Article ID: 1006-8775(2002) 02-0113-08

THE TEMPORAL AND SPATIAL CHARACTERISTICS OF MOISTURE BUDGETS OVER ASIAN AND AUSTRALIAN MONSOON REGIONS

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ABSTRACT: Apparent moisture sink and water vapor transport flux are calculated by using NCAR/NCEP reanalyzed daily data for water vapor and wind fields at various levels from 1980 to 1989. With the aid of EOF analysis method, temporal and spatial characteristics of moisture budgets over Asian and Australian monsoon regions are studied. The results show that there is apparent seasonal transition of moisture sink and water vapor transport between Asian monsoon region and Australian monsoon region. In winter, the Asian monsoon region is a moisture source, in which three cross-equatorial water vapor transport channels in the "continent bridge", at 80°E and 40°E ~ 50°E transport water vapor to the Australian monsoon region and southern Indian Ocean which are moisture sinks. In summer, Australian monsoon region and southern Indian Ocean are moisture sources and by the three cross-equatorial transport channels water vapor is transport to the Asian monsoon region which is a moisture sink. In spring and autumn, ITCZ is the main moisture sink and there is no apparent water vapor transport between Asian monsoon region and Australian monsoon region.

Key words: Asian-Australian monsoon region; moisture budgets; temporal and spatial characteristics

CLC number: P426 **Document code:** A

1 INTRODUCTION

Moisture budget is one of the important issues in general circulation. It not only links with moisture content in the general circulation and synoptic systems but with, more essentially, possible latent heat release or heating in the atmosphere. It is a substantial part of dynamic and thermodynamic workings in the climate system. In the Northern Hemisphere, which is mostly covered with land, the Tibetan Plateau is unique for its terrain, which gives rise to Asian monsoon, the most vital and influential of its kind. Interacting with the austral Australian monsoon, it acts as an integral member in the so-called Asian-Australian (AA) monsoon system. Transporting immense amount of moisture from the ocean to monsoon regions, the AA monsoon system greatly contributes to precipitation. It is also noted that research on moisture budgets of the AA monsoon region is of far-reaching economic and social significance, as 60% of the world's population is supplied by precipitation from the AA monsoon system.

As early as in 1958, Xu[1] studied the transfer and equilibrium of moisture in China. In their discussion of moisture transportation over severe precipitation in the Yellow and Huaihe Rivers basins, Xie and Dai[2] suggested close relationship between processes of severe rainfall and moisture input. Tao et al[3]. worked on two cases of 1991 Mei-yu concerning moisture fluxes and regional moisture budgets and isolated the Bay of Bengal and South China Sea as the source of moisture in the Mei-yu process. With the Lagraian method, Lu et al[4]. calculated the trajectory of air particles and substantial lines on isentropic surfaces with the finding showing close

Received date: 2001-10-08; **revised date:** 2002-10-11
Foundation item: Part One in Development Planning for National Key Fundamental Research (G1998040900); "South China Sea Monsoon Experiment Studies"—Scaling Project A of National Ministry of Science and Technology
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relationship between heavy rainfall in southern China and summer monsoon in 1994. With their study on the distribution and transportation of moisture in the Asian monsoon region in August 1994, Zhou et al[5]. pointed out that areas from 120°E to 133°E in the western Pacific and the Bay of Bengal were source regions and the South China Sea was a sink region, of moisture, and precipitation in northern China was mainly affected by two monsoon systems in Asia. Li[6] worked on moisture flux and equilibrium in the South China Sea during late boreal spring and summer and suggested that the sea, like a "water storing pool" due to its special geographic location, was a sink of moisture at the time. In their study on the difference of moisture transportation between the East Asian monsoon region and South Asian monsoon region, Huang et al[7]. revealed that the transportation was mainly meridional in the former region but mainly zonal in the latter region. Yi et al[8]. pointed out that there was obvious transportation of moisture in meridional circulation of summer monsoon, making the subtropical and mid-and-high latitude regions accessible to moisture from the equator and tropics. In their study on moisture budget in monsoon regions, Yasunari et al[9]. showed that moisture transfer fluxes and divergences, which were highly regional and seasonal, were dependent on the background of general circulation. The research summed up above is mainly on moisture budget in the Asian monsoon region, with no mention of inter-links of moisture budget between it and the Australian monsoon region and most of the attention on summertime rather than transitional seasons. It is therefore the aim of the current work to study the temporal and spatial distribution of moisture budget in the AA monsoon region.

