NOTES AND CORRESPONDENCE

On the Seasonality of the Hadley Cell

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ABSTRACT

The annual march of the climatological mean meridional circulations (MMCs) in the NCEP–NCAR reanalyses is dominated by two components of roughly comparable mean-squared amplitude: 1) a seasonally invariant pair of ''Hadley cells'' with rising motion centered near and just to the north of the equator and subsidence in the subtropics, and 2) a seasonally reversing, sinusoidally varying ''solsticial'' cell with ascent in the outer Tropics of the summer hemisphere and subsidence in the outer Tropics of the winter hemisphere. The meridional structure and seasonal evolution of the solsticial cell are suggestive of a close association with the monsoons. These results are consistent with previous analyses of the mean meridional circulation based on radiosonde data.

The mean meridional circulation (MMC) envisioned by Hadley (1735) and other authors cited in Lorenz's (1967) historical review, consists of a pair of equator-to-pole, thermally direct cells, one in each hemisphere, symmetric about the equator. The ''Hadley cell'' appellation continues to be used for the tropical, annual mean MMC dominated by the year-round rising motion over the equatorial belt and sinking motion over the subtropics (Glickman 2000), but the same term is also widely used to denote tropical MMC in general.

Analysis of global radiosonde observations by Oort and Rasmusson (1970), Newell et al. (1972), Peixoto and Oort (1992), and Oort and Yienger (1996), have shown the existence of a more complicated, seasonally varying distribution of MMC, dominated by a cross-equatorial cell with low-level flow from the winter Tropics into the summer Tropics, and an upper tropospheric flow in the reverse sense. This general scheme is confirmed in the 1979–2001 National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis shown in Fig. 1. Here, as in the previous analyses, the Stokes streamfunction Ψ is derived from a downward integration of the meridional mass flux, using data at all available levels (in this case, 10, 20, 30, 50, 70, 100, 150, 200, 250, 300, 400, 500, 600, 700, 850, 925, and 1000 hPa). A small correction is applied at the lowest four levels to ensure that $\Psi = 0$ on the bottom boundary. A closer comparison to analyses using rawinsonde data (i.e., Oort and Yienger 1996) shows that, in the NCEP reanalysis, the maximum Ψ values are somewhat smaller than those derived from radiosonde data by Oort and Yienger (14–16 versus 20×10^{10} kg s^{-1}), and the Southern Hemisphere cell is slightly more strongly emphasized relative to the Northern Hemisphere cell.

Lindzen and Hou (1988, hereafter LH) drew attention to the cross-equatorial cell, characterizing it as a ''solsticial pattern,'' as opposed to the classical, equatorially symmetric ''equinoctial pattern.'' Based on their visual inspection of the 1958–63 meridional cross sections in Oort and Rasmusson (1970), they remarked that ''the meridional circulation is almost always in a solsticial pattern; the idealized equinoctial pattern is almost never realized.'' Their theoretical analysis suggested that the distribution of MMC is highly sensitive to small equatorial asymmetries in the imposed temperature of the underlying surface: so much so that the displacement of the thermal equator from the geodetic equator by even a few degrees of latitude would give rise to a solsticial (or equatorially asymmetric) circulation as strong or stronger than the classical, equatorially symmetric ''Hadley cell.'' Mindful of this sensitivity, they predicted that the solsticial component would dominate the tropical MMC throughout most of the year and that its

