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Decadal variations of Hadley and Walker circulations in the tropics

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सार - उष्णकटिबंध में अंतःदशकीय परिवर्तनों से संबद्ध हेडले और वॉकर अपसारी परिसंचरण का 50 वर्षीय पुनः विश्लेषित ऑकड़ों से प्रारम्भिक आकलन किया गया है और उनकी तुलना इसी तरह के अंतःवार्षिक ऑकड़ों के साथ की गई है। हार्मोनिक विश्लेषण का उपयोग करते हुए अंतःदशकीय और अंतःवार्षिक घटकों को पृथक किया गया है तथा हेडले और वॉकर परिसंचरण की प्रबलता का आकलन करने के लिए रेखांशिक और क्षेत्रीय द्रव्यमान अभिवाह धारा क्रियाओं का उपयोग किया गया है। हेडले और वॉकर परिसंचरण अंतःदशकीय असंगतियों के परिमाण की प्रमुख अंतःवार्षिक परिवर्तनों से संबद्ध असंगतियों से तुलना की जा सकती है। क्षेत्रीय जलवायु को अंतःदशकीय और अंतःवार्षिक अपसारी परिसंचरण की सर्वाधिक प्रबलता किस प्रकार से प्रभावित करती है इसके बारे में इस शोध पत्र मे चर्चा की गई है।

ABSTRACT. Preliminary estimate of divergent Hadley and Walker circulation associated with inter-decadal variations in the tropics is made with 50-year reanalysis data and compared with their inter-annual counterparts. Inter-decadal and inter-annual components are seperated using harmonic analysis and meridional and zonal mass flux stream functions are used to calculate the strength of Hadley and Walker circulations. The magnitude of inter-decadal Hadley and Walker circulation anomalies are shown to be comparable to those associated with dominant inter-annual variations. How superposition of inter-decadal and inter-annual divergent circulations may influence regional climate is discussed.

Key words – Hadley circulation, Walker circulation, Inter-annual variability, Tropical precipitation zone, El-Nino, La-Nina.

1. Introduction

The climate in the tropics is affected by several important inter-annual and decadal - multi decadal variations. While spatio-temporal structure of the inter-annual variations such as the El Nino and Southern Oscillation (ENSO) is well documented (Philander, 1990; Wallace *et al.*, 1988), the decadal - multi decadal oscillations have so far been studied mainly with surface data (Kripalani and Kulkarni, 1997; Parthasarathy *et al.*, 1993; Allan, 1993; Allan *et al.*, 1995; Kachi and Nitta, 1997; Zhang *et al.*, 1997). This is partly due to non-availability of coherent global upper air data for a sufficiently long period of time to decipher the three dimensional structure of the decadal - multi decadal oscillations. The upper air analyses available from operational weather prediction centers archived from early seventies suffered from climate jumps introduced artificially by the changes in the prediction model and data assimilation system.

The ascending and descending branches of the Walker and the Hadley circulations determine the climate of various tropical regions. Hence, variations (in strength and/or in location) of the ascending the descending branches of the Walker and Hadley circulations influence climate variability in the tropics. To understand how the decadal - multi decadal oscillations modulate tropical climate, a clear idea of the nature of variability of the Walker and Hadley circulations associated with the observed decadal - multi decadal oscillations is essential. It requires knowledge of the three dimensional structure of these circulations associated with the decadal - multi decadal oscillations. The primary objective of the present study is to obtain quantitative measure of variations of the Walker and Hadley circulations on decadal - multi decadal time scales and compare them with those on inter-annual time scale. The mass flux stream function is used as a measure of the intensity of Hadley and Walker circulations in this study.

Some recent studies have addressed the inter-annual variations of the Hadley and Walker circulations. For example, Oort and Yienger (1996) used 26 - year daily upper air observations between 1964 and 1989 and calculated inter-annual variations of mass fluxes associated with the Hadley circulation. Due to lack of consistent global upper air data for a sufficiently long time, studies on the spatial structure of the decadal-multi decadal circulation were not feasible so far. With the availability of 50-year reanalyzed data from the NCEP/NCAR reanalysis project, a homogeneous set of upper air data is now available to investigate the three dimensional structure of these modes. In the present study, we make use of the upper air data at 12 vertical levels and by separating the decadal - multi decadal component from the inter-annual component we bring out the three dimensional structure of these circulations. The structure of the Walker and Hadley circulation associated with the dominant decadal modes are constructed and compared with their inter-annual counterparts to understand how the climate in different parts of the tropics is governed by the superposition of the decadal and inter-annual Walker and Hadley circulations.

2. Data and Method of Analysis

The circulation data used in this study are the products of NCEP/NCAR reanalysis project [see Kalnay *et al.*, 1996 for detail] that is based on a frozen state-of-the-art global data assimilation system that includes a forecast model with T62 horizontal resolution and a data base as complete as posssible. The reanalysed data is expected to be devoid of any artificial climate jumps as the analysis system and the forecast model remain unchanged throughout the analysis period. Monthly mean zonal and meridional winds and vertical pressure velocity at 1000 hPa, 925 hPa, 850 hPa, 700 hPa, 600 hPa, 500 hPa, 400 hPa, 300 hPa, 250 hPa, 200 hPa, 150 hPa and 100 hPa were obtained for the period January 1949 to December 1998. The monsoon variability, represented by the all India Monsoon Rainfall (IMR), is based on June to September rainfall observations at 306 land stations uniformly distributed over India (Parthasarathy *et al.*, 1994). The original time series published by Parthasarathy *et al.*, (1994) has been updated for the recent years to cover the peirod 1949-1998.

The sea surface temperature data is taken from the Comprehensive Ocean Atmosphere Data Set (COADS, Woodruff *et al.*, 1987) for the period 1949 to 1989. For the period 1989 to 1998 the SST data is taken from the Optimum Interpolation SST (OISST) data set (Reynolds and Smith, 1994). Both data sets are of 2 degrees latitude by 2 degrees longitude resolution. Climatological SST is calculated separately for the COADS and OISST and monthly anomalies are calculated with respect to their individual climatologies. Then the anomalies of the two data sets are merged to obtain anomaly data set from 1949 to 1998. Monthly anomalies of the circulation data are also calculated by removing the climatological annual cycle. The decadal-multi decadal variations are separated from inter-annual and higher frequency variations using a harmonic analysis. The inter-annual and higher frequency variations are reconstructed from all the modes with period less than 7 years while the decadal - multi decadal oscillations are reconstructed from all the modes with period larger than 7 years. The decadal/multi-decadal component separated this way is also referred to as low pass filtered (LF) field while the inter-annual component is referred to as 'residual' field.

