NOTES AND CORRESPONDENCE

Equatorial Zonal Circulations from the NCEP–NCAR Reanalysis

By Stefan Hastenrath

Department of Atmospheric and Oceanic Sciences, University of Wisconsin, Madison, USA

(Manuscript received 25 June 2000, in revised form 18 December 2000)

Abstract

The NCEP–NCAR 1958–97 upper-air dataset has been evaluated for evidence of equatorial zonal circulation cells around the globe. For this it is essential not only to isolate the divergent part of the wind but also to ascertain the continuity following the flow between the centers of upward and downward motion. Over the eastern to central Pacific a well developed cell persists all year round, with subsidence in the East, but with the compensating divergent westward flow concentrated in the realm of a midtropospheric jet rather than at the surface. A cell over the western Atlantic in January is characterized by subsidence in the East and divergent westerly flow at the surface. In the Indian Ocean sector during July, a small cell is recognized over the western part of the basin, contained in the upper-to mid-troposphere and with subsidence over the East African coast. In October a well developed cell spans the entire basin, with subsidence over the East African coast and eastward flow in the lower troposphere.

1. Introduction

The widespread belief in vertical-zonal circulation cells along the Equator can be traced to an intuitive paper by Bjerknes (1969), based on five years of radiosoundings at three stations in the equatorial belt (5°N–5°S). With reference to a zonal cross section along the Equator (his Fig. 8), he proposed a circulation cell in the vertical-equatorial plane over the Pacific, which he named Walker Circulation, with subsidence in the East, easterlies at the surface, ascending motion in the West, and westerly return flow in the upper troposphere. The dynamics of this cell in the near vicinity of the Equator are characterized by vanishing Coriolis acceleration and thus balance between the pressure gradient and frictional accelerations. Subsequent publications hypothesized other such cells for other longitudes around the globe (review in Hastenrath 1995, p.198–201). Thus Flohn (1971) inferred four zonal circulation cells along the Equator from the zonal profiles of sea surface temperature (SST) and satellite-inferred convection. Newell (1979) perceived five equatorial circulation cells from wind observations (Newell et al. 1972, 1974, p.151), as did Chervin and Druyan (1984) from numerical modeling experiments. Krishnamurti (1971) and Krishnamurti et al. (1973) analyzed the circumpolar 200 mb wind field for one winter and one summer season to infer zonal circulation cells in broad bands away from the Equator. In the process Krishnamurti (1971) pioneered the analysis method appropriate for the study of divergent flow.

The NCEP–NCAR Reanalysis has opened new prospects for tropical diagnostics. While based on the model assimilation of observations, it constitutes an internally consistent system. This upper-air dataset invited a re-appraisal of widely held notions on equatorial circulation cells. With this motivation, a sequel of recent studies examined the evidence for equatorial zonal circulation cells over the Pacific, the Indian Ocean, and the Atlantic sector (Hastenrath 1999, 2000, 2001a). The present paper places these results into global context.
2. Data and methods

The data source for this study is the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Reanalysis (Kalnay et al. 1996) for the years 1958–97. Data were processed into individual monthly mean fields. Elements of interest here are the fields of wind and vertical velocity for the levels surface (10 m), 1000, 925, 850, 700, 600, 500, 400, 300, 200 and 100 mb.

From the total wind field at selected levels, velocity potential and streamfunction were computed as described in Krishnamurti (1971) and Krishnamurti et al. (1973), with full coverage from 75°N to 75°S and a grid spacing of 2.5 degrees. An inner subdomain from these near-global fields is used here. Maps of divergent wind component and divergence were then constructed from the fields of velocity potential.

Essential for the study of circulation cells in the tropics is the analysis of the divergent part of the wind field and of divergence at various levels and especially in the upper troposphere. From this one obtains the fields of vertical motion, especially in the mid troposphere. In light of the implied dynamics of the Walker Circulation (Bjerknes 1969), zonal-vertical cross sections are appropriate for a narrow latitude strip in the near vicinity of the Equator. These may combine the distributions of vertical motion and of the zonal component of the divergent part of the wind field. However, this is not sufficient to discern closed circulation cells: while having a zonal component, the divergent flow may not be directed along the Equator but substantially across it. This may be appreciated from maps of the divergent flow at indicative levels. Accordingly, maps of 200 mb divergence and divergent flow and of 500 mb omega vertical motion are presented here for the strip 15°N–15°S, and zonal-vertical cross sections of vertical and divergent zonal motion and of total zonal flow in the narrow strip 25°N–25°S, both extending all around the globe. The maps were all analyzed at the available 2.5 degree spatial resolution, but the vectors of the divergent wind were then combined into 5 degree blocks, for effective map presentation.

