9.8 Approximate Co-location of Precipitation and Low-level Westerlies in Tropical Monthly Means

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1. Introduction

In summer monsoon regions the monthly mean precipitation regions coincide approximately well with regions of westerlies at low-levels. Fig. 1.a shows a 15-year (1979-1993) mean August 850 hPa zonal wind from NCEP/NCAR reanalysis dataset (Kalnay et al. 1996) and Xie-Arkin precipitation. It shows a region of westerlies covering most of Northern Indian Ocean and extending to northwestern Pacific. This region coincides well with the region with precipitation greater than 6 mm/day. Obviously, the coincidence is not exact; the region of largest zonal wind in the Arabian Sea is in a region of relatively low precipitation and is far from the region of maximum precipitation in Bay of Bengal. Also, in a zonally averaged sense between 40E and 140E, the latitude of maximum precipitation is slightly higher than that of the maximum zonal wind. Low-level westerlies are also found in regions west of Central America and in western Africa north of the equator. These regions are also closely associated with precipitation centers. Across equator from these westerlies regions there are regions of strong easterlies. Also, on their poleward side the westerly regions are flanked by weaker easterly regions. In February, (Fig. 1.b) similar observation can be found in the Australian monsoon area and in South America monsoon region; again the regions of westerlies coincide well with regions of maximum precipitation. As in the northern hemisphere, the maximum precipitation is found to the east of the maximum zonal wind. The two maxima lie almost at the same latitude with that of the westerlies slightly closer to the equator. In the non-monsoon seasons the low-level westerlies can also be found in the tropical precipitation regions, the longitudinal range of the westerlies is undiminished and the speed of the westerlies is not much weaker than that found in February.

The interpretation of these observational facts is the goal of this investigation. The approach taken is numerical simulation with the Goddard Earth Observation Systems atmospheric general circulation model (GEOS-AGCM), described in Takacs et al (1999), and its aqua-planet version, combined with theoretical arguments. A full account of this investigation is given in Chao and Baode (1999.) In this extended abstract we will give a brief summary of the results of the numerical models and a physical interpretation based on the Gill solutions.

2. Brief summary of GCM study

The aqua-planet model results, when the sea surface temperature is zonally uniform, show in the monsoon season a much stronger Hadley cell to the south of the precipitation peak (the ITCZ) and a much weaker Hadley cell to the north. The interpretation for such large disparity in the strength of the two Hadley cells is that the Hadley cell on the equator side of the precipitation peak experiences a smaller Coriolis force than the Hadley cell on the poleward side. The stabilizing effect of the Coriolis force, which hinders vertical motion, makes the Hadley cell on the poleward side weaker (Schubert, et al. 1992). Because of the dominance of the southern Hadley cell the ITCZ gets its air supply from the south and thus the zonally averaged meridional wind in the boundary layer is positive in most part of the ITCZ. It is the convergence of this northward flow (after crossing the equator) that provides air mass for the upward branch of the Hadley cell. Thus the zero meridional wind in the boundary layer lies well north of the ITCZ peak. This feature is the same as what is shown in the observation. However just above the boundary layer at 850 hPa positive v extends only to the latitude of the peak precipitation. The cross equatorial meridional flow, as part of the southern Hadley circulation in the model, is confined in the bottom 200 hPa, which compares well with the NCEP reanalysis. The convergence of this meridional wind corresponds to the upward motion in the ITCZ. The Coriolis force acting on this meridional wind generates westerly wind at the low-levels; thus westerlies covers the entire ITCZ latitudinal domain in the low-levels. The sum of the Coriolis force and the meridional advection of the zonal wind is balanced by the damping (surface friction and vertical diffusion) force acting on the westerly.

The full GCM integration was conducted for four years using initial condition of January 1 1987 and the observed boundary conditions. For the August precipitation the model has successfully simulated the precipitation band just south of the equator in the Indian Ocean and the precipitation b in Bay of Bengal and western Pacific at around 10N. The precipitation minimum in the western Arabian Sea is well simulated. However, the model results show precipitation peak shifted slightly southward and the precipitation maximum to the east of the Philippines is not simulated. Also the precipitation peak values are higher than those in the observation. Despite the discrepancies in detail the model successfully simulated the general patterns of precipitation and winds including the approximate co-location of precipitation and low-level westerlies.

In the Indian monsoon region in the full GCM integration the momentum balance show the same behavior as in the aqua-planet integration. The main balance is between the v(f-du/dy) and the surface friction (plus vertical diffusion) term. The same conclusion can be drawn for the Australian monsoon.

