

The Zonal Walker Circulation

Introduction

In addition to the mean meridional Hadley circulation, there also exist zonal overturning circulations that contribute to the meteorology and climatology of the tropics. Together, these overturning circulations are commonly referred to as the Walker circulation. In this section, we first explore the history and basic structure of the Walker circulation. Later, we reintroduce the shallow water equations to demonstrate how prescribed heating leads to equatorially-trapped Kelvin and equatorial Rossby waves that comprise the Walker circulation. In so doing, we tie these features back to the Hadley cell circulation and provide motivation for subsequent lectures on the El Niño Southern Oscillation and monsoons.

Key Questions

- What is the zonal Walker circulation?
- What drives the Walker circulation?

What is the zonal Walker circulation?

As previously discussed, tropical circulations result from heating. More specifically, they result from a combination of both asymmetric and symmetric heating, where symmetry is defined here by the symmetry of the heating source with respect to the Equator. Owing to considerations of continentality and seasonality, the Hadley circulation is an example of an *asymmetric* heating-driven tropical circulation wherein its rising branch is typically displaced off of the Equator. Conversely, the mean equatorial east-west (or zonal) circulation in the Pacific Ocean is an example of a *symmetric* heating-driven tropical circulation. This circulation is known as the Walker circulation, named after Sir Gilbert Walker who first recognized its existence from observations of sea-level pressure between Darwin, Australia and the island of Tahiti in the tropical Pacific. In recent years, however, the term “Walker circulation” has come to refer to not just the equatorial zonal circulation in the Pacific but also that of the equatorial zonal circulations across the Atlantic and Indian Oceans as well.

Much like the Hadley cell, the Walker circulation is a thermally direct circulation, wherein ascent is found in regions of relative warmth and descent is found in regions of relative cold. As will be shown shortly, it is such a distribution of heating that drives the Walker circulation in the first place. In the mean state, ascent is favored on the western extent of the three equatorial circulations and descent is favored on the eastern extent of these three equatorial circulations. The corresponding lower and upper tropospheric zonal winds are easterly and westerly, respectively.

The Walker circulation is primarily driven by heating on the western flanks of the equatorial circulations. This heating is both atmospheric and oceanic in nature. Atmospheric heating is driven by the sensible heating of the equatorial land masses of Indonesia, Africa, and South America and the latent heat release associated with deep, moist convection that forms in the moist, unstable environment resulting from a combination of such heating and an abundant supply of lower tropospheric moisture. Weak to modest contributions to the development of deep, moist convection are provided by upslope flow on the eastern side of the mountain ranges of Africa and South America. Oceanic heating reflects sensible heating associated with the zonal variability in sea surface temperatures and oceanic heat storage as

driven by the easterly trades. These trades promote upwelling in the eastern portion of the oceanic basins and downwelling in the western portion of the oceanic basins. As ocean temperatures cool with increased depth, this promotes cooler sea surface temperatures (SSTs) to the east and warmer SSTs to the west.

This heating promotes ascent, which from the continuity equation can be shown to be found in conjunction with mean lower-tropospheric convergence. This, in part, contributes to the presence of and longitudinal variability (stronger west, weaker or reversed east) in the easterly trades of the equatorial latitudes. Compensating divergence is found near the tropopause, resulting in mean westerly upper-tropospheric flow across much of the tropics. To the east of the ascending branch of the Walker circulation, outward-moving air parcels gradually descend, drying as they do so. It is this circulation that largely modulates zonal variability in near-equatorial rainfall and, with it, the location of clouds and precipitation associated with the near-equatorial lower tropospheric convergence zones such as the intertropical convergence zone and monsoon troughs of western Africa and Indonesia.

