Lecture Notes
on
Synoptic Meteorology

For

Integrated Meteorological Training Course

By

Dr. Prakash Khare
Scientist E
India Meteorological Department
Meteorological Training Institute
Pashan,Pune-8

IMTC SYLLABUS OF SYNOPTIC METEOROLOGY
(FOR DIRECT RECRUITED S.A'S OF IMD)

Theory (25 Periods)

- ❖ Scales of weather systems; Network of Observatories; Surface, upper air; special observations (satellite, radar, aircraft etc.); analysis of fields of meteorological elements on synoptic charts; Vertical time / cross sections and their analysis.
- ❖ Wind and pressure analysis: Isobars on level surface and contours on constant pressure surface. Isotherms, thickness field; examples of geostrophic, gradient and thermal winds: slope of pressure system, streamline and Isotachs analysis.
- ❖ Western disturbance and its structure and associated weather, Waves in mid-latitude westerlies.
- ❖ Thunderstorm and severe local storm, synoptic conditions favourable for thunderstorm, concepts of triggering mechanism, conditional instability; Norwesters, dust storm, hail storm. Squall, tornado, microburst/cloudburst, landslide.
- ❖ Indian summer monsoon; S.W. Monsoon onset: semi permanent systems, Active and break monsoon, Monsoon depressions: MTC; Offshore troughs/vortices. Influence of extra tropical troughs and typhoons in northwest Pacific; withdrawal of S.W. Monsoon, Northeast monsoon,
- ❖ Tropical Cyclone: Life cycle, vertical and horizontal structure of TC, Its movement and intensification. Weather associated with TC. Easterly wave and its structure and associated weather.
- ❖ Jet Streams – WMO definition of Jet stream, different jet streams around the globe, Jet streams and weather
- ❖ Meso-scale meteorology, sea and land breezes, mountain/valley winds, mountain wave.
- ❖ Short range weather forecasting (Elementary ideas only); persistence, climatology and steering methods, movement and development of synoptic scale systems; Analogue techniques- prediction of individual weather elements, visibility, surface and upper level winds, convective phenomena.

Scales of weather systems, Network of Observatories, surface, upper air, special observations (satellite, radar, aircraft etc.), analysis of fields of meteorological elements on synoptic charts, Vertical time / cross sections and their analysis.

Wind and pressure analysis, Isobars on level surface and contours on constant pressure surface, Isotherms, thickness field, examples of geostrophic, gradient and thermal winds: slope of pressure system, streamline and Isotachs analysis.

Introduction:

The word synoptic is made up of two words i.e. ***SYN - TOGATHER*** *and* ***OPTIC – VIEW; THIS MEANS THE VARIOUS MET. ELEMENTS ARE VISULISED TOGATHER AT THE SAME TIME ALL OVER THE GLOBE.***

Thus it is a branch of meteorology in which the plotting of weather elements, its analysis and the study of the atmosphere is made. These things are performed in order to understand the behaviour of the atmosphere and to predict the future performance of the different systems and their movement for the sake of short range forecasting (valid up to 72 hrs). The basic sciences for Synoptic Meteorology are the Dynamics and Physical meteorology. The basic tools which are required for the study are the weather charts.

Scales of atmospheric Motions

Scale of the weather systems, vary widely in space and time for e.g. formation of dew in plant leaf, millimetres of dimension & period of few minutes. The variation is from less than 1 km. to > 1000 km in horizontal, in vertical the variation can be from less than one meter up to the > 10 kms. The life period of the systems can vary from few minutes to large number of days. Depending upon these variations the Synoptic systems can be divided in to the following categories:

1) Microscale 2) Mesoscale 3) Synoptic scale 4) Planetary Scale, OR Macro scale

1) **Microscale systems**: Horizontal extension is less than one km and time period is few minutes while vertical extension, upto 10 meters. These systems include formation of dew or small air eddy currents which are there in very lower levels of the atmosphere. Similarly smokes generated by industries are also the examples of this scale. To study these microscale systems we should have observations at every few meters and at the intervals of few minutes or the continuous observations. Forecast- short range-very short.

2) **Mesoscale systems**: Horizontal extension is from 1 km to 100 km. Vertical extension is from 1 to 10 kms time is about 1 day or little more. Examples are Thunderstorms (Group of convective clouds, tornado, dust storm, squall lines, fog, Land and see breeze. To study this weather phenomenon the observations should be available at every 10 kms and at the interval of every half an hour. Forecast- short range-very short. Most of the meteorological services do not study these Micro and Mesoscale Phenomenon as a routine basis. As this much close network of observatories is not available. These systems may studied in detail form of special project.

3) **Synoptic Scale** : Horizontal extension i.e. diameter of this scale systems is about 100 to 1000 kms and vertical extension is about 10 km. Time scale is few days examples for this scale of systems are low pressure areas, High pressure areas, Depressions, Cyclonic storms, troughs and ridges etc. To study Synoptic scale motions we should have surface observations at every 150 kms and upper air observations at every 300 kms. Interval for surface observations is every 3 hrs., and for upper air observations is every 12 hrs. Forecast- (Short range, Medium range.)

4) **Planetary scale**: This scale is also known as Macro scale. Horizontal scale is > 1000 kms and vertical scale is > 10 kms. Time scale is large number of days. These types of systems give rise to abnormalities in precipitation and in temperatures over a large region. Example for this scale is Global circulation, Blocking highs, I.T.C.Z., Monsoon trough. To study this phenomenon Synoptic scale network is sufficient. But along this, the meteorological rocket sonde observations are also used to study planetary scale observations for a large number of days. Forecast-Long Range Forecast.

Synoptic Observations:

First of all the main and important tool for studying the atmosphere is the observations of different elements. These observations are then plotted on the different type of charts and the analysis of these charts will help in understanding the three dimensional picture of the various systems or atmosphere. To study the atmosphere some important variables are there. They are:

1) Pressure *2) Temperature* *3) Water vapour* *4) Wind*

First three variables are the scalar quantities are called as the *Physical variables*. The last one wind is a vector quantity which consists of two parts its direction and speed and is called as *Kinematics variable*. These all properties are continuous in space and time and they are called as the *Field Variables*.

There are various types of observations which are used to study different Synoptic systems:

1) Surface Observations

i) Land stations	ii) Sea stations		
	Fixed ocean vessels fixed weather ships which carry regular surface & UA observations	Mobile ships	Automatic ship station or BUOYS

2) Upper air observations at various levels

i) Land stations	ii) Sea stations

The types of observations are as follows:

1) Pilot Balloon	2) Radio wind	3) Radio sonde
(Wind)	(Wind)	(Temperature, Humidity, Wind and height) and GPS based observations.

3) Satellite Observation(Polar orbiting and Geostationary)

Clouds (OLR)	Wind	Temperatures,(SST and atmospheric sounding)

4) Aircraft Observation

i) Commercial or the military frights	ii) Reconnaissance flights
(Wind, Temp. & Pressure)	(all types of observations)

5. Radar Observations :

All these observations are plotted on the different types of synoptic charts. viz.

Synoptic Charts

1) Surface charts

2) Pilot charts

3) Auxiliary charts - change charts

4) Constant pressure charts (C.P. Charts)

5) Cross section charts,

6) Vertical time section,

7) Vertical cross section

8) Te-phi-gram

9) Radar echo charts

Other charts

Coverage of these charts depends upon the area for which the forecast is to be given. They are:

1) Regional charts

2) National charts

3) Extended charts - used particularly at aerodromes where the long route forecast is to be issued.

4) Hemispherical charts

5) Global charts - Mostly they are used at World Meteorological centres

Synoptic Observations

Now we will see the standard hours of observations and the chart by chart in detail standard hours of observations for Surface observations.

00, 06, 12 & 18 UTC is standard hrs. for International.

03, 09, 15 & 21 UTC is Intermediate hrs.

But in India, main synoptic hrs. are 03 and 12 UTC.

For upper air - 00, 06, 12 & 18 main International times.

But in India for RS and RW - 00 and 12 UTC and

for pilot Balloon - 00, 06, 12 and 18 UTC.

Analysis of Weather Charts

Surface chart:

Various elements are plotted on this chart. The main elements are mean sea level pressure, surface wind (its direction and speed both), horizontal visibility, dry bulb and dew point temperatures, present and past weather, amount and type of cloud, height of low cloud, and rainfall. In addition to this for coastal stations wind wave and swell wave observations are plotted and for ships the sea surface temperature is also plotted in addition to wind wave and swell wave. The analysis done on this chart is the Isobaric analysis. Isobar (lines passing through equal pressure values, lines of equal pressures values) are drawn on this chart. Analysis is nothing but the pictorial representation of the variables. Isobaric analysis is a scalar analysis. Isobar is an isoline of pressure.The isoline of temperature is isotherm, of wind speed is isotach, of rain is isohyte, of mixing ratio is isohygric, of density is isophyenic and if it is of equal height on CP chart is contours.

Analysis on the surface chart

Following are some points which should be kept in mind while doing the Isobaric analysis. Analysis of any scalar value.

1) No isoline cuts or breaks abruptly any where in between except at the limit of chart i.e. Isobars should not terminate any where in between the chart. Either you should draw the closed curves or they should be drawn from one end of the chart to the other end.

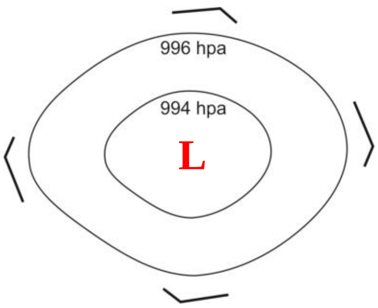
2) No two isobars isolines can pass through one point or they do not intersect each other or they should not fork. (i.e. break in to two).

3) Each isobar divides the field of variable in to two regions one side the values are higher than the isobar value and on the other side the value should be less than the isobar value.

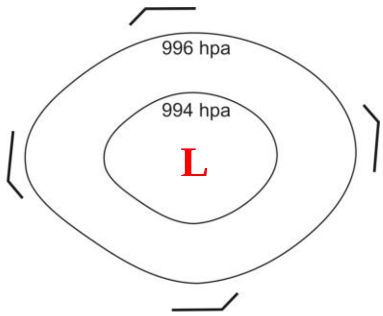
4) Along the isobar the value of pressure does not change.

By drawing the isobars on surface chart we can delineate the closed low pressure areas, closed high pressure areas, trough and ridges. Apart from pressure systems it provides the useful tool to demark the discontinuity lines in dew point we can infer at a glance the past and present weather and the distribution of clouds (by shading the weather and important clouds by different colour after analysis. Now we can see how the lows, highs, troughs & ridges will look like.

Low Pressure Area :



Northern Hemisphere

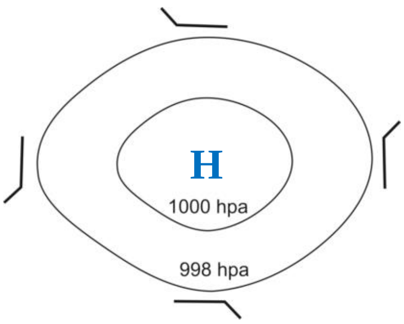


Southern Hemisphere

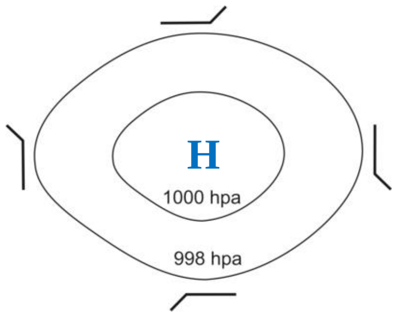
The shape of the closed low pressure area is shown in figure. The shape of the isobars need not be circular. The pressure at the centre of the low is the lowest one. As we move away from the centre the pressure increases in all the directions. The winds around the low pressure area blow in anticlockwise direction in the Northern Hemisphere while in the Southern Hemisphere opposite are the case the winds blow in a clockwise direction. The low pressure area is associated with positive vorticity, convergence and upward motion of the air. In the low usually clouds and rainfall are present. On the charts it is marked as "L" in red colour pencil. Centre of the low pressure is a singular point.

High Pressure Area:

High pressure area is a closed pressure system. The pressure at the centre of the high pressure is highest and as we go away from centre the pressure decreases in all the directions.



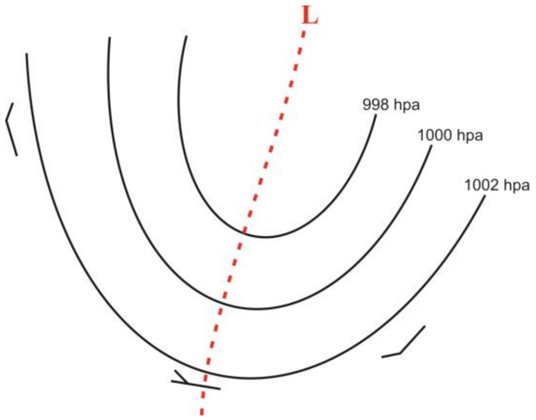
Northern Hemisphere



Southern Hemisphere

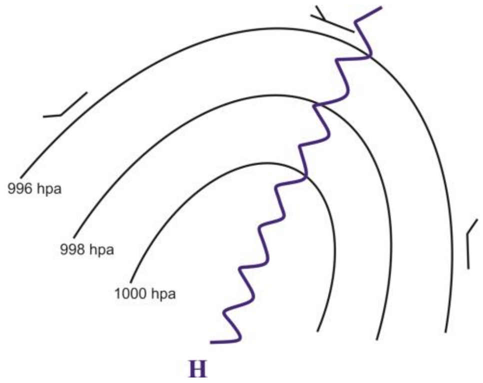
The isobars around the high pressure are also need not be circular one. The winds around the high pressure turn in the clockwise direction in the northern hemisphere and in the southern hemisphere opposite case is there, they will blow in anticlockwise direction. The high pressure area is associated with negative vorticity, divergence and down ward motion of the air. i.e. subsidence. Generally the high pressure areas are cloud free and fair weather. Near the centre the winds are light High pressure area on surface is marked as **"H" in blue** colour pencil. As low centre, centre of the High pressure is also a singular point.

Trough :



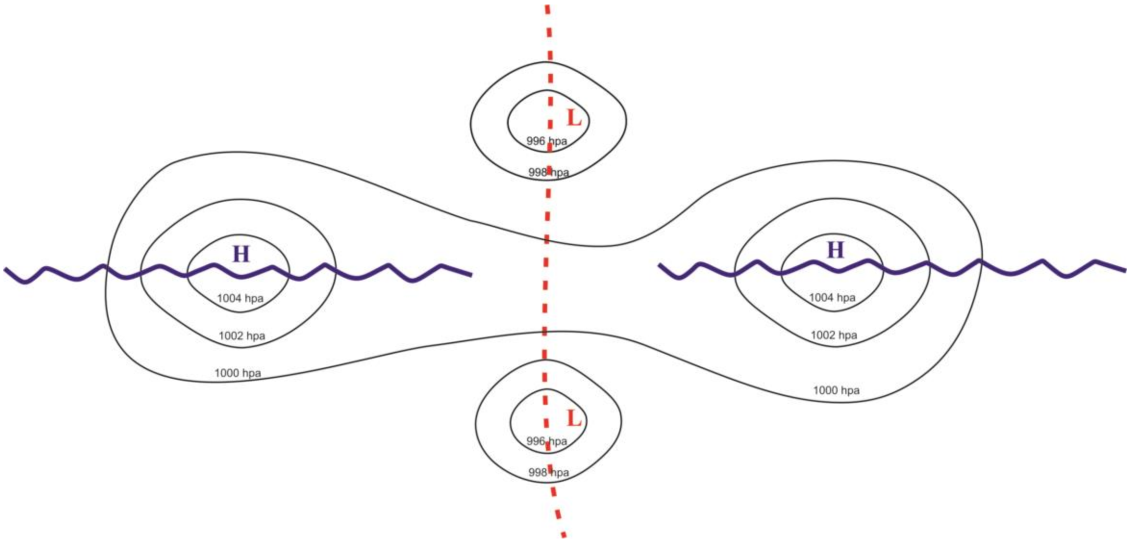
Trough is also a low pressure system but it is not a closed isobaric system. It is a line along which the direction of winds changes abruptly. From this trough line if one observes the pressures then it will increase on both the sides of this line. It is a line which may need not be a straight but can be curved also. The orientation of this line may be north-south oriented as well as east-west oriented also. Even it can be oriented in any direction. The winds are changing in the anticlockwise fashion in northern hemisphere. The positive vorticity, convergence is associated with trough and hence the clouding and precipitation are also associate as the weather along the trough. The trough on the chart is shown as a dotted line........ **in red** pencil.

Ridge:



Ridge is a high pressure system but not a closed isobar. It is also a line along which the direction of winds changes abruptly. From this ridge line if one observes the pressures then it will decrease on both the sides of this line. Just like the trough this line also may not be straight but can be curved also. The orientation of this line may also be east-west or in the north-south direction. It is also the line along which the winds turn abruptly. The winds are changing in clockwise direction along ridge in northern hemisphere. The negative vorticity and divergence are associated with ridge and hence fair and cloudless weather is associated along the ridge. The ridge on the chart is shown as a wavy line as above or zigzag line in **blue** colour pencil.

COL Region - On surface chart :



It is a region of intersection between a trough line and a ridge line and a region between two high pressure areas and two low pressure areas. Pressure gradient gradually changes and reverse the direction across a COL. Near the centre of the region the pressure gradient is very weak (In the Col area winds are very weak light and variable. Normally pressure systems remain stationery in the COL region.)

2.4.2 Auxiliary chart or change chart :

Past weather	Min. / Max. Temp.	Min. / Max. Temp. change for 24 hrs.	Min. / Max. Temp. departure from normal
	Dew pt. temp. change	Sat. cloud imagery	Direction of cloud
Station level pressure change for 24 hrs. $\mathbf{P_{24}}$ $\mathbf{P_{24}}$		Mean sea level pressure departure from normal	

This chart is prepared twice daily for main synoptic hrs. for India 03 UTC and 12 UTC In this chart left hand side corner past weather is plotted past weather means amount of rainfall - if it is a 12 UTC chart rainfall and weather from morning 03 UTC is plotted and if it is a 03 UTC chart rainfall & weather from previous days 03 UTC is plotted 24 hrs. pressure change and 24 hrs. departure from normal is plotted. Dew point change for 24 hrs., satellite cloud imagery and direction of low clouds are plotted. And on the 3 charts above at 03 UTC chart min. temp., Min. temp change 24 hrs. and departure of min. temp. from normal is plotted and on 12 UTC chart all these things for max. temperature is plotted.

On the change charts isolines are drawn - temperature isotherms and for change and departure of pressure and temps. also isolines are drawn.

The change charts gives the following information.

1. *The past weather and amount of rainfall realised over the country or any particular area.*
2. *Max. and Min temperature distribution and their changes during 24 hrs.*
3. *Identify the areas of heat wave and cold wave conditions.*
4. *Identify the areas of systematic increases decrease of moisture which can help in temperature forecasting.*
5. *Identify the isobaric field and movement of the systems.*
6. *Identify the intensity of pressure system from pressure departures from normal.*

Pilot chart:

This chart is a constant height chart. The wind are plotted at specific height. On this chart, the observations obtained through pilot balloon Radio theodolite and Radar are plotted. The observations are plotted at 0.3 km, 0.6 km, 0.9 km, 1.5 km. (850 hPa), 2.1 km, 3.1 km (700 hPa), 3.6 km, 4.5 km, 5.8 km (500 hPa), 7.6 km(400hPa), 9.0 km (300 hPa), 10.5 km(250hPa), 12.0 km (200 hPa), 14.1. km, 16.0 km (100 hPa) are plotted. This chart now a days plotted in two parts in weather section, Pune. In addition to these levels maximum winds, tropopause height and the wind at 925 meter level are plotted in W.S., Pune. On this chart the streamlines and Isotach analysis is done as the wind is the vector quantity and consists of two parts:

i) Direction (streamlines - vector analysis) ii) Speed (Isotach).

In practice the streamlines can be converging, diverging, cyclonic or anticyclonic circulation etc.

Streamlines can be drawn by two methods:

1) ***Direct - free hand method***
2) ***Isogon method.***

First, for direction (vector analysis) - actually the lines of equal direction are Isogons. But in practice, it is very difficult to draw Isogons and again they don't give the true picture of the flow of the wind motion and to draw the Isogon is very laborious and time consuming work. In actual practice, to represent the wind direction the streamlines are drawn by free hand method. Streamlines analysis is also known as a kinematics analysis (analysis wind vector).

Streamline: - It is a line which is everywhere tangential to the instantaneous wind vector.

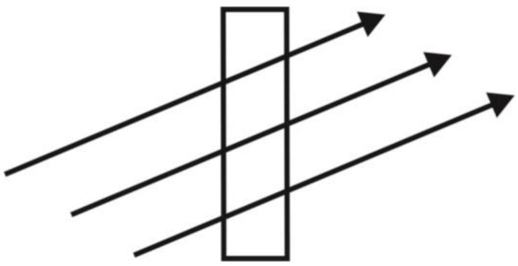
It is a flow pattern of wind.

Some of the basic characteristics of streamlines are

1) *There can't be a flow across the streamline.*
2) *Streamline spacing varies inversely with velocity of flow. The relatively narrow packing indicates relatively higher speeds.*
3) *Streamlines do not cross.*
4) *Streamline can start in between the chart or again it can be break also in between.*
5) *Streamlines can converge or diverge.*

PATTERNS OF STREAM LINES

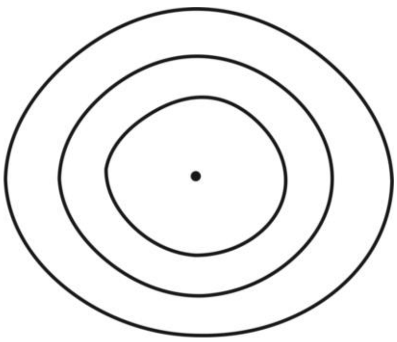
1) **Pure translation** : It is the field pure translation. The stream lines are parallel straight lines. In this case any particle kept in the field moves by the wind along with the streamline, then the movement is called as translation.



2) **Pure Rotation :** Streamlines will be concentric circles with common centre with different radii will contribute in the field of rotation. This field can be -

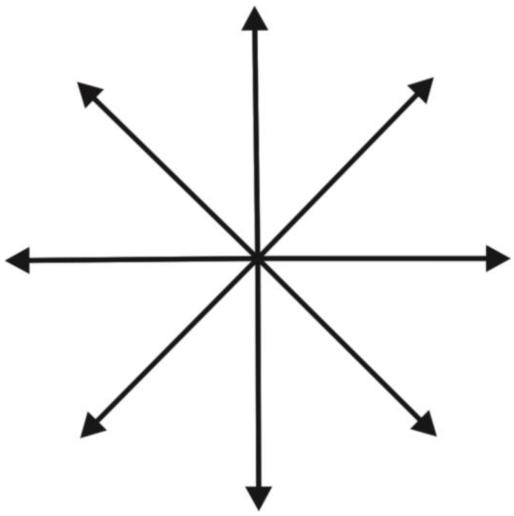
i) Cyclonic rotation ii) Anticyclonic rotation.

