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TELLUS

Trend and interannual variability of Walker, monsoon and Hadley circulations defined by velocity potential in the upper troposphere

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ABSTRACT

In this paper, we attempt to divide the global divergent field at the upper troposphere in contributions from the Hadley, Walker and monsoon circulations, using a monthly mean velocity potential field at 200-hPa level. First, the zonal mean of the velocity potential is analysed to represent the Hadley circulation. The deviation from the zonal mean is then divided into its annual mean and the seasonal cycle parts, which are considered to represent the Walker and monsoon circulations, respectively. The intensities of each circulation are measured by their peaks in the velocity potential field separated in each component. According to this separation, the mean intensities of the Walker, monsoon and Hadley circulations appear to be 120: 60: 40 ($\times 10^5$ m^2 s^{-1}) in January and 120: 90: 45 ($\times 10^5$ m^2 s^{-1}) in July, respectively.

Based on this simple definition, interannual variabilities of each circulation are then examined quantitatively using the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis. The time series of the intensity of the Walker circulation coincides with the Southern Oscillation index (SOI), and the intensity has weakened in recent decades. That of the Hadley circulation indicates intensifying trend in boreal winter.

Finally, the same analysis is applied for the model atmosphere by the Meteorological Research Institute (MRI) coupled atmosphere–ocean general circulation model (CGCM1) with a gradual increase in CO_2 at a compound rate of 1% yr^{-1} for 150 yr. It is shown that the Hadley circulation intensifies by 40% and the monsoon circulation decays by 20% in boreal summer when the global warming has occurred in a century later. The result demonstrates that the proposed simple separation of the tropical circulation in the Walker, monsoon and Hadley components is useful, although it is not rigorous, for the initial assessment of the model response to the global warming.

1. Introduction

Large-scale tropical circulations, such as Hadley, Walker and monsoon circulations, are the strongest driving force of the general circulation in low latitudes. The year-to-year variations of these circulations give rise to a great impact upon the Earth's climate variability. These circulations are tightly coupled with each other producing the strongest convection centre around the western equatorial Pacific. The coupling is extensively investigated by numerous researchers (e.g. Angell, 1981; Rasmusson and Carpenter, 1982; Meehl, 1987; Webster and Yang, 1992; Yasunari and Seki, 1992; Ju and Slingo, 1995; Yang and Lau, 1998; Kawamura, 1998). In particular, the coupling of the Asian/Australian monsoon with the atmosphere/ocean system in the equatorial Pacific is referred to as the monsoon/atmosphere–ocean system (MAOS) by Yasunari and Seki (1992), and the seasonal to interannual variability of the coupled system is discussed comprehensively in reference to the recent trend and variability of the climate system (Yasunari, 1991, 1996).

The variability of individual circulation intensities has long been measured by various circulation indices. For example, the intensity of the Walker circulation has been quantified by the Southern Oscillation index (SOI) defined by the surface pressure difference between Tahiti and Darwin (Walker and Bliss, 1932). The Walker circulation is driven by the temperature difference in the underlying sea surface temperature (SST) along the equatorial Pacific. The SOI offers a good measure of the equatorial trade wind and indicates a strong coupling with the El Niño/La Niña phenomenon in the ocean. However, the circulation index using only the two surface stations may undergo considerable

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noise by the local weather conditions. Wang (2002) used the vertical velocity anomaly difference between the eastern and western Pacific at the 500-hPa level for the alternative choice of the Walker circulation index. Mathematically, the intensity of the Walker circulation can be measured by a line integral of tangential wind speed along a closed circle, i.e. circulation, associated with the Walker circulation over the equatorial vertical sector. The accuracy of the SOI representing the intensity of the Walker circulation needs to be examined using the alternative measure of the circulation index with the accumulated analysis data.

The term monsoon generally stems from the seasonal reversal in both precipitation and wind fields. As long as the wind is concerned, the monsoon circulation is characterized as a climate system with seasonal reversal in winds over and around the continents. The intensity of the monsoon, however, has long been quantified by precipitation rather than the wind field. Parthasarathy et al. (1992, 1994) proposed to use all Indian summer rainfall averaged over all Indian subdivisions for June to September as the index of the intensity of monsoon. Although the index has widely been used by the monsoon community for studies of the El Niño Southern Oscillation (ENSO) or tropical biennial oscillation (e.g. Shukla and Paolino, 1983; Meehl, 1987; Shukla and Mooley, 1987; Yasunari, 1991), it is not clear how well it represents the large-scale summer monsoon in south Asia and its interannual variability.

To reflect the interannual variability of the broad-scale monsoon, Webster and Yang (1992) introduced a monsoon index defined by a time-mean zonal wind (U) shear between 850 and 200 hPa (U850–U200) averaged over south Asia from the equator to 20°N and from 40 to 110°E. As expected, however, the index often provides a rather disparate measure of the monsoon compared with the all Indian summer rainfall index. According to Ailikun and Yasunari (1998), the definition by Webster and Yang reflects more of the convective activity over the western Pacific rather than over the south Asian monsoon region. Because the correlation between these two monsoon indices is so poor, they concluded that these two indices represent rather different quantities in the Asian/western Pacific monsoon region. Considering this discrepancy, Kawamura (1998) proposed another monsoon index defined by the meridional gradient of upper-tropospheric thickness (200–500 hPa) anomalies over the Indian subcontinent. The index is highly correlated with the index of Webster and Yang because these are connected through the thermal wind relation. Yet, the correlation with that by the all Indian summer rainfall remains low, because the kinematical monsoon circulation is clearly different from the monsoon defined by precipitation that is a function of both the wind convergence and moisture fields.

Goswami et al. (1999) proposed a monsoon Hadley circulation index defined by the meridional wind (V) shear between 850 and 200 hPa (V850–V200) averaged over regions not only for the Indian subcontinent but also for the northern Bay of Bengal and a portion of South China. In this definition, the Hadley circulation is clearly combined with the intensity of the monsoon circulation because V850–V200 indeed is the local meridional circulation. This monsoon Hadley circulation index is compared with the other monsoon index of total summer rainfall averaged over the same extended area, showing a significantly high correlation (Goswami et al., 1999). The result implies that the intensity of the Hadley circulation controls the intensity of the large-scale summer monsoon. A confusion comes from the fact that they called the meridional monsoon circulation a local Hadley circulation. The local meridional circulation induced by the monsoon may be different from the traditional Hadley circulation in the context of the general circulation. For these reasons, the choice of a proper Asian summer monsoon index is an enigma, and the active controversy for the better choice of the monsoon index seems to be diverging in the monsoon community (see Wang and Fan, 1999).

Traditionally, the Hadley circulation has long been defined as a zonally symmetric meridional circulation with an ascending motion over the Intertropical Convergence Zone (ITCZ) and a descending motion over the subtropical high-pressure belt (e.g. Oort and Yienger, 1996; Trenberth et al., 2000). In the context of the general circulation, it is driven by the meridional differential heating in the global radiative process. The Hadley circulation is a fundamental tropical circulation which exists even under a hypothetical aqua-planet with no land–sea contrast. As long as the heat contrast is imposed on the aqua-planet by the meridional differential heating, the axisymmetric Hadley circulation would be excited. Therefore, the modification by the land–sea thermal contrast in the real atmosphere may be considered as a part of the monsoon rather than a local Hadley circulation, considering the different driving force between the two. A terminology of modified Hadley circulation was introduced by Lorenz (1969), when the zonally symmetric circulation is modified by the zonal asymmetry due to the thermal contrast and orographic forcing. The dynamical modification was investigated by Schneider (1987), where the asymmetry is considered as part of the Hadley circulation.

The definition of the Hadley circulation seems to have been extended locally to any local meridional circulation. For example, Wang (2002) discussed the local Hadley circulation induced by ENSO, where the anomalous meridional Hadley circulation occurs in the eastern Pacific while the Hadley circulation is, in the opposite sense, in the western Pacific during ENSO. Such a local meridional Hadley circulation with opposite directions may be treated as part of the Walker circulation because it is induced by the anomalous SST. The local Hadley circulation is therefore inseparable from the monsoon circulation or from the Walker circulation as discussed by Goswami et al. (1999).

When the interannual variability of the Hadley circulation is argued, the intensity change of the Hadley circulation is difficult to separate from that of monsoon circulation or from the Walker circulation as long as the concept of the local Hadley circulation is introduced regardless of the origin of the driving force. For this reason, it may be intriguing to reconsider the Hadley circulation as a zonally symmetric component of the complex meridional circulation in the tropics, and to quantify the intensity by the circulation as a line integral over a vertical-meridional sector associated with the Hadley circulation. According to Owada and Akiyama (private communication), the intensity of the Hadley circulation measured by the intensity and location of the subtropical high has increased in the last two decades, and the recent trend is argued in connection with recent global warming. More extensive and comprehensive assessment would be desired to quantify the interannual variability of the Hadley circulation separated from the monsoon and Walker circulations.

The purpose of this paper is to separate the Hadley, Walker and monsoon circulations, considering their different driving forces and to quantify the circulation intensity based on the computation of the mathematical circulation. One may criticize the fact that the circulations are inseparable from the beginning by their complex interactions. In this paper we attempt such a separation as a working hypothesis to find whether the simple separation is useful or not for the quantitative study of the interannual variability of the tropical circulations. As mentioned above, the terminology of the monsoon circulation is distinguished from the monsoon in this study. The former concerns only the kinematical circulation while the latter is mostly defined by precipitation as well as wind. Once the circulation is quantified, the interannual variability of the circulation intensity is examined with reference to previous studies using the SOI and Asian monsoon indices. Moreover, the impact of global warming upon these tropical circulations in the future climate is examined for the individual components of the Hadley, Walker and monsoon circulations.

For that purpose, the time series of the upper air (200 hPa) velocity potential field is separated in components of the Hadley, Walker and monsoon circulations, considering the axisymmetric part as the essence of the Hadley circulation and the seasonal cycle as the essence of the monsoon circulation. Similar decomposition of the tropical circulation has been performed by Tanaka and Kimura (1996) by means of the empirical orthogonal function (EOF) analysis in the time domain. We used the monthly mean data provided by the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis for 1966 to 2001 (see Kalnay et al., 1996).

After the examination of the definition of these tropical circulations, the same analysis is applied to a global coupled atmosphere–ocean general circulation model atmosphere (CGCM1; Tokioka et al., 1995). We are interested in the anticipated changes in these tropical circulations when global warming takes place by the increased anthropogenic greenhouse gases.

