The Apparent Water Vapor Sinks and Heat Sources Associated with the Intraseasonal Oscillation of the Indian Summer Monsoon

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ABSTRACT

The possibility of using remote sensing retrievals to estimate apparent water vapor sinks and heat sources is explored. The apparent water vapor sinks and heat sources are estimated from a combination of remote sensing, specific humidity, and temperature from the Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit (AIRS) and wind fields from the National Aeronautics and Space Administration (NASA)’s Goddard Space Flight Center (GSFC)’s Modern Era Retrospective-Analysis for Research and Applications (MERRA). The intraseasonal oscillation (ISO) of the Indian summer monsoon is used as a test bed to evaluate the apparent water vapor sink and heat source. The ISO-related northward movement of the column-integrated apparent water vapor sink matches that of precipitation observed by the Tropical Rainfall Measuring Mission (TRMM) minus the MERRA surface evaporation, although the amplitude of the variation is underestimated by 50%. The diagnosed water vapor and heat budgets associated with convective events during various phases of the ISO agree with the moisture–convection feedback mechanism. The apparent heat source moves northward coherently with the apparent water vapor sink associated with the deep convective activity, which is consistent with the northward migration of the precipitation anomaly. The horizontal advection of water vapor and dynamical warming are strong north of the convective area, causing the northward movement of the convection by the destabilization of the atmosphere. The spatial distribution of the apparent heat source anomalies associated with different phases of the ISO is consistent with that of the diabatic heating anomalies from the trained heating (TRAIN Q1) dataset. Further diagnostics of the TRAIN Q1 heating anomalies indicate that the ISO in the apparent heat source is dominated by a variation in latent heating associated with the precipitation.

1. Introduction

The vertical distribution of atmospheric heating plays a key role in defining the atmospheric circulation (e.g., Hartmann et al. 1984). Many studies have applied dynamical equations to estimate the apparent heat source Q1 of the atmosphere, which is directly related to the large-scale atmospheric circulation (Hagos et al. 2010; Lin and Johnson 1996; Schumacher et al. 2008; Shige et al. 2004, 2007; Yanai et al. 1973). Latent heating is a key component in the apparent heat source during precipitation events and results from phase transitions of water in the atmosphere. To have a complete description of atmospheric heating processes, it is necessary to know the atmospheric water vapor budget along with the atmospheric heating. The dynamical approach can also be applied to estimate apparent water vapor sink Q2 (Schumacher et al. 2008; Shige et al. 2008; Yanai et al. 1973).

Many estimates of apparent water vapor sink and heat source using the dynamical approach are based on purely reanalysis data (e.g., Hagos et al. 2010; Xavier et al. 2007) or field campaign temperature and water vapor data with winds (e.g., Lin and Johnson 1996; Schumacher et al. 2008). However, no investigation to date has attempted to apply remote sensing retrievals of water vapor and temperature for such estimation and quantified whether the atmospheric water vapor/temperature sounding datasets are physically consistent with other independent rainfall retrievals/diabatic heating estimates with regard to describing the variability of global hydrological/thermodynamic processes.
The advantage of using remote sensing retrievals to estimate apparent water vapor sink and heat source is that they can provide global coverage of climatological records of the quantities with minimal influence from model parameterizations.

The Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit (AIRS) (Divakarla et al. 2006; Fetzer et al. 2004, 2006; Susskind et al. 2006) on board the *Aqua* satellite (launched on 4 May 2002) provides accurate data with global coverage for the long-term study of the hydrologic and thermodynamic structures of the atmosphere. Because of the advantages in spatial coverage and accuracy, we will use AIRS retrievals of specific humidity and temperature together with the National Aeronautics and Space Administration (NASA)'s Goddard Space Flight Center (GSFC)’s Modern Era Retrospective-Analysis for Research and Applications (MERRA) (Bosilovich et al. 2008) wind products to estimate the apparent water vapor sink and heat source.