Thus any particle or parcel of air will rotate above the centre.

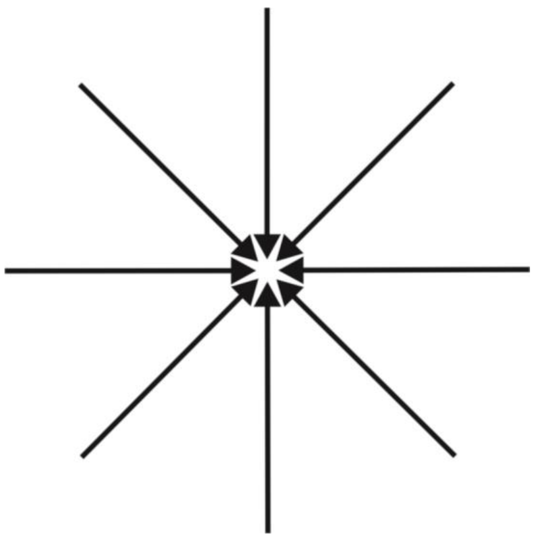


3) **Pure Divergence/Convergence** :

Divergence (Expansion):- A set of straight streamlines which are originating from a single one point. Then it is called as a field of divergence.

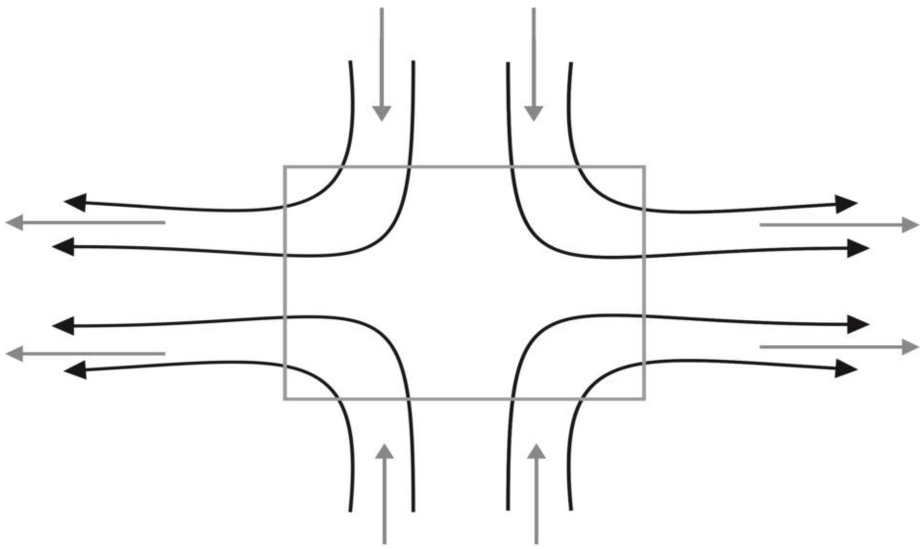


Convergence (Contraction):- A set of straight streamlines which are meeting at a single point is called as field of convergence. These two fields are very important in the meteorology. A air parcel in divergence field will be uniformly pull in all the directions, so the area of air parcel will increase and the areal expansion will take place. Similarly under convergence for the areal parcel, contraction will take place. The convergence and divergence is two dimensional field but the air parcel is three dimensional. The convergence and air contraction will make the air ascent. For clouds and rain formation air ascent is required.



4) **Pure Deformation** :- Deformation is a field in which a set of streamlines which are Hyperbolic in shape. If you place a air parcel in middle then the air parcel will be subjected to pushing on two parallel sides and pulling on two other parallel sides. In this case the square air parcel will become rectangle. and the form of air parcel will changed. Thus the air parcel will deformed therefore the field is called as field of deformation. In this case the area of air parcel will remain the same.

These four fields are pure fields of stream lines. In practice wind field is combination of such two or more fields.



Converge : Two or more streamlines can come together and then they will flow as One streamline lines.

Diverge : One streamline can fork and become three or four ones.

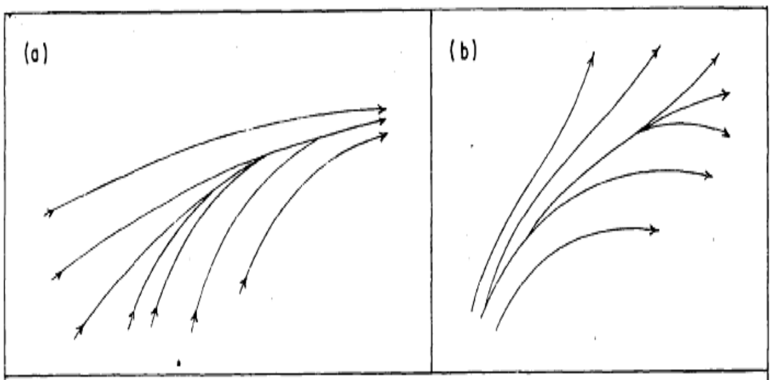


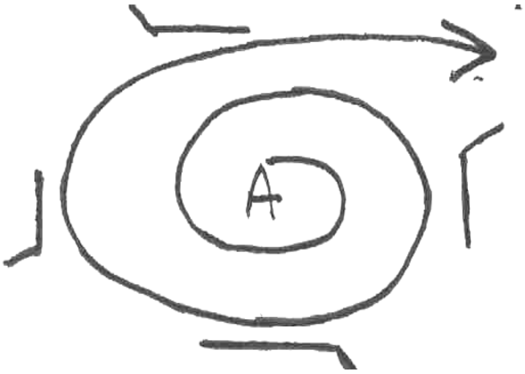
FIG. 10 - ASYMPTOTES OF (a) CONVERGENCE (b) DIVERGENCE

By drawing streamline analysis we can locate cyclonic and anticyclonic circulations, Trough, Ridge and COL Region. A cyclonic circulation is one in which the winds are changing in the anticlockwise direction in northern hemisphere and the cyclonic circulation will have inflow of the winds.

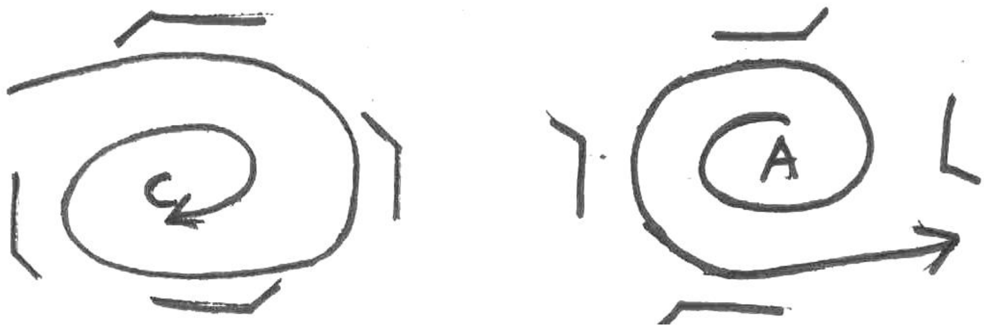
In anticyclonic circulation, the winds are changing in a clockwise direction in the Northern Hemisphere and it will have always outflow of winds. Cyclonic and anticyclonic circulations are nothing but the reflection of low pressure area and high pressure area on the surface chart respectively. By streamlines we can identify the vertical extent of the pressure system and its tilt along with the height (e.g. the monsoon depression tilt south or south-westwards with height). Along with cyclonic or anticyclonic circulations we can identify the Trough and Ridges also in the wind field.

Cyclonic circulation in Northern Hemisphere :

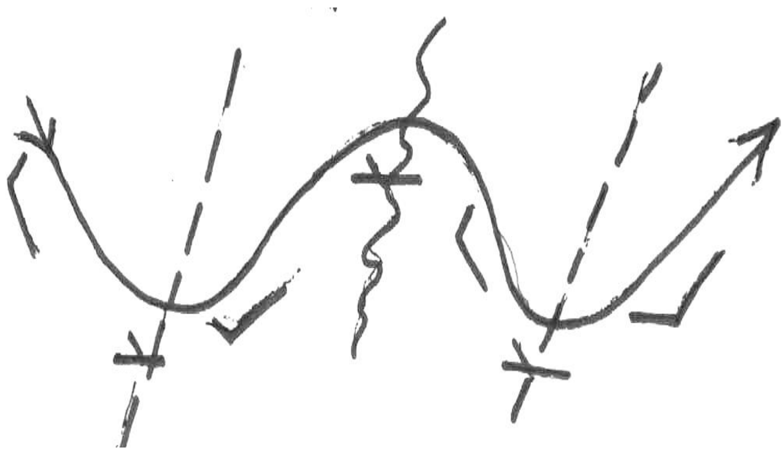
Anticyclonic circulation in Northern Hemisphere :



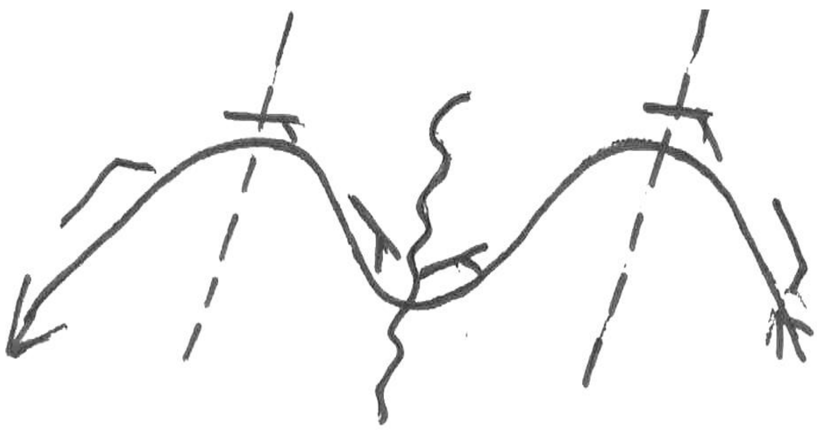
In Southern Hemisphere :



Trough in westerlies and ridges in westerlies in Northern Hemisphere (mid and upper tropospheric westerlies) :

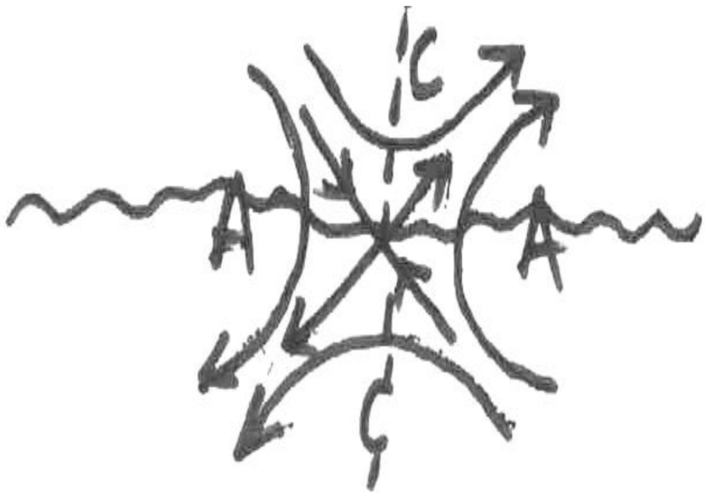


Troughs and ridges in Easterly regime (mostly low level Easterlies) :



COL region on upper air charts:

It is a region of intersection between a trough line and a ridge line or a region between two cyclonic and two anticyclonic circulations. (In the Col area winds are very weak light and variable. Normally pressure systems remain stationery in the COL region.)



As already explained, we have to do two types of analysis on pilot chart. Streamlines the vector analysis we have already seen, now we have to see other analysis, the wind speed analysis. It is a normal scalar analysis of lines of equal wind speeds i.e. Isotach analysis. This is normally done on the charts of higher levels i.e. levels 5.8 kms & above that level. This helps in identifying the areas of maximum winds, Jet streams etc.

Constant Pressure Charts: These charts are plotted with the observations which are obtained from Radio-sonde observation. They are plotted for the standard isobaric level viz. 850,700, 500, 300, 250, 200, 150, and 100 hPa levels. The elements plotted on this chart are:

1) Height in gpm (geopotential meter)
2) Wind direction and Speed.
3) Dry Bulb Temperature
4) Dew point Temperature

These charts are prepared twice daily at 00 UTC and 12 UTC (They are prepared now a days in INOSHAC). The analysis done on this chart.

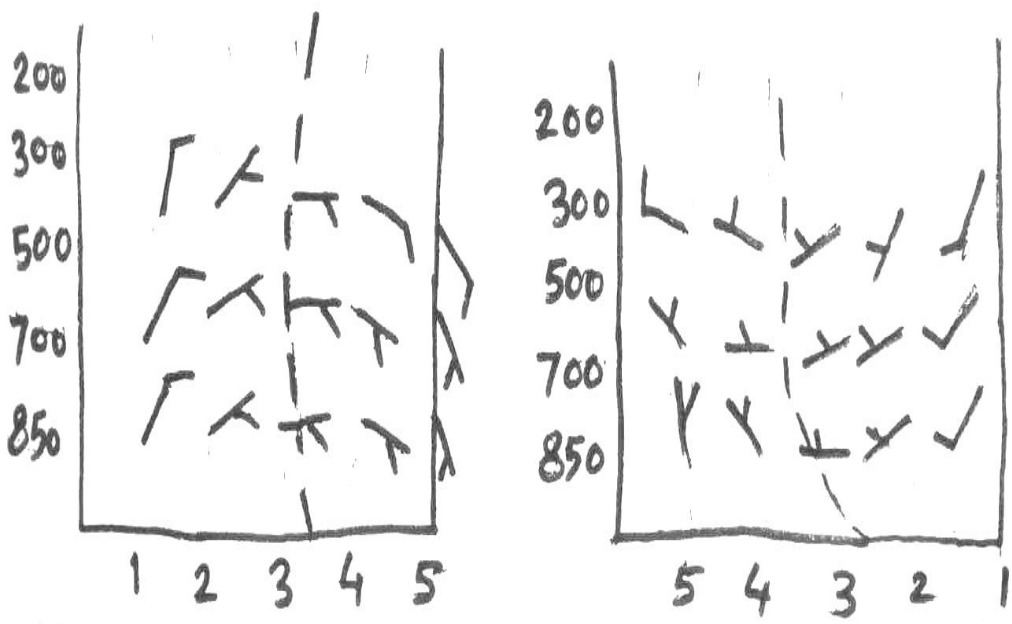
1) Constant height lines are drawn and they are called as countour lines - The countour analysis is also a scalar analysis just like the Isobars on surface charts.
2) Isotherms are drawn for temperatures.
3) On higher level charts Isotachs for wind speed.

Advantages of Constant Pressure chart.

1) Computation of thickness and thermal wind between two pressure levels - Thermal wind is a useful too in weather forecasting.
2) Dynamical study of location and analysis of the Jet stream. Jet streams are closely related to the thickness lines.
3) Dynamical study of vertical extent, movement and characteristics of pressure systems. The movement of low and Depressions and storms and their strengthening or weakening is controlled by thickness lines which in turn depends upon the temperature field. Height difference between two layers is called as the thickness. Thickness, Thermal winds and temperatures are inter-related.

Vertical Time Section Chart:

So far, whatever charts we have studied, on those charts the time factor and the level factor was constant and on all over the charts the different stations were plotted. But in this vertical time section chart the various data of only one station, for number of days and for number of levels are plotted. This is prepared for the stations which are having Radio-sonde data. The elements plotted are: i) Wind (direction and speed) ii) Height iii) Temperature (dry bulb) iv) Moisture (mixing ratio) v) Tropopause and vi) Maximum wind. On x axis the date and time is plotted and on the y axis the above data is plotted for the various standard levels and down below the surface observation is plotted. Purpose for making this chart is to study the systems moving in the atmosphere. In the area of w westerly wind field the systems can move from west to east for e.g. W.D. or troughs in mid and upper tropospheric westerlies in winter. For this type of systems the time section is plotted from east to west.



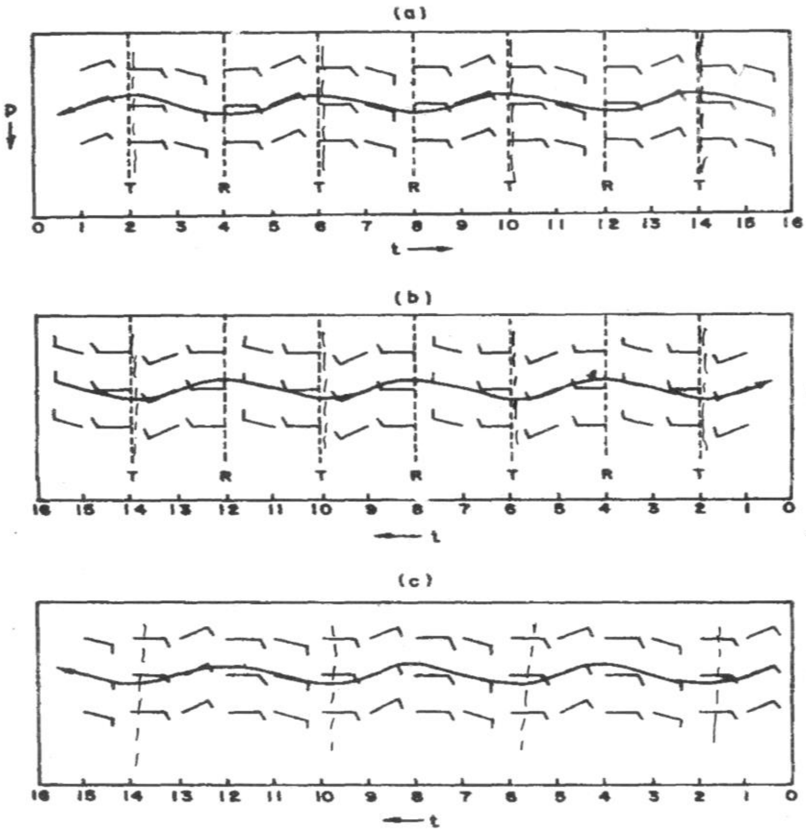


FIG. 1.3(1) : Vertical-time section chart.
Station in northern hemisphere is affected by :–
a) Easterly wave (time *t* increases eastwards)
b) Westerly wave (time *t* increases westwards)
c) Easterly wave (time *t* increases westwards).

Some systems especially over peninsular India during past monsoon and winter they move from east to west.For this the time section is plotted from west to east systems for e.g. are easterly waves, trough of lows etc. This chart helps in locating movement of troughs and ridges over the station. On this chart the analysis is done for temperature (Isotherms) wind speed (Isotachs) and mixing ration (Isohygric) lines.

Thus with help of this the moving system can be seen and it helps in forecasting of weather in down stream systems with the help of this chart.

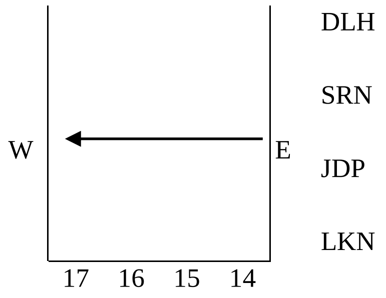
Vertical time section chart clearly shows the passage, depth and intensity of weather systems particulars station. This chart provides the information regarding intensity, depth, tilt, rate of movement and possibility of intensification or weakening of pressure systems and associated changes in the wind field. We can locate

i) Vertical fluctuations in the moisture context on different days
ii) Fluctuation in maximum wind level.

This chart also helps in keeping continuity from chart to chart. This is very helpful at the time of advance of monsoon over Kerala.

Vertical Cross Section Chart: - In this chart again the time is constant but the different stations are plotted on this type of chart.

1) Cross section along particular longitude, longitudinal or meridional cross section.
2) Cross section along particular latitude, latitudinal cross section.



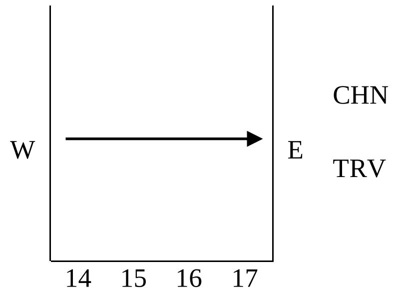
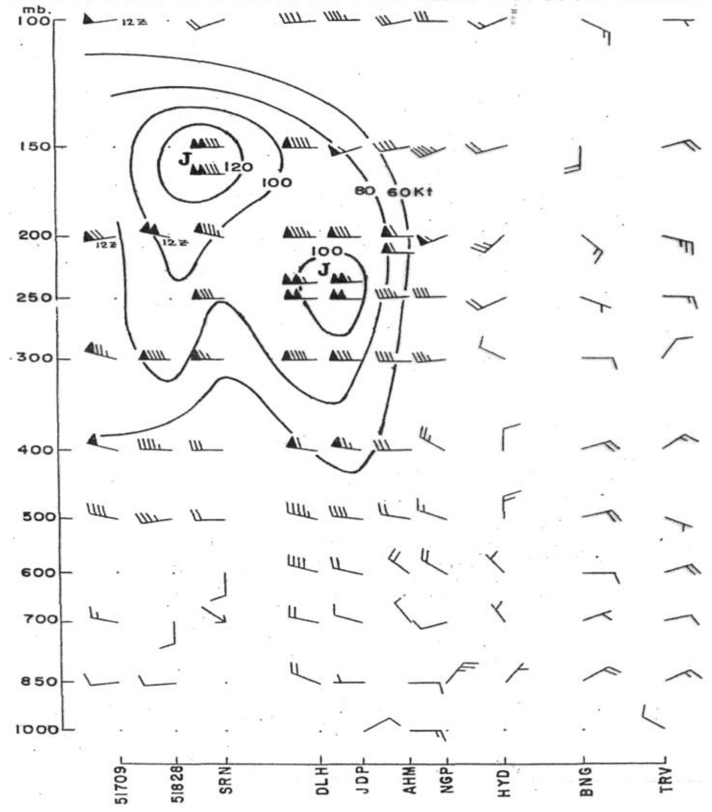


FIG. 33·2(a) VERTICAL CROSS SECTION ALONG 77°E: 00 GMT 10 DEC.70



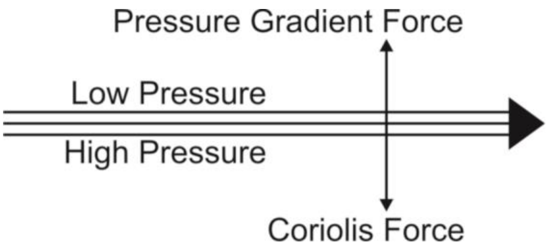
Thermal wind : It is a pure imaginary wind and arise due to temperature difference in two levels. Thermal wind can be defined as the vectorial difference between the higher level geostropic wind and the lower level geostropic wind. If vg1 and vg2 represent the lower level and upper level geostropic winds respectively then the thermal wind at a station between the two levels is given by Vt = Vg2 - Vg1

Thermal wind in the Northern Hemisphere blows keeping low (cold) temperatures and low thickness values to its left and high (warm) temperatures and high thickness values to its right.