In Section 2, we present the data and analysis method to separate the tropical circulations. In Section 3, the seasonal variation of velocity potential in climate is separated in the Hadley, Walker and monsoon circulations to justify the method and definition for the quantification. In Section 4, the interannual variability of these circulations is examined and compared with those by previous studies. In Section 5, the analysis is applied to the Meteorological Research Institute (MRI) CGCM1 to assess the circulation changes as a result of global warming. Finally, a concluding summary is given in Section 6.

2. Data and the method

2.1. Data

The observational data used in this study are the monthly mean NCEP/NCAR reanalyses on a $2.5^\circ \times 2.5^\circ$ grid at 200-hPa level for January 1966 to July 2001. The climate is computed from 33-yr mean of the reanalysis from January 1966 to December 1998.

For comparison, we also used the simulation data by a global CGCM1 developed at the MRI for 150 yr (see Tokioka et al., 1995). In order to identify the impact of global warming upon the tropical circulations, a model simulation with a fixed CO_2 concentration (C-run) is compared with a gradual increase in CO_2 at a compound rate of 1% yr^{-1} (G-run).

In order to quantify the mathematical circulation, i.e. a line integral of tangential wind speed along a closed circle of the respective circulations, velocity potential χ at the 200-hPa level is selected in this study as a suitable variable reflecting the large-scale features of the tropical circulations. The velocity potential χ is calculated using the horizontal wind vector V at the 200-hPa level following the definition by Krishnamurti (1971):

$$D = \nabla \cdot V = -\nabla^2 \chi. \tag{1}$$

It is noted that the original definition by Lamb (1945) has no minus sign on the right-hand side. We followed, however, the recent convention by the Climatological Observation Report of the Japan Meteorological Agency (JMA), where the divergent wind V_χ flows from the maximum to the minimum of the velocity potential field. The divergence D is calculated in the spectral domain by means of the spherical harmonic expansion of the wind vector. The velocity potential is then evaluated by the inverse spectral transform of the weighted expansion coefficients under the wave truncation of triangular 42. Newman et al. (2000) compared the 200-hPa wind divergence fields from the NCEP/NCAR, the European Centre for Medium-Range Weather Forecast (ECMWF) and the National Aeronautics and Space Administration (NASA) reanalyses. Although the details of the divergence fields are different among these analyses, basic patterns of the integrated variable of velocity potential are reasonably consistent (also see Trenberth et al., 2000).

2.2. Analysis method

The velocity potential at the 200-hPa level contains information concerning the overall intensity of the tropical circulations of Hadley, Walker and monsoon. These tropical circulations are driven by different dynamical causes. For example, the

Hadley circulation in the general circulation context is driven by meridional differential heating. The essential structure may be considered as axisymmetric because it occurs even in the hypothetical aqua-planet. The Walker circulation, on the other hand, is driven by the different SST along the equatorial tropics. Zonal asymmetry of the SST created by the continental interruption of major oceanic circulations may be the main cause of the Walker circulation. The monsoon circulation is driven essentially by the heat contrast induced by the land–sea distributions. Therefore, the annual cycle with the seasonal reversal in the direction of the circulation between summer and winter may be the essential part of the definition of the monsoon.

A separation in terms of the characteristics in the space–time domain appears to be useful. An attempt has been performed in Tanaka and Kimura (1996) by means of the EOF decomposition of the velocity potential in the time domain. Meaningful features of individual tropical circulations demonstrate the usefulness of the statistical orthogonal separation by means of the characteristics in the space–time domain.

Based on this argument, we define the Hadley circulation first as an axisymmetric part of the circulation. We assume that information is contained in the zonal mean field of the velocity potential, i.e. $[\chi(t, y)]$. Also, we assume that information on Walker and monsoon circulations is contained in the deviation field from the zonal mean, i.e. $\chi^*(t, x, y)$, where x, y and t represent longitude, latitude and time, and $[()]$ and $()^*$ denote the zonal mean and the deviation from it, respectively. Secondly, we define the monsoon circulation as part of the seasonal change of the deviation field. For this reason, the seasonal mean is subtracted from the deviation field to define the monsoon circulation, i.e. $\chi^{*\prime}(t, x, y)$. Finally, we define Walker circulation as the remainder which is the annual mean of the zonal deviation field, i.e. $\bar{\chi}^*(x, y)$, where $\bar{()}$ and $()'$ denote the annual mean and the deviation from it, respectively. With these simple definitions of the tropical circulations, the velocity potential is divided into the following linear combinations of three orthogonal spatial patterns:

$$\begin{aligned}\chi(t, x, y) &= [\chi(t, y)] + \chi^*(t, x, y),\\ &= [\chi(t, y)] + \bar{\chi}^*(x, y) + \chi^{*\prime}(t, x, y). \qquad (2)\end{aligned}$$

The first line of the equation represents a decomposition in zonal and eddy components, while the second line separates the eddy component in its time mean and the transient components. On the right-hand side of the second equation, the first, second and third terms are thus defined in this paper as components of the Hadley, Walker and monsoon circulations, respectively. In analysing interannual variability, 12-month running means are used in place of $\bar{()}$, and $()'$ is the deviation from the running mean.

Although the tropical circulations are separated in a superposition of the three orthogonal components by the characteristics in the space–time domain, the definition in this study may be too simple to separate the complex tropical circulations. Because they are highly interacting nonlinearly, we know that the separation is not perfect. For example, the Walker circulation has no seasonal variation, which is one of the major shortcoming of the present definition. All seasonal cycles were deposited in the monsoon. However, we expect that the present definition retrieves a large fraction of the tropical circulations. Because we are interested in the interannual and decadal variability of the Walker circulation, the problem may not be critical. The separation is a working hypothesis of this study, and the utility of this definition will be discussed later by observing the analysis result.

3. Velocity potential in climate

3.1. Seasonal change

The seasonal variation of velocity potential in the climatological mean is analysed before examining the interannual variability of the tropical circulations. Figure 1 illustrates the monthly mean velocity potential at 200 hPa in climate averaged for 1966 to 1998 in January, April, July and October. The corresponding divergent wind is also presented. In January, the positive peak of the velocity potential with the value of 120 ($\times 10^5$ m^2 s^{-1}) is located at the equatorial western Pacific. The minimum is seen over western Africa with the value of -100 ($\times 10^5$ m^2 s^{-1}). Hereafter, the units of the velocity potential are always measured by 10^5 m^2 s^{-1} for simplicity. The zonal wavenumber one dominates in the velocity potential field, and minor small-scale patterns are superimposed on it. The divergent wind flows from the positive peak of χ over the western Pacific to the minimum of it. There is a strong upward motion associated with the convection centre over the western Pacific in the Southern Hemisphere which flows northward to south Asia and eastward to the equatorial eastern Pacific. The pattern indicates the dominant Walker circulation in the east-west direction associated with the zonal wavenumber one superimposed on the meridional circulation associated with Hadley circulation. In April, the overall pattern is similar to that in January, but the positive peak over the western Pacific decreases to 80 units. In July, the positive peak reaches its full strength with the value of 200 units. The location has shifted to the northwest near the Philippines. Strong divergent wind is seen from the Northern Hemisphere to the Southern Hemisphere associated with the Hadley circulation. The minimum also has shifted to the South Atlantic Ocean. In October, the positive peak has moved eastward, and the intensity has reduced to 120 units.

The convection centre near the Philippines in July results from the combination of the Asian monsoon, Walker and Hadley circulations. The goal of this study is to split them in each contribution. In January, the centre moves to the north of Australia associated with the Australian monsoon. The seasonal variation caused by the land–sea thermal contrast may be a part of the monsoon circulation. The persistent (non-seasonal) wavenumber one pattern, which may be regarded mostly as the Walker circulation,

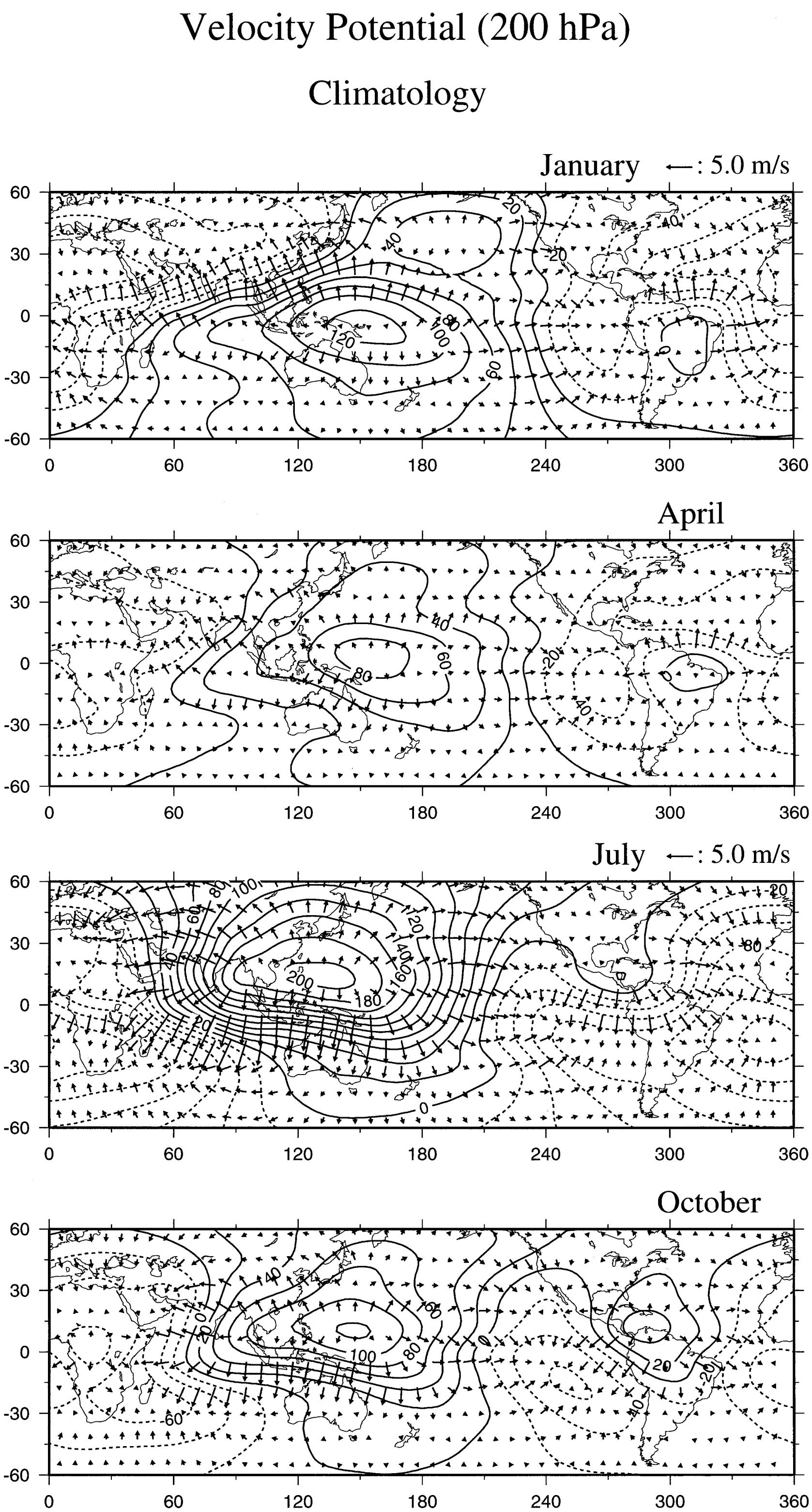

Fig. 1. Monthly mean velocity potential and divergent wind at 200 hPa for the climate (1966–1998) in January, April, July and October. The units are 10^5 m^2 s^{-1}.

is not the monsoon circulation by definition (see Krishnamurti, 1971). Lastly, the zonal mean component of the meridional circulation, which reverses the direction over the equator between January and July, may be regarded as the contribution from the Hadley circulation. We attempt in the next subsection to separate the circulation pattern into these three components based on the characteristics of the seasonal change.

