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Comparison of river basin hydrometeorology in ERA-Interim and ERA-40 reanalyses with observations

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[1] The changes between the ERA-40 and ERA-Interim in the seasonal cycle of primarily temperature, precipitation and evaporation, the surface radiation budget, and the cloud fields are evaluated over three river basins, the Amazon, Mississippi, and Mackenzie, for the period 1990–2001, using a variety of surface observational data sets and the International Satellite Cloud Climatology Project data. In ERA-Interim over the Amazon, the unrealistic interannual drift of precipitation has been reduced, and annual precipitation is largely unbiased, although the seasonal amplitude of precipitation remains too small. However, ERA-Interim has a large cold 2-m temperature bias. The clear-sky surface shortwave flux in ERA-Interim is lower than that in ERA-40 and closer to observations. Low cloud cover has increased dramatically in ERA-Interim, and total reflective cloud cover has a larger positive bias in comparison with observations. The ratio of the precipitation heating of the atmosphere to the surface shortwave cloud forcing is much higher in the observations than that in both reanalyses. The diurnal cycle of precipitation has improved somewhat with the removal of a spurious early morning peak. For the Mississippi and Mackenzie river basins, the spin-up of precipitation in 24-h forecasts has been greatly reduced. Temperature biases are small in both reanalyses, but summer precipitation and evaporation exceed observational estimates. For the Mississippi river basin, reflective cloud cover in ERA-Interim has increased in winter and decreased in summer compared with that in ERA-40, giving a closer fit to the observations in both seasons. For the Mackenzie river basin, similar reflective cloud changes in ERA-Interim improve the fit to the observations in summer but not in winter.

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1. Introduction

[2] The hydrometeorology in the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, known as ERA-40 [*Uppala et al.*, 2005] of three American river basins, the Amazon, Mississippi and Mackenzie Rivers, was compared against observations by *Betts et al.* [2003a, 2003b, 2005]. They found substantial drifts over the 45 years of the ERA-40 reanalysis, associated with changes in the observational data; and with difficulties in the assimilation of the satellite data in recent decades [*Andersson et al.*, 2005; *Simmons et al.*, 2004]. The spin-up of the dynamic fields and precipitation in the first 24 h was also substantial in midlatitudes. Over the Amazon, there was a spurious early morning peak in the diurnal cycle of precipitation [*Betts and Jakob*, 2002]; and long-term trends in the water cycle could not be determined, because of the drifts in column water vapor and precipitation [*Hagemann et al.*, 2005]. The biases in 2-m temperature on river basin scales in the 1990s were however small. A later paper [*Betts*, 2007] showed that ERA-40 has a low bias in cloud cover over the Mississippi in all seasons except summer. A new interim reanalysis (ERA-Interim, which we shall abbreviate as ERA-Int in Figures), with improved variational bias correction of the satellite observations, and using a more recent cycle of the ECMWF model, was initiated for the period 1989–present. There have been significant improvements in the global hydrological cycle in terms of water vapor, clouds and precipitation in ERA-Interim versus ERA-40, especially over the oceans [*Uppala et al.*, 2008]. This paper is a preliminary comparison, which presents some of the differences in the land-surface climate between the two reanalyses averaged over the Amazon, Mississippi and Mackenzie River basins for their overlap period.

1.1. Model Changes

[3] There are substantial differences between the models used for these two reanalyses. ERA-40, a 3D variational assimilation system, used model cycle 23R4, at a horizontal resolution of T_L-159 with 60 levels in the vertical. ERA-Interim is a 4D variational assimilation system, running model cycle 31R2 at a horizontal resolution of T_L-255 with the same 60 levels in the vertical. The extensive model changes between cycle 23R4 in June 2001 and cycle 31R2 in

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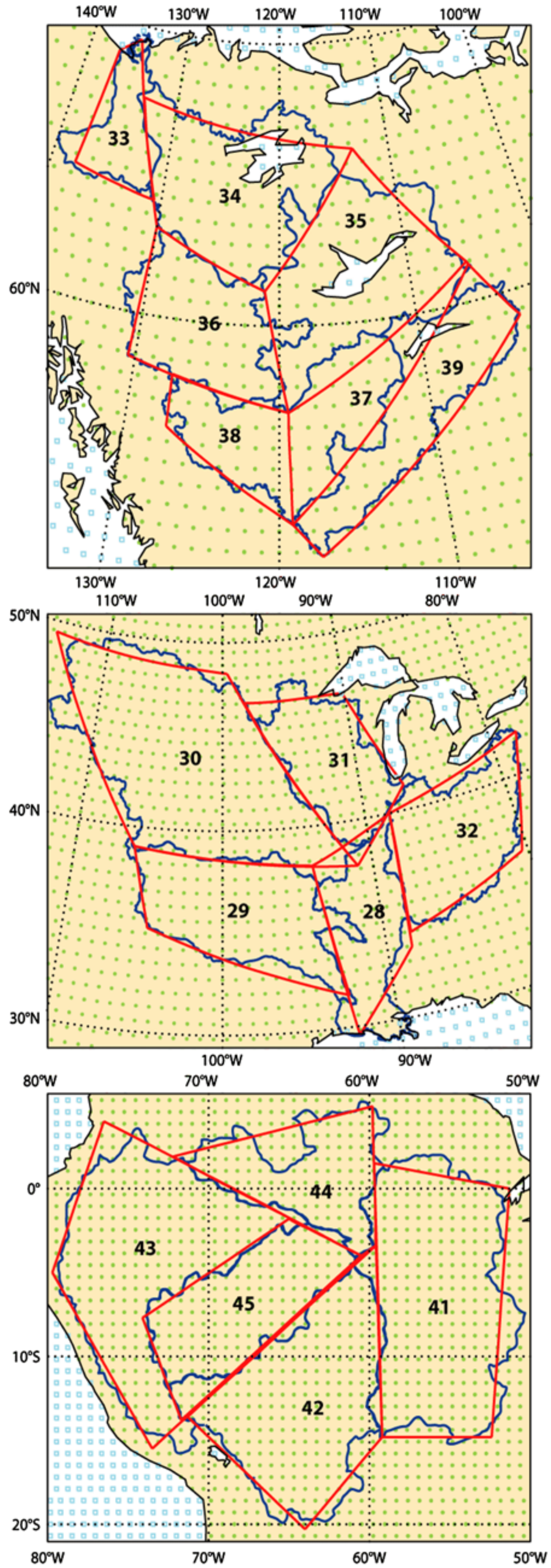

Figure 1. River basins selected from ERA-40 and ERA-Interim hourly archives.

December 2006 are listed at http://www.ecmwf.int/products/data/technical/model_id/index.html.

[4] The data assimilation changes include a completely revised humidity analysis, wavelet-based background error covariances and variational bias correction of radiance data, which results in a much reduced unrealistic drift in the hydrological cycle [*Simmons et al.*, 2006; *Uppala et al.*, 2008]. The model physics changes are substantial between the two reanalyses. *Tompkins et al.* [2004] give a detailed review of the model changes in moist physics from ERA-40 up to cycle 28R3. There are changes to the cloud, convection [*Bechtold et al.*, 2004] and boundary layer schemes [*Köhler*, 2005], a new treatment of orographic drag [*Beljaars et al.*, 2003], a new shortwave radiative transfer scheme and a new aerosol climatology [*Morcrette et al.*, 2007]. The tiled land-surface model, acronym TESSEL [*van den Hurk et al.*, 2000], has changed very little between ERA-40 and ERA-Interim, and specifically the snow and hydrology models have not been revised. As a result, ERA-Interim has the same early snow melt error as ERA-40, and no surface runoff, except over frozen ground; so these aspects of the surface hydrology will not be discussed here.

