NOTES AND CORRESPONDENCE

Changes of the Boreal Winter Hadley Circulation in the NCEP–NCAR and ECMWF Reanalyses: A Comparative Study

HUA SONG AND MINGHUA ZHANG

Institute for Terrestrial and Planetary Atmospheres, Marine Sciences Research Center, Stony Brook University, Stony Brook, New York

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ABSTRACT

Both the ECMWF and the NCEP–NCAR reanalyses show a strengthening of the atmospheric Hadley circulation in boreal winter over the last 50 years, but the intensification is much stronger in the ECMWF than in the NCEP–NCAR reanalysis. This study focuses on the difference of these trends in the two reanalyses. It is shown that trends in the Hadley circulation in the two reanalyses differ mainly over the tropical western Pacific. This difference is found to be consistent with respective trends of the atmospheric transport of moist static energy, longwave cloud radiative forcing, and upper-level clouds in the two reanalyses. Two independent datasets of upper-level cloud cover and sea level pressure from ship-based measurements are then used to evaluate the reanalyses over the tropical western Pacific. They are found to be more consistent with the trends in the NCEP–NCAR reanalysis than those in the ECMWF reanalysis. The results suggest a weakening of the vertical motion associated with the Hadley circulation in the tropical western Pacific.

1. Introduction

The Hadley cell, defined as the zonally averaged meridional circulation of the atmosphere in the Tropics, is of significant importance both theoretically and practically in climate science. Recently, several studies have attempted to evaluate the changes in the intensity of Hadley circulation over the last several decades. Chen et al. (2002) used satellite observations to indirectly infer the Hadley circulation and reported strengthening since 1983. Quan et al. (2004) and Tanaka et al. (2004) documented changes of the Hadley circulation in the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) and reported its intensification since the 1950s. Quan et al. (2004) further attributed this trend to both the warming of the tropical ocean and the increased El Niño frequency and amplitude after 1976. Mitas and Clement (2005) examined the intensity of the Hadley circulation as depicted in the NCEP–NCAR and the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005) as well as in radiosonde data. They found statistically significant intensification of the Hadley circulation in the reanalyses in the northern winter season, but no discernible trend in the global rawinsonde observations. They also reported that the intensification of the Hadley circulation in the two reanalyses differed greatly in magnitude, with the ECMWF reanalysis about 3 times as strong as that in NCEP–NCAR reanalysis.

Observational evidence of the Hadley circulation trend thus remains controversial. The reanalysis products from the operational weather centers are arguably the only datasets that contain the direct information of vertical circulation. However, they suffer from the impact of sparse radiosonde input data and model deficiencies. Possible trend biases in the radiosonde temperature in low latitudes (Sherwood et al. 2005) can further complicate the issue greatly (Mitas and Clement 2006).

The present study focuses on the trend difference of

Corresponding author address: Dr. Hua Song, Institute for Terrestrial and Planetary Atmospheres, Stony Brook University, Stony Brook, NY 11790-5000.
E-mail: hsong@atmsci.msrc.sunysb.edu

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the Hadley circulation in the two reanalyses products. Both the NCEP–NCAR and ECMWF reanalyses used similar input data of operational radiosondes and satellite measurements, but they showed significant differences in the intensity trend over the last 50 years. The first purpose of our study is to reveal consistent as well as inconsistent features of the Hadley circulation in the two reanalyses. The second purpose is to evaluate which product is more realistic. The rest of this paper is organized as follows. Section 2 briefly discusses the data and method used in this study. The main results are presented in section 3. The last section contains the summary and discussion.

2. Data and method

We use the monthly mean winds from January 1948 to April 2006 in the NCEP–NCAR product and from September 1957 to August 2002 in ERA-40 in this study. Several diagnostic measures have been used in the past to infer the intensity of Hadley circulation. These include the magnitude of the maximum streamfunction of the meridional circulation, strength of the meridional wind or divergent wind in the lower or upper troposphere, and magnitude of the 200-hPa velocity potential. They are all related to each other and have been found consistent in the description of the long-term trends (Tanaka et al. 2004; Quan et al. 2004; Mitas and Clement 2005). In this paper, the meridional component of the divergent wind V_d at 200 and 850 hPa is used as an index to study the Hadley circulation. The Helmholtz theorem (e.g., Arken 1985) states that the horizontal wind vector $\mathbf{V}$ may be divided into a rotational component $\mathbf{V}_\psi$ and a divergent component $\mathbf{V}_d$. The rotational part does not contribute to atmospheric divergences associated with vertical motion despite the fact that it is usually larger than the divergent part (Huang et al. 2004). The zonal average of meridional divergent wind V_d is the same as that of the total meridional wind. Because the trends are only statistically significant in the boreal winter season in both reanalyses, we restrict our study to the December–February (DJF) season.

