition across the globe [Trenberth, 1997; McPhaden, 2002].
Indian Ocean Dipole

CLIMATOLOGICAL SST (°C)

JAN  |  JUL

MAR  |  SEP

MAY  |  NOV

40E  |  60E  |  80E  |  100E  |  120E

30S  |  20S  |  10S  |  EQ    |  10N  |  20N  |  30N

22  |  24  |  25  |  26  |  27  |  28  |  29  |  30  |  31
The Indian Ocean Dipole (IOD) is a coupled ocean-atmosphere phenomenon in the Indian Ocean. It is normally characterized by anomalous cooling of SST in the south eastern equatorial Indian Ocean and anomalous warming of SST in the western equatorial Indian Ocean. Associated with these changes the normal convection situated over the eastern Indian Ocean warm pool shifts to the west and brings heavy rainfall over the east Africa and severe droughts/forest fires over the Indonesian region. Saji et al., (1999); Webster et al., (1999)
Indian Ocean Dipole (IOD)

- The IOD and the ENSO have complementarily affected the ISMR during the last four decades. Whenever the ENSO-ISMR correlation is low (high), the IOD-ISMR correlation is high (low).

- Positive DMI of Indian Ocean Dipole is favourable for Indian monsoon

- The IOD plays an important role as a modulator of the Indian monsoon rainfall and influences the correlation between the ISMR and ENSO.

- Ashok et al, using an AGCM, have discovered that the ENSO-induced anomalous circulation over the Indian region is either countered or supported by the IOD-induced anomalous meridional circulation cell, depending upon the phase and amplitude of the two major tropical phenomena in the Indo-Pacific sector.
Dipole Mode Index (DMI) = WEIO - EEIO

Intensity of the IOD is represented by anomalous SST gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the south eastern equatorial Indian Ocean (90E-110E and 10S-0N). This gradient is named as Dipole Mode Index (DMI). When the DMI is positive then, the phenomenon is refereed as the positive IOD and when it is negative, it is refereed as negative IOD.

Normally an IOD event *evolves in spring (May/June)*, peaks in fall (October–November) and terminates in early winter (December) [Saji et al., 1999].

As phase locking of ENSO to the seasonal cycle, the peak IOD events also tend to occur during October–November. This means that both IOD and ENSO may influence the TC activity in BoB during October–December.
The El Niño–Southern Oscillation (ENSO) is the most dominant interannual mode of tropical coupled ocean-atmosphere system.

Many earlier studies have investigated the relationship between ENSO and seasonal TC activity in different tropical basins.

Peak of ENSO events tend to occur during November–January. Hence, ENSO may significantly influence the primary TC peak season.

Camargo et al. [2007] studied the effect of ENSO on the genesis potential index in the world ocean and reported that there is a shift in the genesis potential from the northern to southern part of the BoB between La Niña and El Niño year and it was mainly due to wind shear.

Singh [2008] reported the relationship between September and October dipole mode index (DMI) and cyclone frequency during November in the BoB.

Girishkumar and M. Ravichandran1 (2012) The genesis location of TC shifts to the east (west) of 87 E in the BoB during La Niña (El Niño) regime due to the variability in convective activity. The probable reason for the intense TC during a La Niña regime is likely explained in terms of longer track for TCs over warm SST and high TCHP due to eastward shifting of genesis location together with other favorable conditions.
Graphical Representations of Parameters with Locations

OBS SST (OND) and CDs during OND

OBS SST (JJAS) and CDs during OND

OBS SST (OND) and CDs during OND

OBS SST (JJAS) and CDs during OND
The Madden Julian Oscillation (MJO) is characterized by an eastward progression of large regions of both enhanced and suppressed tropical rainfall, observed mainly over the Indian Ocean and Pacific Ocean.

The anomalous rainfall is usually first evident over the western Indian Ocean, and remains evident as it propagates over the very warm ocean waters of the western and central tropical Pacific.