The capability of the estimated water vapor sink, referred to as the AIRS–MERRA water vapor sink, in reproducing the global pattern of surface water vapor exchange as well as its seasonal cycle will be discussed in a separate paper (Wong et al. 2011). Here we focus on evaluating the capability of the AIRS–MERRA water vapor sink and heat source in reproducing hydrological and thermodynamic processes associated with the Indian monsoon intraseasonal oscillation (ISO).

Precipitation associated with the Indian monsoon is a dominant global rainfall component and provides an ideal test bed for datasets of heat and water vapor budgets. The ISO of the Indian monsoon rainfall is associated with a south-to-north propagation of the precipitation anomaly, from the tropical Indian Ocean to the Indian continent and Bay of Bengal (the India–Bengal region), that generates active and break cycles of precipitation (Goswami 2005). The ISO of the Indian monsoon has been studied for decades (Goswami 2005; Jones et al. 2004; Lau and Chan 1986; Lawrence and Webster 2001; Wang and Rui 1990) and is associated with the northward propagation of tropical deep convection at a time scale of 30–60 days. Many studies have suggested the mechanism behind the northward propagation of convection over the Indian Ocean (e.g., Jiang et al. 2004; Kemball-Cook and Wang 2001; Lau and Peng 1990; Lawrence and Webster 2001; Wang and Xie 1997; among others). Briefly, it involves a vorticity anomaly, generated by the vertical easterly wind shear, to the north of the convective area in the tropics, followed by low-level convergence of moisture. The moisture–convection feedback then helps the convection propagate northward [see Fig. 2.16 in Goswami (2005) for a brief schematic summary].

In this study, we will investigate if the apparent water vapor sink and heat source estimated from the AIRS–MERRA data are consistent with the suggested mechanism behind the Indian monsoon ISO. The apparent water vapor sink will be compared with independent surface precipitation and evaporation estimates, and the apparent heat source will be compared with independent estimates of diabatic heating rates. The data used and the method of calculating the apparent water vapor sink and heat source are described in section 2. Results for the evolution of the atmospheric water vapor sink and heat source associated with the Indian monsoon precipitation ISO are presented in section 3. Conclusions and discussion are included in section 4.

2. Data and method

AIRS level 3 [version 5 (V5), space–time averaged retrieval] specific humidity and temperature are used in this study for the estimation of the water vapor apparent sink \( S \) and the apparent heat source \( Q \), defined as

\[
S(x, y, p, t) = -\left( \frac{\partial q}{\partial t} + \frac{u \partial q}{\partial x} + v \frac{\partial q}{\partial y} + \omega \frac{\partial q}{\partial p} \right)
\]

(1)

\[
Q(x, y, p, t) = \frac{\partial T}{\partial t} + \frac{u \partial T}{\partial x} + v \frac{\partial T}{\partial y} + \frac{\partial T}{\partial p} \frac{\partial p}{\partial T} - \kappa \omega T
\]

(2)

Here \( q \) and \( T \) are the AIRS V5 level 3 specific humidity and temperature, respectively. The wind data \((u, v, \omega)\) are obtained from the MERRA wind products. MERRA uses the Goddard Earth Observing System, version 5 (GEOS-5) (Rienecker et al. 2008) to assimilate observations, including AIRS radiance data, for analysis. The last term in Eq. (2) is the adiabatic heating, in which \( \kappa \) is the ratio of the dry-air ideal gas constant to the air specific heat capacity at constant pressure (i.e., \( R_c/\epsilon_c \)). Note that our definition of \( S \) differs from Q2 in the literature by a factor equal to the water latent heat of evaporation \( L \).

Equations (1) and (2) are applied to daily data. Since AIRS makes tropical measurements around 0130 and 1330 local time, the daily averaged temperature and specific humidity at each location are actually the averages of the two measurements. Missing data in cloudy area hinder the calculation of temperature and moisture gradients, so we have tested that averaging AIRS daily temperature and specific humidity onto a 10° longitude \( \times 5° \) latitude grid mesh provides acceptable spatial coverage of the temperature and specific humidity gradients needed in the calculation of \( Q \) and \( S \) over the Indian monsoon area.