2.1. *Mass flux stream function - Ψ :Hadley circulation*

To estimate the monthly variations in the intensity of the Hadley circulation, the mass flux stream function (Ψ) corresponding to mean meridional overturning is used. From the zonally averaged continuity equation, the mass flux stream function, Ψ may be given by the equations,

$$\left[\bar{v}\right]=\frac{g}{2\pi R\cos\phi}\frac{\partial\Psi}{\partial p} \tag{1}$$

$$\left[\bar{w}\right]=-\frac{g}{2\pi R^{2}\cos\phi}\frac{\partial\Psi}{\partial\phi} \tag{2}$$

where $\bar{v}$ is the monthly mean meridional velocity and [ ] represents the zonal mean, $\bar{w}$ is the monthly mean pressure vertical velocity, R is the mean radius of the earth, ϕ is the latitude and g is the acceleration due to gravity. Ψ is calculated by assuming Ψ=0 at the top of the atmosphere and integrating eqn (1) downward to the surface. It may be noted that positive (negative) latitudinal gradient of Ψ would correspond to negative (positive) [$\bar{w}$] or mean ascending (descending) motion. We use a positive sign for the stream function in the case of clockwise rotation and a negative sign for an anti-clockwise rotation as seen in the p-ϕ cross sections (Oort and Yienger, 1996).

The integration is carried out using the finite difference technique. The mass weighted vertical mean value $\int_{p_o}^{p}$ [$\bar{v}$]dp/p_o is found to be nearly zero, thus ensuring vertical mean mass balance. To calculate the mean meridional mass flux stream function Ψ, we need the zonal mean of $\bar{v}$. In the tropics, the $\bar{v}$ is fairly uniform and hence the zonal mean [$\bar{v}$] is quite reliable. However, in the extra tropics, [$\bar{v}$] is a statistical residual of large, almost compensating northward and southward $\bar{v}$. Near the jet - stream region, we find local $\bar{v}$ velocities of the order of 10-20 m/s whereas typical [$\bar{v}$] is of the

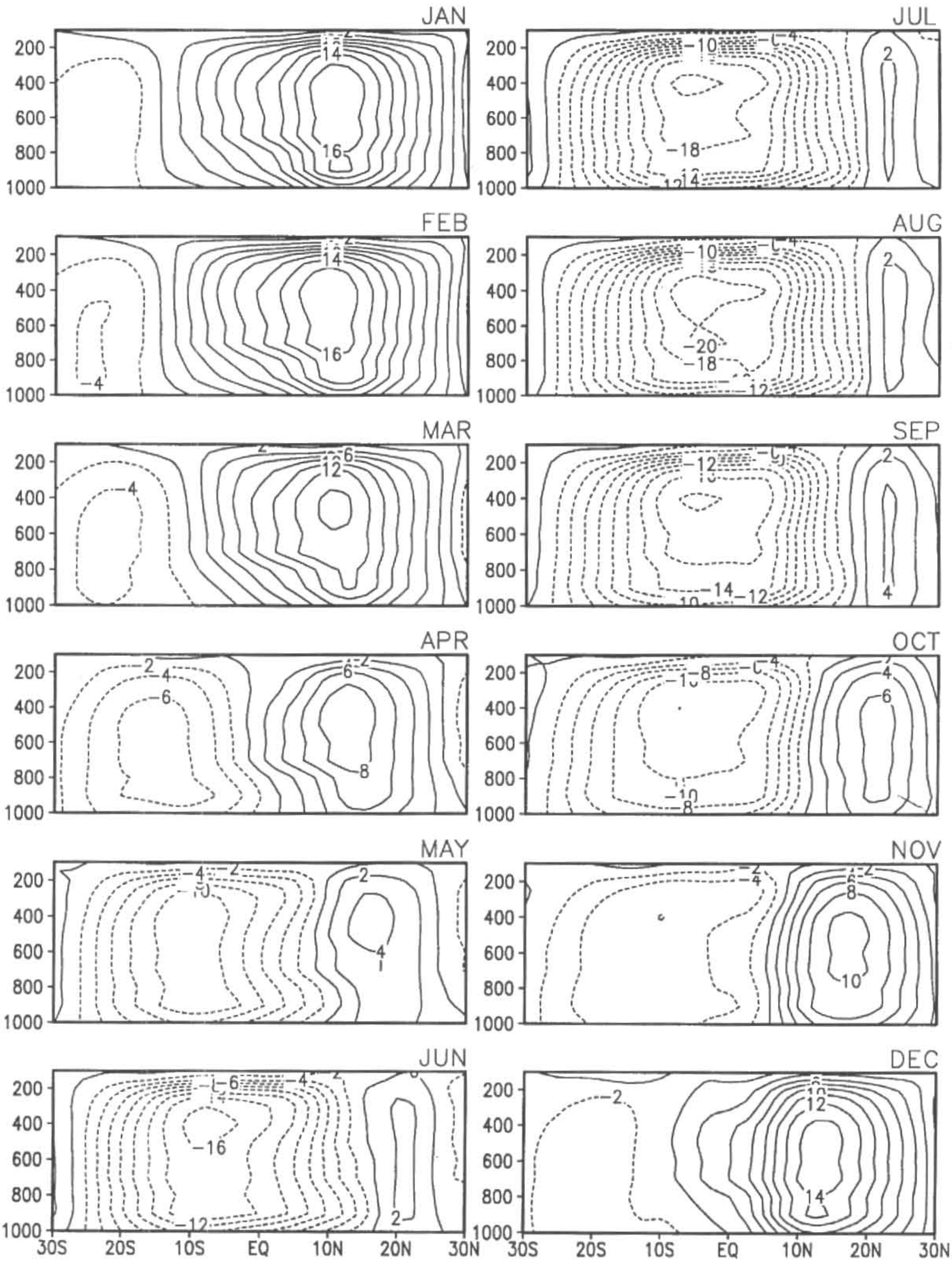
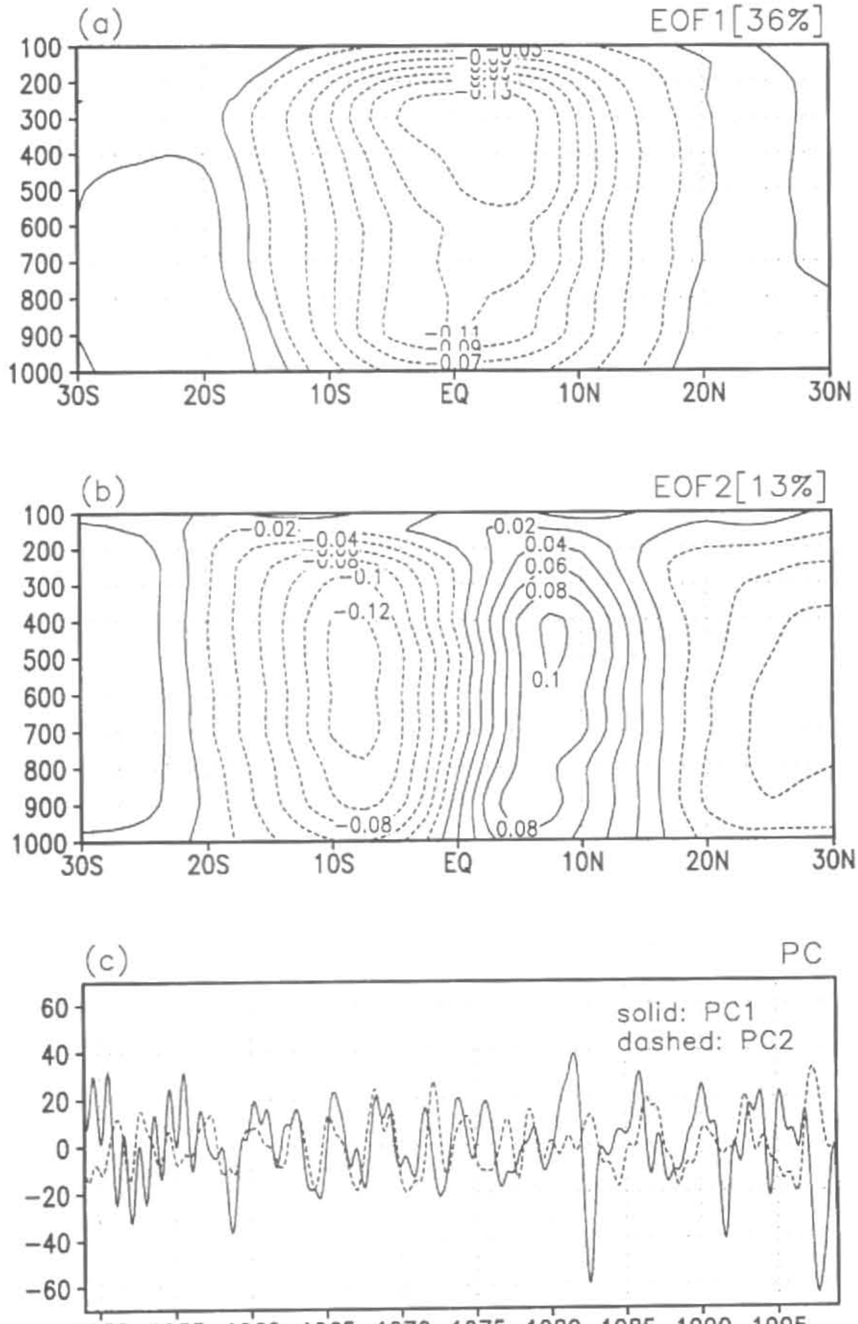