3. Analysis

The mean upper-air circulation from the NCEP–NCAR 1958–97 dataset is presented here for the months January, April, July and October. Maps portray the fields of upper-tropospheric divergence and divergent flow (Figs. 1a to 4a) and of mid-tropospheric vertical motion (Figs. 1b to 4b). Cross sections for the narrow equatorial strip 2.5°N–2.5°S depict the flow in the zonal-vertical plane (Figs. 1c to 4c and 1d to 4d). These analyses serve to isolate not only the divergent part of the wind but also ascertain the continuity following the flow between the centers of upward and downward motion, prerequisites indispensable for the identification of circulation cells.

The January conditions are portrayed in Fig. 1. The map (Fig. 1a) of upper-tropospheric divergence and divergent wind component features three centers of divergent outflow over Africa, South America and the central Pacific, and two centers of convergent inflow over the Atlantic and the eastern Pacific. Westward directed divergent flow extends from the central Pacific across the Indian Ocean into the divergence center over Africa, from where the flow is mainly northward; the divergent outflow from South America is directed mainly northward and to a lesser extent eastward to the Atlantic convergence center, and westward to the convergence center over the eastern Pacific; the latter further receives divergent to convergent inflow from the central Pacific. In accordance with Fig. 1a, the map (Fig. 1b) shows ascending motion in a broad zone extending from the Pacific across the Indian Ocean to Africa and over South America, and subsidence over the eastern Pacific and the Atlantic. The zonal-vertical cross section (Fig. 1c) features at its eastern extremity, or Indonesia, the greatest lower-tropospheric convergence, strong ascending motion and upper-tropospheric divergence, and divergent outflow, directed in part westward (although more prominently northward). Over the western Indian Ocean, there is upper-tropospheric convergent inflow with a westward component, subsidence, divergence in the mid to lower troposphere, and divergent outflow eastward concentrated around 700 mb. Over the African continent, ascending motion feeds into upper-tropospheric divergence, with a westward outflow to a center of convergence over the eastern to central Atlantic, which further receives convergent inflow from a center of divergent outflow over the Amazon basin and the adjacent Atlantic. Concordant with the upper-tropospheric divergence distribution, there is subsidence over the eastern Atlantic, and in the lower troposphere divergent to convergent flow westward, feeding into the ascending motion over the western Atlantic and
Fig. 1. The 1958–97 mean upper-air circulation in January. (a) Map of 200 mb field of divergent wind with arrows scaled at one degree latitude for 2 ms$^{-1}$. Divergence is shown with isoline spacing of $2 \times 10^{-4}$ ms$^{-1}$ and dashed lines indicating negative values. (b) Map of 500 mb omega vertical motion, with isoline spacing of $10^{-4}$ mb s$^{-1}$ and dashed lines indicating negative values or upward motion. (c) Zonal-vertical cross section of zonal circulation at 2.5°N–2.5°S along the Equator. Shading distinguishes domains of convergence from those of divergence, with thin solid lines enclosing values beyond $1 \times 10^{-4}$ s$^{-1}$ in absolute amount. The scaling of arrows is as follows: 2 ms$^{-1}$ corresponds to a horizontal length of 3 degrees longitude, and $2 \times 10^{-4}$ mb s$^{-1}$ to a vertical length of 35 mb. (d) Cross section of total zonal wind component with isotach spacing of 5 ms$^{-1}$ and dashed lines indicating flow from the East.
Amazon basin. This supports upper-tropospheric outflow which is overwhelmingly directed northward (Fig. 1a). Some divergent outflow is also directed westward, and this converges downstream and flows into the subsidence centered over the eastern Pacific. The compensating outflow converges downstream and feeds into the center of ascending motion and upper-tropospheric divergence over the central to western Pacific. Upper-tropospheric outflow from there is in part directed eastward; it becomes convergent downstream and feeds into the center of subsidence over the eastern Pacific. From the western Pacific upper-tropospheric divergent flow is also directed westward towards the Indian Ocean. The total zonal flow (Fig. 2d) is again strongly easterly throughout much of the upper to mid-troposphere, while westerlies prevail in the lower troposphere over the central Indian Ocean, the western portion of Africa and the easternmost Pacific. Upper-tropospheric westerlies over the Atlantic and eastern Pacific are weak.