1.2. River Basin Archive

[5] The ECMWF reanalyses archive [*Kållberg et al.*, 2004] contains averages, at an hourly time frequency, over many river basins around the globe. Figure 1 shows the three river basins that we use in this paper: from top to bottom the Mackenzie, Mississippi and Amazon. Each is divided into subbasins, with the hydrological boundaries as shown, and each subbasin is approximated in the reanalyses by averages over all grid points within the numbered red quadrilaterals. These are labeled 33–39 for the Mackenzie, 28–32 for the Mississippi and 41–45 for the Amazon. The grid points shown are for ERA-Interim. We use two products. For the broad seasonal cycle comparisons, we use monthly averages over the three large basins, derived from the 6- to 30-h forecasts from the 00 UTC analysis. ERA-40 ended in August 2002, and ERA-Interim began in 1989, so the primary overlap period we have chosen for comparison is 1990–2001. From the twelve years, four months have substantial missing data in this ERA-Interim river basin archive and we have been omitted them from our analysis, but the impact of doing this is very small. To compare the diurnal cycles and some aspects of the daily cloud statistics, we shall use the subbasins for the year 1994. For this we have 36-h forecasts from both the 00 and 12 UTC analyses, so we can also compare the spin-up of precipitation in the first 36 h.

1.3. Observations

[6] This paper illustrates differences in the land-surface climate between the two reanalyses, and is focused on a few variables: temperature, humidity, precipitation and evaporation, radiation and cloud fields. We shall use for comparison primarily the same observations used in previous papers [*Betts et al.*, 2003a, 2003b, 2005], coming from various sources. For the Amazon, where data is sparse, the monthly and seasonal means come from *Jones and Moberg* [2003], *Dai et al.* [2004] and *Dai* [2006], and the period 1990–2001 is covered. For the Mississippi, our monthly data set comes from the hydrological analysis of *Maurer et al.*

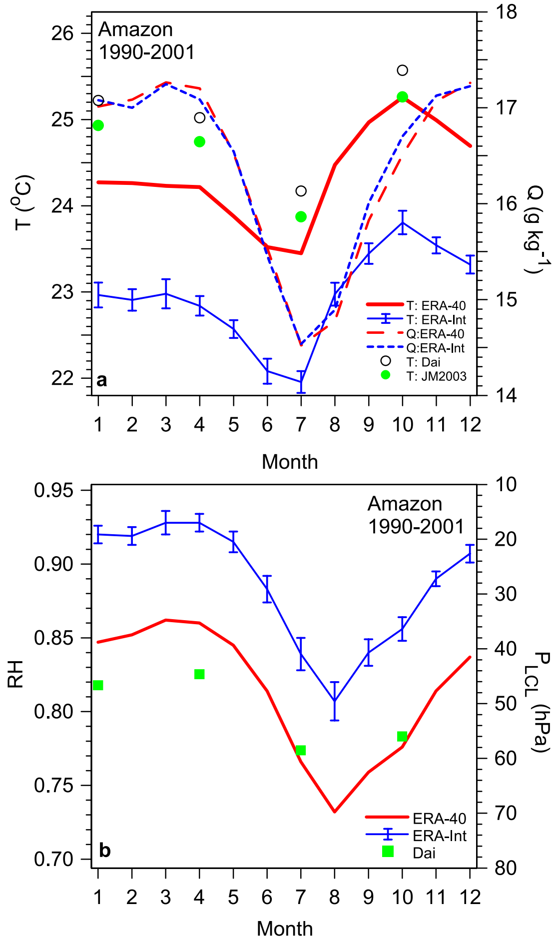

Figure 2. Mean annual cycle of (a) 2-m temperature and specific humidity and (b) 2-m relative humidity and pressure height to lifting condensation level.

[2002], and for these data we have only the years 1990–1999 for comparison. We shall also use a daily precipitation mean for 1994 from *Betts* [2007]. For the Mackenzie River, we use the observations processed [*Louie et al.*, 2002] for the Mackenzie GEWEX Study, MAGS [see *Woo et al.*, 2008], which cover the eight years, 1990–1997, for temperature and precipitation, and 1990–1996 for evaporation. For our analysis of the systematic changes in the land-surface climate between ERA-40 and ERA-Interim, the small differences in time period extent for the many different data sets is not significant.

[7] For the incoming shortwave radiation and an estimate of the shortwave cloud albedo, we use data from the International Satellite Cloud Climatology Project (ISCCP) [*Rossow and Zhang*, 1995; *Zhang et al.*, 1995, 2004, 2006, 2007], averaged over the same river basins in Figure 1. This time series, with a 3-hourly time resolution, covers the period July 1983 to December 2006; and we will use the 12 years, 1990–2001 for this study.

2. Annual Cycle for River Basins

2.1. Amazon Basin

[8] Figure 2a compares the basin mean annual cycle of 2-m temperature, T, and specific humidity, Q, from ERA-40 and ERA-Interim with a basin mean derived from surface observations. The error bars on ERA-Interim in Figures 2a and 2b are the standard deviations of the monthly mean differences between the two reanalyses. ERA-Interim is 1.4K cooler than ERA-40, which was already a little cooler than the two observational estimates shown (seasonal means from *Dai et al.* [2004], *Dai* [2006] and *Jones and Moberg* [2003], abbreviated JM2003). Specific humidity is little changed between the two reanalyses. Figure 2b shows the comparison of 2-m relative humidity, RH, and the corresponding pressure height of the lifting condensation level, P_{LCL} (with slight approximation). ERA-Interim has a surface RH that is about 7% higher throughout the year with a corresponding mean LCL, almost 20 hPa lower. This is a significant drop in mean cloud base. Again ERA-40 is closer to the observations than ERA-Interim.

[9] Figure 3 (upper curves) compares the annual cycle of precipitation (from the 6- to 30-h forecast from the 00 UTC analysis) with an observational estimate from *Dai et al.* [2004]. The standard deviations (only shown for the data) of the interannual variability of monthly precipitation of data and reanalyses are similar: about ±0.3 mm day^{-1} in the dry season and ±0.6 mm day^{-1} in the rainy season. The lower curves are the differences of ERA-Interim from ERA-40 and the observations. ERA-Interim has more precipitation in all seasons than ERA-40, which reduces the dry bias in the rainy season, but increases the model wet bias in the dry season. Evaporation, which has very little interannual variability (≈0.1 mm day^{-1}) is slightly lower in the dry season in ERA-Interim, and we shall see later in Figure 5c that this is associated with a drop in surface net radiation. With increased precipitation and reduced evaporation, ERA-Interim has increased deep runoff (not shown).

[10] Figure 4 shows the mean annual temperature and precipitation bias of ERA-40 and ERA-Interim from the observations. For temperature, the much larger cold bias in ERA-Interim is again visible, and the interannual variability of the bias is small. For precipitation, the bias in ERA-Interim is smaller than in ERA-40; which shows an unrealistic negative drift in the bias during these years, as noted in earlier work [*Betts et al.*, 2005]. It appears that the improved variational bias correction of the satellite obser-

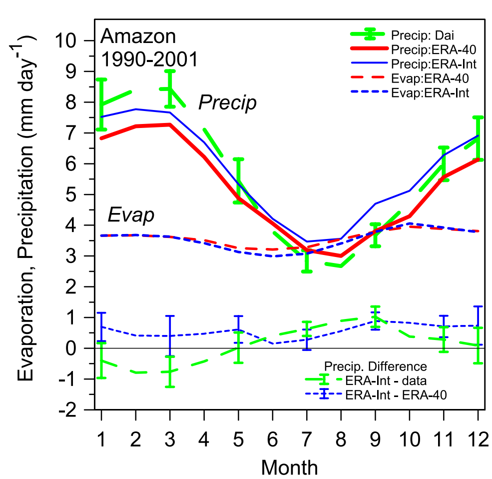

Figure 3. Annual cycle of precipitation and evaporation for the Amazon basin.