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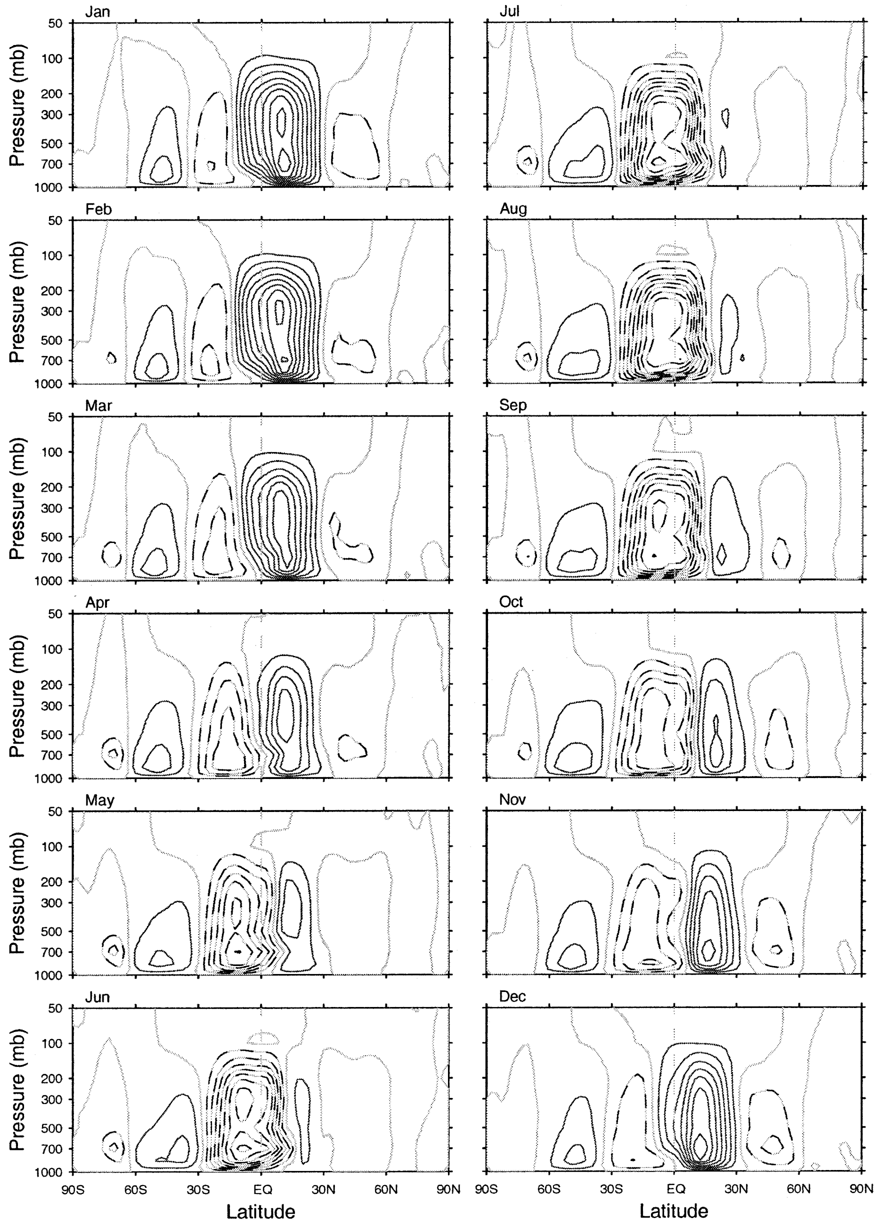

FIG. 1. Monthly variation of the climatological-mean streamfunction in the NCEP–NCAR reanalysis. Contour interval 2×10^{10} kg s^{-1}. Solid contours are positive, dashed contours are negative, and the zero contour is gray. Cells surrounding positive centers are characterized by clockwise circulations and vice versa.

amplitude would exhibit more of a ''square wave'' than a sinusoidal dependence on Julian day. Fang and Tung (1999) extended the analysis in LH to a time-dependent model and found that the seasonal transitions were not as abrupt as LH had predicted. Nonetheless, the notion that the solsticial cell might be driven primarily by rather modest displacements of the thermal equator persists as an alternative to the traditional view that it is largely a reflection of the regionally concentrated monsoon circulations (Newell et al. 1972; Das 1986). Here we analyze the MMC in the NCAR–NCEP reanalyses with emphasis on the relative importance and seasonal progression of the solsticial component and the residual derived by subtracting the solsticial component from the total field.