3.2. *Hadley circulation*

The zonal mean of the velocity potential in climate is presented in Fig. 2 for January, April, July and October. In January, the velocity potential at 200 hPa is negative in the Northern Hemisphere with its peak at 25°N and positive in the Southern Hemisphere with the corresponding peak at 15°S. These peaks represent the locations of sinking and rising motions with the zonally symmetric meridional divergent flow from the Southern Hemisphere to the Northern Hemisphere. The pronounced meridional divergent flow over the equator clearly represents the upper tropospheric branch of the zonally symmetric Hadley circulation in the boreal winter. The ITCZ associated with the Hadley circulation is located at 15°S where the positive peak is seen in the figure. The peak in velocity potential does not necessarily coincide with the core of the upward motion. Yet, they are known to coincide for the plain waves. In April, there is a positive peak over the equator and two major negative peaks at 25°N and 25°S. The positive (negative) peak indicates the location of upward (downward) motion. The ITCZ is located just over the equator. The pattern represents two zonally symmetric Hadley circulation cells in the respective hemispheres. In July, the velocity potential at 200 hPa is positive in the Northern Hemisphere with its peak at 15°N and negative in the Southern Hemisphere with the corresponding peak at 25°S. The ITCZ has moved to 15°N. The meridional divergent wind is obviously stronger than that in January. The strong zonally symmetric divergent wind flows from the Northern Hemisphere to the Southern Hemisphere, indicating a pronounced overturning of the Hadley circulation cell over the equator. In October, there is a positive peak at 10°N and a negative peak at 25°S with a minor minimum at 30°N. The ITCZ is located in the Northern Hemisphere, and the southern cell is stronger than that in the Northern Hemisphere. The northern and southern circulation cells become comparable in November (not shown).

Based on the result, the seasonal change of the Hadley circulation is well represented by the zonal mean velocity potential at 200 hPa. Hence, we define the intensity of the Hadley circulation by the peak value of the zonal mean velocity potential. The difference between the positive and negative peaks can be another possible choice of the definition of the intensity. Yet, the restriction such that the global mean is always zero permits us to choose one of the peak values for the alternative simple measure of the intensity. Considering the poor data quality in the Southern Hemisphere, the peak value in the Northern Hemisphere may be more representative for the definition. Based on this argument, the positive (negative) peak value of the velocity potential in the Northern Hemisphere will be referred to as a Hadley circulation index in July (January) in this paper. The intensity is thus −40 units in January and 45 units in July. It may be worth noting that the Hadley circulation in July is stronger than that in January. The result suggests that the Hadley circulation contains the impact of axisymmetric land–sea thermal contrast between the hemispheres which may be regarded as an axisymmetric monsoon. Such a global monsoon is contained in the Hadley circulation by the present definition. The purpose of this paper is to quantify the individual intensities of the circulations by a rather simple definition, and the application of the index to the study of the interannual variability. For this reason, we avoid a further complication of the definition.

Figure 3 illustrates the deviation field of the velocity potential from the zonal mean in January, April, July and October, subtracting the zonal mean in Fig. 2 from the raw value in Fig. 1. Because the Hadley circulation has been removed by definition, the pattern should contain the Walker and monsoon circulations. A pronounced wavenumber one pattern throughout the year indicates the dominant Walker circulation with rising motion over the western Pacific and sinking motion over the eastern Pacific as well as over the Atlantic. Such an annual mean pattern without the seasonal change may not be the monsoon circulation by definition.

In January, the positive peak location moves to the western Pacific. Quantitatively, the peak value decreases to 100 units compared with that in Fig. 1. The location becomes just over the equator. Another positive centre over the north Pacific is emphasized. The negative peak has split in two centres over the eastern Pacific and eastern Atlantic over the equator. In April, the positive centre has broadened in the meridional direction. In July, the positive centre is located in approximately the same location, but the intensity is now 160 units. The positive centre is almost symmetric about the equator, and the meridional scale is further broadened. In October, the pattern is similar to that in Fig. 1, but it becomes more symmetric about the equator. According to the result of the deviation fields, we notice the predominant zonal wavenumber one associated with the Walker circulation, and the monsoon circulation is hidden as the minor component with the seasonal change superimposed on it.

3.3. *Walker circulation*

By the definition, the annual mean should have no monsoon circulation because there is no seasonal change. The monsoon circulation should thus be contained in the seasonal change, and the rest of the annual mean component should contain the Walker circulation. For this reason, the zonal deviation field in Fig. 3 is further divided in components of its annual mean and the seasonal change.

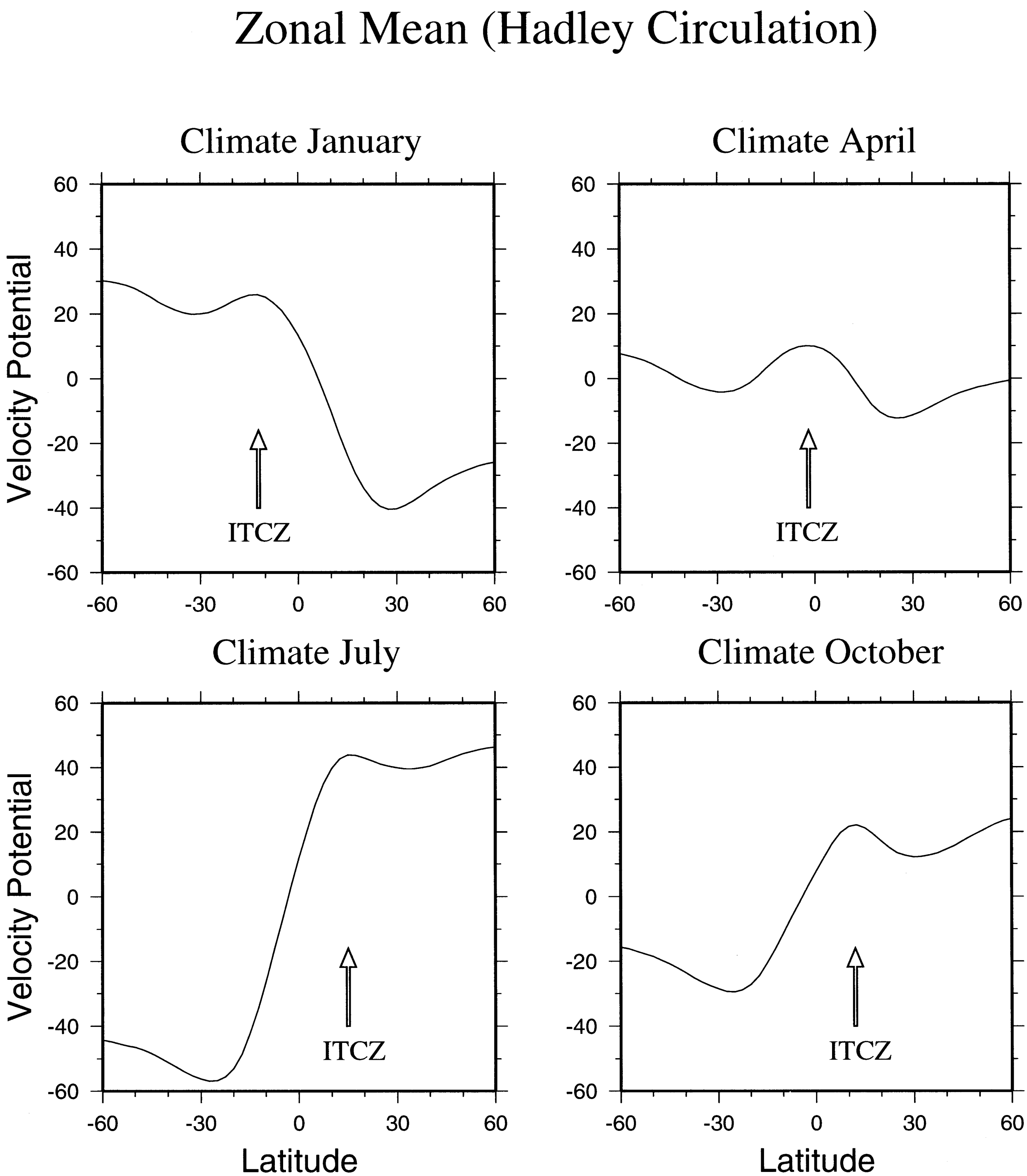

Fig. 2. Zonal mean of the velocity potential in Fig. 1 for the climate in January, April, July and October. The units are 10^5 m^2 s^{-1}. Hadley circulation is defined by the zonal mean.