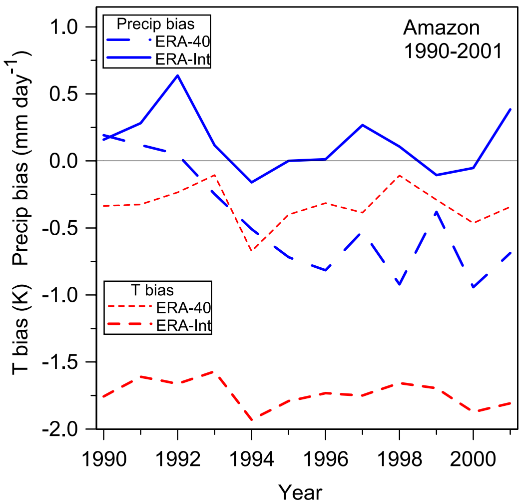

Figure 4. Mean annual bias of temperature and precipitation for the Amazon basin.

vations in ERA-Interim has successfully reduced the drift of precipitation over the Amazon during this period [*Uppala et al.*, 2008].

[11] Figure 5 shows several aspects of the radiation balance and cloud cover. Figure 5a shows that the clear-sky and all-sky downward shortwave fluxes, SW_{down}, are substantially lower in ERA-Interim than ERA-40, probably because of the differences in the aerosol climatology between ERA-40 and ERA-Interim [*Tompkins et al.*, 2005]. The atmospheric shortwave reflection is greater in ERA-Interim than ERA-40, and in the dry season (June to August) the downwelling shortwave clear-sky flux has decreased by 16 Wm^{-2}. The ISCCP calculation of the clear-sky flux [*Zhang et al.*, 2004] agrees with ERA-40 in the rainy season and ERA-Interim in the dry season. The standard deviations (not shown) of the interannual variability of the clear-sky fluxes are small for the ISCCP data ($\approx$2 Wm^{-2}), which uses a monthly and annually varying aerosol climatology [see *Zhang et al.*, 2004]; and tiny for the reanalyses ($\approx$0.5 Wm^{-2}), where the aerosol climatology has no interannual variability. Figure 5a also shows the surface all-sky SW_{down} estimate from the ISCCP data set [*Zhang et al.*, 2004]. In comparison with the ISCCP estimate, both the reanalyses have less incoming shortwave radiation at the

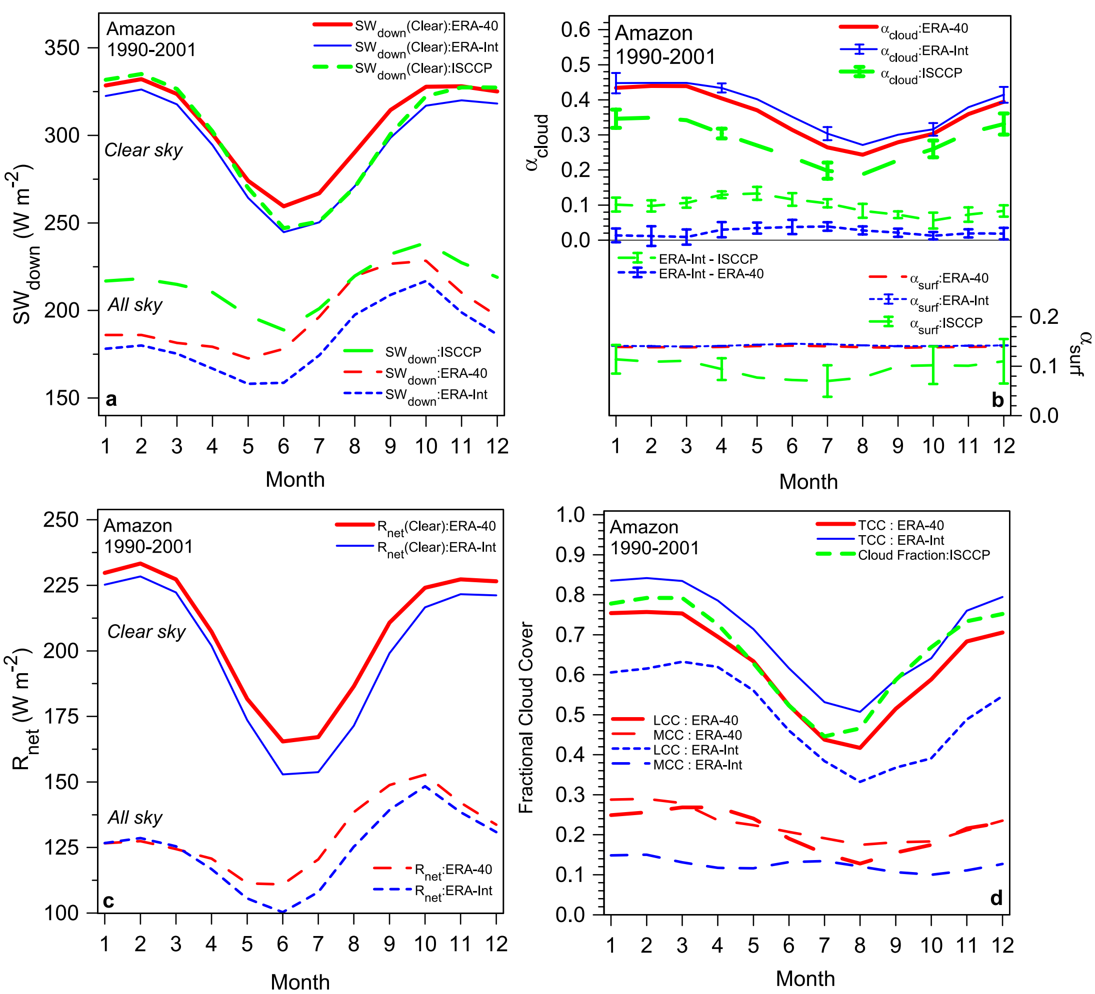

Figure 5. Mean annual cycle of (a) clear-sky and all-sky downward shortwave flux, (b) effective cloud albedo and surface albedo, (c) clear-sky and all-sky net radiation, and (d) fractional cloud cover.

surface during the November to May rainy season. ERA-40 agrees with ISCCP only during the dry season in August, when ERA-40 has a higher clear-sky flux, so it is clear there must be substantial differences in the shortwave cloud forcing.

[12] A useful nondimensional measure of the surface shortwave cloud forcing was proposed by *Betts and Viterbo* [2005] and *Betts* [2007]. We define an effective cloud albedo from the surface shortwave cloud forcing, SWCF, as

$$\alpha_{\mathrm{cloud}} = -\mathrm{SWCF}/\mathrm{SW}_{\mathrm{down}}(\mathrm{Clear}) \quad (1)$$

where

$$\mathrm{SWCF} = \mathrm{SW}_{\mathrm{down}} - \mathrm{SW}_{\mathrm{down}}(\mathrm{Clear}) \quad (2)$$

The clear-sky flux has a substantial seasonal variation with solar zenith angle, which is even larger at high latitudes (see later Figures 8 and 10). The scaling, given by (1), removes this seasonal dependence, and gives an effective cloud albedo, in the range $0 < \alpha_{\mathrm{cloud}} < 1$. Furthermore, the surface net shortwave can then be written in terms of two albedos

$$\mathrm{SW}_{\mathrm{net}} = \mathrm{SW}_{\mathrm{down}} - \mathrm{SW}_{\mathrm{up}} = (1 - \alpha_{\mathrm{surf}})(1 - \alpha_{\mathrm{cloud}})\mathrm{SW}_{\mathrm{down}}(\mathrm{Clear}) \quad (3)$$

where the surface albedo, α_{surf}, is computed as the ratio $\mathrm{SW}_{\mathrm{up}}/\mathrm{SW}_{\mathrm{down}}$. In the symmetric form given by (3), we can compare directly the relative importance of the cloud and the surface albedo on the surface SW budget.

