Summertime quadruplet heating pattern in the subtropics and the associated atmospheric circulation

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[1] A quadruple heating pattern is found over each subtropical continent and its adjacent oceans in summer based on data diagnosis. The ocean region to the west is characterized by strong longwave radiative cooling (LO); the western and eastern portions of the continent are dominated by sensible heating (SE) and condensation heating (CO), respectively; and the ocean region to the east is characterized by double dominant heating (D), with LO prevailing CO. These compose a LOSECOD heating quadruplet. Its general feature is heating over the continent and cooling over the oceans. A distinct circulation pattern accompanies this heating pattern: in the upper troposphere, anticyclonic circulation over the continent is accompanied by cyclonic circulations over the oceans on its western and eastern sides; near the surface, cyclonic circulation over the continent is accompanied by anticyclonic circulations over the oceans on both sides. This circulation feature is interpreted as the atmospheric thermal adaptation to the quadruplet heating. It is further demonstrated that the global summer subtropical heating and circulation may be viewed as "mosaics" of such a quadruplet heating and circulation patterns, respectively. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3319 Meteorology and Atmospheric Dynamics: General circulation; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions. **Citation:** Wu, G., and Y. Liu, Summertime quadruplet heating pattern in the subtropics and the associated atmospheric circulation, *Geophys. Res. Lett.*, *30*(5), 1201, doi:10.1029/2002GL016209, 2003.

1. Introduction

[2] Many studies [*Queney*, 1948; *Charney and Eliassen*, 1949; *Bolin*, 1950; *Yeh*, 1950; *Rodwell and Hoskins*, 2001] have shown the importance of large-scale mountains in the formation of atmospheric circulation in winter. However, the circulations in summer subtropics seem to be more related with thermal forcing, and the formation mechanism is more complicated compared with other latitudes [*Hoskins*, 1987]. In recent years, the impacts of monsoon condensation heating on the formation of subtropical anticyclones have been reported [*Hoskins*, 1996; *Wu et al.*, 1999; *Wu and Liu*, 1999; *Liu et al.*, 1999, 2001; *Rodwell and Hoskins*, 2001; *Chen et al.*, 2001]. All of these studies show that the surface anticyclones forced by monsoon heating alone are too weak compared to observations. *Liu et al.* [2001, Figure 8] further showed in a numerical experiment with monsoon condensation heating as the sole external forcing, that the induced South Asian High in the upper troposphere is also too weak, whereas the middle tropospheric subtropical anticyclones over western oceans are too strong. They then demonstrated that the introduction of land surface sensible heating to the simulation brought them close to the observed strength. On the other hand, as *Rodwell and Hoskins* [2001, Figure 8] showed, the local cooling over eastern oceans does significantly enhance the *in situ* subsidence and subtropical anticyclones over the oceans. All of these results indicate that different diabatic heatings play different roles in the formation of subtropical anticyclones [*Liu and Wu*, 2000], and should be considered in synthesis. In this regard, the present study employs the reanalysis data of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) [*Kalnay et al.*, 1996] from 1980 to 1997 to demonstrate the distributions of individual as well as total diabatic heating against circulations in the summer subtropics.

2. A Quadruple Heating Pattern and the Associated Circulation Pattern

[3] The July-mean column-integrated heating over the eastern North Pacific, North American and the western North Atlantic (PNAA, 150–40°W) is presented in Figure 1a. Its prominent feature is cooling over ocean and heating over continent in the subtropics. Figure 1b demonstrates the distributions of the intense longwave radiative cooling (LO) and dominant local heating in the area. Because over the oceans, LO usually overwhelms other heatings, only those LO stronger than -220 Wm^{-2} are shown in the figure so that the secondary heating can be observed. To confirm the dominance of different heatings in different locations, the vertical profiles of LO, diffusive sensible heating (SE), deep convective heating (CO), and total heating (TH) at four typical sites L (30°N, 122°W), S (30°N, 108°W), C (30°N, 80°W) and D (30°N, 60°W) within different heating lobes as shown in Figure 1b are presented in Figure 1c, respectively.