Figure 4 illustrates the annual mean of the zonal deviation field in Fig. 3. The divergent wind is also presented superimposed on the velocity potential field. The pattern clearly contains information on the Walker circulation with the core of the upward motion at the equatorial western Pacific and the downward motion at the eastern Pacific. Another downward motion is seen at the equatorial eastern Atlantic. We thus confirm that the annual mean component in Fig. 4 is a reasonable representation for the

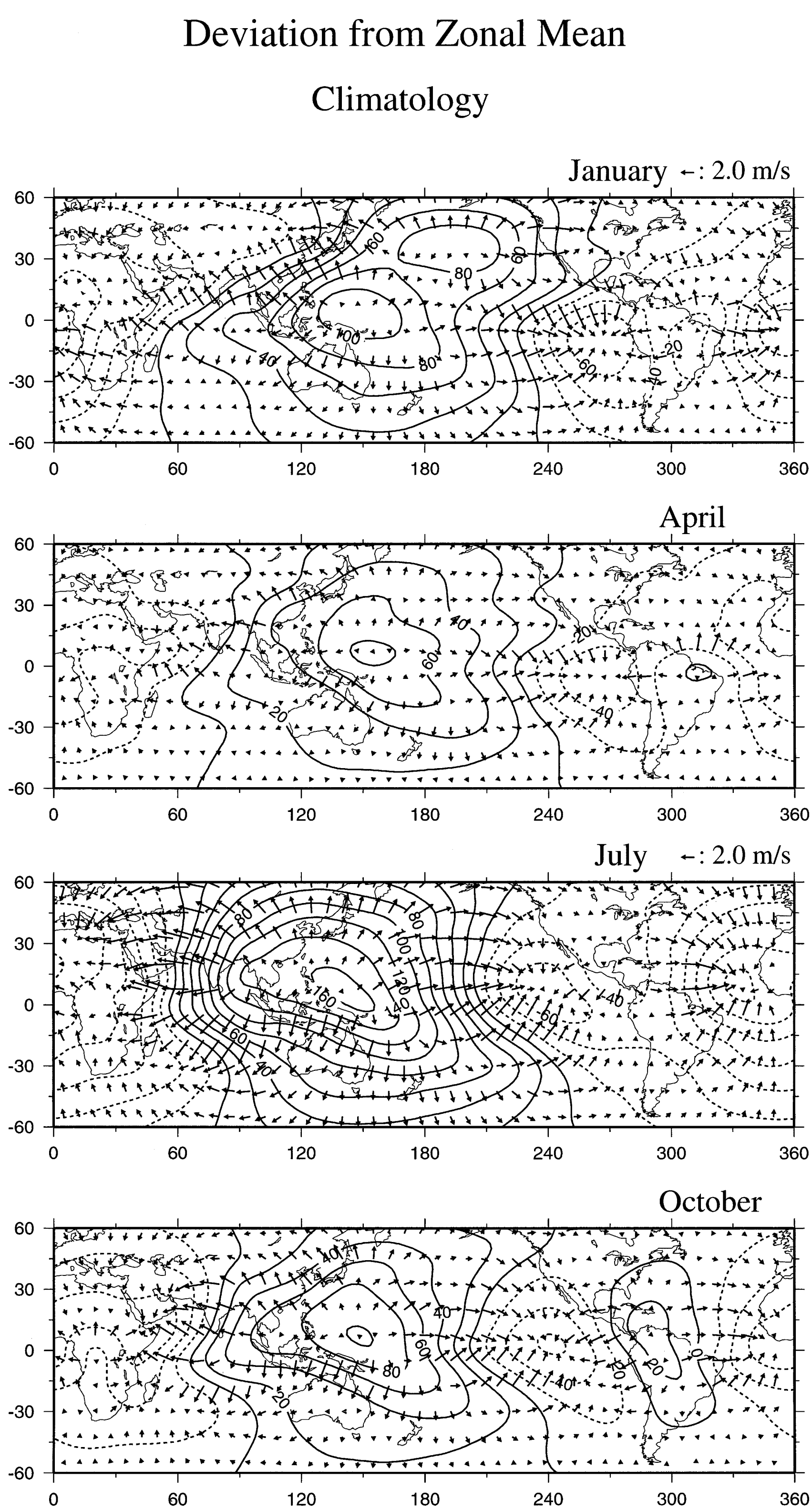

Fig. 3. Deviation from the zonal mean of the velocity potential for the climate in January, April, July and October. The units are 10^5 m^2 s^{-1}. The divergent wind is evaluated from the deviation field.

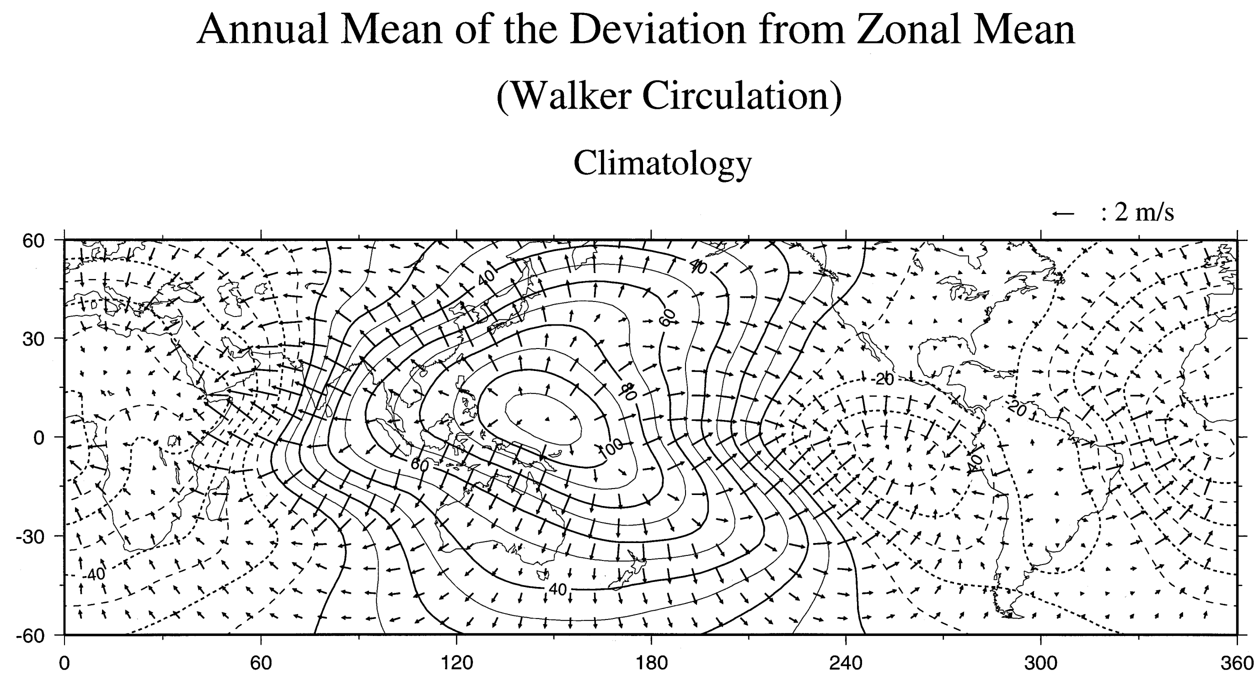

Fig. 4. Annual mean of the velocity potential in Fig. 3 for the climate. The units are 10^5 m^2 s^{-1}. The divergent wind is also plotted from the velocity potential field. The Walker circulation is defined by the annual mean of the velocity potential in Fig. 3.

Walker circulation. It should be noted that the Walker circulation so defined contains the local meridional circulation as well as the east-west circulation over the equator. This meridional circulation has been considered as the local Hadley circulation (e.g. Goswami et al., 1999; Wang, 2002). The persistent upward motion and the upper-level divergent flow over the convection centre is induced mostly by the existence of the warm pool in SST at the western Pacific, and the local meridional circulation has a close link to ENSO as described by them. Its long-term variability indicates high correlation with ENSO events. Hence, the (non-seasonal) local meridional flow in Fig. 4 may be considered as a part of the Walker circulation (clearly not the monsoon).

The intensity of the Walker circulation is measured by the value of the positive centre over the western Pacific. In Fig. 4, it is 120 units, and the intensity is three times stronger than that of the Hadley circulation in Fig. 2. We will refer to it as the circulation centre rather than the convection centre because there is no corresponding reality of convection there when separated from the monsoon or Hadley circulation.

The corresponding negative centre off shore Peru shows -40 units. The difference between the positive and negative centres becomes $\Delta\chi = \chi_{\max} - \chi_{\min} = 160$ units over the distance of $\Delta L = 12\,000$ km. The ratio describes the mean divergent wind $V_\chi = \Delta\chi/\Delta L$. The intensity of Walker circulation may be defined by a line integral of divergent wind V_χ along a closed curve on the vertical section over the equatorial Pacific. It may be very natural to quantify the intensity of the Walker circulation by the mathematical circulation. The closed curve for the computation of the mathematical circulation starts from the upward motion at the western Pacific, via upper air westerly to the eastern Pacific, via downward motion there, and to the western Pacific by the low level easterly. The result of the intensity of the circulation would be approximated by $2 \times \Delta\chi$ if we disregard the vertical component of the line integral and assume that the low-level divergent wind has the same magnitude. Moreover, under the restriction such that the global integral of χ is zero, the intensity of the circulation may be estimated by $4 \times \chi_{\max}$. Therefore, the positive peak value $\chi_{\max}$ is a good quantitative measure of the intensity of the Walker circulation despite the very simple quantity. In this paper, we simply measure the intensity by the positive peak value over the western Pacific.

3.4. *Monsoon circulation*

Finally, Fig. 5 illustrates the deviation from the zonal and annual mean of the velocity potential in Fig. 3 in January, April, July and October for the climate. By our definition, this component is regarded as the monsoon circulation.

In January, a negative peak of velocity potential of -60 units is located over east Asia, and a positive peak of 60 units over the northeast Pacific. Another notable positive peak of 30 units is seen over south Indian Ocean. The distribution in northern winter indicates an upper air convergence with descending motion over the east Asia associated with the winter monsoon which is compensated by divergent motions both from the Pacific and Indian Oceans. In April, a negative peak of -40 units is located