In addition to the winds, cloud fields and their radiative impacts in the reanalyses are also used. They are compared with the ship-based cloud observations from the Extended Edited Cloud Report Archive (EECRA; courtesy of J. Norris). Detailed information of the EECRA cloud data can be found in Hahn and Warren (1999) and Norris (2005). The EECRA is a collection of individual synoptic surface cloud observations with coincident meteorological observations obtained from the Comprehensive Ocean–Atmosphere Data Set. It contains over 73 million cloud observations from December 1951 to December 1997. The EECRA cloud data are independent of the two reanalyses.

Sea level pressures (SLPs) in the two reanalyses are also used. They are compared with the observed SLP data in the extended reconstructed sea level pressure (ERSLP) analysis of the National Oceanic and Atmospheric Administration (NOAA) National Climate Data Center from January 1950 to December 2000. The ERSLP data are detailed in Smith and Reynolds (2004).

3. Results

Figures 1a,b show the DJF climatology of the zonally averaged meridional wind V_d at 200 and 850 hPa in the NCEP–NCAR and ERA-40 reanalyses. The red line represents the zonal mean V_d at 200 hPa and the green line represents the zonal mean V_d at 850 hPa. A closed Hadley cell, as highlighted by the arrows, is seen clearly with northward wind at the upper level and southward wind at the lower level that peak between 5° and 10°N, consistent in the two reanalyses. The maximum rising motion, which can be judged roughly from the slopes of the curves, is at around 10°–5°S; and the maximum sinking motion is at around 20°–30°N. Figures 1c,d show the time evolution of the zonal mean 200-hPa V_d anomalies relative to the respective climatology in the two reanalyses since the 1950s. The data length in ERA-40 is slightly shorter than in the NCEP–NCAR reanalysis. It is seen that both reanalyses show consistent intensification of the 200-hPa northward meridional wind from 10°S to 20°N.

The intensification of the Hadley circulation is contributed by the climate shift in the 1970s that coincided with the introduction of satellite data around 1979 (Hurrell and Trenberth 1999). However, Figs. 1c,d suggest that this increasing trend is present even before and after the 1970s transition period. This is most clearly seen in Figs. 1e,f, which show the time series of the difference between the maximum zonal mean V_d at 200 hPa and the minimum zonal mean V_d at 850 hPa in the two reanalyses. Figures 1e,f also show that the increasing trend of the Hadley circulation is much larger in the ERA-40 than that in the NCEP–NCAR product, consistent with what Mitas and Clement (2005) found. The linear trends are about 1.94 and 4.15 m s^{-1} (100 yr)$^{-1}$, respectively, in the NCEP–NCAR and ECMWF reanalyses.

To understand the trend differences, Fig. 2 shows the spatial patterns of the meridional divergent winds at 200 hPa and their trends in the two reanalyses. While V_d is not the actual meridional flow, they can be used to