[13] Figure 5b shows both these albedos for the ISCCP data and the reanalyses. Effective cloud albedo peaks in February in the rainy season and has a minimum in August in the dry season (upper curves). For the mean annual cycle, the bars show the interannual variability for the ISCCP and ERA-Interim data. The middle curves are the mean differences, ERA-Interim-ISCCP Data and ERA-Interim-ERA-40, with their standard deviations, which are small. ERA-Interim has about 1%–3% greater cloud albedo than ERA-40, and 6–13% greater cloud albedo than the ISCCP data. The difference between these two curves is the difference of ERA-40 from the ISCCP data. Since the ISCCP surface shortwave cloud forcing is quite tightly constrained by the observed top-of-the-atmosphere reflected shortwave flux, it is clear that both reanalyses have too much reflective cloud, and the cloud increase from ERA-40 to ERA-Interim has increased the high bias.

[14] The lower dashed curves show surface albedo, α_{surf}. These are similar in the reanalyses with little seasonal change and almost no interannual variability (<0.1%). In contrast, the mean ISCCP surface albedo estimate (recomputed from the monthly mean shortwave fluxes) falls from 11% in the rainy season to 7% in the dry season, a value that seems unrealistically low for the Amazon. This is the 12-year mean, and although all years show a similar seasonal cycle, the standard deviation of the ISCCP interannual variability shown is large. In fact there large differences between years. For example, for the years 1992–1994, the ISCCP surface albedo falls from 15% in the rainy season to 11% in the dry season, but for the years, 1996–2000, the annual range is from 9% in the wet season to only 5% in the dry season (not shown). This reduction of 6% in the estimate of surface albedo occurs in April 1995, when the coverage of the Amazon by the geostationary METEOSAT-3 is replaced by a GOES satellite; so the likely cause of this albedo change is the rather different spectral response of the radiometers on these two satellites (W. B. Rossow, personal communication, 2008). *Zhang et al.* [2007], in a detailed comparison, suggest that the uncertainty in surface broadband albedos derived from different global data sets is of order 7%. This is an area that needs more attention. Fortunately, the surface albedo errors have a negligible impact on the surface $\mathrm{SW}_{\mathrm{down}}$ (Clear), and the cloud optical thickness is less sensitive to the satellite change; so the effective cloud albedo shows no systematic change before and after 1995.

[15] Figure 5c shows the clear-sky and all-sky surface net radiation, $\mathrm{R}_{\mathrm{net}}$, for the two reanalyses. The reduction in the clear-sky net flux in ERA-Interim is dominated by the reduction in the clear-sky $\mathrm{SW}_{\mathrm{down}}$ flux seen in Figure 5a. The all-sky net flux is substantially modified by the larger LW cloud forcing in ERA-Interim (not shown), so that the $\mathrm{R}_{\mathrm{net}}$ in ERA-Interim, while lower than ERA-40 in the dry season, is barely affected in the rainy season. We will not compare with the ISCCP $\mathrm{R}_{\mathrm{net}}$ fluxes (not shown), because in addition to the uncertainties in the surface albedo, the surface $\mathrm{LW}_{\mathrm{net}}$ flux (not shown) has a significant bias. Over the Amazon the ISCCP estimate of the surface skin temperature is 5K lower than the air temperature in the rainy season, and this impacts the upward longwave flux. We believe that cloud contamination is the cause of this low skin temperature bias, because truly cloud-free scenes are rare over the Amazon. The ISCCP surface temperature bias over the Amazon is larger than the typical 2–3 K monthly, regional-mean uncertainty for surface skin temperature [*Zhang et al.*, 2007; *Tsuang et al.*, 2008].

[16] Figure 5d compares model low cloud cover, LCC, middle-level cloud cover, MCC, and total cloud cover, TCC. ERA-Interim has about 30% more low cloud cover, LCC, than ERA-40, but less middle and high cloud (not shown), giving a smaller reduction in total cloud cover. The model changes in the boundary layer and cloud schemes in ERA-Interim have increased low cloud cover, cooled the surface and lowered cloud base substantially, with a detrimental impact on the model land-surface climate over the Amazon. The ISCCP cloud fraction estimate has a similar seasonal cycle to TCC in the reanalyses. Comparing Figure 5b, which is a quantitative measure of SW cloud forcing and the total fractional area of cloud in 5d, suggests that the clouds in the reanalyses are on average optically thicker than the estimate from the ISCCP observations.

[17] Figure 6 shows that the coupling between reflective cloud and precipitation is quite different in observations and the two reanalyses. The mean annual cycle is represented by 6 points, each an average of 2 months: e.g., 1 denotes January, February, the peak of the wet season; while 4 is July, August, the peak of the dry season. Figure 6a shows that ISCCP α_{cloud} and observed precipitation have a tight relationship; one that is shifted to lower α_{cloud} in comparison with the reanalyses. ERA-Interim shows a broader spread of α_{cloud} over the annual cycle than ERA-40. Figure 6b shows that this comes from the radical change in the partition between low- and middle-level cloud cover in ERA-Interim;

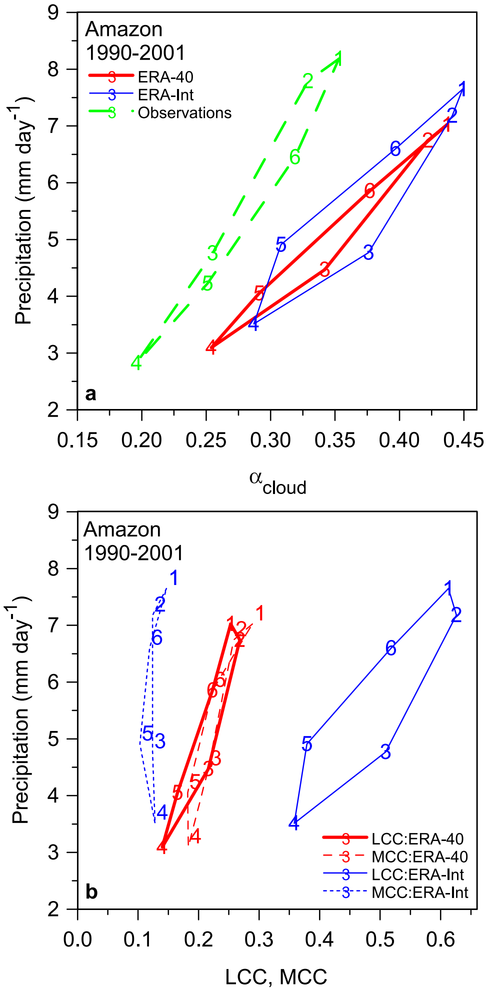

Figure 6. Mean annual cycle of relation between (a) cloud albedo and precipitation and between (b) low cloud and precipitation.

associated with the major revisions to the cloud, convection and boundary layer schemes (discussed above and in section 1.1). There is a decrease in MCC, and a large increase in LCC (seen in Figure 5d), which is greater during and after the rainy season (January to June) than in the dry season (July to October).

[18] Because α_{cloud} is directly related to SWCF through (1), Figure 6a shows that, over the Amazon, the ratio of the precipitation diabatic forcing to the surface SWCF is much larger in the observations that the reanalyses. Section 4, later, will show that the reverse is true over the Mississippi.

2.2. Mississippi Basin

[19] For the Mississippi basin, our comparison monthly data sets are the analysis of *Maurer et al.* [2002] for T, precipitation and evaporation from 1990–1999; and the ISCCP data for 1990–2001 for the surface shortwave fluxes and effective cloud albedo. Figure 7a (upper curves) shows the mean annual cycle, with the interannual variability shown for the Maurer data. The lower curves (right-hand scale) show the difference of ERA-Interim from the observations and from ERA-40, and the interannual variability of these differences. ERA-Interim is a little cooler than ERA-40, an improvement, but still warmer than the temperature data from the analysis of *Maurer et al.* [2002]. Note that the interannual variability of these differences for this midlatitude basin are much smaller than the mean differences and smaller than the interannual variability of temperature. Specific humidity is barely changed in ERA-Interim from ERA-40 (not shown).