Figure 2 shows a histogram of the difference in the intensities of the northern and southern cells, as given by the average of their extrema in the streamfunction at the 300-hPa level, based on 19 yr of 5-day-mean data (1979–97). When the circulation is equatorially sym-

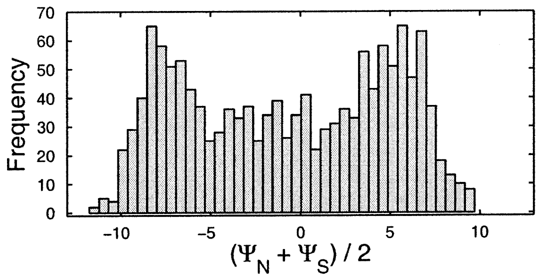

FIG. 2. Histogram showing the difference in strength between the northern and southern tropical circulation cells in 19 yr of 5-day mean data.

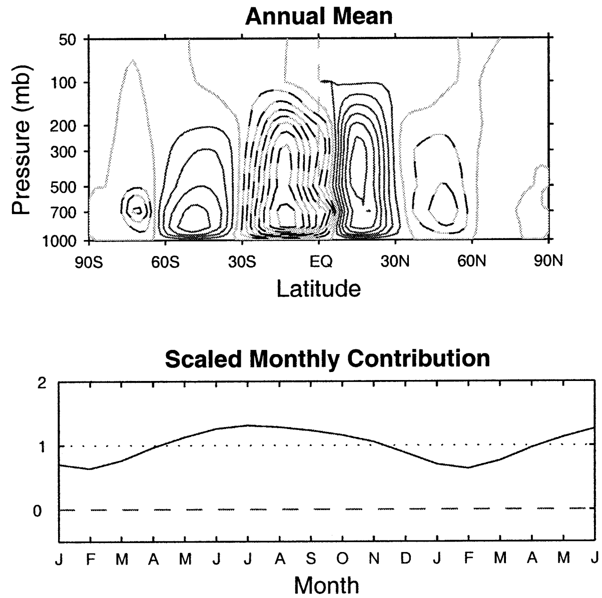

FIG. 3. (a) Annual mean streamfunction field based on the NCEP–NCAR reanalysis and (b) the scaled monthly contribution of the MMC to the annual mean. The contour interval in (a) is 10^{10} kg s^{-1}. The time series in (b) was obtained by projecting the monthly mean climatological MMC onto the annual mean pattern; the time series was scaled so that its time mean equals 1.

metric, the northern and southern cells are of comparable strength, but of opposing sign, yielding an average close to zero; when the northern cell dominates, the average is positive, and when the southern cell dominates, it is negative. The frequency distribution is bimodal with a minimum near the equator, but the minimum is not as pronounced as it would be if the MMC were dominated by a solsticial cell, whose annual march had the shape of a square wave.

The annual-mean streamfunction shown in Fig. 3a is dominated by the equatorially symmetric component, with ascent in the tropical belt and subsidence in the subtropics. Upon close inspection it is evident that the axis of symmetry is not precisely on the equator, but a few degrees to the north of it, and that there is a particularly strong meridional gradient of the streamfunction across 7°N, which corresponds to the mean latitude of the intertropical convergence zone over the Pacific and Atlantic. The region of ascent in between the two cells corresponds closely to the band of heavy near-equatorial rainfall, as illustrated in Figs. 4a,b. The southern cell is slightly stronger than the northern cell. Figure 3b shows the scaled monthly contribution of the climatological MMC to the annual mean pattern (represented in Fig. 3a). The associated time series exhibits only small annual variations about the time mean, thus indicating that the pattern describing the annual mean MMC is present all months of the year, with only minor variations from month to month.