The 3-hourly instantaneous MERRA winds are averaged daily onto the same 10° \( \times 5° \) grid mesh as used for the AIRS data. Finally, the MERRA winds are interpolated or averaged from the 42 pressure levels to the 23 AIRS...
standard pressure levels. After these processes the right-hand side of Eqs. (1) and (2) can be calculated on 10° × 5° longitude–latitude grids, where the gradients are computed by finite differencing in spherical coordinates.

In Eq. (1) S includes physical processes such as evaporation from condensates, condensation to form clouds, and small-scale eddy moisture transport. The vertical integration of S is approximately equal to the water exchange at the surface; therefore, it can be compared with estimates of precipitation and surface evaporation,

\[ \int_{p_t}^{p_s} S(x, y, p, t) \frac{dp}{g} = P(x, y, t) - E(x, y, t), \]  

where S is integrated from the top of the atmosphere \( p_t \) to the surface \( p_s \). We choose \( p_s \) to be 200 hPa—the topmost level where AIRS measurement is sensitive to atmospheric water vapor. Also, \( P \) and \( E \) are precipitation and surface evaporation, respectively.

Precipitation is obtained from the algorithm 3B-42 (version 6) of the Tropical Rainfall Measuring Mission (TRMM) (Huffman et al. 2007), which merged high-quality precipitation estimates to adjust infrared precipitation estimates from geostationary observations. The gridded \( P \) data are three hourly in temporal resolution and 0.25° longitude × 0.25° latitude in spatial resolution, extending globally from 50°S to 50°N. In this study, we averaged the precipitation rates for 10° longitude × 5° latitude grid boxes before comparing to the AIRS–MERRA inferred water vapor budget. The surface evaporation is obtained from the MERRA reanalysis and averaged daily for 10° longitude × 5° latitude grid boxes.

In Eq. (2) \( Q \) includes physical processes such as net radiative heating, latent heating, and small-scale eddy heat transport. In this study, we will compare the apparent heat source with the diabatic heating estimates for the TRMM, referred to as “TRAIN Q1.” The TRAIN Q1 is a combination of the estimates of latent and eddy sensible heating rates, referred to as “Q1R,” in and outside precipitation regions (Grecu and Olson 2006; Grecu et al. 2009; Tao et al. 2001) and of radiative heating, referred to as “QR” (L’Ecuyer and Stephens 2003, 2007; L’Ecuyer and McGarragh 2010). The Q1 data are available over oceans. In the following, we briefly describe the algorithms involved in the TRAIN dataset. Please refer to the above references for detailed information.

The Q1R profiles in regions of precipitation were obtained from a lookup table generated by cloud-resolving model simulations and match the convective/stratiform classification and rain rate from the TRMM precipitation radar (PR). The parameters are then composited using a Bayesian method to find the expected values that are consistent with the TRMM Microwave Imager (TMI) observations. Outside regions of precipitation, the Q1R profiles are estimated such that the diabatic heating rates balance the large-scale vertical advection of potential temperature. QR was estimated by a broad-band radiative transfer model with inputs of ice cloud properties from the Visible Infrared Scanner (VIRS), liquid cloud properties, precipitation profiles, sea surface temperature, water vapor retrievals from the TMI, and vertical profiles of temperature and humidity from the National Centers for Environmental Prediction (NCEP) reanalysis. The TRAIN diabatic heating rates are gridded in 0.5° × 0.5° resolution. They are averaged for 10° longitude × 5° latitude grid boxes and interpolated onto the AIRS standard pressure levels for comparison with the AIRS–MERRA apparent heating rates.

In the following sections, estimates of heating source and water vapor sink are averaged for 5 days, and all analyses are performed in time series of 5 days.