2 DATA AND METHODS OF ANALYSIS

Data used in the work include zonal wind u / meridional wind v at upper and surface levels, vertical p-velocity ω, temperature T, specific humidity q and surface pressure p_s, as provided in the subset of daily data of the reanalysis data from NCAR/NCEP for 1980 ~ 1989. Besides, data of surface precipitation and evaporation were also used for 1950 ~ 1997.

The equation of Yanai et al[10].(1973) was used to calculate the apparent sink of moisture.

$$Q_2 = -L[\frac{\partial q}{\partial t} + v \cdot \nabla q + w\frac{\partial q}{\partial p}]$$

where q is the specific humidity, v the horizontal wind, ω the vertical p-velocity and L the latent heat of condensation.

The equation for vertical integration $\langle Q_2 \rangle$ is expressed as below:

$$\langle Q_2 \rangle = \frac{1}{g}\int_{p_T}^{p_S} Q_2 \,\mathrm{d}\, p$$

Additionally, Yanai once gave $\langle Q_2 \rangle \cong L(P-E)$, in which P was the precipitation rate and E the evaporation rate.

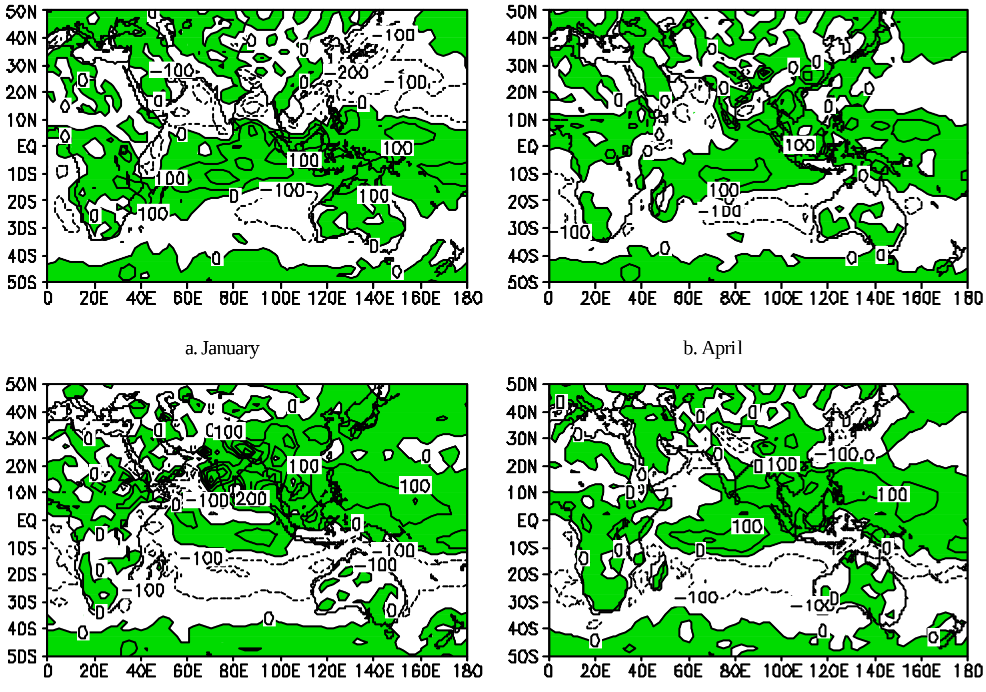
For a given column of air, the flux vector of a whole layer of atmospheric moisture can be determined by the following expression of

$$\vec{Q} = \frac{1}{g}\int_{p_T}^{p_s} \vec{V} \cdot q \,\mathrm{d}\, p = \frac{1}{g}\int_{p_T}^{p_s} (u, v) q \,\mathrm{d}\, p$$

where individual quantities of physics carry the same meaning as previously stated. As there is virtually no moisture above 300 hPa, relevant records cover up to the level of 300 hPa, we then have p_T=300 hPa.