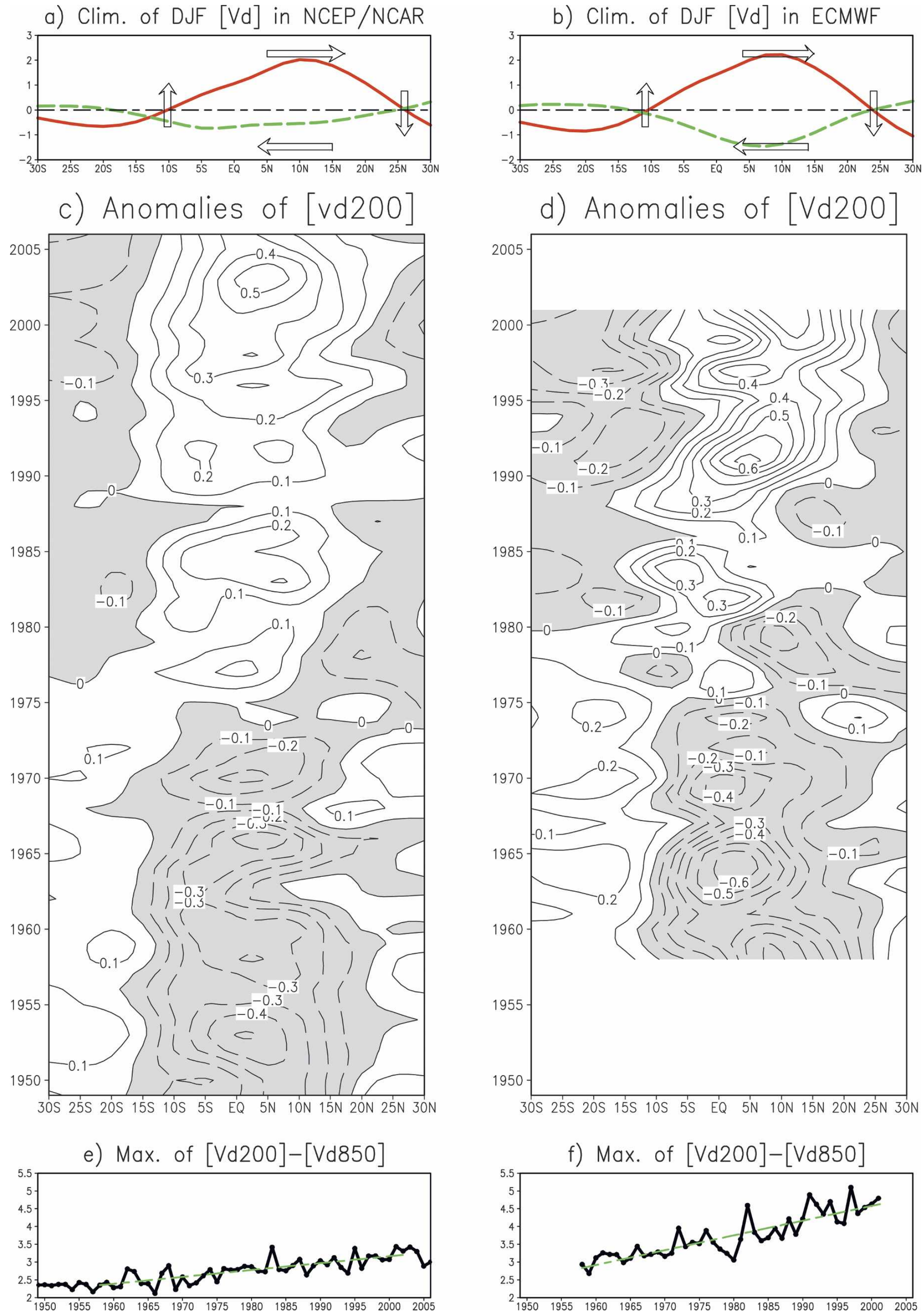

FIG. 1. The climatologies of the DJF zonal mean meridional divergent winds at 200 (solid red line) and 850 hPa (dashed green line) in the (a) NCEP–NCAR and (b) ECMWF reanalyses. The time–latitude cross section of the anomalous zonal mean meridional divergent wind at 200 hPa in the (c) NCEP–NCAR and (d) ECMWF reanalyses. Negative values are shaded in gray. The time series of the maximum differences between the zonal mean meridional divergent wind at 200 and 850 hPa in the (e) NCEP–NCAR and (f) ECMWF reanalyses after a 5-yr running average. Unit of the wind is in m s^{-1}. Trends are 1.94 ± 0.47 m s^{-1} (100 yr)$^{-1}$ in NCEP–NCAR and 4.15 ± 0.71 m s^{-1} (100 yr)$^{-1}$ in ECMWF from 1958 to 2002. The ranges define the 95% confidence intervals for the trends.