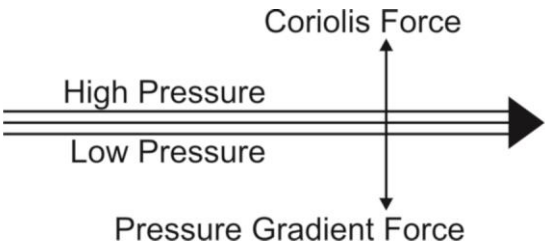
Geostrophic wind : There are three different forces which are acting on moving air a wind.

1) Coriolis force (due to rotation of earth).
2) Frictional force (upto about 1 km of height).
3) Pressure gradient force (acts due to high and low pressure area from high to low).

Let us consider the frictional force is negligible and the magnitude of the pressure gradient force and the Coriolis force is exactly equal. i.e. the pressure gradient force will prevent the deflection of wind due to Coriolis force either to the right or to the left. Then this flow is known as the geostrophic flow and the wind is known as a geostrophic wind.



Geostrophic Flow in N. H.



Geostrophic Flow in S. H.

Coriolis force deflects the wind to the right in the northern hemisphere and to the left in southern hemisphere.

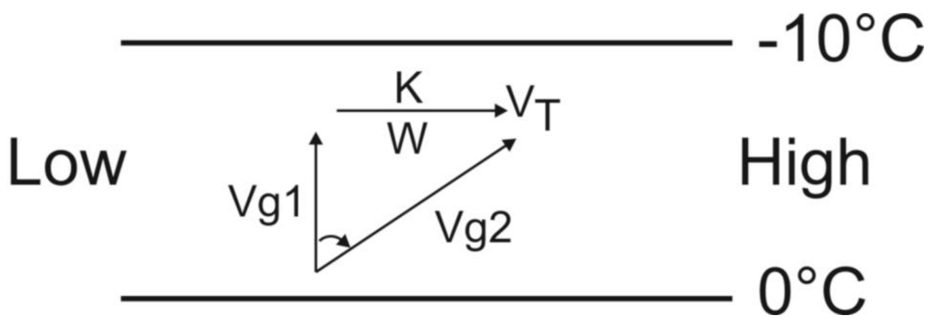
Thermal wind continuation from last page :

$$\xrightarrow[\text{W(Warm Temp)}]{\text{K(Cold Temp)}} V_T \qquad \xrightarrow[\text{High Thickness}]{\text{Low Thickness}} V_T$$

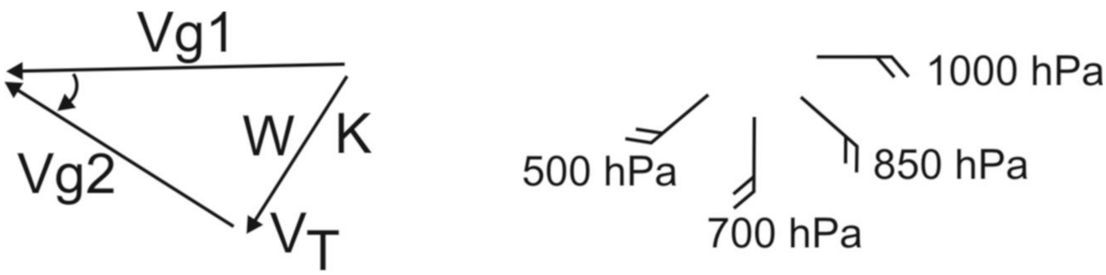
Thermal wind in Northern Hemisphere. Though thermal wind is a imaginary winds, its concept is a very useful tool in weather forecasting.

Veering of Geostrophic wind with height :

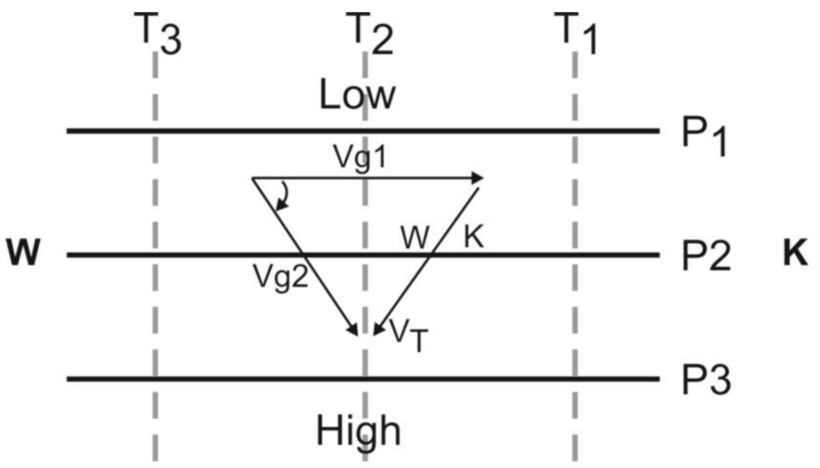
Let us consider that the Geostropic wind at lower levels is southerly and the thermal wind is in westerly direction then the Geostropic wind at the upper levels will be south-westerly. Thus from fig. it can be stated that with warm air advection the Geostropic wind veer with height (clockwise).

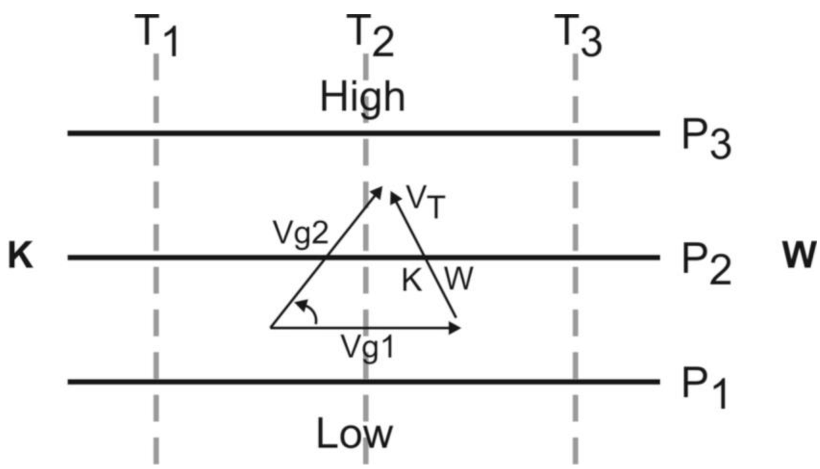


Or in other wards we can say that veering of geostrophic wind with height will bring warm air.



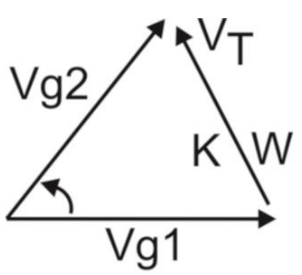
T3 > T2 >T1

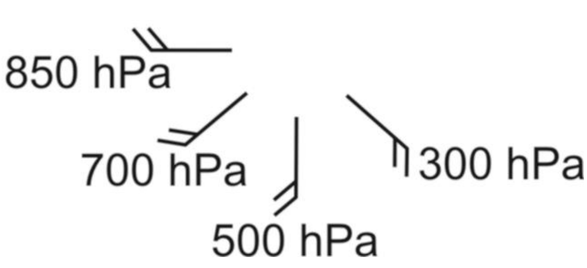




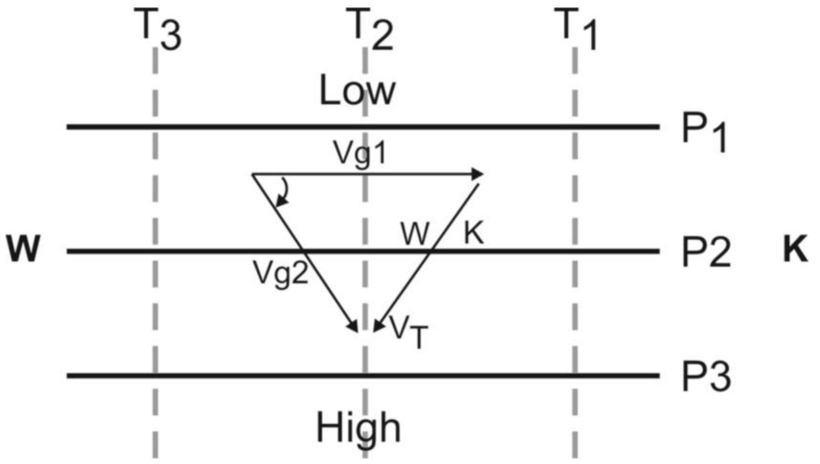
Temp T3> T2 > T1
Pressure P3> P2 >T1

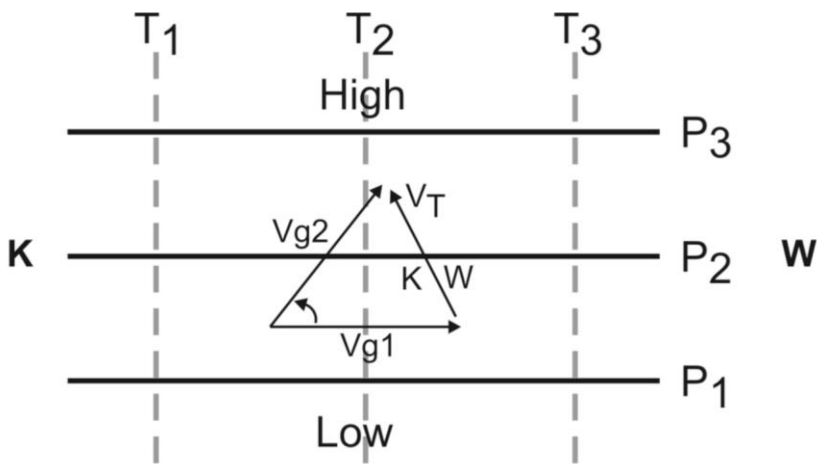
Let us consider that geostrophic wind at lower levels vg1 and (westerly) at higher levels is vg2 - Then the thermal wind between these two levels (north easterly) is NE ly with the temperature distribution in the layer as shown in the diagram from this diagram it is seen that if there is a warm air advection over the station in lower levels (with wind vg1) then vg1 veers with height and becomes the vg2 at higher levels.





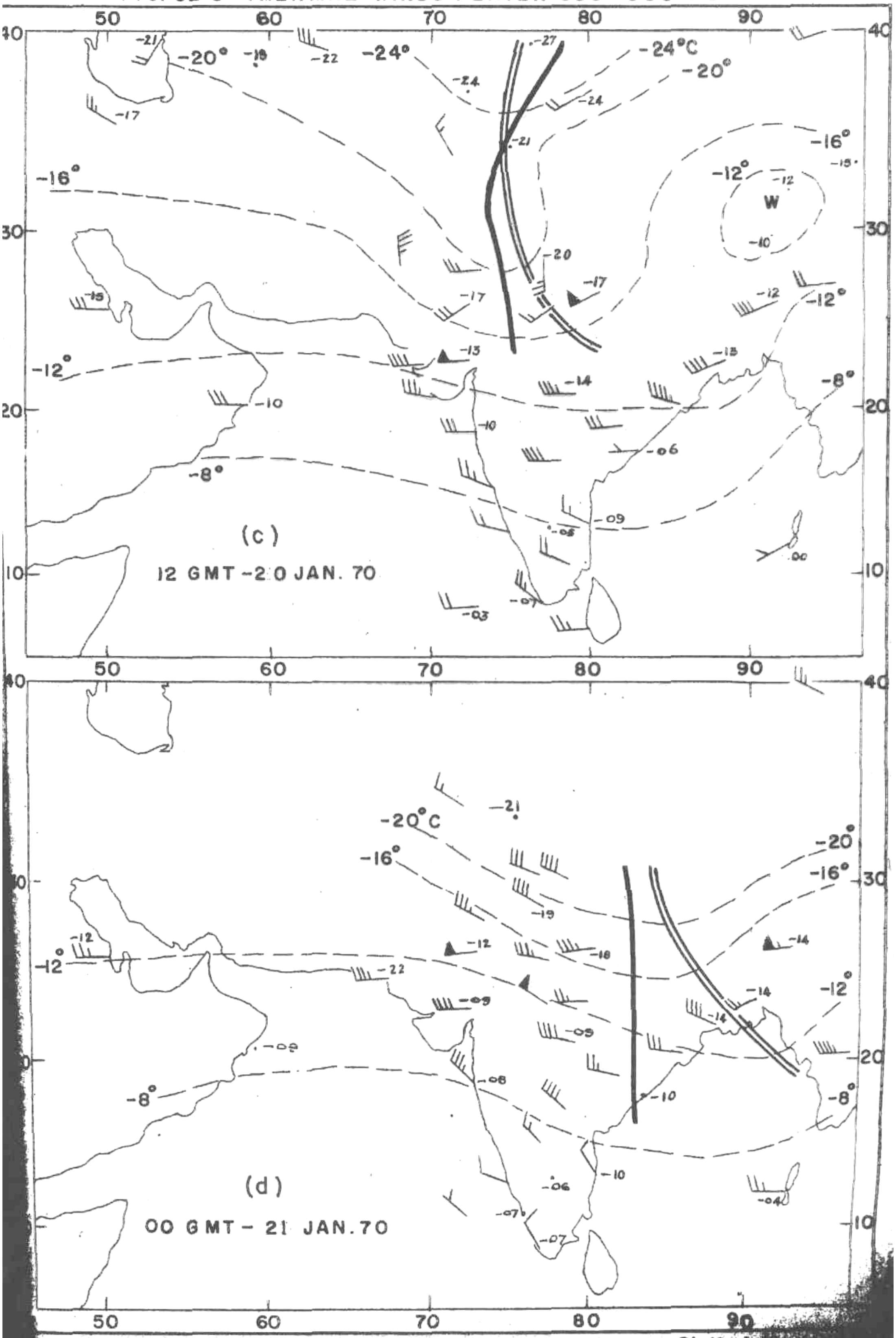
Backing of Geostrophic Wind with Height :





Let us consider that the geostrophic wind at lower level is westerly and geostrophic wind at higher level is south-westerly. Then the thermal wind between these two levels is south-easterly with temperature distribution at the layer as shown. From the above diagram it is shown that the cold air is advected over the station at lower levels and the geostrophic wind at lower level vg1 backs with height and becomes vg2 at higher levels. Or it can be said as with cold air advection at the station the geostrophic wind backs with height. Or in other wards it can be stated as backing of geostrophic wind with height will bring cold air.

FIG. 32·3 THERMAL WINDS : LAYER 850-500 mb



--- Isotherms ═══ Thermal Trough ━━ Pressure Trough. Plott
temperatures at 500 mb

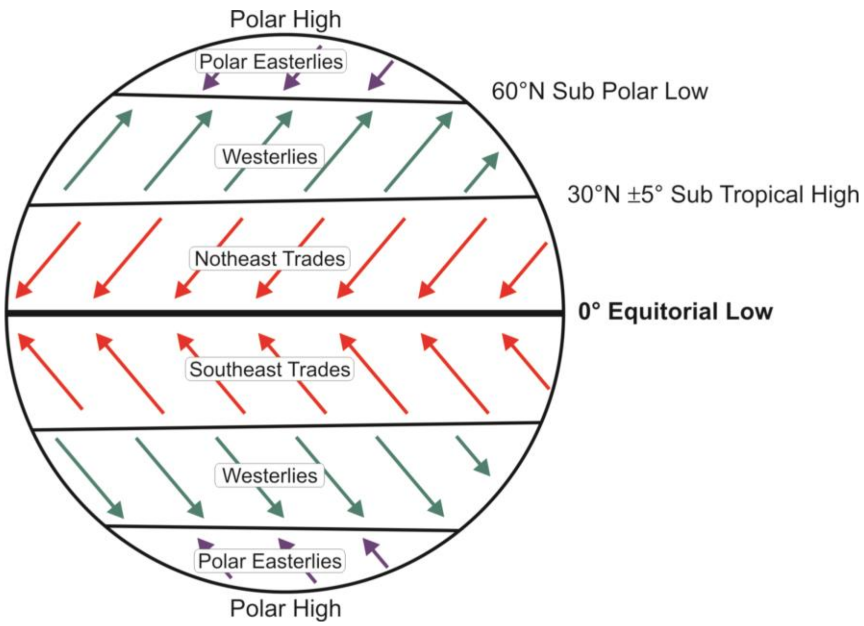
Western disturbance and its structure and associated weather, Waves in mid-latitude Westerlies.

Before starting the discussion of above mentioned topics, primarily related to winter season of Indian region, it is pertinent to develop some background of tropical Synoptic meteorology- as outlined below,

Tropical region is a area in between Tropic of cancer (23 1/2^{0} N) and Tropic of Capricorn (23 1/2^{0} S). In this topic the study of the systems in tropics is done. Tropics are bounded by two sub-tropical highs one in the northern Hemisphere and one in the southern Hemisphere these are called as sub tropical highs.

Idealised Average M.S.L. Circulation Distribution of pressure or wind over globe :

In the general circulation we have got the pressure belts and wind belts.



Actually these pressure and wind belts are shifting north and southwards as per the revolution of earth around the sun. The two extreme positions occur in January and July.

Sub -Tropical Highs : Sub tropical anticyclones are the sub-tropical high pressure belts which are located between 25^{0} to 35^{0} in both northern and southern hemisphere.
1) They will move more pole ward in summer hemisphere and more equatorward in winter hemisphere. 2) The position and intensity also changes due to the differential heating between land and sea. 3) They are more intense in winter months than in the summer months. 4) In the winter months they are located over continental regions and in summer month they are over oceans. (Main reason for all these things is the location of sun and the land areas cool and become warm more rapidly than the sea areas.

Trade winds and Trade wind Inversion :

The winds blowing from sub-tropical high area towards the equatorial regions in both in the northern and southern hemisphere are known as the trade winds. They are NE trades in the northern hemisphere and are SE trades in the southern hemisphere. These winds are originating from sub-tropical high and move towards the equator. (In absence of Coriolis force the winds will be N ly in northern hemisphere and S ly in southern hemisphere but as the Coriolis force deflects the winds to right in the northern hemisphere and deflects the winds to left in the southern hemisphere the winds will become NE ly in northern hemisphere and SE ly in southern hemisphere).

Normally the trade winds blow from the directions stated above but sometimes the direction and speed vary from time to time abide from place to place due to local effects due to the underlying surface, differences in pressure gradients and due to Coriolis force.

The trade winds generally develop due to the subsidence in the sub-tropical high pressure area they are associated with inversion. The trade winds are generally noted for their persistence and steadiness over the oceanic areas they are characterised by cumulus clouds with base at about 1 kilometre and tops at about 2 kms. or so. The restricted cloud development and generally fine weather sometimes associated with trade winds is linked with the trade wind inversion. Subsidence in the high pressure belt produces the inversion. However as the air moves equator ward and westwards towards the equatorial trough, the trade wind inversion begins to weaken and its base become higher. Vertical cloud development then increases, as the instability extends to greater latitudes. Precipitation becomes heavier and more frequent in the vicinity of the equatorial trough. Cumulus clouds generally form upto the base of the inversion. (Inversion means the sharp increase in temperature and decrease in humidity temperature increases as we go up against the normal decrease of temperature.) It does not allow clouds to grow above its base as the inversion layer is a very stable layer. Inversion is generally seen more over the sea areas.

Equatorial Trough:

The low pressure near the equator is called as the equatorial trough. The mean position of the equatorial trough for year as a whole is 5^{0} N and it is called as the Meteorological equator or the heat equator. This position is not coinciding with the real equator - geographic equator. The two sub-tropical highs and equator shift north and south during the year. During the month of January (December 22) when the sun is in the southern most position the mean pressure trough lies near 5^{0} S where as when the sun is in extreme northern most position in July (June 22) the position of pressure trough is near 12 - 15^{0} N. Thus the shift to the north is more than the shift to the south.

This equatorial trough is also the inter-tropical convergence zone (ITCZ). Here the trade winds from both the hemispheres meet in a narrow zone. This ITCZ produces extremely bad weather conditions over a wide area.

WESTERN DISTURBANCES

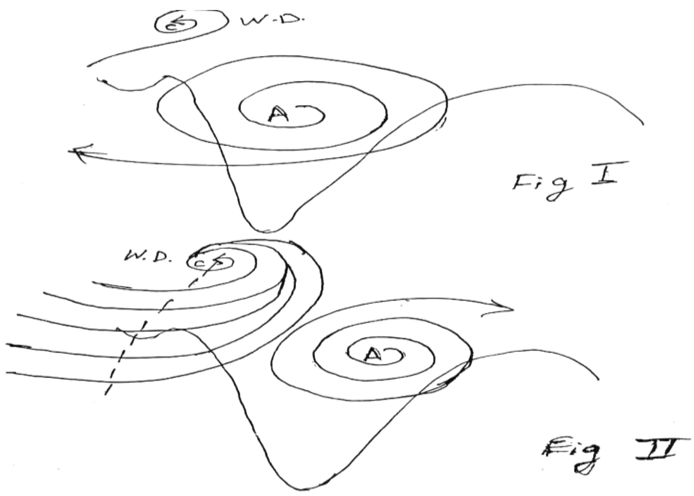
Western disturbances are the synoptic scale weather systems which occur in middle latitude westerlies during the winter season. These systems originate over the Mediterranean Sea, Caspian Sea and Black Sea and approach north-west India, especially northern part of India north of 30^0 N, by moving across Iraq, Iran, Afghanistan and Pakistan.

W.D. can be noticed as the cyclonic circulation or trough in the middle or lower tropospheric levels or as a low pressure area on surface. Sometimes under the influence of the western disturbance, a low or cyclonic circulation develops to the south of the system. Then this is called as the 'Induced low' or the 'induced cyclonic circulation'. ***Whenever two or more closed isobars can be drawn on the surface chart, then the system can be referred as a western depression.***

Along with the winter season the W.D. are also present in pre and post monsoon seasons. During monsoon season also, they are present but are very rare and mostly in the break monsoon situations. Sometimes the W.D's are associated with the troughs in the westerlies of mid and upper tropospheric levels. Movement of W.D. is mainly in ENE ly direction.

Movement and Rainfall associated with W.D's

When the W.D. moves across the country, the anticyclone over the central parts of the country and adjoining peninsula is not at all affected. (Fig. 1)



In this case, the W.D. does not get any fresh supply of moisture to the system.