[4] By comparing Figure 1a with Figure 1b, the PNAA area can be divided into four sub-regions according to their heating features. Over the eastern Pacific, the strong negative TH (a) is due to LO with an intensity exceeding -220 Wm^{-2} (b). Figure 1c (left) demonstrates that over this LO lobe SE is weak, no obvious CO is observed, and strong LO of -6.5 Kd^{-1} appears in the low layer between $\sigma = 0.85$ and 0.95. In Figure 1a, the two heating maximums over western and eastern North America coincide with the SE and CO centers shown in Figure 1b, and possess maximum heating of more than 150 Wm^{-2} and 200 Wm^{-2}, respectively. Over the SE lobe, CO is secondary (Figure 1c, middle left) and SE dominates in the lower troposphere with a maximum of

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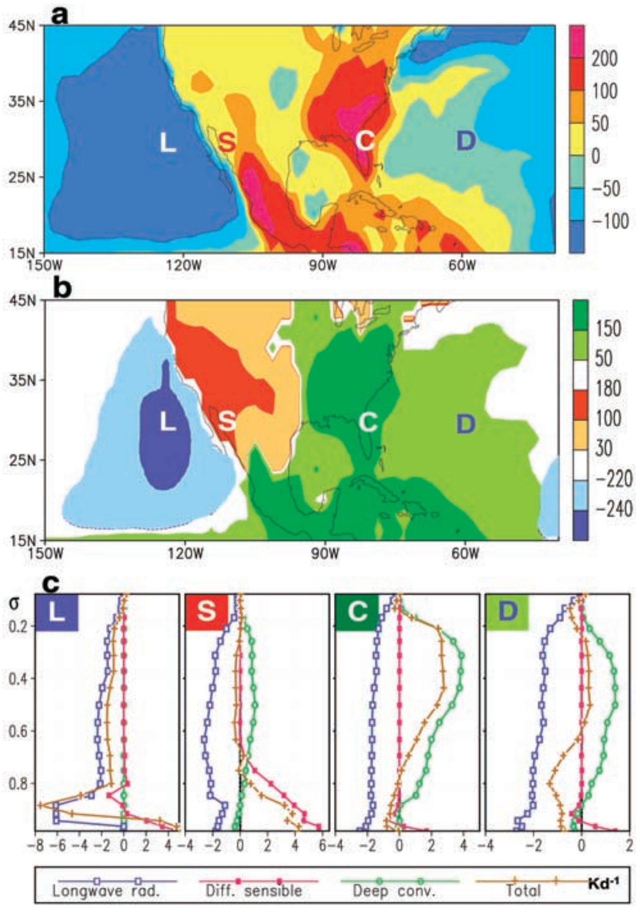

Figure 1. July-mean distribution of column-integrated diabatic heating over the PNAA region. (a) Total heating. (b) Main local heating, blue color denotes longwave radiative cooling (LO); yellow and red, sensible heating (SE); and green, condensation heating (CO). (c) Vertical profiles of different heatings at the marked locations L, S, C, and D representing, respectively, those over the LO, SE, CO, and D lobes. Units: Wm^{-2} in (a) and (b), but Kd^{-1} in (c).

about 6 Kd^{-1} near the surface. Over the CO lobe (middle right), the huge CO of more than 3 Kd^{-1} in the upper troposphere is the main feature. Over the Atlantic to the east, a condensation heating of 50 to 150 Wm^{-2} exists to the west of 45°W (Figure 1b). Figure 1c shows that at site D, CO together with shortwave radiative heating (figure not shown) in the layer between σ = 0.2 and 0.6 exceed LO, whereas above and below this layer they are weaker than LO. The column-integrated heating in this lobe is then negative (Figure 1a). This feature distinguishes lobe D from lobe CO, although significant latent heating and wet climate exist in both lobes. As a whole, the shapes of TH profile over the LO, SE, CO, and D lobes (Figure 1c) are determined respectively by LO, SE, CO, and double dominant heating (D). Therefore, the atmospheric diabatic heating over PNAA demonstrates a quadruplet that is organized as LO over the ocean to the west, SE over the western continent, CO over the eastern continent and D over the ocean to the east, forming as a "LOSECOD" quadruplet, and with heating over land and cooling over ocean in general.