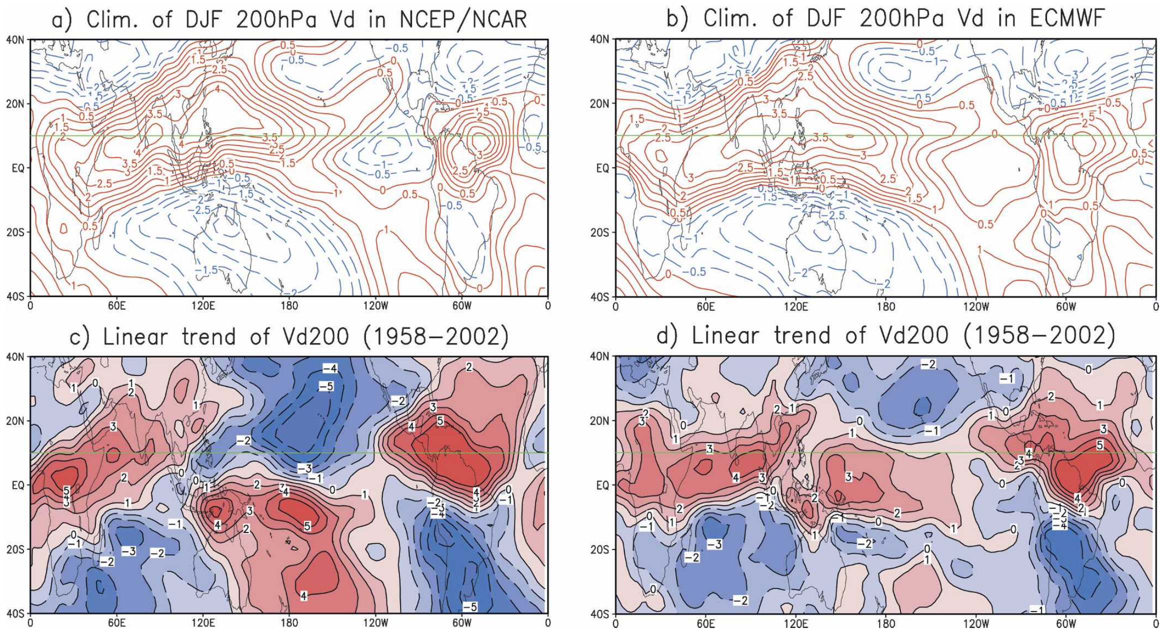

FIG. 2. The climatologies of the DJF 200-hPa meridional divergent wind distributions in the (a) NCEP–NCAR and (b) ECMWF reanalyses. Unit: m s^{-1}. The 10°N latitude line is highlighted. The linear trends of the 200-hPa divergent winds in the (c) NCEP–NCAR and (d) ECMWF reanalyses. Unit: m s^{-1} (100 yr)$^{-1}$.

examine the regional contribution of the divergent wind to the zonal averaged circulation. The 10°N latitude is highlighted around which the zonal-averaged V_d peaks. The climatology of V_d in Figs. 2a,b shows that the 200-hPa V_d around 10°N is northward across the whole Tropics except over the eastern oceans. The maxima are over regions of the Australia monsoon. These are similar in the two datasets.

However, the trends of V_d in the two products exhibit large inconsistencies. In Fig. 2c over the western and central tropical Pacific from 120°E to 140°W south of 10°N, the trend pattern in the NCEP–NCAR reanalysis is out of phase with the climatology of V_d, which suggests a weakening of the overturning cell. In contrast, Fig. 2d shows that in the ECMWF reanalysis south of 10°N the trend pattern is in phase with the climatology of V_d over the tropical western Pacific (TWP), indicating a strengthening of the overturning cell. The trends of V_d over North America, Africa, and the Eurasian continents in the two reanalysis products all have the same signs as the basic climatology that represent the intensification of the circulation. As a result, the two reanalyses all exhibit increasing zonally averaged meridional wind at 200 hPa, but with a much weaker trend in the NCEP–NCAR product, owing to the different trend pattern over the western and central tropical Pacific.

Since the two reanalysis products are all constrained by the radiosonde data in the assimilation process, it is not surprising that the two datasets show somewhat consistent trends over the continents. Over the oceans, however, few direct measurements exist. The divergent winds are essentially a model product.

The trend features in Figs. 2c,d can be characterized by decreasing the 200-hPa meridional divergences in the NCEP–NCAR reanalysis and increasing the divergence in the ERA-40 in the TWP region from 20°S–10°N to 120°E–160°W, a region of the upward branch of the Hadley circulation. Rising motions are associated with outward transport of atmospheric energy in the troposphere because the moist static energy increases with height. The total vertically integrated outward horizontal transport of the atmospheric moist static energy (which is denoted as TET) can be written as

$$\begin{aligned} \mathrm{TET} &= \frac{1}{g}\int_{p_T}^{p_s} \boldsymbol{\nabla}\cdot(\mathbf{V}h)\,dp = \frac{1}{g}\int_{p_T}^{p_m} \boldsymbol{\nabla}\cdot(\mathbf{V}h)\,dp + \frac{1}{g}\int_{p_m}^{p_s} \boldsymbol{\nabla}\cdot(\mathbf{V}h)\,dp \\ &= \frac{1}{g}\overline{h}_{\mathrm{up}}\int_{p_T}^{p_m} (\boldsymbol{\nabla}\cdot\mathbf{V})\,dp + \frac{1}{g}\overline{h}_{\mathrm{low}}\int_{p_m}^{p_s} (\boldsymbol{\nabla}\cdot\mathbf{V})\,dp, \end{aligned} \tag{1}$$