Fig. 1. Climatological mean annual cycle of meridional mass flux stream function (in 10^{10} kg/s)



Figs. 2 (a-c). (a) Spatial pattern of mass flux stream function of Hadley circulation associated with inter-annual EOF1. Units are arbitrary. (b) same as Fig. 2(a) but for EOF2. (c) The principal components (PC) for the two leading inter-annual EOFs of meridional mass flux stream function. Units are in 10^{10} kg/s. PC1 is represented by the solid line and PC2 by the dashed line

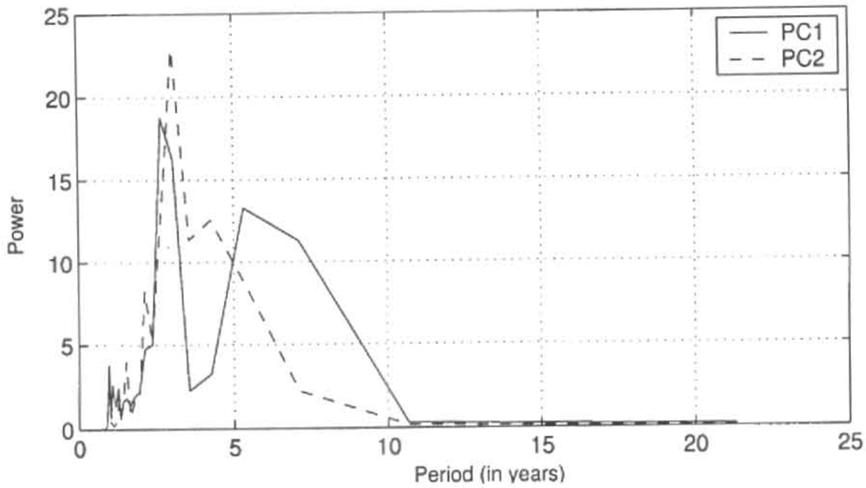


Fig. 3. Spectra of PC1 (solid) and PC2 (dashed) of the meridional mass flux stream function of the dominant inter-annual mode

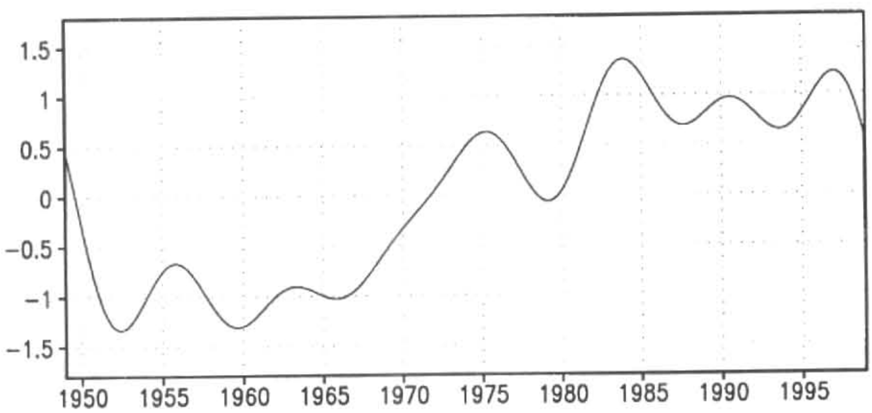


Fig. 4. An index of decadal variability of the Hadley circulation. Time series of the anomalous Hadley circulation index (Ψ_d) in 10^{10} kg/s for the period 1949-1998. (Ψ_d) is the vertically integrated decadal component of the meridional mass flux stream function averaged between 5°S and 5°N

order of 0.5 m/s. Therefore, the [$\bar{v}$] obtained from analyses (or for that matter from original rawinsonde data) may be influenced by sampling and instrumental errors and hence may not be reliable. Therefore, the reliability of the estimated Ψ is latitude dependent. In the tropics between 30°N and 30°S, Ψ is expected to be quite reliable. In the extra-tropics, while the sign may be correct, the magnitudes may not be reliable. Therefore, in most of our discussions we shall confine ourselves to the tropical Hadley circulation.

2.2. *Mass flux stream function - Ψ_ω : Walker circulation*

Walker circulation is the circulation in the equatorial vertical plane characterized by rising motions over the western equatorial Pacific and Indian Oceans and sinking motions over the eastern equatorial Pacific oceans. However, during the El Nino, anomalous warming over eastern equatorial Pacific and anomalous cooling over western equatorial Pacific makes the ascending branch over Indonesia and western Pacific to shift to central and eastern Pacific. To represent the strength of the Walker circulation, the mass flux stream function (Ψ_ω) is computed by vertically integrating the observed zonal winds, ($\bar{u}$) averaged over the equatorial belt between 5°S and 5°N.

$$\Psi_w = -\frac{R}{g}\int_0^p (\bar{u})dp \qquad (3)$$

The sign convention for Ψ_ω is fixed using the following consideration. Positive (negative) longitudinal gradient of Ψ_ω is assumed to be proportional to negative (positive) pressure vertical velocity or ascending (descending) motion.