But sometimes (Fig. 2) a trough from W.D. penetrates into Arabian Sea and the anticyclone over central parts slightly shifts eastwards and the system will get the fresh supply of moisture from the Arabian Sea.

On some occasions (Fig. 3), the anticyclone shifts to the Bay of Bengal alongwith the movement of W.D., in this case the trough also extends from W.D. into Arabian Sea. In this case, the W.D. gets the fresh supply of moisture not only from the Arabian Sea but from the Bay of Bengal also.

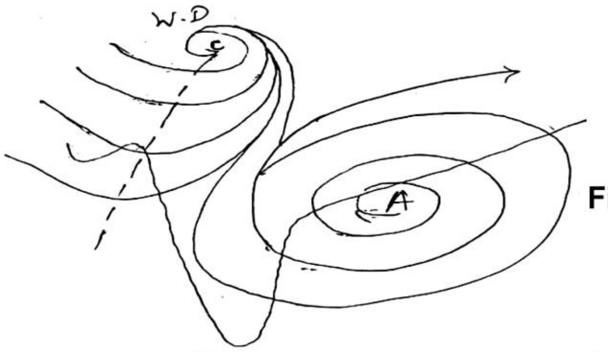


Fig. 3

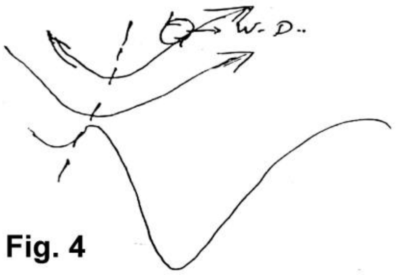


Fig. 4

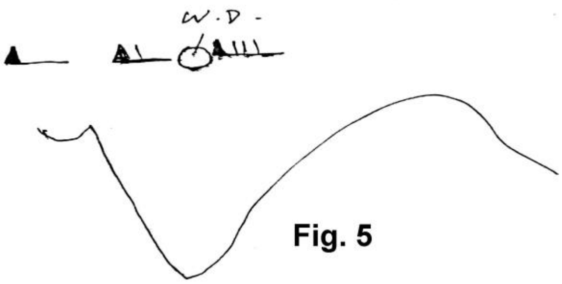


Fig. 5

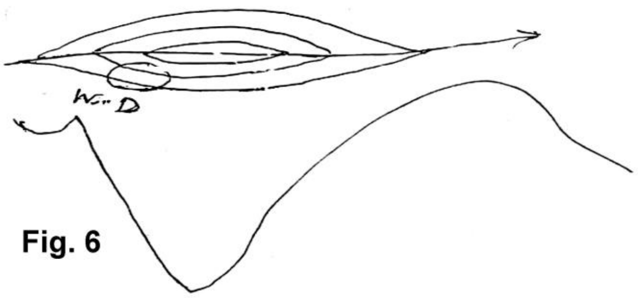


Fig. 6

Intensification of the Western Disturbance

Intensification of W.D. depends upon the divergence available above the W.D. The divergence can be due to a trough in mid and upper troposphere levels, velocity divergence or due to Jet Maxima. (Figs.4,5 & 6).

This divergence in the upper air will intensify the W.D. in the lower levels. Hence activity of W.D. depends upon the upper level divergence and the fresh moisture supply either from the Arabian Sea or the Bay of Bengal.

Important synoptic conditions associated with the approach and after the passage of W.D's over a station.

MET ELEMENTS BEFORE THE APPROACH OF W.D. OVER A STATION:

1. Fall of pressure (can be noticed by P_{24} P_{24} values).
2. Rise in minimum and the dew point temperature.
3. Approaching cloud sequence. First High clouds, then medium and then low clouds and then precipitation and snowfall.

MET ELEMENTS AFTER THE PASSAGE OF W.D. HAS MOVED AWAY FROM A STATION:

1. Rise in pressure.
2. Fall in minimum temperature (cold wave) and fall in dew point temperature indicates dry weather.
3. Clearance of weather.
4. Fog in rear of W.D. after one or two days.

WEATHER ASSOCIATED WITH W.D.

1. Precipitation
2. Cold Wave
3. Fog

1. **PRECIPITATION:** Rainfall / snowfall are the main precipitations associated with W.D's. It occurs over the forward sector of the W.D. Snow fall generally ocure in high mountainous and hilly regions whereas the rainfall moves eastward along with induced system. Rainfall belt extends eastward right up to West Bengal or Assam depending upon the intensity and the movement of the systems.

2. **COLD WAVE**: Cold wave occurs in the rear of the Western Disturbance. It is a relative term with respect to the normal minimum temperature. After the passage of W.D. has moved away or if there is no other system following from the west, the cold air from the north of the country sweeps southwards and the temperatures drops leading to cold wave conditions over the country.

3. **FOG**: This is a weather hazard which is associated with the W.D's. It generally occurs in rear of W.D.'s leading poor visibility conditions, especially over the Northern parts of the country during winter season.

TROUGH IN WESTERLIES

The predominant winds in the mid-latitude regions (sub-tropics between 30^0 to 60^0 latitude) are westerly's. One of the moving systems in this region is a wave perturbation by alternate trough or ridge in it. Mostly these waves are present throughout the year over entire globe. Over India, they mostly affect in winter season but they are also present in other months and in SW monsoon, they are rare. These waves are first studied by *'Rossby'*.

These waves can be divided into two broad classes:

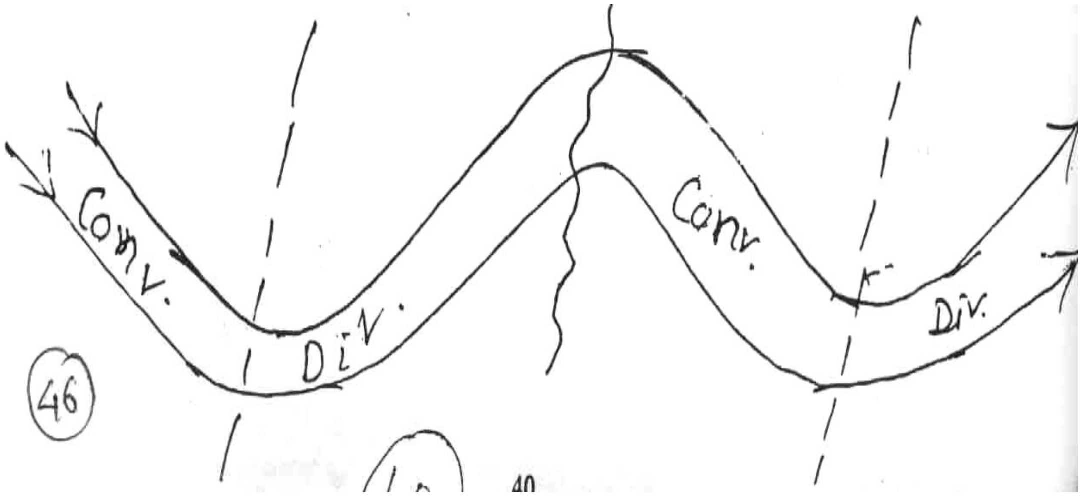
- *Long Waves - are also called as Rossby waves or Planetary waves.*
- *Short Waves - are also known as Cyclone waves because of their association with surface cyclones in middle latitudes.*

Some of the characteristics of these westerly waves or troughs are :

1. Wave length of the long wave is 6000 to 8000 km, while short wave is having a length of 2000 to 3000 km.
2. Normally there are 4 to 5 long waves around the hemisphere.
3. These waves are noticed in the deep layer of atmosphere usually between middle and upper tropospheric levels preferably level are 300 hPa where the patterns are smoother (between 700 to 200 hPa levels).
4. These waves move from west to east. The short waves moves faster than long waves.
5. Long waves are very slow moving, their speed is about 1 to 2 degrees of longitude for 24 hrs at 40^0 N. Short wave moves faster. They will travel at an average rate of 10 to 12 degree of latitude for 24 hrs.
6. Movement of the long waves is related to the contour pattern and the isothermal field on isobaric surface. Long waves can be progressive, stationery or retrogressive.

   a) Progressive Wave - When the amplitude of the contour is less than the amplitude of isotherm, then the wave is progressive in the direction of zonal current.
   b) Stationary Wave - When the isotherm pattern coincides with contour, then the wave becomes stationary.
   c) Retrogressive Wave- In this case the wave will move from east to west against the zonal current, when the amplitude of isotherm is smaller than the amplitude or contour.

7. Short waves are always progressive waves.
8. Normally troughs in waves tilt westwards with height.
9. Ahead of the trough, divergence occurs and helps in the intensification of system on the surface.
10. Thermal structure of long wave is characterised by warm ridge and cold trough. In case of short waves, it is reversed. Troughs are warm and ridges are cold. Thus in case of long waves, the contours and isotherm pattern are nearly in phase. But in short wave, they are largely out of phase.


Conv.
Div.
Conv.
Div.
46

Thunderstorm and severe local storm, synoptic conditions favourable for thunderstorm, concepts of triggering mechanism, conditional instability; Norwesters, dust storm, hail storm. Squall, Ttornado, Microburst/ Cloudburst, Landslide.

CONVECTIVE ACTIVITY OVER INDIA

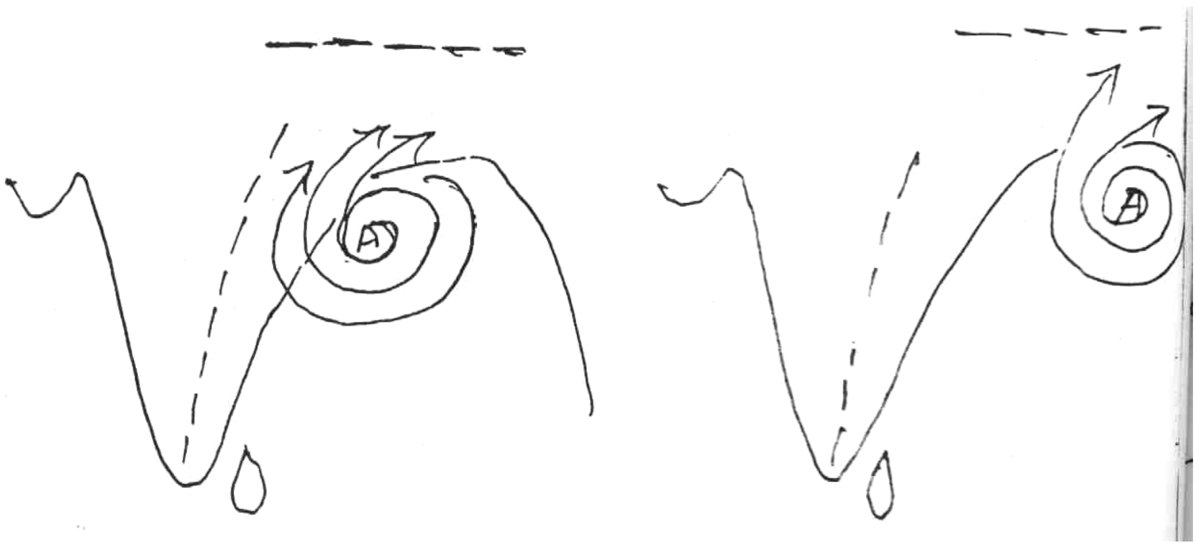
Intense convective activity over India generally occurs during pre monsoon season. March to May in June also it continues in some areas. The synoptic situations which are responsible for the development of convective activity in general are clear skies, intense heating of ground and the large instability. The synoptic features associated with is convective activity can be studied for different parts of India.

1) Convective activity over NE India.
2) Convective activity over NW India.
3) Convective activity over central India.
4) Convective activity over peninsular India.

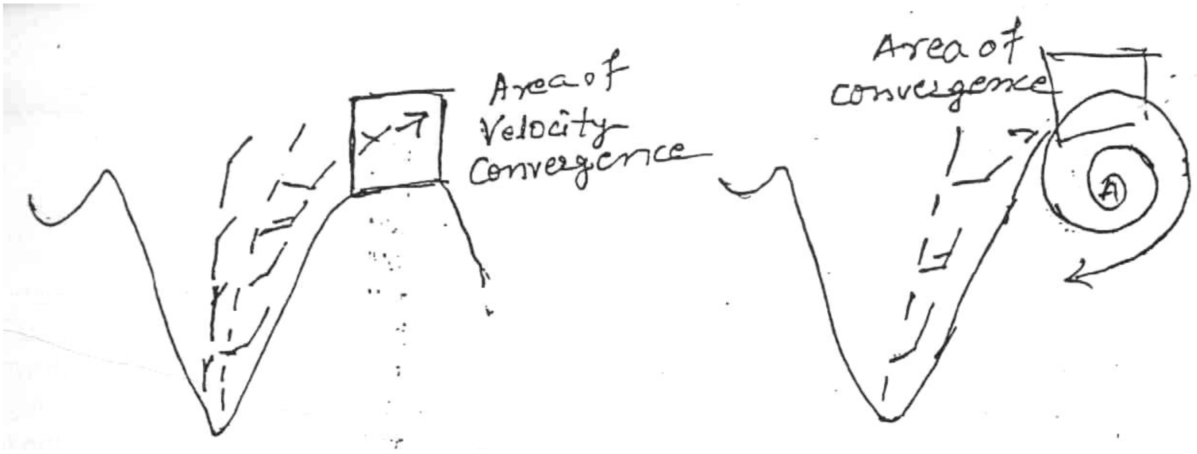
1) Convective activity over NE India:

Local name for ***c***onvective activity over NE India is Norwesters, Kalabaisakhi. This activity starts in month of March and reaches to its maximum in May. This area is one of the high frequency of occurrence of thunderstorms in the country. Violent thunderstorms, squalls, heavy precipitation and hails are quite common over NE India. The synoptic situations associated with these thunderstorms are as follows.

i) Incursion of Moisture: A high pressure area is located over surface and an anticyclone is located overt north and central Bay of Bengal during the pre-monsoon season. The location and the intensity of this anticyclone control the flow of moisture in the different parts of north-east India.

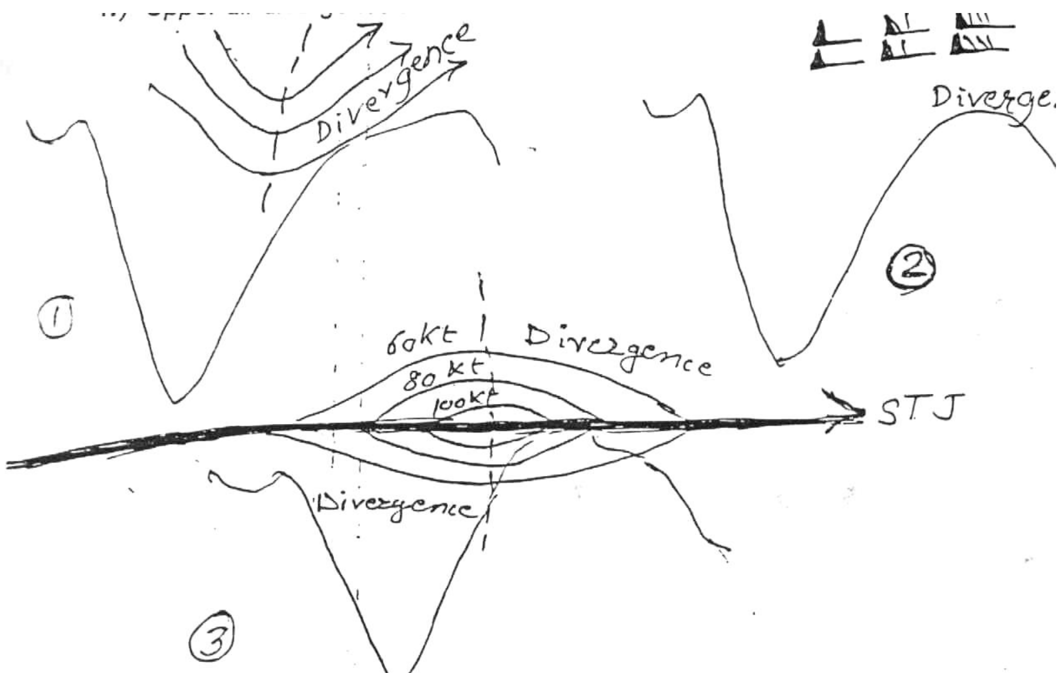


ii) Velocity convergence in the lower levels: During pre-monsoon, a seasonal wind discontinuity / trough extend from east Madhya Pradesh to south Peninsula. The winds west of discontinuity / trough are north-westerly to northerly and to the east of discontinuity are south of south-westerlies or southerlies. In these winds on some occasions, there are some pockets when the wind stream decreases downstream due to which the velocity convergence is there and which will enhance the intense convective activity.



iii) Thermal structure of the Troposphere: During this season over north-east India, there is a warm air advection in the lower tropospheric levels as there is a south of south-westerly flow in lower troposphere. And in middle tropospheric levels, there is a cold air advection as the winds are from the north-westerly direction. Thus increased warm air advection is in the lower levels and increased cold air advection in the middle levels. This type of advection will increase the lapse rate which will result in increased instability over the area.

iv) Upper air divergence :



Normally the convective activity increases over the areas where there is an upper air divergence in the upper tropospheric levels. This divergence in the higher levels will increase lower level convergence and increased convective activity. The upper level divergence can be provided due to :

1) Trough in mid and upper tropospheric westerlies where the divergence is present ahead of the trough i.e. from trough to ridge.
2) Velocity divergence in the westerly flow over northern parts of the country, the wind speeds are increasing downstream.
3) Divergence associated with jet maxima. There is a divergence in right entrance and left exit region of jet maxima area.
4) Along all these things, there is a east-west wind discontinuity / trough is present in lower levels mostly from Uttar Pradesh to Assam or from Bihar to Assam which helps in the enhancing convective activity over north-east India.

2. Convective Activity of NW India:

Convective Activity over NW India is called as "ANDHIS ". The activity starts in the month of April and it continues in June also. This activity occurs due to intense surface heating and instability. Then again due to synoptic scale systems viz. cyclonic circulations, western disturbance and troughs in middle and upper troposhperic westerlies. These systems will give rise to the convergence which helps in the convective activity. If sufficient moisture supply is available, then there will be thunderstorm activity. But mostly due to absence of moisture, there is a downdraft from Cb cloud which gives rise to the sand storms or duststorms over the area. In these storms, the horizontal visibility reduces to less than 1 km due to the raised dust or sand in the atmosphere. There are two types of dust storms or sand storms which are occurring over north-west India.

1) The Convective type 2) The Pressure Gradient type

1) Convective Type : In this type due to intense heating and instability the Cb cloud develops but there is no moisture supply available, in such a case a downdraft from Cb cloud raised the dust or sand upto the height of about 2-3 kms and reducing the horizontal visibility less than 1 km. The duration of convective type of duststorms / sandstorms is from few minutes to the fraction of an hour.

2) Pressure Gradient Type : During pre-monsoon season intense low forms over NW India especially during late April and entire month of May. On some occasions, a strong pressure gradient develops to the south of this low and this will generate the strong winds both at surface and the lower tropospheric levels. The dust or sand raised due to these strong winds will reduce the visibility less than 1 km. This is pressure gradient type duststorm. Duration of this storm is for greater number of hours or may be upto few days. The upper air divergence associated with the westerly trough, velocity divergence or divergence associated with jet stream enhances the convective activity over NW India.

1. Convective Activity over Central India :

The convective activity over central India is generally associated with the low pressure systems or cyclonic circulations which are due to the

1) Systems in westerlies as induced cycirs (cyclonic circulations).
2) Sometimes systems in easterlies.
3) Locally developed systems. 4) Orography of area.

In addition to these, there is wind discontinuity / trough from eastern parts of Vidarbha to south-east Madhya Pradesh in the SW - NE orientation. Again here also the divergence provided with trough in middle and upper tropospheric westerlies, velocity divergence and the divergence associated with jet stream will enhance the lower systems and the thunderstorm activity.

4) Convective Activity over Peninsula:

During the pre-monsoon season, a trough line or wind discontinuity is noticed from east Madhya Pradesh upto extreme south Tamil Nadu upto Kanyakumari. The winds to the west are northerly or north-westerly and the winds to the east are southerly of south-westerly. But this trough line fluctuates to east and west widely. Sometimes it is noticed along west coast or sometimes also east coast. The thunderstorm activity is mainly seen to the east of the tough line. During later part of May the ITCZ comes close to south peninsula and at this time the thunderstorms are mainly over the southernmost parts of peninsula.

Tornado

A rotating column of air ranging in width from a few yards to more than a mile and whirling at destructively high speeds, usually accompanied by a funnel-shaped downward extension of a cumulonimbus cloud. It is a violent thunderstorm, and can be also termed as a whirlwind or hurricane.

A violently rotating column of air extending from a cumulonimbus cloud to the Earth, ranging in width from a few meters to more than a kilometer and whirling at speeds between 64 km (40 mi) and 509 km (316 mi) per hour or higher with comparable updrafts in the center of the vortex. The vortex may contain several smaller vortices rotating within it. Tornadoes typically take the form of a twisting, funnel-shaped cloud extending downward from storm clouds, often reaching the ground, and dissolving into thin, ropelike clouds as the tornado dissipates.
Tornadoes may travel from a few dozen meters to hundreds of kilometers along the ground. Tornadoes usually form in the tail end of violent thunderstorms, with weaker funnels sometimes forming in groups along a leading **squall line** of an advancing cold front or in areas near a **hurricane**. The strongest tornadoes, which may last several hours and travel hundreds of kilometers, can cause massive destruction in a relatively narrow strip along their path. These are the weather systems whose cause of formation are not well understood and are to be ascertained.

Cloudburst

It is an extreme amount of precipitation, sometimes with hail and thunder, which normally lasts no longer than a few minutes but is capable of creating flood conditions. Colloquially, the term cloudburst may be used to describe any sudden very heavy, but brief and unusual amount of rainfall.

Properties

Meteorologists say the rain fall rate equal to or greater than 100 mm (3.94 inches) per hour is a cloudburst. The associated convective cloud, can extend up to a height of 15 km above the ground. During a cloudburst, more than 20 mm of rain may fall in a few minutes. When there are instances of cloudbursts, the results can be disastrous. Cloudbursts are also responsible for Flash flood creation.

Rapid precipitation from cumulonimbus clouds is possible due to so called **Langmuir** precipitation process in which large droplets can grow rapidly by coagulating with smaller droplets which fall down slowly. It is not essential that cloudbursts occur only when a cloud clashes with a solid body like a mountain or whatever. They can occur even when hot water vapor mingles into the cold cloud. Sudden condensation takes place when it happens

Cloudbursts in the Indian subcontinent

In the Indian subcontinent, a cloudburst usually occurs when a pregnant monsoon cloud drifts northwards, from the Bay of Bengal or Arabian Sea across the plains, then onto the Himalaya and bursts, bringing rainfall as high as 75 millimeters per hour.

