

EDDY DRIVEN MONSOON THEORY APPLIED TO MARS. J. S. Sabato¹ and S. C. R. Rafkin², ¹Buffalo State College (1300 Elmwood Ave., Buffalo, NY, USA) sabatojs@buffalostate.edu, ²Southwest Research Institute (1050 Walnut St., Boulder, CO, USA) rafkin@boulder.swri.edu.

Introduction: The large-scale dynamics of the Martian atmosphere is known to be well approximated by axisymmetric theories. However, there is also ample evidence that non-axisymmetric processes (eddies) can play an important role.[1]-[5] The interpretation of transport processes from a zonally symmetric "Hadley Cell" poses difficulty in the cases where longitudinal asymmetries are particularly strong, as is the case on Mars. The zonally averaged flow is nearly angular momentum conserving but there are also significant meridional eddy fluxes of heat and tracers. The apparent discrepancy between the near-conservation of angular momentum (a property of zonally symmetric flows) and the zonally asymmetric transport of tracer species will be examined. We will pay particular attention to what properties of the waves are required to produce a nearly angular momentum conserving flow, while still producing zonally asymmetric transport. The zonal asymmetries on Mars are similar to terrestrial Monsoons in the sense that they produce longitudinal "Walker Cells" and channel transport within certain geographic corridors. They may also be the result of an elevated heat island (Tharsis rise and/or Arabia Terra) as in the case of the Indian Monsoons. We will further investigate the elevated heat island effect as the cause of the zonal asymmetries and attempt to understand the weak impact the strong asymmetries have on angular momentum conservation.

Angular Momentum Conservation in the Martian Atmosphere: Somewhat in contrast to the Earth, the axisymmetric, or zonal mean flow on Mars is very robust. Angular momentum conservation in the terrestrial atmosphere is largely a convenient mathematical device for deriving approximate dynamical relationships. On Mars however, the meridional overturning cell is very angular momentum conserving. The degree of conservation can be seen by noting the coincidence of (or lack thereof) the zonal mean stream lines and zonal mean angular momentum contours (Figure 1). On Earth, zonal mean angular momentum is merely homogenized in the upper (poleward) branch of the cell, while on Mars it is quite nearly conserved (in a Lagrangian sense) over a large portion of the tropical atmosphere, above the boundary layer.

Role of Longitudinal Asymmetries: While axisymmetry is a good approximation for Mars, zonal asymmetries are present and can be important for

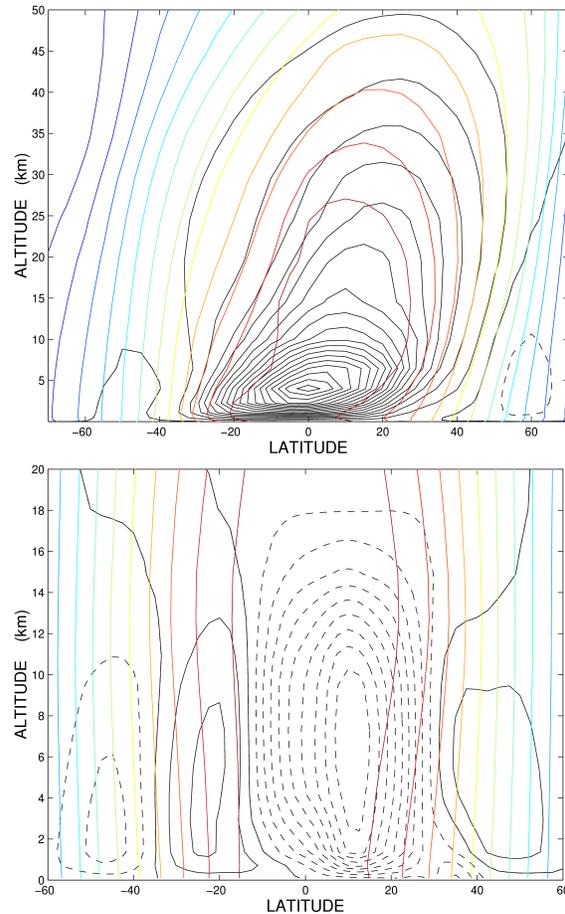


Figure 1: Meridional stream function (black) and zonal mean angular momentum contours (color) at NH winter for the NASA AMES Mars GCM, L_s 270° – 300° (upper) and NCEP/NCAR Reanalysis for Earth, DJF (lower)