Hadley and Walker circulations corresponding to decadal/multi-decadal variations are calculated using the LF fields while those corresponding to inter-annual variations are calculated from the 'residual' fields.

3. Results and Discussions

In this section we examine the climatological mean annual cycle of the meridional mass flux stream function. Further, the structure of the anomalous Hadley circulation associated with the dominant inter-decadal and inter-annual modes in the tropics are discussed.

3.1. *Hadley circulation : Climatological mean*

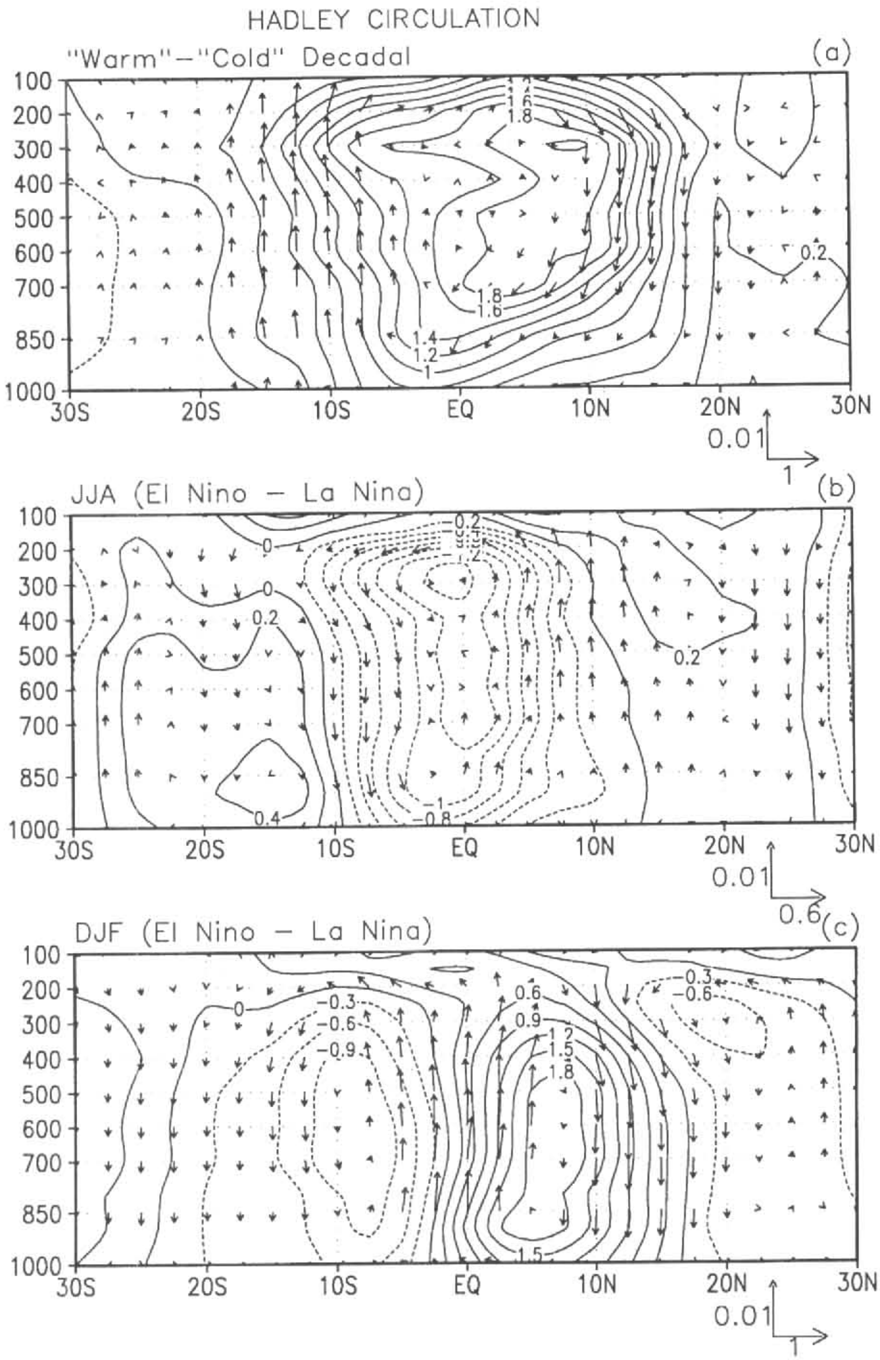
The climatological mean annual cycle of meridional mass flux stream function based on climatological mean [$\bar{v}$] (in 10^{10} kg/s) is shown in Fig. 1. This figure shows that the high values of stream function is observed during the peak winter time in both the hemispheres. In January, *i.e.*, during northern hemispheric (NH) winter, the NH Hadley cell is strong. The southern hemisphere (SH) Hadley cell develops with the approach of NH summer and reaches its peak in August. This seasonal cycle in the tropical Hadley cells is very similar to that found in the earlier studies (Oort and Yienger, 1996). The seasonal extreme values in Ψ are found in winter at around 8° latitude with maximum values of 17×10^{10} kg/s near the 500 hPa level in NH and 21×10^{10} kg/s near the 600 hPa level in SH. During NH winter, the SH Hadley cell is weak and Ψ is of the order of 1×10^{10} kg/s and in SH winter the NH Hadley cell is weak (2×10^{10} kg/s) around 20° latitude. It is rather interesting to note how the SH Hadley cell with its largest ascending motion around 10°S during January migrate northward establishing largest ascending motion around 10°N in July and retreating thereafter. This feature of the meridional stream function is essentially a result of the seasonal north-south shift of the tropical precipitation zone (TCZ).

3.2. *Hadley circulation : Inter-annual Variations*

To bring out the dominant modes on the inter-annual time scale, an empirical orthogonal function (EOF) analysis is carried out using inter-annual mass flux stream function field. The dominant EOFs and the principal components (PCs) associated with them are presented in Fig. 2. The first EOF explains about 36% of the total inter-annual variability and the second about 13%. The first EOF has a single cell with rising motion north of the equator and sinking motion south of the equator while the second EOF pattern shows a two-cell structure with positive stream function values north of the equator upto 20°N and south of 20°S and negative values south of the equator upto 20°S and north of 20°N. The time coefficients of the dominant EOFs (PCs) appear to be associated with the ENSO which is evident from the spectra of PC1 and PC2 shown in Fig. 3. Spectra of both the time series show a dominant periodicity of 3-4 years, corresponding to the periodicity of the ENSO.