Some examples of latest cloud bursts of India

- On September 14, 2012 there was a cloudburst in Rudraprayag district killing 39 people.
- On June 15, 2013 a cloudburst was reported in Kedarnath and Rambada region of Uttarakhand State. Over 1000 killed to date, it is feared that the death toll may rise to 5000. Debris is still being cleared and thousands as still are still missing as of June 30, 2013. It left approximately 84000 people stranded for several days. Indian Army and it's Northern Command launched one of the largest and most extensive human rescue missions launched in its history. Spread over 40,000 square kilometres, 45 helicopters were deployed to rescue the stranded.
- According to a news report this incident was falsely linked with cloud burst, rather it was caused due to disturbance in the two glaciers near Kedarnath.(Source-Isro Report)

Microburst

A **microburst** is a much localized column of sinking air, producing damaging divergent and straight-line winds at the surface that are similar to, but distinguishable from, tornadoes, which generally have convergent damage. There are two types of microburst: wet and dry microburst's. They go through three stages in their life cycle: the downburst, outburst, and cushion stages. The scale and suddenness of a microburst makes it a great danger to aircraft due to the low-level wind shear caused by its gust front, with several fatal crashes having been attributed to the phenomenon over the past several decades. A microburst often has high winds that can knock over fully grown trees. They usually last for duration of a couple of seconds to several minutes.

Firgure of a microburst. The wind regime in a microburst is opposite to that of a tornado.

History of term

The term was defined by senior weather expert Tetsuya Theodore Fujita as affecting an area 4 km (2.5 mi) in diameter or less, distinguishing them as a type of **downburst** and apart from common wind shear which can encompass greater areas. Fujita also coined the term **macroburst** for downbursts larger than 4 km (2.5 mi), a scale of size known as the mesoscale.

A distinction can be made between a **wet microburst** which consists of precipitation and a **dry microburst** which consists of virga. They generally are formed by precipitation-cooled air rushing to the surface, but they perhaps also could be powered from the high speed winds of the jet stream deflected to the surface in a thunderstorm (see downburst).

Microbursts are recognized as capable of generating wind speeds higher than 75 m/s (168 mph; 270 km/h).

Landslide or landslip

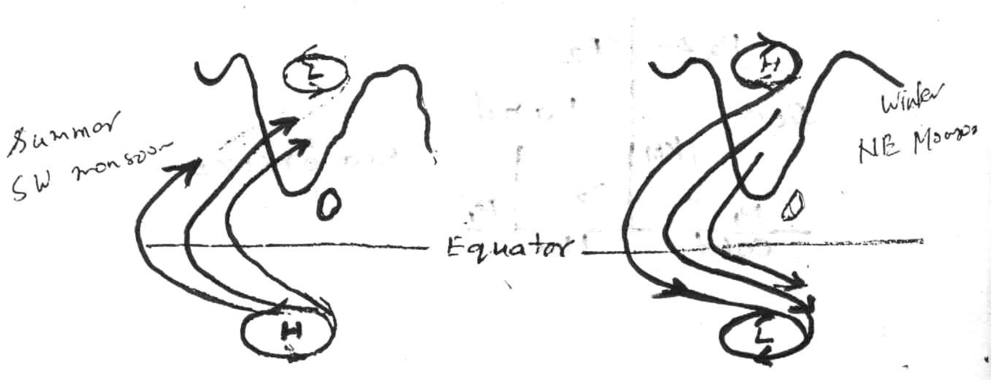
It is a geological phenomenon which includes a wide range of ground movements, such as rock falls, deep failure of slopes and shallow debris flows, which can occur in offshore, coastal and onshore environments. Although the action of gravity is the primary driving force for a landslide to occur, there are other contributing factors affecting the original slope stability. Typically, pre-conditional factors build up specific sub-surface conditions that make the area/slope prone to failure, whereas the actual landslide often requires a trigger before being released.

Indian summer monsoon; S.W. Monsoon onset: semi permanent systems, Active and break monsoon, Monsoon depressions: MTC; Offshore troughs/vortices; Influence of extra tropical troughs and typhoons in northwest Pacific; withdrawal of S.W. Monsoon; Northeast monsoon.

INDIAN SUMMER MONSOONS

Monsoon is a seasonal reversal of winds. This word is derived from the Arabic word "*Mausim".* This reversal of winds arises due to differential heating between land and oceans. In Northern Hemisphere, summer and heating of the land starts in month of March itself. In March, we can locate a low over peninsula, in April it shifts towards north and during May over Punjab area. In short, during summer months of Northern Hemisphere, a low pressure area is located over Africa and Asian continents and a high pressure is over Indian sea in southern hemisphere. The winds will blow from high to low. The winds will be the Southeast "Trades" from high in southern hemisphere, while crossing the equator and going to the northern hemisphere , they will get deflected to the right due to Coriolis force and become south-westerly wind, when they come over peninsular India and central parts of India during summer month.

In winter months of northern hemisphere, the high pressure area is over the Asian continents and the low pressure area is over the south of the equator. The winds will blow from high to low. The winds blowing from high will become Notheasterly over peninsular India and after crossing equator, they will become NW'ly due to the Coriolis force in southern hemisphere.



This reversal of wind over Indian peninsula arises due to the differential heating of the land and sea during the summer and winter.

The south-westerly wind flow during summer gives rise to southwest monsoon over India from June to September and North-Easterly wind flow during winter gives rise to NE monsoon during Oct.-Dec. which affects Tamil Nadu and adjoining areas.

ONSET AND ADVANCE OF SOUTHWEST MONSOON

During middle to end of March, when the sun enters the northern hemisphere (22^{nd} March), the heating starts over land areas of Africa, peninsular India and south-east Asian countries. As the season advances the heat trough starts establishing. The trough is positioned from Africa, Northwest India, to Gangetic plains to Malaysia and Pacific. The movement of ITCZ to north and its merging with the above heat trough is the process which is associated with the onset and advance of the SW monsoon. This process of onset and advance and establishing the trough is the three stage process.

1) A synoptic scale system (e.g. from trough of low, cyclonic circulation in lower troposphere or low pressure area, depression or cyclonic storm) forms over Andaman Sea. This system brings the monsoon over the Andaman and Nicobar Islands, its further advance over bay area establishes the bay branch. Before this the anticyclone over Bay weakens and a weak westerly flow establishes over Bay.

2) A similar type of synoptic system forms over south Arabian sea and Lakshadweep area and this Arabian sea branch brings the monsoon current upto North Arabian Sea, peninsula and up to Gujrat.

3) Formation of any synoptic scale system over North Bay and its westward movement brings the monsoon over North and central parts of the country.

Mostly Arabian sea branch propagates monsoon from South to North, while Bay branch from East to West (This is mainly due to the Orography just as Himalayas prevents the Bay branch to move Northwards). This propagation of both the branches is not systematic and regular event. Some years it is a very rapid process which some years the advance is slow and there is stagnation at different places due to difference in reasons.

Normally monsoon advances over Kerala on June 1 and afterwards over Assam and adjacent states. But in very few years (in rare cases) are there when Assam and adjacent states gets the monsoon before Kerala. Normally monsoon advance over the entire country completes by July, 15.

SYNOPTIC SITUATIONS FAVOURABLE FOR THE ONSET OF SW MONSOON OVER KERALA:

1) Establishment of east-west trough in North Indian Ocean in lower latitudes in lower and middle tropospheric levels.

2) Huge east-west oriented cloudiness from southwest Arabian Sea to South Andaman Sea. First it is seen over SW Arabian Sea & moves eastwards and northwards.

3) Westerly winds over peninsular India in lower tropospheric levels become strong.

4) Easterly winds over peninsular India in upper troposphere also become strong

5) Sub-tropical ridge in upper troposphere over central and Northern parts of the country moves northward.

6) Along with ridge, Sub-tropical Westerly Jet over India weakens and moves northwards.

7) Westerly winds over Thiruvananthapuram in lower troposphere will become strong and the depth of westerly winds also will increase.

8) Moisture in lower and middle troposphere over Thiruvananthapuram also increases.

But in some years the onset over Kerala takes place without any significant changes in the upper trosposperic levels.

Objective Criteria of onset of sw monsoon over Kerala

A. RAINFALL

If after 10^{th} May , 60% of available 14 stations, ***VIZ. MINICOY, AMINI, TRV, PUNALUR, KOLLAM, ALLAPUZA, KOTTAYAM, KOCHI, TRISSUR, KOZHIKODE, TALLESSERY, CANNUR, KASARGODE, AND MANGALORE*** **report** rainfall of 2.5 mm or more for 2 consecutive days, the onset of monsoon over Kerala be declared on the 2^{nd} day, provided the following criteria are also in concurrence.

B. WIND FIELD

Depth of westerlies should be maintained up to 600 hpa in the box equator to Lat. 10^{o} N and Long. 55^{o} E to 80^{o} E. The zonal wind speed over the area bounded by Lat. 5^{o}-10^{o}N, Long. 70^{o}-80^{o}E should be of 15-20 Kts at 925 hpa. The source of data can be RSMC Charts/satellite derived wind.

C. OLR

INSAT derived OLR value should be below 200 wm^{-2} in the box confined by Lat. 5-10^{o} E and Long. 70-75^{o} E.

Further advance of monsoon over the country may be decided as follows.

1. On the basis of occurrence of rainfall over parts of the sub divisions and maintaining the spatial continuity of the N.L.M. of monsoon.

2. Along the west coast, position of maximum cloud zone as inferred by sat. Imageries .

3. Moisture incursion by Satellite water vapour imageries.

SEMI-PERMANENT SYSTEMS OR COMPONENTS OF SW MONSOON

The systems which are located over India and adjoining areas throughout the monsoon season are called as the semi-permanent systems or components of SW monsoon. The positions and intensity of these systems vary from day-to-days and they can influence the monsoon circulation and rainfall distribution.

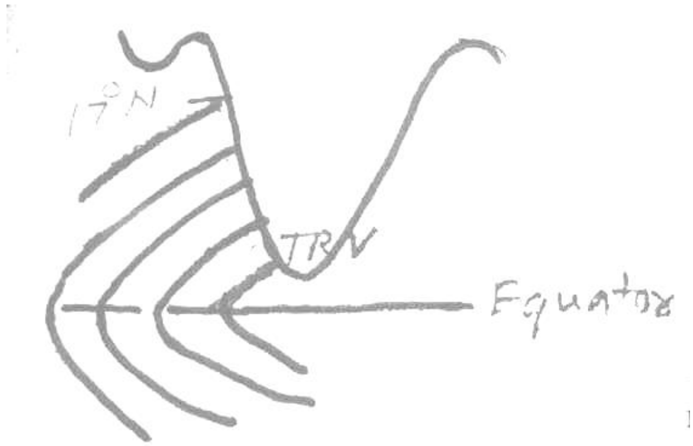
1	**Heat Low**	- Surface.
2	**Monsoon Trough**	- Surface, Lower and Middle Troposphere.
3	**Low Level Jet**	- Surface and upto 2.1 km a.s.l.
4	**Tibetian High**	- Middle and upper Troposphere.
5	**Tropical Easterly Jet**	- Upper Troposphere.
6	**Mascarine High**	- Surface.

First five components are from the Northern Hemisphere over India but last one is from Southern Hemisphere in Indian Ocean.

1) Heat Low - During monsoon season heat low is located over NW Rajasthan and adjoining Pakistan. The heating actually starts in March where heat trough is observed over peninsula mostly on 12 Z chat. In April, heat low is observed over Vidarbha and adjoining Madhya Pradesh. In May, it is seen over Punjab and from June to September over NW Rajasthan and adjoining Pakistan. After September, after withdrawal of SW monsoon heat low vanishes. Ramage has shown that surface pressure at Jacobabad in the heat low region is inversely proportional to the activity of monsoon over Central and North India, specifically between the average rainfall over the strip between 18^0 to 27^0 N. Thus, the intensity of heat low controls the rainfall. The heat low is very shallow and it extends only up to 850 hPa level. Later on it is replaced by a well marked ridge and subsidence.

2) Monsoon Trough : The normal position of the monsoon trough on surface chart passes through Ganganagar-Allahabad-Calcutta to Head Bay. At 850 hPa the position is more or less same. At 700 hPa, it is around 19^0 N and at 500 hPa around 16^0 N The monsoon trough shifts southwards with height. It is due to the fact that temperature to the south of trough is about 2^0C less than that at the North, and low or trough shifts towards cold with height. Generally heavy precipitation is concentrated to the south of the trough. If the Trough is in the North of the normal position, the weak monsoon conditions prevail over the country and if trough is to the South of the normal position, the active monsoon conditions will prevail. Sometimes the trough is along the foothills of Himalayas or it is not at all seen on the surface or lower levels. This situation of chart is associated with a break monsoon / weak condition. Generally, synoptic scale systems (Cyclonic circulations, lows and depressions) move along the trough line from North Bay of Bengal. This trough can fluctuate 5^0 N or S during a day. Sometimes only the western part of trough is seen and not the eastern part but sometimes it happens another way also. The monsoon trough is regarded as the equatorial trough of northern summer in the Indian latitudes.

3) Low Level Jet: This jet is also known as i) Findlater's Jet, ii) Banker's Jet or iii) Somali Jet. Strong south-easterly trades coming from periphery of Mascarine High in southern hemisphere near equator after crossing the equator turn into south-westerly winds due to the Coriolis force become strong and become a low level jet (Core speed of about 40 to 50 kts.) This jet flows from near the Mauritius over northern tip of Madagascar and reaches near Kenya as the south-easterly winds and then after crossing, it blows from Ethiopia and Somalia as southerly and becomes south-westerly in Arabian Sea. Normally it is seen at about 11^0 - 12^0 N. Sometimes this jet splits into two branches, one branch touching TRV and another near 17^0 N. Positive vorticity and convergence is present to the North of Jet core. This low level jet gives very heavy rainfall. Gradual south to north movement of the jet core is noticed.



4) Tibetian High: During monsoon season the intense anticyclone is noticed over the elevated Tibetian Plateau. Intense heating of the elevated locations of the Tibetian Plateau is responsible for the formation of this high. This high is noticed from the 500 hPa level onwards but maximum intensity and size of the high is noticed at 200 hPa level. This anticyclone starts migrating from equatorial region of the south-east Asia from month of March. During the month of March, it is positioned near Tennaserium coast and adjoining Andaman Sea. During April, it is over Burma and adjoining area. During May, it is over Bangla Desh and adjoining area. From June to September it is over Tibetian Plateau and again from October to December, it goes towards south-easterly direction to south-east Asia. If this anticyclone is dislocated and if its position is south-eastwards to its normal position, then the system during monsoon i.e. cyclonic circulations, low or depression move on the periphery of this anticyclone and it may not reach the longitude 85^0 E or 80^0 E. It will just recurve towards north and north-east. But if the anticyclone is noticed towards west or WNW of its normal position, then the monsoon systems will move through Gangetic Plains WNW - wards and reach right up to west Rajasthan and adjoining Pakistan, and will give the good rainfall over central and northern parts of the country.

5) TROPICAL EASTERLY JET: As per the WMO definition Jet stream is a strong core of wind current extending thousands of kilometres in length, hundreds of kms in width and a few kms in depth. In jet stream there are at least more than one velocity maxima of 60 kts or more. The horizontal wind shear is 5 mps per 100 kms and vertical wind shear is 5-10 mps per kilometre. During SW monsoon season tropical easterly (TEJ) is located from east coast of Vietnam to the west coast of Africa. This is a special feature of the monsoon season. These types of strong easterly winds are observed only during SW monsoon season and only over the area mentioned above. These types of strong easterly winds are not observed on any other part of the globe and at any other period.

During monsoon season, due to the intense heating in the northern hemisphere over Indian sub-continents, the warmer temperatures are over the northern parts and colder temperatures are over the southern parts in the troposphere. This type of temperature distribution gives rise to the easterly thermal wind over peninsular India south of 20^{0} N. Thus over westerly strength deceases in the lower troposphere and mid-troposphere upto 500 hPa with height and then the winds will change into easterlies. And this easterly strength increases with height and become stronger and reach to maximum speed in upper troposphere at 150 or 100 hPa level.

The jet stream is in the accelerating state from Vietnam to peninsular India and afterwards it is in the decelerating state from peninsular India to west coast of Africa. The normal position of TEJ over India is located at 13^{0} N at 150 hPa level. However the position and height varies from day to day. During the strong monsoon conditions the JET stream is located to the south of its normal position and it is strong. During the break monsoon conditions, Jet is weak and it is to the north of its normal position. Some times during break monsoon, two jet maxima are seen, one around 15^{0} N and other around 19^{0} N.

6) MASCARINE HIGH : This high is in the southern hemisphere over south Indian ocean. The normal position is 30^{0} S and 50^{0} E. The normal pressure of this high is 1024 hPa in July and August. The position and the intensity of this high is very important in activity of SW monsoon. If this High is more intense, it will give rise to strong SE winds in southern hemisphere and strong SW winds over Arabian Sea and peninsula. This contributes to the strong monsoon conditions. Sometimes this high is dislocated and thus the position and intensity of SW ly winds over Arabian Sea changes.

Synoptic Systems in SW Monsoon Season

1) Monsoon Depressions

2) Low's

3) Mid tropospheric cyclones

4) Off shore trough

5) Off shore vortex

6) Troughs in monsoon westerlies.

The number, intensity and duration of these systems controls the rainfall over the different parts of the country.

Monsoon Depression:-

The depressions which form in the monsoon season are called the monsoon depressions. Monsoon depressions are the intense low pressure areas with two or three closed isobars (at 2 hPa interval) which cause most of the monsoon rains. Depressions in the monsoon season can be of Bay origin, Land origin or Arabian Sea origin. Bay Depressions are more in number and land depressions are less and in Arabian sea they are least in number. The low pressure systems are classified into Low, Depression, Deep depression, Cyclonic storm, severe cyclonic storm and so on depending upon the wind speed on surface when the system is over the sea area. Over land areas the winds at 0.9 km a.s.l. are considered.

Disturbance	*Over Sea Area*	*Over Land Area*
Low	*< 17 kts*	*1 closed isobar in radius of 3 deg.*
Depression	*17 - 27 kts*	*2 closed closed isobars in radius of 3 deg.*
Deep Depression	*28 - 33 kts*	*3-4 closed isobars in radius of 3 deg.*
Cyclonic storm	*34 - 47 kts.*	*5 closed isobars in radius of 3 deg.*
Severe Cyclonic storm	*48 - 63 kts.*	*5 closed isobars in radius of 3 deg.*
Very severe cyclonic storm	*64 -119 kts*	*5 closed isobars in radius of 3 deg.*
Super cyclonic storm	*120 kts. and above*	*5 closed isobars in radius of 3 deg.*

Depressions which form in the monsoon season has got different characteristics compared to the depressions which are forming in Pre and post monsoon seasons.

Origin of Monsoon Depression:

There are three types of origin of the monsoon depressions.

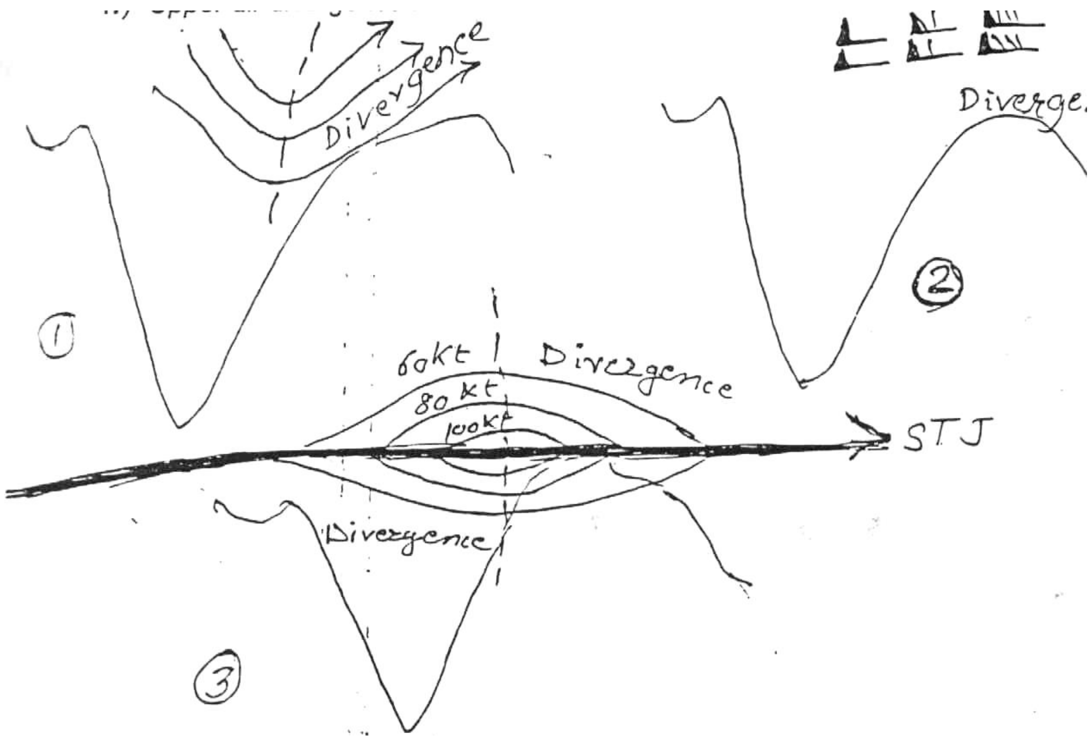
1) In half of cases they develop in situ over head bay. A diffused low pressure field develops over North Bay and adjoining areas.
2) In about 15% of the cases some signs as cyclonic circulation appear in the upper levels up to middle tropospheric levels. Slowly this circulation descends down and under its influence a depression forms over the surface.
3) One third of the depressions formed out of the diffused lows that travel across Burma into north and adjoining central Bay as a isallobaric low. Some of them are the remnants of typhoons in pacific moving westward from South China Sea.

During monsoon season 2 depression forms on an average per month.

Intensification of the M.D.:

The intensification of low into monsoon depression occurs due to the divergence in the higher levels over low pressure area. This upper levels divergence leads to the vorticity generation over surface and in the intensification of the system. This can occur due to,

1) The movement of easterly wave in upper air as there is a divergence ahead of the wave trough.
2) Stream line divergence and velocity divergence in the upper level easterlies.