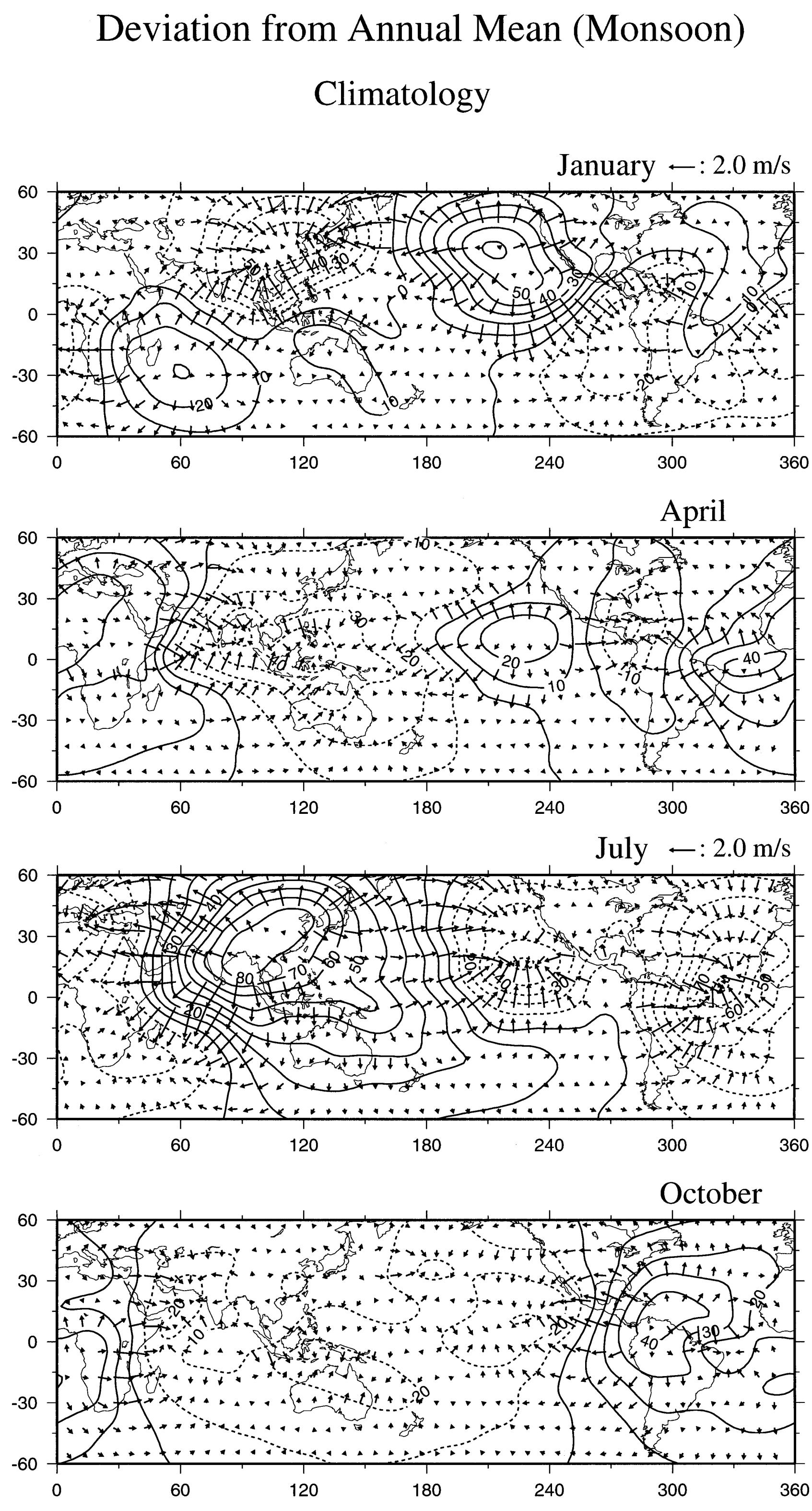

Fig. 5. Deviation from the annual mean of the velocity potential in Fig. 3 for the climate in January, April, July and October. The units are 10^5 m^2 s^{-1}. The divergent wind is also plotted from the velocity potential field. The monsoon circulation is defined by the seasonal variation of the velocity potential in Fig. 3.

over Indonesia, and a positive peak of 30 units over the equatorial east Pacific. The pattern is just the opposite of the Walker circulation although the intensity is too weak. In July, a pronounced positive peak of 90 units is located over the east Asia, and negative peaks of −50 and −80 units over the Pacific and Atlantic Oceans. The distribution in northern summer indicates a strong ascending motion with an upper air divergence over east Asia associated with the summer monsoon, which is connected with the upper air convergence over the Pacific and Atlantic Oceans. In October, the velocity potential is approximately flat with no marked peaks. The strong summer monsoon in July is over, and the pattern is changing toward the winter monsoon. A similar flat pattern is seen in May (not shown) in the seasonal march from the winter to summer monsoon.

The summer monsoon in July produces low-level convergence and upper-level divergence over east Asia while the winter monsoon in January produces low-level divergence and upper-level convergence over the same region. This opposite flow pattern between January and July over the continent is quite consistent with the inherent property of the monsoon circulation. The low-level convergence and ascending motion in July creates continental-scale heat low with cyclonic rotational flow by the Coriolis torque. The importance of the continental-scale heat low is documented by Kawamura and Murakami (1998) as an L-mode for the Asian summer monsoon, and the relation to the onset of Baiu front through the intraseasonal S-mode is discussed in detail by them (see also Ueda et al., 1995). The meridional flow from east Asia to Australia has been referred to as the local Hadley circulation (e.g. Goswami et al., 1999), which is regarded as the monsoon circulation in this paper. Compared with the total pattern of the velocity potential in Fig. 1, the convection centre near the Philippines in July can be explained by superposition of the convection centre near the equator by the Walker circulation (Fig. 4) and the other convection centre over the land by the monsoon circulation (Fig. 5). Quantitatively, the Walker circulation explains 100 units while the monsoon circulation explains 60 units, and the Hadley circulation explains only 40 units, which makes the total of 200 units in Fig. 1.

As demonstrated by this result, many of the monsoon indices in previous studies measure the mixture of the convective intensity of the monsoon, Walker and Hadley circulations. The quantification of the circulation intensities separated in the individual components by a rather simple definition is the most unique point of this study. With reference to the Hadley and Walker circulations, the intensity of the monsoon circulation is measured by the peak value of the positive (negative) centre over east Asia in July (January) for summer (winter) monsoon. The typical value is 90 (−60) units for summer (winter) monsoon in climate. We should note that the intensity so defined in this paper measures only the kinematical circulation associated with the monsoon in contrast to the fact that the monsoon in previous studies is mostly defined by precipitation as well as wind. The location of the peak as well as the intensity will change in the year-to-year variation, which is also an important research subject of this study.

3.5. Comparison of the circulation indices

According to the analysis of the climate, the mean intensities of Walker, monsoon and Hadley circulations are 120: 90: 45 ($\times 10^5$ $m^2\ s^{-1}$) in July and 120: 60: 40 ($\times 10^5\ m^2\ s^{-1}$) in January, respectively. The ratio represents the relative magnitudes measured by a line integral of the circulation. The result shows that the Walter circulation is twice as strong as the monsoon circulation and is three times stronger than the Hadley circulation. In this paper, the Walker circulation contains not only the east-west circulation but also the local meridional circulation. The local meridional circulation was considered as part of the Hadley circulation in other definitions. It would be a matter of definition based simply on the direction of the circulation or that based on the essence of the driving force.

Each large-scale circulation is characterized by its typical horizontal scale. For example, the Hadley circulation has a typical scale of 4500 km from the positive peak to the negative peak in Fig. 2, both for January and July. On the other hand, the monsoon circulation has a typical scale of 8500 km in January and 10 000 km in July from the major positive to the negative peaks in Fig. 5. Likewise, the Walker circulation has a typical scale of 20 000 km as seen from Fig. 4. These scales are approximately proportional to the circulation intensity measured by the peak values of the velocity potential. The circulation intensity divided by the horizontal scale implies the typical intensity of divergent wind, which turns out to be comparable for each tropical circulation. Therefore, the intensity measured by a line integral of circulation reflects the different scale of each tropical circulation. Additional care may be needed in the scale consideration because the Hadley circulation is a zonally symmetric meridional convection whereas the other two are non-zonal (local) thermal convection.

4. Interannual variability of the tropical circulations

4.1. Walker circulation

One of the objectives of this paper is to quantify the individual circulation intensities to investigate the interannual variability of the tropical circulations. In the previous section, the intensity of the Walker circulation has been defined by the positive peak in velocity potential in Fig. 4. In order to investigate the interannual variability, the annual mean in Fig. 4 is replaced now by the 12-month running mean of the long-term monthly data after subtracting its zonal mean. The time series of the positive peak in velocity potential over the western Pacific is referred to as the Walker circulation index in this paper.

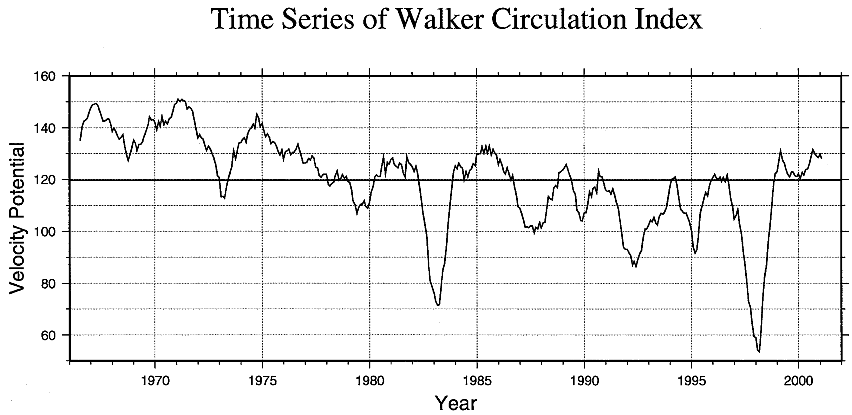

Fig. 6. Time series of the Walker circulation index defined by the 12-month running mean of the peak velocity potential over the Western Pacific in Fig. 4 evaluated for 1966–2001.

Figure 6 presents the time series of the Walker circulation index from 1966 to 2001. The index varies around the mean of 120 ($\times 10^5$ m^2 s^{-1}) with considerable interannual variability ranging from 50 to 150 units. Two noticeable events of the reduced Walker circulation occurred in 1982/1983 and in 1997/1998. These events are clearly related to the largest El Niño events which occurred in 1982/1983 and in 1997/1998 (see Bell and Halpert, 1998). That in 1972/1973 is relatively weak compared to the others. The El Niño, which is a phenomenon of SST, has a close connection to the Southern Oscillation (SO) monitored by the sea level pressure of the atmosphere. The Walker circulation index defined in this study, on the other hand, monitors the divergence field in the upper troposphere. Despite the difference between the indices, we can recognize that these two indices coincide with each other, reflecting the intensity of the Walker circulation. The result is also consistent with the Walker circulation index defined by Wang (2002) using the difference in vertical motions between the eastern and western Pacific. Based on this fact shown in Fig. 6, we can justify that the definition of the Walker circulation index in this paper reasonably represents the intensity of the Walker circulation.

There are some difference, however, between the two indices. According to the result in Fig. 6, the Walker circulation in 1997/1998 is weaker than that in 1982/1983 while the SOI shows almost the same intensity. In the present index, the La Niña event in 1988/1989 is not obvious. The SOI indicates a large positive value in 1996 which is missing in Fig. 6. It seems that the SOI represents the variability of the equatorial trade wind near the surface, while the index in the present paper represents the intensity of the Walker circulation in the upper troposphere. The Walker circulation is becoming weaker for the recent 30 yr, and a three to four year period is recognized after 1980. Because the weaker Walker circulation is accompanied by the more El Niño-like SST pattern, the result in recent decades is consistent with the recent trend of the enhanced El Niño-like SST pattern as reported by IPCC (2001). Although there is a weakening trend in the Walker circulation index in recent decades, the result of the time series is not conclusive because the data quality of the NCEP/NCAR reanalysis is questionable before 1978 when satellite observations were not available (see Onogi et al., 1998).