This pattern of tropical rainfall then generally becomes very nondescript as it moves over the cooler ocean waters of the eastern Pacific but reappears over the tropical Atlantic and Indian Ocean.

The wet phase of enhanced convection and precipitation is followed by a dry phase where convection is suppressed.

Each cycle lasts approximately 30–60 days. Also known as the 30-60 day oscillation, 30-60 day wave, or intraseasonal oscillation (ISO).

The MJO involves variations in wind, sea surface temperature (SST), cloudiness, and rainfall.

The OLR signal in the western hemisphere is weaker, and the recurrence interval for the eastward propagating OLR anomalies in the eastern hemisphere is about 30 to 60 days.

How exactly the anomaly propagates from the dateline to Africa (i.e. through the western hemisphere) is not well understood. The mechanism and cause of the MJO is as yet not very well-understood and is a subject of ongoing study.
Madden-Julian Oscillation

- Intraseasonal Time Scale: ~30-60 days
- Planetary-Scale: Zonal Wavenumbers 1-3
- Baroclinic Wind Structure
- Eastward Propagation
  - E. Hem: ~5 m/s, Surf.+Conv.+Circ. Interactions
  - W. Hem: ~ > 10 m/s, ~Free Tropospheric Wave
- Tendency to be Equatorially Trapped
- Strong Seasonal Dependence:
  - NH Winter: Eastward Propagation
  - NH Summer: ~Northeast Propagation
- Significant Interannual Variability
- Potential Role of Ocean/SST Feedback
- Convection Has Multi-Scale Structure
- Significant Remote and Extra-Tropical Impacts

Madden & Julian, 1972
Typical Variables Used for MJO Analysis

- Cloudy, Low OLR
- Clear, High OLR
- Rainfall
- Typical Variables Used for MJO Analysis

Rainfall Graph
A Typical MJO in N.H. Winter

- Composite rainfall maps derived from merged satellite and in-situ measurements are separated by 10 days.
- Rainfall anomalies propagate in an eastward fashion and mainly affect the Tropical eastern hemisphere.
- These anomalies are accompanied by anomalies in wind, solar radiation, sea surface temperature, etc.
A Typical MJO in N.H. Summer

- Composite rainfall maps derived from merged satellite and in-situ measurements are separated by 10 days.
- Rainfall anomalies propagate in a northeast fashion and mainly affect the Tropical eastern hemisphere.
- These anomalies are accompanied by anomalies in wind, solar radiation, sea surface temperature, etc.
Wheeler and Hendon (2004) fields chosen were:

$15^\circ S - 15^\circ N$ averaged OLR, $u_{850}$, and $u_{200}$.

Only minimal prior removal of lower-frequency variability (e.g. ENSO) was required.

Computed using all seasons of data.
Define MJO Phases 1-8 for the generation of composites and impacts studies. ‘Weak MJO’ when amplitude < 1.0
MJO and Cyclogenesis

[Liebmann et al., 1994; Ho et al., 2006; Kikuchi et al., 2009; Kikuchi and Wang (2010)]

MJO has a large influence on TC activity (cyclogenesis and intensification) in the Indian Ocean region.

[Zhang, 2005]. The MJO undergoes a strong seasonal cycle in both its strength and latitudinal locations. It tends to be more energetic immediately south of the equator during boreal winter, and the second peak season during boreal summer, when its strongest signals are north of the equator.

Kikuchi and Wang [2010] further suggested that climatologically, the seasonal transition of the MJO occurs during the intermonsoon period, when these two modes have comparable influence on TC formation.

Pohl and Matthews [2007] : the amplitude and lifetime of MJO associated with ENSO during OND. The average life time of MJO is relatively short under El Niño conditions compared to La Niña conditions and is due to faster (slower) eastward propagation of the MJO through the Maritime Continent and the western Pacific during El Niño (La Niña) regimes.