Structure of the Monsoon Depression:

The shape of the isobars of the monsoon depressions is roughly elliptical rather than the circular one. Diameter of the M.D. i.e. Horizontal extension of the M.D. is about 1000's of kms on surface. Its vertical extension in the upper air is up to about 6-9 kms. Monsoon depression is a cold core system over surface and in the lower levels and the warm core in the upper levels. The maximum wind strength and the intensity of the monsoon depression can be noticed at the levels of 0.9 or 1.5 kms a.s.l. The monsoon depressions tilt south wards with height. The tilt is less in lower troposphere (up to 700 hPa) but the tilt is more from 700 to 500 or 400 hPa level.

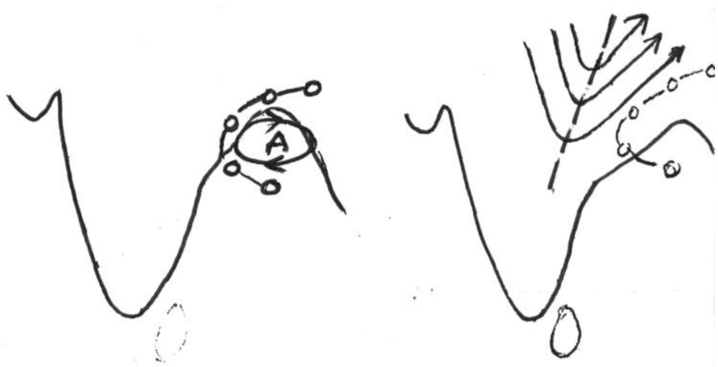
Rainfall associated with M.D.

In association with M.D. rainfall occurs over surrounding areas, however the heavy rainfall is mainly concentrated in the SW quadrant if the depression is moving west ward. If depression recurve & moves to north and north east the heavy rainfall belt shifts to north- east quadrant of the system. The concentration of heavy rainfall in SW quadrant is mainly due to the 1) Relative vorticity, pressure gradient and convergence is more in the SW quadrant as compared to the NW quadrant. In M.D. minimum vorticity is present in NW quadrant & maximum in SW quadrant which gives rise to convergence in SW quadrant. 2) Temperatures are more in NW quadrant as compared to the SW quadrant due to which the additional convergence takes place in the SW quadrant.

Movement of M.D.

Monsoon depressions generally move in a WNW direction. The movement is entirely based on the steering current concept. The synoptic scale system will move along with the wind direction of the level which is just above the circulation level. Movement of the system is guided by the flow in which the system is embedded. For Indian seas we consider 300 or 200 level winds are the steering level winds. For ex. if the winds at this level just above the depression are easterly the system will move in westerly direction. If winds are ESE'ly then the system will move WNW'ly. If the winds are SE' ly then the movement of system will be NW - ward. Monsoon depressions can also recurve just like any other synoptic system. A westward moving system can change the direction to NW, N and finely to NE wards. This re-curvature can occur due to,

1) Shifting of Tibetan anticyclone SE wards in upper levels. The system will recurve on the periphery of this anticyclone
2) Eastward moving of the W'ly trough in upper troposphere to the west of M.D.



Monsoon Lows:

These lows can form over N bay, land areas or Arabian sea. These lows are similar to the monsoon depressions in all the respects only thing is that their intensity is less and these lows do not concentrate in to the depression. But these monsoon lows also are responsible for the substantial amount of rainfall over the entire country.

Mid Tropospheric Cyclones - MTC:

These are the vortices or cyclonic circulations which develop over NE Arabian sea and adjoining Gujarat and north Maharashtra coast in the mid-tropospheric levels. The characteristic of MTC's are:

1) At the sea level only the trough is noticed.

2) The cycir is mainly noticed between 700 and 300 hPa level, sometimes they can be seen between 850 & 500 hPa levels.

3) Maximum intensity of the system is noticed at 600 hPa level. i.e. Maximum wind strength, maximum moisture content, maximum vorticity and maximum convergence are seen at 600 hPa level.

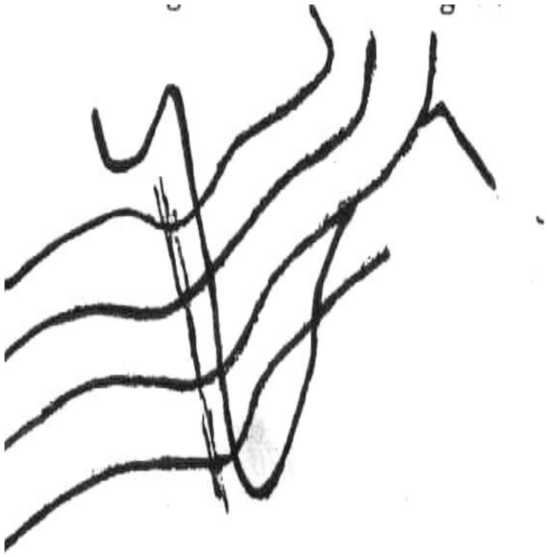
4) MTC's are cold core upto 600 hPa and warm core systems after 600 hPa level i.e. at 700 centre of MTC is colder than environment. At 600 hPa it is nor cold neither warmer, temperature are uniform. But at 500 hPa centre is warmer than the environment.

5) Generally the MTC's do not have any systematic movement. They can be seen near about the same location for number of days. They can be present for one week to 10 days and slowly dissipate afterwards.

6) MTC's are more frequent in first two months of the season as compared to the other two months.

7) In association of MTC heavy to very heavy precipitation is concentrated in the SW quadrant. In that also heavy falls are near the coast.

West Coast Troughs - Off shore troughs :



It is already seen that the advance of SW monsoon over Kerala is associated with a weak trough along and off Kerala coast. This type of trough quite frequently develops along and off west coast of India during monsoon season. This can be a semi permanent trough along and off west coast. This can be located from Gujarat up to Kerala coast or sometimes it can be limited only along certain regions may be Gujarat - Maharashtra or only up to Karnataka, Kerala or along any other parts of west coast. Identification of this trough can be done with the help of coastal and inland station winds, ships observation or by satellite cloudiness.

The coastal winds will become southerly or sometime easterly as against normal south westerly. The heavy clouding is observed along coast. These troughs generally seen from surface upto 0.9 kms a.s.l. or sometimes even upto 1.5 kms a.s.l.. These troughs are responsible for heavy amounts of rainfall of the order of 20 to 25 cm in 24 hrs. and active to vigorous monsoon conditions over the west coast of India. If this trough shifts North the pressure gradient to the South of the trough line increases.

Off shore Vortex :

On some occasions the vortex is noticed off west coast which is embedded in off-shore trough. This may have a diameter of 1 deg. Lat/Long. This may present off shore of W-cot for few days (2 to 3) and then dissipates. Similar to off-shore trough it may also extend upto 0.9 to 1.5 km a.s.l.. It can also be identified by satellite cloudiness, coastal winds and ship observations. Rainfall amounts are very heavy i.e. 25 to 30 cms on occasions. Sometimes even more than 30 cms of rainfall is observed over stations like Mahabaleshwar, Ratnagiri, Panchgani etc, in association with this vortex.

Trough in Monsoon Westerlies:

During weak monsoon conditions when there are no easterlies over entire country weak troughs are noticed to develop in lower tropospheric levels (850 & 700 hPa) mainly to east of 80 deg. E over plains. These troughs are more in July than in other monsoon months. Rainfall is not much heavy as in the field of low or Depressions. But it is more than in the break situation & one or two heavy falls are also noted.

Activity of the Monsoon:

The activity of the monsoon for the particular sub division is categorised as per the IMD criteria in the following way.

Category		***Met Sub-Division rainfall***
1) Weak/ Subdued		Rainfall less that 0.5 times the normal.
2) Normal		Rainfall between 0.5 to 1.5 times the normal.
3) Active	1)	Rainfall more than 1.5 and less than 4 times of normal.
	2)	Spatial distribution should be widespread or fairly widespread.
	3)	At least two stations should record 5 cm or more rainfall for west coast Sub-Divisions and 3 cm or more in case of the other Sub-Divisions
4) Vigorous	1)	Rainfall more than 4 times of normal.
	2)	Distribution should be widespread or fairly widespread.
	3)	At least two stations should record more than 8 cm of rainfall for west coast Sub-Divisions and 5 cm of rainfall in case of the other Sub- Divisions.

Weak / Break Monsoon Conditions

During the monsoon season particularly in July and August there are some spells when the rainfall and cloudiness decrease over the major part of the country except the parts along the foot hills of Himalayas and extreme south peninsula. This type of the situation is referred as the Break monsoon situation. The characteristic features and some synoptic situations which are seen during break period are. These are over surface, and over lower, mid & upper troposphere.

1) Monsoon trough shifts northward and is running close to the foot hills of Himalayas, or sometimes it is not at all seen.
2) Absence of easterly winds over the northern parts of the country from surface upto 1.5 km a.s.l..
3) Increased rainfall activity along the foot hills of Himalayas and decrease in rainfall over central parts and northern parts of peninsula.
4) Over the central parts of the country +ve pressure departures (+4 to +6 hPa) and negative pressure departures along foothills of Himalayas and sometimes over extreme south peninsula.
5) Presence of ridge over central parts of the country, in the mid tropospheric levels (500 hPa).
6) Movement of cyclonic circulation or trough over low latitudes (from east to west) as over south Tamil Nadu or southwest Bay.
7) Western disturbances move along the extreme north of the country.
8) Presence of troughs in middle and upper tropospheric westerlies over northern part of the country.
9) Weak pressure gradient over the west coast and sometimes isobars are running parallel to the west coast on surface chart.
10) In lower troposphere strong westerly winds in the northern parts of the country as compared to the westerlies of the peninsula (weak westerly winds over peninsula).
11) Clouding in southern Hemispheric equatorial trough area increase clouds along foot hills will be more. Very little or no clouds over the country central parts mostly.
12) Tropical easterly Jet is weak and to the north of its normal position. Sometimes double Jet core is seen one along 15^{0}. N and other along 19^{0} N .
13) Some times sub tropical westerly Jet is also seen over the extreme northern parts of the country.

Causes of Break :

1) Due to the movement of synoptic system in Bay. If the system recurves and moves towards foot hills of Himalayas a break can occur.
2) Sometime if typhoon in china sea which are coming from pacific moves north wards north of 30^{0} N. then also there is some chance to move the monsoon trough north wards provided there is no low pressure system in Bay area.
3) Passage of trough in westerlies across Tibetian plateau and adjoining Himalayas in quick succession leads to the Break condition.

Termination of Break:

The break monsoon conditions are terminated when the monsoon trough (at least eastern end) shifts back south wards to its normal position. This may normally happen due to the formation of the low or depression in north Bay.

Strong/ Active Monsoon Conditions

During SW monsoon strong or active monsoon spells are there which will give the very good rainfall activity over the entire country except the extreme northern most parts & Assam area. These spells are normally associated with Monsoon Depressions or monsoon lows. The characteristics during the active monsoon conditions are mostly opposite of the conditions which are prevailing in break. The conditions and synoptic situations which are seen during strong monsoon are:

1) Monsoon trough is located to the south of the normal position (normal is GGN -ALB - CAL - Head Bay) with westerly to south westerly to the south of the trough line and easterly to the north.
2) Very good rainfall activity over central parts of the country and peninsular India & less rainfall over northern most parts.
3) Pressure departures - ve over central parts of the country and **+ve** over northern most parts.
4) Well marked trough is present over central parts at 500 hPa level (mid troposphere) and over the country in lower tropospheric levels also south of normal position.
5) No W.D. or no trough in westerlies is seen.
6) Strong pressure gradient over west coast at surface level.
7) In low troposphere over peninsula strong westerly winds are present as compared to the westerly winds south of the trough.
8) Tropical easterly Jet is strong is to the south of its normal position.

Withdrawal of SW Monsoon

1) Withdrawal from extreme northwest parts of country should not be attempted before 1st Sept. After 1st Sept. following synoptic features are to be seen.

a. Cessation of rainfall activity over the area for continuous 5 days.
b. Establishment of anticyclone in lower troposphere.
c. Considerable reduction in moisture content as inferred from satellite water vapour imageries and T-Φ

2) Further withdrawal from the country-

a. May be declared keeping the special continuity, reduction in moisture as seen from water vapour imageries and prevalence of dry weather for 5 days.
b. It should be withdrawn from Southern Peninsula and hence from the entire country only after 1st October when the circulation pattern indicates a change over from south westerly wind regime.

NORTH-EAST MONSOON

The southwest monsoon period is the principal rainy season over the major portion of India. But the south peninsular India, particularly eastern half comprising of Tamil Nadu, Coastal Andhra Pradesh, Interior Karnataka and Kerala gets significant amount of rainfall during ***October to December***. This period is known as the north-east monsoon period. *In this season, the complete reversal of winds takes place*.

Tamil Nadu including CAP, Rayalseema and interior Karnataka region is a lee ward side of the Western Ghats during SW monsoon season. Agriculture in these regions mainly depends upon north-east monsoon range.

Onset of the north-east monsoon rain is actually is a gradual process. This process begins with a period of transitions. The onset of SW monsoon is much well defined, it progresses along with the northward movement or eastward movement of any synoptic system. While after the withdrawal of SW monsoon from northern parts of the country, the trough shifts southward but still the onset of NE monsoon is not so well defined. On so many occasions, it is not actually clear that distinction between the withdrawal of SW monsoon over peninsular India and the onset of the NE monsoon.

During NE monsoon, westward movement of troughs of lows well marked seasonal trough, low pressure systems viz. storms, depressions and easterly waves will help in enhancing the NE monsoon rainfall over south peninsula. During NE monsoon, the east-west trough is along 13^{0} N along a low near Chennai in Bay region, along with a circulation in lower levels. There is an anticyclone in lower levels, one over central parts of India and another over Burma along with ridge around 25^{0} N. The air flowing around these anticyclones picks up most of its moisture contents in course of its clockwise movement from central and south-western parts of Bay and approach the coast of peninsula as a northeasterly wind flow. This moisture content subsequently helps in giving the winter precipitation over peninsula as Northeast Monsoon. In the middle and upper tropospheric levels, this anticyclone over central India shifts to south of Burma and the upper winds over peninsula become south-easterly rather than North-Easterly.

For declaring the north-east monsoon following synoptic conditions should be observed :

1) *Withdrawal of southwest monsoon up to 15^{0} N latitude.*
2) *Onset and persistence of surface easterlies over Tamil Nadu.*
3) *Depth of easterlies over Tamil Nadu at least up to 850 hPa level.*
4) *Occurrence of fairly wide spread rainfall over Tamil Nadu and adjoining areas.*

Tropical Cyclone: Life cycle, vertical and horizontal structure of TC, Its movement and intensification. Weather associated with TC. Easterly waveS, their structure and associated weather.

TROPICAL CYCLONE

1) INTRODUCTION

Tropical cyclone (TC) formation is one of the least understood topics of tropical meteorology. Research indicates that approximately 80% of all TCs form in or just poleward of the Inter-Tropical Convergence Zone (ITCZ) and monsoon trough (Gray, 1968).

Most of the remainder (about 10%) form from disturbances, embedded in the easterly trade wind flow near the Tropical Upper Tropospheric Trough (TUTT). While the advent of satellite imagery has provided a wealth of data to aid research on this topic, it has also lessened the need for short range forecasting of TC formation. Nevertheless, predicting formation remains an important subject. The tropical cyclones occurring over North Atlantic ocean, are known as Hurricanes and over Pacific ocean are known as Typhoons. T.Cs occurring near to the Australian continent is known as Willy-Willies.
Tropical cyclones do not occur over South Atlantic ocean and in SE Pacific (east of 140^{o} W) mainly because the SSTs are much colder over these areas and ITCZ remains mainly North of equator throughout the year. Over India, Tropical storm is called as the cyclonic storm. Tropical cyclones are the intense low pressures systems where the wind speed in the surface circulation system exceeds 33 Knots.

Categories are derived on the basis of wind speed as follows:

< 17 Kts	**Low**
17-27 kts	**Depression**
28-33 Kt	**Deep Depression**
34-47 Kts	**Cyclonic storm**
48-63 Kts	**Severe cyclonic storm**
64-119 Kts	**Very sever Cyclonic storm**
≥ 120 Kts	**Super cyclonic storm**

The period of formation of Tropical storms in different oceans and areas are given below:

Tropical North Atlantic Ocean	- **June to November**
Eastern North Pacific Ocean	- **June to October**
Western North Pacific Ocean	- **May to November**
Bay of Bengal and Arabian Sea	- **March to May, October to December**
South Pacific (West of 140 W in southern hemisphere)	- **December to April**
South Indian Ocean	- **November to April**

The areas of formation of the tropical cyclone are mainly in the region of equator, but they never form between 5^o N to 5^o S. They form mainly from 5^o N to 5^o S up to 25^o N and 25^o S, respectively.

The tropical cyclone represents an organized tropospheric disturbance that deviates significantly from the tropospheric normal state. Consequently tropical cyclone forecasting is a difficult, specialized task in the realm of modern theoretical and applied meteorology. Worldwide improvements in tropical cyclone forecasting skills in recent decades has been largely due to the,

- International and regional collaboration on communications,
- Development of powerful observational tools including data acquisition and processing systems,
- A growing demand for timely warnings and accurate forecasts, and
- Improved conceptual, theoretical and numerical weather prediction models of tropical cyclone structure and motion.

2. FACTORS AFFECTING TROPICAL CYCLONE FORMATION

There are two primary influences on TC formation: internal and environmental influences. The consensus is that these two influences are equal in importance during the formative stage of a tropical disturbance. There is a requirement for some type of mechanism, which will enhance the low-level convergence and increase the organization associated with a developing tropical disturbance or convective cloud cluster. This enhancement is usually attributed to an external influence, but as the disturbance becomes more organized and self-sufficient, the importance of the environment in maintaining the disturbance's structure lessens, but still has a large influence.

Since TCs have been observed to develop from the inner core outward and also to decay from the inner core outward, it is important to understand the internal processes associated with TC development. For brevity, only those factors, which pertain to initial formation, will be mentioned here.

2.1 Overview of Tropical Cyclone Formation

Pre-existing low-level disturbances and the associated convective cloud clusters occur quite frequently over tropical oceans. The latent heat released by these convective cloud clusters warms the upper-troposphere (500 - 200 hPa) during the initial development stages.

A warm core develops resulting in increased upper level height fields and increased divergence aloft, which lowers the surface pressure.

The atmosphere responds to the lower pressure with increased convergence in the low-levels, which enhances the convection. Additionally, due to the earth's rotation, the converging air begins to rotate cyclonically and a tropical disturbance or depression is formed. Whether or not this disturbance or depression continues to develop is dependent on the surrounding environment's ability to sustain favourable conditions in the vertical column.

3. DYNAMICS OF THE VERTICLA COLUMN

In the 1940s and 50s it was hypothesized that for the above process to occur, some type of upper-tropospheric outflow pattern developed over a disturbance which triggered a corresponding area of low-level convergence.

Gray (1968) suggests that compensation for mass convergence and divergence at any level must always occur at a higher level and that the initial formation stage of a tropical disturbance is the result of a pre-existing area of low- level convergence that develops in an environment favourable for the accumulation of heat within a vertical column. This type of environment is characterized by areas of weak vertical wind shear (Fig.3.1). If heating in the vertical column is allowed to persist, a TC may form (Fig.3.2)

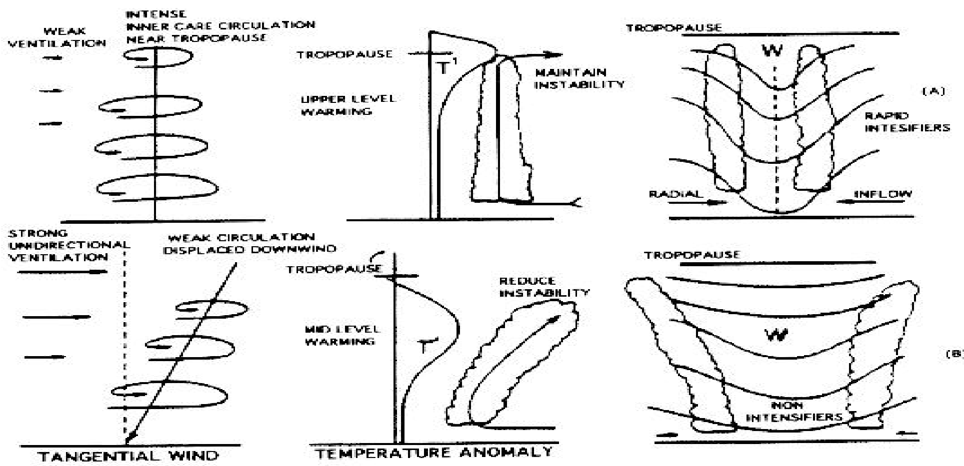


Figure 3.1. Depiction of favorable (top panels A) and unfavorable (bottom panels B) conditions for tropical cyclone development (Mundell, 1990).

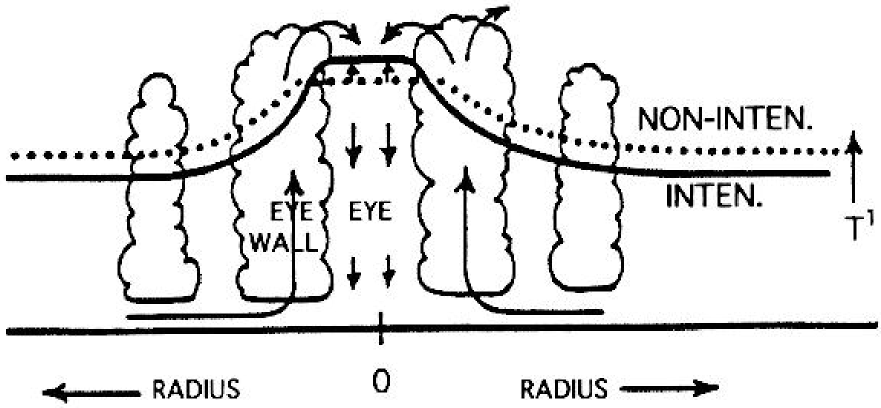


Figure 3.2. A vertical cross section of an established tropical cyclone (Mundell, 1990).

3.1. How do tropical cyclones form?

To undergo tropical cyclogenesis, there are several favourable precursor environmental conditions that must be in place (Gray 1968, 1979):

1. Warm ocean waters (of at least 26.5 C [80 F]) throughout as sufficient depth (unknown how deep, but at least on the order of 50 m [150 ft]). Warm waters are necessary to fuel the heat engine of the tropical cyclone.

2. An atmosphere which cools fast enough with height such that it is potentially unstable to moist convection. It is the thunderstorm activity, which allows the heat stored in the ocean waters to be liberated for the tropical cyclone development.

3. Relatively moist layers near the mid-troposphere (5 km [3 mi]). Dry mid levels are not conducive for allowing the continuing development of widespread thunderstorm activity.

4. A minimum distance of at least 500 km [300 mi] from the equator. For tropical cyclogenesis to occur there is a requirement for non-negligible amounts of the Coriolis force to provide for near gradient wind balance to occur. Without the Coriolis force, the low pressure of the disturbance cannot be maintained.