The July patterns presented in Fig. 3 differ substantially from those of the boreal winter half-year in Figs. 1 and 2. Pronounced in the fields of upper-tropospheric divergence and divergent flow (Fig. 3a) is the broadly southward directed divergent outflow throughout, and particularly in the Asian sector. There is some eastward and westward inflow into a convergence center over the Atlantic, and some eastward component is noted over the Pacific. A band of ascending motion extends all around the globe, with some interuption over the western Indian Ocean (Fig. 3b). The ascending motion over Indonesia (Fig. 3c) is much weaker than in the other mid-season months. Subsidence over the East African coast feeds mainly into an eastward divergent outflow centered on 700 mb; this passes into convergence to fuel the vigorous upward motion around 60°E, mainly upward of 700 mb. Thus a distinct zonal circulation cell is contained in the upper to mid troposphere between about 35 and 70°E. Over the African continent ascending motion is weak. Over the eastern to central Atlantic powerful subsidence is fed by strong upper-tropospheric inflow from northern quadrants (Fig. 3a) with little contributions from the zonal direction. Convergent easterlies continue in the lower layers over the western Atlantic and South America. Over the eastern Pacific subsidence is even stronger than during the winter half-year, but this is fed by upper-tropospheric inflow from the North (Fig. 3a) and is not associated with the ascending motion over South America. The subsidence over the eastern Pacific feeds into the mid-tropospheric westward flow, which fuels the upward motion and upper-tropospheric divergence over the central to western Pacific. The upper-tropospheric outflow is di-
Fig. 3. As Fig. 1 but for July.
Fig. 4. As Fig. 1 but for October.
rected in part eastward, changes downstream from divergent to convergent, and feeds into the subsidence over the eastern Pacific. From the western Pacific and Indonesian region upper-tropospheric divergent outflow has some component westward, although the map (Fig. 3a) manifests the prevalent outflow towards the Southsouthwest and South-west. The total zonal flow (Fig. 3d) is prevailing from the East. The Tropical Easterly Jet (TEJ) in the upper troposphere is apparent from the Indian Ocean over Africa to the Atlantic sector. A mid-tropospheric easterly speed maximum extends from the Americas to the Pacific, a manifestation of the EMTEJ. Over the Indian Ocean sector a strong westerly speed maximum is centered around 700 mb and 60–90°E. Westerlies persist in the lowest part of the troposphere over the western portion of Africa and the easternmost Pacific.

The October patterns (Fig. 4) resemble those of July (Fig. 3). The fields of upper-tropospheric divergence and divergent wind component (Fig. 4a) continue to show the prevailingly southward directed divergent to convergent flow, especially in the Asian sector; zonal inflow takes place into the convergence centers over the Atlantic and eastern Pacific. The map of mid-tropospheric vertical motion (Fig. 4b) features ascending motion at most longitudes, strongest in the realm of the centers of upper-tropospheric divergent outflow over Asia, Africa, South America, and the central Pacific, with some subsidence over coastal East Africa, the Atlantic, and eastern Pacific (Fig. 4b). The zonal-vertical cross section (Fig. 4c) shows over Indonesia strong lower-tropospheric convergence, ascending motion, and upper-tropospheric divergence, with divergent outflow towards the West and South (Fig. 4a). Subsidence prevails over the coast of East Africa, with upper-tropospheric convergent inflow from Central Africa in the West and particularly from the Indian Ocean in the East. Indeed in this season divergent easterly flow along the Equator is well developed (Fig. 4a). Similar to July (Fig. 3c), the subsidence over the East African coast feeds primarily into divergent outflow eastward centered around 700 mb, where a core of strong westerlies extends from about 50 to 90°E. At about 60–90°E the westerlies extend all the way to the surface. Over the African continent, ascending motion is stronger than in July. The subsidence and upper-tropospheric convergence over the eastern Atlantic are fueled largely by inflow from northern quadrants (Fig. 4a), with little contributions from the zonal direction, similar to July. The upward motion over South America is more vigorous than in July; the associated outflow into southern quadrants has little zonal component. Convergent easterlies continue in the lower layers over the western Atlantic and South America. Over the eastern Pacific subsidence is strong, and it is fed by upper-tropospheric convergent inflow from the Northeast (Fig. 4a). The subsidence over the eastern Pacific is compensated by outflow in the mid to lower troposphere, directed eastward and more prominently westward, with convergence and upward motion over the western half of the Pacific basin and the greater Indonesian region. This ascending motion supports upper-tropospheric divergence, with outflow eastward into the center of upper-tropospheric convergence and mid-tropospheric subsidence over the eastern Pacific and westward to the Indian Ocean. However, again, the map (Fig. 4a) bears out the overwhelming outflow toward southerly and northerly quadrants. The total zonal flow (Fig. 4d) is prevailing from the East. Westerlies persist in the lower layers over Africa and the easternmost Pacific; and westerlies appear in the upper troposphere over the Atlantic, Americas, and Pacific, as further precursor manifestation to the boreal winter conditions.