[20] Figure 7b shows that ERA-Interim has more precipitation and evaporation than ERA-40, which was already greater than the Maurer data [*Betts et al.*, 2003b]. The ERA-Interim precipitation differences (lower curves) are largest in April and May and very small in July and August, so that the seasonal maximum of precipitation in the reanalyses is in May, rather than as observed in June. Both reanalyses have no seasonal cycle in leaf area index, and this is one source of error in the seasonal cycle of evaporation and precipitation [*van den Hurk et al.*, 2003]. For this midlatitude basin (unlike for the Amazon, Figure 3), the interannual variability of the differences are much smaller than the interannual variability of precipitation, shown for the Maurer data.

[21] Figures 8a and 8c show that the clear-sky SW_{down} and R_{net} fluxes are reduced in ERA-Interim, although not as much as over the Amazon, seen in the corresponding Figures 5a and 5c. In summer the ERA-Interim clear-sky

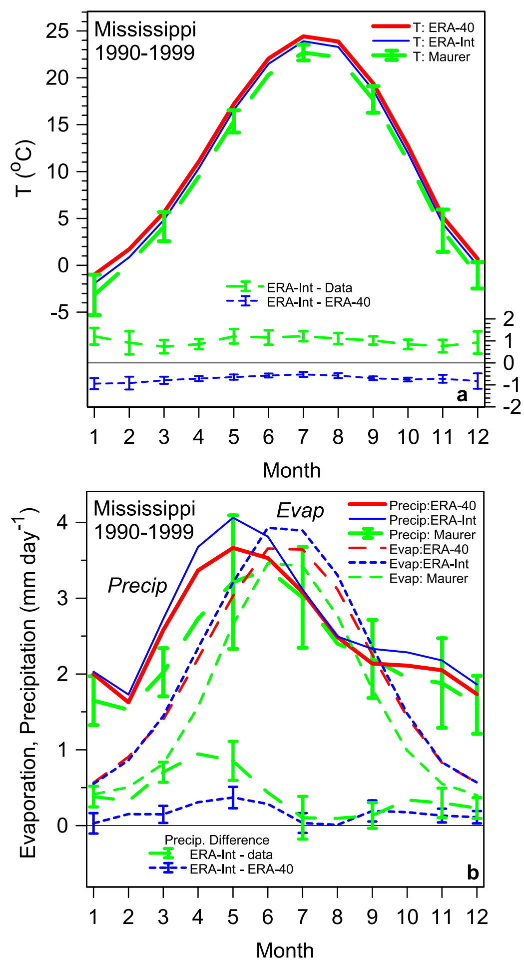

Figure 7. Mean annual cycle of (a) temperature (b) precipitation and evaporation for the Mississippi.

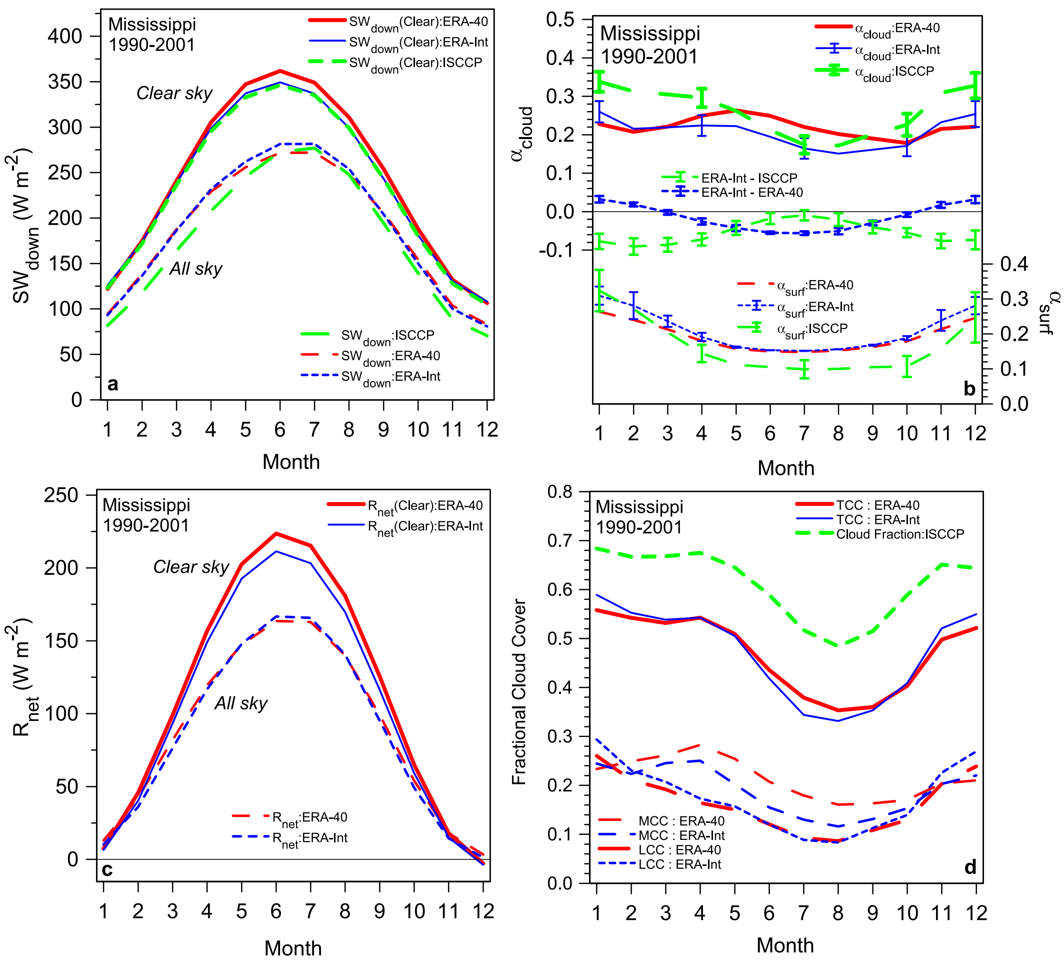

Figure 8. Same as Figure 5 for the Mississippi.

fluxes are very close to the ISCCP clear-sky flux. The surface all-sky SW_{down} estimate from the ISCCP data set is less than the reanalyses for most of the year (Figure 8a).

[22] Figure 8b shows the three derived effective cloud albedos. The upper curves again show the means and the interannual variability for the ISCCP and ERA-Interim data. The middle curves show the ERA-Interim differences and their interannual variability. The reduction of reflective cloud cover in ERA-Interim in summer has reduced the bias from the ISCCP data to zero in July; while the small increase in winter in ERA-Interim has also slightly reduced the bias from the data. Note that for this midlatitude basin, the variability of the difference between ERA-Interim and ERA-40 is very small (smaller than in Figure 5b for the Amazon), only half the variability of the ERA-Interim-ISCCP bias. However the reflective cloud decrease in summer in ERA-Interim is associated with an increase in precipitation (Figure 7b). This makes the ratio of diabatic precipitation forcing to surface SWCF, which was too high in ERA-40 [*Betts*, 2007], even higher in ERA-Interim (see section 4 later).

[23] The ISCCP estimate of mean surface albedo (Figure 8b, lower curves) is about 10% in summer, considerably less than the value used in the reanalyses (about 15%). However, again there is significant interannual variability (shown by the bars). As discussed in the previous section for the Amazon, the ISCCP estimate of surface albedo is 5% higher for the years 1992–1994 than for 1996–2000 (not shown). The bars on surface albedo for ERA-Interim show interannual variability which is negligible in summer, but about ±3% in winter because of variable snow cover.

[24] Figure 8c shows that all-sky R_{net} is unchanged between the reanalyses, as the reduction in cloud in ERA-Interim cancels the reduction in the clear-sky flux. The warm season reduction in cloud cover in ERA-Interim is primarily in middle level cloud cover (MCC), not in the low cloud cover (Figure 8d). These changes in cloud cover between the two reanalyses over the Mississippi are quite different from the Amazon, where ERA-Interim has a large increase in low cloud cover in all months. Again the comparison of the Figure 8b and Figure 8d suggests that the clouds in the reanalyses are optically thicker than those observed by ISCCP.