3. Results

a. Comparison between AIRS–MERRA and TRMM data

The ISO of the Indian monsoon rainfall is shown as the 30–80-day filtered time series of the TRMM 3B-42 precipitation averaged over the region of 10°–25°N, 70°–90°E (Fig. 1). The fluctuation has larger amplitudes during summer and is much weaker during winter. The time series can serve as an ISO index (Goswami 2005) for studies of the variation of precipitation associated with the ISO. Extrema in the time series mean that the rainfall in the India–Bengal region reaches either maxima (the ISO peaks) or the minima.
Figure 2 shows the Hovmöller diagram of the meridional propagations of the AIRS–MERRA column-integrated apparent water vapor sinks (Fig. 2a) and of the TRMM precipitation–minus–MERRA evaporation (P – E) anomaly averaged over 70°–90°E (Fig. 2b). The time lag composites are calculated by averaging the P – E anomalies with a time lag with respect to the maxima in Fig. 1 that exceed one standard deviation (the dashed line in Fig. 1). The anomalies are the difference from the seasonal cycle, which is calculated as the 50-day (10 pentads) window means.

The AIRS–MERRA data can reproduce the northerward propagation of precipitation associated with the ISO, although AIRS–MERRA in general underestimates the amplitudes (~50% of the TRMM P – MERRA E). The precipitation rate over the tropical Indian Ocean reaches a maximum about 10 days before it reaches a maximum over the India–Bengal region. The time span of the subsequent active peaks (or breaks) is about 40 days, consistent with the results of previous works (Krishnamurti and Subrahmanyan 1982; Murakami et al. 1984; Webster et al. 1998; Lawrence and Webster 2001). The smaller amplitudes in the AIRS–MERRA data indicate that the variance of water vapor convergence in the intraseasonal time scale is not large enough to reproduce the variance of the precipitation. Possible reasons for this underestimation may include sampling biases of AIRS around cloudy/heavy precipitation areas and/or the variability of wind convergence in the intraseasonal regime.

b. Preconditioning over the India–Bay of Bengal region for deep convection

To further understand the processes behind the northward propagation of the precipitation anomaly, we plot in Fig. 3 the corresponding Hovmöller diagrams of time lag composites of anomalies for water vapor in 700–850 hPa, temperature in 925–1000 hPa, and the convective available potential energy (CAPE), which is a measure of the air column’s conditional instability and calculated using the 10° × 5° gridded AIRS temperature and water vapor profiles. We see that the positive water vapor anomaly propagates northward from the tropical Indian Ocean to the India–Bengal region, as does the precipitation anomaly. The lower-tropospheric specific humidity and temperature begin to increase over the India/Bengal region about 15 days before the precipitation maximum. As a result, the atmosphere over the India/Bengal region becomes unstable at this time by the increase in CAPE. Such preconditioning of the lower troposphere for convection was consistent with the results reported by Fu et al. (2006) and Yang et al. (2008).

The AIRS–MERRA apparent water vapor sink not only reproduces the northward propagation of the precipitation anomaly but also the evolution of the geographical distribution of the anomaly (Fig. 4). As in Fig. 3, both the AIRS column-integrated apparent water vapor sinks and the TRMM data show that strong precipitation occurs over the tropical Indian Ocean approximately 10 days before the precipitation maximum over the India–Bengal region (Figs. 4a and 4d). This tropical precipitation anomaly migrates toward the western Pacific, while it also propagates northward along the 60°–90°E longitude belt toward the India–Bengal region (Figs. 4b and 4c or Figs. 4e and 4f).