3 SEASONAL CHANGES OF APPARENT MOISTURE SINKS <Q_2> VERTICALLY INTEGRATED FOR AA MONSOON REGION

Fig.1 (a, b, c & d) respectively gives the distribution of apparent moisture sinks vertically integrated for January, April, July and October averaged over years 1980 ~ 1989 (0° ~ 180°E, 50°S ~ 50°N). The shaded areas are where moisture sinks. In January, the Asian monsoon region is the largest source of moisture while ITCZ and the Australian monsoon region the largest sink of moisture. Specifically, the centers of the moisture sink are over the areas of kuroshio current, South China Sea, Bay of Bengal and Arabian Sea with central value over –200 W/m^2. The ITCZ is relatively southward, being one of the sink centers apart from austral Indonesia and northern Australia, with the central value more than 100 W/m^2. It deserves attention that general distribution of weak moisture sources in continental Asia is mingled with scattered weak moisture sinks, which reflects the land-sea contrast as well as seasonal change. Precipitation is the dominant phenomenon over landmass over which moisture and evaporation are both scarce while evaporation is the major play over ocean, which is rich in moisture. Such distribution of land and ocean for the Asian monsoon region is the consequence of seasonal change superposed on land-sea contrast. As what is easily observed, seasonal change has a bigger impact than land-sea contrast.



a. January b. April

c. July d. October

Fig.1 Distribution of vertically integrated moisture sinks averaged over multiple years of 1980～1989 (0～180 ° E，50 ° S～50 ° N).

In April, the axis of ITCZ lies around the equator and the corresponding areas of moisture sink are symmetrically located in both hemispheres. Moisture sinks are obvious over southern China and south of the Changjiang River (the Yangtze) with the center being 200 W/m^2, signaling the onset of the yearly first season of rainfall in southern China. In the meantime, moisture sources weaken over the South China Sea, Bay of Bengal and Arabian Sea and even change to moisture sources of small values in austral areas from south of 10°S to northern Australia between 110°E and 140°E, and moisture sources increase over southern Indian Ocean so that a center of –200 W/m^2 appears, though with low intensity.

In July, horizontal distribution of moisture sources and sinks are just reversed across the two hemispheres, with the dividing line largely along the equator. The Asian monsoon region in the Northern Hemisphere is a significant moisture sink while the Australian monsoon region and southern Indian Ocean are significant moisture sources. The ITCZ is northward relative to the equator. Specifically, the largest center of moisture sinks is near the Tibetan Plateau; moisture sources are present over India, Bay of Bengal, South China Sea and basins of Changjiang and Yellow Rivers and southern China while moisture sinks are found over the Australian monsoon region and Arabian Sea; moisture sources are much enhanced over southern Indian Ocean; the contour of –100 W/m^2 increases the coverage; there is a center of moisture source with intensity of –200 W/m^2 west of Australia and east of Madagascar; moisture sources join near 40°E for the austral Indian Ocean and the Arabian Sea. The distribution of moisture budget over the AA monsoon region is almost the opposite from that in January.

In October, the ITCZ remains northward relative to the equator. It is acting as a major moisture source while other sources weaken significantly over the Asian monsoon region. Waters off the coast of eastern China have turned into sources of moisture with central intensity of –200 W/m^2 but the Bay of Bengal and South China Sea-western Pacific remain sinks of moisture. The moisture source becomes much weaker over Australia, the –100 W/m^2 contour breaks off over southern Indian Ocean and the –200 W/m^2 center disappears east of Madagascar and west of Australia.

A source is one in which atmospheric moisture evaporates to the whole column of atmosphere while a sink is one in which it precipitates. An apparent moisture sink is defined as net expense of atmospheric moisture resulting from subtraction of precipitation from evaporation. In a difference chart (figure omitted) calculated for the evaporation and precipitation averaged over 48 years (1950 ~ 1997), we note that the distribution is generally consistent with the vertically integrated apparent sink of moisture $<Q_2>$. No attempts will be made to elaborate it.