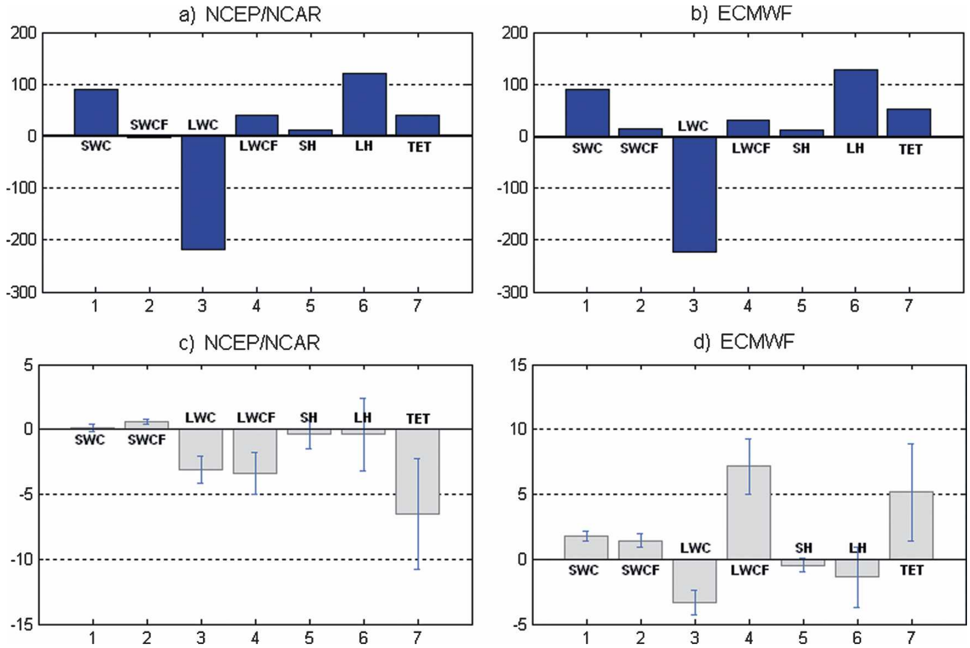

FIG. 3. The climatologies of SWC, SWCF, LWC, LWCF, SH, LH, and TET over the TWP in the (a) NCEP–NCAR and (b) ECMWF reanalyses. Unit: W m^{-2}. The changes of SWC, SWCF, LWC, LWCF, SH, LH, and TET over the TWP in the (c) NCEP–NCAR and (d) ECMWF reanalyses between epochs 1980–2000 and 1958–75. Unit: W m^{-2}. The error bars represent the 95% confidence intervals for the changes.

where $h = c_pT + gz + L_vq$ is the moist static energy of the atmosphere; p_T, p_m, and p_s represent the pressures at the top of the divergence layer, at the divergence transition interface in the middle of the troposphere, and the bottom of the surface convergence layer, respectively; and $\overline{h}_{\rm up}$ and $\overline{h}_{\rm low}$ are the wind-weighted moist static energy in the upper and lower troposphere, respectively.

By using the vertical velocity ω in the middle of the troposphere,

$$\omega_{\max} = -\int_{p_T}^{p_m} (\nabla \cdot \mathbf{V})\, dp = \int_{p_m}^{p_s} (\nabla \cdot \mathbf{V})\, dp, \qquad (2)$$

Eq. (1) can be rewritten as

$$\mathrm{TET} = -\frac{1}{g}\,\omega_{\max}(\overline{h}_{\rm up} - \overline{h}_{\rm low}). \qquad (3)$$

Hence, the total energy transport can be considered as a proxy of the vertical velocity.

On the other hand, the total energy transport can be further related to other components of the atmospheric energy budget through

$$\mathrm{TET} = \mathrm{SWC} + \mathrm{SWCF} + \mathrm{LWC} + \mathrm{LWCF} + \mathrm{SH} + \mathrm{LH}. \qquad (4)$$

On the right-hand side of the above equation, the terms are the clear-sky shortwave radiative heating in the atmosphere (SWC); shortwave cloud forcing (SWCF); clear-sky longwave radiative heating (LWC); longwave cloud forcing (LWCF); and sensible and latent heating (SH) and (LH), respectively. We note that the reanalyses do not generally conserve mass and energy (e.g., Trenberth 1997). However, because few radiosonde data were available in the TWP region and the reanalyses are mostly model products, the internal imbalance should be of less concern. Furthermore, the energy components are only used here to demonstrate the differences between the two products.

Figures 3a,b show the climatology of all energy components in Eq. (4) averaged from 20°S–10°N to 120°E–160°W. Sources of energy, in magnitude of decreasing order, are latent heating, clear-sky solar radiative heating, longwave cloud forcing, and turbulent heating from sensible heat fluxes. Major sinks of energy are the clear-sky longwave cooling and atmospheric heat transport. It is noted here that the atmospheric shortwave cloud forcing is very little and negative in the NCEP–NCAR reanalysis, while it is positive in the ERA-40, suggesting a possible different amount of absorption of solar radiation in clouds in the two reanalyses. Overall, however, the climatologies are consistent among the two reanalyses.

Figures 3c,d show the differences of these components between the epochs of 1980–2000 and 1958–75 in the NCEP–NCAR reanalysis and in the ERA-40, respectively. The error bars represent the 95% statistical confidence intervals. Consistent with the deductions from the trends of the upward motion in the two reanalysis products, the total outward energy transport (TET) has decreased in the NCEP–NCAR product, but increased in the ERA-40. The largest inconsistency in the two reanalyses is in the LWCF, with the NCEP–NCAR product showing decreased LWCF but the ERA-40 showing increased LWCF. Other components of the trends in Figs. 3c,d are mostly similar in the two reanalyses: 1) enhanced clear-sky longwave cooling, owing to the dominance of the temperature and its lapse-rate effect over the water vapor greenhouse effect (e.g., Zhang et al. 1994); 2) statistically insignificant change of the surface sensible and latent heat fluxes; and 3) increased amount of the sum of clear-sky SWC and SWCF [with the small magnitudes of the change in SWC and SWCF here, the two are better viewed together rather than separately due to the definition of the SWCF (Soden et al. 2004)]. Therefore, the difference in the LWCF largely contributed to the opposite signs in the atmospheric net outward energy transport between the NCEP–NCAR reanalysis and the ERA-40.