Mohapatra and Adhikari (2011) : TC activity over NIO and MJO phases

Girishkumar and Ravichandran (2012) : During the primary TC peak season, more frequent TC activity is observed under MJO phases 3–6.
Girishkumar and Ravichandran (2012): During the primary TC peak season, more frequent TC activity is observed under MJO phases 3–6.
MJO and TC over different ocean basins
Part - II

Extended Range to Seasonal Forecast of Tropical Cyclogenesis
Over the NIO TC forecasting using dynamical models has been considerably improved particularly in the short range up to 72 hrs over the NIO (Mohapatra et al., 2013a,b) which could be due to the improvement in numerical model and use of wide ranges of non conventional data in the assimilation system of the model (Mohanty et al., 2010; Prasad and Rama Rao, 2003; Pattanaik and Rama Rao, 2009, Osuri et al., 2012, Rama Rao et al., 2015 etc).

Some earlier studies (Kotal et al., 2009; Pattanaik et al., 2003) have also discussed the genesis parameters of formations of TCs over NIO based on dynamical variables in the medium range time scales. (Upto 5 to 7 days)

Also there have been some efforts to forecast the genesis of CDs over the BoB in the extended range time scale (2 to 3 weeks) using Multi-model ensemble (MME) based on coupled models outputs (Pattanaik et al., 2013; Pattanaik and Mohapatra 2014; Belanger et al., 2010) over the NIO.

Significant amount of work have been done over the Atlantic and other Basins in forecasting in the extended range. (Monthly to Seasonal)
Two weeks forecast of Typhoon in Atlantic Basin

These two-week forecasts are based on a combination of observational and modeling tools. The primary tools that are used for this forecast are as follows:

1) Current storm activity,
2) National Hurricane Center Tropical Weather Outlooks,
3) Forecast output from global models
4) The current and projected state of the Madden-Julian Oscillation (MJO) and
5) The current seasonal forecast
MME based extended range forecast

It was seen as a LOPAR on 2\textsuperscript{nd}, Nov Depression at 00 UTC of 4\textsuperscript{th}, Deep Depression at 00 UTC of 5\textsuperscript{th} and then intensified into a CS at 0600 UTC of 5\textsuperscript{th}, SCS at 2100 UTC of 5 November 2010. SCS ‘\textit{Jal}’ followed northwestward track during its entire life span.

01-07 November, 2010
MME Forecast 850 hPa wind for ‘Jal’ valid for 01-07 Nov, 2010

Days 5-11 (01-07 Nov, 2010), Based on 28 Oct

Days 12-18 (01-07 Nov, 2010), Based on 21 Oct
MME Forecast 850 hPa vorticity for ‘Jal’ valid for 01-07 Nov, 2010

Days 5-11 (01-07 Nov, 2010)

Days 12-18 (01-07 Nov, 2010)
MME Rainfall for the period 01-07 Nov 2010

Days 5-11 (01-07 Nov, 2010)

Days 12-18 (01-07 Nov, 2010)
Some Facts About the Seasonal Forecast of Typhoon in Atlantic

- It is possible to say something about the probability of the coming year’s hurricane activity which is superior to climatology.

- The Atlantic basin has the largest year-to-year variability of TC so people are curious to know how active the upcoming season is likely to be.

- It is impossible to precisely predict this season’s hurricane activity in early April.

- The forecast is issued to satisfy the curiosity of the general public and to bring attention to the hurricane problem.

- Seasonal forecasts are based on statistical schemes which, owing to their intrinsically probabilistic nature, will fail in some years.

- Moreover, these forecasts do not specifically predict where within the Atlantic basin these storms will strike.