The interannual variability of the geographical centres of the Walker circulation defined by the peak velocity potential in Fig. 4 is analysed for 1966 to 2001 (not shown). We confirm that the circulation centre moves to the east when El Niño occurs. The result is quite reasonable, supporting that the diagram properly represents the interannual variability of the Walker circulation.

4.2. Hadley circulation

For the Hadley circulation, the interannual variability is presented separately for boreal winter (DJF) and boreal summer (JJA). The time series of the intensity is referred to as a Hadley circulation index in this study. Figure 7 presents the time series of the Hadley circulation index in DJF and JJA computed with the time series data for 1966 to 2001. For DJF, the index varies around the mean of -37 ($\times 10^5$ m^2 s^{-1}) with minor interannual variability ranging from -30 to -45 units. Because the value is negative in DJF, there is a clear increasing trend in the intensity of the Hadley circulation. The same trend is detectable for the positive centre of divergence in the Southern Hemisphere. The result is consistent with the previous analysis using the NCEP/NCAR reanalysis (e.g. Schneider et al., 2003). For JJA, the index varies around the mean of 40 units with large interannual variability ranging from 33 to 48 units. The circulation was weak in 1975, 1977 and 1998, and it was strong in 1979, 1981 and 1986. There is no obvious long-term trend for JJA. The time series indicates no significant correlation with ENSO, because the correlation is contained in the Walker circulation. A similar Hadley circulation index is documented by Oort and Yienger (1996). Their index shows insignificant link with ENSO.

4.3. Monsoon circulation

The monsoon circulation intensity is measured based on the deviation from the 12-month running mean as defined for the Walker circulation index. The time series of the intensity is referred to

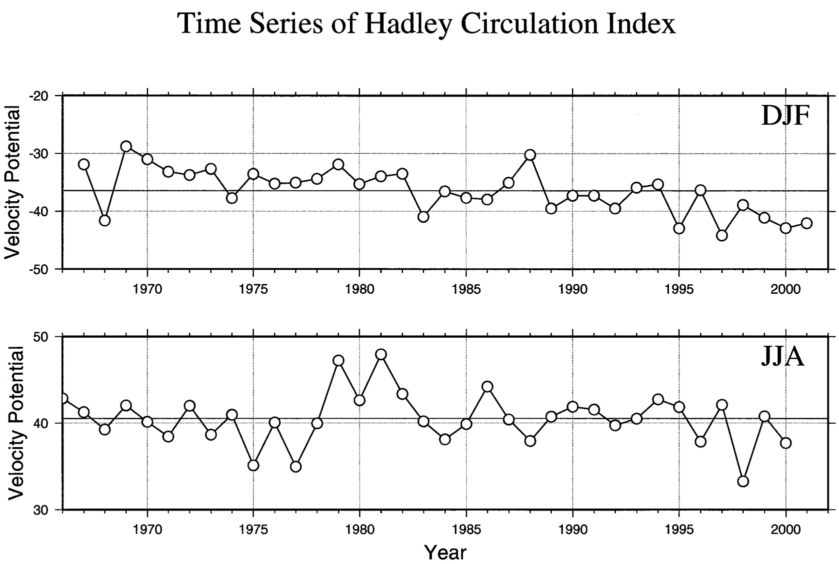

Fig. 7. Time series of the Hadley circulation index defined by the peak velocity potential around 20°N in Fig. 2 evaluated for 1966–2001 in DJF and JJA.

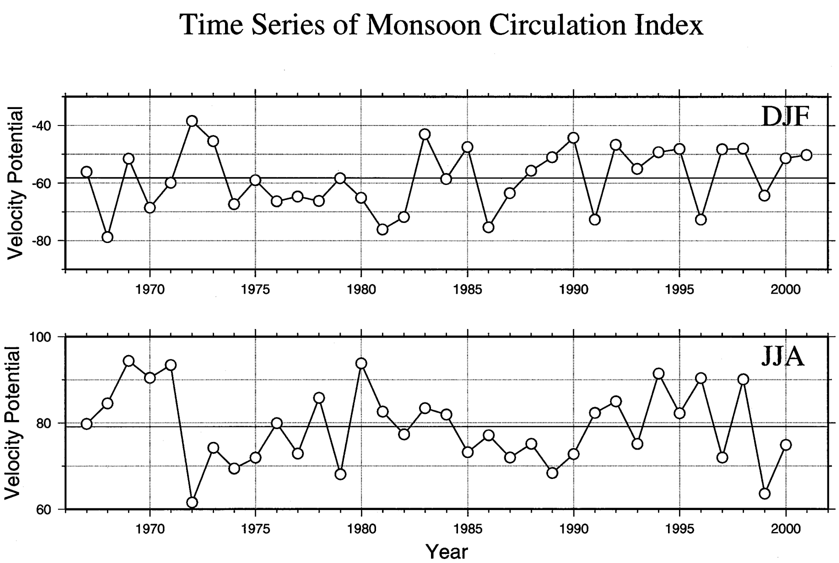

Fig. 8. Time series of the monsoon circulation index defined by the peak velocity potential in Asia in Fig. 5 evaluated for 1966–2001 in DJF and JJA.

as a monsoon circulation index in this study. Figure 8 presents the monsoon circulation index for DJF and JJA. For DJF, the index varies around the mean of -60 ($\times 10^5$ m^2 s^{-1}) with considerable interannual variability ranging from -40 to -80 units. Because the value is negative in DJF, the monsoon circulation is stronger for large negative values. The index shows five to seven year periodicity with strong winter monsoon circulation in 1968, 1981, 1986, 1991 and 1996, and weak circulation in 1972, 1983 and 1990. For JJA, the index varies around the mean of 80 units with large interannual variability ranging from 60 to 95 units. The index shows a decadal variability with an approximately 15-yr period. The summer monsoon circulation was strong in 1969, 1971, 1980, 1994, 1996 and 1998, while it was weak in 1972, 1979, 1984 and 1999. Biennial oscillation is detectable, especially for 1992 to 2000, as discussed by Yasunari (1991), Meehl (1997), Goswami et al. (1999) and Meehl and Arblaster (2002).

Figure 9 illustrates the geographical centres of the monsoon circulation defined by the peak velocity potential in east Asia. The interannual variability of the centres for 1966 to 2001 are presented for DJF and JJA with the different symbol sizes denoting the intensity. According to the result for DJF, the centre of the winter monsoon circulation moves between western and eastern China. Likewise for JJA, the centre of the summer monsoon circulation moves between the Bay of Bengal and east China. In most cases the centre is located at the Bay of Bengal, but it moves to east China every three to four years. Two different types of convection centre are documented by Wang and Fan (1999) related to the Indian summer monsoon near the Bay of Bengal and the southeast Asian summer monsoon near

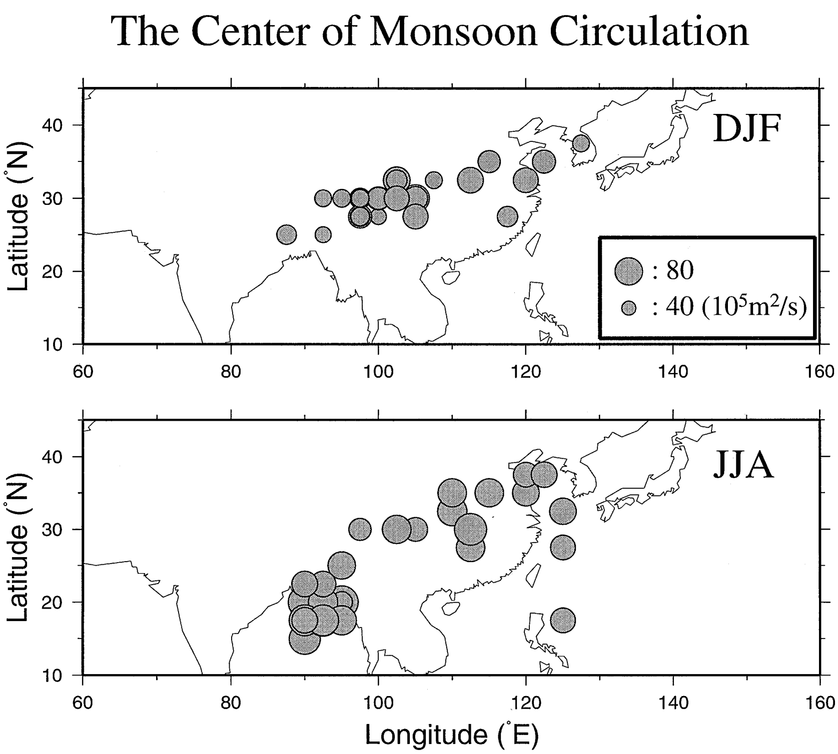

Fig. 9. The centre of the monsoon circulation defined by the location of the peak velocity potential in Asia in Fig. 5 evaluated for 1966–2001 in DJF and JJA. The symbol size indicates the intensity of the monsoon circulation.

the Philippines. They have shown that the convective activities in these two regions have no correlation and have proposed two different monsoon indices based on the Outgoing Long-wave Radiation (OLR) analysis.

The monsoon circulation index examined in this paper is compared with other monsoon indices, such as those by Parthasarathy et al. (1992), Webster and Yang (1992), Kawamura (1998), Goswami et al. (1999) and Wang and Fan (1999). Some indices consider the diabatic heat source as the important measure of the monsoon variability, monitoring the total rainfall or latent heat release over the monsoon region. Others consider the convective activity as the important measure of the monsoon variability, monitoring the OLR distribution. Basically, these indices represent the mixture of the monsoon, Hadley and Walker circulations, which are separated in this paper. The convection centre near the Philippines is explained by superposition of the Asian monsoon centred at east China, the Walker circulation over the equator, and the Hadley circulation. Therefore, care must be taken for a direct comparison of the present index with others.

We should note also that the present circulation index in Fig. 8 represents the intensity of the kinematical circulation of the divergent flow and does not represent the entity of the monsoon system. In general, the intensity of the monsoon is measured mostly by precipitation and the diabatic heat source. For this reason, it is not surprising that the present index appears to have no significant correlation with other previous indices of the monsoon system. The present index, however, has a clear physical and dynamical meaning as the intensity of the mathematical circulation associated with the large-scale monsoon system which is separated from the Hadley and Walker circulations.