3.3. *Hadley circulation : Decadal variations*

To study the dominant decadal mode of anomalous Hadley circulation, we calculate the meridional mass flux stream function (Ψ_d) associated with decadal variations from the LF anomalies. An index of decadal variability is defined as the stream function averaged over all levels and between 5°S and 5°N (Ψ_d). The time series thus obtained is shown in Fig. 4. Two distinct periods of opposite phases are evident from the figure with a major transition from a weak phase to strong phase around 1973. It may be noted that the decadal variation associated with the ENSO-like inter-decadal oscillation (Zhang *et al.*, 1997) has similar temporal variations. However, the major transition to warm phase of the ENSO-like inter-decadal oscillation obtained earlier mainly from surface data (Zhang *et al.*, 1997) takes place in 1976. It is possible that the inter-decadal variability of the Hadley circulation seen here is a combined effect of the ENSO-like inter-decadal variability and some other tropical decadal variability (*e.g.* Atlantic dipole variability). Taking this into account, 'warm' decadal composites have been constructed by taking five consecutive years average (1982-1987) during the warm phase and 'cold' decadal composites are constructed taking five year average (1962-1967) during the cold phase. The boreal winter (DJF) 'warm' minus 'cold' decadal composites are shown in Fig. 5(a). The wind vectors indicating the meridional circulation for these composites shown in the figure are constructed with pressure velocity (ω) taken with a negative sign and zonally averaged meridional winds. The mass flux stream



Figs. 5(a-c). (a) Boreal winter (DJF) decadal zonally averaged ('warm,'-'cold') composite Hadley circulation. Vector winds are constructed with pressure vertical velocity (taken with a negative sign) and meridional velocity. Unit vector for vertical velocities corresponds to 0.01 hPa/s. The contours represents the mass flux stream function associated with the composite in 10^{10} kg/s

(b) Boreal summer (JJA) (El Nino - La Nina) composite for the inter-annual mode. The El Nino and La Nina years used in generating this inter-annual composite are 1963, 1965, 1969, 1972, 1976, 1982, 1987, 1992, 1997 and 1964, 1968, 1971, 1973, 1983, 1988, 1996 respectively. Unit vector for vertical velocities corresponds to 0.01 hPa/s

(c) Same as in Fig. 5(b) but for boreal winter (DJF) (El Nino-La Nina) composite. Unit vector for vertical velocities corresponds to 0.01 hPa/s

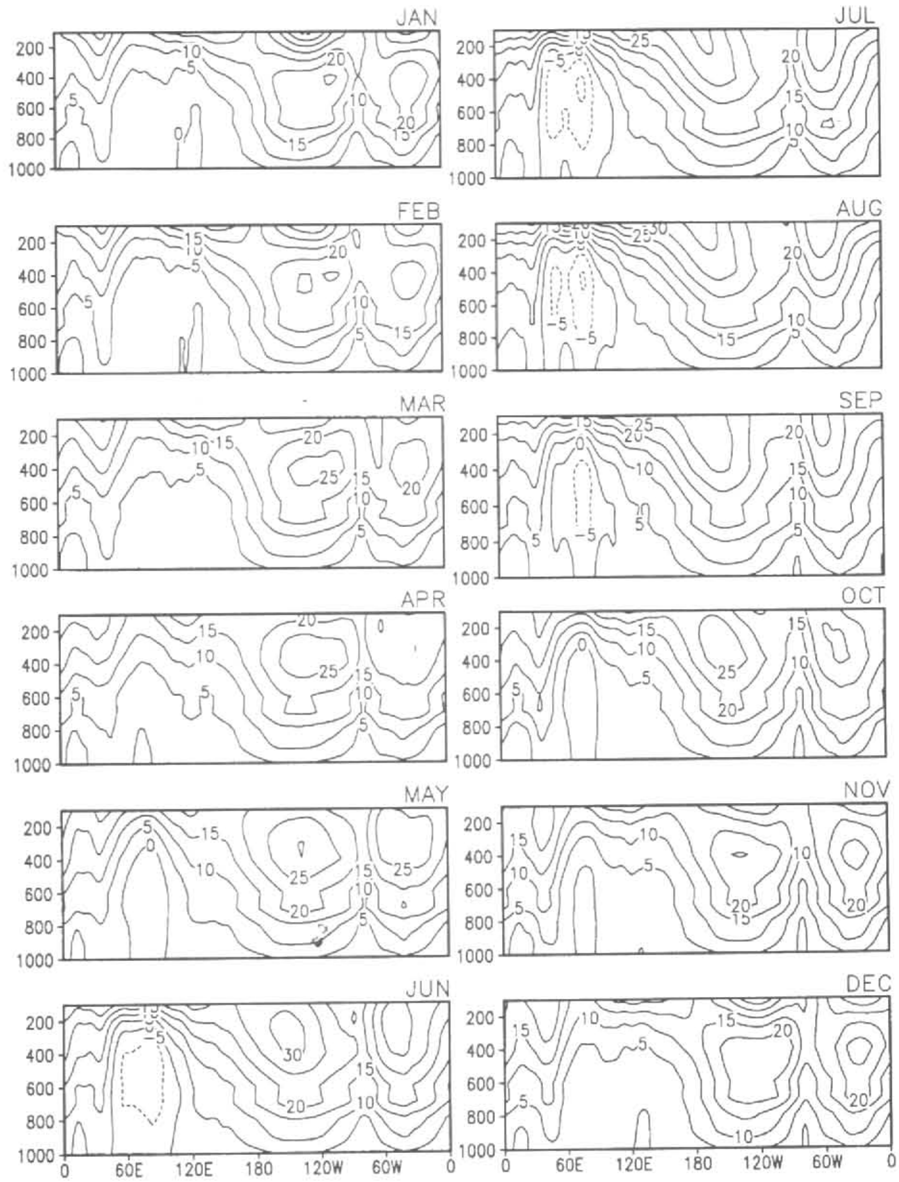
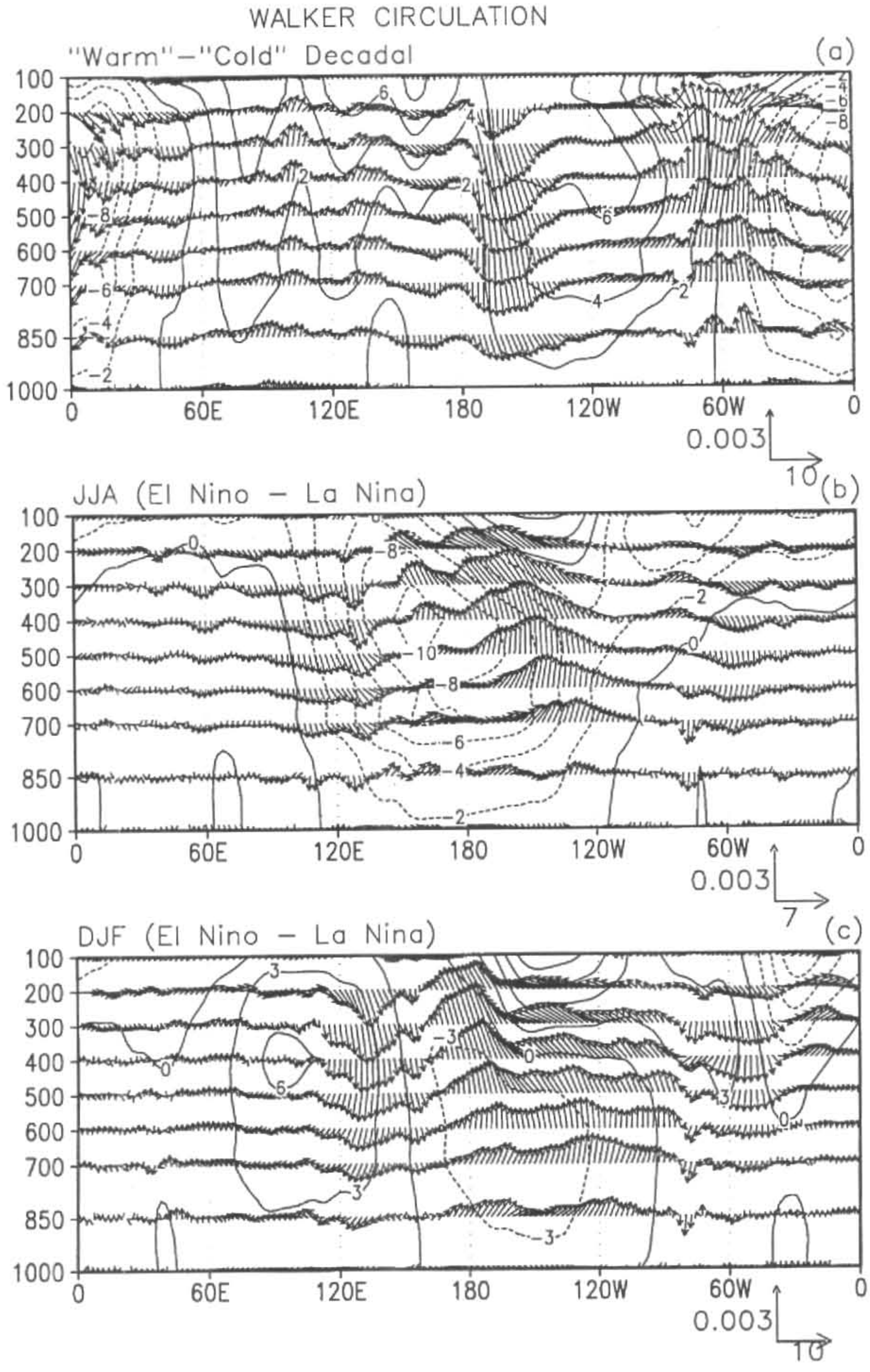