transporting heat and energy, and trace constituents. The extra-tropical zonal jets produced by the angular momentum conserving Hadley circulation are modulated by standing Rossby waves, producing “storm tracks”. [1] There are western boundary currents, where large, pole-ward mass fluxes are localized near the western sides of large “basins”. [4]-[5] Michaels et al. [6] showed that localized flows can have vertical mass fluxes comparable to those of the entire (zonal mean) Hadley circulation, up and down the slopes of the Tharsis Montes once each sol, although the net transport is much smaller. Of course, midlatitude baroclinic eddies can also contribute to zonal asymmetries, even in the absence of zonal asymmetries in the lower boundary. [2]-[3]

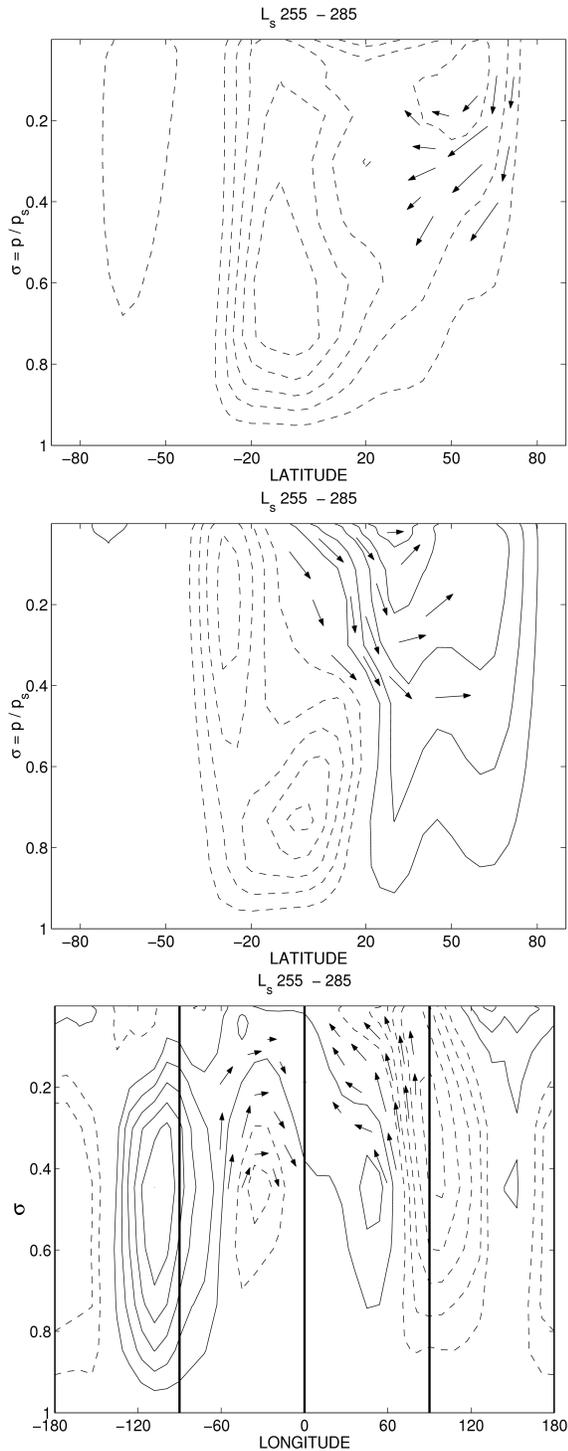


Figure 2: Meridional stream function averaged over the longitudes 0° to 90° E (top) and -90° to 0° E (center) and the corresponding zonal mass flux (stream function) averaged over the latitudes 20°S – 50°N (bottom). Arrows are drawn to indicate general wind direction and are not to scale with the actual winds. The circulation shown in the bottom panel is very robust to changes in season and is insensitive to the choice of latitude band for averaging.