5. A pre-existing near-surface disturbance with sufficient vorticity and convergence. Tropical cyclones cannot be generated spontaneously. To develop, they require a weakly organized system with sizable spin and low level inflow.

6. Low values (less than about 10 m/s [20 kts] of vertical wind shear between the surface and the upper troposphere. Vertical wind shear is the magnitude of wind change with height. Large values of vertical wind shear disrupt the incipient tropical cyclone and can prevent genesis, or, if a tropical cyclone has already formed, large vertical shear can weaken or destroy the tropical cyclone by interfering with the organization of deep convection around the cyclone center.

Having these conditions met is necessary, but not sufficient, as many disturbances that appear to have favourable conditions do not develop. Recent work (Velasco and Fritsch 1987, Chen and Frank 1993, Emanuel 1993) has identified that large thunderstorm systems (called mesoscale convective complexes [MCC]) often produce an inertially stable, warm core vortex in the trailing altostratus decks of the MCC.
These meso vortices have a horizontal scale of approximately 100 to 200 km [75 to 150 mi], are strongest in the mid-troposphere (5 km [3 mi]) and have no appreciable signature at the surface. Zehr (1992) hypothesizes that genesis of the tropical cyclones occurs in two stages:

Stage 1 occurs when the MCC produces a mesoscale vortex and stage 2 occurs when a second blow up of convection at the mesoscale vortex initiates the intensification process of lowering central pressure and increasing swirling winds.

4. LIFE CYCLE OF TROPICAL CYCLONES

There are several schemes that describe the life-cycle of an average T.C. These stages are not really discrete entities, rather they represent a continuous process. Individual stages may even occur more than once during the life cycle of a particular storm.

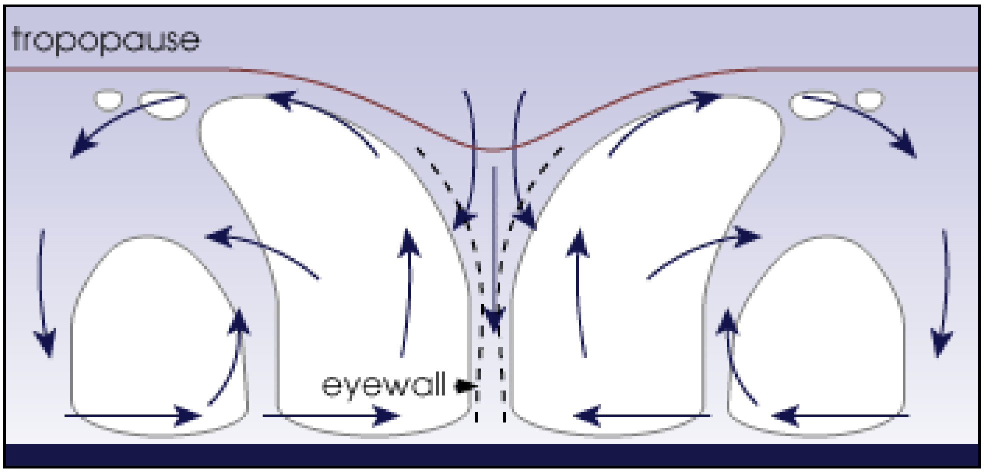


Fig: Mechanics of tropical cyclones :
Tropical cyclones form when the energy released by the condensation of moisture in rising air causes a positive feedback loop over warm ocean waters.

The period from formation of a initial disturbance i.e. low pressure area, its intensification into the depression, Deep depression, up to cyclonic storm and ultimately its weakening is a life cycle of Tropical cyclone.

The life cycle can be decided into 4 stages

1. Formative stage
2. Immature stage
3. Mature stage
4. Decaying stage

Formative stage

Since the nature of TC development is continuous, features associated with earliest stages of the TC life-cycle can overlap. To complicate the issue, there is no standard language for these initial stages. For example, some meteorologists prefer the term "genesis" to describe both the earliest stages of the life-cycle and progression to a mature hurricane or typhoon. Others use the term "genesis" to describe the earliest stages and "formation" to somewhat later stages in the life-cycle.

However, this is a stage in which the initial disturbance of low pressure intensifies into depression, deep depression into Tropical cyclone. At the end of this stage the eye and wall cloud region is formed. For formation of the eye and wall cloud the wind speed should reach 40 kts. The pressure defect difference in pressure from outer most closed isobar to central pressure PO-PC, in this stage is of the order of 10 hPa. Clouds and rain associated with the storm in this stage occurs in a disorganized pattern. Development of the marked circular cloud masses as seen in the satellite cloud pictures also occurs in this stage. The duration of this stage is about few days to 10 days.

Immature stage:

In this stage, primarily, two things occur:

- Rapid fall of pressure in the central region of T.C.
- Strengthening of winds in surface circulation

At the end of this stage lowest pressure and the strongest winds, which are associated with storm, are reached. In this stage the winds, clouds, precipitation pattern become more organized. These form a fight ring around a centre into a spiral band directed inward. Duration of this stage is about 1/2 a day to 2 to 3 days. Duration depends upon the basin (Area) for India and Bay and Arabian Sea it is about 1/2 to 1 day. For Atlantic Ocean it is of 2-3 days.

Mature stage

In this stage the system reaches to the more or less steady state for some level of intensity. Here the central pressure to longer falls and wind strength no longer increases in surface circulation. However the circulation expands in area and the size of the system expands horizontally in all directions and reaches to its maximum size. The strong winds extend as far as up to 200 miles from the center. In this stage the symmetry in circulation that is associated with cyclone is lost completely and the maximum wind and the maximum pressure gradient are concentrated in the right forward sector of the cyclonic storm in the northern hemisphere. The duration of this stage is few days to one week.

Decaying stage

During this stage the T.C weakens rapidly in deep depression, Depression, low and becomes less marked due to two reasons:

- Due to crossing the coast and entering into the land area weakens due to reason of cut off of moisture supply from the ocean.
- Due to the reason that T.C enters into the area of relatively cold waters. Entrance of colder and dry air in lower levels destroys the outside to inside the circulation.
- Sometimes if the T.C enters into the mid latitude westernizes it can get the frontal characteristics and it can become the extra tropical cyclone. This is not weakening but changing the characteristics. Duration of this stage is few hours to one day.

5. HORIZONTAL STRUCTURE OF CYCLONIC STORM

1. Eye of the T.C:-

This is the characteristic feature of the T.C If not seen in extra tropical cyclones this is characterized by the calm winds, clear sky, calm weather but the lowest pressure at the center, Descending motion and sultry conditions are also present in the eye region. The abrupt succession of precipitation is observed when eye region passes over an area Diameter of eye varies from 10 to 50 Kms shape of the eye is generally circular but sometimes elliptical shape is also observed sometimes diffused eye in double eye also can be observed. Inside the eye region the surface temperatures are slightly higher than the surrounding but at the upper levels the temperatures in the eye region are considerably higher.

2. **Wall cloud Region**

This region is just adjustment to the eye of the T.C. This is the most dangerous part of the Tropical cyclone. The width of wall cloud is about 20 Kms. In this region huge Cb clouds towers are notices. In this region maximum pressure gradient, heaviest precipitation and maximum strongest wind associated with T.C are noticed. Pressure gradient in wall cloud region that is associated with T.C is of the order of 0.2 to 0.5 hPa per km. Temperatures in this region are colder than the eye region.

Within the wall cloud at the central region the strongest winds occur and the distance from center to the midpoint of wall clouds can be considered as the radius of maximum winds and incidentally the same can be considered as the radius of maximum reflectivity (RMR).Some times for some TCs double wall cloud regions are noticed. One wall cloud region weakens and then another wall cloud is formed.

If existing wall cloud weakens and double wall cloud forms or double wall cloud is noticed we can noticed that the system is undergoing changes in intensity. Normally in this case the intensity is reducing.

3. Outer storm Region

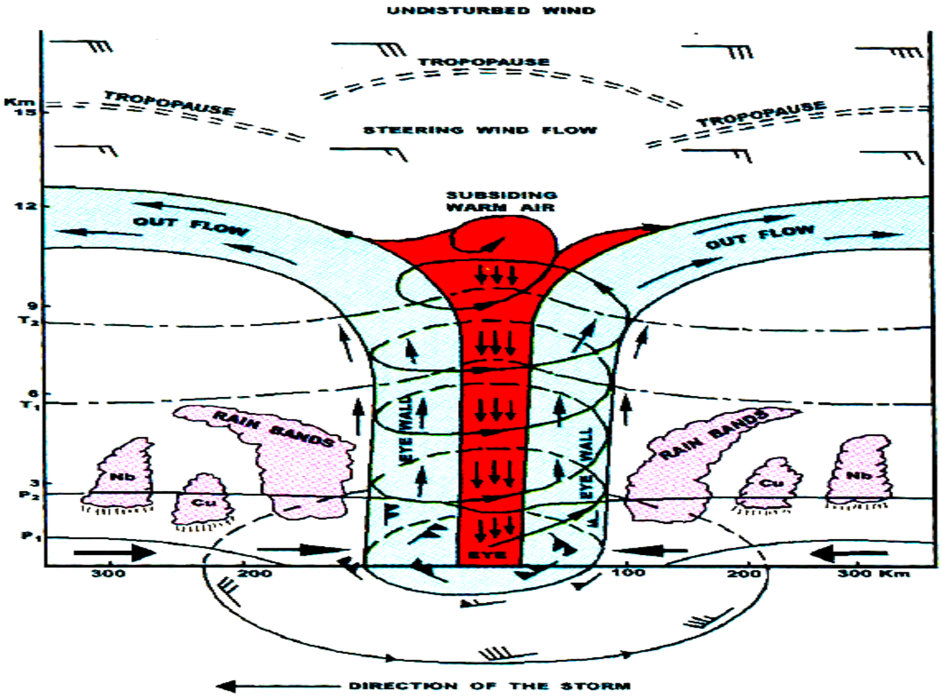
The area from wall cloud to the outermost region of T.C is known as the outer storm region. In this region the wind speed decreases as we move away from wall cloud. Over Indian seas we notice two different types of out storm regions.

- One in which wind speed decreases gradually as we move away from the wall cloud.
- Other one in which the wind speed decreases rapidly as we move away from wall cloud.

6. VERTICAL STRUCTURE OF T.C.

Vertically T.C can be divided into 3 layers.

1. Inflow layer,
2. Middle layer
3. Out flow layer.



Vertical structure of a matured TC.

Inflow layer: - It is a layer in which there is a predominant flow towards the centre of the cyclone from outside is present.

- This layer extends from surface upto about 3 Kms (700 hPa height). In this also strongest or maximum inflow of winds occurs in frictional layer i.e. layer between surface to 1 Km.
- This layer is also called as the planetary boundary layer. Diameter of the T.C. remains more or less same in the inflow layer.

Middle layer: - In this layer the inflow into the centre of the cyclone is compensated by the outflow away from centre of cyclone and hence in this layer at any height if you compute there is neither inflow nor out flow present.

- This layer extends from 3 Km to 7.65 km (700 to 400 hPa above mean sea level.
- In this layer the diameter of T.C decreases rapidly with height.

Outflow layer: This layer occurs above 400 hPa level where there is pre-dominant outflow present i.e. flow away from the centre of the cyclone.

- Maximum outflow occurs at about 200 hPa level and this outflow depends upon the wind flow distribution at that level.

- We can also notice the Cirrus (CI) outflow from T.C through satellite picture. In this layer the diameter of the vortex is small and is about 1deg Lat/ Long at 200 hPa level. At this level sometimes we can see the cyclonic outflow in case of intense systems.

Other points regarding vertical structure

- A mature T.C has got its extension upto about 100-hPa level. The cyclonic circulation or vortex associated with T.C extends into the entire troposphere.
- T.C circulation is vertically straight and it does not tilt with height. Reason is that generally the low-pressure system tilts towards the areas where the cold temperatures are noticed. But in association with T.C the temperature distribution is such that the temperature gradient is more or less same or equal to all the sides (i.e. E, W, N, S etc). This is the reason that the T.C does not tilt with height it is straight in the vertical.
- T.C is the warm core phenomenon where the temperatures at the center are warmer than the surrounding (areas) regions. The maximum warming occurs at the 300-hPa level where the temperatures at the center are warmer by about 8 deg. C as compared to the surrounding areas.
- The diameter of T.C remains same as surface up to about 700 hPa level. Above that it decreases rapidly and at 200 hPa level. Above that it decreases rapidly and at 200 hPa level it is about 1 deg Lat. / 1deg Long.

7. OTHER IMPORTANT POINTS OF T.C.

Rainfall associated with T.C is dependent upon the variation of vorticity in the outer region storm area.

- In vorticity equation curvature term is +ve everywhere but the shear (vorticity) term is –ve. As we move away from cyclone center as the shear vorticity is –ve it reduces the +ve vorticity and this reduction is dependent upon the wind distribution in outer storm region.

- If it is more (rapid decrease of wind speed) the vorticity will be less and rain extends over small area. If is less gradual decrease of wind speed the vorticity will be comparatively more and rainfall will extend to more area.

- In India, Post monsoon season storms are bigger in size as compared to the pre monsoon storms. The average diameter of pre-monsoon storms is about 600 to 800 kms and for post monsoon storms are 1000-1200 kms, however, Intensity does not depend on size.

- In case of T.C in wall cloud region pressure gradient of the order of 0.2 to 0.5 hPa / Km occurs.

- In case of T.C always an angular inflow or the cross isobaric flow into the centre of T.C occurs over the surface and in the fractional layer.

- The angle of cross isobaric flow varies from 25 to 35 deg. on an average it is 30 deg.

- The central pressure associated with T.C can be estimated by using cyclostropic approximation i.e. by using the Flecture's formula.

- The above formula is used for the Pacific and the Atlantic. For Indian seas the modified Flecture's formula is used, which is given by

$$V\ max. = 14.2\sqrt{(Po-Pc)}$$

- Where Po is Pressure of outermost closed isobar and Pc Central pressure of T.C.

- V Max – Maximum wind speed associated with T.C. V Max can be generally obtained by the satellite T Number classifications and Po can be obtained from charts. Thus Pc can be calculated by using above formula.

8. FORECASTING OF MOVEMENT OF T.C.

With the help of the following methods the forecaster can predict the movement of T.C.

1) Climatology
2) Persistence,
3) Analogue
4) Steering concept
5) Numerical Methods
6) Pressure changes
7) Satellite and
8) Radar Technique in 24 hrs.

Climatology

In the initial stages of T.C the climatoloical information is the best source for the prediction of movement of T.C. Based upon the data of more than 100 years for every 2 ½ square of Lat/Lon rid percentage frequency of direction and speed of movement is available for both the Bay of Bengal and the Arabian Sea.

Based upon this the forecaster can give the forecast about the movement of T.C But the climatological method has got its own disadvantages as we know very well that the system/rainfall need not follow past climatology.

Persistence

The concept of persistence arises under the assumption that the past and the existing flow will continue to be same. The previous direction and speed of motion are used for predicting the movement of the cyclone.

In certain cases people give half weightage to climatology and half weightage to persistence track and evaluate the direction of movement and forecast the movement.

Analogue

In this method a cyclonic storm in the past which has developed around the same area and around the same period of month is selected as an analogue cyclone and predicted that the present cyclone will also move as per the track of analogue cyclone. Based upon the above three methods. Some methods are developed by giving equal weightage to climatology, persistence and analogue.

Steering concept

Steering concept is based on the thought that the T.C moves as per the direction of flow of basic current in which it is embedded.

However, where the data over the T.C region is available, generally the average winds at various levels are computed and the average wind for the entire troposphere is computed by giving less weightage to lower and middle tropospheric levels and more weightage to the upper tropospheric levels. It is expected that T.C will move as per that average wind direction and speed.

Over Indian region we consider that the level as a steering level from which the cyclonic circulation of TC is not seen, the TC will move as per the wind direction and speed in that level. Generally for Indian seas 200 hPa is the steering level for the Tropical cyclones. If the winds in this level is E'ly then the T.C will move westwards, if it is South easterly the T.C will move north westerly direction, if it is southerly TC will move northwards.

Numerical method:

Based upon the various NWP methods numbers of model have been developed for forecasting the flow pattern for next 24, 48, 72 and 96 hours. However, still a comprehensive NWP model that can predict storm movement 24 to 48 hrs ahead of crossing the coast with accuracy is still to be developed.

Pressure changes in 24 hours

In addition to all above methods the 24 hrs pressure change will give very crucial indication information about the movement of cyclonic storm, when the C.S comes nearer to coastal area where the pressure changes (-ve) are more the TC is expected to move in that direction.
Sometimes the surface position of the storm may be directly below the COL region in the upper tropospheric flow pattern.
A COL region is an area enclosed between two anticyclones (a high pressure cell) to the east and west and two troughs one to the north in westerlies and one to the south in easterlies. Under such conditions the storm movement is very slow or even stationery some times. This continuous till one of the ridge or trough becomes active relative to the others so that it can be steer the storm. Whenever a storm is likely to change its course its speed generally decreases.

9. RECURVATURE OF T.C.

The change in the direction of motion of T.C is called as the re-curvature of T.C. It recurves due to following reasons.

- T.C recurves on the periphery of an anticyclone in upper troposphere. If T.C. comes under the effect of western limits of the anticyclone it will move northward.
- When T.C moves close to eastern limit of anticyclone then the storm is likely to change its course towards south, however such occasions are rare.
- T.C. also recurves due to the location of though in westerlies to the west of it in upper troposphere.

10. SEVERE ADVERSE WEATHER ASSOCIATED WITH T.C.

1) Heavy rainfall

2) Gale wind

3) Storm Surge

Heavy rainfall

Whenever T.C crosses the coast the very heavy rainfall of the order of 40 to 50 cms for 24 hrs can occur. This will damage the property, damage to crops, collapse of huts and mud houses due to the floods over the low lying areas.

Gale winds

Whenever a wall cloud region crosses the coast very strong winds blow along and off the coast. They will cause uprooting of trees, telephone poles and can collapse the old constructions, or semi permanent structures.

Storm Surge

Storm surge is the movement of the risen or elevated sea water and its inundation into the coastal areas. The sea water enters in the coastal areas with the height of about few meters. This will cause damage of 70 % of lives and 80 % of the properly due to storm surge alone storm surge depends mainly upon four factors.

1. Pressure defect of T.C. i.e. Difference between pressure of outermost closed isobar and central pressure.
2. Radius of Max wind speed.
3. Bathymetry of sea coast (Depth of the bottom of sea near to the coast)
4. Angle and speed with which storm crosses the coast or strikes the coast

In addition to these major factors the height of the surge depends upon some minor factors

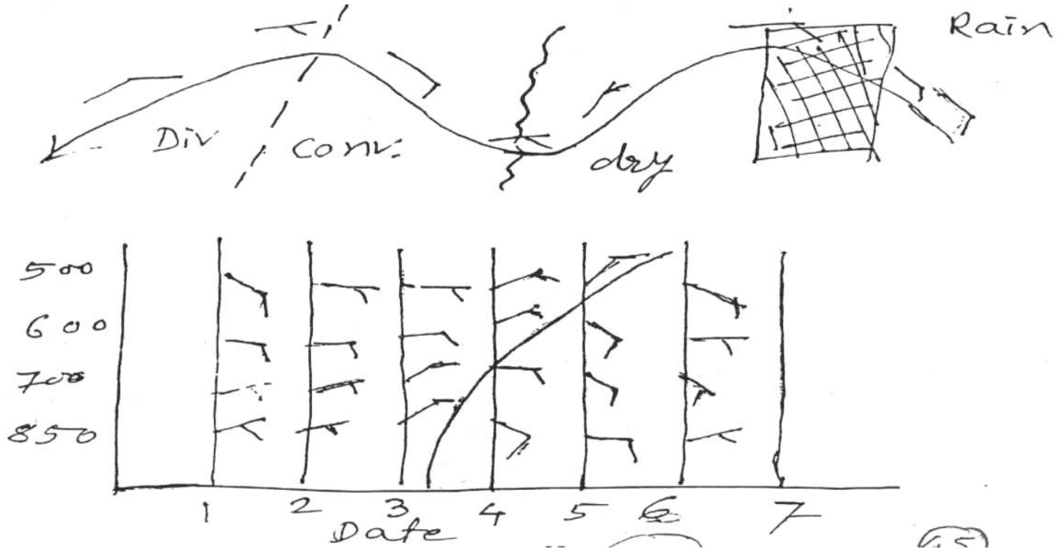
- As Coastal configuration i.e. concave or convex and
- Estuaries i.e. area where the river waters enters the sea coast.
- Time at which storm crosses the coast i.e. the position of the Astronomical tide high or low tide.

EASTERLY WAVES

Waves in easterlies are a weak tropical disturbance which is moving from east to west. They are first studied in West Atlantic initially by Dunnand then by Reihl. They are generally observed over nothern parts of Atlantic, middle parts of Pacific over Indian Seas and then westwards upto Aftrican countries. They are mainly seen in the lower latitudes. Over Indian seas, they are predominent in the winter season. These waves can be indentified with the help of Vertical Time Section chart. As the wave moves, cloudiness and the precipitation belt also moves westwards.

Some of the characteristics of easterly waves are :

1. As the waves approaches the station, the winds are before approaching easterly then first norheasterlies area of the trough and at a trough easterly winds and behind the tough south-easterly winds present and then again easterly.
2. These waves are noticed between 850 to 500 hPa level and its maximum intensity is observed at 600 hPa.
3. The wave tilt eastwards with height. This tilt is governed by the temperature. To the east of the wave, the temperatures are slightly colder then the west. Behind the wave warm air is seen in the lower troposphere and cold air is seen in middle and upper troposphere.
4. The wave generally moves in a WNW direction with a average speed of 10 to 15 kts (13 kts).
5. The wave is associated with rise and fall of pressure and temperature. Ahead of the wave trough, pressure rises and at the trough the pressure fall is maximum over station, and behind the trough again pressure will rise. Ahead of wave, pressure and temperature fall is there and behind wave, pressure and rise of pressure and temperature is there.
6. Approximate wavelength is about 2000 kms.
7. Ahead of trough, divergence is there and behind the trough, convergence is there and it is associated with intense convective activity, chance of thunderstorms, squalls. As we move away from trough line, this weather decreases.



Jet Streams – WMO definition of Jet stream, different jet streams around the globe, Jet streams and weather.