2.3. Mackenzie Basin

[25] For the Mackenzie basin, our comparison data sets were prepared as a monthly climatology for the MAGS experiment: for temperature and precipitation for the period 1950–1997, and for evaporation for the period 1953–1996 [see *Betts et al.*, 2003a]. The MAGS evaporation estimates [*Louie et al.*, 2002] are based on the method of *Morton* [1983]. We will show averages for 1990–1997. The MAGS

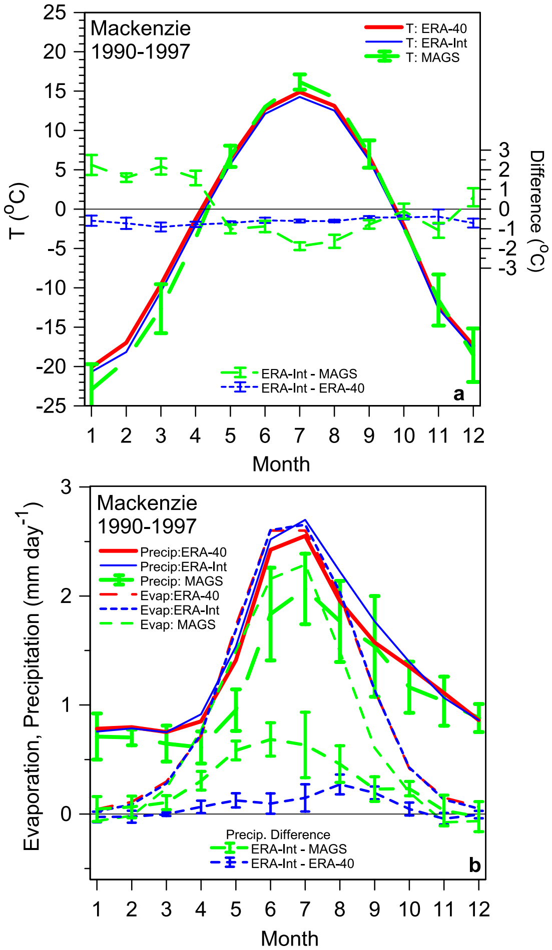

Figure 9. Same as Figure 7 for the Mackenzie.

evaporation estimate is missing for 1997, but the impact is negligible as the interannual variability of monthly evaporation is very small in both the reanalysis and the MAGS data, of order 0.1 mm Mo^{-1} in summer. Figure 9a (upper curves) shows the mean annual cycle, with the interannual variability shown for the MAGS data. The middle curves (right-hand scale) show the difference of ERA-Interim from the observations and from ERA-40, and the interannual variability of these differences, which are much smaller than the mean biases and the interannual variability of temperature. Compared to the MAGS data, both reanalyses are warm in winter and cool in summer. ERA-Interim is slightly cooler than ERA-40 in all seasons, which is an improvement in winter, but not in summer. Specific humidity is barely changed in ERA-Interim from ERA-40 (not shown).

[26] Figure 9b shows that precipitation is slightly higher in ERA-Interim than in ERA-40, but evaporation is unchanged. Both reanalyses have more precipitation and evaporation than the MAGS data, with the largest bias in summer (lower curves). Note that in the reanalyses, summer evaporation and precipitation almost exactly balance. These changes between the two reanalyses in temperature and precipitation for the Mackenzie are qualitatively similar to those for the Mississippi.

[27] For the surface shortwave fluxes and effective cloud albedo, we again compare with the ISCCP data for the period 1990–2001. Figures 10a and 10c show that ERA-Interim has reduced clear-sky SW_{down} and R_{net} in the warm season, although for this northern basin the reductions are smaller than we have seen for both the Amazon and Mississippi. However the surface all-sky SW_{down} in ERA-Interim is greater than in ERA-40 in summer. For both clear and all-sky SW_{down}, ERA-Interim is closer to the ISCCP observations in summer (Figure 10a).

[28] As with the Mississippi, ERA-Interim has less reflective cloud in summer and more in winter than ERA-40 (Figure 10b). This results in a rather small bias in effective cloud albedo in ERA-Interim, except in winter, when the impact on shortwave cloud forcing is however small. The ISCCP surface albedo has a much wider range, 8% in summer to 48% in winter, than the reanalyses, whose summer to winter range is only 14%–28%. The differences in all-sky R_{net} are tiny (Figure 10c) except in midwinter, when the longwave contributions dominate, giving a smaller surface cooling in ERA-Interim. As over the Mississippi, the fall in cloud cover in summer is primarily due to a reduction in middle-level cloud (Figure 10d).

3. Diurnal Cycle

[29] Figure 11 shows the differences in the mean diurnal cycle of precipitation between ERA-40 and ERA-Interim for the Madeira River (southwestern subbasin, 42, of the Amazon in Figure 1); and for the Athabasca River (southeastern basin, 33, of the Mackenzie River in Figure 1). The lower curves compare the daytime cloud albedo for the ISCCP observations and ERA-Interim (the hourly clear-sky shortwave fluxes needed to calculate effective cloud albedo were not included in the river basin archive for ERA-40). Over the Amazon, ERA-40 had a spurious sharp precipitation peak soon after sunrise [*Betts and Jakob*, 2002]. The convective parameterization scheme, which tested lifted surface parcels for instability, activated as soon as the nighttime stable boundary layer was eroded. In ERA-Interim, the scheme was changed to lift thicker layers [*Bechtold et al.*, 2004] and this delays the onset of convective precipitation by about 2 h. However this precipitation peak, just before local noon (1600 UTC) in the 0- to 12-h forecast (FX), and an hour earlier in the 12- to 24-h FX, is still too early in the diurnal cycle. We do not have diurnal rainfall measurements averaged over the Madeira basin, but from a radar-raingage network in Rondonia (within the basin), *Negri et al.* [2002] found maximum rainfall occurred at 1400 LT (1800 UTC) during the 1999 rainy season. For ERA-Interim, we see a spin-up of precipitation at night and a spin-down in the daytime in Figure 11a. Over the Amazon as a whole (not shown), ERA-40 has a very small spin-down of daily precipitation (less than 2% between the 0- to 12-h and 12- to 24-h FX), and in ERA-Interim this spin-down is even smaller (less than 1%). The lower curves show that ERA-Interim has systematically a greater cloud albedo than ISCCP during daylight, consistent with the monthly data for the whole Amazon basin shown in Figure 5b.

[30] Figure 11b for the Athabasca shows the differences in the diurnal cycle of precipitation between the reanalyses in the warm season (May to August) at high latitudes. ERA-40 has an evening precipitation peak, while ERA-Interim has a precipitation peak which is near local noon (1800 UTC).