5. Trend of the tropical circulations in the MRI CGCM1

5.1. *Walker circulation*

Finally, the same analysis is applied for the model atmosphere simulated by the MRI CGCM1 for 150 yr. In order to assess the impact of global warming upon the tropical circulations, a model simulation with a fixed CO_2 concentration (C-run) is compared with a gradual increase in CO_2 at a compound rate of 1% yr^{-1} (G-run). Refer to Tokioka et al. (1995) and Kitoh et al. (1997) for details of the experimental design and the model specifications. According to the model prediction, the global mean surface temperature would increase 1.6°C when the atmospheric CO_2 doubles at 70 yr later.

Figure 10 illustrates the difference in surface temperature between the C-run and G-run computed for the period from 2091 to 2110. The SST warms 1.5°C near the equator and 2–4°C over the South and North Pacific, both in January and July. A wedge-like pattern appears in the central Pacific with smaller warming near the equator surrounded by larger warming in the northwestern and southwestern Pacific.

Figure 11 presents time series of the Walker circulation index for the C-run (dashed line) and the G-run (solid line) for the years 2000–2150. The result shows marked interannual

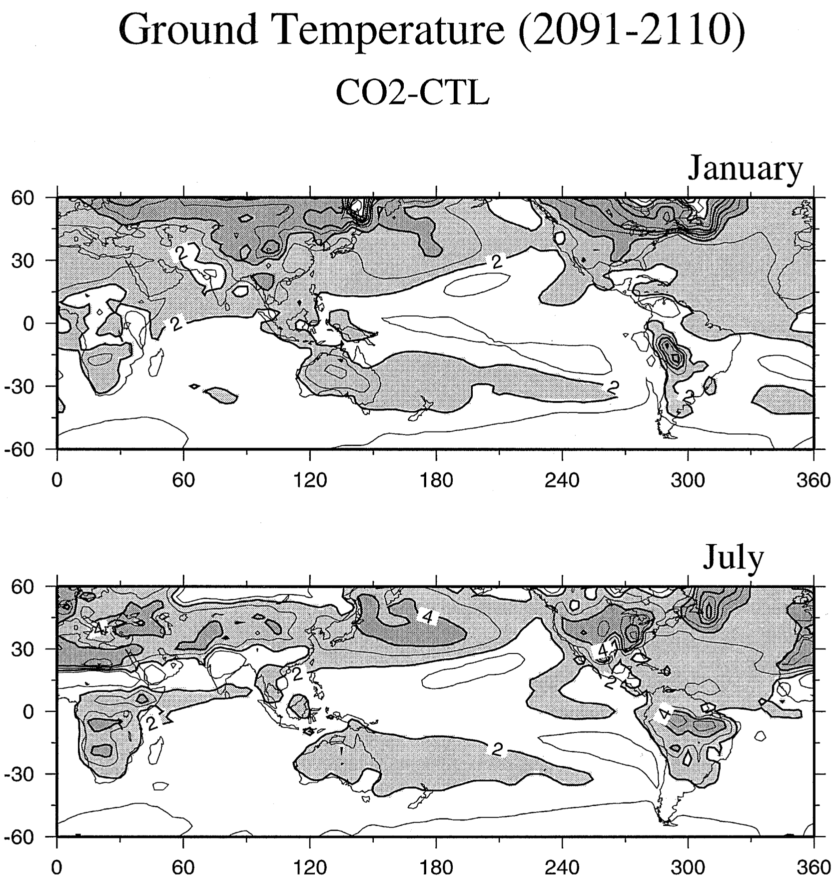

Fig. 10. Difference in surface temperature (K) between the G-run and C-run for the period from 2091 to 2110 simulated by the MRI CGCM1. Upper for January and lower for July.

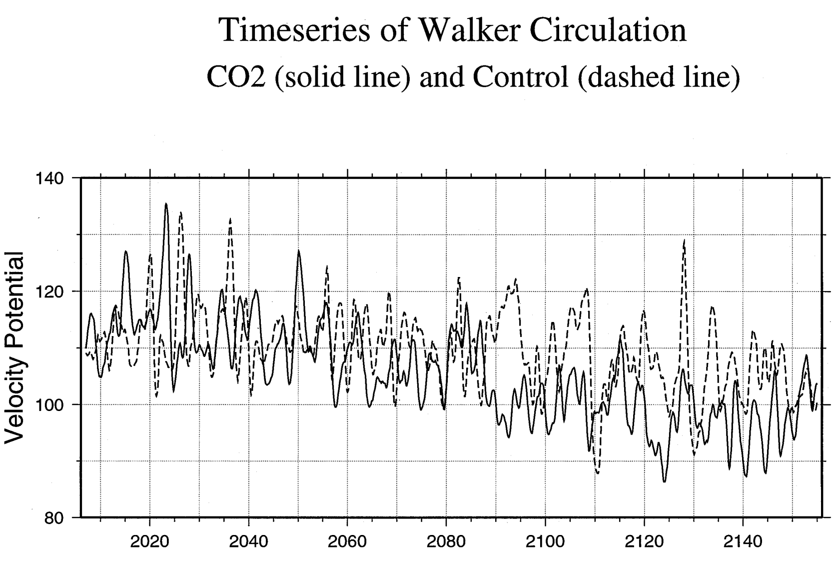

Fig. 11. Time series of the Walker circulation index for the G-run (solid line) and C-run (dashed line) for the years from 2000 to 2150 simulated by the MRI CGCM1.

variability associated with ENSO events in the CGCM1. Both the C-run and G-run indicate decreasing trends from the units of 110 to 100, indicating a decay of the Walker circulation. It seems that the G-run decreases more than the C-run. Because the difference between the two is not clear, the impact of the global warming upon the Walker circulation is not evident in the plot.

Figure 12 illustrates the difference in velocity potential between the C-run and G-run computed for the period from 2091 to 2110. A negative area appears over the Pacific while a positive area appears over the Atlantic both in January and July. The response is consistent with much warmer Atlantic Ocean in Fig. 10. The decreasing Walker circulation index appears to respond to

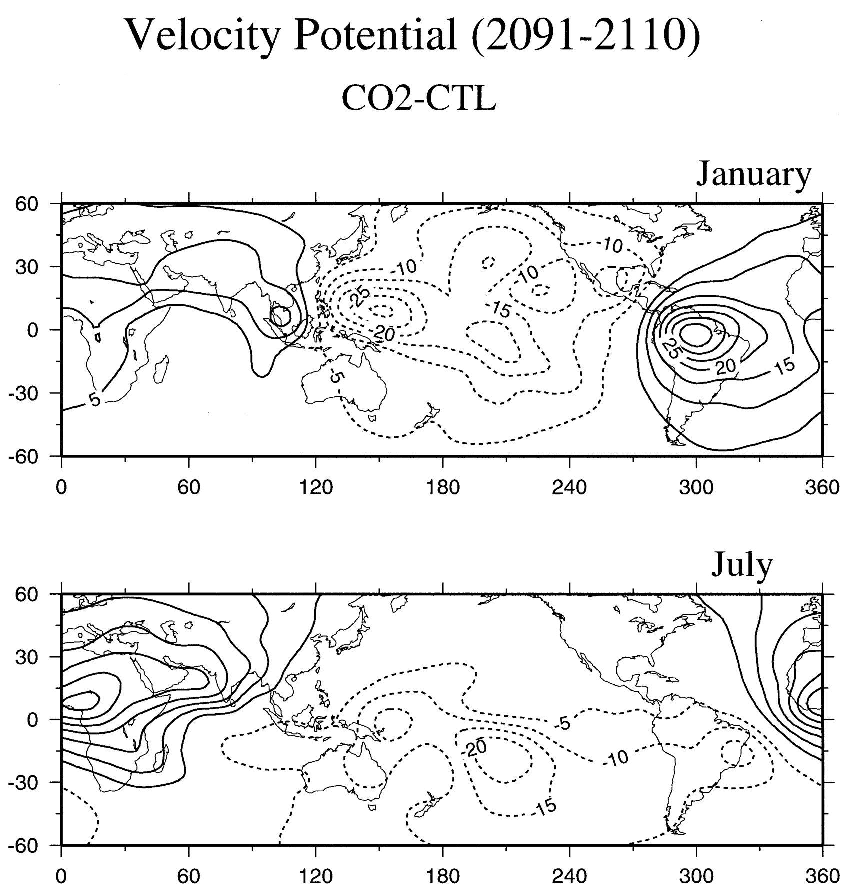

Fig. 12. Difference in velocity potential between the G-run and C-run for the period from 2091 to 2110 simulated by the MRI CGCM1. Upper for January and lower for July. Units are in 10^5 m^2 s^{-1}.

the global-scale changes in the SST, although a wedge-like La Niña pattern is detectable locally over the Pacific.

5.2. *Hadley and monsoon circulations*

Figure 13 presents time series of the Hadley circulation index for the C-run (dashed line) and the G-run (solid line) for the years from 2000 to 2150. A notable impact of the global warming appears in the intensity of Hadley circulation in JJA. The index for the G-run increases consistently by 40% from 25 to 35 units during the analysis period, while the C-run remains constant. There is no obvious trend in DJF time series.

The result after the global warming may be explained, in part, by the warmer SST over the Atlantic compared with that of Pacific in the MRI CGCM1. The warmer SST over the Atlantic results in the enhanced upward motion in the zonal mean, which causes the intensification of the Hadley circulation. Such a speculation needs to be verified by further extensive analyses of the various climate variables.

Figure 14 presents the same time series of the monsoon circulation index. The result shows that the index for the G-run tends to decrease by 20% in JJA while the C-run remains constant. There is no obvious trend in DJF time series. According to Kitoh et al. (1997), the summer monsoon rainfall in India increases notably with global warming, while the kinematical circulation measured by the monsoon wind shear index decreases. They explain that the increased moisture content in the warmer air leads to the increase of rainfall even though the kinematical circulation weakens due to global warming. The result of the present study is consistent with their result and interpretation. The monsoon rainfall does not necessarily correlate with the kinematical monsoon circulation. The result demonstrates the usefulness of the proposed kinematical separation of the tropical circulations in the Hadley, monsoon and Walker components.