The trend difference of LWCF in the two reanalyses is also found to correspond well to that in the high cloud amount in the two reanalyses. This is shown in Figs. 4a,b. In the NCEP–NCAR reanalysis, consistent with the reduced LWCF, upper-level clouds decreased in 1980–97 relative to that in 1958–75 in the tropical western Pacific. In the ECMWF reanalysis however, upper-level clouds increased in the later epoch, consistent with the increased LWCF. Changes of the upper-level clouds between epochs 1980–2000 and 1958–75 for the two reanalyses also show the similar patterns as that in Figs. 4a,b, respectively. Hence, over the TWP, the trends of the atmospheric outward energy transport, the longwave cloud forcing, upper-level clouds, and the intensity of rising motion are all consistent among themselves in each individual reanalysis, but they have opposite signs in the NCEP–NCAR reanalysis and the ERA-40.

The change of upper-level cloud from the independent EECRA data is now shown in Fig. 4c. It is seen that over the TWP, the amount of upper-level clouds has decreased. This is more consistent with the NCEP–NCAR reanalysis in this region than with the ERA-40. While many uncertainties can be attached to the observed cloud data, the trends of EECRA upper-level clouds do show a statistically significant decrease. Further calculation of changes in the total and low cloud amount gives a similar pattern (not shown).

It is beyond the scope of this study to explain the cause of the cloud changes in the two reanalyses. It is plausible that enhanced upward motion increases the amount of high clouds in the reanalysis, due to more vigorous convection and detrainment of cirrus clouds, and vice versa. Here, the association of the trends between rising motions and the upper-level cloud amount over the TWP can be also made through the energy budget consideration of Eq. (4). Namely, strengthening vertical circulation corresponds to more outward energy transport, which is balanced by increasing LWCF due to the increasing amount of clouds, and vice versa.

We gain a second verification on the atmospheric vertical circulation trends in the TWP from the SLP, as used in Zhang and Song (2006) and Vecchi et al. (2006) to report the weakening of the Walker circulation. Figure 5a shows the climatology (contour) and linear trend (image) of the SLP in the NOAA/ERSLP data in DJF from 1950 to 2000 in the tropical Pacific. The ERSLP data exhibits increasing trends of SLP in the TWP and decreasing trends of SLP in the subtropics. The regional meridional gradient of SLP in the tropical western Pacific, a proxy of the intensity of meridional circulation, is therefore decreasing. The time variations of this gradient, when expressed as the difference of the SLP in the two boxes in Fig. 5a (20°S–0° and 110°E–180° versus 15°–30°N and 110°E–180°) in the NOAA/ERSLP data as well as in the two reanalyses, are shown in Fig. 5b. It is seen that this measure of the trend is also more consistent with the NCEP–NCAR reanalysis than with the ERA-40, reinforcing our conclusion from the analysis of upper-level clouds.

4. Summary and discussion

We have illustrated that the difference in the strengthening of the boreal winter Hadley circulation between the NCEP–NCAR reanalysis and the ECMWF reanalysis in the last 50 years is primarily over the western tropical oceans where few atmospheric radiosonde measurements exist. In the NCEP–NCAR reanalysis, the meridional divergent flow of the Hadley circulation over the TWP is weakening, while that in the ECMWF reanalysis is intensifying. Over the continents where more sounding data are available, the two reanalyses all exhibit intensification of the boreal winter Hadley circulation. This explains the intensification