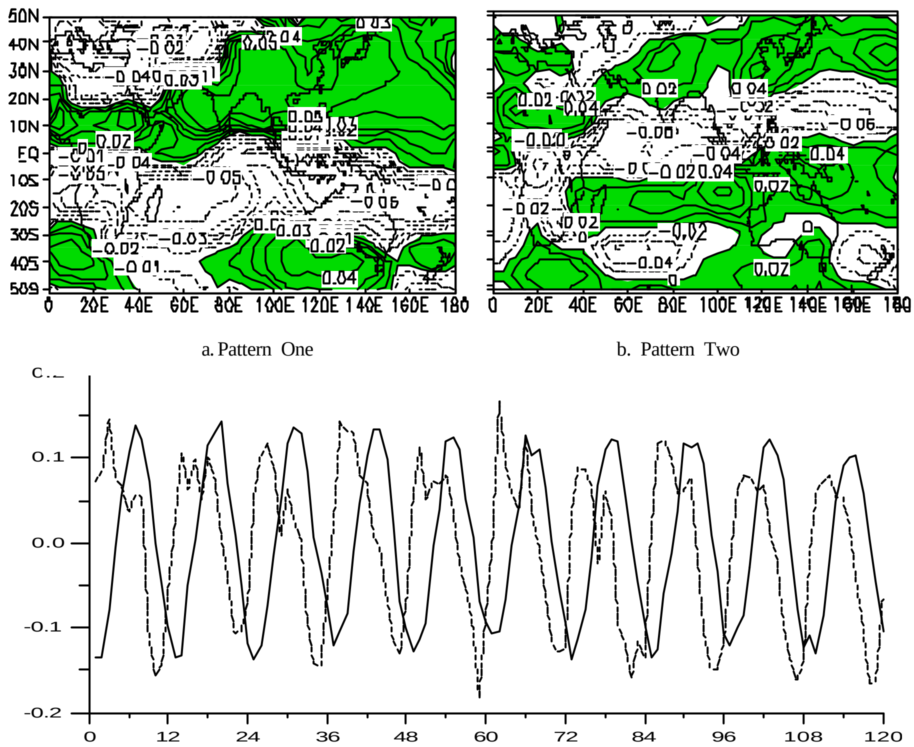
In general, multi-year mean distribution of moisture for the AA monsoon region varies contrarily in winter from that in summer (of boreal season, the same below). The Asian region is a source in winter while the Australian region a sink, with the ITCZ southward relative to the equator. In contrary, the Asian monsoon region is a sink in summer while the Australian region a source, with the ITCZ northward relative to the equator. Spring and summer are transitional seasons during which the moisture sink over the ITCZ plays an important role.

4 ANALYSIS OF PRIMARY COMPONENTS OF APPARENT MOISTURE SINKS $<Q_2>$ VERTICALLY INTEGRATED FOR AA MONSOON REGION

To extract typical spatial distribution of apparent moisture sinks that are vertically integrated, an EOF analysis is carried out. Original data are treated with 9-point smoothing to obtain large-scale information at the expense of local changes. Fig.2 (a, b & c) are Pattern One, Pattern Two and associated time coefficients in the EOF analysis. Fig.2 (a & b) give positive domains in shaded area and the solid lines in Fig.2c are the time coefficient for Pattern One and the dashed lines the time coefficient for Pattern Two.

It is clearly shown in Fig.2a that a typical $<Q_2>$ is north-south distributed, with the Australian monsoon region in opposite pattern with the Asian region by a variance of 33%. Specifically, the zero line lies near the equator with most of the Asian monsoon region in positive domain and maximum positive centers respectively locating over the Bay of Bengal ~ mainland China and South China Sea ~ western Pacific; the Australian monsoon region and southern

Indian Ocean are negative with the centers over Indonesia ~ northern Australia and southern Indian Ocean between 40°E ~ 80°E, the absolute values being comparable for both positive and negative centers. In Fig.2c, time curves for Pattern One show regular distribution of wavetrains with a period of 1 year, being maximum negative in wintertime January but maximum positive in summertime July. By comparing the Pattern One in spatial distribution and associated time curves, we know that the Australian monsoon region is a moisture sink and the Asian one a source, in winter. Things are just the opposite in summer. In Fig.2b, there is a belt of positive values for each of the Asian and Australian monsoon regions, which alternates with a belt of negative values, whose central axis generally coincides with the zero line in Pattern One. The time coefficient curve for Pattern Two also shows variation of 1-year periodicity, which becomes positive maximum in April (spring) but negative maximum in October (autumn). It is exactly 90° in phase difference from the time coefficient curve of Pattern One. Examining Patterns One and Two in comparison, we find that it reflects the transformation process in winter, summer and transitional seasons of moisture sinks and sources in the AA monsoon region. Specifically, Pattern One is mainly reflecting the variations of the region as affected by the monsoon and Pattern Two the seasonal changes of the ITCZ.