Fig. 6. Climatological mean annual cycle of Walker circulation mass flux stream function (in 10^{10} kg/s)

function (Ψ_d) associated with the circulation are represented by the contours. As our primary interest in the tropical Hadley circulation, we have confined ourselves to the region between 30°S and 30°N.

The anomalous Hadley circulations associated with the warm and cold decadal phases of inter-decadal oscillation are characterized by a single meridional cell but of opposite sign. During the warm phase of the oscillation, there is ascending motion between the equator and 20°S and descending motion between the equator and 20°N while during the cold phase, there is a reversal in the circulation. The intensity of Hadley cell, measured in terms of the mass flux stream function corresponding to 'warm-cold' decadal composite is shown in Fig. 5(a). The structure of the Hadley circulation anomalies associated with the decadal component Fig. 5(a) indicate that it is indeed possible to define an index of the decadal



Figs. 7(a-c). (a) DJF ('warm'-'cold') decadal composite anomalies averaged between 10°S and 10°N. Vector winds are constructed with pressure vertical velocity (taken with a negative sign) and zonal velocity. Unit vector for vertical velocities correspond to 0.003 hPa/s. The contours represent the mass flux stream function in 10^{10} kg/s

(b) Boreal summer (JJA) Walker circulation associated with the inter-annual mode. Same as in (a) but composite difference between El Nino and La Nina

(c) Same as in (b) but for boreal winter (DJF)

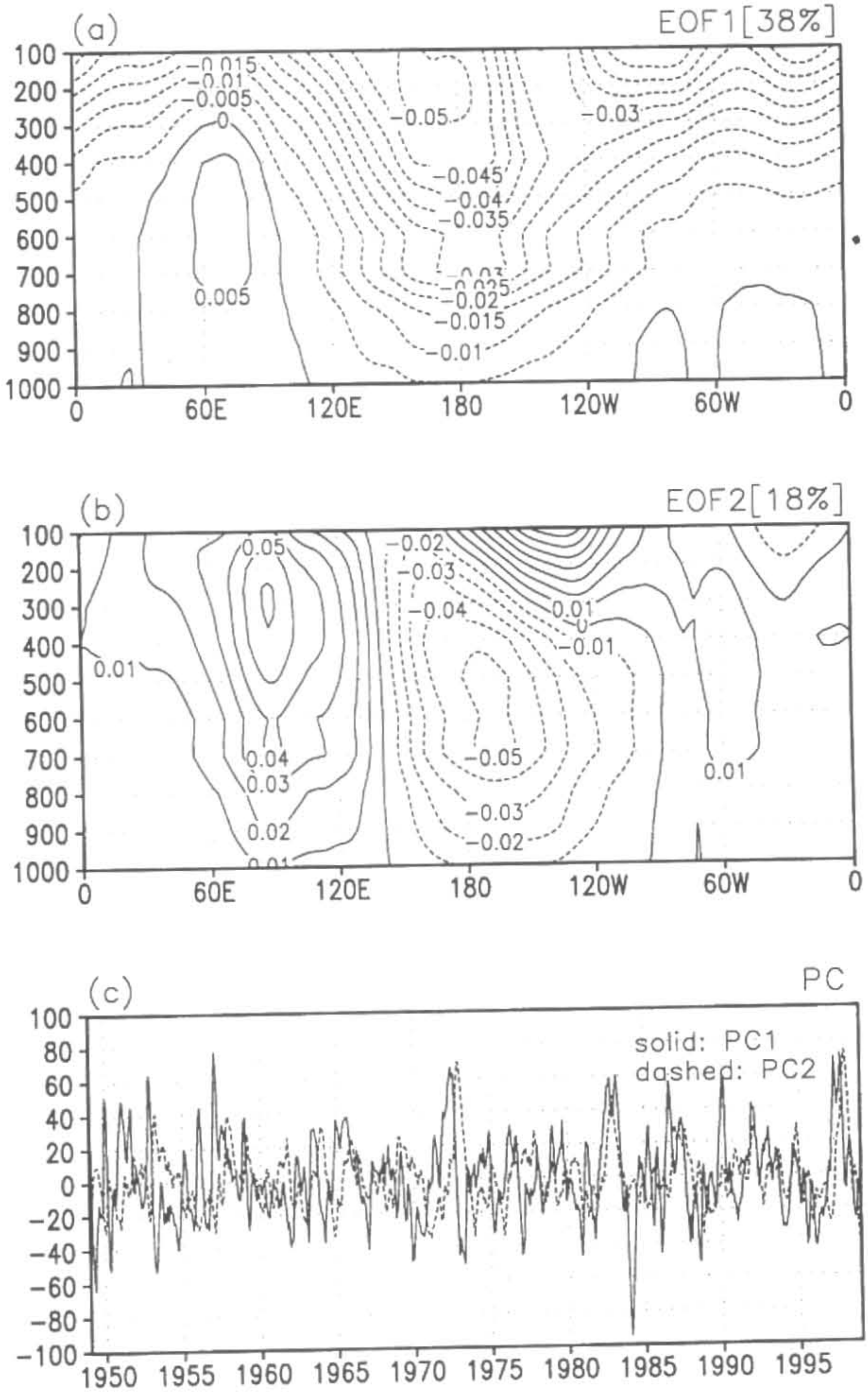


Fig. 8. Same as Fig. 4 but for mass flux stream function of Walker circulation

variations by averaging Ψ_d over the equatorial belt as we have done in Fig. 4.