The boreal autumn circulation cell manifests itself at the surface in the strong and short-lived equatorial westerlies, which drive the likewise intense and short-lived Eastward Equatorial Jet, or Wyrkki Jet (Wyrkki 1973), in the upper atmosphere, are highly correlated with the Short Rains at the coast of East Africa, and accompany interannual and longer-term climatic variability (Hastenrath et al. 1993; Hastenrath 2001b). Thus the boreal autumn circulation cell must be regarded as a major agent in the climate system of the Indian Ocean basin.

4. Conclusions

The intuitive conjectures of Bjerknes (1969) in his seminal paper three decades ago had a sustained impact on notions of quasi-permanent equatorial circulation systems. As a consequence, the existence of zonal-vertical circulation cells in the equatorial plane is widely taken for granted, as apparent in a recent international program document, an expert conference in atmospheric sciences, and even a workshop on paleoclimatology (International CLIVAR Program Office 1999; West African Monsoon Variability and Predictability Workshop,
Dakar, Senegal 1999; Conference on Pole-Equator-Pole Paleoclimate of the Americas, Merida, Venezuela 1998). The empirical basis for such concepts begs examination; pertinent being the divergent part of the wind and continuity following the flow between the centers of upward and downward motion, in particular. In this spirit, maps have been presented here of upper-tropospheric divergence and divergent flow and mid-tropospheric vertical motion, along with zonal-vertical cross sections of vertical and divergent zonal motion and divergence and total zonal flow. The annual cycle was approximated by the mid-seasons months January, April, July, and October.

In the boreal winter half-year, the upper-tropospheric divergent flow is overwhelmingly directed towards northern quadrants, with little zonal contributions except for the westerly component over the eastern Pacific and western Atlantic, and easterly component over the Australasian region. Ascending motion and upper-tropospheric outflow are concentrated over the western Pacific and Indonesian region, central Africa, and the equatorial Americas; centers of upper-tropospheric inflow and subsidence are located over the central Atlantic and eastern Pacific. Most prominently, an equatorial zonal circulation cell persists throughout the year over the central to eastern Pacific, with divergent eastward flow in the upper troposphere and the compensating westward flow in the mid troposphere rather than at the surface. An equatorial zonal circulation cell is apparent over the western Atlantic in January, with divergent eastward flow in the upper troposphere and westward flow near the surface.

In the boreal summer half-year, the upper-tropospheric divergent flow is overwhelmingly directed towards southern quadrants, with some easterly component over the Indian Ocean and westerly component over the western Atlantic and eastern Pacific Oceans. Ascending motion and upper-tropospheric outflow are concentrated over the Australasian region, Africa, and the Americas; contrasting with upper-tropospheric inflow and subsidence over coastal East Africa, the central Atlantic, and eastern Pacific. In addition to the perennial zonal circulation cell over the eastern Pacific, with divergent eastward wind in the upper troposphere and westward flow in the mid troposphere, more short-lived systems are found over the Indian Ocean sector. Thus, in July a distinct zonal circulation cell over the western Indian Ocean features subsidence over the East African coast and divergent eastward outflow concentrated in the mid-troposphere; and in October a well developed zonal cell encompasses subsidence over the East African coast, divergent eastward flow in the lower-troposphere, ascending motion over the eastern Indian Ocean and Indonesia, and upper-tropospheric divergent westward wind. This boreal autumn circulation cell spanning the Indian Ocean basin may play an important role in climatic variability. Overall, however, the evaluation of the NCEP–NCAR dataset indicates that equatorial zonal circulation cells are less common than widely believed.

Acknowledgments

This study was supported by NSF Grant ATM-9732673. At the University of Wisconsin Dierk Polzin and Larry Greischar assisted me with the computations and graphics.

References


Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White,