- The probability of landfall for any one location along the coast is very low and reflects the fact that, in any one season, most U.S. coastal areas will not feel the effects of a hurricane no matter how active the individual season is.
Accumulated Cyclone Energy and Seasonal forecast over Atlantic

The metric that we are trying to predict with these two-week forecasts is the Accumulated Cyclone Energy (ACE) index, which is defined to be all of the named storm’s maximum wind speeds (in $10^4$ knots$^2$) for each 6-hour period of its existence over the two-week period. These forecasts are too short in length to show significant skill for individual event parameters such as named storms and hurricanes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above-Average</td>
<td>Greater than 130% of Average ACE</td>
</tr>
<tr>
<td>Average</td>
<td>70% - 130% of Average ACE</td>
</tr>
<tr>
<td>Below-Average</td>
<td>Less than 70% of Average ACE</td>
</tr>
</tbody>
</table>
Different Centres Producing Seasonal Forecast

(Camargo et al., 2005): Over the North and South Indian Ocean, dynamical models usually perform poorly. It is not clear to what extent this is due to model errors or to a lack of predictability.
Cyclonic disturbances over the Bay and NIO during OCT-DEC (1971-2014)

- NIO (Mean=4.6; SD=1.7)
- BoB (Mean=3.4; SD=1.4)
Cyclonic disturbances over Bay of Bengal during OCT-DEC (1971-2014)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Lower Tercile</th>
<th>Median</th>
<th>Upper Tercile</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bay of Bengal</strong></td>
<td>3.4</td>
<td>1.4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>North Indian Ocean (NIO)</strong></td>
<td>4.6</td>
<td>1.7</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
Composite Tracks during 10 above normal and 11 below normal CDs seasons

10 above normal

11 below normal
SST composite anomalies
Above normal (AN) and below normal (BN)
CC with SST (July-August)
SST composite anomalies
Above normal (AN) and below normal (BN)
CC with V850 hPa wind (June-August)
CC with SLP, U200 and U850
List of parameters used for developing Cross Validated PCR model

<table>
<thead>
<tr>
<th>Predictor No</th>
<th>Parameters</th>
<th>CC (1971-2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>South-east equatorial Indian Ocean 850 hPa meridional wind (June to August)</td>
<td>-0.63</td>
</tr>
<tr>
<td>2</td>
<td>Strength of upper level (200 hPa) easterly jet over Africa (July-August)</td>
<td>-0.52</td>
</tr>
<tr>
<td>3</td>
<td>Monsoon zonal wind at 850 hPa (July-August)</td>
<td>0.40</td>
</tr>
<tr>
<td>4</td>
<td>Strength of Australian high (July-August) SLP</td>
<td>-0.38</td>
</tr>
<tr>
<td>5</td>
<td>sea surface temperature (SST) over the northwest Pacific (July-August) SST1</td>
<td>-0.50</td>
</tr>
<tr>
<td>6</td>
<td>SST over the Nino 4 region (Jul-August) SST2</td>
<td>-0.39</td>
</tr>
</tbody>
</table>

Pattanaik et al., (2014)
Secular Variations of the Predictors- Predictandt Relationship?
Individual CC of the parameters

CC(1971-2010)

PARA1_V850jas
PARA2_U200ja
PARA3_U850ja
PARA4_SLPja
PARA5_SSTja
PARA6_nino4_ja
For statistical prediction methods, cross-validation (Michaelsen, 1987) is needed to help reduce artificial skill that can exist in the training data sample but vanishes when the method is applied to a real-time forecast for the future.

In cross-validation, forecast models are derived from all cases except for one (or more) that are withheld, and these cases are then used as the target(s) of the prediction.

This is repeated with all possible cases, or sets of cases, withheld and used as the target(s).

The anomaly values of the cases withheld must be expressed in terms of the climatology formed from the remaining years, which changes slightly each time a new case(s) is withheld.
Verification of PCR Model for forecast of CDs during OND

1) Bay of Bengal (BoB)

**Deterministic forecast** (CC, MAE, RMSE, Bias)

**Probabilistic forecast** (Hit scores, ROC)

2) North Indian Ocean

**Deterministic forecast** (CC, MAE, RMSE, Bias)

**Probabilistic forecast** (Hit scores, ROC)
Deterministic forecast verification (1971-2014) 
Bay of Bengal

CC = 0.77
Mean Bias = -0.02
RMSE = 1.00
MAE = 0.8
Verification of Category Forecast for the period (1971-2014) (BoB)