To compare the anomalous Hadley circulation associated with the decadal/multi-decadal variation with that associated with the dominant inter-annual variations, boreal summer (JJA) and boreal winter (DJF) composite differences between El Nino and La Nina of anomalous inter-annual Hadley circulation are constructed and are shown in Figs. 5(b) and 5(c). The El Nino and La Nina, years used in generating this composite are 1963, 1965, 1969, 1972, 1976, 1982, 1987, 1992, 1997 and 1964, 1968, 1971, 1973, 1983, 1988, 1996 respectively. The boreal winter composite constitutes of two cells with rising motion around the equator and sinking motion between 10° and 20° latitude in both the hemispheres. A weak cell can be seen with ascent around 30°N and descent over 20°N. The NH Hadley cell 1.8×10^{10} kg/s is twice as strong as the SH Hadley cell (0.9×10^{10} kg/s). The boreal summer composite comprises of a single dominant cell (Ψ_H : 1.3×10^{10} kg/s) with rising motion north of the equator and sinking motion south of the equator. The rising and sinking limbs extends to about 20° latitude in both the hemispheres. A weak Ferrel cell is evident in the SH. Similarly, the summer composite represents one major meridional circulation with ascending motion between 5°S and 20°S. Comparing Figs. 5(b&c) and Fig. 3, it may be noted that the EOF2 pattern corresponds well with the winter composite of the Ψ associated with ENSO. Thus, EOF2 represents the winter phase of the evolution of the meridional circulation associated with ENSO. On the other hand, EOF1 bears a good deal of similarity with the summer composite of ENSO. It is rather intriguing to note that the zonal mean NH summer meridional circulation pattern appears as the dominant mode of inter-annual variability and not the NH winter pattern. Even though the amplitude of the ENSO related anomalies generally tend to be largest during NH winter, their variability from event to event tend to be large during the NH summer preceding the mature events. As seen from PC1 time series, large amplitudes are seen during 1982-1983 and 1997-1998 events. These events are known to be a few events when the summer anomalies were usually high.

It may be noted that the strength of the Hadley circulation associated with the inter-decadal variations are comparable to those associated with inter-annual variations. Moreover, the inter-decadal and inter-annual variations may be considered linearly independent as typical time series representing the two variations are uncorrelated. As a result, climate of any tropical belt at any instant may be obtained by a linear superposition of the decadal and inter-annual components. Thus, during a 'warm' phase of the inter-decadal oscillation, the boreal summer Hadley cell associated with El Nino's (ascending motion in the northern tropics and descending motion in the southern tropics) is weakened while that associated with La Nina (descending motion in the northern tropics and ascending motion in the southern tropics) is strengthened. Similarly, during the cold phase of the inter-decadal oscillation, the summer Hadley circulation associated with the El Nino's is strengthened while that associated with La Nina is weakened or neutralized. Therefore, during a warm phase of the inter-decadal oscillation (such as one prevailing after 1976 till present), we may expect near normal summer precipitation during El Nino's while enhanced precipitation in the SH and decreased precipitation in NH may be expected during La Nina's. During boreal winter (DJF), the inter-decadal Hadley cell remains similar to that during summer, while the inter-annual Hadley circulation associated with the El Nino's and La Nina's change which is evident from the DJF (El Nino - La Nina) composite shown in Fig. 5(c). As a result, in the same phase of inter-decadal oscillation, decreased boreal winter precipitation is expected in the northern tropics during an El Nino while boreal winter precipitation is expected to be near normal during a La Nina.

4. Walker Circulation

As mentioned earlier, the climate of any place is determined by a superposition of the inter-decadal and inter-annual components. The structure of Hadley and Walker circulation associated with the inter-decadal and inter-annual modes will provide insight as to how the inter-decadal oscillations modulate the regional climate on the inter-annual time scale. In this section we study the interaction between the Walker circulation on the inter-decadal and inter-annual time scales.

The climatological mean annual cycle of the mass flux stream function is examined first and is shown in Fig. 6. The climatological Walker circulation is characterized by three cells, with an ascending branch in the western Pacific, a descending branch in the eastern Pacific, an ascending branch in the western Africa and another descending branch in the eastern equatorial Indian Ocean. Unlike the Hadley cell, the annual variation of the Walker cell is not dramatic. Largest variations are in the eastern Indian ocean and in the western Pacific. The branch in the Indian ocean between 70°E and 110°E is strongest during northern summer. The branch weakens and moves eastward of 110°E during the northern winter.

Associated with this, the ascending branch in the western Pacific moves eastward to about the dateline during northern summer. Here, we compare the structure of Walker circulation associated with ENSO and the inter-decadal mode. For this purpose, boreal winter (DJF) 'warm'-'cold' composite of decadal mass flux stream is constructed and is shown in Fig. 7(a) averaged around the equator (10°S-10°N). As the decadal mode does not have much seasonal variation only DJF composite is shown. Similarly, boreal winter (DJF) and boreal summer (JJA) composite differences between 'warm' and 'cold' phases (El Nino and La Nina) of inter-annual variations averaged around the equator (10°S-10°N) are constructed. The magnitude of the mass flux stream function is denoted by the contours. Vector winds for these composites are constructed with pressure vertical velocity (taken with a negative sign) and zonal velocity. The composites are shown in Figs. 7 (b & c) for JJA and DJF respectively.

The anomalous inter-decadal Walker circulation comprises of three cells with descending motion over longitudinal bands 160°E-140°W and 20°W-40°E and ascending motions between 60°E and 140°E, 120°W and 30°W. The inter-annual Walker circulation during boreal summer is characterized by two major cells in the zonal direction with strong rising motions around 150°W and sinking motions towards west of 180° and towards east of 80°W associated with an El Nino. The seasonal changes in the Walker circulation with inter-annual ENSO variations are rather small. During boreal winter Fig. 7(c) too, the structure is similar to the boreal summer one with ascending motion in the eastern Pacific that extends further to the east upto 90°W. To show that these variations of the Walker circulation associated with El Nino and La Nina represents the dominant mode of interannual variability of the Walker circulation, we carried out an EOF analysis of the Walker circulation mass flux stream function. The first two EOFs and the PCs associated with them are present in Fig. 8. The first EOF explains about 38% of the total variability and the second about 18%. The EOF1 pattern is similar to the anomalous summer Walker cell associated with the El Nino phase Fig. 7(b) and the EOF2 pattern is similar to the anomalous winter Walker cell during El Nino phase Fig. 7(c). The PCs show a periodicity of approximately 4 years. The PC1 and PC2 have very similar time variations but with a phase lag. The patterns of EOF1 and EOF2 and the phase lag in the time coefficients represent a slow eastward propagation of the Walker circulation characteristically associated with the evolution of the ENSO cycle (Yasunari, 1985). Thus, the dominant mode of variability of the Walker circulation is indeed related to the ENSO variations.