The dominant variability of the Walker circulation, specifically its equatorial Pacific component, is the El Niño-Southern Oscillation (ENSO). As described above, the Walker circulation is associated with relatively warm SSTs in the western tropical Pacific and relatively cold SSTs in the eastern tropical Pacific. During an El Niño event, however, equatorial wave forcing leads to anomalously warm SSTs in the eastern tropical Pacific and, to lesser extent, anomalously cold SSTs in the western tropical Pacific. In response to this shift in forcing, the intensity of the Walker circulation weakens and its ascending branch shifts eastward. Conversely, during a La Niña event, the SST climatology of the Pacific is intensified, resulting in an enhanced Walker circulation. The two-to-seven year oscillation between these extremes gives rise to the oscillatory terminology of ENSO. In a subsequent lecture, we will discuss ENSO and theories behind its oscillatory nature. Smaller-scale variability in the Walker circulation, again specifically its equatorial Pacific component, is driven primarily by the Madden-Julian Oscillation (MJO), a thirty- to sixty-day oscillation between convectively-active and convectively-suppressed conditions at tropical latitudes. We will discuss the MJO in greater detail in a subsequent lecture.

What Drives the Walker Circulation?

It can be shown that the Walker circulation and its variable zonal structure arise as a natural response to the equatorial heating concentrated in the western portions of the Pacific, Atlantic, and Indian Ocean basins. To a basic first approximation, this can be done using principles of mass continuity and hydrostatic balance, as was done for the Hadley cell. However, a more thorough treatment of the matter illuminates the presence of multiple types of equatorial waves and the fine-scale structure of the circulation as a whole and is thus worth exploring in some detail. The work of Gill (1980), who analytically solved for the Walker (and Hadley) circulations using the shallow water equations in an initially at-rest atmosphere with a small heating rate, is the seminal work on this topic.

Under the assumptions discussed in earlier lectures, the shallow water equations are obtained from the equations of motion and the continuity equation. Below, we express them in the form presented by Gill (1980), describing the system in terms of pressure (rather than fluid height) perturbations and with a prescribed heating that enters into the continuity equation:

$$(1) \quad \frac{\partial u}{\partial t} - \frac{1}{2} yv = -\frac{\partial p}{\partial x}$$

$$(2) \quad \frac{\partial v}{\partial t} + \frac{1}{2} yu = -\frac{\partial p}{\partial y}$$

$$(3) \quad \frac{\partial p}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -Q$$

In these equations, a coordinate (x, y) refers to a non-dimensional distance with x measured eastward and y measured northward from the Equator. (u, v) are proportional to the zonal and meridional velocity, respectively, and p is proportional to the pressure perturbation. This proportionality makes the system given by (1) – (3) appear more accessible than if the direct relationships were used. Q is proportional to the heating rate. (1) and (2) are the momentum equations of the system and (3) is a version of the continuity equation where the vertical velocity w is proportional to $\frac{\partial p}{\partial t} + Q$.

In order to study the response of the system to steady heat forcing, dissipative processes must be included to maintain the steadiness of the system. Such dissipative processes include friction (Rayleigh friction) and cooling (Newtonian cooling). These are introduced into the system given by (1)-(3) above by replacing $\frac{\partial}{\partial t}$ with ε , where ε represents the equal dissipation of momentum and heat within the shallow water system. This enables us to obtain the following set of equations:

$$(4) \quad \varepsilon u - \frac{1}{2} yv = -\frac{\partial p}{\partial x}$$

$$(5) \quad \varepsilon v + \frac{1}{2} yu = -\frac{\partial p}{\partial y}$$

$$(6) \quad \varepsilon p + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -Q$$

$$(7) \quad w = \varepsilon p + Q$$

If we assume that the forcing is of small meridional scale and that ε is small, it can be shown that the εv term in (5) can be neglected. This allows us to re-write (5) as:

$$(8) \quad \frac{1}{2} yu = -\frac{\partial p}{\partial y}$$

On a β plane, or one in which β is constant, (8) is equivalent to saying that the eastward flow u is in geostrophic balance with the pressure gradient. Therefore, our system is now comprised of the momentum equations (4) and (8) and continuity equation (6).