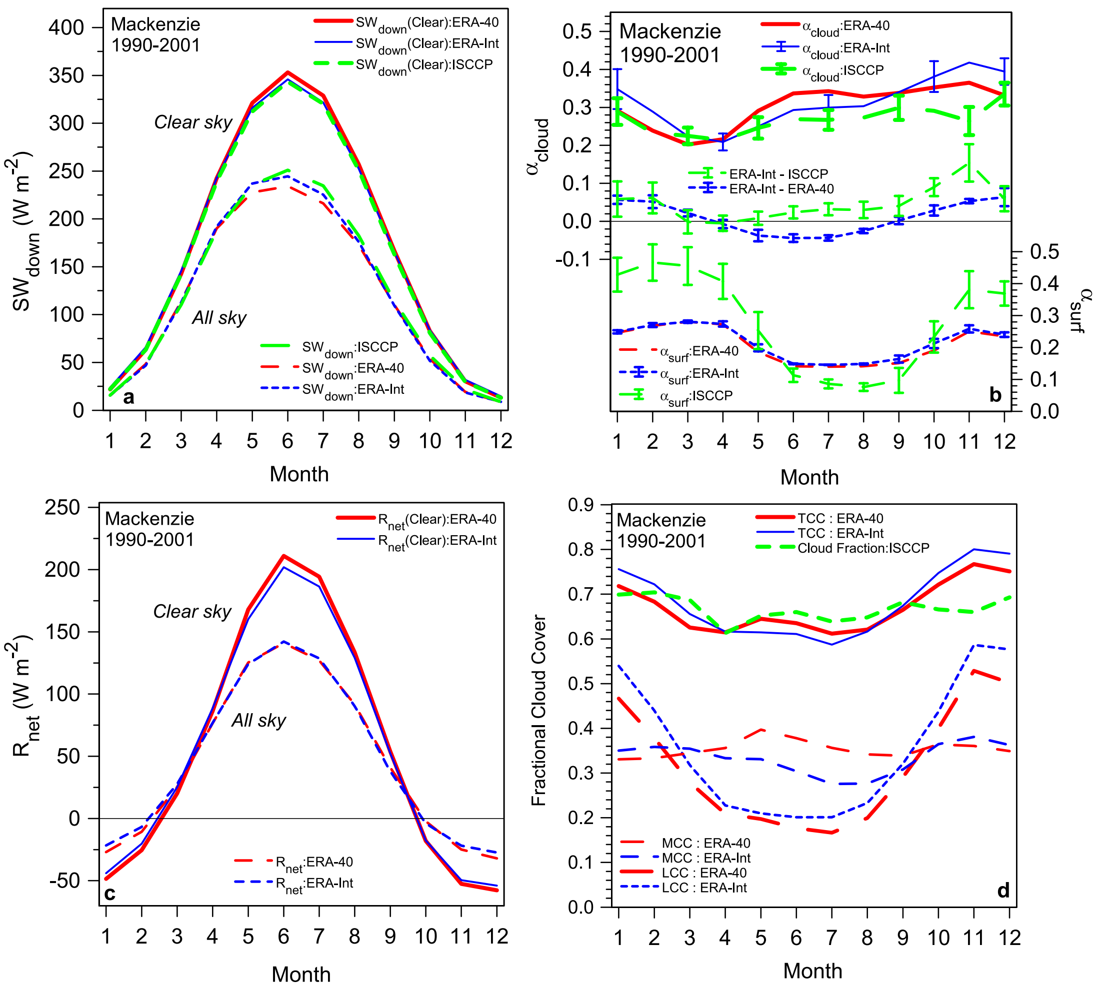

Figure 10. Same as Figure 8 for the Mackenzie.

ERA-40 has a significant spin-up of precipitation, about 15% between the 0- to 12-h FX and 12- to 24-h FX [see also *Betts et al.*, 2003a]. The corresponding spin-up of precipitation in ERA-Interim is much less, of order 5%, for both the Mackenzie (and the Mississippi, not shown). The improved humidity analysis and the 4D variational assimilation system in ERA-Interim are responsible for this improvement. For this subbasin of the Mackenzie, the lower curves in Figure 11b show that the bias in cloud cover between ERA-Interim and the ISCCP data is small.

4. Daily Cloud Statistics and Coupling of Precipitation to Cloud Albedo

[31] In Figure 12a the daily mean data for all 5 Amazon subbasins has been binned by effective cloud albedo. Each daily mean is computed from the 0- to 12-h FX from the two analysis times. The frequency distribution of days in ERA-40, ERA-Interim and the ISCCP data with a given cloud albedo are compared (left-hand scale). The differences shown in Figure 5 on the monthly timescale are reflected here. In comparison with ERA-40, the ISCCP data distribution is shifted substantially to lower cloud albedo values, while the distribution for ERA-Interim is shifted slightly to the right. Model precipitation, binned by model cloud albedo (right-hand scale), increases quasi-linearly with cloud albedo (and the SW cloud forcing), but the two reanalyses differ. The standard deviations in ERA-Interim are smaller, meaning that the coupling between precipitation and cloud albedo is tighter in ERA-Interim. The upward shift of the ERA-Interim precipitation curve (although within the standard deviations) means that the ratio of the precipitation heating of the atmosphere to the surface SWCF (see equation (1)) is slightly larger in ERA-Interim than ERA-40. We do not have daily precipitation data averaged over the Amazon for comparison, but it was clear from the monthly data in Figure 6a, that this important climate ratio is far larger in the observations than both reanalyses.

[32] Four basins of the Mississippi (Red-Arkansas, Missouri, Upper Mississippi and Ohio-Tennessee, which are basins 29–32 in Figure 1) are binned together for the warm season months, May–August, in Figure 12b. The shift toward lower cloud cover in ERA-Interim, seen in summer in Figure 8b, appears as a distribution shift with many more nearly cloud-free days in ERA-Interim, more than are seen in the ISCCP data. For the precipitation comparison on the right-hand scale, we have added daily precipitation, derived by *Betts* [2007] from the data sets of *Higgins et al.* [1996, 2000]. Although the standard deviations are large, it is clear

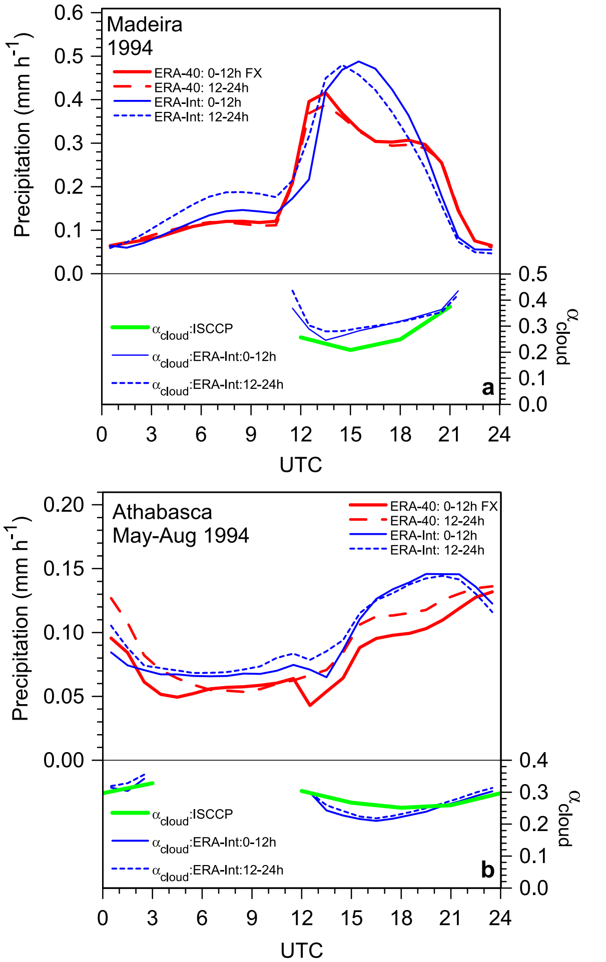

Figure 11. Diurnal cycle of precipitation for the 0- to 12-h and 12- to 24-h FX for ERA-40 and ERA-Interim for (a) Madeira and (b) Athabasca. Lower curves are diurnal cycle of daytime cloud albedo for the 0- to 12-h and 12- to 24-h FX for ERA-Interim and ISCCP observations.

that the two reanalyses and the observations have quite different relationships. For a given precipitation, reflective cloud cover in the reanalyses is too low compared to observations. As noted by Betts, this means that the ratio of the diabatic precipitation forcing to the surface SWCF is too high in ERA-40; and for $\alpha_{cloud} < 0.45$, it is still higher in ERA-Interim.

[33] Figure 12c is the corresponding distribution of cloud cover and precipitation for the 7 subbasins of the Mackenzie. The shift in the distributions from ERA-40 to ERA-Interim is similar to that seen for the Mississippi. However, the reduction in cloud cover in the warm season in ERA-Interim now gives a distribution that is close to the ISCCP distribution. We do not have daily precipitation for the Mackenzie for comparison.