In order to document the variability about the time mean we performed an EOF analysis upon the monthly mean climatological Ψ field (1979–2001). In this analysis the values at each grid point were weighted by the square root of cosine of latitude, and the values at each level were weighted by increments of the pressure that they represent. Figure 5 shows leading standardized principal component (PC) time series and the corresponding regression pattern for Ψ. This mode accounts for 97.4% of the variance of the climatological-mean streamfunction about the annual mean. It is almost perfectly equatorially asymmetric and seasonally reversing, with extrema in January–February and July–August. Its seasonal variation is sinusoidal, with no indication of square wave behavior.

That 1) the annual mean accounts for an appreciable fraction of the mean squared amplitude of the MMC and 2) the solsticial mode accounts for nearly all the seasonal variability about the annual mean guarantees that the residual MMC obtained by subtracting the solsticial mode (Fig. 6) is dominated by the annual mean. Hence, the classical, nearly equatorially symmetric ''Hadley cell'' is not an ephemeral equinoctial feature of the general circulation, as envisioned in LH; it is robust and present year round.

This seasonally reversing solsticial mode and the annual mean together account for 98.5% of the mean-squared amplitude of the climatological-mean Ψ field. The seasonally reversing mode explains somewhat more of the mean-squared amplitude than the annual mean but, owing to its smaller meridional scale, the annual mean explains slightly more of the vertical mass flux. Qualitatively similar results are obtained when the MMC is formally decomposed into equatorially symmetric and asymmetric components (not shown). Thus, the mean and seasonally reversing (or alternatively, the equatorially symmetric and asymmetric) components of the MMC can be considered to be of roughly comparable importance.

In agreement with prior results of Newell et al. (1972) and Schulman (1973), we find a close corre-