There is a cyclonic circulation (centered near 5°N, 80°E in Fig. 4a) associated with the northward-propagating precipitation anomaly. This cyclonic circulation is related to the westward propagation of equatorial Rossby waves associated with the eastward-propagating equatorial
convective activity, as discussed in the studies by Lau and Peng (1990) and Wang and Xie (1997). This cyclonic circulation generates the convergence of precipitable water flux (shown as the arrows in the left panel of Fig. 4) associated with the precipitation anomaly.

c. Evolution of the atmospheric hydrologic budget composites

As the AIRS–MERRA apparent water vapor sink is inferred from the water vapor tendency and advection terms, detailed budget analysis for the mechanism behind the ISO may not be appropriate. However, we can investigate if the evolution of the AIRS–MERRA water vapor budgets is consistent with the suggested ISO mechanism in the literature. To do this, we map the vertical structures of the components of the water vapor and heat tendencies [in Eqs. (1) and (2)] for different phases of the ISO. Figure 5 shows the anomalies of specific humidity (Figs. 5a–d) and the anomalies of water vapor tendency $\partial q/\partial t$ (Figs. 5e–h) for different phases of the ISO. Figure 6 shows the anomalies in horizontal (Figs. 6a–d, $-\omega q/\partial x - \omega q/\partial y$) and vertical (Figs. 6e–h, $-\omega q/\partial p$) advection of water vapor. The anomalies are averaged according to the time lags relative to the ISO peaks (Fig. 1) and then zonally averaged over 70°–90°E to produce the meridional cross sections. Overlaid on the figures are the corresponding anomaly composites for AIRS–MERRA apparent water vapor sinks (positive or solid contours mean an increase in sinks, and negative or dashed contours mean a decrease in sinks) and the TRMM 3B42 precipitation anomalies (the thick solid line at the bottom of each figure). Deep convective events are associated with large positive anomalies of apparent water vapor sinks and precipitation.

About 15 days before the ISO peaks (Figs. 5a and 5e, and 6a and 6e), the large apparent water vapor sink over the tropical Indian Ocean means that convection is occurring (about 5°S–5°N), consistent with the local large precipitation anomaly. There is an ascending anomaly associated with the convection and a descending anomaly over the India–Bengal region, indicating that the regional Hadley circulation is modified (Goswami 2005). Compared to the seasonal climatology, enhanced convection over the tropical Indian Ocean is associated with moister air in the free troposphere (Fig. 5a, 300–925 hPa and 5°S–5°N) and dryer air near the surface (~925–1000 hPa).

At a time lag of ~15 days, water vapor begins to accumulate below 700 hPa over the India–Bengal region (Fig. 5e), where the precipitation anomaly is still low. Below 700 hPa over the India–Bengal region near 10°–20°N, the increase in horizontal moisture advection (Fig. 6a) and the decrease in apparent water vapor sink (dashed contour around 700 hPa) oppose the decrease in tendency due to vertical advection. The moistening of the lower troposphere over the India–Bengal area contributes to the destabilization of the atmosphere, as shown in Fig. 3.

About 10 days before the ISO peaks (Figs. 5b and 5f, and 6b and 6f), the positive anomaly in apparent water vapor sink associated with the large precipitation anomaly is moving toward the India–Bengal region. Moistening (positive anomaly in $\partial q/\partial t$) occurs throughout the troposphere north of the region of deep convection (Fig. 5f). The horizontal moisture advection moistens the atmosphere over the India–Bengal area (Fig. 6b). Over the tropical Indian Ocean, the atmosphere begins to dry

![Figure 3](image-url)
This is associated with the increase in apparent water vapor sink (solid contours) and the decrease in horizontal advection of water vapor (Fig. 6f).

About 5 days before the ISO peaks (Figs. 5c and 5g, and 6c and 6g), the deep convective activity and the associated precipitation anomaly have moved onto the India–Bengal region near 10°–15°N, and dry anomalies begin to appear near the surface over the tropical Indian Ocean (Fig. 5c). Strong atmospheric moistening still occurs north of the region of large precipitation (Fig. 5g). Horizontal water vapor advection moistens the atmosphere north of 10°N (Fig. 6c), and vertical water vapor advection moistens the troposphere throughout above 700 hPa (Fig. 6g).