The heating Q can be considered in two forms: symmetric about the equator (represented by wavenumber zero) or asymmetric about the equator (represented by wavenumber one). At this time, we first consider the solution to the system with symmetric heating Q about the equator. In our study of the monsoons, we will return to this system to consider its solution for asymmetric heating Q about the equator.

In the shallow water system, there are two modes (or solutions) that respond to (or are a function of) symmetric heating. The simplest of these modes represents a Kelvin wave that is damped as it moves eastward. At this point, we are most interested in how this Kelvin wave solution is manifest in the atmospheric motion and pressure fields. Recall that the detailed solution of the Kelvin wave contains no meridional motion (i.e., $v = 0$) such that the wave is exclusively manifest via pressure perturbations and zonal motion.

The full structure of the Kelvin wave describes the basic structure of the Walker circulation with easterly near-surface trade winds flowing parallel to the equator toward the heating source, accelerating as they do so, and subsequently rising through the heat source before flowing eastward aloft. Associated with this circulation is an area of low pressure along the equator with the lowest pressures found at the location of the heating. This portion of the total solution depicted within the lecture materials is primarily that along the equator ($y = 0$).

The more complex response to the symmetric heating corresponds to the westward-propagating long planetary wave, or equatorial Rossby wave. Again, we are most interested with how this equatorial Rossby wave is manifest in the atmospheric motion and pressure fields. The equatorial Rossby wave solution consists of westerly near-surface flow into the heating source that decays rapidly to the north and south of its equatorial maximum. Such flow is associated with twin cyclonic vortices found north and south of the equator immediately rearward of the prescribed heating source. Weak descent through the atmospheric column occurs in the vicinity of the twin vortices. Compensating weak easterly flow to the west of the heating source is noted aloft. The westward extent of this solution is approximately 1/3 of the eastward extent of the Kelvin wave solution owing to slower wave propagation speeds associated with the equatorial Rossby wave solution.

The summation of the Kelvin and equatorial Rossby wave solutions gives the totality of the flow in response to a steady heating source such as found in the western portions of the major tropical ocean basins. In this complex way, we have demonstrated that a modest, localized heat source (of some form) along the equator on the western edge of a domain is the driver of the zonal and meridional circulations of the tropics. The zonal structure is comprised of the Walker circulation whereas the zonally-integrated meridional structure flow describes a Hadley circulation symmetric about the equator. Note that in the immediate vicinity of the heating region, poleward (equatorward) near-surface (upper tropospheric) flow is observed, counter to that of the Hadley circulation. When zonally-averaged, however, the typical (correct) Hadley circulation is obtained. Specifics behind this peculiarity follow from the conservation of absolute vorticity and the nature of the prescribed heating and Newtonian cooling, as discussed by Gill (1980). Both the Walker and Hadley circulations are depicted within the lecture materials. Changing the zonal placement of the heating source will leave the zonally-averaged result (the Hadley circulation) largely unchanged but will result in changes to the structure of the zonal Walker circulation. This is important when considering the impact of El Niño upon the meteorology of the tropics and beyond.

One might ask, why does the shallow-water system produce equatorially-trapped Kelvin and equatorial Rossby waves, and not (or not also) mixed Rossby-gravity or inertia-gravity waves when driven by prescribed heating? Matsuno (1966), discussed in the lecture on equatorial waves, notes that the Kelvin and equatorial Rossby waves are more resonant, or responsive, to prescribed heating. This means that these wave modes grow faster than and, as a result, dominate over their equatorial wave counterparts. Furthermore, the prescribed heating driving the shallow water equations here is symmetric rather than asymmetric. Consequently, the symmetric rather than asymmetric wave modes are those which dominate.

For Further Reading

- Chapter 3, [*An Introduction to Tropical Meteorology, 2nd Edition*](#), A. Laing and J.-L. Evans, 2011.
- Chapter 4, [*An Introduction to Tropical Meteorology, 2nd Edition*](#), A. Laing and J.-L. Evans, 2011.
- Gill, A. E., 1980: Some simple solutions for heat-induced tropical circulation. *Quart. J. Roy. Meteor. Soc.*, **106**, 447-462.