5. Summary and Conclusions

[34] This paper has explored some of the differences between observations, ERA-40 and ERA-Interim over three large river basins, the Amazon, Mississippi and Mackenzie. For the Amazon, precipitation has increased in ERA-Interim, although the amplitude of the seasonal cycle of precipitation remains too low. The diurnal cycle of precipitation has improved in that the spurious peak after sunrise has gone in ERA-Interim, but the precipitation maximum a little before local noon is still too early in the diurnal cycle. The new humidity analysis appears to have removed the inter-

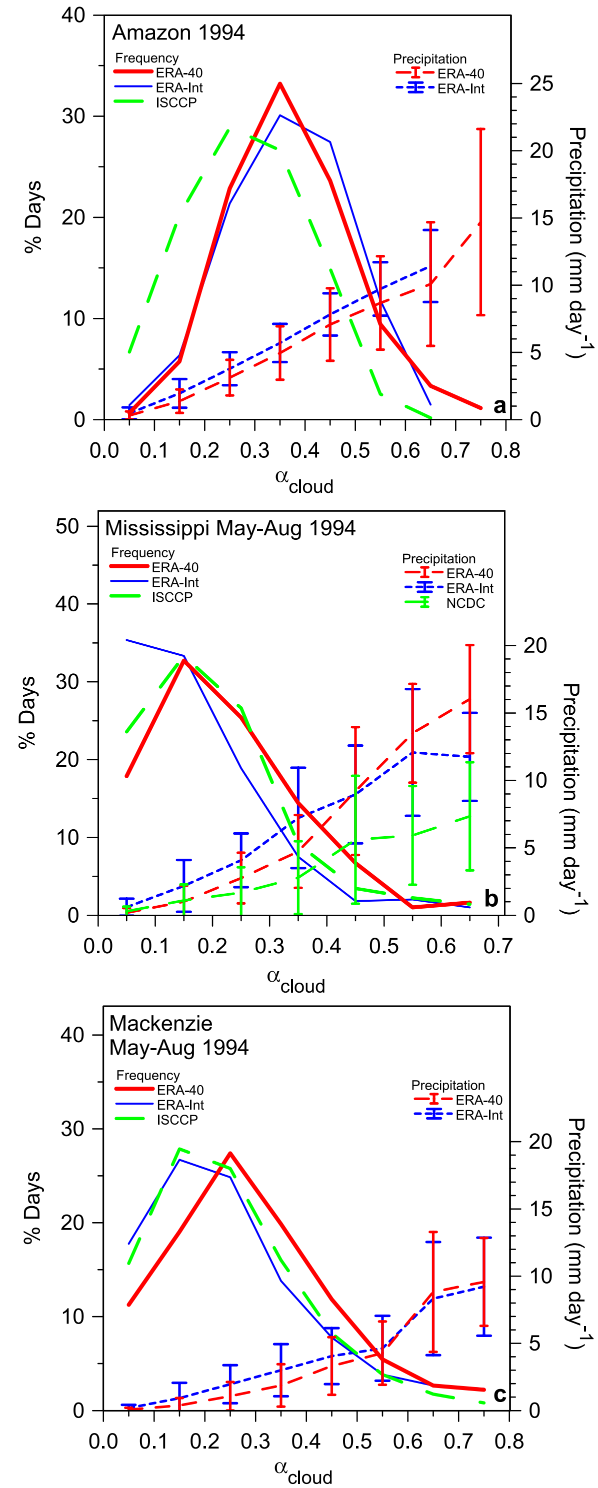

Figure 12. Percentage of days and precipitation as a function of cloud albedo for (a) Amazon, (b) Mississippi, and (c) Mackenzie.

annual drift in precipitation seen in ERA-40 over the Amazon. However changes to the boundary layer and cloud schemes have increased low cloud cover by about 30%; and the small cold bias in ERA-40 of −0.3 K over the Amazon has increased substantially in ERA-Interim to −1.7 K. Low cloud cover over land is difficult to simulate because of the following positive feedback: more LCC cools the surface, which lowers the lifting condensation level, which generally gives more cloud.

[35] The atmospheric shortwave reflection is also greater in ERA-Interim, and in the dry season (June to August), the downwelling shortwave clear-sky flux has decreased by 16 W m^{-2}, closer to the ISCCP observations than ERA-40. The effective cloud albedo is 1%–3% higher in ERA-Interim than ERA-40, and 6%–13% higher than values derived from the ISCCP downwelling shortwave fluxes during the annual cycle. As a result the ratio of the precipitation heating of the atmosphere to the surface shortwave cloud forcing is much higher in the observations than both reanalyses over the Amazon.

[36] For the Mississippi basin, both precipitation and evaporation exceeded the estimates of *Maurer et al.* [2002] in ERA-40, and both have increased further in ERA-Interim. The basin mean temperature is slightly lower in ERA-Interim, and a little closer to observations. Except in summer, ERA-40 has less reflective cloud than the ISCCP observations. In ERA-Interim, cloud cover has decreased in the warm season, so this reanalysis has less cloud than the observations in all months except July; and substantially more days with nearly clear skies from May to August. The ratio of the precipitation heating of the atmosphere to the surface shortwave cloud forcing is higher in ERA-40 than the observations in the warm season [*Betts*, 2007] and it is generally still higher in ERA-Interim.

[37] For the Mackenzie basin, the differences between the reanalyses are for the most part similar to those for the Mississippi basin. For temperature, ERA-Interim is a little cooler, which, compared with observations, gives a smaller warm bias in winter, but a slightly larger cool bias in summer. The differences in the clear-sky shortwave fluxes decrease systematically toward higher latitudes, and they are much smaller over the Mackenzie than in the tropics. For the Mackenzie, a reduction in summer cloud cover from ERA-40 gives a better fit to the ISCCP data.

[38] One systematic improvement in ERA-Interim in midlatitudes is that the spin-up of precipitation in the first 24 h of forecasts, which was 15% or more in ERA-40, has been reduced to about 5%. The improved humidity analysis and the 4D variational assimilation system in ERA-Interim are responsible for this improvement (as well as significant improvements in the global hydrological cycle in terms of water vapor, clouds and precipitation [*Uppala et al.*, 2008], which are not discussed here).

[39] We have compared the performance of two reanalyses over three large river basins in the Americas, evaluating primarily temperature, precipitation and shortwave radiation against observations. The changes between the reanalyses are quite different in tropics and midlatitudes. In some aspects, such as reduced spin-up of the precipitation in midlatitudes, reduced drift of precipitation in the tropics and some improvement in the diurnal cycle in the tropics, ERA-Interim is clearly superior. However; the increase of cloud cover and reduction of the surface shortwave flux over the Amazon is unrealistic and gives a substantial cold 2-m temperature bias.

[40] An analysis of long forecasts with each intermediate model cycle between ERA-40 and ERA-Interim shows that about two thirds of the low cloud increase resulted from cycle 25R3_en, which included cloud numerics and physics and convection upgrades, and about one third from cycle 29R1, which introduced a new stratocumulus scheme [*Köhler*, 2005]. The model development cycles of course have continued. Recent model cycles (later than cycle 31R2 used in ERA-Interim) have reduced Amazon cloud biases, giving a warmer and more realistic 2-m temperature; and the low cloud bias over North America has been halved in the currently operational cycle 33R1. For the Amazon, a reduction in cloud giving a warmer (by about 1–1.5 K) 2-m temperature was mainly achieved by the cycle 32R1 radiation package McRAD, involving the Monte Carlo independent column approximation (McICA) and a new solar radiation code [*Morcrette et al.*, 2008].

[41] ERA-Interim is expected to reach real time at the end of 2008 and will then continue as a climate data assimilation system. The ERA-Interim data is available at a resolution of 1.5deg on the ECMWF data services web page.

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