a. Pattern One

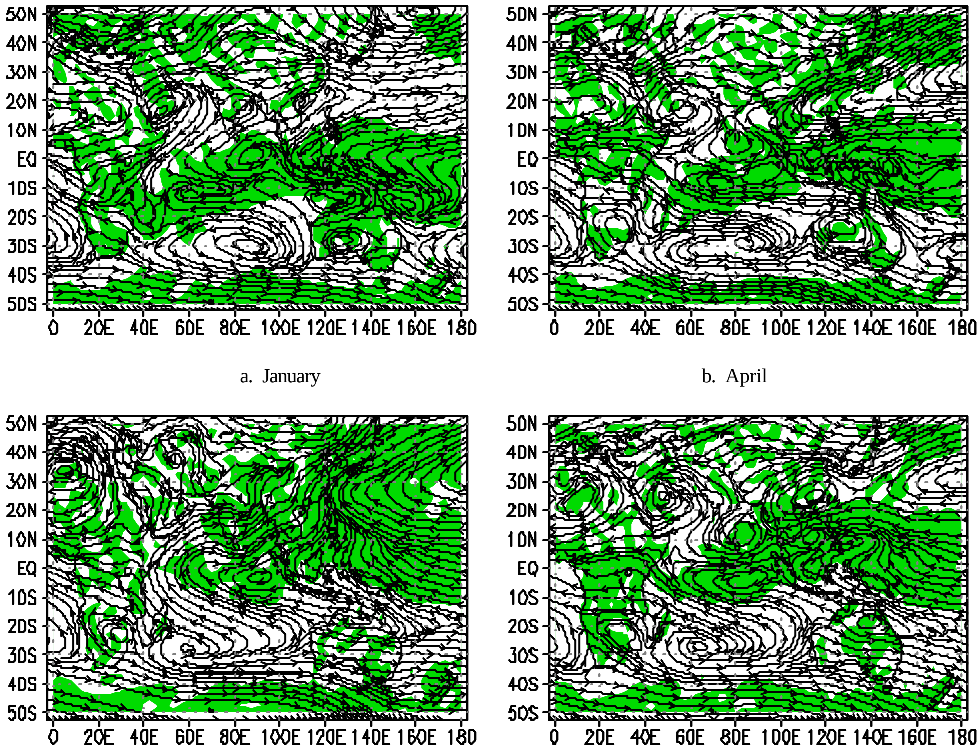
b. Pattern Two

c. Time coefficients for Patterns One (solid line) and Two (dashed line)

Fig.2 Spatial Patterns One (a) and Two (b) in EOF analysis and corresponding time coefficients (c), in which the solid line is of Pattern One and the dashed line of Pattern Two.

5 TRANSPORTATION OF MOISTURE BETWEEN ASIAN AND AUSTRALIAN MONSOON REGIONS

Fig.3 (a, b, c & d) gives the distribution of streamlines and diversity of transportation fluxes of vertically integrated moisture for January, April, July and October averaged over years 1980 ~ 1989 (0° ~ 180°E, 50°S ~ 50°N). The shaded areas are where fluxes of moisture converge.



a. January b. April

c.July d. October

Fig.3 Distribution of vertically integrated moisture transfer streamlines and their diversity, which have been averaged over multiple years of 1980～1989 (0～180 ° E, 50 ° S～50 ° N).

In January, the Asian monsoon region is a moisture sink, from which three cross-equatorial channels transport moisture to the Australian monsoon and southern Indian Ocean. They are specifically (1) between 100°E and 135°E, where the channel near the continental bridge carries moisture from the South China Sea ~ western Pacific to Indonesia, northern Australia and the Australian monsoon region east of it, (2) near 80°E where moisture is carried across the equator from the Bay of Bengal to low-latitude Indian Ocean in the Southern Hemisphere; (3) between 40°E ~ 50°E where moisture is transferred from the Arabian Sea to low-latitude Indian Ocean in the Southern Hemisphere. At the time, the ITCZ and Australian monsoon region is a large-scale moisture convergence while Kuroshio in the Asian monsoon region, South China Sea, Bay of Bengal and Arabian Sea are divergence of moisture.