[5] The July-mean wind field and geopotential height deviation (colored) from its equatorial zonal mean at 100 hPa and 1000 hPa over the PNAA region are shown in Figure 2. The continental area where the SE and CO heating prevail is characterized by the existence of surface cyclonic and upper tropospheric anticyclonic circulations. In contrast, the oceanic area where LO prevails is characterized by the existence of surface anticyclonic and upper tropospheric cyclonic circulations. This can be understood through the PV-θ view, according to which a heating (cooling) can produce lower layer cyclonic (anticyclonic) vorticity and upper layer anticyclonic (cyclonic) vorticity [*Hoskins*, 1991; *Wu and Liu*, 2000]. However, such anticyclonic circulations near the surface (Figures 2b and 3d) are strongly asymmetric about their central meridional axis. That is, over the LO lobe, the equatorward flow is strongly developed, whereas over the D lobe, a band of southwesterly wind extends northeastward from the Florida Peninsula, just in coordination with the band of deep condensation heating over western Atlantic (Figure 1b). Furthermore, the meridional winds over the LO and SE lobes to the west are equatorward near the surface but poleward in the upper troposphere, whereas they are poleward near the surface but equatorward in the upper troposphere over the CO and D lobes to the east. The correspondence between the profile of heating Q and meridional wind v can be interpreted by employing the following Sverdrup balance [*Wu et al.*, 1999; *Liu et al.*, 2001]:

$$\beta v \approx (f+\zeta)\theta_z^{-1}\partial Q/\partial z.$$

The decrease (increase) with height of a heating Q produces negative (positive) vorticity. In a steady state and in the

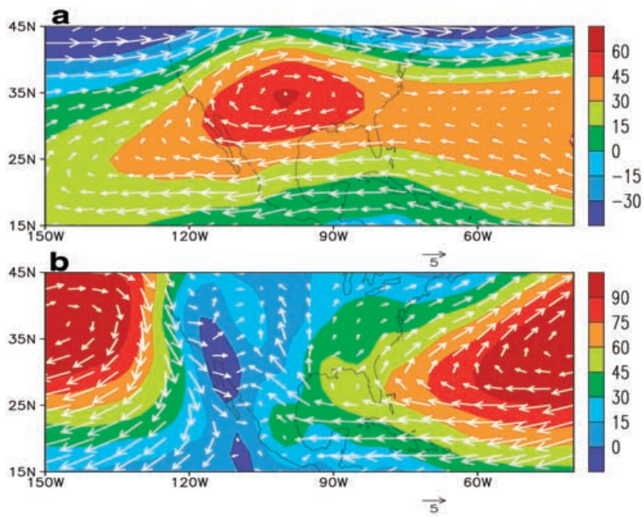

Figure 2. July-mean circulations at (a) 100 hPa and (b) 1,000 hPa over the PNAA region. Coloured shading indicates the deviation of geopotential height from the equatorial zonal-mean in units of geopotential meters (gpm). Arrows represent horizontal winds. In correspondence with the LOSECOD quadruplet heating, the circulations in the region also possess a unique pattern: the lower tropospheric cyclone is over the continent and accompanied by anticyclonic circulations over the oceans on its western and eastern sides, whereas in the upper troposphere, the anticyclone is over the continent and accompanied by cyclonic circulations over the oceans on its two sides.