In the non-monsoon seasons the model simulation misses the weak precipitation maximum just west of Malaysia in both April and November. In both months the model shows too low precipitation over the equatorial Indian Ocean. In November the model shows higher precipitation than observation in Arabian Sea. Despite these deficiencies the model performs reasonably well in terms of simulating the gross features.

3. Insight from modified Gill's solutions

Gill's (1980) solutions of circulation response to a stationary convective heating in shallow water equations put our investigation in its simplest settings. The shallow water equations capture the first baroclinic mode in the tropical atmosphere. Gill specified a mass source in the shallow water equations to represent the stationary convective heating and obtained analytic solutions to the system. The mass source is represented by a function separable in latitude and longitude. The latitudinal function is the parabolic cylinder function and the longitudinal function is a simple cosine function. The solutions consist of two parts. The Kelvin wave response part resides over the heating region and its east side, and the Rossby wave response part resides over the heating region and its west side. Only the Rossby wave component has westerly winds. His solutions were presented (Gill 1980) both for a heating region over the equator (symmetric case, his figure 1) and for a heating region off the equator (asymmetric case, his figure 3). Gill used a cosine function (the positive part) for the longitudinal variation of the heating and zero value outside of the convective region. Plots for his solutions for L=2 [heating confined between x=-L and x=L in non-dimensional domain, unity is equivalent to about 1000km] can be found in Gill (1980). The westerlies are found to the west of the maximum heating; thus the westerlies cover only the western half of the longitudinal domain of the heating region. Therefore a direct application of Gill's solution to the co-location phenomenon is not suitable; some modification of Gill's solutions is necessary.

Since Gill's solutions are linear, a running average of his solutions in the x direction gives a new set of solutions. The running average is defined as:

$$g(x) = \int_{x-5}^{x+5} f(x)dx \,/\, 10$$

in the non-dimensional x domain, where f(x) is the Gill solution. For simplicity, the following discrete computation is used instead, after computing f(x) with L=2 and epsilon=0.1 on grids with 0.25 grid interval in x:

$$g(x) = \frac{1}{41}\sum_{i=-20}^{i=20} f(x + 0.25 \cdot i)$$

This new set of solutions has, instead of a cosine function in longitudinal dependence of the heating source function, a stretched-out cosine function (the positive part) with a flat top covering 120 degrees in longitude, much closer to observed monthly mean precipitation pattern found in western Pacific and Indian Ocean. Figs. 2.a and b show the modified Gill solutions of vertical velocity and pressure (using Gill's figures 1 and 3) for heating asymmetric and symmetric with respect to the equator. Fig. 2.c shows the heating source (Q, as defined in Gill 1980) and zonal winds. It is noted that in the off-equator heating case the maximum westerlies and the maximum convective heating are found at nearly the same latitude, resembling the observations well. Also the core part of the convective region is occupied by the westerlies. This westerly region is flanked by strong easterlies across the equator and by weaker easterlies to the north. These resemble the observation very well.

Furthermore, the modified Gill solutions, with symmetric forcing (Fig. 2.c), show westerlies occupying the core part of the equatorial heating region and weaker easterlies occupying the eastern end part of the heating region; both are found in the observations. The maximum westerly is located west of the heating center; and the westerly region extends far west of the heating region. Also the westerly region is flanked by easterlies to the north and south. Moreover, the maximum westerly in the symmetric heating case is somewhat weaker than that in the asymmetric heating case in consistent with the observations. Thus the gross observed tropical circulation pattern in the monthly means is well captured and explained by the Gill solutions. In view of the fact that Gill's solutions have two components: the Rossby wave and the Kelvin wave, and only the Rossby wave component has westerly winds, one of our major conclusions is that the tropical low-level westerlies that co-locate with precipitation and the flanking easterlies found in the monthly means can be interpreted as the Rossby wave response to monthly mean convective heating in both monsoon and off-monsoon seasons. The easterlies to the east of the precipitation region has previously been identified as the Kelvin wave response to monthly mean heating (Webster 1972 and Gill 1980.)

4. Summary

In summary, the monthly mean fields show approximate co-location of low-level westerlies and precipitation in the tropics in both monsoon and non-monsoon seasons. The westerlies are flanked by easterlies to their north and south. Our numerical studies with the Goddard general circulation model and its aqua-planet version reveal the balance of the Coriolis force and surface friction in the westerlies regions in the monsoon season. Without surface friction the westerlies cannot exist in aqua-planet setting with zonally uniform SST. In the monsoon season the cross equatorial meridional flow extends to the poleward side of the westerlies region as a result of the dominance of the Hadley cell on the equatorial side, which in turn is a result of earth's rotation. To balance the Coriolis force due to this meridional flow, westerlies exist in order to provide surface frictional force to achieve momentum balance. In the non-monsoon season the westerlies are found over the equatorial precipitation region and the surface friction is balanced by pressure gradient force. The origin of the westerlies in the monsoon season is due to the conservation of angular momentum of the cross equatorial flow towards the ITCZ; and that in the non-monsoon season is due to pressure gradient force.