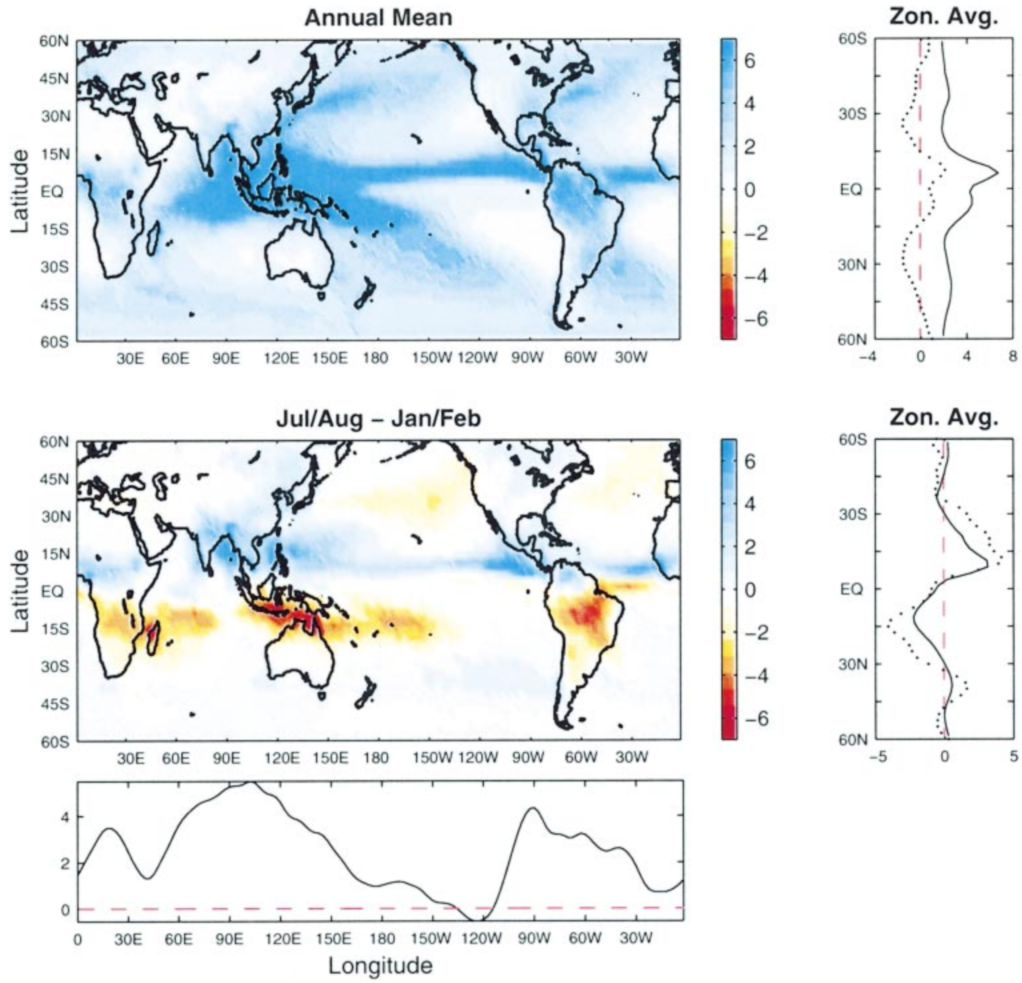

FIG. 4. (a) Annual-mean and (b) seasonally varying components of the precipitation field (upper left panels) and (c) longitudinal contribution of the 15°N–15°S 200-hPa meridional wind to the meridional wind associated with the solsticial cell (bottom). Here, (a) and (b) are based on Climate Prediction Center Merged Analysis of Precipitation data for the 1979–2001 period (units: mm day^{-1}) The seasonally varying component is approximated as half the difference between the Jul/Aug and Jan/Feb mean fields. The panels on the right show the zonally averaged values (solid). Also shown in the right-hand panels are the 500-hPa vertical velocity profiles (units: cm s^{-1}; dotted), rescaled by multiplying them by a factor of 6 to make their profiles more clearly visible in the figure.

spondence between the vertical mass flux in the seasonally reversing cell and the belts of monsoon rainfall over the tropical continents (Fig. 4b). The associated cross-equatorial mass fluxes in the upper and lower branches of the cell reach peak values in excess of 1.75×10^{11} kg s^{-1} and are each sufficient to transfer roughly half of the mass of an entire hemisphere across the equator over the course of the monsoon season.

The peaks in the seasonally reversing ''solsticial cell,'' which are actually observed 6 weeks after the dates of the solstices, correspond closely to the peaks of the monsoon seasons. That the contribution to the solsticial cell [empirical orthogonal function (EOF)1] comes primarily from the monsoonal regions is also apparent in Fig. 4c in which the 200-hPa meridional wind is used to represent the longitudinal contribution of the monthly mean climatological field to the solsticial cell. The maximum contributions come from the continental/monsoonal regions while the minimum contributions come from the ''pure'' oceanic regions (central Pacific). The timing, together with the strong correspondence between the meridional structure of EOF 1 of MMC and the belts of seasonally varying rainfall (Fig. 4b), supports the view that the seasonally reversing solsticial cell is closely associated with the monsoons.

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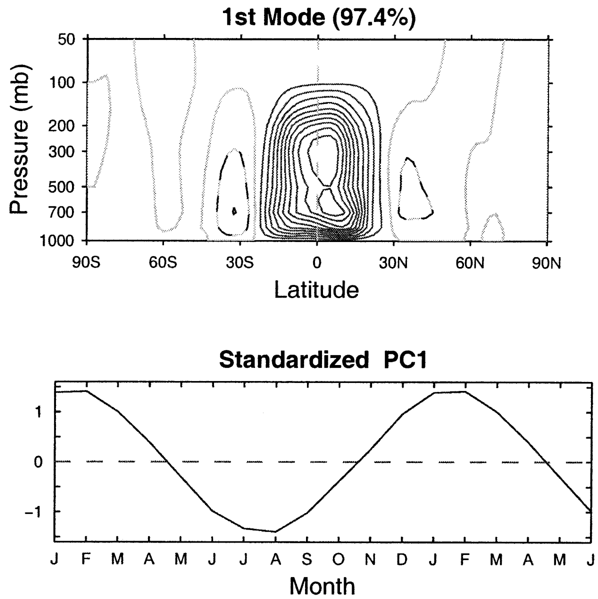

FIG. 5. (a) The streamfunction field regressed upon the leading principal component of the departure of the climatological-mean streamfunction field from its annual mean (contour interval 10^{10} kg s^{-1}). (b) The corresponding standardized principal component.