Relative Operating Characteristic (ROC)

<table>
<thead>
<tr>
<th>Year</th>
<th>Observed CD Frequency (Category)</th>
<th>Forecast Probability in %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Below Normal (BN)</td>
</tr>
<tr>
<td>2011</td>
<td>1 (BN)</td>
<td>66.2</td>
</tr>
<tr>
<td>2012</td>
<td>3 (NN)</td>
<td>29.2</td>
</tr>
<tr>
<td>2013</td>
<td>5 (AN)</td>
<td>27.8</td>
</tr>
<tr>
<td>2014</td>
<td>2 (BN)</td>
<td>49.4</td>
</tr>
</tbody>
</table>

Hit Score = 62.5%

ROC area

(AN) = 0.90
(BN) = 0.87
Deterministic forecast verification (1971-2014)
North India Ocean

- CC = 0.76
- Mean Bias = -0.07
- RMSE = 1.31
- MAE = 1.05
Verification of Category Forecast for the period (1971-2014) (NIO)

**Relative Operating Characteristic (ROC)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Observed CD Frequency (Category)</th>
<th>Forecast Probability in %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Below Normal (BN)</td>
</tr>
<tr>
<td>2011</td>
<td>5 (NN)</td>
<td>70.7</td>
</tr>
<tr>
<td>2012</td>
<td>5 (NN)</td>
<td>24.1</td>
</tr>
<tr>
<td>2013</td>
<td>6 (AN)</td>
<td>26.8</td>
</tr>
<tr>
<td>2014</td>
<td>3 (BN)</td>
<td>49.1</td>
</tr>
</tbody>
</table>

- **Hit Score** = 65%
- **ROC area**
  - (AN) = 0.85
  - (BN) = 0.87
ENSO, IOD, MJO are the major coupled phenomena having significant influences on tropical cyclogenesis over different Ocean basins.

The cross validated 6/5 parameters PCR model is developed for the forecasting of frequency of TCs during Oct-Dec over the Bay of Bengal (BoB) and North Indian Ocean (NIO) during the period 1971-2014.

The PCR model shows very encouraging results both in terms of predicting actual frequency of TCs in a given season and also the probability forecast of above normal or below normal category over the Bay of Bengal and NIO.

The verification scores like CC, RMSE, MAE, bias, Hit score, ROC areas etc shows very significant relationship between observed and forecast frequency of TCs during Oct-Dec over Bay of Bengal as well as NIO.

The observed above normal frequency of TCs over BoB abd NIO during Oct-Dec, 2013, 2014 are very well captured both in the deterministic as well as probabilistic forecasts.
THANK YOU
Verification of Category Forecast for the period (1971-2013) & 2013 NIO

**Relative Operating Characteristic (ROC)**

- **Hit Score**: 70.0%
- **ROC area (Above Normal)**: 0.854
- **ROC area (Below Normal)**: 0.877

**2013 Forecast**: B = 28%, N = 25% A = 47%

**Exceedance Probabilities (2013)**

- Forecast: Index
  - Above: 28%
  - Normal: 25%
  - Below: 47%
PERFORMANCE OF 5 PARA PCR MODEL over Bay

Relative Operating Characteristic (ROC)

- CC = 0.70
- Hit Score = 62.5%
- ROC (Above) = 0.88 (.875)
- ROC (Below) = 0.86 (86)

Variance Explained by EOF Modes
November Tropical Storm Formation by MJO phase

Phase 1 (65 days) 21 storms
Phase 2 (88 days) 16 storms
Phase 3 (89 days) 6 storms
Phase 4 (77 days) 17 storms
Phase 5 (72 days) 20 storms
Phase 6 (91 days) 12 storms
Phase 7 (68 days) 11 storms
Phase 8 (60 days) 14 storms
Null (380 days) 65 storms
Building on much previous research, they applied Empirical Orthogonal Function (EOF) analysis to observed data in the Tropics.