Walker-type Circulations: One can average the zonal transport over a range of latitudes and obtain a longitudinal “cell”. The Walker cell stream function, obtained by integrating the zonal mass flux from the surface upwards, is shown in Figure 2 (bottom panel). The zonal mass fluxes were averaged over latitudes from -20° to 50° and times corresponding to solar longitudes, $L_s = 270^\circ$ to 300° (NH winter). The meridional mass fluxes shown in the top and center panels are the same as in Figure 1 except that they are averaged only over a particular longitudinal band (-90° to 0° E and 0° to 90° E). Figure 2 shows that the “Walker cells” correspond to localized regions of meridional transport (left and center panels). Aloft, the northward(southward) wind (Figure 2 top, center) is directed by the Coriolis effect to the east(west) (Figure 2 bottom). The important fact is that the transport is locally in the opposite direction of the net meridional transport. This zonally varying mass transport could be very important in determining the net transport of tracer species, especially if there is zonal asymmetry in the tracer source region, as there is with water vapor sublimating from the polar cap and dust entrained in the tropics or southern hemisphere. The aphelion cloud belt is often ascribed to water vapor, having been transported from the sublimating cap, condensing in the upper, equatorial atmosphere. Contrary to predictions from an axisymmetric theory for water transport, the cloud belt is more pronounced in certain longitude bands. These bands correspond roughly to the regions where the “local” transport is in the same direction as the zonally averaged transport. In the longitude regions where the transport reverses (thermally indirect, Figure 2, center panel), the clouds are less pronounced in observations.

Eddy Driven Monsoon Theory Applied to Mars: A conceptual framework for understanding the effect of transient eddies on Earth's Hadley Cell was developed by [7]. In this framework the upper level (friction is negligible) zonal momentum balance is averaged longitudinally. In the steady state then, the effect of the eddies can be conceptualized by separating the effects of the zonal mean and eddies on the zonal momentum balance. For the mean meridional circulation

$$-(f + \bar{\zeta}) \bar{v} = 0 \quad \text{or} \quad -f \bar{v}_m = \bar{\zeta} \bar{v}$$

(Equation 1) Multiplying by surface pressure and integrating in sigma gives a mass flux, or stream function, associated with the angular momentum conserving flow. It can be shown that Equation 1 is a statement of angular momentum conservation if the merid