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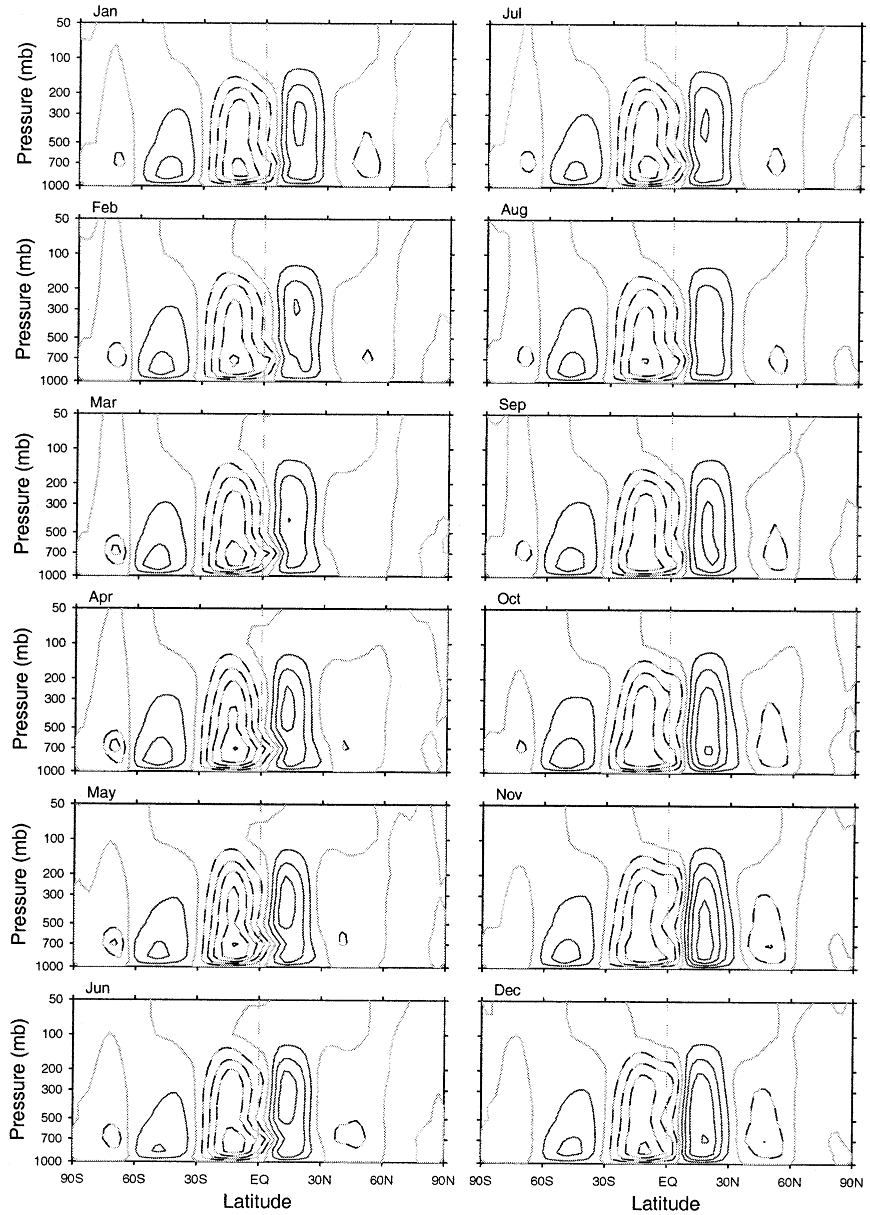

FIG. 6. Monthly mean residual MMC derived by removing the seasonally reversing component associated with the EOF1. (Contour interval 2×10^{10} kg s^{-1}.)