6. Concluding summary

In this paper, the tropical circulations, such as the Hadley, Walker and monsoon circulations, are separated considering their different driving forces. The Hadley circulation should exist even under a hypothetical aqua-planet with no topography or land–sea contrast, because the meridional differential heating of the global radiative process is its essential driven force. The Hadley circulation in this paper is thus defined as the zonally symmetric meridional circulation ascending over the mean ITCZ and descending over the subtropical high-pressure belt. We consider that the remainder of the non-zonal component contains information on the Walker and monsoon circulations. Among these,

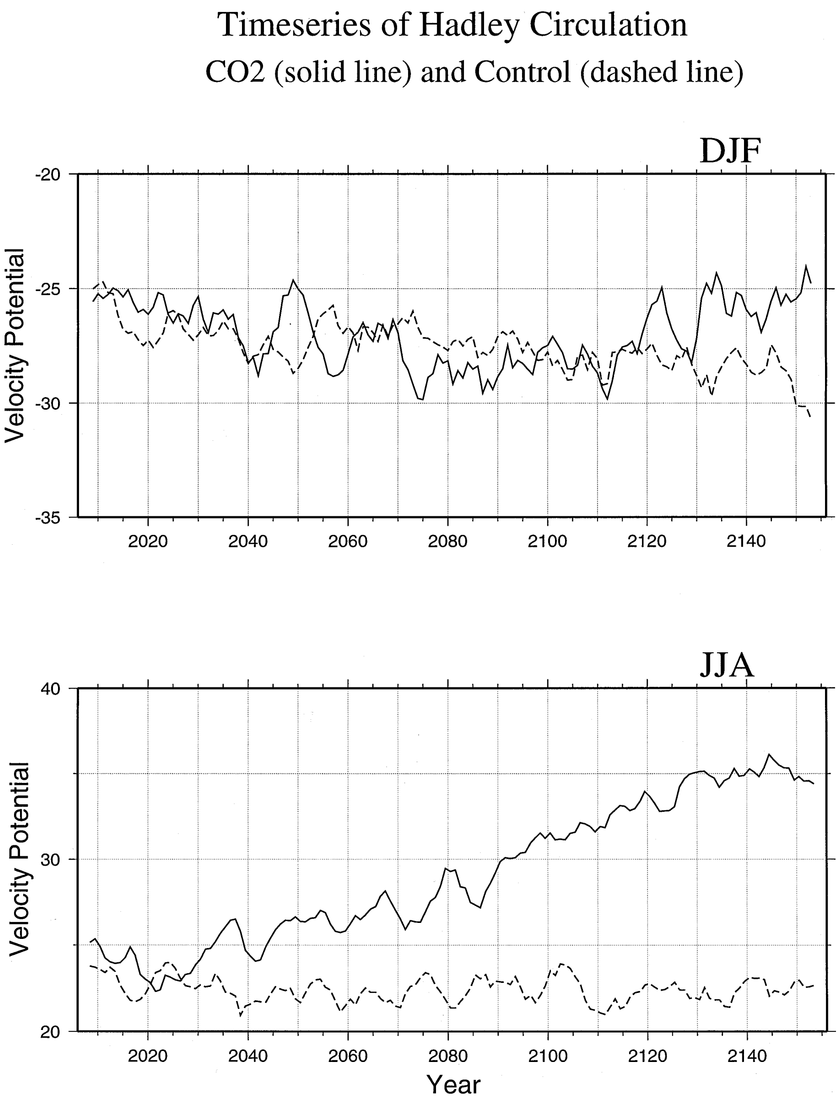

Fig. 13. Time series of the Hadley circulation index for the G-run (solid line) and C-run (dashed line) for the years from 2000 to 2150 simulated by the MRI CGCM1. Upper for DJF and lower for JJA.

the seasonally changing component reflects the essence of the monsoon circulation because the annual mean component should not be associated with the monsoon. Based on this reasoning, the seasonally changing part is considered as the monsoon circulation, and the rest of the annual mean component is defined as the Walker circulation in this paper.

In order to analyse the large-scale characteristics of these thermally induced circulations, the upper tropospheric (200 hPa) velocity potential is chosen as the suitable parameter for our purpose. The mean intensities of each circulation are defined by their peaks in the velocity potential field separated in each component (units measured by 10^5 m^2 s^{-1}). The peak value represents the intensity of each circulation system measured by the mathematical line integral of a circulation.

As a result of the analysis, we have shown that the mean intensities of the Walker, monsoon and Hadley circulations appear to be 120: 60: 40 units in January and 120: 90: 45 units in July, respectively. Namely, the Walker circulation is twice as strong as the monsoon circulation and three times stronger than the Hadley circulation. Because the typical magnitude of the divergent wind is comparable, the difference in the circulation comes from the different scale of the phenomena. Based on this separation, we have shown that the convection centre near the Philippines in July is explained by superposition of the contributions from the Walker circulation (100 units), the monsoon circulation (60 units) and the axisymmetric Hadley circulation (40 units).

Once the intensity of each circulation is quantified, we then investigate the pattern and interannual variability of each circulation. The Walker circulation indicates upward motion with upper-level divergence centred at the equatorial western Pacific. The upper-level divergence is linked with the convergence at the eastern equatorial Pacific and Atlantic. The interannual variability of the Walker circulation index reasonably coincides with the

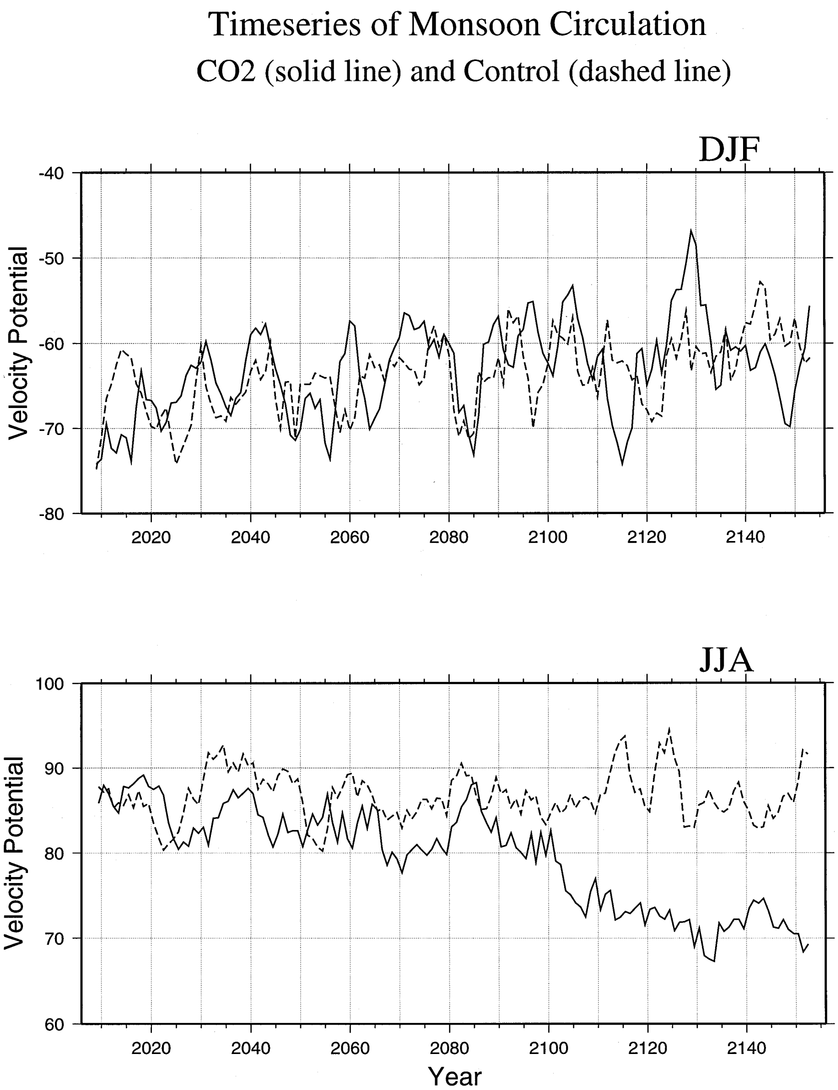

Fig. 14. Time series of the monsoon circulation index for the G-run (solid line) and C-run (dashed line) for the years from 2000 to 2150 simulated by the MRI CGCM1. Upper for DJF and lower for JJA.

SOI with marked ENSO events in 1982/1983 and 1997/1998. There is a significant weakening trend in the Walker circulation in the last decades, at least after 1979. The result is, however, not conclusive due to the data quality in the NCEP/NCAR reanalysis before 1979 when satellite data were not available.

The Hadley circulation indicates an intensifying trend especially for the boreal winter. The circulation for the boreal summer indicates no obvious long-term trend. It was weak in 1975, 1977 and 1998, and strong in 1979, 1981 and 1986. The strong ENSO signal is contained in the Walker circulation in this paper, and no significant connection remains in the Hadley circulation.

The monsoon circulation for boreal summer indicates the upward motion with upper-level divergence centred at east Asia and the compensating convergence at the eastern Pacific and at the Atlantic. It may be important to note that the centre of the monsoon circulation is located on the land instead of the maritime continent. For boreal winter, the divergent wind pattern appears to reverse showing downward motion with upper-level convergence at east Asia, as expected from the inherent characteristics of the monsoon circulation system. The intensity of the monsoon circulation is measured by the peak value of the velocity potential over east Asia. For boreal winter, the winter monsoon circulation shows five to seven year periodicity with strong circulation in 1968, 1981, 1986, 1991 and 1996. For the boreal summer, the summer monsoon circulation shows decadal variability with an approximately 15-yr period. The circulation was strong in 1969, 1971, 1980, 1994, 1996 and 1998, while it was weak in 1972, 1979, 1984 and 1999. Biennial oscillation is detected, especially for 1992 to 2000, as discussed by Yasunari (1991), Meehl (1997), Goswami et al. (1999) and Meehl and Arblaster (2002).

In previous studies, many indices were proposed to represent the intensity of the monsoon system (e.g. Parthasarathy et al., 1992; Webster and Yang, 1992; Kawamura, 1998; Goswami et al., 1999; Wang and Fan, 1999). Because these indices represent the mixture of the monsoon, Hadley and Walker circulations, care must be taken for a direct comparison of the present index with others. In general, the intensity of the monsoon is measured mostly by precipitation and the diabatic heat source. We should note here that we are concerned only with the intensity of the kinematical circulation associated with the monsoon system. The choice of a better index may depend on the objectives of the study.

Finally, the same analysis is applied for the model atmosphere for 150 yr provided by the MRI CGCM1. In order to assess the impact of global warming upon the tropical circulations, a model simulation with a fixed CO_2 concentration (C-run) is compared with a gradual increase in CO_2 at a compound rate of 1% yr^{-1} (G-run) documented by Tokioka et al. (1995) and Kitoh et al. (1997). According to the result of the analysis, it is shown that the Hadley circulation would intensify by 40% and monsoon circulation would decay by 20% in boreal summer when the global warming has occurred a century later. Although the cause of such a trend needs to be pursued by further investigation, the result demonstrates the usefulness of the proposed simple separation of the tropical circulations in the Hadley, monsoon and Walker circulations for the assessment of the model response to global warming.

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