(e.g. Lau and Chan 1985; Knutson and Weickmann 1987; Maloney and Hartmann 1998; Slingo et al. 1999; Matthews 2000)

However, instead of applying EOFs to a single field of bandpass filtered data, we applied it to unfiltered data with multiple fields combined.
The EOFs describe the convectively-coupled vertically-oriented circulation cells of the MJO that propagate eastward along the equator.
Bay

NIO
119 TS (422 Days)
Objective Definition (Index)

Genesis Potential Index from climate models

The index is defined:

\[ I = 10^6 \eta^2 \gamma^2 \left( \frac{H}{50} \right) \left( \frac{V_{pot}}{70} \right)^3 \left( 1 + 0.1 V_{shear} \right)^{-2}, \]

where

- \( \eta = \text{absolute vorticity (s}^{-1}) \),
- \( V_{pot} = \text{potential wind speed (ms}^{-1}) \),
- \( H = 600 \text{ mb relative humidity (\%)} \),
- \( V_{shear} = \left| V - \frac{V_{850} - V_{250}}{2} \right| \text{ (ms}^{-1}) \).

Objective Definition (Index)

Genesis Potential Parameter

Genesis Potential Parameter (GPP)

Genesis Potential Parameter (GPP) is defined as:

\[ \text{GPP} = \begin{cases} \frac{\zeta \text{ vert}}{\text{S}} & \text{if } \zeta_{850} > 0, M > 0 \text{ and } I > 0 \\ 0 & \text{if } \zeta_{850} \leq 0, M \leq 0 \text{ or } I \leq 0 \end{cases} \]

Where, \( \zeta_{850} \) = Low level relative vorticity (at 850 hPa) in \( 10^{-6} \text{ s}^{-1} \)
- \( S = \text{Vertical wind shear between 200 and 850 hPa (knots)} \)
- \( M = \frac{\text{RH}_{700} - \text{RH}_{500}}{50} = \text{Middle troposphere relative humidity} \)

Where, RH is the mean relative humidity between 700 and 500 hPa

\( I = (T_{850} - T_{500}) \text{ °C} = \text{Middle-tropospheric instability (Temperature difference between 850 hPa and 500 hPa). All the variables are estimated by averaging of all grid points over an area of radius 2.5° around the centre of cyclonic systems using model analysis field.} \)

Webster and Belanger

- Suzuki-Parker tracking scheme (Holland et al. 2010)
- Identify cyclonic vortices using local minimum in mean sea level pressure
- Key Thresholds:
  - \( \zeta \) at 850 hPa > 1 \times 10^{-4} \text{ s}^{-1}
  - \( V_{sfc} > 16 \text{ kts (8.2 m s}^{-1}) \)
  - Warm Core: -\( V_T^L > 20 \); -\( V_T^U > 25 \), \( \beta < 20 \)
  - Lifetime of at least 1 day
The index is defined:

\[ I = 10^5 \eta^{3/2} \left( \frac{\mathcal{H}}{50} \right)^3 \left( \frac{V_{\text{pot}}}{70} \right)^3 \left( 1 + 0.1 V_{\text{shear}} \right)^{-2}, \]

where

\[ \eta = \text{absolute vorticity} \ (s^{-1}), \]

\[ V_{\text{pot}} = \text{Potential wind speed} \ (ms^{-1}), \]

\[ \mathcal{H} = 600 \text{ mb relative humidity} \ (%), \]

\[ V_{\text{shear}} = \begin{vmatrix} V & -V \\ 850 & 250 \end{vmatrix} \ (ms^{-1}). \]
EQWIN: negative of anomaly of zonal surface wind over 60° –90°E, 2.5°S-2.5°N (normalized by its standard deviation), so that positive values of EQWIN are favourable for the monsoon.

EQWIN is highly correlated with the difference in the OLR over EEIO and WEIO.