During the ISO peaks (Figs. 5d and 5h, and 6d and 6h), the precipitation anomalies and apparent sinks of water vapor reach maxima over the India–Bengal region near 10°–20°N. At the same time, they reach minima over the tropical Indian Ocean. The specific humidity tendency anomalies (Fig. 5h) over the India–Bengal region are positive in the upper troposphere (above 700 hPa) but negative in the lower troposphere (below 700 hPa), consistent with the convection stabilizing the atmosphere. Over the
tropical Indian Ocean (Fig. 5h), the lower troposphere begins to be moistened. This may indicate that the preconditioning process is occurring over the tropical Indian Ocean for the next cycle of the Indian monsoon ISO.

Tian et al. (2006, 2010) compiled the vertical structure and corresponding temporal variation of water vapor anomalies associated with the Madden–Julian oscillation in the tropics. Our evolution of water vapor anomalies

![Diagram](image-url)
over the tropical Indian Ocean (Figs. 6a–d) is generally consistent with that seen in Tian et al. (2006, 2010). The increase in horizontal moisture advection northward of the deep convective area is in agreement with the moisture–convection feedback mechanism. Jiang et al. (2004) suggested that this horizontal advection is caused by both the advection of background moisture by the perturbed winds and the advection of increased moisture by the mean southerly flow in the planetary boundary layer.

We summarize the consistency between the AIRS–MERRA water vapor budget and the moisture–convection feedback mechanism as follows: (i) the large positive anomaly in the AIRS–MERRA apparent water vapor sink moves northward coherently with the TRMM 3B42

![Fig. 6. As in Fig. 5, but for (a)–(d) the horizontal and (e)–(h) the vertical advection of water vapor (g kg⁻¹ day⁻¹).](image)
precipitation anomaly; (ii) atmospheric moistening north of the deep convective area helps convection move northward toward the India–Bengal region (Figs. 5e–h); and (iii) the positive anomaly in the horizontal moisture advection north of the deep convective area moves northward together with the deep convective area (Figs. 6a–d).

d. Evolution of the atmospheric thermodynamic budget composites

Formation of precipitation through water vapor condensation (a moisture sink) should be consistent with the estimates of apparent heat source through latent heating. Therefore, we investigate in this section the consistency between the northward propagation of the apparent heat source and water vapor sink. Figure 7 shows the temperature anomalies (Figs. 7a–d) and the temperature tendency anomalies $\partial T/\partial t$ (Figs. 7e–h) for different phases of the ISO. Figure 8 shows the anomalies of the dynamical heating rate (Figs. 8a–d) and the apparent heat source (Figs. 8e–h). The dynamical heating rates are the sum of the heating rates due to advection ($-\omega T/\partial x - \omega T/\partial y - \omega T/\partial p$) and the adiabatic heating rates ($\kappa\omega T/p$), which dominate the dynamical heating rates by advection. Overlaid on the figures are the corresponding anomaly composites for the apparent water vapor sinks (contours in the figures) and the precipitation anomalies (both are as in Figs. 5 and 6).

About 15 days before the precipitation reaches a maximum over the India–Bengal region, the precipitation anomaly and deep convective activity are located over the tropical Indian Ocean, while the lower troposphere over the India–Bengal region begins to warm (Figs. 7a and 7e, below 700 hPa). The warming is associated with the increase in dynamical heating (Fig. 8a) caused by the descending branch of the anomalous Hadley cell. The increase in temperature near the surface also contributes to destabilize the atmosphere over the India–Bengal region. Over the tropical Indian Ocean ($5^\circ S$–$5^\circ N$), where deep convection is located, the increase in the apparent heat source in the free troposphere (400–850 hPa) is associated with an increase in dynamical cooling caused by the ascending motion in the anomalous Hadley circulation. There is a positive temperature tendency in the upper troposphere over the deep convective region (Fig. 7e, 300–500 hPa).

As the convection approaches the India–Bengal region, the positive temperature tendency in the upper troposphere follows the migration of the convection (Figs. 7f and 7g, 300–700 hPa) but cooling begins in the lower troposphere over the India–Bengal region (negative anomalies below 800 hPa in Figs. 7f and 7g). The northward migration of the positive anomaly of the apparent heat source (Figs. 8e–g) is coherent with that of the positive anomaly of the apparent water vapor sink.