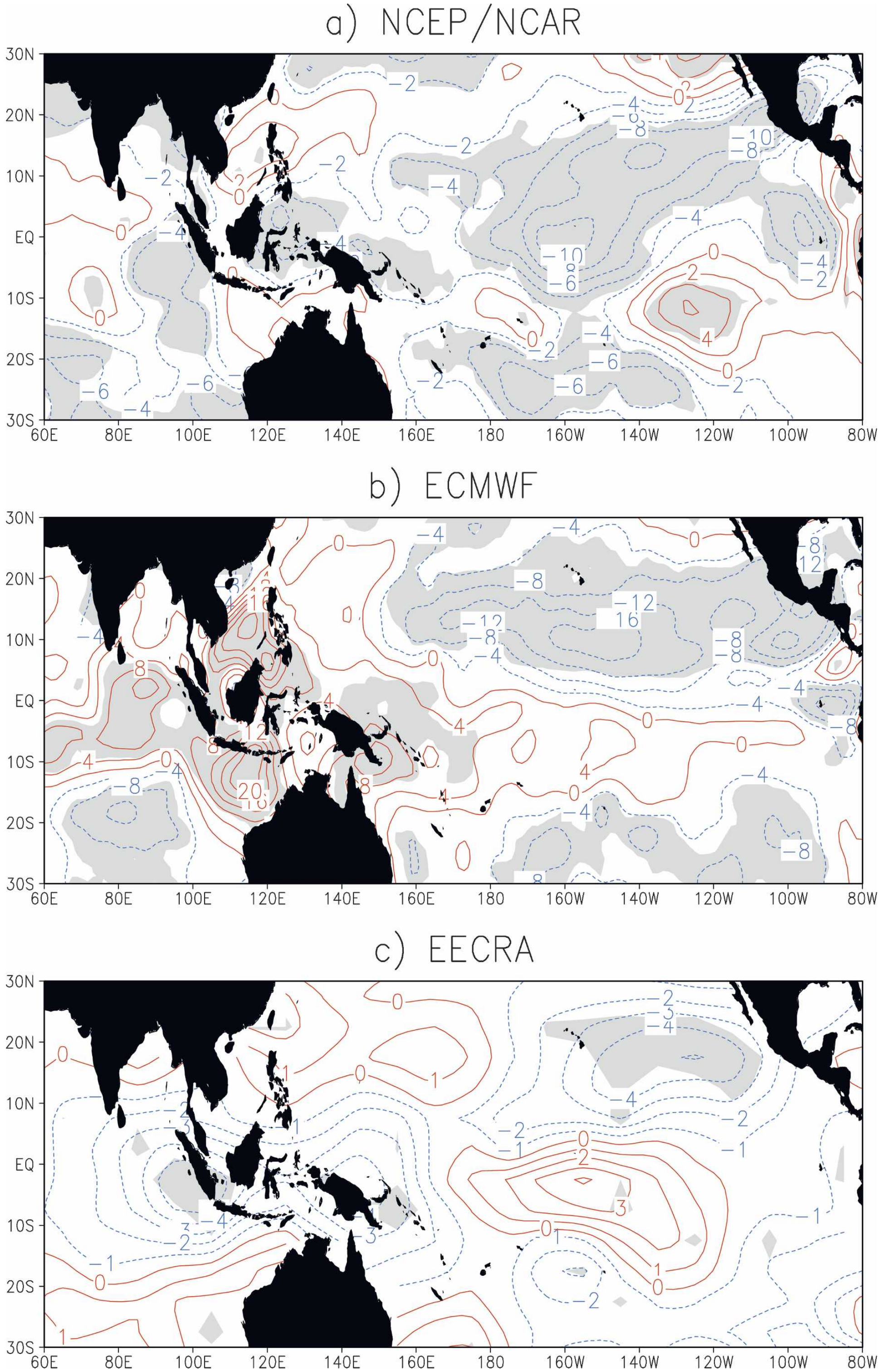

Fig. 4. The changes of upper-level cloud cover in the (a) NCEP–NCAR, (b) ECMWF, and (c) EECRA between epochs 1980–97 and 1958–75. Unit: %. Values greater than 95% significance are shaded in gray.