We note from Fig. 7 that the mass fluxes associated with the decadal and inter-annual Walker circulation are comparable. Therefore, the inter-annual variations can be significantly affected by the decadal circulations in its different phases. Thus, during the warm phase of the decadal oscillations (*e.g.* between 1977-98), the Walker cell in the central Pacific and northern South America during an El Nino phase of the inter-annual variations would be weakened or neutralized while that associated with the La Nina phase of inter-annual oscillation would be strengthened. The effect will be reversed during the cold phase of the decadal oscillation (*e.g.* : between 1950-1975). This is the major process that modulates the severity of the effect of El Nino's over places like eastern Indian ocean - Indonesia - northern Australia and eastern equatorial Pacific - northern South America.

5. Conclusions

The climate in the tropics in general and the precipitation distribution in particular, are primarily determined by the ascending and descending branches of the Walker and the Hadley circulations. Several decadal or multi decadal climatic fluctuations have been identified in the tropics and extra-tropics from long records of surface data. To assess the role of these decadal - multi decadal oscillations in influencing climate in different regions, it is important to know the structure of the Hadley and Walker circulations associated with these decadal - multi decadal oscillations. However, the three-dimensional structure of these climate oscillations could not be studied earlier as homogeneous global upper air data for a sufficiently long period of time was not available. The NCEP/NCAR reanalysis project produced a 50-year record of homogeneous global data set that became available recently. This 50-year reanalysis is used to bring out the Hadley and Walker circulations associated with the dominant decadal oscillations in the tropics noted earlier from surface data.

The decadal - multi decadal component has been separated from the inter-annual and other high frequency oscillations using a harmonic analysis. The variations in the intensity of Hadley and Walker circulations is estimated by computing the mass flux stream function. The climatological mean annual cycle of the meridional and zonal mass flux stream function is also studied. The maximum meridional mass flux stream function is observed during the peak winter time in both the hemispheres. The seasonal extreme values in Ψ are found in winter at around 8° latitude with maximum values of 17×10^{10} kg/s near 500 hPa level in the NH and

21×10^{10} kg/s near 600 hPa level in SH. The zonal mass flux stream function structure remains similar throughout the year.

The temporal variation of decadal Hadley circulation is seen to be similar in some respect to that of the ENSO-like inter-decadal oscillation. Moreover, the dominant mode of inter-annual variation of the meridional circulation is found to be closely related to the ENSO. It is also shown that the boreal summer Hadley circulation anomalies associated with the inter-decadal and the inter-annual modes are both characterized by a single cell meridional structure around the equator in the tropics but are out of phase. It is also found out that magnitude of inter-decadal Hadley circulation anomalies are comparable to those associated with the inter-annual variability. As a result, during a 'warm' phase of the inter-decadal oscillation (such as one prevailing after 1976 till present), we may expect near normal summer precipitation during El Nino's, while enhanced precipitation in the SH and decreased precipitation in NH may be expected during La Nina's. The effects are expected to reverse during the 'cold' phase of the inter-decadal oscillation.

To gain insight as to how the inter-decadal oscillations modulate the regional climate on the inter-annual cycle, the interaction between the Walker circulation on the inter-decadal and inter-annual time scales is also studied. As in the case of the Hadley circulation, it is shown that the mass fluxes associated with the decadal variations are comparable to those associated with the inter-annual variations. The structure of the inter-annual Walker cell exhibits similarity with the decadal Walker cell. However, the ascending/descending motion in Central Pacific and northern South America during El Nina (La Nina) are out of phase with those in inter-decadal warm (cold) phases. Therefore, during the warm decadal phase there is a weakening of the Walker cell in the Central Pacific and northern South America during an El Nino phase of the inter-annual variations while the effect will be reversed during the cold decadal phase. This is the major process that modulate the severity of the effect of El Nino's over places like eastern Indian Ocean - Indonesia - northern Australia and eastern equatorial Pacific - northern South America.

While the results presented has probably provided first zero order estimate of divergent circulation anomalies associated with the decadal/multi-decadal climate variations in the tropics, they are based on a relatively short data span (50 years) and hence rigorous statistical significance of the results could not be tested. Therefore, these results should be considered as preliminary to be tested with longer data sets as it becomes available.

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References

Allan, R.J., 1993, "Historical fluctuations in ENSO and teleconnection structure since 1879 : Near global patterns", *Quaternary Australiasia*, **11**, 1, 17-27.

Allan, R.J., Lindesay, J.A. and Reason, C.J.C., 1995 : "Multi-decadal variability in the climate system over the Indian Ocean region during austral summer", *J. Climate*, **8**, 1853-1873.

Kachi, M., and Nitta, T., 1997, "Decadal variations of the global ocean-atmosphere system", *J. Meteor. Soc. Japan*, **75**, 657-675.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetma, A., Reynolds, R., Jenne, Roy and Joseph, Dennis, 1996, "The NCEP/NCAR 40 year Reanalysis Project", *Bull. Am. Meteor. Soc.*, **77**, 437-471.

Kripalani, R.H. and Kulkarni, A., 1997, "Climate impact of El Nino/La Nina on the Indian monsoon : A new perspective", *Weather*, **52**, 39-46.

Oort, A.H., and Yienger, J.J., 1996, "Observed interannual variability in the Hadley circulation and its connection to ENSO", *J. Climate*, **5**, 2751-2767.

Parthasarathy, B., Rupa Kumar, K. and Munot, A. A., 1993, "Homogeneous Indian monsoon rainfall : Variability and prediction", *Proc. Ind. Acad. Sci. (Earth & Planet. Sci.)*, **120**, 121-155.

Parthasarathy, B., Munot, A.A. and Kothawale, D.R., 1994, "All India monthly and seasonal rainfall series : 1871-1993", *Theor. Appl. Climatol*, **49**, 217-224.

Philander, S.G.H., 1990, "El Nino, La Nina and the Southern Oscillation", Academic, San Diego, Calif. 293pp.

Reynolds, R.W. and Smith, T.M., 1994, "Improved global sea surface temperature analysis using optimum interpolation", *J. Climate*, **7**, 929-948.

Wallace, J.M., Rasmusson, E.M., Mitchell, T.P., Kousky, V.E., Sarachik, E.S. and Von Storch, H., 1998, "On the structure and evolution of ENSO related climate variability in the tropical Pacific : Lessons from TOGA", *J. Geophys. Res.*, **96**, 15137-15146.

Woodruff, S., Slutz, R., Jenne, R., and Steurer, P., 1987, "A comprehensive Ocean Atmosphere Data Set", *Bull Am. Meteor. Soc.*, **68**, 1239-1250.

Yasunari, T., 1985, "Zonally propagating modes of global east-west circulation associated with southern oscillation", *J. Meteor. Soc. Japan*, **65**, 81-102.

Zhang, Y., Wallace, J.M., and Battisti, D.S., 1997, "ENSO - like interdecadal variability", 1900-93, *J.Climate*, **10**, 1004-1020.