In April, moisture transportation is not significant between the Asian and Australian monsoon regions so that the meridional component of flux vector is almost zero for the equatorial moisture transportation. Zonal transportation is a major feature. The axis of moisture transfer convergence for the ITCZ is near the equator. The warm and humid moisture shifted to southern China from tropical ocean surface of the Bay of Bengal and northern South China Sea is forming convergence of moisture over the area to feed precipitation needed in the yearly first raining season there.

In July, the Australian monsoon region and southern Indian Ocean are sources of moisture, from which three channels transport moisture to the Asian monsoon region in what turns out an opposite completion in January. The channels are respectively (1) between 110°E and 135°E, in which the continental bridge carries moisture from the Australian monsoon region and Indonesia to the South China Sea ~ western Pacific tropical monsoon region and East Asian subtropical monsoon region, (2) near 80°E where moisture is carried from southern Indian Ocean ~ the monsoon region in the Bay of Bengal to the South China Sea ~ western Pacific tropical monsoon region and East Asian subtropical monsoon region, and (3) between 40°E and 50°E where moisture is carried from southern Indian Ocean to the Indian monsoon region via the Arabian Sea. Regions of India, Bay of Bengal, South China Sea / western Pacific and East Asian Pacific subtropics are where moisture converges while the Australian monsoon region and southern Indian Ocean are where moisture diverges, on large scales.

In October, the situation is similar to that in April. Moisture transportation is mainly zonal on the equator and the meridional component is small. There is no significant moisture shift inside the AA monsoon region. The converging moisture transfer for the ITCZ is northward while the Bay of Bengal and South China Sea are still places of convergence of moisture transfer.

As moisture concentrates on lower levels, distribution of flux vectors in moisture transportation is studied for the level of 850 hPa (figure omitted). It also shows obvious transportation of moisture within the AA monsoon region in both summer and winter, which is highly consistent with the distribution of flux vectors of vertically integrated moisture transfer. No detailed discussions are attempted here in the work.

In general, winter is a season when cross-equatorial channels carry moisture from the Asian monsoon region to the Australian monsoon region and southern Indian Ocean while summer is a time when they send moisture from the Australian monsoon region and southern Indian Ocean to the Asian monsoon region.

6 CONCLUDING REMARKS

In this paper, we have discussed the temporal and spatial characteristics of moisture budgets over the AA monsoon region and the main findings may be summarized as follows:

a. In winter, the Asian monsoon region is a source of moisture and the Australian monsoon region a sink of moisture. In spring, the ITCZ is a major area of moisture sink. In summer, the Asian monsoon region is a sink of moisture and the Australian monsoon region a source of moisture. In autumn, the ITCZ is northward and the South China Sea and Bay of Bengal remain sinks of moisture.

b. As shown in relevant EOF analysis, a typical distribution pattern for apparent moisture sinks that are vertically integrated over the AA monsoon region is a north-south one (spatial Pattern One), i.e. the Australian monsoon region being in opposite distribution with the Asian one. The pattern changes substantially with season and varies with periodicity of 1 year in associated time coefficient. It is negatively maximum in every January but positively maximum in every July. In other words, the Australian monsoon region is a source of moisture and the Asian one a sink of moisture in July and otherwise is true in January. Patterns One and Two, which resulte from combined EOF analysis, reflect on moisture budget of the AA monsoon region in both winter and summer and transformation of transitional seasons.

c. There is obvious transportation of moisture within the AA monsoon region. By way of three cross-equatorial channels moisture is transported from the Asian monsoon region to the Australian monsoon region and southern Indian Ocean in winter. They do just the opposite in winter. There is not any significant transfer of moisture in both spring and autumn.

In this work, climatological characteristics are studied of moisture budget in the AA monsoon region using multi-year mean data. Additional attempts will be made in future work to address its interannual variation and the relationship with ENSO.

Acknowledgements: Mr. CAO Chao-xiong, who works at the Guangzhou Institute of Tropical and Oceanic Meteorology, China Meteorological Administration, has translated the paper into English.

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