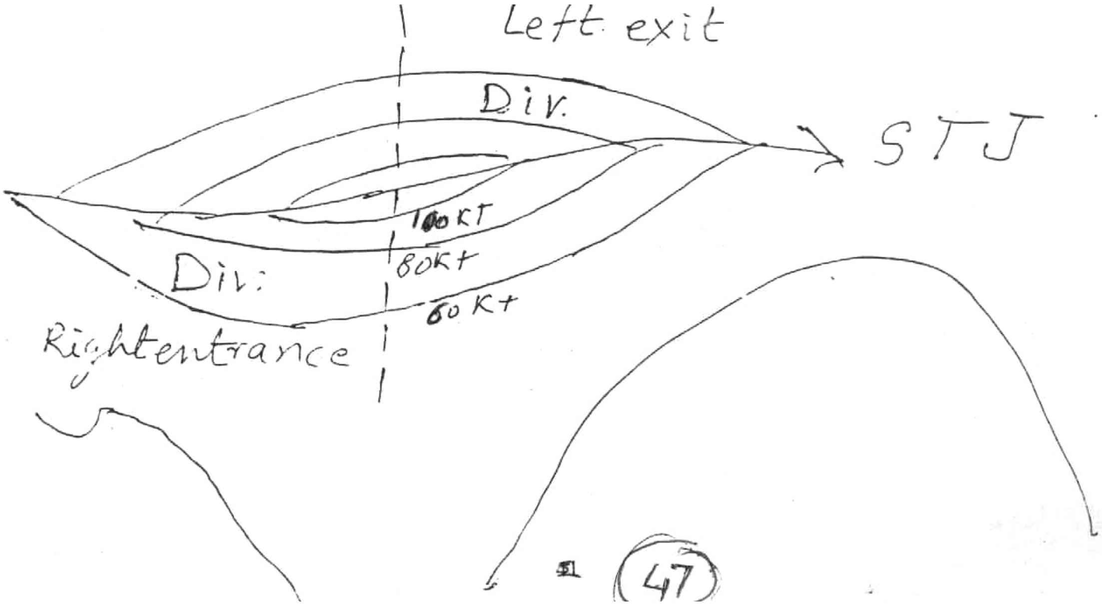
SUB-TROPICAL WESTERLY JET STREAM

WMO recommended definition of the **Jet Stream** " *A jet stream is a strong narrow current concentrated along a quasi-horizontal axis in the upper troposphere or in the stratosphere characterised by strong vertical and lateral wind shears and featuring one or more velocity maxima."*

Normally jet stream is thousands of kms in length, hundreds of kms in width and some kms in depth. The vertical wind shear is of the order of 5 to 10 mps per km and the lateral wind shear is of the order of 5 mps per 100 km.

Some of the chief characteristics associated with the westerly Jet Stream are :

1. The mean position of Jet over Indian sub-continent is at 27^{0} N at height of about 12 Kms (200 hPa)
2. There is a down stream strengthening of the wind speeds in Jet stream. This is from Jodhpur to Gauhati across the country. The Jet continues further north-eastwards across China and Japan with core speeds increasing progressively reaching maximum over south Japan (200 hPa).
3. The STWJ lies entirely within the tropical troposphere about 3-4 Kms below the tropical tropopause. The Jet is in the region of a break in tropopause between the tropical tropopause (near 100 hPa) and the middle tropopause (near 200 -250 hPa)
4. The jet is caused by the concentration of the horizontal temperature gradient below the jet level and the reversal of the gradient above the jet level at and near the jet level the temperature gradient is very small or zero.
5. Sub-tropical jet is very steady phenomenon and can be seen daily on the charts. At more or less same position and can occur in mean charts also.
6. STJ is located near the poleward boundary of the Hadley cell.
7. Deep troughs in westerlies and active WD across India shifts the jet south of the normal position where as a pronounced ridge is present jet will shifts northwards of its normal position.
8. Generally jet stream over India is associated with clear weather but on some occasions there is cloudiness and rainfall.
9. Associated with the high speed centres along a jet axis we have upper air divergence in the left exit and right entrance sectors caused by the advection of positive vorticity. If any low pressure system in lower levels (over north and central India) is observed below these areas then there will be well marked weather and thunder storm activity.



It is a large scale feature of the upper air circulation. It is a high speed core which can be distinguished from the general wind current sub tropical westerly jet stream is a phenomenon seen in the mid latitude westerlies over the entire Globe both in southern and northern hemisphere.

OTHER JET STREAMS

1.Polar front jet stream :

In addition to sub-tropical westerly jet stream, we have got polar front jet stream which can be located on the daily charts. It appears just below the tropopause almost directly above the 500 hPa position of the polar front. It can be seen at about 400 or 300 hPa level. The latitudinal position of the polar front jet stream varies considerably on the daily charts. It moves equatorwards and polewards generally between latitudes 40^0 N and 70^0 N. The mean position varies with the season. This jet is located at the poleward boundary of the Ferrel cell of general circulation.

The other two jet streams occurring in SW monsoon season we have already seen.

1. Low level jet (on surface)

2. Tropical easterly jet (at 100 hPa level)

- **Meso-scale meteorology, sea and land breezes, mountain/valley winds, mountain wave.**
- **Short range weather forecasting (Elementary ideas only); persistence, climatology and steering methods, movement and development of synoptic scale systems; Analogue techniques- prediction of individual weather elements and their variations, etc.**

Mesoscale meteorology:

It involves the study of weather systems smaller than synoptic scale systems but larger than micro scale systems. Horizontal dimensions generally range from around 5 kilometers to several hundred kilometers. Examples of mesoscale weather systems are sea breezes, squall lines, and mesoscale convective complexes.

Vertical velocity often equals or exceeds horizontal velocities in mesoscale meteorological systems due to non-hydrostatic processes such as buoyant acceleration of a rising thermal or acceleration through a narrow mountain pass.

Sea breeze and Land breeze:

Sea-breeze (or **onshore breeze**) is a wind from the sea that develops over land near coasts. It is formed by increasing temperature differences between the land and water. These create a pressure minimum over the land due to its relative warmth, and forces higher pressure, cooler air from the sea to move inland. Generally, air temperature gets cooler relative to nearby locations as one move closer to a large body of water. The cold air from the sea meets the warmer air from the land and creates cumulus clouds. If the air is humid and unstable, cumulonimbus clouds may form and can sometimes trigger thunderstorms. If the flow aloft is aligned with the direction of the sea breeze, places experiencing the sea breeze passage will be benign, or fair, weather for the remainder of the day. At the warm air continues to flow upward and cold air continually moves in to replace it and so the bteeze moves progressively inland. Its speed depends on whether it is assisted or hampered by the prevailing wind, and the strength of the thermal contrast between land and sea. At night, the sea-breeze usually changes to a land breeze, due to a reversal of the same mechanisms.

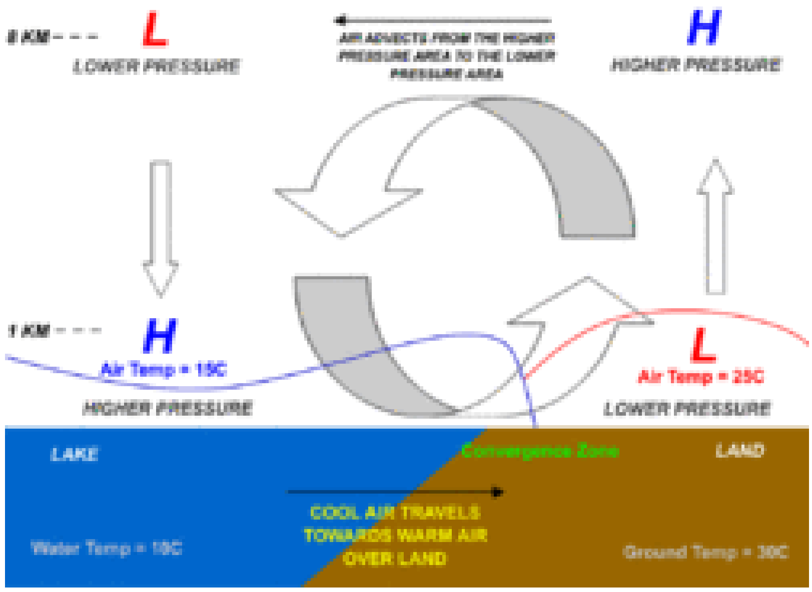
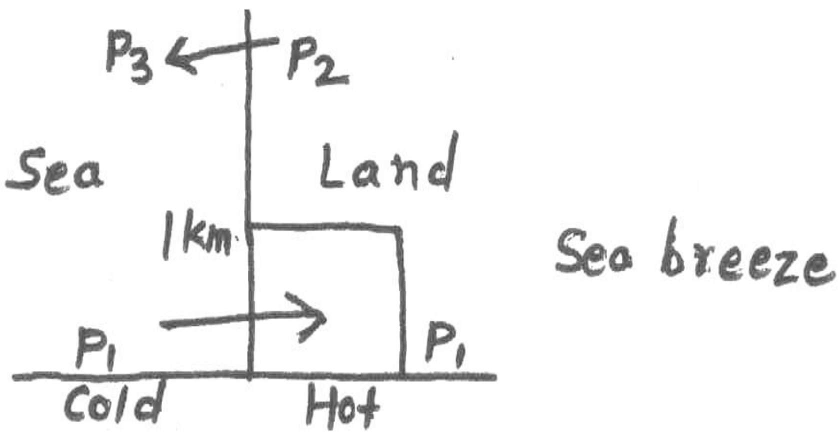


Fig- Lake - Sea breeze and atmospheric depth

At night, the land cools faster than the ocean due to the differences in their capacity of absorbing the heat capacity. This results the decaying / dissipation of the day time sea breeze. The land temperature cools faster than the adjacent sea surface temperatures. Hence, the pressure over the water will be lower than that of the land, setting up a land breeze as long as the environmental surface wind pattern is not strong enough to oppose it. If there is sufficient moisture and instability available, the land breeze can cause showers or even thunderstorms, over the ocean/water. Overnight thunderstorm development offshore due to the land breeze can be a good predictor for the activity on land the following day. This is mainly because the strength of the land breeze is weaker than the sea breeze. This land breeze may die, once the land starts warming up again the next morning. This is the most important diurnal effect which is a feature of the coastal area.

The mechanism of forming of land and sea breezes may be explained using the following figure. As we know sea breeze blows during day time and the land breeze blows during night time. Pressures over land and sea are same in the morning at about 00 or 03 Z. Afterwards the land gets more heated and the sea gets less heated. The air over land in lower levels also gets heated. Hot air is lighter. At 1 km to 1.5 km level above the land pressure is P_2 and on sea pressure is P_3 such that $P_2 > P_3$. Thus the pressure gradient is created. The air at about 1 to 1.5 kms above tries to go to sea i.e. air is removed from land at higher level and the low pressure is created over land surface and air from sea goes to land at lower level at 1 or 1.5 kms above air from land goes to sea. This is a sea breeze effect. Towards evening sea breeze effect goes on reducing and it will stop. Then during night land becomes colder than sea. The sea surface will be relatively hotter and there will be land breeze effect i.e. in lower levels the air will blow from land to sea and at 1 or 1.5 km above the flow of air will be from sea to land. Solar heating is the main reason for this land and sea breeze.



In tropics this effect is present almost for the entire year and the associated wind speeds are strong. In extra-tropics or temperate latitudes the effect is very less.

Normally sea breeze effect is stronger at about 10 to 20 kms. than the land breeze at about 5 to 10 kms. Sea breeze is effective upto about 1.5 kms. level. As there is a friction near the ground the winds little above the ground are stronger. Initially the winds are just from High to Low after the air just start moving the Coriolis force come into the picture. Thus the initial W - E winds will become more N - S one and the winds will be more parallel to the coast. Thus the sea breeze winds cannot penetrate inside the land area more they will penetrate hardly 50 kms in the temperate latitudes but in tropics they can penetrate upto about 200 kms. The main reason is value of Coriolis force is less in the tropics than in the extra-tropics. The difference between temperatures of land and sea is less during day time than during the night time. But during day because of heating little convection or vertical motion is there and during night no such mechanism is present. Thus the sea breeze is strong than the land breeze.

During dry days sea breeze is more for ex. Dry day - clear day in summer - land is hot and dry and sea is cold and moist. Thus as the sea breeze starts drop in temperature and the in increase in humidity will be observed. If the sea breeze starts early temperature decrease will be there but if it does not start early then the temperatures will be high and then it will be very uncomfortable then the human discomfort comes in to the picture. Autographic charts are very useful to study these breezes.

During winter season the winds are NE at Mumbai, unless the sea breeze is strong we will not feel the sea breeze at Mumbai. Due to this breeze a sort of wind discontinuity will form. This discontinuity will move inland during the day and towards the sea during night. If the air cover land is not stable the sea breeze will bring the moisture it will become moist then convergence and the air Cb cloud formation will be there and heavy showers during day time. For e.g. this can happen during summer over east coast.

Mountain waves

In meteorology, the most common form of **mountain waves are lee waves** which are are atmospheric standing waves. These may also be referred as atmospheric internal gravity waves. They were discovered back in 1933 by two German glider pilots, ***Hans Deutschmann and Wolf Hirth***. These waves are the periodic changes of atmospheric pressure, temperature and heights above mean sea level in a current of air caused by vertical displacement, for example orographic lift when the wind blows over a mountain or mountain range. They can also be caused by the surface wind blowing over an escarpment or plateau, or even by upper winds deflected over a thermal updraft or cloud street.

The vertical motion forces periodic changes in speed and direction of the air within this air current. They always occur in groups on the lee side of the terrain that triggers them. Usually a turbulent vortex, with its axis of rotation parallel to the mountain range, is generated around the first trough is called a **rotor**. The strongest lee waves are produced when the lapse rate shows a stable layer above the obstruction, with an unstable layer above and below.

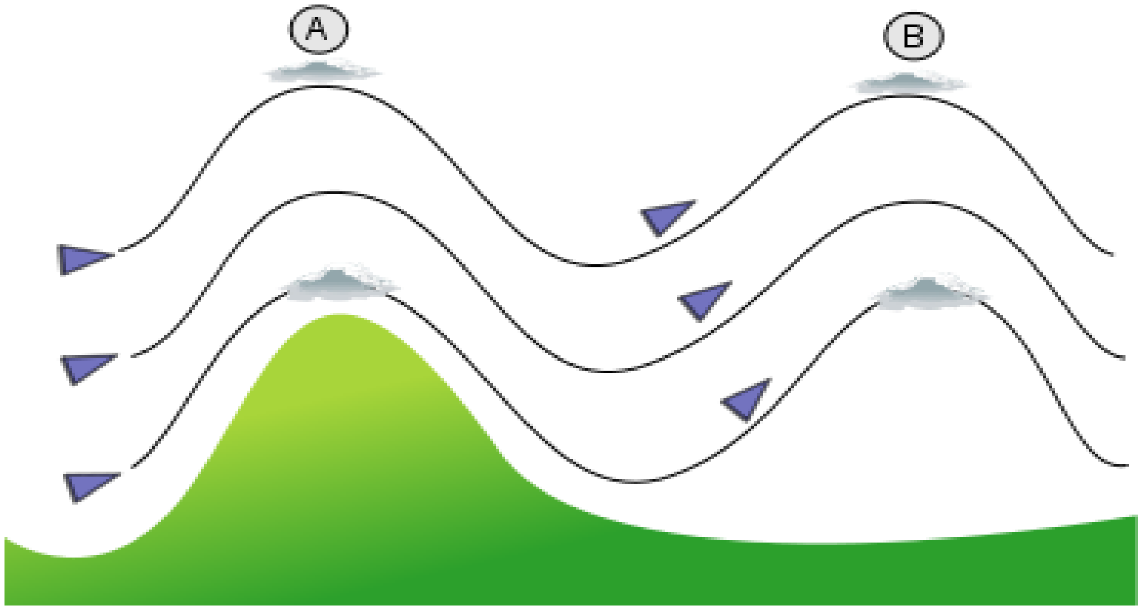


Fig- ***Mountain Wave*** [The wind flows towards a mountain and produces a first oscillation (A). A second wave occurs farther and higher with lenticular clouds (a very smooth, round or oval, lens-shaped cloud that is often seen, singly or stacked in groups, near a mountain ridge) stuck on top of the flow (B). This configuration is used to access high altitudes with gliders.]

Weather forecasting

Depending upon the validity period the weather forecasting can be classified into the following categories:

Short Range Forecasting (SRF)	**< 3 days**
Medium Range Forecasting (MRF)	**3-10 days**
Extended Range Forecasting (ERF)	**11-30 days**
Long Range Forecasting (LRF)	**> 30 days**

Forecasting of SRF:

Different charts and techniques as given below ***are considered as the basic tools used for SRF***:

Surface Chart, Change Chart, Pilot Chart, Constant Pressure Chart, Vertical Time Section Chart, T-Φ grams, Satellite Cloud Pictures Radar Pictures.

Synoptic techniques used for forecastingof movement of a system

With the help of the following methods the forecaster can predict the movement of synoptic scale systems.

1) Climatology
2) Persistence,
3) Analogue
4) Steering concept
5) Numerical Methods
6) Pressure changes

Climatology

In the initial stages of T.C the climatoloical information is the best source for the prediction of movement of T.C. Based upon the data of more than 100 years for every 2 ½ square of Lat/Lon rid percentage frequency of direction and speed of movement is available for both the Bay of Bengal and the Arabian Sea.

Based upon this the forecaster can give the forecast about the movement of T.C But the climatological method has got its own disadvantages as we know very well that the system/rainfall need not follow past climatology.

Persistence

The concept of persistence arises under the assumption that the past and the existing flow will continue to be same. The previous direction and speed of motion are used for predicting the movement of the cyclone.

In certain cases people give half weightage to climatology and half weightage to persistence track and evaluate the direction of movement and forecast the movement.

Analogue

In this method a cyclonic storm in the past which has developed around the same area and around the same period of month is selected as a analogue cyclone and predicted that the present cyclone will also move as per the track of analog cyclone. Based upon the above three methods. Some methods are developed by giving equal weightage to climatology, persistence, and Analogue

Steering concept

Steering concept is based on the thought that the T.C moves as per the direction of flow of basic current in which it is embedded.

However, where the data over the T.C region is available, generally the average winds at various levels are computed and the average wind for the entire troposphere is computed by giving less weightage to lower and middle tropospheric levels and more weightage to the upper tropospheric levels. It is expected that T.C will move as per that average wind direction and speed.

Over Indian region we consider that the level as a steering level from which the cyclonic circulation of TC is not seen, the TC will move as per the wind direction and speed in that level. Generally for Indian seas 200 hPa is the steering level for the Tropical cyclones. If the winds in this level are E'ly then the T.C will move westwards, and if it is SE'ly then the T.C will move north westerly direction. Similarly, if it is S'ly then it may turn to northwards.

Numerical method:

Based upon the various NWP methods numbers of model have been developed for forecasting the flow pattern for next 24, 48, 72 and 96 hours. With the help of a comprehensive NWP model it is now possible to predict the movement of storm with the moderate accuracy.

Pressure changes in 24 hours

In addition to all above methods the 24 hrs pressure change will give very crucial indication information about the movement of cyclonic storm, when the C.S comes nearer to coastal area where the pressure changes (-ve) are more the TC is expected to move in that direction. Sometimes the surface position of the storm may be directly below the COL region in the upper tropospheric flow pattern. A COL region, as explained in preceding sections, is an area enclosed between two anticyclones (a high pressure cell) to the east and west and two troughs one to the north in westerlies and one to the south in easterlies. Under such conditions the storm movement is very slow or even stationery some times. This continuous till one of the ridge or trough becomes active relative to the others so that it can steer the storm. Whenever a storm is likely to change its course its speed generally decreases

Diurnal and Local effects

All the weather parameters pressure, temperature etc. change due to synoptic systems. But these parameters change without having any system also and these changes will occur mainly due to the solar radiation which is a most important factor which controls the weather. The changes which occur regularly without any synoptic system are called as the diurnal changes they will occur due to solar radiation due to presence or absence of sun. The local changes will occur due to mainly topography of the station. Diurnal changes affect practically all the parameters. Some most important parameters are.

1) Pressure 2) Wind 3) Cloud and weather (Rainfall) 4) Temperature.

Thus for issuing the local forecast for short range duration one has to take into account these elements and the also the time of issuing the forecast.

Pressure - Diurnal Variation:

Diurnal variation of pressure is very important. It has got double maxima (10 hrs. and 22 hrs. local time) and double minima (04 hrs. and 1600 hrs. local time.) Diurnal change of pressure is more marked in tropics. As we move towards northern latitudes this variation becomes less and less. Near equator it is of the order of 3 hPa and 45 deg. N it is 1 hPa. Thus in the tropics the variation of pressure is more important. On 12 GMT synoptic charts (local time is about 1730) low pressure systems are more marked. If a system is approaching station on 12 Z chart fall of pressure may be due to the system approaching station or due to the diurnal variation of the pressure. Sometimes when a depression is close to the coast then on 12 Z chart due to low pressures the disturbance could be appeared that it has crossed coast but again on next day morning chart it can be over sea. Thus on the basis of 12 Z chart only, it cannot be said that the depression has crossed the coast.

Clouds and Weather (Convective type) - Diurnal Variation:

Diurnal variation of convective clouds and convective type of weather is more or less common in tropical areas and this is just like diurnal variation of temperature which is having minimum in morning and maximum in evening. This variation is more marked on land. Morning hours are clear i.e. cloud free, however towards afternoon hrs. i.e. about 1000 to 1100 hrs. (Local time) clouds start developing and large and huge clouds may develop towards evening leading to some possibility of thunder storm occurrence before sunset. After the sunset, clouds may disappear.

Although over the sea areas the variation of clouds is reverse. During night time there is more possibility of development of clouds and occurrence of rainfall.

Variation of Rainfall: Due to effect of Orography there may be some local variation in the rainfall. Over mountains there are heavier amounts of rainfall than over the land areas. For example the Western Ghats in Maharashtra during monsoon season, especially in the month of July and August, experiences heavy to very heavy amounts of rainfall.

Over these Ghats rainfall is maximum, near the coast slightly less but on the lee ward side of Ghats the rainfall goes on decreasing. Lee side is called as the rain shadow area. Ex. Mahabaleshwar - Max. rain, Mumbai - slightly less and Pune - much less rainfall. This type of effect is also observed over Khashi hills in Meghalaya where Cherrapunji and Mawsynram receive maximum rainfall. However, over the very high mountains like Himalayas, the rainfall increases only upto certain limits and later on it decreases due to high altitudes cold temperatures reducing the capacity of atmosphere to contain/absorb moisture.

References:

1) P. K. Das : Monsoon
2) C.S. Ramage : Monsoon meteorology
3) H. Riehl : Tropical Meteorology
4) E. Palmen & C.W. Newton : Atmospheric Circulation Systems
5) Y. P. Rao : Southwest Monsoon. Met. Monograph Synop. Met. No. 1/76
6) Tropical Meteorology (Vol- I,II,III)- By G.C.Asnani
7) WMO compendium of lecture notes on meteorology (Vol. II)