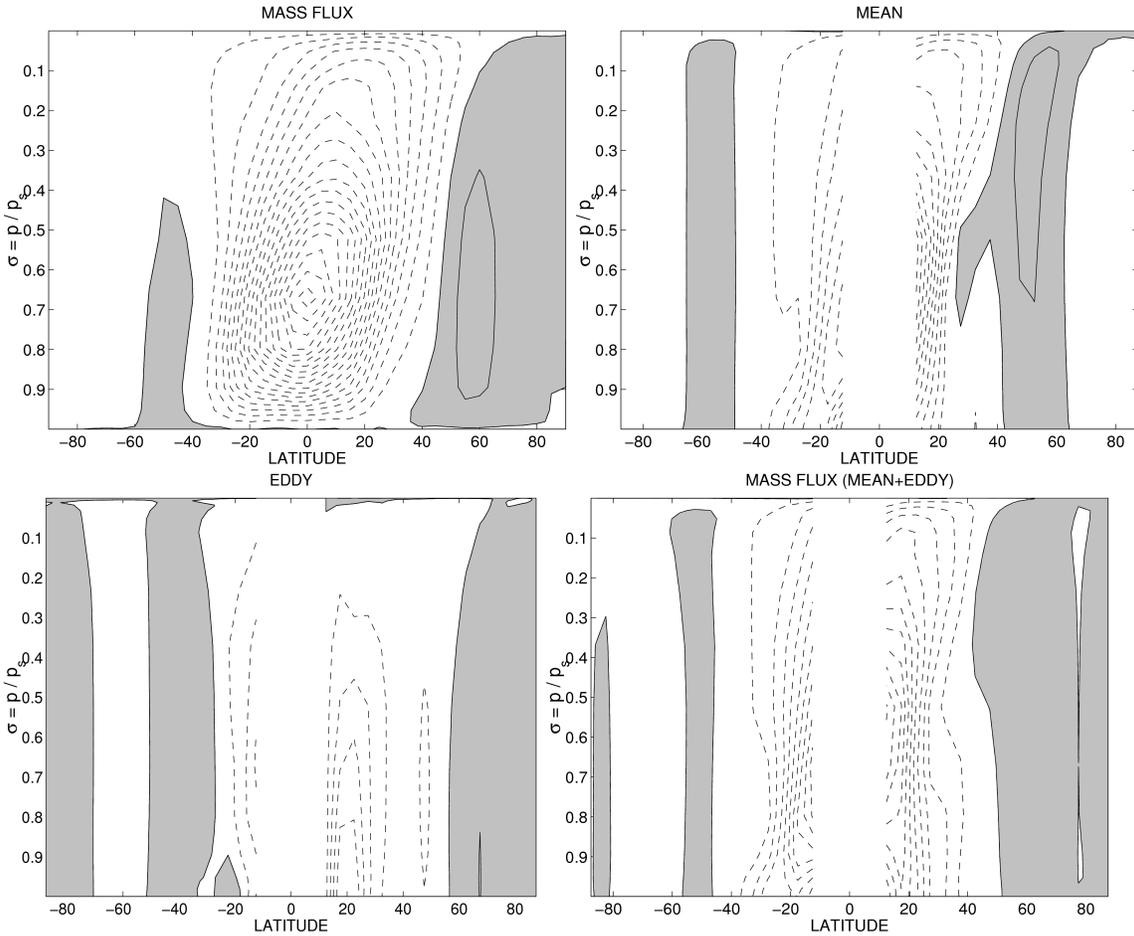


Figure 4: Zonal mean mass flux directly from the GCM (upper left), according to Equation 1 (upper right), according to Equation 2 (lower left) and the sum of Equations 1 and 2 (lower right).

ional flow is assumed not to vanish. This, along with a statement of energy conservation, is the classical theory for the Hadley circulation.[8]-[9] Axisymmetric theory reproduces the width of the Hadley cell and explains the homogeneous angular momentum in the upper branch of the terrestrial Hadley cell (Figure 1). To the eye, the Martian tropics appears to conserve angular momentum even more robustly than on Earth. However, as outlined above, there are significant zonal asymmetries in the lower boundary and the free atmosphere of Mars. In the extreme case where zonal asymmetries dominate, the zonal flow is “eddy driven”. Examining this case requires setting the mean meridional circulation terms to zero and obtaining

$$-f \bar{v}_e = \overline{v' \zeta'} - \overline{\sigma' \frac{\partial u'}{\partial \sigma}} - \frac{R}{A \cos \phi} \overline{T' \frac{\partial \ln p_s'}{\partial \lambda}}$$

(Equation 2) This equation contains terms associated with the horizontal redistribution of momentum, vertical advection and a term associated with the sigma-coordinate. Neglecting the term correlating eddy surface pressure and temperature, Figure 3 shows stream functions calculated according to Equations 1 and 2, along with the actual mass flux. The mean flow aloft can be captured, to a large extent, by the angular momentum conserving model (Equation 1) and zonal asymmetries appear to have little effect. This gives a clue as to the nature of the waves. The divergence of the eddy flux of zonal momentum (or equivalently, the meridional flux of vorticity) is responsible for altering the zonal mean zonal flow in the eddy driven theory. This mechanism of generating zonal jets requires a meridional propagation, and ultimately breaking, of Rossby waves. *If the waves were to propagate only in the zonal direction, they would be able to generate zonally varying eddy and mean flow statistics, without altering the zonal mean angular*

momentum budget. The last term in Equation 3 is probably negligible for most terrestrial applications but, again, may be of vital importance on Mars, given the extreme topographic and thermal variations of the surface. As the Sun heats up the surface, the elevation change between the peaks and valleys is large enough to suppose it might have an effect similar to the Himalayas. This elevated heat island could be responsible for the zonal momentum dynamics and the effects could be viewed as “dry Monsoon”.

References: [1] Hollingsworth, J. L., et al. (1996) *Nature*, 380, 413–416. [2] Barnes, J. R. (1984) *J. Atmos. Sci.*, Vol. 41, 1536-1550. [3] Barnes, J. R., et al. (1993) *J. Geophys. Res.*, Vol. 98 No. E2, 3125-3148. [4] Joshi, M., et al. (1997) *J. Geophys. Res.*, Vol. 102, No. E3, p. 6511. [5] Joshi, M., et al. (1995) *J. Geophys. Res.*, Vol. 100, No. E3, 5485-5500. [6] Michaels, T. I., et al. (2006) *Geophys. Res. Lett.*, Vol. 33, L16201. [7] Schneider, T. and Bordoni, S. (2008) *J. Atmos. Sci.*, Vol. 65, 915-934. [8] Held, I. M., and Hou, A. Y. (1980) *J. Atmos. Sci.*, Vol. 37, 515-533. [9] Lindzen, R. S. and Hou, A. Y. (1988) *J. Atmos. Sci.*, Vol. 45, 2416-2427.