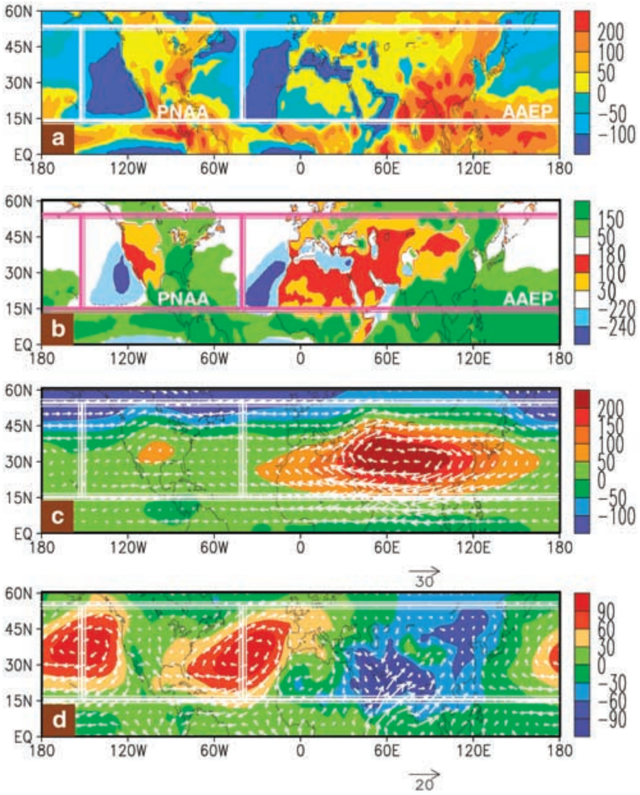

Figure 3. July-mean distributions in the northern hemisphere of the column-integrated (a) total heating and (b) main local heating in units of Wm^{-2}, and the wind vector and deviation of geopotential height from the equatorial zonal-mean at (c) 100 hPa and (d) 1000 hPa with units of gpm. The heating distributions (a and b) demonstrate a mosaic of the quadruplet LOSECOD heating patterns, and the circulations (c and d) also demonstrate a mosaic of the circulation patterns as shown in Figure 2.

absence of zonal advection, this must be balanced by positive (negative) planetary-vorticity advection that is brought in by meridional winds from high (low) latitudes. Since the TH in the LO and SE lobes decreases with height rapidly in the lower layer, but increases with height in the deep upper layer (Figure 1c), the *in situ* strong near-surface equatorward flow and weaker upper-layer poleward flow should be generated, as demonstrated in Figure 2. A similar argument applies in the CO and D lobes. In summary, the circulation pattern shown in Figure 2 is primarily forced by the LOSECOD quadruple heating pattern.

3. Mosaics of the Heating Quadruplet and Circulation Pattern

[6] In the northern subtropics there are two big continents. Besides the PNAA region, the rest is defined as the Atlantic- Africa- Eurasia- Pacific region, or AAEP. It will be shown elsewhere that the heating quadruplet is mainly forced by the land distribution. Therefore the lateral boundaries are chosen at the longitudes over the oceans where SH is negligible and the surface meridional wind components vanish. The distribution of the July-mean column-integrated heating and main local heating over the entire northern subtropics are respectively presented in Figures 3a and 3b. They agree with the distributions of the apparent heat source Q1, apparent moisture sink Q2 [*Yanai et al.*, 1973], and outgoing longwave radiation calculated from the same data source from 1980 to 1994 [*Yanai and Tomita*, 1998]. The vertical profiles of the heating in each lobe are similar to those presented in Figure 1c and shown by *Yanai et al.* [1992] and *Yanai and Tomita* [1998], and are thus not shown here. Despite the huge area occupied by AAEP, a heating quadruplet similar to the one over PNAA can be identified. A strong LO lobe is located over eastern North Atlantic. A SE lobe occupies the vast western and central AAEP area. A very intense CO lobe is found over the East Asian monsoon region. Although a deep condensation heating of more than 50 Wm^{-2} extends from the East China Sea to Japan (Figure 3b), radiative cooling overwhelms the heating over western Pacific (Figure 3a).

[7] The July-mean circulations of the northern hemisphere at 100 and 1000 hPa are shown in Figures 3c and 3d, respectively. Along the subtropics over AAEP, the circulation pattern as demonstrated in Figure 2 can also be detected, and is well coordinated with the LOSECOD quadruplet. At 1000 hPa, a cyclonic low prevails in the SE and CO lobes. At 100 hPa, in correlation with the vast longitude-span of the SE and CO lobes, the anticyclone covers the whole AAEP domain with a deviation height about three times as strong as its counterpart over PNAA. This is because in the absence of advection, the intensity of the geopotential height of a forced cyclone/anticyclone is proportional to the strength and the squared zonal half-length of the forcing. Furthermore, when the circulation patterns over AAEP and PNAA are placed side by side, the two troughs at 100 hPa and the two strong subtropical anticyclones at 1000 hPa appear just at the joined edges. It becomes apparent that for each strong oceanic surface subtropical anticyclone, its eastern part is substantially affected by radiative cooling and continental sensible heating, whereas its western part is to a great extent affected by radiative cooling as well as condensation heating associated with the summer monsoon.

[8] In the southern subtropics there are three continents. By selecting the three longitudes of 110°W, 20°W, and 90°E as boundaries, the southern subtropics can be divided into three regions: the Pacific- South America- Atlantic (PSAA), Atlantic- South Africa- Indian Ocean (ASAI), and Indian Ocean- Australia- Pacific (IAUP) regions, as shown in Figure 4. The distribution of the January-mean TH is presented in Figure 4a, and the main local heating, in Figure 4b. The LOSECOD quadruplet can also be identified between 15° and 35°S in each region, with the central heating lobes SE and CO located over the continent, and radiative cooling over the oceans.