When the ISO peaks (Figs. 7d and 7h, and 8d and 8h), the deep convection is located over the India–Bengal region, with warm anomalies in the upper troposphere but cold anomalies in the lower troposphere. This profile of temperature anomalies and the profile of specific humidity anomalies shown in Fig. 5h provide a negative feedback to the convection. At the same time, the lower troposphere over the tropical Indian Ocean begins to warm (Figs. 7d and 7h; $5^\circ S$–$5^\circ N$ below 700 hPa), providing a temperature anomaly profile favorable for convection. This warming anomaly over the Indian Ocean is associated with the reduction in dynamical cooling (Fig. 8d) caused by the reduction in the upward motion. Together with the specific humidity tendency anomalies shown in Fig. 5h, the stability over the tropical Indian Ocean begins to decrease, preconditioning for the next cycle of the ISO.

We compare the AIRS–MERRA apparent heat source anomalies (Figs. 8e–h) with independent estimates of diabatic heating rate anomalies from the TRAIN Q1 for different phases of the ISO (Figs. 9a–d). Since TRAIN Q1 data are available only over oceans, the heating rates shown in Fig. 9 are mainly weighted over the Bengal Bay area for latitude over approximately $10^\circ N$. The spatial patterns and the northward propagation of the AIRS–MERRA apparent heat source anomalies (Figs. 8e–h) are consistent with those of the TRAIN Q1 (Figs. 9a–d). However, the anomalies in the AIRS–MERRA apparent heat source are about half of those in the TRAIN Q1, consistent with the result that the anomalies in the column-integrated AIRS–MERRA apparent water sink is about half of the amplitude of anomalies of TRMM $P$ minus MERRA $E$. (Fig. 2).

We further decompose TRAIN Q1 anomalies into $Q1R$ (Figs. 9e–h) and $QR$ (Figs. 9i–l). It is clear that the diabatic heating anomalies associated with the Indian monsoon ISO are mainly contributed by the changes in latent and sensible heating associated with the precipitation. This is consistent with the finding by Xavier et al. (2007) that latent heat release plays an important role in the heating budget of the Indian summer monsoon.

About 15 days before the precipitation reaches maxima over the India–Bengal region, convection begins to occur over the tropical Indian Ocean and results in positive anomalies in diabatic heating over the tropical area. The reduction in latent heat release over the India–Bengal region results in a negative anomaly in diabatic heating over the region. The latent heating in the mid- to upper troposphere strengthens and migrates with the rainfall from the tropical Indian Ocean toward the India–Bengal region. At this time, the AIRS–MERRA heating
anomalies are over the India–Bengal region with maxima located over 300–800 hPa (Fig. 8h), while the corresponding TRAIN Q1 anomaly maximum is located at 400 hPa (Fig. 9h). Further study is necessary to diagnose such detailed discrepancy.

4. Conclusions and discussion

The intraseasonal oscillation (ISO) in precipitation associated with the Indian monsoon is used as a test bed to evaluate the apparent water vapor sinks and heat sources
estimated from the AIRS water vapor and temperature retrievals, and the MERRA wind fields. The apparent water vapor sinks and heat sources are estimated by subtracting from the tendencies the effects of large-scale advection and adiabatic heating, which are calculated from the AIRS water vapor, temperature, and the MERRA reanalysis wind fields. We map the distributions of the apparent water vapor sinks and heat sources together with other budget terms contributed from the changes in large-scale circulation for different phases of the ISO (relative to the time when precipitation over the India–Bengal region reaches a maximum).

Integrated over the atmospheric column, the AIRS–MERRA apparent water vapor sinks can reasonably

Fig. 8. As in Fig. 7, but for (a)–(d) dynamical and (e)–(h) apparent heating rates (K day$^{-1}$).
match the phase of the precipitation ISO observed by the TRMM, in particular, the south-to-north propagation of the precipitation anomaly. The amplitudes of the column-integrated AIRS–MERRA water vapor sink variation are about 50% of those of $P - E$ estimated from TRMM precipitation and MERRA evaporation. Using estimated precipitation from the Global Precipitation Climatology Project (GPCP), instead of TRMM 3B42, yields a similar result. This may imply that the temporal variation of water vapor convergence in the intraseasonal time scale is not strong enough in the AIRS–MERRA data.