Zonal running mean of Gill's solutions captures very well the monthly mean flow in and around the precipitation region. These solutions provide a simple interpretation that the low-level westerlies, approximately co-locating with core precipitation, and their flanking easterlies to the north and south are the Rossby wave response to a longitudinally-elongated precipitation region in both monsoon and non-monsoon seasons. These solutions also show different balance in the momentum equation in different regions.

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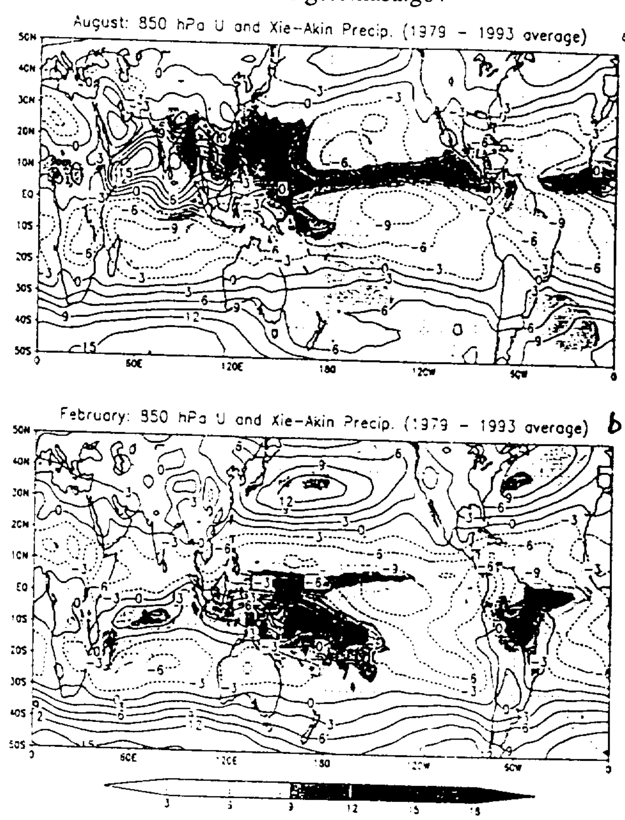
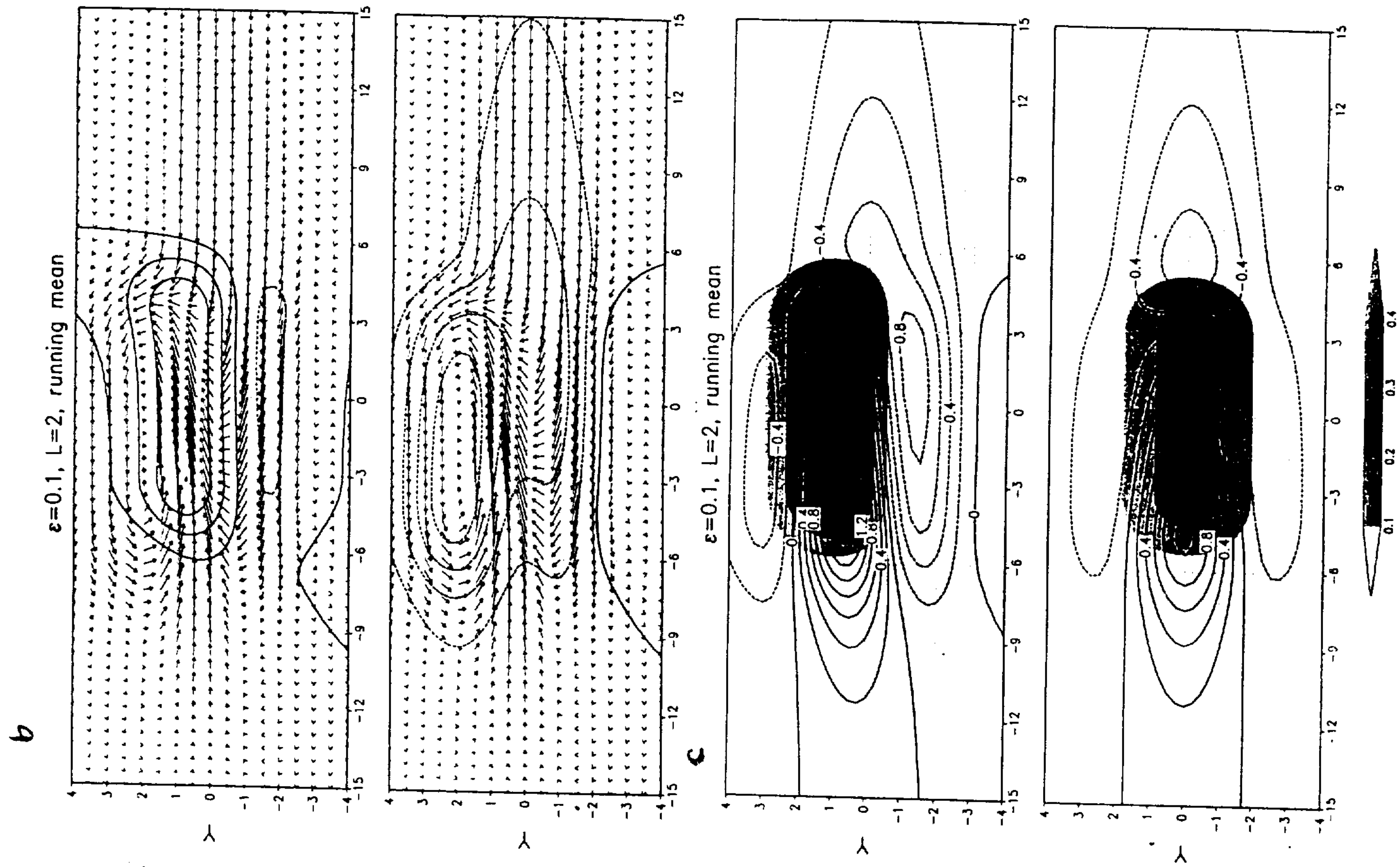