[9] The January-mean circulations of the southern hemisphere at 100 and 1000 hPa are shown in Figures 4c and 4d, respectively. Again, the circulation pattern as seen in Figure 2 is prominent over each continent. The longitude spans of the individual heating patterns in the southern subtropics differ very little from each other. Therefore, the intensities of the three upper tropospheric anticyclones (greater than 30 gpm) are similar (Figure 4c). When the three circulation patterns are tiled side by side, troughs in the upper troposphere and anticyclones near the surface are

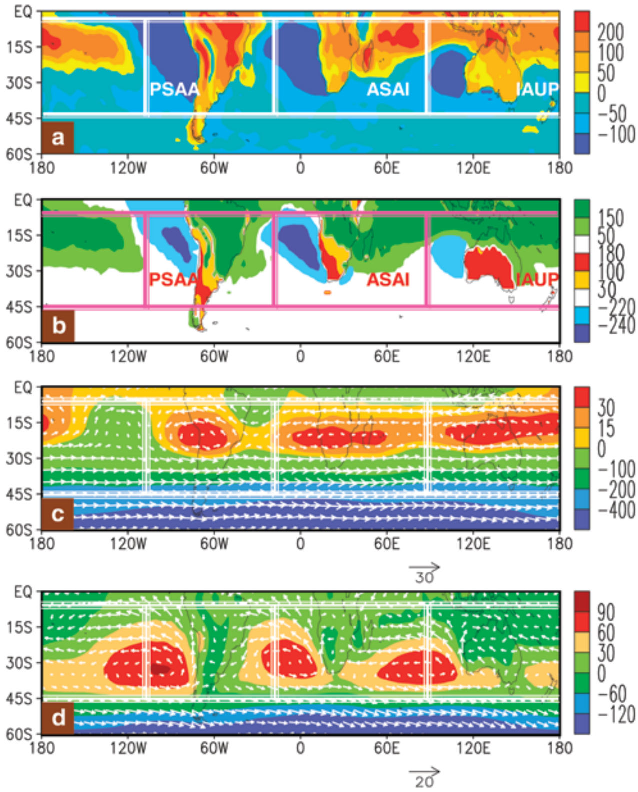

Figure 4. Same as in Figure 3 for the January-mean distributions in the southern hemisphere.

found at the three joined edges, as is the case in the northern hemisphere.

4. Conclusions and Discussions

[10] We have shown that over each continent and its adjacent oceans in summer subtropics, there exist a heating quadruplet LOSECOD and an associated circulation pattern with surface cyclonic and upper-layer anticyclonic circulations over the continent but surface anticyclonic and upper-layer cyclonic circulations over the oceans, and the summer subtropical circulations can be considered as a mosaic of such circulation patterns. In this mosaic, the subtropical anticyclones in the upper troposphere appear over the centers of the circulation patterns, whereas near the surface they appear at the edges of the two adjacent patterns. Because the zonal sizes within the quadruplet are comparable in all regions except AAEP, the mosaic intensities are similar over the other regions but very strong over AAEP. Consequently, over the AAEP region are observed the most pronounced upper tropospheric anticyclone (the South Asian High), the most vast and severe deserts (the Sahara, Takla Makan and Gobi deserts etc.), and the most intense summer monsoon (Asian summer monsoon).

[11] The observed climate distribution over the whole globe is very complicated. It depends not only on the land-sea distribution but also on the earth's orography, the interactions between different climate subsystems, and different circulation patterns in different latitudes, and so forth. Although as a first approximation, the circulation pattern shown in Figure 2 can be considered as the thermal adaptation of the atmosphere to the LOSECOD quadruplet heating through the PV-θ view and the Sverdrup balance, many dynamical aspects of the formation of the subtropical circulation remain unclear. For instance, how does the local meridional circulation, including the Hadley cell, interact with the subtropical circulation? To what extent do the heating patterns themselves depend on the atmospheric circulation pattern? How do zonal advection and mountain forcing affect their configurations? A more important issue concerns why the heating is organized in such a quadruplet pattern. In any case, an understanding of the peculiar LOSECOD quadruplet heating and the associated circulations in the summer subtropics will help us in the study of climate variability and predictability.

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