The water vapor and heating budgets associated with the ISO indicate that the atmosphere over the India–Bengal region is destabilized when the convection is strongest over the tropical Indian Ocean. Positive anomalies in the specific humidity tendency are located north of the convective area (Figs. 5e–h), while positive anomalies in temperature tendency are located in the mid–upper troposphere of the convective area (Figs. 6e–h). The descending branch of the anomalous Hadley circulation warms the lower troposphere of the India–Bengal region. The warmer and moister troposphere north of the convective maximum helps the convection migrate northward to the India–Bengal region.

The positive anomalies of the specific humidity tendency and those of the temperature tendency follow the northward migration of the convective activity. The

Fig. 9. Meridional cross sections of the time lag composites of anomalies in TRAIN (a)–(d) Q1, (e)–(h) Q1R, and (i)–(l) QR averaged over the Indian sector. Units are K day$^{-1}$. Time lags relative to the peaks in Fig. 1 are shown in the title of each figure in the left column. Thick solid lines at the bottom indicate the meridional distribution of the precipitation anomaly. Black areas indicate areas with missing data.
apparent water vapor sink and heat source also move northward coherently with the precipitation anomaly. The precipitation over the India–Bengal region reaches maxima approximately 10 days after the convection is strongest over the tropical Indian Ocean. This process confirms the previously suggested moisture–convection feedback mechanism by Jiang et al. (2004). When the convection has reached the India–Bengal region, the moisture and temperature tendencies act to suppress convection there while destabilizing the atmosphere over the tropical Indian Ocean, preconditioning the next cycle of the ISO.

The AIRS–MERRA apparent heating anomalies associated with the Indian monsoon ISO (Figs. 8e–h) have similar spatial patterns compared with the diabatic heating anomalies computed from the TRAIN O1 (Figs. 9a–d). The AIRS–MERRA underestimates the heating anomalies by about 50%, consistent with its underestimation compared to the TRMM precipitation minus MERRA evaporation. The diabatic heating anomalies associated with the Indian monsoon ISO are mainly contributed by the variation in latent and sensible heating associated with the precipitation (Figs. 9e–h).

AIRS does not retrieve atmospheric temperature and water vapor below thick clouds when precipitation occurs, so sampling effects are partly mitigated in the calculations of apparent water vapor sinks and heat sources by averaging over large areas, such that the immediately surrounding cloudy areas are included. Nevertheless, sampling may introduce systematic biases in the estimated apparent water vapor sinks and heat sources. The MERRA data assimilate AIRS radiances and fill the gaps in AIRS retrievals over cloudy scenes. Comparison between the apparent water vapor sinks and heat sources calculated using the AIRS data and those using the MERRA data show agreement (not shown). Consequently, the missing data in AIRS temperature and water vapor retrievals do not significantly influence the conclusions of the work. Progress in remote sensing techniques for retrievals of water vapor and temperature in cloudy areas is necessary to increase the horizontal resolution of estimates, along with other improvements in methods discussed here.

Since AIRS and TRMM are two independent measurements, the consistency between the two datasets in aspects of water vapor and energy budgets indicates that AIRS water vapor retrieval can be used to understand the variability in global hydrological and energy cycles. Moreover, this work provides a framework to test the closeness of the atmospheric component of the hydrological and energy cycles measured by different remote sensing instruments. Waliser et al. (2003) evaluated the performance of atmospheric general circulation models in the simulation of the rainfall associated with the Asian monsoon ISO. The water vapor and heat budgets inferred from the AIRS retrievals can be further used to evaluate hydrological and thermodynamic budgets in atmospheric general circulation models.

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