Fig. 1 15 year (1979-1993) averaged observed (NCEP/NCAR) precipitation (mm/day) and zonal wind (m/s) at 850 hPa for August (a) and February (b).



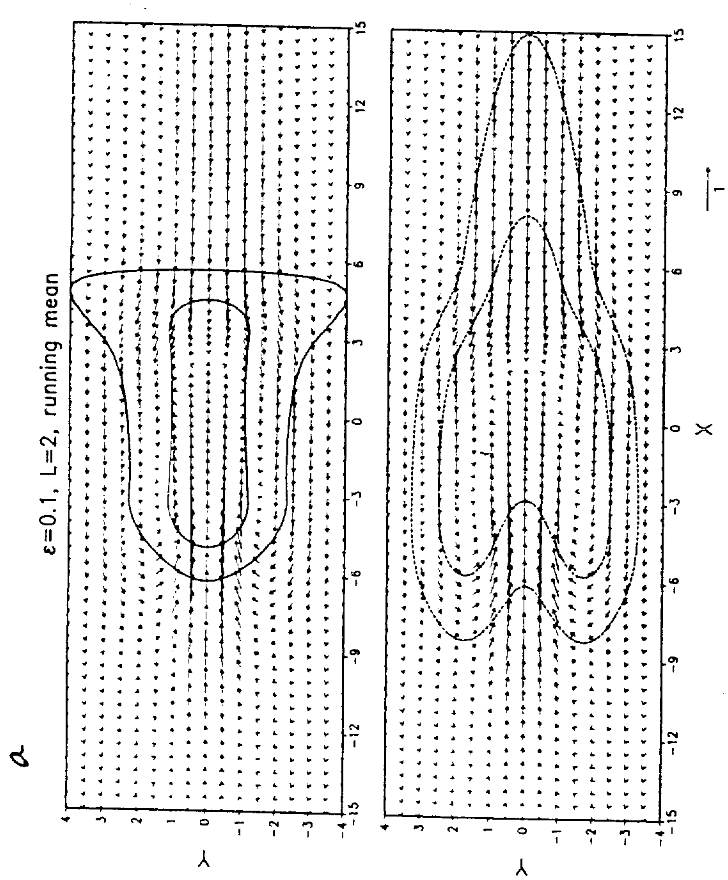


Fig. 2 Modified Gill's non-dimensional solutions: (a) the asymmetric heating case; Upper: contours at 0.1 interval show vertical velocity. The first solid line is zero. Lower: contours at 0.3 interval shows pressure; (b) the symmetric heating case; (c) heating field (Q. as defined by Gill 1980) (shaded at 0.1 contour interval) and zonal wind for asymmetric heating (upper) and symmetric heating (lower).