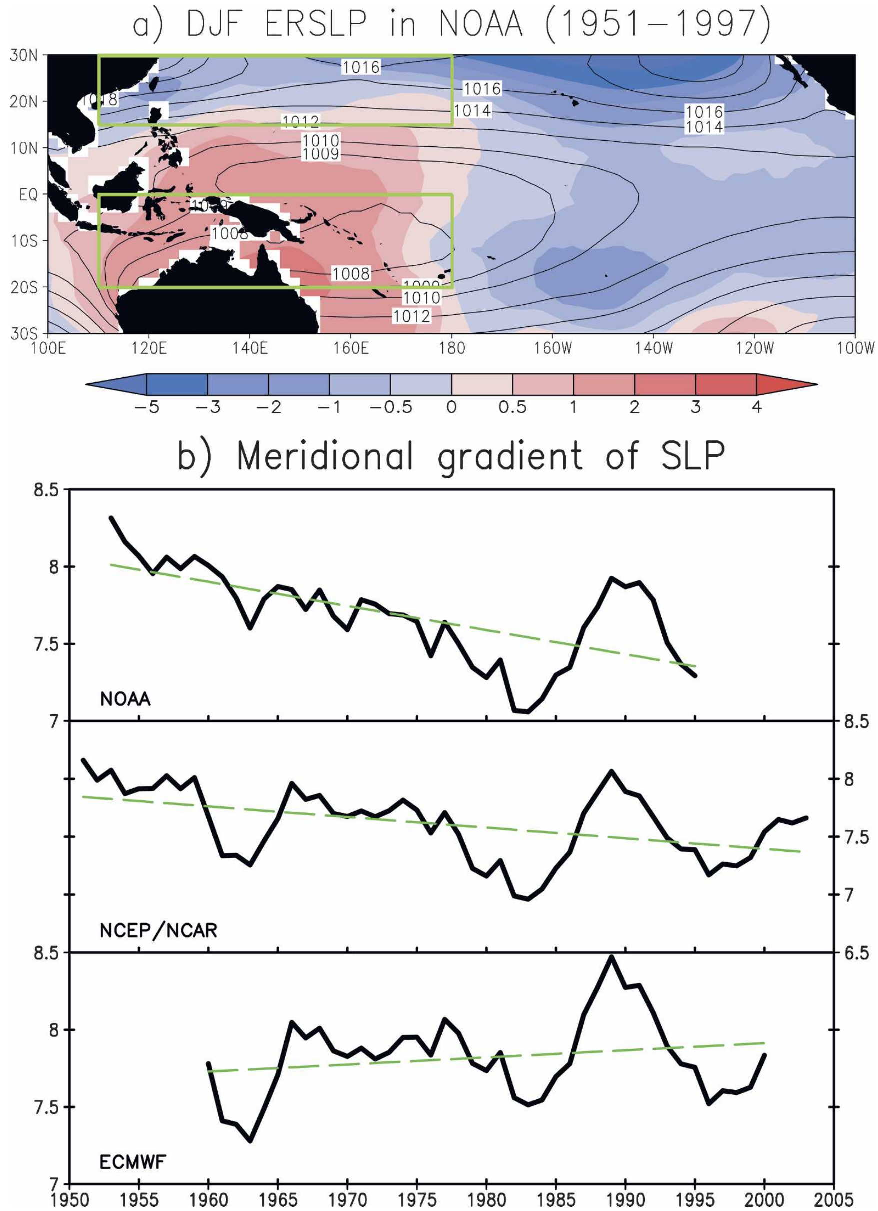

FIG. 5. (a) The climatology (contour) and linear trend (image) of the DJF ERSLP from NOAA; (b) the time series and linear trends of the SLP differences between the two boxes in the western subtropical and tropical Pacific regions in (a) from the NOAA ship-based observations, NCEP–NCAR, and ECMWF reanalyses. Plotted are 5-yr running averages. SPL unit of SLP: hPa. Linear trend unit: hPa (100 yr)$^{-1}$. Trends are -1.56 ± 0.55 hPa (100 yr)$^{-1}$ in NOAA, -0.92 ± 0.48 hPa (100 yr)$^{-1}$ in NCEP–NCAR, and 0.46 ± 0.67 hPa (100 yr)$^{-1}$ in ECMWF. The ranges define the 95% confidence intervals for the trends.

of the zonally averaged Hadley circulation in the two reanalyses, with the trend in the ECMWF reanalysis about 2–3 times stronger than that in the NCEP–NCAR reanalysis.

We have also demonstrated corroborative trends of the atmospheric transport of moist static energy out of the TWP, the longwave cloud forcing, and upper-level cloud cover with those of the vertical circulation in either the NCEP–NCAR or the ECMWF reanalysis. We reported decreasing trend in all these variables over the TWP in the NCEP–NCAR reanalysis, but increasing trends of all these variables in the ECMWF reanalysis. We then showed that the cloud trend from ship-based measurements is more consistent with the NCEP–

NCAR reanalysis than with the ECMWF reanalysis. Evaluation of the trend of the meridional gradient of sea level pressure over the TWP from independent data reached the same conclusion, all indicating weakening of the meridional flow of the Hadley circulation over the TWP.

While both the NCEP–NCAR and ECMWF reanalyses show intensification of the zonally averaged Hadley circulation in the boreal winter season in the last 50 years, it is still an open question whether this trend truly exists in the real atmosphere. Several previous studies cautioned on the quality of the reanalysis data in describing the humidity and water cycle (Trenberth and Guillemot 1998; Trenberth et al. 2001) and remarked on the possible impact on the trend of the introduction of satellite measurements around 1979 (Bengtsson et al. 2004; Kinter et al. 2004). The more serious challenges are, however, from the following two perspectives. First, direct analysis of winds from the historical rawinsonde archive does not support a statistically significant trend of the Hadley circulation (Mitas and Clement 2005). Second, temperature in the historical radiosondes may contain a systematic trend bias, owing to daytime warm bias of the radiosonde that has been gradually phased out in the last several decades (Sherwood et al. 2005). This temperature bias could have a direct impact on the Hadley circulation trend in the reanalyses through the data assimilation system (Mitas and Clement 2006). Nevertheless, these two arguments do not automatically rule out the strengthening of the zonally averaged Hadley circulation in the real atmosphere, because the rawinsonde stations are sparse in the Tropics and the quantitative impact of the temperature trend biases on the reanalyses has yet to be assessed. It is therefore necessary to investigate the Hadley circulation trend from different perspectives. The present study examines this problem by isolating a special feature in the two reanalyses in trying to understand the puzzle.

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